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A progressive study into Offshore Wind Farm Maintenance Optimisation using Risk Based Failure Analysis

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Abstract

Offshore Wind Farm consists of an array of Wind Turbines electrical, communication, command and control systems. At present the cost of maintaining Wind Turbines in the offshore locations is very high (about 35% of lifetime costs). This work puts emphasis on using failure analysis as a basis for designing a condition based prognostic maintenance plan in order to control cost of power and make maintenance more efficient. An essential aspect of such failure analysis is to identify wind turbine components, ascertain their failures and find root causes of the failures. However as a first step, identification of prominent failures in the critical assemblies of a wind turbine using available inspection methods and making provisions to control their occurrence would make significant contribution in improving wind turbine reliability. This work introduces Failure Modes Effects and Criticality Analysis (FMECA) as an important failure analysis tool that has in the past successfully benefitted the airlines, marine, nuclear and spacecraft industries. FMECA is a structured failure analysis technique that can also evaluate the risk and priority number of a failure and hence assist in prioritising maintenance works. The work shows, how with a slight modification of the existing FMECA method, a very useful failure analysis method can be developed for offshore wind turbines including its operational uniqueness. This work further proposes modifying the format for calculating the Risk Priority Number (RPN) for wind turbine failure. By using wind turbine gearbox as a case study, this work illustrates the usefulness of RPN number in identifying failures which can assist in designing cost effective maintenance plan. Some preliminary results of a FMECA tool that has been developed to automatically evaluate the effects and criticality of a failure in a wind turbine at the component level is included.

Keywords: *FMECA, offshore wind turbine, optimal maintenance, consequences of failure, RPN Number*

1. Introduction

1.1. Background

Primarily there are three maintenance schemes: Time Based Maintenance (TBM), Failure Based Maintenance (FBM) and Condition Based Maintenance (CBM). In TBM and FBM schemes, maintenance is performed at fixed intervals and on machine failures respectively, however in CBM maintenance is performed based on the condition of machine components. So while in TBM simple failures may get aggravated and result in long downtimes, and in FBM, maintenance planning for every failure increases the overall operations cost, CBM has on many occasions proved to be an economical maintenance scheme that has utilised resources efficiently[1,2,3,4]. However for CBM maintenance scheme it is important that information about the condition of machine components are as accurate as possible so that a simple (severe) failure can be economically serviced without them turning into a severe (catastrophic) failure. For CBM it is equally important that a database exists that contains categorisation and ranking of all major failures so that in the event of a failure such database can be referenced to readily determine the consequences of a failure. Such a database can be made by analysing failures right at the machine component level. So failure analysis is the first step in planning for a prognostic CBM so as to make maintenance more economical.

(a) (b) (c) (d) (e) (f) (g)

Figure 1. Examples of visual inspection of wind turbine gearbox (a) Air Breather Filter (oily), (b) ring Gear Intermediate Shaft (Pitting), (c) Planet Gear Low Speed Side (Meshing Interference), (d) Pinion Intermediate Speed Shaft (heavy corrosion), (e) Pinion High Speed Shaft (Pitting), (f) Oil Level Indicator (low oil level), (g) Intermediate Shaft Bearing Generator Side (Heavy Pitting) (Pictures: Stork Technical Services, Aberdeen)

The above pictures (Figure 1) show examples of failures in a wind turbine gearbox. By observing the extent of failure and by finding the impact of such failure from failure analysis, valuable information about the consequences of a failure can be obtained which can then be used to plan for maintenance. Failure analysis can also help ascertain the nature and root causes of a failure and its effects, clues which can assist in redesigning and manufacturing better machine parts or to incorporate compensatory provisions. The next section shows how failure analysis can economise maintenance.

1.2. Role of Failure Analysis in economising maintenance

Some major advantages of failure analysis in the economisation of machine maintenance are:

- Capable of identifying the root cause of a failure
- Assist in designing control systems to mitigate failures/effects
- Improve product designs[5]
- Ascertain the damage caused by failure on machine (low, medium, sever etc.)
- Ascertain the local and widespread impact of a failure in the machine
- Analyse performance changes due to failures
- Ascertain downtime and estimation of maintenance costs
- Provides rational for maintenance implementation
- Improves the reliability of the overall system without incurring appreciable downtime

However there are some limitations to failure analysis, and they are:

- It is probabilistic and subjective as it is largely based on personal experiences and knowledge
- Inaccurate failure analysis can results in under- or over maintenance and hence increase costs
- Failure caused due to combined effect of many reasons is difficult to analyse using such technique
- It is a time consuming and repetitive process and needs periodic updating

A major advantage of having a reference database containing failure analysis results is that by having knowledge about a failure and its consequences, arrangements can be made for maintenance prior to the time of actual failure. Under ideal situations, a time should be chosen when consequences of the failure do not outweigh the benefits of maintenance so that the lifetime maintenance cost is as economical as possible. A decision flow diagram for maintenance planning upon detecting adverse consequences of failures in a wind farm is shown in Figure 2. It can be inferred from Figure 2 that maintenance in itself is a useful aspect of failure analysis which reduces the consequences of failure.

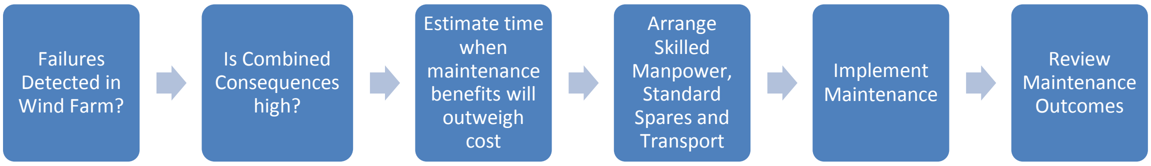


Figure 2 A decision flow diagram for maintenance using CBM

1.3. Failure Modes Effects and Criticality Analysis (FMECA)

Several failure analysis methods and tools are now available to identify the reasons machine components do not work well. Some of them are: Cause-Consequence Analysis, Checklist Analysis, Event Tree Analysis, Fault Tree Analysis, Hazard & Operability Analysis, Failure Modes and Effects Analysis (FMEA), Failure Modes Effects and Criticality Analysis (FMECA), What-If Analysis, etc.[6]. FMECA[7] was initially designed for the aviation sector which later was also used in the nuclear, railways, marine and many other risk based industries. A distinctive advantage of FMECA is its highly sequential and structured approach towards finding the effect, severity and consequence of a failure. FMECA is a 2 step process - (1) Failure Modes and Effects Analysis (FMEA), and (2) Criticality Analysis (CA). The process for performing FMEA and CA are given below in Step 1 and Step 2.

STEP 1: FMEA

- Define system, find its subsystems and components and make their block diagram
- Identify failure modes and failures for each block diagram
- Analyse local and high level effect of such failures
- Identify failure detection, isolation, compensation and resolution techniques
- Evaluate the after effects of failure resolution

STEP 2: CA

- **Qualitative Approach (when data is unavailable)** – Rank failures into 5 levels according to occurrence. Level A – Frequent, Level B – Probable, Level C – Occasional, Level D – Remote, Level E – Unlikely
- **Quantitative Approach (when data is available)** – Rank failures according to Criticality Number, where

$$\textbf{Criticality Number } (C_m) = \beta\,\alpha\,\lambda\,t, \textbf{ Item Criticality Number} = \Sigma\,(C_m) \qquad \textbf{Equation 1}$$

Where, β = Failure Effect Probability, α = Failure Mode Ratio, λ = Part Failure Rate, t = Operating Time

Ranking failures according to their risk is vital information obtained from FMECA. Unlike *Criticality Number* (Equation 1), which is used to rank machine parts according to their criticality, *Risk Priority Number (RPN)* is used to rank failures according to their Severity, Occurrence and Detection. RPN number is calculated using Equation 2 where Severity denotes the extent of consequences of a failure, Occurrence denotes the likelihood of a failure and Detection denotes the ease of detecting a failure. For values of Severity, Occurrence and Detection (S,O,D), several references exists with different types of rankings, one amongst which is given in Table 1. According to this table, RPN values vary from 1 and 1000 and denote an increasing trend towards the need for maintenance.

$$\boldsymbol{Risk\ Priority\ Number = Severity * Occurance * Detection} \qquad \textbf{Equation 2}$$

Rating	Severity (S)	Occurrence (O)		Detection (D)
		Probability	Description	
1	Effect is not noticed	$< 10^{-5}$	Extremely Less	Certain
2	Very slight effect noticed	10^{-5}	Remote	Very high
3	Slight effect causing annoyance	10^{-5}	Very Slight	High
4	Slight effect causing return of product	$4*10^{-4}$	Slight	Moderate
5	Moderate Effect causing return of product	$2*10^{-3}$	Occasional	Medium
6	Significant Effect	$1*10^{-2}$	Moderate	Low Chance
7	Major Effect	$4*10^{-2}$	Frequent	Slight
8	Extreme Effect, system inoperable, safety issue	0.20	High	Remote
9	Critical Effect, System shutdown, Safety risk	0.33	Very High	Very Remote
10	Hazardous, Without warning, life threatening	>=0.5	Extremely High	No Chance, no inspection

Table 1 Rating of Severity, Occurrence and Detection[8]

1.4. Wind, Wind Farm and Wind Turbines

Wind energy is a universally available perpetual reserve of abundant power that is convertible into electricity using the Wind Turbines. United Kingdom is rich in its terrestrial and oceanic winds that has resulted in the installation of many wind farms in the onshore (6.4 GW, growth rate 17%/year) and offshore (3.6 GW, growth rate 46%/year) locations[9]. However in-spite of increasing wind farm numbers, maintenance on average can cost up to 35% of the total costs (even more in some cases). It is estimated that wind farm maintenance would cost over 2 billion pounds each year by 2020[10] in the United Kingdom alone and hence there is acute requirement to control such high maintenance costs.

A primary reason for such high costs is our limited understanding of wind turbine failures in the open spaces, especially in the offshore locations where we still need a reliability database. A preliminary requirement to control this cost is by making turbines components more resilient towards failure while operating in the outdoor conditions, a requirement which can be achieved by analysing wind turbine failures and making suitable recommendations to improve component design, replace component with changed specifications or proactively maintain its critical assemblies to reduce downtime. The first step of this process is to identify components of wind turbine and then analyse its component level failures. EU FP7 ReliaWind Consortium proposed a list of wind turbine parts that it grouped into subsystem, assembly, subassembly and components, where wind turbine was treated as a system. An abridged list of this proposal is given in Table 2 that shows different subsystems, assemblies etc. for a wind turbine. Although many components of this list can be further bifurcated, primarily those which are costly, however such information is useful to start a failure analysis.

SYSTEM (WIND TURBINE)			
SUBSYSTEMS	ASSEMBLIES	SUBASSEMBLIES	COMPONENTS
Drive Train Module	Gearbox	Bearing	Hose, Pump, Radiator, Thermostat, Motor
Electrical Module	Generator	Cooling System	Bushing, Case, Mounting, Torque Arm
Nacelle Module	Main Shaft Set	Lubrication System	Filter, Debris/Level/Pressure/Temp Sensor
Rotor Module	Auxiliary Electrical System	Metrological / Nacelle/ other Sensors	Fan, Resistance Controller, Lamination
Support Structure	Control & Communication System	Rotor / Stator	Slip Ring, Encoder, Wattmeter, Magnet
Collection System	Frequency Converter	Structural & Mechanical	Coupling, Rotor Lock, Shaft, Transformer
Metrological System	Power Electrical System	High / Low Speed Side	High speed / position sensor, Fan, Fuse
Substation	Hydraulic System	Mechanical Brake	Relay, Switch, Power Point, Pushbutton
	Nacelle Auxiliary	Electrical Services	Space Heater, Surge Arrester, UPS
	Yaw System	Lightening Protection System	Circuit Breaker, Cable, Analogue Digital I/O
	Blade	Ancillary Equipment	Data logger, Protocol Adapter Card, CPU
	Pitch System	Communication System	Watch Dog Unit, Control Software
	Foundation	Condition Monitoring System	Power / Vibration / Watch Dog Switches

Table 2 An abridged listing of EU FP7 ReliaWind Consortium proposed wind turbine parts

More than 150 different types of components are listed for a wind turbine by the EU FP7 ReliaWind Consortium. So if on average each component is assumed to fail in 5 different failure modes and each failure mode is assumed to have about 5 different root causes, there would be a total of about 3750 types of failures for analysis purpose. In view of the accuracy required from failure analysis and for the fact that failure analysis of about 3750 instances of failure is time consuming, costly to perform and requires association of maintenance professionals, few critical assemblies can be identified in a wind turbine and a failure analysis can for done on them as a starting point. Such failure analysis framework can then act as precedence for other assemblies. The next section aims to identify the main critical assemblies in a wind turbine.

2. Results

2.1. Identification of Wind Turbine Cost and Operation Critical Assemblies (WT-COCA)

Identification of critical assemblies has operational advantages as maintenance can be prioritised for those prized assemblies of the wind turbine that will assist in significantly cutting down the consequences arising from downtime, spares requirement and the overall maintenance costs. Wind Turbine Cost and Operation Critical Assemblies (WT-COCA) is a name given to a group of wind turbine assemblies which satisfy majority of the following criterions.

- High maintenance cost
- Failure causes high downtime
- Components critical for operation
- High cost of spares / replacement, and
- High frequency of failure

In Table 3, a comparison has been made between the wind turbine nacelle assemblies to find WT-COCAs. Wind Turbine tower and foundation assembly failures are not considered in this work. It can be observed from Table 3 that Gearbox and Generator assemblies satisfy the conditions for being WT-COCA.

Parameter / Assembly	Maintenance Cost	Spares Cost	Failure Downtime	Failure Frequency	Critical for Operation
Gearbox	Very High	Very High	Very High	Medium	Very High
Generator	Very High	Medium	Very High	High	Very High
Main Shaft Set	High	High	High	Low	Very High
Auxiliary Electrical Sys.	Medium	Low	Low	Very High	Medium
Control & Communication	Low	Low	Low	Low	Very High
Frequency Converter	Medium	Low	Low	Low	High
Power Electrical System	Low	Low	Low	High	Medium
Hydraulic System	Low	Low	Low	Medium	Low
Nacelle Auxiliary	High	Medium	Medium	Low	Medium
Yaw System	High	High	High	Low	High
Blade	Very High	Very High	Very High	Low	Very High
Pitch System	High	High	High	Low	High

Table 3 Identifying COCA in Wind Turbine

Above result is supported by another study[11] where Gearbox and Generator were found to contribute towards the highest downtime and failures in a year and whose results are shown in Figure 3.

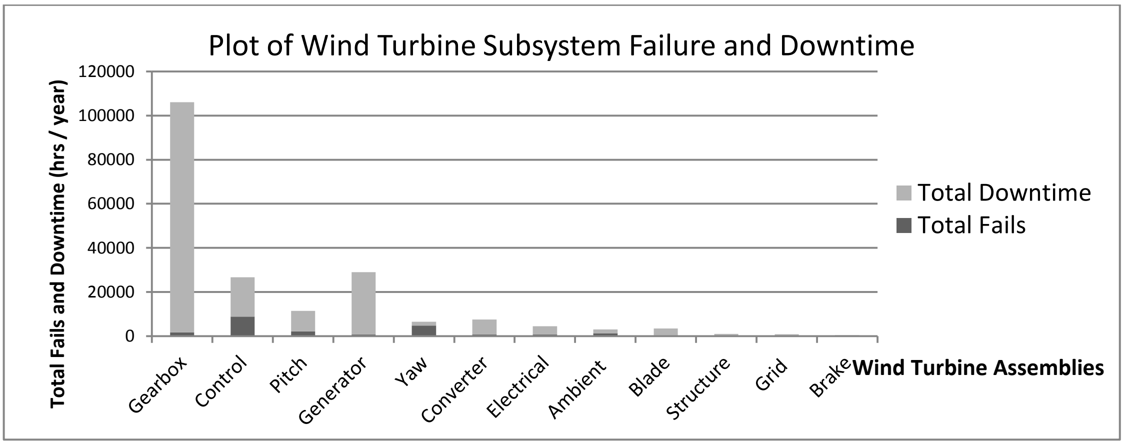


Figure 3 Plot of Wind Turbine subsystem failure and downtime (Quail, 2012)

There were some other studies as well which showed similar results based on their failure patterns. One study found that the Pitch System, Frequency Converter, Yaw System, Control System, Generator and Gearbox Assemblies were WT-COCA[12], while another study has reported Blade, Generator, Gearbox, Electrical System and Yaw System to be the WT-COCA[13] while yet another study has identified Electrical System, Rotor, Frequency Converter, Generator, Hydraulics System and Gearbox[14] to be the WT-COCA, and many other studies also supported such findings. Such studies show that irrespective of wind turbine model and operating conditions, Gearbox and Generator were the common WT-COCA assemblies, results that support observation from Table 3.

Electrical Systems have been often reported to be a major contributor of the most frequent failures in a wind turbine, contributing around 25%[15]- 45%[16] of all reported failures in some of the cases. Although inexpensive to repair, replace and maintain, as compared to Gearbox and Generator parts, frequent repairs in the offshore location can be very costly and add to the wind turbine lifetime costs. So, there is a need to devise compensatory provisions (fail safe systems) for electrical components so that frequency of offshore visits can be controlled. There is a need to prioritise Gearbox, Generator and the Electrical System works in order to optimise wind turbine maintenance. To limit the scope of this paper this work will only consider wind turbine Gearbox as a test specimen to demonstrate the usefulness of failure analysis.

2.2. Prerequisites from Failure Analysis of Wind Turbines

For failure analysis to be of real use in wind turbines and to assist in designing an economical maintenance plan, failure analysis needs to answer, as reasonably as possible, many additional questions which were not asked in the traditional FMECA. They have been listed below.

- What is the effect of external agents (wind, temperature, water wave) on a failure?
- How do time varying operating conditions affect a failure?
- Can we identify all major agents that can act together to cause a failure?
- Can we identify qualitatively predicted failures relating to duration a wind turbine is in operation
- How much time will it take for a typical repair to be done (MTTR)?
- If maintenance is deferred, what effect it has on the operation with time?
- Can we rank failures using other schemes as may be useful for wind turbine maintenance?

In addition to such prerequisites, inherent deficiencies in traditional FMECA also need solution, like:

- ***Subjectivity***: Numbers chosen for (S, O, D) from Table 1 are based on individual's perception of failure and hence RPN values differ with people and across industries
- ***Prognostic Approach***: Current format is based on analysing the present condition of component failure only and no estimate is made to find component condition at a future time
- ***Influence of External Agents***: Current format is incapable of analysing failures arising from the influence of many agents at a single time
- ***Internal Agents***: Current format is incapable of proposing the effect on failure if some parameter change abruptly

Hence, from wind turbine perspective, there is a need to expand upon the conventional FMECA technique of failure analysis and accommodate new fields to cater to the novel requirements of wind turbine. The next section discusses such fields in FMECA.

2.3. Proposed FMECA Method for Wind Turbine Failure Analysis

The above section discussed about the various fields that are necessary for analysing wind turbine failures. This section aims to recommend a structure of FMECA to analyse wind turbine failure that incorporates the above requirements. This is given in Table 4 that is subdivided into:

- *Define System – Identify different parts of a generic wind turbine*
- *Define Failure – Identify the nature and type of failures in different parts of wind turbine*
- *Root Cause – Identify the root causes of failures*
- *Effect of Agents – Identify the effect of different agents on failure, like humidity, temperature etc.*
- *Effect of Prolonging Upkeep Work – find the effect of postponing maintenance on failure*
- *Futuristic Condition of Failure – identify the future condition of a failure if servicing is postponed*
- *Failure Effect Analysis – identify the effect of a failure*
- *Resolve Failure – identify techniques to detect and resolve failures*
- *Quantitative Analysis – when prior failure data is unavailable, evaluate the likelihood of the failure*
- *Qualitative Analysis – when data is available, statistically determine the key failing components*
- *RPN Number – evaluate the ranking of a failure*

- *Costs – Evaluate the costs associated with maintenance or no maintenance*
- *Prioritising Failures – rank failures according to failure effect, future condition, RPN number etc.*
- *Risk – Identify if the failure is prone to human error, specification conflict and management error*

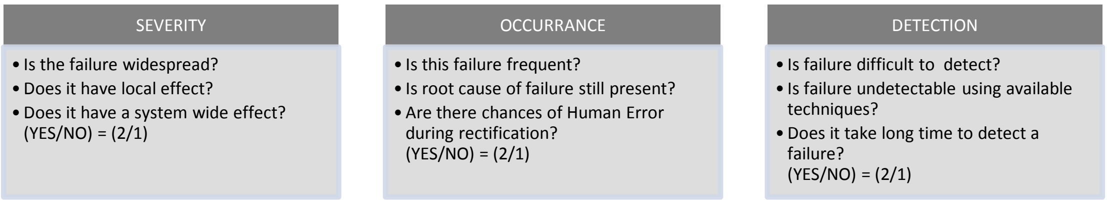
	Fields		Fields		Fields
Define System	Subsystem	Futuristic Condition of Failure	Time	Qualitative Analysis	Level A – Frequent
	Assembly		Effect of Failure Causes		Level B– Reasonably Probable
	Sub-Assembly		Effect of Subassembly		Level C – Occasional
	Component		Effect of Assembly		Level D – Remote
Define Failure	Description		Effect of Subsystem		Level E - Unlikely
	Mode	Failure Effect Analysis	Effect on Component	RPN Number	Severity
	Nature		Effect on Subassembly		Occurrence
	Type		Effect on Assembly		Detection
Root Cause	Cause 1		Effect on Wind Turbine		RPN Number
	Cause 2	Resolve Failure	Detection Method	Costs	Spares
	Cause 3		Isolation Method		Services
	Primary Cause		Compensation Method		Transport
Effect of Agents	Wind		Rectification Method		Miscellaneous
	Humidity		MTTR	Prioritising Failures	According to Effect
	Water Waves	Quantitative Analysis	Failure Effect Probability		According to Future Conditions
	Temperature		Failure Mode Ratio		According to RPN Value
Effect of Prolonging Upkeep	Effect on Failure		Part Failure Rate		According to Maintenance Cost
	System Performance		Operating Time		According to MTTR
	Consequences Rating		Criticality Number		Prevailing Future Condition
	Downtime		Item Criticality Number	Risk	Prone to Human Error?
	MTTR		System Criticality Number		Prone to Specification Conflict?
	Maintenance Cost		Wind Farm Criticality Number		Prone to management Error?

Table 4 Lists Recommended Fields for Analysing Wind Turbine failure

RPN values for prioritising failures is a subjective technique whose value varies with the choice of the reference table[17,18,19] and the skillsets of the user. Based on user preferences, the value of RPN may range tremendously. For example a variation of 1 point in each of the values of (S,O,D = 4,6,4) taken from Table 1 would result in a changed RPN value of 175 (S,O,D = 5,7,5) instead of 64, an increase of about 3 times the original RPN number. Such an ambiguity in failure analysis can lead to over and under maintenance of machines. In situations involving high costs, such deviating results could hinder identification and prioritisation of components needing repairs. Hence there is a need to reduce such subjectivity without affecting the accuracy and importance of RPN value. The scope of such work should incorporate:

1. Limiting the number of levels to fewer options
2. Investigate into a general value system for Severity, Occurrence and Detection
3. Limits the upper bound of RPN to a maximum value, and
4. Design a scheme that improves coherence between RPN values calculated by different users

A scheme is proposed below to provide a value to Severity, Occurrence and Detection. In this scheme (Figure 4) three relevant questions are asked under each category with an expected answer of either 'YES' (Value = 2) or 'NO' (Value = 1). The answers to each of the questions under (S,O,D) headings are then multiplied to give RPN value. So the minimum and maximum values of (S,O,D) would be (1,1,1) and (8,8,8), that would give RPN values (Equation 1) of 1 and 512. By restricting the number of possible answers it is more likely that a coherent RPN values can be obtained (Table 5). In order to improve the accuracy of RPN number, these questions would need to be customised for different components. For example questions related to Severity (Figure 4) may be quite right for bearing and casing, however for an electrical system such questions can change to "Does failure result in complete loss of power generation?", "Can we detect current?" and "Is output available on screen?".



SEVERITY
- Is the failure widespread?
- Does it have local effect?
- Does it have a system wide effect?
(YES/NO) = (2/1)

OCCURRANCE
- Is this failure frequent?
- Is root cause of failure still present?
- Are there chances of Human Error during rectification?
(YES/NO) = (2/1)

DETECTION
- Is failure difficult to detect?
- Is failure undetectable using available techniques?
- Does it take long time to detect a failure?
(YES/NO) = (2/1)

Figure 4 A new scheme to provide values to (S,O,D)

2.4. Failure Analysis of Wind Turbine Gearbox

In Figure 5 a functional block diagram of a gearbox has been shown along with its lubricating and cooling systems but without sensors. It can be seen that a failure in either of the Couplers, bearing, shaft, gear, case, mounting etc. will directly lead to the failure of the whole system. An abridged failure analysis is shown in Table 5 for a gearbox for brevity. From Table 5 we can identify different types of failure modes, their root causes and determine the RPN number of these failures. RPN number evaluated by the traditional (Table 1) and the modified schema (Section 2.3) are compared in the Table 5. By comparing the RPN values from the two systems we can see that housing mounting upon excessive play would determine the maximum value of RPN in the traditional system (196), according to the proposed system housing adjustment (128) would rank higher in terms of failure RPN number. Service personal can greatly benefit by the use of the recommended system.

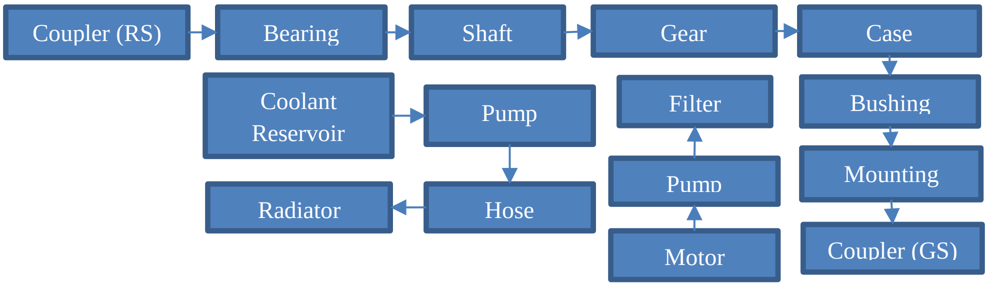


Figure 5 A functional block diagram of a gearbox assembly

3. A Software Tool to find FMECA of Wind Turbine failure

A software tool has been designed using C# programing language and SQL database. A database has been designed using the fields shown in Table 4 that acts as an easy reference for evaluating the effect, risk and service cost for a failure in a wind turbine. In its present form this tool can only show the generic failures of wind turbine components but that needs to be updated in time as wind turbine failures data becomes available. This tool is generic and as it is capable of evaluating the key fields of FMECA. Some screenshots of this FMECA tool is shown in Figure 6 where it is seen that failure probability for a rotor exciter is 0.5 while for a hollow shaft is 0.33.

4. Conclusion

Wind Turbine maintenance is costly as they operate in uncontrolled environments where failure can occur due to internal/external reasons or their mixture. this study lists the limitations of using traditional FMECA method. It further broaden the utility of FMECA technique by incorporating additional fields and hence make it more useful in making maintenance decisions for wind turbines. A new system for allocating values to Severity, Occurrence and Detection was seen to provide better results to evaluate the RPN number. Since management and analysis of big database, such as a FMECA database for wind turbine, is quite labour intensive work, a need was felt for construction of a tool to study this database. This work shows evidence of a software tool that is designed to assist in studying the database.

5. Acknowledgement

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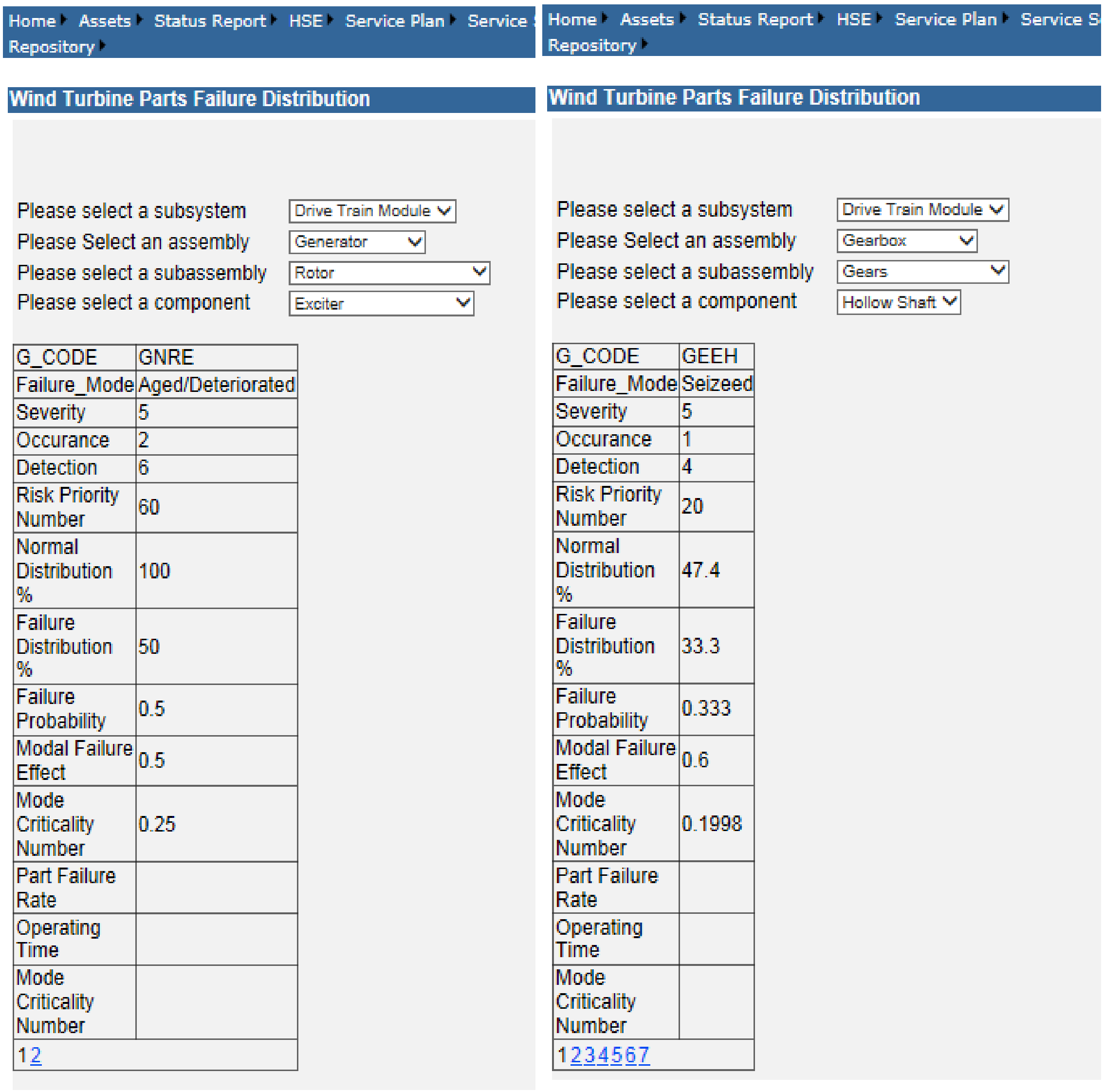
Table 5 An abridged FMECA for Wind Turbine COCA - Gearbox

Sub Assembly	**Component**	Failure Mode	Cause	Traditional (S,O,D)	Proposed (S,O,D)	Traditional RPN	Proposed RPN
Bearing	X	Worn	Worn Out, Fatigue	(5,3,6)	(4,2,1)	90	9
Bearing	X	Binding/Sticking	Binding, Sticking, Seized, Jammed	(7,2,4)	(4,2,1)	56	8
Bearing	X	Excessive Play	Worn-Excessive Play	(5,2,7)	(8,1,4)	70	32
Bearing	X	Loss of Lubrication	Lubricant Dried Out	(7,3,3)	(8,1,1)	63	8
Cooling System	Hose	Broken	Broken	(3,1,2)	(2,1,1)	6	2
Cooling System	Hose	Worn	Worn Out	(3,1,6)	(1,1,1)	18	1
Cooling System	Hose	Cracked/Fractured	Cracked/fractured	(3,2,3)	(2,1,1)	18	2
Cooling System	Hose	Leaking	Leaking	(4,1,3)	(2,1,1)	12	2
Cooling System	Pump	Leaking	Leak, Leaking	(2,1,5)	(4,2,1)	10	8
Cooling System	Pump	No Operation	No Transmission, Catastrophic-Failure While Running	(7,3,3)	(8,1,1)	63	8
Cooling System	Pump	Shorted	Short	(5,2,4)	(8,2,1)	40	16
Cooling System	Radiator	Leaking	Internal Leak	(3,3,5)	(2,1,2)	45	4
Cooling System	Radiator	Out of Adjustment	Needs Adjustment/Out of Adjustment	(3,2,8)	(2,2,2)	48	8
Cooling System	Radiator	Needs Replacement	Needs replacement	(3,3,5)	(2,2,2)	45	8
Cooling System	Reservoir	Leaking	Leaking	(3,2,2)	(4,2,2)	12	16
Gears	Hollow Shaft	Seized	Worn Shaft/Keyway, Seized	(8,2,8)	(8,4,1)	128	32
Gears	Hollow Shaft	Cracked, Fractured	Cracked, Fractured	(7,2,7)	(8,4,2)	98	64
Gears	Hollow Shaft	Bent, Dented, Warped	Warped	(7,3,6)	(4,4,4)	126	64
Housing	Bushing	Loose	Vibration, Loose Screw, Misfire	(5,2,9)	(2,2,2)	90	8
Housing	Bushing	Corroded	Corroded, Seized	(1,2,3)	(2,2,2)	6	8
Housing	Case	Cracked, Fractured	Cracked, Vibration Cracked	(7,2,7)	(2,2,4)	98	16
Housing	Case	Out of Adjustment	Out of Adjustment	(5,3,7)	(8,4,4)	105	128
Housing	Case	Broken	Broken, Damaged	(8,2,8)	(4,2,2)	128	16
Housing	Mounting	Excessive Play	Internal Failure, Excessive Play	(7,4,7)	(4,2,8)	196	64
Lubrication System	Motor	Broken	Broken	(3,5,4)	(2,2,2)	60	8
Lubrication System	Motor	Excessive Play	Internal Failure, Excessive Play, No Failure, Excessive Play	(4,2,2)	(4,2,2)	16	16
Lubrication System	Motor	Aged/Deteriorated	Aged, Deteriorated, Leaking Hydraulic Oil, Unserviceable, Aged	(6,3,4)	(4,2,2)	72	16
Lubrication System	Filter	Broken	Broken Damaged, Part Struck	(7,4,3)	(8,2,4)	84	64
Lubrication System	Filter	Cracked/Fractured	Part Struck-cracked	(4,3,5)	(2,4,2)	60	16
Lubrication System	Filter	Aged/Deteriorated	Deteriorated/Aged - Cracked	(3,3,6)	(4,1,2)	54	8
Lubrication System	Pump	Fails during Operation	Catastrophic Fails while running	(3,5,3)	(2,2,1)	45	4
Lubrication System	Pump	Degraded Operation	Degraded	(6,3,5)	(2,1,2)	90	4
Sensors	Debris	Zero or Maximum Output	Catastrophic -Zero or Maximum output	(4,2,5)	(2,4,4)	40	32
Sensors	Oil Level	Degraded Output	Erratic Output, High/Low Value	(6,2,6)	(4,1,2)	72	8
Sensors	Pressure	No Operation	No Function with Signal	(8,2,4)	(4,4,4)	64	64
Sensors	Temperature	Change in Resistance	Low Resistance Value	(6,3,2)	(1,2,2)	36	4

It is seen from above analysis that many high ranking failures in the traditional RPN system were actually countered by the proposed RPN system. The questions asked during the analysis constrains a user to focus on the problem and investigate further, thereby getting to know more about the failure. It is also reasonably possible to assume that in such circumstances chances of two users getting wide spread RPN values is less which thus brings coherence in RPN number system.



Please select a subsystem: Drive Train Module
Please Select an assembly: Generator
Please select a subassembly: Rotor
Please select a component: Exciter

G_CODE	GNRE
Failure_Mode	Aged/Deteriorated
Severity	5
Occurance	2
Detection	6
Risk Priority Number	60
Normal Distribution %	100
Failure Distribution %	50
Failure Probability	0.5
Modal Failure Effect	0.5
Mode Criticality Number	0.25
Part Failure Rate	
Operating Time	
Mode Criticality Number	

Please select a subsystem: Drive Train Module
Please Select an assembly: Gearbox
Please select a subassembly: Gears
Please select a component: Hollow Shaft

G_CODE	GEEH
Failure_Mode	Seizeed
Severity	5
Occurance	1
Detection	4
Risk Priority Number	20
Normal Distribution %	47.4
Failure Distribution %	33.3
Failure Probability	0.333
Modal Failure Effect	0.6
Mode Criticality Number	0.1998
Part Failure Rate	
Operating Time	
Mode Criticality Number	

Figure 6 A Software Tool that shows FMECA results

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