A Survey of Diagnostic of Fuel Cell Stack Systems

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. Abstract: Fuel cells are electrochemical energy conversion devices that convert hydrogen and oxygen into water, producing electricity and heat in the process. Fuel cell is one of the best alternatives of fossil energy. Recently, the research community of fuel cell has shown a considerable interest for diagnosis in view to ensure safety, security, and availability when faults occur in the process. These faults must be detected early and sometime estimated and accommodated. Therefore, they are vulnerable to faults that can cause the stop or the permanent damage of the fuel cell. To guarantee the safe operation of the fuel cell systems, it is necessary to use systematic techniques to detect and isolate faults. The present paper presents a survey and analysis of different techniques used for diagnostic of Fuel Cell Stack System.

1. INTRODUCTION

In the last decade, the fuel cell is the interest focus as the most promising power generation technology. Fuel Cell (FC) development has generated much interest in technological and research community. Fuel cells (FCs), the devices that convert chemical energy, such as hydrogen, are an ideal electrical power source: lower/zero emission, silent, high efficiency. A FC produces only electricity, water, and heat, thereby eliminating pollution at the energy conversion. This is one of the reasons why fuel cell is attractive.
Research and development of Fuel Cell Systems (FCS) for various applications has dramatically been increased in the last decade. Proton Exchange Membrane Fuel Cell (PEMFC) system is one of the most promising candidates to substitute traditional systems such as internal combustion engines. The PEMFC is an attractive candidate not only for transportation systems but also for other applications such as stationary systems, portable systems due to its higher power density and lower operating temperature compared to other types of fuel cells.
Recently, the research community of FC has shown a considerable interest for Fault Detection and Diagnostic (FDD) in order to ensure safety, security, when faults occur. These faults must be detected early and some time estimated and accommodated.
FC science and technology cuts across multiple disciplines, including materials science, interfacial science, transport phenomena, electrochemistry, and catalysis. It is always a major challenge to fully understand the thermodynamics, fluid mechanics, FC dynamics, and electrochemical processes within a FC. These are the reasons for that the energy generation systems based on FCs are so much complex. Moreover these systems need a set of auxiliary elements (valves, compressor, sensors, controllers, etc.) to make the FC works at the pre-established optimal operating point.
Therefore, they are vulnerable to faults that can cause the stop or the permanent damage of the FC. To guarantee the safe operation of the FCS, it is necessary to use systematic techniques to detect and isolate faults for the purpose of diagnostic.
On the one hand, diagnostic tools can help distinguish the structure-property-performance relationships between a FC and it components. On the other hand, results obtained from diagnostic also provide benchmark-quality data for fundamental models, which further benefit in prediction, control, and optimization of various transport and electrochemical processes occurring within FCs.
The present paper presents a review and analysis of different techniques used for diagnostic of Fuel Cell Stack System (FCSS).
The paper is organized as follows: Section 2 describes the FCSS and the main faults which may affect the system based on failure modes. Section 3 deals with description of FC Diagnostic methods. In Section 4, knowledge-based approaches applied to FCSS and developed this last decade are presented. Section 5 presents the application of model-based approaches to FCSS. Finally, concluding remarks are presented in the last section.

2. ANALYSIS OF FCSS SUBJECT TO FAULTS

2.1. FCSS description and faults

Figure 1 shows the scheme of fuel cell system and the possible faults occurring in this system. The system consists in four circuits of matter and energy: air, hydrogen,

humidification and electrical circuit. Hydrogen valve: it is used to control the flow of fuel gas H_2; air filter and compressor: The purpose of the air filter is to remove solid particles such as dust, pollen, molds and bacteria. The motor-compressor's role is to increase the air pressure by reducing its volume; humidifier: it is a device that increases the moisture in the air compressed and filtered through the circuit of humidification; fluid manifold: with one input and multiple outputs, it can distribute the gas under uniform guaranteeing the supply of fuel gas of each cell of stack; FC: it is the heart of the system which consists of several cells depending on the power that was almost required; cooling group: an electric fan is placed next to the compressor and the humidifier to cool. A second fan ensures the low temperature of the stack in normal operation; batteries and converter DC / AC: batteries allow storage of electrical energy generated by the battery and inverter allows conversion DC / AC.
To measure the physical variables of fuel cell system (FCS), several sensors were installed: flow and pressure of hydrogen, air flow, current and velocity of compressor, water pressure coming out of stack current, voltage and temperature of stack. Sometimes, electrical storage devices are used to prevent any stiff electrical transient on the FC stack and to enable braking energy recovery in case of use in transportation. Most of details of the description of FCSS can be found in [1], [2].

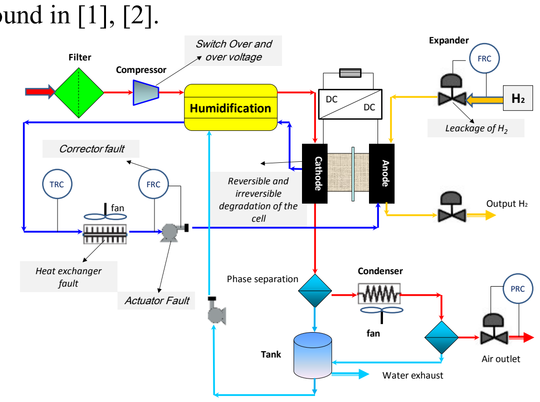

Fig.1: FCSS with possible faults

2.2. *Fault trees analysis of FCSS*

Figure 2 shows the scheme of faults tree of a part of FCSS. In our case, we have not taken account of faults of battery, converters, storage, etc.. There are three classes of failure at high level for the global system: failure of hydrogen circuit, compressor failure and failure of fuel cell stack. In each class, it was shown several types of faults at second level and causes of failures at third level (Fig. 2.). From this fault tree, we can see that the hydrogen circuit is sensitive to leak faults of hydrogen and capping. Two possible failures can affect the compressor on the mechanical and electrical part. In addition, there is also a failure of the controller which controls the engine and a hydraulic failure due to the reduction of the effect of compressibility. Inside the FC, it is shown that the distribution of water in the channel of the membrane may cause drying or flooding. In addition to water generated by the electrochemical reaction, the temperature of the fuel cell can affect drying and flooding faults. Because of the existence of parasitic reaction, it is possible to detect contamination of the feed gas by N2, CO or CO2 especially in stack systems that use hydrogen produced from a fuel reformer or for systems operating in an environment polluted.

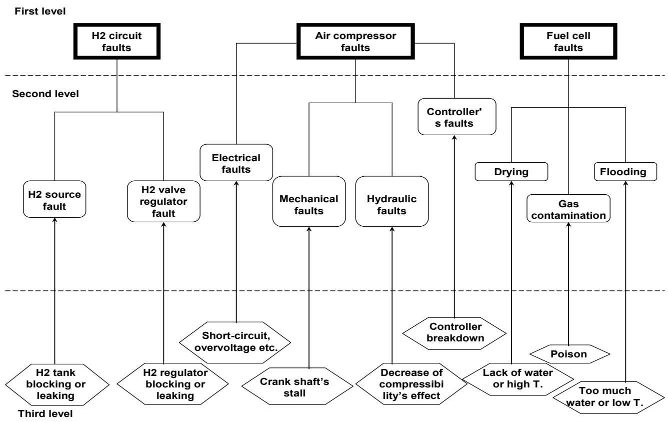

Fig. 2. Fault trees of Fuel Cell Stack System

3. FUEL CELL DIAGNOCTIC APPROACHES

3.1. Classification of Diagnostics methods for FCSS

The proposed scheme is illustrated in Fig. 3. This classification of different approaches of Diagnosis is based on the literature. There are classified on two types of methods: model-based approaches and knowledge-based or non model-based approaches.

3.1.1 Model based approaches

Model-based approaches are classified generally in two categories: qualitative model-based and quantitative model-based. Reviews of qualitative methods and quantitative methods respectively up to 2003 are given in [3], [4].
Most qualitative model-based approaches include: abstraction hierarchy (functional and structural analysis), causal models (signed direct graphs [5], fault tree analysis [6], qualitative physics). Most quantitative model-based approaches include Analytical Redundancy Relations (ARRS) or parity space relations, Observers, Kalman filters and parameter estimation methods.
The performances of the quantitative model-based methods depend essentially on the model accuracy. The model of FC system is very complex containing nonlinearities and involving coupling between several energy areas: electrical, thermodynamic and electrochemical.

3.1.2 Knowledge-based approaches

In contrary to the model-based approaches where *a priori* knowledge about the model of the process is assumed, in non model-based methods only the availability of large amount of historical process data is assumed [7]. Knowledge-based methods are mainly built on the availability of a sufficient and well defined data base which is used to perform learning, pattern recognition, qualitative reasoning and statistical analysis.
As shown on Fig. 3, the most knowledge-based approaches are: signal processing approaches: magnetic resonance imaging, acoustic emission, magnetic field, neutron radiography; artificial intelligence approaches: fuzzy logic, neural network, expert system; experimental methods: voltage measurement, impedance spectroscopy, polarization

curve interpretation, spatial current density distribution, pressure drop and gas chromatography.

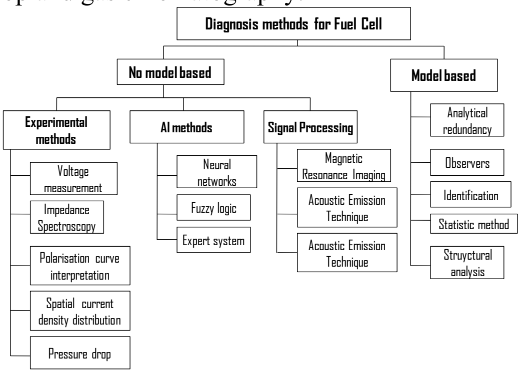

Fig.3: Classification of different approaches of Diagnostics for FCSS

4. KNOWLEDGE BASED APPROACHES FOR FCSS

4.1 Diagnostic by Signal Processing Approach

Acoustic emission (AE) technique for real time survey of the evolution of the hydration state of the membrane in PEMFCs has been used by Legros *et al* [8]. The aim of this study is to determine if the phenomena linked to water management (hydration, dehydration, flooding) are acoustically active, and if this AE activity is significant.

Reference [9] presented a novel diagnostic test method which allows the determination of the distribution of water in the membrane across the active area by the combination of galvanostatic discharge with current mapping. In Ref. [10], liquid water distribution in the flow field of fuel cell was obtained by using magnetic resonance imaging.

A method based on images by neutron radiography is used by [11]]. Partial flooding is detected in the fuel cell with help of visualization of the liquid water inside the flow channel and gas diffusion media in real operating conditions. Ref. [12] developed a similar methodology used by [11] to detect drying and flooding. This technique is powerful but requirement of a neutron source with a high fluence rate limits its wide application.

Other techniques can be used as optical diagnostics used in many research works in order to delineate the origin and development of flooding with high spatial and temporal resolution.

4.2 Diagnostic by Artificial Intelligence Approach

The AI approach is grouped into the type without model since no detailed mathematical modeling of all components and their interactions mentioned in this approach which only observable input-output behavior as a black box. In [13], an approach using artificial neural networks to alleviate the task of on-board diagnostic for FC vehicles was presented.

As one of the AI methods, expert systems are applied by [14] dealing with the detection and diagnosis of faults when they develop in different parts of a PEMFC system. In this paper, the diagnosis algorithm is based on a singular pencil model and on-line expert systems.

Fuzzy logic which needs a fuzzy model is one of the most approaches used in AI. In [15], a diagnosis-oriented model in Sugeno type of a FC power generator dedicated to automotive applications is proposed. A genetic algorithm was used for tuning of the fuzzy diagnosis model. Through this method, the accumulation of water and nitrogen in the anode compartment in case of a dead-end mode use of the FC was diagnosed as well as the drying of the proton exchange membrane localized by the configuration of threshold.

4.3 Diagnostic by Experimental Approach

Experimental diagnostic approaches for FCS have already become mature and systematic techniques. Most of these approaches are based on physico-chemical phenomena inside the FC. Most of these approaches are based on phisico-chemical phenomena inside the FC. References [16],[17] provides a review of diagnostic methods using experimental measurements. In [16], electrochemical techniques such as the polarization curve, current interruption, and Electrochemical Impedance Spectroscopy (EIS) are presented. EIS consists in applying a very small amplitude signal (current) over a wide range of frequency and to register the response. The ratio of the variation voltage and current gives the magnitude of the impedance and the phase shift. Based on the published papers, the majority of AC impedance studies of PEMFC cells involve in situ measurements because they offer the most pertinent data on PEMFC. In [17], several physical/chemical methods are presented for PEMFC diagnostic: Pressure drop measurement, Gas chromatography. In that case, the permeating of reactant gas can be detected. In [18], the authors used dependence between current density and formation of water in FC to analyze the effect on the fuel cell's performance. Other approaches for the diagnostic of FC use characterization of electric components based on spectrometric impedance [19]. Even if this methodology provides good results for the detection of flooding in FC, its implementation is still complex and costly. Therefore, a method using a simpler instrumentation was proposed by Barbir *et al.* [20]. They use load losses measurements in the stack as a diagnostic tool to detect flooding. Ref. [21] studied the 500W Ballard Mark V PEMFC stack with EIS for diagnostic problem. The developed method is based on effect analysis of temperature, flow rate, and humidity on the stack impedance spectra. In the second part of this paper, individual cells of the same fuel cell stack were studied with AC impedance approach. Two methods were utilized for measuring the impedance spectroscopy of the individual cells. The results demonstrate that the AC impedance method is a sensitive technique for detection of the degree of membrane hydration which could be an indicator for flooding and drying in FCs. Voltage measurement is one of the most interesting method as it appears to be the only variable allowing a measurement at the cell level while still being non intrusive. In [15], the diagnostic solely depends on the processing of steady-state current/voltage data. This proves to be efficient as far as fault detection is concerned, but leads to an indetermination when it comes to fault isolation since flooding and drying out both cause a voltage drop. Thus, when considering a FC in a given state with no available history, fault isolation is impossible.

Besides of AC impedance approach, the pressure drop can also be as diagnostic tool for FCS. The measure of the differential pressure drop between the inlet and outlet of gas channel could be used in order to diagnose liquid water accumulation [22], [23], [24].

Barbir *et al.* [20] also conducted preliminary studies on pressure drop as a diagnostic based on physic-tool for water flooding in PEMFC.

A plot of cell potential against current density under a set of constant operating conditions, known as a polarization curve, is the standard electrochemical technique for characterizing the performance of FC. Therefore, failures can be detected and isolated from that information. A non-steady state polarization curve was obtained using a rapid current sweep in [25]. Any changes of parameters such flow rate, temperature, and relative humidity could become diagnostic signals for water state management.

An appropriate humidity [26] can also prevent irreversible degradation of internal composition such as the catalyst or the membrane. A good indicator of the humidification state is the membrane resistance [27] that can be obtained by measuring the voltage and the current variations in high frequency. Reference [28] proposes a method for checking the humidification state of the membrane by exploiting the connection of a boost converter to the fuel cell.

One of the most important advantages of experimental diagnostic approaches consists in detailing deep insight into the mechanisms that cause performance losses and spatial no uniform distribution. Therefore, experimental approaches are in situ diagnostic tools thus bad suited for online FDD. Most of the experimental approaches can only be realized in off-line conditions. Isolation performances depend on deep expertise or pattern recognition and learning of normal and faulty operating modes.

To minimize the drawback of experimental method, in [29], is showed how a model-based approach coupled with EIS measurements could help identify a set of parameters exhibiting a much greater sensitivity and selectivity to flooding and drying than the voltage does.

6. MODEL BASED APPROACH

As developed before, the isolation performances of no model based methods need historical data in normal and in abnormal situations, thus every fault mode has to be represented. In the real processes, especially for FCS, realization of such modes experimentally cannot be envisaged. This is why FDD model based approaches can be an alternative.

The principle of Model Based Diagnosis (MBD) consists in checking the consistency of observed behavior with analytical model in fault detection phase while isolating the component that is in fault isolation phase. Generally, two parts (residual generation and residual evaluation) can be contained in the model based diagnosis. The internal structure of a MBD system consists therefore in two subsystems: residual generator and residual evaluation. The purpose of the residual generator is to generate the residual signals and the purpose of the residual evaluator is to evaluate the residuals and generate a fault decision ([30]-[32]).

All of MBD diagnostic approaches can generally be regrouped into four classes: analytical redundancy relation (ARR) or parity space, observers and parameter identification and stochastic approaches . In consulted literature, few papers deal with model based FDI for Fuel Cell stack systems.

4.1 Diagnostic by ARRs

Material redundancy (use of several sensors which measure the same variable) is widely used in industry, but this method allows detecting only sensor fault and is costly. Analytical Redundancy Relation (ARR) is an equation that is deduced from analytical model which use solely known variables (measured). ARRs must be consistent in absence of faults with physical operating modes. It utilizes the information embodied in the mathematical model of a system for fault detection and isolation. The actual behavior of the system is compared to that expected on the basis of the model; deviations are indications of faults (or disturbances, noise or modeling errors). The parity (consistency) equation method is the direct implementation of the analytical redundancy concept.

In [33], a fault diagnosis and accommodation system with a hybrid model for fuel cell power plant was presented. Faults in this paper were diagnosed by using analytical redundancy method, where the actual plant was compared with a neural network augmented nominal model, which served as a reference on how the state and output variables should behave in normal situations. The ARRs in the fault detection are sometimes given as form of test quantities. In [34], two hydrogen leakage test quantities were presented and compared. These two test quantities were created by the model for the anode based on mass balances. Traditionally, the residuals deduced from ARRs are static and sensible to faults to be detected. Recently, a new model based FDD methodology based on the relative fault sensitivity has been presented and tested in [36]. The innovation of this methodology is based on the characterization of the relative residual fault sensitivity. Recently, [37] presented a FDI of PEMFCS based on nonlinear ARRs. Residuals are generated by an extended parity space approach in order to detect and isolate the input voltage drop of compressor, over current of FC, pressure drop in supply manifold and pressure in the return manifold.

4.2 Diagnostic by Observers

In the literature, very few papers are presented about the fuel cell systems diagnosis based on observers. Most of the work with observer development in fuel cell systems concentrates in parameter estimation but no mention of diagnosis. Since several parameters are seriously sensitive to failures in the system, the fault detection and isolation could be realized by monitoring the variations of these parameters. In [38], a voltage based observer was developed to estimate membrane water content in PEM fuel cells. Similarly, other nonlinear observers for fuel processing reactors in fuel cell systems were designed in [39] where hydrogen content can be estimated and then , the gas fluid faults can be detected.

In [39]-[41], it is considered the problem of flooding diagnosis based on liquid water volume and gases physical behaviour model. In this work, the strategy employed for diagnosis is based on the state estimation of volume of liquid water and pressure. Since the goal is only to estimate the volume of liquid water and not all the state, author proposes to solve the problem using a functional observer.

In [42], a nonlinear observer is designed for the estimation of the mass flow rates of reactant gases which their precise estimation is necessary and important for diagnostics of FCS. In the particular sense of inlet manifold of FCS, appropriate air mass flow is very critical for proper maintenance of chemical reactions in the cathode.

In [43], a Linear Parameter Varying (LPV) observer was used in order to compute residuals. The algorithm developed is able to identify and estimate multiple sensor faults for PEM fuel cell.

4.3 Diagnostic by Parameter identification

The parameter identification method for FDD design consists in comparing identified or estimated parameters of the FC system with observed ones. In [44], some parameter estimation methods for a PEM fuel cell based on current interrupt test and a system identification approach have been presented. Because of the association between major losses (activation and ohmic) and flooding or drying faults, the detection and isolation of these faults could be done through the parameter identification of voltage variation caused by major losses. However, there are few papers for FC diagnosis based on parameter identification approach

4.4 Diagnostic by Stochastic Approach

For stochastic diagnostic approaches, the residual signals are random processes whose statistic analysis can sometimes be difficult. Therefore, databases which record the fault effects and probabilistic methods such as the Bayesian-Score and Markov Chain Monte Carlo (MCMC) with a graphical--probabilistic structure are needed. In [45], four types of faults in PEMFCs are considered. The diagnosis is executed at a specific moment, only if abnormal evolution of any variable is monitored; the idea is to associate this evolution with symptoms of incipient faults. The Bayesian-Score K2 and MCMC algorithms were implemented for the construction of a network structure which defines the cause-effect relationship among the variables. While these two probabilistic methods capture the numerical dependence among these variables. In [46], the algorithm is was applied on line in order to detect faults. Another stochastic diagnosis for fuel cell system was presented in [47]. By using cell voltage probability density functions as clustering parameter, different working conditions including several induced failure modes are characterized. From this characterization, normal operation and failure zones are defined either by arbitrary selection of a given region or by natural clustering of experimental results.

4.5 Structural analysis for Fuel cell

The problematic for FDD of FC consists in that the model is complex where occur several kind of energy (Electrical, mechanical, electro-chemical, ...) and the numerical values are not always known. This is why structural model (based on existence or not of the links between variables and the relations) is well suited. The basic tool for structural analysis is based on the concept of matching on a bipartite graph [30]. Few works deal with structural analysis applied to fuel cell systems. In [49], it is shown how the structural monitorability (ability to detect and isolate faults) and the fault signatures can be deduced directly from FCSS multi-energy bond graph model with no need for any numerical calculation. Therefore, before industrial design, an optimal sensor placement to provide which faults can be detected and or isolated and how to make them monitorable can be proposed.

In [50], the results of structural monitorabilitry show that drying, flooding, contamination by gas pipe, compressor faults and some sensor faults (velocity, current, air mass flow) are detectable and isolable. To isolate other faults, it is necessary to add sensors, i.e., hydrogen leakage.

The efficiency of the structural methods depends principally on the model accuracy and has to be validated with numerical value.

5. CONCLUSION

As shown in this review, most of the contributions to FC diagnostics are based on experimental methods which usually have to be realized in off-line condition (except for signal based). Furthermore, most of these experiments are intrusive and are not suited for embedded applications. The isolation performances of those methods based on experimental analysis depend on learned faulty modes. In the real processes, especially for FC, the obtention of such modes experimentally cannot be envisaged. This is why FDD model-based can be an alternative. The problem of FC diagnostics can be summarized as follows: insufficient instrumentation architecture, pattern recognition (for faulty modes determination) is costly, complex and non stationary dynamic models, numerical values of parameters are not always known, cells is serial connection (monitoring of each cell individually is not envisaged), working in disturbed environment (transportation system).

AKNOWLEDGMENTS

This work was produced in the Framework of i-MOCCA (**i**nterregional **MO**bility and **C**ompetence **C**entres in **A**utomation) PN-7-022-BE i-MOCCA , a European territorial cooperation project part-funded by the European Regional Development Fund (ERDF) throuch the INTERREG IV A 2 seas Programme.

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