Renewable and Sustainable Energy Reviews 93 (2018) 121–144

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

A comprehensive review on parameter estimation techniques for Proton Exchange Membrane fuel cell modelling

K. Priya, K. Sathishkumar, N. Rajasekar*

Solar Energy Research Cell, School of Electrical Engineering, VIT University, Vellore, India

ARTICLE INFO

Keywords:
Fuel cell modelling
Parameter estimation
Efficiency and metaheuristic algorithms

ABSTRACT

The widespread use of Proton Exchange Membrane fuel cell for its unique advantages compelled researchers for precise modelling of its characteristics. Since, modelling becomes extremely important for better understanding, simulation, design, analysis and development of high efficiency fuel cell system. However, due to its non-linearity, multivariate and strongly coupled characteristics; mathematical modelling based on empirical equations was widely adopted. But, the shortage of data, complexity in modelling, and number of unknown parameters favored the use of optimization methods. Many optimization methods have been endeavored to model Proton Exchange Membrane fuel cell characteristics. However, no prior attempt has been made to consolidate the contributions. Hence, this paper comprehensively describes and discusses the various Artificial Intelligence/bio inspired methods applied for fuel cell parameter estimation problem. The methods background theory and its application to the problem is elaborated. It is envisioned that, this review will be a one stop solution to the researchers and engineers working in the area of fuel cell systems.

1. Introduction

Stringent environmental reforms and enforced low carbon footprint stimulated interest towards emission-free green power generation. Factors such as high efficiency, low noise, good dynamic response and low aggression to environment elevated the research focus on Fuel Cell (FC) systems in recent years [1,2]. Moreover, compared to other renewable energy resources, FCs are reliable and durable electrochemical devices that convert input hydrogen fuel to electricity continuously [3,4]. Among many types, Proton Exchange Membrane Fuel Cell (PEMFC) remains as an unmatched choice of interest; especially in the field of automotive research, distributed generation and portable electronic applications [5–8]. In addition, its distinguished characteristics like high efficiency, no waste generation, high power density, low operating temperature, and pressure make PEMFC unique [9].

Since PEMFC systems are complex, multivariate and strongly coupled; it is hard to model its characteristics for design and performance evaluation. Over the decades, significant research progresses have been made in understanding the behavior of PEMFC characteristics via mathematical modelling [10–17]. Meanwhile, modelling attains high importance in view of simulation, design, analysis and development of high efficiency fuel cell systems. Despite many modelling approaches, mathematical modelling derived from empirical and semi-empirical equations developed by Amphlett [10] conceived acceptance for its closeness in predicting the behavior of the PEMFC at different operating conditions.

Unlike mechanistic models, nevertheless these models attempt to simulate heat, mass and electrochemical phenomenon occurring within it; rather it predicts the effect of different input parameters variations on the voltage-current (V-I) characteristics of the fuel cell without having deep insight on the physical and electrochemical phenomenon. Therefore, it becomes convenient to analyze the PEMFC performance at different operating conditions. However, the key issue that is pertinent with this approach is the unavailability of the precise fuel cell model parameters. Since these parameters relate too closely to the operating conditions, it requires a set of parameters for each operating point [18].

At the same time, it is to be noted that PEMFC systems are complex, non-linear, multi variable and strongly coupled that are hard to be modeled by conventional methods. Therefore, with the features of flexibility, robustness and parallel computing, Artificial Intelligence (AI)/soft computing methods have become the preferred choice to model PEMFC. Since, many methods were used so far for modelling; their details, suitability, and method's performance still remain scattered. Yet, there is no systematic effort taken to gather all these information in a comprehensive manner such that it becomes a one stop reference point for researches. Moreover, no attempt has been made to comprehensively describe/analyze various SC methods used for PEMFC parameter extraction. Therefore, with the growing interest in this topic,

* Correspondence to: School of Electrical Engineering, VIT University, Vellore, Tamil Nadu 632014, India.
E-mail address: natarajanrajasekar@gmail.com (N. Rajasekar).

https://doi.org/10.1016/j.rser.2018.05.017
Received 17 May 2017; Received in revised form 13 April 2018; Accepted 13 May 2018

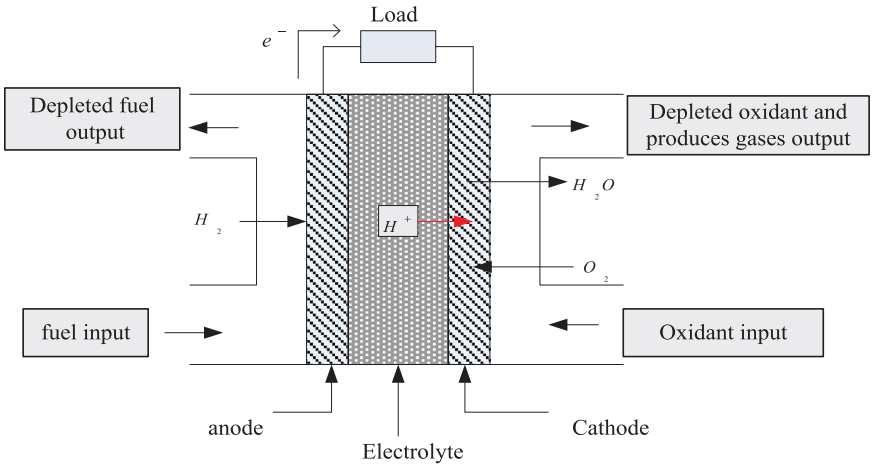

Fig. 1. PEMFC chemical reaction [12].

the authors attempt to compile all the related works in the field of PEMFC parameter estimation especially applying AI/soft computing methods and present it as a single reference. Further, it summarizes the various important discoveries made so far in the field of PEMFC parameter extraction. The paper is organized as follows: Section 2 briefly explains the mathematical modelling of PEMFC operation. Importance of PEMFC parameter estimation and various soft computing methods along with its merits, demerits and its application to PEMFC modelling are explained in Sections 3 and 4 respectively. New bio inspired methods evolved for parameter estimation is discussed in Section 5. Following the brief analysis a comprehensive comparison based on various benchmarking parameters is presented in Section 6. Discussions and conclusions arrived based on the review is detailed in Sections 7 and 8 respectively.

2. PEMFC model

Typical PEMFC schematic with its chemical reaction is outlined in Fig. 1. The PEMFC system consists of two electrodes viz., a cathode, anode and a proton-conducting membrane as an electrolyte. Fuel input (H_2 gas) on the anode side spread over the electrode until they reach the catalytic layer to form protons and electrons [19]. The protons pass through the catalytic layer via electrolyte to the cathode; while the electron takes an external circuit generating electric power. The oxygen supplied at the catalytic layer of the cathode combines with electrons and hydrogen ions to form water. The overall electrochemical reactions that happen within PEMFC can be described as follows [12]:

At anode

$$H_2 \rightarrow 2\,H^+ + 2e^- \tag{1}$$

At cathode:

$$2H^+ + 2e^- + 1/2\,O_2 \rightarrow H_2O \tag{2}$$

The overall chemical reaction of PEMFC can be expressed as

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{3}$$

2.1. Mathematical modelling of PEMFC

A typical single cell polarization curve operating at about 70 °C temperature and normal air pressure is shown in Fig. 2. The curve is characterized by three important regions: activation polarization, ohmic polarization, and concentration polarization. The initial part of V-I curve (activation polarization) is strongly non-linear and sluggish indicating the nature of the reactions. The central portion (ohmic polarization) reflects the ohmic losses caused by the membrane, electrical

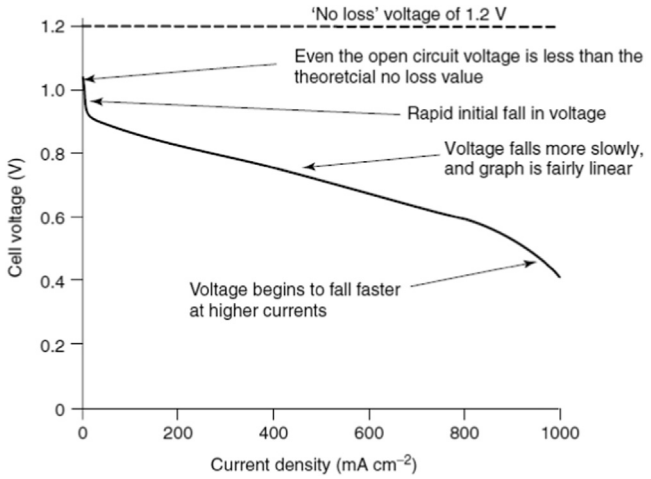

Fig. 2. Typical polarization of PEM fuel cell [2].

and contact resistance. The final part of the curve i.e., concentration polarization indicates the concentration gradient caused by electrochemical reaction [20].

The overall output voltage of a single cell can be written as [8]:

$$V_{cell} = E_{nernst} - V_{act} - V_{ohmic} - V_{conc} \tag{4}$$

where 'E_{nernst}' is the reversible voltage, 'V_{act}' is the activation losses, 'V_{ohmic}' is the ohmic drop and 'V_{conc}' is the concentration loss.

When 'n' cells are connected in series to form a stack; the terminal voltage of the stack 'V_s' can be determined using [13]:

$$V_s = n \times V_{cell} \tag{5}$$

2.2. Fuel cell open circuit voltage

The cell reversible voltage (E_{nernst}) is the open circuit thermodynamic balance (without load) calculated from the basic Nernst equation with an extra term to take into account the effect of temperature changes. Thus, the Nernst reversible voltage equation is given by [10,11]

$$E_{nernst} = 1.22 - 8.5{*}e^{-3}(T - 298.15) + 4.3085{*}e^{-5}{*}T\left(\ln\left[P_{H_2} + 0.5P_{O_2}\right]\right) \tag{6}$$

where, P_{H_2}, P_{O_2} are the partial pressures of hydrogen and oxygen in (atm) respectively and T is the cell temperature in K. Since the partial pressure value changes with cell current hence they are given by [10]: