Journal of Power Sources 241 (2013) 212–218

Contents lists available at SciVerse ScienceDirect

Journal of Power Sources

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

Control of proton exchange membrane fuel cell system breathing based on maximum net power control strategy

Qi Li [a,*], Weirong Chen [a], Zhixiang Liu [a], Ai Guo [a], Shukui Liu [b]

[a] School of Electrical Engineering, Southwest Jiaotong University, Chengdu, Sichuan Province 610031, China
[b] Chengdu Electric Power Bureau, Chengdu, Sichuan Province 610000, China

HIGHLIGHTS

- Analysis for maximum net power characterization of PEMFC system is carried out.
- A MNPC strategy based on IGPC and a reference governor is proposed.
- The IGPC based on EIA-PSO is developed to solve the predictive control law.
- The results demonstrate that the proposed strategy has better robust performance.

ARTICLE INFO

Article history:
Received 2 March 2013
Received in revised form
11 April 2013
Accepted 12 April 2013
Available online 23 April 2013

Keywords:
Proton exchange membrane fuel cell
Oxygen excess ratio
Maximum net power control
Implicit generalized predictive control
Effective informed adaptive particle swarm optimization

ABSTRACT

In order to achieve the maximum net power, the analysis for the maximum net power characterization of a proton exchange membrane fuel cell (PEMFC) system is carried out. A maximum net power control (MNPC) strategy based on an implicit generalized predictive control (IGPC) and a reference governor is proposed to keep optimal oxygen excess ratio (OER) trajectory. The IGPC based on an effective informed adaptive particle swarm optimization (EIA-PSO) algorithm is developed to solve the predictive control law and reduce the computational complexity in the rolling optimization process. The simulations of three conditional tests are implemented and the results demonstrate that the proposed strategy can track the optimal OER trajectory, reduce the parasitic power and maximize the output net power. The comprehensive comparisons based on three conditional tests verify that the MNPC–IGPC has better robust performance in the presence of large disturbances, time delay and various noises. The experimental comparison with internal control system of Ballard 1.2 kW Nexa Power Module testifies the validity of the MNPC–IGPC for increasing the net power. Hence, this proposed strategy can provide better behavior to guarantee optimal OER trajectory and the maximum net power even though the disturbances and uncertainties occur.

1. Introduction

Fuel cells that convert chemical energy of the fuel into electricity without combustion are studied worldwide. Due to its high efficiency, low operating temperature and low pollution, a proton exchange membrane fuel cell (PEMFC) is considered as one of the most promising technologies for a wide range of applications [1–3]. The PEMFC is generally viewed as a dependable power source, such as distributed power generation, automobile and portable power source [4–7].

A PEMFC system is a strongly coupled, nonlinear, complex system. The stack current changes when the droved load changes. Simultaneously, the electrochemistry reaction is accelerated corresponding to the variation. If the flow rate of oxygen in cathode is too low, the output power of PEMFC system could be decreased because of lacking oxygen, which is so-called starvation. However, excess oxygen replenishment into the cathode will cause power waste, consequently leading to a decrease in the net power of overall system. Several studies have addressed these undesired phenomenon, proposing that the oxygen excess ratio (OER) should be controlled to prevent oxygen starvation and excess oxygen replenishment [8–10]. For the PEMFC system considered in this paper, the air supply subsystem has slower dynamics compared with the hydrogen supply subsystem, hence the oxygen starvation and excess oxygen replenishment are the more obstinate problems during fast transient operation, such as accelerated and decelerated process of electrical vehicle [9,10]. Hence, it is so significant to

* Corresponding author. Tel.: +86 2887603332; fax: +86 2887605114.
E-mail addresses: liqi0800@163.com, liqi0800@gmail.com (Q. Li).

0378-7753/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jpowsour.2013.04.067

utilize an effective control strategy to maintain optimal OER for the maximization of net output power of PEMFC system.

A variety of control strategies have been used to PEMFC system during recent years. Pukrushpan et al. [10] have designed feedforward and feedback strategies to control the voltage of compressor in a PEMFC air supply system. The desired OER is set to a constant value for starvation prevention, neglecting the optimal OER trajectory. Schumacher et al. [11] have proposed a water management method of PEMFC using fuzzy control. Jing Sun et al. [12] have proposed a robust nonlinear reference governor approach for fuel cell oxygen starvation. According to the experimental data, Almeda et al. [13] have utilized artificial neural network to control output voltage and optimize the parameters of fuel cell system. Woon Ki Na et al. [14] have presented a nonlinear pressure controller based on a nonlinear PEMFC model to prolong the stack life. Qi Li et al. [15] have used state feedback exact linearization to design a nonlinear H_∞ optimal controller for minimizing the pressure deviations between the anode and cathode of PEMFC. Alicia Arce et al. [16] have reported a control architecture based on a constrained explicit model predictive control (MPC) law suitable for real time implementation. Winston et al. [17] have proposed and tested the regulation of OER on a real fuel cell using sliding mode control (SMC) theory. However, in these works the proposed control strategies had not adequately considered the influence of uncertainty and disturbance, such as neglected variations of system parameters due to environmental change, time delay and nonlinearities of PEMFC system.

Generalized Predictive Control (GPC) developed by Clarke et al. [18,19] have been widely applied in the process industry due to its capability of obtaining a stable control for systems with varying parameters, time delay, high model order and non-minimum phase. However, the future control-increment vector is derived by recursively solving the Diophantine equation for a given predictive horizon, which is time consuming. Furthermore, many other drawbacks such as complex mathematical derivation and too many tuning parameters are appeared in GPC. In order to reduce the online computation time, a short predictive horizon or a short control horizon is utilized. But this is against the basic principle of the GPC to some extent, which sometimes leads to poor control performance [20,21]. At present, many improved schemes have been proposed to avoid the matrix operation and reduce the computation while keeping a long control horizon at the same time [22–25].

The rolling optimization process is an important part of the GPC, which plays a key role on control effect. Hence it is necessary to seek a highly efficient optimization method. However, this optimization problem is usually very complicated with various constraints. It is difficult to solve this constrained optimization problem by using traditional methods. Currently the intelligence computation technique has attracted attention for the control system design, such as particle swarm optimization (PSO) algorithm which is a swarm intelligence optimization algorithm based on observations of the social behavior of bird flocking [26–29]. In this paper, an effective informed adaptive particle swarm optimization (EIA-PSO) algorithm which was proposed by our team in [30] for improving inherent drawbacks of PSO is utilized to solve the predictive control law in the rolling optimization process.

In this paper, a maximum net power control (MNPC) strategy based on an implicit generalized predictive control (IGPC) and an OER reference governor is proposed for the PEMFC system. The predictive control law which is solved by the EIA-PSO algorithm in the IGPC does not involve the Diophantine equations so that the computational complexity is reduced. The parameters of the output predictive equation are directly identified using the characteristics of the parallel predictors. The control strategy allows a safe and efficient OER control while maximizing the net power of PEMFC system. The simulations of three conditional tests are carried out and the experimental comparison with the commercial Ballard Nexa Power Module internal control system for the maximum net power is also developed.

This paper is organized as follows. Section 2 is dedicated to the maximum net power characterization of PEMFC system. PEMFC net power control algorithm is fully explained in Section 3. Section 4 details results and discussions. Finally, the main conclusions are drawn in Section 5.

2. Maximum net power characterization of PEMFC system

A PEMFC stack needs to be integrated with several auxiliary components to form a complete PEMFC system as Fig. 1 shown. In this paper, a dynamic model of PEMFC system based on [9,10] is utilized by using electrochemical, thermodynamic and fluid mechanics principles. This model of PEMFC prototype is a commercial Ballard 1.2 kW Nexa Power Module which is widely used in vehicle applications. Furthermore, this model describes the thermal system of PEMFC. More details of this PEMFC system model can be found in [9,10].

The majority of the parasitic power for the PEMFC system is spent on the air pump, thus, it is important to determine the proper air flow for maximizing the net power P_{net}. The air flow excess is reflected by OER, defined as the ratio of oxygen supplied $F_{O2,in}$ to oxygen used $F_{O2,ret}$ in the cathode. After an optimum value is reached, however, further increase in OER will result in an increase in pump power so that P_{net} decreases [8–10]. The OER is expressed as follows

$$\mathrm{OER} = \frac{F_{O_2,in}}{F_{O_2,ret}} \tag{1}$$

An experimental testing system consists of a Ballard 1.2 kW Nexa Power Module, an electronic load, and measurement devices installed at School of Electrical Engineering, Southwest Jiaotong University. The Ballard Nexa Power Module is an autonomous commercial system supplying power to the load and all its auxiliary components from its own stack power, composed by an air-cooled stack of 46 cells with internal air humidification and other auxiliary systems. The experimental testing system is setup as shown in Fig. 2. The internal control system of Nexa Power Module has regulation strategy for the air pump voltage that is intended to avoid oxygen starvation.

The analysis of control objectives is shown in Fig. 3, where the behavior of the net power P_{net} as a function of OER in constant net current curves is presented. These net power curves describe the effective power delivered to the load when the demanded net current I_{net} changes from 5A to 35A. The maximum net power

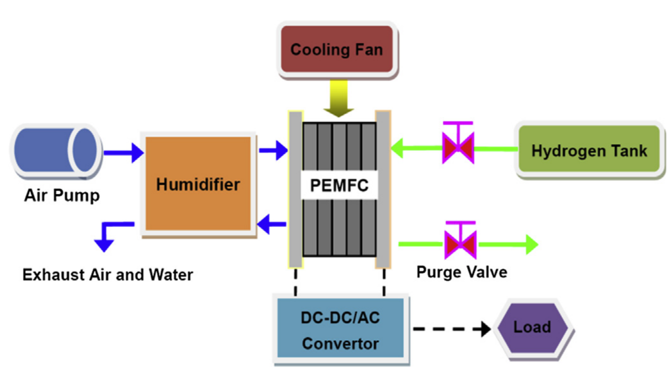

Fig. 1. Schematic diagram of PEMFC system.