Experimental validation of an active fault tolerant control strategy applied to a proton exchange membrane fuel cell

Etienne Dijoux [1,2*], Nadia Yousfi Steiner [2], Michel Benne [1], Marie-Cécile Pera [2] and Brigitte Grondin Perez [1]

[1] University of La Reunion, ENERGY Lab- LE2P, member of the French national research network on hydrogen (FRH2 CNRS), Saint-Denis, France.
[2] FEMTO-ST Institute, FCLAB, Univ. Bourgogne Franche-Comté, member of the French national research network on hydrogen (FRH2 CNRS), Belfort, France
* Correspondence: etienne.dijoux@univ-reunion.fr

Abstract: Proton exchange membrane fuel cells (PEMFCs) reliability is a major issue for a large industrialization and commercialization. Indeed, performance can be degraded because of abnormal operating conditions, namely faults, that lead either to a transient decay of the fuel cell performance or to a permanent damage that cannot be recovered. The literature shows that a long-time exposure to faults leads to the fuel cell degradation. Therefore, it is necessary to use tools that can not only diagnose these faulty conditions but also modify the fuel cell operations in order to recover a healthy operating point. For that purpose, one approach is the Active Fault Tolerant Control (AFTC) strategy which is composed of three functions. First a diagnosis part allows the fault detection and identification. Then a decision part, which is an algorithm aiming at finding a new operating point that mitigates the occurring fault. Finally, a control part applies the mitigation strategy established by the decision algorithm. The present work focuses on the decision part.

This paper aims at bringing a new contribution to PEMFCs reliability improvement and addressing water management issues, namely the cell flooding and membrane drying out with the developed AFTC tool. The strategy is tested and validated on a single PEMFC cell and results are presented, analyzed and discussed.

Keywords: Reliability; decision algorithm; fuel cell degradation; active fault tolerant control; experimental validation; PEMFC water management fault mitigation; online fault mitigation.

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1. Introduction

Fuel cell systems suffer from a lack of reliability and can be subjected to different faulty operating modes as detailed in a previous literature review [1]. Faults can be classified according to some criteria such as effects, response time, character (reversible or irreversible) or location. The most recurrent faults appearing during the operation of the proton exchange membrane fuel cells (PEMFCs) are those related to water management [2]–[9]: flooding of the supply channels or electrodes, and drying out of the membrane. Flooding is defined as an accumulation of liquid water in the feed line or gas diffusion layer (GdL) of the electrodes, limiting the access of the reactants to the active areas, decreasing thus the reaction rates. Membrane drying out is defined as an insufficient hydration of the ion exchange membrane (IEM) that reduces its proton conductivity. Indeed, the commercial IEM Nafion is composed of hydrophobic backbone and hydrophilic sulfonic acid groups, only when hydrated, the hydrophobic-hydrophilic phase separation leads to the effective proton transfer paths for Nafion. When the membrane is dry, the proton cannot pass through the membrane effectively. Their occurrence can lead to a temporary decrease of PEMFC performance. But in the case of a too long-time exposure, some irreversible degradation can appear and reduce the PEMFC lifetime.

Therefore, fault occurrences must be reduced as much as possible to avoid degradations. For this purpose, Fault Tolerant Control (FTC) can be used to manage the fuel cell operation and mitigate the occurring fault without jeopardizing the service continuity. The literature shows some works dealing with fault mitigation strategies. In a previous work [10] for instance, two kinds of FTC strategies were depicted : Active FTC and Passive FTC. This paper, only focuses on the Active strategy. Indeed, this kind of strategies consists in accommodating the system operating point to healthy conditions by adjusting controllers' setting

AFTC strategies are constituted of a fault detection and isolation (FDI) tool coupled with a control strategy in order to mitigate the occurred faults. For instance, authors in [13], [14] have proposed the application of the strategy. Their goal is to address the water management issue by coupling an FDI algorithm, a reconfiguration mechanism and an adjusting controller. The FDI process is based on a neural network then a self-tuning PID is used as the control tool. Authors also highlight in [11] that self-tuning PID shows robustness against noise and model uncertainties. The approach explained in [13]–[15] consists of a development of a three-module strategy to diagnose a fault occurrence, to decide on a mitigation action, and to apply the dimming strategy. The asset of the method lies in the distribution of the complexity into the three modules which simplifies drastically its implementation. Other work [5] proposed a model-based AFTC strategy for fuel cell temperature sensor failure. Indeed, the authors use a FDI process for real time fault diagnosis and a sliding mode controller for the fuel cell thermal management.

All these works show that fault tolerant strategies already exist, however, only few works meet the PEMFC fault issues such the water management. This work therefore aims to bring a new contribution towards the improvement of PEMFC reliability through the implementation of an active fault tolerant control strategies.

In this paper, we propose a three-modules AFTC strategy and proceed to its validation on an experimental setup. Several protocols of fault mitigation processes are applied on flooding and membrane drying out. Metrics are defined to quantify the asset of the proposed AFTC process.

The paper is divided in five sections. First, a presentation of the AFTC strategy and some metrics are defined to quantify the strategy's strength. Then, the experimental setup is described and faults' generation process is explained. After these presentations, the experimental validation of strategy is done on each generated fault. An analysis and a discussion are proposed to highlight the best AFTC strategies. The paper finally ends with a conclusion of the study.

2. Design of active fault tolerant control strategies for PEMFC water management issues and metrics for their performance analysis

Before designing a fault mitigation strategy, it is relevant to understand what faults are being considered and how they disturb the normal operation of a PEMFC. This section is thus dedicated to the presentation of two faults selected for the present study.

1.1 Faults related to PEMFC water management

Flooding

In [2], the authors identify the flooding as the most recurrent fault for PEMFCs and point out that the cathode --being the place of water production -- is particularly affected. In addition, the probability of flooding increases for high current densities or when the vapor partial pressure is higher than vapor saturation pressure. The gas flow rate is also a major factor for flooding occurrence because the lower the gas flow rate is, the lower the amount of water discharged, and the higher the flooding severity are.

Some researches [2], [16] highlight that the flooding issue is a water disrupt along the gas flow channel. This water accumulation clogs the gas flow in the channels and leads to a decrease of the reactant flow at the catalyst layer. Moreover, the water accumulation also clogs the gas diffusion layer (GdL) which diffuses the reactant to the catalyst.

Membrane drying out

Membrane drying out occurs when the membrane is not sufficiently hydrated, resulting in an increase of its proton resistivity. Drying out occurs especially when the vapor partial pressure inside the PEMFC is too low [17]. Indeed, the membrane water content results from a mass balance transfer between two phenomena. The chemical reaction between hydrogen and oxygen produces water that participates to the membrane moisturization, just like the hydrated input gas flows.

Among the methods referenced in the literature to address cause and effect problems, Fault Tree Analysis (FTA) is a suitable approach to characterize the events causing flooding and membrane drying out. The next section therefore deals with literature flooding and membrane drying out FTA.

The next step is to set an AFTC strategy in order to diagnose faults and mitigate their impact.

1.2 Active Fault Tolerant Control strategy

The chosen AFTC architecture is a three-module structure composed of a diagnosis module, a decision module and a control module based on [14]. In this AFTC architecture the diagnosis module is considered as a “fault sensor” module. Indeed, the identification of a fault triggers the decision module in charge of computing a new setpoint to mitigate the fault. This setpoint is then applied to the PEMFC through the control module which is composed of a set of controllers. This strategy is executed in an iterative process until complete mitigation of the occurred fault.

1.2.1 Diagnosis module

The diagnosis module is composed of a residual based diagnosis tool using an artificial neural network (ANN) depicted in [18]. Based on the Matlab toolbox nnarx, an ANN model is used to estimate the pressure drop ΔP_{cath} and cathode voltage. The cathode pressure drop is the pressure difference between inlet and output cathode pressure. These estimations are then compared to the measured values to generate two residuals (Residual 1 and Residual 2). Each residual is compared to a threshold (respectively *Threshold 1 for* ΔP_{cath} and *Threshold 2 for* V_{fc}), selected prior to the test process and formally dependent on the PEMFC configuration and test bench features.

The diagnostic module concludes to flooding if both ΔPcath and Vfc thresholds are crossesd, or to drying out if only the threshold Vfc is crossed. The fault diagnosis process is represented on the Figure Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.***-1**Erreur ! Source du renvoi introuvable.**.

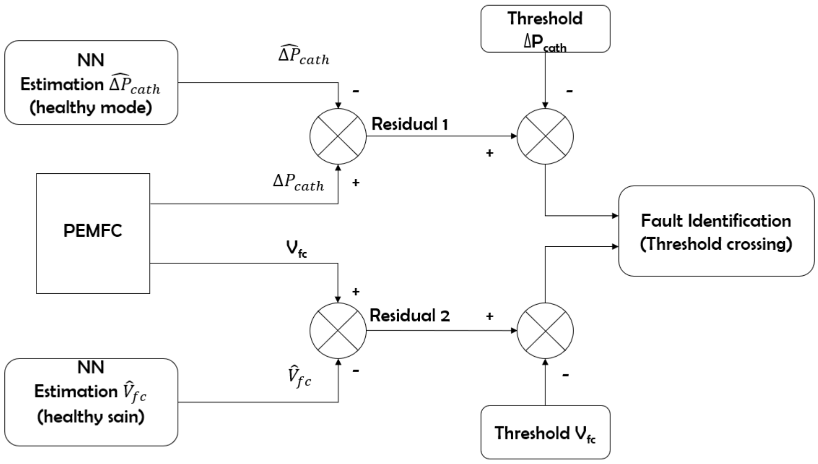


Figure ***Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.***-1 : Fault diagnosis process

The Figure Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.***-1 shows that the diagnosis process is divided into two parts that identify both flooding or membrane drying out. The first one performs the calculation of a residual (**Residual 1**) between a measured pressure drop and an estimated value. The second residual (**Residual 2**) is computed from the measured fuel cell voltage value and the estimated value. Residuals are then compared with two threshold values which. When both are crossed, a flooding is identified. Indeed, the accumulation of water inside the gas feed channels induces an increasing pressure drop. Thus, a flooding provokes two thresholds to be crossed because the fuel cell voltage also decreases. Regarding the membrane drying out identification, since there is no accumulation of water in the supply channels, only the fuel cell voltage decreases. Therefore, the crossing of a single residue (the voltage threshold) makes it possible to identify the membrane drying out.

1.2.2 Decision module

After the diagnosis process and in case of fault identification, a decision algorithm is used to select a mitigation strategy. The decision consists of the modification of the operating setpoint from a faulty state to a healthy state. Indeed, the decision algorithm changes the setpoint for fault mitigation at each faulty diagnosis period. The goal is to find a new setpoint which is antagonist to the detected fault and that does not induce other types of faults. Therefore, the decision process needs relevant control variables and a decision algorithm to perform a fault mitigation.

1.2.2.1 Control variable for mitigation

Fault tree analysis (FTA)

In [19], a FTA highlights the combination of events which lead to PEMFC flooding and membrane drying out. It aims to highlight the relationships between a fault occurrence and thus to understand which variables are involved in their occurrence. Authors points out that flooding and membrane drying out can be caused by inappropriate operating settings of the following variables: PEMFC temperature (T_{fc}) ; input flow rate (q_{x_in}); PEMFC current (I_{fc}); output flow rate (q_{x_out}); pressure (P_{H2O} and P_{H2Osat}) ; relative humidity (RH%). This knowledge is very relevant for the AFTC design because it allows the selection of control variables for fault mitigation. However, PEMFCs are strongly coupled systems and the change of a parameter can lead to their destabilization. FTA only allow to understand the fault formation mechanism from the combination of basic events. However, in case of a fault mitigation strategy these same variables (the basic events) should be used to mitigate their occurrence. But while these variables may indeed have on the fault, they can also disrupt other system operations. For this reason, the literature provides some structural analyses as Fault Structural Analysis (FSA) which highlights the coupling [20] in PEMFC. Indeed, the FSA approach synthesizes the knowledge about PEMFC fault water management and highlight through a graphical represent the interactions between the internal system variables and the fault.

The choice of the mitigation variables should be based on the previous FTA. However, if the FTA brings enough information about fault generation, it is not necessarily sufficient to set up a mitigation strategy for all faults, as some faults may not be characterized.

To enhance the FTA information, a structural analysis should be carried out as proposed in the Fault Structural Analysis tool (FSA). By providing a way to identify the variables that influence a system, the FSA makes it possible to highlight its coupling effects.[20].

FTA thus provides four control variables which can be used in the AFTC strategy: inlet gas pressure (P_{tot_in}), inlet gas flow (q_{O2_in}), inlet gas flow relative humidity (q_{O2hum}), and the fuel cell temperature (T_{fc}). To complete the FTA, the FSA approach highlights the effects of control variables on the fuel cell operating point as depicted in [20]. The FSA shows that temperature has an influence on several functionalities of the PEMFC. A change of the fuel cell temperature could modify others fuel cell functionalities such as the thermodynamic equilibrium between the gas diffusion layer water content and the membrane water content. Therefore, the modification of T_{fc}, can lead to fuel cell functionalities disturbance.

Regarding the membrane drying out, the FSA shows that it only has an influence on the membrane water content. The only control variable which can have a direct influence on the membrane water content is the PEMFC temperature.

The FSA highlights five control variables for flooding and membrane drying out mitigation: P_{tot_in}, q_{O2_in}, q_{O2hum}, and T_{fc}. Pressure variables are not considered as control variables because they are assigned to diagnosis tool. Flow rate variables and temperature are considered as control variables for fault mitigation in the decision algorithm.

1.2.2.1 Decision algorithm

The decision algorithm connects diagnosis and control tools. Its objective is to define the best mitigation decision for each detected fault, by merging two types of decisions: transient decisions and deferred decisions. The goal of transient decision is to alleviate fugitive faults by punctually modify the fuel setting point. But in case of a non-fugitive fault, the PEMFC setting point should be modify permanently, and this is the aim of the deferred decision

A transient decision results in a non-permanent setpoint change, which allows to reach a two-fold aim: first to target a fast corrective action after the occurrence of a fault, and second to eliminate a fleeting fault condition (such as local condensation, for example, the occurrence of which does not necessarily require a change in the PEMFC operating point):

control variables that can be changed quickly by the system actuators and the system has a short time response to this change, the mitigation of the fault can occur quickly by reducing the time exposure of the fuel cell to a degrading condition, which gives time to slow down the dynamics of decision and adjustment action or by completely deleting it,

transient decisions also allow the fuel cell setpoint being temporarily changed to mitigate the occurrence of a fleeting fault; the modified variable is then reset at the end of the fault mitigation process.

All other decisions that are not classified as transient decisions are defined as deferred decisions for which the mitigation variables are used regardless of their dynamic time scale. This kind of decision implies a non-fleeting fault occurrence that cannot be mitigated with a transient decision. This means that the PEMFC operating point is no longer suitable for healthy operations. Therefore, the deferred decision changes the operating point of the PEMFC by adjusting the controller set point to a value antagonistic to the fault occurrence in order to mitigate it.

Both decision processes (transient and deferred) modify each controller set point and find iteratively an adjusted one without the fault occurrence. It is assumed that the speed of the iterative process depends on the fault severity, so that the adjusted set point can be found rapidly for a low level of severity, whereas it could be longer to find for a high level of severity. Therefore, if the occurred fault is assessed to have low severity by the diagnosis algorithm, decisions will modify the operating point with small increments. Else, is in case of higher severity, increments would be are more important.

1.2.2.3 Decision Protocols

The test protocols consist of several decision cases strategies, each decision case corresponding to a method in which the decision algorithm triggers the control variables for fault mitigation. The number of the decision cases depends on the quantity of available control variables. The scheduling of each triggering has also to be considered and leads to five decision cases. Each case provides the hierarchy of the actions. All cases are considered as possible paths toward a fault mitigation.

Figure *Erreur* ***! Il n'y a pas de texte répondant à ce style dans ce document.***-2 is a representation of each possible case for fault mitigation.

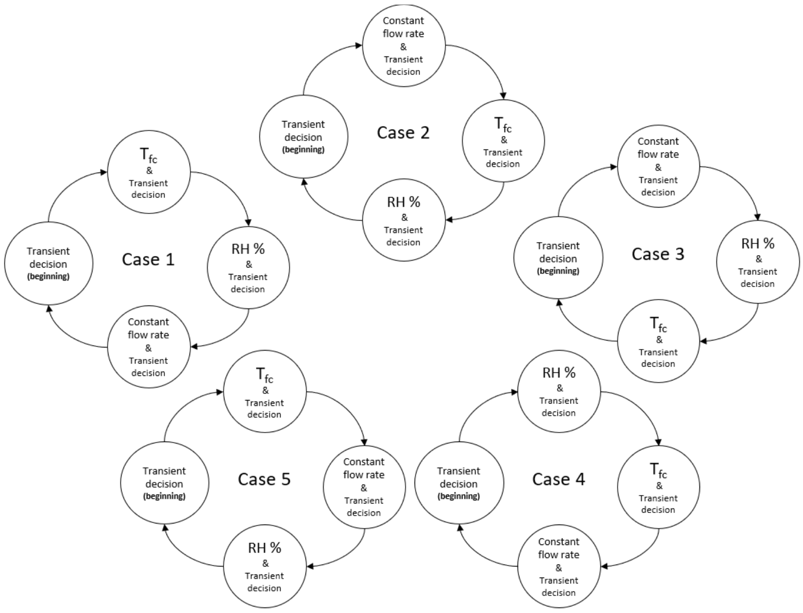


Figure ***Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.***-2: Representation of each possible case for fault mitigation.

On the Figure Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.***-2 each circle represents the action to take after a fault occurrence. There are four possible actions: modifying the input gas flow rate, going back to the initial value (transient decision), modifying the fuel cell temperature, modifying the input gas flow rate and keeping it or modifying the input gas relative humidity (the 3 of them are considered as deferred decision).

Each control variable is sequentially modified and the decision process transition from a variable to another is represented by the arrows. The cases also show that the transient decision is triggered along with the control variables because this produces the fastest effect on the fault mitigation. Therefore, triggering a transient decision is systematic when a fault is identified, while the deferred decision is only triggered if the transient decision does not allow a sustainable fault mitigation. Figure Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.***-2 is a representation of this process. In all cases, a transient decision is always triggered because it always has an antagonistic influence on the occurred fault.

However, regarding each case it appears that only the first one is relevant for a fault mitigation and is considered in the mitigation strategy. Indeed, for the case 2 and 3, the second mitigation variable is the same as the transient decision

1.2.3 Control module

For seeking a simplified system, the control module consists of regulators which are already available on the system, so that only set points are changed according to the decision algorithm. However, these set points modifications do not take into consideration the PEMFC State of Health (SoH) that could lead to the system destabilization. Indeed, a too high or too low change of the set points could lead to a transient response which degrades the PEMFC SoH. As there is not suitable online SoH determination tools, a "near-blind" reconfiguration of the controllers set point is operated. This kind of manipulation leads to adjust the PEMFC operating point toward a more suitable point, which no longer allows faults occurrence. It is therefore possible to find iteratively a suitable point for healthy operation.

1.2.4 Metrics for AFTC analysis

Metrics are used to compare a system performance in several environments and for different operating modes. Regarding the AFTC experimental process on a PEMFC, appropriate metrics should be specified to quantify the faults mitigation quality, such as (i) the number of mitigation actions, (ii) the duration of the actions, (iii) the time to return back to healthy conditions, (iv) the number of sensors used for the mitigation processand (vi) the levels of increments (LoI) of the control variables. LoI is the way a control variable is modified for fault mitigation.

A combination of metrics is used to determine the best AFTC process for fault mitigation. The next section is dedicated to experimental validation of the AFTC strategy on PEMFC flooding and membrane drying out, it quantifies the level of actions that mitigates a fault once diagnosed.

2. Experimental validation of the AFTC strategy

2.1 Experimental setup

The AFTC strategy is applied on a test bench of the FCT brand [21] which can supply a fuel cell with hydrogen at the anode and either pure oxygen or air at the cathode. In this work, all experimentations are carried out with pure oxygen. The tested fuel cell is a 50 W N117 ION POWER single-cell of 50 cm^2 [22]. The normal operating conditions recommended by the supplier are 20 A with 1.5 and 2 for H_2 and O_2 stoichiometries respectively. The fuel cell temperature (T_{fc}) is fixed at 70 °C and oxygen relative humidity (RH_{O2}) at 70 %. The test bench is equipped with two flow rate controllers to manage the input reactant flows. A humification system is placed on the O_2 and H_2 line feeders and their relative humidity is regulated with the gas temperature controllers. Two back pressure controllers are placed at the event of the anode and cathode lines to manage the internal fuel pressures. An electronic load connected to the FC terminals can absorb a power of 1800 W. The whole system is monitored with a Labview virtual instrument.

2.2 Fault generation

The objective of the following subsections is to present the changes in the operating conditions of the PEMFC to provoke intentional flooding and membrane drying out.

2.2.1 Flooding generation at the PEMFC cathode

As shown on the Figure 2-1, the test bench in use feeds the PEMFC with reactants through a humidifier and a temperature-controlled canalization. Indeed, input flow (q_{O2_in}) crosses the humidifier (q_{O2_hum}) and emerges at the same temperature of the humidifier (T_{hum}) which is the dew point temperature and at hundred percent of relative humidity. The gases temperatures are then modified by the canalization temperature controller (T_{canal}) to allow water to condense inside the pipe. Higher canalization temperatures lead to decrease the relative humidification rate and a lower temperature leads to water condensation.

It is thus through this latter process that liquid water is produced inside the cathode gas feeding line at the upstream of the PEMFC. Condensed water is then pushed in the PEMFC causing a flooding. This way of generating the fault guaranties the presence of liquid water in the canalization and then the introduction of liquid water inside the cell. Figure 2-1 shows the variations of the operational conditions and the flooding generation.

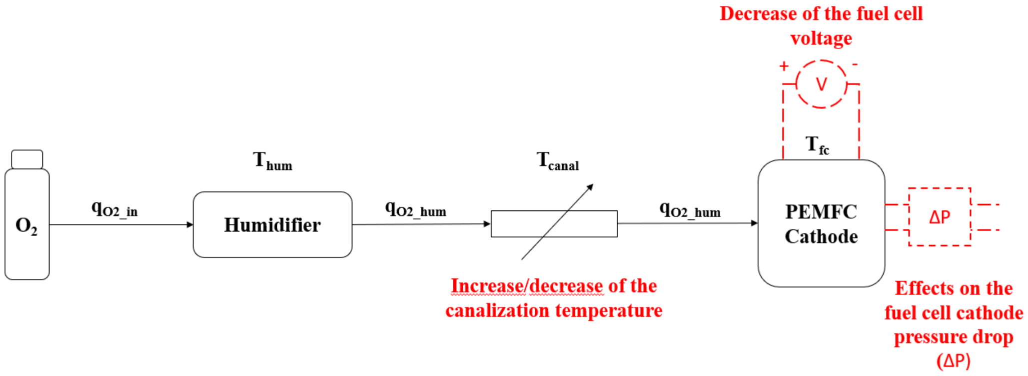


Figure **Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.**-3 : Cathode line gas feeding with water condensation to provoke a fuel cell flooding.

2.2.2 Drying out generation

Membrane drying out occurs when the membrane water content decreases too substantially. Therefore, to provoke the membrane drying out, the input cathode gas flow rate (q_{O2_in}) is increased in order to drain as much water as possible which leads to limit the membrane hydration. Then, the amount of steam injected into the gas feeding is reduced by increasing the canalization temperature of the cathode gas feeding (T_{canal}) which also limits the PEMFC membrane hydration. Finally, increasing the PEMFC temperature (T_{fc}) is also performed to decrease the vapor partial pressure.

Table Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.****-1* summarizes the operating conditions for fault generation (flooding and drying out).

	Normal operating conditions	Flooding operating conditions	Drying out operating condition
I_{fc} (A)	20 (0,4 $A.cm^{-2}$)	20 (0,4 $A.cm^{-2}$)	20 (0,4 $A.cm^{-2}$)
λ_{H2}	2.5	2.5	2.5
λ_{O2}	3	3	**10**
T_{fc} (°C)	70	70	70
T_{canal} (°C)	70	**50**	70
T_{hum} (°C)	62	**62**	**55**
RH%	70	**100 + condensation**	**50**

Table **Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.**-1 : Operating conditions for faults generation

In the Table Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.**-1* λ_{O2} and λ_{H2} represent the oxygen and hydrogen stoichiometries, respectively and describes the oxygen stoichiometry as:

$$\lambda_{O2} = \frac{q_{O2\_in}}{q_{O2\_consumed}}$$

2.3 Fault Mitigation: validation of the AFTC

To validate the proposed AFTC strategy, the following sequences have been implemented on test bench following faults generation as described above.

2.3.1 Flooding mitigation strategy

To validate the proposed AFTC strategy for flooding mitigation, we applied the first case protocol described on Figure Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.***-2 (case 1). The diagnosis algorithm is launched periodically with a period T. After the period 2T a diagnosis process is applied (*Fault diagnosis 1*) and triggers the next transient decision which increases the input gas flow (q_{O2_in}) as well as a deferred decision to T_{fc} of ± 5 °C. This T_{fc} increase must be set small enough to prevent the MEA thermal stress and high enough to allow fast evaporation of clogged water with decreasing vapor pressure.

At the end of *Diagnosis 1* and after a period *T*, a *Diagnosis 2* is triggered. If the same fault is re-diagnosed a transition decision is triggered (namely q_{O_2in}), as well as a deferred one: this time, RH% is modified by ± 10%.

Both decision processes (transient and deferred) modify each controller set point and find iteratively an adjusted one without the fault occurrence. The increments which are considered in the mitigation algorithm for two levels of fault severity are given in the **Erreur ! Source du renvoi introuvable.Erreur ! Source du renvoi introuvable.**.

Table ***Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.***-2 : Increments of the input gas flow thanks to flooding severity (transient decisions)

Relative magnitude increases	**Low level of increases**	**Medium level of increases**
Incrementation of the total input gas flow	Δ_{O2} = + 50 %	Δ_{O2} = + 135 %

The **Erreur ! Source du renvoi introuvable.** summarized the increases link to deferred decisions.

Relative magnitude increases	**PEMFC Temperature**	**Input gas relative humidity**
Relative magnitude increments of mitigation variables	T_{fc} = + 5 °C	RH% = + 10 %

The next step consists in validating the proposed AFTC strategy on a PEMFC regarding flooding and membrane drying out faults. The next section is therefore dedicated to the experimental validation of the proposed AFTC strategy.

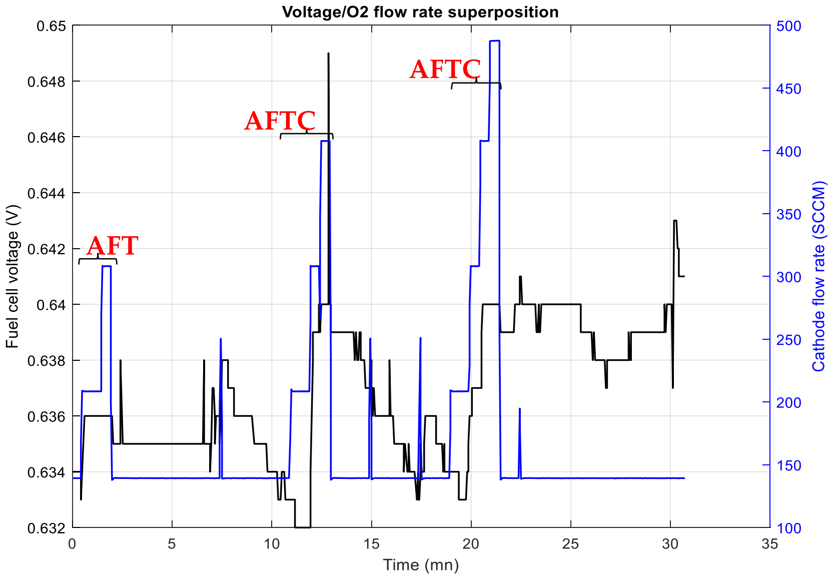
2.3.2 Flooding AFTC results

For the following flooding experiments, the fault mitigation processes are modified with the tunning of two parameters of the AFTC strategy. First, the diagnosis triggering period *T* is set to 30 seconds. Then to 15 seconds and finally to 60 seconds. The level of incrementation (LoI) is set the low level for these three periods. By this way, it is possible to quantify the effect of the triggering period on the flooding mitigation.

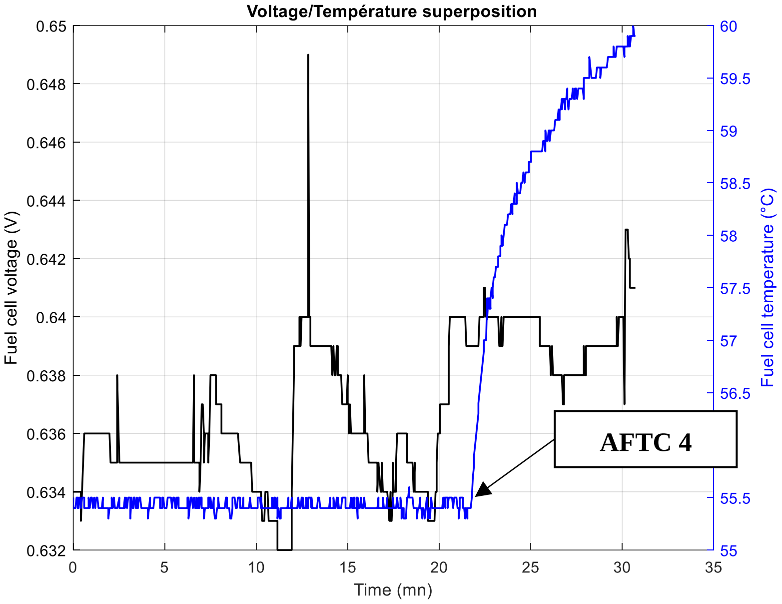
The second step of the experiment consist to repeat the same process with the three diagnosis triggering periods and modify the LoI to the medium level. This step allows quantifying the effect of LoI on the flooding mitigation.

2.3.2.1 Diagnosis period of 30 s and for a low level of increment

Figure Erreur **! Il n'y a pas de texte répondant à ce style dans ce document.**-4 shows a flooding mitigation with a diagnosis triggering period Tdiag = 30s. The fault is mitigated with a low level of increment of a variable for the transient decision.



a) Fuel cell voltage and input gas flow superposition



b) Fuel cell voltage and temperature superposition

Figure **Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.**-4 : Pressure drop, oxygen flow rate and temperature superposition with the fuel cell voltage for T = 30s, a - Fuel cell voltage and input gas flow superposition, c - Fuel cell voltage and temperature superposition.

Figure Erreur **! Il n'y a pas de texte répondant à ce style dans ce document.**-4-a associates the evolution of the fuel cell voltage with the cathode pressure drop. As explained in 0Figure *Erreur* ***! Il n'y a pas de***

texte répondant à ce style dans ce document.-1, the diagnosis tool managed to identify a flooding based on the monitoring of these two variables, used as the 2 flooding fault indicators.

If a flooding is identified, an increase of the cathode flow rate is performed to drain as much liquid water as possible. This is the **transient decision** for flooding mitigation. When the periodically-launched diagnosis tool indicates that there is no longer a fault, the flow rate value is reset to its initial setpoint. 3 transient decisions are marked *AFTC 1* to *3*. Each change of cathode flow rate is plotted on Figure Erreur **! Il n'y a pas de texte répondant à ce style dans ce document.**-4 – b.

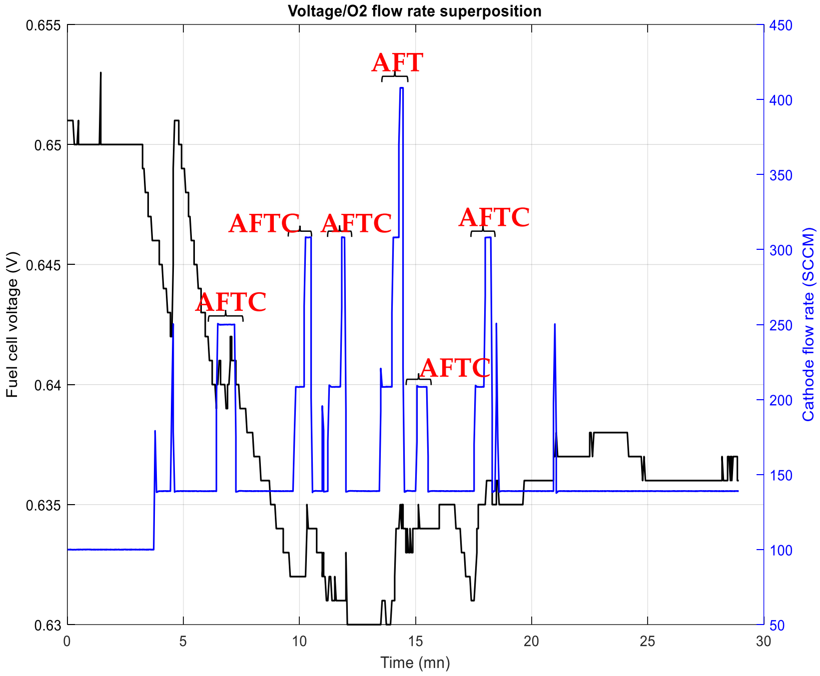
Figure Erreur **! Il n'y a pas de texte répondant à ce style dans ce document.**-4 – c shows the fuel cell voltage and temperature evolutions The change of temperature setpoint is a **deferred decision (**AFTC 4) that has been triggered by reoccurrence of flooding after the third transient decision mitigation AFTC 3 on the Figure Erreur **! Il n'y a pas de texte répondant à ce style dans ce document.**-4 – b.

Figure Erreur **! Il n'y a pas de texte répondant à ce style dans ce document.**-4 – c shows that fuel cell temperature is incremented of 5 °C. After this temperature increase, the fuel cell voltage recovers while the O_2 relative humidity remains unchanged. Following these decisions, the flooding is no longer present. The PEMFC operating conditions therefore allows a healthy fuel cell operation.

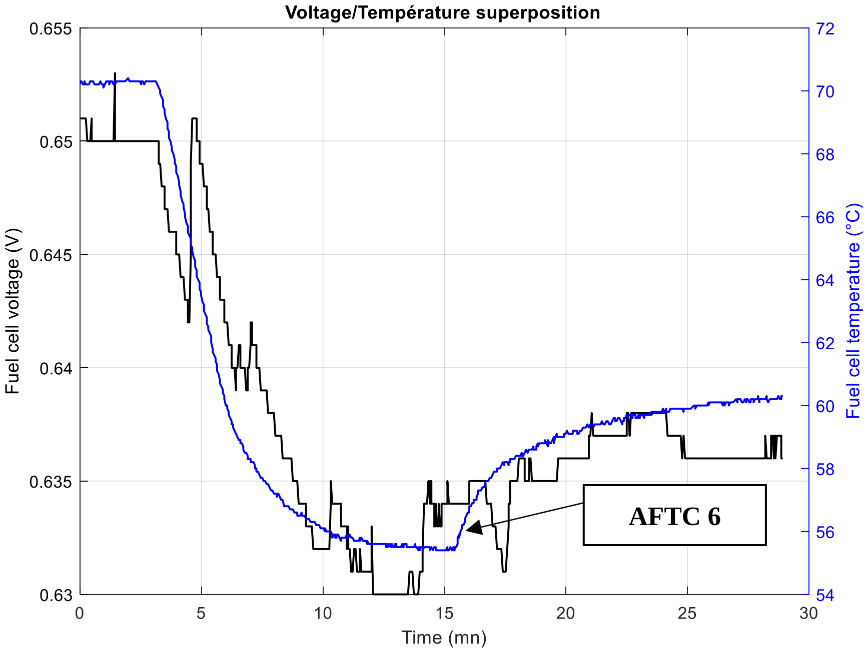
In this experimentation, the flooding fault is permanently mitigated in about 25 minutes after its 1st detection. Three incrementations of O_2 flow rate value and one of temperature were needed. This first experiment shows that fuel cell temperature variable and the level of increments influence the fault mitigation speed. These two actions are thus full of interest for the further study.

2.3.2.2 Diagnosis period of 15 seconds and for a low level of increment

Figure Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.***-5 represents a flooding mitigation process with a diagnosis triggering period T = 15s. The fault is also mitigated with a low level of command magnitude.



a) Fuel cell voltage and input gas flow superposition



b) Fuel cell voltage and temperature superposition

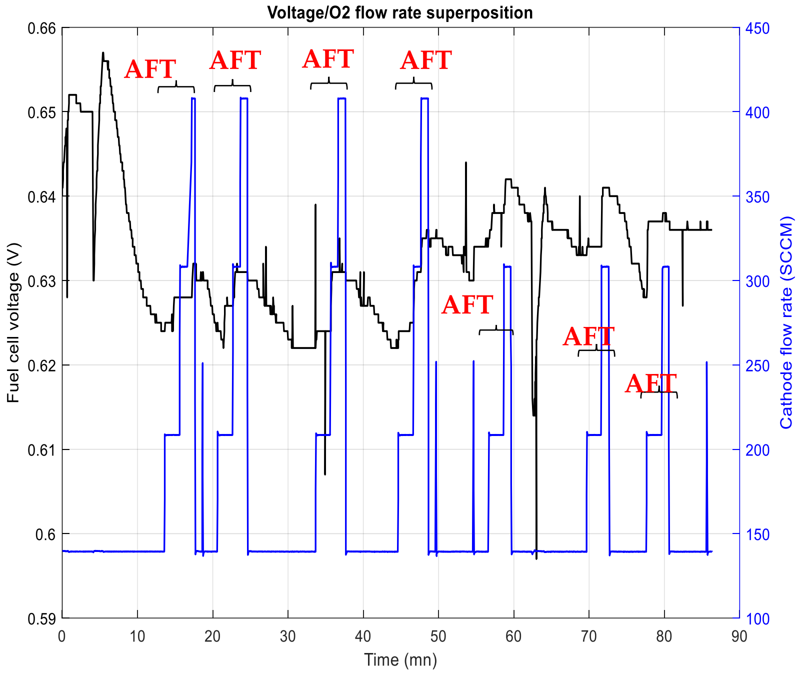
Figure ***Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.***-5 : Pressure drop, oxygen flow rate and temperature superposition with the fuel cell voltage for T = 15s.

In this experimentation, the flooding is permanently mitigated after about 15 minutes. Six O_2 flow rate incrementations have been performed

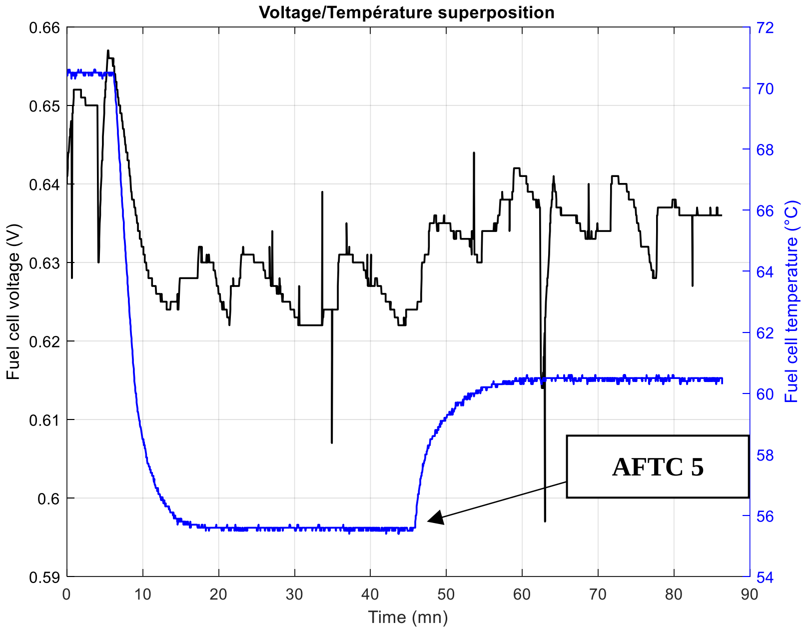
(*AFTC 1* to *5* and *AFTC 7*) and the fuel cell temperature has been increased by 5 °C after 11 minutes (*AFTC 6*).

2.3.2.3 Diagnosis period of 60 seconds and for a low level of increment

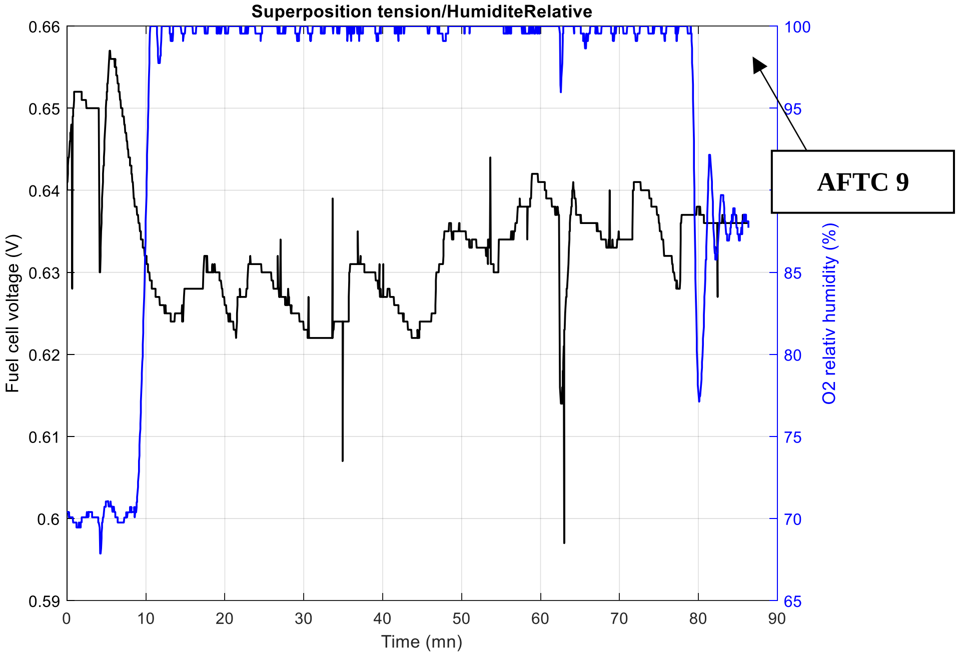
The Figure Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.***-6 represents a flooding mitigation process with a diagnosis triggering period T = 60s. The fault is also mitigated with a low level of increment.



a) Fuel cell voltage and input gas flow superposition



b) Fuel cell voltage and temperature superposition



c) Fuel cell voltage and relative humidity superposition

Figure ***Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.***-6 : Pressure drop, oxygen flow rate, relative humidity and temperature superposition with the fuel cell voltage for T = 60s, a - Fuel cell voltage and input gas flow superposition, b - Fuel cell voltage and temperature superposition, c - Fuel cell voltage and relative humidity superposition.

In this experimentation, the flooding is permanently mitigated in about 70 minutes. Seven flow rate incrementations (*AFTC 1* to *AFTC 7*) have been performed and the fuel cell temperature has been increased of 5 °C after 45 minutes. The cathode gas relative humidity has been decreased of 10 % after 65 minutes.

The flooding AFTC mitigation has also been tested for the medium level of transient increments and for three periods of diagnosis triggering. Results are presented in Table Erreur **! Il n'y a pas de texte répondant à ce style dans ce document.**-3.

Table **Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.**-3 : Flooding mitigation experimentation synthesis.

Flooding	**T = 15 sec and low LoI**	**T = 30 sec and low LoI**	**T = 60 sec and low LoI**	**T = 15 sec and medium LoI**	**T = 30 sec and medium LoI**	**T = 60 sec and medium LoI**
Number of transient decisions	6	3	7	11	10	7
Number of deferred decisions	1	1	2	1	1	1
Deferred decision triggering time	11 mn	23 mn	45 mn and 65 mn	5 mn	10 mn	20 mn
Mitigation time	15 mn	25 mn	70 mn	15 mn	20 mn	25 mn

Table Erreur **! Il n'y a pas de texte répondant à ce style dans ce document.**-3 summarized the number of transient decisions and deferred decisions triggered for each test. It also gives the trigger time for deferred decisions and the fault mitigation times.

The next step of the experimental validation of the fault mitigation strategy consists of applying it on a membrane drying out occurrence.

2.3.2 Drying out mitigation strategy

As for the flooding mitigation, the AFTC strategy manages to mitigate the membrane drying out by iteratively changing the PEMFC operating point. For clarity of the Figure Erreur **! Il n'y a pas de texte répondant à ce style dans ce document.**-7, the pressure drop is not given as it is not meaningfull in the membrane drying out diagnosis. The increases which are considered in the mitigation algorithm for two levels of fault severity are given in the

Table ***Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.***-4.

Table ***Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.***-4 : Increments of the input gas flow thanks to drying out severity (transient decisions)

Relative magnitude increases	**Low level of increases**	**Medium level of increases**
increases of the total input gas flow	Δ_{O2} = - 50 %	Δ_{O2} = - 135 %

The

Table ***Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.***-5 summarize~~d~~ the increases associated with to deferred decisions.

Relative magnitude increases	**PEMFC Temperature**	**Input gas relative humidity**
Relative magnitude increments of mitigation variables	T_{fc} = - 5 °C	RH% = - 10 %

Table ***Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.***-5 : Increments of PEMFC drying out mitigation variables (deferred decisions).

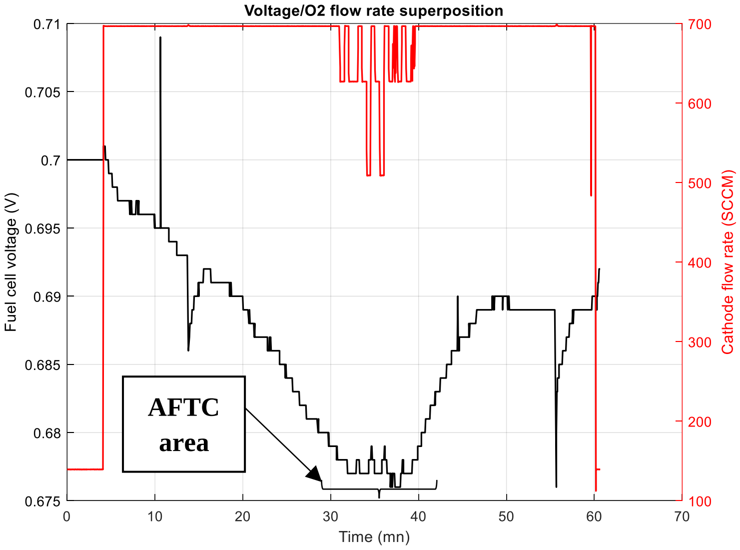
2.3.3 Drying out AFTC results

For the following membrane drying out experiments, the fault mitigation process are modified with the tunning of two parameters of the AFTC strategy. First, the diagnosis triggering period Tdiag is set to 30 seconds, then to 15 seconds and finally to 60 seconds. The LoI is set the low level for these three periods. By this way, it is possible to quantify the effect of the triggering period on the membrane drying out mitigation.

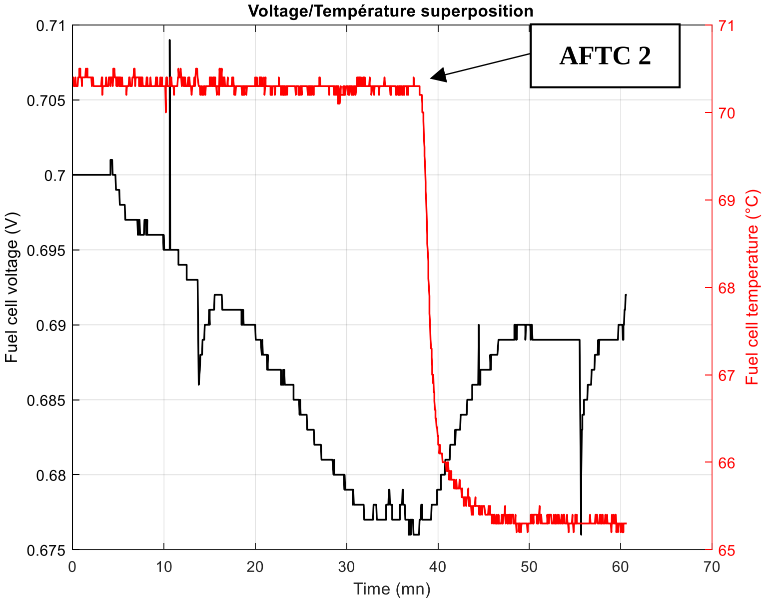
The second step of the experiment consist to repeat the same process with the three diagnosis triggering periods and modify the LoI to the medium level. This step allows to quantify the effect of LoI on the membrane drying out mitigation.

2.3.3.1 Diagnosis period of 30 seconds and for a low level of increment

Figure Erreur **! Il n'y a pas de texte répondant à ce style dans ce document.**-7 presents the membrane drying out mitigation with Tdiag = 30 seconds as diagnosis triggering period. The fault is mitigated with a low LoI.



Input cathode flow and fuel cell voltage superposition



Fuel cell temperature and voltage superposition

Figure **Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.**-7 : Oxygen flow rate and temperature superposition with the fuel cell voltage and T = 30s for membrane drying out, *a* - Input cathode flow and fuel cell voltage superposition, *b* - Fuel cell temperature and voltage superposition.

If a drying out is identified by the diagnosis tool, a rapid decrease of the cathode flow rate is carried out to reduce the amount of drained water. Each change of cathode flow rate is plotted on the Figure Erreur **! Il n'y a pas de texte répondant à ce style dans ce document.**-7. When the diagnosis tool notifies that there is no longer fault identified, the flow rate value is reset to its initial setpoint. As for flooding, the first mitigation process is set through the transient decision phase.

The Figure Erreur **! Il n'y a pas de texte répondant à ce style dans ce document.**-7 - b shows the fuel cell voltage evolution plotted with the fuel cell temperature (AFTC 2). The change of temperature setpoint is due to a membrane drying out reoccurrence after the third mitigation process. The graph shows that fuel cell temperature is decreased by 5 °C. This temperature modification should allow reducing the saturation vapor pressure which leads to increase the PEMFC water content. This kind of decision corresponds to the deferred decision phase because it changes permanently the PEMFC operating point.

After this temperature modification, the fuel cell voltage rises again. The O_2 relative humidity remains unchanged. After these decisions, the membrane drying out is no longer present. The PEMFC operating conditions therefore allows a healthy operation.

In this experimentation, the fault is permanently mitigated after about 16 minutes after the first drying out occurrence. Three flow rates decreasing have been necessary and the fuel cell temperature has been reduced by 5 °C after 8 minutes since the first fault identification.

The membrane drying out mitigation has also been tested for the medium level of transient increments and for three periods of diagnosis triggering.

Results are presented in the **Erreur ! Source du renvoi introuvable.** Table Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.***-6.

Drying out	**T = 15 sec and low LoI**	**T = 30 sec and low LoI**	**T = 60 sec and low LoI**	**T = 15 sec and medium LoI**	**T = 30 sec and medium LoI**	**T = 60 sec and medium LoI**
Number of transient decisions	13	7	4	6	4	4
Number of deferred decisions	1	1	1	1	1	1

Deferred decision triggering time	20 mn	8 mn	6 mn	9 mn	7 mn	14 mn
Mitigation time	25 mn	16 mn	10 mn	20 mn	17 mn	24 mn

Table ***Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.***-6 : Membrane drying out mitigation experimentation synthesis.

The next section aims to proceed to the experiment's discussion and analysis.

3. Discussion

In this part, we will discuss the results of the flooding and membrane drying out mitigation process.

3.1 Flooding mitigation analysis

The influence of three diagnosis periods and two levels of increments have been studied and several metrics used to compare each AFTC strategy performance after a flooding. Indeed, five metrics has been defined to quantify the flooding mitigation and only three of them are relevant metrics for flooding: number of transient decisions; fault mitigation time; deferred decision triggering time. The number of used sensors and deferred decisions are useless metrics for these experiment because of the strong positive effects of the first deferred decision which is the temperature.

3.2 Membrane drying out mitigation analysis

Like for flooding, membrane drying out fault has been tested. The two LoI and the three diagnosis triggering periods considered are the same as for flooding.

Regarding Table Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.***-6 it appears that the triggering period of 60 seconds combined with a low LoI allows the fastest drying out mitigation. Indeed, the long-lasting transient decisions allow a better decrease of the water drainage from the membrane. The deferred decision on the PEMFC temperature is also triggered shortly after the first transient decision that enhanced water presence in the membrane.

For the medium LoI, the experiments show that fastest membrane drying out mitigation is for the period of 30 seconds. Indeed, the LoI is more important that allows a fastest fault mitigation and reducing the water drainage from the PEMFC. The number of transient decisions is also reduced compared to the low LoI experiments and the mitigation time is lower. That corroborates the positive effect of the LoI on the drying out mitigation. Moreover, the deferred decision is triggered earlier, and that also leads to a fastest drying out mitigation. Indeed, this is an important behavior of the mitigation algorithm because in some cases the transient decision could not be sufficiently efficient and leads to a faster trigger of the deferred decision.

Table Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.***-6Table Erreur ***! Il n'y a pas de texte répondant à ce style dans ce document.***-6 shows that there is a compromise between the triggering period of the diagnosis and the LoI of the transient decision. The experimentations show that the trigger period limits the holding time of transient decision because the longer the trigger period is, the longer the transient decision is maintained for fault mitigation. The level of the increments of the transient decision is therefore a major factor that has to be fine-tuned to have significant effect on the fault occurrence.

These observations of the effects of the trigger period and the LoI are corroborated in [23] which indicates that the membrane electrode assembly hydration is carried out after 100 seconds. Therefore, by a strong reduction of the cathode input gas flow and by maintaining it for a sufficiently long time, the fault can be mitigated more efficiently.

In this case there are also only three metrics which could be relevant metrics for membrane drying out in case of low LoI: number of transient decisions; fault mitigation time; deferred decision triggering time. The number of used sensors and deferred decisions are useless metrics for these experiment because of the strong positive effects of the first deferred decision which is the temperature.

However, regarding the experiment with medium LoI only two metrics are relevant: fault mitigation time; deferred decision triggering time. The reason is that the deferred decision are earlier triggered that allows fastest drying out mitigation.

Conclusion

An active fault tolerant control is proposed in this paper to mitigate the fuel cell water management fault issues. For this purpose, a three-modules architecture is proposed with a diagnosis part, a decision part and a control part. The diagnosis part is chosen on the basis of a previous work that manages to identify a flooding and a membrane drying out. Regarding the control module, it only contains the controller which is already implanted on the system in use. This module is designed to allow the strategy to change the fuel cell operating point by acting on the input gas flow, the temperature and the gas relative humidity. The decision allows the link between diagnosis and control. It considers the diagnosis module as a fault sensor and uses the control module to apply its fault mitigation strategy. The proposed decision algorithm thus proposed a fault mitigation into two steps. A transient decision step which allows mitigating a fleeting fault and does not change permanently the operating parameters. The second step is called the deferred decision which modifies the fuel operating parameters permanently toward a healthy operating condition.

This mitigation strategy has been tested on a single-cell proton exchange membrane fuel cell. The tested protocol aims to generate two faults (flooding and drying out), and evaluate the effect of two parameter (namely, diagnostic frequency and level of corrective parameters increments on the mitigation strategy performances.

Results show that by increasing the input gas flow in order to evacuate the clogged water, external water upstream is pushed into the cathode channels which worsens the fault. In this case it is relevant to change the fuel cell temperature in order to increase the saturating steam pressure coupled with the increase of the input gas flow to enhance the water drainage and to evaporate accumulated water. In fact, the same fault can have different causes, and the origin of fault is a very important input for the AFTC performance as it allows to define and tune properly the corrective actions. Moreover, the earlier a fault is identified and the mitigation actions triggered, the better are the AFTC performances.

Regarding the membrane drying out, the results show that transient decisions coupled with the decreasing of the fuel cell temperature is relevant for its mitigation. The tests also showed that maintaining the input flow rate at a low value better has shown better membrane hydration conditions.

The decision module appears as a milestone of the designed strategy. It relies on the designer expertise and information given by the diagnosis tool to adapt the new operating parameters. The used architecture is thus limited by each module response time, reliability and accuracy. Another design as a parallel or serial-parallel of the decision module with the diagnosis could be most suitable for the fault mitigation process. Indeed, the present work only focus on a serial mode strategy with all limitations exposed above. By parallelizing some modules, the limiting effect of a full serial architecture would be reduced and a gain of response time and a better genericity of architecture could be raised. Finally, the strategy has been tested on single-cell fuel cell and should be validated on a PEMFC stack. This stack validation constitutes the next step of our work.

Acknowledgements

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