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Optimization of the proton exchange membrane fuel cell hybrid power system for residential buildings

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A B S T R A C T

A real-time optimization (RTO) strategy to find the optimal value of the fuel flow rate of a Fuel Cell Hybrid Power System (FCHPS) for residential buildings is proposed here, which is shortly named as Air_LFW-RTO strategy due to the use of Load-Following (LFW) technique to control the air flow. The optimization strategy uses the Global Extremum Seeking (GES) algorithm to adjust the fuel flow rate and harvest the FC power by using two GES control schemes. The performance obtained with Air_LFW-RTO strategy proposed herein is shown compared to Static Feed-Forward RTO strategy, where both fueling rates are controlled by the FC current. The performance have been estimated for 8 kW residential building based on following indicators: the fuel consumption efficiency, the FC system efficiency, and the fuel economy during a variable load demand. The fuel consumption efficiency and the energy efficiency could increase with more than 11.47 W/lpm and 2.13% for a FCHPS under 8 kW constant load. The fuel economy could be up to 263 lpm for a FCHPS under variable load cycle using the Air_LFW-RTO strategy.

1. Introduction

The Polymer Electrolyte Membrane Fuel Cell (PEMFC) stack generates electrical energy and heat, which can be used in electric and heating system of a building after the energy and heat are appropriately converted and recovered [1,2]. This mixed solution could increase the PEMFC efficiency up to 70% [3]. Thus, in last decade, the concept of Zero Energy Building (ZEB) was implemented in residential systems based on hydrogen (regenerative PEMFC) and Renewable Energy Sources (RES) such as solar energy, wind power and biomass [4]. The hydrogen can be produced by the electrolyser supplied by RES (when the RES power exceed the load demand) and stored in fuel tanks to supply the PEMFC used as backup energy source (when the RES power is lower than the load demand) [5]. The hybrid system combining building-integrated photovoltaics with other RES and PEMFC may be designed as a stand-alone ZEB system that operates efficiently and reliable under variable load [6,7].

Besides the variable load with unknown profile, the PEMFC will mitigate the RES power variability so that RES/FC HPS will operate safely [8]. This means that fueling flow rates are limited up to safe values by the slope limiters from the fueling regulators. This delay in generating power on the DC bus mandatory requests the use an Energy Storage System (ESS) to dynamically compensate the power flow balance on DC bus. So, a large and sharp change in the load connected on DC bus could produce a large voltage drop until the PEMFC will generate the needed power, but this is lack in power will be quickly compensated by appropriate control power storage device (ESS-P) based on voltage error, $e_v = V_{DC} - V_{DC(ref)}$, and other state variables if it is necessary (see Fig. 1). Furthermore, this is the reason for choosing the DC voltage regulation on the control side of the power storage device. The DC voltage regulation could be implemented at the control side of the PEMFC system, but also at the control side of the battery (if active ESS topology is used instead of one of semi-active type). Besides these design solutions, safe issues, and ways to split the load demand for PEMFC and ESS, the optimal operation of the HPS will be discussed in this paper considering large steps (up and down) in the load demand and variable RES power. Thus, the both load and RES power flows on DC bus will be considered variable here (see Fig. 1).

So, this study analyzes the possibilities to optimize the PEMFC system operation and the energy conversion in a FC Hybrid Power

Abbreviations: AirFr, Air Flow rate; AV, Average Value; BIPV, Building-Integrated Photovoltaic; BPF, Band-Pass Filter; CHP, Combined Heat and Power; DP, Dynamic Programming; ECMS, Equivalent Consumption Minimization Strategy; EMU, Energy Management Unit; ES, Extremum Seeking; ESS, Energy Storage System; FC, Fuel Cell; FCHPS, Fuel Cell Hybrid Power System; FuelFr, Fuel Flow rate; GES, Global Extremum Seeking; GMPP, Global Maximum Power Point; GMPPT, GMPP tracking; HPF, High-Pass Filter; LC, Load Cycle; LFW, Load-Following; LPF, Low-Pass Filter; MEP, Maximum Efficiency Point; MPC, Model Predictive Control; PV, Photovoltaic; PEMFC, Proton Exchange Membrane Fuel Cell; PMP, Pontryagin's Minimum Principle; RES, Renewable Energy Sources; RTO, Real-Time Optimization; SOFC, Solid Oxide Fuel Cell; sFF, Static Feed-Forward; ZEB, Zero Energy Building

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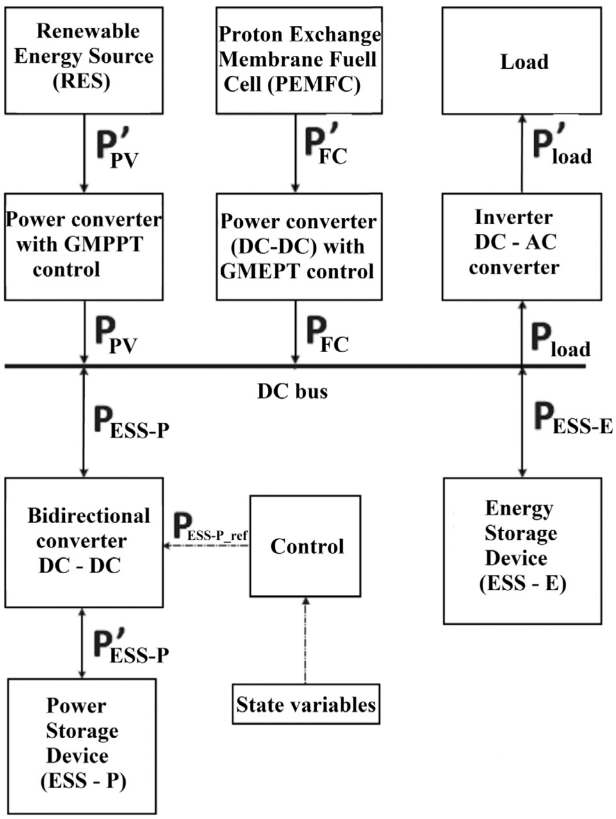

Fig. 1. The HPS architecture.

System (FCHPF) used in ZEB system under variable power flow on DC bus given by (1):

$$p_{DC} = p_{load} - p_{RES} \tag{1}$$

where p_{RES} and p_{Load} are the RES power and the load demand on DC bus. The power flow balance on DC bus for the RES/PEMFC/ESS HPS shown in Fig. 1 is given by (2):

$$C_{DC} u_{dc} \frac{du_{dc}}{dt} = p_{FC} + p_{ESS} - p_{DC} \tag{2}$$

where C_{DC} is the capacitor on DC bus (which is used to filter the voltage on DC bus, u_{dc}), and p_{FC} and $p_{ESS} = p_{ESS\text{-}P} + p_{ESS\text{-}E}$ are the FC net power and the ESS power on DC bus.

The hybrid ESS uses semi-active topology using battery and ultracapacitors (UCs) as energy storage device (ESS-E) and power storage device (ESS-P). The other technologies that can be used for storing energy and power will be briefly discussed in Section 2.

Different fuel cells technologies have been successfully used to supply with energy and heat the commercial and office buildings, hotels, and other types of buildings [9]. The economic analysis of FC installations based on price and complementary technologies recommend as ZEB solutions for residential buildings the Combined Heat and Power (CHP) [10], the Solid Oxide FC (SOFC)-based micro-CHP plants (with electrical efficiency up to 60% [11]), and the PEM technologies of high [12] and low [13] temperature. Due to the high operating temperature, the FC technologies operating at high temperature have more disadvantages than PEMFC technology at low temperature related to life cycle, complex control and energy management [14]. So, PEMFC for residential buildings have been intensively studied as modeling [15], optimization [16], and energy, exergy and exergo economic analyses [17,18].

Furthermore, a lot of optimization strategies were proposed in literature for buildings based on polygeneration systems [19] and FCHPS, the latter being briefly reviewed in the next section.

The objectives of this paper are: (1) to highlight the performance of proposed Air_LFW-RTO strategy for a FCHPS under variable load profile, which is the case of a residential building with power demand range up to 8 kW; (2) to estimate the fuel economy by using Air_LFW-RTO strategy instead of sFF-RTO strategy; (3) to enhance the fuel economy considering a mixed optimization function based on FC net power and the fuel consumption efficiency.

The main outcomes of this study are as follows: (1) a new Air_LFW-RTO strategy is proposed for efficient operation of FCHPS under unknown load profile; (2) the superiority of the Air_LFW-RTO strategy in comparison with the reference strategy (the Static Feed-Forward (sFF) strategy) was shown in range of 0.75–1.25% from nominal power of the 6 kW FCHPS; (3) the fuel economy could be up to 263 lpm for unknown load profile with average value (AV) of 6.25 kW. The paper is structured as follows. The hybrid ESS topologies and energy storage devices technologies used in this study are presented in Section II. Section III reviews the main optimization strategies used for FCHPS. Section IV presents the 6 kW FCHPS, the optimization function and control loops involved in this study. The performance indicators are defined in Section V. The results obtained for constant and variable load profile, with and without RES power, are shown in Section VI based on optimization function defined as weighting function of the FC net power and fuel consumption efficiency in order to analyze the improvement in fuel economy. The results obtained are discussed in Section VII. Last Section concludes the paper.

2. Energy storage system (ESS)

Energy storage devices usually used in ESSs are the batteries, regenerative fuel cells, and flywheels. The hybridization of the ESS with power storage devices (such as UCs, Superconducting Magnetic Energy Storage (SMES), and high speed flywheels) is mature technique for mobile [20,21] and stationary applications (including ZEB) [22–24].

2.1. Hybrid ESS topologies

ESS hybridization avoids some disadvantages of the battery ESS related to maintenance and environmental hazards that potentially can appear [25,26]. The most used hybrid ESS topology is the semi-active topology (see Fig. 2), but also active topology could be used due to their flexibility and performance. Both have clearly advantages compared with the passive topology.

In this study the semi-active ESS topology uses 100 Ah lithium-ion batteries' stack (connected directly at the 200 V DC) and 100F ultracapacitors' stack (connected via a bidirectional buck-boost converter). The latter is used to regulate the DC voltage (u_{dc}) at $V_{DC(ref)} = 200$ V. Both will sustains the instantaneous power flow balance on the DC bus (1).

The energy and power storage devices technologies that could be potential candidates for hybrid ESS are briefly described in next two sections.

2.2. Energy storage devices technologies

The battery are first candidates even if the current Li–ion-batteries have energy densities is less than 150 Wh/kg for [27].

2.2.1. Batteries

The ESS designer can choose from various technologies used for batteries: lead acid batteries (if very low costs, low cycle and energy density is required), nickel metal and nickel cadmium hydride batteries (if high energy density is required; about twice higher compared with that of lead acid batteries), sodium-based batteries (if high energy density is required (same as nickel-based batteries) and battery must operate at very high temperatures), and lithium-ion batteries (with energy density twice higher compared with nickel-based batteries)