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A review on prognostics and health monitoring of proton exchange membrane fuel cells

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Abstract

Fuel cell technology can be traced back to 1839 when British scientist Sir William Grove discovered that it was possible to generate electricity by the reaction between hydrogen and oxygen gases. However, fuel cells still cannot compete with internal combustion engines. Fossil fuels are cheaper and present very high volumetric energy densities compared with the hydrogen gases. Furthermore, hydrogen storage as a liquid is still a huge challenge. Another important disadvantage is the lifespan of the fuel cells because of their durability, reliability and maintainability. Prognostics is emerging technology in failure prevention through reliability assessment and remaining useful lifetime estimation. Hence prognostics and health monitoring can play a critical role in enhancing the durability, reliability and maintainability of the fuel cell system. This paper presents a review on the current state-of-the-art in prognostics and health monitoring of Proton Exchange Membrane Fuel Cells (PEMFC), aims at identifying research and development opportunities in this fields. This paper ultimately aims at encouraging academics and engineers to extend their research interests into Failure Modes, Mechanisms and Effects Analysis (FMMEA) in PEMFCs.

Keywords: PEMFC, hydrogen fuel cells, health monitoring, prognostics, FMMEA, State of health

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1. Introduction

A fuel cell is simple electro-chemical device as shown in Figure 1 which converts chemical energy into electrical energy from a hydrogen fuel or hydrogen-rich fuels [1]. Fuel cells basically consist of three main components: anode, cathode and electrolyte. The electrolyte, which is made of non-conductive materials, allows charges to pass through and is sandwiched between catalytic electrodes, i.e., the anode and the cathode. Electricity is produced from the cathode to the anode, i.e., electrons flow from the anode to the cathode through an external circuit [2, 3]. Based on the materials used for the electrolyte, the anode and the cathode, there are many different types of fuel cells, particularly based on the non-conductive materials used for the electrolyte, such as alkaline fuel cell (AFC), proton exchange membrane fuel cell (PEMFC), direct methanol fuel cell (DMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) [4, 5]. An individual fuel cell typically delivers low voltages and high currents. Typical voltage and current ranges are from 0.4 to 0.9V and from 0.5 to 1A/cm² respectively [6, 7]. For example, the fuel cell developed at the Sustainable Energy Technologies, University of Hertfordshire, is reported to produce about 0.7V (after losses) and 0.6A/cm² [8]. In order to achieve higher power output, the fuel cells need to be stacked together as shown in Figure 2. Depending on the power output and the applications, fuel cells come in various shapes and sizes [9]. Fuel cells have demonstrated to be an attractive alternative energy generation technology from hydrogen-rich fuels [2, 3, 5]. Fuel cells do not have any mechanical moving parts, but have high energy efficiency, and zero emissions i.e., deliver no pollution to the environment during operation. Hence, there is a good potential for fuel cells to gradually replace internal combustion (IC) engines in the future [10, 11]. Fuel cells are used in many applications, such as in aerospace and automotive vehicles, in small and large scale power generation plants, in portable power generators, in

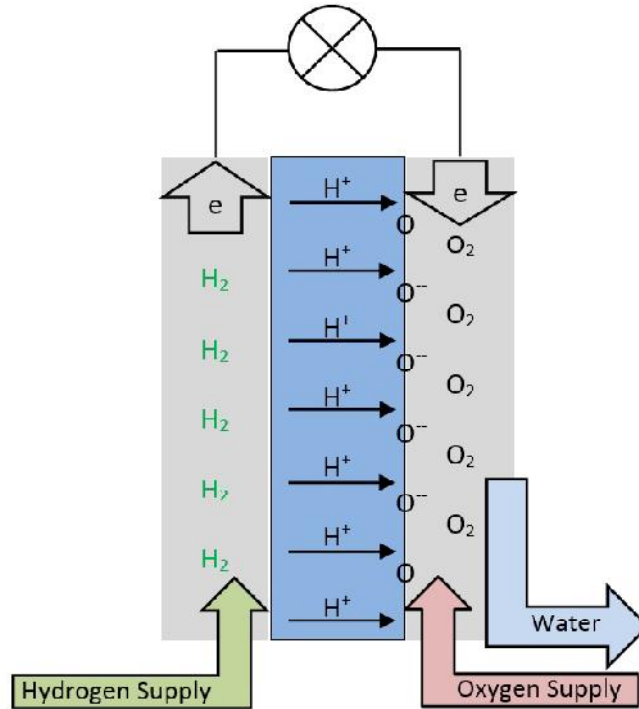


Figure 1:

combined heat and power (CHP) generation, and in backup power applications
 30 [12]. PEMFCs are the most suitable type of fuel cells for many applications be-
 cause of their operating temperature range (between 20°C and 100°C) and quick
 response time compared with other types of fuel cells. Particularly, hydrogen
 PEMFCs were found suitable for portable power generators such as those used
 in spaceships or automotive vehicles [13]. However, main drawbacks are the cost
 and the lifespan of fuel cells because of durability, reliability and maintainabil-
 35 ity issues associated with them [13, 14, 15]. So far, general life expectancy of
 a fuel cell is not up to the expectation of the industry. For example, a typical
 life expectancy of the PEMFC is around 2500 hours, whereas transportation
 applications require at least 5000 hours and stationary applications require at
 40 least 40000 hours [16, 17].

Health monitoring has been used in engineering systems for many years
 to ensure performance, safety, availability and reliability [18, 19, 20]. Generally
 speaking, sensors are used to monitor the operating conditions, performance and
 loading cycles. Anomalies and faults can be detected on time, hence avoiding

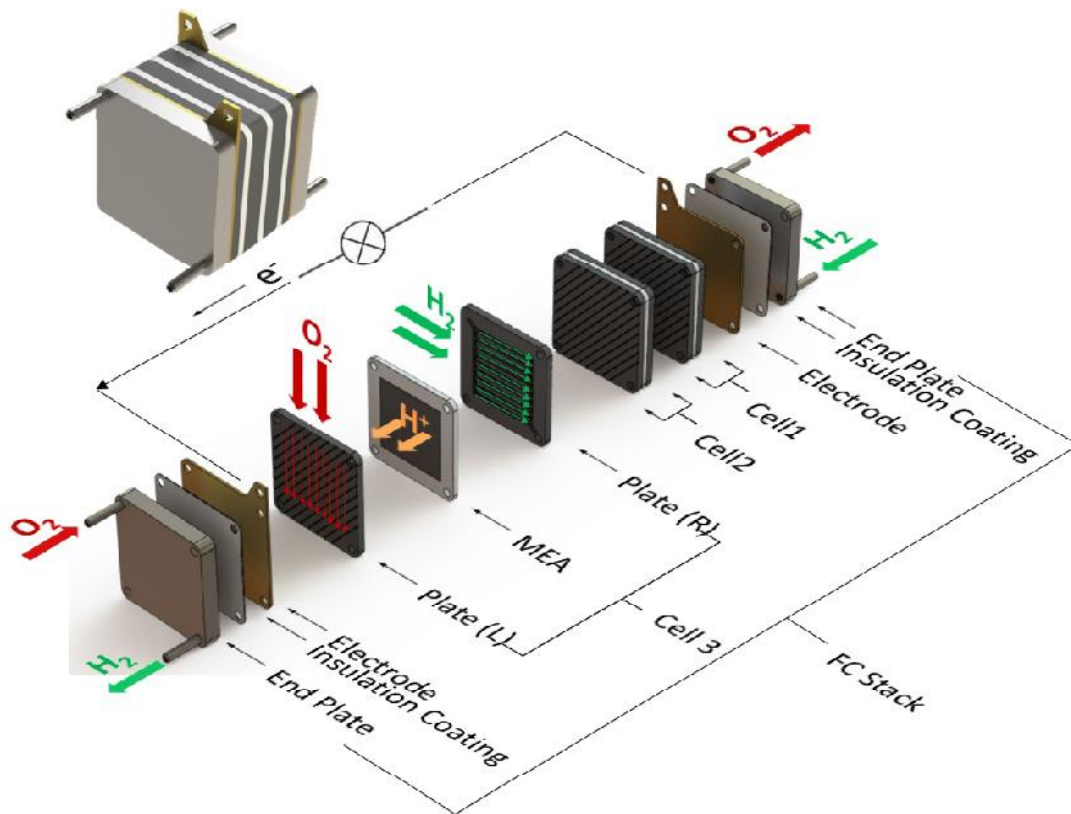


Figure 2:

45 otherwise unpredicted incidents, down time and fault propagation [21]. Typically, small faults in a part of the system may develop as a major fault, and ultimately the system may fail adversely. If the fault can be detected or predicted at an early stage, then the system can be scheduled to maintenance on time before the fault develops into something more serious [22]. Therefore,

 50 applying health monitoring techniques will be a definite advantage, not only for the safety reasons, but also because it can considerably reduce unscheduled maintenance costs. [23].

Prognostics is an engineering process of diagnosing, predicting the remaining useful lifetime (RUL) and estimating the reliability of a system [24, 25, 26, 27].

 55 It has emerged in the last decade as one of the most efficient approaches in failure prevention, reliability estimation, RUL prediction of various engineering systems and products [28, 29]. There are three different approaches to prognostics, namely (1) data driven approach, (2) model driven approach, and (3) fusion approach [24]. As prognostics can provide state-of-health (SOH) and

60 RUL information of the fuel cell, the operation of the fuel cell can be optimised using an appropriate control strategy. Maintenance tasks can be scheduled, thus reducing down time. Although prognostics was used in safety critical system in early days, it is nowadays an integral part in many engineering systems, products and applications [24]. Hence application of Prognostics, along with health
65 monitoring to PEMFC, can be used to improve the reliability, sustainability and maintainability (through evidence based decision making), reduce the life cycle cost, and can also provide feedback to the design and validation process [30, 31, 32]. Health monitoring sensors can be used to monitor the important parameters such as precursor parameters and loading conditions [33]. Prognos-
70 tics could use these sensor information to predict the remaining useful life time (RUL), to diagnose failures well before they develop into a serious problems, and provide information to control systems to automate contingency management [34, 35, 36]. Hence both health monitoring and prognostics can play a vital role in improving the durability, reliability, and maintainability of PEMFC system.
75 This will help to overcome the main challenges faced by the PEMFC industry today.

Although some developments have been reported in prognostics for PEM fuel cells, more research needs to be done in the field. Development of prognostics for PEMFC has become a hot topic in the recent years as PEMFC has the potential
80 of replacing the internal combustion engine in the future. PEMFC is a very sensitive electrochemical device which involve heat transfer, charge transport, electrochemical reaction and multi-phase flows, hence developing a prognostics methodology has become a complex and complicated process [16]. Although fuel cells have no mechanical moving parts, membrane electrode assembly (MEA)
85 undergoes degradation processes similar to the mechanical systems because of the electrochemical reaction and multi-phase flows. These degradation processes might be natural in some cases but most of these processes of degradation could be accelerated by loading cycles, operating conditions, etc. Furthermore failures in MEA is very difficult to measure or observe directly as MEA is placed between
90 the bipolar plates. Failure modes, mechanisms and effects of MEA are not very

well researched and understood. Therefore detail study of FMMEA is necessary for two main reasons: (1) apply prognostics at the deployment stage of the fuel cell systems and (2) understand the underlying physical process of degradation and improve the design of MEA and other components using novel materials which have high resistance to the degradations. FMMEA study can also help to identify the precursor of failures in the MEA to start the process of prognostics and health monitoring.

2. Prognostics

Prognostics is a technology used to monitor degradation in engineering systems, predict when failure may occur, improve reliability, and provide a cost effective strategy for scheduled maintenance [37]. Prognostics of engineering systems or products has become very important as degradations in the individual parts may cause a severe (and irreversible) damage to the entire system, environment and users. Ultimately, it may lead to failures and will result in significant costly repairs, that could otherwise have been avoided. Adopting prognostics techniques requires continuous monitoring of performance, loading cycles and precursors of failures, and detecting any anomalies in these parameters.

Figure 3 illustrates the three main approaches to prognostics, which are (i) Data driven, (ii) Model driven and (iii) Fusion approach. Fusion approach is combination of both (i) and (ii) methodologies. Figure 3 also shows the classifications of prognostics approaches. Data driven approach can be further classified into statistical and machine learning techniques. Statistical techniques can be either parametric or non-parametric. Machine learning techniques can be either supervised learning where test data is available or unsupervised learning where test data is not available. Model driven approach can be based on physics of failure models or system models. Physics of Failure (PoF) models are based on the underlying physical phenomena of failures which requires details FMMEA study. System model relates the system' output to its input, and it

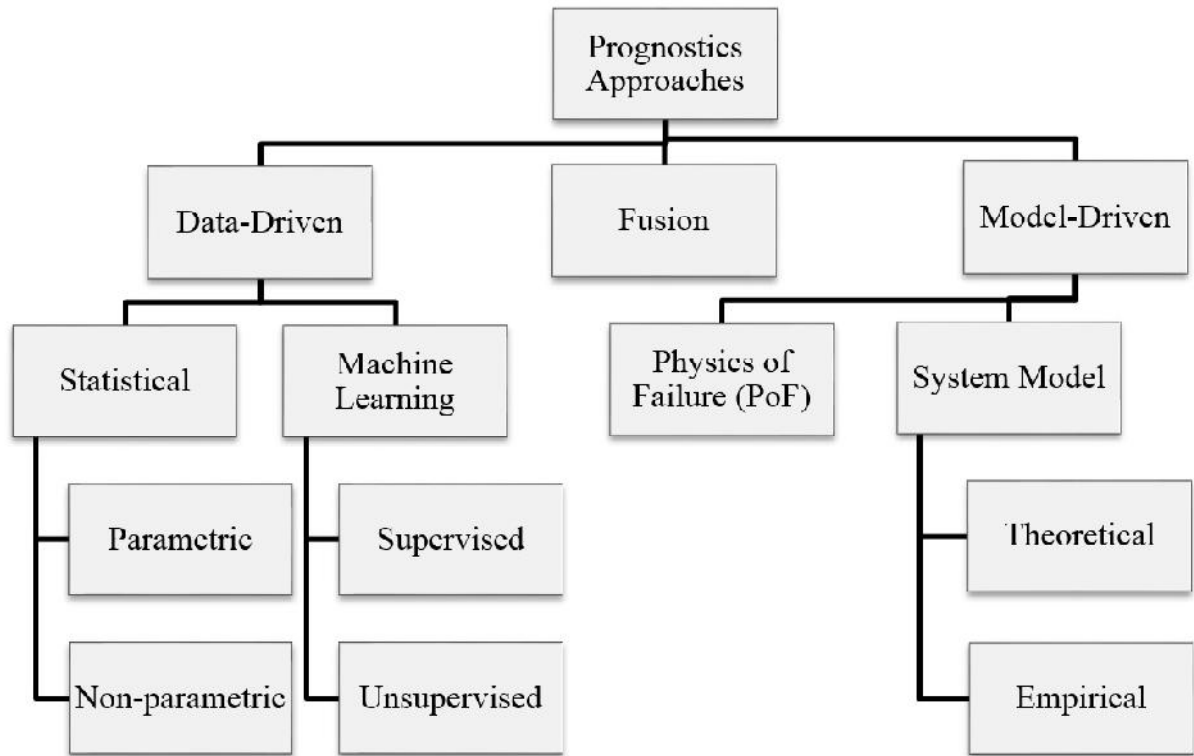


Figure 3:

120 can be derived from the first principles or test data. Fusion approach entails
 a combination of data driven and model driven approaches which incorporates
 the benefits and eliminates the drawbacks from both approaches [24].

2.1. Data Driven Approach

Data driven approach is considered as a black box approach to prognostics
 125 as they do not require system models or system specific knowledge to start
 the prognostics [38]. Monitored and historical data are used to learn the sys-
 tems' behaviours and used to perform the prognostics. Hence the data driven
 approach is suitable for the systems which are complex and whose behaviours
 cannot be assessed and derived from first principles. The implementation of
 130 data driven techniques for the purpose of health monitoring and prognostics is
 generally based on the assumption that the statistical characteristics of system's
 performance will not be changed until fault occurs [38]. Therefore, the main
 advantage of the data driven approach is that the underlying algorithms are
 quicker to implement and computationally more efficient to run compared with

135 other techniques [39]. However, it is necessary to have historical data and knowl-
edge of typical operational performance data, the associated critical threshold
values and their margins. Data driven techniques completely rely on the analy-
sis of data obtained from sensors and exploit operational or performance related
140 signals that can indicate the health of the monitored system. Data driven strate-
gies to prognostics have been applied in a number of engineering applications
[40, 41, 42, 43, 44, 45, 46].

The principal disadvantage of the data driven approach is that the confidence
level in the predictions depends on the available historical and empirical data.
Historical and empirical data are required in the data driven approach to define
145 the respective threshold values. In some instances it is difficult to obtain or have
historical data available, for example in the case of a new system or device that
may require long time and/or expensive tests to failure to generate this data.
However, there are techniques and procedures, that can be used to overcome
this disadvantage [47, 48]. Three of the strategies could be used to address this
150 challenge are based on the use of:

1. Hardware-in-the-Loop simulations (HiL): Hardware-in-the-Loop is a com-
puter simulation which is used to test a real product or system by con-
necting it to the hardware that applies simulated loads as in a real appli-
cation. It is very fast and cheap to implement. In addition, several failure
155 parameters (i.e., operational and environmental) can be controlled inde-
pendently. HiL can also be used to develop algorithms, test and validate
the algorithms, benchmarking and development of metrics for prognostics
[47].
2. Accelerated Life Test (ALT): Accelerated life test is designed to cause the
160 product to fail more quickly than under normal operating conditions by
applying an accelerated (elevated) stress condition which responsible for
a particular failure mechanism. ALT becomes an important methodology
in the development of the prognostics. Several environmental and loading
conditions can be applied independently to accelerate failures [29, 48, 49,

165 50, 51].

3. Online Learning (Semi supervised/Unsupervised learning): Online learning is based on the assumption that a new system performance data represents the healthy system and that they do not fail for a certain period of time. This type of approach can also be called semi supervised or unsupervised learning as only healthy data or no reference data is available. Reinforcement learning approach is also suitable for this strategy [52].

2.2. Model Driven Approach

The model driven approach uses mathematical equations that predict the physics governing failures and therefore is sometimes referred to as the Physics of Failure (PoF) approach. It requires knowledge of the failure mechanisms, geometry of the system, material properties and the external loads that are applied to the system. An accurate mathematical model can benefit the prognostics process, where the difference between the output from a mathematical model and the real output of the system can be used to find the anomalies, malfunctions, disturbances, etc. [24, 53]. Using the difference between the model and the data values for a performance parameter, the early warnings for failures and RUL can be predicted. Many prognostics work have been reported based on the model-driven approach [54, 44, 45, 55, 56, 57, 58, 59]. A block diagram of a typical model based approach is shown in Figure 4. Typical model driven approach is based on the system/physics of failure model for which the health monitoring system will provide required sensor data. Once fault is detected by feeding the sensor data into the model, damage parameter is isolated and damage is estimated. The damage trend will then be used to estimate the RUL [24].

2.3. Fusion Approach

The fusion approach is based on the advanced features of both the data driven and model based methods. This approach requires an accurate mathematical model of the system for the physics based failure approach, and enough

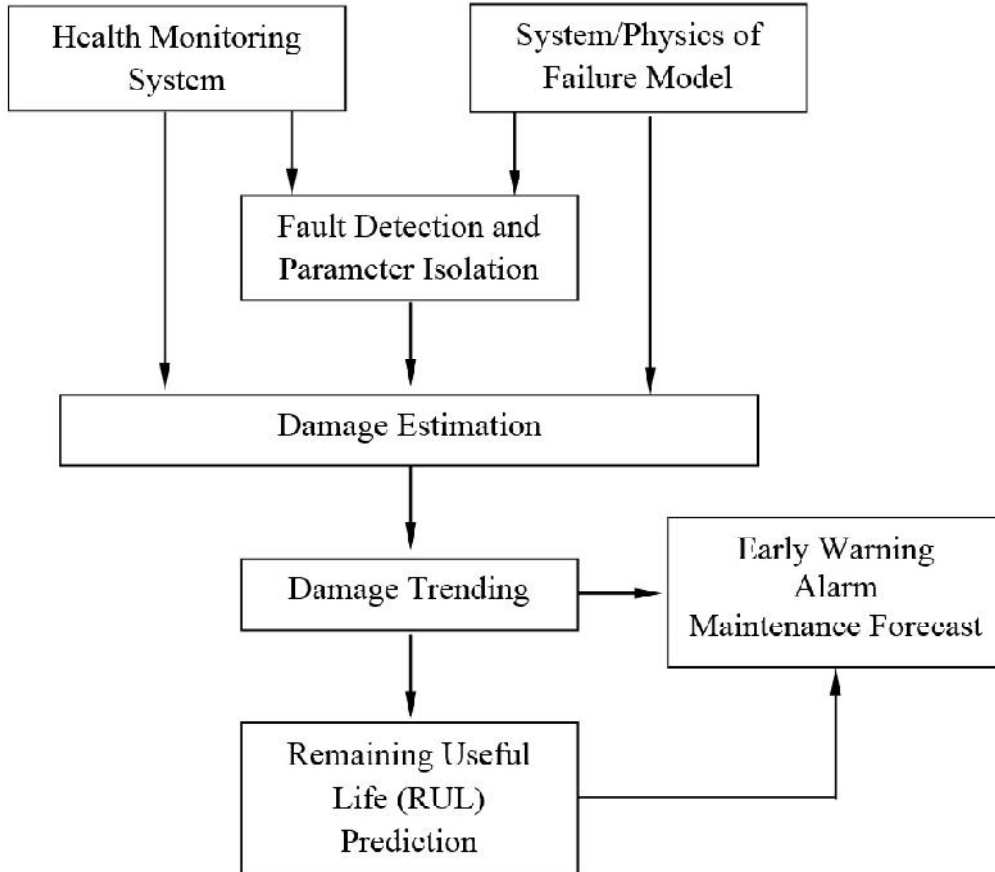


Figure 4:

historical data and knowledge of typical operational performance data, for the
 195 data driven approach. The aim of the fusion approach is to overcome the limita-
 tions and disadvantages of both model and data driven approaches to estimate
 the remaining useful life [24]. Therefore, the accuracy of the fusion approach
 should be higher than both model and data driven approaches when used in-
 individually [24], although for a real-time analysis it may not be suitable due to
 200 the significant computational resources required. The fusion approach has been
 reported to be used in many applications before [24, 60, 61, 62, 63, 64, 65].

3. Applications of Prognostics to PEMFC

Although prognostics is used in many engineering systems and products
 including batteries [66, 67, 68, 69, 70, 71, 72, 73], to assess the remaining useful
 205 life and enhance the durability and reliability, prognostics is rarely discussed
 with respect to fuel cells. Jouin et al. (2013a, 2013b) discussed the benefits

of applying the prognostics techniques to monitor the SOH and estimate the RUL of PEMFC, aiming at improving their durability and reliability, and hence extend their life spans [74, 75]. They also discussed layer approach (based on
210 different tasks) to prognostics and health management (PHM) and degradation mechanisms in these review papers. Lack of experimental and failure data, and complete models which incorporates all wear mechanisms were also reported as main challenges [74, 75].

Most fuel cells need a health monitoring system in place to assess their per-
215 formance. They are generally used to give early warnings or change the control strategy if an anomaly is detected in the performance variable or in any key monitoring parameters [21]. Sensors are used to monitor the parameters that need to be watched. Because a fuel cell is very sensitive to the supplied fuel, oxidant, load current and the amount of water and heat produced, health monitoring
220 becomes a vital component to control the fuel cell system [2]. Furthermore, prognostics and health monitoring can provide information to a prognostics system to estimate RUL, schedule maintenance and improve the sustainability of the fuel cells.

This review is focused on PEMFC and organised under the subsections of
225 degradation mechanisms, modeling for prognostics, accelerated testing, monitoring parameters and techniques, diagnosis and RUL estimation. Before start the prognostics of PEMFC it is necessary to understand the most effective degradation mechanisms of PEMFC. Under this section degradation mechanisms responsible for failures in PEMFC is reported. For the model driven approach
230 to prognostics, PEMFC failure models are necessary. Models could be derived from the first principle or test data. PEMFC models used for diagnosis and prognostics are discussed next. Accelerated test is discussed for the purpose of failure data collection, and understand effect of different degradation in the performance of PEMFC. After that monitoring parameters and techniques for
235 health monitoring and prognostics of PEMFC is investigated from the literature. Finally, from the prognostics models, test data, monitoring parameters and monitoring techniques, how PEMFC could be diagnosed failure conditions?

and how RUL is estimated? are discussed respectively.

3.1. Degradation Mechanisms

240 A membrane electrode assembly is the key component of the fuel cell. MEA consists of electrodes and membrane which is sandwiched between two electrodes. Fuel cell stack will have many MEA stacked together. Failure in any component i.e., membrane and electrodes of any one of MEA in the stack, will cause complete failure of the stack even though all the other MEA are
245 functional. Although there no mechanical moving parts in the fuel cell, fuel cell components undergo degradation process similar to the mechanical components. It is therefore necessary understand the degradation mechanisms of the fuel cell components particularly the membrane. Membrane degradation could be categorized into followings: (1) Chemical degradation, (2) Mechanical
250 degradation and (3) Membrane shorting [76, 77, 78]. Chemical degradation occurs when the membrane decompose because of electrochemical reaction caused by poisonous substances and radicals which are produced in the cathode and anode during the chemical reaction [79]. Some of the typical radical elements are peroxide (HO^-) [80] and hydroperoxide (HOO^-) [81, 82, 83]. Mechanical
255 degradation occurs when membrane undergoes mechanical degradation such as fracture because of thermal stress [76], humidity [84, 85], pressure and mechanical stress. Membrane shorting occurs when membrane allows current to pass through. Mechanical degradation may cause early failures because of manufacturing defects and improper MEA fabrication [81]. Mechanical failure may
260 also be caused by excessive or non-uniform pressure [81]. Fuel cell undergoes thermal and humidity cycling which may lead to additional mechanical stress on the MEA. These degradations could lead to decrease in the performance of the fuel cell and ultimately lead to failures in membrane hence complete failure in the fuel cell stack.

265 Platinum (Pt) based catalyst are used in the electrodes to increase the rate of chemical reaction. This catalyst typically undergo variable potential cycling from 0.6 to 1.0 V. It may also undergo higher potential spikes and higher poten-

tial voltage during uncontrolled operations [86]. Sudden increases in the load current may result in decreasing the catalyst area [76]. Pt dissolution is generally caused by chemical oxidation by the oxygen in the cathode electrode [87]. These
270 condition may expose the catalyst into electrochemical stress and may result in irreversible degradation in the catalyst. Some of the other operating conditions which may accelerate the failures are relative humidity [88], reactant starvation [89, 90], carbon monoxide poisoning at the anode catalyst [91, 90, 92], cathode
275 flooding and membrane drying [92, 93, 94, 95, 96]. Fuel cell runs close to its open circuit voltage, accelerates different degradation mechanism in membrane and catalyst [97].

Many degradation mechanisms were investigated theoretically and experimentally. But the data related to which failure mechanisms cause more failures
280 and which failure mechanisms cause less failures are not available. Failures and their corresponding failure mechanisms are needed to be investigated related to the applications such as stationary, automotive, backup, combined heat and power etc. Hence it is necessary to carryout application specific failure modes, mechanisms and effects analysis.

285 *3.2. Modeling for Prognostics*

Once the failure modes, mechanisms and their effects are understood, physics of failure or underlying physical process of failure needs to be modeled. Prognostics-oriented fuel cell catalyst aging model has been reported by Zhang and Pisu (2014) [98]. Catalyst degradation model is based on on the platinum dissolution kinetic model proposed by Darling and Meyers [99, 100] and simplified for
290 the purpose of prognostics. Aging parameters for this model are electrochemical surface area and membrane gas crossover. Burlatsk et al (2012) have reported a mathematical model to predict the life of PEM fuel cell under hydration dehydration cycling. Stresses associated with hydration and dehydration cycle have
295 been modeled mathematically particularly a model of relative humidity (RH) distribution in gas channels, a model of membrane stress and a model of damage accrual [101]. This model predict membrane lifetime as a function of RH

cycle amplitude and membrane mechanical properties. A viscoplastic model of Nafion[®] has been reported in the literature by Solasi et al (2008) [102]. Experimental results were used to develop a nonlinear time-dependent constitutive model to predict the hygro-thermomechanical behaviour of Nafion[®]. Rong et al (2008a & 2008b) have developed a rate-dependent isotropic plasticity model with temperature and humidity dependent material properties to understand the viscoplasticity properties of catalyst layer components. Numerical simulation was used to investigate the crack initiation in the material [103, 104].

PEM fuel cell models have been developed by number of researchers mainly for the purpose of control. Generally models for each part of the fuel cell such as catalyst layers, gas diffusion layers etc. were developed and then integrated to simulate and understand the behaviors of fuel cell under different operating conditions [105, 106, 107]. But underlying physical process of failures or physics of failure models have not been fully developed i.e. integrated failure model for most of its failure mechanisms. Hence it is very important to develop failure models for each failure mechanisms and integrated into a model which can predict most of the failures.

3.3. Accelerated Testing

Accelerated test is a useful tool to collect failure data, understand the failure mode and mechanisms, and develop prognostics strategies. Accelerated test on PEM fuel cell could be carried out under load cycling [108, 109, 110], RH cycling [108, 111, 112, 113?], elevated temperature [114], thermal cycle [115], load ripples [116], anode flooding, membrane drying, carbon corrosion [83], Pt dissolution [83, 51] etc. Under the accelerated test effect of one parameter could be investigated effectively by keeping all the other parameters at normal conditions and changing the particular parameter between two possible extreme values. Accelerated test could be also carried out for radical elements and external poisoning by introducing these elements into the fuel cell.

Accelerated test under combined RH cycling and load cycling have been reported by Wu et al (2014). Under these conditions, severe chemical degradation

was observed in the membrane using transmission electron microscopy (TEM) and scanning electron microscopy (SEM) cross sectional images [108]. Petrone et al (2015) proposed a new approach and protocol to accelerated test for the purpose of prognostics and lifetime prediction based on adaptable load cycling [117]. It is important to have such general protocol to conduct accelerated test on PEM fuel cell for the purpose of prognostics and life time prediction.

3.4. Monitoring Parameters and Techniques

3.4.1. Voltage

Cell voltage is amongst the cheapest and easiest ways to implement monitoring techniques. It also is one of the quickest approaches to monitor a fuel cell, as voltage measurements do not require expensive and specialized sensors. Most of the fault modes of the fuel cell cause a voltage drop in the fuel cell. Anode flooding at low current densities was investigated by O'Rourke et al. (2009) based on cell voltage measurements [118]. These cell voltages were then compared with median cell voltage. If the difference between any cell voltage and median cell voltage was higher than a predetermined value, then the cell could be under anode flooding. This method is a more efficient approach than the low frequency ($< 6Hz$) impedance measurement. The low frequency impedance measurement technique may take a longer period of time to identify flooding. Once flooding occurs and the cell voltage has already been decreased, it is likely that the irreversible phenomenon has already been started [118].

Membrane drying and cell flooding were investigated by Frappe et al. (2010) [119]. In this work, it was observed that membrane drying increased the membrane resistance because of insufficient water. Cell flooding blocks a part of the active area therefore the active area of the fuel cell reduces. Frappe et al. (2010) proposed that it was possible to monitor only a group of cells instead of monitoring every individual cell in the stack. Thus, sample groups of cells were selected to monitor at the inlet, outlet and center of the stack. State-of-health indicator of the fuel cell stack was proposed as the voltage difference between the center group and the inlet/outlet group. Based on this indicator, Frappe

et al. (2010) proposed that if there were no voltage variations (the difference is zero), then this implied no fault condition; if all the voltages dropped together at the same time (again the difference is zero), then this implied a load varia-
360 tion; if the voltage of the center group dropped, there was possible drying; and if the voltage of the inlet/outlet group dropped, there was possible flooding. This approach was backed up with experimental data and results [119].

Xue et al. (2006) investigated model based condition monitoring of a PEMFC
365 based on a lumped parameter dynamic fuel cell model and by employing the Hotelling T^2 statistical analysis [54]. Fault detection of the PEMFC was facilitated by comparing the real time fuel cell output voltage measurements with the baseline voltage by employing the Hotelling T^2 statistical analysis. The baseline voltages were used to evaluate the output T^2 statistics under normal operating
370 conditions. Upper control limit for the fault was established and fault condition was declared if the T^2 statistics of real-time voltage measurements exceeded the upper control limit [54].

3.4.2. Impedance

Alternating current (AC) impedance is generally used to estimate the state-
375 of-health (SOH) of fuel cells and batteries [120, 121]. AC impedance could also be used as an in-situ health monitoring technique for PEMFCs. An AC impedance measurement technique coupled with a model-based approach was suggested by Fouquet et al. (2006) [120]. In this study, a 150cm^2 hydrogen PEMFC stack consisting of six cells was used. Test data was then fitted to
380 parameters of a Randles-like equivalent circuit. In order to improve the quality of the fit, classical Randles was replaced with a constant phase element instead of a standard plane capacitor. It was reported that this modified model of Randles equivalent circuit was an efficient and robust way to monitor the SOH of hydrogen PEMFCs with respect to water content on MEA. Flooded and dry
385 conditions were identified with respect to the variation of the parameters of the proposed modified Randles equivalent circuit model for PEMFC [120]. Unlike Fouquet et al. (2006), Kurz et al. (2008) reported a predictive control strategy

based on impedance measurements [121]. From the impedance measurements at two different frequencies (one at low and one at high frequency), the voltage drop caused by the flooding and drying phenomena was detected. Kurz et al. (2008) used this information to run the fuel cell at an optimal operating point [121].

Rubio et al. (2007, 2008) proposed a current interruption method to estimate the PEMFC model parameters such as double layer capacitance, diffusion resistance, charge transfer resistance, diffusion related time constant and membrane resistance (i.e. impedance) [122, 123]. It was found a correlation between the cathode flooding phenomenon and the diffusion resistance. It was also reported that impedance model parameters can be used to diagnose other degradation phenomena such as membrane drying, cathode drying, membrane degradation, and anode poisoning. The current interruption method was shown to be easy to use as an in-situ health monitoring method [122, 123]. An implementation of continuous real-time impedance spectroscopy was carried out by Bethoux et al. (2009) [124]. This work showed that small sinusoidal current of known amplitude and frequency could be sent into the fuel cell stack while it was operating. A low pass filter was proposed to retrieve the signal back from the fuel cell stack without any electrical disturbances to the load. Using the collected data, complex impedance can be estimated and equivalent Randles circuit parameters can be computed [124].

Cooper and Smith (2006) investigated four electrical measurement techniques for on-line measurement of ohmic resistance: current interrupt, AC resistance, high frequency resistance and electrochemical impedance spectroscopy (EIS) [125]. Internal resistance measurements of PEMFC based on all four techniques were compared. Current interrupt and high frequency resistance methods correlated well if the high frequency measurement technique was in the suitable range. For hydrogen PEMFCs operating with moderately humidified reactants, the ohmic resistance measurements determined with the current interrupt technique, high frequency resistance and EIS were within 10 – 30% of each other. It appears that there are considerable differences between these three techniques

and there is no agreement about which method is the most suitable for on-line
420 electrical measurement of ohmic resistance of hydrogen PEMFCs [125].

Rubio et al. (2010) classified PEMFC degradation phenomena based on time
scale, i.e., time taken to observe a variation in the performance of the fuel cell
[92]. Cathode flooding, membrane drying, catalyst poisoning, and contamina-
tion of the hydrogen or oxidants were reported as short time scale phenomena.
425 Slow rate chemical degradations such as corrosion and membrane degradation
were mentioned as long time scale phenomena. PEMFC internal resistance was
reported as a monitoring parameter and Rubio et al. (2010) showed that differ-
ent phenomena could be observed from the relative increment of the PEMFCs
internal resistance [92]. Generally short time scale phenomena of degradation
430 are reversible if the control system takes an appropriate action (such as purg-
ing) on time so that the fuel cell recovers from the short time scale degradation
phenomena. But the long time scale degradation phenomena is generally irre-
versible and the rate of degradation depends on the rate of chemical reaction
such as corrosion and membrane degradation.

435 *3.4.3. Temperature*

Temperature measurement of PEM fuel cell is important for the safety pur-
poses and for the health monitoring purposes. Thermal stability of the PEM
fuel cell is important for better performance and long life. Hence most real
world PEM fuel cell system will have temperature monitoring components and
440 this data will be used to control the fuel cell operation for optimum power gen-
eration. Generally temperature measurements are taken multiple places which
could be identified through numerical heat transfer simulations [126]. Location
of these temperature measurements may vary with the structure of the stack,
type of cooling i.e. water or air, size of the stack, material properties of fuel cell
445 components, etc.

Correlation between local temperature and local current density was ob-
served by G. Zhang et al (2010) and local temperature rises with the local
current density with decreasing operating voltage. Hence temperature and cur-

rent data could provide detail information about the stack and could be used
450 for prognostics and health monitoring of fuel cell.

3.4.4. *Acoustic Emission Technique*

Acoustic emission (AE) is a transient elastic waves in a solid structure, which is generated when the solid structure subject to an irreversible changes such as crack, plastic deformation. Acoustic emission could be used to monitor deformation in the membrane due to the water contents. This have been investigated
455 and reported by B. Legros et al (2010). AE has been investigated a diagnostic tool for water management i.e. hydration and dehydration. AE showed good sensitivity to different operating conditions such as gas humidification levels and MEA water uptake. It means AE could be used as online non-invasive
460 monitoring strategy for PEM fuel cells [127]. B. Legros et al (2011) have also investigated electrochemical noise (EN) as a tool for the diagnosis of the PEM fuel cell when it undergoes flooding and drying [128]. EN was increased during the drying of the fuel cell and also with current level.

3.5. *RUL Estimation*

Zhang and Pisu (2012) presented what possibly is the first systematic work
465 on prognostics and RUL estimation of PEMFC [129]. They investigated a physics-based model for the purpose of prognostics based on an electro-chemical surface area (active area) under different operating conditions [129]. This work was based on the spatially lumped model and kinetic expression for platinum oxidation and dissolution presented by Darling and Meyers (2003, 2005) [99, 100]
470 and on the 64-particle catalyst degradation model proposed by Zhang and Pisu (2012) [98]. The method was demonstrated by simplifying the model to a first order dynamic model, where the dynamics of platinum oxide coverage during load cycling was neglected. Hence, this work is a model based approach. Low
475 pass filter and Unscented Kalman Filter (UKF) were used to capture the slow degradation in the residual between the model of the catalyst and actual catalyst [129]. Later, Zhang and Pisu (2014) developed a diagnostic-oriented fuel

cell model which incorporated the fault of water flooding inside the fuel cell. UKF were then developed for channel flooding and gas diffusion layer flooding [130].

Jouin et al. (2014a) proposed a particle filtering framework for the prognostics of PEMFC [131]. A voltage drop representing irreversible degradations was used as the aging indicator of the PEMFC. Two sets of test data were used in this work: (1) aging under a constant 70A current load; and (2) aging under a high frequency small ripple current load of 70A. Tests under similar stable environmental conditions were carried out on a 5-cell PEMFC stack with an active area of 100cm^2 . The voltage evolution with time was modelled and used as the state model. Three different state models which could be used to represent voltage evolution were used: (1) linear model, (2) exponential model and (3) logarithmic model. Performance metrics of these three models were compared and the logarithmic model's predictions were found more accurate with greater stability [131]. Later, Jouin et al. (2014b) applied particle filtering framework based on power evolution with time and estimated the RUL using the same data [132]. Power evolution, acceleration of power degradation and recoveries of the power degradation were considered, modelled and incorporated with Particle Filtering (PF) framework by Jouin et al. (2014b) [132]. Predictions from this particle filtering framework produced less error compared with other particle filtering frameworks [133].

An adaptive particle filter algorithm based approach to prognostics and RUL estimation was proposed by J. K Kimotho et al (2014) for the IEEE PHM data challenge [134]. J. K Kimotho et al (2014) introduced a self-healing factor after each characterization and the adaptation of the degradation model parameter to fit the change in the degradation behaviour at various stages of the PEM fuel cell lifetimes [134]. SOH prediction based on physics driven and data driven model was reported by T. Kim et al (2014). Voltage degradation and 4 parameters equivalent circuit model were developed bases on underlying physical phenomenon. These model then trained for the training data set, test and validated on test data set. The four parameters from the equivalent circuit model

exhibited linear relationship with the voltage degradation which could be used
510 to estimate the RUL of the PEM fuel cells [135].

An Adaptive Neuro-Fuzzy Inference System (ANFIS) was applied to the
voltage drops caused by the degradation during normal operation of PEMFC
stacks by Silva et al. (2014) [136]. A data driven approach based on an Echo
State Network (ESN), which consists of the use of a dynamical neurons reservoir,
515 was studied as a prognostics system enabling an estimation of the remaining
useful life of a PEMFC by Morando et al. (2014) [137]. This work was also based
on cell voltage. In particular, the mean cell voltage was used to forecast the
degradation of PEMFC [137]. A sensitivity analysis for this Echo State Network
(ESN) based on data driven prognostics approach was studied by Morando et
520 al. (2014), where the Analysis of Variance (ANOVA) statistical technique was
used [138].

As fuel cells are complex electrochemical devices and multiphysics systems,
to drive a model from first principles might be a difficult task. However, some
research work has been carried out in order to model the PEMFC for the pur-
525 pose of controlling and capturing their dynamic behaviour [105, 139, 106, 140].
Other researches were also reported on fuel cell modelling for the purpose of
prognostics and health monitoring of PEMFC to capture the fault based on the
water flooding inside the fuel cell [130] and electrochemical surface area and
membrane gas crossover [98].

530 **4. Conclusions**

An overview of the current state-of-the-art on the fields of health monitoring
and prognostics on PEMFC systems was presented in this paper.

It was found that, although some important research work have already been
reported on prognostics and estimation of the RUL of PEMFC stack systems,
535 this field of knowledge still is at its early stage and more developments are still
required.

One of the main problems today is related to the lack of test and failure

data available. Hence, FMMEA in PEMFCs is a subject that is not completely understood yet. For example, in the case of the transportation industry, vibrations and air pollution are known to speed up the degradation of the fuel cell, often resulting in unexpected failure. However, how these parameters correlate with damage is not exactly known yet.

It is also not clear which failure mechanisms cause most failures in the PEM fuel cells and which failure mechanisms cause least failures in the PEM fuel cells.

FMMEA of PEMFC is essential for the design and optimisation of fuel cell systems, as it can increase performance from the early introduction of mitigation mechanisms from known failure modes. Accelerated life tests (ALT) can be used to better understand failure mechanisms by accelerating only the parameter that needs to be studied. These parameters include vibration, temperature, flooding, CO poisoning, but there may be others. However, ALTs can be costly, since these are destructive tests that must be carried out in a technology that still is considerably expensive.

It is clear that this is an area that will receive much growing attention within the following years, so there is an opportunity for researchers and the industry to become amongst the first in the development of this technology.

With the better understanding of FMMEA in PEMFC, models can then be further developed and integrated in order to achieve more reliable prognostics' forecasts. Control system strategies for PEMFC can then be based on these models in order to improve the life expectancy and efficiency of PEMFC.

Collaboration between researchers, designers and manufacturers is therefore paramount for information and data to be shared with respect to health monitoring and prognostics. Thus, the work presented herein is a contribution to the understanding that research and development on health monitoring and prognostics on PEMFC stack systems is vital, so that emission free PEMFC technology can become a real tangible alternative for energy generation in the nearby future.

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