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Management of fuel cell power and supercapacitor state-of-charge for electric vehicles

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ABSTRACT

In this paper a power management system (PMS) is designed to achieve, for automotive applications, a control strategy aiming to split the load power between a fuel cell and a supercapacitor accounting for the fuel cell limited dynamics, its rated power and bounded supercapacitor voltage. The power sources are connected to a DC bus through boost and buck-boost converters. The converters are controlled to regulate the Dc bus voltage and the supercapacitor current must track a reference provided by the PMS unit. The fuel cell is the main source and the supercapacitor is the auxiliary one, which recovers power at a braking or a decelerating mode. The supercapacitor current is also controlled in order to keep the state-of-charge (SOC) within accepted bounds. Thus, the fuel cell charges the supercapacitor when the SOC is too low, and, the supercapacitor feeds the power-train, whenever it is overcharged. Meanwhile, the fuel cell dynamics is perfectly controlled during algorithm commutations. Theoretical analysis and results, for a practically validated high-fidelity simulation model, show that the proposed controller and the power management system meet all the objectives.

1. Introduction

Scientists agree on the greenhouse effects of fossil fuels and their depletion is inevitable, that have encouraged researchers and industry to seek clean and sustainable energy sources. Among the promising electric sources is fuel cell because it consumes hydrogen and its byproduct is merely water and heat [1,2]. Even though, a fuel cell (FC) is a source that has relatively low power level. Furthermore, it cannot neither provide power to fast changing loads nor recover braking energy. Therefore, an energy storage system (ESS) is necessary to ensure better performance in hybrid electric vehicles [3]. An ESS can be implemented by a battery or a supercapacitor (SC). In confronting these two storage devices, the supercapacitor charging time is advantageous because it can reach 1–10 s, compared with the new fast lithium-ion battery which can be charged at 70% in few minutes [4]. In addition, the supercapacitor can provide with better performances peak powers, it have a long lifecycle and it's virtually free of maintenance. Therefore, in this work, we consider a supercapacitor bank as an energy storage system.

The use of this technology combining the two sources of energy has an undeniable asset for the following reasons:

- The fuel cell will be employed to meet the average and permanent power demand of the vehicle,
- The supercapacitor, meanwhile, will be used to meet the peak and transient power demand. It also allows energy recovery during braking and deceleration phases.
- As the fuel cell is not used to support rapid load changes, it would avoid the problem of 'fuel starvation' which would cause permanent damage to the proton exchange membrane of the cell [4].

This combination gives an efficient fuel cell hybrid power system because the fuel cell has relatively lower efficiency at low and high output power [5]. Moreover, this hybridization can downsizing the fuel cell then reducing the power system cost because the FC is the most expensive component [6].

In this work, we develop a new power management system based on a multi-loop nonlinear controller for a boost and buck-boost converters connected respectively, to a FC, as a main source, and to a SC as an auxiliary one. The whole control unit is designed

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Nomenclature

c_k, $k=1,2$	Design parameters
C_{dc}	DC link capacitor [F]
δ, λ	Tuning parameter of the power management system
e_k, $k=1,2$	Error between the variable ξ_i and its reference
H_i, $k=1,2$	Binary outputs of the hysteretic blocs
$\bar{i}_1$	Average value of the boost output current (A)
i_k, $k=1,2$	Converters output currents (A)
I_{fcref}	Reference signal of the fuel cell output current (A)
I_{scref}	Reference signal of the supercapacitor current (A)
i_m	Input courant of the inverter (A)
i_o	Load current of the hybrid source (A)
i_{fc}	Fuel cell output current (A)
i_{sc}	Supercapacitor output current (A)
I_{scref}	Reference signal of the supercapacitor current (A)
L_i	Input inductance of the boost converter [H]
L_2	Input inductance of the buck-boost converter [H]
λ_o	Efficiency of the buck-boost converter in the boost mode
λ_u	Efficiency of the buck-boost converter in the buck mode
m	Binary code of the buck-boost converter operating mode
μ_k, $k=1,..3$	Duty cycles of the binary inputs μ_k, $k=1,..3$
μ_{12}	Average value of the common input variable of the buck-boost converter
P_{scref}	Reference signal of the buck-boost output power (W)
P_{sc}	Output power of the buck-boost converter (W)
P_o	Output power of the hybrid DC source (W)
P_{of}	Power management filter output (W)
$P_{fc\,\min}$, $P_{fc\,\max}$	Low and high limits values of the fuel cell output power (W)
θ_h	Design parameter of the high gain observer
R_i	The equivalent series resistance (ESR) of the inductance L_i [Ω]
R_{sc}	Supercapacitor equivalent series resistance (ESR) [Ω]
$\hat{x}$	Estimate value of the variable x
$\tilde{x}$	Estimation error of the variable
$\dot{x}$	Time derivative of the variable x
ξ_1	Average value of supercapacitor current i_{sc} [A]
ξ_2	Average value of the DC link voltage v_{dc} [V]
ξ_3	Average value of the fuel cell current i_{fc} [A]
u_{12}	Common binary input variable of the buck-boost converter
u_k, $k=1,..3$	Binary inputs variables of the converters
v_{dc}	DC link voltage [V]
V_{dcref}	Reference value of the DC link voltage [V]
v_{sc}	Supercacitor output voltage (V)
v_{fc}	Fuek cell output voltage (V)
V_{cth1}	High theoretical limit of the supercapacitor voltage (V)
V_{cth2}	Low theoretical limit of the supercapacitor voltage (V)
$V_{c\,\min}$, $V_{c\,\max}$	Low and high limits values of the supercapacitor voltage (V)
V_i, $k=1,2$	Intermediate variables of the hysteretic blocs (V)
ΔV_i, $k=1,2$	Tuning variables of the supercapacitor voltage nominal (V)
V	Lyapunov functions
V_{cnom}	Nominal value of the supercapacitor voltage (V)
v_c	Supercapacitor voltage defined by $v_c = v_{sc} + R_{sc} i_{sc}$
ω_n, Z	Natural frequency and damping ratio of the power management filter

to meet the four main objectives: (i) a tight regulation of the DC bus voltage; (ii) the SC current must track its reference; (iii). The load power must be split between the two sources accounting for the FC rated power and its low power slope; and (iv) the recovery power at a braking or a decelerating mode must be stored in the supercapacitor whilst the SC voltage must be kept in the feasible bounds.

There is many works which dealing with the subject of energy management in FC/SC hybrid power systems as an optimization problem which can be carried out off-line for a specific driving cycle. A cost function is minimized, satisfying some constraints, aiming, mainly, minimizing hydrogen consumption [1,4,7–9]. The optimization problem can also be solved with a Model Predictive Control (MPC) [10]. In Ref. [11] a linear control strategy is designed based on a sharing of load power between the two sources taking into account the slow dynamics of the fuel cell. In Refs. [12,3] a flatness control strategy accounts for fuel cell output rated power and its slow dynamics, it also allows limiting the current of an SC during charging and discharging processes. The work in Ref. [13] proposes an effective energy management strategy based on the Passivity Based Control (PBC) using Fuzzy Logic estimation. In Ref. [14–16] many controllers are designed based on the Lyapunov approach without considering the dynamics limits of the fuel cell and the supercapacitor SOC constraints.

In this work we consider an on line power management system. It achieves a control strategy aiming the power split between the sources accounting for, the fuel cell slow dynamics, its weak rated power and bounded SC state-of-charge (SOC). The power management algorithm is designed based on a controller developed according the Lyapunov stability tools [17]. The PMS generates a single output which is the SC current reference, whereas the FC current reference is utilized for regulating the DC bus voltage. Therefore, SC delivers the transient load power and recovers braking or decelerating energy in a way that the FC gives power in steady states with limited dynamics and rated power. Furthermore, the control algorithm maintains the SC voltage within accepted bounds. When the supercapacitor is overloaded, it provides some of the energy required by the load in the steady state. In addition, when the SC state- of-charge becomes critical, it receives energy from the fuel cell. In both latter SOC cases the PMS allows bring the voltage of the supercapacitor to its nominal value, and the dynamics of the FC is perfectly controlled during algorithm commutations.

Compared to the existing literature, the present contribution contains several novelties, among which the following.

a) A power management system is designed based on Lyapunov controllers for the first time, whereas in the existing literature using this kind of controllers, the fuel cell dynamics is not accounted for Refs. [14–16].
b) The SC voltage limitation algorithm accounts for FC slow dynamics in order to avoid discontinuities and fast changes in the fuel cell output power, even if the SC state-of-charge is out of bounds. That is, in the previous studies [3,11,12,17], the fuel cell constraints are only treated in the normal case of the supercapacitor SOC.
c) Compared with the previous works [14–16] the closed loop system is of second order which leads to less complicated control lows.