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DOI:

[10.1016/j.renene.2015.09.038](https://doi.org/10.1016/j.renene.2015.09.038)

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Document Version

Peer reviewed version

Citation for published version (Harvard):

García Márquez, FP, Pinar Pérez, JM, Marugán, AP & Papaelias, M 2016, 'Identification of critical components of wind turbines using FTA over time', *Renewable Energy*, vol. 87, no. 2, pp. 869-883.
<https://doi.org/10.1016/j.renene.2015.09.038>

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Checked Jan 2016

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1 Identification of critical components of wind 2 turbines using FTA over time

3
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14 **Abstract:** Wind energy is currently the most widely implemented renewable
15 energy source in global scale. Complex industrial multi-MW wind turbines are
16 continuously being installed both onshore and offshore. Projects involving utility-
17 scale wind turbines require optimisation of reliability, availability, maintainability
18 and safety, in order to guarantee the financial viability of large scale wind
19 energy projects, particularly offshore, in the forthcoming years. For this reason,
20 critical wind turbine components must be identified and monitored as cost-
21 effectively, reliably and efficiently as possible. The condition of industrial wind
22 turbines can be qualitatively evaluated through the Fault Tree Analysis (FTA).
23 The quantitative analysis requires high computational cost. In this paper, the
24 Binary Decision Diagram (BDD) method is proposed for reducing this
25 computational cost. In order to optimise the BDD a set of ranking methods of
26 events has been considered; Level, Top-Down-Left-Right, AND, Depth First
27 Search and Breadth-First Search. A quantitative analysis approach in order to
28 find a general solution of a Fault Tree (FT) is presented. An illustrative case
29 study of a FT of a wind turbine based on different research studies has been
30 developed. Finally, this FT has been solved dynamically through the BDD
31 approach in order to highlight the identification of the critical components of the
32 wind turbine under different conditions, employing the following heuristic
33 methods: Birnbaum, Criticality, Structural and Fussell-Vesely. The results
34 provided by this methodology allow the performance of novel maintenance
35 planning from a quantitative point of view.
36

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

39 1 Introduction

40

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

50

51 Blanco [2] showed that the Operation and Maintenance (O&M) costs can be
52 20%–30% of the total Level Cost of Electricity (LCOE) over the project's
53 lifetime. Although larger turbines may reduce the O&M costs per unit power,
54 the cost per failure increases due to the combined cost associated with
55 emergency corrective maintenance and loss of production during downtime [3].
56 By employing a suitable Condition Monitoring (CM) technique, many faults can
57 be detected and controlled under operational conditions. Early detection of
58 incipient faults prevents major component failures and allows for the
59 implementation of predictive repair strategies [4]. Therefore, appropriate actions
60 can be planned in time to prevent major failures which in the case of corrective
61 maintenance procedures would result in significant O&M costs and downtimes.
62 CM techniques provide useful information that support operational efficiency
63 and contribute to the improvement of new turbine designs.

64

65 Some components fail earlier than intended by their design and cause
66 unscheduled downtimes which reduce the productivity of the wind farm.
67 Condition Monitoring Systems (CMS) can contribute to the improved operational
68 control of the critical components [5], [6] and [7]. CM techniques, such as
69 vibration and oil analysis, acoustic emission, temperature measurement, etc.,
70 together with advanced signal processing methods and data trending, provide
71 continuous information regarding the status of the component being monitored
72 [8] and [9]. CM techniques are used to collect the main functional parameters of
73 critical components, such as the gearbox, generator, main bearings, blades,
74 tower, etc. [10]. This paper presents a novel approach for determining the
75 critical components of any WT in different conditions based on a real case
76 study. The results reported herewith support the optimisation of CM design and
77 investment. For this purpose a method based on fault tree analysis (FTA) that
78 allows qualitative analysis is presented. Quantitative Fault Tree Analysis (FTA)
79 is performed by employing Binary Decision Diagrams (BDDs). In section 2 are
80 presented the FTAs, BDDs, the conversion from FTA to BDD and some
81 experiments to test and verify the approach. In section 3, importance measures
82 for the Fault Tree (FT) have been presented and tested in order to identify the
83 events that are more important for the fault of the top event. Finally, in section 4,
84 a case study of an FT for a WT has been developed considering large research
85 studies and analysed qualitatively and quantitatively, where the main results are
86 presented in section 5. The main components of WTs and their relationship

87 have been set taking into account the comments of industrial experts involved in
88 the European Projects NIMO [11] and OPTIMUS [12]. The critical components
89 have been set according to different scenarios. This study will be a useful
90 reference for those involved in the optimisation of the design of the CMS and
91 therefore the investment required.

92

93 **2 Reliability analysis**

94

95 *2.1 Fault tree analysis and binary decision diagrams*

96

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

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

113

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

121

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

128

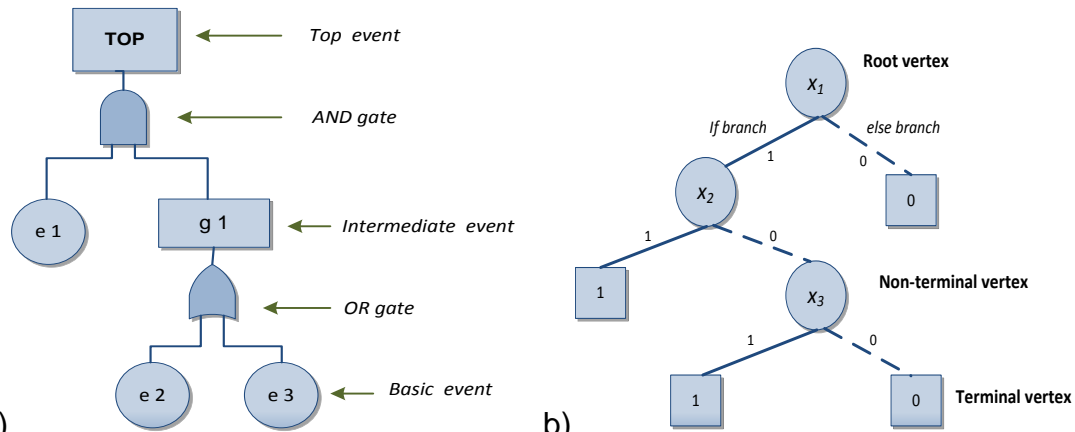


Figure 1. Structure of: a) FTs; b) BDDs

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2.2 Conversion from FTA to BDD

132

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

141

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

147

2.3 Rankings for Events

148

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

150

- 151 • The “Top-Down-Left-Right” (TDLR) method generates a ranking of the
152 events by ordering them from the original FT structure in a top-down and
153 then left-right manner [18]. The listing of the events is initialized, at each
154 level, in a left to right path adding the basic events found in the ordering
155 list. In the case that an event had been considered previously and
156 located higher up then it is ignored.
- 157 • The “Depth First Search” (DFS) approach goes from top to down of a
158 root and each sub-tree from left to right. This procedure is a non-
159 recursive implementation and all freshly expanded nodes are added as
160 last-input last-output process [19].
- 161 • The “Breadth-First Search” (BFS) algorithm orders all the basic events
162 obtained, expanding from the standpoint by the first-input first-output
163

164

- 165 procedure. The events not considered are added in a queue list named
 166 “open”, where they are being taken into account in the procedure, and
 167 the list is recalled “closed” list when the all the events are studied [20].
- 168 • The “Level” method creates a ranking of the events according to their
 169 level. The level of any event is understood as the number of the gates
 170 that is higher up a tree until the top event. In case that two or more
 171 events have the same level, the event which will have highest priority is
 172 the one appearing earlier in the tree [21].
 - 173 • The “AND” criterion states that the importance of the basic event is
 174 based on “and” gates located between the k event and the top event as
 175 these gates imply redundancies in the FTA systems [13]. Basic events
 176 with the highest number of “AND” gates will be ranked at the end. In case
 177 of duplicated basic events, the event with less “AND” gates has
 178 preference. Finally, basic events with the same number of “AND” gates
 179 can be ranked using the TDLR method.

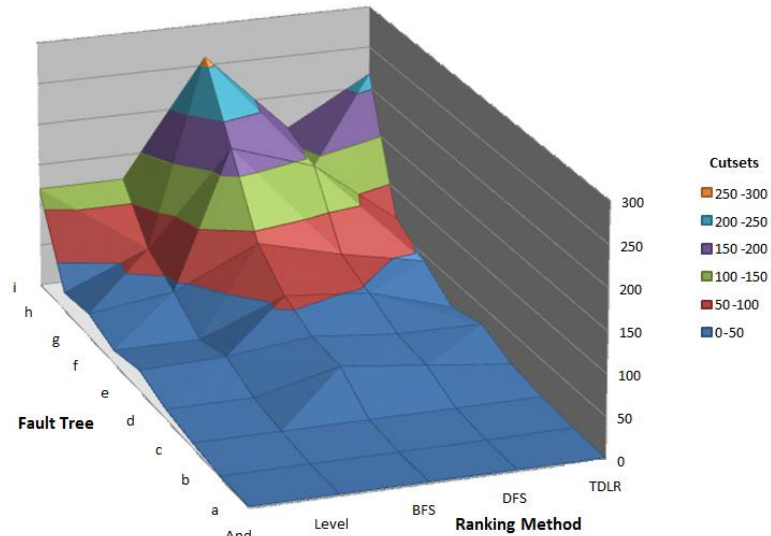
181 A set of FTs have been considered in order to test the ranking obtained by the
 182 methods aforementioned and are presented in Table 1. Different sizes of trees
 183 and structures (number of “AND” and “OR” gates, and levels) have been
 184 considered.

185
 186 The Level, TDLR, AND, DFS and BFS methods have been employed and
 187 analysed together regarding to the C-Ss number obtained by the BDD of the
 188 FTs showed in Table 1. If the size of C-Ss increases, then the computational
 189 time required for calculating the probability of the top event rises. The numbers
 190 of C-Ss of the FTs are shown in Figure 2. BFS generates generally poor results,
 191 especially when the FT has a high number of events, levels and “or” and “and”
 192 gates. Otherwise, the Level and AND methods generate small number of C-Ss.
 193 The conclusions regarding to Level, DFS and TDLR approach should be
 194 studied for each FT.

195 **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

196



197
198 **Figure 2. Numbers of C-Ss given by AND, Level, BFS, DFS and TDLR methods**
199

200 **3 Importance Measures**
201

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

- 208
- 209 • Birnbaum introduces a measure of importance of a FTA based on the
210 probability caused to the fault of the system by each component k [2].
 - 211 • The Criticality importance measure considers the fault probability of an
212 event [22].
 - 213 • A new index based on the theoretical development completed by
214 Birnbaum is defined by Lambert [22] in order to define the Structural
215 method.
 - 216 • The IM of Fussell-Vesely of any event is given by the conditional
217 probability that at least one minimal C-S that contains component i ,
218 considering that the system is failed [23]. This measurement considers
219 the highest importance to the largest probability of being the cause of the
220 system failure [24].

221
222 The FT example showed in Figure 3 is used to test the different IM methods.
223

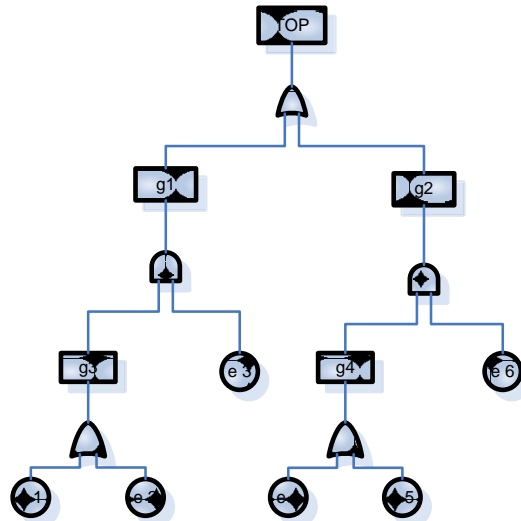


Figure 3. FTA Example

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

233
234

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

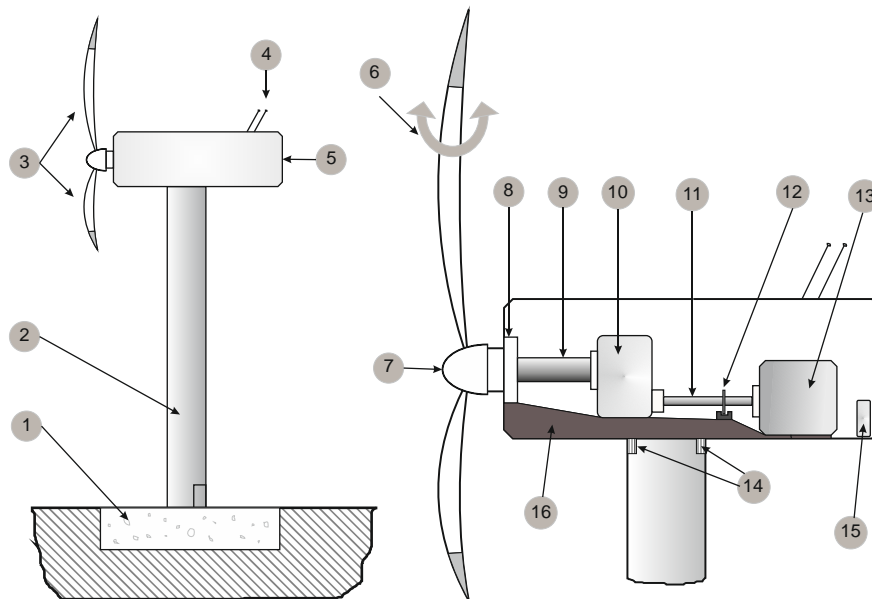
Events	Birnbaum	Criticality	Structural	Fusell-Vesely
e_1	0.010	0.249	0.094	0.505
e_2	0.010	0.249	0.094	0.254
e_3	0.020	0.500	0.281	1.000
e_4	0.010	0.249	0.094	0.500
e_5	0.010	0.249	0.094	0.249
e_6	0.020	0.500	0.281	1.000

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4 FTA for WTs

239 The main components of the WTs are illustrated in Figure 4. The blades,
240 connected to the rotor via the hub, are moved by the wind blowing on them. The
241 rotor transmits the mechanical energy via the low speed shaft through the
242 gearbox to the high speed shaft, ending in the generator. The low speed shaft is
243 supported by the main bearing. The alignment to the direction of the wind is
244 controlled by a yaw system that turns the housing (or “nacelle”) for that purpose.
245 The nacelle is mounted at the top of a tower, and the tower is assembled on a
246 base or foundation. The pitch system in each blade is a mechanism that turns
247 the blade to control the wind power captured. This can be employed as an
248 aerodynamic brake as well as for increasing the efficiency of power production.
249 The WT has also a hydraulic brake to stop the WT. The meteorological unit, or

250 weather station, provides the weather data (e.g. wind speed and direction) to
 251 the control system. The data from the meteorological unit provide the required
 252 information for controlling effectively the pitch system, brake, yaw, etc.
 253



254

255 **Figure 4. Components of the WT: 1-Base/Foundations; 2-Tower; 3-Blades; 4-**
 256 **Meteorological unit (vane and anemometry); 5-Nacelle; 6-Pitch system; 7-Hub;**
 257 **8-Main bearing; 9- Low speed (main) shaft; 10-Gearbox; 11- High speed shaft;**
 258 **12-Brake system; 13-Generator; 14-Yaw system, 15-Converter, 16-Bedplate.**
 259 **N.B. Drive train = 9+11.**
 260

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

268

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

271 **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
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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

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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).

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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].

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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.

295
296

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]	
Electrical components	High speed train failure	
	<table border="1"> <tr> <td>Shaft [29][33][46]</td> </tr> <tr> <td>Critical brake failure [29][51]</td> </tr> </table>	Shaft [29][33][46]
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]	

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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.

302 4.1 Foundation and Tower

303

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

312

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

323

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

328

329 On the top of the tower, the yaw system turns the nacelle in an optimum angle
330 with respect to the wind direction. Powered by electromechanical or hydraulic
331 mechanisms (in this paper the electromechanical mechanism is considered),
332 the yaw systems can seize to operate due to the failure of the yaw motor or the
333 meteorological unit failure [33] resulting in a wrong yaw angle. Structural failures
334 could appear when the yaw motor is damaged or it does not have power supply
335 [57], in addition to extreme wind speed or turbulences and some structural
336 faults. These structural failures can cause the collapse of the tower [27]. Design

337 load cases (DLC) must be taken into account for different design situations and
 338 wind or other conditions. The IEC 61400-1 relative to design requirements for
 339 wind turbines shows some DLCs that shall be considered as minimum [62]. For
 340 example, the event e012 (High wind speed/ turbulence) will occur when DLCs
 341 are exceeded. Table 5 presents the basic and intermediate events for the FT of
 342 the foundation and tower illustrated in Figure 5.

343

344

345

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

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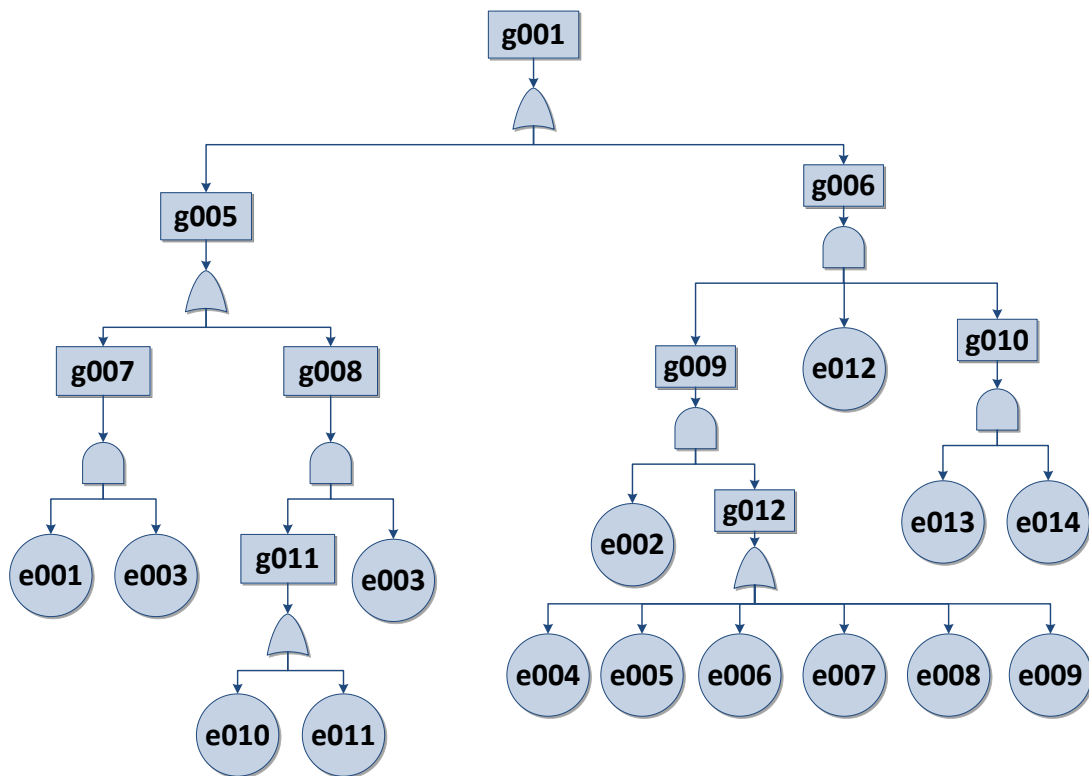


Figure 5. Fault tree of the foundation and tower

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4.2 Blade System

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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].

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

381

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

388

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

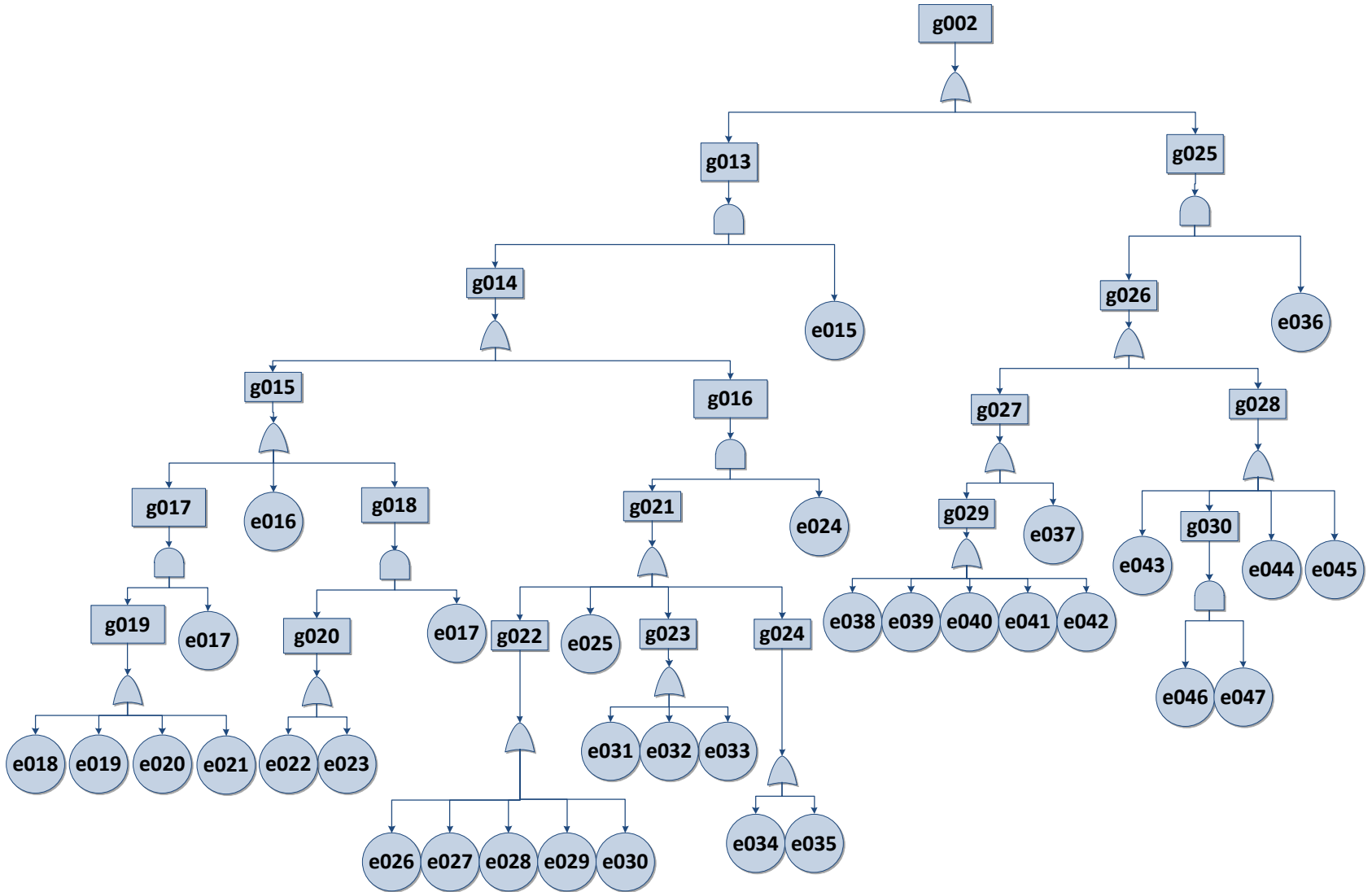


Figure 6. Fault tree of the blades

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393 **4.3 Generator, electrical and electronic components**

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

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

415 **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 T ^a 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

416
 417 Figure 7 presents the FT for the main elements of the generator, electrical and
 418 electronic components given in Table 7.
 419

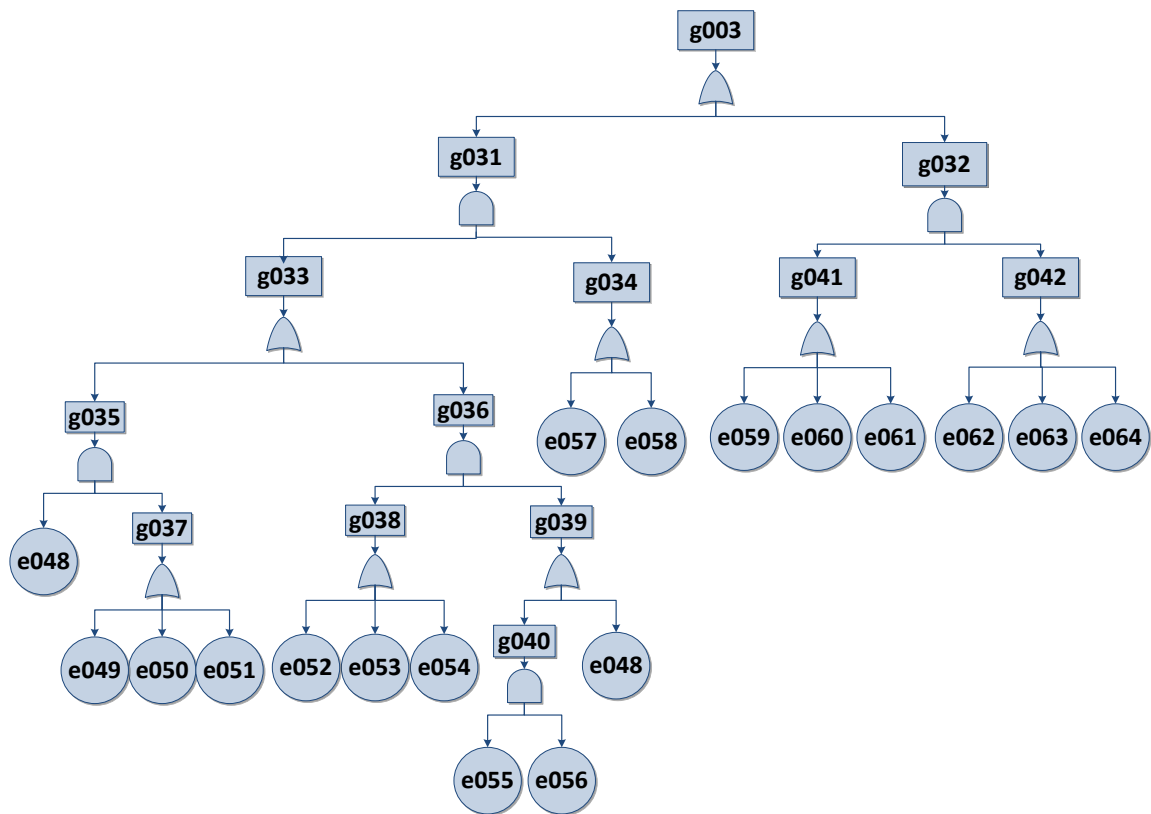


Figure 7. Fault tree of the generator, electrical and electronic components

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,

445 gear eccentricity, gear tooth deterioration, offset or other potential faults [41]
446 and [33].

447

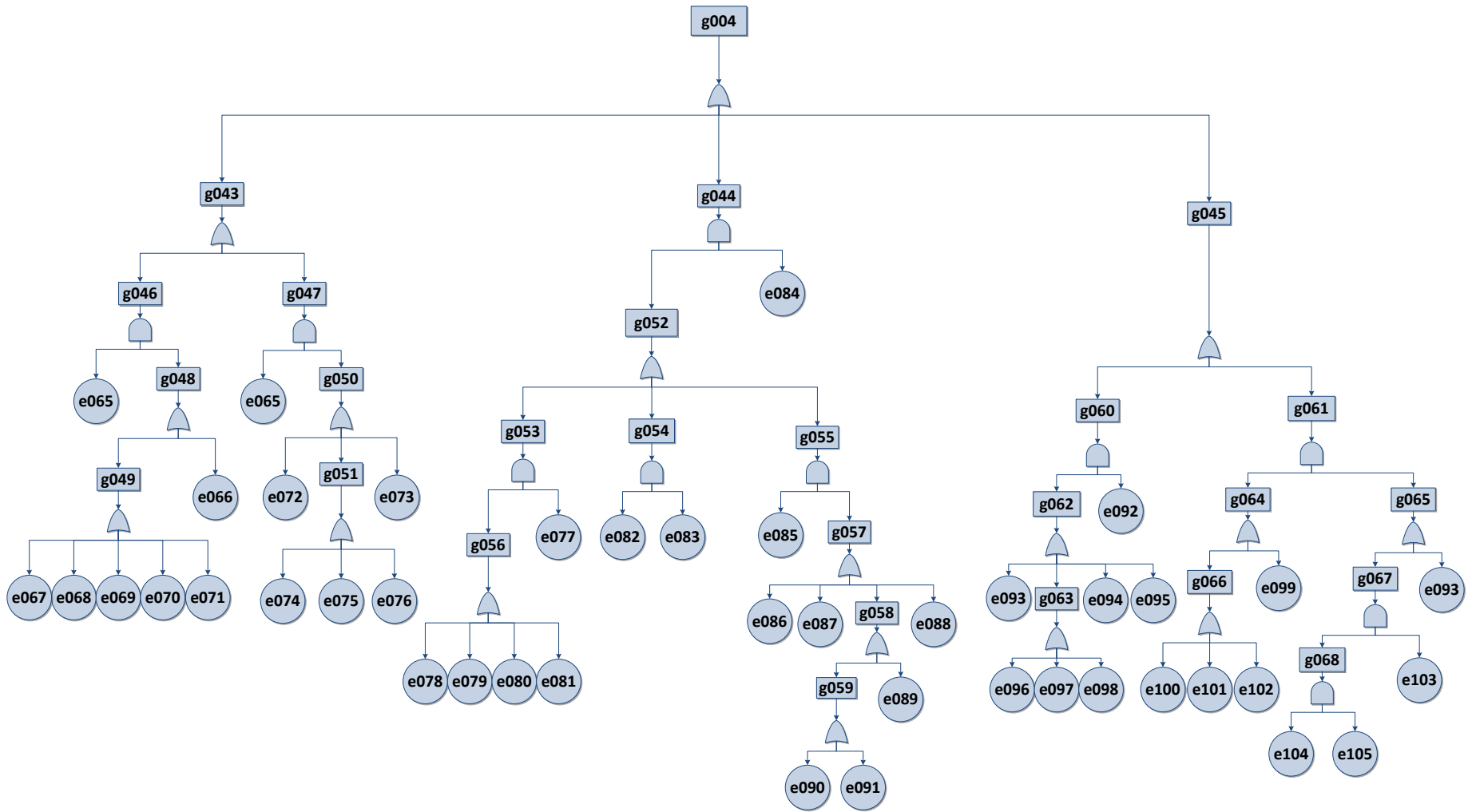
448 Overheating can appear in shafts due to the rotational movement of the high
449 speed train. The wear and fatigue, that can initiate cracks [33] and mass
450 imbalance [46], are the principal source of failures in the high speed shaft. The
451 main failure causes of brakes are overpressure or oil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

454

455

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
		T ^a sensor error (brake)	e104
		T ^a above limit	e105



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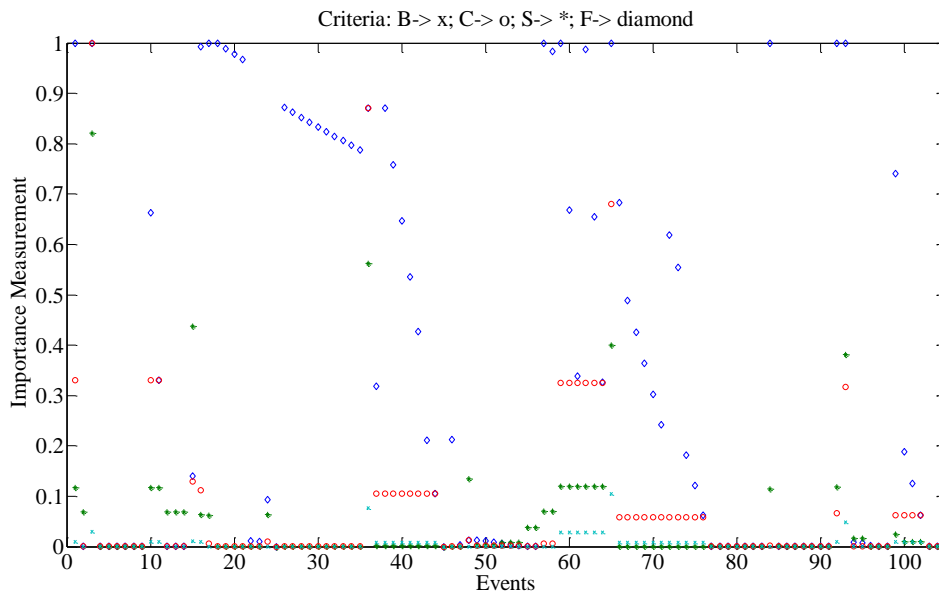
Figure 8. Fault tree for the power train.

460 **5 Results**

461

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

475



476

477 **Figure 9. Importance measures for the WT.**

478

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

488

I. *Constant probability*

489

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

490

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

491

II. *Exponential increasing probability*

492 In this model, probability function assigned is:
 493 $P(t) = 1 - e^{-\lambda t}$, where λ is a parameter that takes only positive values
 494 and determines the rising velocity of the probability.

495 *III. Linear increasing probability*

496 In this model, probability function is:
 497 $P(t) = mt$, where m determines the rising velocity of the probability.

498 *IV. Periodic probability*

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

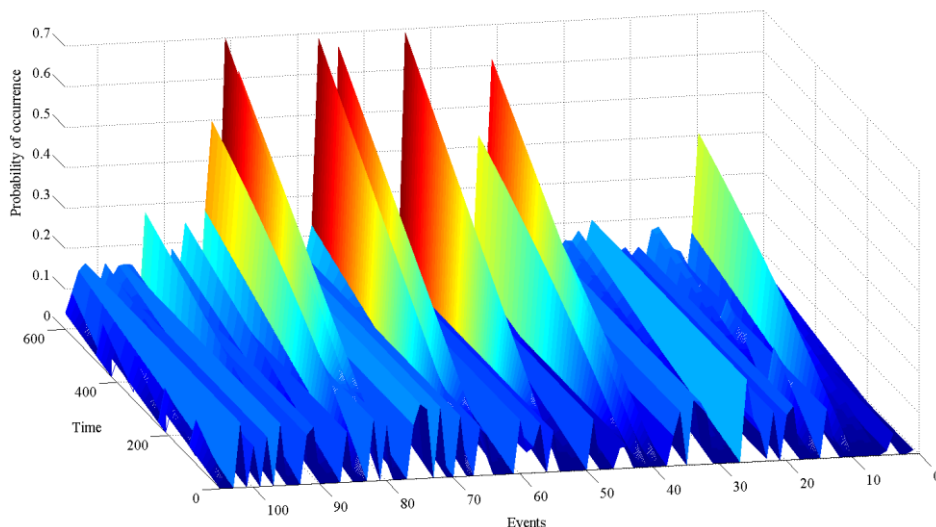
501 $P(t) = 1 - e^{-\lambda(t-n\alpha)}$, $n=1, 2, 3\dots$

502 where:

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

506
 507 The Appendix I shows the fault probability functions assumed for each event.
 508 The experiences of wind turbine operators involved in the NIMO [11] and
 509 OPTIMUS FP7 European projects [12] have been considered in order to set the
 510 parameters of the time-dependent probability functions. The main purpose of
 511 this study is to show an example as close to reality as possible. This model
 512 could be adjusted to the specific wind turbine analysed, or to specific
 513 components.

514
 515 Figure 10 shows the failure probability assigned to each event throughout time.
 516 This probability has been obtained for 600 samples where each sample
 517 represents one day. The events of the FT have different behaviours according
 518 to their nature and the values of their parameters.
 519



520
 521 **Figure 10. Probabilities of occurrence of the events over the time.**
 522

523 Figure 11 presents the probability of failure of the wind turbine ($Q_{sys}(t)$) over
 524 the time. It is not continuously rising because there are events involved in
 525 preventive maintenance tasks, defined in Appendix I as periodic functions.

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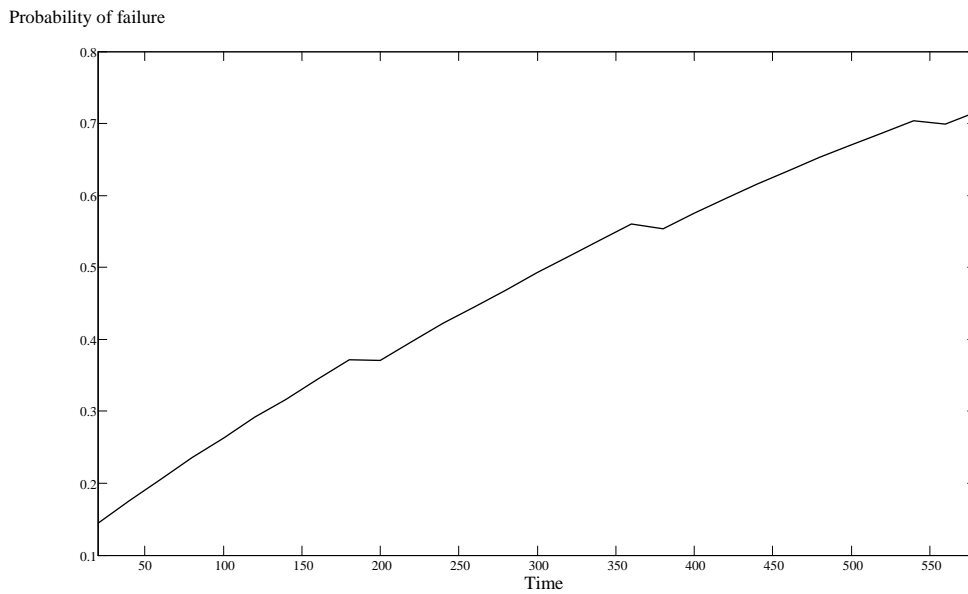
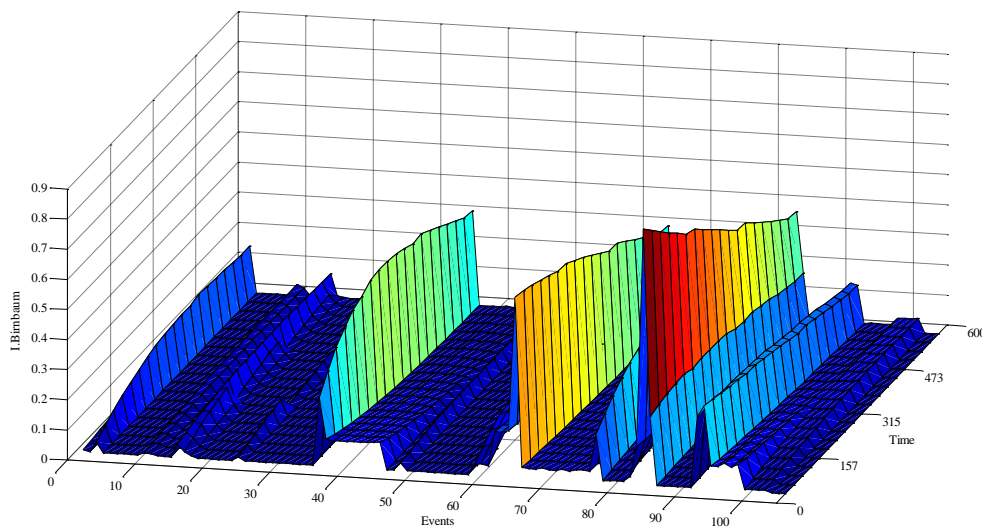


Figure 12 shows the IMs employing the methods Birnbaum (B), described in Section 3 and applied to the FT above depicted. The events e084, e036, e065 have the highest IM according to the Birnbaum criterion over the time, these events should be studied in detail because the method provide a large IM value. 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.



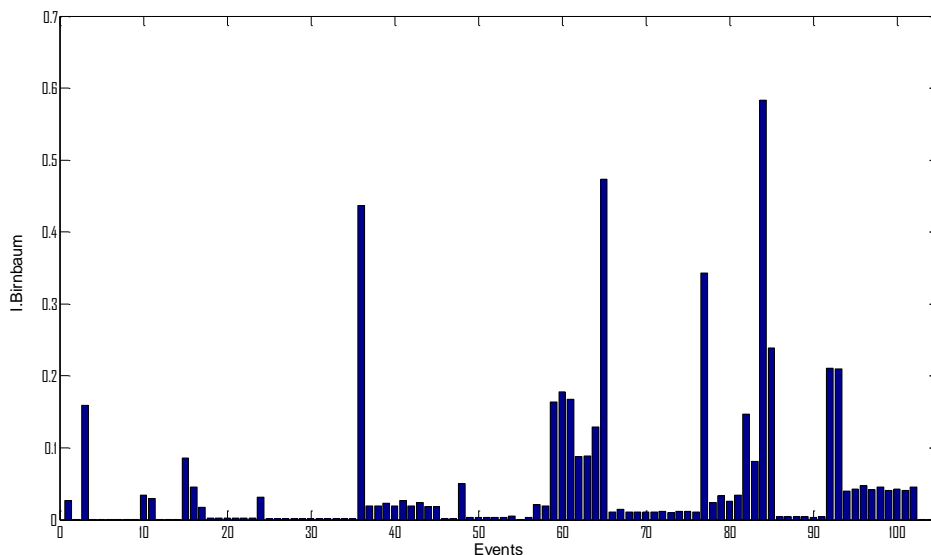
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Figure12. Birnbaum importance over the time.

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

559 Therefore, scheduled maintenance strategies can be implemented more
560 effectively. The behaviour of the system over time allows operators to obtain
561 optimal maintenance decisions since identified components can be repaired or
562 replaced based on their effect on the global system.
563

564 For example, let the maximum allowable probability of system failure be 0.5.
565 (Figure 11 shows that this value is reached at the 300th sample). It is ensured
566 that the unavailability of the system is normal until the mentioned sample, and it
567 is required the maintenance tasks before reaching that value. Once the system
568 is in the critical iteration in which the maximum allowable unavailability is
569 reached, it is necessary to act upon the components in order to reduce the
570 failure system probability. Figure 12 provides useful information about how to
571 focus the efforts to reduce such probability. Figure 13 corresponds to a cross
572 section of Figure 12 and it shows the Birnbaum I.M. of the events at the 300th
573 sample.
574



575
576 **Figure13. Birnbaum importance in a certain time.**
577

578 According to Figure 13, the most relevant information is the ranking of events
579 that can be gathered from the Birnbaum I.M. The first three events that should
580 be taken into account to plan a maintenance strategy are the events e084,
581 e065, e036, i.e. corresponding to overheating gearbox, and abnormal
582 vibrations.
583

584 **6 Conclusions**

585
586 The condition of the WTs is analysed in this paper using an FT-based
587 approach. The qualitatively FTA requires a high computational cost. In this work
588 the BDD is used for the quantitatively FTA and reducing the computational cost.
589 The cut sets (combination of basic events whose simultaneous occurrence
590 causes the top event to happen) generated by BDD will depend on the events

591 ordering. The “Level”, “Top-Down-Left-Right”, “AND”, “Depth-First Search” and
592 “Breadth-First Search” methods have been considered for listing the events,
593 and a comparative analysis of them has been done. The Level and AND
594 methods create the listing of the events that provide a reduced number of cut
595 sets. The Level, Depth-First Search and Top-down-Left-Right methods should
596 be studied for each FT. Finally, the Breadth-First Search is the ordering method
597 that provides a higher number of C-Ss. Importance measures for the FT have
598 been also considered. They are used to identify the critical events that are more
599 important for optimizing the condition monitoring system. A set of experiments
600 are carried out for testing the importance measures, finding that all the
601 approaches used give similar solution.

602
603 An illustrative FT example for a WT has been developed. It is very important to
604 mark that the FTs for the main components of the WT could be simplified or
605 extended, but the authors, following the opinion of the experts and the research
606 works considered, have set them in order to show the most relevant events.
607 The importance measures were calculated and studied by a novel FT dynamic
608 analysis that allows using the information for performing diagnostics and
609 prognostics tasks and planning maintenance strategies.

610

611 **Acknowledgements**

612 The work reported herewith has been financially supported by the European
613 Commission under the European FP7 Projects Demonstration of Methods and
614 Tools for the Optimisation of Operational Reliability of Large-Scale Industrial
615 Wind Turbines, OPTIMUS project, (OPTIMUS, Ref.:FP-7-Energy-2012-TREN-
616 1:322430, www.optimusfp7.eu), and the Spanish Ministerio de Economía y
617 Competitividad, under Research Grant DPI2012-31579.

Appendix I. Probability distributions for the events

FT 1 Foundation and Tower Failure				Probabilistic model assignment	
intermediate event	code	final event	code	assignment	model
Yaw system failure	q005	Yaw motor fault	e001	Constant	
Structural failure	q006	Abnormal vibration I	e002	Linear increasing	
Yaw motor failure	q007	Abnormal vibration H	e003	Linear increasing	
Wrong yaw angle	q008	Cracks in concrete base	e004	Constant	
Severe structural failure (foundation and tower)	q009	Welding damage	e005	Constant	
No electric power for yaw motor	q010	Corrosion	e006	Linear increasing	
Meteorological unit failure	q011	Loosen studs in joining foundation and first section	e007	Linear increasing	
Structural fault (foundation and tower)	q012	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	assignment	model
Severe blade failure	q013	High wind speed / turbulence	e015	Periodic	
Blade failure	q014	Blade angle asymmetry	e016	Exponential increasing	
Pitch system failure	q015	Abnormal vibration A	e017	Exponential increasing	
Structural failure of blades	q016	Hydraulic motor failure	e018	Exponential increasing	
Hydraulic system failure	q017	Leakages in hydraulic system	e019	Constant	
Wrong blade angle	q018	Over pressure in hydraulic system	e020	Constant	
Hydraulic system fault	q019	Corrosion in hydraulic system	e021	Exponential increasing	
Meteorological unit failure	q020	Vane damage	e022	Constant	
Structural fault of blades	q021	Anemometer damage	e023	Constant	
Leading and trailing edges damage	q022	Abnormal vibration B	e024	Constant	
Shell damage	q023	Root Cracks in the structure of blades	e025	Constant	
Tip damage	q024	Cracks in edges of blades	e026	Constant	
Rotor system failure	q025	Erosion in edges of blades	e027	Exponential increasing	
Rotor system fault	q026	Delamination in leading edges of blades	e028	Exponential increasing	
Rotor bearings fault	q027	Delamination in trailing edges of blades	e029	Exponential increasing	
Rotor hub fault	q028	Debonding in edges of blades	e030	Exponential increasing	
Wear in bearings of the rotor	q029	Delamination in shell	e031	Exponential increasing	
Imbalance of blade system	q030	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	assignment	model
Critical generator failure	q031	Abnormal vibration G	e048	Exponential increasing	
Power electronics and electric controls failure	q032	Cracks	e049	Constant	
Mechanical failure (generator)	q033	Imbalance	e050	Exponential increasing	
Electrical failure (generator)	q034	Asymmetry	e051	Exponential increasing	
Bearing generator failure	q035	Air-Gap eccentricities	e052	Linear increasing	
Rotor and stator failure	q036	Broken bars	e053	Linear increasing	
Bearing generator fault	q037	Dynamic eccentricity	e054	Linear increasing	
Rotor and stator fault	q038	Sensor T error	e055	Constant	
Abnormal signals A	q039	Temperature above limit	e056	Periodic	
Overheating generator	q040	Short circuit (generator)	e057	Constant	
Electrical fault (power electronics)	q041	Open circuit (generator)	e058	Constant	
Mechanical fault (power electronics)	q042	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	assignment	model
Low speed train failure	q043	Abnormal vibration D	e065	Constant	
Critical gearbox	q044	Cracks in main bearing	e066	Constant	
High speed train failure	q045	Spalling in main bearing	e067	Linear increasing	
Main bearing failure	q046	Corrosion of pins in main bearing	e068	Linear increasing	
Low speed shaft failure	q047	Abrasive wear in main bearing	e069	Constant	
Main bearing fault	q048	Deformation of face & rolling element (main bearing)	e070	Linear increasing	
Wear in main bearing	q049	Pitting (main bearing)	e071	Exponential increasing	
Low speed shaft fault	q050	Imbalance of low speed shaft	e072	Constant	
Wear in low speed shaft	q051	Cracks in low speed shaft	e073	Linear increasing	
Gearbox failure	q052	Spalling (low speed shaft)	e074	Constant	
Bearings (gearbox)	q053	Abrasive wear in low speed shaft	e075	Constant	
Lubrication of the gearbox	q054	Pitting (low speed shaft)	e076	Constant	
Gear failure	q055	Abnormal vibration F	e077	Linear increasing	
Wear bearing gearbox	q056	Corrosion of pins (bearing gearbox)	e078	Exponential increasing	
Gear fault	q057	Abrasive Wear (bearing gearbox)	e079	Linear increasing	

Tooth wear (gears)	q058	Pitting (bearing gearbox)	e080	Constant
Offset of teeth gears	q059	Deformation of face & rolling element (bearing gearbox)	e081	Linear increasing
High speed shaft fault	q060	Oil filtration (gearbox)	e082	Constant
Critical brake failure	q061	Particle contamination (gearbox)	e083	Exponential increasing
High speed structural damage	q062	Overheating gearbox	e084	Linear increasing
Wear of high speed shaft	q063	Abnormal vibration E	e085	Periodic
Brake failure	q064	Eccentricity (gear)	e086	Constant
Abnormal signals B	q065	Pitting (gear)	e087	Linear increasing
Hydraulic brake system fault	q066	Cracks in gears	e088	Exponential increasing
Abnormal signals C	q067	Gear tooth deterioration	e089	Exponential increasing
Overheating brake	q068	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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620 **References**

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622 [1] F.P. García Márquez, A. Tobias, M. Papaelias and J.M. Pinar Pérez.
623 Condition Monitoring of Wind Turbines: Techniques and Methods.
624 Renewable Energy 2012; 46:169-78.

625 [2] M.I. Blanco. The economics of wind energy, Renewable and Sustainable
626 Energy Reviews 2009; 13:1372–82.

627 [3] F. Spinato, P.J. Tavner, G.J.W. van Bussel, E. Koutoulakos. IET Reliability of
628 WT subassemblies. Renewable Power Generation 2009; 3(4):387-401.

629 [4] D.J. Pedregal, F.P. García Márquez, C. Roberts. An Algorithmic Approach for
630 Maintenance Management. Annals of Operations Research 2009; 166:109-
631 24.

632 [5] F.P. Garcia Marquez. An Approach to Remote Condition Monitoring Systems
633 Management. The IET International Conference on Railway Condition
634 Monitoring 2006; 156-160.

635 [6] F.P. Garcia Marquez, C. Roberts and A. Tobias. Railway Point Mechanisms:
636 Condition Monitoring and Fault Detection. Proceedings of the Institution of
637 Mechanical Engineers, Part F, Journal of Rail and Rapid Transit.
638 Professional Engineering Publishing 2010; 224(1):35-44.

639 [7] F.P. Garcia Marquez, D.J. Pedregal and C. Roberts. Time Series Methods
640 Applied to Failure Prediction and Detection. Reliability Engineering & System
641 Safety 2010; 95(6):698-703.

642 [8] F.P. García Márquez, A. Tobias, M. Papaelias and J.M. Pinar Pérez.
643 Condition Monitoring of Wind Turbines: Techniques and Methods.
644 Renewable Energy 2012; 46:169-78.

645 [9] G. Giebel, G. Oliver, M. Malcolm, B. Kaj. Common Access to Wind Turbines
646 Data for Condition Monitoring. Riso National Laboratory. In Proceedings of
647 the 27th Riso international symposium on material science; 2006, Denmark;
648 p. 157-64.

649 [10] F.P. García Márquez, V. Singh, M. Papaelias. A Review of Wind Turbine
650 Maintenance Management Procedures. The Eighth International Conference
651 on Condition Monitoring and Machinery Failure Prevention Technologies;
652 2011, Cardiff, United Kingdom; p.1-14.

653 [11] Development and Demonstration of a Novel Integrated Condition
654 Monitoring System for Wind Turbines, NIMO project. (NIMO, Ref.:FP7-
655 ENERGY-2008-TREN-1: 239462). www.nimoproject.eu. (accessed 30
656 January 2012)

657 [12] Demonstration of Methods and Tools for the Optimisation of Operational
658 Reliability of Large-Scale Industrial Wind Turbines, OPTIMUS project.
659 (OPTIMUS, Ref.: FP-7-Energy-2012-TREN-1: 322430).
660 www.optimusproject.eu (accessed 25 February 2014)

- 661 [13] M. Xie, K.C. Tan, K.H. Goh and X.R. Huang. Optimum Prioritisation and
662 Resource Allocation Based on Fault Tree Analysis. *International Journal of*
663 *Quality & Reliability Management* 2000; 17(2):189-99.
- 664 [14] C.Y. Lee. Representation of switching circuits by binary decision
665 diagrams. *Bell System Technology* 1959; 38:985-99.
- 666 [15] S.B. Akers. Binary Decision Diagrams, *IEEE Transactions on Computing*
667 1978; 27:509-16.
- 668 [16] B. M. E. Moret. Decision Trees and Diagrams. *Computing Surveys* 1982;
669 14:413-6.
- 670 [17] R.E. Bryant. Graph-based algorithms for Boolean functions using a
671 graphical representation, *IEEE Transactions on Computing* 1986; C-
672 35(8):677-91.
- 673 [18] L.M. Bartlett. Progression of the Binary Decision Diagram Conversion
674 Methods. *Proceedings of the 21st International System Safety Conference*;
675 August 4-8, 2003, Ottawa, Westin Hotel; p 116-25.
- 676 [19] T.H. Cormen, C. E. Leiserson, R. L. Rivest and C. Stein. *Introduction to*
677 *Algorithms*, Second Edition. MIT Press and McGraw-Hill. Section 22.3:
678 Depth-first search; 2001, p.540–9. ISBN 0-262-03293-7.
- 679 [20] Jensen R., and Veloso M. M. OBDD-Based Universal Planning for
680 Synchronized Agents in Non-Deterministic Domains. *Journal of Artificial*
681 *Intelligence Research* 2000; 13:189–226.
- 682 [21] S. Malik, A.R. Wang, R.K. Brayton, A. S. Vincentelli. Logic Verification
683 using Binary Decision Diagrams in Logic Synthesis Environment. In
684 *Proceedings of the IEEE International Conference on Computer Aided*
685 *Design, ICCAD'88*; 1988, Santa Clara CA, USA, p. 6–9.
- 686 [22] H.E. Lambert. Measures of importance of events and cut sets. *Reliability*
687 *and Fault Tree Analysis*. SIAM; 1975, p.77-100.
- 688 [23] J.B. Fussell. How to Hand Calculate System Reliability and Safety
689 Characteristics. *IEEE Transactions on Reliability* 1975; R-24(3).
- 690 [24] T. Mankamo, K. Pörn, J. Holmberg (1991). Uses of risk importance
691 measures. Technical report, Technical Research Centre of Finland,
692 Research notes 1245. Espoo 1991. ISBN 951-38-3877-3, ISSN 0358-5085.
- 693 [25] H. Arabian-Hoseynabadi, H. Oraee and P.J. Tavner. Failure Modes and
694 Effects Analysis (FMEA) for Wind Turbines. *International Journal of Electrical*
695 *Power and Energy Systems* 2010; 32(7):817-24.
- 696 [26] RELIAWIND project. European Union's Seventh Framework Programme
697 for RTD (FP7). <http://www.reliawind.eu/> (accessed 22 January 2014)
- 698 [27] J.-S. Chou and W.-T. Tu. Failure analysis and risk management of a
699 collapsed large wind turbine tower. *Engineering Failure Analysis* 2011;
700 18:295-313.

- 701 [28] International Electrotechnical Commission. IEC 61400-1 3rd edition
702 2005-08 Wind turbines - Part 1: Design requirements, 2005.
- 703 [29] C.C. Ciang, J.R. Lee and H.-J. Bang. Structural health monitoring for a
704 WT system: a review of damage detection methods. *Measurement Science*
705 *and Technology* 2008; 19:22.
- 706 [30] K.A. Stol, Disturbance tracking control and blade load mitigation for
707 variable speed wind turbines, *Journal Solar Energy Engineering* 2003;
708 125:396-401.
- 709 [31] Caithness Windfarm Information Forum 1 January 2012. Summary of WT
710 Accident data to 31st December 2011. <http://www.caithnesswindfarms.co.uk/>
711 (accessed 30 January 2012)
- 712 [32] N.Cotton, Jenkins and K. Pandiaraj. Lightning Protection for WT Blades
713 and Bearings. *Wind Energy* 2001; 4:23–37.
- 714 [33] Z. Hameed, Y.S. Hong, Y.M. Cho, S.H. Ahn and C.K. Song. Condition
715 monitoring and fault detection of WTs and related algorithms: A review.
716 *Renewable and Sustainable Energy Reviews* 2009; 13:1-39.
- 717 [34] W.J. Padgett. A multiplicative damage model for strength of fibrous
718 composite materials. *IEEE Transactions on Reliability* 1998; 47:46-52.
- 719 [35] Z. W. Birnbaum. On the Importance of Different Components in a
720 Multicomponent System, *Multivariate Analysis*; 1969, p. 581-92.
- 721 [36] E.R. Jørgensen, K. K. Borum, M. McGugan, C.L. Thomsen, F.M. Jensen,
722 C.P. Debel and B.F. Sørensen. Full scale testing of WT blade to failure -
723 flapwise loading. Report Risø National Laboratory, Roskilde. Germany 2004.
724 ISBN: 87-550-3181-1.
- 725 [37] F. M. Jensen, B. G. Falzon, J. Ankersen and H. Stang. Structural testing
726 and numerical simulation of a 34 m composite wind turbine blade. *Composite*
727 *Structures* 2006; 76:52-61.
- 728 [38] K.K. Borum. M. Mc Gugan, and P. Brondsted. Condition monitoring of
729 WT blades. In *Proceedings of the 27th Riso International Symposium on*
730 *Materials Science: Polymer composite materials for wind power turbines;*
731 *2006, Denmark, p 139-45.*
- 732 [39] H.V. Leeuwen and D. V. Delft. Comparing fatigue strength from full scale
733 blade tests with coupon-based predictions. *Trans ASME special issue: Wind*
734 *Energy Journal Solar Energy Engineering* 2002; 124:404-11.
- 735 [40] D.A. Griffin and M. D. Zuteck. Scaling of Composite WT Blades for
736 Rotors of 80 to 120 Meter Diameter. *Journal of Solar Energy Engineering*
737 2001; 123:310-9.
- 738 [41] G.M.J. Herbert, S. Iniyar, E. Sreevalsan and S. Rajapandian. A review of
739 wind energy technologies. *Renewable and Sustainable Energy Reviews*
740 2007; 11:1117–45.

- 741 [42] C.S. Gray, S. J. Watson. Physics of Failure approach to WT condition
742 based maintenance. *Wind Energy* 2010; 13(5):395–405.
- 743 [43] J.R. Maughan. Technology and reliability improvements in GE's 1.5 MW
744 WT fleet. In *Proceedings. 2nd WT Reliability Workshop*; 2007, Albuquerque,
745 NM.
- 746 [44] W. Liu, B. Tang and Y. Jiang. Status and problems of WT structural
747 health monitoring techniques in China. *Renewable Energy* 2010; 35:1414-18.
- 748 [45] O. Parent and A. Ilinca. Anti-icing and de-icing techniques for wind
749 turbines: Critical review. *Cold Regions Science and Technology* 2011; 65:88-
750 96.
- 751 [46] B. Lu, Y. Li, X. Wu and Z. Yang. A Review of Recent Advances in WT
752 Condition Monitoring and Fault Diagnosis. *IEEE Power Electronics and
753 Machines in Wind Applications* 2009; 1-7.
- 754 [47] J. Ribrant. Reliability performance and maintenance - a survey of failures
755 in wind power systems. Master's thesis, KTH School of Electrical
756 Engineering; 2006, Stockholm.
- 757 [48] K. Fischer, F. Besnard, and L. Bertling. A Limited-Scope Reliability-
758 Centred Maintenance Analysis of Wind Turbines. In *European Wind Energy
759 Conference EWEA*; 2011, Brussels; p. 89-93.
- 760 [49] P. Guo, and N. Bai. Wind Turbine Gearbox Condition Monitoring with
761 AAKR and Moving Window Statistic Methods. *Energies* 2011; 4(11):2077-93.
- 762 [50] Y. Feng, Y. Qiu, C.J. Crabtree, H. Long, P.J. Tavner. Use of SCADA and
763 CMS Signals for Failure Detection and Diagnosis of a WT Gearbox. In
764 *Proceedings of Europe Premier Wind Energy Conference*; 2011, Brussels,
765 Belgium, p.14–7.
- 766 [51] M. Entezami, S. Hillmansen, P. Weston and M. Papaelias. Fault
767 detection and diagnosis within a WT mechanical braking system. In the
768 international conference on condition monitoring and machinery failure
769 prevention technologies (CM 2012 and MFPT 2011); 2011, Cardiff.
- 770 [52] L.M. Popa, B.B. Jensen, E. Ritchie and I. Boldea. Condition monitoring of
771 wind generators. In *Industry Applications Conference, 38th IAS Annual
772 Meeting*; 2003; 3: p. 1839-46.
- 773 [53] H. Douglas, P. Pillay and A. Ziarani. Broken rotor bar detection in
774 induction machines with transient operating speeds. *IEEE Transactions on
775 Energy Conversion* 2005; 20:135-41
- 776 [54] D. Hansena and G. Michalke. Fault ride-through capability of DFIG wind
777 turbines. *Renewable Energy* 2007; 32:1594–610.
- 778 [55] N. Bazeos, G.D. Hatxigeorgiou, I.D. Hondros, H. Karamaneas, D.L.
779 Karabalis and D.E. Beskos. Static, seismic and stability analyses of a
780 prototype WT steel tower. *Engineering Structures* 2002; 24:1015–25.
- 781 [56] Entec UK Limited. *Black Law Wind Farm Environmental Statement* 2002;
782 1: p.357.

- 783 [57] L.W.M.M. Rademakers, A. Seebregt and B. van Den Horn. Reliability
784 analysis in wind engineering. Presented at the ECWEC93 Conference; 1993,
785 Travemunde.
- 786 [58] G.J.W. Van Bussel, M.B. Zaaijer. Estimation of WT Reliability Figures
787 within the DOWEC Project, Report Nr. 10048; 2003:4.
- 788 [59] P. Tavner, Y. Qiu, A. Korogiannos, and Y. Feng. The Correlation
789 between WT Turbulence and Pitch Failure. In Proceedings of EWEA 2011.
- 790 [60] A.P. Wu and P. L. Chapman. Simple expressions for optimal current
791 waveforms for permanent-magnet synchronous machine drives. IEEE
792 Transactions on Energy Conversion 2005; 20:151-7.
- 793 [61] F. Spinato, P.J. Tavner, G.J.W. van Bussel, E. Koutoulakos. IET
794 Reliability of WT subassemblies. Renewable Power Generation 2009;
795 3(4):387-401.
- 796 [62] International Electrotechnical Commission. IEC 61400-1 3rd edition
797 2005-08 Wind turbines - Part 1: Design requirements, 2005.