Journal of Power Sources 300 (2015) 164–174

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Autocorrelation standard deviation and root mean square frequency analysis of polymer electrolyte membrane fuel cell to monitor for hydrogen and air undersupply

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HIGHLIGHTS

- Real-time health monitoring of a PEM fuel cell for H_2 and O_2 starvation.
- Fault diagnosis using autocorrelation standard deviation analysis.
- Fault diagnosis using root mean square frequency analysis.

ARTICLE INFO

Article history:
Received 11 August 2015
Received in revised form
13 September 2015
Accepted 16 September 2015
Available online 25 September 2015

Keywords:
PEMFC
Autocorrelation
RMSF
Hydrogen supply capacity
Fuel cell performance
Health monitoring

ABSTRACT

Proton exchange membrane fuel cells are a promising energy conversion device which can help to solve urgent environmental and economic problems. Among the various types of fuel cells, the air breathing proton exchange membrane fuel cell, which minimizes the balance of plant, has drawn a lot of attention due to its superior energy density. In this study a compact, air breathing, proton exchange membrane fuel cell based on Nafion and a Pt/C membrane electrode assembly was designed. The fuel cell was tested using a Scribner Associates 850e fuel cell test station. Specifically, the hydrogen fuel and oxygen starvation of the fuel cell were accurately and systematically tested and analyzed using a frequency analysis method which can analyze the input and output frequency. The analysis of the frequency variation under a fuel starvation condition was done using RMSF (root mean square frequency) and ACSD (autocorrelation standard deviation). The study reveals two significant results: first, the fuel starvations show entirely different phenomenon in both RMSF and ACSD and second, the results of the Autocorrelation show clearer results for fuel starvation detection than the results with RMSF.

1. Introduction

Due to the growing problem of global warming and the depletion of petroleum energy, many studies have looked at alternative energy sources. Fuel cell systems have become popular and attractive because they have a high efficiency and do not affect the environmental conditions. Fuel cell systems are more beneficial to the environment because their only emissions are water and heat with no exhaust. Fuel cell systems also have certain disadvantages. Fuel cell systems are slow to start up, takes time to reach steady state, and have trouble responding to sudden load changes.

When the load changes, the output voltage of the fuel cell system is changed in accordance with the current characteristics (VI). The voltage output will decrease because of a change in the fuel supply or wear due to age of the electrodes or membrane electrode assembly (MEA). The voltage variations and changes can take place as rapidly as the degradation occurs. Time frequency analysis alone is difficult to capture the characteristics of fault signals that can happen in a short amount of time. Therefore, it is an estimate of the

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http://dx.doi.org/10.1016/j.jpowsour.2015.09.062
0378-7753/

Nomenclature

ACSD	autocorrelation standard deviation value
F	Faraday's constant (96485 As mol^{-1})
I	current (A)
j	imaginary number
k	index of summation
n	number of samples
n_{fc}	number of fuel cells
N	width of window
P_e	electric power (W)
RMSF	root mean square frequency value
Rxx(t)	autocorrelation of the input function
t	time (s)
τ	lag (s)
μ	mean value of a set
V_c	cell voltage (V)
x(t)	input function
X(k)	frequency component
$\otimes$	correlation
w_H	Hamming window

parameter based on the pole and having a high resolution in a short time for the AR (auto-regressive) model of the feature vector extraction trip signal in the signal is easy to fit to the fault diagnostics system. The fuel cell is used as an index for checking the state of the system temperature, output current, and output voltage. Webb et al. proposed a novel measuring technique to monitor the output voltage of an individual cell in a fuel cell stack [1]. They introduced a low cost and lightweight multiplexer circuit based on a resistor-diode circuit. The prototype that they developed had 200 channels and was capable of 8 readings per cell and a scan rate of 19 cells per second. Brunner et al. designed a robust cell voltage monitoring system for fuel cells and battery systems [2]. Their system is based on electromechanical relays to monitor the voltage in order to check for anode flooding and airflow blocking and was designed for use on fuel cell battery hybrid buses.

Fuel cell fault diagnosis systems have become an important and growing part of the research community to alleviate some of the potential reliability problems. Wu et al. discusses various diagnostic tools used in research [3]. They specifically look at the electrochemical methods of fault diagnosis, such as polarization curves and current interruptions, and discuss the experimental implementation and data processing of each technique. In part two, Wu et al. discuss the various physical and chemical fuel diagnosis techniques that are used in research, such as pressure drop measurement and gas chromatography [4]. Grot and Meltser developed a technique that consisted of measuring the voltage and the output hydrogen flow [5]. From this information they are able to monitor for unacceptable levels of performance and then alert the operator of failures. Many laboratory measurement devices used in research are expensive and bulky, making them impractical for actual application. Mulder et al. investigated the design of an on-site cell voltage monitor [6]. Their system consists of individual cell voltage monitoring devices that send signals to a controller that monitors the state of health of the entire system.

Zheng et al. performed a review of polymer electrolyte membrane fuel cell (PEMFC) diagnosis methodologies [7]. In their paper, they separated the methodologies into 3 overall groups: artificial intelligence, statistical methods, and signal processing methods. Artificial intelligence (AI) methods are effective and do not require a thorough knowledge of the structure of the system. Neural networks (NN) are a popular AI method used because of their exceptional pattern recognition characteristics. Many neural network methods are model-based [8–10], but several more are non-model based. Kim et al. used a Hamming neural network to monitor the state of health of a PEMFC [11]. This was done by measuring the output voltage of 20 individual fuel cells and then statistically analyzing the data for patterns. The representative pattern is then applied to the fuel cell of interest and monitored for deviations from normal behavior. Chang showed that neural networks are exceptional at approximating nonlinear behavior and can operate with signal noise [10]. The disadvantages of neural networks are a time consuming setup process and a complex network design. Another common AI method used in fault diagnosis is fuzzy logic which is usually performed by clustering. This involves clustering data points into groups, such as certain types of failure modes, and then monitoring measured data points for a detection of one of the fault clusters. Fuzzy logic diagnosis methods are beneficial because of their quantitative and discrete method. Jang found a way to combine the quantitative features of fuzzy clusters and exceptional diagnosis abilities of neural networks to create ANFIS (adaptive network-based fuzzy inference system) [12]. This method allows the fuzzy inference system to adjust its parameters by using the adaptive features of a neural network. Due to the benefits of using ANFIS it has been applied to a number of studies involving monitoring the state of health of a PEMFC [13–15]. AI fault diagnosis methods in general have been shown to be good at monitoring nonlinear systems, but they are also complex in their application and design.

Another way to diagnose failure in a fuel cell system is statistical methods. These statistical methods often involve dimension reduction that looks at the correlation of certain parts of data collected from the fuel cell. One common statistical method is PCA (principal component analysis). Placca et al. used PCA to monitor faults in the stack voltage and stack current [16]. They used a testing system to measure and monitor more than 100 variables and then used PCA to check for changes in performance. These variables were then linked to the voltage and current using linear regression. PCA can be applied to fuel cells as a principal component model and a combined PCA and NN model. The main disadvantage of PCA fault diagnosis methods is that it displays poor performance for nonlinear processes [17].

A popular dimensional reduction method is FDA (Fisher discriminant analysis). The main concept of FDA is to determine a set of discriminant vectors by maximizing the separation between groups; but, minimizing the variation within classes [18]. Du et al. presents a fault diagnosis method using FDA to determine multiple fault modes [19]. They proved that FDA can be used to distinguish between multiple faults by measuring a fault score and analyzing it. FDA has proven to be a reliable fault detection method; but, it is a linear technique so, like PCA, it does not perform well for nonlinear systems.

One final statistical approach commonly used in fault diagnosis of fuel cells is a Bayesian network (BN). A BN is used to monitor fuel cells by using probabilistic graphical models with nodes representing random variables and arcs representing conditional independence [20]. Riascos et al. did this by using the BN to show the cause-effect relationship between the voltage, current, and temperature [20]. Wasterlain et al. applied the BN method to monitor PEMFC stacks for faults [21]. They achieved a positive diagnosis rate of 91% using this method. They also explained the construction of the BN which involved creating the network structure and then measuring data to find the conditional probabilities. The BN method has proven successful and applicable; but, has yet to been used widely in the fuel cell field. One disadvantage of this method is