Risk assessment of a wind turbine: A New FMECA-Based tool with RPN threshold estimation

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Risk Assessment of a Wind Turbine: A New FMECA-Based Tool With RPN Threshold Estimation

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ABSTRACT A wind turbine is a complex system used to convert the kinetic energy of the wind into electrical energy. During the turbine design phase, a risk assessment is mandatory to reduce the machine downtime and the Operation & Maintenance cost and to ensure service continuity. This paper proposes a procedure based on Failure Modes, Effects, and Criticality Analysis to take into account every possible criticality that could lead to a turbine shutdown. Currently, a standard procedure to be applied for evaluation of the risk priority number threshold is still not available. Trying to fill this need, this paper proposes a new approach for the Risk Priority Number (RPN) prioritization based on a statistical analysis and compares the proposed method with the only three quantitative prioritization techniques found in literature. The proposed procedure was applied to the electrical and electronic components included in a Spanish 2 MW on-shore wind turbine.

INDEX TERMS Reliability engineering, failure analysis, risk analysis, fault detection, wind energy.

I. INTRODUCTION

Wind energy is one of many renewable energy sources that offer an alternative to burning fossil fuels [1] and is now one of the most widely used sources of renewable energy [2]. Wind energy is popular because of the lower investment cost and well-developed technology compared to the other renewable energy sources [3].

In compliance with WindEurope, (i.e. the Association for Wind Energy in Europe), the European Union (EU) is moving toward renewable energy sources, with hundreds of billions invested in renewable energy development and many new installations. About 95% of all new EU power installations in 2018 were for renewable energy: 19.8GW out of a total 20.7GW of new power capacity [4]. To put this into context, in the last ten years, coal and natural gas have been the main form of power generation in Europe, each with a total installed capacity of 150GW to 200GW [4].

The inevitable power fluctuations represent one of the greatest drawbacks of wind energy, as they introduce serious technical challenges into the electric power grid, such

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as power system quality and reliability, system protection, and power flow control [3]. Moreover, compared to other electricity generation systems, wind turbines (WTs) have relatively higher failure rates because of the harsher operation conditions and higher maintenance costs due to their relative inaccessibility [5].

Consequently, the main purpose of this work is to propose a simple procedure based on the standardized Failure Modes, Effects and Criticality Analysis (FMECA) which must be both cost-effective and cost-efficient. There are few studies on FMECA for wind turbines presented in literature. Some paper simply presents the results of a classical FMEA or FMECA on on-shore or off-shore wind turbine (see for instance but not only [6]–[8]) without explain how to set the optimal risk threshold. Other papers [9], [10] integrate the aspects of traditional FMEA with some economic parameters. Arabian-Hoseynabadi *et al.* [11] presents the results obtained using a suitable FMEA software package. Tavner *et al.* [12] uses the FMECA to compare the prospective reliabilities of three versions of the geared R80 turbine with different drive train solutions. Kahrobaee and Asgarpoor [10] presents a quantitative approach called Risk-Based-FMEA, based on the failure probabilities and incurred failure costs instead of
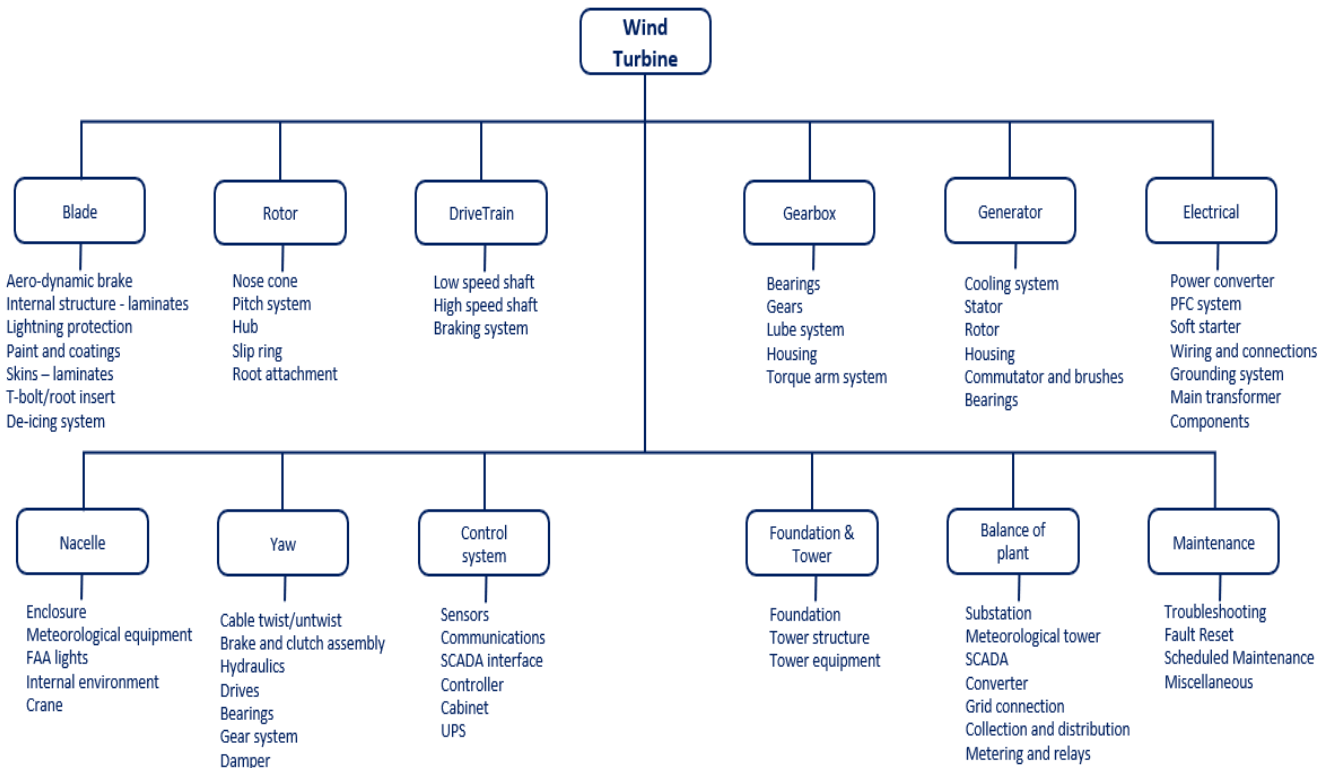
FIGURE 1. Taxonomy classification of the wind turbine under analysis. The turbine is divided in twelve different subsystems, each one composed by several subunits.

rating scales. Dinmohammadi and Shafiee [13] develop a fuzzy-FMEA approach for risk and failure mode analysis in offshore wind turbine systems.

The proposed approach is helpful to identify the most critical components and optimize the maintenance plan in order to reduce the unprogrammed system downtime due to corrective maintenance operation. Moreover, the international standard IEC 608212 [14] that regulate the FMECA technique misses to consider a method to identify a risk threshold and consequently to divide the failure modes in critical modes and negligible modes, as well as the existing literature on FMECA for wind turbine. Therefore, this paper introduces a new approach to evaluate the optimal risk level based on statistical parameters and compares it with three different threshold estimation method found in literature. Finally, the paper proposes a case study to test and validate the potentiality of the proposed methodology. A horizontal-axis wind turbine is a complex system that can be broken down into several subsystems, including nacelle, rotor, tower, and blades [15], [16]. The nacelle is an enclosure containing the electrical/electronic (the topic of this paper) and mechanical components needed to produce electricity (e.g. gearbox, brake, yaw mechanism, generator, control system, etc.).

Following the guidelines provided by the international standard ISO 14224 (2016) [17], figure 1 illustrates the low-level taxonomy of the turbine tested during this analysis (in compliance with [16]). The turbine is divided in twelve different subsystems, and each of them is composed by several

subunits and components. The state of the Art for wind turbine taxonomy is RDS-PP®, however in this paper a different approach was chosen because the classical taxonomy leaded by the guidelines included in the international standard ISO 14224 represents a better solution as initial step to carry out the FMECA procedure.

II. FMECA METHODOLOGY FOR ONSHORE WIND TURBINE

Failure modes and effects analysis (FMEA) is a systematic procedure to identify potential failure modes, their causes, and their effects on system performance [14]. FMECA (Failure Modes, Effects, and Criticality Analysis) is an extension of FMEA to include a means of ranking the risk related to the failure modes to allow prioritization of countermeasures. This is done combining the frequency of occurrence rank (usually called O), the severity measure rank (usually called S) and the detection index (usually called D) as follow [14], [18]:

$$RPN = O \cdot S \cdot D \qquad (1)$$

More details on FMEA and FMECA processes and applications are given in references [19]–[25].

Table 1 summarizes the factors that influence the criticality index and the rules to assess the rating of each one. The table highlights that parameters O, S and D are generally measured on a 10-point scale wherein greater O and S numbers stand for increasing values of the frequency of occurrence and of the severity respectively, whereas D is ranked

TABLE 1. Evaluation criteria for Occurrence, Severity and Detection according to IEC 61508.

Criticality Index	Influence Factor	Rating
Severity S	Effects of the failure on the system, on the operator and on the environment	1 2 3 4 5 6 7 8 9 10 Low Max
Occurrence O	Probability that a failure will happen (failure rate)	1 2 3 4 5 6 7 8 9 10 Low Max
Detection D	Probability of diagnose the failure	1 2 3 4 5 6 7 8 9 10 Max Low

TABLE 2. Proposed evaluation criteria to assess occurrence for a wind turbine.

Occurrence	Rating	Mode failure rate $\lambda^{(M)}$ [h^{-1}]
Remote	1	$\lambda \leq 1 \cdot 10^{-9}$
Low	2	$1 \cdot 10^{-9} < \lambda \leq 5 \cdot 10^{-9}$
	3	$5 \cdot 10^{-9} < \lambda \leq 1 \cdot 10^{-8}$
Moderate	4	$1 \cdot 10^{-8} < \lambda \leq 5 \cdot 10^{-8}$
	5	$5 \cdot 10^{-8} < \lambda \leq 1 \cdot 10^{-7}$
	6	$1 \cdot 10^{-7} < \lambda \leq 5 \cdot 10^{-7}$
High	7	$5 \cdot 10^{-7} < \lambda \leq 1 \cdot 10^{-6}$
	8	$1 \cdot 10^{-6} < \lambda \leq 5 \cdot 10^{-6}$
Very high	9	$5 \cdot 10^{-6} < \lambda \leq 1 \cdot 10^{-5}$
	10	$\lambda > 1 \cdot 10^{-5}$

in a reversers order, namely the higher the detection value, the lower the detection probability of the failure mode. Consequently, the RPN index assumes values within the range from 1 to 1000; a higher RPN indicates the necessity to solve the failure mode with maximum priority.

The FMECA is a powerful tool to carry out a risk analysis [25]. Therefore, this paper discusses the risk assessment using a FMECA tool of a Spanish onshore 2MW wind turbine located in the region of Aragon. As the number of WT installations continues to grow worldwide, the need for fault detection systems is increasingly important. Since most wind turbines are situated on high towers, installed in remote rural areas or offshore, distributed over large geographic regions, exposed to harsh environment, and subject to relatively high failure rates, their maintenance requires significant effort and cost [26]–[31]. A FMECA makes possible to study every possible problem that might arise from malfunctions of the system being tested and to implement the optimal fault detection and diagnosis system. The investigation should start at the lowest taxonomic level and continue to the equipment unit level.

The first phase of the work focuses on the identification of all the failure modes and their respectively causes for each of the electrical and electronical components inside the turbine. Each failure mode can have several failure causes, and every cause must be included in the FMECA final report. Thus, all the possible scenarios will be considered in the risk assessment. This is an important issue because a neglected cause could produce an un-studied situation linked to risk for the environment, the operator and the system itself, with a consequent loss of availability and safety.

The following step is the failure rate evaluation because the failure rate is an important and useful parameter linked to the failure probability and can be used to rank occurrence. The failure mode probability, usually expressed by α, represents the percentage of time that the equipment will fail in a given mode [32].

Thus, if λ is the failure rate of the component, then the mode failure rate $\lambda^{(M)}$ is given by:

$$\lambda^{(M)} = \alpha \cdot \lambda \qquad (2)$$

Table 2 shows the criteria proposed to assess occurrence based on the mode failure rate. As the table shows, occurrence is ranked on a scale from 1 (best case) to 10 (worst case);

this scale appears on standard FMECA forms. The rating is based on the methodology proposed in the international standards IEC 60812 (2006) [33] and IEC 60812 (2018) [14]. In particular, a 1-to-10 scale is assessed, where the higher is the mode failure rate, the higher is the occurrence rate. In order to determine the mode failure rate intervals, data coming from the owner of the wind turbine tested are used. In particular, the minimum and the maximum mode failure rate was used to set the range for occurrence $O = 1$ and occurrence $O = 10$ respectively. The intermediate ranges are determined in such a way to set them with all the same length.

The consequences of each failure mode on system element operation, function, or status need to be identified, evaluated and recorded. Failure effects are classified as local and global effects. The local effects describe the consequences of a failure mode on the operation, function, or status of the specific item under consideration, while the global effects stand for the consequences on the operation, function, or status of the higher-level taxonomy categorization. In this work, it refers to the effects on the nacelle and the whole wind turbine. In addition, this paper includes two effective parameters to evaluate the risk level:

- Turbine functionality: this parameter gives the turbine operational status after the failure:
  - No impact: the turbine continues its work although the failure mode has occurred.
  - No impact in the short term: initially the turbine continues its work with all functionality, but a maintenance action is needed.
  - Reduced: Redundancy and auxiliary systems allow the turbine essential functionality; the turbine continues to provide electricity, but some operations are not available.
  - Strongly reduced: Most operations are not available; the turbine continues to provide electricity with low efficiency.

– Doesn't work: The turbine can't produce electricity.
- Safety loss: This parameter indicates if the failure modes could reduce the safety level, with a consequent risk for the environment, the operator, or the turbine itself.

Table 3 shows the rules to assess severity based on the two previous parameters: turbine functionality and safety loss.

At the initial phase of a project, little information about diagnostic systems is generally available. Therefore, detection is classified on a 3-value scale, from 1 (best case) to 3 (worst case), where 2 represents the partially detectable scenario, as shown in Table 4.

This solution is used to mitigate one of the RPN drawbacks that many papers pointed out, that is the same relative importance of O, S and D in equation (1) [18], [34]–[39]. The use of a 1-3 scale introduces a different importance between the three parameters, saving the nature of the standard RPN and giving more weight to Severity and Occurrence.

According to these ratings, using eq. (1), the RPN can assume value in the interval [1; 300].

III. APPLICATION TO E/E/PE COMPONENTS OF THE WIND TURBINE

The wind turbine tested is a G80/2000 machine manufactured by Gamesa Corporación Tecnológica. The turbine is mounted on the top of a 60-meter tubular tower and is operated by Vestas Wind Systems.

TABLE 3. Proposed evaluation criteria to assess severity for a wind turbine.

Severity	Turbine functionality	Safety loss	Rating
None	No impact	NO	1
None	No impact in short term	NO	2
None	Reduced	NO	3
Moderate	No impact	YES	4
Moderate	No impact in short term	YES	5
Moderate	Strongly reduced	NO	6
High	Reduced	YES	7
High	Turbine doesn't work	NO	8
Hazardous	Strongly reduced	YES	9
Hazardous	Turbine doesn't work	YES	10

TABLE 4. Proposed evaluation criteria to assess detection for a wind turbine.

Criteria	Rating
Completely detectable	1
Partially detectable	2
Impossible to detect	3

This study focuses on the (E/E/PE) components (i.e. electrical/electronic/programmable electronic items) inside the turbine. As Figure 1 shows, all the E/E/PE items are gathered together in two subsystems: the control system and the electrical system.
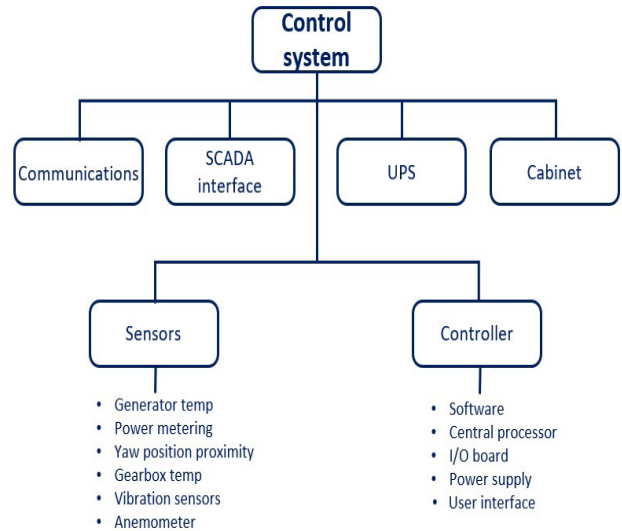

FIGURE 2. Control system taxonomy classification.

Figure 2 shows the taxonomy of the control system level "Equipment unit (6)," as per ISO 14224 [17]. The items inside the top boxes belong to the "Subunit (7)" level; the "Maintainable Items (8)" level boxes are at the bottom of the figure.

The control system is a very critical unit characterized by several purposes, such as:

- To collect information coming from the SCADA (Supervisory Control and Data Acquisition) system and from the other external sensors;
- To communicate with the operating center sending information about the current status of the turbine, including process information and diagnostic data useful for evaluate the health state of the system;
- To process the acquired data in order to manage all the turbine functionalities using the actuators, such as the movement of the nacelle toward the wind direction, the activation of the brake when the wind speed is too high, the management of the gearbox and the generator and so on;

The electrical equipment unit (see Figure 3) is a generic subsystem containing all the electrical components in the turbine, except the generator. The taxonomy of the electrical level, "Equipment unit (6)," shown in Figure 3, contains the following equipment:

- A power converter including an IGBT module, a rectifier bridge, a crowbar system and other discrete components;
- A PFC system used to improve the power factor;
- A soft starter used with AC electrical motors to temporarily reduce the load and torque in the power train and electric current surge of the motor during start-up;

TABLE 5. Extract of the FMECA-tool for the risk assessment of the E/E/PE components of the WT under test.

| ITEM OVERVIEW			STANDARD FMEA				USEFUL PARAMETER					RISK			
Upper level taxonomy	Taxonomy	Function	Failure modes	Failure causes	Local effects	Global effects	Turbine functionality	Safety loss	Failure rate λ_i	α [%]	Mode failure rate	O	S	D	RPN
WT Control system	SCADA Interface	Monitor and control local equipments, store the data in a specific database	No data stored due to HW error	Processor halt Workstation PC fault Server PC fault	No data logging, no info about process state	No impact only if the other sensors are working, otherwise inoperative WT	Strongly reduced	YES	3,00E-07	66,7	2,00E-07	6	9	3	162
			NO data stored due to SW error	Incorrect input data Intruder attack Design fault	Incorrect operation, system crash	No impact only if the other sensors are working, otherwise inoperative WT	Strongly reduced	YES		33,3	1,00E-07	5	9	3	135
WT Control system Controller	Central processor	Elaborate data and manage all the turbine facilities	Input Open	Electrical failure Welding failure	Partial reduction of the control system functionality	Partial WT functionality loss	Strongly reduced	YES		36,0	7,20E-08	5	9	2	90
			Output Open	Electrical failure Loss of power supply Welding failure	Impossibility to manage the actuator	Nacelle can't move	Strongly reduced	YES		36,0	7,20E-08	5	9	2	90
			Supply Open	Power supply damage Facility blackout	Control system can't work	Inoperative WT	Doesn't work	NO	2,00E-07	12,0	2,40E-08	4	8	2	64
			Output Stuck Low	SW error Nearby welding RF interface	Impossibility to manage the actuator	Nacelle can't move	Strongly reduced	YES		9,0	1,80E-08	4	9	2	72
			Output Stuck High	SW error Nearby welding RF interface	Impossibility to manage the actuator	Nacelle can't move	Strongly reduced	YES		8,0	1,60E-08	4	9	2	72
WT Control system Sensors	Anemometer	Measure the speed and the direction of the wind	Erratic Output	Reduced signal level Impedance mismatch A/D conversion error Noise	Nacelle can't be oriented according to the wind direction	Turbine can't work at maximum available power	Reduced	NO	5,00E-07	66,7	3,34E-07	6	3	3	54
			Corrosion	Integrity failure due to the weather Overvibration	Nacelle can't be oriented according to the wind direction	Turbine can't work at maximum available power	Reduced	NO		33,3	1,67E-07	6	3	2	36
WT Electrical PFC	Harmonics filter	Pass current only at center frequency	Center Frequency Drift	Deterioration HF parasitic component	Filter passes current at different frequency, power factor decrease	WT efficiency reduction	Reduced	NO	1,20E-08	80	9,60E-09	3	3	3	27
			No Output	Electrical failure Damage due to Overvoltage Damage of the welding	Current can't pass the filter, no output power	Turbine can't provide output voltage	Strongly reduced	NO		20	2,40E-09	2	6	3	36
WT Electrical Component	Motor contactor	Transmit the electrical current to the motor	All contacts remain in the energized position when the coil is de-energized	Jam Deterioration Error in control signal	Impossible to disconnect the motor	Possible damage of the other equipments	Strongly reduced	NO		25	3,13E-08	4	6	3	72
			All contacts remain in the de-energized position when the coil is energized	Jam Deterioration Error in control signal	Impossible to connect the motor	Turbine can't work	Doesn't work	NO		25	3,13E-08	4	8	3	96
			Contacts will not open/close	Dust Jam Deterioration	Impossible to connect/disconnect the motor	Turbine can't work	Doesn't work	NO	1,25E-07	20	2,50E-08	4	8	3	96
			Short circuit	Dust Electrical failure Deterioration	Motor can't work	Turbine can't work	Doesn't work	NO		20	2,50E-08	4	8	3	96
			Simultaneous closing of normally open and normally closed contacts	Electrical failure Error in control signal	No effects on the motor functionality	-	No impact	NO		10	1,25E-08	4	1	3	12
WT Electrical Power conv	Crowbar system	Prevent an overvoltage condition of a power supply	Fail high/low	Electrical failure Overheating	Possible over voltage or under voltage condition	Possible control system damage	Doesn't work	YES	3,40E-07	53	1,80E-07	6	10	3	180
			No Output	Electrical failure	Power converter can't work	Control system can work only if UPS is working	Strongly reduced	NO		47	1,60E-07	6	6	3	108
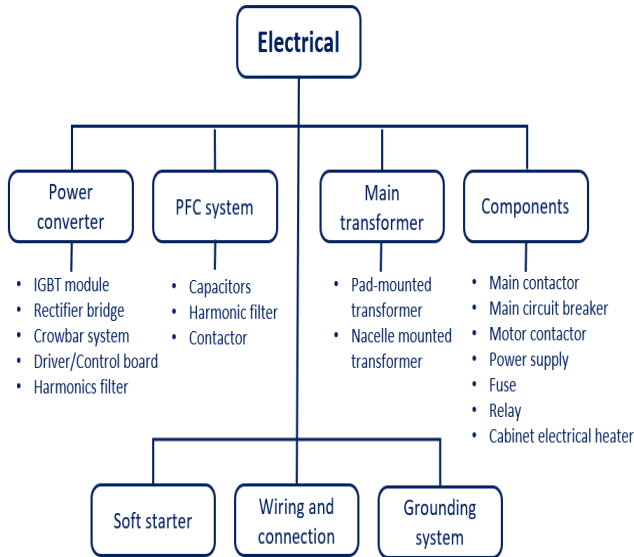
FIGURE 3. Electrical subsystem taxonomy classification.

- A grounding system;
- Transformers;
- Other generic electrical components, such as contactors, relays and so on.

Table 5 shows an extract of the FMECA assessed for the E/E/PE components of the G80/2000 WT. The complete report includes 100 different failure modes: 38 modes refer to the control system, while 62 modes refer to the electrical subunit.

The proposed approach should be carried out at the early phase of the design so that it is more cost-effective and efficient. Field data about components' failures of the turbine under test are not available during design phase, and the statistics available in literature may not be as detailed as necessary for the investigation, therefore are not taken into account. Since there are no specific standards or handbooks containing failure data of wind turbine, then many generic handbooks are used to carry out the functional failure analysis of the G80/2000 WT tested in this work. The main sources are: HDBK-217plus (2015) [40], Telcordia SR-332 (2016) [41], MIL-HDB 338B (1998) [42], IEC TR 62380 (2004) [43], Italtel IRPH (2003) [44] and Siemens SN 29500-1 (2010) [45].

The first section of Table 5 gives an overview of the studied components. The "Upper level taxonomy" column includes the higher hierarchical levels; the "Classification" column shows the current taxonomy level; the "Taxonomy" column identifies the components, and the "Function" column explains the objective of the components. The table has a second section for the standard FMEA procedure including the "Failure Mode", "Failure Cause," and a detailed explanation of the failure effects, as described in the previous section. Some useful parameters are included in the third section, such as the "Turbine functionality" and the "Safety loss" used to assess the "Severity rate" and the mode failure rate
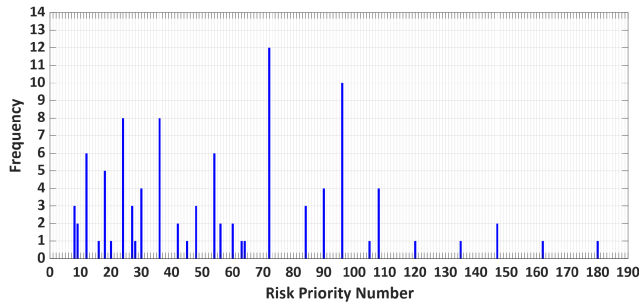
FIGURE 4. Number of occurrences of each RPN assessed for the turbine under test.

FIGURE 5. Evaluation of RPN threshold using Bluvband method.

information used to evaluate the "Occurrence rate". The final section of the table illustrates the risk evaluation carried out assessing the Risk Priority Number using the O, S, and D indexes.

Figure 4 summarizes the complete results of the RPN values assessed for the E/E/PE components of the G80/2000 WT.

IV. RISK THRESHOLD EVALUATION

The components covered by the FMECA procedure are usually very different from a risk value point of view. The most important failure modes, characterized by a high RPN, should be separated from those characterized by a significantly lower RPN value. The selection of "high priority" failure modes is a very critical issue for the development of corrective action plans. The question is: "How can such separation be achieved?"

The international standard IEC 60812 (2018) [14] which define and standardize the FMECA procedure miss to consider a method to evaluate the RPN threshold, as well as recent literature. Usually companies define this threshold using questionnaires to take into account the judgement of multiple experts in qualitative manner. Only three quantitative approaches were found in literature, and they are explained below.

A. BLUVBAND METHOD

Bluvband *et al.* [46] and Bluvband and Grabov [47] recommend the application of a simple but effective graphical tool for RPN analysis. This tool creates a graph of ordered RPN values, much like the Scree Plot used in principal component analysis. Scree Plot settings require preliminary ordering of RPN values by size, from smallest to largest. These values are then plotted by size across the graph. The calculated RPNs usually form a right-skewed distribution, with a first tail on the left (negligible risk values) and a second tail on the right (critical risk values representing "outliers" from the distribution analysis point of view). The long lower part of the plot is characterized by a gradual increase of the RPN values, usually in a straight line $f_1(x)$ with a slight slope. The RPN values scattered around this line should be considered a kind of "information noise", as they do not require immediate attention. The short uppermost part of the Scree Plot is characterized by a very steep increase of the RPN values
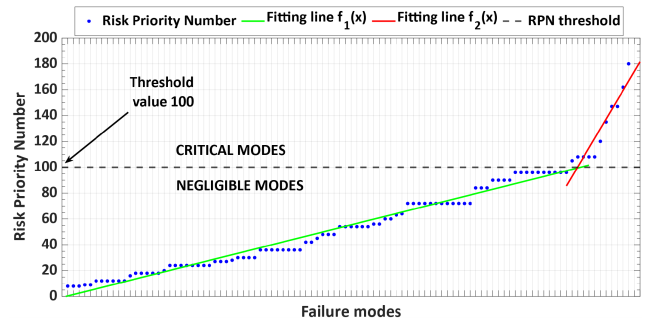
(RPN jumps), in the form of a straight line $f_2(x)$ with a very strong slope. The RPN values scattered around this line are related to the most critical issues of FMECA and must be dealt with promptly. The Risk Priority Numbers evaluated in the previous section were subjected to the Bluvband method to determine the most hazardous failures. The "Curve Fitting Tool" by MATLAB could be used to implement the linear regression method to evaluate the algebraic description of the straight lines $f_1(x)$ and $f_2(x)$. The coefficients in the following equation are evaluated at a 95% confidence level:

$$f_1(x) = p_1 \cdot x + p_2 \quad where \begin{cases} p1 = 1.101 \\ p2 = -0.748 \end{cases} \tag{3}$$

$$f_2(x) = p'_1 \cdot x + p'_2 \quad where \begin{cases} p'_1 = 7.391 \\ p'_2 = -572.3 \end{cases} \tag{4}$$

Note that the slope of the two straight lines $f_1(x)$ and $f_2(x)$ is considerably different. In particular, the line that fits the uppermost part of the plot is almost seven times greater than the other line.

$$\Delta_{slope} = \frac{p'_1}{p_1} = \frac{7.391}{1.101} = 6.7130 \tag{5}$$

The results of the proposed method are illustrated in the Scree Plot in Figure 5.

Analysis of the Scree Plot in Figure 5 makes it possible to define an RPN threshold value that represents the division between the negligible failure modes and the critical failure modes from the risk value point of view.

The threshold can be identified by evaluating the ordinate of the intersection between the two fit lines in Figure 5, and the result is approximately 100.

B. ZHAO METHOD

Zhao *et al.* [48] propose an alternative method to evaluate the RPN threshold value as follows:
- Create Scree plot, following the rules explained in Section IV.A.
- Fix the turning point of the RPN plot linear growth trend using the linear regression method. Fit the RPN values into a straight line and obtain the turning point using the confidence interval.
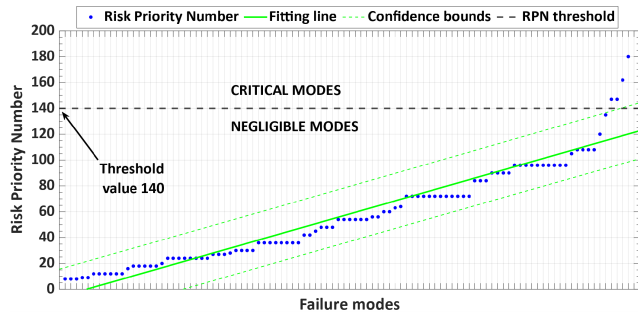
FIGURE 6. Evaluation of RPN threshold using Zhao method.

FIGURE 7. Evaluation of RPN threshold using Pareto chart and 80:20 principle.

- Determine the threshold value of RPN from the turning point.

The results of the procedure applied on the E/E/PE component of the WT under test considering a 95% confidence level are illustrated in the Scree Plot in Figure 6.

The RPN threshold provided by the Zhao procedure using the linear regression method and with a 95% confidence level is approximately 140. The 1st-degree polynomial fitting curve is the following:

$$f_{Zhao}(x) = p_1^z \cdot x + p_2^z \quad where \quad \begin{cases} p_1^z = 1.262 \\ p_2^z = -6.024 \end{cases} \quad (6)$$

C. 80/20 PARETO METHOD
The use of the 80:20 Pareto principle is the most established approach in reliability analysis to rank failure modes according to their RPN value and to optimize corrective actions for critical components. The Pareto diagram is helpful to visualize the differences between the rankings for the failures and effects.

The 80:20 principle can be explained as follow: 80% of the total Risk Priority Numbers calculated during the FMECA procedure comes from only the 20% of the potential failure modes.

Pareto analysis starts with the prioritization of failure modes by ranking them in order, from the highest risk priority number to the lowest. The Pareto chart combines a bar graph with a cumulative line graph; the bars are placed from left to right in descending order, while the cumulative line distribution shows the percent contribution of all preceding failures. The combined chart uses the 80:20 rule to indicate where the engineering effort should be focused more [49]–[56].

The results of the analysis are illustrated in Figure 7. Each blue bar stands for the RPN assessment of the corresponding failure mode (y-scale on the left side of the chart), while the red curve represents the cumulative percentage distribution of the RPN (y-scale on the right side of the chart).

According to the 80:20 rule, the RPN threshold provided by the Pareto chart is approximately 48. Figure 7 shows the evaluation of the threshold using Pareto method. The first step is the identification of the 80% of the cumulative distribution of the Risk Priority Numbers, then the RPN threshold value is
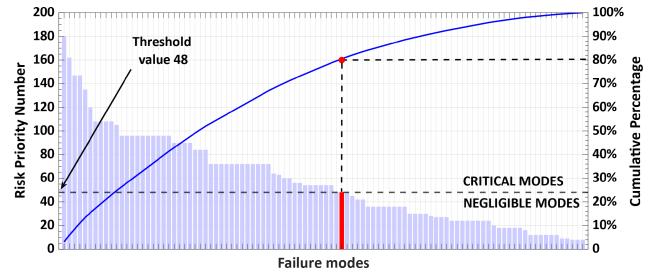
given by the value of the Risk Priority Number of the failure mode linked to the 80% of the cumulative percentage.

V. A NEW APPROACH FOR RPN THRESHOLD EVALUATION
The three procedures analyzed above give quite different results. The Zhao technique suggests considering only four failure modes inside the group of the most critical failure modes (threshold equal to 140), whereas the Bluvband approach recommends considering 11 failure modes inside this group (threshold equal to 100), and the Pareto chart indicates that 55 failure modes are critical (threshold equal to 48).

Analyzing in detail the obtained results, it is clear that all the previous techniques have some critical drawbacks. For instance, according to the 80:20 rule of the Pareto method, 80% of the criticality should arise from 20% of the causes. The study's results suggest this principle does not fit very well with this kind of application. As a matter of fact, 80% of the RPNs of the E/E/PE components in the wind turbine represent 55% of the failure modes. The Pareto chart cannot be considered a powerful technique to identify the RPN threshold of a system, actually the principle used to select the numerical value of the threshold should be reviewed and specifically defined for each kind of application. In this case, it is absolutely not reasonable select a threshold of 48 indicating that more than half of the failure modes are critical.

Quite the opposite, the Zhao method suggests for the system under test that only four failure modes are critical. More generally, this technique provides untrustworthy results for many applications because of the manner in which the threshold is evaluated. In fact, using this procedure very few risk priority numbers overpass the 95% confidence bound falling in the critical modes group.

The Bluvband method provides interesting results, both threshold value and number of modes considered critical is reasonable. Anyway, the procedure for the threshold evaluation is vague and extremely subjective. According to the authors, the calculated RPNs form a right-skewed distribution, with a first tail on the left and a second tail on the right with very different slopes, but no information about how to divide the distribution in two sections are given. As a consequence, the identification of the threshold is dependent on the judgment of the designer that carry out the procedure.

Therefore, a new approach has been introduced to overcomes the limits of the previous methodologies. The proposed procedure consists of the following steps:

1) Calculation of the Risk Priority Numbers according to the guidelines provided in section II;
2) Identification of the main statistical parameters of the RPN set (25th percentile, mean value, median value, 75th percentile, outliers, minimum and maximum value);
3) Generation of the boxplot of all the assessed RPNs;
4) The negligible modes are all the failure modes with RPNs below the median value;
5) The critical modes are all the failure modes with RPNs above the 75th percentile;
6) The interval between the median value and the 75th percentile is considered ALARP ("as low as reasonably practicable") region.

As the acronyms suggests, the ALARP region refers to reducing risk to a level that is as low as reasonably practicable. In practice, this means that the operator has to show through reasoned and supported arguments that there are no other practicable options that could reasonably be adopted to reduce risks further [57].

If a failure mode is characterized by an RPN value that falls inside the ALARP zone, then designers have to analyze possible countermeasures to reduce the risk bearing in mind the benefits resulting from its acceptance and taking into account the costs of any further reduction. Then designers could choose to apply countermeasures or not based on the previous consideration. The upper and lower limits of the ALARP region must be considered as low as reasonably practicable too.

Instead, if the RPN is above the 75th percentile then the risk is regarded as intolerable and cannot be justified in any ordinary circumstance, so corrective actions must be implemented.

The proposed approach was applied to the case study described in the previous sections, and the results of the statistical analysis are the following:

- Range of admissible values [1; 300]
- Minimum: 8
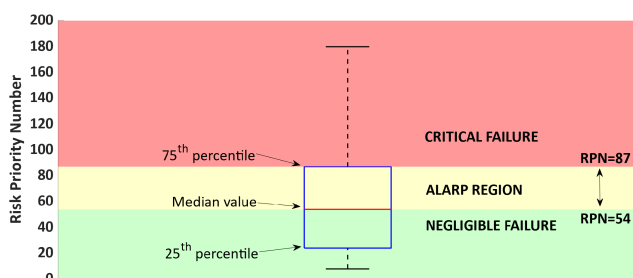- Maximum: 180
- 25th Percentile: 24
- Median: 54

FIGURE 8. Proposed approach for the Risk Priority Number threshold based on boxplot.

TABLE 6. Comparison between proposed method and existing techniques.

Method	Threshold	Critical modes	ALARP
Boxplot	87	25	Between 54 and 87 27 modes
Bluvband	100	11	NOT ALLOWED
Zhao	140	4	NOT ALLOWED
Pareto	48	55	NOT ALLOWED

- 75th Percentile: 87
- Outliers: none (considering outliers all the RPNs more than three standard deviations away from the median).

Figure 8 shows the boxplot of the RPNs for the WT under test, highlighting with different colors the area of interest. The green zone (below the median) stands for the negligible failures, the yellow region represents the ALARP and the red region (above the 75th Percentile) indicate the critical failure modes.

In particular, the proposed method suggests 25 failure modes inside the critical group (RPN higher than 87), 27 failure modes inside the ALARP region and 48 negligible modes (RPN lower than 54).

Table 6 compares the results obtained with the proposed approach and the other methods (100 failure modes were identified in the subsystems under test).

The threshold to identify the critical modes of the proposed approach falls between Bluvband and Pareto method, as well as the number of critical modes. Considering only the red zone of figure 8, the Boxplot method is a more conservative approach respect to the one proposed by Bluvband. Designers must always choose the best solution in terms of cost and risk level. It is generally more advisable to select the worst-case scenario, that is, the procedure providing the lowest RPN threshold, considering a larger number of failure modes in the critical area. In this application, the worst-case scenario is the 80:20 rule applied in the Pareto chart, but it provides not reasonable results in terms of the cost of the corrective actions. Indeed, it is not possible to apply countermeasures on the 55% of the failure. Therefore, the optimal trade-off between cost and threshold level is provided by the proposed method. Moreover, the new technique allows to introduce also an ALARP zone where each mode could be considered critical or negligible, depending on the scenario.

VI. CONCLUSION

This paper focuses on risk assessment of a 2MW onshore wind turbine using a new procedure based on Failure Mode, Effects, and Criticality Analysis.

The proposed procedure starts with a functional failure analysis that is mandatory during the initial phase of the system design to identify every possible failure mode, failure cause, and failure effect related to the component tested.

Every analyzed failure mode is reported in Figure 4 in RPNs in ascending order, highlighting the frequency of the repetition of each RPN value.

To separate the failure modes into critical and negligible failures, the paper compares three different RPN prioritization procedures: the 80:20 rule applied in the Pareto chart and two graphical procedures proposed respectively by Bluvband and Zhao. The Bluvband method includes 11 failure modes inside the group of the most critical failure modes, but the procedure is vague and extremely subjective. The Zhao method is too optimistic because it provides only two critical modes. The Pareto chart is just the opposite; it is too conservative and considers more than 50% of failure modes as critical. This is mainly linked to the way the Pareto method is defined and evaluated. In theory, the 80:20 rule suggests that 80% of the criticality should arise from 20% of the causes, therefore considering the 80% as threshold value the 20% of the modes should be critical. Actually, the case study presented in this paper highlights that this is not true. With this kind of dataset, the 80:20 relationship is not verified, and the number of critical modes is much higher than the 20%, leading to inaccurate and too conservative results.

Therefore, this paper introduces a new approach based on a statistical analysis and a boxplot to separate negligible and critical modes. The proposed methodology represents the optimal trade-off between cost and threshold level, and it has several advantages:

- It is an easy, practical and repeatable solution;
- Unlike other methods it takes into account the ALARP region;
- It is based on statistical analysis;
- It suffers no subjectivity in threshold definition.

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