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The software reliability analysis tool used for these studies was Relex Reliability Studio 2007 Version 2.

Failure Modes and Effects Analysis (FMEA) for Wind Turbines

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Abstract

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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]-[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 for many power generation engineering systems. There is no published record of an FMEA applied to a WT, although the method may have been used individually by WT assembly manufacturers.

The main objective of this paper will be to carry out a comprehensive FMEA on a complete 2 MW, variable speed, geared drive WT, considering all the major assemblies 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 investigate the relationship between quantitative FMEA results and WT field assembly failure rates.

A third objective will be to examine how the method deals with a significant proposed design change to the WT.

The paper is arranged as follows:

Section two reviews the FMEA method and its components. The procedure which is used for WT in this paper is based on a standard FMEA with some amendments introduced in this section.

Section three describes the WT itself, including different types and configurations. The WT assembly subdivision considered for the FMEA is described in section four, together with the 2 MW, variable speed, geared drive WT configuration, incorporating a Doubly Fed Induction Generator (DFIG), to be analyzed in the paper.

Section five shows FMEA procedure for this WT, including Root Causes and Failure Modes considered and assigning quantitative values to them.

Section six introduces three specific purpose software tools for the FMEA and describes the facilities of the selected software tool. The procedure of WT FMEA in the software is explained in section seven.

Section seven shows the quantitative results of the FMEA and compares it with reliability field data from similar size turbines to find a relationship between them.

Section nine considers the effect on the WT FMEA of incorporating a Brushless Doubly Fed Generator (BDFG) is considered in for comparison with the main configuration of a DFIG.

Section ten reviews the more frequently occurring failure modes and root causes in the WT FMEA.

Section eleven presents the conclusions and recommendations.

2. FAILURE MODE AND EFFECT ANALYSIS

The FMEA is a powerful design tool that provides a mean to compare, from a risk point of view, alternative machine system 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 value RPNs the most risky elements of the design can be addressed. RPN is calculated by multiplying the Severity by the Occurrence by the 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 outlines 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 [7]. 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.

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 [7] 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 [7]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 standard [7] 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. WT 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 [8];
- Significant audible noise;
- Difficulty in stopping WTs under emergency conditions using only mechanical or air brakes;
- Poor power quality.

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 [8]. However, the DFIG geared technology is currently the most widely used in the industry because of its low capital cost and good energy yield [9].

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 [10].

4. R80 WT SYSTEM CONSIDERED IN THIS PAPER

This paper focuses on a WT incorporating either a DFIG or BDFG which will be a 2 MW, 80m diameter, named in RELIAWIND [11] as R80, a reference configuration for the indirect drive concept, with a variable speed system and active blade pitch control. The gearbox used in the R80 has three stages consisting of one planetary and two parallel stages.

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 FMEA study. Table 4 shows the assemblies considered in this paper, based on [12]. It is evident that not all of these assemblies may be available in some types of WTs.

Table 4
R80 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

An intermediate level of detail was also chosen, as shown in Figure 1, with the Wind Turbine being analyzed to Levels 3 & 4 where possible.

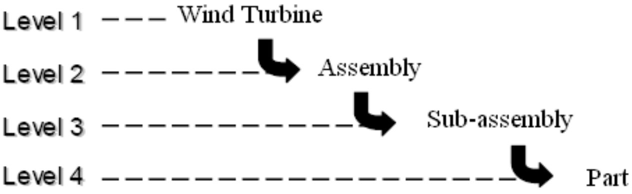

Fig. 1. WT construction hierarchy for FMEA

As an example the subassemblies which are considered for the Generator (DFIG) are shown in Table 5. The power electronic converter, considered in some literature as a subassembly of DFIG, is considered in the separate Electrical Controls assembly here.

Table 5
R80 Generator subassemblies

Generator (DFIG) Subassemblies
Enclosure System
Ventilation System
Stator
Rotor
Instrumentation

Parts considered for Enclosure subassembly of the Generator assembly, are tabulated in Table 6. The similar procedure was conducted for other assemblies.

Table 6
R80 Generator Enclosure system parts

Enclosure System Parts
Frame
Drive End Bearing
Non Drive End Bearing
Bearing Lubrication System
Shaft
Main Terminal Box

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 Generator (BDFG) to compare the two configurations; at that stage some amendment will also be necessary in the gearbox assembly.

5. 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 7 shows the 16 common Failure Modes for the R80 WT identified in three related columns.

Table 7
R80 WT Failure Modes

Mechanical	Electrical	Material
Mechanical	Electrical Insulation	Material
Rupture	Electrical Failure	Fatigue
Uprooting	Output Inaccuracy	Structural
Fracture	Software Fault	
Detachment	Intermittent Output	
Thermal		
Blockage		
Misalignment		

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 8 shows 25 common Root Causes identified in three related columns.

Table 8
R80 WT Root Causes

Structural	Wear	Electrical
Design Fault	Corrosion	Calibration Error
External Damage	Excessive Brush Wear	Connection failure
Installation Defect	Fatigue	Electrical Overload
Maintenance Fault	Pipe Puncture	Electrical Short
Manufacturing Defect	Vibration Fatigue	Insulation failure
Mechanical Overload	Overheating	Lightning Strike
Mechanical Overload-collision	Insufficient Lubrication	Loss of Power Input
Mechanical Overload-wind		Conducting Debris
Presence of Debris		Software Design Fault

One of the drawbacks of field failure data available from WT systems [12] 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 7-8 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.

6. SOFTWARE BASED FMEA

The system reliability studies software tools, including FMEA, considered in this paper are as follows:

- XFMEA [13]
- Isograph Reliability Workbench [14]
- Relex Reliability Studio 2007 V2[15]

The XFMEA software [13] has a basic user interface due to its spreadsheet format, two windows and minimal tool bars. A system hierarchy is used to show how the components of the FMEA are linked and systems can be collapsed or expanded to show the full extent of the detail used in calculating the FMEA. There is no facility to enter data about the reliability of a component, this limits the use of the software to smaller projects where this data is not considered important or is unavailable due to low complexity.

The Isograph Reliability workbench program [14] is similar to XFMEA in using a spreadsheet format. It has a simple user interface allowing efficient data input and software handling. The use of libraries for apportionment and phrasing allows recording of commonly occurring components and their Failure Modes giving consistency to the system.

Relex Reliability Studio 2007 V2 [15] is a comprehensive reliability software that can be used not only for the FMEA but also Reliability Prediction, Fault Tree Analysis, Markov Modeling, Wiebull Analysis and Reliability Block Diagrams. The modules in Relex can be linked, so that a particular system can be analyzed from different reliability points of view.

7. THE USE OF THE SOFTWARE FOR A WT FMEA

Due to the flexibility of Relex it has been adopted for the R80 FMEA in this paper.

Three FMEA types are available in the software, functional, process or component FMEAs, based on FMEA standards. The component FMEA is the most appropriate for analyzing the WT system due to the philosophy discussed in previous sections.

Severity, occurrence and detection tables can be defined in the software by the user, although the software includes most standard FMEA definitions within its databases. The Root Causes, Failure Modes and failure effects assigned within an FMEA project can also be summarized on completion by the software in separate databases.

An essential feature of the software FMEA module are its Roll-up and Build features as shown for example in Table 9 for a gearbox assembly.

Roll-up is exemplified by the fact that after inserting a Failure Mode and its local effect at part level the software automatically rolls this upwards as a Failure Mode in the subassembly above.

Build is exemplified by the fact that after inserting a local effect at assembly level the software automatically builds this downwards as a next effect in the subassembly below.

These effects are shown in Table 9, where the shaded cells will be filled automatically by the Roll-up and Build features.

Table 9
Roll-up and Build of Failure Modes and Effects

		Failure Mode	**Local Effect**	**Next Effect**	**End Effect**	**Severity**
Assembly	Gearbox	*B*	C	D	E	Marginal
Subassembly	Oil Lubricate	*A*	B	*C*	*D*	*Marginal*
Part	Flow rate monitor	False Output	A	*B*	*C*	*Marginal*

A: System will not operate at desired level
B: Reduction in the systems ability to cool oil
C: Gearbox cannot achieve optimum power production
D, E: WT cannot achieve optimum power production

Each part level Failure Mode can have several Root Causes, for which their occurrence and detection values can be specified, based upon the rules set at the start of the FMEA project. Eventually the severity values for Failure Modes and the occurrence and detection figures of related Root Causes will be multiplied to find the RPN for each part, subassembly, assembly and finally system.

The R80 WT subdivision in section four was used to build the main system tree configuration in the software. The proposed Failure Modes for all of the parts was considered from a 16 elements set, similarly Root Causes came from a 25 set. The FMEA model selected in the software permitted multiple Root Causes and a single effect for each Failure Mode, considered reasonable for this study.

The results of R80 WT FMEA and another configuration with equivalent BDFG replacing the DFIG in R80, built upon the main system tree of R80 with necessary modifications, will be presented and compared with reliability field data in next sections.

8. INTERPRETING THE FMEA RESULTS FOR THE R80

Reliability data about WT assemblies has become available in recent years from surveys [12] , [16]. A useful outcome of an FMEA on a WT could be a comparison between the R80 assemblies' FMEA RPN results and their field failure rates, this is investigated here using field failure rate data from [12].

The RPNs for the R80 WT assemblies from the software FMEA module, based on the criteria tables of 1-3, are tabulated in Table 10. The assemblies are sorted in descending order of their RPNs.

Table 10
R80 assembly RPNs

Order	Assembly	RPN
1	Rotor and Blades Assembly	1609
2	Generator	1204
3	Electrical Controls	925
4	Hydraulics	921
5	Gearbox	909
6	Grid and Electrical system	872
7	Yaw System	813
8	Pitch Control System	692
9	Tower, Foundation and Nacelle	508
10	Mechanical Brake	336
11	Main Shaft	246

Failure rates and RPNs have different scales so a per unit system has been used for comparison, whereby failure rates and RPNs are normalised to the highest assembly failure rate and RPN respectively.

Such a comparison is shown in Figure 2 where the horizontal axis represents the WT assemblies based on Table 10. No field failure rate data was available for the Tower, Foundation and Nacelle assembly. Figure 2 shows some similarity between field failure rate and RPN data for individual assemblies. However, there is a problem in comparing field failure rate and RPN because severity information cannot be concluded from failure rate data. However, detect ability is linked to failure rate because if a Root Cause is hard to detect, a failure is more likely to occur.

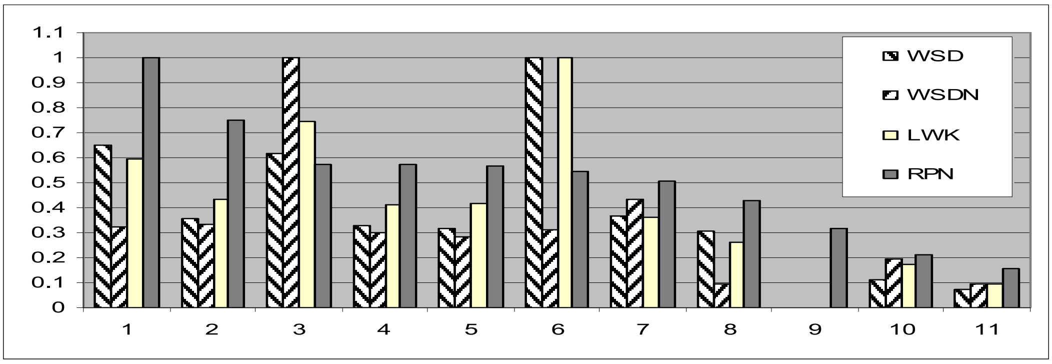

Fig. 2. R80 per assembly RPN comparison with field failure rate data

Therefore if field failure rate were to be compared with RPN, the failure rate should be multiplied by some measure of severity, such as the Mean Time To Repair (MTTR). Reviewing the definition of RPN and comparing it with the failure rate in reliability theory therefore suggests that direct comparison may not be reasonable.

It would seem more reasonable to compare the field failure rate data not with RPN but with the product of occurrence and detection. This is shown in Figure 3. The same per unit system is used but the product of occurrence and detection is divided by the highest RPN in Table 10 to show the reduction of these values compared to the RPN.

In addition [12] showed that the majority of Danish WTs in that reference were old and small compared to more modern German WTs, therefore as the R80 is a modern 2MW WT the Danish data has been omitted from Figure 3.

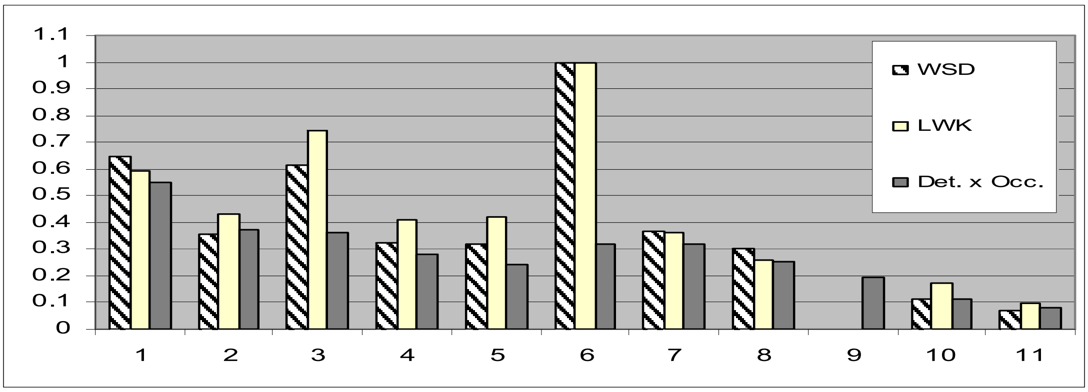

Fig. 3. R80 per assembly Detection x Occurrence comparison with field failure rate data

Following these adjustments comparison between Figures 2 & 3 shows a meaningful similarity between field failure rate and the product of occurrence and detection in Figure 3.

It is noticeable that the main differences occurred for the electrical assemblies, Electrical control (3) and Grid and electrical system (6). It seems that failure rate of these assemblies are higher than would be predicted from the FMEA. This may be due to electrical failures being more detectable than mechanical or material failures.

This analysis shows that it is reasonable to compare the qualitative results of an FMEA, specially the product of occurrence and detection, to quantitative field failure rates. This could be useful in situations where there is a lack of the field failure rate data or during the design stage of a new configuration.

9. USING THE FMEA ON A CHANGED R80 WT

The R80 WT system is now changed by replacing the DFIG for a BDFG as proposed by [10] and calling the WT R80*. The DFIG in the R80 is a 4-pole machine with a rated shaft speed of 1500 rev/min at 50 Hz. The equivalent BDFG has 4 and 8-pole main and control stator windings respectively and a 6-pole rotor, hence a natural speed at 50 Hz. of 500rev/min. The lower mean operating speed of the BDFG necessitates a change in the gearbox ratio which means that only a 2 stage rather than a 3 stage gearbox is needed, therefore one of the parallel stages of the R80 gearbox can be eliminated.

Due to the absence of brushes in the BDFG compared to the DFIG it is expected that BDFG will have a lower RPN but it has an extra stator winding and a special rotor winding design. The rotor considered will be a “nested-loop” design with insulated bars and an end ring as described in [10]. No reliability field data is available for this configuration, because the BDFG is new, so an FMEA of such a configuration and comparison with a conventional DFIG R80 could show the advantages or disadvantages before a WT is built.

Due to changes only in the generator and gearbox the R80* FMEA was performed again for these two assemblies only. The subassembly RPNs’ percentage of this new generator configuration is compared with the R80 generator (DFIG) in Table 11.

Table 11
DFIG and BDFG subassemblies’ RPN percentage

Subassembly	**RPN Percentage**	
	DFIG	**BDFG**
Enclosure System	37%	46%
Stator	11%	24%
Rotor	40% (Including slip rings & brushes)	15%
Others	12%	15%

The RPN of the R80* generator (BDFG) and gearbox (two stages) compared to the R80 generator (DFIG) and gearbox (three stages) are shown in Table 12.

Table 12
Generator and Gearbox data comparison

WT Generator	Generator		Gearbox	
	RPN	**Failure rate**	**RPN**	**Failure rate**
DFIG	1204	0.206	909	0.36
BDFG	972	0.172 (expected)	749	0.29 (expected)

Although the BDFG has three windings, compared to the DFIG's two, the reduction in its RPN shows that the brushes and slip rings were dominant in generator RPN values. It was also predictable that the two stage gearbox RPN is less than the three stages.

The relationship between RPNs and failure rates investigated above suggests that a 20% reduction in generator and gearbox RPNs, indicates that the R80* will have a lower failure rate than the R80 due to the reduction in generator and gearbox faults. However, the introduction of BDFG technology into WTs may cause an initial increase in failure rate at the start of operation.

10. FAILURE MODE & ROOT CAUSE HIERARCHY

A final useful analysis from the FMEA results is the occurrence frequency of the different Failure Modes and Root Causes. As mentioned before there are 16 main Failure Modes and 25 Root Causes considered in the R80 FMEA. These limited numbers of Failure Modes and Root Causes were repeated in 107 parts of the R80 structure. Counting these Failure Modes and Root Causes over the whole FMEA gives histograms for each, identifying the top 10 Failure Modes in Figure 4 and the same for Root Causes in Figure 5.

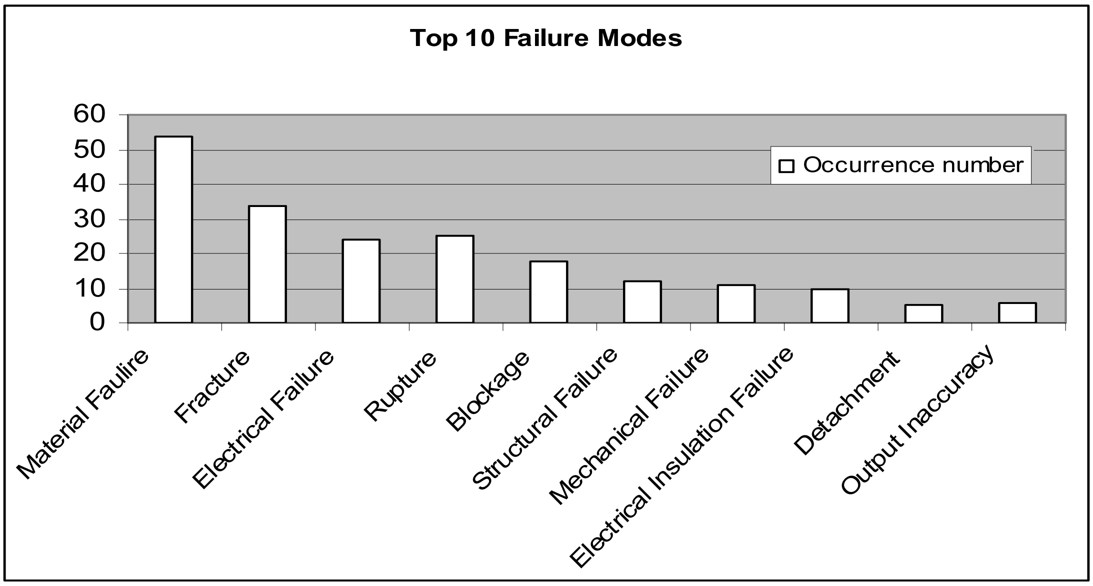

Fig. 4. Top 10 Failure Modes in R80 FMEA

As it could be seen from Figure 4, the most significant Failure Mode is material failure, so improved material quality in WTs must be key point for reliability enhancement.

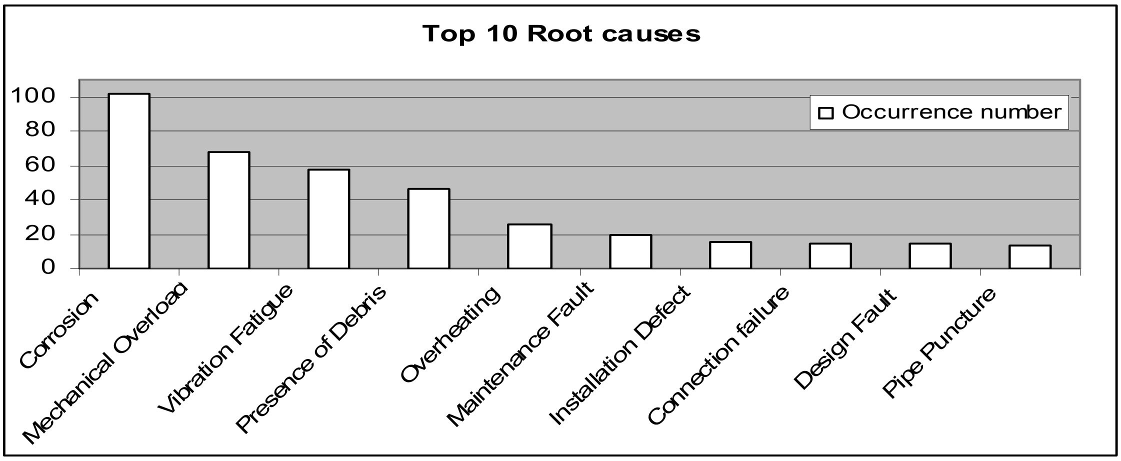

Fig. 5. Top 10 Root Causes in R80 FMEA

Similarly the most frequent Root Cause is corrosion, which affects the material quality. This will be more important in future offshore WTs, so remedial design actions in this regard must be considered.

Identifying the most frequent Failure Modes and Root Causes will assist design improvement and maintenance optimization. A cost-benefit analysis for reducing WT failures could be conducted based on a priority list of the most frequent Failure Modes. A similar analysis could also be considered based on Failure Modes severity, for example by summating the severity of each Failure Mode in the FMEA, ranking the results and considering the costs incurred to alter the ranking.

11. CONCLUSIONS

A suitable FMEA software package has been chosen and successfully applied to a typical 2MW indirect drive, variable speed WT (R80). It has been shown that the software tool can serve as a preliminary failure rate prediction tool. This is an encouraging result which demonstrates that the FMEA could be developed further for this purpose.

The software tool was then successfully applied to a 2MW WT incorporating a BDFG (R80*). The results showed that the R80* was more reliable than the R80 due to the more reliable generator and gearbox assemblies.

The RPN data calculated from the FMEA has been compared with field failure rate data for assemblies, showing some 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.

12. ACKNOWLEDGEMENTS

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Dear Editor(s)

This paper applies the Failure Modes and Effect Analysis (FMEA) method for Wind Turbines and compares the FMEA results with reliability field data. This is a joint research program between Sharif University, Tehran, Iran and Durham University, Durham, UK.

FMEA is a basic method in design stage and authors tried to find a relationship between FMEA results and reliability field data to predict the reliability index of new designs which are used in wind turbines like Brushless Doubly Fed Generators (BDFG), as there is no reliability field data available for them.

Reliability field data of European wind turbines were used and the authors used the support of the RELIAWIND Project funded by the European Union Framework Program 7, Energy Project RELIAWIND, Contract Number 212966.

We appreciate you to review our paper to find if it will have the chance to be published in your journal.

Sincerely yours,
H.Arabian, P.J.Tavner, H.Oraee