An Electric Vehicle Battery Modular Balancing System Based on Solar Energy Harvesting

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***Abstract* - This paper proposes a solar energy harvesting based modular battery balance system for electric vehicles. The proposed system is designed to charge the battery module with minimum SOC/voltage by solar power during charging and discharging. With the solar power input, the useful energy of the battery can be improved while vehicle driving. For vehicle charging, the charging energy from grid and total charging time can be reduced as well. Simulation analysis shows that for a 50Ah rated battery pack, the overall pure electric drive mileage can be improved by 22.9%, while consumed grid energy and total charging time can be reduced by 9.6% and 9.3% respectively. In addition, the battery life can be improved around 10%~11%. The prototype design and test of a 48V battery pack vehicle consisting of four 12V battery modules are carried out. The experimental results validate that the system has good modular balance performance for the 100Ah battery modules with 5~7A charging current from solar power, and the overall usable battery energy has been increased.**

Index Terms - Batteries balancing, electrical vehicle, solar power, energy storage, state-of-charge (SOC).

I. INTRODUCTION

Battery systems have been widely used in industry, transportation and other applications as energy storage and power source for a long time. In high power applications such as electric vehicles (EV), aircrafts and ships, the battery packs are usually formed by battery modules connected in series to increase the voltage and connected in parallel to increase the capacitance. Each battery module contains cells connected in series and parallel. However, due to manufacturing caused variations and varying operation conditions the imbalances reduce the usable energy [1-5]. Battery pack imbalances may lead to negative results such as early and late charging and discharging process cut-off [6-8]. It can be even more harmful that excessive charging or discharging of battery cells/modules can cause permanent damage [2]. In order to solve the imbalance problem of battery packs, different equilization topologies and control algorithms of battery cell are researched and developed. [2-11].

Due to the advantages of low cost and simple control, passive balancing is one of the most widely applied scheme in battery management system (BMS) [4]. The operating algorithm of passive balancing is simple: when a single cell reaches the charge voltage limit, it will be discharged by a power resistor, which makes other batteries can be fully charged [3, 4]. The other methodology, active balancing circuits balance the battery by transferring energy from cells with high state-of-charge (SOC) to cells with lower SOC. There are three active balancing methods based on the energy transfer components: Capacitior based, Inductor based and DC/DC converter based. Some researches have adopted some of these methods to battery modular balancing [12,13]. However, there is almost no modular balancing applied in productions EVs and modular imbalance could lead to worse over-charge and over-discharge damaging. This is because the battery modules are usually with high energy, thus the energy difference between unbalancing modules is much higher than that of cells. In this case, the balancing power demand, efficiency and heat dissipation will be problems for energy transfer components. As a result, an ideal solution to the modular balancing is to charge low SOC modules with energy source out of the battery pack. In [15], a solar power-based battery modular balancing system is proposed with a storage cell and discharging circuit to actively discharge the battery module with highest SOC/voltage during battery charging. This system may suffer from high cost and complex mode control when applying to production. In this paper, a much simpliefied system is proposed. During battery charging and discharging process, the system records the battery module SOC/voltage and connects the module with lowest SOC /voltage to the solar panel (PV) circuit. When all the battery modules are equilized, the whole battery pack will be charged by the PV with the buck-boost converter. The advantage of this system is that much higher balancing power than traditional cell balancing schemes can be generated by the PV. More important, by harvesting the solar energy, the useful capacitance of the battery pack can be improved during vehicle driving and consumed grid energy can be reduced during vehicle charging.

II. SYSTEM CONFIGURATION

Fig. 1 shows the system architecture of the proposed solar energy harvesting based battery modular balancing system. Take a battery pack with 4 modules in series as an example. The system is formed by a PV, a DC/DC converter and a switch box. The DC/DC converter should be able to charge either the whole battery pack or a single module bu adjusting output voltage. To achieve this, it detects the input and corresponding output voltage, then charges the battery module connected to the output with maximum power point tracking (MPPT) technique. The switch box is used to connect the battery module that needs to be charged to the lowest SOC/voltage output of the DC/DC converter and disconnect the PV when the battery pack is fully charged. The topology of the switch box is shown in Fig. 2.

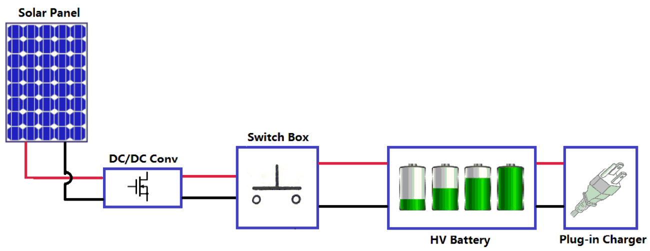


Fig. 1 System architecture of the proposed system.

As shown in Fig. 2, the switch box is formed by 8 digital controlled switches S1-S8. For the battery pack with n modules in series, tthere will be $2n$ switches. These switches can be MOSFETs/IGBTs assembled into a small circuit board integrated into the DC-DC converter or BMS. Therefore, there is no need to modify or redevelop the battery pack, which makes the system easy to be added on. When the system is initialized, all switches are off at beginning. The control unit measures the voltage of each battery module or estimates SOC and commands corresponding switches to connect the battery module with lowest SOC/voltage to the DC/DC converter. Meanwhile, only 2 switches will be closed. For example, to charge module 2, S2 and S5 are off. Switches connected to the same terminal or same polarity of the DC bus must not be closed simultaneously to prevent short through. Dead-band is inserted to switch control signals for short circuit prevention and during dead-band, the control unit makes the voltage/SOC measurements.

When driving the vehicle, the battery pack is being discharged for supplying energy to the powertrain of vehicle. The system charges the module with lowest SOC/volateg by the PV.

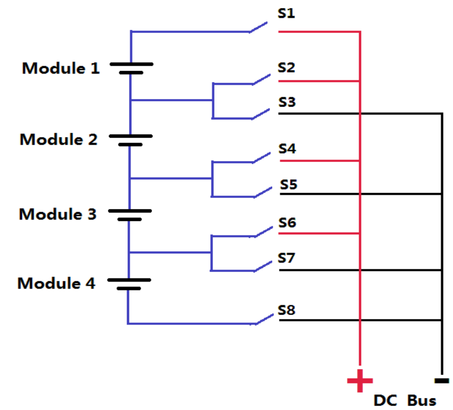


Fig. 2 Switch box circuit topology.

Once all the battery modules are balanced, the system closes S1 and S8 to charge the whole battery pack. Therefore, the solar energy can still be harvested. When the vehicle is parked and charged in the sun, the system works in the same way to fully charge all battery modules. In addition, with the extra solar energy harvested, the total charging time and energy from grid can be reduced. It is noticing that in this scenario, when the battery pack is fully charged, all the switched will be opened to disconnect the PV for preventing over-charge. Table I shows the awitch status of the proposed system. The maximum power the PV provides to is given by

$$P_m = (n_s \times V_m) \times (n_p \times I_m) \times \eta_c \quad (1)$$

Where P_m is the maximum power charged to the battery module by the PV, n_s and n_p are the number of series and number of parallel panels in array. V_m and I_m are the module voltage and current for each panel at maximum power point. η_c is the efficiency of the DC/DC converter.

III. System Modeling & Simulation

The system has been modeled and simulated in order to estimate the improvements on energy saving and battery life. Dynamic balancing performance of the system has been evaluated by the simulation as well.

TABLE I
SOLAR-BALANCING MODE SWITCH STATUS

S1	S2	S3	S4	S5	S6	S7	S8	Charged Module
CLOSE	OPEN	CLOSE	OPEN	OPEN	OPEN	OPEN	OPEN	Module 1
OPEN	CLOSE	OPEN	OPEN	CLOSE	OPEN	OPEN	OPEN	Module 2
OPEN	OPEN	OPEN	CLOSE	OPEN	OPEN	CLOSE	OPEN	Module 3
OPEN	OPEN	OPEN	OPEN	OPEN	CLOSE	OPEN	CLOSE	Module 4
CLOSE	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	CLOSE	Balanced
OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	Fully Charged

The vehicle simulation model is developed in MATLAB/Simulink as a backward model. The input of the model is a standard drive-cycle. A vehicle dynamics subsystem calculates the mechanical power required to overcome road resistance and acceleration drag. A powertrain subsystem including motor and inverter estimates the electric traction power. The battery discharging current is extracted from the electric traction power. The vehicle model parameters are shown in Table II. This vehicle is modeled as a golf car with four 12V/50Ah-rated Li-ion battery modules connected in series with slightly different capacities and internal resistance. Manhattan Bus Cycle (MBC) is choosed as the input drive-cycle. This is because the maximum speed of MBC is 25mph, which describes the driving conditions of most golf cars. The equivalent SOC of the whole battery pack is given by equation (2).

$$\mathrm{SOC}_{\mathrm{all}} = \frac{C_1 \times SOC_1 + C_2 \times SOC_2 + C_3 \times SOC_3 + C_4 \times SOC_4}{C_1 + C_2 + C_3 + C_4} \qquad (2)$$

Where C_1, C_2, C_3 and C_4 are the Ah capacities of the 4 battery modules, respectively.

TABLE II
SIMULATION VEHICLE MODEL PARAMETERS

Description	Value
Vehicle Curb Weight	244kg
Driver and Load Weight	100kg
Vehicle Cross Section	2.37m2
Drag Coefficient	2.51
Rolling Friction Coefficient	0.04
Mass Factor	1.1
Motor Rated/Max Power	3kW/8kW
Differential Gear Ratio	16.82
Motor Efficiency (constant)	90%
Inverter Efficiency	95%
Balancing Efficiency	95%
Module 1 Capacity/Internal R	50Ah/0.00315Ω
Module 2 Capacity/Internal R	49Ah/0.0032Ω
Module 3 Capacity/Internal R	47Ah//0.0033Ω
Module 4 Capacity/Internal R	48Ah/0.0034Ω
Initial Discharge SOC	100%
Initial Charge SOC	20%
Battery Internal Resistance	15mΩ

Three scenarios with proposed balancing schemes and no balancing as baseline were simulated: discharge period, charge period and battery end-of-life (EOL). The solar power input for vehicle discharging balancing is shown in Fig. 4(a) and repeated as necessary. The solar power in Fig. 4(a) is from an actual 100W-rated solar panel onboard charger. The solar panel and the charger have been installed on a vehicle that runs a random city cycle, moves in all directions in sunlight and passes through the shadow of buildings / trees. This makes the data applied to simulation close to real traffic situation. The solar power input for vehicle charging balancing is shown in Fig. 4(b). The solar power curve during charging shown in Fig. 4 (b) was scaled from daylight power of a 3.3kW rated roof solar power system to the 100W on board panels.

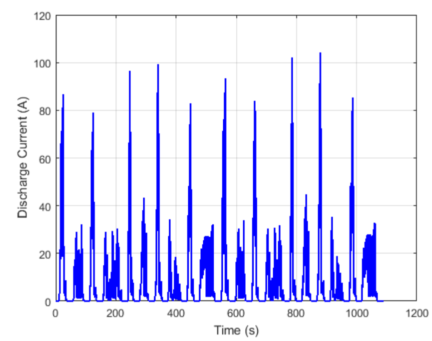
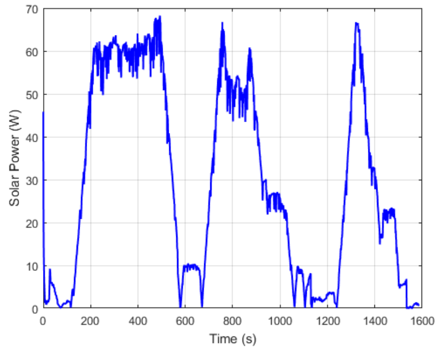


Fig. 3. Battery discharging current of the modeled vehicle for MBC

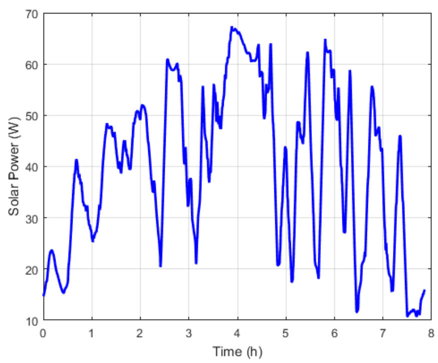
For discharge simulation, the vehicle runs MBCs repeatly to discharge the battery pack SOC defined in equation (2) from 100% to 20%, for with and without solar assisted balancing. From Fig.5(a) it can be observed that the SOC gaps become obvious with the driving time. As a result, the low SOC modules will be over-discharged. However, with the proposed balancing schemes, the SOC difference during driving can be eliminated as shown in Fig.5(b), thus the over-discharging can be prevented. As an extra benefit, the harvested solar energy also improves the battery capacity thus the driving range. As stated in Table III, the pure electric driving range has been improved from 38.28km to 49.63km with the solar balancing schemes, which is around 22.9%.

TABLE III
VEHICLE DISCHARGING TOTAL MILEAGE

With W/O Balancing	No Balancing (Baseline)	Solar-Balancing
Drive Mileage	38.27km	49.63km

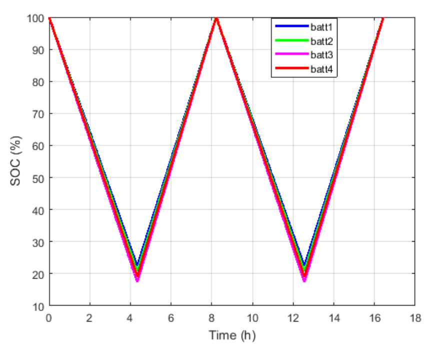


(a) Recorded solar power for a random city cycle.

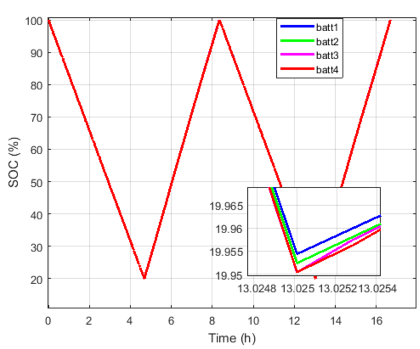


(b) Scaled power of a 3.3kW roof solar system.

Fig. 4. Balancing solar power for vehicle simulation.



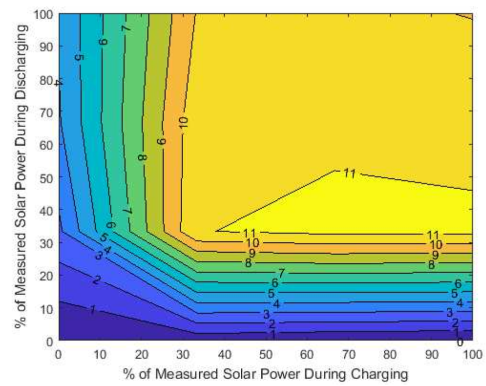
(a) No balancing.



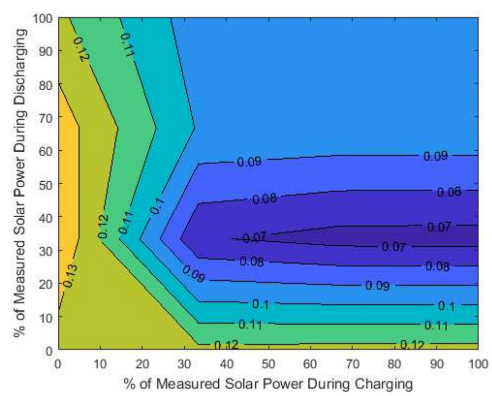
(b) Solar energy harvesting based balancing.

Fig.5. Battery module SOCs during charging and discharging

Constant Current charging algorithm is performed for the charging simulation. All the battery modules are with 20% initial SOC and are charged by 10A constant current from charger. When the battery pack SOC defined in equation (2) reaches 100%, the charging will be terminated. Fig.5 shows the difference of SOC and over-charging issue are not very relevant during charging, so the main benefit of the proposed balancing system is energy and charging time saving by harvesting solar energy. Table IV shows the consumed energy from grid and total charging time for no balancing and solar based balancing. With the balancing schemes based on solar energy harvesting, the total charging energy from grid and charging time can be reduced by 9.6% and 9.3% respectively.



(a) Battery life cycles percentage improvement from baseline.



(b) Battery module imbalace improvement.

Fig.6. Battery module SOCs

TABLE IV
VEHICLE CHARGING GRID ENERGY AND TIME FOR EACH BALANCING SCHEME

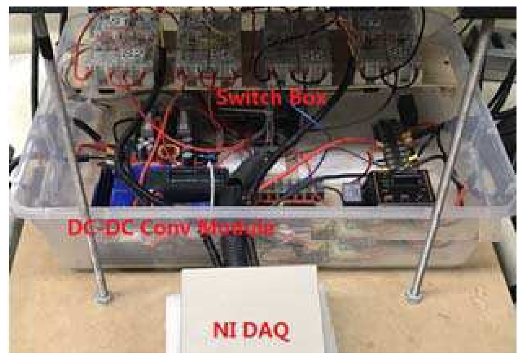
Balancing Scheme	No Balancing (Baseline)	Solar-Balancing	Saved %
Grid Energy	2.195 kWh	1.985 kWh	9.6%
Charging Time	14401 s	13060 s	9.3%

To estimate the life improvement effects of the proposed system, battery end-of-life simulation has been carried out. Firstly, the charge-discharge cycle in Fig.5(a) has been continuously repeated till the capacity of the weakest module, battery 3 reaches 75% of it's original value. Since the battery modules are connected in series, the whole battery pack is considered at end-of-life as the its Ah capacity is limited by the weakest module. The battery capacity imbalance at EOL has been calculated from (max capacity – min capacity)/average [14]. Then the simulation with proposed balancing schemes has been performed, with different level of solar power input during charging and discharging at each cycle. This is because the idea solar conditions in Fig.4 will not be available all the time, considering the senarios that vehicle is driven in cloudy days and charged at nights. Therefore, test cases with solar balancing power during discharging and charging to be 10%, 20%, 30%.... of the recorded values in Fig4(a) and (b) has been generated to form a matrix. Each test case has been simulated till the battery 3 capacity become 75% of it's original value. Then the total charge-discharge cycle numbers as well as the capacity imbalance are compared to the baseline, the results are shown in Fig.5. From Fig.5 it can be observed when average solar balancing power during charge and discharge during battery life beyond 30% of the ideal values, the overall cycles can be improved by 10%~11%. On the other hand, the modular imbalance can be reduced from 0.13 to 0.07~0.08, which indicates a better utilization of all battery modules.

IV. EXPERIMENTALLY PROOF OF CONCEPT

In order to validate the functionality and performance of the proposed system experimentally, a prototype has been developed according to the diagram in Fig. 1 and combined with a vehicle. The vehicle is a golf cart equipped with 48V/3kW electric powertrain. Two 18V/50W-rated PVs are installed on the top of the cart in parallel with the total rated power of 100W. The 48V battery pack of the vehicle is composed of four 12V/100Ah-rated aged lead-acid batteries in series. The vehicle prototype and integrated system are shown in Fig. 7.

(a) Prototype vehicle.



(b) Battery modular balancing system.

Fig. 7 Prototype of the proposed system.

The battery modular balancing system is mounted onboard of the vehicle and connected to the solar circuits. The DC/DC converter is composed of a buck-boost module and a buck module as shown in Fig.8. The buck-boost converter is utilized to output a constant voltage without disturbance on the input side due to cloud, shadow or driving direction change. The buck module auto-recognize the battery terminal volatge and perform the MPPT techniques to charge the battery with optimized output voltage.

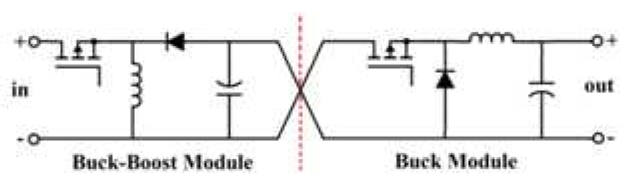
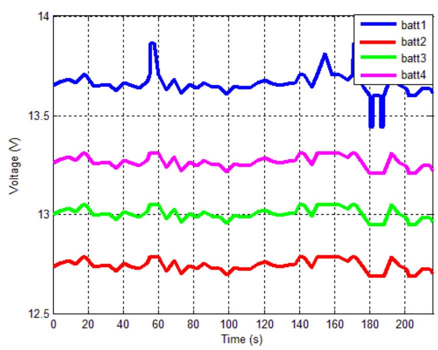


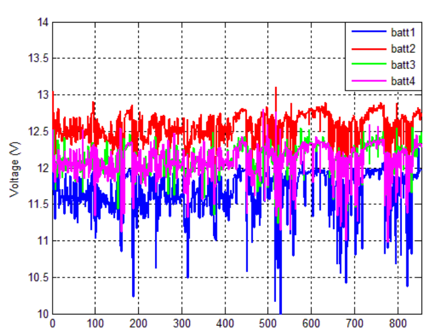
Fig. 8 DC/DC Converter Module Circuit

The control unit of the system is a National Instrument (NI) DAQ connected to an onboard desktop. The NI DAQ monitors the voltage of each battery module and controls the switches S1~S8. Each switch of S1~S8 consists of two solid state relays controlled by DC. The relays are connected consecutively to prevent short circuit. Both the relays are driven by the identical gate signal.

The prototype was tested for the first time without battery balance under charge and discharge conditions, which served as a benchmark for future comparison. When charging, the battery pack was powered by a 48V lead-acid charger supplies 10A/50.8V CC-CV mode. Fig. 9(a) shows the battery module voltages during 220s of charging. It can be seen from the figure that the voltage of battery 1 is higher than other 3 batteries with >1V voltage difference, which means under CC-CV, battery 1 would be over-charged while the remaining batteries will not be fully charged. For discharging, the vehicle was running a random city cycle for 840s without balancing. Fig. 9(b) shows the battery voltages during discharging, where battery 1 has the lowest voltage while battery 2 has the highest, the voltage difference is >1.5V. It can be seen from the charging and discharging voltage that the capacity of the battery 1 is most degraded, while battery 2 is the largest. Battery modular balancing is absolutely necessary for this pack.

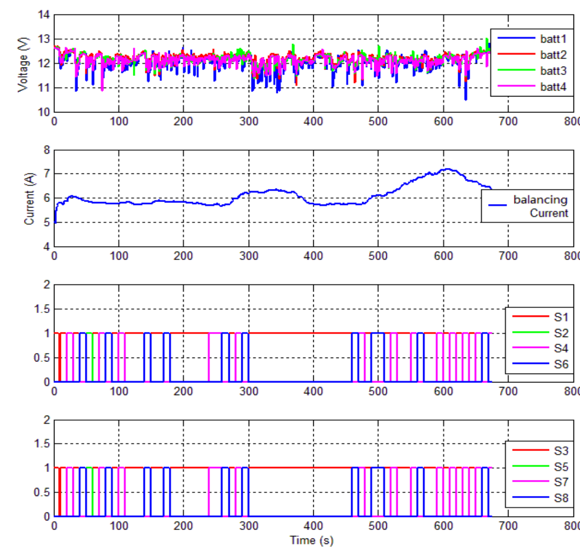


(a) Battery module voltages during charging W/O balancing.

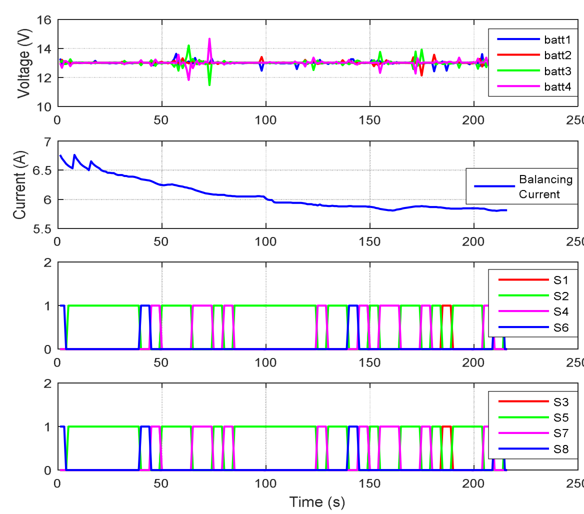


(b) Battery module voltages during discharging W/O balancing.
Fig. 9 Battery module voltages W/O balancing.

For discharging testing, the vehicle was traveling a random city cycle under a sunny weather. Fig.10(a) displays the data of one road test. It can be seen from the switch state that the designed system works normally when selecting different battery modules for charging. The battery pack was well balanced with voltage difference <0.4V by 6~7A current from the PV. For charging testing, the vehicle was parked outdoor and being charger by the same CC-CV plug-in charger. Fig.10(b) shows the data of a 250s charging period, from where it can be observed that the voltage difference is suppressed to <0.2V with 5.5~6A current from PV.



(a) Battery module voltages during discharging with solar balancing.



(b) Battery module voltages during charging with solar balancing.
Fig. 10. Battery module voltages with solar balancing.

V. Conclusions

This paper proposes a modular balance system for electric vehicle batteries based on solar energy harvesting. The system is designed to charge the battery module with the lowest SOC/voltage, or the whole battery pack when all modules are balanced. The proposed system can be applied during both vehicle charging and discharging. With the input balancing power from PV, the battery modules can be balanced faster and more efficient than conventional EV battery systems without modular balancing. At the same time, useful energy can be increased during vehicle driving, while charging energy from grid and charging time can be reduced during vehicle charging with the solar energy harvested. Furthermore, the battery life can also be improved by avoiding over-discharge and over-charge with the balancing. A prototype has been developed on a golf-cart with 100W-rated power PV and fout 100Ah-rated aged battery modules. The actual road testing and charging testing of the system prototype prove the functionality of the system. With 5~7A solar current, the proposed balancing system can successfully balance the battery modules under different discharge and charging conditions.

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