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USING AN FMEA METHOD TO COMPARE PROSPECTIVE WIND TURBINE DESIGN RELIABILITIES

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Abstract
Failure Modes and Effects Analysis (FMEA) has been shown to be an effective way of improving machinery design reliability. This paper applies the FMEA to the design for availability of a 2MW, geared, exemplar R80 wind turbine design used in the EU FP7 ReliaWind Consortium.
The technique will be used to compare the prospective reliabilities of three versions of the geared R80 turbine with different drive train solutions. These solutions have been proposed to reduce overall wind turbine failure rate and raise its availability. The first solution incorporates a conventional LV Doubly Fed Induction Generator (DFIG) with partially-rated Converter; the second solution incorporates an innovative Hydraulic Converter coupled to an MV Synchronous Generator (SG); the third solution incorporates an innovative LV Brushless Doubly Fed Induction Generator also with a partially-rated Converter.
The paper proposes modifications to the FMEA method to analyse availability and applies that approach to these three alternative designs to identify their relative merits.

Keywords: Failure Modes and Effect Analysis (FMEA), Wind turbine, Doubly Fed Induction Generator (DFIG), Brushless Doubly Fed Generator (BDFG), Synchronous Generator (SG)

1. INTRODUCTION

Wind power is the fastest growing renewable energy resource and wind power penetration in power systems increases at a significant rate as [1] demonstrates.
The high penetration of wind power into power systems in the present and near future will have several impacts on their planning and operation. One of these impacts the effect of wind power on power systems reliability, emphasized because wind power is intermittent. So the reliability of the wind turbines (WT) delivering this power will become an essential consideration over the next few years. Due to the competitive environment of the power generation industry developers and operators prefer the most economically productive WT configurations. Long-term cost-analysis of WTs, including their first investment and operation & maintenance (O&M) costs, will result in better WT configuration choices. This is only possible if such analysis includes the reliability of the different WT technologies.
The reliability of WTs as part of a large power system have been assessed in a number of references [2][3][4] [5]. Such studies consider the wind as a stochastic process, using an appropriate time series to model the wind, and combining it with the power-speed curve of the WT.
There have been few studies of the reliability of WTs as isolated systems rather than as part of a large power system [6]. This paper focuses on the reliability analysis in design stage of a WT as a single, complex system, consisting of several mechanical, electrical and auxiliary assemblies.
The reliability analysis methods used in the design stage of power generation systems are qualitative, depending on comparison with data from similar systems, whereas after several years power generation O& reliability analysis can become more quantitative, depending on field statistical data.
Failure Modes and Effects Analysis (FMEA), the best candidate for reliability analysis at the design stage, is well-defined and has been used successfully in many power generation engineering systems. The only published record of an FMEA being applied to a WT is [7], although the method has been used individually by WT manufacturers and their suppliers.

The main objective of this paper will be to carry out an FMEA on a complete 2 MW, variable speed, geared drive WT, considering all the major assemblies in the drive train and the effects of their failure on the overall turbine performance, to demonstrate the applicability of this technique to WT systems.
The first objective of the work is to provide WT designers a modus operandi for the application of FMEA techniques to their product and to provide feedback for WT design improvements and the optimization of wind farm O&M. A second objective will be to examine how the method deals with a significant proposed design change to the WT. Also a new logarithmic scale for FMEA procedure is proposed in this paper.
The paper is arranged as follows:
Section 2 reviews the well known FMEA method and its components. The first procedure which is used for WT in this paper is based on a standard FMEA with some amendments introduced in this section.
Section 3 introduces modified FMEA method using logarithmic scales which claimed to have benefits compared to conventional FMEA. Section 4 describes the WT itself, including different types and configurations. The WTs assembly subdivision considered for the FMEA is described in Section 5, together with three different 2 MW, variable speed WTs incorporating a system with Doubly Fed Induction Generator (DFIG) or Brushless Doubly Fed Induction Generator (BDFIG) or Hydraulic Converter coupled to a Synchronous Generator to be analyzed in the paper. Section 6 shows FMEA procedure for WT system, including Root Causes and Failure Modes considered and assigning quantitative values to them. Section 7 shows the quantitative results of the FMEA and compares three selected WTs from the reliability point of view using FMEA tool for this purpose. Section 8 discusses the FMEA quantitative results. Section 9 presents the conclusions and recommendations.

2. CONVENTIONAL FAILURE MODE AND EFFECT ANALYSIS

The FMEA is a powerful design tool that provides a means, from a risk point of view, of comparing alternative machine configurations. The FMEA is also useful for considering designs improvements for a technology which is changing or increasing in rating, as WT configurations are.
The FMEA is a formalized but subjective analysis for the systematic identification of possible Root Causes and Failure Modes and the estimation of their relative risks. The main goal is to identify and then limit or avoid risk within a design.
Hence the FMEA drives towards higher reliability, higher quality, and enhanced safety. It can also be used to assess and optimize maintenance plans.
An FMEA is usually carried out by a team consisting of design and maintenance personnel whose experience includes all the factors to be considered in the analysis.
The causes of failure are said to be Root Causes, and may be defined as mechanisms that lead to the occurrence of a failure. While the term failure has been defined, it does not describe the mechanism by which the component has failed. Failure Modes are the different ways in which a component may fail. It is vitally important to realize that a Failure Mode is not the cause of a failure, but the way in which a failure has occurred. The effects of one failure can frequently be linked to the Root Causes of another failure.
The FMEA procedure assigns a numerical value to each risk associated with causing a failure, using Severity, Occurrence and Detection as metrics. As the risk increases, the values of the ranking rise. These are then combined into a Risk Priority Number (RPN), which can be used to analyze the system. By targeting high RPN values the most risky design elements can be addressed. RPN is calculated by multiplying the Severity, Occurrence and Detection of the risk.
Severity refers to the magnitude of the End Effect of a system failure. The more severe the consequence, the higher the value of severity will be assigned to the effect.
Occurrence refers to the frequency that a Root Cause is likely to occur, described in a qualitative way. That is not in the form of a period of time but rather in terms such as remote or occasional.
Detection refers to the likelihood of detecting a Root Cause before a failure can occur.
Since FMEA is used by various industries, including Automotive; Aeronautical; Military; Nuclear and Electro-technical, specific standards have been developed for its application. A typical standard will outline Severity, Occurrence and Detection rating scales as well as examples of an FMEA spreadsheet layout. Also a glossary will be included that defines all the terms used in the FMEA. The rating scales and the layout of the data can differ between standards, but the processes and definitions remain similar.
SAE J 1739 was developed as an automotive design tool, SMC REGULATION 800-31 was developed for aerospace but the most widely used standard is MIL-STD-1629A (1980), drafted by The United States Department of Defense [8]. With over 30 years usage and development, it has been employed in many different industries for general failure analysis. Due to the complexity and criticality of military systems, it provides a reliable foundation on which to perform FMEAs on a variety of systems. It also contains formulae for predicting the failure rates of electrical and electronic systems, whose coefficients are based on accelerated life tests.
In conventional FMEA the Severity, Occurrence and Detection factors are individually rated using a numerical scale, typically ranging from 1 to 10. These scales, however, can vary in range depending on the FMEA standard being applied. However, for all standards, a high value represents a poor score (for example catastrophically severe, very regular occurrence or impossible to detect). Once a standard is selected it must be used throughout the FMEA.

In this paper [8] was used but with some amendment, principally to change the Severity, Occurrence and Detection criteria by which the RPN is calculated. These modifications were necessary to make the FMEA methodology more appropriate to WT systems.
The modified Severity scale and criteria are shown in Table 1. The original scale of 1-4 was maintained but changes were made to the category criteria definitions to emphasis their implications for a WT.

Table 1: Severity rating scale for WT FMEA

Scale #	Description	Criteria
1	Category IV(Minor)	Electricity can be generated but urgent repair is required.
2	Category III(Marginal)	Reduction in ability to generate electricity.
3	Category II(Critical)	Loss of ability to generate electricity.
4	Category I(Catastrophic)	Major damage to the Turbine as a capital installation.

The modified Occurrence scale and criteria are tabulated in Table 2.

Table 2: Occurrence rating scale for WT FMEA

Scale#	Description	Criteria
1	Level E(Extremely Unlikely)	A single Failure Mode probability of occurrence is less than 0.001.
2	Level D (Remote)	A single Failure Mode probability of occurrence is more than 0.001 but less than 0.01
3	Level C(Occasional)	A single Failure Mode probability of occurrence is more than 0.01 but less than 0.10.
5	Level A (Frequent)	A single Failure Mode probability greater than 0.10.

The Level B of standard [8] was removed as the presence of Level A and C were considered adequate for the WT as it was originally difficult to make a clear distinction between Levels A, B and C.
The number of Detection levels were reduced by removing 2, 3, 5, 6 and 8 as the presence of the remaining four levels was adequate for this analysis. The modified Detection scale and criteria are tabulated in Table 3.

Table 3:Detection rating scale for WT FMEA

Scale#	Description	Criteria
1	Almost certain	Current monitoring methods almost always will detect the failure.
4	High	Good likelihood current monitoring methods will detect the failure.
7	Low	Low likelihood current monitoring methods will detect the failure.
10	Almost impossible	No known monitoring methods available to detect the failure.

It can be concluded that the minimum RPN for any Root Cause is 1 and the maximum is 200. As long as the rating scales of a selected FMEA procedure remain fixed, it can be used for the comparison of alternative designs and identification of critical assemblies.
Defining these three criteria tables based on MIL-STD-1629A is the first step in performing an FMEA. As mentioned before the basic principles of an FMEA using different standards are similar and simple;

- The system to be studied must be broken down into its assemblies
- Then for each assembly all possible Failure Modes must be determined
- The Root Causes of each Failure Mode must be determined for each assembly.
- The End Effects of each Failure Modes must be assigned a level of Severity, and every Root Cause must be assigned a level of Occurrence and Detection
- Levels of Severity, Occurrence and Detection are multiplied to produce the RPN

Therefore the first stage in the FMEA procedure is obtaining a comprehensive understanding of the WT system and its main assemblies.

3. MODIFIED FMEA WITH LOGARITHMIC SCALES

As discussed in Section 2 the scales for Severity, Occurrence & Detection suggested in FMEA standards start from a value of one and then increase linearly in steps of one, but when comparing RPNs for two parts it is essential that the difference in the Severity, Occurrence & Detection of the two parts is represented by a comparable difference in RPN. It is therefore important that for each of the criteria a single increase in value, at any level of the criteria, should have the same effect on the RPN. However, when using linear scales this is not the case.

A simple mathematical interpretation demonstrates that the difference in RPN as a result in a change in level of either scale will only be equal for situations where the level of severity, occurrence and detection were all the same. Under this condition only will the percentage change in RPN always be the same, regardless of which criteria increases. It is suggested that the scales need to be modified such that the same change in RPN is experienced for any combination of levels not just this one particular condition.

The use of exponential/power law scales can be used to completely satisfy the condition where any single change in the level of each criterion has the same effect on the RPN. Hence the following scales have been considered for severity, occurrence and detection:

$$\begin{aligned} severity &= n^{sev} \\ occurrence &= n^{occ} \\ \det ection &= n^{\det} \end{aligned} \tag{1}$$

Where n >1 and Severity, Occurrence & Detection range from 0 to 4. Using the above scales for severity, occurrence and detection the value for RPN can be expressed by

$$RPN = n^{sev} * n^{occ} * n^{\det} \tag{2}$$

Hence by using these scales they increase exponentially for any individual change in Severity, Occurrence or Detection resulting in the same change in the RPN, as required. In this paper FMEAs have been completed using these scales in order to establish their effect on the WT FMEA. The value of n was set to be two; hence for any change in level on each of the scales the RPN would be doubled.

4. WIND TURBINE SYSTEMS

WTs can be categorized in two main configurations, fixed and variable speed. Early fixed speed WTs, produced until the late 1990s with the ratings below 1 MW, used a multistage gearbox and a standard squirrel-cage induction generator, directly connected to the grid. Some improvements were made and termed semi-variable speed systems as follows:

- Using two distinct stator windings with different pole numbers giving a two speed system;
- Using a wound rotor induction generator with external resistors connected via brush and slip rings;
- Or using the patented OptiSlip® system.

From the late 1990s new fully variable speed WTs were introduced in wind power industry from approximately 1 MW. The need to change to variable speed WTs was the result of shortcomings of the fixed speed system, as follows:

- Low energy yield [9];
- Significant audible noise;
- Difficulty in stopping WTs under emergency conditions using only mechanical or air brakes;
- Poor power quality to the grid.

The first generation of fully variable speed WT systems used a multistage gearbox, a relatively low-cost standard wound rotor induction generator as a DFIG and a power electronic converter feeding the DFIG rotor with a rating approximately 30% of the rating of the turbine.

Since 1991, there have also been variable speed WT systems using gearless generator systems, so-called direct-drive generators, designed to eliminate gearbox failures, a fully-rated power electronic converter is then necessary for the grid connection [9]. However, the DFIG geared technology is currently the most widely used in the industry because of its low capital cost and good energy yield [10].

The new technology of the Brushless Doubly Fed Generator (BDFG) has been claimed as the next generation to the DFIG in the WT as it eliminates the need for brushes and slip rings but it is in the first stage of feasibility study for large rating WTs [11] and only one such generator is fitted in a wind turbine.

5. WT SYSTEMS CONSIDERED IN THIS PAPER

This paper focuses on a geared drive WT with a 2 MW, 80m diameter rotor, named in ReliaWind [12] as R80, an exemplar configuration for the indirect drive concept, with a variable speed system incorporating an LV DFIG and active blade pitch control. This geared drive WT then will be compared with novel WT systems incorporating either an LV BDFIG or a hydraulic converter coupled to an MV synchronous generator, which has been fitted in a number of 2 MW WTs. The gearbox used in the

conventional R80 has three stages consisting of one planetary and two parallel stages while the BDFIG operates at a lower speed and uses a similar two stage gearbox while the hydraulic converter uses an identical two stage gearbox but incorporates its own gearbox to adjust speed.
To achieve consistency in the FMEA it is essential to consider the level of detail needed for a true representation of the system without complicating the analysis. If, the system is broken down to individual components it would become complex, requiring detailed system knowledge. For WTs, where many different configurations and designs are similar, with complex assemblies lacking of accessible detail on all components, it is acceptable to carry out the FMEA down to assembly level, for example to the lubrication oil system of the gearbox rather than to individual pumps, pipes and valves.
In this paper eleven main assemblies are considered for the R80 in the FMEA study, Table 4 shows those assemblies, based on [13].

Table 4
WT subdivision

WT Assemblies
Rotor and Blades Assembly
Mechanical Brake
Main Shaft
Gearbox
Generator
Yaw System
Pitch Control System
Hydraulics
Grid and Electrical system
Electrical Controls
Tower, Foundation and Nacelle

It is evident that not all of these assemblies may be needed in each incarnation of the R80 WT as our third system uses a hydraulic converter. The generators used in the 3 WTs would be DFIG, BDFIG and Synchronous generator as shown in Figure 1.
An intermediate level of detail was also chosen, as shown in Figure2, with the WT being analyzed to Levels 3 & 4 where possible.

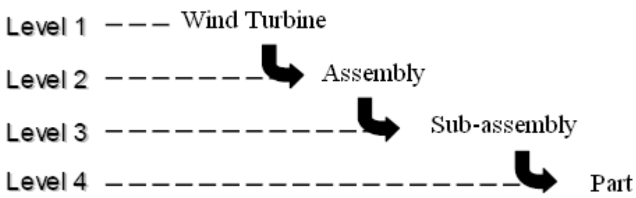
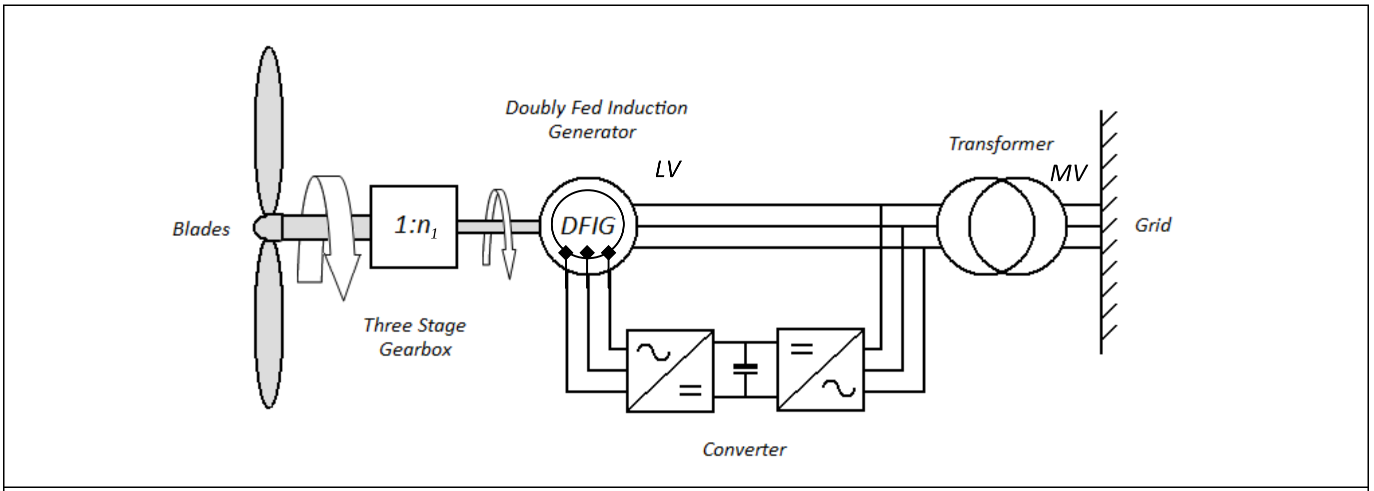


Fig.2. WT construction hierarchy for FMEA

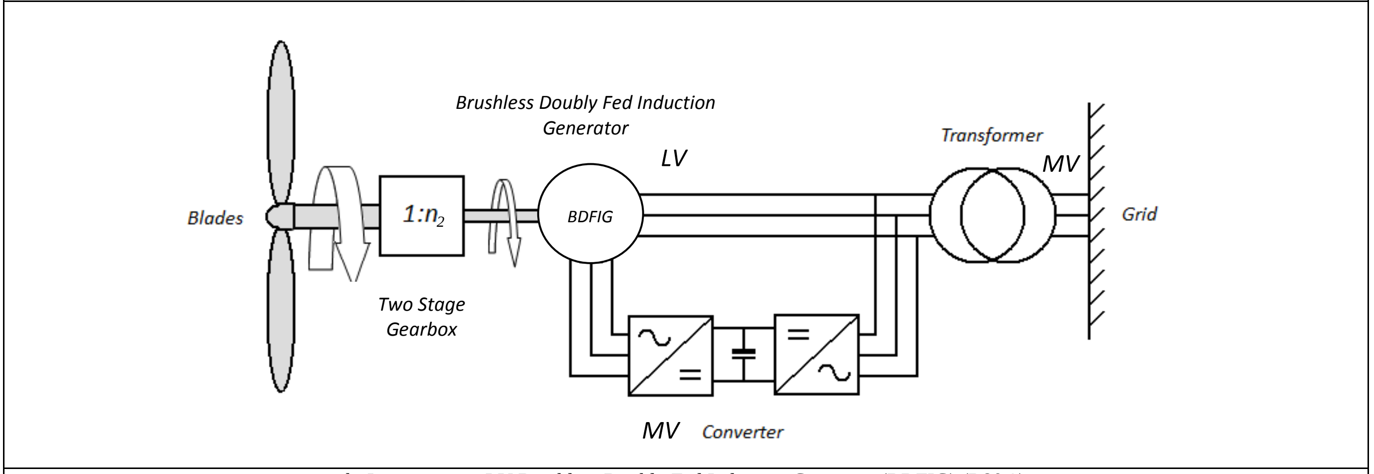
This 11 assembly WT has a total of 40 subassemblies and 107 parts. This level of subdivision was based on the data available about the reliability of different parts of the WT at the start of the analyses.
The final step in this paper will be to replace the DFIG in the R80 with an equivalent Brushless Doubly Fed Induction Generator (BDFIG) and substitution of drive train by hydraulic converter and synchronous generator to compare the three configurations; at that stage some amendment will also be necessary in the gearbox assembly.

6. WT FMEA PROCEDURE

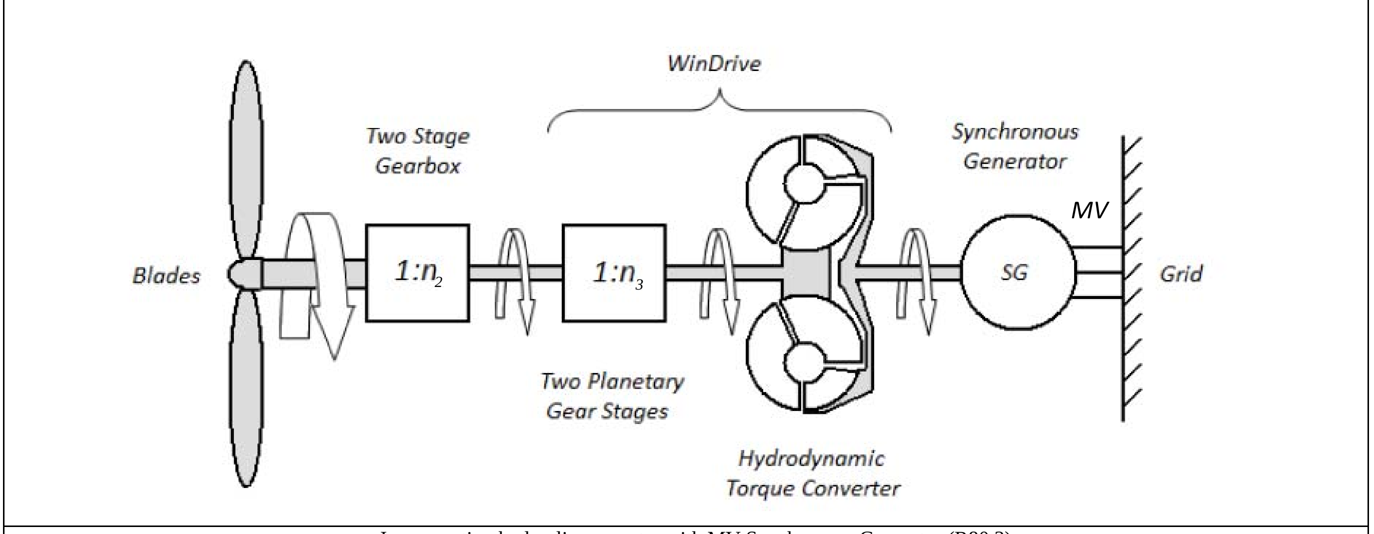
After subdivision of the selected WT system the probable Failure Modes are generated. The expected Failure Modes were considered for all 107 parts in the R80 and many were found to be common between various parts. Table 5 shows the common Failure Modes for the WT.



a: Incorporating LV Doubly Fed Induction Generator (DFIG) (R80.1)



b: Incorporating LV Brushless Doubly Fed Induction Generator (BDFIG) (R80.2)



c: Incorporating hydraulic converter with MV Synchronous Generator (R80.3)

Fig. 1. Schematic of the ReliaWind R80 exemplar geared turbine with 3 alternative conversion systems

Table 5: Generic WT Failure Modes

Failure Mode	Description
Structural Failure	*Failure of any part or assembly that forms part of a supporting structure*
Electrical Failure	*Failure of a part or assembly as a result of an electrical defect*
Mechanical Failure	*Failure of a part or assembly as a result of a stress related defect*
Blockage	*Failure of a part or assembly as a result of a reduction in flow of a Fluid- typically caused by debris and increased viscosity of the fluid*
Material Failure	*Failure of a part or assembly as a result of a defect/non homogeneous composition of the material with which the part is made*
Detachment	*Failure of a part or assembly where by it is unintentionally no longer rigidly connected to its frame or structure*
Electrical Insulation Failure	*Failure of a part or assembly with a high resistance to the flow of electrical current, resulting in leakage of current from a conductor*
Thermal Failure	*Failure of a part or assembly as a result of an incapacity to tolerate any exposed high temperatures, resulting in a reduction in rigidity*
Output Inaccuracy	*Failure of a part or assembly as a result of a signal output inaccuracy*
Misalignment	*Failure of a part or assembly as a result of an unintentional change in the parts position or orientation, with particular reference to parts rotating about coincident axis*
Intermittent output	*Failure of a part or assembly as a result of an irregular and uncontrollable change or pause of the intended output*

Following identification of part Failure Modes, the expected Root Causes must also be found. As with the Failure Mode analysis, the expected Root Causes for the WT will be a limited set, and in this study Table 6 shows 21 common Root Causes.

Table 6:Generic WT Root Causes

Root Causes		
Calibration Error	High Cycle Fatigue	Maintenance Fault
Connection failure	Installation Defect	Manufacturing Defect
Corrosion	Insufficient Lubrication	Mechanical Overload
Design Fault	Insulation degradation	Overheating
Electrical Overload	Lightning Strike	Presence of Conducting Debris
Excessive Brush Wear	Loss of Power Input	Presence of Debris
External Accidental Damage	Low Cycle Fatigue	Software Design Fault

One of the drawbacks of field failure data available from WT systems [13] is that Failure Modes and Root Causes for particular failures are not usually recorded. The FMEA has the ability to relate each Failure Mode to its Root Causes and then calculate the frequency of occurrence for each Root Cause so there could be some advantage in combining measured failure rate data with the FMEA procedure.

When completing the list of Failure Modes and their Root Causes, the effects of these parts' Failure Modes on related subassemblies must be considered. Although similar to Root Cause consideration, several effects could be considered for each Failure Mode but here only the main effect of each part Failure Mode is taken into account.

In an FMEA the main Failure Modes are those related to parts in the system hierarchy, which in this case are the 16 Failure Modes presented in Table 7. The effects of parts' Failure Modes will be the Failure Modes of their related subassembly and the effects of subassembly Failure Modes will be the assembly Failure Modes

The last steps in the FMEA are:

- Adjusting the severity of each Failure Mode to an appropriate level due to its effect.

- Assigning occurrence and detection figures for the related Root Causes.

Use of Tables 5-6 and engineering judgment are the bases for this procedure.

For each Failure Mode with several Root Causes, multiplying the occurrence and detection values for each Root Cause by the Failure Mode severity results in related root cause RPN. Summating these Root Cause RPNs then gives the selected Failure Mode RPN. Aggregating the part Failure Mode RPNs builds the part RPN.

Aggregating the part RPNs builds the subassembly RPN.

Aggregating the subassembly RPNs builds the assembly RPN.

Therefore an FMEA can be completed by subdividing a WT down to its part level, considering Failure Modes, Root Causes and Failure Mode effects, expanding the Failure Modes effects at each level into Failure Modes at a higher level, then continuing this procedure until all levels of the WT have been considered.

On completion the WT RPN is the summation of all part RPNs, therefore the share of each assembly, subassembly and part in the WT RPN can be seen and high risk assemblies, subassemblies and parts identified by their RPNs.

It is possible to perform FMEA procedure by hand or using Microsoft Office Excel, however there are specific software tools for this purpose[14][15][16].

7. FMEA RESULTS FROM THE 3 SELECTED WTS

The results from the FMEA on these three R80 WT drive train configurations are shown in Table 7, where the RPNs have been normalized to the highest RPN, which is for the R80.1 Conventional LV Doubly Fed Induction Generator with 3 stage gearbox, partially-rated Converter and Transformer.

Table 7:Three different WT Concept Drive Trains, Comparing Normalised Risk Priority Numbers (RPN) from FMEA

Subassembly	Description	RPN
Drive Train	**R80.1, Conventional LV Doubly Fed Induction Generator with 3 stage gearbox, partially-rated Converter and Transformer**	**100.0**
	R80.2, Innovative LV Brushless Doubly Fed Induction Generator with 2 stage gearbox, partially-rated Converter and Transformer	**82.2**
	R80.3, Innovative Hydraulic Converter with 2 stage gearbox and MV Synchronous Generator.	**69.1**
Generator	R80.1- DFIG	17.5
	R80.2- BDFIG	15.6
	R80.3- Synchronous Generator	16.1
Gearbox	R80.1- Three Stage (1st stage Planetary)	30.4
	R80.2- Two Stage (1st stage Planetary)	22.4
	R80.3- Two Stage (1st stage Planetary)	26.0
Converter	R80.1- Electrical Converter+Control	21.7
	R80.2- Electrical Converter+Control	21.7
	R80.3- WinDrive+Control	27.0
	Two stage Planetary Gearbox	17.9
	Torque Converter	9.1
Transformer	R80.1- Transformer	3.3
	R80.2- Transformer	3.3
	R80.3- No Transformer	0.0

8. DISCUSSION

The results show that the conventional DFIF R80.1 has the highest RPN for this FMEA technique, with the BDFIG R80.2 having a lower and therefore more reliable result. Finally the benefit of the Hydraulic Converter R80.3 is very substantial, suggesting that this has the potential to achieve high reliability based on the use of a high reliability synchronous generator, the elimination of the transformer and of the Electrical Converter. Furthermore this configurations use of two separate gearboxes signals a potential to improve the reliability still further by eliminating one and integrating it into the hydraulic torque converter. Such results could be enhanced by more detailed study of the measured failure rates in individual subassemblies [17].

9. CONCLUSIONS

An FMEA method has been chosen and applied to three alternative 2MW geared, variable speed WTs, based on the R80 exemplar WT developed for ReliaWind, incorporating three diverse drive trains as follows:

- R80.1, a conventional LV Doubly Fed Induction Generator with 3 stage gearbox, partially-rated Converter and Transformer;
- R80.2, an innovative LV Brushless Doubly Fed Induction Generator with 2 stage gearbox, partially-rated Converter and Transformer;
- R80.3, an innovative Hydraulic Converter with 2 stage gearbox and MV Synchronous Generator.

It has been shown that the method can serve as a preliminary failure rate prediction tool. The method demonstrates that the the Hydraulic Converter has the best potential to lower the failure rate and an additional potential for improvement if its two gearboxes can be integrated into a single three stage gearbox. The BDFIG WT also has a better reliability than the conventional DFIG machine by a substantial margin,

This is an encouraging result which demonstrates that the FMEA could be developed further for this purpose.

Modified FMEA method incorporating logarithmic scales has been proposed and showed more realistic results.

The RPN data calculated from the FMEA should be compared with field failure rate data for assemblies, to find any probable similarity between them. Further investigation has shown that comparison between the product of occurrence and detection and field failure rates gives the closer comparison, giving confidence in the FMEA process. The product of occurrence and detection under-estimates field failure rates, however this could be a useful tool for predicting failure rates in new turbine designs.

Once FMEA data was produced, it was ranked in assembly order giving a clear picture of the unreliability of assemblies, subassemblies and parts. This could be a useful tool for designers to identify weak points in the WT design.

A suggestion for improving this procedure would be to undertake the FMEA with the aid of a WT designer and O&M engineer. This would focus on the problems of individual subassemblies and would provide a stronger indicator for those that need improvement making the process less subjective.

The FMEA has the potential to improve the reliability of WT systems especially for the offshore environment, where reliability will play a much stronger part in prospective cost-effectiveness. Furthermore, it is believed that in time, it will play a major role in the development of WTs, which require little or no maintenance, making wind a more cost-effective and sustainable energy resource.

10. ACKNOWLEDGEMENTS

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