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Design and Modelling of the Powertrain of a Hybrid Fuel Cell Electric Vehicle

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Abstract

This paper presents a Fuel Cell Electric Vehicle (FCEV) powertrain development and optimization, aiming to minimize hydrogen consumption. The vehicle is a prototype that run at the Shell Eco-marathon race and its powertrain is composed by a PEM fuel cell, supercapacitors and a DC electric motor. The supercapacitors serve as an energy buffer to satisfy the load peaks requested by the electric motor, allowing a smoother (and closer to a stationary application) working condition for the fuel cell. Thus, the fuel cell can achieve higher efficiency rates and the fuel consumption is minimized.

Several models of the powertrain were developed using MATLAB-Simulink and then experimentally validated in laboratory and on the track. The proposed models allow to evaluate two main arrangements between fuel cell and supercapacitors: 1) through a DC/DC converter that sets the FC current to a desired value; 2) using a direct parallel connection between fuel cell and supercapacitors.

The results obtained with the direct parallel connection (with the appropriate sizing of the overall capacity) have highlighted a significant efficiency advantage, while the DC/DC converter insertion enables an improved control of the fuel cell current and requires a smaller capacitance.

Furthermore, a sizing methodology for the supercapacitors capacitance is proposed for both layouts: with the DC/DC converter it mainly depends on the energy range provided by supercapacitors to the electric motor, while in the direct parallel connection the supercapacitors sizing is outlined by concurrently evaluating the circuit's predicted hydrogen consumption and granting the most suitable conditions to increase the fuel cell performance.

Finally, the results obtained from the model were validated by comparing them with experimental data obtained in the laboratory and on the track.

Introduction

According to data from the International Energy Agency, the transport sector accounts for 29% of total energy consumption and 24.6 % of total CO_2 emissions [1, 2]. The global transport system has doubled CO_2 emissions in the last 30 years so this requires a strong cut in emissions in order to fight the irreversible climate change [3]. For these

reasons, in order to reduce the impact of the transport sector on the environment, it is necessary to use alternative fuels.

Therefore, in order to decarbonise the transport system through a long-term strategy, it is necessary both to reduce vehicle total mass with lightweight techniques [4, 5] and improve aerodynamic drag [6, 7, 8] and use low-carbon fuels with highly efficient powertrain [9, 10, 11, 12, 13]. So as regards the ICEs the choice falls on biofuels and as regards electric vehicles there are various options.

ICE: the main biofuels used within the ICEs are bioethanol and bio-diesel which lead to a reduction in CO_2 emissions, greater independence from oil-producing countries and in many cases also a more rational use of arable land [14];

MHEV: A mild hybrid system refers to a system consisting of a reversible electric machine that recovers energy under braking and in certain driving phases supplies the thermal engine with additional power.

HEV: A hybrid system has a larger battery compared to a MHEV that allows you to travel short electric distances with limitations regarding power and speed [13].

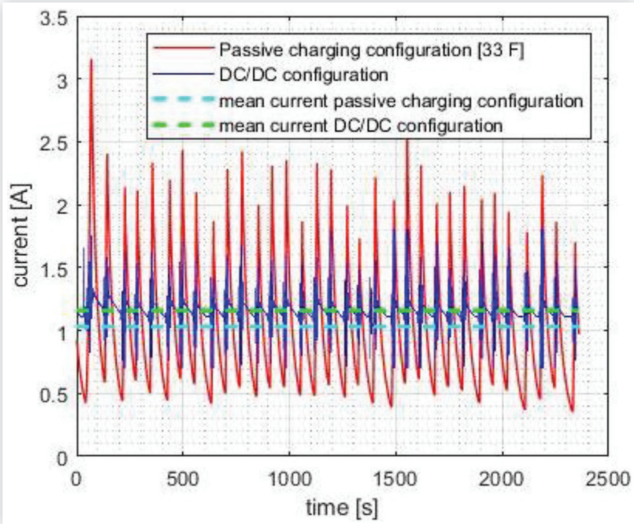
PHEV: Compared to HEV, this system has a larger battery that allows greater autonomy and the possibility of recharging through the power socket and regenerative braking.

BEV: it has the absence of an internal combustion engine and therefore always has zero emissions in each work cycle with autonomy varying according to the capacity of the battery pack.

FCEV: It incorporate a fuel cell that powers an electric motor, sometimes in combination with battery and supercapacitors (HFCEV).

The FCEVs therefore have intermediate characteristics compared to the BEV and ICE vehicles, and therefore represent one of the most interesting proposals for future mobility for a series of reasons:

FIGURE 28 Comparison experimental data: passive charging vs DC/DC configuration



FC provides the base load while the supercapacitors ensure the compensation of the peaks required by the motor. The power curve of the supercapacitors reaches negative values during the coast down phase, which therefore represents a charging phase, being the power required by the load lower than the average power supplied by the FC.

By analysing Figure 28, it can be seen how the DC/DC configuration is able to guarantee lower oscillations compared to the passive charging configuration but the average value of the current is higher than that of passive charging and therefore the consumption of hydrogen will be higher.

Conclusions

This paper presents different possible configurations for the powertrain of an FCEV and it analyses in detail, using a simulation model, the sizing criteria for supercapacitors and the optimization processes. The models were validated through experimental tests in the laboratory and on the track.

During these tests it was noted how the use of supercapacitors represents a suitable solution for all the applications where a variable load is required. Specifically, the configuration with the DC/DC converter guarantees greater control while the "passive charging" configuration guarantees greater efficiency.

It was also analysed how the passive charging configuration requires an oversizing of the supercapacitor capacitance in order to maximize efficiency and reduce current oscillations. This oversizing consequently leads to an increase in weight, it will therefore be necessary to trade-off between the increase in efficiency and the greater losses due to vehicle dynamics.

These models are useful in order to quantify the hydrogen consumption for the different configurations. It is possible to study which configuration is the more suitable for a particular application, and so they can be useful in the design phases of the powertrain of a FCEV, another possible application concerns road vehicles. By including this model into an integrated model of the vehicle (which then considers the dynamics of the vehicle, the motor and its driver) it allows for calculating the consumption of a specific route. This could allow, for example, for self-driving vehicles to choose the route with the lowest consumption. Therefore, with a view to sustainable development and reduction of emissions, the FCEVs represent an excellent solution.

Future developments on this paper will focus mainly on the development of tests on the track regarding the "passive charging configuration" and the in-depth tests performed with the bank of supercapacitors with higher capacitance.

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Definitions/Abbreviations

FCEV - Fuel Cell Electric Vehicle
PEM - Proton-exchange membrane.
ICE - Internal Combustion Engine
MHEV - Mild Hybrid Electric Vehicle
HEV - Hybrid Electric Vehicle
PHEV - Plug-in Hybrid Electric Vehicle
BEV - Battery Electric Vehicle
FC - Fuel Cell
SC - Supercapacitor
DOH - Degree of hybridization
EDLC - Electric double-layer capacitors
LIC - Lithium-ion supercapacitor
MOSFET - Metal Oxide Semiconductor Field Effect Transistor

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