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Optimization-based energy management strategy for a fuel cell/battery hybrid power system

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HIGHLIGHTS

- We propose an adaptive optimal power splitting EMS for PEMFC/battery hybrid system.
- An online optimization problem based on the Pontryagins Minimum Principle was developed to minimize the hydrogen consumption.
- An extremum adaptive-seeking control layer was proposed to take into account the PEM-FC performances drift.
- The proposed optimal adaptive EMS is verified by simulation for two PEMFCs with different degree of degradation.
- The classical EMS led to mismanagement when the operating parameters change whereas the adaptive EMS meet the power demand.

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ABSTRACT

This paper addresses the energy management strategy (EMS) for a fuel cell hybrid electric vehicle (FC-HEV). The purpose of this paper is to ensure an optimal power splitting between the fuel cell system (FCS) and the battery pack, taking into account the operating conditions of the FCS. The FCS is a multi-physics system, and consequently, its energetic performances depend on the operating conditions (i.e., temperature, gas relative humidity, gas stoichiometry, pressure and ageing). Specific techniques must be used to reach the best performances of the FCS. In this work, models are identified online by using the adaptive recursive least square (ARLS) method to seek a variation in the FCS performances. Then, an optimization algorithm is used on the updated model to find the best efficiency and power operating points. This process is used into an optimal EMS based on Pontryagin's minimum principle, for a FC-HEV. The effectiveness of the proposed EMS is demonstrated by conducting studies on two FCSs with different levels of degradation.

1. Introduction

A promising solution to produce zero local emission electricity in an embedded (as hybrid vehicles) or stationary system is the fuel cell system (FCS). The most practical FCS for embedded applications is the proton exchange membrane fuel cell (PEM-FC) because of its low operating temperature and pressure, tolerance to carbon dioxide and solid membrane [1]. Furthermore, the consumed hydrogen can be produced with renewable energies, such as electrolysis and biomass processes to produce near zero global emission electricity [2,3]. In practice, a good durability is ensured for the PEM-FC when slow load dynamics are applied [4]. Consequently, an energetic buffer (battery, supercapacitor, flywheel) must be used between the PEM-FC and the load to satisfy the fast dynamic load for the traction power on a vehicle DC bus [5,6]. As the energy is distributed between two sources, energy management strategy (EMS) is required.

In the literature, two classes define the EMS of the FC-HEV: the rule-based and the optimization-based controls. The rule-based controls use expert testimony, appear in deterministic (for example, thermostatic EMS), adaptive or predictive forms and are easily adaptable in real-time systems. The second approach is based on optimization of a cost function, which frequently defines the criterion of the fuel consumption, system efficiency, or system power [7].

Feroldi et al. [8] develop heuristic and optimal strategies based on the static efficiency map and validate them in real time. Their results show that the power split is enhanced by reducing hydrogen consumption. Bernard et al. [9] design an EMS based on Pontryagin's minimum principle (PMP) to reduce the hydrogen

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consumption and perform experimental validation. Farouk et al. [10] propose the study of two strategies: one strategy based on fuzzy logic and the other strategy based on the PMP. Their experimental study shows that PMP can outperform the fuzzy logic power split.

In most cases, the drawback of these strategies is that they depend on static models which are validated in a given operating range [11,12]. Indeed, the PEM-FC is a multi-physics system [13], and its energetic performances depend on operating condition (e.g., temperature, gas relative humidity, gas stoichiometry, pressure and ageing) [14]. It is therefore necessary to take into account these changes in operating conditions in a global EMS of the hybrid system.

There are two ways to identify the performance of a FCS, in real time. The first is the use of extremum seeking strategies, such as the maximum power point tracking (MPPT). Besides literature provides results on the topic regarding PEM-FCs. dan Zhong et al. [15] designed a MPPT algorithm based on an enhanced perturb and observe algorithm. Bizon [16] defined an additional MPPT algorithm to improve the tracking speed and displayed it in a numerical simulation. Guo-Rong et al. [17] designed a MPPT algorithm based on resistance matching and implement it on a hybrid energy system. The second method is to use a parametric identification online coupled to an optimization algorithm. However, this method requires a PEM-FC model. Once again, two solutions are possible. (i) A direct solution is to consider the multi-physics behavior of the PEM-FC in complex models. However, their design (and validation) can be difficult and time-consuming processes [18]. (ii) Another solution is to use online parameters adaptation on black-box models. The parameters are estimated regardless of the multi-physics fluctuations. Meiler et al. [19] achieved a state of the art of the possible models for online identification of the behavior of a FCS and conclude that the best results are given by the Ursyon model. Yang et al. [20] used a model to emulate the behavior of the FCS and validated the control with an experienced bench.

In our study, the two-step method is used. An identification algorithm is applied to a semi-empirical model of a PEM-FC. Then the identified model is used to optimize the performances (power and efficiency) of the PEM-FC. A semi-empirical model is used because it offers a trade-off between the physical meaning and the calculation cost [21]. The two-step method is chosen to enable, in future works, the identification versus several input parameters (temperature, pressure, and stoichiometry). In this study, only one parameter is optimized (the current of the PEM-FC i_{fc}).

Various studies propose contributions on the topic of online identification coupled with optimization of FCSs in order to find the best performance. Methekar et al. [22] has developed an adaptive control of the FCS with a Wiener model and proposed a numerical validation. Dazi et al. [23] simulated a predictive control to determine the maximum power operation of the FCS. Ramos et al. designated a MPPT control thanks to hardware in the loop [24]. Gene et al. [25] conducted an experiment to validate real-time optimization of a solid oxide FCS. Kelouwani et al. [26] presented an experiment on the pursuit of maximum efficiency of the PEM-FC. The study of Kelouwani et al. is based on a polynomial model of the efficiency of the PEM-FC and seeks the best efficiency by tuning the control variables (current, stoichiometry, temperature).

In summary, there are methods to split the power between two sources in a hybrid system (such as battery and PEM-FC for example) and research methods to determine the best performances of the PEM-FCs. However, it should be noted that there are few EMSs that link the power splitting in a hybrid system and extremum seeking method on PEM-FC. This work is based on a previous experimental study [21], where it has been shown that an identification algorithm which determines the performance (better efficiency and power) of a semi-empirical model of a PEM-FC is adaptable in real time. In another study, an adaptive EMS based on a hysteretic behavior is implemented [27]. Now, the objective of this paper is to present an Adaptive EMS based on Pontryagin's Minimum Principle (A-PMP). The aim of the A-PMP strategy is to reach an optimal power split between the two sources (PEM-FC and battery pack). But besides that, this strategy will take into account the change in maximum power and efficiency, according to the degradation of the PEM-FCs. A specific emphasis is placed on the operating parameter drift by using two PEM-FCs with different levels of degradation. Through this test bench, the maps of two PEM-FCs were obtained in experimentation. One PEM-FC is healthy with approximately 20 h of operation while the second is degraded with approximately 300 h of operation as shown in Figs. 1 and 2. In the following chapters, these maps are employed to validate the developed algorithms.

The rest of the paper is organized as follows. Section 2 presents the architecture of the hybrid system, whereas the three steps EMS is described in Section 3. The experimental results of optimal seeking are presented in Section 4. The validation study is performed in Section 5. The conclusion and perspectives are discussed in Section 6.

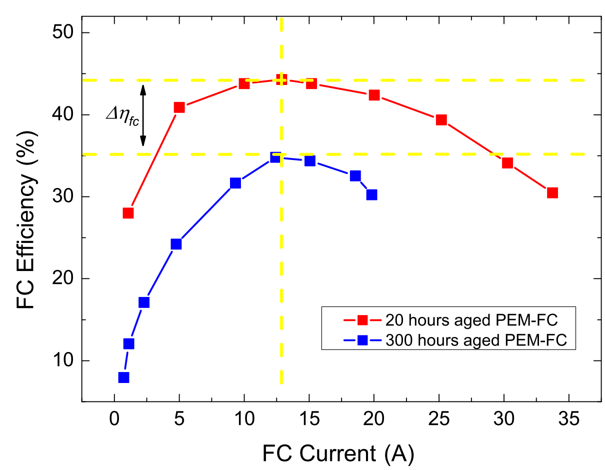

Fig. 1. Efficiency curves for two PEM-FCs with different degrees of degradation at T_{fc} = 35 °C.

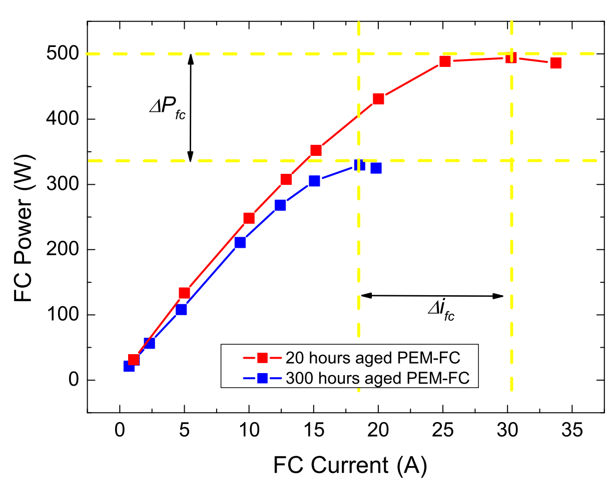

Fig. 2. Power curves for two PEM-FCs with different degrees of degradation at T_{fc} = 35 °C.