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An Evaluation Study of Current and Future Fuel Cell Hybrid Electric Vehicles Powertrains

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Abstract

The powertrain control strategy and component sizing can significantly influence the vehicle performance, cost and fuel economy. This paper presents an evaluation study of the current and future Fuel Cell Hybrid Vehicles (FCHEVs) powertrains from the point of view of the fuel economy, volume, mass and cost. In this research, different FCHEV powertrains (such as Fuel Cell/Supercapacitor (FC/SC), Fuel Cell/Battery (FC/B), and FC/SC/B) and different control strategies are designed and simulated by using Matlab/Simulink. In this paper, two standard driving cycles (NEDC and FTP75) are used to evaluate the fuel consumption. Within this study, two control strategies based on the knowledge of the fuel cell efficiency map are implemented to minimize the hydrogen consumption of the FCHEV powertrains. These control strategies are control strategy based on Efficiency Map (CSEM) and control strategy based on Particle Swarm Optimization (CSPSO). Furthermore, a comparative study of different FCHEV powertrains is provided for adequately selecting of the proper FCHEV powertrain, which could be used in industrial applications.

Keywords: Fuel cell Hybrid Electric Vehicle (FCHEV), Powertrain Modeling, Particle Swarm Optimization (PSO), Control Strategy, Efficiency Map Control, Fuel Economy

1 Introduction

In recent decades, Fuel Cell (FC) technologies are expected to become a viable solution for vehicular applications because they use alternative fuel converters and are environment friendly. Although there are various FC technologies available for the use in vehicular systems, the proton exchange membrane FC (PEMFC) has been found to be a good candidate, since PEMFC has high power density with lower operating temperatures when compared to the other FC systems [1]-[4]. A stand-alone FC system integrated into an automotive powertrain is not always sufficient to satisfy the load demands of a vehicle. Although FC systems exhibit good power capability during steady-state operation, the response of fuel cells during transient and instantaneous peak power demands is relatively poor. Consequently, the high cost and slow dynamics of the FC systems are the major challenges for the commercialization of fuel cell electric vehicles (FCEVs).

To overcome these challenges, the FC system should be hybridized with single or multiple energy storage systems (ESS) (such as battery and supercapacitor) to meet the total power demand of a hybrid electric vehicle (HEV) and to improve the efficiency [5], [7], [8], [9]. In the last decades, many research studies in the power distribution strategy of hybrid vehicles and sizing have been done. Some control algorithms, based on a priori knowledge of a scheduled driving cycle, have been proposed to achieve fairly fuel economy with minimum cost [3]-[9]. For example, in [6], [7], the power management and the design optimization of FC / battery HEV were obtained by using dynamic programming (DP). However, this methodology did not consider the variation of the battery parameters in function of the state of charge (SoC).

Furthermore, the DP can achieve the minimum value, but it has many drawbacks such as high computational load and high memory storage capacity. In [7], [8], [9], PSO algorithm was proposed to achieve the optimal design and power flow of FC/battery and FC/supercapacitor hybrid electric vehicles.

The main objective of this paper is to give an evaluation study of different FCHEV powertrains from the point of view of the fuel economy, cost and powertrain component sizing. In addition, the FCHEV powertrains are designed and simulated by using Matlab/Simulink over different driving cycles (such as NEDC and FTP75). CSPSO and CSEM control strategies are utilized to minimize the fuel consumption. This paper is organized as follows: Section II presents the FCHEV powertrains description. The modeling of the vehicle, the dynamic modeling of a PEMFC, the dynamic modeling of the battery system and the dynamic modeling of the SC are described in section III. The control strategies (CSPSO and CSEM) are illustrated in section IV. Simulation results are presented in Section V. Section VI is the conclusion.

2 FCHEV Powertrains

The investigation of different FCHEV powertrains (i.e., FC/B, FC/SC, and FC/B/SC) is explained in detail. In this paper, an interleaved Multiple-input power electronics converter (IMIPEC) is used to connect multiple sources with common dc-link in order to reduce the size of the passive components of the DC/DC converter and to reduce the input/output ripples. The IMIPEC can improve the efficiency of the DC/DC converter, which is used in vehicle powertrain especially at low load. In the IMIPEC, the FC is connected to DC-link via a three-phase interleaved boost DC/DC port ($\eta_B = \eta_{conv}$), while the battery and SC are connected to DC-link through bidirectional three-phase interleaved DC/DC ports ($\eta_{B/B} = \eta_{conv}$). In this study, the desired value of the DC-link voltage is selected to be 500 V with variations of ± 5% are permissible.

The power supplied by the powertrain has to be obtaining from the power demand predicted by the dynamics of the vehicle. The efficiency of each component in the FCHEV powertrain is considered in this study. The detailed models of the powertrain are developed by using Matlab /Simulink. Figure 1, Fig. 2 and Fig. 3 illustrate the block diagrams of the FC/B powertrain, FC/SC powertrain and FC/B/SC powertrain, respectively.

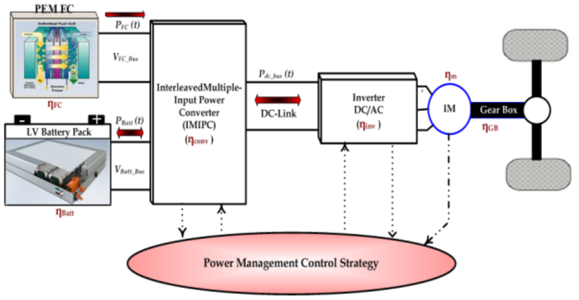


Figure 1: Block Diagram of FC/Battery HEV powertrain

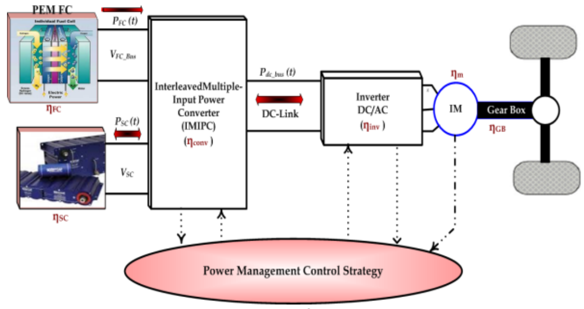


Figure 2: Block Diagram of FC/SC HEV powertrain

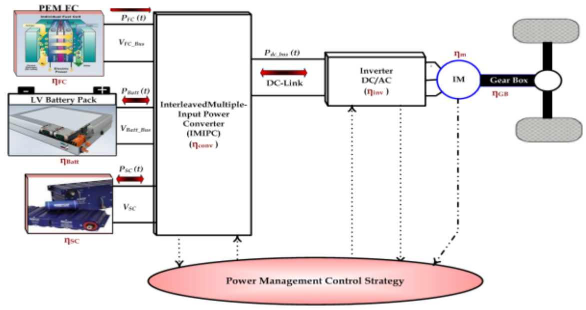


Figure 3: Block Diagram of FC/B/SC HEV powertrain

3 Powertrain Modeling

3.1 Modeling of the vehicle power demand

The load force of the vehicle comprises gravitational force (F_g), rolling resistance (F_{roll}), aerodynamic drag force (F_{AD}) and acceleration force (F_{acc}), as shown in Fig.4. Hereby, the required load power for vehicle acceleration can be written as follows:

$$P_{load} = \frac{(F_g + F_{roll} + F_{AD} + F_{acc})\,V}{\eta_{GB}} \quad (1)$$

Where

$$\begin{aligned} F_g &= M.g.\sin(\alpha) \\ F_{roll} &= M.g.\, f_r.\cos(\alpha) \\ F_{AD} &= 0.5\rho_a.C_D.A_F.V^2 \\ F_{acc} &= M.\frac{dV}{dt} \end{aligned} \quad (2)$$

$V = \omega_w . r_w$

The total electric power required from the sources is given by

$$P_{req} = \frac{P_{load}}{\eta_m . \eta_{Inv} . \eta_{conv}} \quad (3)$$

The parameters of the vehicle are reported in Table 1. The analysis of FCHEV powertrains is performed on two standard driving cycles (such as *NEDC* and *FTP75*) in order to evaluate their performance. In this paper, suppose that the average efficiencies of the gearbox (η_{GB}), the motor (η_m), inverter (η_{Inv}), and DC/DC converter ($\eta_{Conv}= \eta_B= \eta_{B/B}$) are 0.90, 0.95, 0.94 and 0.95, respectively.

Table 1: The vehicle parameters [5], [8],[9]

M	Vehicle mass (kg)	1450
f_r	Rolling Resistance Coefficient	0.013
C_D	Aerodynamic Drag Coefficient (C_D)	0.29
A_f	Front Area (m^2)	2.13
r_w	Radius of the wheel (m)	0.28
ρ_a	Air density (kg/m^3)	1.202

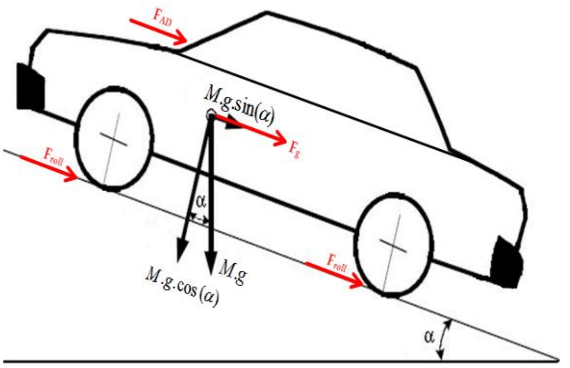


Figure 4: Forces acting on a vehicle

3.2 Dynamic Modeling of a PEMFC

The electrical model of the PEMFC system predicts the output voltage and the partial pressures of hydrogen and oxygen in the FC stack at a certain electric current. The voltage signal is fed to a control voltage source in Matlab/simulation. In this study, FC system comprises a FC stack with N_{fcs} cells that are connected in series, and N_{fcp} strings that are connected in parallel. The output voltage of the FC stack can be calculated as follows [3], [7], [9]:

$$V_{fc} = E + \eta_{act} + \eta_{ohmic} \quad (4)$$

where

$$\eta_{act} = -B \ln(CI_{fc}) \quad (5)$$

$$\eta_{ohmic} = -R^{int} I_{fc} \quad (6)$$

$$E = N_{fcs} \left[E_0 + \frac{RT}{2F} \log\left[\frac{p_{H2}\sqrt{p_{O2}}}{p_{H2O}}\right]\right] \quad (7)$$

The Matlab/Simulink-based PEMFC system is modeled in this paper using the aforementioned equations. The specifications of the PEMFC system are mentioned in Appendix A.

3.3 Dynamic Modeling of an ELDC

The natural structure of the supercapacitor (SC) is appropriate to meet the transient and instantaneous peak power demands. The SC is also known as electrochemical double layer capacitors (ELDCs). The simulated ELDC is a Maxwell PC2500 whose characteristics are reported in Appendix A. The ELDC Module consists of N_{scs} cells that are connected in series and N_{scp} strings that are connected in parallel. The output voltage of the ELDC can be expressed as follows [3], [7], [9]:

$$V_{SCcell} = i_{cell} . R_s + v_C \quad (8)$$

where

$$v_C = \frac{1}{C}\int i_C(t)dt + v_C(t=0) \quad (9)$$

$$i_C = i_{Cell} + \frac{i_C}{R_P} \quad (10)$$

$$SoCsc = \left(\frac{v_C}{V_{cell,max}}\right)^2 . 100 \quad (11)$$

$$v_C(t=0) = V_{cell,max} . \sqrt{\frac{SoCsc0}{100}} \quad (12)$$

3.4 Dynamic Modeling of Li-Ion Battery

In this section, the mathematical modeling of the Li-Ion battery package used in the simulation program is defined as a Thevenin battery model. In this study, all elements are functions of the battery state of charge ($SoCb$). The battery system comprises a package with N_{batts} cells that are connected in series and N_{battp} that are connected in parallel. The terminal voltage of the battery pack V_{batt} can be denoted as follows [8], [9]:

$$V_{batt} = N_{batts} \left[V_{oc} + I_{batt} R_{sb} - V_{cp} \right] \quad (13)$$

$$SoCb = SoCb_{init} + \frac{1}{3600}\int \frac{I_{batt}}{C_b} dt \quad (14)$$

Where:

$$I_{batt} = \frac{I_{Load}}{N_{battp}} \quad (15)$$

$$\frac{dV_{cp}}{dt} = -\frac{V_{cp}}{C_p R_p} + \frac{I_{batt}}{C_p} \quad (16)$$

4 Power Control Strategies

4.1 Control Strategy Based on Efficiency Map (CSEM)

This control strategy is applied to minimize the hydrogen consumption for each driving cycle. Therefore, the simulations are performed for each driving cycle in such a way that the FC works alternately in two operating points, namely “On” and “Off”, according to the actual state of charge of the energy storage system (ESS) ($SoC_{ESS}(k)$). These operating points are given as follows [3], [7], [8]:

1- When $SoC_{ESS}(k) < SoC_{init}$, the FC is operated at its point of maximum efficiency (called “On” point), and

2- When $SoC_{ESS}(k) > SoC_{init}$, the FC is turned off (called “Off” point).

Where SoC_{init} represents the initial state of charge, where $SoC_{ESS}(k)$ is the actual SoC of the ESS. Figure 5 shows the CSEM control scheme with the FC operation to perform the operation of the system.

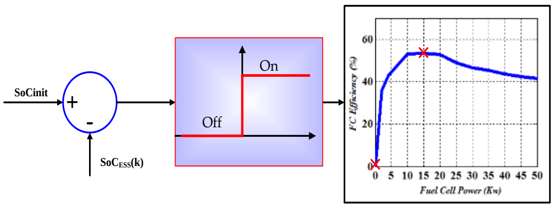


Figure 5: The scheme of the control strategy based on Efficiency Map (CSEM)

4.2 Control Strategy Based on PSO (CSPSO)

The main objective of the CSPSO is to instantaneously distribute the power between the multiple sources with the aim to minimize the hydrogen consumption while maintaining the SoC of the ESS over the driving cycle [5], [6]. Figure 6 illustrates the block diagram of the optimal power control based on CSPSO. It can be observed in Figure 6 that the input variables of the CSPSO control scheme are the demand power from the energy sources, the SoC of the ESS (defined by SC or battery), and the driving cycle, while the outputs are the optimal power of the FC and ESS. The parameters of the PSO, which are used in this study, are mentioned in Appendix A.

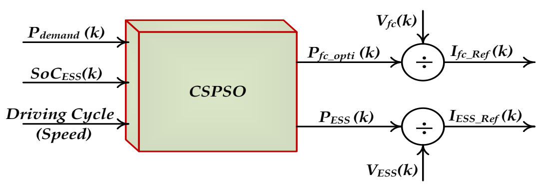


Figure 6: The block diagram of the optimal power sharing

The sum of power from both sources has to be equal to the required power at all times [9]:

$$P_{req}(t) = P_{fc}(t) + P_{ESS}(t) \tag{17}$$

And

$$k_{fc}(t) = P_{fc}(t)/P_{req}(t) \tag{18}$$

The net energy consumed from the FC at time *t* can be computed as follows:

$$E_{fc}(t) = \int_0^t \frac{P_{fc}(t)}{\eta(P_{fc}(t))} dt \tag{19}$$

Then, the hydrogen consumption of the FC is calculated by

$$M_{H2} = \frac{1}{E_{low,H2}} \int_0^t \frac{P_{fc}(t)}{\eta(P_{fc}(t))} dt \tag{20}$$

where M_{H2} is the hydrogen mass, and $E_{low,H2}$ is the lower heating value of the hydrogen, here $E_{low,H2} = 120\ MJ/kg$.

In this study, the components of the fitness vector are the fuel consumption, H_2, and the variation of the SoC, which have to be minimized. The cost function can be formulated as follows:

$$F(x) = \frac{1}{E_{low,H2}} \sum_{k=0}^{N} \frac{P_{fc,opti}(k)}{\eta(P_{fc,opti}(k))} \Delta T \tag{21}$$

The Optimal FC power output ($P_{fc,opti}$) is calculated based on the SoC of the ESS and power demand P_{req} as follows:

$$P_{fc,opti}(k) = k_{fc}(k).P_{req}(k) + k_{SoC}(k)(P_{fc,max} - P_{fc,min})\left[\frac{SoC_{ref} - SoC(k)}{(SoC_{max} - SoC_{min})^2}\right] \tag{22}$$

where *N*= *T/ΔT* is the number of samples during the driving cycle [T] and ΔT=1 sec is the sampling time. In this paper, the time is only discretized because the standard driving cycles are defined every 1 sec.

In this article, the control objective is to determine the value k_{fc} , degree of hybridization, for each t in [0,T], which minimizes the fuel consumption (hydrogen), and to evaluate the proportional controller gain k_{soc} which maintains the SoC_{ESS} ($SoC_{ESS}(T) = SoC_{init}$) during the charging period from the FC.

5 Simulation Results

To investigate the FCHEV powertrains, the required vehicle performance and the power of the powertrain corresponding to standard driving cycles (such as NEDC and FTP75) are simulated and presented. Furthermore, a comparative study of the vehicle performance between FC/B, FC/SC and FC/B/SC powertrains is provided in order to select the appropriate powertrain. Simulation results are obtained by using Matlab/Simulink and SimPowerSystems by implementing the detailed mathematical and electrical models of the FCHEV powertrains that are described earlier in Section 2.

Figure 7 and Fig.8 show the comparative of the cost and the mass of the FC and ESS at different driving cycles, respectively. The volume of the FC and ESS of each powertrain is shown in Fig.9.

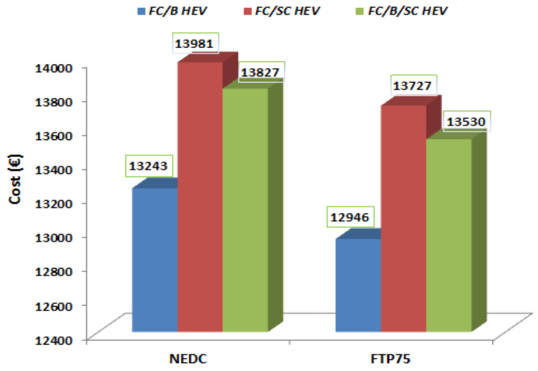


Figure 7: Comparison of the total cost of the electric sources based driving cycles

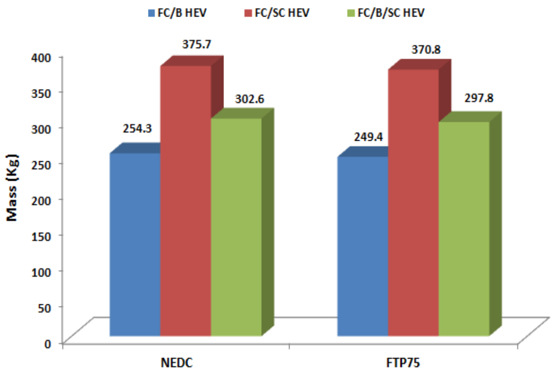


Figure 8: Comparison of the total mass of the electric sources based driving cycles

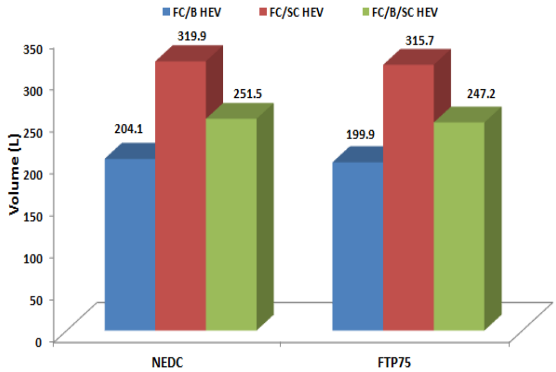
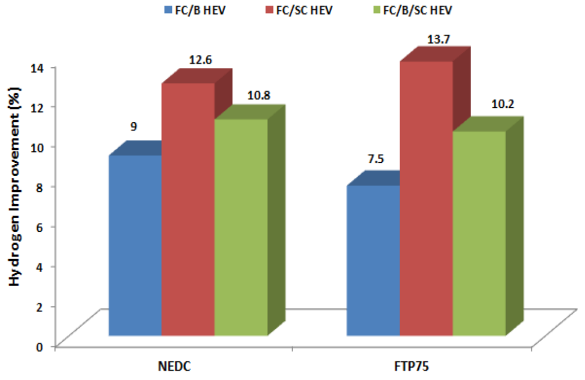
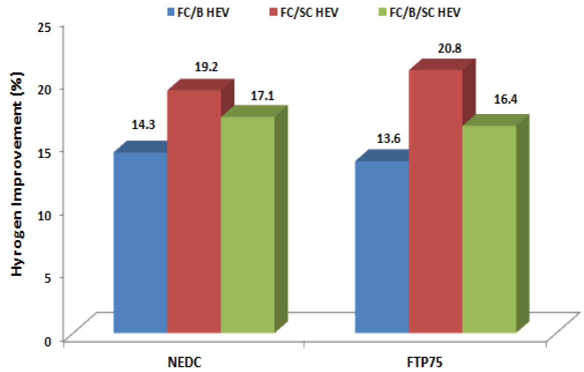


Figure 9: Comparison of the total volume of the electric sources based driving cycles

Figure 10 demonstrates the comparative of the hydrogen improvement between the FCHEV powertrains over different driving cycles. For example, Fig. 11 presents the power sharing between the FC and SC, and the evolution of the SoCsc during CSPSO running on the NEDC driving cycle. Figure 12 presents the power sharing between the FC and battery, and the evolution of the SoCb during CSPSO running on the NEDC driving cycle. Furthermore, Fig. 13 shows the power sharing between the FC, SC and battery when applying the CSPSO on the NEDC driving cycle.



(a) The hydrogen improvement after using CSEM



(b) The hydrogen improvement after using CSPSO

Figure 10: The hydrogen improvements with respect to FC alone without hybridization with ESS

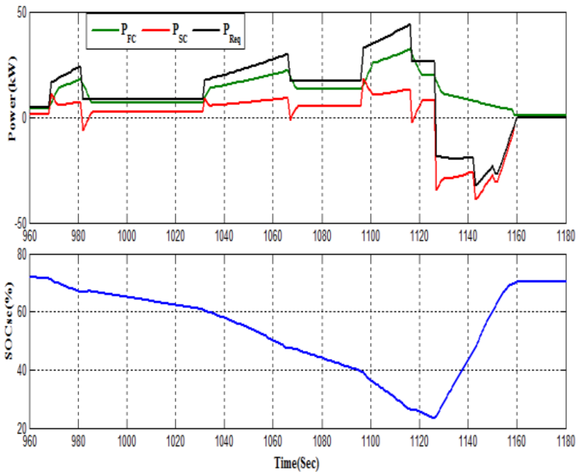


Figure 11: The optimal power splitting between FC and SC running on NEDC based CSPSO

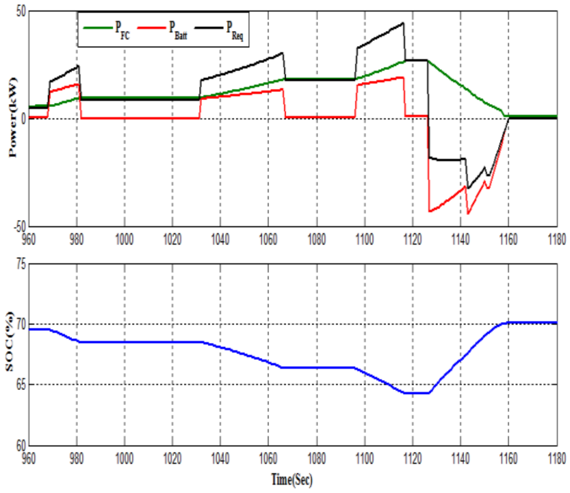
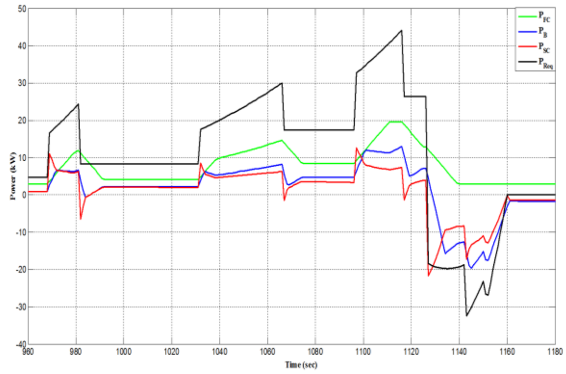
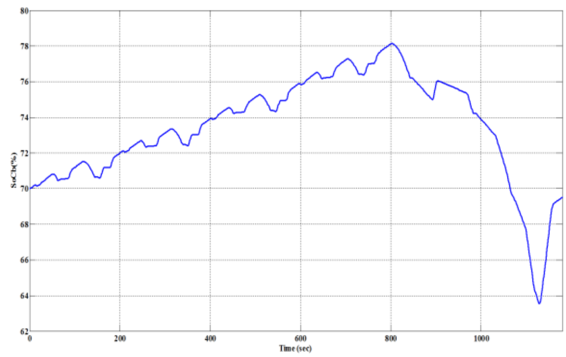


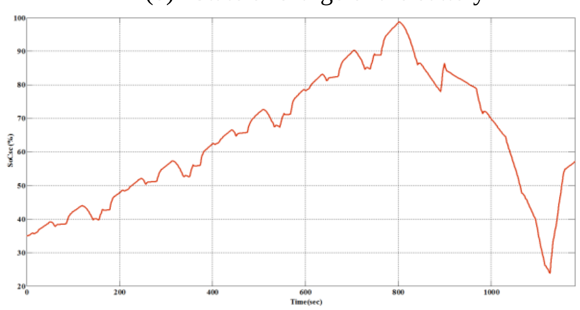
Figure 12: The optimal power splitting between FC and Battery running on NEDC based CSPSO



(a) Power sharing between sources



(b) State of charge of the battery



(c) State of charge of the SC

Figure 13: The optimal power splitting between FC, SC and Battery running on NEDC based CSPSO

6 Conclusion

This paper gives an evaluated study of different fuel cell hybrid electric vehicle powertrains from the point of view of the fuel economy, cost, mass and volume. In this paper, three powertrains are considered and investigated over different driving cycles including the efficiency of each component. These powertrains are Fuel Cell/Supercapacitor (FC/SC) HEV, Fuel Cell/Battery (FC/B) HEV, and FC/B/SC HEV. In addition, two control strategies (i.e. CSPSO and CSEM) have been used to minimize the fuel consumption.

By evaluating and comparing the results, the FC/SC HEV has slightly higher fuel economy than the FC/B HEV and FC/B/SC HEV powertrains. This is due to the use of the efficient supercapacitors for the majority of the transient-power requirements (the SC can be charged or discharged at a high current, in which the battery cannot function at this current). The fuel economy is higher despite the fact that the vehicle is heavier and more expensive. It is important to point out that FC/B/SC HEV may provide a good solution for FCHEVs from the point of view of battery lifespan, component sizing and transient periods. Finally, it is shown that the selection of the appropriate FCHEV configuration and control strategy are very important for the development of the FCHEV powertrains. It is necessary to evaluate the advantages and drawbacks of the different powertrains, particularly for future vehicle generations.

Appendix A

Table A1: PEMFC Model Parameters [7], [8], [9]

Activation voltage constant (B)	0.04777(A^{-1})
Activation voltage constant (C)	0.0136 [V]
Faraday's constant (F)	96484600 [C/kmol]
FC internal resistance (R_{int})	0.00303 (Ω)
No load voltage (E_0)	0.95 V
Nominal voltage	0.81 V
Nominal power per cell	3.4 W
FC absolute temperature (T)	343 [K]
Utilization factor (U)	0.85
Universal gas constant (R)	8314.47 [J/ kmol K]
Volume (V1)	0.0142
Cost (C1) (€) per cell	1
Weight (M1)	16.28 g

Table A2: The cell battery parameters [8], [9]

Li-Ion battery			
Nominal cell Voltage [V]	3.3	Mass (kg) [M2]	0.365
Energy (Wh/kg)	80.2	Volume (L) [V2]	0.220
Power (W/kg)	383.3	Cost (€) [C2] per cell	9.22

Table A3: The used parameters of the SC [7], [8], [9]

Capacitance (*C*)	2500 F
Internal resistance (*Rs*)	0.65mΩ
The parallel resistance (R_p)	2kΩ
Max_ Cell voltage [$V_{maxcell}$]	2.5 V
Initial State of Charge (*SoCSC0*)	80%
Rated current	625 A
Weight (M2)	725 g
Volume (V2)	0.6 L
Cost (C2) (€) per cell	14.38

Table A4: PSO Parameters and Bounds [6]

Parameter	Value	Parameter	Value
Population size	20	r1	[0,1]
Max. iteration	100	r2	[0,1]
c1	0.5	Lower Bound *[Ksoc]*	0
c2	0.5	Upper Bound [K_{soc}]	10
Max. weight	1.2	Lower Bound [K_{fc}]	0
Min. weight	0.1	Upper Bound [K_{fc}]	1

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