Journal of Power Sources 328 (2016) 250–261

Contents lists available at ScienceDirect

Journal of Power Sources

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

Nonlinear predictive control for durability enhancement and efficiency improvement in a fuel cell power system

Julio Luna [a, *], Samir Jemei [b, c], Nadia Yousfi-Steiner [b, c, d], Attila Husar [a], Maria Serra [a], Daniel Hissel [b, c]

[a] Institut de Robòtica i Informàtica Industrial (CSIC-UPC), C/Llorens i Artigas 4-6, 08028, Barcelona, Spain
[b] FEMTO-ST UMR CNRS 6174, University of Bourgogne Franche-Comté (UBFC), France
[c] FCLAB (FR CNRS 3539), Belfort, France
[d] LABEX ACTION CNRS, France

HIGHLIGHTS

- We model a PEMFC-based system to improve efficiency and enhance durability.
- A nonlinear observer is designed to estimate the local conditions in the catalyst.
- We design a NMPC controller to improve efficiency while avoiding local starvation.
- The designed controller is tested with the New European Driving cycle.
- Comparison between the proposed strategy and a fixed stoichiometry control strategy.

ARTICLE INFO

Article history:
Received 2 April 2016
Received in revised form
22 July 2016
Accepted 3 August 2016

Keywords:
Proton exchange membrane fuel cell
Distributed parameter system
Nonlinear observer
Model predictive control
Degradation
Starvation

ABSTRACT

In this work, a nonlinear model predictive control (NMPC) strategy is proposed to improve the efficiency and enhance the durability of a proton exchange membrane fuel cell (PEMFC) power system. The PEMFC controller is based on a distributed parameters model that describes the nonlinear dynamics of the system, considering spatial variations along the gas channels. Parasitic power from different system auxiliaries is considered, including the main parasitic losses which are those of the compressor. A nonlinear observer is implemented, based on the discretised model of the PEMFC, to estimate the internal states. This information is included in the cost function of the controller to enhance the durability of the system by means of avoiding local starvation and inappropriate water vapour concentrations. Simulation results are presented to show the performance of the proposed controller over a given case study in an automotive application (New European Driving Cycle). With the aim of representing the most relevant phenomena that affects the PEMFC voltage, the simulation model includes a two-phase water model and the effects of liquid water on the catalyst active area. The control model is a simplified version that does not consider two-phase water dynamics.

1. Introduction

Governments, industry and society in general are becoming aware of the problems derived from the energy dependency on fossil fuels and other non-renewable energies. In this context, proton exchange membrane fuel cells (PEMFC), which have hydrogen as fuel, are gaining increasing attention as clean and efficient energy conversion devices for a broad range of applications, such as automotive, stationary, combined heat and power (CHP) and portable systems.

To operate properly, different physical variables have to be measured from the PEMFC. This makes it possible to implement feedback control techniques that can improve the lifetime and efficiency of the system. Specifically, efficiency and degradation of the PEMFC are greatly affected by its internal conditions. However, while some of the internal variables can be measured using the existing sensor technology, there are parts of the system that are inaccessible. Henceforth, dynamic fuel cell modelling [1–4], fuel

* Corresponding author.
E-mail address: jluna@iri.upc.edu (J. Luna).

http://dx.doi.org/10.1016/j.jpowsour.2016.08.019
0378-7753/

cell model-based control [5–7] and model-based observation and identification of parameters [8–11] are compelling research topics in the field.

Regarding the efficiency in PEMFC-based systems, besides the hydrogen supply subsystem, the air supply subsystem plays a crucial role [12]. In particular, the air pressure at the cathode and the oxygen excess ratio are directly related with the efficiency of the system and thus, this subsystem has to be considered in a control strategy aiming at efficiency improvement [13–15].

Concerning degradation, the lifetime of PEMFCs is mainly reduced as a result of catalyst metal degradation and carbon-support corrosion. Both of these degradation mechanisms are linked and supplement each other [16–18] because the platinum (Pt) catalyses the carbon-support oxidation. At the same time, the loss of carbon releases carbon-supported Pt particles and therefore it produces active surface area loss. In the literature, accelerated durability tests have been carried out to study degradation mechanisms in PEMFCs [19] and other types of fuel cells [20].

Three degradation categories can be distinguished [21]: baseline degradation, cycling degradation and incident-induced degradation. The baseline degradation is due to long-term material degradation and it is unavoidable (it exists as long as the fuel cell is operating). Moreover, degradation is accelerated by cycling conditions [21]. Finally, severe degradation occurs when the fuel cell is subject to an unexpected incident which may cause global or local reactant starvation. Controllers can aid to avoid starvation-induced degradation and thus reduce the impact of cycling as well as the impact of unexpected operating changes.

Using advanced control techniques that consider the inherent nonlinear behaviour of PEMFC systems, the improvement of efficiency and durability can be achieved. Model predictive control (MPC) has an intrinsic capability of considering several manipulable variables and control objectives (multi-objective control) as well as the capability to deal with systems constraints in a systematic and straightforward manner [22]. These properties make MPC a promising control strategy for PEMFC-based systems.

A common situation in PEMFC-based energy systems is that the fuel cell works in a wide range of dynamics and power demands. The nonlinear MPC (NMPC) approach [23,24] takes into consideration the proper system dynamics in the whole range of operation and integrates them into a closed-loop control scheme. Nonetheless, one of the main problems that can be encountered when using this control strategy is the high computational burden.

Until now, most of the works focused on PEMFC control have addressed the improvement of PEMFC efficiency [25] and durability [26] separately. The present paper proposes a global solution to tackle the efficiency and durability improvement of the PEMFC power system at the same time, using state-of-the-art nonlinear control and observation techniques. The simulation results consider the New European Driving Cycle (NEDC) as the case study.

The main contribution of this paper relies on the development of a NMPC strategy based on a nonlinear distributed parameters model [3] of a PEMFC power system. Due to implementation reasons, the control model is a simplified version of the simulation model and it does not have the two-phase water model. The controller objective is to maximise the efficiency of the system and to limit the internal gas concentration distributions in order to improve the durability of the PEMFC avoiding possible local starvation scenarios. The control strategy makes use of a nonlinear distributed parameters observer (NDPO) [9] to estimate the fuel cell internal conditions which are restricted in the optimisation problem. The PEMFC simulation model used in this work is a distributed parameters model derived from the discretisation of the partial differential equations that describe the nonlinear dynamics of the system, considering spatial variations along the gas channels. In addition, for a more realistic description of the PEMFC voltage dynamics, the cathode side of the PEMFC includes a two-phase multi-scale water transport model that combines macroscopic two-phase flow of water with mesoscopic pore filling effects in the diffusion and catalyst layers [27]. Moreover, the cathode is fed with a compressor whose modelled parasitic demand is considered in the control objective of net efficiency improvement.

The paper is organised as follows. In Section 2, the general system description and the simulation model is introduced. In Section 3 the NDPO used to estimate the internal conditions of the system is presented. In Section 4, the NMPC strategy is stated and developed based on a simplified version of the PEMFC model introduced in Section 2. The simulation scenario and simulation results are presented in Section 5. Finally, Section 6 summarises the overall results of this paper and proposes some research lines for future work.

2. Problem formulation

2.1. System description

The system is presented in Fig. 1 and it contains four main parts:

1. The PEMFC stack and load
2. The hydrogen delivery and recirculation auxiliaries
3. The air delivery and humidification auxiliaries
4. The refrigeration system

It is assumed that all the power is delivered by the fuel cell stack, henceforth, no additional power sources are considered. The hydrogen is stored in a high-pressure container. The cathode is fed with a compressor and the air is humidified before entering the stack. All modelling variables and parameters are collected in Table 1.

Part of the power delivered by the PEMFC is used to feed the compressor and other auxiliaries. The total net electrical power delivered by the fuel cell system is expressed as

$$P_{net} = P_{fc,elec} - P_{cmp} - P_{aux}, \tag{1}$$

where $P_{fc,elec}$ is the gross electrical power generated by the fuel cell, P_{cmp} the power consumed by the compressor and P_{aux} the total power consumption of the rest of auxiliary systems (hydrogen recirculation and refrigeration pumps and heat exchanger), which will be measured experimentally.

2.2. PEMFC model

The model presented in this section is the simulation model that emulates the fuel cell system in the present work. The control model is introduced in Section 4.1. The control model is a simplified version of the simulation model. This is done to improve the computational cost of the controller.

2.2.1. Electrochemical model

The PEMFC power can be modelled as the summation of the electrical and thermal power generation

$$P_{fc} = P_{fc,elec} + P_{fc,th}. \tag{2}$$

The fuel cell electrical power is expressed as

$$P_{fc,elec} = V_{fc} I_{fc}, \tag{3}$$

being V_{fc} the total fuel cell stack voltage and I_{fc} the total current