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Real-time optimization strategy for fuel cell hybrid power sources with load-following control of the fuel or air flow

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A B S T R A C T

This paper analyses two Real-Time Optimization (RTO) strategies for Proton Exchange Membrane Fuel Cell (PEMFC) system which is used as main energy source for Fuel Cell Hybrid Power Source (FCHPS) of the FC vehicle (FCV). In this study the optimization function was defined as mix of the FC net power and the Fuel Consumption Efficiency by using two weighting coefficients. The Global Extremum Seeking (GES) algorithm is proposed here as RTO method for multimodal optimization surfaces having many peaks on the plateau around the optimal point that is the Global Maximum Point (GMP). One of the fueling rates is Load-Following (LF) controlled in order to adapt the FC net power to load demand and assure the charge-sustaining mode for the battery. The GES algorithm will establish the optimal duty cycle for the Boost converter, so the proposed strategies will be called the Boost-GES-RTO strategies with Air-LF and Fuel-LF, respectively. The Static Feed-Forward (sFF) control strategy will be used as reference for constant and variable load profile. The gaps in performance indicators were estimated for both Boost-GES-RTO strategies. For example, the gaps in FC system efficiency and fuel economy could be up to 1.61% and 142 lpm, and 2.65 and 114 lpm for the Boost-GES-RTO strategies with Air-LF and Fuel-LF. The performance of Boost-GES-RTO strategies was also shown by estimating the fuel economy for 6 kW FCHPS under variable load profile.

1. Introduction

The Real-Time Optimization (RTO) strategies are proposed to efficiently operate different nonlinear energy systems [1] such as the mixed heating systems [2] and photovoltaic arrays [3]. The RTO strategies were recently proposed to increase the fuel economy of the Fuel Cell Hybrid Power Sources (FCHPS) [4], which can also improve their cost, durability and reliability [5]. The RTO strategies must to assure the operation of FCHPS at maximum power efficiency [6] based on efficient control of power flows from renewable energy sources [7]. As it is known, the RTO strategies can be based on optimization's rules (the rule-based strategies) or optimization's functions [8,9]. For example, the tracking efficiencies of 99.60%, 99.41%, and 99.28%, and the tracking times of 12 ms, 33 s, and 25 s is reported in [9] for systems of photovoltaic (PV) panels, fuel cell (FC) stacks, and wind turbines (WT).

The deterministic rule-based strategies are of sub-optimal type and cannot guarantee that the optimal solution (the GMP) will be always found. But these strategies are the easiest to be implemented, so these are already available in the market [10]. On the other hand, even if the optimization-based strategies are difficult to be implemented [1,11], the recent RTO applications for FC vehicle (FCV) request advanced RTO strategies because the GMP must be found in any operating condition requested [7,12].

Besides the well know RTO strategies based on the Equivalent Consumption Minimization Strategy (ECMS) [13,14], the intelligent algorithms [15,16], the Model Predictive Control (MPC) [17,18], and other hybrid techniques using the wavelet-fuzzy logic control [19], the robust-adaptive sliding mode control [20], the combinatorial optimisation approach [21], the multi-scheme method [22], double layer metaheuristic technique [23] and so on [24]. The RTO strategies based on the Extremum Seeking (ES) algorithms have been proposed recently for FCHPS [25] and FC vehicles [26]. The ECMS is most known RTO

Abbreviations: AirFr, Air Flow rate; AV, Average Value; BPF, Band-Pass Filter; 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 Source; FCV, Fuel Cell (FC) vehicle; FuelFr, Fuel Flow rate; GES, Global Extremum Seeking; GMP, Global Maximum Point; GMPT, GMP tracking; HPF, High-Pass Filter; LC, Load Cycle; LF, Load-Following; MEP, Maximum Efficiency Point; MPC, Model Predictive Control; PV, Photovoltaic; PEMFC, Proton Exchange Membrane Fuel Cell; PMP, Pontryagin's Minimum Principle; RTO, Real-Time Optimization; sFF, Static Feed-Forward; WT, Wind Turbine

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strategy used for FCHPS, being applied by considering the Pontryagin's Minimum Principle (PMP) [27] or Dynamic Programming (DP) [10].

The RTO strategies based on classical ES algorithms can be blocked in local extreme [28], this has been shown for PV systems [29] and FC systems [30,31]. Thus, different ES algorithms were proposed to solve this issue [32,25]. The Global ES (GES) algorithm proposed herein is an improved variant of the advanced ES algorithm proposed in [29], which has the feature to search the GMP, being already tested for PV HPS [33,34] using different techniques to implement the GMP searching loop [35].

The Boost-GES-RTO strategy proposed here will use the GES algorithm to optimally control the boost converter that it is used as power interface for FC system to DC bus. The Fuel Flow rate (FuelFr) or Air Flow rate (AirFr) is controlled by the Load-Following (LF) control via the appropriate fuelling regulator in order to adapt the FC net power generated to load demand [36]. Note that the use of the LF control for unknown load profile may reduce the size of the batteries' stack which is used in semi-active topology of the Energy Storage System (ESS), besides the ultracapacitors' stack [1]. Thus, two Boost-GES-RTO strategies (with Fuel-LF and Air-LF) will be analyzed in comparison with the Static Feed-Forward (sFF) RTO strategy [37]. The fuelling rate that is not LF controlled will be regulated by the FC current, which has an optimal value due to use of the Boost-GES-RTO strategy for setting the duty-cycle of the boost command. Note that both fuelling regulators are controlled by the FC current in sFF-RTO strategy, where the FC net power generated to load demand is adjusted by LF control of the boost converter (see Fig. 1, where the switches' position is for the Boost-GES-RTO strategy with Air-LF control). The Boost-GES-RTO strategies will be detailed in next section.

The performance indicators usually used to evaluate the performance of the RTO strategies are the FC net power and the fuel consumption efficiency, and related to them can be used the FC system efficiency and the total fuel consumption. So, the latter two performance indicators will be used here to analyse the Boost-GES-RTO strategies considering a mixed optimization function based on the first two performance indicators.

In general, a RTO strategy must to solve the following problems related to optimization of the FCHPS operation:

Finding of the Maximum Efficiency Point (MEP) on the optimization surface P_{FCnet} = f(*AirFf, FuelFr*) based on GMP tracking (GMPT) algorithm [4,5], instead of other peaks on the plateau around the MEP [1,4]; note that the firmware-based GMPT algorithms operate in two stages, so cannot be used for RTO-strategies due to large response time [3–5];

- Use of the adaptive searching (with appropriate tracking speed for GMPPT algorithm related to response time of the system under test) in order to find in real-time the variable position of MEP [1,3]; for example, the GES algorithm proposed in [34] will track the GMP in less than 10 dither's periods, which means less than 0.01 s for a

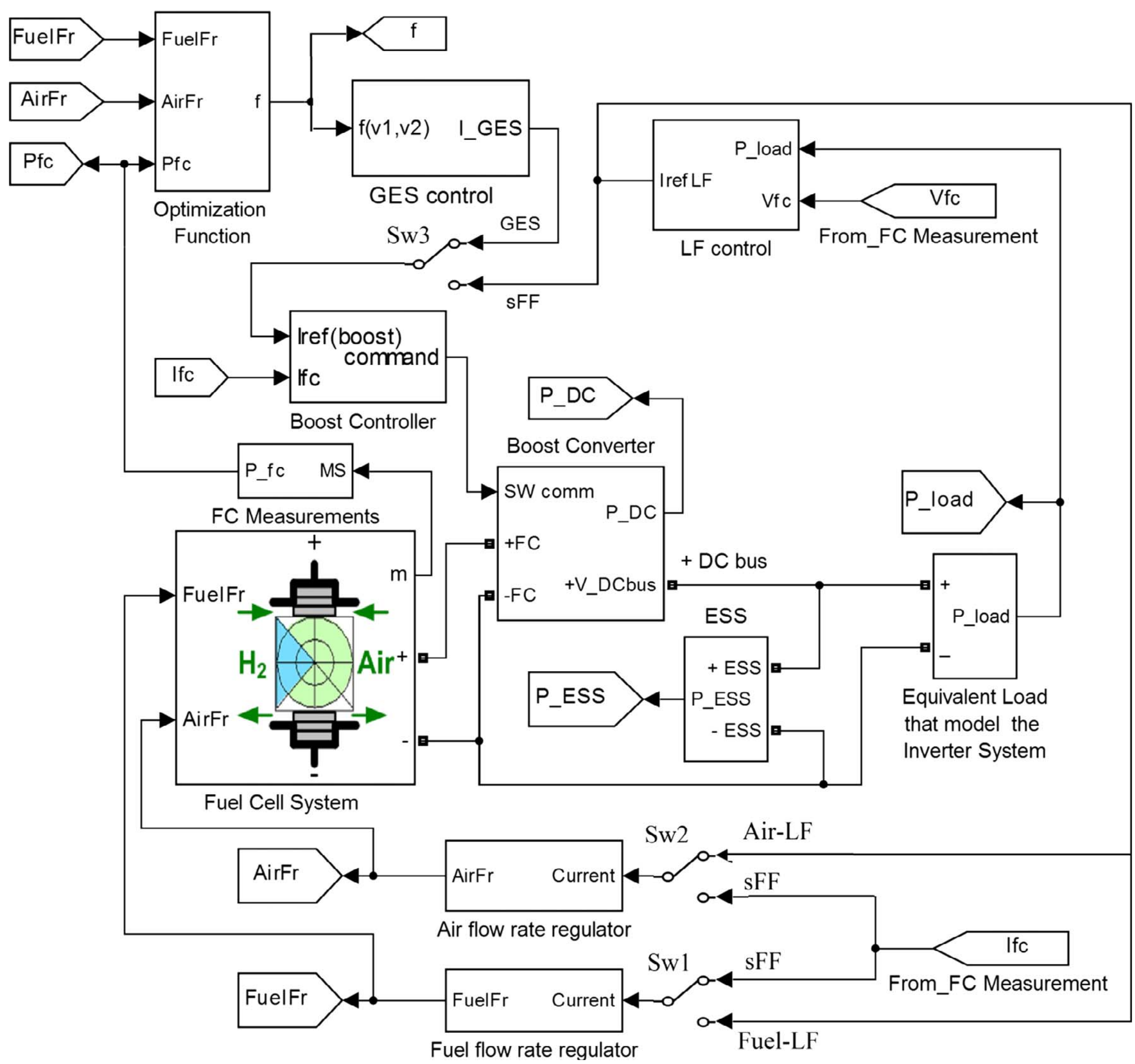

Fig. 1. The diagram of the FCHPS using the Boost-GES-RTO strategies (Air-LF and Fuel-LF) and sFF strategy.