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Novel Energy Management Technique for Hybrid Electric Vehicle via Interconnection and Damping Assignment Passivity Based Control

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A B S T R A C T

The energy management of Hybrid Electric Vehicles (HEV) has witnessed significant academic and industrial attention in recent years. Indeed, the use of different power sources in HEV requires both smart and efficient energy management scheme to split and manage power among them. The energy management strategy should enable continuous supply load balance. In HEVs, the energy management procedure should consider the constraints of load and the different available sources. The fundamental contribution of this paper is the energy management in the HEV in presence of faults in the fuel cell (FC) level while considering battery state of charge constraints. For the flexibility and durability of the proposed energy management scheme, the system mathematical modeling using Port-Controlled Hamiltonian (PCH) approach is developed. Therefore, the Interconnection and Damping Assignment Passivity Based Control (IDA-PBC) is used for a smartly energy management. According to the simulation results, the IDA-PBC is an adequate nonlinear control method that guarantees the stability of the system.

1. Introduction

With the population growth and development of both emerging and developing countries, the energy needs become vital [1]. Therefore, the emission of GreenHouse Gasses (GHG) is directly influenced if the energy sources are based on fossil sources expected to run out [2]. Both transport and energy sectors are the main energy consumers. This former results in significant GHG emissions rate [3]. The HEVs are presented such as a promising solution [4], thanks to oil independency growth [3]. Their autonomy does not allow replacing the conventional thermal car. Thus, where the development of HEV concept is essential [5]. In HEV, the combination of an Internal Combustion Engine (ICE) using fossil fuel and the electric motor or the electric system using at least two sources [6], such as FC, battery, and a supercapacitor (SC) becomes mandatory. For the first hybrid system, the ICE is producing polluting emissions, and it still faces the uncertainty of fossil energy shortage and global warming climate [6]. Hence, the real solution is to consider hybrid electrical system which consists of different energy sources and storage devices to combine the advantages of some and overcome the disadvantages of others [7, 8].

The hybrid vehicle of at least two different energy sources has improved the system overall efficiency. The HEV enables reducing emissions of GHG and toxic gasses, improving the autonomy, cost reduction, fast charging and extending the life of storage devices [9]. However in the HEV, optimizing the management of energy that flows between sources is fundamental [10].

In this work, the hybrid system consists of the FC as the primary source, battery and SC as secondary sources. The SC helps to supply and absorb the transient power. The battery plays a significant role because it is in charge to provide the start-up energy and after that, the FC takes the relay progressively. In presence of the faults in FC systems, the battery allows providing the required energy to cover the load power. The secondary sources used in this work are designed to provide the energy in the short durations of peak power demand. In Table 1, the characteristics show that the two elements have complementary roles because the SC has high power density and low energy density. However, the battery system has low power density and high energy density [11, 12].

This paper addresses the control and energy management of a hybrid multi-source electrical vehicle in presence of a FC faults. The developed fault tolerant control takes into account the limitation on the battery regarding its State Of Charge (SOC).

The novelty of this paper is the smart energy management strategy based on the passivity approach IDA-PBC to find the best energy-share between the sources in presence of faults at the FC

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Table 1
Principal characteristics of the SC and battery [11, 12].

	SC	Battery
Charge time	1s–10s	10s–60s
Discharge time	1s < t < 30s	0.3 h < 3 h
Cell voltage (V)	2.3–2.75 V	3.6–3.7 V
Power density (W/kg)	Up to 10000	1000 to 3000
Energy density (Wh/kg)	5	100–200
Cycle life	1 million or 30,000 h	500 and higher
Charge temperature (°C)	−40 to 65	0 to 45
Discharge temperature (°C)	−40 to 65	−20 to 60 °C

level while considering the battery SOC. In this approach, the assumption used for choosing the energy storage function whose minimum at the desired equilibrium. The originality of the research lies in the choice of equilibrium trajectories enabling the management of the flow of energy at the same time.

This paper is organized as follows: Section 2, an exhaustive literature review on energy management of HEV is presented. The structure and the state space model of the hybrid system is given in Section 3. Section 4 is dedicated to the proposed scenario description considering the battery use for system start-up since the FC presents a slowly start-up. Then, the FC takes gradually the relay to the battery. This passage and relay time is controlled by selecting the equilibrium trajectory of the battery current in a continuous and smartly manner. This allows to reduce the stress on the FC. In addition, the SC provides the energy in the transient phases. Then, the proposed scenario of this study is considering a faulty FC and battery state of charge. The fault is considered on FC level in order to show the role of the storage elements in case of faulty FC. Moreover, the FCs are most susceptible to the fault compared to the battery and the SC. The configuration of the control technique is adopted by managing the requested energy. In Section 5, the studied system is deduced in PCH form and the stability proof is given. In Section 6, the simulation results that reflect the proposed scenario are presented. In the Section 7, the conclusions and perspectives are given.

2. Literature review on energy management

The HEV system composed of the FC as the primary source and such as battery and/or SC as secondary sources is designed to provide the peak power demand [13]. The battery SOC level is one of the most important information that plays a considerable role in the design of the energy management control [14, 15].

In Ref. [16], the authors have studied the energy management of multisource system (FC, battery and SC) used in light electric vehicles. The PI regulator is used for achieving efficient energy management. The result was satisfactory the HEV efficiency of 94% compared to 84.9% obtained from a system based on battery source only, especially in the acceleration mode. In Ref. [16], five control strategies have been reported for the FC-battery-SC HEV which are: the operation mode control, the cascade control, the fuzzy logic control, the equivalent consumption minimization strategy control and the predictive control. These strategies have been tested and compared. The simulation results have demonstrated that the equivalent consumption control gives the lowest hydrogen mass consumption of 3.82 kg. The proposed fuzzy logic control has provided maximum power of 400 kW for 500 kW load.

Different energy management strategy has been studied by the authors in Ref. [16] for the hybrid system equipped with battery, SC and FC. A powerful strategy based on fuzzy logic is used for controlling the energy considering the slow dynamics in FC auxiliaries, the vehicle speed and the SC SOC [17]. In the study, the battery has been employed such as a primary source while the FC and SC were secondary sources. The strategy has been chosen such that when the battery SOC exceeds the reference value, the battery provides the majority of energy while the FC and SC will feed less energy [17]. The study in Ref. [18] has concerned with the comparison of 10 connection types of FC, battery and SC. In all of these links, the FC represents the primary source. In Ref. [18], the energy management allows sharing the input energy between batteries with SC. The obtained results have shown that the studied connections provide lower volume and mass with higher efficiency and longer service life for the battery. The authors in Ref. [19] have described the power control strategy of the FC hybrid system from each source based on optimal control theory to meet the demand of different vehicle loads while optimizing total energy cost and battery life. The simulation of this strategy has been performed in Matlab TM/ Simulink software. The results have shown that the vehicle could reach almost 129 km per hour. The energy management strategies based on fuzzy logic have been used by the authors of [20] to enhance the system performance of HEV in terms of driving economy and autonomy. Various system configurations have been used in Ref. [21] such as FC with battery HEV and FC with a battery in addition to SC HEV. The proposed control strategy can satisfy the power requirement for four standard driving cycles and achieve the power distribution among various sources of energy.

In Ref. [22], the authors have mentioned that the energy efficiency of HEV can be significantly degraded when the battery SOC reaches its boundaries. These parameters have been greatly influenced by the road grade. The authors have used the stochastic model predictive control based energy management strategy considering the traveling direction and the terrain information for HEVs. The proposed method has enabled maintaining the battery SOC within its boundaries. However, the prior knowledge of the car trip is needed. The authors of [23] have studied the efficiency of pivotal components and the electric motors. The energy management strategy, which can keep battery SOC change in a reasonable variation range have been proposed. In Ref. [24], the authors have studied the energy management strategies of a hybrid system composed of motor and battery. To achieve a power split between these two sources, the genetic algorithm has been implemented, and a modified SOC estimation algorithm has been employed to perform parameter optimization and efficient energy management. The most of the hybrid systems require an adapted energy management strategy in order to exploit to the best the potential of the different sources and in order to efficiently use the onboard energy. In the literature, different techniques have been applied to solve the energy management problem in HEV. The general objective is to ensure the continuous power demand along the mission profile while minimizing the cost function.

The dilemma of this study is to find the optimal power distribution between different sources taking into account a faulty FC and battery SOC [16]. This is achieved by controlling the various power converters [25, 26]. In the proposed scenario, the considered fault is expressed in power drop in the FC output by α%, where 0% is the normal situation and 100% is the FC total damage. Obviously, the battery plays a significant role in this study. However, it is necessary to consider battery SOC parameter [27]. For the equilibrium trajectory of the battery current reference. Different values of battery SOC are considered from 0 to 100%, where 0% is the fully discharged the battery, and 100% is the fully charged battery.

The PCH method is an approach of the real-time nonlinear programming. It is based on the passivity of the system to find the optimal point of a source operation. The aim of passivity based control is to control the system by making closed loop system passive [28]. The passive system is one where the stored energy cannot exceed its supplied energy, the difference being dissipated [29]. From the works of [30, 31], the IDA-PBC approach is