Journal of Energy Storage 15 (2018) 8–16

Contents lists available at ScienceDirect

Journal of Energy Storage

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

Parameter optimization of polymer electrolyte membrane fuel cell using moment-based uncertainty evaluation technique

Arvind Rajan[a], Akhil Garg[b,*], V. Vijayaraghavan[c,**], Ye Chow Kuang[a], Melanie Po-Leen Ooi[a,d,e]

[a] School of Engineering, Monash University Malaysia, Bandar Sunway 47500, Malaysia
[b] Department of Mechatronics Engineering, Shantou University, Shantou, China
[c] School of Mechanical and Manufacturing Engineering-UNSW, Library Rd, Kensington NSW 2052, Australia
[d] Unitec Institute of Technology, 139 Carrington Road, Mount Albert, Auckland 1025, New Zealand
[e] Heriot-Watt University, No 1 Jalan Venna P5/2, Precinct 5, 62200 Putrajaya, Malaysia

ARTICLE INFO

Article history:
Received 12 September 2017
Received in revised form 18 October 2017
Accepted 20 October 2017
Available online xxx

Keywords:
PEM fuel cell
Response surface methodology
Optimization
Uncertainty
Robust
Reliability

ABSTRACT

Finding the optimal operational parameters of polymer electrolyte membrane (PEM) fuel cells is very critical for improving its efficiency. The incorporation of uncertainties in the operational parameters during the optimization process is very important to ensure that the fuel cell can operate reliably in real-life deployment. Unfortunately, no attention has been given thus far on studying the effects of parameter uncertainties on the fuel cell performance. In this paper, the output power and hydrogen flow rate are being optimized under uncertain conditions of the stack current, stack temperature, oxygen excess ratio, hydrogen excess ratio and inlet air humidity of the PEM fuel cell. The effective application of a new analytical moment-based uncertainty evaluation technique proposed in combination with response surface methodology provides an accurate and numerically efficient evaluation of the fuel cell performance. The paper has demonstrated that the optimal mean output power under uncertainty is 1329.56 W and its corresponding operating point is different from that of the optimal output power 1545.25 W calculated assuming all parameters are fixed. The results show that, for the selected PEM fuel cell model, meeting probabilistic constraints makes the fuel cell less susceptible to input variations, but this can only be achieved at the expense of optimal output power. The useful framework, analyses and discussions presented in the paper can be adapted into any fuel cell performance evaluation and design optimization.

1. Introduction

Hydrogen fuel cell has been projected to be one of the major energy storage technology that is more environmental friendly and efficient compared to traditional combustion technologies. It has added advantages of low noise, fewer moving parts and highly adaptable to a variety of applications [1,2]. The *Polymer Electrolyte Membrane* (PEM) fuel cell has been widely considered as the most promising one over the other fuel cell technologies, e.g., alkaline, phosphoric acid, molten carbonate, solid oxide, etc., for its comparable high power output, low operating temperature, high efficiency, high current density and structural safety [3,4]. Due to these benefits, PEM fuel cells are specifically useful for small-scale power generation as well as in the automobile industry.

Fig. 1 briefly illustrates the working mechanism of a PEM fuel cell, where an electrolyte is sandwiched between two electrodes, the anode and cathode. The bipolar plates on both sides of the fuel cell help distribute the hydrogen and oxygen gases, and act as current collectors. In PEM fuel cell, hydrogen gas flows to the anode and a catalyst is used to separate the gas into protons and electrons, whereby the protons flow through the membrane to the other side of the cell while the electrons flows through an external circuit to the cathode producing electricity. The oxygen on the other side reacts with the hydrogen ions to form water and this exothermic reaction generates heat.

In efforts to develop commercially-ready fuel cell technology, significant amount of research has been conducted on PEM fuel cells to optimize its efficiency, i.e., minimize its operational cost

---

* Corresponding author.
** Corresponding author at: School of Mechanical and Manufacturing Engineering-UNSW, Library Rd, Kensington NSW 2052, Australia.

E-mail addresses: akhil@stu.edu.cn (A. Garg), ve0005an@e.ntu.edu.sg (V. Vijayaraghavan).

https://doi.org/10.1016/j.est.2017.10.014
2352-152X/

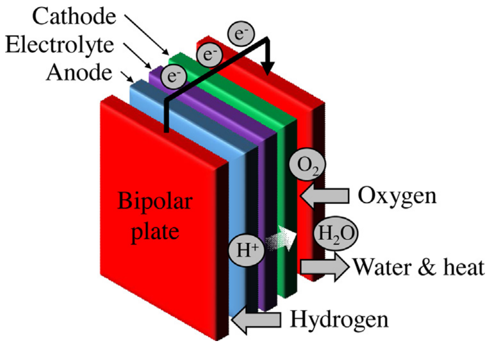

Fig. 1. Illustration of the functioning of Polymer Electrolyte Membrane (PEM) fuel cell.

while maximizing its output power. The works on modelling PEM fuel cell began in the early 1990s, which had set the tone for numerous studies on fuel cell modelling to date. For example, one of the very first fuel cell models was built by Verbrugge and Hill [5,6] to strengthen the electrolyte membrane. Later, Springer et al. [7] and Bernardi and Verbrugge [8] added the two electrodes, anode and cathode, making a sandwich-like model as shown in Fig. 1. They also went on to mathematically model the sandwich fuel cell, and used simulations and experiments to validate the model.

In the early 21 st century, Sylvian et al. [9] and Pukrushpan et al. [10] used mathematical models to express dynamic behaviours of fuel cell. Nam and Kaviany [11] then made extensive study on *gas diffusion layer* (GDL) using one-dimensional partial differential equation. Nam and Kaviany's model was later adopted into the modelling of PEM fuel cells in studies [12–14] using multiphase flow at respective electrode layers. Another ongoing line of active research is the optimization of operational parameters of the PEM fuel cell. For example, Park et al. [15] and Al-Baghdadi et al. [16] introduced a thermodynamic model of PEM fuel cell and optimized the operating parameters using novel algorithms respectively. Sikha and Popov [17] used battery-capacitor hybrid system, and Kim and Peng [18] used stochastic dynamic programming in optimizing the performance of the PEM fuel cell. Despite these efforts, a detailed PEM fuel cell model was lacking. Consequently, Lin et al. [19] went on to present a more detailed model, but optimizing the design parameters of the fuel cell instead of the operational parameters.

Therefore, Xuan et al. [20] presented a more complete dynamic model of PEM fuel cell consisting six sub-models and searched the optimal operating parameters using *response surface methodology* (RSM) [21] and *sequential quadratic programming* (SQP) optimization algorithm [22]. Similar approaches of coupling RSM and optimization algorithms to find the optimal operating conditions of fuel cells was also adopted in more recent works, e.g., in [23–25]. However, to the best of authors' knowledge, no study was performed to optimize the PEM fuel cell operations while at the same time considering the uncertainties in the operating parameters and their propagation to the output uncertainties. Operational parameters uncertainties arising from uncontrollable extrinsic and intrinsic factors and their propagation often play a major role in non-linear systems. In addition, RSM modelling employed in a wide range of fuel cell applications for better computational efficiency, e.g., in [26,27], could also introduce additional (modelling) uncertainty. The operational characteristics of a fuel cell must be optimized to meet engineering, economic and safety requirements. For that reason, it is essential to address this omission in the design of robust and cost-efficient PEM fuel cell considering factors such as manufacturing variations, material variations and uncontrollable operating environments.

This paper addresses the aforementioned methodological gap by presenting a novel framework that explicitly incorporates uncertainty evaluation technique into the design optimization loop of a selected PEM fuel cell. The proposed framework, known as the *moment-based uncertainty evaluation technique* (MUET), is accurate, numerically stable and fast. The method can be easily adapted to any other fuel cell designs. Section 2 describes the research problem formulation whereas the proposed MUET addressing the uncertainties in modelling as well as the operating parameters is presented in Section 3. Section 4 then goes on to demonstrate the use of MUET in finding the optimal operating parameters for maximum output power and low hydrogen flow rate, at the same time ensuring robustness and reliability in the fuel cell outputs. In short, the results show that employment of the proposed uncertainty evaluation technique in the optimization procedure can lead to a simultaneously high-performing and economical fuel cell operation.

2. Research problem formulation

This section discusses the problem statement on optimizing the output power of the PEM fuel cell with regard to the hydrogen mass flow rate in the context of economical fuel cell design. The paper uses a dynamic PEM fuel cell stack from study [20], as shown by the block diagram in Fig. 2. The dynamic model shown in the block diagram is made up of six components, namely, cathode

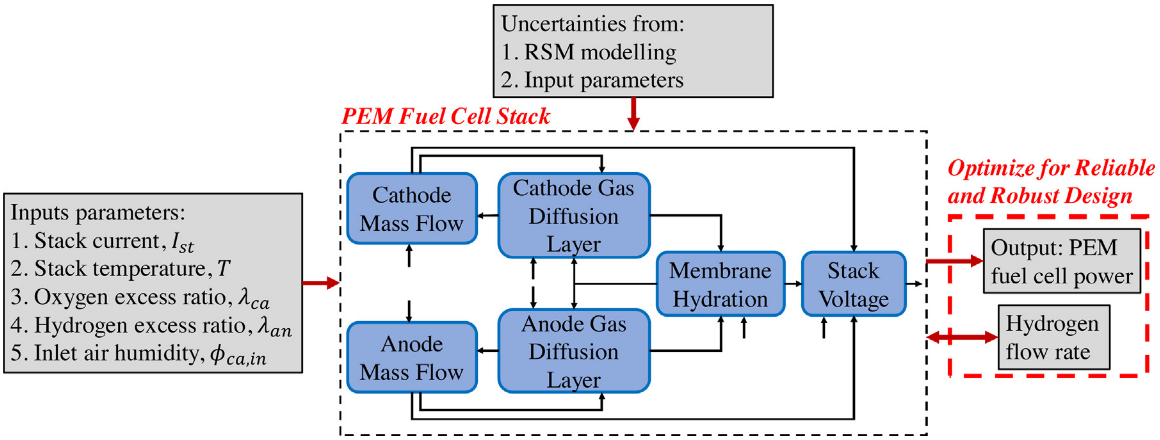

Fig. 2. The dynamical model and the relationship between variables used in the paper. Optimal PEM fuel cell design is sought with optimal power subject to a low hydrogen mass flow rate.