Available online at www.sciencedirect.com

ScienceDirect

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

Fractional order modeling and two loop control of PEM fuel cell for voltage regulation considering both source and load perturbations

Phani Teja Bankupalli [a], *Subhojit Ghosh* [a,*], *Lalit Kumar* [a], *Susovon Samanta* [b]

[a] *Electrical Engineering Department, National Institute of Technology, Raipur, India*
[b] *Electrical Engineering Department, National Institute of Technology, Rourkela, India*

ARTICLE INFO

Article history:
Received 24 November 2017
Received in revised form
8 January 2018
Accepted 28 January 2018
Available online xxx

Keywords:
PEM fuel cell
Fractional order modeling
DC/DC converter
Fractional order two loop control
Real time implementation

ABSTRACT

The growing demand for renewable energy sources has favored attention towards fuel cell and in particular towards Polymer Electrolyte Membrane Fuel Cell (PEMFC) as an alternative energy source. Despite the advantage of possessing high current density, standalone isolated fuel cell operate at low voltage and the output is heavily dependent on the operating condition. This demands the integration of fuel cells with suitable power conditioning units. The present work aims at designing a controller which achieves the objective of regulated output voltage irrespective of variation in both load and source operating condition. The design and integration of the converter with PEMFC necessitates the development of a mathematical model, which can represent the PEMFC dynamics under different operating conditions. PEMFCs are known to exhibit distributed dynamics and possess long term memory, which are more accurately represented by fractional calculus. In this regard, a hybrid optimization based approach for fractional order modeling of PEMFC has been proposed. Further using the model, a fractional order Proportional Integral (FOPI) controller has been designed for regulating the load voltage. The presence of an extra tuning parameter in FOPI allows greater flexibility in achieving the system specification as compared to the classical Integer Order Proportional Integral (IOPI) controller. The effectiveness of the proposed FOPI controller for PEMFC fed PWM DC/DC converter has been validated under varying operating condition of the PEMFC and load perturbations in real time environment.

Introduction

In the past few decades, fuel cells have emerged as a potential alternative solution to fossil fuel based energy sources. Fuel cells are electrochemical sources which are characterized by high efficiency, high power density and pollution free operation. PEMFCs have found wide applications for military, automotive and low power generation as they possess advantages related to operating temperature, ruggedness, less weight, very low noise and zero emission [1]. Though PEMFC is a high current density device, its output voltage per cell is less [2] as compared to other distributed sources, which demands

* *Corresponding author.*
E-mail address: sghosh.ele@nitrr.ac.in (S. Ghosh).
https://doi.org/10.1016/j.ijhydene.2018.01.167
0360-3199/

the series connection of large number of cells into a stack to meet the required DC link voltage. Also, the voltage vary widely with the operating condition (stack temperature, H_2/O_2 pressure, hydration level and membrane characteristics), thus necessitating its integration with power electronic converters [3].

For the design of converters, sources are generally represented by classical integer order equations as they are assumed to be lumped parameter based systems. However, a better representation of the dynamic characteristics of the associated sub-systems (source, converter and controller) could be achieved by applying fractional calculus. For PEMFC, Fractional calculus based models have been found to be more suitable in representing the distributed dynamics and long term memory [4]. In this regard, some models based on fractional calculus have been reported in literature. Most of the work aims at characterizing PEMFC using the data of Electrochemical Impedance Spectroscopy (EIS) [5] or Current Interrupt (CI) test [6]. In Ref. [7], frequential modeling using non integer derivatives, which account for charge transfer and diffusion phenomena has been presented. A model based approach for representing the diffusion phenomena in PEMFC has been dealt in Ref. [8]. An identification method has been used in frequency domain to find the fractional order model parameters based on time series identification of least square method [9], [10]. Further, using the fractional order PEMFC model, a diagnosis methodology of the internal state of fuel cell has been proposed. Fractional calculus has been used to implement pressure and thermal based models of PEMFC [11–13]. Fractional order state-space analysis of PEMFC has been carried out in Ref. [14] by the representation of capacitor as fractional element. The contribution of fractional differentiator for modeling of the electric double layer phenomenon has been explained in Refs. [15], [16].

For the reliable operation of PEMFC, various control strategies like sliding mode for temperature regulation [17] and pressure control [18], robust adaptive neural network control [19] and fractional order $PI^{\lambda}D^{\mu}$ control [20] has been implemented. However, these strategies aim at regulated PEMFC output without concentrating on design of power conditioning unit. For a standalone PEMFC, that possess lower output voltage at the stack, design and control of the integrated DC/DC converter is of prime importance [21], [22]. Various DC/DC boost converter topologies for PEMFC have been proposed in Refs. [23–25] for continuous conduction mode of operation. However, in all the above works the controller design has been carried out considering a fixed DC source i.e. the dynamics of the PEMFC has not been considered while designing the controller. The variation in thermal, physical and electrochemical conditions demands the inclusion of PEMFC dynamics for controller design. Incorporating PEMFC dynamics with DC/DC converter makes the voltage regulation task quite challenging [26]. In this context, several control strategies have been proposed which takes into account the PEMFC characteristics [27], [28].

However the control schemes have been designed assuming uniformity in the source behavior i.e. fixed operating point. Also, in none of the reported works the fractional dynamics of PEMFC has been considered while designing the controller. As compared to voltage mode control, in two loop control, in addition to controller design a better representation of the dynamic characteristics of the PEMFC allows improved closed loop response [22], [29]. For a wide class of closed loop systems, existing literature have confirmed that a properly tuned fractional order controller outperforms the classical integer order controller. In Ref. [30], a meta-heuristic optimization based FOPI tuning for grid connected PV has been implemented and the dynamic performance has been compared with classical PI controller. Various schemes for tuning Fractional Order Proportional-Integral-Derivative (FOPID) tuning have been proposed for power applications [31–36]. Tuning the fractional order controllers for fractional order systems and their effect on closed loop system response has been described in Refs. [37–39]. In this context, considering the effectiveness of fractional calculus in replicating the dynamic behavior of PEMFC, a fractional order model has been developed followed by designing a dual loop FOPI controller with DC/DC converter for output voltage regulation. The controller aims at achieving the objective of maintaining desired DC link voltage irrespective of source and load perturbations. For arriving at the PEMFC model, the modeling and parameter estimation task has been framed as an optimization problem, which searches for the model parameters that minimizes the deviation between the experimental and simulated model output. Similarly for controller tuning, the hybrid optimization [40] approach searches for the tuning parameter that minimizes the error between the predefined DC link voltage and the load voltage following the disturbances. The proposed modeling and controller design approaches has been evaluated for a wide range of source (V–I operating point) and load perturbations. To confirm the effectiveness of proposed controller for real time setting, the scheme has been implemented and validated on a digital platform i.e. OPAL-RT real time simulator.

The novelty and highlights of the paper can be summarized as i) Development of a fractional order model of PEMFC from experimental data. ii) Controller design for output voltage regulation under varying operating and loading conditions. iii) Inclusion of source (PEMFC) dynamics for tuning of controller parameters and iv) Validation of the proposed controller design technique in real time setting.

This paper is organized as follows, in Section System Modeling and Parameter Estimation, a fractional order model of fuel cell is developed and model parameters has been estimated through a hybrid optimization based approach. Section Controller Design details the design with modeling of a DC/DC boost converter for PEMFC and design of FOPI controller for closed loop operation. Section Controller Implementation and Analysis describes the experimental setup and controller implementation results (simulation and hardware) have been discussed. Finally Section Conclusion concludes the paper.

System modeling and parameter estimation

PEMFC modeling

Under the standard assumptions of ideal gas, similar hydrogen and cell temperature, saturation of reaction with vapors and lumped one dimensional characteristics, the

Please cite this article in press as: Bankupalli PT, et al., Fractional order modeling and two loop control of PEM fuel cell for voltage regulation considering both source and load perturbations, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.01.167