Performance and FMECA of a wind turbine based on SCADA and lidar data

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ABSTRACT

This paper presents an approach to identify risks for different failures that could affect wind turbine performance, and reduce the measured annual electrical production (MAEP). The proposed approach is based on FMECA (failure mode, effects and criticality analysis) and wind turbine performance study. We present firstly the methodology of performance calculation based on IEC 61400 standard, then we identify the energy gap between the MAEP and WAEP for the case study, we present an extended and reviewed FMECA, by introducing definition of factors related to environment, health and security. As a result we present an actions plan for similar failures deduced from wind performance study and risk-based FMECA, in order to reduce failure risks and optimize production by consequence. The case study is a 2.3 MW onshore wind turbine, different data that are used in this paper were collected from SCADA and lidar.

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1. INTRODUCTION

Recently, electrical generation has known a large integration of renewable energy, due two different factors which make the choice of this kind of energy justifiable. Wind energy especially is actually one of the best renewable energy because of cost reduction of wind power generation, and due to improvement of the used technology and equipment reliability. Making this energy more reliable and optimizing wind power generation still one of the challenges that confront wind turbine industrials, due to stochastic parts failure and wind speed changes.

Many studies have been done to evaluate wind turbine performance and reliability. Some of these studies focus on studying either wind turbine performances [1-5] or Risk-Based Failure Mode and Criticality Analysis RB-FMECA [6-10]. Otherwise the wind turbine performances and RB-FMECA could be combined to conclude and identify possible similar risks, in order to identify the mainly assemblies or equipment that is affecting and reducing wind turbine performances.

Wind turbine industrials focus to optimize production and maintenance costs, to achieve these tasks different ways are possible, we mention maintenance planning during less windy days, increasing wind turbine performance and reviewing maintenance strategy. In this paper, we present a combined methodology to reduce failures risk, and by consequence optimizing production.

The present paper aims to study wind turbine performances methodology first following IEC 61400 based on Lidar measurement and SCADA, the purpose of IEC 61400 standard is to provide a uniform methodology that ensure consistency, accuracy and reproducibility in the measurement and analysis of power performance by wind turbines. This standard provides guidance in the measurement, analysis, and reporting of power performance testing for wind turbines.

The FMECA is a proactive key to realize this issue. The FMECA helps wind turbine industrials to improve their availability, and also to check turbine performances. Altohough the standard FMECA still need improvement to achieve wind turbine industrials targets, the FMECA is generally based on Occurrence, Frequency and Detection to determine the Risk Priority Number (RPN), but the RPN can't be a good tools for operations manager in a wind farm, in order to make FMECA more self-informative, we add two other factors to this level, we mention the Cost of Priority Number (CPN) and the Environment, Health and Safety factor.

This paper studies 2.3 MW onshore wind turbine performance, in addition to sensors correlation in the second section, then in the third section, we present an extended FMECA and calculate CPN for different assemblies and especially those that could affect turbine performances, after identification for similarities between the used methodologies, we present an actions plan for major and similar failures.

2. WIND TURBINE PERFORMANCES

We present here the MAEP and WAEP calculated following IEC 61400 standards, for a wind turbine 2,3 MW. Wind turbine power curve was designed by Lidar data, positioned at 240 m in front of the studied turbine, to achieve 30 min for data per bins from 4 to 11m/s, data collection was done during one month. The filtered directions sectors were defined as [1].

a. 143° À 217°
b. 125° À 185°

For sectors LIDAR data are generally affected by turbine N°3,4 and 5 as mentioned in Figure 1.

Figure 1. Lidar position

Generic *AEP* is estimated by applying the measured power curve to different reference wind speed frequency distributions. A Rayleigh distribution, which is identical to a Weibull distribution with a shape factor of 2, shall be used as the reference wind speed frequency distribution. *AEP* estimations shall be made for hub height annual average wind speeds of 4, 5, 6, 7, 8, 9, 10 and 11 m/s according to (1-2) [2].

$$\mathrm{AEP} = N_h \sum_{i=1}^{N} \big(F(V_i) - F(V_{i-1})\big)\left(\frac{P_i + P_{i-1}}{2}\right) \quad (1)$$

Where
AEP : is the annual energy production
N_h : is the number of hours in one year ≈ 8760
N : is the number of bins
V_i : is the normalized and averaged wind speed in bin i
P_i : is the normalized and averaged power output in bin i

$$\mathrm{F(V)} = 1 - exp^{\left(-\frac{\pi}{4}\left(\frac{V}{Vave}\right)^2\right)} \quad (2)$$

Where
F(V) : is the Rayleigh cumulative probability distribution function for wind speed
V_{ave} : is the annual average wind speed at hub height
V : is the wind speed.The summation is initiated by setting V_{i-1} equal to V_i – 0,5 m/s and Pi–1 equal to 0,0 kW

We present here the wind turbine power curve, and the power coefficient for the case study. As shown in Figure 2, the real produced energy (blue line) is measured by the LIDAR data and SCADA, then it is compared to the theoretical curve (orange line) given by the constructor for the above wind speeds. From one hand, we can notice for the first wind speed interval [0; 3] that the measured energy is less than the theoretical one. This wind speed interval corresponds to the state where no energy is produced, since the cut-in speed is generally higher than 3 m/s.

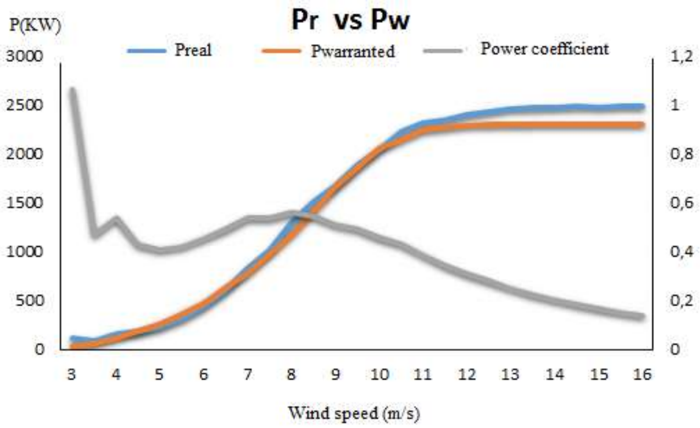

Figure 2. Wind turbine power curve

For the wind speed interval [4; 11], the theoretical and the measured energy produced by the wind turbine are collinear. This is mainly explained by the good performance resulted in this wind speed interval, and also by the efficiency of the maximum power point tracking (MPPT) used on this wind turbine.

When the wind speed exceeds 12 m/s, the turbine's system activates the "power boost" function, it increases the power production of the generator by unleashing the output limitation under certain operating conditions [1]. The activation of this function can be noticed in the measured power generated for wind speeds higher than 12 m/s, the power generated is slightly higher than the theoretical one.

From the other hand, the power coefficient; that reflects the ratio between the kinetic and the mechanic extracted power; does not show any anomalies and present a normal curve.

Furthermore, after calculating the measured and the theoretical power output of the turbine, we can get the MAEP and the WAEP according to the IEC 61400 standard [3]. The MAEP generated during is equal to 5297 MWh, whereas the WAEP is equal to 5267 MWh. This result shows that this turbine generates more than the warranted electrical production, which implies wind turbine outperformance.

Otherwise, we present here different sensors calibration that could affect wind turbine performance, especially wind turbine anemometers, pitch and yaw sensors. Indeed, the LIDAR presented in Figure 1 allows calibrating and assessing these components. The next figure presents the correlations between wind turbine's anemometers, vanes and the LIDAR equivalent sensors:

One can notice in Figure 3, a weak correlation between turbine's primary and secondary anemometers, the yaw system and the LIDAR sensors. This low correlation in the yaw system can lead to yaw misalignment, which can reduce the performance outputs of the turbines. Besides, we notice a weak correlation for the primary and the secondary anemometers for wind speed interval [3; 15], which can lead to a disruption in electricity generation even when wind speeds are favorable for production.

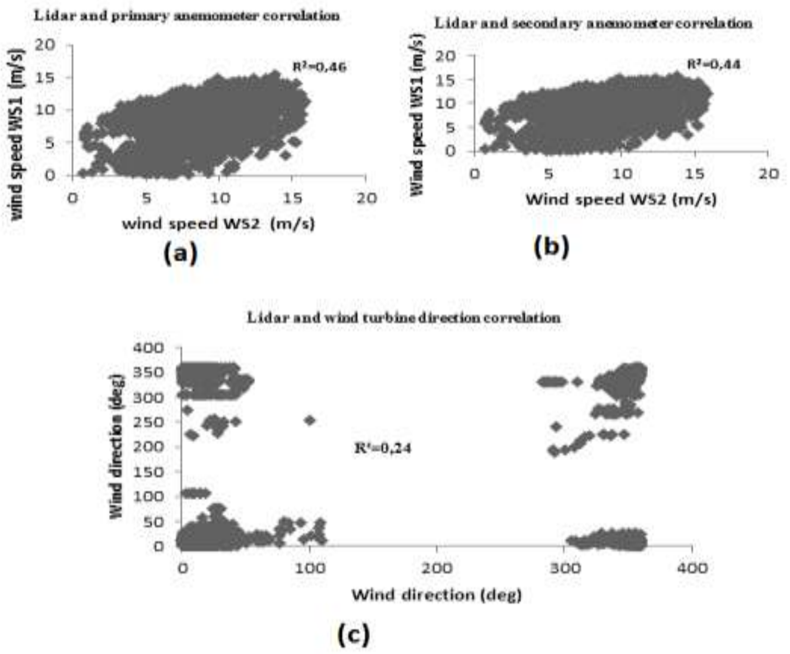

Figure 3. (a) LIDAR and primary anemometer correlation, (b) LIDAR and secondary anemometer correlation, (c) LIDAR and wind turbine direction correlation

To investigate more the causes of this weak correlation, we will inspect next the pitch angles calibrations. For this purpose, we plot the pitch angle of each blade (A, B and C) function of the LIDAR wind speed. This manipulation allows us to assess the pitch states according to the wind speed variation. From Figure 4, we notice an unbalance between pitch position A, B and C for different wind speed bins. Besides, for a wind speed higher than 3 m/s, we record several flag positions, which reflect a possible pitch regulation failure.

To continue our investigation of wind turbines assemblies failures that could affect wind turbine production, we present next a hybrid FMECA study proposed to take into account all the parameters influencing components criticality.

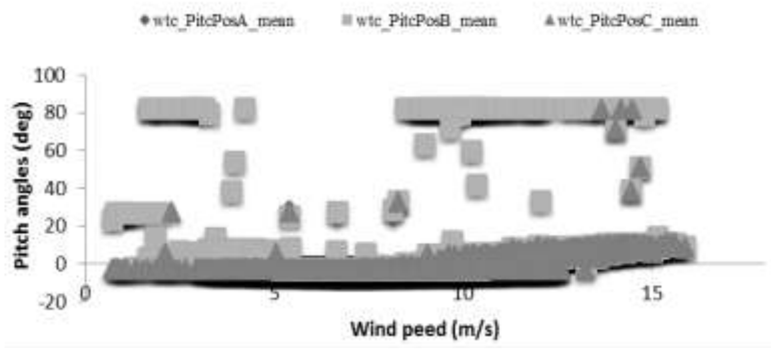

Figure 4. Assessment of pitch angles of the wind turbine

3. FMECA OF WIND TURBINE ASSEMBLIES

The traditional FMECA methodology has been used by industrials to analyze and minimize risks related to potential failures. However, a brief review of the literature shows that only a few researchers have worked on improving the traditional FMECA methodology to make it more practical for wind turbine systems. The procedure of FMECA application includes analysis of potential failure modes, identification of their possible effects and causes and analysis of preventive actions used and actions for failures detection.

Recently, Tavner and his colleagues presented a design-stage FMECA methodology for prioritization of failures in a 2-MW wind turbine system within the Real wind project [7-8].

The standard FMECA methodology only considers three factors; however for wind industrial other factors should be considered, we mention energy losses due to failure duration, Mean Time To Repair MTTR, logistics and transportation of spare parts and others. In order to overcome these drawbacks, we present a mathematical tool for risk and failure mode analysis of wind turbine systems based on three main factors: failure probability, incurred failure costs, and the fault detection possibility. The proposed methodology is applied for an onshore wind turbine 2.3 MW. Our results show that the proposed methodology can have a high potential to improve Environment, Health and Security related to failures [9].

The following FMEA is based on a 2 years SCADA data extracted from a Moroccan onshore wind farm. The studied wind turbine is a 2.3 MW onshore wind turbine. When collecting and analyzing all the alarms from the SCADA, we generate the failure durations for the different wind turbine assemblies. These structures are represented as:

- Grid connections: it represent the total components that connect the wind turbine to the grid
- System: it represents the command system of the turbine
- Controller: it includes a part of wind turbine sensors and communication tools
- Converter: converter of the turbine and its units
- Miscellaneous: it contains inter-alia the pressure warning sensors, main bearing temperature sensors, Avilight
- Gears : contains mainly High shaft speed , Intermediate shaft speed, Low shaft speed and planet
- Brake: mechanical brake of the turbine
- Hydraulic: the hydraulic part of the turbine, including a part of pitch sensors
- Grid inverter
- Generator
- Generator inverter
- Rotor
- Environment: it represents primary and secondary anemometers and turbine vane
- TCM (turbine condition monitoring): includes vibration sensors of generator, low & high speed shafts and planetary gearbox
- Yaw system
- Transformer
- Main bearing

We present here the alarms history by hours during two years for the studied wind turbine assemblies:

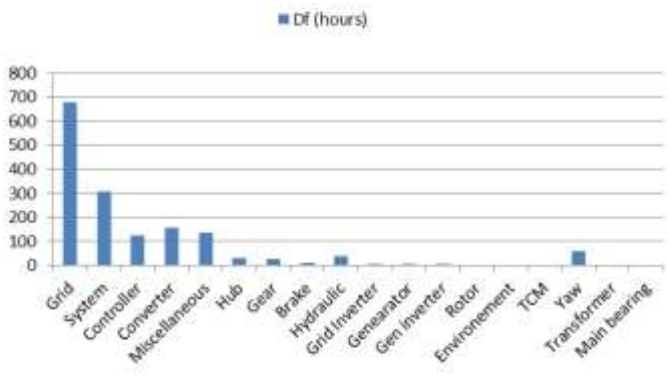

Figure 5. Failures duration for different assemblies

Following this alarms history, the grid remain the most unavailable assembly, during the two studied years by a total unavailabilities hours of 678 hours. Otherwise, we focus on different assemblies that could affect wind turbine performance, mainly yaw and hydraulic assemblies. Indeed, wind energy extracted is generally depending to the power coeffiscient , which represent the ratio of kinetic wind energy and extracted wind energy; we present here the kinetic power.

$$P_w = \frac{1}{2}mv^2 = \frac{1}{2}\rho S v^3 \quad (3)$$

Where m is the air mass, ρ is the air density, v is the wind speed and S is the covered surface of the turbine. And the wind mechanical power is given by:

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

And

$$C_p = \frac{Pm}{Pw} \leq 1 \quad (5)$$

Otherwise C_p is function of pitch angle (β*)* and tip speed (*λ*), which explains that a failure of wind speed anemometers or pitch sensors will affect directly wind turbine performances. The power coefficient maximum of is known as the limit of Betz [2].The power coefficient is given by:

$$C_p = C_1\left(\frac{C_2}{\lambda i} - C_3\beta - C_4\right)e^{-\frac{C5}{\lambda i}} + C_6\lambda \quad (6)$$

Where

$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta_3+1}$, $\lambda = \frac{\omega_m.R}{v}$ and C_i are constants given by the turbine constructor

Assuming that β is constant and equal to 0 for small wind speed less than 10m/s, C_i are constant given by turbine manufacturer. To investigate more , we start extended FMECA for different assemblies and equipment , especially those of yaw and pitch systems due to their relation to wind turbine performances.The proposed FMECA methodology contains other factors that could help turbine industrials to analyze and identify the most critical failures and their related equipment or sub equipment.

As presented in the introduction, the standards FMECA still not really informative for a wind turbine. Technologies used in wind turbine are not the same, we find turbine with gear box or gearless, with full scale converter or partial scale converter, wind turbine could use also a large kind of generators, like PMSG and DFIG.

Consequently the damage of PMSG converter does not have the same impact and cost of DFIG converter damage. The evaluation of RPN is not reflecting the real impact of some failures. In order to overcome this issue, we introduce CPN, environment and safety factors, these factors aim to make the FMECA more realistic. In several time, a failure is generating unavailability and in sometimes their resolution is not possible due to wind speed, which is more than the threshold of safety work. The CPN is given by:

$$CPN(i) = P_F(i)xP_{ND}(i)xC_F(i) \quad (7)$$

Where ‘’i’’ is the index of the failure. The calculated CPN is expressed in euro € and can be easily compared for different failure modes.

P_{ND} is calculated by dividing the number of the actual failures, N_F, to the total Number of Failure Vulnerabilities, N_{FV}, as:

$$P_{ND}(i) = \frac{N_F(i)}{N_{FV}(i)} \quad (8)$$

Number of Failure Vulnerabilities is defined as the number of any possible failure and the actual failures, and the number of detected possible failures prior to their occurrences. Different failures detection could be made by TCM or maintenance inspections [9].

The cost of failure C_F is depending on failure severity, in term of the lost energy, the MTTR (the Mean Time To Repair failure) and other factors. To assess component criticality, we introduced a new parameter called “environment, health and security” (EHS), this parameter expresses any delay due to external environment, health and security. In wind farms, maintenance cannot be done if wind speed is higher than 18 m/s or if the health and environment conditions are not favorable. Indeed, where these parameters are generally not taken into account in previous FMECA analysis [6][7][8], power losses due to the inaccessibility of the turbine due to wind conditions are important. Thus, one can generate the possible costs generated by this effect using (9).

$$C_{EHS}(i) = P_{EHS} x D_{EHS} x C_{EHS} \quad (9)$$

Where "P_{EHS}" is the probability of failure occurrence during periods with wind speeds higher than 18 m/s or other conditions related to health and environment. "D_{EHS}" is the total downtime due to EHS conditions, and "C_{EHS}" is the cost of the energy loss during this period.

Indeed EHS side is generally neglected, but it could in several times cost an enormous non delivered energy and unavailability to resolve some failures. In this study we define this factor, the criticality measurement of this factor will be a well informative key for wind industrial to assess an actions plan. Therefore, the cost of failure is defined by (9) [9-10].

$$C_F(i) = C_p(i) + C_s(i) + C_o(i) + C_L(i) + C_{EHS}(i) \quad (10)$$

C_F is based on five major costs. C_p is the cost of spare parts, which should be replaced due to the failure. C_s is the cost for scheduled maintenance containing all costs associated; we mention consumable like grease, rags, MHR (Man Hour Rate) and others. C_o represents the non-delivered energy costs given by [7]:

$$C_o(i) = D_f(i) x P x Energycost \quad (11)$$

P is the expected power during failure time and D_f is the failure duration without counting time related to EHS conditions. C_L is the total cost of repair work; it is expressed by (12).

$$C_L(i) = D_f(i) x N_C x MHR \quad (12)$$

N_c and MHR are the number of repair crew and Man Hour Rate respectively.

We present in the following figure the CPN for the case study, different data are extracted form alarms history of SCADA [7]. Different CPN are classified by order of most critical assemblies.

Following the extended FMECA, and the Figure 6, we notice clearly that system, yaw and hydraulic assemblies are ranking failures. By comparing this analysis to wind turbine performances presented in section II, we conclude some similarities in term of yaw misalignment and pitch problems. As a conclusion we confirm following this analysis to retrofit yaw, pitch assemblies and their equipment.

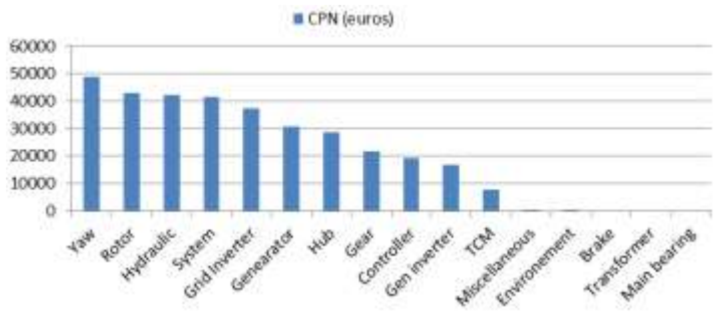

Figure 6. CPN given by critical orde

Otherwise, we propose to check the following element for yaw and pitch equipment [9-10]:
1. Scheduled maintenance and corrective maintenance checklists
2. Oil samples
3. TCM analysis
4. Temperature curves of bearings, oil, grease
5. Spare parts change historic

In this part, and following some conclusions deduced from the second and third parts, we present Figure 7, a flowchart to different steps before proposing making the proposed actions plan:

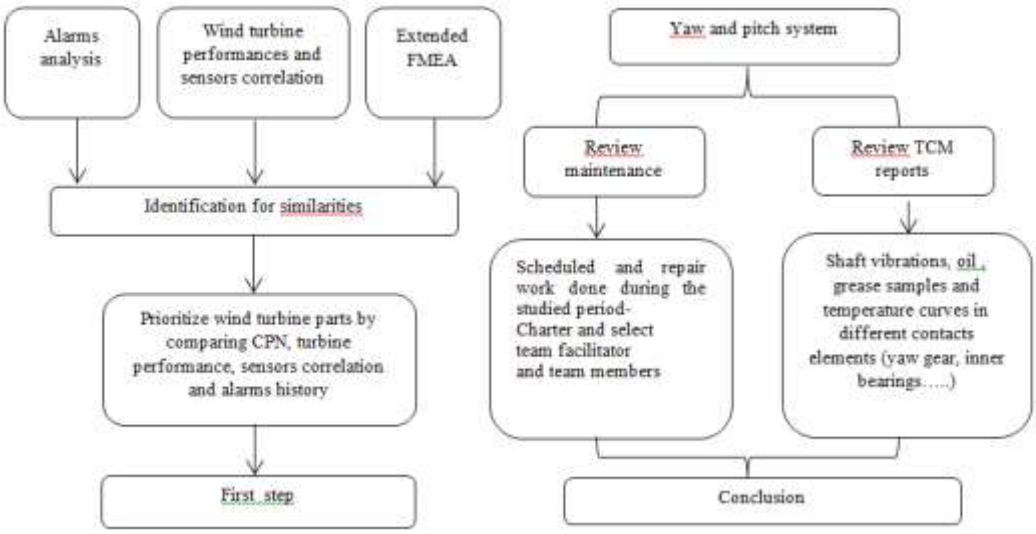

Figure 7. Actions plan

To identify similarities between wind turbine performances, alarms history and extended FMECA, we retain in the second section that pitch and yaw assemblies presented some deviation and low correlation in comparison to Lidar measurement. In the third section and as mentioned in Figure 8, these assemblies remains the most critical CPN.

Assemblies	Sub-assemblies	D_f (hours)	Occurrence	Severity	Detection	RPN	P_F (Probability o failure)	PND (Probability o f not detection)	C_p	C_s	C_L	C_0	C_{EHS}	C_F (euros)	CPN (euros)
Grid	-	678,01	4	3	2	24	0,25	0,7	-	71296	3390,1	42877	0	-	-
System	-	308,18	4	2	2	16	0,18	0,9	165000	71296	1540,9	19489	0	257326,2032	**41686,8449**
Controller	-	122,07	4	3	1	12	0,12	0,6	187640	71296	610,35	7720	0	267266,0568	**19243,1561**
Converter	-	156,28	2	2	3	12	0,09	0,8	-	71296	781,4	9883	0	-	-
Miscellaneous	-	136,35	2	2	2	8	0,005	0,6	57670	71296	681,75	8623	0	138270,524	414,811572
Hub	Pitch A,B and C tracking during operation Pitch A,B and C tracking during stop Pitch lubrification Pitch A,B and C encoder error Others	30,66	4	2	3	24	0,181	0,8	122995	71296	306,6	1939	109976	198475,4768	**28739,249**
Gear	-	25,82	2	3	2	12	0,088	0,9	200000	71296	516,4	1633	0	273445,2568	**21656,8643**
Brake	-	9,36	1	2	2	4	0	0,9	20000	71296	187,2	591,9	0	92075,1264	0
Hydraulic	Pitch hydraulics superheated Low pitch hydraulic error Low pitch oil pressure start Pitch pump too long Yaw hydraulic pump superheated Yaw hydraulic pressure sensor error Yaw temp sensor error Yaw hydraulic oil level low Others	40,24	4	3	2	24	0,204	0,8	183552	71296	402,4	2545	0	257795,1776	**42072,173**
Grid Inverter	-	0,52	2	2	3	12	0,022	0,8	115000	71296	2,6	32,88	0	186331,4848	**37266,297**
Genearator	-	0,015	2	3	2	12	0,027	0,9	118500	71296	1,26	0,949	0	189798,2086	**30747,3098**
Gen inverter	-	0,01	2	2	2	8	0,015	0,7	127000	71296	0,05	0,632	0	198296,6824	**16656,9213**
Rotor	-	0	1	0	0	0	0	0,8	527000	71296	0	0	0	598296	**43077,312**
Environement	-	0	1	0	0	0	0	0,6	-	71296	0	0	0	71296	213,888
TCM	-	0	1	0	0	0	0	0,6	-	71296	0	0		71296	7742,7456
Yaw	Yaw motors superheated Yaw time limit exceeded Yaw parameter error Untwisting cables Yaw system failure Others	60,13	4	3	2	24	0,26	0,9	113954	71296	5050,9	3803	15265	209368,5412	**48992,2386**
Transformer	-	0	1	0	0	0	0	0,6	12000	71296	0	0	0	83296	0
Main bearing	-	0	1	0	0	0	0	0,8	950	71296	0	0	0	72246	0

Figure 8. Spredsheet of the extended FMECA

The main task of this study is to identify failure, in order to reduce likelihood failure of another similar event related to yaw or pitch assemblies. Following the already found similarities, realized maintenance during two years and team chattering, we conclude that pitch and yaw should be retrofitted [11].

As an actions plan, we propose to check system alignment, to check the hydraulic system and especially the pitch pump, as we record a highest MTBF for this system equipment following our review of maintenance plan. We recommend a new wind turbine performance study after this retrofit, to check the impact factor for the proposed actions plan and their validity to improve wind turbine performance [12].

4. CONCLUSION

This paper presents a new approach to diagnosis wind turbine failures, this approach combine the power performances and an extended FMECA, by the introduction of new parameter related to EHS. This method was applied to an onshore 2,3MW wind turbine. The wind turbine performances was realized by using a Lidar and SCADA Wind, to calculate the MAEP and WAEP following IEC 61400, calculation had shown good turbine performances , however some deviations was recorded in pitch and yaw assemblies.

The extended FMECA had introduced an EHS factor, which remain a key factor for wind turbine industrials to identify critical risks. Otherwise CPN of Yaw and pitch assembly is more than 30,000.00 euros for the case study, these assemblies which had recorded less correlation in second section. As an actions plan, we recommend to retrofit yaw equipment and pitch pump, because of their higher CPN and misalignment detected during the second section.

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NOMENCLATURE

MAEP	: Measured annual electricity production	WAEP	: Warranted annual electricity production
AEP	: Annual electricity production	WT	: Wind turbine
LIDAR	: (LIDAR)	N	: Number of bins
V_i	: Normalized and averaged wind speed in bin i	P_i	: Normalized and averaged power output in bin i
F(v)	: Rayleigh cumulative probability distribution function	Cp	: Power coefficient
FMECA	: Failure mode, effects and criticality analysis	RPN	: Risk priority number
CPN	: Cost priority number	AEP	: Annual energy production
P_f	: Failure probability	P_{nd}	: Probability of failure vulnerabilities
C_F	: Cost of failure	C_s	: Cost of scheduled maintenance
C_0	: Cost of non-delivered energy cost	C_L	: Cost of repair work
C_{EHS}	: Cost generated by delays due to environment, health and safety measures	SCADA	:Supervisory Control And Data Acquisition