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Reliability 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), a Failure Mode Effect and Criticality Analysis (FMECA), a Hazard and Operability Analysis (HAZOP), and a Fault Tree Analysis (FTA). 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), Fault tree analysis, The Failure Modes, FTA Block Diagram*

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), a Hazard and Operability Analysis (HAZOP), and a Fault Tree Analysis (FTA).

II. FTA

2.1 Analysis

The Fault Tree Analysis (FTA) is top down approach which starts with identifies how a failure mode effect the rest of a system. This achieved by allowing the user to create a logical representation of a system, allowing each failure mode to be traced to a consequence. In the 5M wind turbine example, the possible failure modes which cause the wind turbine failure were identified using logical gates. The FTA was used in the 5M wind turbine project to find identify the following;

- The failure modes of the 5M wind turbine with its criticality.
- To understand the reliability of the 5M wind turbine system.
- To determine critical failure modes of the wind turbine.
- List the combinations of wind turbine components failure which lead to wind turbine failure.

The following steps were taken in the wind turbines' FTA;

- Defining the top (wind turbine failure).
- Construction of Fault tree with logical symbols for each events and conditions of the wind turbine.
- Qualitative analysis (an inspection of logical gates for each events and conditions of the turbine).
- Quantitative analysis (reliability calculation of the wind turbine FTA block).

By analysing the FTA for the wind turbine, it can be seen that the blade and lubrication system have been identified as areas likely to fail, leading to turbine failure. Therefore, these areas should be considered as particularly important when designing preventative measure.[1]

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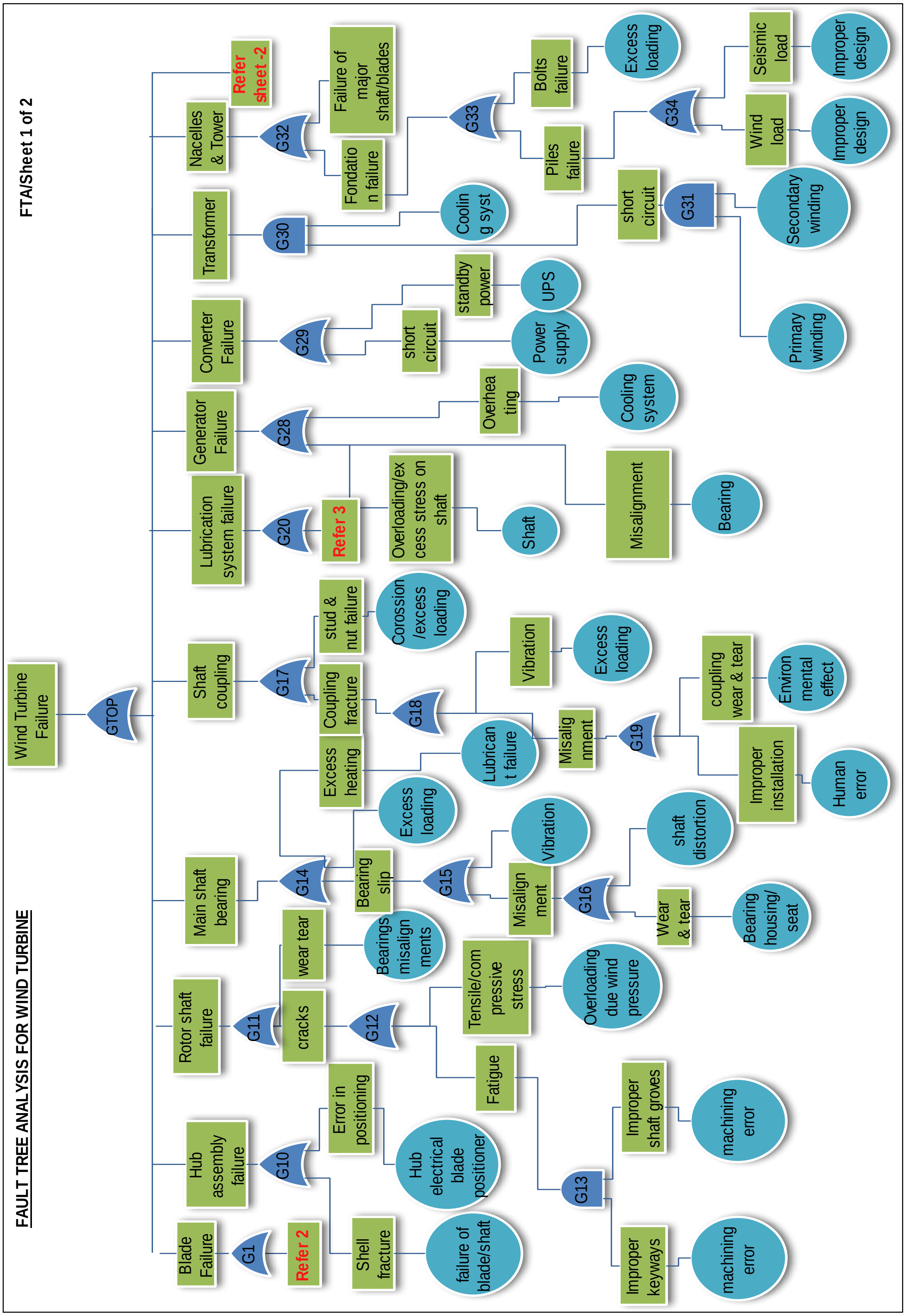

Figure 1 Fault tree analysis of wind turbine 1/2

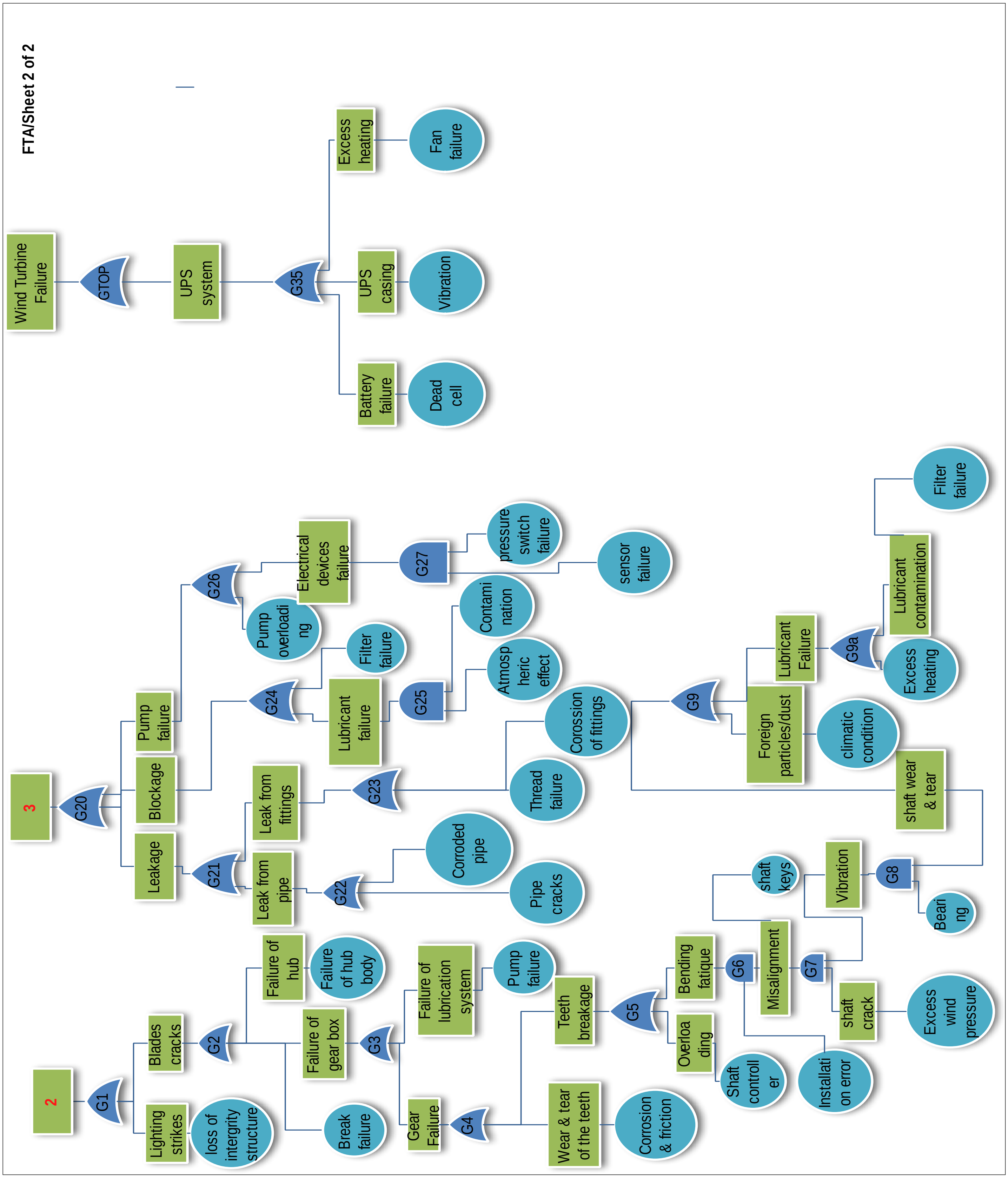

Figure 2 Fault tree analysis of wind turbine 2/2

2.2 FTA Block Diagram

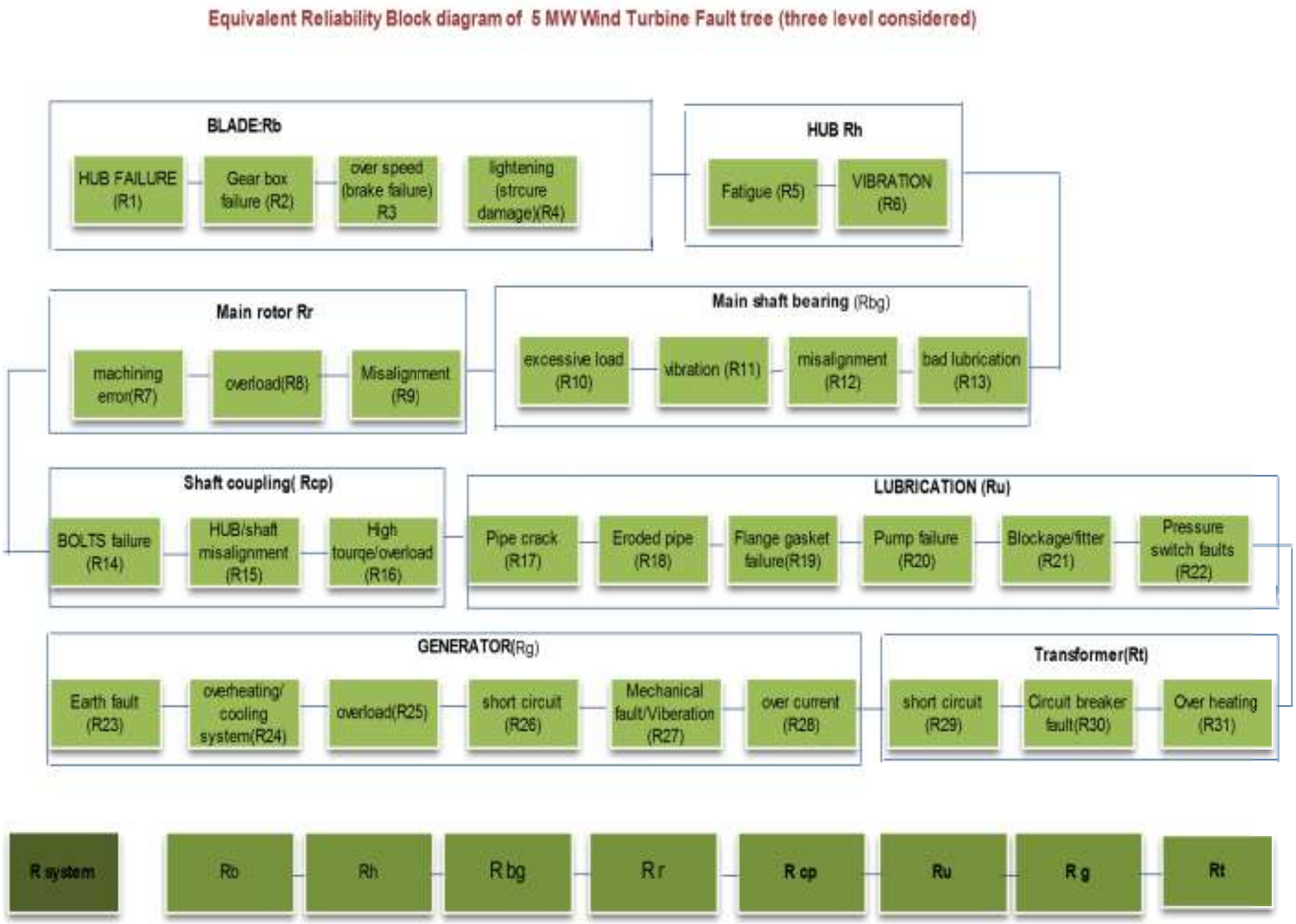

Figure 3 Equivalent block diagram

2.3 FTA Block Diagram Calculations

The following calculations are based on information taken from the FTA. Three levels from the FTA have been converted into a reliability block diagram. All reliability values for each individual component were taken from the initial wind turbine reliability calculations. From this, the following reliability values were calculated;[3],[1]

Rb = 0 .67991562
Rh = 0.679915
Rbg = 0.841305
Rr = 0.886096
Rcp = 0.788513
Rg = 0.7326
Rt= 0.995523

This resulted in a total system reliability value of;

R system = 0.2223 = 22.23%

Therefore, the probability of the top event occurring is;

F = 1 - 0.2223 = 77.76%

When converting an FTA to its equivalent reliability block diagram the resultant blocks include components, and also events. The calculation presentd above only focus on the components reliability, as no reliability value for an event could be identified. It is important to note, the system reliability value obtained through this method is slightly higher than the previous reliability analysis. This was due to the reduction in components included in the analysis.

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III Probability of Failure Pie Chart

A pie chart detailing the probability of failure of each component was obtained from the system reliability calculations. The probability of failure of each component detailed in section 2 has been incorporated in to the pie chart.
Pie Chart of Probability of Failure

No.	*Component*	*Probability of Failure*
1	Blade	0.6856
2	Hub	0.32
3	Main rotor shaft	0.1139
4	Main shaft bearing	0.2592
5	Shaft coupling	0.2115
6	Main gear box	0.2115
7	High speed shaft	0.1139
8	Lubrication system	0.6708
9	Generator	0.2674
10	Convertor	0.45735
11	Transformer	0.0045
12	UPS system	0*
13	Controller	0*
14	Pitch system	0.4796*
15	Yaw system	0.6738*
16	Nacelles & Tower	0*
	∑	4.4691

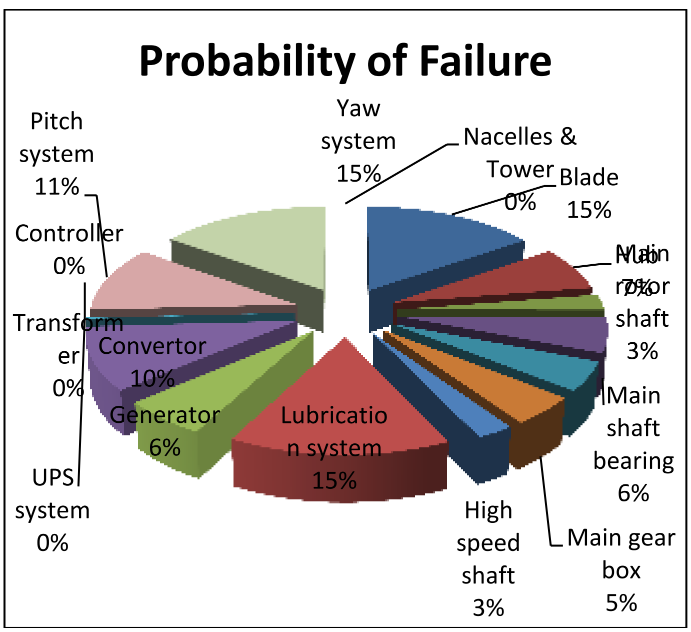

Figure 4 Pi chart

The results in the table above show that the probility of failure of the whole wind turbin system was rather high. The pie chart provides a clear indication as to which comonents present the highes probability of failure. These items are the lubrication system and turbine blades.

IV FE Analysis:

4.1 Failure Mode Analysis

The wind turbines' tower has been chosen for the reliability finite element analysis (FEA). Failure mode under considered in this analysis is failure due to excessive loading in extreme wind conditions.

4.2 Component Details

The wind turbines' tower is constructed from hollow tubular sections made from steel. The individual sections are attached together using flanges. In addition to attachment, the flanges also provide additional support to the tower by preventing ovalizing of the tubing. The specific dimensions of the tubular section, and the tower's overall height, are dependent of the turbines exact application. For the purpose of this analysis, a 5M tower detailed in REpower's 2004 press release has been used. The tower is made up of 5 sections, totalling a height of 114m, and tappers in diameter from 6m at the base, to 5.5m at the top. The wall thickness is not specified in this report. However, it has been shown that towers of a similar specification use a diameter to wall thickness ratio of 320. With this in mind, it possible to estimate the wall thickness to be 18.75mm.

4.3 Analysis

A 3D model of the tower was created using Solid Works computer aided design (CAD) software and imported into Ansys FEA software. A simplistic approach was required for the failure mode analysis. This was to ensure that the meshing and analysis of the tower was quick to execute. With this in mind, the tower was modelled as a continuous shaft, and all interconnecting flanges were neglected.
The mesh used in the analysis was created using Ansys's automated mechanical method. There was no need to specify a specific meshing mode, as the automated approach provided a uniform mesh throughout the model. However, the mesh relevance was adjusted from course to fine, as it provided increased detail without incurring excessive node increases.
As there was very little detail on the specific steel used in the tower's fabrication, Ansys's default Structural Steel was used. The material has the following properties:

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Table 1 – Material Specification [4],[5]

Young Modulus	211e+09 Pa
Poisson's Ratio	0.3
Density	7850 Kg/m^3

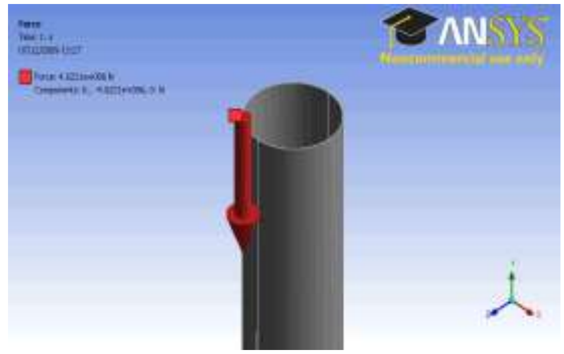
Tensile Yield Strength	2.5e+08 Pa
Compressive Yield Strength	2.5e+08 Pa
Tensile Ultimate Strength	4.6e+08 Pa
Compressive Ultimate Strength	0 Pa

$Load\ 1 = (Roter\ Mass + Nacelle\ Mass) \times 9.81$

$Load\ 1 = (120{,}000 + 290{,}000) \times 9.81$

$Load\ 1 = 4022100\ N$

Load is positioned as a force acting on the top face of the tower. The force–y direction.



$Load\ 2 = A \times \rho_{AIR} \times V^2 \times C_D \times 0.5$

$A = Turbine\ Rotor\ Area = 472.5\ m^2$

$\rho_{AIR} = Air\ Density = 1.275\ Kg/m^3$

$V = Air\ Velosity = 30\ m/s\ \&\ 40\ m/s\ \&\ 50\ m/s$

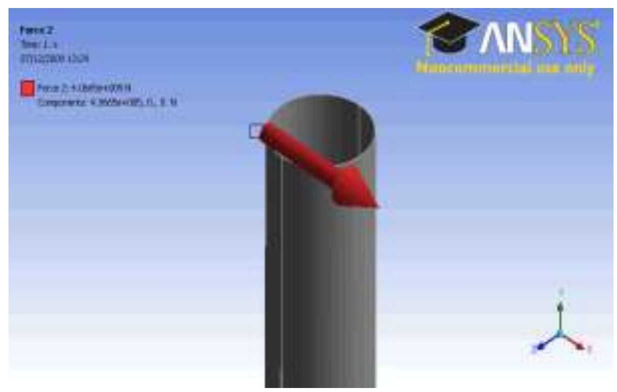
$C_D = Drag\ Coefficient = 1.5$

$Load\ 2\ (30\ m/s) = 406645.313\ N$

$Load\ 2\ (40\ m/s) = 722925\ N$

$Load\ 2\ (50\ m/s) = 1129570.313\ N$

Load is positioned as a force acting on the top face of the tower. The force operates along the x direction.



$Load\ 3 = Standard\ Earth'sGravety = 9.81\ m/s$

Load is positioned as n inertia acting on the entire model. The inertia operates along the –y direction.

Figure 5 FE Analysis

Three loads were used to simulate the working conditions of the tower in different wind speeds. Load one represents the force of the turbine rotor and nacelle. Load 2 represents the force on the tower created by wind drag on the turbine rotor and nacelle. Load three is an inertia, and represent the effects of earth's gravity.

The 5M wind turbine is designed to operate in wind speeds up to 30m/s. With this in mind, three analyses were run with wind speeds of 30m/s, 40m/s and 50m/s. As the turbine's rotor will not operate in these conditions no loading due to the effect rotational mass of the rotor has been considered. The force due to wind loading was calculated using a standard drag force calculation. A number of assumptions were needed to obtain a force due to wind. The blades were assumed to have an effective width of 2.5m and a drag coefficient of 1.5 was used. The high drag coefficient was used to accommodate additional drag caused by the hub and nacelle and to ensure that wind force was not underestimated. The following table details each loading condition:

4.4 Results

To provide sufficient detail on how the turbine tower reacts to the differing wind loads, three different result values were extracted from the FEA data. These were von-Mises stress distribution, directional deformation, and safety factor. Table 2 details all of the result values for each loading condition.

The von-Mises stress distribution give an indication of which areas on the tower will be subjected to the highest stress levels. As expected, the area subjected to the highest stress was towards the base of the tower, with the area under compression exhibiting the highest stress levels. Moving away from base towards the top of the tower the stress levels reduces. Please refer to Figure 6 for details.

The directional deformation results show the expected deflection of the tower under loading conditions. The results show a direct correlation between wind loading and deflection, with the highest wind speed producing the largest deflection. Please refer to Figure 7 for details.

The safety factor results evaluate the von-Mises stress levels against the materials yield strength properties. As a result, the safety factor distribution closely follows the von-Mises stress distribution. Please refer to Figure 8 for details.

Figure 5 details values obtained from the three results of each analysis. The values clearly show that increased wind loading results in higher stress levels, increased deflection and reduced safety factor. Importantly, the maximum recorded stress level at 50 m/s wind loading is higher than the yield properties of the material. This indicated that the material has exceeded it elastic limit and begun to plastically deform. This observation is reinforced by the minimum safety factor on the tower under this loading. A value under 1 indicates failure.

Table 2 – Analysis result

Wind Speed	Max von-Mises Stress (Pa)	Min von-Mises Stress (Pa)	Max Deformation (m)	Min Safety Factor
30 m/s	1.1479e+08	1.2689e+05	0.56213	2.1778
40 m/s	1.8439e+08	6.2863e+04	0.99933	1.3558
50 m/s	2.7386e+08	4.3694e+05	1.5614	0.91286

Plotting the wind speed against observed von-Mises stress levels give a clear indication of how wind speed effects stress levels. The results from the FEA indicate that the turbine tower's material will begin to fail at wind speeds of approximately 47 m/s

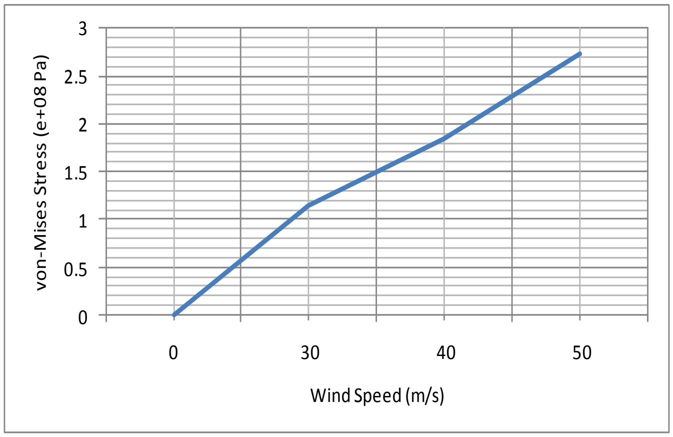


Figure 6 Von-Mises stress against wind speed

4.5 Conclusion

Through the use of FEA, it has been possible to simulate a failure mode of the wind turbines' tower. In addition, the approximate minimum wind speed at which failure will begin has been identified as 47 m/s. However, due to the simplifications made in this analysis, the results do not represent a definitive answer to maximum allowable wind speed.

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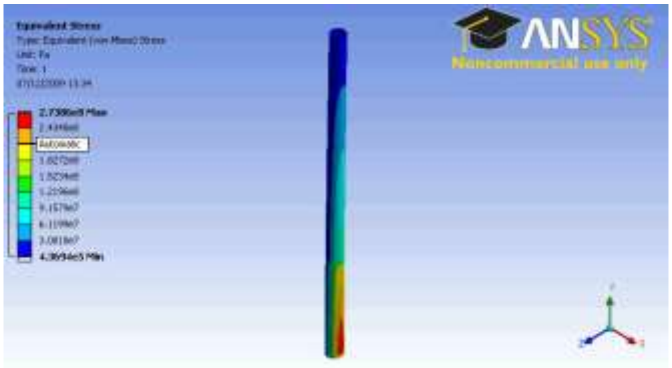

Figure 6 Von-Mises stress (50m/s)

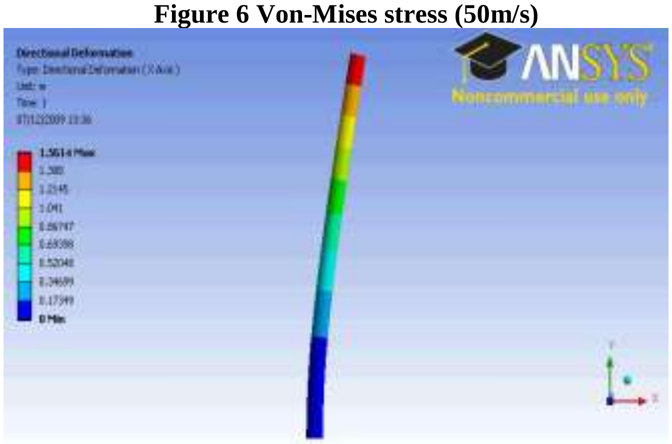

Figure 7 Deformations (50 m/s) (Deformation Amplified by 10)

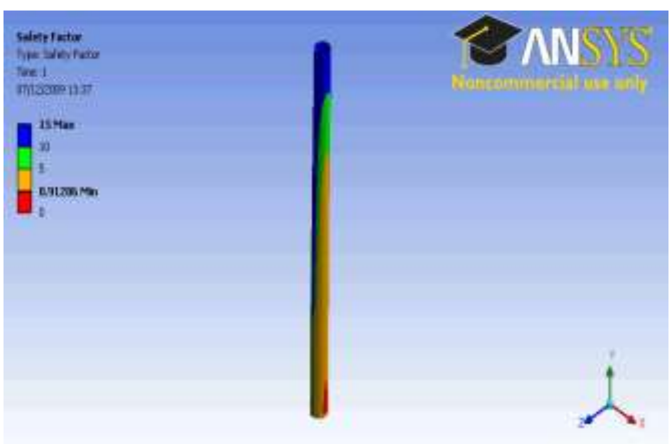

Figure 8 Safety factor (50m/s)

V HAZOP:

The HAZOP is a method used to identify Hazards. The method is a team work practice focused on establishing the various hazards that might occur in the operation of a machine or process. As many hazards as possible need to be covered, these can include process and pinworks spills, external events, personnel accidents, dropped objects, structural events, blowouts, fire, and system fault-based incidents[1]

A fully defined outcome to the HAZOP analysis of Repower's 5M wind turbine could have been achieve if the HAZOP team were in full possession of machine documentation such as:

- Piping and instrumentation diagrams.
- Component's detail design drawings and layout
- As built drawings and vendors commissioning procedures /full load commissioning performance records
- Design specifications

The following points can be taken from the HAZOP presented in this paper:

- The wind turbines' speed control and braking system are particularly important, as they prevent excessive rotation speeds, creating hazardous consequences for personnel and equipment.
- Lubrication system leakage detections and monitoring is essential during start up, operation, and shutdown, as failure to identify leaks could result in massive equipment failure and fire.
- External hazardous factors such as environmental conditions on offshore turbines need specific measures to reduce the possibility of accidents

Events that lead to excessive wind turbine vibration and or fire risk present a high hazardous rating in offshore turbines

VI 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 wind turbines' 21.74% reliability rating indicates that a high level of maintenance is required to sustain its operation.

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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