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# Sizing for fuel cell/supercapacitor hybrid vehicles based on stochastic driving cycles

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## HIGHLIGHTS

- A sizing procedure based on the fulfilment of real driving conditions is proposed.
- A methodology to generate long-term stochastic driving cycles is proposed.
- A parametric optimization of the real-time EMS is conducted.
- A trade-off design is adopted from a Pareto front.
- A comparison with optimal consumption via Dynamic Programming is performed.

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ABSTRACT

In this article, a methodology for the sizing and analysis of fuel cell/supercapacitor hybrid vehicles is presented. The proposed sizing methodology is based on the fulfilment of power requirements, including sustained speed tests and stochastic driving cycles. The procedure to generate driving cycles is also presented in this paper. The sizing algorithm explicitly accounts for the Equivalent Consumption Minimization Strategy (ECMS). The performance is compared with optimal consumption, which is found using an off-line strategy via Dynamic Programming. The sizing methodology provides guidance for sizing the fuel cell and the supercapacitor number. The results also include analysis on oversizing the fuel cell and varying the parameters of the energy management strategy. The simulation results highlight the importance of integrating sizing and energy management into fuel cell hybrid vehicles.


## 1. Introduction

Fuel cell/supercapacitor hybrid vehicles are a promising alternative for efficient and clean propulsion. This type of hybrid vehicles exploits the advantages of both Polymer Electrolyte Membrane Fuel Cells (FCs) and supercapacitors. FCs have several advantages, including high efficiency, low-temperature operation, and are clean functioning (the only by-products are heat and water). These characteristics make FCs an excellent option for vehicles, mainly in urban environments where the problem of air pollution is more severe. However, the dynamics of FCs are relatively slow, primarily because of the dynamics of the air compressor and manifold-filling dynamics [1]. Alternatively, supercapacitors are able to store energy with high specific power but low specific energy. The presence of an Energy Storage System (ESS) in the hybrid topology provides a helpful way to operate the powertrain efficiently because the power generation may be decoupled from the load. This means that the fuel cell can be used at a more convenient point of operation, while the supercapacitors absorb or supply the remaining power to meet power requirements. The fuel cell operating point is determined by the Energy Management Strategy (EMS).

Several approaches are reported in the literature for sizing and energy management in fuel cell hybrid vehicles (FCHV). However, most of them address these issues separately despite the deep interrelationship between them. In [2], an integrated optimization approach for component sizing and energy management is presented. However, the EMS that was employed is a rule-based strategy. With regard to sizing, some approaches are oriented to optimize design parameters based on standard driving cycles. Although standard driving cycles are extremely important for evaluating the performance of FCHVs, it is necessary that the design ensures the fulfilment of specific drivability requirements.

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## Nomenclature

*Greek letters*

| | |
|---|---|
| $\alpha$ | road slope [%] |
| $\alpha_s$ | road slope in Test 2 [%] |
| $\gamma_{FC}$ | weight-to-power ratio of the fuel cell [kg kW$^{-1}$] |
| $\Delta P_{FC,min}$ | minimum fuel cell fall rate [W s$^{-1}$] |
| $\Delta P_{FC,max}$ | maximum fuel cell rise rate [W s$^{-1}$] |
| $\Delta t$ | sampling time [s] |
| $\delta_{v_t}$ | tolerance band |
| $\eta_B$ | efficiency of the boost converter [–] |
| $\eta_{B/B}$ | efficiency of the buck/boost converter [–] |
| $\eta_{GB}$ | efficiency of the gear box [–] |
| $\eta_{g,FC}$ | global efficiency of the FC [–] |
| $\eta_{g,Prop}$ | global efficiency of the propulsion system [–] |
| $\eta_{SC}$ | efficiency of the supercapacitor bank [–] |
| $\eta_{FC}$ | efficiency of the fuel cell [–] |
| $\eta_{inv}$ | efficiency of the inverter [–] |
| $\eta_m$ | efficiency of the electric motor [–] |
| $\rho$ | air density [kg m$^{-3}$] |

*Upper cases*

| | |
|---|---|
| AR | Artemis Road driving cycle |
| AU | Artemis Urban driving cycle |
| AC | alternating current |
| $A_F$ | frontal area of the vehicle [m$^2$] |
| $Br/H_2$ | braking/hydrogen ratio [%] |
| $C_{AD}$ | aerodynamic drag coefficient of the vehicle [–] |
| $C_v$ | speed compliance [%] |
| $C_{v_t}$ | speed compliance target [%] |
| CDC | Combined Driving Cycle |
| $C_{H_2}$ | hydrogen consumption [g s$^{-1}$] |
| $C_{RR}$ | rolling resistance coefficient [–] |
| DC | direct current |
| $E_{SC,max}$ | capacity of the supercapacitor modules [Wh kg$^{-1}$] |
| ECMS | Equivalent Consumption Minimization Strategy |
| EMS | Energy Management Strategy |
| ESS | Energy Storage System |
| FCHV | Fuel Cell Hybrid Vehicle |
| $H_2$ | hydrogen |
| $H_{2,cons}$ | normalize hydrogen consumption [g km$^{-1}$] |
| HEV | Hybrid Electric Vehicle |
| HWFET | Highway Fuel Economy Test driving cycle |
| $L$ | length of the driving cycle [–] |
| $LHV_{H_2}$ | Lower Heating Value of hydrogen |
| $N_{SC}$ | number of supercapacitor modules [–] |
| $N_{SC,max}$ | maximum number of supercapacitor modules [–] |
| $N_{SC,min}$ | minimum number of supercapacitor modules [–] |
| MT | microtrip |
| MI | microidle |
| $N_{ms}$ | number of missed-speeds [–] |
| $P_{AD}$ | power to overcome the air resistance [W] |
| $P_{acc}$ | power required to accelerate [W] |
| $P_{FC}$ | fuel cell power [W] |
| $P_{FC,i}$ | fuel cell power in Test $i$ [W] |
| $P_{FC,max}$ | fuel cell maximum power [W] |
| $P_{FC,min}$ | fuel cell minimum power [W] |
| $P_{FC,ref}$ | reference for the fuel cell power [W] |
| $P_g$ | power required to climb a slope [W] |
| $P_{load}$ | power consumed by the load [W] |
| $P_{req}$ | power required to the powertrain [W] |
| $P_{roll}$ | power required to overcome the rolling resistance [W] |
| $P_{SC,lim}$ | power limit of the supercapacitor bank [W] |
| SC | supercapacitor |
| SDC | Stochastic Driving Cycle |
| SOC | state of charge of the supercapacitor bank [–] |
| $SOC_{ref}$ | reference SOC [–] |
| $SOC_{max}$ | maximum SOC [–] |
| $SOC_{min}$ | minimum SOC [–] |
| UDDS | Urban Dynamometer Driving Cycle |
| $V_{SC,min}$ | SC minimum voltage [V] |
| $V_{SC,max}$ | SC maximum voltage [V] |
| $V_{SC,oc}$ | SC open circuit voltage [V] |

*Lower cases*

| | |
|---|---|
| $a$ | acceleration of the vehicle [m s$^{-2}$] |
| $a_i$ | polynomial coefficients |
| $b_i$ | polynomial coefficients |
| $c_i$ | polynomial coefficients |
| $g$ | gravity acceleration [m s$^{-2}$] |
| $k_s$ | scale variable [–] |
| $m_c$ | cargo mass [kg] |
| $m_{v,b}$ | base mass of the vehicle (without including the fuel cell or the SC mass) [kg] |
| $m_v$ | total vehicle mass [kg] |
| $m_{FC}$ | mass of the fuel cell [kg] |
| $m_{SC}$ | mass of a supercapacitor module [kg] |
| $v$ | speed of the vehicle [km h$^{-1}$] |
| $s_i$ | parameter in ECMS [–] |
| $v_{si}$ | sustained speed in Test $i$ [km h$^{-1}$] |
| u | control input vector |

Moreover, some sizing approaches are based on drivability requirements [3,4]. These methods are robust and compatible with industry requirements. In contrast, other approaches propose methodologies where a minimization problem is solved. For example, in some studies [5,6], component sizing is determined within a feasible region based on Pontryagin's minimum principle. Other works address a multi-objective optimization problem, obtaining a quasi-optimal solution [7–9]. Optimization with multi-objective genetic algorithms can also be used [10], while convex programming has been applied successfully in some works concerning sizing and energy management [11,12].

The energy management can be divided into two classes: heuristic and optimization approaches [13]. EMS for fuel cell-based hybrid electric vehicles (HEVs) in combination with a battery and/or supercapacitors has been reviewed [14]. An important conclusion was that the combination of the fast transient response of supercapacitors and the slow transient response of fuel cells is an attractive alternative for improving the efficiency and performance of HEVs. The optimization approach based on the Equivalent Consumption Minimization Strategy (ECMS) has important advantages, that allow it be used in real-time [15–17].

Previous studies have used other optimization techniques. Model predictive control oriented towards energy management has been used [18]. In [19], a stochastic self-optimizing power management strategy for a fuel cell/battery-powered hybrid electric scooter is proposed. In [20], an improved dynamic programming approach is presented, where several look-up tables are constructed to permit online operation. Alternately, approaches based on rules or heuristics can be more appropriate for real-time application [21–26]. Fuzzy logic is another heuristic approach used in some works [27–29].

From the literature, despite the many existing approaches, the sizing issue is generally addressed, assuming some critical considerations in view of real applications. These assumptions include