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Failure Mode and Effect Analysis of Repower 5M Wind Turbine

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Abstract

The following paper presents a reliability analysis of REpower's 5M wind turbine. The 5M turbine, with a 5 megawatts power rating and 126 metre rotor diameter, is one of the world's largest and most powerful wind turbines. The turbine has been designed for both on-shore and off-shore application, and when utilized in a wind farm, can provide outputs similar to a conventional power plant. A number of reliability and maintainability tools were used throughout the paper to assess the turbines reliability characteristics. These include a Failure Mode and Maintenance analysis (FMMA), a Failure Mode and Effect Analysis (FMEA) and a Failure Mode Effect and Criticality Analysis (FMECA). Following the identification of the various failure modes associated with the 5M turbine, an investigation into a particularly mode was carried out using Finite Element Analysis (FEA). Please note, throughout this paper, the wind turbine is deemed to have failed if it is incapable of producing electricity.

Keywords— *Reliability analysis, Wind turbine analysis, The Failure Mode and Effect Analysis (FMEA), Failure Mode and Maintenance Analysis (FMMA), The Failure Modes, Effects and Criticality Analysis (FMECA)*

I. INTRODUCTION

A Wind turbine is the device that converts kinetic energy from the wind to electrical power. Wind turbine has number of parts attached with each other and makes the complete assembly which generate the electrical power under stated condition. The following paper presents a reliability analysis of REpower's 5M wind turbine. The 5M turbine, with a 5 megawatts power rating and 126 metre rotor diameter, is one of the world's largest and most powerful wind turbines. Components of the wind turbine are given in the hardware details section. If we want to calculate the reliability of the complete wind turbine assemble than first we have to find the relationship with the each component of wind turbine assembly, failure mode of the each component as well as their effect and criticality. For the above exercise a number of reliability and maintainability tools are available to assess the turbines reliability characteristics. These include a Failure Mode and Maintenance analysis (FMMA), a Failure Mode and Effect Analysis (FMEA), a Failure Mode Effect and Criticality Analysis (FMECA)

II. HARDWARE DETAILS

The following section provides details on the various components and systems which make up a 5M wind turbine. This hardware has been considered throughout the reliability analysis process.

2.1 Blade

The complete rotor assembly has a weight of 120 tons and 126 metre diameter. The rotor consists of three rotor blades and a hub. Each of the three rotor blades is 51 metres in length and weighs 18 tons. The rotor blade uses load optimised glass fibre reinforced plastic construction (GFRP), and is made of two shells and two rigid underpinning beams, infused with resin. Each blade incorporates a lightning protection system and a load and status monitoring system. [2]

2.2 Hub

The one-piece hub shell is made of cast iron and attaches the blades to the main shaft. The hub incorporates two major components, a blade pitch system and elastomer bearings for the battery boxes. In addition, the hub is designed to allow maintenance to be carried out directly from the nacelle.[2]

2.3 Main Rotor Shaft

The wind turbine converts kinetic energy into mechanical energy via the main rotor shaft. This shaft has a 1.5-meter diameter and supports the 120 Ton rotor assembly. Two bearing support the turbine rotor shaft. Turbine shaft is made from the cast iron.[2]

2.4 Main Shaft Bearings

There are two main bearings which support the main rotor shaft. A movable CARB bearing sits at the rotor end of the shaft, while a fixed spherical roller bearing sits at the other. The CARB bearing provides the shaft with a limited amount of axial moment which helps to prevent damage due to misalignment.[2]

2.5 Shaft Coupling

The shaft coupling connects the main shaft to the gearbox. The coupling is normally in the form of a clamping unit, consisting of a selection of rings, which when tightened, compress against the main shaft and the gearbox input.[2]

2.6 Main Gearbox

The gearbox is positioned between the main rotor shaft and the high speed shaft, which lead to the generator. The gearbox consists of two planetary helical stages and one double helical spur gear stage and provides a gear ratio of 97:1. The gear box is capable of operating at low temperatures due to an oil/air exchanger oil cooling system and is equipped with a condition monitoring system. [2]

2.7 High Speed Shaft

The high speed shaft transfers rotational movement from the gear box to the generator.

2.8 Lubrication System

Lubrication system plays a vital role in facilitating service task for every mechanical system. The centralised lubrication system is employed to increase the life span of the wind turbine by avoiding expensive unplanned repairs and downtime. The aim of this system is to ensure lubricant is reliably fed by six pumps to the bearings, drives & generators eleven metering devices. Electrical devices (pressure switch & ultrasonic sensor) are used to monitor the supply of lubricant and trigger an alarm when lubricant levels are low.

2.9 Generator

The double fed-asynchronous generator is used in the 5M wind turbine, and converts the mechanical energy to electrical energy. The generators receive it mechanical energy via a high speed which is run from the gearbox. The generator connects through to the convertor and transformer.

2.10 Convertor

The aim of the convertor is to convert the DC supply received from Generator to an AC current. The convertor is water cooled and includes a redundancy control system.

2.11 Transformer

The cast resin Transformer is used with water cooled IGBT frequency convertor. Transformer converts the capacities up to 5KV-ampere to various voltage levels & feeds to grid for further distribution.

2.12 Uninterruptible Power Supply System

Continuous data transmission from sensors within the turbine to the central control unit is critical to the efficient and safe operation of the turbine. The uninterruptible power supply (UPS) system provides a constant power supply to these system and other additional electrical systems in the event of power failure. The system is built to withstand extreme offshore conditions, such as high temperatures, high humidity, and high salinity levels. [2]

2.13 Controller

The controller is responsible for monitoring all of the safety sensors, the operational function of the wind turbine, and external factors such as wind speed and direction.

2.14 Pitch system

The electronic pitch control system is used to rotate the turbine blades, enabling the blades to provide maximum speed and torque at the output shaft in differing wind conditions. The pitch control system allows each blade to be positioned independently depending on wind conditions. The most efficient blade pitch angle it determined through two independent measuring systems. The unit consist of a electro-mechanical actuator, automatic lubricating track and gearing, abd two independent measuring systems.

2.15 Yaw system

The yaw system directs the wind turbines' rotor towards the wind direction and is located between the nacelle and the tower. The system consists of 8 yaw drives called Azimuth drives, each consisting of an electric motor, hydrodynamic coupling, gearbox and drive pinion. The yaw system also includes 8 yaw bearings, gear rims and brake callipers. In addition, the yaw system also introduces damping to the wind turbine, beneficial for counteracting instabilities such as lateral tower and blade edge oscillations, eliminating the need for a tail vane system.

2.16 Nacelles & Tower

The nacelle is 6 metres wide, 6 metres high and 18 metres long and accommodates all of the above equipment. The nacelle is constructed from approximately 4 tons of glass fibre reinforcements and 9 tons of polyester resin.

The tower is fabricated from steel and reaches a height of approximately 114 metres. The tower is constructed using a modular method, assembled in section, and tappers from 6 metre diameter at the base to 5.5 metres at the top.

III FMMA

Failure Mode and Maintenance Analysis (FMMA) analyses the failure mode(s) of each component and the corresponding ways to maintain them or prevent the incidence from occurring. The results from this analysis indicate that long term monitoring of various components should be incorporated in order to establish when maintenance need to be carried out.[1].

Component/ system	Failure mode	Cause of failure	Consequence of failure	Maintenance action
3.1 Blade				
Rotor	Fatigue and fracture.	High induced stress levels due to operation in high winds, cyclic loading or lightning strike.	Blade delaminating and fracturing.	Installation of sensors to monitor blade stress levels.
Sensors	Corrosion or deterioration.	Integrity failure due to weather effects.	Inability to monitor blade, reduced turbine efficiency.	Sensors to continual monitored and replaced when appropriate.
Lightning Protection System	Corrosion or deterioration.	Fittings deteriorate due to weather effects or repeated lightning strikes.	Blades become vulnerable to lightning strike	System should be checked for visual damage or loose parts regularly and replaced if necessary.
3.2 Hub				
Hub	Fatigue and fracture.	High stress levels due to extreme loading or lightning strikes.	Fracture in the shell, rotor breaks, leading to wind turbine failure.	Acoustic analysis to be used to identify fractures in hub's material.
3.3 Main Rotor Shaft				
Main Rotor Shaft	Fatigue and fracture.	Fatigue induced due to stress raiser such as improper grooves or welding defects, or misalignment.	Generates cracks in shaft, leading to shaft failure. Misalignment results in excessive loading on shaft and bearing.	Proper analysis on shaft and alignment to detect deficiencies.
3.4 Main Shaft Bearing				
Main Shaft Bearings	Seizure Corrosion Surface distress	Poor or incorrect lubrication. Presence of corrosive substances in the bearing. Excessive loading through shaft misalignment.	Bearing failure due to excessive heat. Pitting of raceways and other surfaces of the bearing leading to bearing failure Small, shallow craters with crystalline fracture surfaces, leading to bearing failure.	Sensors to monitor bearing temperature and vibration. Improve sealing. Use lubricant with better rust inhibiting properties. Monitor shaft alignment.
3.5 Shaft Coupling				
Shaft Coupling	Accelerated wear and early failure.	Excessive loads and insufficient maintenance.	High stress levels leading to rapid deterioration of coupling components.	Regular Inspection of Couplings.
3.6 Main Gearbox				
Main Gearbox	Pitting Shock loading	Inherent Errors in the gears, presence of water in lubrication. Sudden shock load above design limit.	Increased wear of gear system. Fracture of gear components	Gear system should be monitored for abnormal noise or vibration. Lubricant should be regularly replaced.
3.7 High Speed Shaft				
High Speed Shaft	Fatigue and fracture.	Fatigue induced due to stress raiser such as improper grooves or welding defects, or misalignment.	Generates cracks in shaft, leading to shaft failure. Misalignment results in excessive loading on shaft and bearing.	Proper analysis on shaft and alignment to detect deficiencies.

3.8 Lubrication System				
Lubrication Pumps	Blockage.	Debris within pump system.	Lubricant will not be supplied. Increased wear of bearings, and overheating.	Appropriate filtration system to be used and monitored.
Electric Motor Drives	Bearing failure.	Bearing fatigue leading to fracture.	Temperature raises rapidly creating increased wear on components.	Temperature sensors should be installed to monitor lubrication effectiveness.
3.9 Generator				
Generator Bearing	overloading/fatigue/ misalignment.	Bearing fatigue, Improper lubrication.	High vibration of system and excessive heat generation leading generator failure.	Generator to be condition monitored, with fault detection alarm installed.
Cooling System	Overheating.	Fault on cooling system	Damage the windings on stator & rotor.	Generator to be condition monitored, with fault detection alarm installed.
3.10 Converter System				
Converter System	Electrical overload by drawing current above its rated level. Short circuit.	Electrical current surge. Low insulation levels cause electrical failure.	Wind energy fails to be converted into usable energy. Wind energy fails to be converted into usable energy.	Automatic regulators should be integrated into the system. Proper insulation should be provided and regularly inspected.
3.11 Transformer				
Oil tank	Leakage.	Corrosion or gasket failure.		Visual checks on tank should be conducted. Oil level monitors should be installed.
Cooling System	Overheating.	Poor lubrication of fan bearings or bushings	Transformer failure.	Standby cooling fan and temperature sensors should be integrated.
Transformer Primary & Secondary Windings	Short circuit.	Low oil quality (conducted particle or water in the oil). Lightening strike.	Hot spots leading to fault in insulation material. Transient overvoltage leading to mechanical damage.	Transformer oil sample tests should be conducted at intervals. Concise lightening protection system should be used.
3.12 UPS System				
UPS Batteries	Dead battery cells.	Ageing battery units.	UPS system fails.	Battery integrity monitors should be installed.
UPS Casing	Fracture in UPS casing.	Improper handling.	Moisture penetrates sensitive areas, leading to UPS failure.	Visual Inspection should be carried out at Intervals.
UPS Fan	Cooling fan cannot move.	Poor lubrication of bushings or bearings, corrosion.	Fan fails to move leading to systems failure due to overheating.	Proper lubrication of cooling fan should be ensured.
3.13 Controller				
Controller Circuit Board	Short Circuit.	Moisture penetration or lightening strike	Inability to transfer information to the control room.	Proper Insulation and sealing of controller. Lightening protection system should be used on controller.
3.14 Pitch System				
Electro-mechanical Actuator	Overloading or misalignment of bearings. Electrical overload.	Failure due to wear, excessive vibration or environmental conditions. Use of current above its rated level.	Pitch system will fail to correctly orientate blade and efficiency will reduce.	Bearing vibration, temperature and lubricant level should be monitored. An electricity regulator to be integrated into the system.
Gearing System	Pitting	Through wear, fatigue or excessive loading.	Pitch system will fail to correctly orientate blade and efficiency will reduce.	Gear system should be monitored for abnormal noise; Proper lubrication should be ensured.

Measuring System	Wrong pitch angle.	Poor calibration	Pitch system will fail to correctly orientate blade and efficiency will reduce.	Proper calibration and monitoring of pitch system
3.15Yaw System				
Yaw Drive	Electric motor failure.	Motor component(s) failure.	Turbine rotor gets stuck in a position and loses wind power.	Standby yaw drives should be serviced at intervals to ensure their availability.
Yaw Bearing	Seizure Corrosions	Poor or incorrect lubrication Presence of corrosive substances in the bearing.	Bearing failure due to excessive heat Pitting of raceways and other surfaces of the bearing leading to bearing failure.	Sensors to monitor bearing temperature and vibration characteristics. Improve sealing. Use lubricant with better rust inhibiting properties.
Gear Rim	Worn gear teeth.	Inherent errors in the gears, presence of water in the lubricant, sudden shock load above design limit.	Damage of the gear system.	Gear system should be monitored for abnormal noise; Proper lubrication should be ensured.
Brake Assembly	Hydraulic leakage.	Wear or excessive pressure on hydraulic lines.	Rotor fails to stop at the right wind path.	Brake system should be inspected at intervals; Sensors required to monitor brake hydraulic fluid level.
3.16Nacelle & Tower				
Tower	Corrosion, fatigue and fracture.	Weather effects and extreme wind conditions.	Loss of structural integrity and subsequent collapse.	Integrity of tower should be inspected at intervals. Anticorrosion treatment should be used and monitored.
Nacelle	Corrosion	Weather effects	Loss of structural integrity and subsequent collapse	Integrity of nacelle should be inspected at intervals. Anticorrosion treatment should be used and monitored.

IV FMEA & FMECA

4.1. FMEA

The Failure Mode and Effect Analysis (FMEA) is the process of identifying failure modes, determining the effect they have on the system, and the likelihood of them occurring. The probability and consequences of each failure mode is assigned a value. The multiplication of these values determines the failure mode's criticality rating. A high criticality rating results identifies which components or failure modes which need the most constant monitoring and maintenance.[1]

Component/ Object	Sub Component/ Object	Failure Mode	Consequence	Probability Rating (y) 1: 5	Consequence Rating (x) 1:10	Criticality Rating (x,y)
Wind Turbine Blade	-Blade gear for angle control -Blades	-Gear teeth slip -Blade crack	-Blades not able to adjust angle of attack -Wind turbine stops working	4 3	8 4	32 12
Wind Turbine Hub Assembly	-Hub, electrical blade positioning. -Hub, cast iron shell	-Error in positioning. -Fracture in the shell	-Blade disconnect from the hub -Rotor breaks, leading to wind turbine failure	2 3	4 7	8 21

Turbine Shaft	-Shaft	-Fatigue cracks -Distorting the shape of the shaft	-Generates cracks in shaft resulting collapse of wind turbine system. -Collapse of wind turbine system.	2 4	4 8	8 32
Main Shaft Bearing	-Bearing	-Bearing slips	-Rotor rotation does not transfer to generator	2	8	16
Shaft Coupling	-Coupling	-Misalignments -Fracture and decouple	-Due to vibration energy lost -Transmission of mechanical energy in to the generator is stopped	3 2	6 6	18 12
Gear Box	-Gear	-Gear teeth slip -Fracture in Gear teeth	-Energy transmission stop -Energy transmission stop	3 2	7 6	21 12
High Speed Shaft	-Shaft	-Fatigue cracks -Distorting the shape of the shaft	-Generates cracks in shaft resulting collapse of wind turbine system. -Collapse of wind turbine system.	2 2	4 4	8 8
Main brakes (Hydraulic)	-Main brakes (Hydraulic)	-Wear caused due to stop the turbine from full speed. -Excess heating due to low level of hydraulic fluid.	-Uncontrolled speed of the rotor/yaw causing failure of other components. -Will not give satisfactory result for braking function for rotor/yaw.	3 3	6 6	18 18
UPS System	-UPS batteries -UPS casing -UPS fan	-Dead battery cells. -Fracture in UPS casing -Fan fails to move leading to systems failure	- UPS system fails. - Moisture gets into sensitive areas and may lead to UPS failure - UPS system fails	3 2 2	7 6 6	21 12 12
Centralised Lubrication System	-Pump of lubrication system -Electrical devices of lubrication system.	-Pump failure Due to overloading -Electronic devices failure Due to shorting circuit	-Lubricant will not be supplied & wear & tear of bearings, drives etc. -Lubricant level will not be maintained causing excess heat generation in bearings, drives etc.	2 3	8 6	16 18
Generator	-Generator shaft -Generator rolling bearing -Generator Overheating	-Shaft failure Due to excessive loading/fatigue /misalignment -Bearing failure Due to misalignment with shaft/improper lubrication system -Overheating due to improper cooling system	-The Generator system will be collapsed. -Causes vibration, wear & tear leads to cracks in shaft, bearing, stator & rotor. -Damage the windings on stator & rotor.	2 2 2	7 7 6	14 14 12

Converter	-Convertor	-Shorting the circuit due to excess heating	- Converter system will not work & electrical energy will not be transmitted to Transformer.	3	6	18
Transformer	-Transformer primary & secondary windings	-Shorting the circuit due to excess heating	-Transformer system will be collapsed & will not transfer the electrical energy to grid.	3	6	18
Controller	Controller	Faulty output	Failure of other parts/system of turbine	3	8	24
Pitch System & Yaw System	-Electro-mechanical actuator -Gearing System -Measuring System	-Devise suffers electrical overload by drawing current above its rated level. -Low insulation levels causes electrical failure. -Through wear, fatigue or excessive loading -Electrical failure due to current overload	-Pitch system will fail to correctly orientate blade and efficiency will reduce. -Pitch system will fail to correctly orientate blade and efficiency will reduce -Pitch system will fail to correctly orientate blade and efficiency will reduce. -Pitch system will fail to correctly orientate blade and efficiency will reduce.	1 2 2 3	8 7 7 7	8 14 14 21
Nacelle & Tower	-	-Fracture in the body	-Environmental conditions effect other parts -Unsafe structural integrity	3 2	6 9	18 18

The above table identifies the turbine blade, turbine shaft, hub and controller as parts with a high criticality rating. Therefore, a detailed investigation into the most appropriate monitoring and maintenance of these components is requires.

4.2. FMECA

The Failure Modes, Effects and Criticality Analysis (FMECA) is an extension of the FMEA. It is the process of identifying failure modes, determining the effect and causes for these modes, assigning severity, occurrence and detection and calculating the loss frequency λo. Above Table details the results of an FMECA of an 5M wind turbine.[1]
In the table;

$\lambda p = \lambda * k1 * k2$ = total failure rate (failure per million hours)

$\lambda o = \lambda p * \alpha * \beta$ = loss of frequency

k1 and k2 = environmental factors

α= failure mode proportion

β= probability of failure effect

α and β are estimated value based on engineering judgment, aided by the results of the FMEA.

As expected, the FMECA results relay a similar, more detailed, overview presented by the FMEA. The FMECA identifies the most critical part of the turbine as blade, hub assemble, and wind turbine shaft.
Please note, due to size constraints, the FMECA has been printed on a separate sheet.

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V Results & conclusions

The results of this reliability analysis indicate that the overall reliability of the 5M wind turbine is very low. Furthermore, this analysis focused on failure when the turbine was unable to produce any electrical power. If the definition of failure was widened to take into account pitch and yaw system failure, the reliability of the turbine would be heavily reduced.

The Paper has also identified key areas susceptible to failure, such as the turbine blades and lubrication system, and highlighted the need for condition monitoring to enable effective maintenance. It is recommended that sensors to monitor stress level on the blade should be installed, and regular visual inspection should be carried out. In addition, the lubrication's filtration system and temperature levels should be continually monitored. The introduction of procedures such as this, and others presented in the FMMA, will allow the turbines mean time between failure to be increased, providing increased efficiency.[1]

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