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A Review on Fault Diagnosis tools of the Proton Exchange Membrane Fuel Cell*

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***Abstract*—Fuel Cells received a major research interest in the past few years. However, despite their promising features, Fuel Cell systems still lack a solid fault diagnosis and predictive maintenance study. There are numerous faults that have to be detected and diagnosed on a fuel cell power generator system, ranging from chemical faults, to electrical and power electronics faults. Several fault diagnosis techniques were proposed in literature. This paper presents an overview on all those fault diagnosis tools, analyze their effectiveness, and highlight their drawbacks if any.**

I. INTRODUCTION

A Fuel Cell (FC) is an electrochemical device that converts the chemical energy of a supplied fuel into DC electrical energy. Since this process produces minimal pollutants, fuel cells are considered as one of today's green technologies [1]. There are six different types of fuel cells in practice that are classified according to the choice of electrolyte and fuel. However, Proton Exchange Membrane Fuel Cell (PEMFC) – also known as polymer electrolyte fuel cell – is the fuel cell type that is currently undergoing rapid development.

The basic physical structure, or building block, of a PEMFC consists of a Nafion electrolyte layer (membrane) sandwiched between two electrodes (anode and cathode) as depicted in Figure 1.

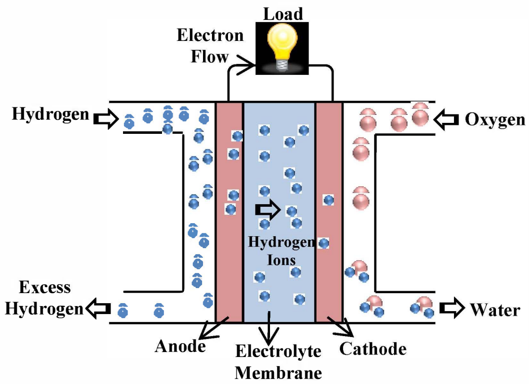

Figure 1. The schematic diagram of a PEMFC.

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Typically, hydrogen fuel is fed continuously to the anode and oxygen (from air) is fed continuously to the cathode [1]. In order to break the hydrogen, a Platinum (Pt) catalyst or a Platinum-Ruthenium (Pt –Ru) alloy catalyst is usually used in the electrodes [2]. The electrochemical reactions take place at the electrodes to produce an electric current through the electrolyte, while driving a complementary electric current that performs work on the load [1].

Proton Exchange Membrane Fuel Cells (PEMFCs) suffer from lifetime and reliability issues when working at a strongly changing charge conditions. Moreover, the complexity of the PEMFCs increases the chances of failures and defects. Thus, an increased attention has to be paid to the reliability, safety and fault tolerance of PEMFCs by implementing fault diagnostic techniques [3, 4, 6, 7, 8]. The faults which may affect their operation can be divided into two main groups: permanent (fatal) faults and transient faults [1]. A third group of faults that can affect the performance of fuel cell systems are faults external to the fuel cell stack, i.e., faults related to the interface, inverters, Pressure regulators, humidifiers, etc.

In this paper, thorough reviews on the different types of faults that can affect the performance of a PEMFC as well as an extensive review on the available fault diagnosis tools in literature are presented. Furthermore, the severities of the faults and the effectiveness of the proposed fault diagnosis tools are analyzed. To our best knowledge, such a review on all the different types of PEMFC faults does not exist in literature. Therefore the main contribution of this paper is that it compiles all available fault diagnosis techniques aiming at tackling all the different types of faults that can affect the performance of a PEMFC system.

This paper is organized as follows: Section II reviews all types of permanent faults and discusses the fault diagnosis tools available in literature that tackled permanent faults of PEMFCs. Section III, on the other hand, concentrates on transient faults, while Section IV focuses on external faults. Finally, summary and concluding remarks are given in Section V.

II. PERMANENT FAULTS

As the name implies, permanent faults are irreversible because they result in a permanent damage to the fuel cell. Once such a fault occurs, the fuel cell's performance will always be lower than its usual performance measures at similar operating conditions [5]. Thus, the only possible solution is to replace the damaged cell. Permanent faults usually fall under one of the following categories:

A. Membrane Deterioration:

This type of fault takes place with time in terms of the system's evolution towards new equilibrium points. In this case the diffusion constants of the system are significantly altered and the pressure gradients between the cathode and anode channels drop [5].

Hernandez *et al.* used two strategies to diagnose membrane deterioration. Their first strategy was based on an electrical circuit equivalent model of the PEMFC [5,6]. In this approach, the parameters of the circuit model are analyzed to determine variations in the circuit parameters. A deteriorated membrane can be detected by a drop in the pressure gradient between the cathode and the anode while all other parameters remain unaffected.

In the second strategy, Hernandez *et al.* [5] used a statistical approach that analyzes the information available from each individual cell to adequately classify patterns of dysfunction in the stack for three different causes: membrane deterioration, flooding and drying.

In [7], three relatively high load resistances and a voltmeter were used to record the voltages and output powers of each cell in the stack when connected to each of the three resistive loads. If the output voltage of any of the cells was close to zero, then this indicates that its membrane is broken. However, this approach is impractical for stacks with high number of cells.

Electrochemical Impedance Spectroscopy (EIS) has been used extensively in the area of PEMFC fault diagnosis. However, EIS is usually applicable to single cells or small stacks of less than 10 cells due to technological limits of the classical impedance meters [8]. Moreover, EIS does not provide complete accurate information on the structure of the fuel cell's membrane and the catalyst activity at the electrodes [8]. Because of this, Wasterlain *et al.* developed a new EIS test instrument in [8] allowing the test of large stacks to study membrane permeability as well as loss of platinum activity.

B. Absence of catalyst:

This fault happens when the catalyst falls out for some reason reducing the active area of the cell, and thus causing a huge deterioration in the cell's performance. This type of fault was tackled in [8] by the use of EIS as previously discussed. Moreover in [7], the same technique discussed in the membrane deterioration section was also used to detect a catalyst problem. The authors noted that if the output power of a cell increases with the decrease of the load resistance then the cell's catalyst is invalid.

C. Carbon monoxide poisoning:

Carbon monoxide poisoning is one of the major health concerns in PEMFCs. Research showed that as the CO content in the supplied fuel increases, the cell's performance degrades. This is because CO poisons the anode reaction by adsorbing to the platinum surface and thus blocking the active sites [9]. The reactions at the anode of a PEMFC with a platinum catalyst can be expressed as [10]:

$$H_2 + 2(Pt) \rightarrow 2(Pt - H) \tag{1}$$

$$2(\mathrm{Pt} - \mathrm{H}) \rightarrow 2(\mathrm{Pt}) + 2\mathrm{H}^+ + 2\mathrm{e}^- \tag{2}$$

However, if the hydrogen fuel is contaminated with CO, the CO can adsorb onto the platinum in one of the following forms, thus blocking the active platinum sites at the anode [10]:

$$\mathrm{CO} + (\mathrm{Pt}) \rightarrow (\mathrm{Pt} = \mathrm{CO}) \tag{3}$$

$$2\mathrm{CO} + 2(\mathrm{Pt} - \mathrm{H}) \rightarrow 2(\mathrm{Pt} = \mathrm{CO}) + \mathrm{H}_2 \tag{4}$$

Several approaches to mitigate the CO poisoning problem were proposed in literature:

- The replacement of the platinum catalyst by an alloy catalyst platinum-ruthenium (Pt–Ru) changes the anodic reactions to be as follows, thus significantly reducing the CO adsorption by allowing a water-gas shift reaction to occur if the fuel is humidified before it is fed into the cell's anode [9-11]:

$$(\mathrm{Pt}) + \mathrm{H_2O} \rightarrow (\mathrm{Pt} - \mathrm{OH}) + \mathrm{H}^+ + \mathrm{e}^- \tag{5}$$

$$\mathrm{Ru} + \mathrm{H_2O} \rightarrow (\mathrm{Ru} - \mathrm{OH}) + \mathrm{H}^+ + \mathrm{e}^- \tag{6}$$

$$(\mathrm{Pt} = \mathrm{CO}) + (\mathrm{Ru} - \mathrm{OH}) \rightarrow (\mathrm{Pt}) + \mathrm{Ru} + \mathrm{CO_2} + \mathrm{H}^+ + \mathrm{e}^- \tag{7}$$

- Bleeding a small amount of air into the anode along with the fuel which causes the oxygen available in the fed air to oxidize the CO adsorbed in the catalyst layer forming CO_2. This would clean enough of the Pt sites for electro-oxidation with H_2 [9,12,13].
- Operating the cell at a higher temperature values could also improve the cell's tolerance towards CO poisoning. However, this might alter the dynamics of the PEMFC and limit its applications [9,14].
- An advanced power convertor could be used to send a pulsing current of specific amplitude at low frequencies, thus creating a sufficient anode over potential to force the CO to electro-oxidize into CO_2, thus freeing enough of the catalyst layer in the PEMFC. This approach was found to increase the PEMFC's power by 50% when supplied with a hydrogen fuel containing a 500 parts per million (ppm) CO [15].

However, all these proposed solutions only tend to mitigate the negative effects of CO poisoning, but they do not eliminate the problem.

D. Reactant Leakage in the fuel cell stack:

In hydrogen fed fuel cells, there is always an accepted leakage rate that should never be exceeded since hydrogen gas is generally known for its high combustibility, especially when confined in small non-ventilated spaces. Once the leakage rate is increased due to cracks in the graphite plate, seal ruptures or membrane cross-leaks, there would be a critical hydrogen concentration due to the accumulating hydrogen in a small space leading to an inevitable explosion [16].

Ingimundarson *et al.* [16] argued that in order to accurately detect hydrogen leakage in a fuel cell, the presence of water vapor in the anode must be taken into account. Therefore in addition to the mass flow sensor and the anode pressure sensor already employed in fuel cells; a relative humidity sensor – although it is very expensive – was employed with an adaptive alarm threshold to eliminate false alarms.

Tian *et al.* [17, 18] on the other hand, aimed at detecting reactant leakage in aged cells in the anode/cathode crossover region and the anode/cooling compartment by monitoring the open circuit voltages of the cells and analyzing them at different operating conditions which helped locate defective cells.

Anode/cathode leakage was detected using signal based fault detection, by studying the amount of time needed by each cell in a stack to reach a preset voltage threshold of 0.5 V after stopping the reactant flows. It was noted that some cells reached the set threshold fast while it took other cells long time to reach it. As a next step, a normal probability curve was used to discriminate real faults from outliers.

Anode/cooling compartment leakage on the other hand was detected by studying the correlation between the reactant gas flow dynamics and the water level in the expansion vessel.

Escobet *et al.* [19] modified the PEMFC simulator model that was developed by Pukrushpan *et al.* in [20] to include the following several faults, namely; increase in the friction of the compressor motor, overheating of the compressor motor, increase in fluid resistance due to water blocking the channels or flooding in the diffusion layer, air leakage in the air supply manifold, increase in the voltage causing compressor motor to stall, and the increase in stack temperature due to failure in temperature controller. A model based fault diagnosis methodology was proposed based on the relative fault sensitivity of the different faults. The same set of faults was also tackled by Rosich *et al.* in [21, 22]. However, their proposed diagnosis approach was based on residual generation using causal computations.

In [23] an online control and monitoring system for an uninterruptable power supply (UPS) system based on PEM Fuel Cells for backup power applications was introduced. The proposed fault monitoring system was composed of a knowledge base, an interface engine and a user interface system based on LabVIEW which monitors three fault modes: drying of the membrane, hydrogen and air starvation of electrochemical reaction and membrane leakage. The authors based their approach on the fact that membrane leakage is usually caused by a fracture or a hole in the membrane. Holes in the membrane may be caused by the presence of a hot spot while fractures result from mechanical stress when the cell is operated under dynamic operating conditions, resulting in a pressure difference that would break the membrane. Therefore; a hydrogen pressure controller was employed to avoid leaks in the membrane.

E. Fuel Cell Aging:

Durability is one of the major limiting factors of the fuel cell technology. Fuel cells are known to have a short lifetime after which their performance starts to degrade significantly. In [24], a pattern recognition based approach was used to estimate the fuel cell's operating time and its remaining life duration using dynamic stack information based on electrochemical impedance spectroscopy (EIS). Two feature extraction methods were employed in the process: using an empirical model for feature extraction on polarization curves to extract and keep only relevant descriptors and using a latent regression model to automatically split the imaginary part of the spectra into several segments that are approximated by polynomials.

Both approaches were evaluated on real data sets and were able to estimate the fuel cell's lifetime with a mean error of 214 hours over a global operating duration of 1000 hours using the first method, a mean error of 142 hours using the second method and a mean error of 95 hours, when using features extracted using both methods.

Moreover in [25], the authors developed another pattern recognition based approach using both static and dynamic stack information based on polarization curve and EIS to improve the operating time estimation. This improved method was able to estimate the fuel cell's lifetime with a mean error of only 2 hours over a global operating duration of 1000 hours. The effect of time on the stack's EIS and polarization curve are presented in Figures 2 and 3.

Wasterlain *et al*. [26] studied the effect of severe operating conditions on the durability of PEMFCs by feeding a 3 cell stack dry hydrogen and low humidified air while operating at over nominal temperature for 1000 hours. The polarization curve and EIS measurements were monitored during the test for different gas flow rates. One of the cells failed at the 450th hour of operation while only a weak performance degradation rate was noticed in the other two cells.

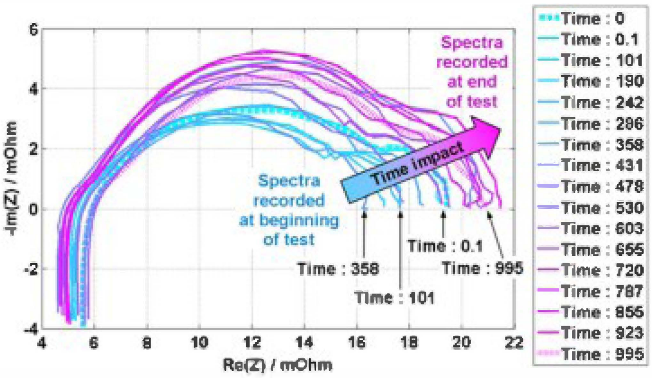

Figure 2. Time impact on the stack's electrochemical impedance spectroscopy [24].

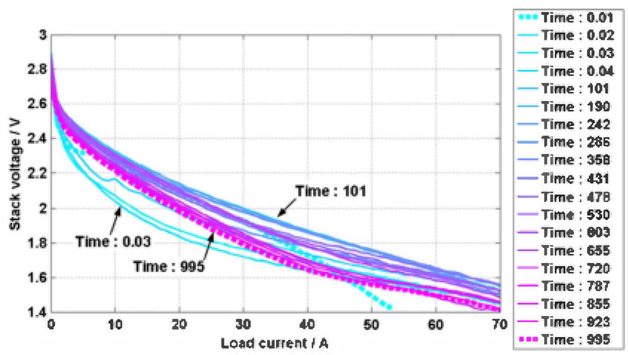

Figure 3. Time impact on the stack's polarization curve [25].

The effect of high frequency ripple current on PEMFC aging was studied experimentally in [27] on a 5 cells stack. Modeling analysis showed that the current ripple does not seem to impose severe local conditions. However, the findings of this work are inconclusive as a specific membrane model must be developed to better understand the real impact of ripple currents.

Zhang *et al.* [28] developed two protocols that could be used to accelerate the PEMFC lifetime testing. One protocol was based on operating the stack at an extremely high temperature of about 300°C. Analysis showed that after 24 hours of testing there was an extreme degradation on the stack's performance as depicted in Figure 4.

The other protocol was based on subjecting the stack to an unusually high current density of 2 A/cm^2. Analysis showed that this protocol accelerates the stack's performance degradation as depicted in Figure 5.

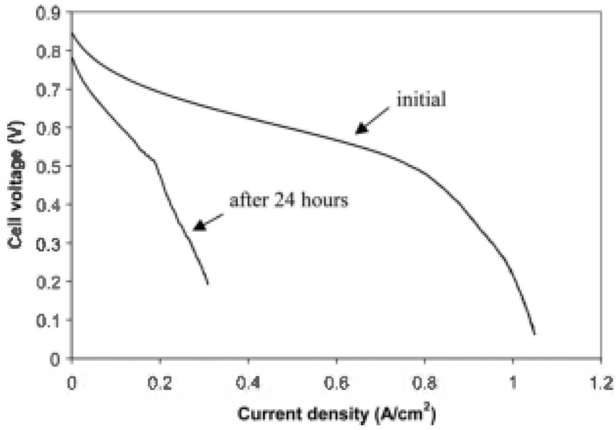

Figure 4. Time impact on the stack's polarization curve when operated at 300°C [28].

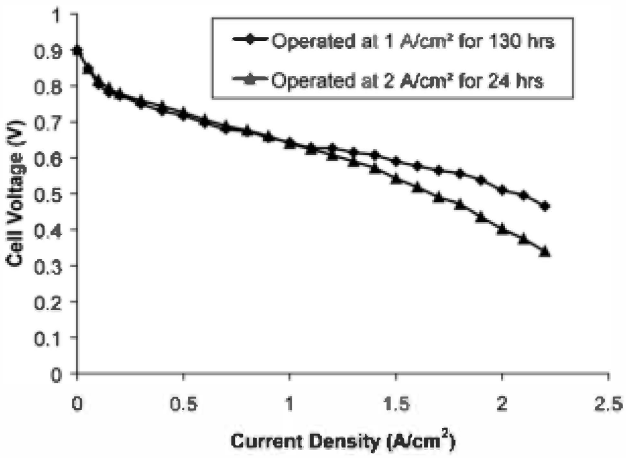

Figure 5. Comparison of the time impact on the stack's polarization curve when operated at nominal conditions with a current density of 1 A/cm^2 and when operated at extreme conditions with a current density of 2 A/cm^2 [28].

Hissel *et al.* proposed two aging tests in [29]. In the first test, the stack was operated under nominal conditions with a constant 50 A current for 1000 hours while being fed with dry hydrogen. In the second test the stack was operated under dynamical load current for 1000 hours while also being fed with dry hydrogen. To evaluate the performance degradation, they utilized the polarization and internal resistances as well as the maximal absolute phase extracted from the EIS.

III. Transient Faults

Transient faults are completely reversible, and they are usually related to the fuel cell state and the control strategy. The common PEMFC transient faults are:

A. Flooding:

Since PEMFCs operate at relatively low temperature values ranging from about 60°C to 80°C, water management is always a key issue. The cell's membrane has to be fully water saturated in order to enhance its ionic conductivity. However, if the membrane becomes flooded with water, this would obstruct the gas transport to the reaction sites thus reducing the active surface area of the catalyst. This would significantly increase the cell's activation and concentration losses which therefore reduces the cell's efficiency [30].

B. Drying:

If the membrane dries out, its resistivity increases also causing a reduction in the cell's efficiency. Moreover, if the cell operates for a long time with low water content this would significantly reduce its lifetime [30]. Note from Figure 6 that flooding and drying result in the same V-I characteristics except for when the cell's voltage reaches below its minimum rated voltage (0.4 V).

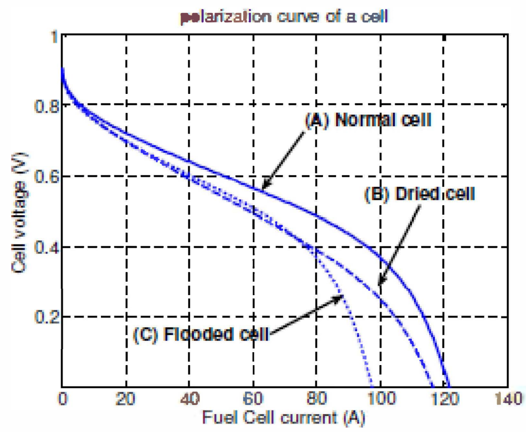

Figure 6. Effect of drying and flooding on the polarization curve [30].

Most of the researches conducted in the area of PEMFC fault diagnosis focus on flooding and drying of the membrane. The voltages of independent cells in a stack differ from one another. It is generally noted by many researchers that the cells nearest to the fuel inlet have higher voltage than those farthest (nearest to air inlet) due to the uneven gas distribution or water flooding. Moreover, it is generally noted that the temperatures of the center cells are relatively higher that the rest and thus they are at a higher risk of drying but rarely get flooded since flooding usually occurs at the cooler cells [30]. Therefore, Frappé *et al.* [30,31] monitored the voltages of a group of representative cells at the inlet, and outlet of the stack to detect flooding and at the center of the stack to detect drying.

Another approach presented in [32] uses the PEMFC's voltage drop and impedance response to detect both flooding and drying of the membrane. It was noted that in the case of flooding, the back pressure of the unreacted oxygen drops, and both the imaginary and real parts of the cell's impedance increase. However, although the magnitude response of the cell tended to increase during flooding, its phase response was found to remain unaffected.

During drying, the cell's power output was found to drop by 50%, and the imaginary and real parts of the cell's impedance increase. However, unlike the flooding case, a negative phase shift appeared at low frequencies in the phase response of the cell. This made it possible to detect both flooding and drying by measuring voltage drops as well as phase shifts at low frequencies (0.01 – 1 Hz).

Barbir *et al.* [33] on the other hand, noted that the pressure drop on the cathode side of the PEMFC can be utilized as an indicator for membrane flooding while the increase in the cell resistance gives an indication of a drying membrane.

However, Chen [34] argued that the use of pressure drop alone as a diagnostic tool for flooding is not enough for two reasons:

1. The pressure signal contains high frequency oscillations which makes it difficult to judge flooding.
2. Considering the relatively low pressure drop (<1000 Pa), signal noises could affect the accuracy of the diagnosis.

Therefore Chen proposed the use of the dominant frequency of the pressure drop signal obtained by fast Fourier transform (FFT) rather than the pressure drop signal itself to indicate flooding.

In Hernandez *et al.* [5, 6] electrical equivalent circuit diagnosis strategy previously discussed, they noted that in the case of flooding, the input and output resistances at the cathode side increase, the gas diffusion rate decreases, and the circuit's capacitance decrease.

On the other hand, drying tends to increase the electrical resistivity of the stack and limit the maximal current density and electro-osmotic drag coefficient. Moreover, the membrane's width and the gas diffusion constants will also be affected by dehydration [5, 6].

Yousfi-Steiner *et al.* addressed the PEMFC water management issue in several papers. In [35,36] they utilize a black box model of PEMFC based on neural networks that stimulates the evolution of pressure drop at the cathode as well as the cell's voltage in the healthy operation case of the PEMFC. Two residuals are then calculated by comparing the experimental results with those of the neural network to indicate the flooding or drying of the membrane. However, in [37], their presented approach to detect flooding and drying was based on discrete wavelet transform.

Another approach presented in [38], utilized fuzzy logic as a diagnosis tool for membrane flooding and drying in automotive applications.

Moreover, they also conducted a general review on PEMFC water management in [39] and the different strategies used to overcome them (reactant humidity control, reactant flow rate control, temperature control, pressure control, current density modification and a convenient fuel cell design). Another review on PEMFC flooding issues was performed by Li *et al.* in [40].

IV. External Faults

External faults are faults related to parts of the fuel cell system that are external to the fuel cell stack as demonstrated in Figure 7. However, those components are conventional and not specifically designed for use with fuel cells, and thus little to no work on PEMFCs fault diagnosis tackles faults related to those external components.

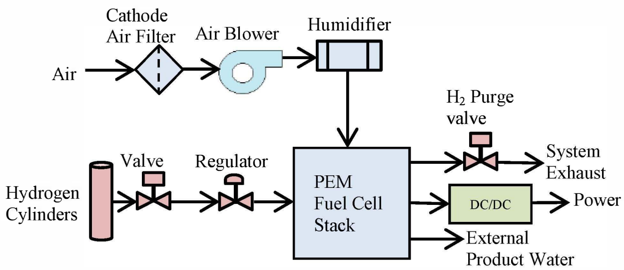

Figure 7. Simple PEMFC system.

A. *Humidification Failure:*

As explained previously, the cell's membrane has to be fully water saturated in order to enhance its ionic conductivity. In case the humidifier coupled with the PEMFC failed, the membrane will dry out thus reducing the cell's efficiency.

Narjiss *et al.* [41] proposed an approach that utilizes the DC/DC convertor that is already coupled with the fuel cell to perform an online fault diagnosis on a PEMFC. The DC/DC convertor was controlled by a digital signal processor (DSP) and a capacitor was added in parallel to the fuel cell stack in order to reduce the current harmonics. Then the PEMFC's online state of health was judged using impedance spectroscopy by injecting a low sinusoidal current signal to the cell at different frequencies. It was noted that with the use the DSP controller, no pulse width modulation noise was present at the cell's output. The authors then illustrated how the EIS can be used to give an indication on the cell's humidification. The higher the percentage of humidification, the lower is the measured impedance. Moreover, the spectroscopy can also be used to judge the gas flows since the impedance tends to increase with the decrease of gas flows at constant loads.

B. *Power Electronics Interface Failure:*

PEMFCs are usually coupled with DC/DC converters in order to boost the fuel cell's voltage and provide adequate power to the load. However the large variance between the magnitude of the input and output signals imposes severe mechanical stress on conventional DC/DC converters [42]. Therefore, some researchers started modifying the conventional converters' topology to better suit the fuel cell application.

In [43], a transformer with multiple secondary coils was added in series to a full bridge converter to increase the fuel cells efficiency. In [44] however, a boost converter was used to regulate the output voltage of the fuel cell before reaching the DC/DC converter. And in [45], the authors used a full bridge DC/DC converter with an H bridge inverter. This topology was found to decrease the voltage/current stress with minimal added cost.

Other researchers tended to design new converters for the specific use with fuel cells. Three examples are the high step-up DC/DC converter with a coupled inductor in [46], the wide input range fuel cell power conditioner in [47] and the three phase transformer isolated DC/DC converter in [48].

C. Cooling System Failure:

The temperature of the PEMFC is maintained at a desired value using a cooling system in order to ensure high reaction efficiency over all operation. A failure in the deployed cooling system will reduce the cell's efficiency. In [49], a control strategy for a fuel cell cooling system was presented based on a μ-synthesis linear controller which helped maintain performance robustness despite the presence of parameter and input uncertainties.

Another approach that utilizes PEMFC model based fault diagnosis techniques to detect several types of faults including the increase in the stack's temperature due to cooling system failure was presented in [50]. This model based fault diagnosis approach is based on the online comparison between the real-time behavior of the system and its dynamic model. When discrepancies are detected, they are analyzed to determine the type of fault.

ZigBee wireless sensors with Modbus interface were also used successfully to detect several PEMFC faults including cooling system failure [51]. In this approach, 13 different output characteristics are used to detect system faults based on an extension neural network (ENN).

D. Air Supply System Failure:

Such as oxygen hole blockage, blower/compressor failure, etc. These faults will prevent the oxygen reactant gas from reaching the reaction sites of the PEMFC. The proposed fault diagnosis techniques in [50] and [51] also tackled several air supply system failure modes such as compressor failure due to increased friction, overheating and increased voltage, air leakage in the air supply manifold [50] and oxygen hole blockage [51]. Another model based fault diagnosis approach for detecting air supply system faults was presented in [52].

E. Hydrogen Supply System Failure:

This means that no or little hydrogen reactant reaches the reaction sites of the PEMFC, causing the cell's operation failure. The ENN approach of [51] was also utilized to detect such faults.

F. Air Exhaust Failure:

The fuel cell's air exhaust is used to dispose of the excess un-reacted hydrogen, excess air, and bi-products (such as CO_2) into the atmosphere. Failure of the air exhaust system will severely compromise the fuel cell's operation, since those gases will accumulate inside the relatively small fuel cell area causing in some cases an explosion as previously explained due to the accumulation of Hydrogen in a confined space. The utilization of ZigBee wireless sensors with Modbus interface and ENN training was utilized to detect air exhaust failure [51].

G. Sensor Network Failure:

In case of a faulty sensor or in case of failure of the communication system between the sensors and the controllers then the controllers will fail to control the PEMFC system. Communication system failure was tackled in [51] using ENN. Moreover, in another approach, a Principal Component Analysis (PCA) model of the fuel cell was developed and then trained in order to detect sensor network failure in PEMFC operated vehicles [53].

V. CONCLUSION

Fuel cells are an extremely attractive renewable energy source with the capability of someday replacing fossil fuels in the areas of power generation and transportation, while helping clean the environment by significantly lowering the world's pollution rates. However, to turn this green technology dream into reality, a fuel cell system designer should develop a complete understanding of fuel cell systems and establish a solid fault diagnosis scheme and control strategy.

In this paper, a thorough review on all possible faults that could affect the performance of PEMFCs was presented, and the available fault detection/isolation techniques of the said faults in literature were discussed, compared and analyzed. The findings of this review are summarized in Table 1.

TABLE I. SUMMARY OF PEMFC FAULT DIAGNOSIS

Faults		***Fault Detection Techniques***	***Fault Isolation/Mitigation Techniques***
Permanent Faults	***Membrane Deterioration***	• Electrical circuit model [5,6] • Statistical approach [5] • High load V/P characteristics [7] • EIS [8]	NA
	Absence of Catalyst	• EIS [8] • High load V/P characteristics [7]	NA
	CO Poisoning	• EIS [8] • High load V/P characteristics [7]	• Replace Pt by (Pt-Ru) [9 – 11] • Air Bleeding [9,12,13] • Operating at higher Temp. [9,14] • Advanced Power Converter [15]
	Reactant Leakage	• Model based fault diagnosis [19] • Using causal computations[21,22] • Using relative humidity sensor [16] • Open circuit voltage [17,18]	NA
	Fuel Cell Aging	• Polarization Curve [25,26,29] • EIS [24 – 26,29]	NA

Faults		Fault Detection Techniques	Fault Isolation/Mitigation Techniques
Transient Faults	***Flooding***	• Model based fault diagnosis [5,6,19] • Statistical approach [5] • Polarization curve [30 – 32] • EIS [32] • Monitoring cells voltage at inlet/outlet/center of stack. [30,31] • Dominant frequencey of cathode pressure drop [33,34] • Neural Networks [35,36] • Discrete wavelet transform [37] • Fuzzy Logic [38]	NA
	Drying		
External faults	***Humidification***	• EIS [41]	NA
	Power Electronics Interface	NA	• Modifying the DC/DC converter topology [42 – 48]
	Cooling System	• Model Based Fault Diagnosis [50] • Using causal computations [50] • Neural Networks [51]	• Using μ-synthesis linear controller [49]
	Air Supply System	• Model Based Fault Diagnosis [50, 52] • Using causal computations[50] • Neural Networks [51]	NA
	Hydrogen Supply System	• Neural Networks [51]	NA
	Air Exhaust	• Neural Networks [51]	NA
	Sensor Network	• Neural Networks [51] • Principal Component Analysis [53]	NA

a. NA stands for not available

REFERENCES

[1] EG&G Services, Inc, *Fuel Cell Handbook*, 7th ed., Science Applications International Corporation, DOE, Office of Fossil Energy, National Energy Technology Laboratory, 2004, ch. 1.

[2] B. Sørensen, *Hydrogen and Fuel Cells: Emerging Technologies and Applications*, 2nd ed., Academic Press, Elsevier Inc., 2012. ch. 3.

[3] J. Korbicz, J.M. Koscielny, Z. Kowalczuk, and W. Cholewa (Eds), *Fault Diagnosis. Models, Artificial Intelligence, Applications*, Springer, 2004.

[4] J. Korbicz, J.M. Koscielny (Eds.), *Modeling, Diagnostics and Process Control. Implementation in the DiaSter Systems,*Springer, 2010.

[5] A. Hernandez, R. Outbib, and D. Hissel, "PEM Fuel Cells with Bio-Ethanol Processor Systems, A Multidisciplinary Study of Modeling, Simulation, Fault Diagnosis and Advanced Control: Fault Diagnosis of PEM Fuel Cell", in *Springer*, 2012, pp. 151 – 183.

[6] A. Hernandez, D. Hissel, and R. Outbib, "Modeling and Fault Diagnosis of A Polymer Electrolyte Fuel Cell Using Electrical Equivalent Analysis", in *IEEE Transaction on Energy Conversion*, vol. 25, no. 1, pp. 148 – 160, March 2010.

[7] Z. Lin, C. Wang and Y. Liu, "The Fault Analysis and Diagnosis of Proton Exchange Membrane Fuel Cell Stack", in *Advanced Materials Research*, vol. 197 – 198, pp. 705 – 710, 2011.

[8] S. Wasterlain, D. Candusso, F. Harel, D. Hissel, and X. François, "Development Of New Test Instrument And Protocols For The Diagnostic Of Fuel Cell Stacks", in *Journal of Power Sources*, vol. 196, no. 12, pp. 5325 – 5333, Jun. 2011.

[9] J.J. Baschuk, and X. Li, "Carbon Monoxide Poisoning Of Proton Exchange Membrane Fuel Cells", in *International Journal of Energy Research*, vol. 25, pp. 695 – 713, 2001.

[10] A. Rodrigues, J. C. Amphlett, R. F. Mann, B. A. Peppley, and P. R. Roberge, "Carbon monoxide poisoning of proton-exchange membrane fuel cells", in *Proceedings of the 32nd Intersociety Energy Conversion Engineering Conference IECEC*, vol. 2, pp. 768 – 773, Jul. 27–Aug. 1, 1997.

[11] Z. Qi and A. Kaufman, "CO-tolerance of low loaded Pt/Ru anodes for fuel cells", in *Journal of Power Source*, vol. 113, no. 1, pp. 115 – 123, 2003.

[12] S. Gottesfeld and J. Pafford, "A new approach to the problem of carbon monoxide poisoning in fuel cells operating at low temperature", in *Journal on Electrochemical Society*, vol. 135, no. 10, pp. 2561 – 2562, 1988.

[13] F. A. Uribe, T. A. Zawodzinki, J. A. Valerio, and F. H. Garzon, "PEMFC reconfigured anodes for enhancing CO tolerance with air bleed", in *Journal on Electrochemical Society*, vol. 7, no. 10, pp. A376–A379, 2004.

[14] M. Murthy, M. Esayian,W.-K. Lee, and J.W. Van Zee, "The effect of temperature and pressure on the performance of PEMFC exposed to transient CO concentrations", in *Journal on Electrochemical Society*, vol. 150, no. 1, pp. A24–A34, Jan. 2003.

[15] W. Choi, P. N. Enjeti, and A. J. Appleby, "An advanced power converter topology to significantly improve the CO tolerance of the PEM fuel cell power systems", in *Conference Record of the 39th IEEE Industry Applications (IAS) Annual Meeting*, pp. 1185 – 1191, 2004.

[16] A. Ingimundarson, A.G. Stefanopoulou, and D.A. McKay, "Model-Based Detection of Hydrogen Leaks In A Fuel Cell Stack", in *IEEE Transactions on Control Systems Technology*, vol. 16, no. 5, pp. 1004 – 1012, Sept. 2008.

[17] G. Tian, S. Wasterlain, D. Candusso, F. Harel, D. Hissel, and X. François, "Identification of Failed Cells Inside PEMFC Stacks In Two Cases: Anode/Cathode Crossover And Anode/Cooling Compartment Leak", in *International Journal of Hydrogen Energy*, vol. 35, no. 7, pp. 2772 – 2776, Apr. 2010.

[18] G. Tian, S. Wasterlain, I. Endichi, D. Candusso, F. Harel, X. François, M.C. Péra, D. Hissel, and J.M. Kauffmann, "Diagnosis Methods Dedicated To The Localisation Of Failed Cells Within PEMFC Stacks", in *Journal of Power Source*, vol. 182, no. 2, pp. 449 – 461, Aug. 2008.

[19] T. Escobet, D. Feroldi, S. de Lira, V. Puig, J. Quevedo, J. Riera, and M. Serra, "Model-Based Fault Diagnosis in PEM Fuel Cell Systems", in *Journal of Power Sources*, vol. 192, pp. 216 – 223, 2009.

[20] J. Pukrushpan, H. Peng, A. Stefanopoulou, "Modeling And Analysis Of Fuel Cell Reactant Flow For Automotive Applications", in *Journal of Dynamic systems, Measurements and Control*, vol. 126, no. 1, pp. 14 – 25, 2004.

[21] A. Rosich, F. Nejjari, and R. Sarrate, "Fuel Cell System Diagnosis Based On A Causal Structural Model", in *The 7th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes*, Barcelona, Spain, pp. 534 – 539, June 30 – July 3, 2009.

[22] A. Rosich, E. Frisk, J. Aslund, R. Sarrate, and F. Nejjari, "Fault Diagnosis Based On Causal Computations", in *IEEE Transaction on System, Man and Cybernetics, Part A: System and Humans*, vol. 42, no. 2, pp. 371 – 381, Mar. 2012.

[23] Y. Zhan, H. Wang, J. Zhu, and Y. Guo, "Fault Monitoring and Control of PEM Fuel Cells as Backup Power for UPS Applications", in *IEEE Energy Conversion Congress and Exposition*, pp. 631 – 638, Sept. 2009.

[24] R. Onanena, L. Oukhellou, D. Candusso, F. Harel, D. Hissel, and P. Aknin, "Fuel Cells Static And Dynamic Characterizations As Tools For The Estimation Of Their Ageing Time", in *International Journal of Hydrogen Energy*, vol. 36, no. 2, pp. 1730 – 1739, 2010.

[25] R. Onanena, L. Oukhellou, D. Candusso, A. Same, D. Hissel, and P. Aknin, "Estimation Of Fuel Cell Operating Time For Predective Maintenance Strategiers", in *International Journal of Hydrogen Energy*, vol. 35, no. 15, pp. 8022 – 8029, Aug. 2010.

[26] S. Wasterlain, D. Candusso, F. Harel, X. François, M.C. Péra and D. Hissel, "Durability Test Results of a Polymer Electrolyte Membrane Fuel Cell Operated at Overnominal Temperature With Low

Humidified", in *Journal of Fuel Cell Science and Technology*, vol. 7, no. 2, p. 024502, Apr. 2010.

[27] M. Gerard, J.P. Poirot-Crouvezier, D. Hissel and M.C. Péra, "Ripple Current Effects on PEMFC Aging Test by Experimental an Modeling", in *Journal of Fuel Cell Science and Technology*, vol. 8, no. 2, p. 021004, Apr. 2011.

[28] J. Zhang, C. Song, and J. Zhang, "Accelerated Lifetime Testing for Proton Exchange Membrane Fuel Cells Using Extremely High Temperature and Unusually High Load", in *Journal of Fuel Cell Science and Technology*, vol. 8, no. 5, p. 051006, Oct. 2011.

[29] D. Hissel, D. Candusso, and F. Harel, "Fuzzy-Clustering Durability Diagnosis of Polymer Electrolyte Fuel Cells Dedicated to Transportation Applications", in *IEEE Transactions on Vehicular Technology*, vol. 56, no. 5, pp. 2414 – 2420, Sept. 2007.

[30] E. Frappé, A. De Bernardinis, O. Bethoux, D. Candusso, F. Harel, C. Marchand, and G. Coquery, "PEM Fuel Cell Fault Detection And Identification Using Differential Method: Simulation And Experimental Validation", in *The European Physical Journal Applied Physics*, vol. 54, no. 2, pp. 1 – 11, 2011.

[31] E. Frappé, A. De Bernardinis, O. Bethoux, C. Marchand, and G. Coquery, "Fault Detection And Identification Using Simple And Non-Intrusive Online Monitoring Techniques For PEM Fuel Cell", in *IEEE International Symposium on Industrial Electronics*, pp. 2029 – 2034, Jul. 2010.

[32] A. Gebregergis. P. Pillay, and R. Rengaswamy, "PEMFC Fault Diagnosis, Modeling, and Mitigation", in *IEEE Transactions on Industry Applications*, vol. 46, no. 1, pp. 295 – 303, 2010.

[33] F. Barbir, H. Gorgun, and X. Wang, "Relationship Between Pressure Drop and Cell Resistance As A Diagnostic Tool For PEM Fuel Cells", in *Journal of Power Sources*, vol. 141, no. 1, pp. 96 – 101, Feb. 2005.

[34] J. Chen, "Dominant Frequency Of Pressure Drop Signal As A Novel Diagnostic Tool For The Water Removal In Proton Exchange Membrane Fuel Cell Flow Channel", in *Journal of Power Sources*, vol. 195, no. 4, pp. 1177 – 1181, Feb. 2010.

[35] N. Yousfi-Steiner, D. Hissel, Ph. Moçotéguy, and D. Candusso, "Diagnosis of Polymer Electrolyte Fuel Cells Failure Modes (Flooding & Drying out) By Neural Networks Modeling", in *International Journal of Hydrogen Energy*, vol. 36, no. 4, pp. 3067 – 3075, Feb. 2011.

[36] N. Yousfi-Steiner, D. Candusso, D. Hissel, and Ph. Moçotéguy, "Model-Based Diagnosis For Proton Exchange Membrane Fuel Cells", in *Modelling and Simulation of Electrical Machines*, Converters and Power Systems, vol. 81, no. 2, pp. 158 – 170, Oct. 2010.

[37] N. Yousfi-Steiner, D. Hissel, Ph. Moçotéguy, and D. Candusso, "Non-Intrusive Diagnosis Of Polymer electrolyte Fuel Cells By Wavelete Packet Transform", in *International Journal of Hydrogen Energy*, vol. 36, no. 1, pp. 740 – 746, Jan. 2011.

[38] N. Yousfi-Steiner, Ph. Moçotéguy, and D. Candusso, D. Hissel , A. Hernandez, and A. Aslanides, "A Review on PEM Voltage Degradation Associated With Water Management: Impact, Influence and Characterization", in *Journal of Power Sources*, vol. 183, no. 1, pp. 260 – 274, Aug. 2008.

[39] D. Hissel, M.C. Péra, and J.M. Kauffmann, "Diagnosis of Automotive Fuel Cell Power Generators", in *Journal of Power Sources*, vol. 128, no. 2, pp. 239 – 246, Apr. 2004.

[40] H. Li, Y. Tang, Z. Wang, Z. Shi, S. Wu, D. Song, J. Zhang, K. Fatih, J. Zhang, H. Wang, Z. Liu, R. Abouatallah, and A. Mazza, "A Review Of Water Flooding Issues In The Proton Exchange Membrane Fuel Cell", in *Journal of Power Sources*, vol. 178, no. 1, pp. 103 – 117, Mar. 2008.

[41] A. Narjiss, D. Depernet, D. Candusso, F. Gustin, and D. Hissel, "Online Diagnosis of PEM Fuel Cell", in *The 13th International Power Electronics and Motion Control Conference (EPE-PEMC 200*8), pp. 734 – 739, Sept. 2008.

[42] X. Yu, M.R. Strake, L.M. Tolbert, and B. Ozpineci, "Fuel Cell Power Conditioning for Electric Power Applications: A Summary", in *IET Electric Power Applications*, vol. 1, no. 5, pp. 643 – 656, Sept. 2007.

[43] M. Cacciato, F. Caricchi, F. Giuhlii, and E. Santini, "A Critical Evaluation and Design of Bi-directional DC/DC Converters for Super-Capacitors Interfacing in Fuel Cell Applications", in *IEEE Industry Applications Society Annual Meeting*, vol. 2, pp. 1127–1133, Oct. 2004.

[44] H.J. Cha, and P.N. Enjeti, "A New Soft Switching Direct Converter for Residential Fuel Cell Power System", in *IEEE Industry Applications Society Annual Meeting*, vol. 2, pp. 1172–1177, Oct. 2004.

[45] J. Wang, F.Z. Peng, J. Anderson, A. Joseph, and R. Buffenbarger, "Low Cost Fuel Cell Converter System for Residential Power Generation" in *IEEE Transaction on Power Electronics*, vol.19, no.5, pp. 1315–1322, 2004.

[46] RJ. Wai, and R.Y. Duan, "High Step-Up Converter with Coupled-Inductor", in *IEEE Transaction on Power Electronics*, vol. 20, no. 5, pp. 1025–1035, Sept. 2005.

[47] M.H. Todorovic, L. Palma, and P. Enjeti, "Design of A Wide Input Range DC–DC Converter With a Robust Power Control Scheme Suitable for Fuel Cell Power Conversion", in *IEEE Industry Applications Society Annual Meeting*, vol. 1, pp. 374–379, 2004.

[48] C.R. Liu, A. Johnson, and J.S. Lai, "A Novel Three-Phase High-Power Soft-Switched DC/DC Converter for Low-Voltage Fuel Cell Applications", in *IEEE Transaction on Industry Applications*, vol. 41, no. 6, pp. 1691–1697.

[49] R.T. Meyer, and B. Yao, "Control Of A PEM Fuel Cell Cooling System", in *Proceedings of ASME International Mechanical Engineering Congress and Exposition (IMECE)*, Chicago, Illinois, USA, Nov. 2006.

[50] D. Feroldi, "PEM Fuel Cells with Bio-Ethanol Processor Systems, A Multidisciplinary Study of Modeling, Simulation, Fault Diagnosis and Advanced Control: Fault Diagnosis and Fault Tolerant Control of PEM Fuel Cell Systems", in *Springer*, pp. 185 – 206, 2012.

[51] M.H. Wang, and M.J. Chen, "Design of a Fault Diagnosis System for PEM Fuel Cells", in *International Symposium on Computer, Consumer and Control*, pp. 460 – 463, June 2012.

[52] Q. Yang, A. Aitouche, and B.O. Bouamama, "Structural Analysis For Air Supply System Of Fuel Cell", in *International Renewable Energy Congress*, Sousse, Tunisia, Nov. 5–7, 2009.

[53] J. Hua, J. Li, M. Ouyang, and L. Xu, "Proton Exchange Membrane Fuel Cell System Diagnosis Based On Multivariate Statistical Method", in *International Journal of Hydrogen Energy*, vol. 36, no. 16, pp. 9896 – 9905, Aug. 2011.