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Novel battery/photovoltaic hybrid power source for plug-in hybrid electric vehicles

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ABSTRACT

A plug-in hybrid electric vehicle (PHEV) uses an internal combustion engine to extend its cruising range, and to produce the electric power needed to be supplied to its electric motor when the charge level of the vehicle's battery becomes low and reaches a predetermined state of charge (SOC). Because of environmental issues, utilizing a gasoline-powered internal combustion engine in a PHEV is not an optimal solution. This paper provides a better solution by replacing the internal combustion engine with a small-size photovoltaic (PV) module mounted horizontally on the roof of the PHEV, and so this study proposes a novel battery/PV hybrid power source to be utilized in PHEVs. The proposed power source equipped with vehicle-to-grid (V2G) technology utilizes a 19.2 kWh Lithium (Li)-ion battery as the main energy storage device and a 200 W PV module as the clean and renewable energy based auxiliary power source. A prototype of the battery/PV hybrid power source has been constructed, and experimental verifications are presented that explicitly demonstrate utilizing the PV module adds 13.4 km to the cruising range of a PHEV with the weight of 1880 kg in a normal operation of the PHEV during two sunny days, and provides higher power efficiency (91.1%) and speed (121 km/h). Highly accurate DC-link voltage regulation and producing an appropriate three-phase stator current for the traction motor by using PWM technique are the other contributions of this work.

1. Introduction

Because of environmental issues and economic considerations, there is an upward trend in developing the usage of electric vehicles (EVs), hybrid electric vehicle (HEV) and PHEVs rather than the vehicles with internal combustion engines (Adnan et al., 2017; Fathabadi, 2015), so that there is an ascending demand for different types of EV charging stations in some countries (Kim et al., 2017; Fathabadi, 2017a). A PHEV utilizes its electric motor to provide the power needed for propulsion, and is more efficient compared to a traditional HEV that mainly uses an internal combustion engine (Dong et al., 2016). The V2G technology implemented in PHEVs is the other benefit that makes them more advantageous and popular (Fathabadi, 2017b,c). In particular, the advantage of a PHEV is highlighted when it is connected to a microgrid or a smart grid to manage and balance load demand (Hota et al., 2014; Mou et al., 2015). A through survey of the current literature shows that the research works concerning PHEVs can be classified into the three categories. The first category includes the researches performed to improve the performance of the batteries used in PHEVs. For instance, an analysis about the battery aging in a PHEV by using the experimental data about the voltage recovery and internal resistance of the battery was reported in Canals Casals et al. (2016). Some other related works are analyzing the effect of V2G connection on PHEVs' batteries (Bishop et al., 2013), determining a suitable Li-ion battery pack for a PHEV (Xue et al., 2014), evaluating the impact of ultracapacitors on degradation of the performance of a Li-ion battery used in a PHEV (Hochgraf et al., 2014), and maximization of the income of charging the batteries of PHEVs (Zhao et al., 2014). The second category is composed of the research works that have proposed some peripheral devices and facilities for PHEVs such as the wireless charging mechanism applicable to PHEVs (Zeng et al., 2017), and the resonant converter based battery charger suitable for a PHEV (Deng et al., 2015). Finally, the third category comprises the articles that propose different strategies to combine the charging and discharging process of PHEVs with other power sources such as renewable energy resources to satisfy load demand in a grid (Peng et al., 2012). Some examples are utilizing PHEVs in a smart grid to optimize the electrical parameters of the grid by providing distributed demand response (Fan, 2012), and the energy management scheme proposed for an integrated energy system including PHEVs (El-Zonkoly, 2014). A solar car is powered just by a PV array composed of many PV cells distributed on the external surface of the car. The literature survey shows that five solar cars have been designed and manufactured since 2006 (Gören, 2017). The experiences of the five solar cars demonstrated that a solar car cannot be used in practical

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Nomenclature

C_1	parasitic capacitance of the N-MOSFET switch of the converter connected to the PV module (F).
C_2	secondary-side capacitor of the converter connected to the PV module (F).
C_{pv}	input capacitor of the converter connected to the PV module (F).
C_{dc}	DC-link capacitor (F).
D_1 & D_2	diodes of the converter connected to the PV module.
D_{char}	duty cycle of the control signal supplied to the converter connected to the Li-ion battery in charging mode.
D_{disc}	duty cycle of the control signal supplied to the converter connected to the Li-ion battery in discharging mode.
D_{pv}	duty cycle of the converter connected to the PV module.
f_s	constant switching frequency of the converter connected to the PV module (Hz).
G	solar irradiance on the PV module surface (Wm^{-2}).
I_{bat}	Li-ion battery output current (A).
I_{load}	load current supplied to the three-phase inverter and traction motor (A).
I_{pv}	PV module output current (A).
I_{pv-mpp}	PV module output current at maximum power point (A).
L_{lk1}	primary-side leakage inductor of the transformer of the converter connected to the PV module (H).
L_{lk2}	secondary-side leakage inductor of the transformer of the converter connected to the PV module (H).
L_m	equivalent magnetizing inductor of the transformer of the converter connected to the PV module (H).
$n = N_2/N_1$	turns ratio of the transformer of the converter connected to the PV module.
P_{pv}	PV module output power (W).
P_{char}	charging power of the Li-ion battery (W).
$P_{dischar}$	discharging power of the Li-ion battery (W).
P_{load}	total electric power supplied to the three-phase inverter and traction motor (W).
P_{pv-mpp}	PV module output power at maximum power point (W).
$R_{bat-esr}$	equivalent series resistance (ESR) of the Li-ion battery (Ω).
R_{esr}	ESR of the DC-link capacitor (Ω).
R_{in}	input resistance of the converter connected to the PV module (Ω).
R_L	equivalent load resistance observed from the output terminal of the converter connected to the PV module (Ω).
$R_{L_{bat}}$	resistance of the inductance L_{bat} of the bidirectional boost-buck converter connected to the Li-ion battery (Ω).
S_{pv}	N-MOSFET switch used in the converter connected to the PV module.
T	PV module temperature (°C).
T_s	switching period of the converter connected to the PV module (sec).
T_b	switching period of the control signal supplied to the converter connected to the Li-ion battery (sec).
V_{bat}	Li-ion battery output voltage (V).
V_{dc}	DC-link voltage (V).
V_{pv}	PV module output voltage (V).
V_{pv-mpp}	PV module output voltage at maximum power point (V).

applications because of its limitations in design and implementation. For instance, a solar car should be lightweight, and this enforces the manufacturers to use polymer composites in manufacturing process that makes a solar car unsafe in practical applications such as daily trips, traveling abroad, etc (Gören, 2017). A few research works addressing solar energy harvesting in EVs and HEVs are also available that all are simulation based works (models) Ezzat and Dincer, 2016. Modeling and simulation of utilizing a PV power source in a fuel cell hybrid electric vehicle (FCHEV) with a small-scale 3 kW electric motor was performed in Matlab/Simulink environment (Mokrani et al., 2014). Similarly, a mathematical model implemented in Matlab/Simulink environment theoretically showed that a PV based power generation system can be used in small-scale HEVs (Chowdhury et al., 2016).

The main drawback of a PHEV is that it uses an internal combustion engine to extend its cruising range, and to produce the electric power needed to be supplied to its electric motor when the charge level of the vehicle's battery becomes low and gets to a predetermined SOC. It is clear that utilizing a gasoline-powered internal combustion engine in a PHEV cannot be considered as an optimal solution because of environmental issues. A detailed overview in the literature demonstrates that there is not any research work giving a solution. This study addresses this problem by presenting a novel battery/PV hybrid power source to be utilized in PHEVs. In the proposed hybrid power source, the internal combustion engine has been replaced with a small-size PV module located on the roof of the PHEV, and solar energy has been utilized as a clean and renewable energy to extend the cruising range of the PHEV. A prototype of the battery/PV hybrid power source has been built, and experimental verifications are given that explicitly substantiate utilizing the PV module adds 13.4 km to the cruising range of a PHEV with the weight of 1880 kg during a sunny day, and provides higher power efficiency (91.1%) and speed (121 km/h). Highly accurate DC-link voltage regulation and producing an appropriate three-phase stator current for the traction motor by using PWM technique are the other contributions of this work. The rest of this paper is organized as follows. The proposed battery/PV hybrid power source is designed and implemented in Section 2. Details about the constructed hybrid power source and experimental verifications are given in Section 3, and the paper is concluded in Section 4.

2. Implementation of the battery/PV hybrid power source proposed for PHEVs

The configuration of the battery/PV hybrid power source proposed to be utilized in PHEVs is shown in Fig. 1. It is composed of a Li-ion rechargeable battery used as the main energy storage device, a bidirectional DC/DC boost-buck converter connected to the Li-ion battery, a single-phase bidirectional DC/AC inverter connected between the battery and grid to provide V2G operation, a PV module used as the auxiliary power source, a unidirectional DC/DC boost converter connected to the PV module, a three-phase bidirectional PWM DC/AC inverter connected the traction motor which is practically a three-phase permanent magnet synchronous motor (PMSM), and a combined power control and maximum power point tracking (MPPT) unit. It is reminded that in a PV system, the MPPT unit tracks the maximum power point (MPP) of the PV module connected to the system (Fathabadi, 2016a). The DC-link voltage is continuously regulated to a designated constant value. Fig. 2 shows the electric circuit of the unidirectional DC/DC boost converter connected to the PV module. The average power efficiency of the converter is 98% and its gain is given as (Fathabadi, 2016b):

$$\frac{V_{dc}}{V_{pv}} = \frac{n}{1-D_{pv}} \tag{1}$$

so, the PV voltage is given as:

$$V_{pv} = \frac{(1-D_{pv})V_{dc}}{n} \tag{2}$$

As mentioned the DC link voltage is a constant value, so in