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Improving fuel economy and performance of a fuel-cell hybrid electric vehicle (fuel-cell, battery, and ultra-capacitor) using optimized energy management strategy

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ABSTRACT

Fuel-Cell System (FCS) is the primary energy supply of a Fuel-Cell Vehicle (FCV). Battery or Ultra-Capacitor (UC), as a secondary power source, is used along the FCS to improve the FCV's power response. Battery and UC composition, as a hybrid power source presenting the term of Fuel-Cell Hybrid Electric Vehicle (FCHEV), provides the FCV with the advantages of high energy density and high dynamic response. The supervisory system of the FCHEV could be managed efficiently to exploit the benefits of battery and UC at the same time. As a matter of fact, in such a combination, the performance of the hybrid powertrain largely depends on how to distribute the requested power through different types of energy sources.

In this paper, we design the powertrain elements of an FCHEV in advance, with FCS/Battery/UC considerations. The energy management strategy (EMS) is achieved by presenting a novel power sharing method and by implementing an intelligent control technique constructed based on Fuzzy Logic Control (FLC). The control parameters are accurately adjusted by the genetic algorithm (GA) while considering targets and restrictions within a multi-objective optimization function over a combined city/highway driving cycle. This optimized supervisory system is examined by Advanced Vehicle Simulator (ADVISOR) to evaluate the performance of the proposed EMS over 22 different driving cycles and some specific performance tests. The results of simulation show that the presented strategy progressively affects the vehicle characteristics. Fuel economy enhancement, vehicle performance improvement, battery charge-sustaining capability, and optimal energy distribution are some of the significant outcomes achieved by the optimized FLC-based EMS.

1. Introduction

Fuel-Cell Vehicle (FCV) is known as an electric vehicle equipped with FCS [1]. Integrating FCS with battery or UC is a well-known method to mitigate FCS limitations. Battery/UC composition as a hybrid power source which presents the term of Fuel-Cell Hybrid Electric Vehicle (FCHEV), provides the FCV with the advantages of high energy density and high dynamic response. In such a combination, designing an optimal energy management strategy (EMS) plays a vital role in the success of the FCHEV supervisory system [2,3].

There are various EMSs designed and optimized for the hybrid supervisory system [3–7]. Linear programming and PID controller [8–10], state flow algorithms and multiple operation mode control [11–15], dynamic programming techniques [16–18], fuzzy logic control (FLC) [14,19–21], convex programming [22], model predictive control [23,24], and optimal control theory [25,26] are some of the applied strategies. To have an optimal EMS, we need both of control methods and optimization techniques. The EMS deals with hybrid power sources to meet commanded power whereas optimization procedure tries to have a more efficient power balance. In other words, considering powertrain condition, the requested power should be distributed by the EMS while achieving the best fuel economy and vehicle performance [14].

In the FCHEV configuration, the battery is a well-known secondary power source. In the recent studies, Ettihir et al. [26] proposed two adaptive EMSs to be used in the FCS/Battery supervisory system: hysteresis and optimal power splitting. The first strategy tried to keep the battery charge level around its reference value while the second one uses the FCS current as a control variable to distribute power between FCS and battery pack. These strategies were compared based on consumed hydrogen energy and battery energy in a sample cycle. In Ref. [27] three operation modes, including traction/braking/stopping, were presented with an FCS/Battery hybrid vehicle. Ensuring the feasibility of FCV power production, their proposed EMS limited the battery load

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Nomenclature

Abbreviations

ADVISOR	Advanced Vehicle Simulator
ADV-PTC	ADVISOR's Power Track Control
Cold-Start	Cold-Start Driving Condition
DOE	Department of Energy
$\mathrm{eff}_{\mathrm{batt}}$	Average Efficiency of Battery
$\mathrm{eff}_{\mathrm{FC}}$	Average Efficiency of FCS
EMS	Energy Management Strategy
ESS	Energy Storage System
FCHEV	Fuel-Cell Hybrid Electric Vehicle
FCS	Fuel-Cell System
FCV	Fuel-Cell Vehicle
FLC	Fuzzy Logic Control
FTP	Federal Test Procedure
GA	Genetic Algorithm
Hot-Start	Hot-Start Driving Condition
HWFET	Highway Fuel Economy Test
MPG	Miles per Gallon
MPGGe	Miles per Gallon Gasoline Equivalent
NEDC	New European Driving Cycle
NOVC	Not Off-Vehicle Charge Capable
NREL	National Renewable Energy Laboratory
Opt-FLC	Optimized FLC
SOC	State of Charge
SOC^{*}	desired charging level
$\mathrm{SOC}_{\mathrm{high}}$	maximum charging level
$\mathrm{SOC}_{\mathrm{low}}$	minimum charging level
UC	Ultra-Capacitor
ΔSOC	difference between final and initial SOC

Symbols

μ	mutation rate [Dimensionless]
A	vehicle front area [m^2]
C_D	drag coefficient [Dimensionless]
C_E	total energy capacity of UC [W h]
C_P	proportion of usable energy [%]
E	stored energy in ESS [W h]
g	gravity [$\mathrm{m\ s^{-2}}$]
m	vehicle mass [kg]
m_{module}	mass of a battery/UC cell [kg]
n_{bat}	number of battery cells [Dimensionless]
n_{UC}	number of UC modules [Dimensionless]
P_{Batt}	battery power [W]
P_{char}	maximum power to regulate charging level [W]
P_{comm}	commanded power [W]
P_{fc}	fuel-cell power [W]
P_{m}	maximum power of electric machine [W]
P_{PS}	power of secondary power source [W]
$P_{\mathrm{PS\text{-}charge}}$	charge power of power supply [W]
$P_{\mathrm{PS\text{-}discharge}}$	discharge power of power supply [W]
P_S	battery specific power [$\mathrm{W\,kg^{-1}}$]
P_{UC}	ultra-capacitor power [W]
V	vehicle speed [$\mathrm{m\ s^{-1}}$]
w_i	weighting factors [Dimensionless]
X_{rate}	selection rate [Dimensionless]
δ	mass coefficient of rotary elements [Dimensionless]
ΔE_{max}	energy of secondary power source [W h]
η_b	efficiency of battery [Dimensionless]
η_m	efficiency of electric machine [Dimensionless]
η_t	efficiency of transmission system [Dimensionless]
θ	road grade [Deg]
ρ	air density [$\mathrm{kg\ m^{-3}}$]

while the battery charge occurred under traction and braking modes.

UC is another type of power source used in the hybrid configuration mainly due to its high power density [4]. UC plays a vital role in providing instantaneous power, particularly in acceleration and regenerative braking. In fact, its power density, durability, and efficiency in charge/discharge cycles give more advantages in comparison with battery and FCS [28,29]. In the recent studies, Sami et al. [10] presented an EMS based on two main modes for an FCV integrated with UC. Despite the first mode in which the FCV operated with both FCS and UC, the UC was the sole power unit in the second operating mode in case of fuel limitation. During the first mode operation, a PI controller was applied to preserve the optimum performance of FCS and UC. Based on their experimental results, UC can meet load requirements in both modes. In Ref. [25], Li et al. employed an optimal control theory to find the optimal control laws used in their proposed hybrid configuration. The objective of this research was to minimize the hydrogen fuel consumption while considering FCS durability and charge level of UC. In the presented strategy, FCS provided more power which led to a smaller change in UC charge level.

All the strategies mentioned above, in general, tried to minimize FCS/Battery or FCS/UC energy consumption. Despite benefits of these configurations, there are some other distinctive features giving advantages to the FCHEV by considering FCS/Battery/UC composition. There are several techniques used in the literature to manage the power sources in this hybrid structure [29–34]. A large amount of power density of the UC and energy density of the battery provide FCHEV with the opportunity to respond to high power and energy demands such as commanded power in acceleration or uphill [4]. Despite the mentioned benefits, this hybrid scheme makes the FCHEV powertrain more complex, and correspondingly it needs an advance EMS. In Ref. [30], the author presented an operation mode control for a typical FCHEV. Battery and UC charging and discharging modes occurred with a simple relation between load power and fuel-cell power. Equivalent consumption minimization strategy is one of the strategies used in the recent literature [29,32,34]. In the current studies to distribute the power demand to the FCS/Battery/UC hybrid tramway, a multi-mode strategy based on the equivalent consumption minimization strategy was proposed by the authors in Ref. [34] and Ref. [32]. Odeim et al. in Ref. [35] proposed a real-time strategy to minimize the hydrogen consumption and battery contribution based on an offline algorithm as a benchmark. In order to have battery current limited, authors in Ref. [33] presented an algorithm evaluated in a drive cycle to control the energy flux in the FCS/Battery/UC hybrid vehicle. On the other hand, considering the vehicle's main targets, an optimization method should be employed to ensure the optimality of the proposed strategy during an indexed drive cycle. Having an optimized EMS, authors in Ref. [36] and Ref. [35] employed Multi-objective optimization method to minimize the defined cost functions while considering fuel economy and system durability. Moreover, in Ref. [35], GA was employed by the authors to find the best values for FCHEV control parameters, which led to improvement in the battery lifetime.

Whereas finding an optimal EMS for FCVs through conventional control techniques is a well-researched topic, there has been far less work on the still challenging tasks of optimal EMS designing problems, which faces FCHEVs. Having our experience in FCV power-train developing in hand, we try to propose an EMS to work out the issues associated with FCHEV power sharing as a constrained multi-objective problem while integrating fuel economy improvement and vehicle targets. In this paper, we are going to present a new optimal EMS based on an intelligent control method and power track control (PTC)