Research Article

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Preliminary Results for Detection Evaluation in Failure Modes and Effect Analysis Study: 600 kW Wind Turbine Case Study

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Abstract

In recent years, the need for renewable and sustainable energy is greater than ever before. Wind turbines in a variety of sizes, appear in every available area and participate in our effort to reverse the energy crisis. However, these complex electromechanical systems are defined by low availability and substantial downtime periods. The Levelised Cost of Energy (LCOE) and the Internal Rate of Return (IRR) only recently started to be encouraging for investors. One of the key factors to be taken into consideration is that the reliability of these systems is often compromised due to their ever-growing nominal power and harsh operating conditions, fault appearances increase exponentially from 1 MW wind turbine to 10 MW or more. To assess the reliability of a case-study wind turbine of 600 kW, a Failure Modes and Effects Analysis (FMEA) was used to identify the potential causes of downtimes. In this paper, a novel way to approach detection evaluation in the FMEA study is proposed. The results indicate a reliable way to identify the most critical components of a complex system.

Keywords: wind turbines, FMEA, failure detection, critical subsystems, RPN

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1.Introduction

Harvesting the power of wind has been at the forefront of engineering for more than 20 years. Onshore and offshore wind turbines (WT) of ever-growing sizes and shapes (Vertical Axis Wind Turbines-VAWT, Horizontal Axis Vertical Wind Turbines-HAWT, etc.) have been installed in the European fields and mountains every year, in an attempt to increase the penetration of Renewable Energy Sources (RES). The Global Wind Energy Council (GWEC), at its latest report, announced reforms that will assist and speed up the energy transition worldwide. The cumulative installations reached 591 GW and are anticipated to increase by 50 GW each year until 2023 [1-2]. Due to this exponential growth in installed capacity (see Fig. 1), optimizing the operation of WT will be the key factor of the energy transition. WT, as shown in Fig. 2, are complex electromechanical systems that exploit the kinetic energy of the wind and transform it into electrical energy [3].
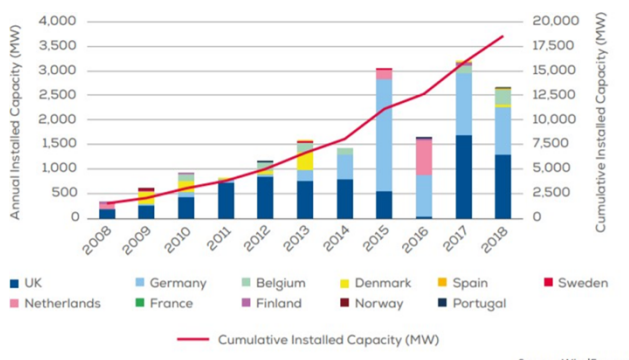

Fig. 1. European cumulative installed capacity from wind turbines, in MW, 2008-2018

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FMEA is a bottom-up analysis, which evaluates the riskiness of a failure occurring at the bottom level of the structure of a system, at the component level [8]. It is commonly used on WTs in many different variations and approaches. A. Benouk et al performed a Risk-Based FMECA (a combination of FMEA and Criticality Analysis) using SCADA and Lidar systems, to propose maintenance actions, on a 2.3 MW onshore WT, and achieved positive changes in turbine performance [9]. Anmei Zhou et al, approached FMECA's results via ontology to more accurately assess the outcome of the analysis and provide to the maintenance personnel, structured data [10]. Guerrero A. Crespo et al. proposed a novel approach using asset maintenance based on ISO: 14224 and the OREDA database to enrich an FMECA study and present to the maintenance personnel reliability information about the WT [11].

The aforementioned approaches to FMEA took into consideration the generic faults of its risk classification tool, Risk Priority Number (RPN). The RPN consists of three parameters, each expressing an aspect of the failure mode. These parameters are the Severity of the failure (S), the probability of occurring-Occurrence (O) and its possibility of Detection (D). In 1993, Gilchrist et al. characterized RPN as inconsistent and thus introduced cost in the model [12].

N. R. Sankar proposed a new approach to FMEA to better classify the parameters, which contribute to the assessment of the risk at RPN [13]. Kuei-Hu Chang et al. were the first to introduce a new method, exponential RPN (ERPN), of combining the parameters which constitute the RPN [14]. Their work was continued and enhanced by Hadi A. Khorshidi et al. who approached the calculation of the RPN number using the Universal General Function (UGF) [15]. Their approach was named URPN (Universal RPN) and the parameters of the RPN were separated and special weight had been given to the most important (Severity).

However, the rich bibliography surrounding FMEA studies, little emphasis has been given at the classification and the distinction of the parameters involved and the transition from qualitative to quantitative. John B. Bowles et al. introduced the fuzzy logic approach when tackling the prioritization of the failure modes and the enhancement of the distinction of the three parameters [16]. Another major issue is the definition of the way the three values are estimated. The Guidelines for the Naval Aviation Reliability-Centered Maintenance Process refers to the parameter of Severity as the measure of the impact the failure has on the functionality of the system [17]. Occurrence has been presented as the expression of the probability of the appearance of the failure during the lifetime of the system. Detection has been referred to as the quantification of the possibility the measurement method will detect the failure when it occurs [18]. As far as detection (D) is concerned, the quantitative equivalent of the quality remark of the detection method is subjected to the teams' expertise and ability to accurately evaluate it.

In this paper, a novel approach has been proposed, to mathematically approach D of the FMEA study. Two parameters are used for the evaluation, one refers to the Applicability of the Detection Method to each system's requirements and the second examines the Detectability of the Failure in each Failure Mode. To analyze the risk and determine the causes of the downtime periods of onshore WTs, in this paper, Failure Modes and Effect Analysis (FMEA) will be used on a 600 kW onshore WT which is part of a 10 WT-park.

The paper is divided as follows: the FMEA application on the case study of a 600 kW WT is presented in section 2, in section 3 the proposed method is presented, results and further discussion of the findings are in section 4 and conclusions are in section 5.
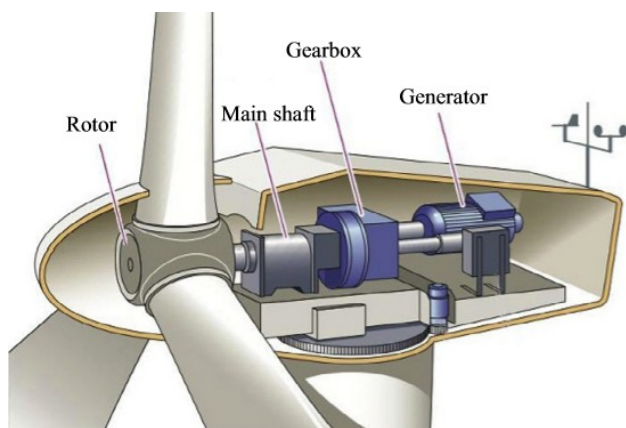

Fig. 2. Subsystems located at a typical WT nacelle [10]

2 FMEA Study for The Case Study Of A 600 Kw Wt

2.1 Defining the Objectives of FMEA study
FMEA is a bottom-up approach of a system's numerous ways of failing. Bottom-up approach, because it focuses on identifying all the different failure modes at a component level, thus it is been referred to as component FMEA [18]. Component FMEA is subjected to the task 101 of the MIL-STD-1629A of the Department of Defense-USA (DoD) and is the main focus of the study presented in this paper [8]. The objectives when conducting an FMEA are:

- preparation for the worst-case-scenarios for every component of the system

- minimization of the downtimes of the system and the cost of repair due to preventive measures
- help the maintenance personnel identify and prioritize the most critical subsystems in a risk priority order (RPN) [18].

2.2 Case study of 600 kW WT
For this study, a system of a 600 kW WT has been chosen due to the access provided to some of the data of a 10-WT park in Southern East Greece, required to conduct the FMEA. The first step was the identification of the system's complexity and the definition of the failure's conveyance mechanism on the FTAs [19-20]. The selection of the most critical subsystems for the case study is presented in Tab. 1.

Table 1. Subsystems and Components of the 600 kW BONUS

Subsystem	Component
Yaw System	Failure of Internal Gear Slewing Bearing System
	Failure of Yaw Drive Shaft-Pinion System
	Failure of Yaw Gearbox System
	Failure of Lubrication System
	Failure of Yaw Motor System
Gearbox	Failure of Clamping Unit System
	Failure of Gearbox Cover System
	Failure of Gearbox Suspension System
	Failure of Planet Wheels System
	Failure of Sun Wheel System
	Failure of Internal Gear Ring System
	Failure of Two Stage Fixed Axis Geared System
	Failure of Lubrication Oil System
Electrical and Control	**Electrical System**
	Failure of Power Feeder Cables System
	Failure of Grounding System
	Failure of Lightning Protection System
	Failure of Electrical Protection System
	Failure of Capacitor Bank System
	Failure of Thyristor System
	Failure of Transformer System
	Control System
	Failure of Controller System
	Failure of Uninterruptible Power Supply (UPS)
	Failure of Signal Networking Hardware System
	Failure of Meteorological Station
	Failure of Cable Twist Protection System
	Failure of High-Speed Centrifugal Release Unit
Hydraulics	Failure of Electric Motor System
	Failure of Pump System
	Failure of Oil Tank System
	Failure of Filters System
	Failure of Tubing-Hoses System
	Failure of (Pipe) Fittings System

Failure of Valves System
Failure of Rotating Union System
Failure of Centrifugal Release Unit

Table 2. Severity estimation: qualitative to quantitative

Linguistic Approach	Severity Effect	Rank
The appearance of the failure has no significant effect in the overall functionality of the system	Unimportant Effect	1
There is no obvious sing of obstruction in the functionality of the system	Minor Effect	2
Because of the failure, the system had to be stopped and repair was necessary	Medium Size Effect	3
The failure caused severe damage to the system and most probably are not repairable	Significant Effect	4
The failure occurs without warning and when it does, it has a catastrophic effect on the EHS	Catastrophic Effect	5

After reviewing all the components' subsystems, the identification of the failure modes in each of them is to be determined. The failure of the component conveys upwards to a subsystem level and becomes the failure mode for the subsystem. The process of the failure conveyance has been repeated until the system level. The following step in Task 101, FMEA, is evaluating the S, O, D for the different failure modes. Ford Motor Company was the last to review the classification of the S, O, D and the proposed method of value assignment is given in Tab. 2 and Tab. 3. [21].

The corresponding table for Occurrence is not applicable in the present case study because of the lack of an accurate historical data for the WTs under consideration. Instead, O was approached as the mean time of failures for each component, for the 8.5 years of operation of the wind park. Severity is been approached in a 5-ranking scale

While conducting the case study, it should be noted that FMEA study is taking into consideration failures that happen individually, while the rest of the system operates properly. Each failure has no cause-effect relationship with the other.

3 Proposed Method: Detection Evaluation By Defining Two Parameters

The evaluation of the D parameter of the FMEA study takes into account the ability of the measurement method (or the existence of a method that detects the failure). The difficulty lies, however, in the complexity of the system and the approachability of the component which has failed. In this study, a two-parameter approach is proposed which consists of the Applicability and the Detectability parameter. For calculating the first parameter, a thorough bibliographic review has been made to filter out the detection methods applied to the components under study. Building on the work of Konstantinidis et al., the S, O values for the respective components are as presented in Tab. 4 [20].

Table 3. Detection estimation: qualitative to quantitative

Linguistic Approach	Probability	Detection Prob-Rank
The measurement instrument will detect the failure	Certain Detection	1
The probability of detecting the failure is high	High Probability of Detection	2,3
There is a possibility, the measurement instrument will detect the failure	Probability of Detection	4,5
The probability of detection is relatively low	Low Probability of Detection	6,7
It is highly unlikely, the measurement instrument will detect the failure	Unlikely Detection	8,9
There is no likelihood of detection. There no known measurement instruments which detect the failure mode	No Detection	10

3.1 1st Parameter: Applicability

This parameter refers to the total number of components, of the system under consideration that the detection method detects. As shown in Fig. 3, each of the 9 methods, when applied, detects the failures of the components (marked with red asses). The goal of this parameter is to determine the adequacy of the method when applied to a system with a certain complexity. In the case study of the critical subsystems of the WT, Fig. 3 depicts the Applicability of the methods to the system. The calculation of the Applicability parameter (A_d) is as shown in Eq. 1.

$$A_d = \frac{\sum_{c=1}^{c=N} X}{\max_X \sum_{c=1}^{c=N} X} \times \frac{100\%}{20} \qquad (1)$$

Where N is the total number of components, c is the components whose failure is been detected with the method. The multiplication with 100 is used in order to extract the percentage of the applicability of the detection method. The division with 20 is used in order to cut down the result in a *5-scale* system.

The equation returns a non-integer number which is then rounded-up to the nearest integer. The higher the value of A_d the greater the applicability of the method in the respective system. Vibration analysis, for example, detects 22 from the total of 37 failures,

$$\frac{22}{37} \times \frac{100\%}{20} = 2,97$$

which rounds up in $A_d = 3$. This value is calculated for all 9 detection method

Table 4. Severity and Occurrence values for the failures of the respective components [20]

Subsystem	Component	S	O
Yaw System	Failure of Internal Gear Slewing Bearing System	2	5
	Failure of Yaw Drive Shaft-Pinion System	3	1
	Failure of Yaw Gearbox System	2	1
	Failure of Lubrication System	3	1

Component	Failure Mode		
	Failure of Yaw Motor System	2	1
Gearbox	Failure of Clamping Unit System	2	1
	Failure of Gearbox Cover System	1	1
	Failure of Gearbox Suspension System	2	1
	Failure of Planet Wheels System	1	2
	Failure of Sun Wheel System	5	2
	Failure of Internal Gear Ring System	2	2
	Failure of Two Stage Fixed Axis Geared System	4	2
	Failure of Lubrication Oil System	5	7
Electrical and Control	**Electrical System**		
	Failure of Power Feeder Cables System	4	1
	Failure of Grounding System	5	1
	Failure of Lightning Protection System	5	1
	Failure of Electrical Protection System	5	4
	Failure of Capacitor Bank System	5	6
	Failure of Thyristor System	2	1
	Failure of Transformer System	0	1
	Control System		
	Failure of Controller System	5	2
	Failure of Uninterruptible Power Supply (UPS)	5	3
	Failure of Signal Networking Hardware System	5	4
	Failure of Meteorological Station	3	2
	Failure of Cable Twist Protection System	5	2
	Failure of High-Speed Centrifugal Release Unit	5	1
Hydraulics	Failure of Electric Motor System	1	1
	Failure of Pump System	5	1
	Failure of Oil Tank System	1	1
	Failure of Filters System	1	2
	Failure of Tubing-Hoses System	1	2
	Failure of (Pipe) Fittings System	1	2
	Failure of Valves System	5	1
	Failure of Rotating Union System	5	2
	Failure of Centrifugal Release Unit	5	1

Table 5. Applicability of Detection Methods for the Components under study

System	Vibration analysis	Ultrasonic	Acoustic emissions	Oil analysis	Thermography	Strain measurement	Shock Pulse Method	Performance monitoring	Electrical effects
INTERNAL GEARED SLEWING BEARING SYSTEM	1		1		1		1		
YAW DRIVE SHAFT-PINION SYSTEM	1	1			1		1		
YAW GEARBOX SYSTEM	1	1	1	1	1	1	1	1	
LUBRICATING SYSTEM				1	1				1
YAW MOTOR SYSTEM	1	1	1	1	1	1	1	1	
CLAMPING UNIT SYSTEM	1	1	1	1	1	1	1	1	
GEARBOX COVER SYSTEM	1				1		1	1	
GEARBOX SUSPENSION SYSTEM	1	1	1				1	1	
PLANET WHEELS SYSTEM	1	1	1	1	1			1	
SUN WHEEL SYSTEM	1				1		1		
INTERNAL GEARED RING SYSTEM	1				1	1	1	1	
TWO STAGE FIXED AXIS GEARED SYSTEM				1	1	1		1	
LUBRICATING OIL SYSTEM	1	1	1	1	1			1	
POWER FEEDER CABLES SYSTEM	1	1			1				1
GROUNDING SYSTEM	1	1			1	1	1		1
LIGHTNING PROTECTION SYSTEM					1				
ELECTRICAL PROTECTION SYSTEM					1				1
CAPACITOR BANK SYSTEM	1	1			1			1	1
THYRISTOR SYSTEM	1				1			1	
TRANSFORMER SYSTEM					1				1
CONTROLLER SYSTEM					1				1
UNINTERRUPTIBLE POWER SUPPLY (UPS) SYSTEM					1			1	1
SIGNAL NETWORKING HARDWARE SYSTEM	1	1			1				
METEOROLOGICAL STATION SYSTEM	1								
CABLE TWIST PROTECTION SYSTEM	1	1	1		1			1	1
HIGH SPEED CENTRIFUGAL RELEASE UNIT SYSTEM							1		1
ELECTRIC MOTOR SYSTEM					1				
PUMP SYSTEM				1	1				1
OIL TANK SYSTEM	1						1	1	
FILTERS SYSTEM				1		1	1		
TUBING-HOSES SYSTEM	1	1	1		1	1		1	
(PIPE) FITTINGS SYSTEM						1	1		

VALVES SYSTEM		1	1 1	
ACCUMULATOR SYSTEM	1		1 1	1
ACTUATORS SYSTEM			1 1	1
ROTATING UNION SYSTEM			1	1
CENTRIFUGAL RELEASE UNIT SYSTEM	1		1 1	

3.2 2nd Parameter: Detectability

The term Detectability refers to 1) the ease of detection of the failure according to the complexity of the structure of the system 2) the existence of a suitable detection method for the failure of the respective component. This parameter takes into consideration the number of detection methods that detect the failure and the Applicability parameter of these methods. The calculation of the Detectability parameter results in the final value for the Detection. Eq. 2, 3.

$$D_h = \sum_{m=1}^{m=9} A_d \qquad (2)$$

$$D = \left\{ 10 - \left(\frac{D_h}{\max D_h} \times 10 \right) \right\} + 1 \qquad (3)$$

Where d is the detection methods that detect the failure (marked as red in Fig. 3). Eq. 2 calculates the sum of all the D values of the methods that detect the failure. Eq.3 considers the maximum value possible for the Detectability and is been subtracted by 10 to approach the 10-number-scale of *Detection* parameter. The additional value of 1, is been added to avoid zero-sum values, which are not included in D parameters evaluation. An example is given for the second failure in Fig, 3 (Yaw-drive shaft pinion system) which is detected by Vibration analysis, Ultrasonic, Thermography, and Shock Pulse method. These have A_d values of 3, 2, 5, 1 respectively which add up in 11. The max D_h value is 21 and from eq. 3, the D parameter is 6. The aforementioned process results in D values which will be substantially different from those evaluated with the traditional method (Tab. 3). For the previous example, the traditional method results in $D = 2$ as it takes into consideration only the existence of detection methods for each failure to assign them low Detection values. Two-parameter evaluation does not approach each failure individually but estimates the ease of detection for each of them in the operation of the system. The RPN ranking with the proposed method is given in Tab. 7.

4 Results and Discussion

The results of Tab. 7 suggest that the top-ranked failures belong to the Yaw system, Electrical and Control, and Gearbox. These results agree with the Final Publishable summary of ReliaWind Project (Nr 212966), which ranked the most critical subsystems, as shown in Fig 4. Subsystems that rank high are more prone to fail often and their failures affect the system on a multi-level basis. The detection of these failures is relatively difficult and the methods that detect them are not widely used in WTs. The results for average and standard deviation values are presented in Tab.6:

- Yaw system: The average value of D, with the proposed method, is 5.4 and the standard deviation is 2.4. The other parameters (S, O) present lower average values (2.4 and 1.8 respectively) and standard deviation values of 0.5 and 1.7 which suggests that the components' failures are of the same magnitude. Therefore, the yaw system is ranked high overall, because the failures of its components are hard to detect in the early stages. These results, compile to difficulty in detecting the failures either because of the subsystem's complex structure or because of the lack of appropriate detection methods for the respective failures
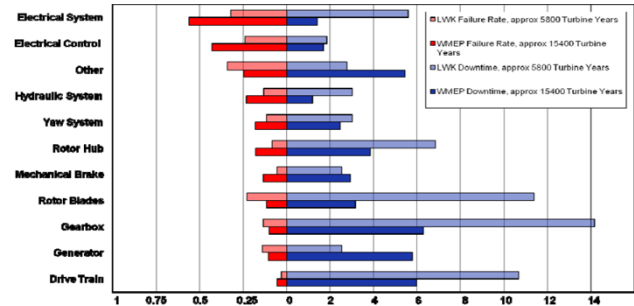

Fig. 3. Onshore WT failure rates and downtime results | Source: ReliaWind Project Nr 212966

- Gearbox system: The average value of D is 4.6 and the standard deviation is 1.7 in the case of the gearbox. Nevertheless, it is ranked as one of the most critical subsystems for the WT. The average values of S and O are 2.2 and 2.3 respectively and the standard deviation of 1.6 and 1.9 which suggests that the subsystem of the gearbox, for the case study, has low impact failures. There is a moderate to high evaluation of the detection difficulty of these failures indicating a need for real-time monitoring of the subsystem to avoid unexpected and undetected failures.
- Electrical system: This particular system has a D value average of 6.4 while the standard deviation value is 1.9. The system is affected by failures that are difficult to detect, have minor effect on the operation of the system (S average 3.8) and do not occur regularly (O average 2.1).
- Control system: D average value, throughout the studied subsystems, is at the highest value, 7.3, while the standard deviation of the values is at 2.1. Control system is characterized, according to the results of the case study, by failures with low impact on the system's operation (S average 4.6) and low frequency of occurring (O average 2.3).
- Hydraulics system: D value for this subsystem is relatively high, at 6.2. Standard deviation (1.9) suggests that the failures occurring at the components are difficult to detect either because there is no detection method to detect some of them, or because the system is poorly designed. For S and O values, average and standard deviation are low (2.7, 1.4 and 2.1, 0.5) which indicate that the failures are not severe and not frequent.

The information on the identification of the most critical subsystems and components, provide useful insights to maintenance operators and design teams [10]. Applying the knowledge acquired by this study, can reduce substantially the cost of maintenance. These results indicate that all the subsystems under study are affected by failures, which are not extremely severe for the operation of the system but are difficult to detect. The difficulty in detection lies at the complexity of the structure of the system and is affected by noise in the measurements due to the proximity of the rotating parts, with each other. In this study, the downtimes and the repair times of the individual failures have not been included. Some of

them are occurring frequently and are difficult to repair or find replacements. The new approach, overall, estimates the D parameter with higher values than the average FMEA study. It should be noted that previous approaches of the parameter, tend to underestimate the values resulting in FMEA studies focused on mitigating the impact of the failure (S) or the frequency of the occurrence (O).

Table 6. Average and Standard Deviation values for the S, O, D values for the 5 subsystems

		Yaw system	Gearbox	Electrical system	Control system	Hydraulic system
S	Average	2.4	2.2	3.8	4.6	2.7
	Std. deviation	0.5	1.6	1.9	0.8	2.1
O	Average	1.8	2.3	2.1	2.3	1.4
	Std. deviation	1.7	1.9	2	1	0.5
D	Average	5.4	4.6	6.4	7.3	6.2
	Std. deviation	2.4	1.7	1.9	2.1	1.9

Table 7. RPN calculations for the failures of the components under study

Subsystem	Component	S	O	D	RPN
Yaw System	**Failure of Internal Gear Slewing Bearing System**	2	5	8	**80**
	Failure of Yaw Drive Shaft-Pinion System	3	1	4	12
	Failure of Yaw Gearbox System	2	1	8	16
	Failure of Lubrication System	3	1	4	12
	Failure of Yaw Motor System	2	1	3	6
Gearbox	Failure of Clamping Unit System	2	1	6	12
	Failure of Gearbox Cover System	1	1	3	3
	Failure of Gearbox Suspension System	2	1	5	10
	Failure of Planet Wheels System	1	2	6	12
	Failure of Sun Wheel System	5	2	6	**60**
	Failure of Internal Gear Ring System	2	2	1	4
	Failure of Two Stage Fixed Axis Geared System	4	2	5	40
	Failure of Lubrication Oil System	5	7	5	**175**
Electrical and Control	**Electrical System**				
	Failure of Power Feeder Cables System	4	1	4	16
	Failure of Grounding System	5	1	8	40
	Failure of Lightning Protection System	5	1	6	30
	Failure of Electrical Protection System	5	4	8	**160**
	Failure of Capacitor Bank System	5	6	9	**270**
	Failure of Thyristor System	2	1	6	12
	Failure of Transformer System	0	1	4	4
	Control System				
	Failure of Controller System	5	2	8	**80**
	Failure of Uninterruptible Power Supply (UPS)	5	3	8	**120**
	Failure of Signal Networking Hardware System	5	4	6	**120**
	Failure of Meteorological Station	3	2	10	**60**
	Failure of Cable Twist Protection System	5	2	8	**80**
	Failure of High-Speed Centrifugal Release Unit	5	1	4	20
Hydraulics	Failure of Electric Motor System	1	1	7	7
	Failure of Pump System	5	1	7	35
	Failure of Oil Tank System	1	1	7	7
	Failure of Filters System	1	2	9	18
	Failure of Tubing-Hoses System	1	2	5	10
	Failure of (Pipe) Fittings System	1	2	6	12
	Failure of Valves System	5	1	7	35
	Failure of Rotating Union System	5	2	2	20
	Failure of Centrifugal Release Unit	5	1	6	30

5 Conclusions

In this paper, a novel approach to evaluating Detection in FMEA studies was proposed. The main task was to propose an evaluation method that can be applied to every system and which considers the complex mechanisms linking the respective components. In order to show the application of the two-parameter approach, which introduces the parameters of Applicability of the Detection method to the complexity of the system and the Detectability of the failure, a case study was presented. The proposed method takes into consideration only the most critical subsystems, resulting to the detection of the components with the higher RPNs. The results of the study highlighted the importance of the Detection parameter, as there was no mathematical way to determine it, in the best knowledge of the authors. The novelty of the method was supported by similar studies (as ReliaWind Project), which confirmed the prioritization of the criticality of the subsystems under study. Lack of historical data, leads to some modifications for the evaluation of the parameters of FMEA. In conclusion, the two-parameter approximation presented promising results that will drive the next steps of this research.

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