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Improving the PEMFC energy efficiency by optimizing the fueling rates based on extremum seeking algorithm

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ABSTRACT

In this paper, the energy efficiency of the Proton Exchange Membrane Fuel Cell (PEMFC) systems based on the fueling rates is systematically investigated. The PEMFC system under dynamic load must be operated close to the Maximum Efficiency Point (MEP) to obtain the highest energy efficiency. This is a difficult task because the MEP is dependent on the PEMFC parameters and the control PEMFC variables, besides the load profile. Thus, the MEP must be tracked dynamically with a safe search speed and funded accurately during the stationary regimes. Consequently, a real-time control is recommended to be used. The Extremum Seeking (ES) control scheme is proposed here to evaluate the FC net power at the MEP under different fueling rates and load profiles. Some interesting conclusions are obtained based on the comparative method proposed using as reference a base control technique or a PEMFC stack: 1) the MEP is different based on the control of the fuel or air flow rate; 2) the energy efficiency increases if both fueling flow rates are controlled; 3) the energy efficiency is less sensitive to power losses if the MEP is tracked by the ES controller based on air flow rate; 4) the strategy of load following control considering the fuel flow rate as an input variable is recommended based on the observation that the MEP is more sensitive to this in comparison to the air flow rate; 5) the design of an appropriate MEP tracking controller should equally focus on safe operation and the increase of the performances such as the search speed and tracking accuracy under dynamic load. All these remarks are based on an extensive numerical simulation, which are highlighted in this paper by the main results shown.

Introduction

Hydrogen is a carrier vector of energy being used to the transport and storage of energy from different sources [1]. Combinations of hydrogen are found in large quantities in nature, but obtaining a molecular hydrogen is an energy consuming process. Thus, the sustainable production of hydrogen is based on the decomposition of water using different renewable energy sources, in particular the solar

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energy [2]. Following the energy generating process, the pure water is produced, which can be consumed or included to the industrial water circuit [3]. In this context, the concept of hydrogen based technology, including the production, storage and use of hydrogen as energy carrier, will be the center of attention for researchers in the field of sustainable energy for coming years [4].

In last decade, a number of topologies hybrid power sources hydrogen based have been proposed and analyzed in terms of improving the energy efficiency, optimizing the control of the DC bus, sizing the energy storage system, and increasing the life cycle and durability under dynamic load etc [5,6]. Among the various types of fuel cell, the PEMFC systems are most used because they are suitable for both automotive and residential applications due to the high energy density, low emissions and low temperature operation [7,8].

The PEMFC stack is an electrochemical device in which chemical energy is converted directly into electrical energy. The PEMFC stack operates with hydrogen and oxygen to generate energy with an efficiency of 45–50%, reaching 80% yield if heat is also recovered [7,8].

The hydrogen is generated by electrolysis or taken from a hydrogen tank, using different supply modes with hydrogen [9]: flow-through, dead-end anode, or with recirculation. Regarding the fuel supply modes, it can be noticed the following: the continuous-flow mode is not used for normal applications due to the dangers associated with excess hydrogen that is eliminated outside of PEMFC system [10]; the dead-end anode feed mode requires special attention on the frequency and duration of purging to ensure efficient and stable operation [11,12]; the recirculation mode is most efficient [9], but can be unpractical to implement it for small power applications [13]. This paper will analyze the energy efficiency of the PEMFC system based on the hydrogen flow rate measured at the input of the PEMFC stack in order to cover all fuel supply modes. It is obvious that the fuel consumption depends by the fuel supply modes used, but this is outside the scope of this paper.

Also, it is known that FC net power depends by air flow rate measured at the input of the PEMFC stack [14,15]. Thus, the control of the PEMFC system to increase the energy efficiency is a challenging action if both fueling rates are considered [16,17]. In addition, it is known that other two control systems must to be appropriately designed to maintain the energy efficiency obtained by optimizing the air/fuel fueling rates of the PEMFC system [18,19]: the water supply and the heat management. The analysis presented in this paper is focused on improving the energy efficiency by controlling both air and fuel flow rates. The possibilities to maximize the energy efficiency of the PEMFC system under different load power levels will be analyzed in this paper considering the ensemble composed from the PEMFC stack and the fueling subsystems (Fig. 1).

It is known that the PEMFC system contains other various auxiliary equipments (including the air compressor, humidifier, pumps, cooling water circulation, and the measurement, control, signalizing and protection circuits),besides the PEMFC stack. The power consumption of air compressor is up to 80% power of the overall auxiliary equipments [20], and this represents up to 20% of the FC power available [21]. Thus, the PEMFC systems must operate close to the MEP in order to obtain high

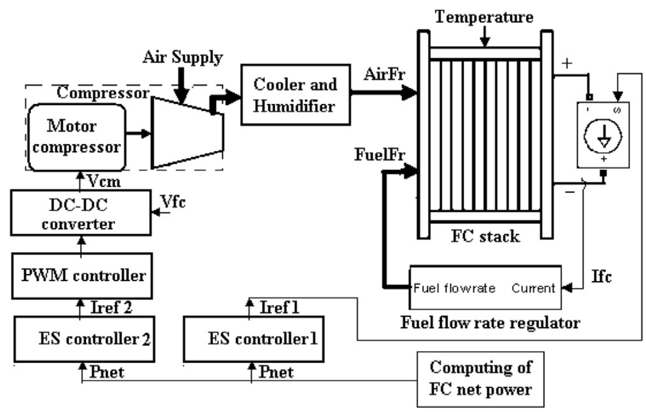

Fig. 1 – The PEMFC system.

energy efficiency [14,22]. On the other hand, the MEP is difficult to be tracked because the operating point depends by the PEMFC system parameters and the load dynamic [23,24]. Consequently, the recent research was focused in this direction to maximize the output power of the PEMFC system [25].

To find a better solution for the management of air supply, different control algorithms were proposed: the dynamic feed-forward–feedback control [26], sliding mode control [27], supper twisting algorithm [15,28], perturb and observe algorithm [29], ES control [30,31], model predictive control [32,33], and intelligent control based on neural networks [34] and fuzzy logic [35,36]. Advanced control schemes based on LQR/LRS strategies [37,38], nonlinear differential flatness-based control [39,40], time delay control [41], and adaptive control [42] where proposed in the last years, too. Also, the optimization strategies have been considered to maximize the efficiency of the whole PEMFC system or the operation of the compressor [43]. The proposed strategies regulate the air pressure to the required load power, increasing the FC net power with about 3%–10% in comparison with the power obtained in constant pressure mode. It can be noticed that not all control schemes aforementioned tolerate the uncertainty on state variables of the PEMFC system [44].

In this paper, the MEP tracking control based on Single-Input Dual-Output Extremum Seeking (SIDOES) control scheme proposed in Ref. [45] will be used. This SIDOES control scheme assures higher search speed and improved tracking accuracy of the MEP, improving the basic performances of the classical ES control schemes [46,47].

The static feed-forward (sFF) control technique [21] will be used as reference to report the improvements on FC net power. Then the SIDOES control scheme will be used (see Fig. 2). The improvements on FC net power will be highlighted by the achievements obtained for the PEMFC system under test in comparison with the reference.

The main goal of this paper is to show that energy efficiency of the PEMFC system can be further improved by controlling both fueling rates. The SIDOES scheme is used to accurately determine the unknown MEP of the PEMFC system under constant and dynamic load. The experiments under dynamic load were performed by numerical simulation to show the high search speed of the SIDOES scheme. Also, this paper contributes to research the fueling flow rates control of the PEMFC