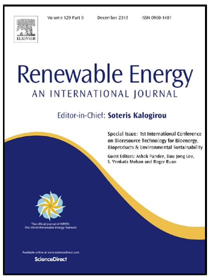

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Fault Tree Analysis of Floating Offshore Wind Turbines

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ABSTRACT: With the development of offshore wind power, the reliability analysis of offshore wind turbines is increasingly significant due to the system complexity and negative impacts in harsh operating conditions. In this study, the Fault Tree Analysis method is adopted for both qualitative and quantitative evaluation of semi-submersible floating offshore wind turbine failure characteristics. The floating offshore wind turbine is divided into several assemblies, including support structures, pitch and hydraulic system, gearbox, generator and the other systems. Failure rates of relevant offshore structures are collected from previous studies, reports and reliability databases. On this basis, the quantitative assessment of Minimum Cut Sets and Importance Measures are achieved. The calculated results are generally in conformity with statistical data, indicating that most of the failures are caused by several basic factors. Marine conditions, especially the salt-spray and high wind speed, show the most significant impact on floating offshore wind turbine performance.

KEYWORDS: Floating offshore wind turbine; Reliability analysis; Fault Tree Analysis; Minimum Cut Sets; Importance Measures

1 INTRODUCTION

The economic efficiency of fixed offshore wind turbines decreases with the increase of water depth. The wind turbines, installed on the floating structures, offer a feasible solution to deal with this problem (Global Wind Energy Council, 2014). The advantages of floating offshore wind turbines (FOWTs) in comparison to fixed turbines can be listed as follows:

- More flexible construction and installation procedures
- More insensitive to water depth
- Higher wind speed
- Less noise pollution
- Lower demolition cost

The major constraints for offshore wind development is the costs. FOWTs are installed far from shore, leading to higher installation and construction expenses because of the complex marine conditions (Castro-Santos et al., 2016). Besides, the difficulty of maintenance procedure calls for vast expenditure (Santos et al., 2015a). One way to provide effective maintenance is through reliability analysis, by predicting the weak points in the system at the design stage (Santos et al., 2016). Blanco (2009) showed that the Operation and Maintenance (O&M) costs can be 20%-30% of the total Level Cost of Electricity (LCOE) over the project's lifetime. Early detection of incipient faults prevents major component failures and allows for the implementation of predictive repair strategies (Yang *et al*, 2012). Therefore, appropriate actions can be planned in time to prevent major failures which would result in significant O&M costs and downtimes.

The statistical data of wind turbine failures have been analysed in a number of references. Perez et al. (2013) compared wind turbine failure data from a selection of major studies in the literature, and concluded that except the downtimes of gearboxes, blades and hydraulics, the reported failure information do not vary much between different studies. Carroll et al. (2015) provided failure rates for offshore wind turbine subassemblies and their maintenance information, including repair times, average repair costs and average number of technicians required for repair. An onshore to offshore failure rate comparison is also carried based on statistical data. Santos et al. (2015b) provided the results of an analysis of accidents and failure data, which gave an idea of the more problematic components in wind turbines.

Several reliability and risk assessment approaches have been employed in previous literature. Arabian-Hoseynabadi et al. (2010a) introduced Failure Modes and Effect Analysis (FMEA) to wind turbine risk assessment. By identifying the most hazardous failure modes and root causes, design improvement and maintenance optimization could be conducted. On this basis, Dinmohammadi and Shafiee (2013) developed a fuzzy-FMEA approach for risk and failure mode analysis of offshore wind turbines when field data is missing or is censored. Santos et al. (2015c) used generalized stochastic Petri Nets and Monte Carlo method to model and simulate operation and maintenance activities of offshore wind turbines considering logistic resources, times and costs, and weather constraints. Guo et al. (2015) accomplished the reliability allocation of FOWT through Reliability Block Diagram (RBD) method and the results show that mooring system, a typical module of FOWT, is the most failure-prone component for the whole system. Ossai et al. (2016) developed a six state Markov model using the failure rates and downtimes information, in order to establish the impacts of wind turbine components maintenance on downtime and failure risks.

Fault Tree Analysis (FTA), which is an effective methodology for analysing reliability and safety, has been applied to the wind energy industry due to its feasibility to determine the critical components and failure causes. For instance, Bharatbhai et al. (2015) analysed a 5M wind turbine through FTA and the results indicated that the overall reliability of is low and the maintenance process should be well planned. Marquez et al. (2016) developed a Fault Tree (FT) for onshore wind turbines and performed a quantitative analysis through Binary Decision Diagrams (BDD). Zhang et al. (2016) developed a dynamic FT model of FOWT and determined the average maintenance period. Nevertheless, this tree model was simplified and the Importance Measures (IMs) of the components were not taken into consideration.

This work presents a FTA of FOWT, dividing the system into eight major subsystems according to the functions and their sub-trees are further developed and analysed. The results would provide suggestions for reliability allocation and O&M management. Historical failure data of basic events is required to implement the quantitative FTA, which is difficult to achieve due to the insufficient FOWT samples. Through the integration of failure cases of offshore structures, data of the FOWT's floating foundation and mooring system are estimated. Failure information of tower is collected referring to wind turbines onshore. Most failure data involves information review of OREDA and some related references (Arbian-Hoseynabadi et al., 2010a, Bharatbhai et al., 2015, Santos et al., 2015b, Katsavounis et al., 2014, Perez et al., 2013, Fischer et al., 2012, Faulstich et al., 2011, Zhang et al. 2016). Expert elicitation is introduced to evaluate the remaining failure rates which are unavailable through historical cases.

Since the lack of enough failure data of FOWTs, only four detailed sub-trees of critical assemblies are analysed quantitatively. Based on the research of Carroll et al. (2015), the biggest contributor to the overall failure rate for offshore wind turbines is the pitch and hydraulic systems, which make up over 13% of the overall failure rate. The generator is the second largest contributor with 12% of the overall failures. Gearbox is the third largest failure contributor with the longest downtime. However, in their research the mooring system, a typical module of FOWT, is not considered. Guo et al. (2015) accomplished the reliability allocation of FOWT and the results show that mooring system is the most failure-prone component for the whole system.

Kang et al. (2016) have started the FT modelling of FOWT and they have covered support structures and the blade system. Therefore, the specifically quantitative analysis in this research is focused on pitch and hydraulic system, generator, gearbox, and structural failure. The paper proceeds as follows. In section 2, the FTs of each assembly are developed. The analysis of results is in section 3. Conclusions are addressed in the last section.

2 FAULT TREE MODELS

2.1 Fault Tree Analysis

The Fault Tree Analysis (FTA) is a well-established and well-understood technique, widely used to determine system dependability (Kabir, 2017). In a fault tree (Figure 1), the logical connections between faults and their causes are represented graphically. A fault tree is a directed acyclic graph consisting of two types of nodes: events and gates. An event is an occurrence within the system, typically the failure of a subsystem down to an individual component. Events can be divided into basic events, which occur spontaneously, and intermediate events, which are caused by one or more other events. Basic events are the elements that cannot be further decomposed and are normally characterized by their probability of failure eventually derived from failure statics. Intermediate events are represented by the combination of basic events and other intermediate events through logic gates, and they are important to demonstrate the process of failure evolution. The event at the top of the tree, called the top event, is the event being analysed, modelling the failure of the system under consideration. Gates represent how failures propagate through the system, i.e. how failures in systems can combine to cause a system failure. Each gate has one output and one or more inputs. FTA is deductive in nature, meaning that the analysis starts with the top event (a system failure) and works backwards from the top of the tree towards the leaves of the tree to determine the root causes of the top event. The results of the analysis show how different components failures or certain environmental conditions can combine together to cause the system failure.

After construction of a fault tree, the analyses of the model are carried out in two levels: a qualitative level and a quantitative level. Qualitative analysis is usually performed by reducing fault trees to minimal cut sets (MCSs), which are a disjoint sum of products consisting of the smallest combinations of basic events that are necessary and sufficient to cause the top event. In quantitative analysis, the probability of the occurrence of the top event and other quantitative reliability indexes such as Importance Measures (IMs) are mathematically calculated, given the failure rate or probability of individual system component (Ruijters and Stoelinga, 2015). The results of quantitative analysis give analysts an indication about system reliability and the events with high IMs values will be considered as the critical elements where the main inspection and maintenance tasks are recommended in order to guarantee the system safety.

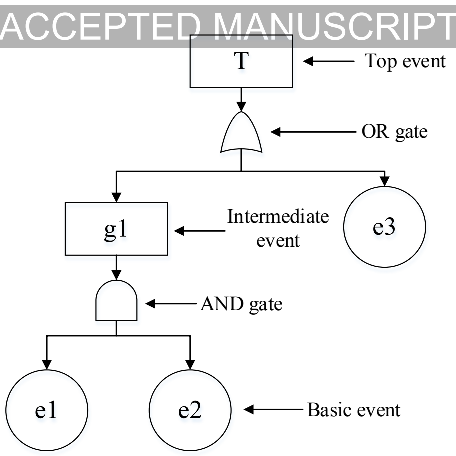

Figure 1. Structure of a Fault Tree

2.2 Complete Fault Tree

The FOWT can be divided into eight major subsystems according to the functions, namely, support structures, pitch and hydraulic system, gearbox, generator, speed train, electronic components, blades system and yaw system (Uzunoglu et al. 2016). The support structures provide mechanical support to the turbine. Blades, speed train and generator functions to receive, transit and convert energy. The rest of subsystems ensure the FOWT obtains as much energy as possible. Failure of any of subsystem can lead to the malfunction of the entire system. This is a typical situation of a series system that is modelled in Figure 2, involving eight main systems that are listed in Table 1.

Table 1. Systems composing a FOWT

Codes	Events	Codes	Events
S1	Support structures failure	S5	Speed train failure
S2	Pitch and hydraulic system failure	S6	Electronic components failure
S3	Gearbox failure	S7	Blades system failure
S4	Generator failure	S8	Yaw system failure

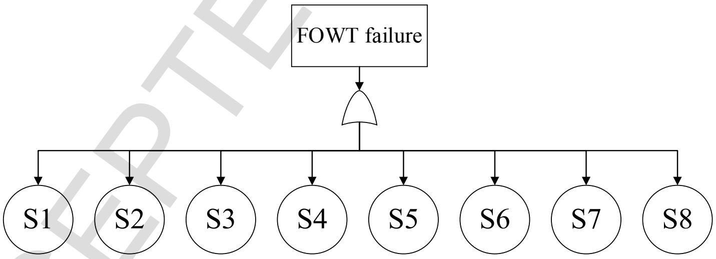

Figure 2. FT of FOWT failure, at system level

In this study, three assemblies, including support structures, electronic components and blades, are integrated by combining several modules together in order to control the number of sub-trees. The sub-FTs of speed train failure (S5), electronic components failure (S6), blades failure (S7) are simplified for quantitative calculation and yaw system failure (S8) is treated directly using the statistic data of the top event instead of develop a simplified sub-FT due to sufficient information of basic events.

2.3 Support structures, pitch and hydraulic system

These systems have been studied by Kang et al. (2016) but for completeness and to help the connection to the rest of the work reported here, the corresponding FT is reproduced in Figure 3.

Table 2. Principal events of support system failure, pitch and hydraulic system failure

Logic gates	Codes	Logic gates	Codes	Logic gates	Codes
Mooring system failure	g01	Tower failure	g02	Floating foundation failure	g03
Devices failure	g04	Extreme sea conditions	g05	Collapse due to environment	g06
Hit by dropped objects	g07	Watertight fault	g08	Other devices failure	g09
Pipe joint failure	g10	Fairlead failure	g11	Mooring lines broken	g12
Mooring lines breakage	g13	Mooring lines wear	g14	Accumulating wear	g15
Hydraulic system failure	g16	Drive alarm	g17	Wrong blade angle	g18
Hydraulic oil failures	g19	Power failure	g20	Meteorological unit	g21

Basic events	Codes	Failure rates (h^{-1})	Basic events	Codes	Failure rates (h^{-1})
Human error	e001	6.00E-6	Resonance	e002	5.00E-6
Faulty welding of tower	e003	7.00E-6	Material fatigue	e004	1.10E-5
Pillar damage	e005	5.00E-6	Capsize	e006	1.00E-6
Anchor failure	e007	1.80E-5	Poor operation environment	e008	7.80E-5
Insufficient emergency measures	e009	1.00E-6	Strong wind and/or wave	e010	5.00E-5
Lightning strike	e011	7.00E-6	Storm	e012	5.50E-5
Typhoon	e013	1.00E-4	Plane crash	e014	1.00E-6
Biological collision	e015	5.00E-6	Insufficient detection	e016	8.65E-6
Pipe joint corrosion	e017	1.30E-5	Pipe joint weld defect	e018	3.00E-6
Pipe joint fatigue	e019	3.00E-6	Fairlead corrosion	e020	1.00E-5
Fairlead fatigue	e021	1.70E-5	Transitional chain wear	e022	1.01E-5
Friction chain wear	e023	6.93E-6	Mooring winch failure	e024	8.00E-6
Buoys friction chain wear	e025	4.19E-6	Anchor pickup device damaged	e026	5.56E-6
Abnormal stress	e027	4.07E-5	Invalid maintenance	e028	3.78E-5
Mooring lines wear	e029	1.60E-5	Mooring lines fatigue	e030	1.70E-5
Mooring lines corrosion	e031	5.38E-6	Hydraulic motor failure	e032	1.00E-5
Over pressure	e033	3.00E-5	Accumulator failure	e034	6.80E-6
Lighting protection failure	e035	1.00E-5	Limit switch fails	e036	1.00E-5
Abnormal vibration	e037	2.14E-6	Oil leakage	e038	4.80E-5
Filters failure	e039	7.90E-7	Power 1 failure	e040	5.70E-5
Power 2 failure	e041	5.70E-5	Vane damage	e042	7.00E-6
Anemometer damage	e043	1.80E-5			

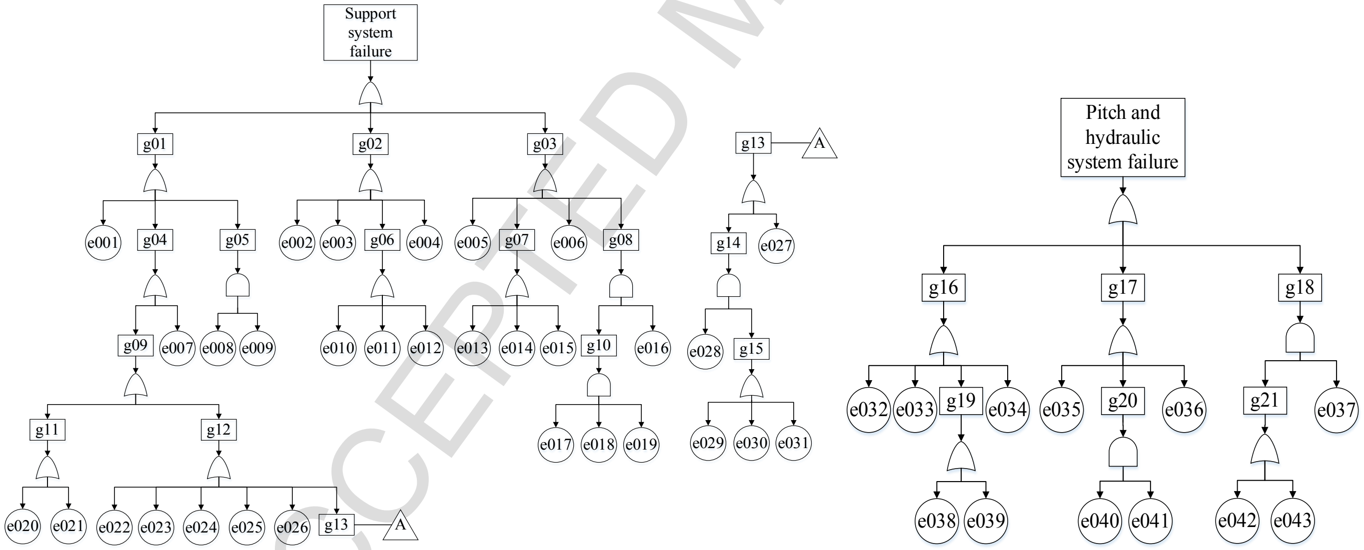

Figure 3. FTs of support system failure, pitch and hydraulic system failure (Kang et al. 2016)

After analysing the proposed FT, Kang et al. (2016) determined the most important events inducing the failure of the main systems studied.

For the mooring system failure, the commonest failure cause is mooring line breakage. Abnormal stress is the main factor that should be considered to optimize mooring lines reliability. Anchor and fairlead failure are the second and third largest contributors to mooring system malfunction. In terms of tower failure, collapse owing to harsh environment, which is caused by storm, strong wind and/or wave and lightning strike, has the highest probability. Storm and strong wind and/or wave are principal threaten to tower's safety. For the foundation failure, hit by dropped objects, such as objects brought by typhoon, biologics and planes, is the most hazardous cause for floating foundation failure, followed by pillar damage and capsize. As a result, collision protection measures and periodic detection is required to guarantee the pillars' condition. It is concluded that severe sea conditions contributes the most to the failure of support structures. Therefore, sophisticated weather forecasts and emergency response plans are needed to reduce the loss. It is noteworthy that mooring lines and fairlead malfunction are the primary causes of mooring system failure, indicating these two modules require particular attention.

For the pitch and hydraulic system failure, the hydraulic components are the most failure-prone modules for the entire assembly and oil failure is the main reason for hydraulic system malfunction. Drive alarm is the second largest contributor to failure, which principally caused by limit switch failures and lightning protection failures. As a critical assembly with high failure probability, the pitch and hydraulic system demands thorough reliability analysis and risk management.

2.4 Gearbox

The gearbox function is to transform high-torque to low-torque and transform low-speed of the main shaft to high-speed of the generator. Gearbox failure is one of the most typical failures for wind turbines since their malfunctions lead to significant downtimes (Spinato et al., 2009). In a gearbox, the least desirable fault type is the gear crack, because it often leads to other severe failure of the gear unit and hence to the break-down of the unit (Belsak and Flasker, 2007). Erosion caused by the salty air is also a threat for offshore wind turbines' gearboxes. The direct-drive generator with increasingly developed technology will be more widely used in the offshore wind turbine to reduce the Life Cycle Cost (LCC).

The basic failure events of transmission system are listed in Table 4 and the FT is shown in Figure 4. Gearbox failure is the main emphasis of transmission reliability analysis and the failure data are evaluated from previous research (Sheng et al., 2011, Li et al., 2015, Igba et al., 2015).

Table 3. Principal events of gearbox failure.

Logic gates	Codes	Basic events	Codes	Failure rates (h-1)
Lubrication exception	g22	Abnormal filter	e044	1.80E-6
Abnormal gear	g23	Poor quality of lubrication oil	e045	1.80E-6
Bearings fault	g24	Dirt	e046	1.44E-6
Tooth wear (gears)	g25	Abnormal vibration (Gearbox)	e047	2.14E-6
Cracks in gears	g26	Glued	e048	2.40E-7
Offset of teeth gears	g27	Pitting (gear)	e049	1.30E-6
		Corrosion of pins	e050	1.20E-5
		Abrasive wear	e051	1.00E-5
		Pitting (gear bearing)	e052	3.00E-6
		Gear tooth deterioration	e053	3.00E-7
		Excessive pressure	e054	1.00E-6
		Excess temperature	e055	2.40E-7
		Fatigue (gear)	e056	3.00E-7
		Poor design of teeth gears	e057	1.00E-6
		Tooth surface defects	e058	3.00E-7

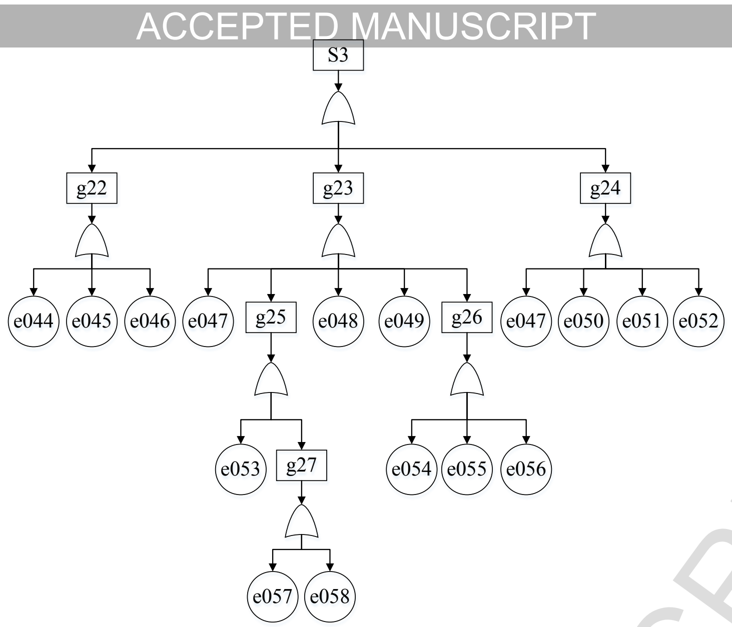

Figure 4. Fault tree of gearbox failure.

2.5 Generator

Generator is installed inside the nacelle. This equipment is used to convert mechanical energy to electrical energy, and to adapt the output energy from the wind turbine to the grid. It is a significant equipment because of its high failure rates, downtime (Faulstich et al., 2011) and repair cost (Carroll et al., 2015). Faults in generators can be the result of electrical or mechanical causes (Hansena and Michalke, 2007). The main electrical faults are due to open-circuits or short-circuit of the winding in the rotor or stator that could cause overheating. Corrosion, dirt and terminal damage are the main mechanical defects (Liu et al., 2010). It is demonstrated that bearings, issues with the rotor, slip ring issues, problems with the generator grease pipes and fan replacement are the top five reasons of generators failure (Carroll et al., 2015). The bearing malfunctions are usually induced by wear, fatigue, and asymmetry (Wu and Chapman, 2005). The rotor and stator failures are primarily caused by broken bars, air-gap eccentricities and dynamic eccentricities (Lu et al., 2009).

The basic events and FT model of generator are presented in Table 4 and Figure 5. Related failure data are obtained from the database of OREDA (2015) and other literature (Perez et al., 2013, Arbian-Hoseynabadi et al., 2010b).

Table 4. Principal events of generator failure.

Logic gates	Codes	Basic events	Codes	Failure rates (h^{-1})
Rotor and stator failure	g28	Parameter deviation	e059	1.63E-5
Bearing failure	g29	Wire fault	e060	1.00E-7
Abnormal signals	g30	External facilities media leak	e061	8.40E-5
Rotor and stator fault	g31	Asymmetry	e062	5.85E-6
Overheating	g32	Structural deficiency	e063	1.17E-6
		Abnormal vibration G	e064	2.14E-6
		Abnormal instrument reading	e065	2.17E-6
		Fail to synchronize	e066	3.61E-6
		Broken bars	e067	2.10E-7
		Fail to start on demands	e068	2.89E-6
		Sensor failure	e069	7.08E-6
		Temperature above limit	e070	0.72E-6

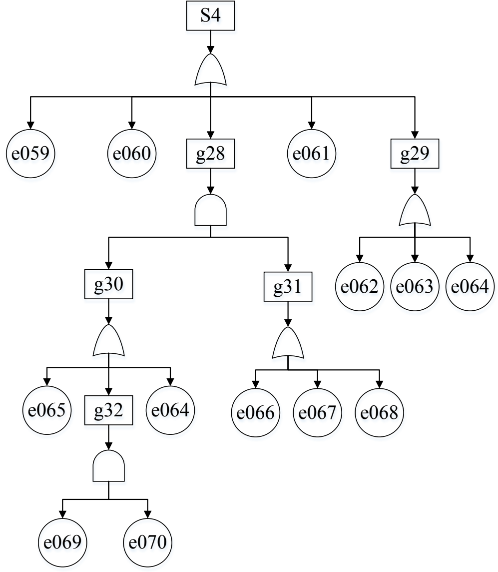

Figure 5. Fault tree of generator failure

2.6 Speed train

The speed train is installed in the nacelle and is compound by the low speed train, the high speed train and the brake system. Through the main bearing, the rotor is attached to the low speed shaft that drives the rotational energy to the gearbox. The low speed train failure includes main bearing and low speed shaft defects. Severe vibrations can appear due to existing cracks in any component, or to the mass imbalance in the low speed shaft. Overheating caused by the rotational movement can lead to high speed train malfunctions. Wear and fatigue can initiate crack and mass imbalance, resulting in high speed shaft failures. The principal sources of brake failure are overpressure or oil leakages, cracking of the brake disc and calipers. The FT is shown in Figure 6. The low and high speed train are combined as drive train in order to simplify FT structure. Failure information of speed train are listed in Table 5 and Table 6, according to the data of Faulstich et al. (2011).

Table 5. Principal events of speed train failure.

Logic gates	Codes	Logic gates	Codes	Logic gates	Codes
Low speed train failure	g33	High speed train failure	g34	Low speed train fault	g35
High speed shaft fault	g36	Brake failure	g37	Wear in low speed train	g38
Cracks in low speed train	g39	Structural damage	g40	Brake fault	g41
Abnormal signals	g42	Wear of high speed shaft	g43	Cracks in high speed shaft	g44
Hydraulic brake system fault	g45	Overheating brake	g46		
Basic events	**Codes**	**Basic events**	**Codes**	**Basic events**	**Codes**
Abnormal vibration L	e071	Abnormal vibration H	e072	Abrasive wear L	e073
Deformation L	e074	Pitting L	e075	Spalling L	e076
Fatigue L	e077	Corrosion L	e078	Imbalance	e079
Overheating	e080	Cracks in brake disk	e081	Cracks in high speed shaft	e082
Spalling H	e083	Abrasive wear H	e084	Pitting H	e085
Fatigue H	e086	Corrosion H	e087	Motor brake fault	e088
Oil leakage	e089	Over pressure	e090	Temperature sensor error	e091
Temperature above limit	e092				

Table 6. Failure data of speed train failure.

Basic events	Failure rates (h^{-1})
Drive train failure	5.71E-6
Brake failure	1.80E-6

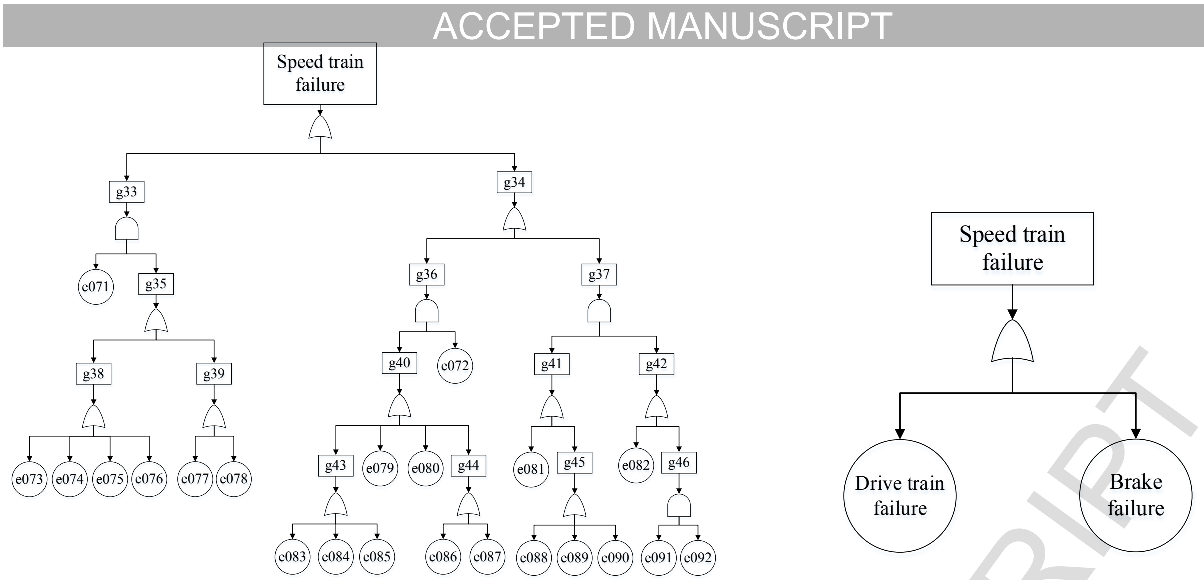

Figure 6. Detailed and simplified fault tree of speed train

2.7 Electronic components

In this study, electronic components are an integration of controls, transformer, sensors and converter. Control elements ensure that the FOWT gets as much energy out of the wind as possible and operates safely by limiting the forces. Transformer and converter adapt the output energy from the generator to the characteristics of the grid. Sensors function to collect FOWT operating data, including vibration, temperature, pressure, fluid property, among others. Short-circuit faults, open-circuit faults and gate drive circuit faults are the three major electrical faults of the electronic components. Corrosion caused by salt mist and moisture is the main mechanical defect. The failure information of electronic components is shown in Table 7 and Table 8 according to the research of Carroll et al. (2015). The FT is presented in Figure 7.

Table 7. Principal events of electronic components failure.

Logic gates	Codes	Logic gates	Codes
Electrical fault	g47	Mechanical fault	g48
Basic events	Codes	Basic events	Codes
Short circuit	e093	Open circuit	e094
Gate drive circuit	e095	Corrosion	e096
Dirt	e097	Terminals damage	e098

Table 8: Failure data of electronic components.

Basic events	Failure rates (h^{-1})
Controls failure	4.91E-5
Transformer failure	7.99E-6
Sensors failure	3.77E-5
Converter failure	2.05E-5

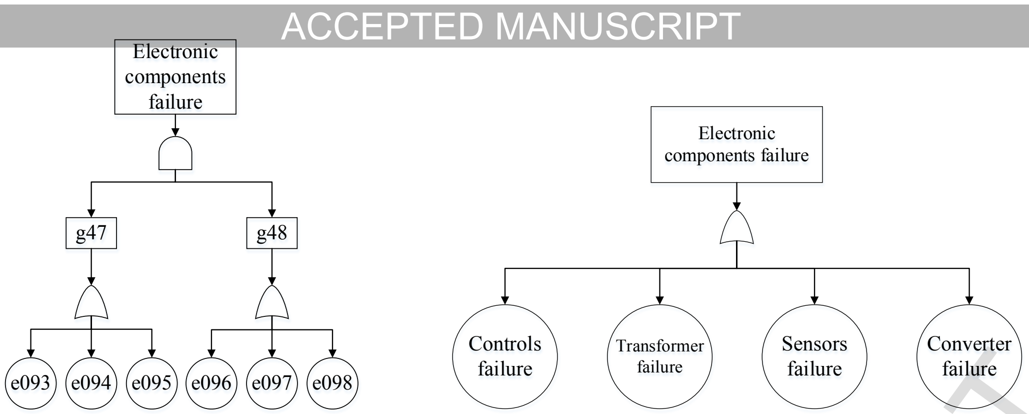

Figure 7. Detailed and simplified fault tree of electronic components

2.8 **Blades system**

In this paper, the blades system consists of rotor hub, rotor bearings and blades. The rotor hub is made from cast iron and holds the blades in position as they turn. The heavy loads it supports can lead to faults such as clearance loosening and surface roughness. Rotor bearings are used to withstand the varying forces and loads generated by the wind. The bearings can be damaged by wear produced by pitting, deformation of outer face and rolling elements, spalling and overheating. The blades are attached to the rotor shaft by the hub and they are mounted on bearings in the rotor hub. The blades are one of the most important components of FOWT. Blade structural faults are predominantly made up of tip damages, edge damages and shell damages, which primarily result from cracks, erosion, delamination, debonding, strength and fatigue of the fibrous composite materials. Figure 8 shows the FT of blades system. The failure information is listed in Table 9 and Table 10 based on existing literature (Faulstich et al., 2011, Carroll et al., 2015).

Table 9. Principal events of blades system failure.

Logic gates	Codes	Logic gates	Codes	Logic gates	Codes
Structural fault	g49	Rotor system failure	g50	Tip damage	g51
Edges damage	g52	Shell damage	g53	Hub failure	g54
Bearings fault	g55	Imbalance of blade system	g56	Wear in bearings of the rotor	g57
Basic events	Codes	Basic events	Codes	Basic events	Codes
Open tip	e099	Lightning strike on tip	e100	Cracks in the edge of blades	e101
Erosion in edges of blades	e102	Delamination in leading edges	e103	Delamination in trailing edges	e104
Debonding in edges of blades	e105	Delamination in shell	e106	Crack with structural damage	e107
Crack on the beam-shell joint	e108	Clearance loosening at root	e109	Cracks in the hub	e110
Surface roughness in the hub	e111	Cracks in bearings of rotor	e112	Mass imbalance in the hub	e113
Fault in pitch adjustment	e114	Corrosion of pins in bearings	e115	Abrasive wear in bearings	e116
Pitting in bearings of rotor	e117	Deformation	e118	Lubrication fault in bearings	e119

Table 10. Failure data of blades system.

Basic events	Failure rates (h^{-1})
Blades structural failure	1.26E-5
Hub failure	2.74E-5
Bearings failure	5.25E-6

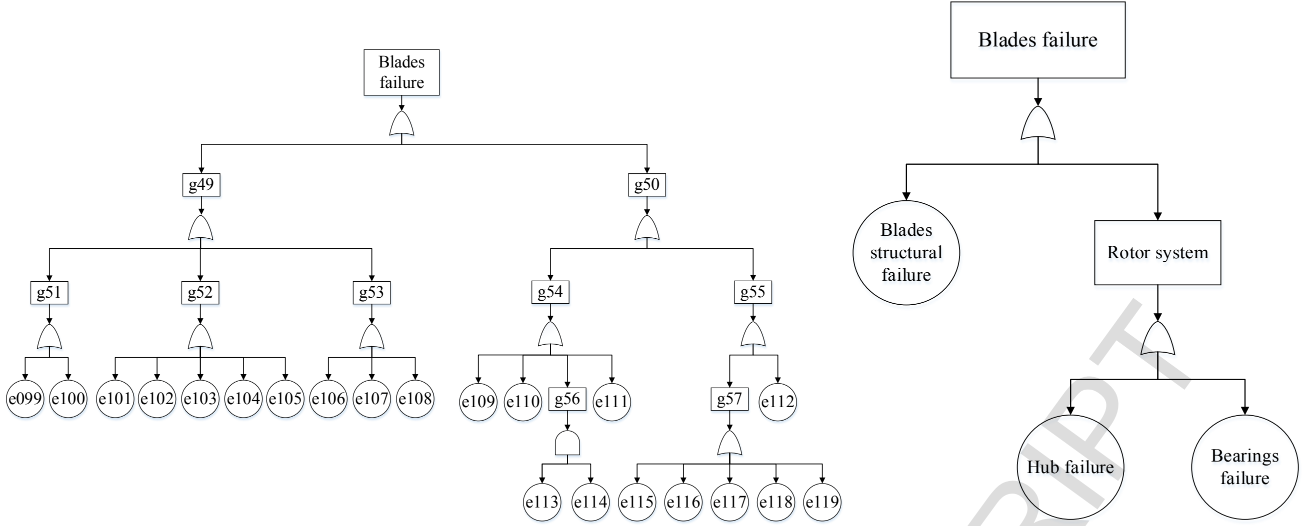

Figure 8. Detailed and simplified fault tree of blades

2.9 Yaw system

The yaw system functions to keep the wind turbine aligned with the main wind direction, as it changes. Under normal operating conditions, the rotor torque fluctuations during yawing and the resistance torque variation in response to changes in the yaw angle or wind speed generate load fluctuations in the yaw system. These load fluctuations result in further speed fluctuation in the yaw system, which affects the vibrations of the blades, tower and nacelle and even threatens the safety of the wind turbine (Wan et al. 2015). According to the Figure 3 of Carroll et al. (2015), the failure rate of yaw system is 2.16E^{-5} h^{-1}. The information of principal events is listed in Table 11 and Figure 9 shows the detailed FT.

Table 11. Principal events of yaw system failure.

Logic gates	Codes	Logic gates	Codes	Logic gates	Codes
Yaw motor failure	g58	Drive alarm	g59	Meteorological unit fault	g60
Limit switch failure	g61	Meteorological unit failure	g62		
Basic events	**Codes**	**Basic events**	**Codes**	**Basic events**	**Codes**
Yaw motor fault	e120	Abnormal vibration A	e121	Lightning module failure	e122
Cabinet switch trip	e123	Limit switch fault	e124	Limit slider fault	e125
Vane damage	e126	Anemometer damage	e127		

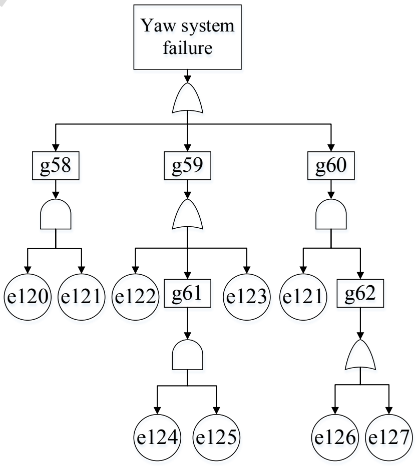

Figure 9. Detailed fault tree of yaw system

3 ANALYSIS OF RESULTS

In order to identify the critical failure events of FOWT, two methods are employed: MCS and IMs. A cut set in a fault tree is a set of basic events whose occurrence (at the same time) ensures that the top event occurs. A cut set is said to be minimal if it cannot be reduced without losing its status as a cut set. For small and simple fault trees, it is feasible to identify the MCS by inspection without any formal procedure and the MOCUS (Method for Obtaining Cut Sets) is a common algorithm to solve large or complex fault trees (Rausand, 2004).

In this study, two widely used IMs, Birnbaum and Fussell-Vesely measure are applied. Birnbaum's measure of importance of component *i* at time *t* is

$$I_B(i\,|\,t) = \frac{\partial h(t)}{\partial p_i(t)} \ (1 \le i \le n)$$

where $h(t)$ is the system reliability, $p_i(t)$ is the reliability of component *i*. Birnbaum's measure is thus obtained by partial differentiation of the system reliability with respect to p_i. This approach is well known from classical sensitivity analysis (Rausand, 2004). If $I_B(i|t)$ is large, a small change in the reliability of component *i* will result in a comparatively large change in the system reliability at time *t*.

Fussell-Vesely's measure of importance, $I^{FV}(i|t)$ is the probability that at least one minimal cut set that contains component *i* is failed at time *t*, given that the system is failed at time *t*. Fussell-Vesely's measure takes into account the fact that a component may contribute to system failure without being critical (Rausand, 2004). This IM can be achieved by

$$I_{FV}(i\,|\,t) = \frac{\Pr\left[D_i(t)\right]}{\Pr\left[C(t)\right]} \ (1 \le i \le n)$$

where $D_i(t)$ represents that at least one minimal cut set which contains component *i* is failed at time *t*. $C(t)$ represents that the system is failed at time *t*.

According to the results of Marquez et al. (2016), many events share the same Birnbaum value while the Fussell-Vesely measurements of different events are evenly scattered throughout the interval, indicating that the Fussell-Vesely is more capable to distinguish events' importance. As a result, Fussell-Vesely value is regarded as the primary IM in this study. The MCS results are listed in Table 8, considering that the service life of FOWT is 20 years. Fussell-Vesely results are shown in Figure 10-12. It should be noted that since support structures, pitch and hydraulic system have been treated in Section 2.3, here the analysis of results will concentrate on the gearbox, generator and the other systems.

3.1 Minimum Cut Sets

In order to determine the MCS, the FT is first translated to its equivalent Boolean equations, and then the "top-down" substitution method is employed. The probabilities of each MCS are calculated. The results of the FOWT system are listed in Table 12.

Corrosion of pins (B1), abrasive wear of bearings (B2) and abnormal vibration (B3) are the top three causes of gearbox malfunction, followed by bearing pitting (B4). The results indicate that bearing is the most hazardous element, which makes up 70% of the overall gearbox failures. Corrosion of offshore gearbox bearings is always more noteworthy than onshore ones, because salt-spray will accelerates the corrosion process. Offshore bearings also suffer more load than onshore ones due to the higher wind speed, which results in larger failure probabilities. Therefore, anti-corrosion measurements of gearbox (especially the bearings) must be highlighted and the maintenance procedure should be well planned and fully implemented in order to reduce economic losses.

Table 12 Failure probabilities ranking of MCS

Support structures failure					
Cut sets	Probability	Components	Cut sets	Probability	Components
S1	7.13E-6	e027	S14	2.39E-12	e008, e009
S2	3.15E-6	e007	S15	9.64E-6	e012
S3	2.98E-6	e021	S16	8.76E-6	e010
S4	1.77E-6	e022	S17	1.93E-6	e004
S5	1.75E-6	e020	S18	1.23E-6	e011
S6	1.40E-6	e024	S19	1.23E-6	e003
S7	1.21E-6	e023	S20	8.76E-7	e002
S8	1.05E-6	e001	S21	1.75E-5	e013
S9	9.74E-7	e026	S22	8.76E-7	e015
S10	7.34E-7	e025	S23	8.76E-7	e005
S11	1.97E-11	e028, e030	S24	1.75E-7	e014
S12	1.86E-11	e028, e029	S25	1.75E-7	e006
S13	6.24E-12	e028, e031	S26	9.54E-25	e016-019
Pitch and hydraulic failure					
Cut sets	Probability	Components	Cut sets	Probability	Components
P1	8.41E-6	e038	P6	1.19E-6	e034
P2	5.26E-6	e033	P7	1.38E-6	e039
P3	1.75E-6	e036	P8	9.97E-11	e040, e041
P4	1.75E-6	e035	P9	1.18E-12	e043, e037
P5	1.75E-6	e032	P10	4.60E-13	e042, e037
Gearbox failure					
Cut sets	Probability	Components	Cut sets	Probability	Components
B1	2.10E-6	e050	B9	2.28E-7	e049
B2	1.75E-6	e051	B10	1.75E-7	e054
B3	7.50E-7	e047	B11	1.75E-7	e057
B4	5.26E-7	e052	B12	5.26E-8	e053
B5	5.26E-7	e056	B13	5.26E-8	e058
B6	3.15E-7	e044	B14	4.20E-8	e048
B7	3.15E-7	e045	B15	3.50E-8	e055
B8	2.52E-7	e046			
Generator failure					
Cut sets	Probability	Components	Cut sets	Probability	Components
G1	1.47E-5	e061	G7	2.40E-13	e066, e065
G2	2.86E-6	e059	G8	1.92E-13	e068, e065
G3	1.02E-6	e062	G9	1.40E-14	e065, e067
G4	3.75E-7	e064	G10	9.78E-20	e069, e066, e070
G5	2.05E-7	e063	G11	7.83E-20	e069, e068, e070
G6	1.75E-8	e060	G12	5.69E-21	e069, e070, e067
Other systems					
Cut sets	Probability	Components	Cut sets	Probability	Components
O1	8.60E-6	Controls failure	O6	2.21E-6	Blades structural failure
O2	6.61E-6	Sensors failure	O7	1.50E-6	Brake failure
O3	4.80E-6	Hub failure	O8	1.40E-6	Transformer failure
O4	3.80E-6	Yaw system failure	O9	1.00E-6	Drive train failure
O5	3.59E-6	Converter failure	O10	9.20E-7	Bearings failure

In terms of the generator malfunction, external facilities media leak (G1) is the largest contributor, followed by parameter deviation (G2) and asymmetry (G3). Cracks caused by abnormal vibrations and insufficient maintenance are two common reasons for media leak. Parameter deviation and asymmetry are always caused by inaccuracies during design and install phrase. Under high humidity circumstance, the moisture increases the failure probability of slip ring, rotor and stator, so appropriate moisture and corrosion preventive measures are required. Sufficient condition monitoring and maintenance are also needed to sustain system availability.

Electronic components failure (O1, O2, O5 and O8) is the most failure-prone assembly among the other systems, followed by blades failure (O3, O6 and O10). Yaw system failure (O4) is the third largest contributor of other systems' malfunctions.

3.2 Importance Measures

In addition to failure probability, the IMs value is a key parameter that can be used to compare and rank the main failure causes. According to the calculations, the Birnbaum value of most events is 1, which can be explained by the fact that the most basic events can directly cause the failure of the system. Fussell-Vesely method shows a better discriminating ability in this research, and the IMs results are primarily analysed according to Fussell-Vesely values.

Figure 10 shows that material degradation is the most notable failure mode of gearbox. In Figure 11, media leak which generally caused by structural damage is the most important events for generator safety. It can be concluded that structural malfunction is the main threat to gearbox and generator. Since these two components are critical for the entire FOWT system, the condition monitoring and reliability prognostics are required to guarantee their safety. Corrosion predominates among all the reasons of material failures, implying that anti-corrosion technology is especially important for FOWT system.

In terms of the other systems IMs (Figure 12), electronic components is the most crucial assembly. Controls and sensors are the most important two modules of electronic components. Blades system is also a notable assembly, among which the most important element is the hub, followed by blade structure and bearings.

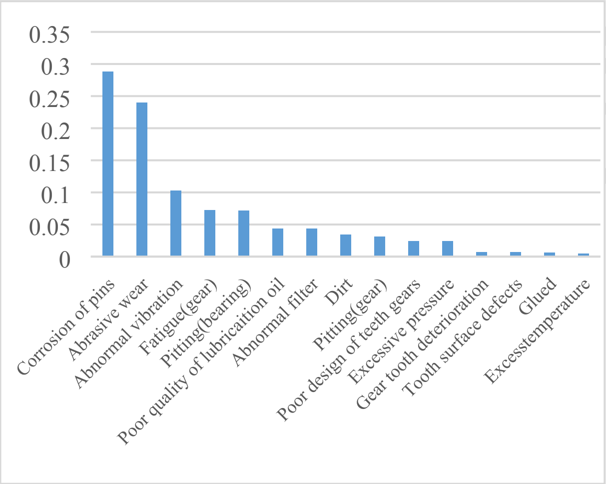

Figure 10. Fussell-Vesely of gearbox failure basic events

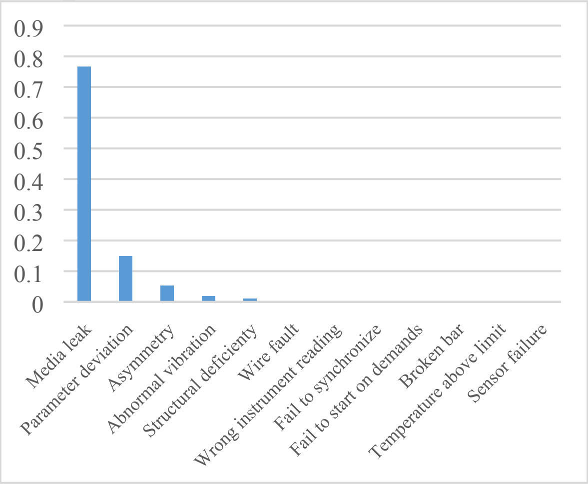

Figure 11. Fussell-Vesely of generator's basic events

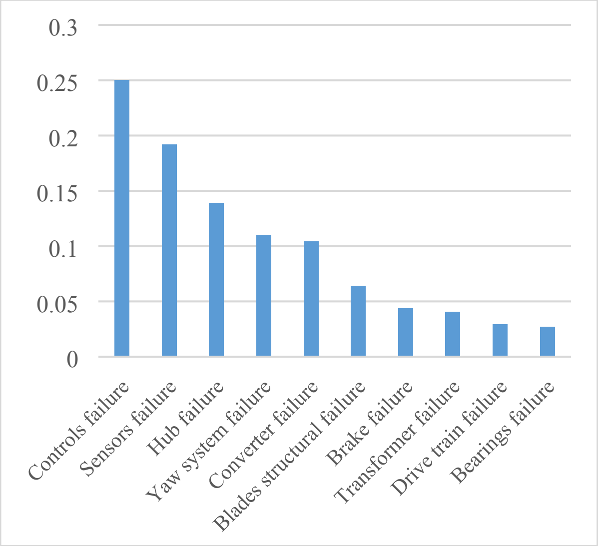

Figure 12. Fussell-Vesely of other systems basic events

3.3 FTA of FOWT systems

Having studied the various systems separately, it is now possible to combine the whole information to consider the FTA of the whole FOWT and depicted in fig 2. According to FTA consequences, the failure information of each assembly are derived considering the service life of FOWT is 20 years. The results are presented in Table 13.

Table 13 Failure information of FOWT's FT

Codes	Events	Prob. failure	Failure rate (h^{-1})
S1	Support structures failure	6.54E-5	3.73E-4
S2	Pitch and hydraulic system failure	2.02E-5	1.16E-4
S3	Gearbox failure	7.29E-6	3.90E-5
S4	Generator failure	1.92E-5	1.10E-4
S5	Speed train failure	2.50E-6	1.43E-5
S6	Electronic components failure	2.02E-5	1.15E-4
S7	Blades system failure	7.93E-6	4.52E-5
S8	Yaw system failure	3.85E-6	2.17E-5
Total		1.47E-4	8.34E-4

The calculated probability of failure of the FOWT system is 1.47E-4 and the failure rate is 8.34E-4 h^{-1}, indicating that the Mean Time Between Failures (MTBF) is 1199 hours. As a result, the planned maintenance period must be shorter than 50 days. The order of magnitudes of failure rates are around E-4 and E-5 in Table 10. Support structures is the most crucial assembly of FOWT. The failure rates of pitch and hydraulic system, electronic components and generator are close to each other, higher than the rest assemblies.

The MTBF result of this study is 13% longer than the statistical data of Carroll et al. (2015). There are two explanations. One is that the mooring system and floating foundation failures are not included in the statistical data, but FOWT safety is significantly affected by these two systems because mooring system and floating foundation are affected by wave load, current load, corrosion, etc., but also more torque caused by the high FOWT structure and high wind speed. The other explanation is that some of the failure data are collected from onshore wind turbine, leading to a lower failure probability. It can be proved by the failure data comparison between offshore and onshore wind turbines. The onshore wind turbines treated by Faulstich et al. (2011) and Arbian-Hoseynabadi et al. (2010) fail 1.86 times and 1.43 times per year respectively. In terms of offshore wind turbines failures, the calculated result in this paper and statistic data of Carroll et al. (2015) are 7.31 times and 8.27 time per year, about four times higher than the onshore ones.

The comparison of several systems between offshore and on shore wind turbine is notable. Generators are markedly affected by marine environment. The failure rate of FOWT generators is nearly 7 times larger than onshore ones, much higher than average. Speed train and gearbox malfunctions are not sensitive to operation condition. In Table 10, the failure rate of these two assemblies are closed to onshore data. The results indicate that marine environment shows more influence on electrical and electronic components than on structures.

4 CONCLUSIONS

The present work develops a FT for a generic FOWT. According to this FT, both qualitative and quantitative FTA are analysed based on a set of generic failure information.

In order to identify high-risk failure modes and failure causes, MCS probabilities and IMs values of several critical assemblies, namely, support structures, pitch and hydraulic system, generator, gearbox and the other systems, are calculated. IMs values suggest that extreme sea conditions are the main causes of structural malfunction. Stress caused by strong wind and wave predominates the other failure reasons. Pitch and hydraulic system is mostly affected by leakage and over pressure. Nearly 68% malfunctions are induced by these two events. Leakage is also the largest contributor of generator failures, followed by parameter deviation and asymmetry. Corrosion and wear, which caused by harsh operation environment, are primary issues of the gearbox failures and most of the failures are comprised by bearings. It can be concluded that most of the failures are caused by several basic factors, e.g. storm, corrosion and leakage. It can be concluded that marine conditions, especially the salt-spray and high wind speed, show the most significant impact on FOWT reliability and availability. These two issues ought to be stressed for the improvement of system performance. Since FOWT is a multi-components equipment with numerous failure modes and failure causes, the risk-based design, condition monitoring and Reliability Centered Maintenance (RCM) efforts should concentrate on these critical factors in order to enhance the analysis efficiency.

In terms of the entire FOWT system, the calculated failure rate is 8.34E-4 h^{-1}, indicating that the system fails on average 7.31 times per year. The results are approximately in conformity with statistical data, suggesting that the planned maintenance period should be 50 days in order to ensure the system performance. Support structures, pitch and hydraulic system, electronic components are the top three contributors to overall failures. They should be well treated during the reliability allocation and O&M management. According to the comparison between previous data and the calculated results in this study, it is notable that all systems have a higher failure rate offshore than they do onshore. The overall failure time of FOWTs per year is about four times higher than the onshore ones. In terms of each subsystems, the onshore to offshore failure rate difference is greater in electrical and electronic components than in gearbox and speed train system, indicating that the electrical and electronic units are more vulnerable than structural components.

The limitation of this research is that partial failure information is collected from onshore wind turbine due to the lack of sufficient data. The results could be updated when further information is available. Besides the data collection, future work should also include developing a more specific FT, considering the failure probability distributions for the events, and other improvements.

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Fault Tree Analysis of Floating Offshore Wind Turbines

Jichuan Kang, Liping Sun, Carlos Guedes Soares

Highlights

- Fault Tree Analysis method is proposed for evaluation of floating offshore wind turbine failure
- The floating offshore wind turbine is divided into several assemblies
- Failure rates of relevant offshore structures are collected from previous studies
- Quantitative assessment of Minimum Cut Sets and Importance Measures are achieved
- Salt-spray and high wind speed, show the most significant impact on wind turbine performance