DIN
GMA

Quaderni di ricerca

Nona giornata di studio
Ettore Funaioli

17 luglio 2015

A cura di
Umberto Meneghetti e Vincenzo Parenti Castelli

SOCIETÀ EDITRICE ESCULAPIO

AlmaDL
University of Bologna Digital Library

Quaderni del **DIN – GMA**

Atti di giornate di studio – 9

A cura di:
Umberto Meneghetti e Vincenzo Parenti Castelli

Coordinatore di redazione:
Alessandro Zanarini

DIN
Dipartimento di Ingegneria Industriale
http://www.ingegneriaindustriale.unibo.it

GMA
Gruppo di Meccanica Applicata
http://wpage.unina.it/dellaval/GMA/GMA_homeold.htm

Accademia delle Scienze dell'Istituto di Bologna
http://www.accademiascienzebologna.it/AccademiaScienze/default.htm

Nona giornata di studio Ettore Funaioli

17 luglio 2015

A cura di:
Umberto Meneghetti e Vincenzo Parenti Castelli

Nona giornata di studio Ettore Funaioli – 17 luglio 2015 / A cura di Umberto Meneghetti e Vincenzo Parenti Castelli
Bologna: 2016 – pp. 232; 17 cm

ISBN 978-88-7488-965-5

Versione elettronica disponibile alla pagina
http://amsacta.unibo.it/5237/

Stampa a richiesta eseguita da:

SOCIETÀ EDITRICE ESCULAPIO

40131 Bologna – Via U. Terracini 30 – Tel. 051- 6340113 – Fax 051- 6341136
www.editrice-esculapio.com

INDICE

Prefazione

U. Meneghetti
Analisi dinamica di un maglio antico 1

I. Gnilitskyi, L. Orazi
Laser nanotexturing e sue applicazioni industriali 13

C. Bandini, B. Reggiani, L. Donati, L. Tomesani
Sviluppo di user routines con Qform per la predizione della microstruttura delle leghe di alluminio durante processi di estrusione 21

E. Dragoni
Optimal design of tapered roller bearings for maximum rating life under combined loads 29

A. Strozzi, A. Baldini, M. Giacopini, E. Bertocchi, S. Mantovani
Bielle automobilistiche: un repertorio di collassi 51

G. Boschi, E. Mucchi, G. Dalpiaz, M. Luczak
On the use of experimental modal analysis for damage detection of a tripod supporting structure for an offshore wind turbine 59

A. Sanchez Sanchez, I. Esdras Martinez Garcia, S. Barbati, E. Mucchi
Reliability and failure mode analysis of a 10MW offshore wind turbine 69

A. Spaggiari, G. Scirè Mammano, E. Dragoni
Progettazione di molle ad anelli superelastici ad elevata capacità dissipativa 83

R. Carrabotta , A. Martini, M. Troncossi, A. Rivola
Optimized gravity compensation solutions for the *Antrop* palletizing manipulator 99

M. Conconi, V. Parenti Castelli
From articular surfaces to patient specific joint motion 105

M. Cocconcelli, N. Sancisi, C. Mazzotti, R. Rubini, V. Parenti Castelli
Rilievo del movimento del dito indice: confronto fra stereofotogrammetria e accelerometri 123

G. Bellavita, M. Cocconcelli, D. Castagnetti, R. Rubini
Sviluppo e validazione di un modello numerico per l'ottimizzazione di un'ortesi per arto inferiore 135

D. Castagnetti, F. Dallari
Un convertitore di energia da vibrazioni basato su molle coniche: progettazione e convalida sperimentale 147

M. Peruzzini, T. Campioli, A.O. Andrisano, M. Pellicciari
Design to cost of automatic machines: an industrial case study 171

A.O. Andrisano, F. Pellicano, M. Strozzi
Nonlinear dynamics of carbon nanotubes 183

A.O. Andrisano, F. Gherardini, C. Renzi, E. Bonazzi, F. Leali
Applicazione della norma ISO 16792:2006 per la specificazione geometrica di prodotto 3D in ambito automotive 195

A.O. Andrisano, E. Oliva, M. Gadaleta, M. Pellicciari, G. Berselli
Metodologia per la determinazione delle perdite energetiche in servoazionamenti per macchine automatiche 219

Indice degli autori 231

RELIABILITY AND FAILURE MODE ANALYSIS OF A 10MW OFFSHORE WIND TURBINE

Alejandro Sanchez Sanchez
University of Ferrara, Italy
E-mail: alejandro.sanchez@relexsoftware.it

Itamar Esdras Martinez Garcia
Relex Italia Srl.,
Rome, Italy
E-mail: itamar.martinez@relexsoftware.it

Stefano Barbati
Relex Italia Srl.,
Rome, Italy
E-mail: s.barbati@relexsoftware.it

Emiliano Mucchi
Department of Mechanical Engineering,
University of Ferrara, Italy
E-mail: mccmln@unife.it

***Abstract**. In this paper, investigations regarding the reliability on a typical 10MW offshore wind turbine have been carried out; in particular, different analysis methods and failure modes are considered. Moreover, the effect of propagation of each functional failure through the wind turbine is accounted. It has to be underlined that an onshore 5MW wind turbine data-base has been used; thus in order to convert the data from a 5MW onshore wind turbine into 10 MW offshore wind turbine, a proper conversion factor has been used. The reliability and availability of the whole offshore wind turbine have been calculated through the Reliability Prediction and Reliability Block Diagram (RBD). In addition, a failure mode analysis is done through FMECA, in order to pointed out the most important terms in a risk priority order. The reliability analysis has been developed using PTC Windchill Quality Solution tool.*

***Keywords**: reliability, failure mode, effects and criticality analysis (FMECA), offshore wind turbine, maintenance.*

Acronyms
FMECA: Failure Mode, Effects and Criticality Analysis
MTBF: Mean Time Between Failure
OWT: Off-Shore Wind Turbine
PCNR: Percentage of Component Nominal Rating
RPN: Risk Priority Number

1. INTRODUCTION

In the last decade, the installed capacity of offshore wind turbines is higher than other renewable energy sources. Offshore wind farm developments have a short history of less than 30 years. On this time, offshore wind turbines have been getting bigger and higher rated power. Therefore, wind power is achieving 10MW from 450kW when the first offshore wind turbine was built on the coast of Denmark in 1991. During the first six months of 2015, 15 offshore wind farms have been installed with a combined capacity of 2,342.9 MW. Hence, the energy increase induces new researches for improving efficiency in terms of performances and costs.

One of the targets of the European Commission is to increase the production of the renewable energy generated by the offshore wind turbine to 40GW by 2020 and 65GW by 2030, allowing wind energy to make up more than 25% of electricity generation in Europe. The relevance of this topic has been well understood by the European Commission, which had promoted in 2008 a research projects named “Reliawind” [1-5], based on a reliability study for an onshore wind turbine. In 2014, when the “Marewint” [6] project has been approved focus on offshore wind energy, a step forward has been moved in order to achieve the forecast. A wind power system located in offshore shows higher failure rate, lower reliability and availability and higher operation and maintenance (O&M) costs due to the high complexity of the operation [7-14].

According to the considerations above, reliability and availability evaluations allow to optimize the design and the life cycle management from a cost/efficiency point of view. In addition, a proper maintenance plan is indispensable to predict the energy loss, minimizing failures in order to improve reliability and making offshore wind energy profitable.

In order to get this aim, along this paper is explained the Reliability and the FMECA that has been done for an Off-Shore Wind Turbine. Relex Italia Srl. has available a large onshore database which has been used (over a thousand components). Published reliability offshore databases are not available since wind turbine manufacturers do not show information regarding their turbines. A literature review about free database has been done. Moreover, a conversion factor is applied to this database. The FMECA is used to identify reduce system failures and nowadays put into practice for OWT.

2. METHOD

Reliability Prediction

Reliability prediction is a quantitative analysis technique that has been used to predict the failure rate (λ) using an established model with defined operating conditions. The goal of reliability prediction is to predict the rate at which components and systems fail. The general formulation for the reliability through time is shown in Eqn. (1):

$$R(t) = e^{-\int_0^t \lambda(x)dx} \tag{1}$$

Where *R* is the reliability and $\boldsymbol{\lambda}$ is the failure rate (number of failures per million of hours) and *t* is the time. In addition, for a deeper explanation, see [4].

Component’s lifetime is often described by three phases. During the first phase, the failure rate decreases down early with time and failures are attributable to manufacturing and quality problems. After that in the second phase, failure rate $\lambda(t)$ is approximately constant (chance failures). The failure rate in the third phase increases with time due to aging, wear out, fatigue, etc. Hence, if it is consider that the failure rate is constant along time (second phase):

$$\lambda(t) = \lambda \tag{2}$$

Thus, the reliability function Eqn. (1) can be expressed as Eqn. (3).

$$R(t) = e^{-\lambda t} \tag{3}$$

The reliability exponential function (Eqn. (3)) has been selected as the way to describe the component's reliability.

Reliability Block Diagram (RBD)

Reliability Block Diagram is a visual representation of the portions of the system through blocks (representing items) linked together (Fig. (1)) and shows how they are connected logically to fulfill the system requirements.

Since reliability predictions assume that all components in a system are in series, they cannot be used to analyze a system with redundant components. RBDs are used to evaluate the reliability of systems that are complex in their configurations. RBDs also provide an efficient and effective way to compare various configurations to find the best overall system design.

The goal of the Reliability Block Diagram is the determination of reliability and maintainability metrics of a complete system such as Reliability, Availability, Failure rate and MTTR (mean time to repair).

The elements which are necessary for the required function are so connected in series, while elements which can fail with no effect on the required function are connected with redundancies. There are three types of redundancies: parallel, load sharing and standby.

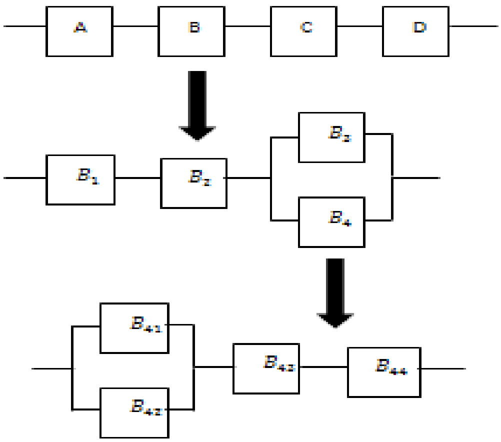

Figure 1. Development of RBD within a system.

The Availability is the probability that the system is operating satisfactorily at any point in time when used under stated conditions, where the time considered includes operating time, active repair time, administrative time and logistic time. Through this report is calculated the inherent availability, in which the proportion of the total time that the item is available is the steady-state availability.

FMECA

FMECA is one of the most used analysis in the engineering field for developing designs, processes and services. Developing a FMECA, potential failure modes are analysed to determine their effects all along the system, classified according to their severity (FMEA) and probability of occurrence (FMECA).

The main target of the analysis is to discover the weakest parts of the offshore wind turbine, understanding their failure modes, the effects associated and then improve their availability introducing possible redundancies or design changes and updating the preventive maintenance. Other objectives that are possible to achieve through this analysis are:

- Anticipate the most important problems.
- Prevent failures from occurring.
- Minimize the failure consequences as cost effectively as possible.
- Give technical information to maintenance personnel about failures that might come out during system life.
- Compare results with previous maintenance reports and update again the analysis.
- Provide necessary information to create a cost/benefit analysis.
- Provide those modes that need preventive maintenance in a risk priority order.

FMECA is a bottom up approach analysis by which the system design and performance are studied. With this analysis the potential failure modes are defined, as well as the occurrence and severity of each failure effect associated to them.

The analysis can be done in two ways: component level (referred as component FMEA) or functional level (referred as functional FMEA). A component FMECA has been chosen based on the tasks 101 and 102 of the military standard “MIL-STD-1629A” [15].

FMECA can be initiated at any system level but due to the complexity, huge amount of components and the lack of data, a proper level of indenture of our Off-Shore Wind Turbine has been chosen.

The FMECA has been performed starting from the line replaceable unit (LRU) level. A bottom-up approach is used, noting the failure modes of the lowest level items of the system and then moving up the hierarchy and noting the effect of the failure to the end item (OWT). In Fig. (2), it can be seen the distribution mentioned before.

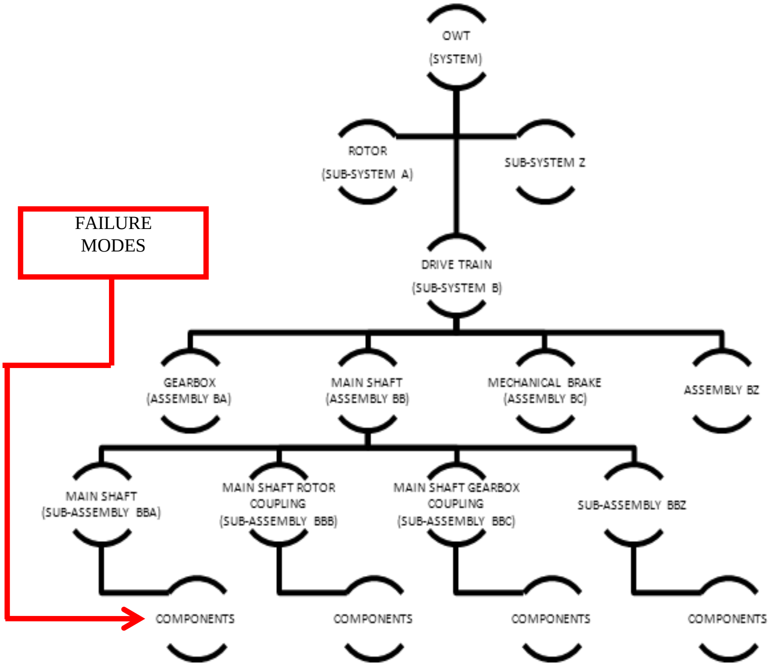

Figure 2. Example of the hierarchy structure used to perform the FMECA.

The criticality analysis completes the FMEA using two parameters: occurrence and severity. With these parameters the risky parts of the systems are calculated.

The calculation of criticality numbers gives the possibility to define the criticality of each item and its associated failure modes by a quantitative point of view, even though this method is only used when enough data is available.

The mode criticality number "C_m" (number due to one of its failure modes under a particular severity classification) and the item criticality number "C_r" (Number of system failures of a specific type expected due to the item's failure modes), are calculated according to "MIL-HDBK-1629" [15].

These numbers are defined in the Eqn. (4) and Eqn. (5).

$$C_m = \alpha * \beta * \lambda_p * t \quad (4)$$

$$C_r = \sum_n^j (C_m)_n \text{ for } n = 1,2 \ldots j \quad (5)$$

Where:

C_r= Criticality number for the item

C_m= Criticality number for a failure mode under a particular severity classification.

α= Failure mode ratio. The probability, expressed as a decimal fraction, that the part or item will fail in the identified mode.

λ_p= Part failure rate.

β= Conditional probability of mission loss given that the failure mode has occurred. Values are classified between 0 and 1 depending on the effects. If there is not effect, β value is assumed as 0. Possible loss and probable loss are corresponding with a β value from 0.1 to 0 and 1 to 0.1 respectively. If the effect causes actual loss, β is equal to 1.

t= Mission time.

n= The failure modes in the items that fall under a particular severity classification.

j= Last failure mode in the item under the severity classification.

The other method is qualitative and allows representing the criticality results using a Risk Matrix. The matrix is constructed by inserting the total number of OWT failure modes in the matrix areas representing the severity classification and the frequency level assigned. The frequency is calculated as the ratio between failure mode probability of occurrence in a certain time interval and the overall system probability of occurrence in the same time interval, which is defined as:

$$f = \frac{\lambda_p * \alpha * t}{\lambda_s * t} = \frac{\lambda_p * \alpha}{\lambda_s} \tag{6}$$

where f is the frequency and λ_S the Total system failure rate.

The results of the analysis for the OWT are summarized in the Criticality Matrix in which three risk areas can be identified, Green area (Low occurrence and low severity), Red area (High occurrence and high severity) and Yellow area (Medium risk)[15].

The matrix provides a way to identify and compare failure modes each other respect to their associated severity and frequency [15]. Severity is classified into four ranks depending on the impact of the failure mode. Each of them is associated with a RPN analysis value. Frequency degrees assigned to failure modes are based on five ranks which evaluate the frequency of the failure mode.

The process used to perform the FMECA is based on ‘bottom up’ technique. The procedure for component FMECA is the following:

1) Construct a OWT FMECA system tree;
2) Identify all potential items;
3) Evaluate failure modes (from mode library) of each component;
4) Evaluate the local effect for each component failure mode;
5) Roll-up all local effects at higher level (at higher level, the rolled-up effect becomes the failure mode at that level);
6) Repeat step 5 until system level;
7) For each end effect at system level identify the detection, severity and occurrence;
8) Build down the FMECA by transferring all the end system effects and severity to sub-system, assembly and component level.

3. ANALYSIS OF THE RESULTS APPLIED TO THE OWT

The theory explained has been applied to the OWT which has pointed out three different results. A complete analysis will be shown starting from reliability prediction, going on with the RBD which predicts parameters of reliability/availability applied to offshore environment.

Reliability Prediction Results

Since published reliability data of offshore wind farms are extremely rare, a database of an onshore wind turbine of 5MW has been used. Thus, it has been necessary to convert the failure rate data from onshore into offshore. Before starting the reliability prediction, a literature review regarding published data sources (Windstats, WMEP, LWP and Swedish Wind) has been done. The Reliawind data-base has been chosen as most suitable for this research [1-5].

Since this turbine operates in different environments and it has different power from the Reliawind turbine, a conversion factor has been introduced in order to convert the database from 5MW onshore wind turbine into 10 MW offshore wind turbine.

This conversion factor has been derived, according with the literature [16, 17], as a combination of two parameters. First parameter "K_1", takes into consideration the environmental stress factor and it is defined as the effect of environmental condition (e.g. weather and humidity condition) on the OWT. Parameter "K_2" is based on the power rating stress factor that depends on the operating power ranges of the wind turbine.

Eqn. (7) is used to describe how to calculate the failure rate for the offshore wind turbine.

$$\lambda_{offshore} = \lambda_{onshore} \cdot (K_{1\,offshore} \cdot K_{2\,offshore}) \tag{7}$$

There are different environmental conditions which have an associated value of the environment stress. In our case K_1 is supposed as Naval Sheltered for items within the nacelle. Naval exposed is chosen for the items that are fully exposed to marine environment. $\mathrm{K}_{1\,\text{onshore}}$ factor is supposed to be $\mathrm{K}_{1\,\text{onshore}}$ equal to 1 and $\mathrm{K}_{1\,\text{offshore}}$ has been supposed to be between naval sheltered and exposed ($1{,}5 \leq \mathrm{K}_{1\,\text{offshore}} \leq 2$).

The other parameter K_2 is obtained taking into consideration the windiness of the wind farm site. The windiness of the OWT is measured by the capacity factor of the wind turbine. This average capacity factor is assumed to be 25% for onshore, 35% for near-offshore and 45% for far-offshore [18-22]. The wind farm is considered to be allocated on near-offshore. In Fig. (3) is plotted the exponential relationship between the power stress factor and the component nominal rating. The exponential curve is also based on the equation which is shown in Fig. (3). According to previous considerations, the difference between the average capacity factor for far-offshore and for onshore is 20% (45%-25%). Accepting the capacity factor of 25% as the average onshore, which is assumed as a PCNR value of 100% and accordingly, $\mathrm{K}_{2\,\text{onshore}}$ is equal to 1. Therefore, the PCNR of far-offshore is calculated as $45\% - 25\% + 100\% = 120\%$ and so from Fig. (3), $\mathrm{K}_{2\,\text{far-offshore}}$ is equal to 2.

PCNR of near offshore is calculated by the same method which has been used for the far-offshore assuming the near offshore capacity factor of 35%, then $35\% - 25\% + 100\% = 110\%$. $\mathrm{K}_{2\,\text{near-offshore}}$ is calculated with Eqn. (8) through the PCNR value of 110%.

$$K_2 = 0.0541 \cdot \mathrm{e}^{0.0301 * \mathrm{PCNR}} \tag{8}$$

In conclusion, $\mathrm{K}_{2\,\text{near-offshore}}$ is equal to 1.483 and it is introduced in Eqn. (7).

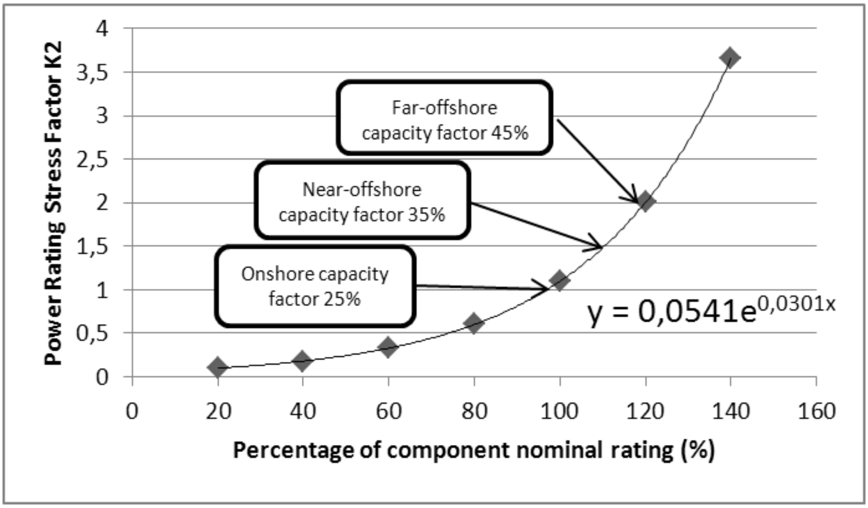

Figure 3. Percentage of component nominal rating plotted against stress factor K_2.

When the conversion factor is applied, the reliability prediction can be carried out. Consequently, through reliability prediction, problematic parts are identified and a first estimation of the failure rate is calculated. The system failure rate value obtained is 1866.36 failures per million of hours. The Rotor Module is pointed out as the part with highest failure rate (2.9 failures per year). The failures of the auxiliary equipment are not included in the results.

Reliability Block Diagram Results

A functional reliability model is created in order to evaluate the real configuration on the typical 10MW wind turbine which is shown in Fig. (4).

RBD results are shown in Fig. (5) and Fig. (6). Fig. (5) shows the failures per year through the main sub-systems. In addition, from Fig. (6) can be seen that the MTBF is equal to 3723.37 hours (2.37 failures per year). According with theory, the value of MTBF is the time at which the reliability value is 0.37. The inherent availability is calculated with a year mission time (8760 h) and at that time the value of inherent availability is about 99%.

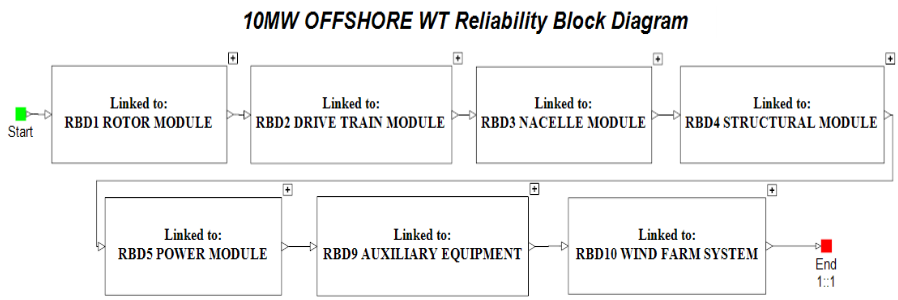

Figure 4. Main RBD of the Offshore Wind Turbine.

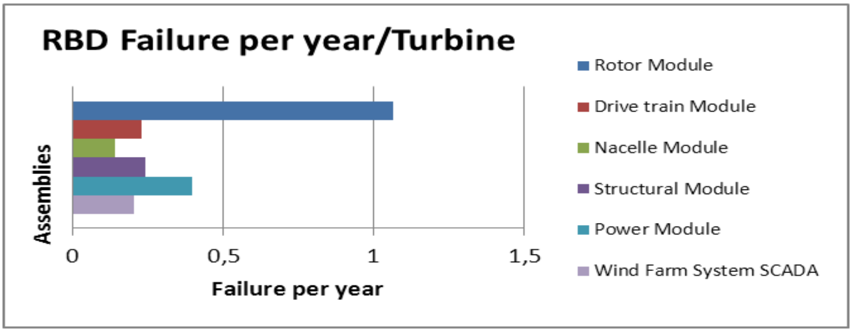

Figure 5. Results RBD on sub-systems.

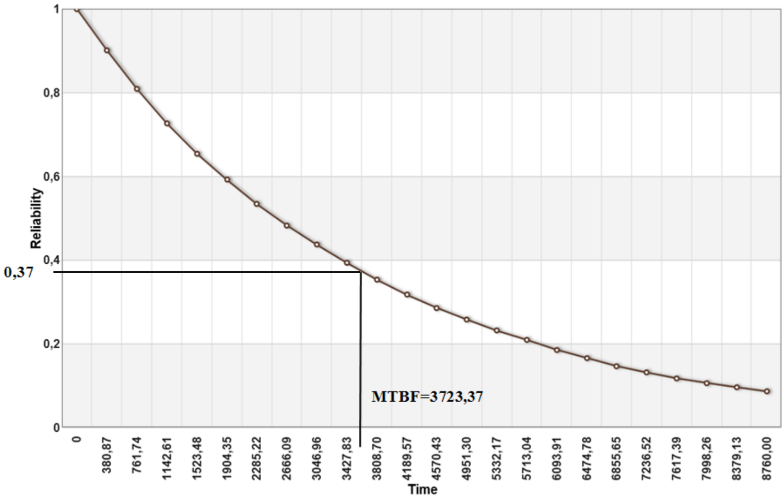

Figure 6. Reliability through time in a year operation for the 10MW OWT.

FMECA Results

Risk Matrix is probably one of the most widespread tools for risk evaluation. Fig. (7) reports the number of failure modes that lead to the end effect with those severity and frequency. Moreover, seven failure modes are showed in Fig. (7), located in yellow zones where actions to control or monitor them must be taken (Three of them are: The Drive train Module Failure, the Power Module Failure and the Structural Module Failure).

In addition, twenty four failure modes whose risk is considered to be low in the green areas and three failure modes located in the red areas where actions must be taken (The Auxiliary Power Equipment Failure in Marginal-Frequent, The Rotor Module Failure in Critical-Frequent, and the Nacelle Module Failure in Catastrophic-Occasional).

Frequency	Frequent (V)		1	1	
	Reasonably probably (IV)				
	Occasional (III)	3	4	2	1
	Remote (II)	6			1
	Extremely Unlikely (I)	8	1	6	
		Minor	Marginal	Critical	Catastrophic
		Severity			

Figure 7. Risk Matrix.

In the case of the Auxiliary Power Equipment, the great amount of items which composes it gives that position. The result of the Rotor Module is due to the high failure rate of the Blades assembly. For the Nacelle Module Failure, the reason why it is placed in a red zone is that the Nacelle is one of the main structures of the WT where the majority of the main assemblies are located.

According to previous sections, it has been performed another analysis from the quantitative point of view. From what have been seen before, the MTBF of the system is 3723.37 hours (2.37 failures per year). For this reason, the time until system fails has been taken as mission time.

It can be deducted that:

- 6 Marginal failure modes have the highest criticality number for the system.
- 9 Critical failure modes have almost the same criticality number as Marginal failure modes.
- 17 Minor failure modes have more than three times criticality than 2 Catastrophic failure modes and the half value of criticality number with respect to Marginal and Critical failure modes.

From Eqn. (4), Eqn. (5) and Eqn. (6), it is got the Eqn. (9) which clearly explains why the item criticality numbers are so high.

$$C_r = \sum_n^j (f_n * t * \beta * \lambda_s) \tag{9}$$

Considering that “t“does not change, λ_s is constant and β values are the same for all failure modes it is got the Eqn. (10). Therefore, for the marginal classification, high values of frequency and a high number of failure modes are the reason of its high level.

$$C_r = k * \sum_n^j f_n \tag{10}$$

The ten modes with the highest criticalities are reported in Fig. (8).

Blades are well known as the parts that most suffer in wind turbines due to their continuous work under adverse environmental conditions; in fact Rotor Module Failure (which includes the Blades) is characterized by the highest mode criticality value (mode criticality of 2.88).

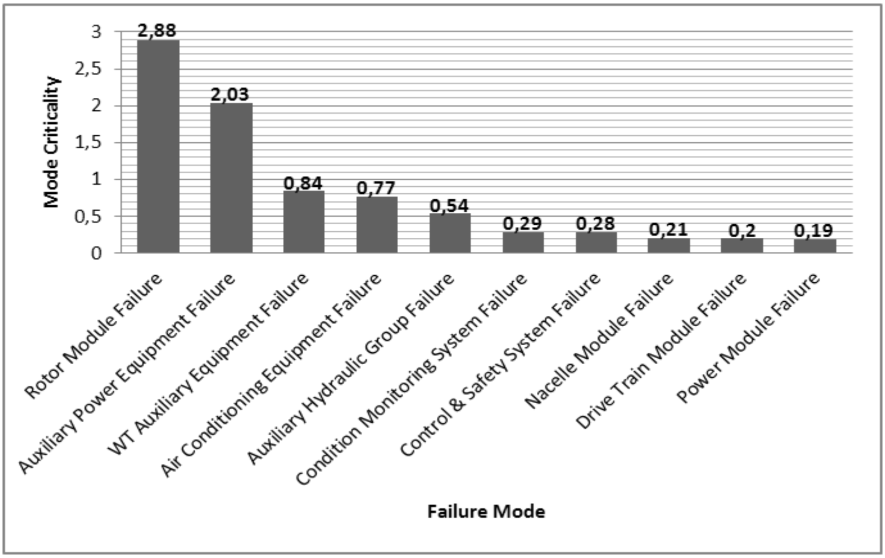

Figure 8. Top 10 Mode Criticalities.

Unifying all Auxiliary Equipment failure modes could be obtained the first highest mode criticality of 3.41 for the great amount of assemblies by which is composed this Sub-System, however the failure modes have been sorted in this way in order to clarify to which equipment belong to. Even with these equipment separated, the second highest mode criticality belongs to Auxiliary Power Equipment Failure, while the third and fourth positions match the WT Auxiliary Equipment Failure and the Air Conditioning Equipment Failure, respectively.

RPN is a criticality study in which the severity, occurrence and detection are multiplied in order to obtain information about the riskiest failure modes. Therefore, also in this graph greater attention has been paid to the critical parts. The Eqn. (11) is used to get RPN numbers.

$$\text{RPN} = \text{Severity} * \text{Occurrence} * \text{Detection} \tag{11}$$

As result of these multiplications, Fig. (9) shows the consequent risk priority classification with the highest RPNs of the OWT. Detection values come from [23] which are classified in ten ranges depending on the possibility of detection of the failure mode.

In this case, The Rotor Module Failure is still in a high position because of its high occurrence and severity and also its low detection level comparing to the others, followed now by the Structural Module Failure and the Nacelle Module Failure due to its high severity and low detection. The rest of the failure modes have such combinations that give them a gradual position on the graph until getting a value of 200 for the last 2 modes.

It is important to note that the mode criticality graph and the RPN graph give different lists of the riskiest failure modes of the OWT. The reason of this is that, the mode criticality analysis focuses the importance on the probability of occurrence while the RPN analysis concerns to detection parameter combined with severity and occurrence.

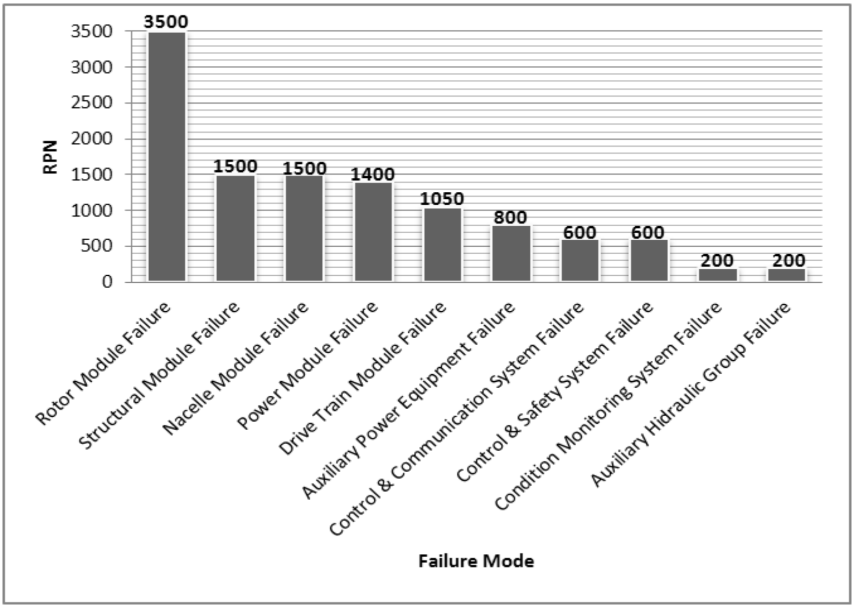

Figure 9. Top 10 RPN.

4. CONCLUSIONS

The reliability analysis for a 10MW offshore wind turbine has pointed out which sub-systems, assemblies and sub-assemblies have a high failure rate. The sub-systems with highest failure rate are Rotor Module, and Drive Train Module. In particular, the Rotor Module is exposed to a high stress and fatigue during all its operation time due to uneven high air pressure around it. It should be also noted that the gearbox does not appear between the less reliable assemblies of the OWT as it could have been expected. These results also confirm the data pointed out from Reliawind project.

The RBD shows an offshore wind turbine failure rate of 2.37 failures per year which is about twice larger than the onshore wind turbine failure rate. This value could be accepted for an onshore wind turbine; however it is a high failure rate for the OWT due to its limited accessibility to perform preventive or corrective maintenance.

The huge dimensions of the wind turbine, its complexity and the environment have risen up the failure rate of the system. Through quality improvements of components and using condition monitoring on critical assemblies, the downtime can be reduced allowing an accurate scheduled maintenance.

Nowadays, availability improvements have been looked for in order to reduce energy losses and do offshore wind energy profitable. In general, commercial offshore wind turbines can achieve an availability value of about 90%, but, depending on the maintenance assumptions, this value could grow up to 95%. However in this analysis, logistic delays, maintenance delays and supply delays have not been taken into account; therefore, an availability value (inherent availability) of 99% has been achieved.

Regarding the FMECA, it can be concluded that: the change in environment has increased the probability of some failures to happen, directly or indirectly. For the Rotor Module and the Structural Module, the analysis confirms that their failures are mainly caused by the hazardous environment. For the Drive Train Module and Rotor Module, the abrupt changes in wind direction lead to continuous variation on their load conditions and consequently in stress and fatigue. As the offshore wind turbine usually works in extreme temperature conditions, the Air Conditioning Equipment has to increase its power to maintain good environmental conditions and in the same way increase its failure rate.

From the result of the RPN and Mode Criticalities analysis, it can be seen how each method could give different lists of riskiest parts of the system; for this reason both analysis are suggested in order not to leave any important failure mode out of consideration.

FMECA takes into consideration only non-simultaneous failure modes. In other words, each failure mode is considered individually, assuming that other system items work as usual. Future studies will reduce the criticisms and doubts, which has been created by the classical FMECA.

As future work, a successful scheduled preventive and predictive maintenance program should be done, for reducing maintenance costs and increasing the availability of the offshore wind turbine without risks for the system, personnel or environment.

REFERENCES

[1] Barbati L., Barbati S., 2011. *Whole System Reliability Model, D.2.0.4.a.,* Relex Italia-Reliawind Project.

[2] Barbati L., 2008. *Functional Block Diagrams Specifications*, D.2.0.2 Relex Italia- Reliawind Project.

[3] Barbati S., Barbati L., 2011. *Whole System Reliability Model (Appendixes), D.2.0.4.b,* Relex Italia- Reliawind Project.

[4] Barbati S., 2008. *Common Reliability Analysis Methods and Procedures, D.2.0.1,* Relex Italia-Reliawind Project.

[5] Barbati S., 2011. *Design for Reliability FMECA Study*, EWEA Side Event, Relex Italia-Reliawind Project.

[6] MareWint Project 2013. European Commission. http://www.marewint.eu/home/.

[7] Echavarria E., Hahn B., Van Bussel G., Tomiyama T., 2008. *Reliability of Wind Turbine Technology Through Time.*

[8] Jesús María P., Fausto G., Andrew T., Mayorkinos P., 2013. *Wind turbine reliability analysis.*

[9] Haitao G., Simon W., Tavner P. Jiangping., 2009. *Reliability analysis for wind turbines with incomplete failure data collected from after the date of initial installation*.

[10] Paul R., 2010. *Relating onshore wind turbine reliability to offshore application*. Durham University.

[11] Seebregts, Rademakers, 1993. Horn. *Reliability Analysis on Wind Turbine Engineering*.

[12] Van Bussel G., Zaaijer M., 2004. *Reliability, Availability and Maintenance aspects of large-scale offshore wind farms, a concepts study.*

[13] Wilkinson M., 2011. *Measuring Wind Turbine Reliability-Results of Reliawind Project*. Garrad Hassan.

[14] Zafar H., Jørn V., 2012. *Important challenges for 10 MW WT from RAMS perspective.*

[15] Department of Defense USA, 1980. *Military Standart MIL- STD-1629A*, USA.

[16] Karyotakis A., 2011. *On the optimization of operation and maintenance strategies for offshore wind farms*, University College of London.

[17] Davidson J,. 1994. *The reliability of mechanical systems*. Mechanical engineering, 90-100

[18] Boccard N., 2008. *Capacity Factor of Wind Power*, Realized Values vs. Estimates.

[19] British wind Energy Association (BWEA), 2000. *Prospects for offshore wind energy*, A report written for the EU.

[20] CA-OWEE, 2001. *Offshore wind energy ready to power a sustainable Europe*. Final report, CA-OWEE NNE5-1999-00562, Supported by EC.

[21] Department of Trade and Industry (DTI), 2002. *Future Offshore, a strategic framework for the offshore wind industry*.

[22] The Crown Estate, 2010. *A Guide to an Offshore Wind Farm*, BVG Associates.

[23] Shafiee M., Dinmohammadi F., 2014. *An FMEA-Based Risk assessment Approach for Wind Turbine Systems: A Comparative Study of Onshore and Offshore*, Energies.

In questo volume è raccolta la maggior parte delle memorie presentate in occasione della “Nona Giornata di Studio Ettore Funaioli”, che si è svolta il 17 luglio 2015 presso la Scuola di Ingegneria e Architettura dell’Alma Mater Studiorum – Università di Bologna.
La Giornata è stata organizzata dagli ex allievi del Prof. Ettore Funaioli con la collaborazione del DIN – Dipartimento di Ingegneria Industriale e della Scuola di Ingegneria e Architettura dell’Alma Mater Studiorum – Università di Bologna, e con il patrocinio dell’Accademia delle Scienze dell’Istituto di Bologna e del GMA – Gruppo di Meccanica Applicata.

Questo volume è stato stampato con il contributo di G.D S.p.A.

ISBN 978-88-7488-965-5

AlmaDL
University of Bologna Digital Library

ISBN 978-88-7488-965-5