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Utilizing solar and wind energy in plug-in hybrid electric vehicles

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ABSTRACT

For the first time, this study has provided a renewable energy based replacement for the internal combustion engine of a plug-in hybrid electric vehicle (PHEV). A novel battery/PV/wind hybrid power source is proposed to replace the internal combustion engine with a small-size photovoltaic (PV) module positioned on the roof of the PHEV, and a micro wind turbine located in front of the PHEV, behind the condenser of the air conditioning system. The proposed power source equipped with vehicle-to-grid (V2G) technology is composed of a 19.2 kWh Lithium (Li)-ion battery used as the main energy storage device, and a PV module and a wind energy conversion system (WECS) including the micro wind turbine used as the clean and renewable energy based auxiliary power sources. A prototype of the battery/PV/wind hybrid power source has been constructed, and experimental verifications are presented that explicitly demonstrate utilizing the PV module and micro wind turbine adds 19.6 km to the cruising range of a PHEV with the weight of 1880 kg during two sunny days, and provides a higher power efficiency and speed of, respectively, 91.2% and 121 km/h compared to the normal operation of the PHEV. Highly accurate DC-link voltage regulation and producing an appropriate three-phase stator current for the traction motor by using pulse width modulation (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 electric vehicles (EVs), hybrid electric vehicle (HEV) and PHEVs rather than the vehicles equipped with internal combustion engines [1,2], so that, there is an ascending demand for different types of EV charging stations in many countries [3,4]. A PHEV utilizes its electric motor to power all aspects of propulsion, and is more efficient compared to a traditional HEV that mainly uses an internal combustion engine [5]. The V2G technology implemented in PHEVs is the other benefit that makes them more advantageous and popular [6,7]. In particular, the advantage of a PHEV is highlighted when it is connected to a microgrid or smart grid to manage and balance load demand [8–10]. The activities carried out to improve the technology of PHEVs can be classified into three main categories. The first category focuses on enhancing the quality of the batteries used in PHEVs. Some researches performed in this field are analyzing the battery aging in a PHEV based on the voltage recovery and internal resistance of the battery [11], analyzing the effect of V2G connection on PHEVs' batteries [12], providing a suitable Li-ion battery pack for a PHEV [13], evaluating the impact of ultracapacitors on degradation of the performance of a Li-ion battery [14], and maximization of the income of charging the batteries of PHEVs [15]. The second category consists of the researches proposing some peripheral devices and facilities applicable to PHEVs such as wireless charger [16] and resonant converter based battery charger [17]. The research works belonging to the third category propose different strategies to combine the charging and discharging process of PHEVs with other power sources to satisfy load demand in a grid [18]. In this regard, utilizing PHEVs in a grid to optimize the electrical parameters of the grid by providing distributed demand response was reported in [19], and an energy management scheme applicable to an integrated energy system including PHEVs was analyzed in [20]. The main drawback of a PHEV is that it uses an internal combustion engine 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 state of charge (SOC). It is clear that because of environmental issues, utilizing a gasoline-powered internal combustion engine in a PHEV is not an acceptable solution. A through survey of the current literature explicitly demonstrates that there is not any research work providing a practical solution. However, some researches have been performed to utilize solar energy in some types of vehicles, in particular, small unmanned vehicles. In this regard, a set of required conditions that should be satisfied in a solar powered small unmanned aerial vehicle was introduced and analyzed in [21]. Adding a PV power generation system to a fuel cell electric vehicle was modeled and evaluated in [22]. A microcontroller was designed and proposed to optimally charge a small-size solar-powered robotic vehicle [23]. The use of solar energy in

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Nomenclature

C_1	parasitic capacitance of the N-MOSFET switch of the two converters connected to the PV module and WECS (F)
C_2	secondary-side capacitor of the two converters connected to the PV module and WECS (F)
C_{pv}	input capacitor of the converter connected to the PV module (F)
C_{we}	input capacitor of the converter connected to the WECS (F)
C_{dc}	DC-link capacitor (F)
D_1 & D_2	diodes of the two converters connected to the PV module and WECS
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
D_S	duty cycle of the switching pulse supplied to the switch N-MOSFET S_1
D_{we}	duty cycle of the converter connected to the WECS.
f_s	constant switching frequency of the two converters connected to the PV module and WECS (Hz)
G	solar irradiance on the PV module surface (W m^{-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)
I_{we}	WECS output voltage (A)
L_{lk1}	primary-side leakage inductor of the transformer of the two converters connected to the PV module and WECS (H)
L_{lk2}	secondary-side leakage inductor of the transformer of the two converters connected to the PV module and WECS (H)
L_m	equivalent magnetizing inductor of the transformer of the two converters connected to the PV module and WECS (H)
$n = N_2/N_1$	turns ratio of the two transformers of the two converters connected to the PV module and WECS
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_{char}	sensitivity of the charging power of the Li-ion battery (WΩ^{-1})
$S_{dischar}$	sensitivity of the discharging power of the Li-ion battery (WΩ^{-1})
S_{pv}	N-MOSFET switch used in the converter connected to the PV module
S_{we}	N-MOSFET switch of the converter connected to the WECS
T	PV module temperature (°C)
T_s	switching period of the two converters connected to the PV module and WECS (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_{in}	input voltage of the converter (V)
V_{pv}	PV module output voltage (V)
V_{pv-mpp}	PV module output voltage at maximum power point (V)
V_{we}	WECS output voltage (V)

small capacity electric vehicles was assessed in [24], and it was concluded that solar energy cannot be used in vehicles with realistic weight and size.

For the first time, this study addresses the aforementioned problem by presenting a novel battery/PV/wind hybrid power source to be utilized in PHEVs. In the proposed hybrid power source, the internal combustion engine of a PHEV has been replaced with a small-size PV module located on the roof of the PHEV, and a micro wind turbine located in front of the PHEV, behind the condenser of the air conditioning system. Thus, solar and wind energies have been utilized as clean and renewable energy to extend the cruising range of the PHEV. A prototype of the battery/PV/wind hybrid power source has been built, and experimental verifications are given that explicitly substantiate utilizing the PV module and micro wind turbine adds 19.6 km to the cruising range of a PHEV with the weight of 1880 kg during two sunny days, and provides a high power efficiency of 91.2% and a speed of 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/wind 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/wind hybrid power source proposed for PHEVs

The configuration of the battery/PV/wind 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 WECS used as the other auxiliary power source, a unidirectional DC/DC boost converter connected to the WECS, 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 [25]. The WECS itself consists of a micro wind turbine, a permanent magnet synchronous generator (PMSG), and a three-phase rectifier. The DC-link voltage is continuously regulated to a designated constant value. Fig. 2 shows the electric circuit of the two similar unidirectional DC/DC boost converters connected to the PV module and WECS. The average power efficiency of the converter is 98% and its gain is given as [26]:

$$\frac{V_{dc}}{V_{in}} = \frac{n}{1-D_S} \quad (1)$$