A review of fault tolerant control strategies applied to proton exchange membrane fuel cell systems

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A review of fault tolerant control strategies applied to proton exchange membrane fuel cell systems

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ABSTRACT

Fuel cells are powerful systems for power generation. They have a good efficiency and do not generate greenhouse gases. This technology involves a lot of scientific fields, which leads to the appearance of strongly inter dependent parameters. This makes the system particularly hard to control and increases fault's occurrence frequency. These two issues call for the necessity to maintain the system performance at the expected level, even in faulty operating conditions. It is called "fault tolerant control" (FTC). The present paper aims to give the state of the art of FTC applied to the proton exchange membrane fuel cell (PEMFC). The FTC approach is composed of two parts. First, a diagnosis part allows the identification and the isolation of a fault; it requires a good a priori knowledge of all the possible faults. Then, a control part allows an optimal control strategy to find the best operating point to recover/ mitigate the fault; it re quires the knowledge of the degradation phenomena and their mitigation strategies.

1. Introduction

Fuel cells (FC) are recognized as efficient and environmentally friendly systems for power generation. Their operation involves however, several scientific fields, which results in strongly corre lated parameters. This makes these systems particularly complex and hard to control, and increases the probability of fault occur rence. Low reliability and short lifetime are still bottlenecks to be overcome for a wide deployment of these systems.

Therefore, the last few decades have seen several researches aiming at better understanding and improving the operation of these systems. For instance, Wakizoe et al. [1] studied three different fuel cell's membranes, and highlighted their physico chemical effects on performance. They showed that the current density, the electrode kinetic parameters or the value of membrane resistance in the linear region (ohmic region) of the polarization curve have consequences on fuel cell's performance. Other studies are dedicated to the energy consumption [2−7], to the safety [8,9] and to the performance improvement [10−16]. Jouin et al. [17] addressed the PEMFC system short lifetime issue and proposed to use a prognostic and health management (PHM) approach in order to extend the FC life span. The authors enumerated each step of the PHM as follows: data acquisition, data processing, data assessment, diagnosis, prognostic, decision support and human machine

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interface. For now, a lot of work has been covering the steps ranging from data processing to prognostic [3,7,9,18 94], and many papers dealing with the fuel cell control were published [2,4,5,10−13,15,16,95−105]. However, the major part of these papers suffer from a lack of FC State of Health considerations in the design of the control itself, when it is known that setting appropriate control actions to counteract faulty operating modes, results on higher availability, reliably and larger lifespan.

Defining the control actions by taking into account the fault diagnostics is known as Fault Tolerant Control (FTC), and as far as we know, FTC applied to fuel cells has not been studied a lot, and represents a novel approach for performance optimization of PEMFC. It is a very efficient approach to guaranty PEMFC's survivability, reliability and maintainability.

This paper is organized as follows: the second section describes the existing faults in PEMFC and their characteristics. This part enables to get a better understanding of their mechanisms and effects on the system, and to identify the relevant associated parameters. Then, possible alternative approaches for different faults mitigation are given in the same section, while control and fault tolerant tools are presented in the following sections III. In section IV, the most suitable strategy according to the performance requirements and experimental constraints is given. Sections V analyzes fault mitigation strategies for PEMFC performance and lifespan. The section VI concludes the paper.

2. PEMFC diagnosis

2.1. Faults

PEM fuel cell stacks and systems can be subject to different faulty operating modes. Piechowiak et al. [106] define the fault as a system's performance degeneration caused by significant or minimal degradations, and several studies classify faults according to different criteria such as effects, response time, reversibility and localization.

To ensure a proper operation of the FC, the operating parameters must be kept in a narrow range of operation. For instance, water management is a complicated task in PEMFCs since any disequilibrium in the water balance, leads to issues such as cell flooding or membrane drying out. Flooding is defined as an accumulation of liquid water in the gas channels or electrodes, impeding the access of reactive gases to the active layers, and therefore decreasing the reaction rate [58]. Li et al. [58] identified flooding as one of the most recurrent PEMFC's faults, and stated that the cathode is more subject to flooding as it is the locus of water production. The flooding probability increases with high current levels, higher inlet gases temperature than the stack's one, or when the humidification of inlet gases is excessive. The lower the O_2 diffusion rate is, the more important the flooding will be: the authors defined four magnitudes of flooding, where a higher magnitude calls for more important performance loss [58]. At the opposite, a drying out can occur if the membrane is not sufficiently hydrated, which results in membrane resistance' increase. It occurs when the inlet gases' temperature is below the FC operating one [21] or when the inlet gases are insufficiently humidified. The phenomenon is detectable by any increase of cell resistance.

Another kind of faults is the short circuit. Silva et al. [79] studied its impact on a 3.8 kW PEMFC performance: during a couple of seconds, a short circuit reaction produces a large quantity of water, decreasing the cell membrane resistivity and eliminating oxygenated species from the platinum surface, which increases the system's performance. However, during short circuit conditions, high thermal gradient appears and local hot spots occurs at the membrane. Moreover, reactant cannot be injected fast enough, therefore

a concentration gradient and local starvation occurs and induces irreversible degradations. Yousfi Steiner et al. [90] defined the starvation as an undersupply of reactants that could occur either at local or global level. The first one refers to local undersupply of reactants associated with irregular reactants distribution, while the overall supply at cell level is high enough. The global starvation denotes an overall undersupply of reactants at cell level. In both cases, the gas flow rate and the relative humidity will exacerbate the starvation that could rapidly induce irreversible corrosion phenomena such as carbon reduction or platinum oxidation.

Another potential fault linked to reactants supply is FC poisoning [70]. At the anode side for instance, the lower the purity of intake reformate hydrogen is, the higher the risk of hydrocarbons traces will be: the adsorption phenomenon due to CO poisoning at the platinum anode catalyst surface induces a catalyst deactivation that leads to performance loss [86,88]. The CO poisoning depends on the inlet gases content, inlet flow rate, humidity, residence time and temperature.

When a fault occurs, its effects are not instantaneous, due to the characteristic duration of the fault setting. The response time of flooding and drying out reflects the dynamics of water (from one second to several minutes). In the case of hydrocarbons poisoning, the response time span is longer. It starts from one second to a day during long term operations. Starvation is much faster, with a response time ranging from one millisecond to approximately one second. As electric phenomenon, the short circuit has the fastest response time, and its response time interval varies from one microsecond to several milliseconds [84]. Table 1 summarizes these faults by response time, involved parameters, effects and reversibility capabilities.

As stated before, each fault has a specific response time and influences differently the FC performance. The cell exposure time to the fault is a key factor that determines the capability to recover performance, for the major part of the faults. Therefore, defining corrective actions is crucial. Furthermore, a sole corrective action cannot be considered for all possible faults and an efficient correction should be adapted to the nature of the identified fault: a suitable control strategy has to be applied for each fault and, in some cases, each level of faults' severity. This is why a proper diagnosis of the fault is needed prior to define the involved parameters, the adapted corrected actions and the suitable control.

2.2. Diagnosis tools for PEMFC

As summarized in Fig. 1, diagnosis techniques are generally divided into two groups: residual based and data based methods. The residual based diagnosis compares a healthy PEMFC's model outputs to the real system measurements. Residuals are analyzed to detect the fault occurrence, and symptom matrix is generated to identify the faults. The data based diagnosis uses data processing techniques. It is based on the human knowledge or on techniques that utilize a set of input and output data to rule on a fault occurrence. Data are then analyzed to determine the distance between faulty operating conditions and nominal operating ones, and to take decision regarding diagnostics. Some works are based on neural networks NN [78,89] or Bayesian network BN [74]. Yousfi Steiner et al. [89] for instance, used a NN to diagnose flooding and drying out. The model inputs are: current; airflow rate; saturation temperature; stack temperature and the outputs are voltage and anode/cathode pressure difference. Residuals are then computed and a threshold function is used for decision making. Riascos et al. [74] developed a BN to detect faults in the air fan, in the refrigeration system or for the growth of FC crossover and the hydrogen pressure. Authors used the Bayesian score (K2) and Markov chain Monte Carlo algorithms for an automatic generation

Table 1
Faults in PEMFC, effects, response time, relevant parameters and reversibility.

| Fault	Response time (second)	Effects	Reversibility	Involved parameters
Short-circuit	10^{-6} to 10^{-2}	Membrane and catalyst layer degradation [79]	Irreversible in the case of local heating or starvation	Relative humidity, temperature, gas flow rate, partial pressure (example of this phenomenon in Ref. [107])
Starvation	10^{-3} to 10^{1}	Catalytic layer degradation [90]	Irreversible	Relative humidity, temperature, gas flow rate, partial pressure, current (example of this phenomenon in Ref. [107])
Flooding	10^{0} to 10^{3}	Performance losses and slow system degradation due to starvation and material alteration [58]	Entirely **reversible if treated in time**	Gas flow rate, current, relative humidity (example of air starvation in the article of A. Taniguchi et al. [81])
Drying	10^{0} to 10^{3}	Performance losses and pinhole degradation of the membrane [21]	**Entirely reversible if treated in time**	Stack temperature, relative humidity, gas composition, exposure time [90]
CO Poisoning	10^{1} to 10^{5}	Performance losses and then starvation [70]	Reversible depending on exposure time, temperature and inlet gas composition	Relative humidity, temperature, gas flow rate, partial pressure (example of this phenomenon in Ref. [107])
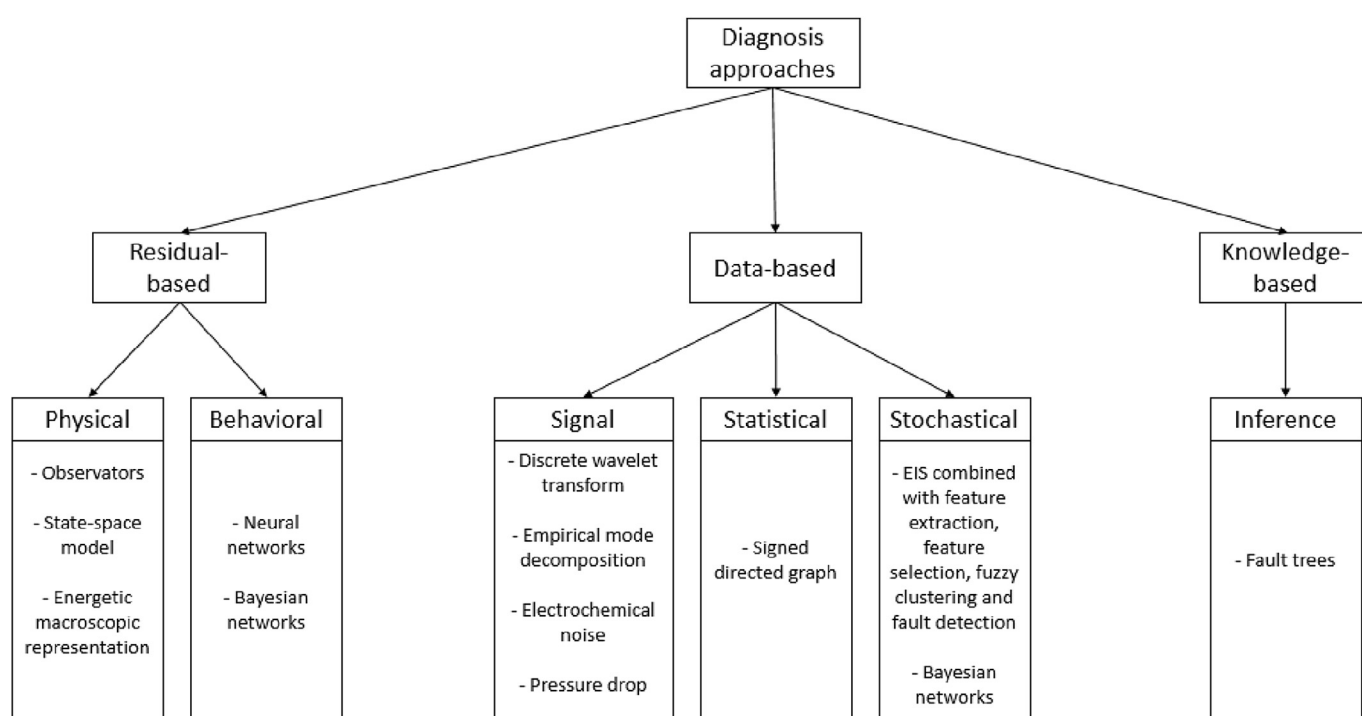
Fig. 1. Approaches and methods for diagnosis.

of the graph.

Other works focused more on signal processing tools: Pahon et al. [69] propose a novel method that consists of applying a discrete wavelet transform (DWT) to the PEMFC output voltage or pressure drop. The comparison of the resulting coefficients to the healthy ones allowed a proper diagnosis of a high air stoichiometry condition. Another proposed method by Damour et al. [31] consisted of using the empirical mode decomposition (EMD) to decompose a signal in intrinsic mode functions, on a sliding window of 60 s and with a sampling frequency rate of 1 kHz. The online method allows to detect and identify a flooding and a drying out fault. In another work, Legros et al. [56], explored the frequency domain with power spectral densities (PSD) to detect and identify flooding and drying out faults. This PSD is based on the online measurement of the electrochemical noise (EN) which is directly done on the fuel cell electrodes and digitized at several sampling rates. They highlighted that EN is lower under humidified gas operation than in dry conditions. Finally, Ma et al. [108] used the pressure drop (PD) signal as diagnostic tool to study the dynamics behaviors of a PEMFC. Their goal was to correlate the pressure drop at inputs/outputs of the channels with their liquid water content. The study showed that the PD measurement is well correlated to the liquid water content and therefore is a suitable diagnosis tool for flooding.

Zheng et al. [93] made use of characterization tool such as the electrochemical impedance spectroscopy (EIS) to diagnose oxygen starvation, water flooding and drying: Through a 4 steps Pattern recognition (PR) methodology (feature extraction, feature selection, fault detection and fuzzy clustering), the authors were able to rule on fault occurrence. Other PR tools, such as support vector machine (SVM) are also used by Li et al. [59] and Data based statistical methods such as Signed Directed Graph Method (SDG) by Hua et al. [48] and Giurgea et al. [42].

The choice of one approach over the other depends mainly on the user's knowledge and available data. In general, the diagnosis should provide the closest results to reality (reliability), with a good

processing time (quickness) that allows real time applications (rapidly triggering corrective actions will reduce the exposure time to fault). It should also react to a large range and different amplitudes of faults (sensitivity), be applicable for different fuel cells (genericity) and have a strong on line capability to allow supervision [71]. Furthermore, the nature of the diagnosis is a key criterion of choice: passive diagnostics uses only the existing input/output system signals to detect the fault, while active one consists of exciting the system to detect faults faster or to amplify the FC system response [41]. Table 2 gives an overview of the methods and their criteria of choice:

The table A1 in annex A summarizes each previous method. When experimental data are used, information on the considered stack or cell is given to detail the validation domain of the presented tool.

3. Control strategies for PEMFC

Many kinds of control strategies for a PEMFC system exist, and some of them are presented below. Indeed, each control strategy describes different ways to regulate flow rates, input gases temperature and humidity. For instance in case of mass transfer phenomenon for PEMFC, Wang et al. [2] designed a robust control with a H_{inf} controller to regulate hydrogen flow rate in order to improve the fuel cell performance. The principle is to define the features of a nominal plant and the features of a disturbed one, to minimize the maximum gap between them. This kind of controller allows reducing the hydrogen consumption while guaranteeing fuel cell performance. In their article, Garcia Gabin et al. [10] proposed a single input single output Sliding Mode and a feedforward action to control the air feed of a PEM fuel cell. The feedforward action aims to provide a swift move to reach the final steady state value with reference to the current of the stack. The sliding mode controller is also used to mitigate the transitory effects of the load change and any other considered disturbances. Again a sliding mode strategy has been used by Kunusch et al. [12] to control the inlet flow rate of oxygen for a PEM fuel cell (transportation applications). In this case, a super twisting algorithm allows to avoid chattering phenomenon. Another technic based on backstepping controller with an adaptative one has been used by Li et al. in Ref. [11]. These controllers are directly applied on the nonlinear system model without linearization. Here, the aim is to maintain the oxygen excess ratio around the desired value. Another work has been done by Liu et al. [109] on a 150 kW hybrid tram heavy duty PEMFC engine. They developed a semi mechanical semi empirical air supply system model that is embedded in the control fuel cell system. The goal is to control a centrifugal air compressor following the duty cycle on the engine. The control system is also composed by a feed forward PID controller that shows good response time and accuracy during simulation and experimental tests. This work is relevant because the air supply control and therefore of the compressor is a big issue

for fuel cell lifetime as air starvation has to be avoided and consumption of the compressor which decreases the output net power. Then, Sanchez et al. [110] propose an air feed system control of a PEM fuel cell system by an adaptive neural network. The neuro controller is then used on a PEMFC hardware in the loop emulator.

Fuel cell and inlet gases temperature are also leading parameter involving research for control strategies. For instance, Cheng et al. [111] proposed to control a fuel cell temperature of city bus to improve its efficiency. Indeed, they work on a warm up method to optimize the global efficiency. Authors justifying the value of their work by comparing the maximum equivalent energy consumption case with their strategy. They underline that it can save 4.69 MJ when the warm up time is 1000s.

A fuzzy logic based water heating control was proposed by Tabanjat et al. [102]. The goal is to control the water supply of a PEM electrolyzer to a pre determined temperature *via* a controlled water flow circuit in order to enhance PEM efficiency. Here, a fuzzy logic controller is used to maintain the water temperature to its reference value.

Another work related with energy management has been done by Sid et al. [6] proposing an optimal command for the energy management of a PEMFC hybrid vehicle. The objective is presented as an optimization problem based on the minimum Pontryagin principle and on Hamiltonian function. The goal is to minimize the fuel consumption for a given profile.

Finally some dealing with control optimization and degradation decreasing through model predictive controllers. One of the proposed work was done by Barzegari et al. [112] applied on a cascade type PEMFC. The aim is to track the desired voltage trajectory of a stack which operates in a dead end mode. The MPC makes an on line optimization of the future control moves. Authors underline the good performance of their strategy in tracking desired trajectories and give the maximum relative error between the simulation and experimental results less than 10%. Zhang et al. [113] also work on a model predictive controller. They have shown interest for irreversible degradation of internal composition such catalyst layer or membrane and propose to focus their work on water management in PEMFC. The work is based on a water management system model and a model predictive control by using a recurrent neural network. The goal of this strategy is to avoid fluctuation water concentration in cathode and extend the lifetime of the fuel cell. The work of Zhang et al. [113] took into consideration the fuel cell state of health. Indeed, their control objectives is to maintain an appropriate water distribution in the anode side. By this way, some degradations and thus loss of performance due to the water concentration can be reduced. This kind of consideration is a major issue for fuel cell lifetime and should be extended to other fuel cell fault for a better lifetime improvement.

The previous articles highlight two mains control objectives. The first one is to minimize the fuel consumption. These types of control make sense because of the high costs of hydrogen. The

Table 2
Classification of diagnosis method with their constraints.

Diagnosis and data computing tools	On line	reliability	Quickness	Sensitivity	Genericity	Non linear response
DWT	Yes	High	High	High	High	High
EMD	Yes	High	High	High	High	High
EN	Yes	Good	Good	Good	High	High
EIS with pattern recognition and classification tools	Usually no, but it is possible with a converter on a static point [93]	Good	High	High	High	High
BN	Yes	High	High	High	High	High
NN	Yes	High	High	High	High	High
SDG	Yes	High	High	High	High	High

second one focuses on the fuel cell state of health. Indeed, the willingness in some cases to reduce the transitional effects and to inject gas with the best fuel cell operating temperature is a major issue for the fuel cell lifetime. This is due to the relatively short lifetime of fuel cell systems. However, it is important to note that except for the last cited work [113], in all the other cases most of control laws hardly consider fault occurrence, and therefore fuel cell state of health (SoH). table A2 is a summary of papers dealing with PEMFC control.

4. Fault tolerant control

Fault Tolerant Control (FTC) is the ability of a system, through its control, to absorb any unexpected event while continuing to deliver the required performance [114].

For PEMFC systems, fault occurrence is highly probable, due to the strong parameter coupling. In order to improve the reliability, a fault tolerant control strategy is therefore needed to make the system fulfill the application requirements and fulfill its mission. However, the challenge is to develop a control law for faults occurrence in real time. Therefore, faults have to be identified fast enough to avoid any irreversible degradation. Zhang et al. [92] proposed two ways to develop a FTC strategy: the Passive FTC (PFTC) and the Active FTC (AFTC). Each strategy has particular strengths and drawbacks.

Lebreton et al. [115] and Oudghiri et al. [116] defined the PFTC as an anticipated compensation of faults, with the following characteristics:

- In the PFTC strategy, the control is designed to be robust to a small range of predefined faults, which allows avoiding both the use of a diagnosis tool and the reconfiguration of the control law.
- This strategy is only tolerant to the predefined and considered faults (usually small set of predefined faults).
- If too many faults are considered, it could decrease the controller performance. It is also able to reject these predefined faults while maintaining the optimal performance in closed loop.
- The PFTC is designed off line, and all of its parameters are pre defined [114]. This implies a low computation time suitable for real time applications, no diagnosis nor control reconfiguration is needed.

The AFTC strategy has the ability to give an appropriate response to any variation of the physical parameters of the system (fault). It requires therefore a diagnosis tool to maintain the system stability and performance. As for PFTC, in case of unrecoverable faults or partially recoverable faults, AFTC maintains the system stability, even in a degraded mode. Fig. 2 shows the different possible control strategies for a FTC.

For an AFTC architecture, a diagnosis and a decision making system are introduced to determine the best control strategy for a fault mitigation. Fig. 3 shows a combination of the diagnosis, the decision making system and the controller results in the AFTC strategy:

4.1. Decision making structure

The decision making module is the link between the diagnosis module and control module in the case of FTC strategy. Zhang et al. [117] cited in their paper some existing reconfigurable controller as the linear quadratic regulator, the eigen structure assignment,

multiple model, and others. They highlight that these methods suppose a perfect diagnosis tool and the post fault model completely known. For this reason, in the case of a FTC strategy on a PEMFC system, a decision making module is needed to compensate the lack of both diagnosis reliability for online application and a good system knowledge. It allows ruling with more accuracy about faults occurrence or taking decision about the best action for fault mitigation. Several kinds of decision module can be designed depending on the studied system and the considered fault. For example, Lebreton et al. [14] design a decision making module for PEMFC system to avoid uncertainties from the diagnosis tool. Indeed, the authors used a 20 s sliding window which corresponds to 5 successive experimental points. The principle is to assign a label to each point. These labels are tied to a fault. If the number of points assigned to a fault is more than a half, the associated fault is considered. This method is relevant in the case of fault with low response time such as flooding or low anode and cathode stoichi ometry. In the case of faster ones, like cathodic starvation, the considered sliding window could be too big. Fig. 4 is an illustration the decision process based on the sliding window.

Another work has been published by Xu et al. [118], who work on a fuel cell hybrid powertrain. They used a decision making module to choose some predefined actions for fault mitigation. Indeed, authors associate an action to a fault occurrence. In this case, the diagnosis result is considered with no uncertainties, which improves the diagnosis processing time and therefore the fault mitigation delay. It however implies a high level of confidence for the diagnosis module. Fig. 5 gives a synthesis of how this approach could be applied to a PEMFC.

Zidani et al. [119] work on fault tolerant control applied to an induction motor drives against sensor failures, using fuzzy decision systems. In their paper they consider two kinds of controllers. First, a sliding mode controller (SMC) used sensors to control the system. Then, a fuzzy logic controller used for a sensorless control. Indeed, in the case of a sensor failure, the FTC strategy has to be able to switch to a sensorless control with a good transition smoothness in terms of speed and torque transients. The change of controller is managed by a fuzzy decision that assures the transition. Here, the authors also consider a diagnosis result without uncertainties because a sensor is failed or not. Indeed, they only focus on control decision and not on diagnosis reliability. The Fig. 6 represents a decision process done on sensor or sensorless controller.

Another work of Zhang et al. [120] of nonlinear uncertain sys tems used decision process. In their paper the decision process due to a fault occurrence is made when the modulus of at least one of the estimation error components exceed its corresponding bounds. Authors combined the fault detection with a fault isolation decision to rule on the fault occurrence. Therefore, the decision process is integrated in the diagnosis module: when the diagnosis system rules on a fault occurrence, a fault tolerant controller is activated. This kind of decision process has thus two levels of decision. First, it helps the diagnosis module to avoid uncertainties, then it takes a decision on controllers to mitigate the fault occurrence. The Fig. 7 illustrates the decision process based on diagnosis uncertainties avoidance with predefined actions for fault mitigation.

Noura et al. [121] illustrate in their book a diagram of functional breakdown of control and diagnosis structures. It is stratified into several levels. The first level is composed of several control mod ules, which are monitored by coordination and synchronization modules at higher level. Then, a supervision module manages these control modules. In parallel with this control structure, a diagnosis module is designed. Finally, at the top of the diagram, the decision
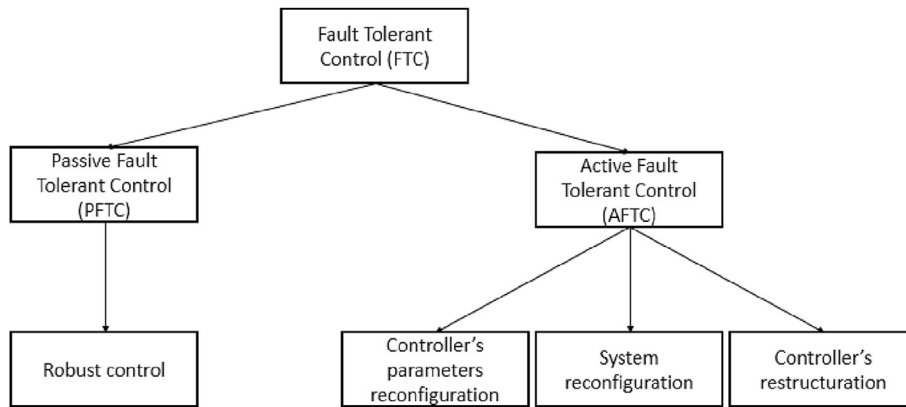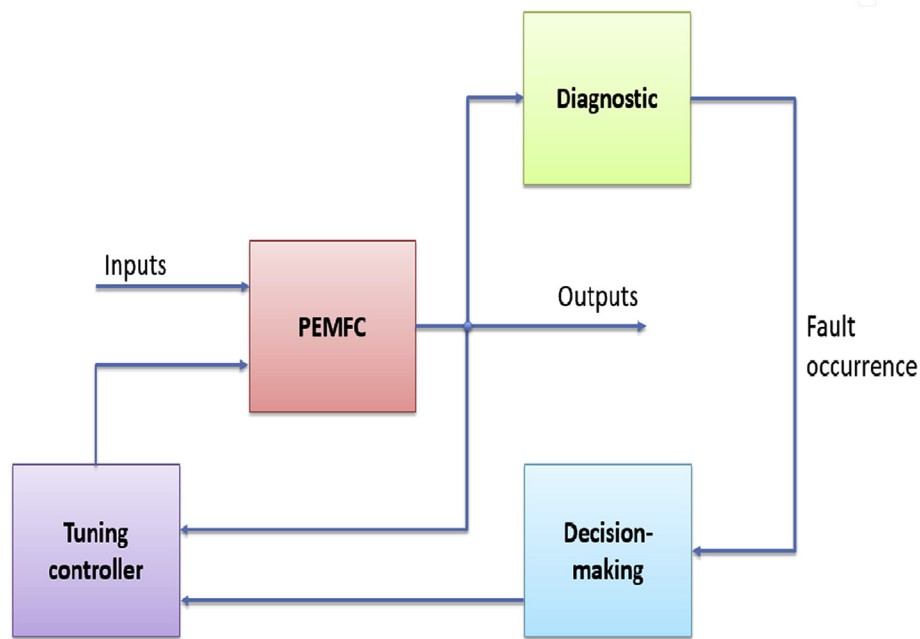
Fig. 2. FTC strategies.

Fig. 3. AFTC strategy.

Fig. 4. Decision process based on a sliding window.
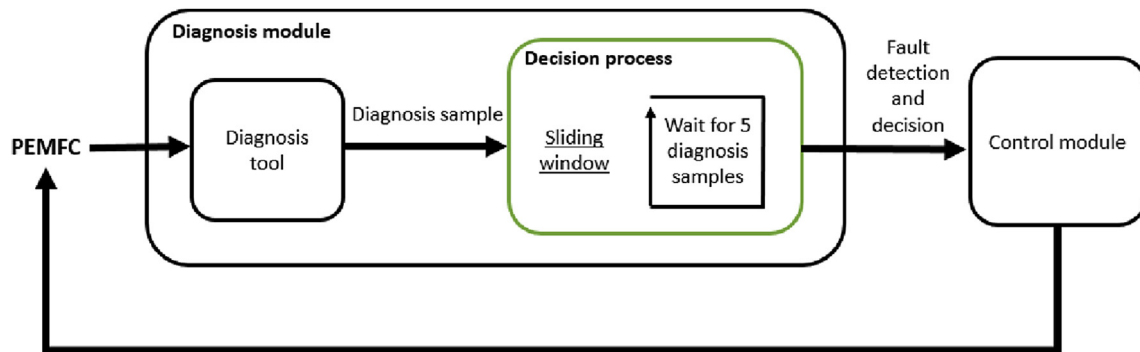
making module and resources management are used to coordinate the diagnosis process with the control structure. It should be noted that authors distinguish the decision process with the resources management, which represents another aspect of the decision making module. Indeed, previously the emphasis was put on diagnosis uncertainty avoidance and on the best control action for
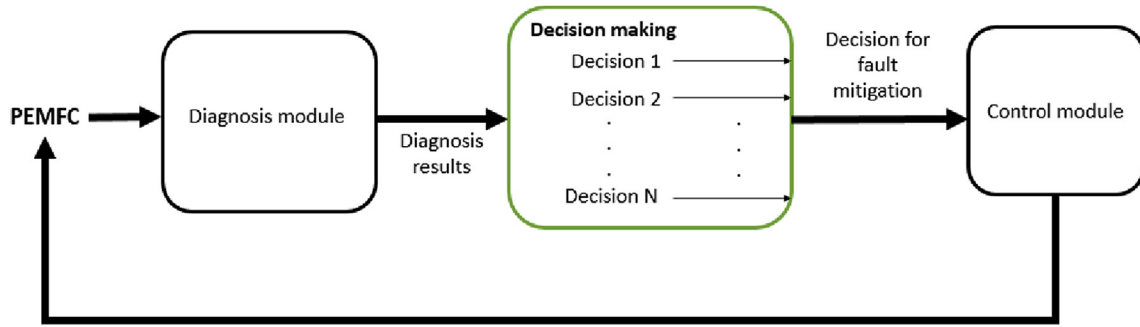
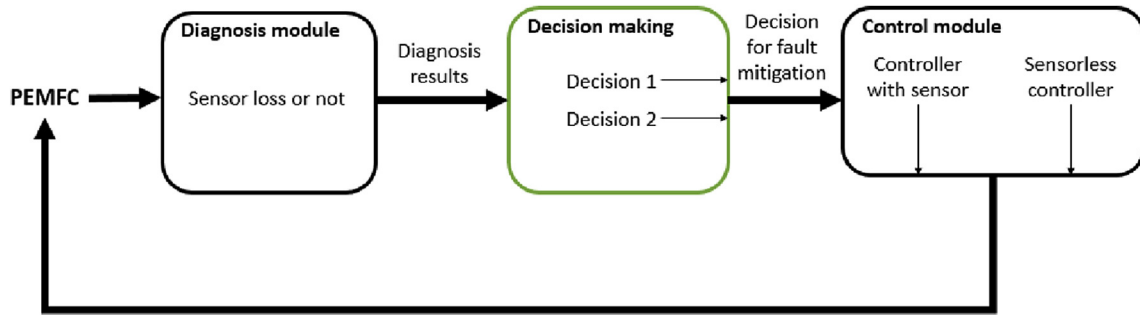**Fig. 5.** Decision process based on predefined action for fault mitigation.

Fig. 6. Decision process based on predefined controller with sensor or sensorless controller.
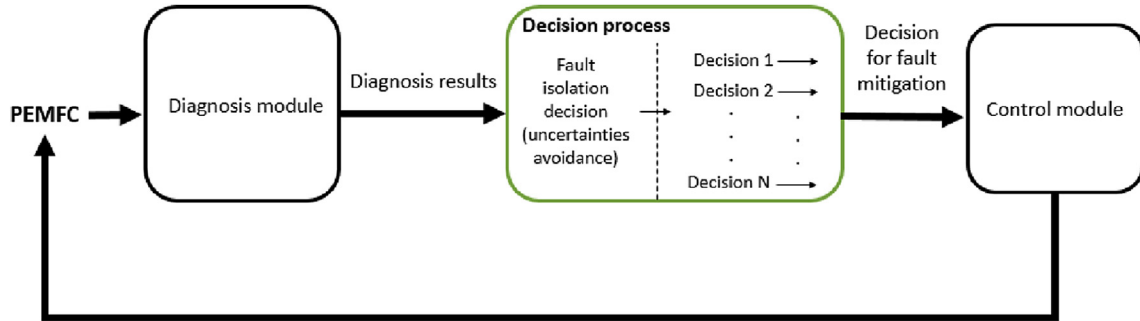

Fig. 7. Decision process based on diagnosis uncertainties avoidance and predefined actions for fault mitigation.

fault mitigation.

Miksch et al. [122] use a decision module for an active fault tolerant model predictive control (AFTMPC) strategy. In their work, when a fault occurs, an accommodation block is used for fault mitigation, which leads to change the objective function parameters and the tuple of constraints set. The feasibility of the accommodated objective function is then tested into an analysis and decision block and if the feasibility is not achieved, a corrected set is done to build a new objective function. An infeasibility appears when the new set of parameters for the model mismatch with the system. If no valid control law can be found, the system is shutdown and waits for user interaction. This kind of controller could be used for PEMFC application. Fuel cell fault should be taken into consideration and the feasibility of the set of controller parameter based on them. However if the set of controller parameters takes time to be computed, the fuel cell fault with fast response time as starvation could degrade the PEMFC.

As seen above, the decision making module is the link between the diagnosis module and control module in the case of FTC strategy. Several kinds of decision module can be implemented and depends on some criteria as the confidence in diagnosis tool, the fault response time, the study system or the type of the control architecture. In the case of a PEMFC application, all these criteria must be taken into consideration, and several decision methods should be merged for an optimal fault mitigation.

4.2. Active fault tolerant control

Blanke et al. [123] defined two types of AFTC. The first one consists of predefining off line controller's parameters (associated to predefined faults) and switching to the relevant ones when the corresponding fault occurs. This method allows the AFTC to satisfy the real time constraints and can be quoted as a restructuration of the control law. The second one can be used when the actualization of the controller's parameters, as consequence of fault occurrence, enables to maintain the system stability. In this case, it can be quoted as controller's parameters reconfiguration. Therefore, an AFTC strategy must respect the following constraints:

- the detection and isolation of any fault have to be done with accuracy, on line and in real time,
- the restructuration or reconfiguration of the actualized control laws must be made on line and on real time,
- the fault recovery needs to be done in real time.

AFTC strategies present some advantages such as taking into account a large set of predefine faults, and providing the system stability even in degraded mode. It has also some drawbacks such as (i) the AFTC's implementation is considerably more complex than the PFTC's, due to the implementation of an online diagnosis tool, coupled with a decision strategy which manage a control part, (ii) a high computing time in case of controller reconfiguration, which could have impacts on the real time aspects of the imple mentation, and (iii) the use of a very sensitive diagnosis tool is required to detect and isolate any fault with accuracy. This sensitive constraint substantially reduces the choice of diagnosis tools.

For a AFTC system, it is possible to consider four sub systems: a reconfigurable controller; a diagnosis system; a controller recon figuration mechanism and a reference set. Blanke et al. [123] and Zhang et al. [92] highlighted some constraints for AFTC's applica tion, due to real time aspect:

- controller's parameters have to be adjusted in real time,
- controller have to be automatically restructured using a trial and error method,
- the whole computational process has to provide a solution, even if there is no optimal one.

It should be noted that these two methods are complementary. As a matter of fact, detection and isolation can be time consuming, and lead to a system divergence. In order to prevent any system divergence due to time delay, a PFTC could be applied to maintain the system stability during the diagnosis process, before an AFTC mechanism takes over for an adequate control.

In order to present some practical ways to apply fault tolerant control approaches, few examples are given below, highlighting different applications. For instance, Majdzik et al. [124] presented a fault tolerant control strategy applied on a battery assembly sys tem. They used a residuals generation based diagnosis block in an FTC algorithm: the algorithm consists of a switch to the suitable control law if a fault is diagnosed. This is an interesting way for fast fault mitigation. Indeed, the switch means that the control law has been built offline and improves the fault mitigation quickness. In their paper, Zhang et al. [92], developed a closed loop control strategy which tolerates FC system faults by maintaining suitable operating conditions. This kind of FTC is defined as a combination of fault diagnosis with a control strategy that aims at maintaining an acceptable performance level during operation in faulty mode. Another example of Maharjan et al. [106] consists in applying a FTC strategy for a battery energy storage using a cascade PWM (pulse width modulation) converter. Their goal is to provide a continuous operation of battery units, even if the converter cell or the battery unit is in faulty condition. Li et al. [57] propose in their paper an architecture based on a diagnosis system and three sliding mode controllers (SMC). The fault tolerant control strategy is applied to an electric vehicle in order to control its longitudinal speed, lateral speed and the trajectory deviation. They use for their study an active fault tolerant control.

Several papers dealing with fault tolerant control also exist in many other fields, such as in transport and energy storage [107−109] or in electronic manufacturing services [112]. Miksch et al. [122] use an active fault tolerant model predictive control

(AFTMPC) for a real time implementation. The simulated fault are: actuator faults like saturation; freezing and total loss. In the case of a fault occurrence, an accommodation or reconfiguration process can be activated. They define the accommodation as the change of the control law for a fault mitigation. The reconfiguration consists of a change of the control loop and the control law. Indeed, ac commodation and reconfiguration are major topics for fault tolerant control strategies. These two points need to be further detailed in the case of PEMFC applications because faulty condi tions have large span action. Another research on FTC has been done by Li et al. [125] for nonlinear Lipschitz stochastic distribution systems. They highlight the problem of the diagnosis system ac curacy. Indeed they proposed, in addition to the diagnosis system, a fault estimation (FE). Authors investigated some possible ap proaches as the sliding mode observer technique (SMO), adaptive approach or unknown input observer method. They underlines a big issue of diagnosis systems. Indeed, the compromise between the speed, reliability and genericity of the diagnosis tool could provoke a decrease of diagnosis result accuracy. The type of faults which can occur in the system is also a problem for fault diagnosis accuracy. For this reason, in FTC strategies, it is generally useful to consider an additional module for diagnosis results filtering. Badihi et al. also used a AFTC strategies [126] applied in an offshore wind farm. For their study they used a fault detection and diagnosis (FDD) system in a fault tolerant control strategy. Any faulty event can be analyzed by the FDD from the system powers and generate an information about any faulty condition. An automatic signal correction and an accommodation are set on the faulty turbine.

Shahbazi et al. [127] study a six leg back to back fault tolerant converter. In their system, fault can occur in each leg and are diagnosed by comparing the estimated and measured pole volt ages. They assume that a reconfiguration of the control strategy is enough to ensure a minimum performance. The reconfiguration mechanism consists of a bidirectional switch to change the con verter structure from six leg to five leg. This paper assumes that an investigation of the possible degraded mode has been made. Indeed, authors highlight the possibility to consider the system to operate with minimal performance.

In the medical domain, Su et al. [128] study microfluidic bio chips. They used this technology for patient health monitoring and for this reason, its reliability have to be ensured. In order to do so, a fault tolerant strategy is applied on the biochip to keep its func tionalities even in faulty conditions. In the article, authors consid ered a uniform failure probability to estimate fault tolerant capacity of the biochip. This kind of applications warns about the system reliability and the necessity to keep performance during faulty conditions. Redundancies or high diagnosis system performance can be used to avoid degradations.

Guilbert et al. [13,15] applied a FTC strategy to the DC/DC con verter of a PEMFC. The considered converter is made with 3 legs. An electronic control unit (ECU) is used as diagnosis system to detect any faulty condition. In this case, the FTC mechanism consists in degrading the converter performance to bring back the PEMFC to optimum operating conditions.

Fukuhara et al. [129] worked on an open cathode fuel cell. They stated that anodic flooding, which causes carbon corrosion, is one of the recurrent fault. For this reason, a work on the exhaust gas management is done to improve the time delay between two purges. The goal of this fault tolerant strategy is to mitigate the effect of the water for the extension of the fuel cell lifespan. They also develop a physics based anodic chamber model, in order to generate residuals to diagnose a flooding in the anode chamber. Here, authors underline that it exists some permanent processes

that always generate a fault. In this case, a bad water management can increase the water accumulation and finally degrade the system.

One of the few research on (A)FTC applied to PEMFC, have been done by Lebreton et al. [14] [115] dealing with water management and air feeding system. They used a neural network to compute on line the new PID self tuning parameter values to recover the detected fault. In their study, the FTC strategy computes on line and in real time a new oxygen stoichiometry value adapted to the fault occurrence. However, this kind of fault mitigation is relevant if authors consider the occurrence frequency of the same fault. The occurrence frequency is the number of appearance of a fault on a given time. Indeed, a decision which is only based on stoichiometry can mitigate the fault but it has no influence on the occurrence frequency. For this reason, the decision tool should be designed to include the fault occurrence frequency. Wu et al. [130] also performed a FTC strategy applied to a PEMFC. They used a diagnosis method based on residual generation with a back propagation neural network model, reconfiguration mechanism and three adjustable nonlinear controllers. The diagnosis system is designed by the generation and analysis of residuals between the real system data and a back propagation neural network to detect a flooding, drying out or normal operating conditions. Their controller consists of feedback linearization and is used to change the voltage and pressure difference depending on normal or faulty conditions. Some researchers applied a FTC strategy on auxiliaries' faults of PEMFC systems. In their paper, Nouri et al. [131] aim to improve the photovoltaic system efficiency by proposing a fault tolerant control using diagnosis tools and a reconfiguration mechanism on a multilevel dc dc converter. In their study, when a fault is detected, a flag variable is raised, then a reconfiguration circuit is activated for a fault recovery. In the case of less complex systems than fuel cells, the processes are well known. For this reason and because fault behavior is known, offline configuration is the best methodology for fault mitigation.

The table A3 gives a summary of papers dealing with fault tolerant control.

There are many possible combinations of control laws with diagnosis tools and decision blocs to develop a FTC strategy. The best one strongly depends on the constraints imposed by the studied system and the considered faults. The FTC strategy has to detect, isolate and compute the adapted control law to recover the fault before any degradation occurs.

5. Discussion

There are many possible combinations of control laws with diagnosis tools and decision blocks to develop a FTC strategy. The best one strongly depends on the constraints imposed by the studied system and the considered faults. The FTC strategy has to detect, isolate and compute the adapted control law to recover the fault before any degradation occurs.

Yet, for the complex PEMFC systems, each fault has a specific response time and influences differently the performance. The cell exposure time to the fault is a key factor that determines the capability to recover performances, for the major part of the faults. Therefore, defining online, real time corrective actions is crucial for these systems. Because a sole corrective action cannot be considered for all possible faults, and an efficient correction should be adapted to the nature of the identified fault, a suitable control strategy has to be applied for each fault and, in some cases, each level of faults' severity (magnitude). This is why a proper diagnosis of the fault is needed prior to define the involved parameters, the adapted correction actions and the suitable control.

The existing publications on fuel cell control address two main objectives: either minimizing the cost (fuel consumption) and/or optimizing the performance. Very few works consider fault occurrence and therefore fuel cell state of health (SoH) and lifetime, which are real issues for fuel cell systems deployment. This could be explained by the difficulty to develop online, real time, sensitive and accurate enough diagnostics, combined with online, real time control laws reconfiguration. Besides, the high interdependence of the complex fuel cell parameters makes the system stabilization very sensitive to any post diagnostic adjustment of the controller parameters.

In a FTC strategy, the decision making module is the link between the diagnosis module and control module. Several kinds of decision making modules can be implemented taking into account criteria such as the confidence in diagnosis tool, the fault response time, the studied system or the type of the control architecture. In the case of a PEMFC application, several decision methods should be merged for an optimal fault mitigation and besides all these criteria, two important considerations should be taken into account, namely the occurrence frequency of the same fault and the magnitude of the fault. The occurrence frequency is the number of appearance of a fault on a given time. For instance, a decision which is only based on stoichiometry can mitigate the water management related fault but it will have a limited influence on the occurrence frequency. On the other hand, the major part of the faults appears gradually, therefore, adapted decision to the fault magnitude can be chosen. However, it is far from easy to determine a fault magnitude with the existing diagnosis tool, and this is the reason why, fault magnitude is hardly considered in the existing decision strategies.

Therefore, a fault mitigation has to be done with three considerations: the fault has to be mitigated as fast as possible (stoichiometry action in case of FTC for water management for instance); the fault magnitude has to be known to take the best decisions (that means the use of an accurate online diagnosis tool); the decision tool has to decrease the fault occurrence frequency.

6. Conclusion

Low reliability in PEM fuel cells remains one of the major obstacles to a large commercialization. For this reason, a fault mitigation strategy, also called a FTC must be set up. This paper reviews the possible fault tolerant control FTC strategies and discusses their use in PEMFCs systems. The different steps of a FTC strategy, namely diagnostics, decision and control are given. If many studies have been already made about control of a fuel cell through auxiliaries, the literature does not provide a lot of information about FTC strategies applied to PEMFC systems, which can be considered as a milestone to increase the reliability of PEMFC systems. Indeed, several faults occur in PEMFC and each of them affects it differently and degrades it more or less rapidly. For this reason an accurate online fault diagnosis remains a major issue for FTC strategies. Actually, the more accurate the diagnosis tool is, the more efficient the control action is. In addition an additional module is needed: a decision making module. It allows avoiding the diagnosis uncertainties and taking decision about the best control strategies for optimal fault mitigation.

Acknowledgements

APPENDIX A

A1

A summary of papers dealing with fault diagnosis.

Auteurs	Description of the diagnosis approach	Faults	Variables & parameters
Zheng et al. [94]	Fuzzy logic and classification, data acquisition with spectroscopy method by electrochemical impedance.	- Water management issues - air starvation	- Anodic relative humidity - Cathodic relative humidity - Hydrogen stoichiometry - Air stoichiometry - Stack temperature
de Beer et al. [32]	Using EIS through rapid injection of in-signals across the membrane	Flooding - Drying	Signal variation between 1 Hz and 1 kHz Cathode Stoichiometry 2.4 Anode Stoichiometry 4
Chevalier et al. [30]	2D modeling of the impedance spectrum (AC) of a PEMFC	Flooding - Drying	- Thickness of cells 0.1 m - Width cathode channels 1.10^{-3} m - GDL thickness 300 0.10^{-6} m - Membrane thickness 89.10^{-6} m - Membrane conductivity 0.45 S.m^{-1} - Anode current exchanged 80 A m^2 - Cathode current exchanged $6.8.10^{-2}$ A.m^{-2} - Anode charge transfer anode 1 - Cathode charge transfer 0.583 - Porosity GDL 0.43 - Double layer capacity 240 F m^{-2} - Temperature 313 K - Absolute pressure 1 bar - Air flow 0.4 L min^{-1} - H2 flow 0.16 Lmin^{-1} - Air relative humidity 100% - Hydrogen relative humidity 100%
Damour et al. [31]	Empirical mode decomposition method	Flooding - Drying	- Fuel cell temperature 70 °C - Anode/cathode pressure 300 kPa - O2 and H2 relative humidity 80% - Saturated H2 stoichiometry 2 - Saturated O2 stoichiometry 5
Hua et al. [49]	statistical methods such as the Signed Directed Graph Method	No information	- Vehicle mass $1.4672.10^{.}4$ kg - Vehicle frontal area 7.5 m^2 - Drag coefficient 0.7 - Rolling resistance coefficient $1.8.10^{-2}$ - Mechanical efficiency 95% - Masse factor 1.1 - PEM fuel cell rated power 80 kW - DC/DC rated power 80 kW - Ni-MH battery rated capacity 80 kW - Electric motor peak power 150 kW - Electric motor peak torque $1.121.10^3$ N m - Electric motor rated power 100 kW - Electric motor maximal rotational speed 6.10^3 rpm
Steiner et al. [80] & Pahon et al. [69] [50]	stack voltage signa processing l by wavelet transform (WT)	Flooding - Drying	Current, individual cell voltage Extraction of the « feature vector » from the WT analyze to get a corresponding parameter set
Benouiouaa et al. [23]	Extracting singularities from the stack voltage signal using the method of WT	- Anodic & cathodic starvation - Cooling system fault - CO poisoning	- Air & hydrogen stoichiometry - Pressure - Temperature - Presence of CO (ppm)
Banerjee et al. [20]	Using of two-phase pressure drop multiplier as a diagnosis tool for characterizing PEM fuel cell performance	Flooding - Drying	- Temperature (30 60 °C) - Cathodic relative humidity (0 95%) - Current density (0.4 0.8 A/cm^2)
Ma et al. [108]	Using the pressure drop as a diagnosis tool	Flooding - Drying	- Current density - Humidification and cell temperature 60 °C - O2 flow speed in channels - Anode et cathode pressure 0.1 Mpa(AFTC)- H2 flow rate 87 ml min^{-1}
Li et al. [61]	Data clustering methodologies (Fisher Discriminant Analysis & Support Vector Machine).	Flooding - Drying	- Cell area 100 cm^2 - Cells number 20 - Flow field structure serpentine - Nominal output power 500w - Nominal operating temperature 40 °C - Operating temperature region 20 65 °C - Maximum operating pressures 1.5 bar - Anode stoichiometry 2 - Cathode stoichiometry 4
Riascos et al. [74]	Bayesian network. A mathematical model for a 500 W stack	- Air fan fault - Refrigeration system fault - Growth of the fuel crossover - Hydrogen pressure fault	- Cells number 32 - Membrane active area 64 cm^2 - Membrane thickness 178 μm - O2 pressures 0.2095 atm - H2 pressures 1 atm - Contact resistance to electron flows 0.003 ohm - Fuel crossover and internal loss current 3 mA cm^2

Auteurs	Description of the diagnosis approach	Faults	Variables & parameters
Shao et al. [78]	Neural networks	- Stack cooling system - Air delivery system - Hydrogen delivery system	- O2 & H2 pressure - Maximum electrical current density 0.469 A cm^2 - Stack power 500 W - Number of cells 36 - Environmental T 5 30 °C - Unit dimensions: 22.5*12.5*17.5 cm^3 - Weight: 2.5 kg - Reference potential E0 44.15 V - limit of current density 0.468 A cm ^{2}
Steiner et al. [89]	Neural networks	Flooding - Drying	- Cells number 20 - Total active area 100 cm^2 - Temperature range 25 65 °C - Thickness 25 μm - Platinum load (anode & cathode) 0.4 mg cm ^{2} - Gas diffusion layer thickness 420 μm - Porosity 84% - Flow channel (geometry) used: serpentine - Reactant stoichiometry ratio (anode/cathode): 2/4 - Compressive force/torque used to assemble the stack 8 Nm - Gas purity: Hydrogen with max 8 ppm impurity (<3 ppm H2O, <1 ppm O2, <0.5 CO + CO2, <5 ppm N2) - Ion resistivity of DIW used for humidification of reactants Deionized with conductivity < 10 μS cm ^{1}

A2

A summary of papers which dealing with PEMFC control.

Authors	Description/Advantages	Applications	Variables/Parameters
Wang et al. [2]	Robust Control based on H infinite norm to regulate the hydrogen flow rate. PEMFC power supply management.	2 stacks of 3kw 1 battery Li-Fe	- Cells number 80 - Max power supply DC 3.2 kw - Input voltage 24 VDC - Output voltage 42-80 VDC - Weight 40 kg - Fuel input temperature −15 to 55 °C - Fuel input pressure 0.36 bar - Air input temperature 10 50 °C
Wang et al. [3,5]	Discussion of several power management strategies on a PEM fuel cell using a robust control based on H infinite norm.	Fuel cell of 500 W used in a car	For the [3] - Fuel cell voltage 24 37 V DC - Nominal power 500 W - Efficiency for 500 W > 47% - Dimensions (cm˜3) 11.7*11.3*25 For [5] - Cell's number 37 - Surface 47 cm^2 - Max power supply <500 W - Output voltage 22 37 V - Efficiency for 500 W > 47% - Dimensions (cm˜3) 11.7*11.3*25 - Weight 2.4 kg - Stack temperature <55 °C
Wang et al. [103]	Multivariable robust control of a proton exchange membrane fuel cell system	The PEMFC is modeled as a MIMO system	- Number of cells 15 - Active area 50 cm^2 on each - Maximum efficiency of the fuel cell stack is 37% under dry H2/air and humidification-free Control variables are: - H2 flow rate - Air flow rate - Pump voltage
Hilairet et al. [99]	Online humidification diagnosis of a PEMFC using a static DC DC converter The system is modeled with a Randles equivalent circuit	PEMFC's stack of 500 W.	- Number of cells 23 - Active Area 100 cm^2 - Activation losses 8.3 V - Double layer capacitor 20 mF - Membrane resistivity 40 mOhm - Current ripple 3.5 peak-to-peak - Series inductor 35 nH
Zhiyu et al. [105]	Optimal control of the air-cooling and self - humidification by using a predictive control negative feedback	Stack of 56 cell and a power supply of 2 kW	- Output current between 0 et 75 A - Max temperature 75 °C - Hydrogen pressure 0.36 bar - Output voltage between 28 V et 56 V
Tabanjat et al. [102]	Control of the water temperature at the electrolyzer input to improve the efficiency of the PEMFC. Using a PI	Application on a PEMFC electrolyzer of 59 kW powered by a photovoltaic	- Stack current 300 A - Cell's number 90 - Hydrogen pressure 1.09*10^5 Pa

Authors	Description/Advantages	Applications	Variables/Parameters
	controller combined with a correction based on fuzzy logic	generator - through a " boost- converter "	- Oxygen pressure 10^5 Pa - Surface 0.06 m^2 - Active area 0.0016 m^2 -Membrane thickness $130*10^{-6}$ μm
SID et al. [6]	Minimizing the consumption of hydrogen to maintain the battery's charge state. Using the principle of minimum Pontryagin.		- Number of battery element 30 - Mass of a battery element 3.76 kg - Nominal capacity of the battery 12Ah - Max state of charge 90% - Min state of charge 40% - Max power of the fuel cell 30 kW - Min power of the fuel cell 600 W
Garcia-Gabin et al. [10]	Describes a method of control sliding mode based on a SISO model. The purpose of control here is to act in oxygen starvation.	Ballard's PEMFC stack of 1.2kw. The stack is composed of 46 cells and each of them with an 110 cm^2 membrane.	Controller parameters: - Sliding surface - Tuning parameters of the sliding surface - Tuning parameters of the controller - Times constants Stack's parameters: - Oxygen excess ratio - Stack current - Air mass flows from compressor - Compressor voltage in %
Kunusch et al. [12]	Control by sliding mode on a PEM fuel cell system. Stability is improved by a " Super Twisting " algorithm	Applied to a 75kw PAC system and powered by a 14kw compressor. Integration on an electric vehicle	- Stack temperature - Cathode volume - Atmospheric pressure - Ambient temperature - Electric motor resistance - Compressor diameter - Motor inertia
Li et al. [11]	Adaptative control on a fuel cell by using the backstepping technique. - Control is done without linearization - Controller is easily implemented on the practical application - Stability of the closed-loop system - Using a neural network to approximate the unknown non-affine function	The controller is applied on a 75 kW PEM fuel cell system.	The model only includes the air flow model States of the used model: - cathode pressure - air pressure in the supply manifold - the rotational speed of the compressor
Benchouia et al. [97]	Adaptative fuzzy logic controller for PEMFC	The controller is applied on PEM fuel cell system of 4 cells	Controlled variable: hydrogen molar flow. - Temperature 298.15 K - E^0 1.229 V - Membrane resistivity 0.126 S - Limit current density 0.01496 A cm^{-2}
Matraji et al. [16]	Robust control of the PEM fuel cell air-feed system via sub-optimal second order sliding mode The objective is to maintain optimum net power output by regulating the oxygen excess ratio in its operating range, through the air compressor.	On a Hardware-In-Loop test bench with a twin screw compressor and real time fuel cell emulation system.	- Number of cells 90 - Fuel cell temperature 353.15 K - Compressor inertia 671.9×10^{-5} kg m^2 - Motor friction 0.00136 V.(rad $s^{-1})^{-1}$ - Motor constant 0.31 N m A^{-1} Cathode volume 0.0015 m^3 - Supply manifold volume 0.003 m^3 - Cathode inlet orifice constant 0.3629×10^{-5} kg (Pa s) - Cathode outlet orifice constant 0.76×10^{-4} kg(Pa s)

A3
A summary of some papers which uses FTC strategies.

FTC strategies	Description	Architecture	Variables/Parameters
Guilbert et al. [13]	Fault tolerant control applied to the DC/DC converter of a PEMFC.	The study is made on an Interleaved Boost Converter with 3 legs The diagnosis tool is a software which discusses with the Electric Control Unit (ECU) of the PEMFC. Here FTC consists of degrading converter performances.in order to bring back the PEMFC in an optimum operating condition	- PEMFC rated power 1 kW - PEMFC rated current 42 A - PEMFC voltage range 25 32 V - Inductor value 120 μH - DC bus voltage 100 V - Switching frequency 20 kHz - Duty cycle range 0.68 0.74
Guilbert et al. [15]	FTC method which involve the change of the Pulse-width modulation gate control signal. The method is applied to the electric vehicle using a PEMFC stack.	IBC topology (Interleaved DC/DC Boost Converter). Interest is compensation to the extent that if a branch is in fault, another branch takes over.	- PEMFC power 1kw - Current 42 A - Ripple current 2 A - Voltage span 25 32 V - Inductance 150 μH - Bus DC voltage 100 V - Switching frequency 20 kHz
Lebreton et al. [14]	Method allowing the detection of PEM fuel cell faults related to water management. A combined neural network in a self-tuning PID controller is used.	The used architecture is based on a diagnosis system into neural networks and a self-tuning controller for a reconfiguration of the controller parameters.	- PID parameters Kc, Ti, Td - Necessary parameters for the number of I/O - A parameter for the trajectory tracking error

FTC strategies	Description	Architecture	Variables/Parameters
Li et al. [57]	- Control of the longitudinal speed - Control of the lateral speed Control of the trajectory deviation rate on the road - Restructuration controller	Architecture based on a diagnosis system and three sliding mode controllers. FTC applied to an electric vehicle.	-Vehicle mass - Widths of the front and rear of the vehicle - Longitudinal stiffness of the tires - Moment of inertia of the vehicle around the axis of deflection - Radius of the wheel - Moment of inertia of the wheel - Reducing factor adhesion of the wheel
Aouzellag et al. [4]	Energy management and FTC strategies for fuel cell/ultracapacitor hybrid electric vehicles	Speed regulation by Sliding Mode Control (SMC) Bus voltage regulation and UC converter control by PI controller. The diagnosis tool is based on an algorithm	- Vehicle mass 1300 kg - Rolling resistance force constant 0.01 s^2 m ^{2} - Air density 1.2 kg m^3 - Frontal surface area of the vehicle 2.6 m^2 - Tire radius 0.32 m - Aerodynamic drag coefficient 0.3 - Acceleration due to the gravity 9.8 m s ^{2}
Puig et al. [101]	Fault-tolerant explicit MPC of PEM fuel cells	The controller is pre-determined offline. It allows changing in real-time controller parameters without recomputing the MPC controller or having a bank of pre-computed MPC controller. The simulated fault is the starvation.	- Control action on oxygen excess ratio - Number of cells 381 - Membrane Nafion 117 - Active area 280 cm^2 - Nominal stack voltage 45 V - Nominal stack current 191 A - Maximum power 75 kW
Wu et al. [130]	Active fault tolerant control used to recover flooding and/or drying out. The Strategy is applied on a PEMFC.	They used a back-propagation neural network (BPNN) model to compute residuals to rule on normal or faulty conditions. Three backup controllers are used to regulate the pressure difference and PEMFC voltage. This regulation allows to change the set point when a fault occurs. The reconfiguration mechanism consist of a switch between the three available controllers.	Inputs of BPNN model: - Injected water flowrate in humidifier - Water flowrate of the coolant - Anode inlet pressure - Humidifier inlet pressure - The load current
Wang et al. [132]	Fault tolerant control on a civil aircraft. The reconfiguration mechanism is used in this case.	Structures are predetermined. The principle is to "switch" on a controller with appropriate parameters to changes the physical behavior of the system	No information

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