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# Fuel cell hybrid electric vehicle (FCHEV): Novel fuel cell/SC hybrid power generation system

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ABSTRACT

A fuel cell hybrid electric vehicle (FCHEV) is more advantageous compared to a gasoline-powered internal combustion engine based vehicle or a traditional hybrid electric vehicle (HEV) because a FCHEV only uses one electric motor instead of an internal combustion engine or an electric motor in combination with an internal combustion engine. This study proposes a novel fuel cell (FC)/supercapacitor (SC) hybrid power source to be utilized in FCHEVs. The power source includes a 90 kW proton exchange membrane fuel cell (PEMFC) stack used as the main power source, and a 600 F SC bank used as the auxiliary energy storage device. A prototype of the FC/SC hybrid power source has been constructed, and experimental verifications are presented that explicitly substantiate having a power efficiency of 96.2% around the rated power, highly accurate DC-link voltage regulation and producing an appropriate three-phase stator current supplied to the traction motor by using PWM technique are the main contributions of this work. Providing a maximum speed of 158 km/h, 0–100 km/h acceleration in 12.2 s and a cruising range of 435 km for a FCHEV with the weight of 1880 kg are the other advantages. The proposed FC/SC hybrid power source is also compared to the state of the art of all kinds of power sources used in FCHEVs that clearly demonstrates its better performances such as higher power efficiency, speed and acceleration.

## 1. Introduction

Nowadays, environmental problems and economic considerations cause an upward trend in developing electric vehicles (EVs) rather than the vehicles with internal combustion engines [1]. In particular, a traditional HEV consists of an internal combustion engine used as the main power source and an auxiliary energy storage device with the capability of storing energy such as a battery. The auxiliary energy storage device is mainly used to extend the cruising range of the vehicle, to provide the extra energy needed whenever the vehicle accelerates, and to store the regenerative energy produced during braking. A FCHEV is a type of HEV that utilizes a FC stack as the main power source combined with a SC and/or battery used as the auxiliary energy storage device to power the vehicle's traction motor which is an electric motor, not an internal combustion engine [2]. A FCHEV is more advantageous compared to a traditional HEV or an internal combustion engine based vehicle because as mentioned it uses an electric motor instead of a gasoline-powered internal combustion engine, so it not only satisfies the environmental issues but also is more efficient [3]. It is reminded that even a plug-in hybrid electric vehicle (PHEV) uses an internal combustion engine to extend its cruising range [4,5], and to produce the electric power needed to be supplied to the vehicle's electric motor when the level of the vehicle's battery becomes low and gets to a predetermined state of charge (SOC) [6]. A FC stack produces electric power through the chemical reaction basically occurs in the presence of hydrogen, oxygen and an electrolyte. Compared to an internal combustion engine based power source, relatively higher efficiency [7], lower pollution, the usage of clean energy resources with lower price such as methanol [8], and being appropriate for various industrial applications [9] such as distributed power generations [10] and vehicular systems [11,12] are some benefits of utilizing FC stacks. Among the different FC systems available in the market, the PEMFC technology is more appropriate to be utilized in vehicles because of higher density in electric power production along with lower heat generation causing a lower temperature which is a necessity in a vehicle equipped with a FC stack [13,14]. The first drawback of utilizing a FC stack in a vehicle is that, the FC stack cannot provide appropriate responses to sudden variations in the load demand of the vehicle [15–17]. For instance, the FC stack cannot efficiently respond to the sudden upward and downward powers needed respectively during accelerating and decelerating, or the considerable initial electric power required to start up the vehicle [18,19]. The second drawback is that the FC stack cannot store the regenerative power produced during decelerating and braking, so an extra energy storage device such as a rechargeable battery or SC bank is also needed

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**Nomenclature**

| | |
|---|---|
| $C_1$ | parasitic capacitance of the N-MOSFET switch of the converter connected to the PEMFC stack (F) |
| $C_2$ | secondary-side serial capacitor of the converter connected to the PEMFC stack (F) |
| $C_{dc}$ | DC-link capacitor (F) |
| $D_1$ & $D_2$ | Diodes of the converter connected to the PEMFC stack |
| $D_{char}$ | duty cycle of the control signal supplied to the converter connected to the SC bank in charging mode |
| $D_{disc}$ | duty cycle of the control signal supplied to the converter connected to the SC bank in discharging mode |
| $D_{fc}$ | duty cycle of the converter connected to the PEMFC stack |
| $f_s$ | constant switching frequency of the converter connected to the PEMFC stack (Hz) |
| $I_{sc}$ | SC bank output current (A). |
| $I_{fc}$ | PEMFC stack output current (A). |
| $I_{load}$ | load current supplied to the three-phase inverter and traction motor (A) |
| $L_{lk1}$ | primary-side leakage inductor of the transformer of the converter connected to the PEMFC stack (H) |
| $L_{lk2}$ | secondary-side leakage inductor of the transformer of the converter connected to the PEMFC stack (H) |
| $L_m$ | equivalent magnetizing inductor of the transformer of the converter connected to the PEMFC stack (H) |
| $n = N_2/N_1$ | turns ratio of the transformer of the converter connected to the PEMFC stack |
| $P_{fc}$ | PEMFC stack output power (W) |
| $P_{char}$ | charging power of the SC bank (W) |
| $P_{dischar}$ | discharging power of the SC bank (W) |
| $P_{load}$ | total electric power supplied to the three-phase inverter and traction motor (W) |
| $R_{esr}$ | equivalent series resistance (ESR) of the DC-link capacitor (Ω) |
| $R_{sc-esr}$ | ESR of the supercapacitor bank (Ω) |
| $R_{in}$ | input resistance of the converter connected to the PEMFC stack (Ω) |
| | equivalent load resistance observed from the output terminal of the converter connected to the PEMFC stack (Ω) |
| $R_{L_{sc}}$ | resistance of the inductance $L_{sc}$ of the bidirectional boost-buck converter connected to the supercapacitor bank (Ω) |
| $S_{fc}$ | N-MOSFET switch used in the converter connected to the PEMFC stack |
| $T_s$ | switching period of the converter connected to the PEMFC stack (s) |
| $T_{sc}$ | switching period of the control signal supplied to the converter connected to the SC bank (s) |
| $V_{sc}$ | SC bank output voltage (V) |
| $V_{dc}$ | DC-link voltage (V) |
| $V_{fc}$ | PEMFC stack output voltage (V) |

[20,21]. The two above-mentioned drawbacks demonstrate that an additional device with a suitable storage capacity and high-speed dynamic response should be utilized as an auxiliary energy storage device along with the FC stack, so that some research works have been carried out on this topic. For instance, wavelet-fuzzy logic and neural network-wavelet based load sharing schemes were introduced to be used in FC/SC hybrid vehicular power system [22,23]. As other example, power sharing and state machine based energy management systems were successfully implemented in a FC/battery/SC tramway [24,25].

Because of the advantages of FCHEVs explained in detail, this study focuses on this type of HEV, and proposes a novel FC/SC hybrid power source to be utilized in FCHEVs. The power source includes a 90 kW PEMFC stack used as the main power source and a 600 F SC bank used as the auxiliary energy storage device. A prototype of the FC/SC hybrid power source has been built, and experimental verifications are presented that demonstrate having a power efficiency of more than 96% around the rated power, highly accurate DC-link voltage regulation and producing an appropriate three-phase current by using pulse-width modulation (PWM) technique, which is supplied to the traction motor, are some contributions of this work. The power source presented in this study is also compared to the state-of-the-art power sources used in FCHEVs that demonstrates the better capability of the proposed power source. The rest of this paper is organized as follows. The proposed FC/SC hybrid power source is designed and implemented in Section 2. Details about the constructed power source, experimental verifications and comparing the proposed power source to the state-of-the-art power sources used in FCHEVs are given in Section 3. Finally, the paper is concluded in Section 4.

## 2. Implementation of the FC/SC hybrid power source proposed for FCHEVs

Fig. 1 shows a simple schematic diagram of a typical FCHEV in which a PEMFC stack has been used as the main power source to supply the power needs of the FCHEV, in particular, its traction motor which is an electric motor. Electric power is produced in the PEMFC via a set of the chemical reactions which can be summarized as [26]:

$$\begin{aligned} &\text{At Anode:} \quad 2H_2 \rightarrow 4H^+ + 4e^- \\ &\text{At Cathode:} \quad O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \\ &\text{Over all:} \quad 2H_2 + O_2 \rightarrow 2H_2O \end{aligned}$$

The configuration of the FC/SC hybrid power source proposed to be utilized in FCHEVs is shown in Fig. 2. It is composed of a PEMFC stack used as the main power source, a SC bank used as the auxiliary energy

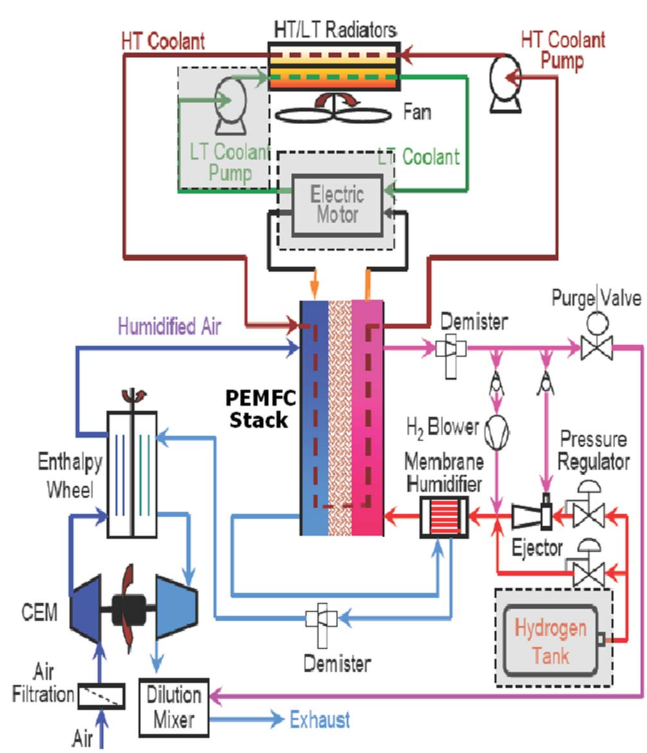


**Fig. 1.** Schematic diagram of a typical FCHEV.