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Tracking the maximum efficiency point for the FC system based on extremum seeking scheme to control the air flow

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HIGHLIGHTS

- The Maximum Efficiency Point (MEP) is tracked based on air flow rate.
- The proposed Extremum Seeking (ES) control assures high performances.
- About 10 kW/s search speed and 99.99% stationary accuracy can be obtained.
- The energy efficiency increases with 3–12%, according to the power losses.
- The control strategy is robust based on self-optimizing ES scheme proposed.

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ABSTRACT

An advanced control of the air compressor for the Proton Exchange Membrane Fuel Cell (PEMFC) system is proposed in this paper based on Extremum Seeking (ES) control scheme. The FC net power is mainly depended on the air and hydrogen flow rate and pressure, and heat and water management. This paper proposes to compute the optimal value for the air flow rate based on the advanced ES control scheme in order to maximize the FC net power. In this way, the Maximum Efficiency Point (MEP) will be tracked in real time, with about 10 kW/s search speed and a stationary accuracy of 0.99. Thus, energy efficiency will be close to the maximum value that can be obtained for a given PEMFC stack and compressor group under dynamic load. It is shown that the MEP tracking allows an increasing of the FC net power with 3–12%, depending on the percentage of the FC power supplied to the compressor and the level of the load power. Simulations shows that the performances mentioned above are effective.

1. Introduction

Polymer Electrolyte Membrane Fuel Cells (PEMFCs) are electrochemical devices that convert the chemical energy stored in hydrogen and oxygen (air), used as combustible and combustive reactants, directly into electricity [1,2]. PEMFC is a promising alternative for transportation and distributed generation applications based-on stationary or portable FC Hybrid Power Sources (FCHPS). PEMFC has higher energy efficiency (which is in the range of 40–50% or close to 85% in the cogeneration mode) in comparison with the competing technologies (which is in the range of 30–35%) [2,3]. Controlling the PEMFC system to further increase energy efficiency is a challenging action for the FCHPS designers. Three main control systems must to be designed for a PEMFC system [4,5]: (1) the air/fuel supply, (2) the water supply, and (3) the heat management. The control problem presented in this paper is focused on the regulation of the air supply to the cathode.

Besides the FC stack, which is the main component, the PEMFC system needs various auxiliary equipments (including air compressor, humidifier, pumps, cooling water circulation, and measurement and control equipment) to safe operate it. The power consumption of air compressor is the highest in comparison with the other auxiliary equipments (up to 80% power of the overall auxiliary equipments) [6]. The compressor motor is powered by the PEMFC system itself and can consume up to 20% of the FC power [7]. So, maximizing the FC net power is one of the control goals related to energy efficiency. Thus, the PEMFC systems must operate safety close to the Maximum Efficiency Point (MEP) [8,9]. In comparison with the Maximum Power Point (MPP), the MEP is difficult to be tracked because the FC operating point depends on a large numbers of related parameters, for instance, the feeding and the humidification systems, cooling control circuit, and

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electrical interface, beside the dynamic load [10,11]. Even if the energy efficiency of the PEMFC system operating at the MPP is a little bit lower than the maximum value obtained at the MEP, the MPP tracking control schemes are usually implemented because of their relative simplicity [12,13]. In this paper we propose using a MEP tracking control based on advanced Extremum Seeking (aES) scheme [13]. This aES control scheme improves the basic performances of the ES control schemes [14,15], assuring higher search speed and improved tracking accuracy of the MEP.

Starting with the static feed-forward (sFF) and static feed-forward with PI control [7,16] that are usually used as references, different MEP tracking control algorithms were proposed in the last decade based on the feedback linearization [17], dynamic feed-forward-feedback control techniques [18], sliding mode control [19], supper twisting algorithm [20], perturb and observe algorithm [9,21], ES control schemes [22–24], model predictive control [25,26], neural networks [27], fuzzy logic [28,29], LQR/LRS strategies [30,31], nonlinear differential flatness-based control [32,33], time delay control [34], and other adaptive control strategies [35–37].

Most of the previous studies cited are based on different types of feedback control loops and look-up tables that need different FC system state variables, which are acquired using many sensors or observers, and proper design of the controller to tolerate FC system uncertainties [38]. The designed controller could theoretically produce accurate results, but the complex computational algorithms are not suitable for implementation into the embedded controllers.

If an air mass flow sensor will be used to evaluate or control the oxygen excess ratio (OER), then the following drawbacks appear: (1) slow response time (about 1–2 s), (2) less accuracy (with 1–10%), short life time (up to 3 years), and a high price. Thus, a sensor-less approach is of interest for controlling the Air Flow rate (AirFr) via a compressor. However, it is obvious that designing advanced AirFr controllers is an important issue for improving the energy efficiency of the PEMFC system.

Hydrogen and oxygen must be supplied to the fuel cell in order to fulfill the stoichiometric relation required to produce the current demanded by a dynamic load. The recommended values for the OER are in range 1.5–3, but some of the cited approaches have considered as a reference OER = 2 [7]. It can be noted that it is difficult and costly to estimate the OER during the stationary regime and some major errors could appear during the transitory regime [39]. The cited works obtained good results in terms of AirFr, considering that the anode pressure follows the cathode pressure value [32]. Therefore, a fast electro-valve is required to control the anode pressure in order to maintain the pressure equilibrium between the cathode and anode. So, the air and fuel supply subsystems must be controlled simultaneously with the dynamic load to avoid oxygen starvation [7,32]. A simple and cheap control technique is the sFF control technique or one of the improved sFF control techniques that is based on FC current, but these control techniques are not robust and are showing slower responses to track the optimal value of OER [7,21]. Because this study is partially focused on the stationary tracking accuracy of the MEP, the sFF control technique will be used as a reference in reporting the results and comparing these results with other studies that use the same control reference.

All the cited studies, excepting the ES control techniques, need an accurate PEMFC model. The PEMFC system model is still under study in order to consider all the new phenomena observed under dynamic load [32]. In addition to the dynamic load, changes in operating conditions, such as temperature and humidity, or the nonlinearities of the compressor also influence the system parameters. Therefore it is necessary to consider parametric uncertainty for designing robust controllers. Thus, if some parameters of the fuel cell air subsystem are considered constant, then the results are difficult to be implemented in practice.

It is known that ES control scheme is an effective method for optimization problems when the system dynamics are not well known, offering a guaranteed convergence and a proved internal robustness.

A novel constrained ES method for maximizing the FC net power is presented in [23]. The penalty functions effectively enforce the set constraints and enable the use of higher values for both closed loop gain and dither amplitude ES parameters to increase the search speed. The authors noted that this action leads to tracking accuracy depreciation: high overshoots and stationary ripple appear. The same conclusions are given in [24]. To overcome these drawbacks, the aES control scheme is proposed and improved here by adding a minimum dither signal. This assures the dither persistence during the stationary regime and improves the stationary tracking accuracy. The search speed during transitory regime could be set at safe limit for the PEMFC stack [39,40]. The safe limit could be adapted to the FC current level based on constrained ES method [41].

To ensure the ES control scheme convergence to a neighborhood of the optimum, three assumptions are necessary [24,42]: (1) the system is input-to-state stable, (2) a convex map exists between the control input and the performance output parameter, and (3) the dither persistence is assured. All these assumptions are satisfied for the PEMFC system controlled by the OER or AirFr parameter [24].

The OER is a lumped variable that cannot be measured directly, depending mainly on the AirFr, FC current, the relative humidity, and the cathode inlet pressure and temperature [25,39]. Consequently, it is better to use the convex map that exists between FC net power and AirFr [21].

The feed forward control based on aES (FFaES) scheme proposed here, presents several advantages: (1) it is robust based on an integrator block that is included in the control loop (see Fig. 1) [21,43]; (2) It is not based on measurements of the PEMFC system's states, being based only on measurement of the FC net power, which can be obtained with high accuracy, using inexpensive transducers for current and voltage; and (3) it has high performances at a reduced computational power for the embedded controller [13].

The FFaES control scheme is of adaptive closed-loop control type used for searching unknown MEP (see Fig. 1). The stationary accuracy is defined as percentage based on relation $100\cdot(P_{net}/P_{net(max)})$, where $P_{net(max)}$ is the power of the FC system operating at MEP and P_{net} is the FC net power extracted. The dynamic accuracy is dependent to search speed, which must be high in order to track the power profile of a dynamic load.

The goal of this paper is to show that the proposed FFaES scheme can be used to accurately determine the unknown MEP of the FC system that supply a dynamic load. The experiments to analyze the both sFF and FFaES control schemes under dynamic load were performed by numerical simulation. Thus, this paper contributes to research on airflow control in PEMFC systems based on FFaES control scheme.

The paper is organized as follows. Section 2 briefly presents the issues related to the system modeling and control, and gives details for relations and parameters used in simulation. Section 3 deals with the modeling and control of the compressor. The control of the air flow rate is shown in Section 4 based on aES control scheme proposed here. After a short review of the advantages of the aES control scheme in comparison with the classical ES control schemes, the aES control scheme is detailed. The performances on FC net power obtained using the FFaES and sFF control schemes are shown in Section 5. The comparative simulation results are mentioned for different load power sequences. First, it is shown the availabilities in maximizing the FC net power by regulating the air flow. Second, it is shown the dynamic performances of this