Application of Fault Tree Analysis to Fuel cell diagnosis

Journal:	*Fuel Cells*
Manuscript ID:	fuce.201100072.R1
Wiley - Manuscript type:	Communication
Date Submitted by the Author:	n/a
Complete List of Authors:	Yousfi Steiner, Nadia; EIFER, Fuel Cells Hissel, Daniel; University of Franche-Comté, FEMTO-ST/ ENISYS / FC LAB Moçotéguy, Philippe; EIFER, Fuel Cells Candusso, Denis; IFSTTAR / FC LAB Marra, Dario; University of Salerno, Department of Industrial Engineering Pianese, Cesare; University of Salerno, Department of Industrial Engineering Sorrentino, Marco; University of Salerno, Department of Industrial Engineering
Keywords:	SOFC, PEFC, Diagnosis, Degradation, Fuel Cell

SCHOLARONE™
Manuscripts

For Peer Review

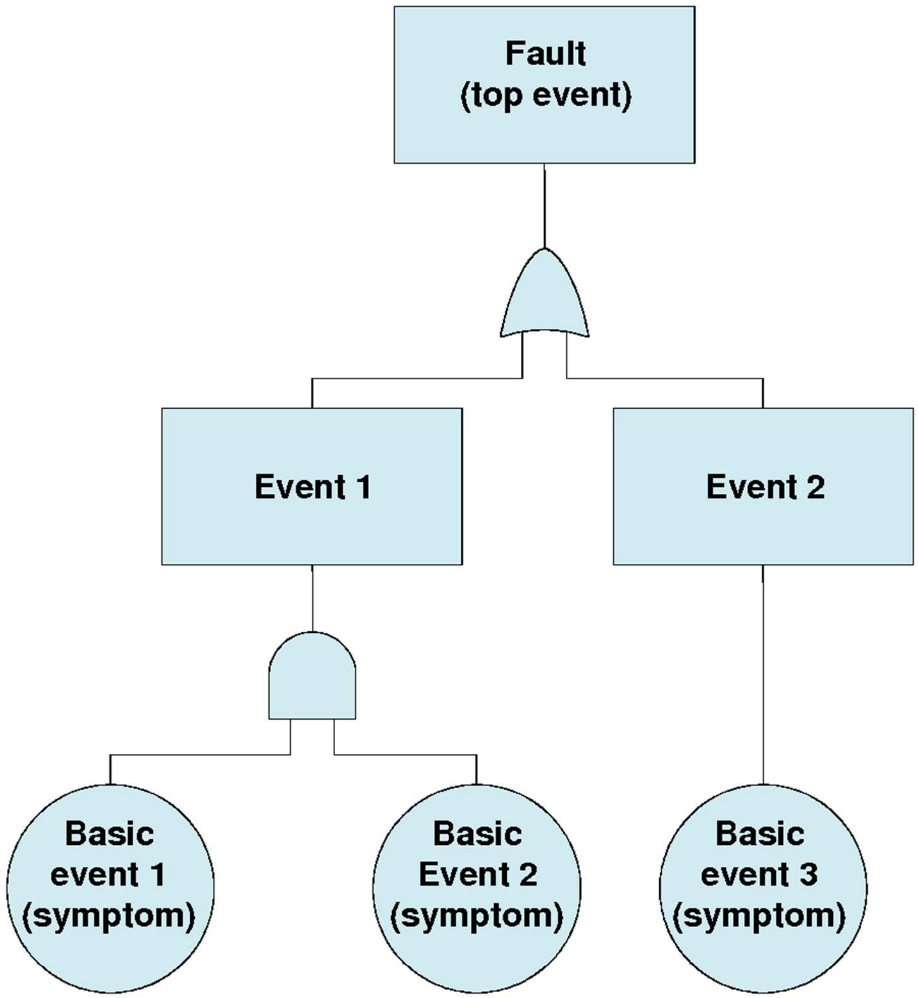


Fig. 1 Example of fault tree [6].
83x92mm (300 x 300 DPI)

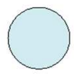
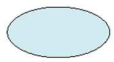
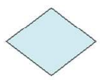
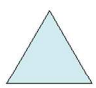
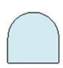
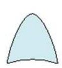
	basic event / symptom	A basic initiating fault requiring no further development or the corresponding symptom
	conditioning event	Specific conditions or restrictions that apply to any logic gate
	undeveloped event	An event which is no further developed either because it is of insufficient consequence or because information is unavailable
	top/intermediate event	A fault event that occurs because of one or more antecedent causes acting through logic gates
	transfer	Indicates that the tree is developed at the occurrence in other pages. it is used to avoid extensive duplication in a fault tree
	and	Output fault occurs if all of the input faults occur
	or	Output fault occurs if at least one of the input faults occurs

Fig. 1 Example of fault tree [6].
108x103mm (300 x 300 DPI)

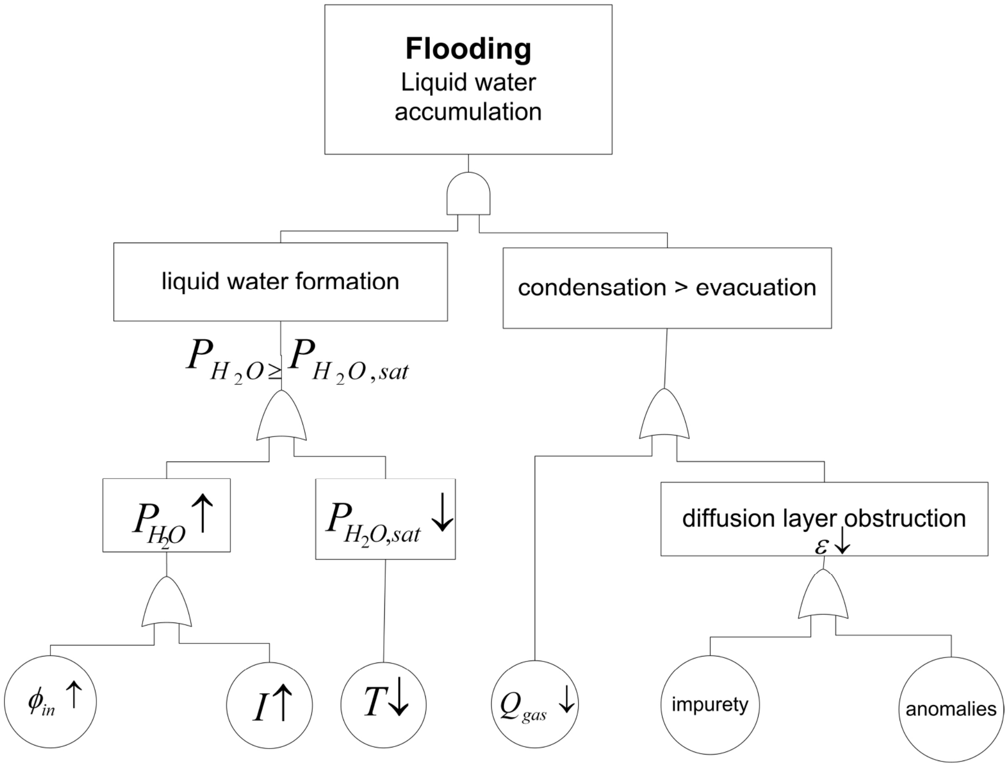


Fig. 2 Fault trees linked to (a) membrane drying out and (b) stack flooding [10].
106x80mm (600 x 600 DPI)

review

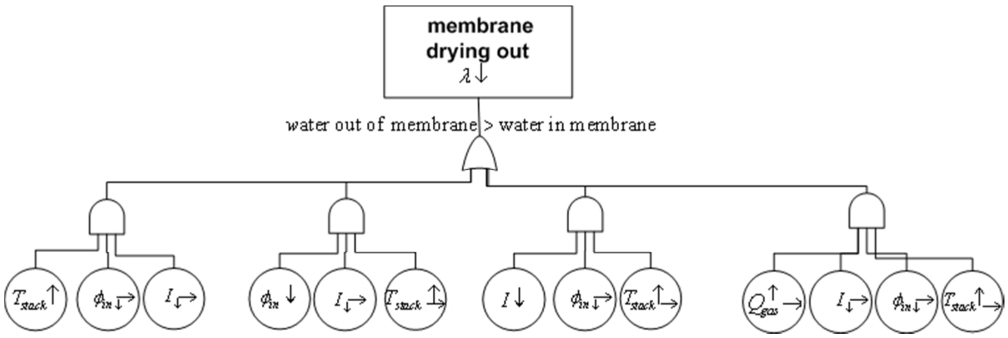
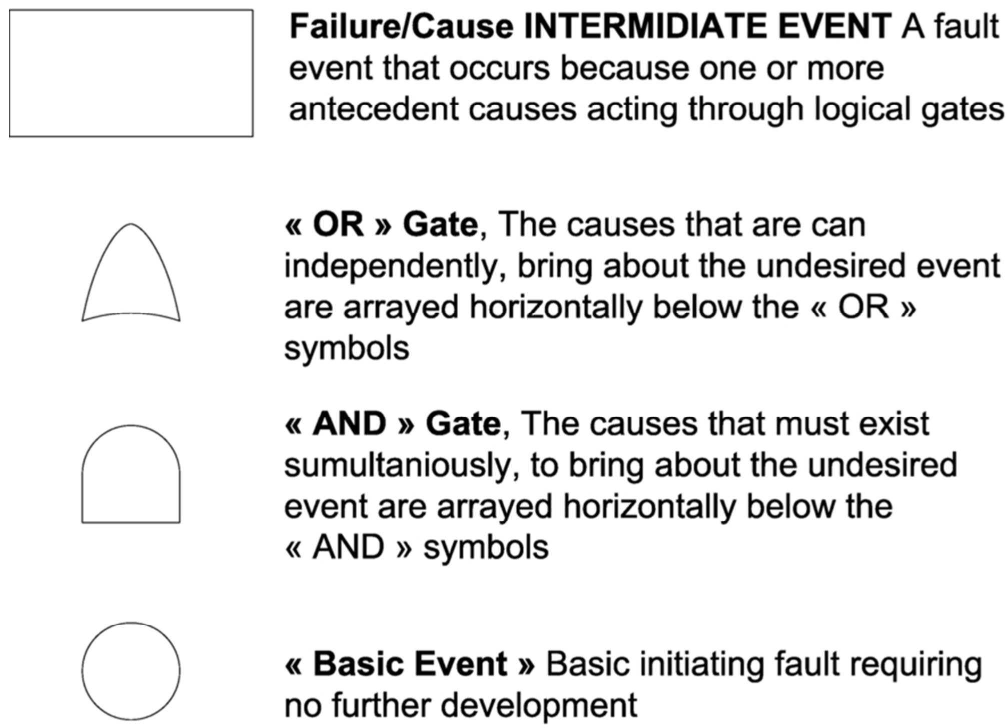


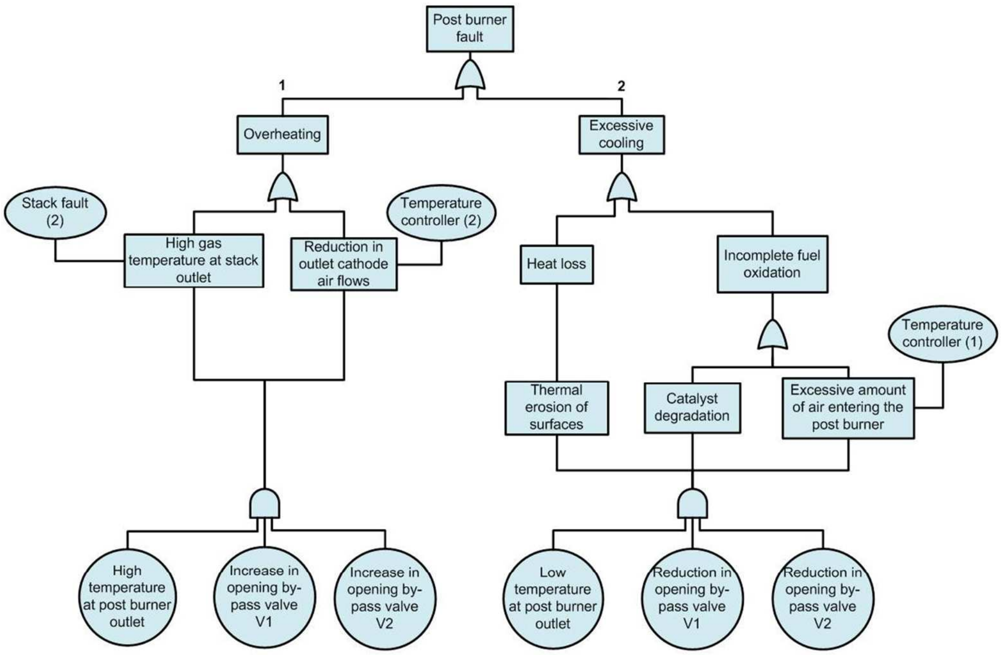
Fig. 2 Fault trees linked to (a) membrane drying out and (b) stack flooding [10].
201x66mm (96 x 96 DPI)

or Peer Review



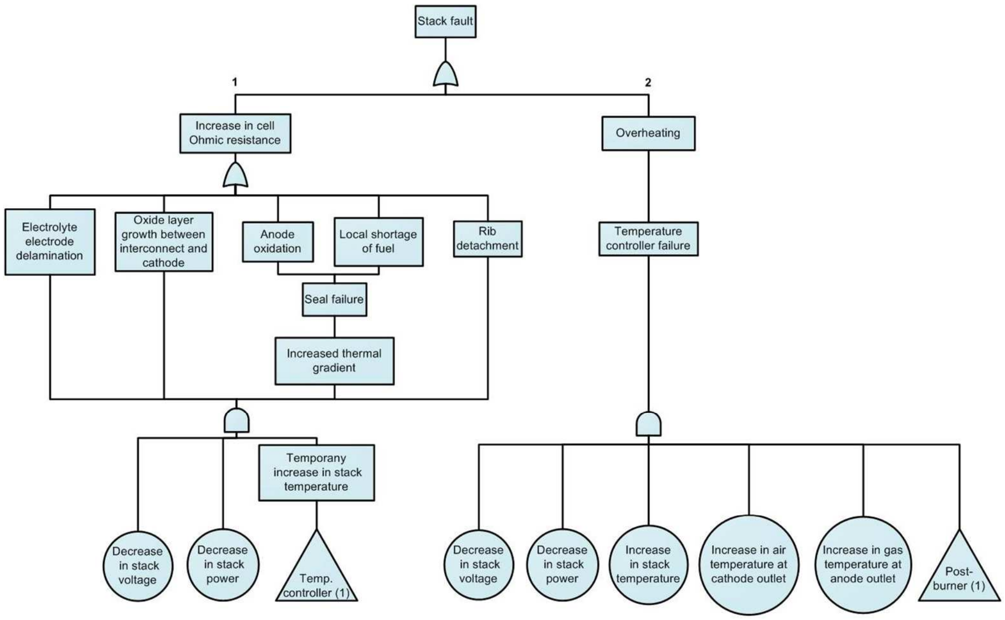
74x54mm (300 x 300 DPI)

Review



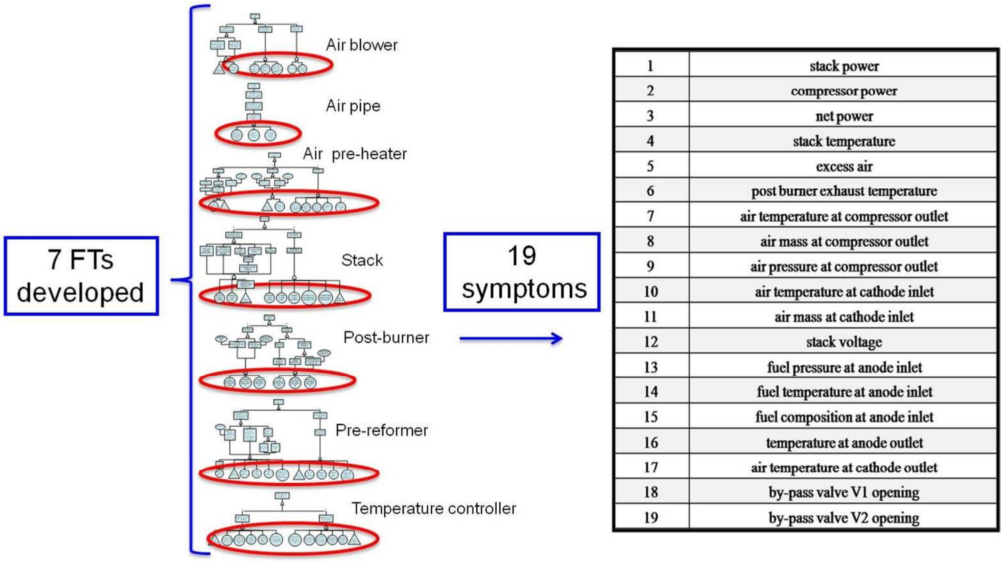
211x140mm (150 x 150 DPI)

Review

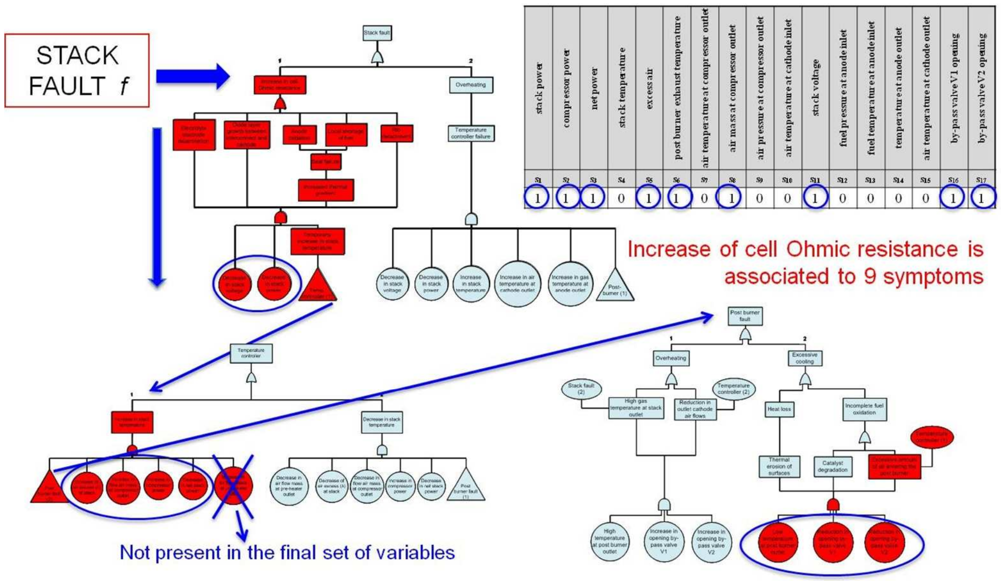


249x152mm (150 x 150 DPI)

er Review



257x144mm (150 x 150 DPI)



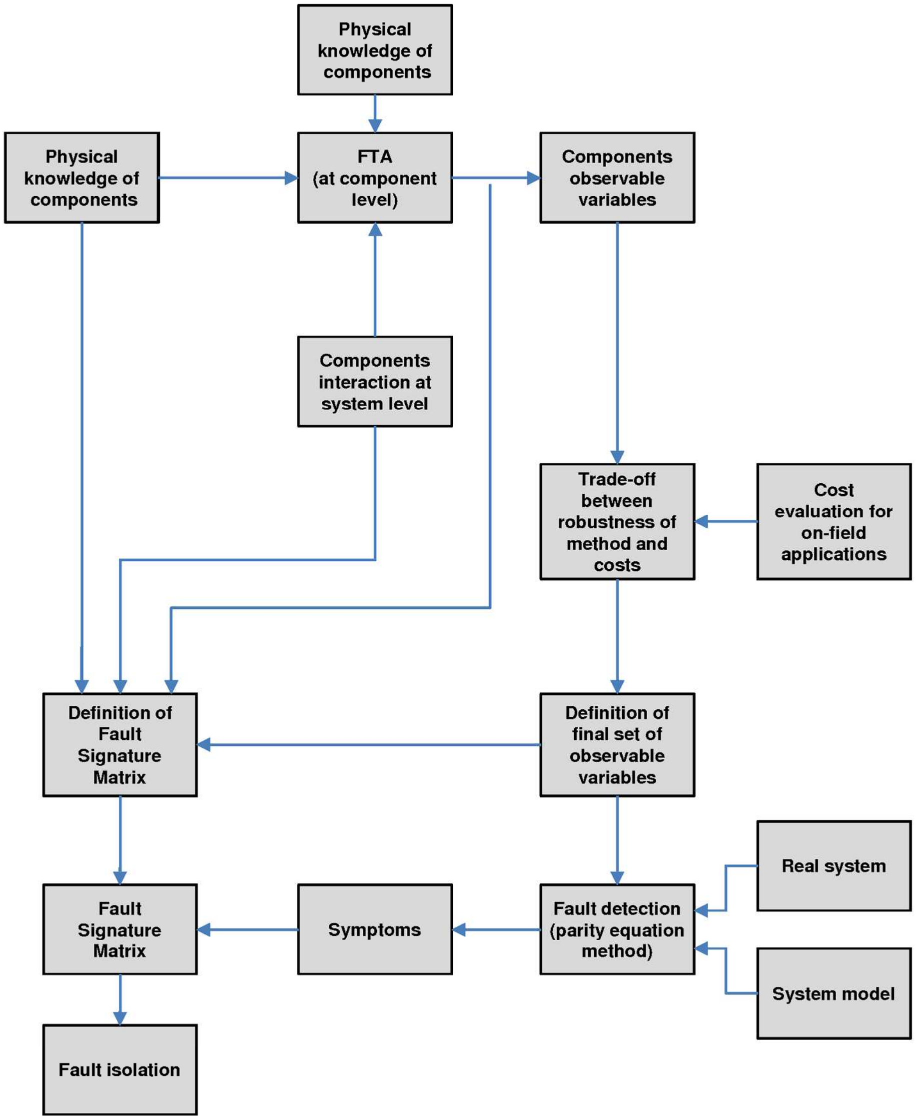
248x145mm (150 x 150 DPI)

er Review

		stack power	compressor power	net power	stack temperature	excess air	post burner exhaust temperature	air temperature at compressor outlet	air mass at compressor outlet	air pressure at compressor outlet	air temperature at cathode inlet	stack voltage	fuel pressure at anode inlet	fuel temperature at anode inlet	temperature at anode outlet	air temperature at cathode outlet	by-pass valve V1 opening	by-pass valve V2 opening
		s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}	s_{16}	s_{17}
Air blower fault: increase in mechanical losses	f_1	0	1	1	0	1	1	1	1	0	1	0	0	0	0	0	1	1
Air blower fault: air leakage in inlet compressor manifold	f_2	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Air pre-heater: air flow outlet cooling	f_3	0	1	1	0	1	1	0	1	0	1	0	0	0	0	0	1	1
Air pre-heater: air leakage in inlet plenum	f_4	0	1	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0
Air pipe fault: air leakage	f_5	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Pre-reformer fault: catalyst degradation	f_6	1	1	1	0	1	1	0	1	0	0	1	1	1	0	0	1	1
Pre-reformer fault: heat exchange surface corrosion	f_7	1	1	1	0	1	1	0	1	0	0	1	0	1	0	0	1	1
Post-burner fault: excessive cooling	f_8	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1
Stack fault: increase in cell Ohmic resistance	f_9	1	1	1	0	1	1	0	1	0	0	1	0	0	0	0	1	1
Stack fault: overheating	f_{10}	1	0	0	1	0	0	0	0	0	0	1	0	0	1	1	0	0

236x152mm (150 x 150 DPI)

Review



156x183mm (300 x 300 DPI)

Application of Fault Tree Analysis to Fuel cell diagnosis

N. Yousfi Steiner[1*], D. Hissel[2], P. Moçotéguy[1], D. Candusso[3], D. Marra[4], C. Pianese[4], M. Sorrentino[4]

1 EIFER, European Institute for Energy Research, Emmy-Noether Str., 11, Karlsruhe, Germany.

2 FEMTO-ST/ ENISYS / FC LAB, UMR CNRS 6174, University of Franche-Comté, rue Mieg, 90010 Belfort Cedex, France.

3 IFSTTAR / FC LAB, Institute of Science and Technology for Transport, Development and Networks, rue Mieg, 90010 Belfort Cedex, France.

4 Department of Industrial Engineering, University of Salerno, 84084 Fisciano, SA, Italy.

(*) Corresponding Author, nadia.steiner@eifer.uni-karlsruhe.de

For Peer Review

Abstract

Reliability and lifetime are common issues for the development and commercialization of fuel cells technologies'. As a consequence, their improvement is a major challenge and the last decade has experienced a growing interest in activities that aims at understanding the degradation mechanisms and at developing fuel cell systems diagnosis tools.

Fault Tree Analysis (FTA) is one of the deductive tools that allow "linking" an undesired state to a combination of lower-level events via a "top-down" approach which is mainly used in safety and reliability engineering.

The objective of this paper is to give an overview of the use and the contribution of Fault Tree Analysis (FTA) to both SOFC and PEFC diagnosis.

Keywords: Fuel Cells, SOFC, PEFC, Diagnosis, Degradation, Fault Tree Analysis.

1 Introduction

The needs of a better understanding of fuel cells degradation mechanisms and developing fuel cell diagnosis tools arose from the targets fixed by US department of Energy (DoE), European Union and Japan. Indeed, for transportation applications, the target is 5000h for the full range of external environmental conditions, which is the minimum requirement for vehicles in practical use. For stationary applications, the target is fixed at 40 000h of operation [1]. These objectives are defined for 2010 by the DoE and for 2015 by the European Union and by the NEDO (New Energy and Industrial Technology Development Organization) in Japan.

To achieve these objectives, an adequate diagnosis procedure has to be defined and set up. This requires a full understanding of degradation mechanisms and a proper definition of the parameters involved in the fuel cell operation and degradation. Indeed, a good knowledge of the influent parameters in a degradation phenomenon as well as their interactions is a mandatory step that **allow**s properly defining adapted mitigation strategies.

Fault Tree Analysis (FTA) is one of the deductive tools that allow linking an undesired state to a combination of lower-level events via a "top-down" approach.

The application of FTA for fuels cells diagnosis has also been performed in the frame of two projects: DIAPASON [2] (non intrusive diagnosis of PEFC systems) and GENIUS [3] (GEneric diagNosis InstrUment for SOFC Systems), respectively funded by the French ANR (Agence Nationale de la Recherche) and the European Commission through its Join Technology Initiative (JTI) program Fuel Cell and Hydrogen Joint Undertaking. Other works developed fault trees where the occurrence of events could be taken into account and the failure rate can be estimated using an experiments feedback [10] [9].

The first part of this work presents some generalities about the Fault Tree Analysis. Then, the application of FTA to PEFC and SOFC is proposed in paragraphs 3 and 4. Finally, paragraph 5 concludes this paper.

2 Generalities about Fault Tree Analysis

In operating safety and reliability science, the Fault Tree Analysis is widely used tool to clear out the contributions of different parameters in an undesired event [4][5]. A fault tree is defined as a graphical representation of the relationship between an undesired event (called a top event) and all its potential causes. The analysis proceeds in a "top-down" approach, starting with the top event (failure, malfunction…) and determining all the causes that can lead to it. It determines how these top events can be caused by individual or combined lower level failures or events.

An example of a fault tree is given by Figure 1 **(a)** [6]. In this figure, the fault (top event) can be caused either by event 1 or event 2. The event 1 is caused by the contemporary occurrence of the basic events 1 and 2 (i.e. symptoms). On the other hand, the event 2 is correlated to just one symptom (i.e. basic event 3).

(Figure 1a) (Figure 1b)

3 Application to PEFC stacks

In a review of degradation linked to water management in PEFCs, N. Yousfi Steiner et al. [7] developed fault trees for the issues linked to water management (stack flooding and membrane drying out) (Figure 2a) and flooding (Figure 2b) in PEFC.

In fact, stack flooding and membrane drying out are among the most frequently encountered faults in PEFCs stacks. Several works dealing with water management issues have been published these last few years [8]. These issues are mainly related to disequilibrium in water balance inside the fuel cell. A high temperature and high gas flow contribute to mitigate flooding by promoting liquid water evaporation favoring membrane drying out, while high current density results in high water production that promotes flooding just like low flow rate and high relative humidity.

(Figure 2a) (Figure 2b) (Figure 2c)

The main objective of these fault trees is to clear out the relationships existing between operating parameters and those given fault. The complexity of the PEFCs systems and the existence of a strong interaction among different variables make building fault trees very useful to ~~clear out these relationships and to~~ select relevant parameters for control and diagnosis.

For Peer Review

The isolated operating parameters in the "final leaves" of the trees are used to feed neural models aiming at diagnosing these issues. More details about the models could be found in [9].

4 Application to diagnosis of SOFC stacks and systems

4.1 Stack level

In SOFC stacks, the increase in cell ohmic resistance can be caused by electrode delamination, local shortage of fuel, anode oxidation or oxide layer growth and rib detachment.

Electrode delamination consists of the detachment of one of the electrodes from the electrolyte, which is due to the mismatch in thermal expansion characteristics of the cell's different layers during thermal cycling. Delamination has severe consequences on the performance, since it increases the ohmic resistance of the cell proportionally to the delaminated area. Furthermore, it makes the affected area electrochemically inactive as a consequence of the high aspect ratio of the cell, which inhibits the transport of ions in the in-plane directions [10].

Local shortage of fuel and anode oxidation can be caused by seal failures, which can occur at the interfaces during heating at start-up and cooling at shutdown, due to the mismatch in thermal expansion between metal and ceramic SOFC component. A sealing failure in SOFC stack causes gas leakage, which in turn, decreases the overall performance and lifetime of the stack.

Oxide layer growth between the interconnect and the cathode is the growth of an electrically less conductive oxide layer between the interconnect plate and the electrodes, especially the cathode [10]. Chromium layers grow on the interconnect surface, degrading the electrical conductivity of the interconnect-electrode interface. This oxide layer is dense and adherent, providing the substrate protection against further oxidation.

Rib detachment is the deformation of the planar cell components, with detrimental consequences associated with contact degradation between the interconnect and the electrodes, due to the thermal excursions. This phenomenon is referred to as rib detachment, and together with oxide layer growth causes an increase in the total resistance of the cell [11].

On the other hand, the excessive overheating, which could be caused by a malfunction in the temperature controller or a lack in the air flow mass, due to an air blower fault is indicated by the increase in the temperature stack, which could lead to system failure.

The above mentioned faults related to the SOFC stacks and their interactions are summarized in the fault tree of Figure 3.

(Figure 3)

4.2 System level

Arsie et al. [6] applied fault tree analysis to SOFC, taking into account many components at system level (e.g. air blower, air pre-heater, pre-reformer, post-burner, air leakage in pipe connecting air blower and air pre heater and to stack).

The FTA is proposed in this case as a tool for fault isolation process and the knowledge gained through it is exploited to understand the mutual interactions among all the devices within the entire SOFC system. Each of

For Peer Review

the above mentioned faults is correlated, via a top-down approach, to corresponding symptoms (in total 7 fault trees were built) and a fault signature that links conveniently system-level symptoms to specific component faults has been defined.

Figure 4 presents, for instance, the fault tree associated with the post-burner.

(Figure 4)

The post-burner is used to complete the oxidation of the residual fuel at anode outlet and, in some systems, also to preheat the FC system during start-up. The main faults considered for this component are the overheating (branch 1) and cooling (branch 2). Following a top-down approach, 6 symptoms of this undesired event are isolated. They represent the "leaves of the fault tree presented in Figure 4.

After developing a fault tree for each system component, a set of system variables is identified as shown in Figure 5.

(Figure 5)

A final set of 17 variables is selected according to the trade-off between the robustness of the method and the cost evaluation for the in-field implementation (Table 2).

(Table 2)

Building a fault matrix

According to the FTA at component level and the knowledge of components interactions at system level, each fault is associated with a vector of symptoms, which contains 1 if the symptom is associated with that fault and 0 otherwise.

The procedure is illustrated in Figure 6: starting from the fault, through an approach top/down, all the symptoms (circles) linked to the fault are individuated. The symptoms considered are both those of the specific component fault tree, and all the other ones present in the related components fault tree (through the triangle).

(Figure 6)

The procedure must be repeated for each fault and every symptoms vector must be different from each other; thus it is possible to isolate univocally a fault. Once all the faults are considered it is possible to generate a so-called Fault Signature Matrix (FSM). The FSM has in rows the system faults and in columns, the symptoms associated to define a set of variables (Figure 7).

(Figure 7)

According to this approach, residual are generated by comparing the defined set of system variables observed in the real system and their equivalent ones in a system model, which simulates the system in nominal (non faulty) condition. The Fault Detection and Isolation (FDI) proposed in this work (Figure 8) is then based on the analysis of these residuals. More details can be found in [6].

For Peer Review

(Figure 8)

5 Conclusion

This paper has reviewed different works dealing with the application of Fault Tree Analysis to fuel cells stacks and systems.

The fault tree representation appeared to be a good way to clear out the connections and interactions between the different operating parameters responsible of a given fault. It allows a better understanding of degradation phenomena and a judicious choice of the impacting parameters. These parameters are then very useful to feed models in an optimized way or to construct Fault Signature Matrixes.

Acknowledgement

The authors wish to thank the European Commission and the ANR (French National agency of research) for their financial support through the European FP7 funded project GENIUS and the PAN-H funded project DIAPASON respectively.

References

[1] DOE "Department of Energy", US Department Of Energy, **2004**.
[2] DIAPASON, Agence Nationale de Recherche ed., Plan d'action National sur l'Hydrogène et les piles à combustible (PAN-H), **2006**.
[3] GENIUS, https://genius.eifer.uni-karlsruhe.de, **2010-2013**.
[4] R. Isermann, *Fault Diagnosis System, An Introduction from Fault Detection to Fault Tolerant*, Springer, Verlag, , Berlin Heidelberg, Germany, **2006**.
[5] Y. Mortureux, in *Techniques de l'Ingénieur: Security et gestion du risque, Vol. SE4010*, **2002**, pp. 1-24.
[6] I. Arsie, A. Di Filippi, D. Marra, C. Pianese, M. Sorrentino, in *ASME 2010. Eight International Fuel Cell Conference, Engineering and Technology, Brooklyn, New York*, **2010**.
[7] N. Yousfi Steiner, P. Moçotéguy, D. Candusso, D. Hissel, A. Hernandez, A. Aslanides, *J. Power Sources* **2008**, *183*, 260-274.
[8] aF. A. de Bruijn, V. A. T. Dam, G. J. M. Janssen, *Fuel Cells* **2008**, *8*, 3-22; bJ. St-Pierre, *J. Electrochem. Soc.* **2007**, *154*, B724-B731; cJ. Stumper, M. Lohr, S. Hamada, *J. Power Sources* **2005**, *143*, 150-157.
[9] N. Yousfi Steiner, D. Hissel, P. Moçotéguy, D. Candusso, *Int. J. Hydrogen Energy* **2011**, *36*, 3067-3075.
[10] H. Yokokawa, H. Tu, B. Iwanschitz, A. Mai, *J. Power Sources* **2008**, *182*, 400-412.
[11] J. I. Gazzarri, O. Kesler, *J. Power Sources* **2008**, *176*, 138-154.

Figures captions

Fig. 1 (a) Example of fault tree (b) legend.

Fig. 2 Fault trees linked to (a) membrane drying out and (b) stack flooding (c) symbols.

Fig. 3 Fault tree for the SOFC stack.

Fig. 4 Fault tree for the post burner.

Fig. 5 Procedure to select symptoms from fault trees.
Fig. 6 Procedure to generate fault/symptoms association vector.
Fig. 7 Example of Fault Signature Matrix (FSM).
Fig. 8 FDI process scheme.

For Peer Review

Tables

Table 1 Nomenclature.

Variable	Description
P_x	Partial pressure of x [Pa]
Φ_{in}	Relative humidity of the inlet gases [%]
I	Current [A]
T, T_{stack}	Stack Temperature [°C]
Q_{gas}	Volumetric flow rate [$m^3.s^{-1}$]
ε	Electrode porosity
λ	Membrane water content

Table 2 Final set of variables to be monitored in the system.

1	stack power [kW]
2	compressor power [kW]
3	net power [kW]
4	stack temperature [°C]
5	excess air [/]
6	post burner exhaust temperature [°C]
7	air temperature at compressor outlet [°C]
8	air mass at compressor outlet [kg/s]
9	air pressure at compressoroutlet [Pa]
10	air temperature at cathode inlet [°C]
11	stackvoltage[V]
12	fuelpressure at anodeinlet [Pa]
13	fuel temperature at anodeinlet [°C]
14	temperature at anode outlet [°C]
15	air temperature at cathode outlet [°C]
16	by-pass valve V1 opening [%]
17	by-pass valve V2 opening [%]

For Peer Review