Contract number 212966

Reliawind

Reliability focused research on optimizing Wind Energy systems design, operation and maintenance: tools, proof of concepts, guidelines & methodologies for a new generation

Collaborative Project: Large Scale Integrated Project
FP7-ENERGY-2007-1-RTD

Summary of Deliverable D 2.0.4

Whole System Reliability Model

Workpackage WP 2 – Design for Reliability

Deliverable leader: PTC-Relex IT

Summarised by Durham University based on original report

<table>
<tr><th colspan="3">Decisional Workflow</th></tr>
<tr><td>Author(s)</td><td>PTC-Relex
Durham University</td><td rowspan="3">Approved by:
☐ WP leader
☐ Task leader
☐ Scientific Director
☐ Project Technical Assessor (European Commission)
☐ Project Officer (European Commission)</td></tr>
<tr><td>Reviewer (s)</td><td>Dr. Yingning Qiu
Prof. Peter Tavner</td></tr>
<tr><td>Scientific Director</td><td></td></tr>
</table>

Description of work

Objective of the WP:

Understanding of the relevant failure modes with respect to the failure mode mechanism and also the physical and chemical responses of these failure modes allows scientists to construct a logical model. This model can be used to study failure mode growth, both within the WTG architecture and over time.

Task description:

Subtask 2.0.4 Integration of the Whole System Reliability Model

Under this task all contributions provided by the partners (RBDs, component FMEA, reliability models, etc.) will be integrated into a system level reliability model.

FMEA is a systematic analysis of potential failure modes aimed at preventing failures. This is intended to be a preventative action process carried out before implementing new or changes in products or processes. An effective FMEA identifies corrective actions required to prevent failures from reaching the Wind Farm Operator and to assure the highest possible yield, quality and reliability of the whole System.

These can be divided into two primary categories: product related and process related. These are often called Design FMEA and Process FMEA and they are often further subdivided to focus on specific areas of product or process development. The main purpose of an FMEA is:

- To identify possible failure modes that could occur in the design, manufacturing or operation of a product.
- To identify corrective actions that could reduce or eliminate the potential for failures to occur.
- To provide documentation of the process.
- To quantify the risk level associated with each potential failure mode.

The subtask summarizes the output information required as FMEA inputs. This information is the output of data processing and decision making models related to the analysed individual wind turbine components.

Expected deliverable:

This deliverable describes the procedure, method and data source to build reliability database and then to predict the wind turbine (WT) reliability and perform FMECA to different WT designs using Relex Studio.

Document identifier

Status:	v.1	Contractual deliverable :	Y ☐ N ☐
Creation :	03/03/2011	Content protection:	Y ☐ N ☐
Contractual deadline:	14/07/2009 (M16)	Access rights:	Y ☐ N ☐
Dependency		Archive on platform	
Delay in delivering	☒		

Workflow

When	Who	Registration	To do
/ /		Y ☐ N ☐	
/ /		Y ☐ N ☐	
/ /		Y ☐ N ☐	
/ /		Y ☐ N ☐	

Dissemination level:

PU	Public	☒
PP	Restricted to other programme participants (including the Commission Services)	☐
RE	Restricted to a group specified by the consortium (including the Commission Services)	☐
CO	Confidential, only for members of the consortium (including the Commission Services)	☐

IP Management

Is there any IP rights associated to this deliverable? Y ☐ N ☒

If yes, please fill-in the specific IP management file available on the project platform.

Resources in person-months

	Partner	Estimated Resources	Allocated Resources
Resources shown in person-months → 0.5 ☐☐ Partner X 0.5 **Peer reviews** **Contributions**	☐ ☐ GAMESA	MM	MM
	☐ ☐ Ecotecnia	MM	MM
	☐ ☐ LM	MM	MM
	☐ ☐ Hansen	MM	MM
	☐ ☐ Drives	MM	MM
	☐ ☐ SKF	MM	MM
	☐ ☐ GH	0.2 MM	MM
	☐ ☐ Relex	0.5 MM	MM
	☐ ☐ UDUR	0.8 MM	MM
	☐ ☐ SZTAKI	0.4 MM	MM
	☐ ☐ Relex IT	3 MM	MM

If any difference between estimated resources and allocated resources, please justify:

Results achieved

Quality Assessment

Task Leader

WP Leader

Scientific Director

Project Officer (European Commission)

Deliverable Technical Description

Contents

1. Introduction

This is a summary of Reliawind WP2 Deliverables D2.0.4.a and D2.0.4.b, Whole System Reliability Model. These two deliverables describe the procedure, method and data sources needed to build a wind turbine (WT) reliability database and then to predict the WT reliability and Failure Modes Effects & Criticality Analysis (FMECA) of different designs using Relex Studio software. The purpose of this report is to summarize and reorganize the contents of these two deliverables in order to make publishable in the public domain. In addition, the generic reliability model and analysis process could be developed to use by others on this or other reliability software.

2. Definitions

Please refer to the original documents.

3. Reliability Model

The wind turbine generator (WTG) Reliability Prediction & Reliability Block Diagram (RBD) models were presented in this report is based on two generic WTG configurations, R80 & R100 as listed in Table I. For the R100, a component FMECA was also performed.

Table I. WTG Specifications

Configuration Criteria	**These two configurations are both pitch regulated, upwind, variable speed wind turbine. Their sub-systems include hydraulic pitch, 3-stage gearbox, DFIG, active yaw and three-blade rotor.**	
	Reliawind R80 **A general 2MW WTG is illustrated in Figure 1.**	**Reliawind R100**
Frequency	50/60Hz	50/60Hz
Nominal Power	1.5—2 MW	3—5 MW
Rotor Diameter	80—90 m	120—130 m
Hub height	60—100 m	100—120 m
Rotational Speed	10—20 rpm	12—14 rpm
Aerodynamic Brakes	Full feather	Full feather
Number of blades	3	3
Class	IIA	IIA
Operating Temperature	-25—40 ^{o}C	-25—40 ^{o}C
Altitude	0—1500 m	0—1500 m
Analysis	Reliability Prediction & RBD	Reliability Prediction & RBD results not shown
		FMECA

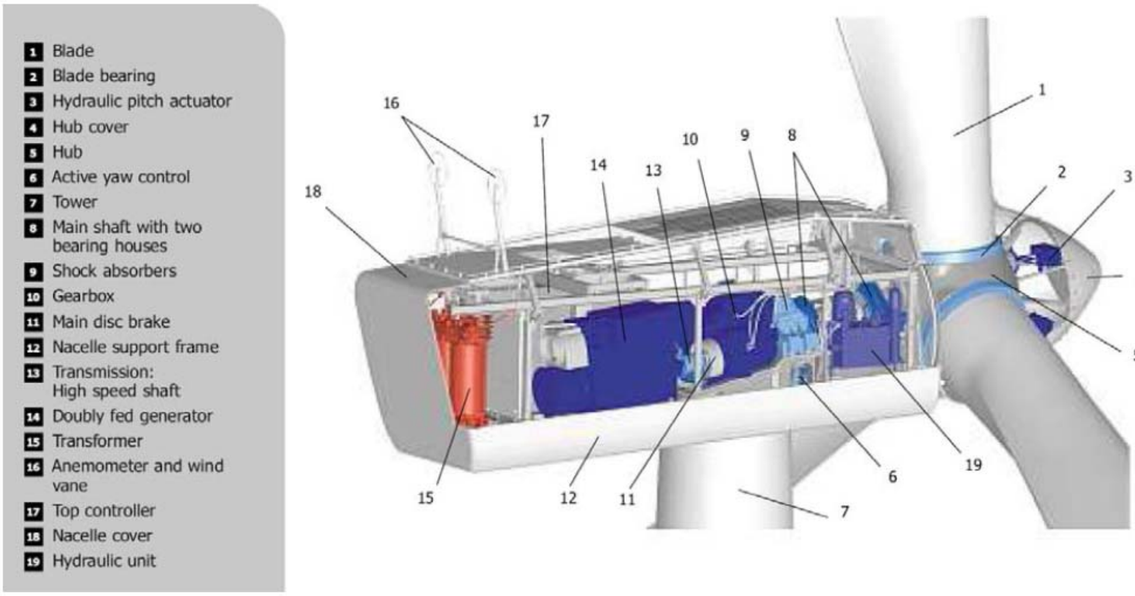


Figure 1. General Structure for the R80 2MW WTG

4. Reliability Analysis Procedure

The Procedure of WTG Design of Reliability is shown in figure 2 below and can be used as a classical reliability design analysis during *Design* and *Redesign* Phase. The reliability design analysis can be performed on the *overall systematic level* as well as *the sub-system levels*.

The aim of overall systematic level reliability analysis is to integrate the whole system reliability model using common reliability analysis procedures which require a WTG system functional block diagram specification and sub-system reliability model specifications.

The sub-system level reliability analysis builds a reliability model for each sub-system in order to analyze the sub-system reliability to:

- Investigate the interaction of the sub-system models on the whole system;
- Develop a design guideline for sub-system design teams;
- Define optimum sensing devices and locations for characterising sub-system failures.

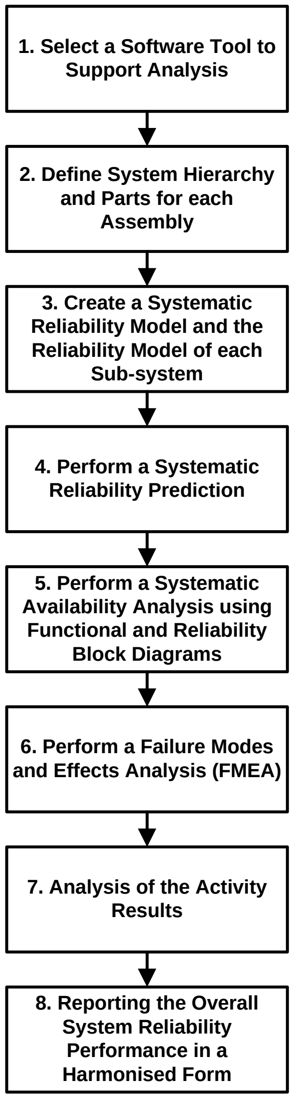


Figure2. Procedure of WTG Reliability Design

In order to realize the reliability design procedure, it is worth pointing out that step 3 above requires work to review and harmonize failure data, including failure rates and failure modes from sub-system manufacturers and suppliers. The FMEA shown in step 6 above needs to be done on all equipment, sub-system and system levels in order to identify weak design points and failure propagation effects within the system. The overall purpose for the reliability analysis is to

- Identify, evaluate and document component failures, the potential impact of each functional or hardware failure on sub-system and systematic level and to eliminate or mitigate unacceptable effects;
- Identify, design and develop possible fault tolerance mechanisms, such as redundancy or back-up systems at component and sub-component level, to ensure that failure propagation is contained at part or component level and that ultimate effects do not impact on the operational availability of the WTG;
- Obtain the information necessary for design improvement of those sub-systems whose inherent reliability proves to be inadequate;
- Ensure realization of the inherent safety and reliability levels of the system/equipment;

- Accomplish these goals at a minimum total cost, including maintenance cost, support costs and economic consequences of operational failures.

Reference documents:

Table II. Reliability Reference Documents

Reliability Analysis Task	Reference Document
Reliability Prediction and RBD	MIL -STD-756B, Reliability Modelling and Prediction MIL-HDBK-217F, Reliability prediction of electronic equipment MIL-STD-785B, Reliability Program for Systems and Equipment Development and Production
FMECA	MIL-STD-1629, Procedures for Performing a Failure Modes, Effects and Criticality Analysis.
	Automobile-style FMEAs various documents
	SAE ARP 5580, Recommended Failure Modes and Effects Analysis (FMEA) Practices for Non-Automobile Applications
Failure mode ratios	NSWC-07 (Parts A & B), Handbook of Reliability Prediction Procedures for Mechanical Equipment, 2007
	NPRD, Non-electronic Parts Reliability Data, 1995
Reliability Definitions	MIL-STD-721C, Definition of Terms for Reliability and Maintainability
Maintenance Prediction	MIL-HDBK-472, Maintainability Prediction

5. Reliability Prediction

Based on the reliability analysis procedure above a reliability prediction is calculated for the R80 WTG.

5.1 General Assumptions

General assumptions, consistent with the present phase of the R80 system Life Cycle, are as follows:

- Failure rates of components are constant during equipment life period. The component time to failure distribution is exponentially distributed (that is, a constant failure rate). There is a considerable justification for using the Exponential Distribution also for mechanical components subject to wear, especially where there is a routine and consistent repair process (as for the system under analysis);
- The failures of different components are considered independent;
- The system model is serial, therefore failure of any component causes system failure;
- The failure rate prediction only takes into account hardware failures and excludes software failures;

- The failure rate prediction makes no statement of the predicted lifetime for the sub-system considered. Mechanical sub-system population life is driven by wear-out mechanisms or retirement by obsolescence. For electrical sub-system lives, ie non-mechanical or electromechanical sub-systems, the wear-out mechanisms are predominantly extended period solder fatigue due to daily thermal cycling or electrolytic capacitance decrease from drying of the dielectric material;
- The failure rate prediction is not precise but rather an approximate estimate. Accordingly, small changes in component count for successive designs or substitution of generic components will not merit a new prediction;
- Component failure rates do not include early life or end of life failure mechanisms but only the steady state part of life.

5.2 Failure Rate Data Source

The following sources have been used for components failure rates:

- Component failure rates derived from service experience for identical components;
- MIL-HDBK-217F, Reliability Prediction of Electronic Equipment;
- SR-332 Issue 2, Reliability Prediction Procedure for Electronic Equipment - Telcordia Technologies;
- IEC 62380, Ed.1 RDF 2003 : Reliability Data Handbook - A universal model for reliability prediction of Electronics components, PCBs and equipment;
- NSWC-07, Handbook of Reliability Prediction Procedures for Mechanical Equipment;
- NPRD-95, Non electronic Parts Reliability Data;
- Supplier data;

Components have been grouped by major categories and, where appropriate, sub-grouped within sub-categories. Due to the inadequacy of the current available data, these failure Rates have been derived also by significant engineering experience obtained by direct questioning of Maintenance Operators and Design Engineers. The most significant component failure rates have been discussed and verified with the Reliawind Partners.

5.3 Basic MTBT Prediction Model (No Redundancy)

The Series Model describes a configuration of several items performing a task, but all sub-systems and components must be fully operational (100%) at all time and are all required for successful operation. The system reliability R_s is expressed as a probability value calculated by:

$$R_s(T) = e^{-\lambda_t T}$$

Where:

$$\lambda_t = \Sigma_n \lambda_i$$

i is unit/component failure rate expressed in number of failures/10^6 h.
T is the mission time (hours) and *n* is the number of units/components.

5.4 Reliability Block Diagram (RBD)

An RBD is a visual representation of the portions of the system to be modelled. Because reliability prediction assumes that all components in a system are in series, RBD cannot be used to analyze a system with redundant components. RBD are used to evaluate the reliability of systems that are complex in their configurations. RBDs also provide an efficient and effective way to compare various configurations to find the best overall system design. The goal of the RBD is the determination of almost all reliability and maintainability metrics: Reliability, Availability, Failure Rate, MTTR, Number of Failures in a fixed period, Total down time per year. The RBD diagram for the R80 and R100 WTGs is shown in figure 3.

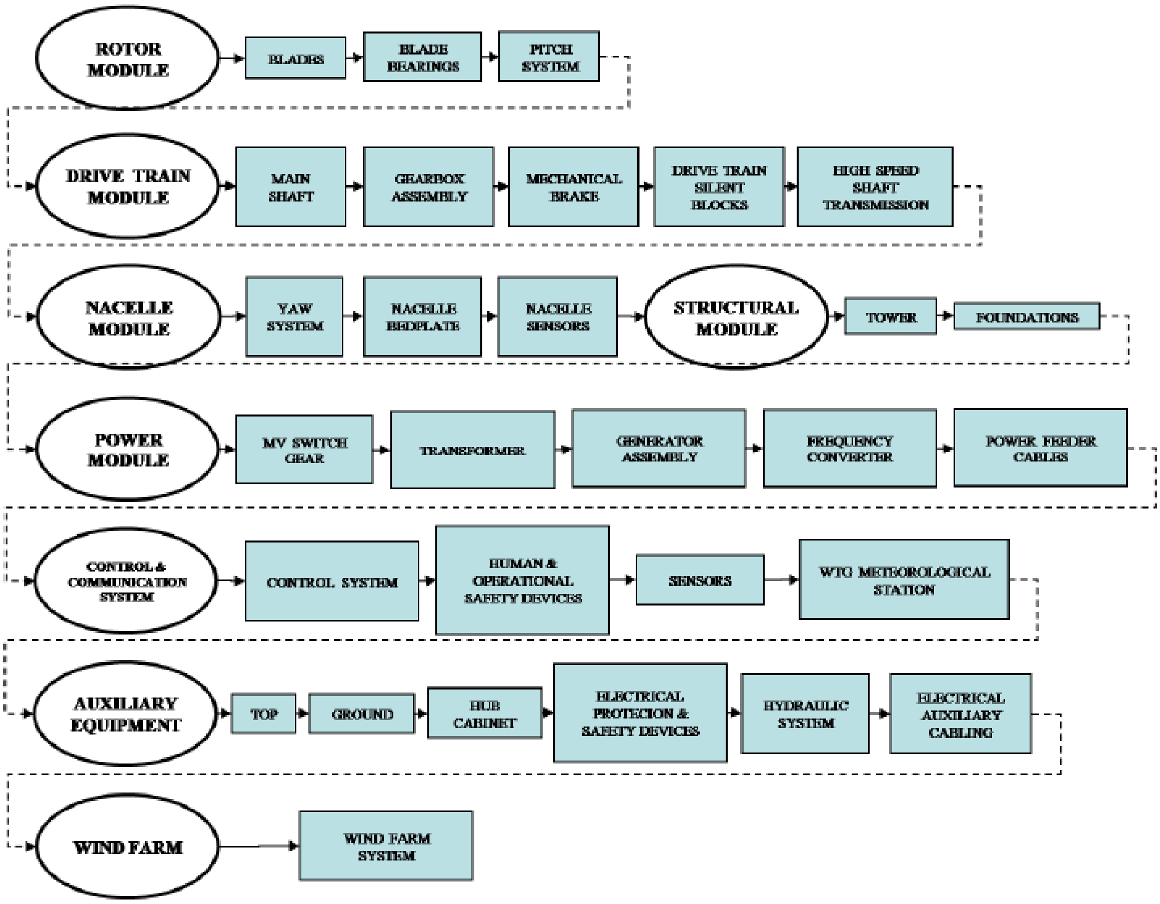


Figure 3. Reliability Block Diagram for the R80 and R100 WTGs.

5.5 Reliability Prediction Results

The predicted failure rates and the availability for the R80 system and the main sub-system are listed in Table III. The failure rate prediction is also shown in Figure 4.

Table III. Predicted failure rates and availabilities for the R80 system

Name	MTTR, %	Failure Rate, %	Availability, %
WTG	14,83	100	--
Auxiliary Equipment	1,72	35.4	99.73
Rotor Module	42,83	26.5	95.3
Power Module	10,83	15.2	99.29
Nacelle Module	1,91	9.2	99.92
Control & Communication System	3,26	4.4	99.94
Structural Module	16,80	3.9	99.72
Drive Train Module	6,89	3.4	99.9
Wind Farm System	0,49	1.7	99.99
Condition Monitoring System	0,43	0.2	99.99

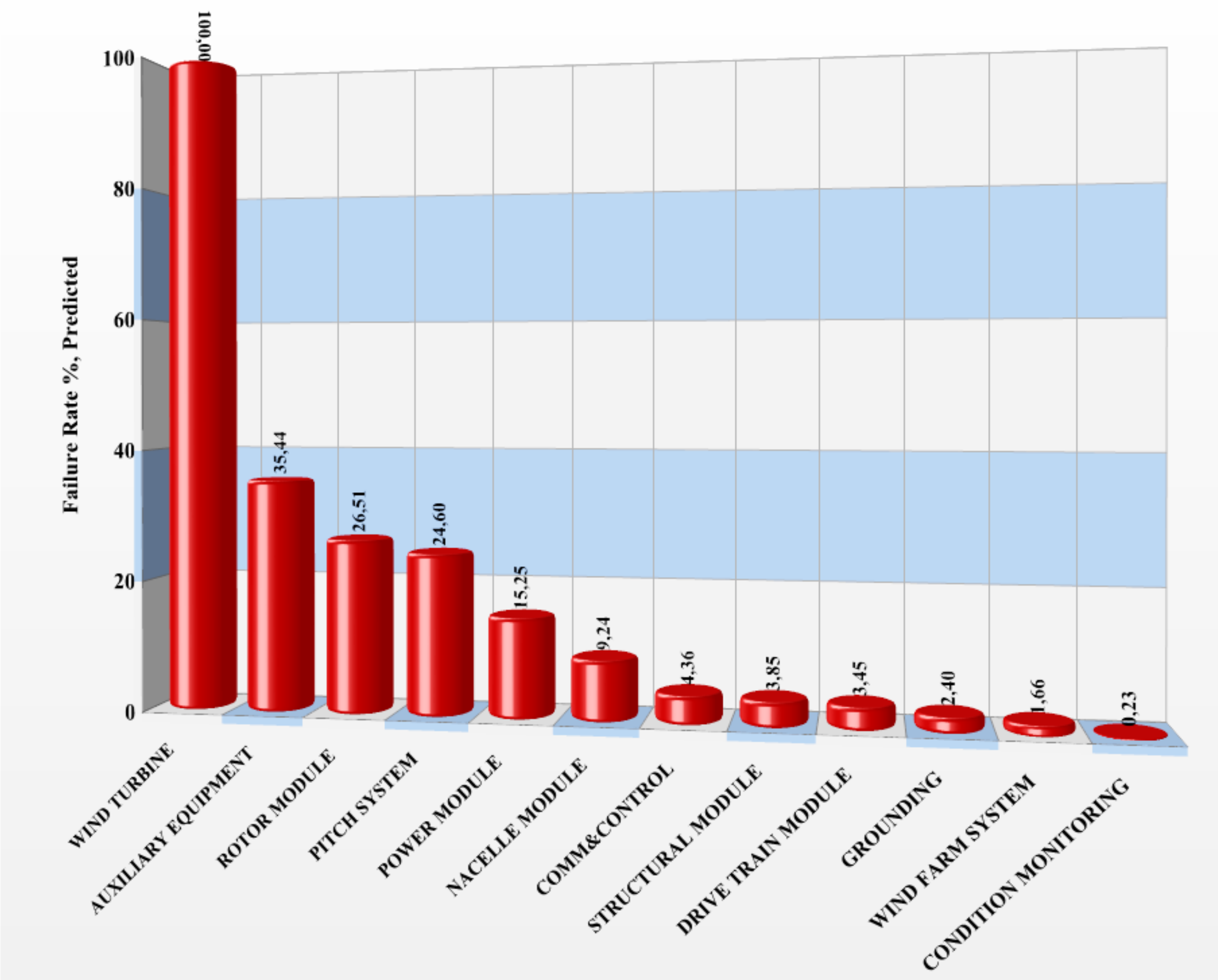


Figure 4. Top 10 Failure Rate for the R80 WTG System and Sub-systems.

From the Table III, by comparing the predicted availability it shows that the most critical sub-systems in the R80 WTG configuration are the Rotor Module, the Power Module, the Structural Module, the Auxiliary Equipment and the Drive Train Module.

Availability, Unavailability and MTBF definitions are list in Table IV.

Table IV. Reliability Characteristics

Hazard Rate	For repairable systems, as in our case, the hazard rate is equivalent to the rate of failure of the system at a specified time given that the system is operational at that time.
Mean Availability	The average availability over time
Steady-State Availability	The availability at time infinity
Failure Frequency	Expected number of failures per unit time at a specified time
Total Downtime	The total downtime between the indicated start and end times (t1 to t2) $TDT(t_1, t_2) = \int_{t_1}^{t_2} U(t)d(t)$
Expected Number of Failures	The total number of failures expected between the indicated start and end times(t1 to t2) $n_f(t_1, t_2) = \int_{t_1}^{t_2} v(t)d(t)$

6. FMECA

6.1 Method

A Failure Mode and Effects Analysis (FMEA), also referred to as an FMECA, is a bottom-up approach to analyzing system design and performance. An FMEA should be performed on a particular level of the system. This can be from the component level, referred to as a piece-part FMEA, or from a higher level, referred to as a functional FMEA. It involves tasks of identifying all potential failure modes, determining the end effect of each potential failure mode and analyzing the criticality of each failure effect. FMEAs can take many forms, but essentially these analyses are used to study a particular system and determine how that system can be modified to improve overall reliability and avoid failures.
There are three types of FMECA as listed in Table II. As the WTGs being analysed are already designed and installed, the piece-part FMECA, starting from component level, has been used according to MIL-STD-1629, which is broken down into various tasks. The methods are similar to each other, but generally analyze different data. Table V gives the list of these tasks.

Table V. FMECA Tasks

Task	Description
Task 101	Failure Mode and Effects Analysis. The purpose of the Failure Mode and Effects Analysis (FMEA) is to study the results or effects of item failure on system operation and to classify each potential failure according to its severity.
Task 102	Criticality Analysis. The purpose of the Criticality Analysis (CA) is to rank each potential failure mode identified in the FMEA according to the combined influence of severity classification and its probability of occurrence.
Task 103	FMEA – Maintainability Information. The purpose of the FMEA – Maintainability Information is to supply early criteria for maintenance planning, logistics support analysis, test planning, inspection and checkout requirements, and to identify maintainability design features that require corrective action.
Task 104	Damage Mode and Effects Analysis. The purpose of the Damage Mode and Effects Analysis (DMEA) is to provide early criteria for survivability and vulnerability assessments.

The general assumptions for the WTG FMECA in this report are:

- FMECA has been performed considering the WTG is in a GF, Ground Fixed, environment;
- No analysis has been carried out for Storage due to the shortage of storage data on component failure modes;
- Only one component fails at a time, unless an obvious chain reaction exists;
- Out-of-tolerance failures have not normally been considered.

6.2 Failure mode data source

The FMECA is based on the configuration of R100 WTG specified in Table I. Component failure rates are calculated correspondingly as described in the previous sections. For each Component Category, the failure Modes and their FM percentages have been analyzed and agreed with Maintenance People. Failure mode ratios are based on two Data Books as list in Table II.

6.3 Severity Classifications

A severity classification category has been assigned to each failure mode according to the following Table VI.

Table VI. Severity of Failure Modes

Description	Category	Definition
CATASTROPHIC	I	A failure Mode which causes Death, WTG loss or severe environmental damage
CRITICAL	II	A failure Mode which causes Severe injury, severe occupational illness, major WTG or environmental damage
MARGINAL	III	A failure Mode which causes minor injury, occupational illness, minor WTG and environmental damage, or mission degradation
MINOR	IV	Less than minor injury, occupational illness, or less than minor WTG or environmental damage

6.4 FMECA Procedure

The procedure used is set out in Figure 5.

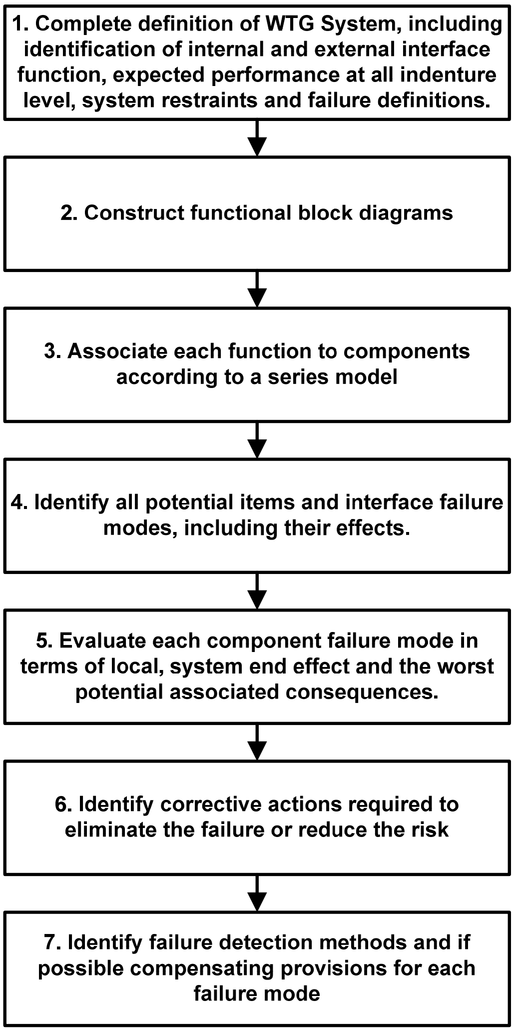


Figure 5. Procedure of FMECA

6.5 FMECA Results

The FMECA was performed at the System and Sub-system level on the R100 WTG. System Failure Mode, the Local and End Failure Effects, the Failure Rate, the Mode Failure Rate, the Severity Classification and Remarks are presented as the result of FMECA. The "No effect" in the FMECA results at high level means the component failure mode that will produce no effect at System level. FMECA investigate the failure effects from lower levels to the subsequence higher levels, i.e. a component's Local Failure Effect will produces a Failure Mode of its higher level and the higher level's Local Failure Effect to the subsequence higher level will be considered as Next Higher Effect from lower level.

The Mode Critical Number, Cm, and Item Criticality Number, Cr, are calculated according to MIL-STD-1629 for a Mission Time of 100 Hours.

The Mode Criticality Cm is a factor used in a criticality matrix representing the degree of criticality of the failure mode under a particular severity classification. Its value is calculated by:

Mode Criticality (Cm)=Failure Effect Probability (β)×Mode Failure Rate×Operating Time (t).

The Item Criticality Number Cr is a calculated field used in the FMECA work sheets. There are up to 4 different item criticalities corresponding to 4 severity levels, which are Catastrophic, Critical, Marginal and Minor respectively. The Item Criticalities are the sum of the Mode Criticalities for all failure modes within a particular severity level.

The results of the analysis are shown in Fig.9 as an example to use the WTG Criticality Matrix to identify and compare each failure mode to all other failure modes in terms of their severity. The WTG Criticality Matrix has been constructed by distributing the total number of WTG failure modes in a matrix by referring to their individual Probability of Occurrence Level as well as the Severity Classifications. The Matrix uses three colours to distinguish Risk Levels, Low Risk – Green, Medium Risk – Yellow and High Risk - Red. The coloured areas in the Matrix can be used to assess the Risk level associated to each WTG Failure Mode.

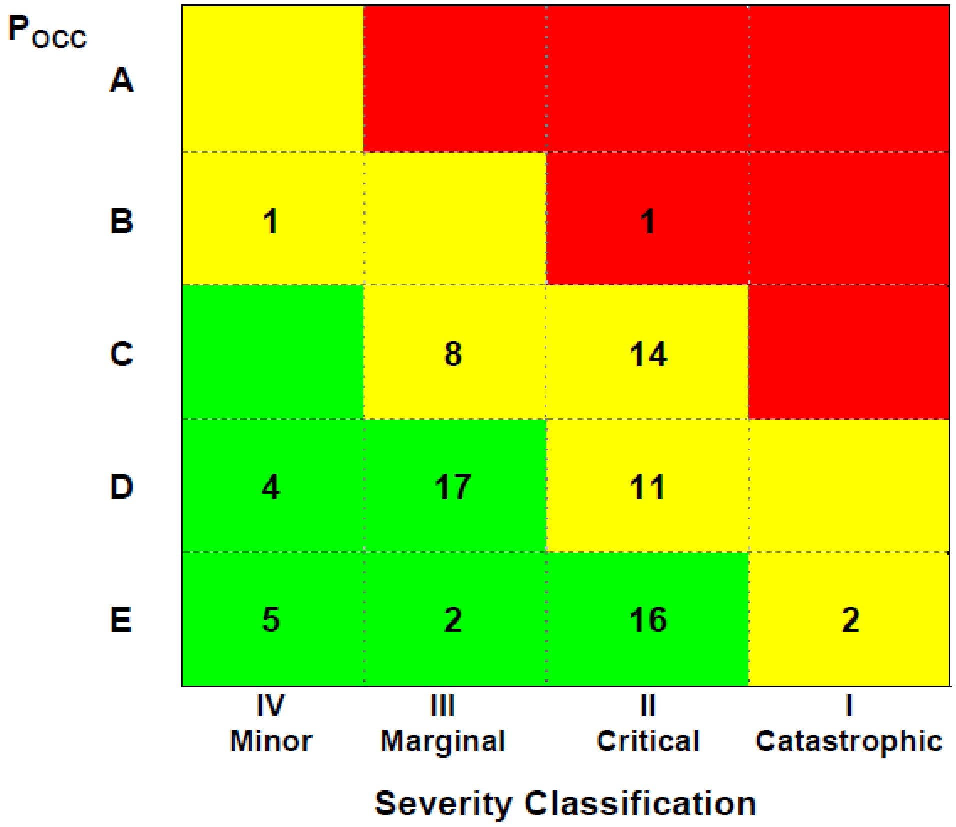


Figure 6. WTG Criticality Matrix

The definitions of five Probability Occurrence Levels are list in Table VII.

Table VII. Severity of Failure Modes

Levels	**Definition**
Level A Frequent	A high probability of occurrence during the WTG operative time interval. High probability may be defined as a single failure mode probability greater than 0.20 of the overall probability of failure during the WTG operative time interval
Level B Reasonably Probable	A moderate probability of occurrence during the WTG operative time interval. Probable may be defined as a single failure mode probability of occurrence which is more than 0.10 but less than 0.20 of the overall probability of failure during the WTG operative time.
Level C Occasional	An occasional probability of occurrence during WTG operative time interval. Occasional probability may be defined as a single failure mode probability of occurrence which is more than 0.01 but less than 0.10 of the overall probability of failure during the WTG operative time
Level D	An unlikely probability of occurrence during WTG operative time

Remote	interval. Remote probability may be defined as a single failure mode probability of occurrence which is more than 0.001 but less than 0.01 of the overall probability of failure during the WTG operative time
Level E Extremely Unlikely	A failure whose probability of occurrence is essentially zero during WTG operative time interval. Extremely unlikely may be defined as a single failure mode probability of occurrence which is less than 0.001 of the overall probability of failure during the WTG operative time

Figure 6 shows that:

- There are two Extremely Unlikely Catastrophic Failures Modes (Level E) which are due to a failure of the Nacelle Body Structure causing the Yaw Brake to be unsupported and the Rear Bearing to be locked in the Hub Structure;
- Within the Critical Failure Modes, the 14 Occasional Occurring (Level C) failures are associated with 13 failures that can induce the WTG to stop working and one failure that can have a possible adverse effect on safety and possible WTG collapse due to a loss of over-speed protection. The Critical Reasonably Probable (Level B) failure Mode is associated with a complete failure of the Converter, ie Converter inoperable.
- The remaining Marginal (27) and Minor (10) failure modes are mainly in the Low and Medium Risk areas being characterized by very low severity and probability of occurrence.

7. WTG Design Guideline and Sensing Device Recommendations

7.1 WTG Design Guideline

One of the main objects of the WP2 of the ReliaWind project was to identify best design practices and provide guidelines that can enhance overall WTG reliability and availability. Availability, often designated by *A(t),* is expressed in terms of *MTBF* and *MTTR* times an exponential function of the time. Assuming continuous operation and a complete renewal after each repair, ie repaired element is as-good-as-new, the availability *A(t)* converges rapidly to the steady-state value. This is true for a time of three or four MTTRs. This steady state value is constant and represents the intrinsic availability.

$A_i = MTBF/\,(MTBF + MTTR)$

MTBF represents the mean operating time between failures of the System.

MTTR is the Mean Time to repair.

Corrective maintenance actions consist of tasks such as preparation, fault isolation, and fault correction, which may be further broken down into disassembly, interchange, reassembly, alignment, and checkout. The times to perform each of these tasks are elements of *MTTR*.

Prolonging *MTBF* and shortening *MTTR,* which enhance WTG reliability and maintainability, are related to the reliability analysis performed at subsystem level during the design and development phase. This must be supported by analytical investigations as well as by design guidelines. Adherence to such guidelines will limit

the influence from those effects which invalidate models assumed for analytical investigation, and then contributes to building in reliability, maintainability in the design of WTG.
During the design phase the key objectives in this respect will be:

- Develop a comprehensive program for designing and manufacturing for Repair & maintenance (RAM) that includes people, reporting responsibility and an RAM Manager;
- Develop a conceptual system model, consisting of components, sub-systems, manufacturing processes and performance requirements. Use the model throughout development to estimate performance and RAM metrics;
- Identify all critical failure modes and degradations and address them in the design;
- Use data from component-level testing to characterize distribution of times to failure;
- Use data from the field. For this dedicated data management and data exchange activity, rules and guidelines are required;
- Conduct sufficient analysis to determine if the design is capable of meeting RAM requirements;
- Design in: diagnostics for fault detection, isolation and elimination of false alarms; redundant or degraded system management for enhanced mission success; modularity to facilitate remove-and-replace maintenance; accessibility; and other solutions to user related needs such as embedded instrumentation and prognostics.

There are a number of guidelines which the designer should be aware of and use to achieve a reliable equipment/system design including:

- Components Management;
- Component derating;
- Reliable circuit design;
- Redundancy;
- Environmental design;
- Human factors design;
- Failure modes and effects analysis (FMEA);
- Fault tree analysis (FTA);
- Sneak circuit analysis;
- Design reviews;
- Design for testability;
- System safety program;
- Finite element analysis.

These guidelines are generally provided through company documentation and applicable standards. Some of these guidelines are more related to reliability aspects while others are more useful to analyze design weaknesses and to improve the maintainability and safety characteristics of the system.

7.1.1 Design Guidelines for Reliability

The most direct way to increase the reliability of a WTG, ie increase the MTBF, is to increase the reliability of its assemblies and components. Many factors affect the ultimate levels of quality and reliability of components. Possibly, the most important factor is the degree to which the manufacturer is able to fabricate defect-free components. This is strictly related to component quality level and production processes. Additional factors affecting components' reliability are the levels to which the component is screened by testing, the application of levels of stress and the manner in which the component is integrated into the system.

Failures characterizing a system during its useful life occur stochastically in random irregular time intervals and their time to failure exhibits a negative exponential distribution.

The major causes of stochastic failures are:

- Stress strength interference during operation;
- Occurrence of random loads higher than expected;
- Occurrence of random strengths lower than expected;
- Insufficient safety margins;
- Human errors in usage;
- Unexplainable causes.

The main Design Guidelines to improve WTG Reliability will include all those guidelines useful to reduce or eliminate all these causes of failure.

- Components Management (Definition and application of a Components Management Plan);
- Component derating (Better understanding of electrical, thermal and mechanical ratings and use derating criteria to reduces component and component stresses);
- Component Reliability Assessment (Reliability Predictions according to approved Standards);
- Reliable component and equipment design;
- Failure modes and effects analysis (FMEA);
- Redundancy (Apply redundancy to increase fault tolerance, either in hardware, software or data duplication);
- Environmental design (To ensure components are maintained in the environment for which components were designed).

7.1.2 Design Guidelines for Maintainability

In order to increase the maintainability of a WTG, ie reduce the MTTR, the Maintainability Guidelines which reduce the time associated with each MTTR element have to be applied. This has generally to be performed project-specifically, because MTTRs depend on WTG location and environment. However, a certain number of design guidelines for maintainability are general and are listed below:

General

- Plan and implement a concept for automatic fault detection and automatic or semi-automatic fault isolation down to the last repairable unit (LRU) level, including hidden failures and software defects, as far as possible; definition and implementation of logical algorithms that will enable to detect, locate, diagnose and correct actual and impending failure conditions (WP3) in a more effective and reliable way;

- Partition the equipment or system into Line Replaceable Units (LRUs) and apply techniques of modular construction, starting from the functional structure; make modules functionally independent and make them electrically and mechanically separable; develop easily replaceable LRUs which can be tested with commonly available test equipment;
- Identify modules subject to wear or greater probability of replacement. Design these modules, assemblies or components so that they can be easily accessed, removed and replaced;
- Use quick fastening and unfastening mechanisms for service items;
- Use common hand tools and a minimum number of hand tools for disassembly and reassembly;
- Minimize serviceable items by placing the most likely items to fail, wear-out or need replacement in a small number of modules or assemblies. Design so that they require simple procedures to replace;
- Use built-in self-test and indicators to quickly isolate faults and problems;
- Eliminate or reduce the need for adjustment;
- Use common, standard replacement components;
- Aim for the greatest possible standardization of components, tools, and testing equipment; keep the need for external testing facilities to a minimum;
- Conceive operation and maintenance procedures to be as simple as possible taking personnel safety into account and describe them in appropriate manuals;
- Consider environmental conditions, thermal, climatic & mechanical, during field operation as well as during transportation and storage.

Accessibility, Exchangeability

- Provide self-latching access flaps of sufficient size, avoid the need for special tools such as one-way screws and Allen screws, use clamp fastenings;
- Plan accessibility by considering the frequency of maintenance tasks;
- Provide for speedy replacement by means of plug-out/plug-in techniques;
- Prevent faulty installation or connection through mechanical keying.

Operation, Adjustment

- Use high standardization in selecting operational tools and make labelling them simple and clear;
- Consider human aspects in defining operating and maintenance procedures;
- Order all steps of a procedure in a logical sequence and document these steps by a visual feedback;
- Describe system status, detected fault, or action to be accomplished concisely in full text;

- Avoid if possible any form of hardware adjustment or alignment in the field, carefully describe all relevant maintenance procedures.

7.2 Wind Farm Design Guideline

By reviewing the End Effects of FMEA there is no Wind Farm System (WFS) element or action which will result in the destruction or automatic shutdown of a WTG. This is because the WFS was not involved in the WTG critical functions, however these do depend upon the communications with the WTGs. Therefore this analysis has focused on WF internal communication problems and those between the WF and its control centre, the WFS. A WFS is constructed from five main sub-systems:

- SCADA Server System;
- WF infrastructure communication;
- WF external communication;
- SCADA Server Rack;
- SCADA Server UPS.

These sub-systems are based on commercial off-the-shelf components and are mounted in a standard 19" rack cabinet with front access for the storage drives and rear access for cabling and network connections. WF communications recommendations:

- Ring Communications Topology: if internal communication within the WF is made in a tree configuration, once a WTG fails, the communication of the rest of turbines in the same branch will be lost.
- Standardization: today's WFs use single-mode fibre optics to connect WTGs with distance longer than 1-2 km and multi-mode fibre optics for shorter distances. This has obliged the use of converters which increase the potential number of failures and makes Ring Communications Topology difficult. Because of the tighter tolerances requirement of single-mode fibre optics, transmitters, receivers, amplifiers and other components for single-mode fibre connection are generally more expensive than for multi-mode components. However, single-mode fibre optic cost is lower than multi-mode fibre optic cost. So the total incremental cost of single-mode over multi-mode fibre optics is not significant. This also applies to communication connections, where serial and Ethernet is being used.
- Component redundancy: some transmitters, receivers, amplifiers and other components must be redundant.

External communications recommendations:

- ADSL or 3G communication: due to accessibility problems data transmission from WFs to control centres is usually via satellite links, which can cause communication to be lost due to limited bandwidth under some weather conditions. The wide extension of ADSL and 3G in latter years makes it possible now to connect WFs to such systems and to increase the volume of data that can be made available.

Software (SW) recommendations:

- Amount of recorded data should be limited to a manageable size by analyzing the main functions of the different systems;
- Limit the number of signals monitored;
- Limit the maximum signal sampling rate;
- Reduce the time span over which data is accumulated;
- Restrict the type of data being accumulated.

Maintainability guidelines:

- Remote access for SW update is another feature that will decrease maintenance time consumption;
- Access panel with quick release of fibre optic connectors should be considered during the cabinets and substation designs. Jointing fibre optic cables is more complex than jointing electrical wire or cable. All connectors should be properly aligned and contain scoop-proof shells to ensure pin damage cannot occur;
- Keep the number of connectors with different standards to a minimum, i.e. whenever possible, use the same type of connector and key in differently if necessary;
- Label and colour each cable where possible to facilitate tracking for troubleshooting, repair or modification;
- All connectors should be corrosion resistant in order to reduce or eliminate the need for scheduled inspections or corrosion prevention measures.

For future WFS design it is recommended to be incorporated in the system specification requirements below:

- Build-In Test (BIT), which consists of an integral capability of the equipment that provides an on board automated test capability to detect, diagnose or isolate system failures, should detect at least 95% of all failures to 3 or less Line Replacable Items (LRIs);
- BIT should isolatable of 95% to 3 or less LRIs;
- Maximum ambiguity group size of 3 LRIs;
- False alarm rate < 5%.

7.3 Sub-systems Sensing Devices and Location Recommendations

7.3.1 Rotor Module Sensing Devices and Locations

The Rotor Module has different systems. The most important from a reliability point of view is the Pitch System (Electric or Hydraulic). The Hydraulic Pitch System is made of the following seven sub-systems:

- Hydraulic Cylinders;
- Distributor Block with Filter;
- Leak Oil Container;
- Accumulators;
- Hydraulic circuit;

- Pitch system brackets;
- Rotating Union.

Most of the Hydraulic Pitch System failure modes are detected by Visual Inspection and Visual Display. The percentage failure modes/detection method distribution is the following:

- Visual Inspection 43%
- Automatic Test 5%
- Undetected 5%
- Visual Display 45%
- N/A 2%

Sometimes, it is unlikely to incorporate additional sensors. The aim is to make all of the failure modes to be detected and isolated by minimum number of Line Replaceable Units (LRU) with automatic test.

7.3.2 Blades Sensing Devices and Locations

For cost effectiveness and operational safety consideration, online monitoring of rotor blades is recommended, especially for offshore installations.

Two approaches are possible:

- Accelerometer measurements:
  - Vibration analysis to determine if blade structure has changing properties -> damage propagation;
  - Load and deflection -> fatigue accumulation calculation possible.
- Indirect load measurements using strain sensors.

Several considerations have to be made when applying sensors to a WTG blade either as a separate measurement system or an embedded part of the structure. The sensors have to be rugged and capable of withstanding vibration and large temperature changes. It is also important that the sensor do not compromise the blade lightning protection system. This means conductive material with sharp edges is unacceptable. It is also important to consider the connection from the sensors to the measurement equipment. Lightning currents passing through the WTG down conductor will inducing currents in the sensor cable that could damage or destroy measurement equipment and potentially harm SCADA or control, causing unwanted downtime.

A key issue is that sensors must not threaten other WTG systems. Taking this into consideration and with the maturing of fibre optic sensor technology the recommendation for sensing devices in blades is minimum optical strain sensors using fibre Bragg gratings (FBG) placed in pairs into blade cross sections. The sensors should ideally be embedded into the blade structure. Measurement of loads in an arbitrary direction based on two sensors relies on the validity of linear superposition. Structural nonlinearities in the composite blade and the supporting turbine components invalidate the application of linear superposition in most components of the blades including the root. By detailed analysis of these nonlinearities optimal areas for sensor positions can be found. The position of the optimal areas is blade dependant. The selection of final sensor positions within these optimal areas relies on practical considerations as regards the production and mounting process.

Establishing a relation between sensor wavelength outputs and bending moment in sensor sections will enable the system to measure absolute values.

The blade residual life can be estimated to the maximum calculated value in the sensor sections using a rainflow-counting algorithm.
Using a threshold for how fast the blades are allowed to deteriorate along with absolute load measurements indicates when an inspection is needed. Being able to determine if overloading of the blade has occurred also contribute in planning inspection and maintenance.

7.3.3 *Blades Bearing Sensing Devices and Locations*

Since the blade bearings operate intermittently and with irregular motion, they are unsuitable to be monitored in the classical sense of using vibration analysis of rotational equipment (as would be applied to gearboxes, for example). Therefore, in order to provide sensor-based information for the purpose of condition monitoring, it is necessary to employ alternative analysis methods, or devices which are sensitive to other properties.
Suitable sensors for online monitoring can detect changes in motion, resistance to motion (friction values), local and overall deformations (such as out-of-roundness, flatness, conicity, etc.) and clearance of internal bearing raceways or in gearing such as would be associated with wear phenomena.
Direct or indirect determination of load might also offer possibilities to evaluate the initiation or progression of damage related to loading and fatigue.
Further, the degradation of non-metallic components such as the lubricating grease and sealing materials may be determined by sensors responsive to chemical effects.
Depending on the particular details of the monitoring and control for the blade actuation and the blade itself, it is recommended to seek opportunities for sensing methods which can be configured jointly between suppliers of the respective sub-systems.
All this may be complemented by visual examination and offline analysis within the context of an overall regime of inspection and maintenance for the blades and rotor.

7.3.4 *Gearbox Sensing Devices and Locations*

From the Gearbox analysis the following recommendations for sensing devices and location are:

- Overall condition monitoring the internal of the Gearbox can be performed using an oil debris sensor placed before the oil filter. If multiple, separated oil flows are present it is advisable to place 1 oil debris sensor per oil flow.
- Using vibration analysis the condition of individual bearings, gears and shafts can be monitored. Based on the serviceability, it makes sense to do this for
  - HS parallel module
  - HS-I parallel module
  - LS-I parallel module
- Location of vibration sensors depends on the structural design of the housing and should have a good transfer path to detect vibration originating from defects of the monitored components.
- Condition monitoring of the lubrication system is possible using filter cleanliness sensors, pressure sensors and oil sump level indicators. Location of the pressure sensors is specifically designed and depends on the number and location of the lubrication paths.

- Condition monitoring of the structural integrity of the housing should be possible as well using the available vibration sensors together with the oil sump level indicators and oil pressure sensors.
- Condition monitoring of the accessories is accessory-dependent and should be discussed with the supplier of the specific accessory if deemed necessary.

7.3.5 *Hub, Main shaft, Main frame, Rear structure, Cover, Tower, foundation, Yaw system Sensing Devices and Locations*

New Sensors

The following new sensors have been proposed for each assembly:

- HUB

  Stress sensors applied to points of both exceptional and representative stress in the hub load behaviour and monitoring.
- MAIN SHAFT

  Accelerometers in the joint components, one in the shrink disk and other in the bolted flange or if for technical reasons it is difficult to locate install accelerometer on the Gearbox frame .
- NACELLE COVER

  Temperature sensors (PT100) on the air intake, air outlet or heat exchanger to detect air flow blockage due to dirt.
- NACELLE STRUCTURE

  Stress sensor on representative points of the forward frame, main frame, and rear frame, to monitor the stress and remaining fatigue life.
- TOWER

  In the same way of nacelle structure, the integration of signal of three sensors by tower sections.
- FOUNDATION

  Three soil movement sensors as some companies are developing this technology.
- YAW

  New redundant sensors should be installed to detect the brake wearing.

Sensor Locations

- HUB

  The correct location is highly dependent of the geometry of hub and must be determine for each case as well as the number.
- MAIN SHAFT

  The accelerometer could be installed in the frame of the Gearbox near to the coupling with the main shaft.
- NACELLE COVER

The number and characteristics of air intake, outlet, and situation of heat exchanger could determine the exact position of temperature sensors. But as a general rule if the temperature of fluid on the exchange is measured, the sensor could by located downstream and measure the difference between the exterior temperature and the temperature of fluid after pass by the exchanger.

- NACELLE STRUCTURE

  The correct location is highly dependent of the frame geometry and must be determined for each case as well as the number. But basically the minimum number should be one sensor per frame.

- TOWER

  Each section needs to be measured independently. Many methods could by developed to compare the fingerprint of normal behaviour with abnormal behaviour. But as a first approach three sensors by section located at 120º each one to each other could be the simplest way to determine the tower section stress solicitation.

- FOUNDATION

  The technology in under development and for this reason is no possible to conclude at the moment the number and exact location.

- YAW

  The additional brake wear sensors specified in previous paragraph should be installed alongside the existing sensors.

7.3.6 Power Module Sensing Devices and Locations

Power Module

Most of the different protective sensors causing the Power Module to trip before fault propagation have not been considered in this analysis. For example, a fault signal for a stopped cooling fan was not considered to predict any failure rate.

Converter recommended sensing devices

The most convenient way to monitor the converter state with as few measurements as possible is to measure the converter temperature. Temperature rise is associated with many different faults in the converter. High temperature is a major failure aggravator for many converter critical components including power modules, control cards and crowbar. Temperatures can also be logged over time against the operating point to monitor performance deterioration. List of recommended temperature measurements are:

- Cabinet air temperature (one measurement per cabinet)
- Coolant incoming temperature
- Coolant outgoing temperature

Coolant outgoing and incoming temperature difference and the cabinet temperature difference with the nacelle ambient temperature should be monitored. Using these measurements it is possible to estimate the dissipation power in respect with the operating point. Grid-side and generator-side converter power differences can be also monitored.

DC-link voltage is a candidate for measurement since it already has to be monitored for DC link overvoltage protection. DC overvoltage is usually a result of a malfunction somewhere in the turbine, often outside the converter, therefore it is difficult to use it as a preventive measurement.

Generator recommended sensing devices

Like the converter, temperature measurement is a good way to monitor generator state. List of recommended temperature measurements in the generator are:

- Stator phase winding temperature, one measurement per phase
- Inner air circulation temperature
- Slip ring casing temperature
- Drive-end bearing temperature
- Non-drive end bearing temperature

Because the generator is a rotating machine, vibration measurements are recommended for monitoring on the bearings:

- Drive-end bearing vibration measurement
- Non-drive end bearing vibration measurement

The slip ring is a component in the doubly-fed generator typically experiencing wear during the turbine lifetime. Therefore it is also recommended to measure when the slip ring brushes are approaching their end-life. Easiest way to do this is to add a micro switch to the brushes, signalling when the brush is in need of change. Recommended switch locations are:

- Micro switches on the slip ring brushes
- Micro switches on the grounding brushes

7.3.7 Control & Communication System Sensing Devices and Locations

The Control System manages hundreds of digital and analogue inputs and outputs interfacing with most of the other WTG systems. The guidelines of the Control System are focus in the management of the information and how to make the control more fault tolerant. To achieve that, it will be mandatory that all critical signals related to the main control loops will be redundant and monitored by BIT, so the failure or deterioration of one signal could be substituted by other one.

These are the requirements that must be implemented in the control system to achieve a higher availability:

- Detect the failed signal: the detection of an incorrect signal could be done by one or several of the next checks:
    - Range check: valid values for the input/output signal will be define, the Control will detect when signal exceeds their specified ranges.
    - Cross check: signal values are verified by comparing in parallel with the other.
    - Model check: a simplified representation of the signal is created, when the model does not meet a given specification, the input is considered failed.
- Isolation of the signal: when a failure occurs, the system must be able to isolate the signal to the component. That is, the sensor, the cable or some PLC's module. For fault isolation a combination of Power-up BIT and Continuous BIT is important to differentiate between all possible components that could contribute to the failure. Also external test equipment or

inspections/checks can be use to isolate the faulty components when BIT is not enough.

- Actions and compensation for the control: Control System should be able to identify those failures which can affect WTG integrity, affect operation or require a future maintenance. Take the appropriate decisions and actions to contain and prevent propagation, maximize availability and inform clearly to the operator.
- Inform operator of the problem: it is important to monitor the event and provide information on identified abnormalities that have happened during operation. They typically fall into the following classification according to the incident's priority:
  - Alarms which may affect WTG integrity; they required urgent action.
  - Alarms which may affect WTG operation; they require immediate maintenance action based on economic reasons.
  - Events that do not stop the WTG (degraded operational mode); maintenance action is required in short term.
  - Events that do not stop the WTG and some maintenance is required when possible.

An Alarm or Event summary will be sent to the WFS to describe each incident that has occurred. The criticality will be calculated to assess priorities, taking into account safety, economics, duration, historical data, etc. These summaries will store all the relevant signals/data information related to the incident during a defined period of time before and after the event for further analysis. Alarms and Events should have a very low false alarm rate; otherwise they will not be an effective maintenance tool.

7.3.8 Auxiliary Equipments Sensing Devices and Locations

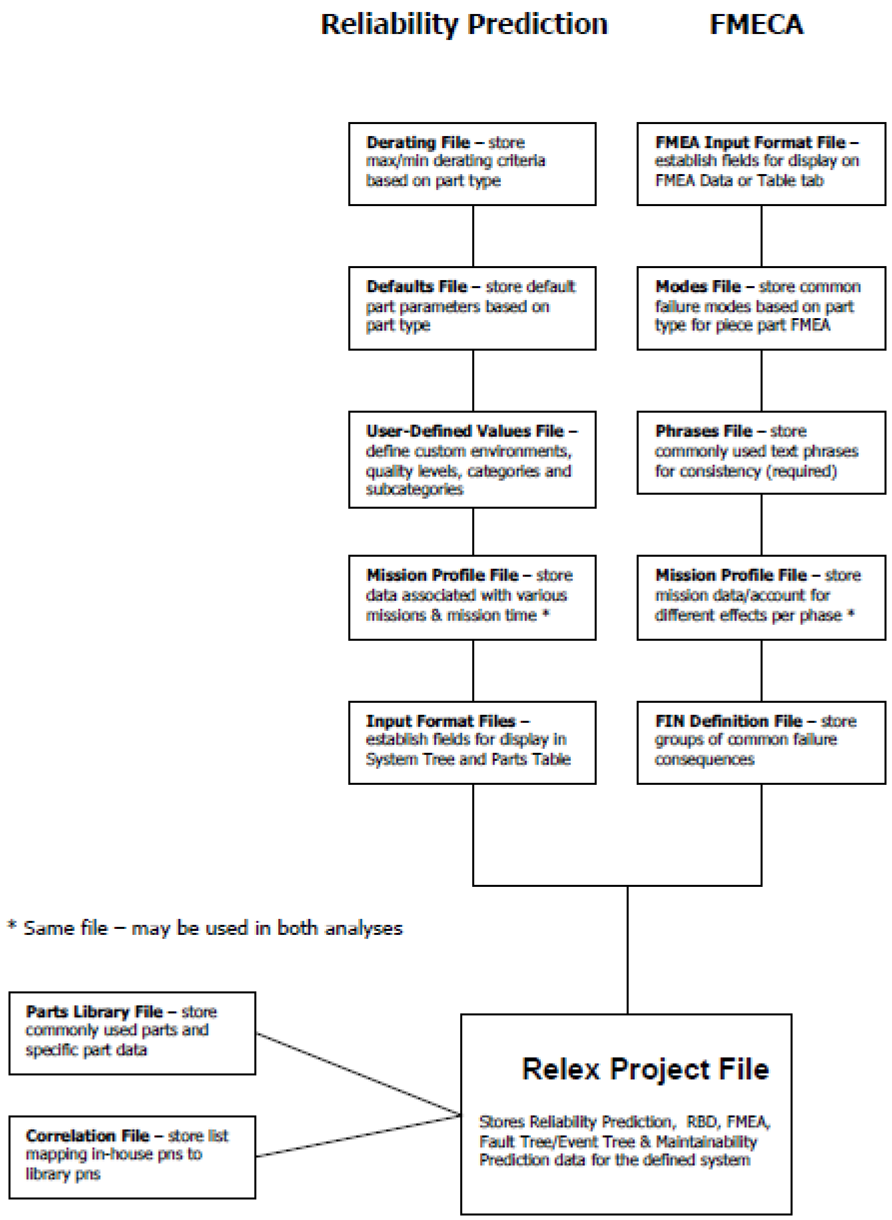
98% of Auxiliary Equipment failure modes are detected by Visual Inspection and Visual Display. It is recommended to include some sensors to improve the detection method for the following components:

- Electrical Ground or Earth
- Recirculation Pump
- Brake Thermistor (include a redundant element to ensure failure detection)

8. Confidentiality

The data contained in this Report was obtained by reliability prediction from hypothetical models, R80 & R100, generated within the Consortium and does not represent the reliability values of real wind turbines manufactured by members of the Consortium.

9. Appendix 1: Reliability Prediction and FMECA structure using Relex



10. Appendix 2: Abbreviations

A	Availability
AE	Age Exploration
Assy	Assembly
CA	Criticality Analysis
Cm	Mode criticality number
CM	Corrective Maintenance
Cr	Item criticality number
FR	Failure Rate
FBD	Functional Block Diagram
FIT	Failures In Time
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode Effects and Critical Analysis
FRACAS	Failure Reporting Analysis and Corrective Action System
FT	Fault Tree
FTA	Fault Tree Analysis
LRU	Line Replaceable Unit
M	Maintainability
M&O	Maintenance and Operations
MDT	Mean Down Time
MP	Maintainability Program
MPA	Maintainability Plan Analysis
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTTR	Mean Time To Repair
PM	Preventive Maintenance
PN	Part Number
PMA	Preventive Maintenance Analysis
PT&I	Predictive Testing and Inspection
Qty	Quantity
R	Reliability
RAM	Reliability, Availability, Maintainability
RBD	Reliability Block Diagram
RCM	Reliability Centered Maintenance
RP	Reliability Program
TBD	To Be Defined
WTG	Wind Turbine Generator

11. Appendix 3: Definitions of Terms

A “Availability”	Probability that an item will perform its required function under given conditions at a stated instant of time
Applicable PM Task	A PM task which is capable of improving equipment reliability by modifying its failure behavior (how or when it fails).
Catastrophic Failure	A failure Mode which causes Death, system loss or severe environmental damage
CM “Corrective Maintenance	Maintenance carried out after fault recognition, intended to put an item back into a state in which it can again perform its required function
Critical Failure	A failure involving a loss of function or secondary damage that could have a direct adverse effect on operating safety, on mission, or have significant economic impact.
Critical Failure Mode	A failure mode that has significant mission, safety or maintenance effects that warrant the selection of maintenance tasks to prevent the critical failure mode from occurring.
Dominant Failure Modes	The failure modes that are most likely to occur during the lifetime of the item, component, or equipment.
Effective PM Task	The characteristic of a preventive maintenance task when it is capable of improving equipment reliability to a given level under specific constraints (i.e., cost-effective).
Failure Effect Probability (beta)	The conditional probability that the failure effect results in the identified criticality classification, given that the failure mode occurs. The beta values represent your judgment as to the conditional probability that the loss occurs and should be quantified in general accordance with the following: Actual Loss, 1.0; Probable Loss, >0.1 to < 1.0; Possible Loss, > 0.0 to = 0.1; No Effect, 0.
Failure Mode and Effects Analysis (FMEA)	Analysis used to determine what parts fail, why they usually fail, and what effect their failure has on the system (End Item). An element of Reliability Centered Maintenance (RCM).
FIT "Failure In Time"	This term defines the number of failures for one billion of Hours.
FR "Failure Rate" (fpmh)	This term defines the number of failures for one million of Hours.
Item Criticality (Cr)	The item criticality is a calculated field used in the FMECA worksheets. There are up to 4 different item criticalities corresponding to up to 4 severity levels (see Severity Classification). The item criticalities are the sum of the mode criticalities for all failure modes within a particular severity level.
Maintainability	A design objective which provides for easy, accurate, safe, and economical performance of maintenance

	functions.
Mode Criticality (Cm)	A factor used in a criticality matrix representing the degree of criticality of the failure mode under a particular severity classification. This value is as follows: Mode Criticality (Cm) = Failure Effect Probability (beta) * Mode Failure Rate * Operating Time (t).
MTBF "Mean time between failure"	This term defines the mean time between failures. Expressed in Hours of operations for a specific module population. It does NOT mean that a module will operate for that many Hours before failure.
MTTF "Mean Time To Failure"	This value is very similar to MTBF and is used when evaluating non-repairable systems. MTBF assumes that a device is to experience multiple failures in a lifetime, and after each failure a repair occurs. For non-repairable systems, there is no repair. Therefore, in the lifetime of a non repairable device, the device fails once and MTTF represents the average time until this failure occurs
MTTR "Mean time to repear"	This term defines the expected mean value of an item's repair time
Performance Standards	Those standards which an item is required to meet in order to maintain its required function. The performance standard defines functional item failure.
PM "Preventive Maintenance"	Maintenance carried out at predetermined intervals and according to prescribed procedures to reduce the probability of failure or the degradation of an item functionality.
Predictive Testing and Inspection (PT&I)	Those testing and inspection activities for facility items that generally require more sophisticated means to identify maintenance requirements than those of preventive maintenance. Sometimes referred to as «Condition-based Maintenance» and «Predictive Maintenance.» Replaces maintenance scheduled at time intervals with maintenance scheduled only when the condition of the equipment requires it. The PT&I data obtained allows for planning and scheduling preventive maintenance or repairs in advance of failure.
Preventive Maintenance (PM)	The planned, scheduled periodic inspection, adjustment, cleaning, lubrication, parts replacement, and minor repair of equipment/systems for which a specific operator is not assigned. Preventive Maintenance consists of many checkpoint activities on items that, if disabled, would interfere with essential system operation, or property, or involve high cost or long lead time for replacement. Also called «time-based maintenance» or «interval-based maintenance.» Depending on the intervals set, PM can result in a significant increase in inspections and routine maintenance; however, it should also reduce the frequency and seriousness of machine failures for components with defined, age-related wear patterns.

Proactive Maintenance	Application of predictive maintenance technologies toward extending machinery life. It seeks to eliminate the need for maintenance through better design, better installation, precision balance and alignment, and root-cause failure analysis.
Reactive Maintenance	Often called «breakdown maintenance,» «reactive maintenance,» or «run to failure (RTF).». Maintenance or equipment repairs are performed only when the deterioration in a machine's condition causes a functional failure. A high percentage of unplanned maintenance work, high replacement part inventories, and the inefficient use of maintenance personnel typify this strategy.
Redundancy	Existence of more than one means for performing a required function in an item
Reliability	The ability of an item to perform a required function under stated conditions for a given time interval (usually expressed as a probability). Reliability is expressed as a probability value (a value between 0 and 1). For constant failure rate systems, the equation for the calculation of reliability is: R = e-λt where t is the mission time, and λ is the failure rate.
Reliability Block Diagram	Block Diagram showing how failures of elements, represented by the blocks, result in the failure of an item
Reliability Centered Maintenance (RCM)	A maintenance strategy that logically incorporates into a maintenance program the proper mix of reactive, preventive, predictive, and proactive maintenance practices. Rather than being used independently, the respective strengths of these four maintenance practices are combined to maximize facility and equipment operability and efficiency while minimizing required maintenance time, materials, and consequently, costs. For example, a small pump might be run to failure, a gasoline engine might be placed on a 1,000-hour PM program, and a critical turbine might be monitored with on-line diagnostic sensors. This strategy often includes performing a so called «Failure Mode and Effects and Criticality Analysis (FMECA),» to identify those processes or systems that statistically exhibit the greatest chance of critical and catastrophic failures.
Repair	That facility work required to restore a facility or component, including collateral equipment, to a condition substantially equivalent to its originally intended and designed capacity, efficiency, or capability. It includes the substantially equivalent replacements of utility systems and collateral equipments
Vibration Analysis	The dominant technique used in predictive maintenance. Uses noise or vibration created by mechanical equipment to determine the equipment's actual condition. Uses transducers to translate a vibration amplitude and

frequency into electronic signals. When measurements of both amplitude and frequency are available, diagnostic methods can be used to determine both the magnitude of a problem and its probable cause. Vibration techniques most often used include broadband trending (looks at the overall machine condition), narrowband trending (looks at the condition of a specific component), and signature analysis (visual comparison of current versus normal condition). Vibration analysis most often reveals problems in machines involving mechanical imbalance, electrical imbalance, misalignment, looseness, and degenerative problems.

11. Appendix 4: Applicable Documents

A. Reliawind Documents

[1]	D.1.2	Reliability Profiles methods
[2]	D.1.3	Reliability Profiles results
[3]	D.2.0.4.b	Whole System Reliability Model (Appendices)
[4]	D.2.0.1	Common Reliability Analysis Methods and Procedures
[5]	D.2.0.2	Functional Block Diagrams Specifications
[6]	D.2.0.3	WTG Reliability Model Specifications
[7]	D.2.1.1	Pitch system Reliability Model
[8]	D.2.1.2	Pitch system Reliability Assessment Report
[9]	D.2.1.3	Pitch system Design Guidelines
[10]	D.2.1.4	Pitch System Recommended Sensing Devices
[11]	D.2.2.1	Blades Reliability Model
[12]	D.2.2.2	Blade Reliability Assessment Report
[13]	D.2.2.3	Blade Design Guidelines
[14]	D.2.2.4	Blades Recommended Sensing Devices
[15]	D.2.3.1	Blade Bearing Reliability Model
[16]	D.2.3.2	Blade Bearing Reliability Assessment Report
[17]	D.2.3.3	Blade Bearing Design Guidelines
[18]	D.2.3.4	Blade Bearing Recommended Sensing Devices
[19]	D.2.4.1	Gearbox Reliability Model
[20]	D.2.4.2	Gearbox Reliability Assessment Report
[21]	D.2.4.3	Gearbox Design Guidelines
[22]	D.2.4.4	Gearbox Recommended sensing devices and location
[23]	D.2.5.1	Hub, Main Shaft, Rear Structure, Cover, Tower Foundation and Yaw Reliability Model
[24]	D.2.5.2	Hub, Main Shaft, Rear Structure, Cover, Tower Foundation and Yaw Reliability Assessment Report
[25]	D.2.5.3	Hub, Main Shaft, Rear Structure, Cover, Tower Foundation and Yaw Design Guidelines
[26]	D.2.5.4	Hub, Main Shaft, Rear Structure, Cover, Tower Foundation and Yaw Recommended Sensing Devices

[27]	D.2.6.1	Converter, Transformer, Switch Gear and Generator Reliability Model
[28]	D.2.6.2	Converter, Transformer, Switch Gear and Generator Reliability Assessment Report
[29]	D.2.6.3	Converter, Transformer, Switch Gear and Generator Design Guidelines
[30]	D.2.6.4	Converter, Transformer, Switch Gear and Generator Recommended Sensing Devices
[31]	D.2.7.1	Control System Reliability Model
[32]	D.2.7.2	Control System Reliability Assessment Report
[33]	D.2.7.3	Control System Design Guidelines
[34]	D.2.7.4	Control System Recommended Sensing Devices
[35]	D.2.8.1	Auxiliary Equipment Reliability Model
[36]	D.2.8.2	Auxiliary Equipment Reliability Assessment Report
[37]	D.2.8.3	Auxiliary Equipment Design Guidelines
[38]	D.2.8.4	Auxiliary Equipment Recommended Sensing Devices
[39]	D.2.9.1	Wind Farm Systems Reliability Model
[40]	D.2.9.2	Wind Farm Systems Reliability Assessment Report
[41]	D.2.9.3	Wind Farm Systems Design Guidelines
[42]	D.2.9.4	Wind Farm Systems Recommended Sensing Devices
[43]	FP7-ENERGY-2007-1-RTD	Reliability focused research on optimizing Wind Energy Systems design, operation and maintenance : Tools, proof of concepts, guidelines & methodologies for new generation

B Reference Documents

[R1]	MIL-STD-785B Not. 2	Reliability Program for Systems and Equipment Development and Production
[R2]	MIL-STD-721C Not. 1	Definition of Terms for Reliability and Maintainability
[R3]	MIL-STD-756B Not. 1	Reliability Modelling and Prediction
[R4]	MIL-HDBK-217F Not 2	Reliability Prediction of Electronic Equipment
[R5]	MIL-HDBK-472	Maintainability Prediction
[R6]	MIL-STD-721	Definitions of Terms for Reliability and Maintainability
[R7]	MIL-STD-1629	Procedures for Performing a Failure Modes, Effects and Criticality Analysis
[R8]	NSWC-07	Handbook of Reliability Prediction Procedures for Mechanical Equipment
[R9]	NPRD-95	Non electronic Parts Reliability Data 1995