2018 UKACC 12th International Conference on Control (CONTROL)
Sheffield, UK, 5-7 Sept 2018

# Hardware Platform Design of Small Energy Storage System using Second Life Batteries

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***Abstract*— As the number of electric vehicles (EV) increases rapidly, the reclamation and repurposing of used EV batteries into energy storage systems (ESSs) becomes a promising way to extend battery life and to generate extra revenues. This research project aims to design, build and experimentally verify an ESS that is based on the integration of mixed technology and mixed state of health battery modules, and this paper presents the hardware platform construction process of an ESS using second life battery modules. Details on system design, key components selection and commissioning are described. The developed ESS is compatible with a variety of battery modules and forms the foundation of test data collection and algorithm verification for further research on new battery management algorithms specifically for second life applications.**

***Keywords—2nd life battery, energy storage system, hardware platform development, battery management system***

## I. Introduction

Electric vehicles (EVs) are rapidly gaining global popularity these years. Compared with conventional vehicles with internal combustion engine (ICE). EVs enjoy some advantageous features, such as high energy efficiency, low noise and superior acceleration performance. The EV can also significantly reduce the exhaust gas emissions, which shows an effective way for global and local environmental protection. Therefore, many countries are proposing regulations and various financial incentives to increase the penetration of EVs within the transport sector [1].

The performance of the EV depends largely on its battery pack. For a battery EV (BEV) that runs solely on stored electrical energy, the driving range and the vehicle power is determined by the size of the battery, which on the other hand, also constitutes a large part of the overall vehicle cost. Among many battery types, lithium ion batteries (LIBs) are generally preferred for EV applications due to their high power/energy density and long service life [2]. One critical issue is that the LIBs degrade with storage time and cycling usage [3]. As the battery ages, its usable capacity drops and the internal resistance increases, which brings down both the energy and power capacity. It is generally accepted the EV battery has reached end of life (EoL) when the capacity drops to 80% of the fresh cell, i.e., 80% state of health (SoH), which occurs usually after about 5-10 years' service.

As the number of EVs increases rapidly, a great number of batteries will retire from their first-life vehicle applications. Battery reclamation and management is becoming an increasingly important issue [4]. On the other hand, although the retired batteries can no longer meet the high power/energy requirements of the EV, they can still be useful for less demanding scenarios, such as in domestic energy storage system (ESS) [5-7]. It is reported that after 8 years' EV service, the battery pack can still work as an ESS for more than 10 years together with household solar panels [8, 9]. Therefore, by repurposing the retired EV batteries, it can not only avoid a waste of resource, but also earn the EV owners extra revenues, which can counteract to a certain level the high initial EV procure cost [10]. As an example, Nissan and BMW are running programmes to turn their used EV batteries into ESS. The 2nd life battery ESS has a wide range of applications, from MWh (mega-watt hour) ESS for grid support, to tens of kWh (kilo-watt hour) uninterruptible power supply to Telecom or hospitals, to just a few kWh units for household application [8]. One obvious advantage of 2nd life battery ESS is the much lower cost than that with fresh batteries.

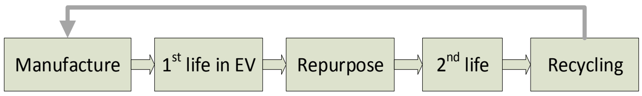


Figure 1 The life cycle of EV batteries

The battery life cycle is given in

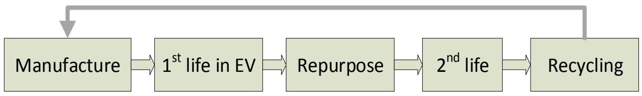


Figure 1. The EV battery can be repurposed at the pack, module or individual cell level. This project focuses on the module level re-aggregation based on the following considerations. First, the imbalance in the battery pack can become significant at the end of 1st life to hinder a direct pack-level reuse. Second, it takes too much effort to disassemble the whole pack into individual cells and then re-assembly into new modules/packs, which is unfeasible economically. On the other hand, the cells within the same module usually experience similar temperature and load conditions, leading to similar aging conditions. Finally, a single module of the BEV usually has a capacity of a couple of kWh, which is enough for small ESSs.

The battery management system (BMS) plays a critical role in the overall battery life cycle [11, 12]. During the first-life EV service, the BMS can protect the battery pack from damages such as over-voltage and over-temperature. Another key BMS functionality is to prolong battery life by implementing smart control logics, such as state of charge estimation and thermal management [13]. Further, the battery history data recorded by the BMS can enable a fast battery characterization and categorization to repurpose the modules according to their different ageing status [6]. Finally, for 2nd life ESS applications, the BMS becomes even more critical since the battery performance degrades and the imbalance among cells becomes a serious issue.

Among many functions of the BMS, including monitoring, modelling, state estimation and control [11], SoH estimation and active balancing stand out as the two most critical for 2nd life battery ESS. The real-time optimization of the battery operation and the end of life prediction depend on the accurate SoH estimation. Besides, active balancing can improve battery performance and extend life, which is particularly important for 2nd life battery applications where the imbalance issue is more critical than new batteries [14, 15]. One aim of this project is the feasibility study of integrating into one ESS battery modules from different EV brands and models with potentially different battery chemistries, size and ageing status. This high flexibility can enlarge the scope of source of 2nd life battery modules to form an ESS. On the other hand, it also requires a smart BMS to deal with the battery variations.

The BMS needs to go through extensive tests before it can be applied to real battery pack. The tests generally include three stages, i.e., software in loop (SiL) test, hardware in loop (HiL) test, and finally plant in loop (PiL) test [16-18]. During the SiL test, the BMS algorithms are verified on a battery model in a software environment; while in the HiL test, both the battery model and the BMS are run in real-time hardware. Finally, the PiL test, where the BMS is tested on real battery pack, is necessary to overcome the limitations of SiL and HiL tests which rely on a battery model that usually has a limited accuracy in representing the real battery dynamics.

This research project aims to design, build and experimentally verify an ESS that is based on the integration of mixed technology and mixed SOH battery modules, and to study BMS algorithms particularly for 2nd life battery ESS. This paper presents the first piece of work on the design and construction of the ESS hardware platform for running tests and data collection, which will underpin future research on the development and verification of BMS algorithms, such as battery modelling, state estimation, and active balancing.

The designed ESS enjoys a high flexibility and is compatible with a variety of 2nd life battery modules. The architecture of the ESS is presented in Section II, with details of all the key components, including the battery local monitoring unit (LMU) and bidirectional DC-DC converter. Commercial products and evaluation boards are purchased from the open market to construct the system. Then commissioning tests are performed in Section III to validate and verify the system for battery test and data collection. This report aims to provide a design reference of ESS hardware platform for researchers interested in BMS technologies, particularly with 2nd life batteries.

## II. SYSTEM DESCRIPTION

### A. *System Requirements*

Since the project aims to study a 2nd life battery ESS with different battery modules, the system requirements are summarized as follows,

1) The system shall accommodate different battery modules, e.g., with different voltage levels (<48V), chemistries and different levels of localised control and monitoring capabilities.

2) The system shall have safety measures to protect the battery modules against over-voltage, over-temperature, over-current and short circuit.

3) The system shall provide an active balancing feature, both among cells within the same module and between different modules;

4) The system shall support automatic test, self-calibration and data collection;

5) The system shall have a graphical user interface (GUI)

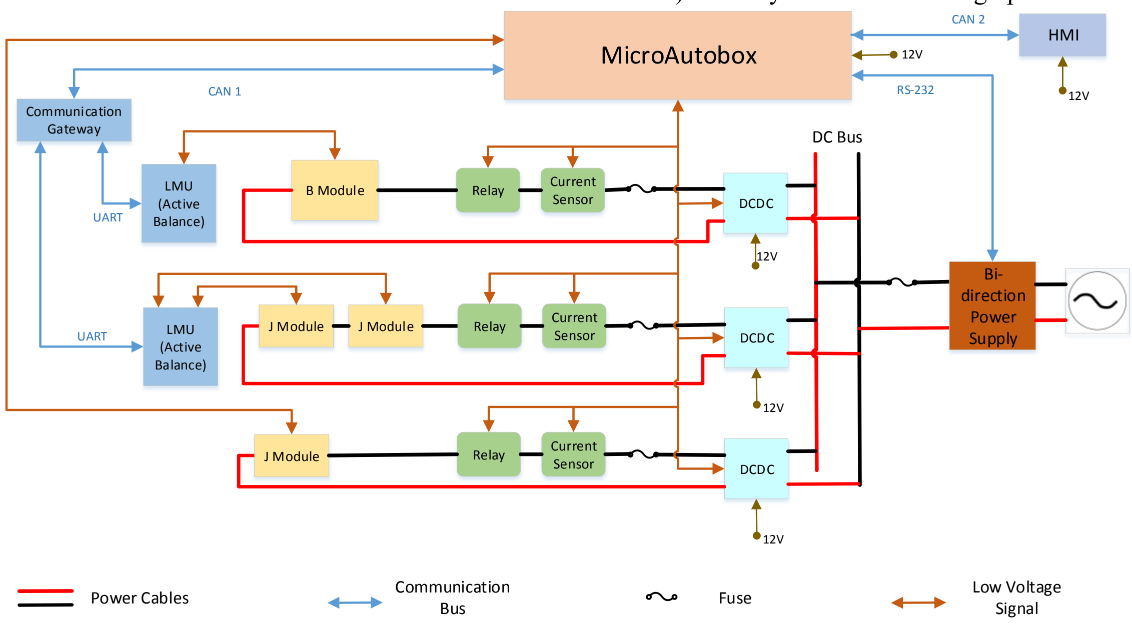


Figure 2 The architecture of the battery ESS

for running test and data visualization.

## *B. System Architecture*

The system architecture and the electrical diagram are given in Figure 2. The ESS currently uses two types of battery modules retired from two different EVs, i.e., B-module and J-module. The batteries are divided into three groups. The first group include one B-module connected directly to the DC Bus (at 44V), and the cell voltages and temperatures are monitored by the new LMU that has an active balancing function. The second group consists of two J-modules (11V for each module) in series, which are then connected to the DC bus through a bidirectional DC-DC converter, and a second LMU is used for monitoring and active balancing. The third group consists of only one J-module connected to the DC bus through another DC-DC converter. A bidirectional power supply is used to charge and to discharge the whole system.

The BMS algorithms are run in the dSpace MicroAutobox, which manages the whole system by controlling the power supply and the DC-DC converters. It also monitors the temperatures and all cell voltages by communication with the LMUs and commands the start/stop of active balancing. It is noteworthy that the cell voltages of the J-module in group three are directly measured by the Autobox without an additional LMU. The BMS also collects other sensing data, e.g., from the current sensors, and actively controls the relays to automatically turn on/off the individual battery groups to protect the battery from hazards such as over-voltage and over-temperature. Bolt-down fuses are used as further protection against accidental short circuit. Finally, a GUI is designed.

## *C. Design Considerations*

The ESS in Figure 2 is designed to be flexible and compatible with a variety of batteries modules. The DC-DC converter decouples the battery modules from the DC bus and thus supports the integration of battery modules at different voltage levels. It also enables active balancing between the battery modules in different groups since the DCDC can transfer energy between the two sides. Another advantage is the additional flexibility of system self-calibration.

Since the EV battery modules may come with their own LMUs, a communication challenge arises when mixing battery modules with different protocols. Therefore, a commination gateway, which supports various protocols such as CAN, UART, SPI and I2C, is adopted between the master BMS in Autobox and the LMUs.

The active balancing LMUs are used since active balancing is considered critical for 2nd life battery ESS.

## *D. System Components*

This section presents the key components of the ESS in Figure 2, including the batteries, LMU and DC-DC converters, and the MicroAutobox that runs the BMS algorithms.

### *1) Battery modules*

The B-module is a LIB pack with 12 cells in series. The cell's rated voltage and capacity are 3.7V and 60Ah, respectively. The pack voltage is thus 44.4V, and the energy capacity is around 2.5 kWh. There are 4 thermistors in the module for temperature measurement.

The J-module also uses LIBs and adopts a 4-parallel-3-series (4P3S) configuration, and each cell is 3.7V 50Ah. The pack is thus 11.1V 200Ah, with an energy capacity of about 2.2 kWh. One thermistor is placed inside each module for temperature monitoring.

Both the J-module and the B-module are taken from EV packs after a few years' service and have been stored at room temperature for extended periods. The history data of the previous usage profile are not available. The visual check and initial voltage characterization conclude that the two modules are both well-balanced. The cell voltage variations in the same module is typically within 5 mV.

### *2) LMU*

The LMU is responsible for voltage and temperature measurement and active balancing between cells. After searching for existing solutions, the EM1402 evaluation board (EVM) manufactured by Texas Instrument (TI) was selected. The key specifications of EM1402 are given in Table 1. More details can be found in the datasheet available on the manufacturer's website.

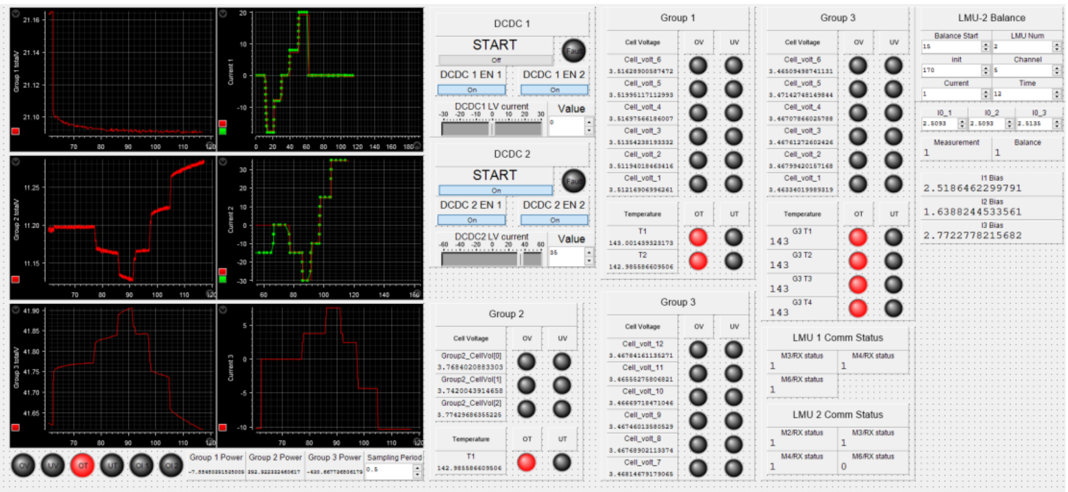


Figure 3 Graphical user interface for charging/discharging test of the ESS

| Table 1 LMU Specifications. *'Temp.'* stands for temperature, and *'Comm.'* for communication | | | | |
|---|---|---|---|---|
| *Supplier* | *Model* | *Core IC* | *No. of Cells* | *No. of Temp.* |
| TI | EM1402 EVM | bq76PL455A | 6-16 | 8 |
| *Cell Vol Error* | *Balance mode* | *Balance Current* | *Comm. Protocol* | *Sampling Frequency* |
| <5 mV | Cell to external source | $\pm 5\,A$ | UART | >20 Hz |

*3) Bidirectional DCDC converter*

A TI evaluation board LM5170 EVM is used as the bidirectional DC-DC converter. The key specifications are given in Table 2, and more details can be found in the associated datasheet.

| Table 2 DCDC Specifications. *'LV'* stands for low voltage, and *'HV'* for high voltage | | | | |
|---|---|---|---|---|
| *LV side* | *HV side* | *Max. Power* | *Control Mode* | *Efficiency* |
| 3-48V | 6-75V | 720W | Current Control | >97% |

*4) MicroAutobox*

MicroAutoBox is a real-time system supplied by dSpace for performing fast function prototyping. The hardware resources include a real-time processor and many different types of input-output (IO) interfaces, such as analogue IO, digital IO, and communication bus (RS232, CAN, LIN). It supports automatic generation of real-time BMS code from Matlab/Simulink. Other dSpace software can help with the design of GUI, automatic test and data collection. As an example, a screenshot of part of the designed GUI for the charging/discharging test of the ESS is given in Figure 3.

## III. System Commissioning Test

A commissioning test is required to validate and verify the ESS for test data collection. Besides the characterization of the accuracy of the voltage and current sensors, which is critical for BMS algorithm verification, the calibration of the actuators, i.e., the DC-DC and active balancing board, is also required.

### *A. Current Sensor*

The Hall current sensor LTS 25-NP is used for current measurement. This current sensor has a 0.2% accuracy and <0.1% linearity error. It also provides built-in galvanic separation between the primary circuit and the secondary circuit, and the sensor's output voltage can be directly measured by the master BMS.

A test is performed on the Hall sensor with static load current, and the results are shown in Figure 4, which demonstrates a high degree of accuracy. The linearization error is less than 0.5mV, which corresponds to circa 20mA current measurement error (with an input-output measurement ratio of 25mV/A). However, when the voltage output of the current sensor is acquired by the MicroAutobox using one of its ADC channels, it adds a further 2-3 mV of measurement error (around 0.1% accuracy) due to the noises on the wires and circuit. Finally, the current measurement error is about 0.1A, within the ±80A measurement range. It is noteworthy that the zero point of the sensor output depends on the voltage supply, which needs to be taken into consideration with only regulated supplies to power the current sensor.

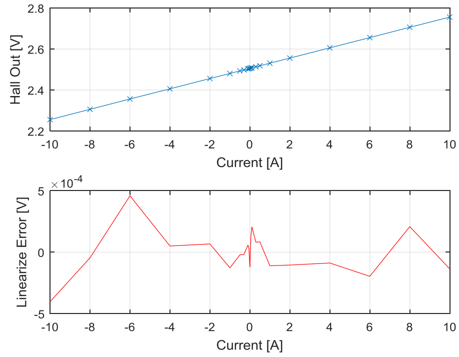


Figure 4 the characterization of the Hall current sensor

The sensor performance under dynamic current load condition has not been tested. The datasheet specifies a frequency range of 100 kHz for DC current with 0-0.5 db noise depression. Considering the BMS measurement frequency of less than 100Hz, this frequency range is more than sufficient and can be assumed instantaneous within the context of controller design.

### *B. Voltage Measurement of the LMU*

The measurement accuracy of cell voltages by the LMU is tested with a static input voltage, and it concludes that the measurement error is around 2-4 mV with the input ranging from 1.5-4.5 V, which covers the typical operating range of LIBs.

One aspect to consider is the synchronization between the current and voltage measurement, since in this ESS design, the currents are measured by the Autobox, and the voltages by LMU. The LMU only starts measurement after receiving a poll command from the Autobox through the communication link, which all together adds a short millisecond delay. This should be taken into consideration when designing the timing of data sampling.

### *C. DC-DC Converters*

The bidirectional DC-DC converter adopts a switching frequency at 250 kHz, and provides fast response that can be assumed instantaneous in the context of BMS controller. After calibrating the current set points, a sequence of step response test is run to verify the DC-DC current control loop, as shown in Figure 5. The test is performed using Group 2 (11 V) and Group 1 (44 V). The positive current stands for boosting. The efficiency of the DC-DC converter was found to be around 97% through experimentation.

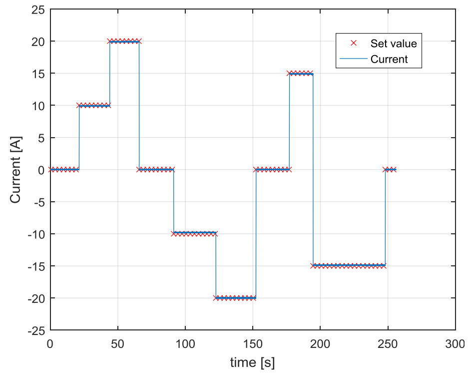


Figure 5 Calibration of the DCDC current control loop

After the current calibration, another test is run using the two DC-DC converters and all the three groups of batteries. The test data are shown in Figure 6. The positive current stands for charging, and, only average cell voltages are shown for each battery group. Figure 6 demonstrates the system's capacity to transfer energy between two different battery groups, i.e., active balancing between battery modules. Note that the battery Group 1 is also serving as the energy buffer on the DC bus.

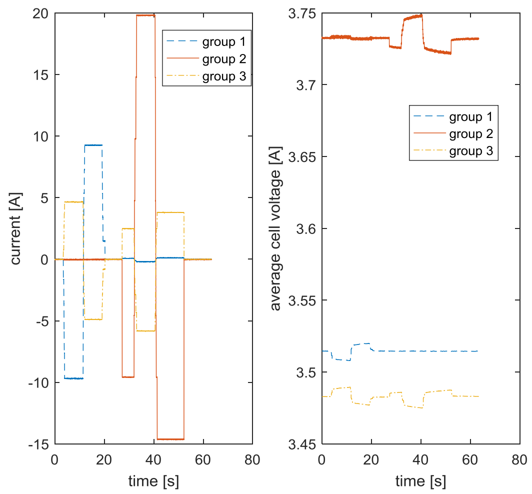


Figure 6 DCDC test for module balancing

*D. Active Balancing LMU*

One problem with the calibration of the active balancing LMU is that the balancing current is not directly measureable. However, according to the EVM datasheet, the balancing current $I_b$ is proportional to a measurable voltage $V_b$, i.e., $I_b = 2.5V_b$, which is used for calibration. A test of active balancing within the B-module is run after calibration of the current control. The cell voltages are monitored, as given in Figure 7, where cell 5 is being charged and discharged several times using the active balancing LMU. First, it shows that the balancing circuit has a fast response (due to the fast switching frequency at 100 kHz). Second, the active balancing has a high impact on the voltage measurement accuracy, due to the current flowing in the shared wires between the balancing and sensing circuits, which not only affects the cell being balanced (cell 5), but also the adjacent two cells (cell 4, 6). Since there is no balancing current flowing into cell 4 and 6, their sudden voltage changes when active balancing turns on are caused by the over-potentials on the sensing wires. Subtracting these two over-potentials from measured voltage on cell 5 will give the true voltage of cell 5.

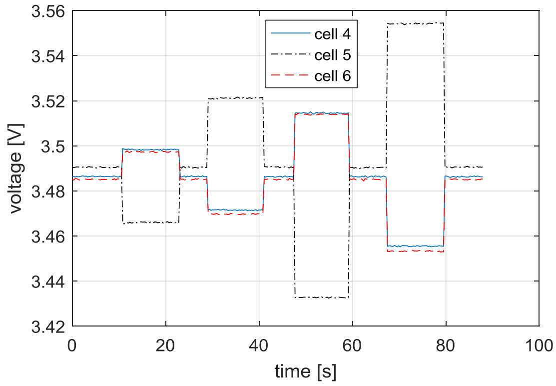


Figure 7 A segment of the battery active balancing test. The balancing current on cell 5 is, in sequence, 0.5A discharge, 0.5A charge, 1A discharge and 1A discharge.

This is an important consideration for the integration of active balancing capability within an existing module and will be the subject of further research into refining the hardware design and also the design of the BMS algorithms. Other components such as the fuses, relay and the bidirectional power supply are also briefly described below, in order to provide a full reference to the ESS design.

*E. Solid State Relay and Fuse*

The Crydom D06D100 solid state relay is used to protect the cells, which has a rating of 60V DC voltage and 100A current. The relay is controlled by the MicroAutobox using a 5V digital output channel to isolate the battery group in the case of over-voltage, under-voltage and over-temperature.

A bolt-down fuse manufactured by Littlefuse is adopted to protect the battery against over-current and accidental short circuit. The fuse has a rating of 100A and 32V.

*F. Bidirectional Power Supply*

An EA bidirectional power supply, model PBS 9000 3U, is used to charge and discharge the whole system. The voltage rating of the power supply is 0-80V, and the current range 0-120A, while the maximum power is limited at 5kW. The power supply has several digital interfaces, such as RS232 and CAN, to control the test, which can be readily integrated into the ESS system to support automatic test and data collection.

*G. Summary of System Features*

The previous test cases have validated and verified that the developed ESS can meet the requirements set in Section II.A. The system features are summarized as follows:

1) The ability to integrate battery modules with different chemistries, voltages (12-48V) and SoH. This feature can enlarge the scope of application of used EV batteries.

2) The ability to support different LMU communication protocols;

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3) The ability to provide battery protection against over-voltage, over-temperature, and over-current;

4) The ability to provide active balancing of cells within the same module, and between different modules;

5) The ability to automatically generate BMS code from Matlab/Simulink for fast function prototype;

6) An automatic test and data collection environment with GUI.

## IV. CONCLUSIONS

This research project studies ESS using retired batteries from EVs, with a particular focus on the experimental verification of mixing various 2nd life battery modules with different chemistry and ageing levels. This paper presents the first part of the research work, i.e., the design and construction of the hardware platform. The designed ESS is flexible and compatible with a variety of battery modules and supports automatic test and data collection.

The future work will study BMS algorithms, such as SoH estimation and active balancing, which are of particular importance to a 2nd life battery ESS. Another objective is to validate and verify smart BMS control logics, such as adaptive model identification, state of charge estimation and load current optimization to prolong the battery service life and to maximize the revenue. The integration of this ESS with a solar panel will also be explored to develop a Micro Grid to support power access in remote areas.

## ACKNOWLEDGMENT

This research is undertaken as part of the Innovate UK funded Project: 2ndhEVen (2nd-Life Energy Storage Systems) and is supported by the WMG High Value Manufacturing (HVM) Catapult.

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