Journal of Power Sources 404 (2018) 81–88

Contents lists available at ScienceDirect

Journal of Power Sources

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

# Online monitoring of fuel starvation and water management in an operating polymer electrolyte membrane fuel cell by a novel diagnostic tool based on total harmonic distortion analysis

N.J. Steffy[a,b,c], S. Vinod Selvaganesh[c], Madan Kumar L[a,d], A.K. Sahu[a,c,*]

[a] Academy of Scientific and Innovative Research (AcSIR), CSIR-Structural Engineering Research Centre Campus, Taramani, Chennai, 600113, India
[b] CSIR-Structural Engineering Research Centre, Taramani, Chennai, 600113, India
[c] CSIR-Central Electrochemical Research Institute - Madras Unit, CSIR Madras Complex, Taramani, Chennai, 600113, India
[d] CSIR- Central Electronics Engineering Research Institute - Chennai Unit, CSIR Madras Complex, Taramani, Chennai, 600113, India

## HIGHLIGHTS

- Impedance analysis with respect to various fuel and relative humidity conditions.
- Total harmonic distortion (THD) analysis in PEMFC online health monitoring.
- Identification of Indicator frequencies for different critical conditions.
- Successful feasibility analysis of THD as a potential diagnostic technique.

## ARTICLE INFO

*Keywords:*
PEMFC
Online monitoring
THD studies
Fuel starvation
Water management
Impedance spectroscopy

## ABSTRACT

The present study deals with a novel diagnostic tool for fuel and water management problems by analyzing the harmonics on an operating polymer electrolyte membrane fuel cell. In this method, a low frequency signal is applied to the fuel cell and the total harmonic distortion contained in the resulting signal is observed under different conditions. The total harmonic distortion is used to monitor and identify the conditions online such as anode drying, anode flooding, hydrogen starvation and cathode flooding prevailing in the cell. This is done by identifying a set of indicator frequencies correspond to the aforementioned critical conditions. Through empirical studies, it is shown that frequency responses lead to a high total harmonic distortion value indicating critical conditions and provide an accurate diagnostic method to detect an even slightly degraded state. These results successfully demonstrate the promise of the proposed method in overcoming performance losses by efficient online monitoring of fuel cells. The relation between the health of the fuel cell and the variations in the harmonics present in the studied signal is characterized and utilized for the diagnostic studies of polymer electrolyte membrane fuel cell.

## 1. Introduction

Polymer electrolyte membrane fuel cells (PEMFCs) are attractive as a clean & sustainable energy source ever since their generated power density values have approached the commercially acceptable levels, such as, in automotive applications, power back-up generators and commercial electronics applications [1,2]. The minimum lifetime target set by the U.S. Department of Energy (DOE) for a commercial fuel cell is more than 5000 working hours for light-weight vehicles and more than 40,000 working hours of stationary power with less than a 10% decay [3]. Presently, the maximum achievable lifetime of PEMFC for transportation is less than 5000 h of operation and hence a major barrier for the worldwide commercialization of PEMFCs [4]. Tackling various engineering challenges associated with fault diagnostics and mitigation in PEMFC by adopting an efficient diagnosis approach for a smooth and reliable operation of the fuel cell is an important engineering and scientific concern.

Fuel starvation and inefficient water management are two critical issues in a running PEMFC which deteriorate the performance and adversely affect its longevity in a number of ways, such as, carbon corrosion, platinum (Pt) dissolution and agglomeration, pinhole formation, hydrogen crossover, change in Nafion morphology etc [3,5–8].

* Corresponding author. CSIR-Central Electrochemical Research Institute - Madras Unit, CSIR Madras Complex, Taramani, Chennai, 600113, India.
*E-mail address:* aksahu@cecri.res.in (A.K. Sahu).

https://doi.org/10.1016/j.jpowsour.2018.10.012
Received 16 July 2018; Received in revised form 17 September 2018; Accepted 6 October 2018

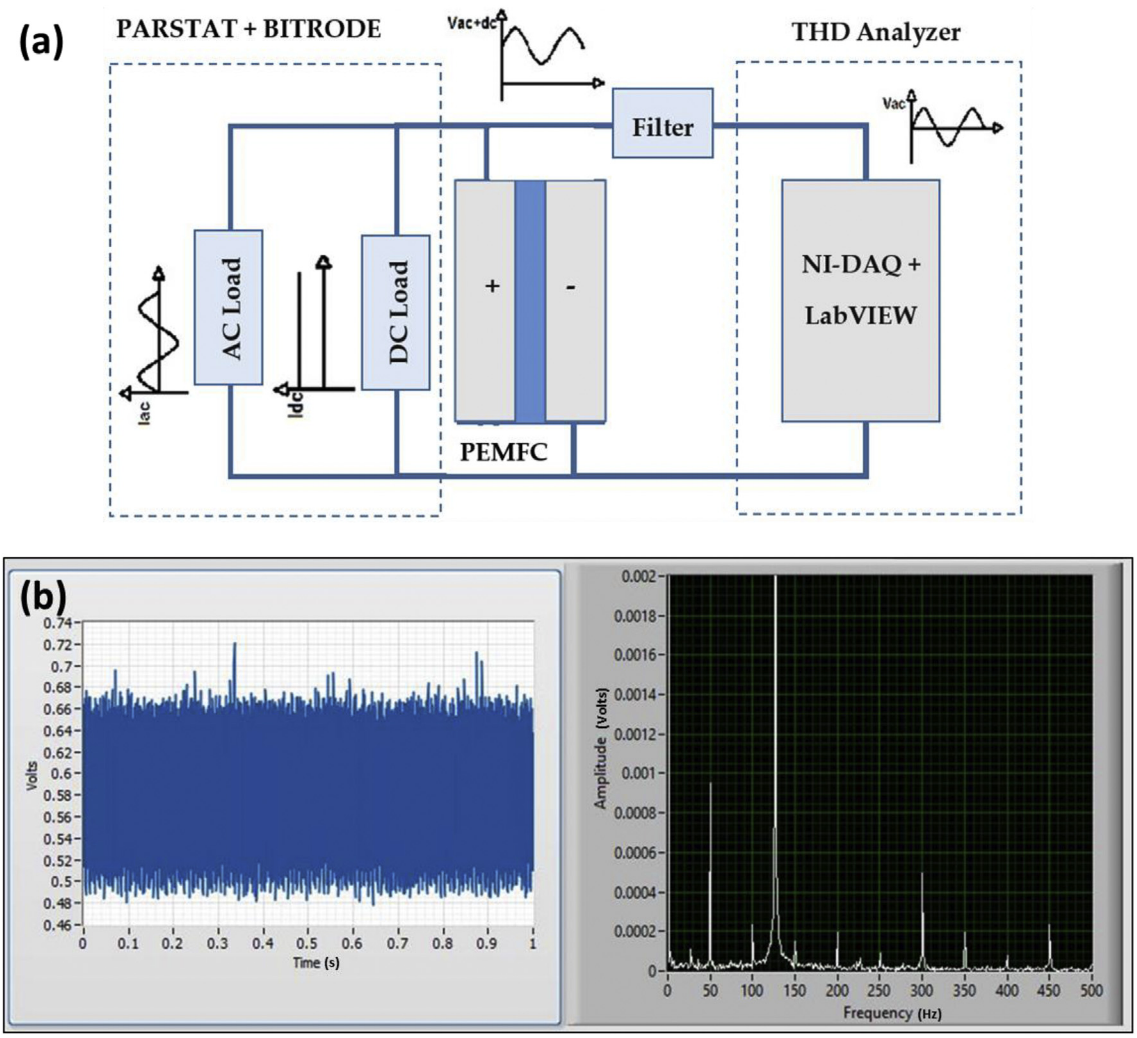


**Fig. 1.** (a) Schematic of the THD analysis setup consisting of a load section and THD analyser connected to a PEMFC through an AC filter.; (b) The LabVIEW front panel showing the output from the fuel cell in the form of Volts Vs Time and the frequency components derived from it by FFT as a function of amplitude (in Volts) Vs Frequency (in Hz) in it. The highest amplitude at 126.96 Hz indicates the presence of impressed AC signal of 126.96 HZ.

Currently, in order to ensure reliable operation of fuel cell, various diagnostic techniques are being used. Such techniques are broadly divided into two main categories: a) electrochemical tests, such as, polarization curve, current interruption, electrochemical impedance spectroscopy (EIS) and cyclic voltammetry (CV); and b) physicochemical tests, such as, pressure drop measurement, gas chromatography (GC), neutron imaging, magnetic resonance imaging (MRI), temperature mapping and current mapping etc [5,9,10]. While electrochemical tests help in investigating overall performance and the different processes involved in PEMFC such as electrode kinetics, electrolyte resistance, mass transport, interfacial resistance, contact resistance etc. [9], the physiochemical tests provides deeper insight into the mechanisms of spatial nonuniform distribution of current, temperature, reactants etc that lead to performance losses in a PEMFC [10]. Besides these, there are model-based diagnostic methods and non-model based diagnostic methods which apply techniques based on artificial intelligence, statistical methods, signal processing algorithms etc. to design or to control or to perform both tasks for the PEMFC system under study [11–13]. Monitoring the health of fuel cells and stacks is central and can be analysed by EIS and cell voltage monitoring (CVM) techniques. These techniques are either complex, as in the case of CVM, or can normally be applied only offline due to practical limitations during online monitoring in the case of EIS [14–16]. Among all the conventional PEMFC characterization techniques, EIS is especially well situated to characterize layers and interfaces by measuring electrolyte resistance, charge transfer resistance, diffusion resistance etc [17,18]. Though availability of high speed and powerful microcontrollers has advanced the EIS measurement system, the precise removal of harmonics in the input signal is still a major challenge. Fuel cell systems are nonlinear systems since they are governed by Buttler-Volmer's equation and thus lead to the generation of harmonics. Therefore the applied perturbation amplitude has to be small enough to ensure the linearity condition in this kind of systems. Since these small amplitude perturbation signals will lead to low signal-to-noise ratios, the calculation of EIS becomes a complicated process and thus lead to higher cost of system [14,15]. In order to reduce the total duration of diagnosis and to tackle the problem of harmonics, one may use several non-harmonically related sine waves [19,20]. However, the processing complexity needed to obtain the results increases multi-folds with an increase in the number of frequencies being measured. Thus, it is imperative to develop an effective and alternate in-situ technique that can monitor the health of the PEMFC system online with minimum complexity and ease of diagnosis.

Ramschak et al. introduced total harmonic distortion (THD) analysis as a diagnosis method for fuel cells and studied the harmonic distortions on low temperature PEMFC and predicted the possibility of its potential in diagnosis of fuel cells [21,22]. In this method, a low frequency signal is superimposed on the PEMFC and solid oxide fuel cell