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A Specification Independent Control Strategy for Simultaneous Optimization of Fuel Cell Hybrid Vehicles Design and Energy Management

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Abstract: The present work proposes an in-deep analysis of a heuristic control strategy, developed in such a way as to enhance model-based design of fuel cell hybrid electric vehicles (FCHEVs). Particularly, suited normalization and denormalization techniques are proposed, so as to adapt optimized control rules to a number of FCHEV powertrains, ranging from low to high degree of hybridization. A scenario analysis was conducted to verify the effectiveness of proposed powertrain-adaptable control strategies, thus revealing their high potential, both to reduce the off-line development phase, as well as to enable simultaneous preliminary optimization of FCHEV powertrain sizing and real-time energy management.

Keywords: Fuel Cells, Fuel Cell Vehicles, Hybrid Vehicles, Energy Management, Specification Independency, Model-based Design, Optimization.

1. INTRODUCTION

Light duties vehicles impact for about 16% (Environmental Protection Agency, 2014) on global CO2 emissions. The associated growing number of environmental problems has made the sustainable transportation paradigm become an increasingly popular solution, thanks to the favorable characteristics of high efficiency and low (or zero) emissions (Onat et al., 2015; Katrasnik, 2013). Particularly, the concepts of electrification and hybridization of cars are nowadays recognized as those to be pursued as soon as possible. If until some months ago such a need appeared not to be so stringent, the recent events, involving traditional cars emission levels, together with the well-known progressive reduction of fossil fuels reserves, caused it to suddenly become more severe. Therefore, main OEMs are now switching from a medium-term development outlook towards a short term one.

When comparing all existing XEV powertrains, hydrogen-fueled vehicles (either FCEVs or FCHEVs) have more advantages over thermal hybrid vehicles (i.e. hybrid electric vehicles-HEVs), such as high fuel-economy (km/kg), related to the use of fuel with higher energy density, high efficiency and reduced environmental impact from a tank-to-wheel point of view. On the other hand, purely electric technology (i.e. electric vehicles-EVs) presents inferior autonomy and performance with respect to FCHEV cars, due to the current technological limits of batteries, and may determine troublesome on electrical grid infrastructure (Sorrentino et al., 2013). Nevertheless, FCHEV technology has not yet had significant market developments, mainly due to the currently very expensive hydrogen production, as well as the absence of distribution and refueling infrastructures that will ensure the dissemination and distribution in a large scale. To tackle the above constraints, governmental and research institutions are now increasing the cooperation with main OEMs, as demonstrated by the increasing awareness of EU funding bodies towards the high potential offered by FCHEV-based hybridization, even in a short-term prospective (The Fuel Cells and Hydrogen Joint Undertaking, 2015).

Moreover, recent proposals of major automakers (Toyota and Honda) show that hydrogen technology is overall ready to start a minimal competition to alternative sustainable mobility (Greene et al., 2013). It is therefore important to focus on increasing the competitiveness of such vehicles in terms of fuel economy, thus overcoming the transitional problems related to hydrogen.

In this context the development of mathematical tools, which can potentially integrate in one single process the optimization of powertrain design and subsequent definition of real-time effective and applicable control strategies, can definitely contribute to speeding-up technological growth of XEVs (Hu and Wu, 2013), and particularly of FCHEVs (The Fuel Cells and Hydrogen Joint Undertaking, 2015). Moreover, the definition of development procedures, which are versatile enough to be deployed on FCHEV powertrains with different degree of hybridization, are nowadays considered as a key factor to promote market penetration of hydrogen fueled cars (European Commission, 2015). To achieve this scope, in the current work the physical meaning of a rule-based control strategy (Sorrentino et al., 2011) is deeply analyzed, with the final aim of extending its applicability to a variety of powertrains, by means of suitable normalization/denormalization techniques. Indeed, such versatile and multi-purpose tools, based on extensive use of normalized models (Sorrentino et al., 2015) and maps, can provide substantial contributions toward a greener transportation paradigm in many research fields (Agbli et al., 2016).

The article is organized as follows: first the basic equations, here utilized to assess mass impact of vehicle hybridization, as well as related traction power demand and hydrogen

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consumption, are briefly recalled. Afterwards, the heuristic control strategy is described, followed by a detailed physical analysis of best rules, as addressed by a model-based optimization analysis run on several hybridization degree values. The normalization and denormalization techniques are then proposed and verified via suitable scenario analyses.

2. MATHEMATICAL MODELS OF THE TOOL

2.1 Mass model

A parametric model was used to assess the impact of hybridization on vehicle mass. By referring to the vehicle architecture shown in Fig. 1, the mass of an FCHEV (M_{FCHEV}) can be obtained by adding the mass of major hybridizing devices to the vehicle body mass (M_{body}). This latter is derived from the mass of the reference conventional vehicle (M_{CV}) by subtracting the contributions due to the original gear box, as follows:

$$M_{body} = M_{CV} - P^*_{ICE,CV} \cdot (m_{ICE} + m_{GB}) \quad (1)$$

Then, vehicle mass can be determined adding the hybridization devices and by imposing that the HFCV power to weight ratio (i.e. ρ_{PtW}) equals conventional vehicle (CV) one, thus ensuring HFCV guarantees the same CV acceleration performance:

$$M_{FCHEV} = M_{body} + P^*_{FC} \cdot m_{FC} + P^*_{EM} \cdot m_{EM} + M_{BC} \cdot N_{BC} + M_{HT} \quad (2)$$

where the last term represents hydrogen tank mass.

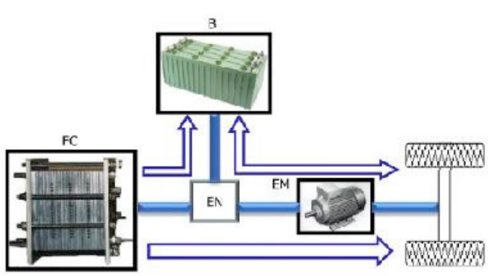

Fig. 1. Fuel cell powertrain schematic (Series architecture).

The number of battery cells (N_{Bc}) is determined by knowing the rated power of the electric motor EM (P_{EM}*) and FC system (P_{FC}*), as well as the power of a single battery cell (P_{Bc}*), assumed hereinafter constantly equal to 1.25 kW (Nelson et al. 2007):

$$Nc = \frac{P^*_{EM} - P^*_{FC}}{P^*_{Bc}} \quad (3)$$

$$M_{HFCV} = \frac{P^*_{EM}}{\rho_{PtW}} = \frac{P^*_{EM}}{\frac{P^*_{ICE,CV}}{M_{CV}}} \quad (4)$$

Table 1 lists the unit mass here assumed for each powertrain component. It is worth remarking that P* variables refer to generic component rated power.

Table 1 Components unit mass (Thomas et al., 1998 - Klell, 2010).

m_{ICE} = internal combustion engine (kg kW^{-1})	2
m_{GB} = gear box (kg kW^{-1})	0.478
m_{EM} = electric motor (including inverter) (kg kW^{-1})	1
m_{FC} = PEM fuel cell system (kg kW^{-1})	3.7
M_{HT} = hydrogen tank (kg kW^{-1})	1.9
M_{BC} = single cell battery mass (kg cell^{-1})	4.67

2.2 Longitudinal vehicle model

Fuel economies in this paper are evaluated by means of a backward longitudinal vehicle model, whose basic equations are presented below. Traction power is estimated as:

$$P_{tr} = M_{HFCV} \cdot g \cdot v \cdot [C_r \cdot \cos(\alpha) + \sin(\alpha)] + 0.5 \cdot \rho \cdot C_x \cdot A \cdot v^3 + M_{eff} \cdot \frac{dv}{dt} \cdot v \quad (5)$$

where α and ρ are the road grade and air density, respectively, while M_{eff} equals 1.1 M_{HFCV} to suitably account for rotational inertia. For non-negative P_{tr} values, the mechanical power to be supplied by the EM is (see Fig. 1):

$$P_{EM} = \frac{P_{tr}}{\eta_{tr}} \qquad \text{if } P_{tr} \geq 0 \quad (6)$$

P_{EM} can also be expressed as a function of fuel cell system and battery power, as follows:

$$P_{EM} = \eta_{EM} \cdot (P_{FC} + P_B) \qquad \text{if } P_{tr} \geq 0 \quad (7)$$

where the η variables correspond to efficiency terms. On the other hand, when $P_{tr} < 0$, the regenerative braking mode is active, resulting in the following expression for the electrical energy delivered by the EM:

$$P_{EM} = \eta_{tr} \cdot \eta_{EM} \cdot P_{tr} \qquad \text{if } P_{tr} < 0 \quad (8)$$

During regenerative braking, battery can be charged by the fuel cell system, thus the following equation holds for negative P_{tr} values:

$$P_B = P_{EM} - P_{FC} \qquad \text{if } P_{tr} < 0 \quad (9)$$

It is worth remarking here that electric motor efficiency is computed by means of normalized maps derived from the model library proposed in (Rousseau et al., 2004). Instead, fuel cell system efficiency is computed by means of the following relationship, obtained by curve fitting experimental data acquired on a dedicated fuel test-bench available at the energy and Propulsion laboratory at University of Salerno (Sorrentino et al., 2013).

$$\eta_{FC} = \frac{p_1 \cdot P_{FC} + p_2}{q_1 \cdot P_{FC}^2 + q_2 \cdot P_{FC} + q_3} \quad (10)$$

3. HEURISTIC CONTROL STRATEGY

3.1 Best rules definition via optimization analysis

This section discusses in detail the two heuristic rules proposed in (Sorrentino et al., 2011) and then extended to fuel cell vehicles in (Sorrentino et al., 2013). The optimal values of electric power supplied by FC (i.e. $P_{FCsupply}$) and