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Off-grid photovoltaic vehicle charge using second life lithium batteries: An experimental and numerical investigation

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HIGHLIGHTS

- ▶ We have examined the feasibility of a second life battery pack for an off-grid photovoltaic vehicle charging system.
- ▶ The second life battery successfully achieved the desired function using simple control methods.
- ▶ The system has been modeled using equivalent circuit techniques.
- ▶ The model can simulate the system's performance under different application scenarios.

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ABSTRACT

Partially degraded lithium batteries from automotive applications, also known as second life batteries, are becoming more available for secondary applications due to the increasing market share of plug-in hybrid and electric vehicles. This study examines the feasibility of installing a second life battery pack in an off-grid photovoltaic vehicle charging system. The system was constructed using a photovoltaic array to charge a battery pack via a maximum power point tracking controller and later charge a vehicle via an inverter. The battery pack was configured using 135 second life $LiFePO_4$ based battery cells, selected based on remaining capacity, connected to form a nine parallel by 15 serial battery pack with accessible storage capacity of 13.9 kW h. Experimental results show that the proposed second life battery system successfully achieves the desired function with a simple system structure and control methods. A numerical simulation was performed by constructing an equivalent system model, where the photovoltaic array and battery pack were modeled using equivalent circuit techniques. The model was parameterized and validated via testing of the system. Coupled with weather data, the model can simulate the system's performance under different application scenarios. The numerical investigation reveals that the proposed system, using second life batteries, can achieve similar performance to systems using new lithium batteries, but at a reduced cost.

1. Introduction

Lithium batteries, with their high power density and long cycle life, are favored as energy storage units for automotive applications. Battery cells are prone to degradation from cycling which leads to capacity fade and increased internal resistance. Lithium battery aging mechanisms have been studied by several other research groups [1–3]. Aged batteries from automotive applications must be replaced to address vehicle safety, efficiency and performance concerns [4]. According to the US Advanced Battery Consortium (USABC) standard for electric vehicles (EVs) batteries, a battery cell has reached its end of life when the current cell capacity has dropped below 80% of the rated capacity or the current power density is less than 80% of the rated power density at 80% depth of discharge (DoD) [5]. The impact of battery pack performance degradation for plug-in hybrid electric vehicles (PHEVs) is less significant, since the performance degradation of battery pack due to aging can be compensated by ICE. As a result, a PHEV battery could degrade more than the USABC standard specifies and still provide value in an automotive application [4]. Consequently, it is expected that battery cells with 80%, or less, of the rated capacity will be retired from PHEV/EV applications and will be available in the second life market.

These partially degraded batteries still have capacity that can be safely used in second life applications with lower cycling c-rates and energy storage demands. As PHEV and EV gain popularity the number of aged vehicle batteries will increase, posing recycling issues and making second life applications more attractive. Second life battery applications can extend the useful battery life,

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Nomenclature

Abbreviations

SPCS	off-grid PV vehicle charge system
NSRDB	national solar resource data base
TMY	typical metrology year
PHEV	plug-in hybrid electric vehicle
EV	electric vehicle
PV	photovoltaic
ECM	equivalent circuit model
SoC	battery state of charge
DoD	depth of discharge
OCV	battery open circuit voltage
FDD	energy full delivery days of SPCS in a year
ICE	internal combustion engine

Symbols

G	sun total irradiance on panel top (W/m^2)
G_b	sun direct bean irradiance on panel top (W/m^2)
α	sun azimuth angle (°)
θ	sun zenith angle (°)
β	PV panel tilt angle (°)
γ	PV panel facing direction (°)
a	coefficient related to panel mount method, −3.56
b	coefficient related to panel material, −0.75
G_T	sun total irradiance on horizontal surface (W/m^2)
ρ_g	sun diffuse reflectance rate, 0.2
G_{ab}	sun direct bean irradiance (W/m^2)
T	panel back temperature
T_a	ambient temperature (K)
WS	wind speed (m/s)
I_p	PV array output current (A)
I_L	photogenerated current (linear with irradiance) (A)
I_0	PV panel diode saturation current (A)
V_p	PV array output voltage (V)
q	electric charge, 1.6×10^{-19} C
R_s	PV panel series resistant
n	PV panel diode quality
k	Boltzmann's constant, 1.38×10^{-23} J/K
n	diode quality factor, 1.5
I_{SC}	PV panel short circuit current (A)
G_{nom}	nominal sun irradiance, 1000 W/m^2
V_{oc}	PV panel open circuit voltage (V)
N_P	number of PV panels connected in parallel
N_S	number of PV panels connected in serial
C_{cap}	battery capacity
C_{polar}	equivalent capacity of battery polarization
R_{ohmic}	battery ohmic resistance
R_{polar}	equivalent resistor of battery polarization resistance
N_{BP}	number of batteries connected in parallel
N_{BS}	number of batteries connected in serial

conserving resources and reducing environmental impacts. Moreover, since lithium ion battery banks are an expensive component in PHEV/EV, promoting second life battery applications will contribute to reducing the life cycle cost of owning a PHEV/EV [6]. Various second life battery applications and cycle life extension strategies have been proposed by researchers including: vehicle to grid applications [7], grid-based stationary applications, off-grid based stationary applications and mobile energy storage applications [8].

PHEV/EVs are promoted as green transportation solutions. However, if a vehicle is charged using electricity from a grid primarily powered by conventional electric power sources (e.g. coal/oil/natural gas), the well to wheel greenhouse gas (GHG) emissions remain high. As a result, implementing green vehicle charging stations is important in reducing GHG emissions. Another potential issue for PHEV/EV adoption is the increased electricity use for charging the vehicle, resulting in expensive electricity bills for PHEV/EV owners. In addition, infrastructure upgrades necessary to meet the increasing grid loads will raise utility expenses [9,10], further increasing costs incurred by PHEV/EV owners. Off-grid photovoltaic (PV) systems account for 8% of overall PV system installation nationwide [11–13] and are beneficial when grid power is unavailable or too costly. These systems are featured as clean, safe and sustainable energy sources [14–20]. Using off-grid PV systems to charge vehicles may help encourage PHEV/EV adoption because of their low emissions, practical storage capacity and modular system size. To develop an off-grid PV system for vehicle charging, energy storage is necessary because electricity harvested by the PV system during the day must be stored for distribution to vehicles at night [21]. The energy storage system should be located in a thermally stable, stationary and contained environment. Since the system does not require high cycle rates, high energy efficiency or very stable performance during cycling and the setup can provide a stable environment, second life batteries may be applicable.

The goal of this study is to examine the feasibility of applying second life batteries in an off-grid PV vehicle charging system by assembling a demonstration system and analyzing the system's performance through numerical simulation and experimental testing. Section 1 describes the system development and design of the second life battery pack. Section 2 details the configuration of an assembled off-grid solar panel vehicle charge system (SPCS) as well as the second life battery pack design procedure. The SPCS numerical model development and experiment methods used to capture the PV and battery model parameters is provided in Section 3. Experimental test data and numerical simulation results are discussed in Section 4.

2. System development

2.1. System configuration

Fig. 1 presents a diagram of the test setup system configuration. The PV modules, made by Solarex, are each rated at 60 W (model MSX-60). The PV array was wired together via six modules in series, and four 6-module strings in parallel with rated power of 1.44 kW. The mounting rack faced south with a slope angle of approximately 30°. A DC–DC maximum power point tracking (MPPT) solar charge controller from Morningstar Corporation (model TS-MPPT-60) was selected to regulate the power that is delivered from the PV array to the battery pack. The peak output current from the controller to the battery is 60 A at 48 VDC. When a vehicle is plugged in, the battery pack discharges via an inverter (3000 W true sine wave DC–AC inverter from Mean Well Enterprises Corporation, model TS-3000) to charge the vehicle. The inverter transfers 48 VDC to 120 VAC and charges the vehicle at 1.44 kW.

2.2. Design of second life battery pack

Two sets of used battery packs were used in this study consisting of 172 lithium ion phosphate cells made by Thundersky (model TS-LFP40AHA). The batteries were categorized into two groups