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Demonstration of reusing electric vehicle battery for solar energy storage and demand side management

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ABSTRACT

This paper demonstrated reusing electric vehicle traction lithium ion batteries for solar energy time shifting and demand side management in a single family house. Batteries retired from electric vehicle usage retain 70% to 80% of their capacity and can be re-purposed as stationary storage system at reduced cost. However, they have mismatched aging conditions and unbalanced state-of-charge levels. Under typical series-parallel connection, the cells in a pack are prone to over charging or discharging due to deviated cycling conditions and misestimated states. The demonstrated battery management system included an extended Kalman filter based states estimator, enhanced current shunting, and protective circuitry to ensure system safety. One novel contribution was the introduction of a worst-difference state-of-charge estimation scheme for the battery pack, which places more computational resources on the battery cell of the worst health. The scheme provided satisfactory overall estimation accuracy and offered a method to optimize computational cost when large number of battery cells was integrated. In addition, a function was proposed to indicate the overall states of the entire energy storage system by aggregating the states of the battery cells within. Therefore, the energy management unit was able to dispatch the battery assembly as a unified pack. Three decision-table-based control strategies were demonstrated with objectives to maximize economic benefits, minimize grid energy consumption, or a balance of both. The data obtained from the demonstrating system located in Davis, CA showed that the battery energy storage system was able to successfully mitigate solar intermittency and energy demand fluctuation by charging from excess solar energy and discharging during the period of peak demand. It reduced daily grid energy consumption by 64%–100% and significantly improved solar penetration.

1. Introduction

The need of grid-connected electricity energy storage (EES) continues to grow due to the furthering penetration of renewables and the increasing demand for a secure and stable grid [1–7]. Pumped hydro is a cost effective (less than 100 $/kWh), durable and efficient (70% round-trip efficiency) EES solution, which accounts for 99% of the grid storage systems operated in the U.S [1]. However, its deployment requires specific geographic location and imposes significant environmental impact. Electrochemical storage systems, such as lithium batteries, lead acid batteries, flow batteries and sodium-sulfur high-temperature batteries [1,8], can provide decentralized, scalable, and responsive EES alternatives. Depending on the cost, their outlook for commercialization varies. As listed in Table 1, 2nd life batteries are batteries retired from plug-in hybrid electric vehicle (PHEV) or electric vehicle (EV) repurposed for a second round of applications. They are expected to provide compatible performance at a reduced cost [3].

An EV battery pack reaches end-of-life when its capacity has dropped below 80% of the rated capacity or its power density has become less than 80% of the rated power density at 80% depth of discharge (DoD) [9]. As PHEVs and EVs gaining popularity, the demand for recycling aged vehicle batteries increases. In the year 2014, the available 2nd life batteries in California could provide 850-megawatt hours of electricity storage capacity, based on the number of EVs expected to be re-purposed [10]. Secondary use is a viable way to extend battery life, reduce the cost of EV ownership and promote recycling. An increasingly renewable-integrated utility grid needs battery storage to improve stability in short-term regulatory actions such as frequency regulation and demand response (DR) [4,11]. and long term bulk managements such as peak shaving, energy time shifting and demand charge [12,13]. A 2nd life battery pack, when properly configured, is able to deliver

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Nomenclature

Symbols

U	Voltage, V
I	Current, a
R	Equivalent resistance, Ω
C	Capacitance, Ah
E	Battery capacity, Wh
τ	Time constant, s
x	State variables
θ	Parameters
y	Output variables
u	Input variables
f	State update function
g	Output update function
w, v	Process/measurement errors
L	Kalman filter gain
ϕ	RLS measurement update
ε	RLS cost function error
z	RLS cost function
α, β	RLS forgetting factors
P	RLS filter coefficient
$TarSoC$	Target SoC to maintain
d	Weighting coefficient

Abbreviations

BMS	Battery management system
DoD	Depth of discharge
EES	Electricity energy storage
EKF	Extended kalman filter
EV	Electric vehicle
MPPT	Maximum power point track
OCV	Open circuit voltage
PHEV	Plug-in hybrid EV
PV	Photovoltaic
RLS	Recursive least squares
SoC	State of charge
SoH	State of health

Subscripts

$BATT$	Battery
$PACK$	Battery pack
$CH, DSCH$	Charge/discharge
$MSMT$	Measurement
BAL	Balancing
H	Hysteresis
O	Battery ohmic
S	Battery transient dynamics
w	Worst battery
i	Battery cell index
j,k	Iteration index
n, m	Index of batteries in parallel/series

equivalent performance as a new battery pack at a lower cost. However, when assembling cells with various capacities, the increased likelihood of a battery pack's capacity imbalance increases the risk of over voltage and/or over current within a battery pack, and therefore requires well-integrated battery management.

The application of 2nd life battery is a timing topic with significant market potential [14]. However, few demonstration projects were presented, and limited performance data was available to provide a clear comparison to other solutions [12]. Also, energy storage plays an important role in smart grid control [15,16]. It is unclear whether 2nd life batteries will deliver the various control objectives. This study presented a real-world demonstration of a PV-battery integrated energy system performing solar energy time shifting and demand side management in a single family home. The performance data was acquired under three different operation modes with unaffiliated tenants in the house. The following tasks were accomplished, with the context of this paper organized accordingly: Section 2, PV-EES integrated home energy system development; Section 3, 2nd life battery pack modeling; Section 4, battery management system development; Section 5, data acquisition and analysis based on system demonstration; and Section 6, conclusion.

2. PV-EES integrated home energy system

As the system diagram illustrates in Fig. 1, A PV array with 12 panels in series was connected to a AC power line via two-step maximum power point tracking (MPPT) converter, providing 2.16 kW of rated power output. A battery pack was assembled with nine batteries in parallel as one bank, and 15 banks in series providing 48 VDC output, 5 kW maximum power capabilities and 12 kWh total capacity. A 48 VDC-120 VAC bi-directional battery converter was deployed. The nominal capacity of the prismatic batteries was 40 Ah. After the application as vehicle traction batteries, these batteries had a remaining capacity of 20–30 Ah. Due to the usage history, the battery pack assembly has imbalances in *SoC*, capacity, and internal resistance, all of which impair its electro performances. An intricate battery management system was applied including automated and manual disconnects, battery balancing and extended Kalman filter based *SoC* estimation. A stitched picture of the developed system is provided in Fig. 2.

3. Second life battery pack

An equivalent circuit model of the selected prismatic LiFePO based battery cell is provided as shown in Fig. 3, in which the battery terminal voltage U_{BATT} is presented as the sum of the open circuit voltage (OCV), the ohmic voltage loss $R_o I_{BATT}$, the overvoltage from battery transient dynamics U_S, and the hysteresis component

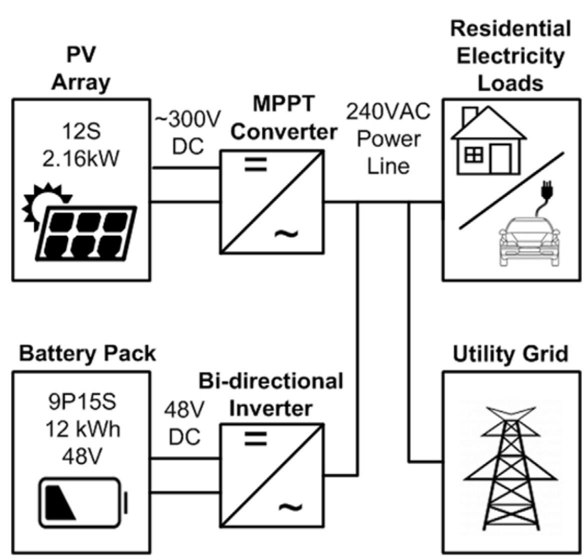

Fig. 1. Diagram of the system energy management layout.