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Identification of critical components of wind turbines using FTA over time

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Abstract: Wind energy is currently the most widely implemented renewable energy source in global scale. Complex industrial multi-MW wind turbines are continuously being installed both onshore and offshore. Projects involving utility-scale wind turbines require optimisation of reliability, availability, maintainability and safety, in order to guarantee the financial viability of large scale wind energy projects, particularly offshore, in the forthcoming years. For this reason, critical wind turbine components must be identified and monitored as cost-effectively, reliably and efficiently as possible. The condition of industrial wind turbines can be qualitatively evaluated through the Fault Tree Analysis (FTA). The quantitative analysis requires high computational cost. In this paper, the Binary Decision Diagram (BDD) method is proposed for reducing this computational cost. In order to optimise the BDD a set of ranking methods of events has been considered; Level, Top-Down-Left-Right, AND, Depth First Search and Breadth-First Search. A quantitative analysis approach in order to find a general solution of a Fault Tree (FT) is presented. An illustrative case study of a FT of a wind turbine based on different research studies has been developed. Finally, this FT has been solved dynamically through the BDD approach in order to highlight the identification of the critical components of the wind turbine under different conditions, employing the following heuristic methods: Birnbaum, Criticality, Structural and Fussell-Vesely. The results provided by this methodology allow the performance of novel maintenance planning from a quantitative point of view.

***Key words*:** Fault Tree Analysis, Binary Diagram Decisions, Wind Turbines, Condition Monitoring, Maintenance Management

1 Introduction

The wind energy industry has undergone considerable development over the past 35 years. This has resulted in wind power becoming the most important renewable energy source available to humanity so far. Many studies predict that the growth trends for wind energy will continue at a strong steady pace at least until 2030 [1]. The size and complexity of industrial Wind Turbines (WTs) will continue to grow with 10 MW-rated devices already being at the design stage. The effective implementation of such large wind turbines will require more cost-effective operations based on optimised levels of Reliability, Availability, Maintainability and Safety (RAMS).

Blanco [2] 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. Although larger turbines may reduce the O&M costs per unit power, the cost per failure increases due to the combined cost associated with emergency corrective maintenance and loss of production during downtime [3]. By employing a suitable Condition Monitoring (CM) technique, many faults can be detected and controlled under operational conditions. Early detection of incipient faults prevents major component failures and allows for the implementation of predictive repair strategies [4]. Therefore, appropriate actions can be planned in time to prevent major failures which in the case of corrective maintenance procedures would result in significant O&M costs and downtimes. CM techniques provide useful information that support operational efficiency and contribute to the improvement of new turbine designs.

Some components fail earlier than intended by their design and cause unscheduled downtimes which reduce the productivity of the wind farm. Condition Monitoring Systems (CMS) can contribute to the improved operational control of the critical components [5], [6] and [7]. CM techniques, such as vibration and oil analysis, acoustic emission, temperature measurement, etc., together with advanced signal processing methods and data trending, provide continuous information regarding the status of the component being monitored [8] and [9]. CM techniques are used to collect the main functional parameters of critical components, such as the gearbox, generator, main bearings, blades, tower, etc. [10]. This paper presents a novel approach for determining the critical components of any WT in different conditions based on a real case study. The results reported herewith support the optimisation of CM design and investment. For this purpose a method based on fault tree analysis (FTA) that allows qualitative analysis is presented. Quantitative Fault Tree Analysis (FTA) is performed by employing Binary Decision Diagrams (BDDs). In section 2 are presented the FTAs, BDDs, the conversion from FTA to BDD and some experiments to test and verify the approach. In section 3, importance measures for the Fault Tree (FT) have been presented and tested in order to identify the events that are more important for the fault of the top event. Finally, in section 4, a case study of an FT for a WT has been developed considering large research studies and analysed qualitatively and quantitatively, where the main results are presented in section 5. The main components of WTs and their relationship have been set taking into account the comments of industrial experts involved in the European Projects NIMO [11] and OPTIMUS [12]. The critical components have been set according to different scenarios. This study will be a useful reference for those involved in the optimisation of the design of the CMS and therefore the investment required.

2 Reliability analysis

2.1 Fault tree analysis and binary decision diagrams

Identification of potential hazardous events, assessment of their consequences and frequency of occurrence is necessary in order to improve the application of CMS for WTs. Efficient CMS can effectively contribute to the reduction of O&M costs, as well as increase the RAMS of WTs. In this paper a FT is proposed as a graphical representation of the logical relationships between the elements that comprise WTs. A FT is compound by different events and logic gates (see Figure 1(a)):

- Top event is an undesirable event. It is unique in the FT.
- Basic events (e_i) perform basic fault inputs to the FT that can occur more than once in a FT.
- Intermediate events (g_i) are represented by the combination of elemental and/or other intermediate events through logic gates. Intermediate events can be repeated in the FT but their branch must be the same.
- Logic gates (**AND/OR**) connect events by the coexistence of all input events (AND), or at least only one of the input events (OR) to reproduce the output event.

Complex systems analysis may produce thousands of combinations of events, or cut-sets (C-Ss), that can result in system failure. The determination of these C-Ss can be a large and time-consuming process. If the FT has many C-Ss, the determination of the exact top event probability also requires lengthy calculations. As a consequence, approximation techniques have been introduced with a loss of accuracy [13]. Herewith, the BDD is proposed to solve the probability of the top event of the FT (see Figure 1(a)).

BDDs, as shown in example in Figure 1(b), are directed acyclic graphs (**V, N**), with vertex set **V** (vertices) and index set **N** (position of v in the order of variables) that represent the Boolean functions introduced by Lee in 1959 [14], and further popularised by Akers[15], Moret [16], and Bryant [17]. BDD provides a new alternative to traditional C-Ss approaches for FTA that leads to the determination of the output value of the function through the inputs values.

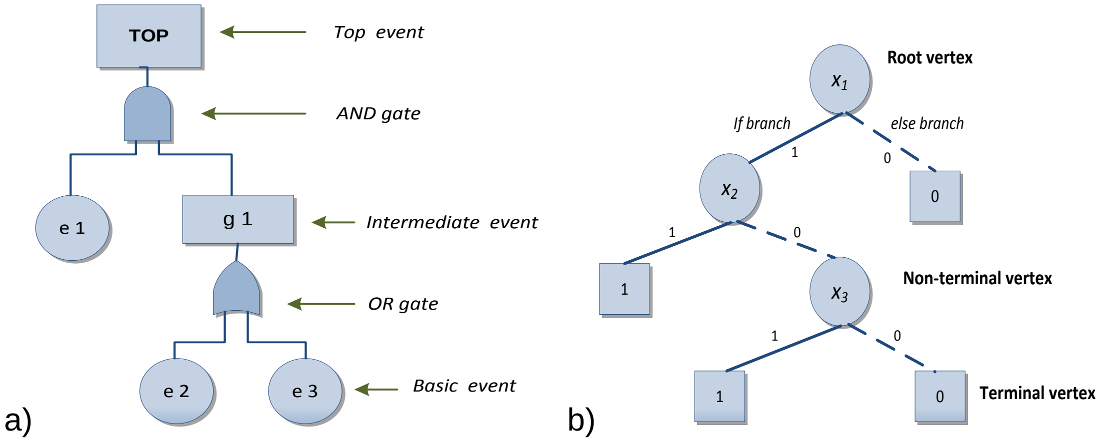

Figure 1. Structure of: a) FTs; b) BDDs

2.2 Conversion from FTA to BDD

The size of a BDD depends on several Boolean variables. An adequate ranking of basic events is crucial in order to reduce the size of the BDD, and therefore the computational cost. There are different methods, and some of them will be more adequate than other depending on the problem structure, number of variables, etc. In this paper, the “Level”, “Top-down-Left-Right”, “AND”, “Depth First Search” and “Breadth-First Search” methods have been considered for listing the events, or vertices A_i, and a comparative analysis has been performed in order to set the best ranking order.

The number of C-Ss is reduced according to the ranking of the events, with the probability of the top event being the same in any case. A suitable ranking will reduce the complexity of the calculation of the top event probability. In order to set a correct ranking of the events, the methods presented in section *2.3* have been considered.

2.3 Rankings for Events

Different methods for ranking events can be used. The main methods include:

- The “Top-Down-Left-Right” (TDLR) method generates a ranking of the events by ordering them from the original FT structure in a top-down and then left-right manner [18]. The listing of the events is initialized, at each level, in a left to right path adding the basic events found in the ordering list. In the case that an event had been considered previously and located higher up then it is ignored.
- The “Depth First Search” (DFS) approach goes from top to down of a root and each sub-tree from left to right. This procedure is a non-recursive implementation and all freshly expanded nodes are added as last-input last-output process [19].
- The “Breadth-First Search” (BFS) algorithm orders all the basic events obtained, expanding from the standpoint by the first-input first-output

procedure. The events not considered are added in a queue list named "open", where they are being taken into account in the procedure, and the list is recalled "closed" list when the all the events are studied [20].

- The "Level" method creates a ranking of the events according to their level. The level of any event is understood as the number of the gates that is higher up a tree until the top event. In case that two or more events have the same level, the event which will have highest priority is the one appearing earlier in the tree [21].
- The "AND" criterion states that the importance of the basic event is based on "and" gates located between the *k* event and the top event as these gates imply redundancies in the FTA systems [13]. Basic events with the highest number of "AND" gates will be ranked at the end. In case of duplicated basic events, the event with less "AND" gates has preference. Finally, basic events with the same number of "AND" gates can be ranked using the TDLR method.

A set of FTs have been considered in order to test the ranking obtained by the methods aforementioned and are presented in Table 1. Different sizes of trees and structures (number of "AND" and "OR" gates, and levels) have been considered.

The Level, TDLR, AND, DFS and BFS methods have been employed and analysed together regarding to the C-Ss number obtained by the BDD of the FTs showed in Table 1. If the size of C-Ss increases, then the computational time required for calculating the probability of the top event rises. The numbers of C-Ss of the FTs are shown in Figure 2. BFS generates generally poor results, especially when the FT has a high number of events, levels and "or" and "and" gates. Otherwise, the Level and AND methods generate small number of C-Ss. The conclusions regarding to Level, DFS and TDLR approach should be studied for each FT.

Table 1. Fault Tree case studies

FAULT TREE	Size	AND gates	OR gates	Levels
A	4	2	2	2
B	5	3	3	3
C	6	3	3	3
D	8	3	3	2
E	12	2	10	7
F	12	3	10	3
G	19	6	8	3
H	25	6	16	12
I	17	8	9	5

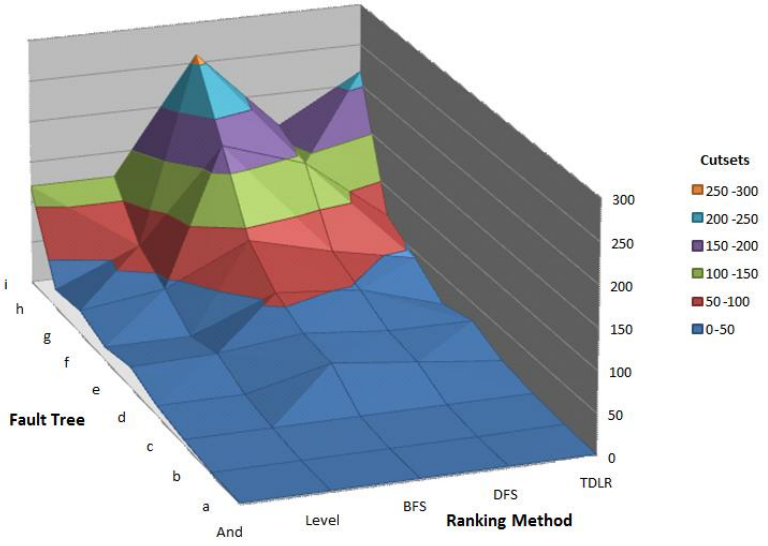

Figure 2. Numbers of C-Ss given by AND, Level, BFS, DFS and TDLR methods

3 Importance Measures

A classification and identification of the events that are more important for the fault of the top event is necessary. The Importance Measures (IMs) can be used to rank basic events with respect to their contribution to the probability of the top event. IMs are calculated by the Birnbaum, Criticality, Structural and Fussell-Vesely heuristic methods considering the same probability of fault (0.01) for each event.

- Birnbaum introduces a measure of importance of a FTA based on the probability caused to the fault of the system by each component *k* [2].
- The Criticality importance measure considers the fault probability of an event [22].
- A new index based on the theoretical development completed by Birnbaum is defined by Lambert [22] in order to define the Structural method.
- The IM of Fussell-Vesely of any event is given by the conditional probability that at least one minimal C-S that contains component *i*, considering that the system is failed [23]. This measurement considers the highest importance to the largest probability of being the cause of the system failure [24].

The FT example showed in Figure 3 is used to test the different IM methods.

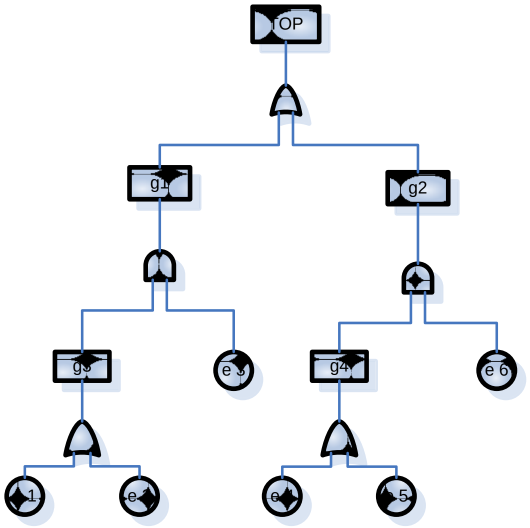

Figure 3. FTA Example

It should be noted that the values obtained by IMs are used to rank the events. Table 2 shows that events e_3 and e_6, from example, have the highest IM for Birnbaum, Criticality, Structural and Fussell-Vesely methods. Therefore, they will be considered as the critical elements where the main maintenance tasks are recommended based on these events in order to guarantee the reliability of the system. It can be seen that all the methods for IMs found similar solutions to rank the events.

Table 2. IM of heuristic methods for the FTA from an example

Events	Birnbaum	Criticality	Structural	Fusell-Vesely
e_1	0.010	0.249	0.094	0.505
e_2	0.010	0.249	0.094	0.254
e_3	0.020	0.500	0.281	1.000
e_4	0.010	0.249	0.094	0.500
e_5	0.010	0.249	0.094	0.249
e_6	0.020	0.500	0.281	1.000

4 FTA for WTs

The main components of the WTs are illustrated in Figure 4. The blades, connected to the rotor via the hub, are moved by the wind blowing on them. The rotor transmits the mechanical energy via the low speed shaft through the gearbox to the high speed shaft, ending in the generator. The low speed shaft is supported by the main bearing. The alignment to the direction of the wind is controlled by a yaw system that turns the housing (or “nacelle”) for that purpose. The nacelle is mounted at the top of a tower, and the tower is assembled on a base or foundation. The pitch system in each blade is a mechanism that turns the blade to control the wind power captured. This can be employed as an aerodynamic brake as well as for increasing the efficiency of power production. The WT has also a hydraulic brake to stop the WT. The meteorological unit, or weather station, provides the weather data (e.g. wind speed and direction) to the control system. The data from the meteorological unit provide the required information for controlling effectively the pitch system, brake, yaw, etc.

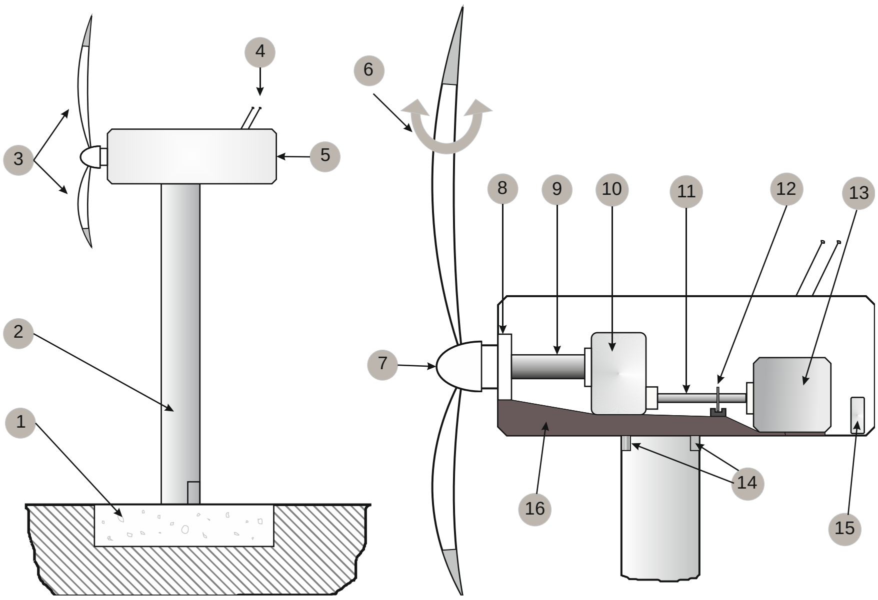

Figure 4. Components of the WT: 1-Base/Foundations; 2-Tower; 3-Blades; 4-Meteorological unit (vane and anemometry); 5-Nacelle; 6-Pitch system; 7-Hub; 8-Main bearing; 9- Low speed (main) shaft; 10-Gearbox; 11- High speed shaft; 12-Brake system; 13-Generator; 14-Yaw system, 15-Converter, 16-Bedplate. N.B. Drive train = 9+11.

A study of failure modes and effects analysis (FMEA) for WTs in 2010 (RELIAWIND project) collected the causes of failure and failure modes of a specific WT of 2MW with a diameter of 80 m [25] and [26]. Some causes of failures (or root causes) are summarised in Table 3. These main causes of the failures can be due to environmental conditions (e.g. lightning, ice, fire, strong winds, etc.) or to defects, malfunctions or failures in the components of the WT (e.g. braking system failure, or be struck by blade, etc.) [27].

Table 4 shows some of the principal component failure modes of the WTs [25] and [28].

Table 3. Root causes of the failures of the components of a WT [25].

Structural	Wear	Electrical
Design fault	Corrosion	Calibration error
External damage	Excessive brush wear	Connection failure
Installation defect	Fatigue	Electrical overload
Maintenance fault	Pipe puncture	Electrical short
Manufacturing defect	Vibration fatigue	Insulation failure
Mechanical overload	Overheating	Lightning strike
Mechanical overload–collision	Insufficient lubrication	Loss of power input

Mechanical overload–wind Presence of debris		Conducting debris Software design fault

Table 4. Failure modes of the failures of the components of a WT [25] and [28].

Mechanical	Electrical	Material
Rupture Uprooting Fracture Detachment Thermal Blockage Misalignment Scuffing	Electrical insulation Electrical failure Output inaccuracy Software fault Intermittent output	Fatigue Structural Ultimate Buckling Deflection

The construction of the illustrative FT studied herewith is focused on a three-blade, pitch controlled geared WT. The WT has been divided into four major groups of elements for a better FTA:

- The foundation and tower;
- The blades system;
- The electrical components (including generator, electrical and electronic components);
- The power train (including speed shafts, bearings and a gearbox).

The elements are connected by AND and OR gates, and their fault probability is unknown. The faults considered in this paper are set by an exhaustive review of the literature and the support of member experts in the NIMO and OPTIMUS FP7 European projects [11] and [12].

Table 5 shows a summary of the failures from the literature taken into account for this paper. It can be seen that gearboxes, generators, blades and electric and control systems have been extensively studied in the literature. Nonetheless, there are not many references which analyse other components of a WT such as brakes, hydraulic and yaw systems.

Table 5. Failures of the main elements of a WT

Foundation and tower	Structural fault [27] [29] [30] [31] [32] Yaw system failure [33]	
Critical rotor	Blade failure	Structural failure [34][35][36][37][38][39][40] [41] Pitch system failure [42] Hydraulic system fault [43] [44] Meteorological unit failure [43] [45]
	Rotor failure	Rotor hub [29][33] Bearings [32][33][44]

Power train	Low speed train failure [33][46] Critical gearbox failure [33][41][46][47][48][49][50]	
	High speed train failure	Shaft [29][33][46] Critical brake failure [29][51]
Electrical components	Critical generator failure [29][46][48][52][53][54] Power electronics and electric controls failure [44][46][48]	

The following sections show the FT for the aforementioned main components of the WT. It is very important to mark that they could be simplified or extended, but the authors, following the opinion of the experts, have set them in order to show the most relevant events.

4.1 Foundation and Tower

The tower supports the nacelle which is located at a suitable height in order to minimize the influence of turbulence and to maximize the wind energy. The tower is assembled by relatively thin-wall steel cylindrical elements welded together along their perimeters in three sections and joined by bolts. This is done in order to enable the transportation of the large structural elements to the wind farm where they need to be assembled in-situ [55]. The base section of the tower is installed on a reinforced concrete foundation comprising a round base [56].

Structural defects associated with the tower, foundation, blades and hub, in the form of fatigue cracks, delamination etc., can initiate and evolve with time [31]. The main causes for structural failures are fatigue induced crack initiation and propagation, extreme wind speeds and distribution, extreme turbulences, maximum flow inclination and terrain complexity [28], and also ice accumulation, hail, bird strikes, dust particle impacts, or lightning bolt strikes. Material fatigue [27] (tower-based fatigue damage has been shown to decrease significantly when using active pitch for the blades [30]), impact of blades on the tower, faulty welding and failure of the brakes [32] are the main representative failure modes.

The literature shows that the major defects found on WT towers are [11]: cracks in the concrete base, corrosion [29], gaps in the foundation section, loosen studs joining the foundation and the first section, loosen bolts joining first/second and second/third sections and welding damages [27].

On the top of the tower, the yaw system turns the nacelle in an optimum angle with respect to the wind direction. Powered by electromechanical or hydraulic mechanisms (in this paper the electromechanical mechanism is considered), the yaw systems can seize to operate due to the failure of the yaw motor or the meteorological unit failure [33] resulting in a wrong yaw angle. Structural failures could appear when the yaw motor is damaged or it does not have power supply [57], in addition to extreme wind speed or turbulences and some structural faults. These structural failures can cause the collapse of the tower [27]. Design load cases (DLC) must be taken into account for different design situations and wind or other conditions. The IEC 61400-1 relative to design requirements for wind turbines shows some DLCs that shall be considered as minimum [62]. For example, the event e012 (High wind speed/ turbulence) will occur when DLCs are exceeded. Table 5 presents the basic and intermediate events for the FT of the foundation and tower illustrated in Figure 5.

Table 5. Principal events in the foundation and tower.

Yaw system failure	g005	Yaw motor fault	e001
Structural failure	g006	Abnormal vibration I	e002
Yaw motor failure	g007	Abnormal vibration H	e003
Wrong yaw angle	g008	Cracks in concrete base	e004
Severe structural fault (foundation and tower)	g009	Welding damage	e005
No electric power for yaw motor	g010	Corrosion	e006
Meteorological unit failure	g011	Loosen studs in joining foundation and first section	e007
Structural fault (foundation and tower)	g012	Loosen bolts in joining different sections	e008
		Gaps in the foundation section	e009
		Vane damage	e010
		Anemometer damage	e011
		High wind speed/ turbulence	e012
		No power supply from generator	e013
		No power supply from grid	e014

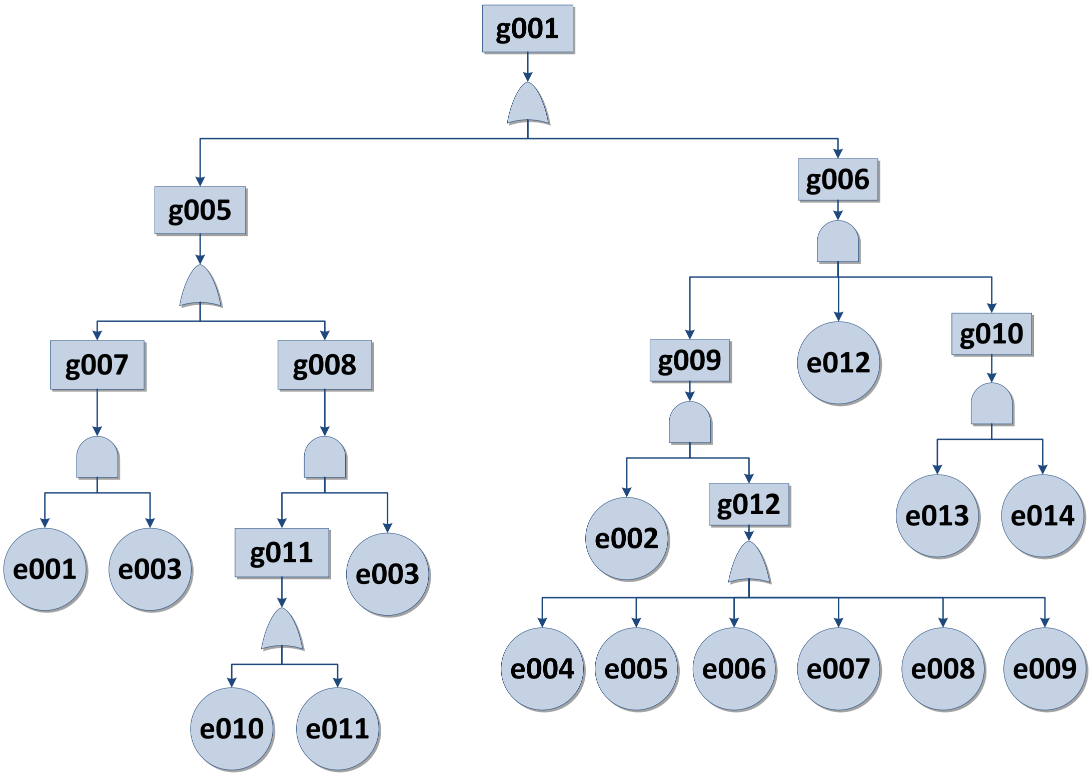

Figure 5. Fault tree of the foundation and tower

4.2 Blade System

The rotor is located inside the nacelle. The blades are attached to the rotor shaft by the hub and they are mounted on bearings in the rotor hub. The blades are the components of the WT with the highest percentage of failures and downtimes [58]. Ciang *et al*. in 2008 done a review of damage detection methods, particularly considering the blades [29]. The rotor hub supports heavy loads that can lead faults such as clearance loosening at the blade root, imbalance, cracks and surface roughness [33]. Bearings between blades and hub can be damaged by wear produced by pitting, deformation of outer face and rolling elements of the bearings [33], spalling and overheating [44]. Cracks can appear due to the fatigue [44]. Fatigue, wear, faults in lubrication and corrosion are typically the main failure cause of bearings.

The blades faults are predominantly related to structural failures, e.g. strength [34] and fatigue of the fibrous composite materials [35]. Other faults, e.g. cracks, erosion, delamination and debonding, could appear in the leading and trailing edges of the blades [36] and [37]. Delamination, debonding or cracks are found in the shell [37] and [38], and also in the root section of the blades [39]. The tip deflections (a structural failure of the blade [40]) increase drag near the end of the blades [41].

A common fault of the blades is associated with the failure of the pitch control system [42]. In pitch-controlled turbines, the pitch system is a mechanism that turns the blade, or part of the blade, in order to adjust the angle of attack of the wind. Turbulence of wind is an important cause for pitch system faults [59]. Pitching motion can be done by hydraulic actuators or electric motors. The hydraulic system leads stiffness of bearings, a little backlash and a higher reliability than the electric motors [46]. The hydraulic system can suffer from possible defects such as leakage, overpressure and corrosion [44].

The weather station or meteorological unit provides information about some characteristics of the wind (direction and speed) to the control system of the WT. The main failures found in the WT weather station are related to the vane and anemometer [45]. These can result in adjusting the pitch of the blade to a sub-optimal angle [43]. Table 6 collects the main faults given in blades, and Figure 6 shows the FT for the blade system.

Table 6. Principal events in the blade system.

Severe blade failure	g013	High wind speed/turbulence	e015
Blade failure	g014	Blade angle asymmetry	e016
Pitch system failure	g015	Abnormal vibration A	e017
Structural failure of blades	g016	Hydraulic motor failure	e018
Hydraulic system failure	g017	Leakages in hydraulic system	e019
Wrong blade angle	g018	Over pressure in hydraulic system	e020
Hydraulic system fault	g019	Corrosion in hydraulic system	e021
Meteorological unit	g020	Vane damage	e022
Structural fault of blades	g021	Anemometer damage	e023
Leading and trailing edges damage	g022	Abnormal vibration B	e024
Shell damage	g023	Root cracks in the structure of blades	e025
Tip damage	g024	Cracks in edges of blades	e026
Rotor system failure	g025	Erosion in edges of blades	e027
Rotor system fault	g026	Delamination in leading edges of blades	e028
Rotor bearings fault	g027	Delamination in trailing edges of blades	e029
Rotor hub fault	g028	Debonding in edges of blades	e030
Wear in bearings of the rotor	g029	Delamination in shell	e031
Imbalance of blade system	g030	Crack with structural damage (shell)	e032
		Crack on the beam-shell joint	e033
		Open tip	e034
		Lightning strike on tip	e035
		Abnormal vibration C	e036
		Cracks in bearings of rotor	e037
		Corrosion of pins in bearings of rotor	e038
		Abrasive wear in bearings of rotor	e039
		Pitting in bearings of rotor	e040
		Deformation of face & rolling element in bearings of rotor	e041
		Lubrication fault in bearings of rotor	e042
		Clearance loosening at root (hub)	e043
		Cracks in the hub	e044
		Surface roughness in the hub	e045
		Mass imbalance in the hub	e046
		Fault in pitch adjustment	e047

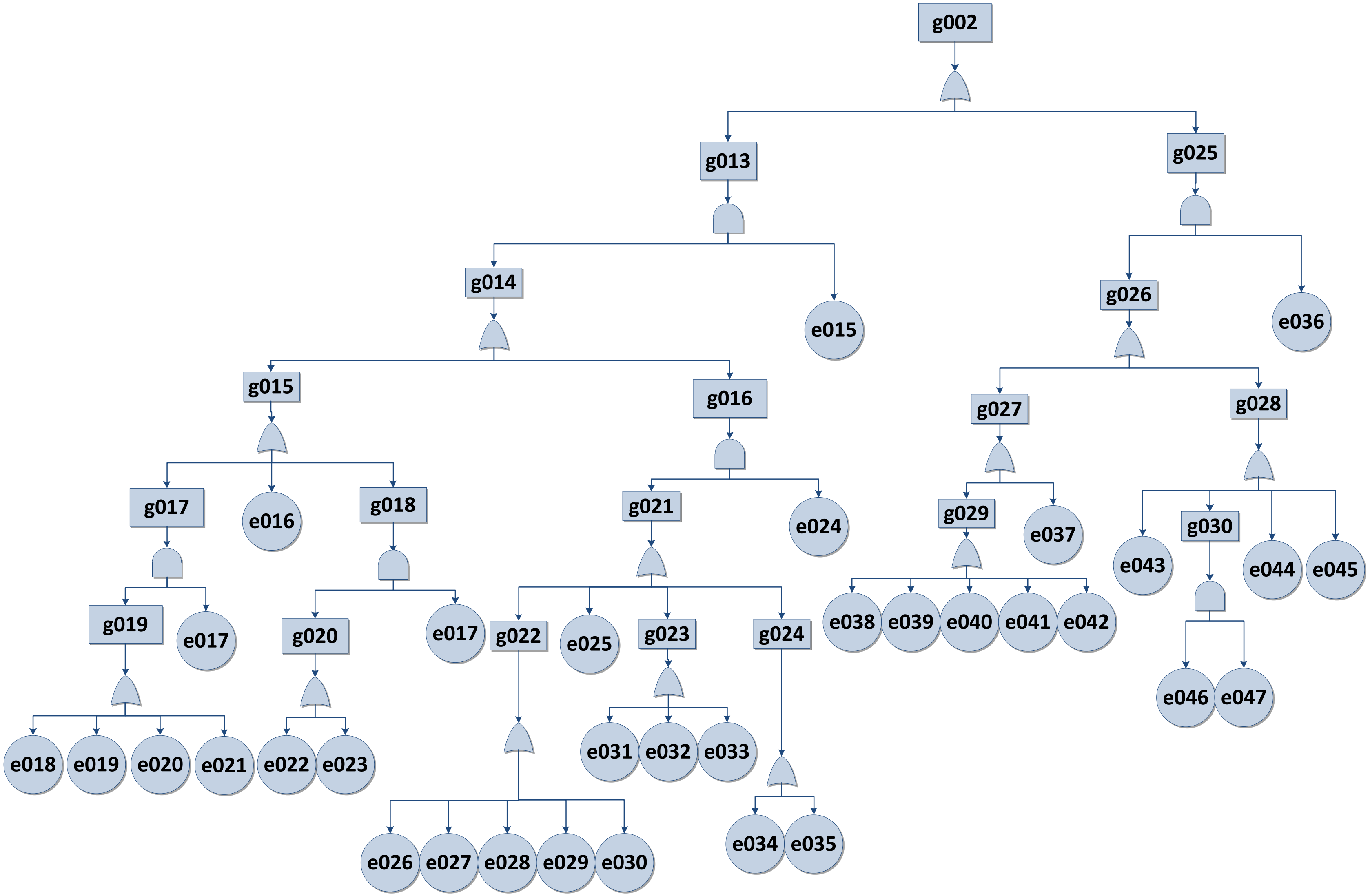

Figure 6. Fault tree of the blades

4.3 Generator, electrical and electronic components

The generator, electrical and electronic components are installed inside the nacelle. The high speed shaft drives the rotational torque to the generator, where the mechanical energy is converted to electrical energy. This conversion needs a specific input speed, or a power electronic equipment to adapt the output energy from the generator to the characteristics of the grid.

Faults in generators can be the result of electrical or mechanical causes [54]. The main electrical faults are due to open-circuits or short-circuit of the winding in the rotor or stator [46] that could cause overheating [33]. Many research works have demonstrated that bearings, rotors and stators involve a high failure rate in WTs [52]. The bearing failures of the generator are usually caused by wear, fatigue cracks, asymmetry and imbalance [60]. The rotor and stator failures can be produced by broken bars [53], air-gap eccentricities and dynamic eccentricities, among other failures [46]. Rotor imbalance and aerodynamic asymmetry can have their origin in the non-uniform accumulation of ice and dirt over the blades system [46]. Short-circuit faults, open-circuit faults and gate drive circuit faults are the three major electrical faults of the power electronics and electric controls in WTs [46]. Corrosion, dirt and terminal damage are the main mechanical defects [44]. The group formed by generator, electrical system and control system, has a relevant rate of failures and downtime in WTs. Table 7 shows the main elements and failures in the generator, electrical and electronic components.

Table 7. Principal faults in the generator, electrical and electronic components.

Critical generator failure	g031	Abnormal vibration G	e048
Power electronics and electric controls failure	g032	Cracks	e049
Mechanical failure (generator)	g033	Imbalance	e050
Electrical failure (generator)	g034	Asymmetry	e051
Bearing generator failure	g035	Air-Gap eccentricities	e052
Rotor and stator failure	g036	Broken bars	e053
Bearing generator fault	g037	Dynamic eccentricity	e054
Rotor and stator fault	g038	Sensor Tª error	e055
Abnormal signals A	g039	Temperature above limit	e056
Overheating generator	g040	Short circuit (generator)	e057
Electrical fault (power electronics)	g041	Open circuit (generator)	e058
Mechanical fault (power electronics)	g042	Short circuit (electronics)	e059
		Open circuit (electronics)	e060
		Gate drive circuit	e061
		Corrosion	e062
		Dirt	e063
		Terminals damage	e064

Figure 7 presents the FT for the main elements of the generator, electrical and electronic components given in Table 7.

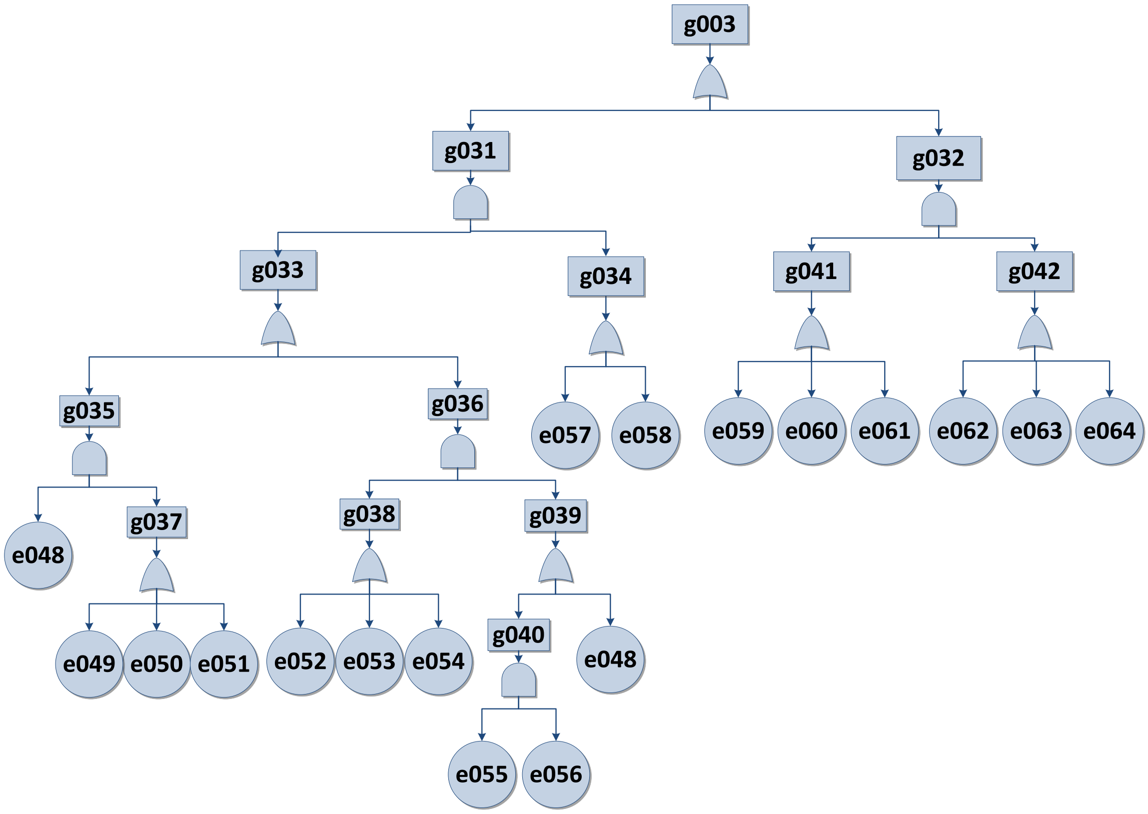

Figure 7. Fault tree of the generator, electrical and electronic components

4.4 *Power train*

The power train, or drive train, is installed in the nacelle and consists of the main bearing, main (low speed) shaft, the gearbox and the generator. Through the main bearing, the rotor is attached to the low speed shaft that drives the rotational energy to the gearbox. The rotational speed of the rotor is generally between 5 and 30 RPM, and the generator speed is from 750 to 1500 RPM, depending on the type and size of generator. A gearbox is mounted between the rotor and the generator in order to increase the rotational speeds. The gearbox output is driven to the generator through the high speed train. A mechanical brake powered by a hydraulic system is usually mounted in the high speed train as a secondary safe breaking system.

The low speed train failure includes main bearing [44] and low speed shaft defects. Severe vibrations can appear due to impending cracks in any component, or to the mass imbalance in the low speed shaft [46]. The gearbox failure is one of the most typical failures [41]. There are many studies about gearboxes in the literature because their failure causes significant downtimes in the system [3]. The most common faults were found in gear teeth and bearings due to lubrication faults [46], e.g. contamination due to defective sealing [42] or loss of oil [48], wear or fatigue damage which can generate pitting, cracking, gear eccentricity, gear tooth deterioration, offset or other potential faults [41] and [33].

Overheating can appear in shafts due to the rotational movement of the high speed train. The wear and fatigue, that can initiate cracks [33] and mass imbalance [46], are the principal source of failures in the high speed shaft. The main failure causes of brakes are overpressure or oil leakages [29], cracking of the brake disc and callipers [51]. Figure 8 shows the FT for the main elements of the power train described in Table 8.

Table 8. Principal faults in the power train.

Low speed train failure	g043	Abnormal vibration D	e065
Critical gearbox	g044	Cracks in main bearing	e066
High speed train failure	g045	Spalling in main bearing	e067
Main bearing failure	g046	Corrosion of pins in main bearing	e068
Low speed shaft failure	g047	Abrasive wear in main bearing	e069
Main bearing fault	g048	Deformation of face & rolling element (main bearing)	e070
Wear in main bearing	g049	Pitting (main bearing)	e071
Low speed shaft fault	g050	Imbalance of low speed shaft	e072
Wear in low speed shaft	g051	Cracks in low speed shaft	e073
Gearbox failure	g052	Spalling (low speed shaft)	e074
Bearings (gearbox)	g053	Abrasive wear in low speed shaft	e075
Lubrication of the gearbox	g054	Pitting (low speed shaft)	e076
Gear failure	g055	Abnormal vibration F	e077
Wear bearing gearbox	g056	Corrosion of pins (bearing gearbox)	e078
Gear fault	g057	Abrasive wear (bearing gearbox)	e079
Tooth wear (gears)	g058	Pitting (bearing gearbox)	e080
Offset of teeth gears	g059	Deformation of face & rolling element (gearbox bearing)	e081
High speed shaft fault	g060	Oil filtration (gearbox)	e082
Critical brake failure	g061	Particle contamination (gearbox)	e083
High speed structural damage	g062	Overheating gearbox	e084
Wear of high speed shaft	g063	Abnormal vibration E	e085
Brake failure	g064	Eccentricity (gear)	e086
Abnormal signals B	g065	Pitting (gear)	e087
Hydraulic brake system fault	g066	Cracks in gears	e088
Abnormal signals C	g067	Gear tooth deterioration	e089
Overheating brake	g068	Poor design of teeth gears	e090
		Tooth surface defects	e091
		Abnormal vibration J	e092
		Cracks in high speed shaft	e093
		Imbalance (high speed shaft)	e094
		Overheating (high speed shaft)	e095
		Spalling (high speed shaft)	e096
		Abrasive wear (high speed shaft)	e097
		Pitting (high speed shaft)	e098
		Cracks in brake disk	e099
		Motor brake fault	e100
		Oil leakage (hydraulic brake)	e101
		Over pressure (hydraulic brake)	e102
		Abnormal speed	e103
		Tª sensor error (brake)	e104
		Tª above limit	e105

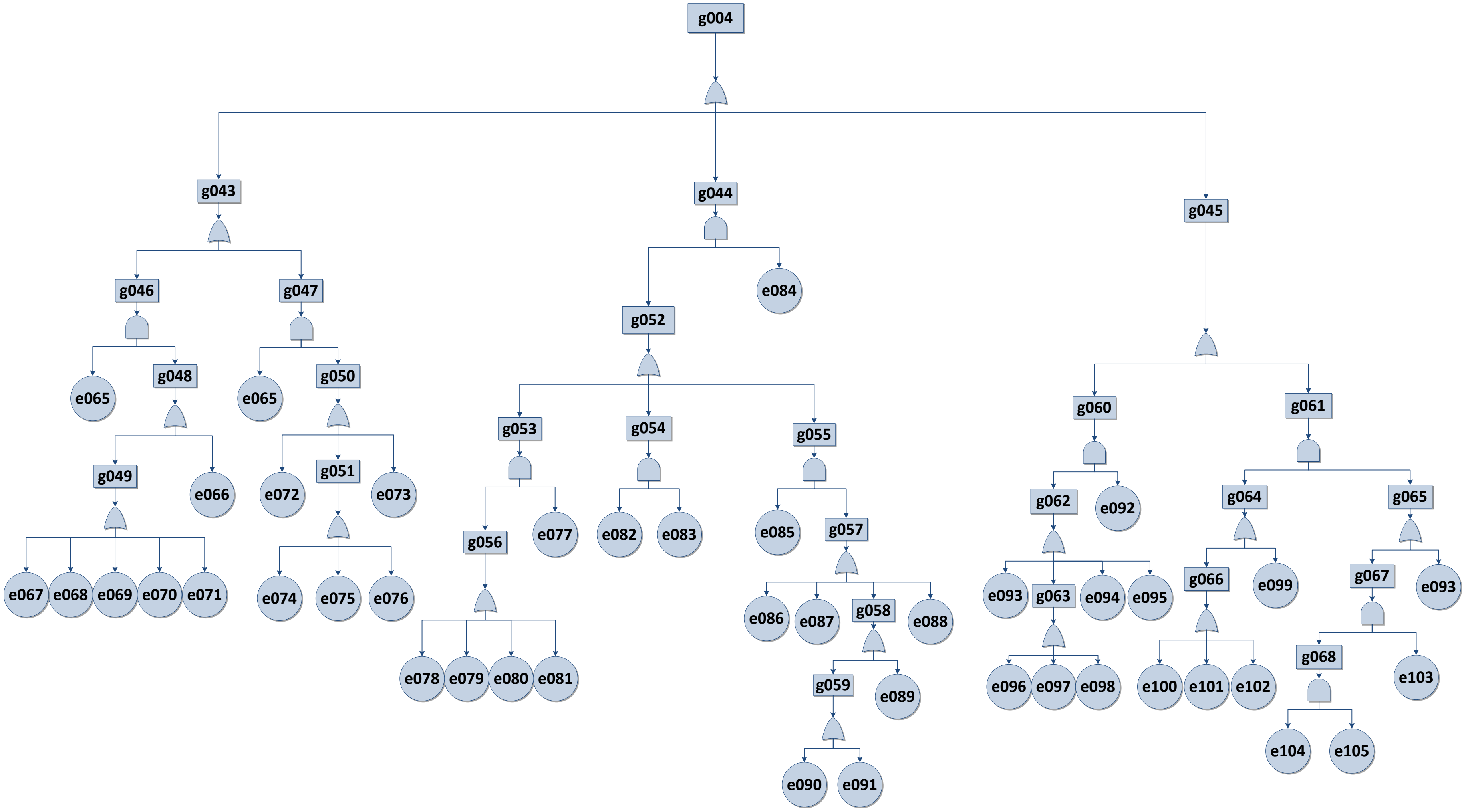

Figure 8. Fault tree for the power train.

5 Results

The most important events according to IM values obtained with the methods Birnbaum, Criticality, Structural and Fussell-Vesely can be identified in Figure 9. In this case, the most important events are e001, e003, e017, e018, e019, e036, e057, e058, e059, e062, e065, e084, e092 and e093, i.e. the events "yaw motor failure" and "abnormal vibration H" must be studied with detail because they probably cause a tower or foundation failure; the events "abnormal vibration A", "hydraulic motor failure", "leakages in hydraulic system" and "abnormal vibration C" are usually involved in a critical rotor failure; the events "short circuit (generator)", "open circuit (generator)", "short circuit (electronics)" and "corrosion" are prone to be the cause of an electrical failure; the occurrence of "abnormal vibration D", "overheating gearbox", "abnormal vibration J" and "cracks in high speed shaft" are the most probably causes of a power train failure.

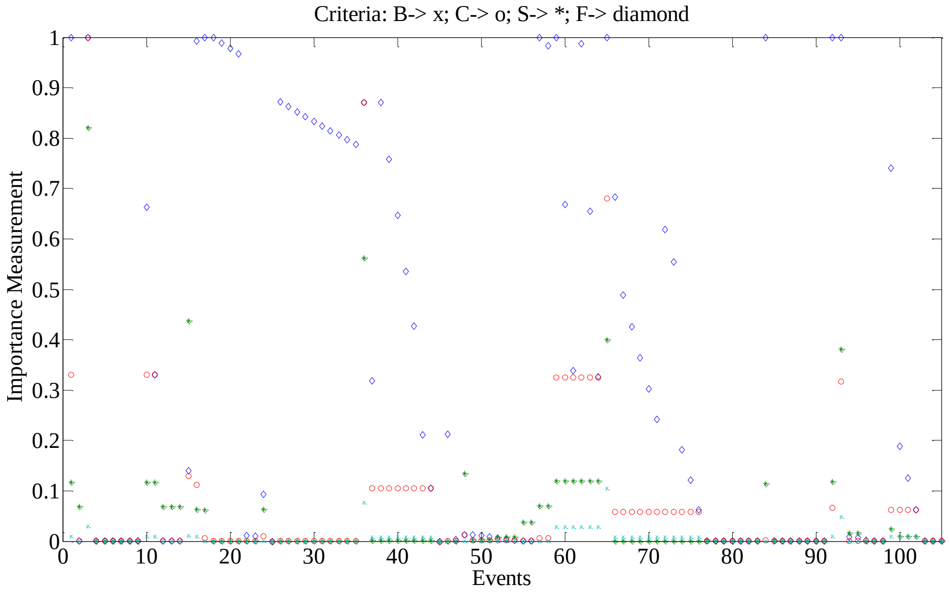

Figure 9. Importance measures for the WT.

Importance measures are limited to a specific point of time as Figure 9 indicates. For this reason, a novel dynamic simulation has been done in order to extend the analysis to a certain period of time. The literature does not include the values of the failure probabilities of the basic events and the WT operators are reluctant to publish it. Moreover, the nature and conditions of the events considered in the dynamic FTA could be very different. Consequently, several probability models are used for this purpose. The following time-dependent probability models are considered in this paper to describe the behaviour of events throughout time.

I. *Constant probability*

In this model the probability of the Event remains constant at all times.

$P(t) = K$, where K is a constant value from 0 to 1.

II. *Exponential increasing probability*

In this model, probability function assigned is:

$P(t) = 1 - e^{-\lambda t}$, where λ is a parameter that takes only positive values and determines the rising velocity of the probability.

III. *Linear increasing probability*

In this model, probability function is:

$P(t) = mt$, where *m* determines the rising velocity of the probability.

IV. *Periodic probability*

In this model, the events have a periodic behaviour following the next expression:

$P(t) = 1 - e^{-\lambda(t - n\alpha)}$, n=1, 2, 3…

where:

- λ is a parameter that is positive and determines the rising velocity of the probability.
- α is a parameter that determines the period size.

The Appendix I shows the fault probability functions assumed for each event. The experiences of wind turbine operators involved in the NIMO [11] and OPTIMUS FP7 European projects [12] have been considered in order to set the parameters of the time-dependent probability functions. The main purpose of this study is to show an example as close to reality as possible. This model could be adjusted to the specific wind turbine analysed, or to specific components.

Figure 10 shows the failure probability assigned to each event throughout time. This probability has been obtained for 600 samples where each sample represents one day. The events of the FT have different behaviours according to their nature and the values of their parameters.

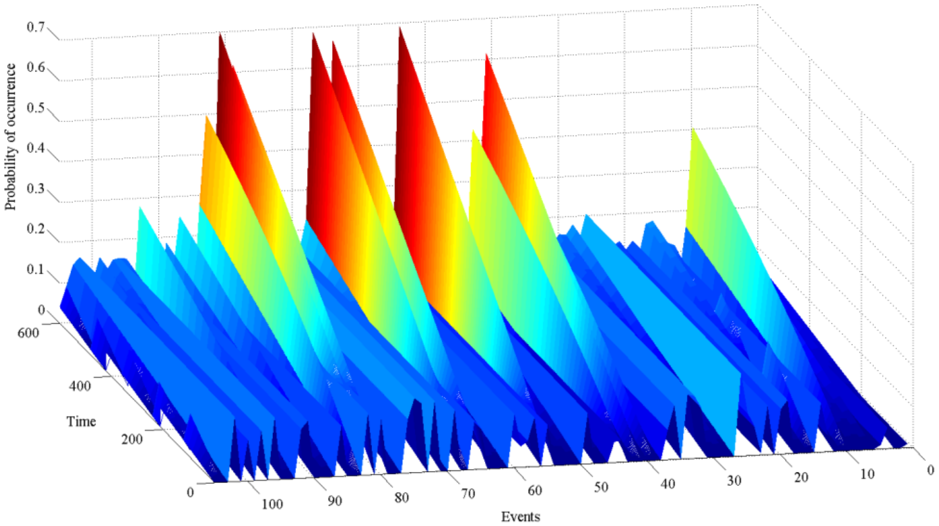

Figure 10. Probabilities of occurrence of the events over the time.

Figure 11 presents the probability of failure of the wind turbine (*Qsys*(*t*)) over the time. It is not continuously rising because there are events involved in preventive maintenance tasks, defined in Appendix I as periodic functions.

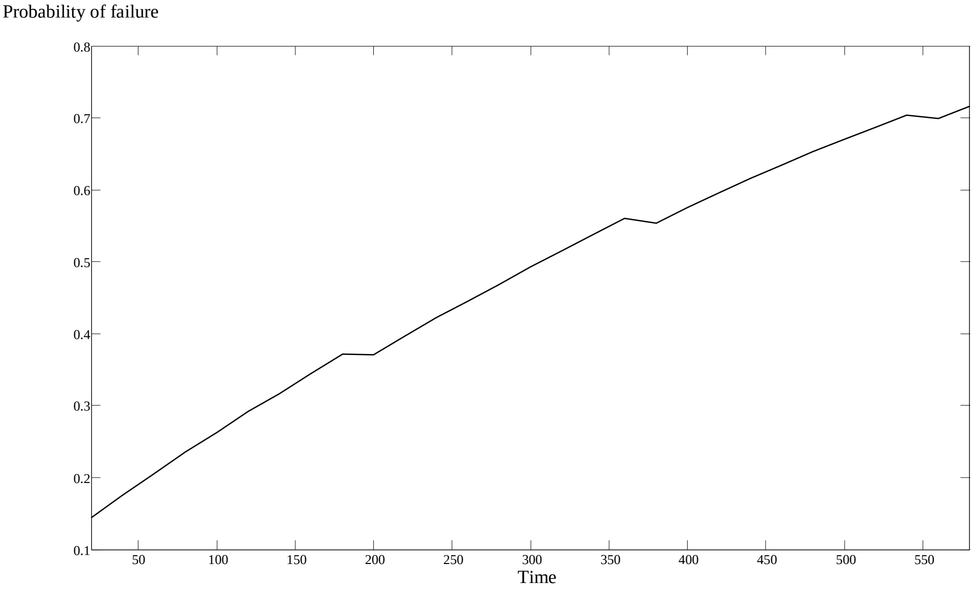

Figure 12 shows the IMs employing the methods Birnbaum (B), described in Section 3 and applied to the FT above depicted. The events e084, e036, e065 have the highest IM according to the Birnbaum criterion over the time, these events should be studied in detail because the method provide a large IM value. There is a set of events with a significant IM over the time, such as events e077, e085, e093, e092 and e003. The rest of the events present lower Birnbaum IMs, i.e. they are usually less involved in the occurrence of the top.

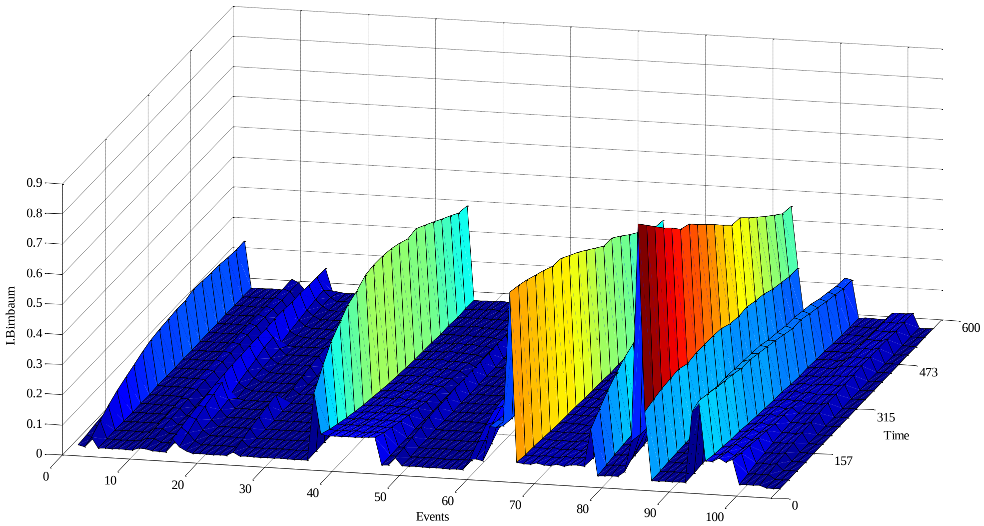

Figure12. Birnbaum importance over the time.

The analysis leads to dynamic decisions from a quantitative point of view, enabling WT diagnostic and prognostic tasks to be carried out efficiently.

Therefore, scheduled maintenance strategies can be implemented more effectively. The behaviour of the system over time allows operators to obtain optimal maintenance decisions since identified components can be repaired or replaced based on their effect on the global system.

For example, let the maximum allowable probability of system failure be 0.5. (Figure 11 shows that this value is reached at the 300th sample). It is ensured that the unavailability of the system is normal until the mentioned sample, and it is required the maintenance tasks before reaching that value. Once the system is in the critical iteration in which the maximum allowable unavailability is reached, it is necessary to act upon the components in order to reduce the failure system probability. Figure 12 provides useful information about how to focus the efforts to reduce such probability. Figure 13 corresponds to a cross section of Figure 12 and it shows the Birnbaum I.M. of the events at the 300th sample.

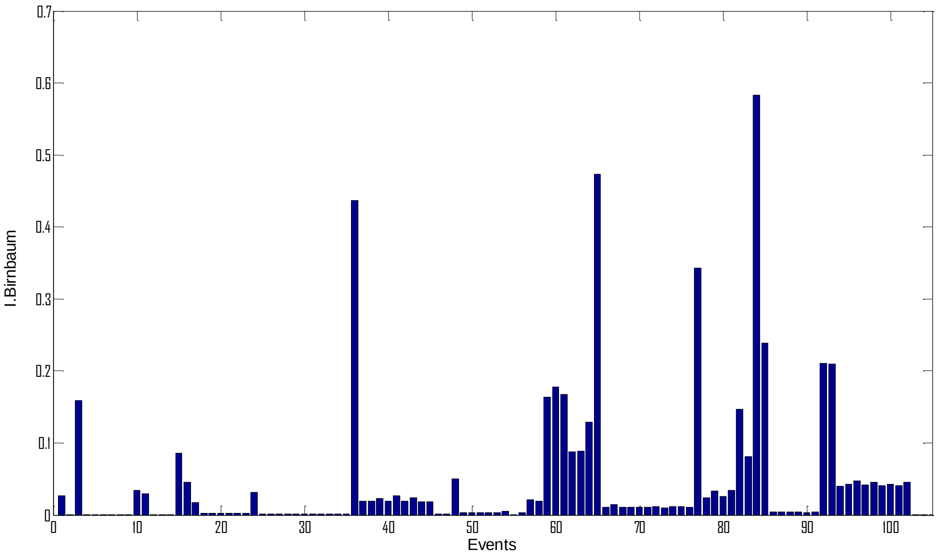

Figure13. Birnbaum importance in a certain time.

According to Figure 13, the most relevant information is the ranking of events that can be gathered from the Birnbaum I.M. The first three events that should be taken into account to plan a maintenance strategy are the events e084, e065, e036, i.e. corresponding to overheating gearbox, and abnormal vibrations.

6 Conclusions

The condition of the WTs is analysed in this paper using an FT-based approach. The qualitatively FTA requires a high computational cost. In this work the BDD is used for the quantitatively FTA and reducing the computational cost. The cut sets (combination of basic events whose simultaneous occurrence causes the top event to happen) generated by BDD will depend on the events ordering. The “Level”, “Top-Down-Left-Right”, “AND”, “Depth-First Search” and “Breadth-First Search” methods have been considered for listing the events, and a comparative analysis of them has been done. The Level and AND methods create the listing of the events that provide a reduced number of cut sets. The Level, Depth-First Search and Top-down-Left-Right methods should be studied for each FT. Finally, the Breadth-First Search is the ordering method that provides a higher number of C-Ss. Importance measures for the FT have been also considered. They are used to identify the critical events that are more important for optimizing the condition monitoring system. A set of experiments are carried out for testing the importance measures, finding that all the approaches used give similar solution.

An illustrative FT example for a WT has been developed. It is very important to mark that the FTs for the main components of the WT could be simplified or extended, but the authors, following the opinion of the experts and the research works considered, have set them in order to show the most relevant events. The importance measures were calculated and studied by a novel FT dynamic analysis that allows using the information for performing diagnostics and prognostics tasks and planning maintenance strategies.

Acknowledgements

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Appendix I. Probability distributions for the events

FT 1 Foundation and Tower Failure				Probabilistic model assignment
intermediate event	code	final event	code	
Yaw system failure	g005	Yaw motor fault	e001	Constant
Structural failure	g006	Abnormal vibration I	e002	Linear increasing
Yaw motor failure	g007	Abnormal vibration H	e003	Linear increasing
Wrong yaw angle	g008	Cracks in concrete base	e004	Constant
Severe structural failure (foundation and tower)	g009	Welding damage	e005	Constant
No electric power for yaw motor	g010	Corrosion	e006	Linear increasing
Meteorological unit failure	g011	Loosen studs in joining foundation and first section	e007	Linear increasing
Structural fault (foundation and tower)	g012	Loosen bolts in joining different sections	e008	Linear increasing
		Gaps in the foundation section	e009	Exponential increasing
		Vane damage	e010	Exponential increasing
		Anemometer damage	e011	Exponential increasing
		High wind speed / turbulence	e012	Periodic
		No power supply from generator	e013	Constant
		No power supply from grid	e014	Constant

FT 2 Critical Rotor Failure				Probabilistic model assignment
intermediate event	code	final event	code	
Severe blade failure	g013	High wind speed / turbulence	e015	Periodic
Blade failure	g014	Blade angle asymmetry	e016	Exponential increasing
Pitch system failure	g015	Abnormal vibration A	e017	Exponential increasing
Structural failure of blades	g016	Hydraulic motor failure	e018	Exponential increasing
Hydraulic system failure	g017	Leakages in hydraulic system	e019	Constant
Wrong blade angle	g018	Over pressure in hydraulic system	e020	Constant
Hydraulic system fault	g019	Corrosion in hydraulic system	e021	Exponential increasing
Meteorological unit failure	g020	Vane damage	e022	Constant
Structural fault of blades	g021	Anemometer damage	e023	Constant
Leading and trailing edges damage	g022	Abnormal vibration B	e024	Constant
Shell damage	g023	Root Cracks in the structure of blades	e025	Constant
Tip damage	g024	Cracks in edges of blades	e026	Constant
Rotor system failure	g025	Erosion in edges of blades	e027	Exponential increasing
Rotor system fault	g026	Delamination in leading edges of blades	e028	Exponential increasing
Rotor bearings fault	g027	Delamination in trailing edges of blades	e029	Exponential increasing
Rotor hub fault	g028	Debonding in edges of blades	e030	Exponential increasing
Wear in bearings of the rotor	g029	Delamination in shell	e031	Exponential increasing
Imbalance of blade system	g030	Crack with structural damage in shell	e032	Constant
		Crack on the beam-shell joint	e033	Constant
		Open tip	e034	Constant
		Lightning strike on tip	e035	Periodic
		Abnormal vibration C	e036	Constant
		Cracks in bearings of rotor	e037	Constant
		Corrosion of pins in bearings of rotor	e038	Exponential increasing
		Abrasive wear in bearings of rotor	e039	Exponential increasing
		Pitting in bearings of rotor	e040	Linear increasing
		Deformation of face & rolling element in bearings of rotor	e041	Linear increasing
		Lubrication fault in bearings of rotor	e042	Linear increasing
		Clearance loosening at root (hub)	e043	Exponential increasing
		Cracks in the hub	e044	Constant
		Surface roughness in the hub	e045	Constant
		Mass imbalance in the hub	e046	Exponential increasing
		Fault in pitch adjustment	e047	Exponential increasing

FT 3 Electrical Components Failure				Probabilistic model assignment
intermediate event	code	final event	code	
Critical generator failure	g031	Abnormal vibration G	e048	Exponential increasing
Power electronics and electric controls failure	g032	Cracks	e049	Constant
Mechanical failure (generator)	g033	Imbalance	e050	Exponential increasing
Electrical failure (generator)	g034	Asymmetry	e051	Exponential increasing
Bearing generator failure	g035	Air-Gap eccentricities	e052	Linear increasing
Rotor and stator failure	g036	Broken bars	e053	Linear increasing
Bearing generator fault	g037	Dynamic eccentricity	e054	Linear increasing
Rotor and stator fault	g038	Sensor T error	e055	Constant
Abnormal signals A	g039	Temperature above limit	e056	Periodic
Overheating generator	g040	Short circuit (generator)	e057	Constant
Electrical fault (power electronics)	g041	Open circuit (generator)	e058	Constant
Mechanical fault (power electronics)	g042	Short circuit (electronics)	e059	Constant
		Open circuit (electronics)	e060	Constant
		Gate drive circuit	e061	Linear increasing
		Corrosion	e062	Periodic
		Dirt	e063	Periodic
		Terminals damage	e064	Linear increasing

FT 4 Power train Failure				Probabilistic model assignment
intermediate event	code	final event	code	
Low speed train failure	g043	Abnormal vibration D	e065	Constant
Critical gearbox	g044	Cracks in main bearing	e066	Constant
High speed train failure	g045	Spalling in main bearing	e067	Linear increasing
Main bearing failure	g046	Corrosion of pins in main bearing	e068	Linear increasing
Low speed shaft failure	g047	Abrasive wear in main bearing	e069	Constant
Main bearing fault	g048	Deformation of face & rolling element (main bearing)	e070	Linear increasing
Wear in main bearing	g049	Pitting (main bearing)	e071	Exponential increasing
Low speed shaft fault	g050	Imbalance of low speed shaft	e072	Constant
Wear in low speed shaft	g051	Cracks in low speed shaft	e073	Linear increasing
Gearbox failure	g052	Spalling (low speed shaft)	e074	Constant
Bearings (gearbox)	g053	Abrasive wear in low speed shaft	e075	Constant
Lubrication of the gearbox	g054	Pitting (low speed shaft)	e076	Constant
Gear failure	g055	Abnormal vibration F	e077	Linear increasing
Wear bearing gearbox	g056	Corrosion of pins (bearing gearbox)	e078	Exponential increasing
Gear fault	g057	Abrasive Wear (bearing gearbox)	e079	Linear increasing

Tooth wear (gears)	g058	Pitting (bearing gearbox)	e080	Constant
Offset of teeth gears	g059	Deformation of face & rolling element (bearing gearbox)	e081	Linear increasing
High speed shaft fault	g060	Oil filtration (gearbox)	e082	Constant
Critical brake failure	g061	Particle contamination (gearbox)	e083	Exponential increasing
High speed structural damage	g062	Overheating gearbox	e084	Linear increasing
Wear of high speed shaft	g063	Abnormal vibration E	e085	Periodic
Brake failure	g064	Eccentricity (gear)	e086	Constant
Abnormal signals B	g065	Pitting (gear)	e087	Linear increasing
Hydraulic brake system fault	g066	Cracks in gears	e088	Exponential increasing
Abnormal signals C	g067	Gear tooth deterioration	e089	Exponential increasing
Overheating brake	g068	Poor design of teeth gears	e090	Periodic
		Tooth surface defects	e091	Constant
		Abnormal vibration J	e092	Constant
		Cracks in high speed shaft	e093	Linear increasing
		Imbalance (high speed shaft)	e094	Periodic
		Overheating (high speed shaft)	e095	Exponential increasing
		Spalling (high speed shaft)	e096	Constant
		Abrasive wear (high speed shaft)	e097	Linear increasing
		Pitting (high speed shaft)	e098	Constant
		Cracks in brake disk	e099	Exponential increasing
		Motor brake fault	e100	Constant
		Oil leakage (hydraulic brake)	e101	Linear increasing
		Over pressure (hydraulic brake)	e102	Constant
		Abnormal speed	e103	Linear increasing
		T sensor error (brake)	e104	Periodic
		T above limit	e105	Periodic

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