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BYOE: Learning Tool for Lithium-Ion Battery Management System

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BYOE: Learning Tool for Lithium-ion Battery Management System

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Abstract

Electrochemical batteries are the primary selection of energy storage systems in electric-drive vehicles (electric vehicles and hybrid electric vehicles) and renewable energies. As the market share of electric-drive vehicles and renewable energy sectors are increasing, safety and reliability of their battery systems are the top concerns of drivers/users. Battery Management System (BMS) handles all of the monitoring, control, cell balancing, and safety of this high-power battery pack which comprises numbers of battery cells series-connected in long strings. It is challenge to teach and train students in BMS for series-connected lithium-ion battery cells in classroom and laboratory environment due to safety and time consuming. This paper presents the development of an interactive and computer-controlled unit that serves as a learning tool for the BMS. The developed learning tool emulates the battery terminal voltage for up to 12 serially connected cells. By manually changing the cell voltage on the fly, the overcharge, over-discharge and balancing condition of each cell can be emulated for student doing the laboratory experiments. This laboratory unit serves an ad hoc learning tool to two undergraduate courses. The developed BMS learning tool not only enhances the advanced energy storage training and education, but also inspires students' interest in the green movement of transportation and renewable energy.

Keywords: battery management system; electric energy storage; electric vehicle; hybrid vehicle; lithium-ion battery pack; renewable energy

1. Introduction

Electrochemical batteries are the primary choice for energy storage systems in electric-drive vehicles, uninterruptible power supplies, and renewable energies. The on-board energy storage systems, particularly rechargeable battery packs, used for traction purposes are generally more complex systems which integrate hardware and software. As the market share of Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) are increasing, safety and reliability are the top concerns of drivers[1, 2]. Both the safety and reliability are subject to not only the electrochemistry technology but also the management system of the battery pack. The main function of the Battery Management System (BMS) is to ensure that the battery pack is operated within safe limits and achieves optimum performance over its usage life and under a wide range of operating and environmental conditions[3, 4]. The battery pack stores electrical energy from the grid charging (for EV and Plug-in HEV) or produced by the vehicle (for HEV via the internal combustion engine, or during regenerative braking). The battery pack then provides electrical energy for use by the vehicle electric-mode propulsion or for HEV during acceleration and peak power demands. The pack needs to do so in a manner that is safe, reliable, and efficient. This includes protecting the vehicle from voltage surges or drop-outs, preventing harmful conditions, minimizing operational stresses, such as excessive temperature, over-discharging or overcharging that can shorten the life of the battery cells. Therefore, a BMS, as the connector between the battery and the vehicle, plays a vital role in improving battery performance and optimizing vehicle operation in a safe and reliable manner.

In view of the rapid growth of the EV and HEV market, it is essential to develop a comprehensive BMS course materials and laboratory for the electric-drive vehicles and advanced energy storage training and education. However, it is challenge to teach and train students in BMS for series-connected lithium-ion battery cells in classroom and laboratory environment due to safety and time consuming. In typical testing of an industry-scale battery pack, several cycling tests (charging and discharging processes) are required in order to monitor the battery's State of Charge (SOC). It could also take many hours or even days to complete the battery cell balancing procedure. Battery cell voltage measurement also is one of the important parameters for developing controls algorithm for the BMS. Responding to the changing needs of society in vehicle electrification and renewable energy, Wayne State University (WSU) has offered undergraduate degree in Electric Transportation Technology (ETT) and Undergraduate Certificate in Advanced Energy Storage. Several courses have battery related topics, such as ETT4150 (Fundamentals of Hybrid and Electric Vehicles), ETT4310 (Energy Storage Systems for Hybrid and Electric Vehicles), ETT4410 (Advance Energy Storage Systems). However, there is no laboratory exercises associated with these 3-credit hour courses due to considerable amount of lecture materials to be delivered in the classroom. Previous learning outcome assessments indicated that most of the students had doubts about some functions of the BMS, such as SOC prediction and cell balancing[5].

The motivation of this project is to develop an interactive and computer-controlled unit that serves an ad hoc learning tool to the BMS context in battery related coursers. This paper presents the upgrade of previous learning tool[5] with exchangeable battery cells and updated software. The enhanced learning tool emulates the battery terminal voltage for up to 12 serially connected cells. Each cell's voltage can be manually adjusted to simulate SOC changes. Connecting this multi-channel battery emulator to a Linear Technology LTC6802 BMS board[6], a safe and quick learning environment can be realized. By manually changing the cell voltage on the fly, the overcharge, over-discharge, and balancing condition of each cell can be emulated and the results can be displayed on the computer monitor via LTC6802 software. The integrated system is computerized for measurement and control hence it is comprehensive and visualized for student doing the laboratory experiments. The developed BMS learning tool not only enhances the advanced energy storage training and education, but also inspires students' interest in the green movement of transportation and renewable energy.

2. Overview of Battery Management System

For an electric-drive vehicle, the battery pack power and energy specifications are dictated by the vehicle's performance and driving range requirements. The battery pack is built up from low voltage, low capacity cells to enable higher voltage and capacity system. The battery cell voltage is fixed by its electrode chemistry. The battery pack needs series connections between cells to increase voltage capacity, and parallel connections to provide required capacity. The power and energy capabilities of a battery pack greatly depend on its operating conditions: charge/discharge current rate, SOC, load characteristics, and temperature. Furthermore, it is important to avoid the circumstances that could damage the battery cell or trigger off safety issues for the surrounding environment. Especially for battery chemistries like the lithium-based ones connected in a high-power context. Due to volatility, flammability and entropy changes, a lithium-based battery could be ignited if overcharged. This is a serious concern, especially in EV and HEV applications, because an explosion could cause a fatal accident. Moreover, over-discharge causes reduction of cell capacity due to irreversible chemical reactions.

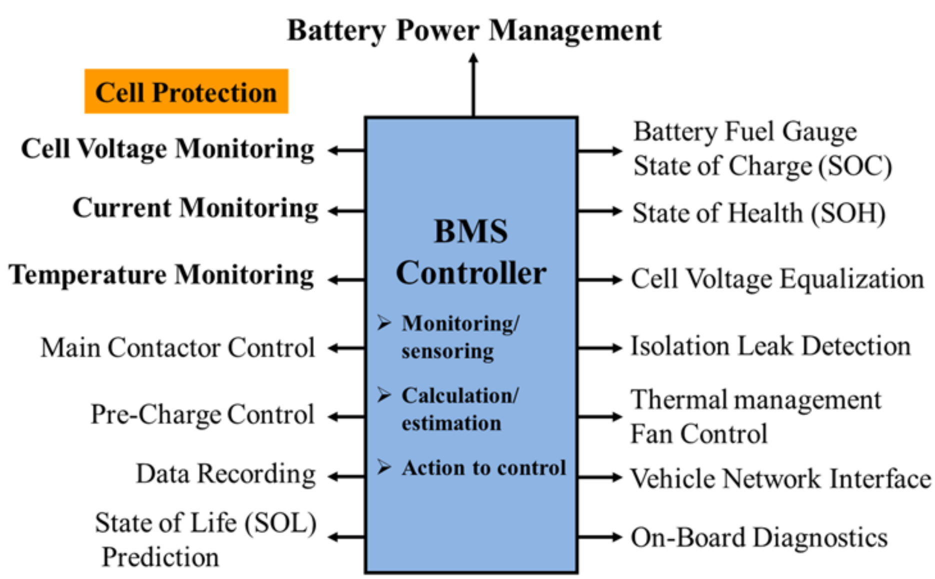

Figure 1. The comprehensive BMS functions

A BMS is an embedded system that is purpose-built electronics plus processing to monitor and control the battery pack. Similar to the engine control unit in a fossil fuel car, a gauge meter will be provided by the BMS in EVs and HEVs. The BMS gauge indicators show the state of the safety, usage, performance, and endurance of the battery pack. As illustrated in Fig. 1, a comprehensive BMS should include the following functions[7]:

(1) Protect the safety of vehicle operator and passengers,
(2) Detect unsafe operating conditions and responds,
(3) Protect the cells from damage (abuse/failure cases), and prolong the life of the battery (normal operating cases),
(4) Maintain the battery in a status which it can fulfill its functional design requirements, and
(5) Inform the vehicle controller how to make the best use of the battery pack (maximum power limits), control the charger, and so forth.

The BMS does not directly control the electrical usage of the battery since a vehicle master controller is responsible for managing energy to propel the vehicle. The BMS monitors and provides accurate data on the state of the battery to the master controller algorithm for proper, safe and reliable operation. The activities of a BMS are typically classified into six areas[8].

(1) Measuring: Measurable characteristics of the battery cells and pack are quantified. Typical measured quantities are voltages, currents, and temperatures, either at the single cell or at the battery pack level.
(2) Computing: The measurement data is processed to determine additional indirectly measurable information. These include the calculated (or estimated) quantities like the SOC, State-Of-Power (SOP), State-Of-Health (SOH), and State-Of-Life (SOL). The SOC and SOP indicate the remaining energy capacity and the instantaneous power availability, respectively. The SOH quantifies the performance deviation from original condition due to aging.
(3) Monitoring: Some of the measured or calculated characteristics are checked against pre-defined thresholds. A warning is issued in case the measurement violates the critical threshold.
(4) Communicating: The information from monitoring, measuring, and calculating functions is provided to other subsystems or devices in a useful manner.
(5) Control: The BMS may have direct control on critical aspects of the battery pack, such as interrupting current during charge or discharge, or altering the thermal management system.
(6) Balancing: Cells are usually matched during the assembling of battery modules and pack. Over time, an imbalance in the SOC may develop between cells and reduce the overall capacity of the pack. This can be due to slight differences in self-discharge, temperature, or many other factors, between cells. In practice, the cells will be unbalanced, and one cell will be the first to be fully charged and then be overcharged. Once a cell is fully charged, it cannot take more current while the other cells in series still get their needed charge. Continue charging the fully charged cells will rapidly increase the voltages of those cells and possibly to dangerous levels. Implementing a control strategy that equalizes the SOC of the cells allows the battery pack to operate safer and longer.

3. Establishment of a BMS Learning Tool Unit

The BMS of an electric-drive vehicle battery pack comprises hardware and software to monitor pack status and optimize performance. One of its important functions is to execute algorithms that continuously estimate battery SOC, SOH, and available power. The objective of the learning tool is to provide students with hands-on experience on industry standard multi-cell lithium battery measurements and control functions. The developed learning tool utilizes commercially available hardware and software in BMS. The scope of the learning tool development includes software and hardware integration, hardware interface setup, and experiments design. There are 3 circuit cards for the unit setup as shown in Figs. 2 and 3. First, a battery module consists of 12 cells (18650 size) are serially connected which can provide 12 sensor data of cell voltages and two temperature data. The other two circuit cards are from Linear Technology[9, 10]. The main circuit card is the Cell Voltage Measurement Board (DC1393B) which provides interface to the battery module. The USB Interface Board (DC590B) receives the commands from computer and communicates with the Cell Voltage Measurement Board. To lower the overall battery module voltage and protect cells during short condition, a 1Amp fuse is installed in the connections between cell number 6 and 7. The fuse serves as a manual switch and it needs to be plugged in for normal operation. In the event of a short, the fuse will be blown to prevent over-discharge of the battery cells.

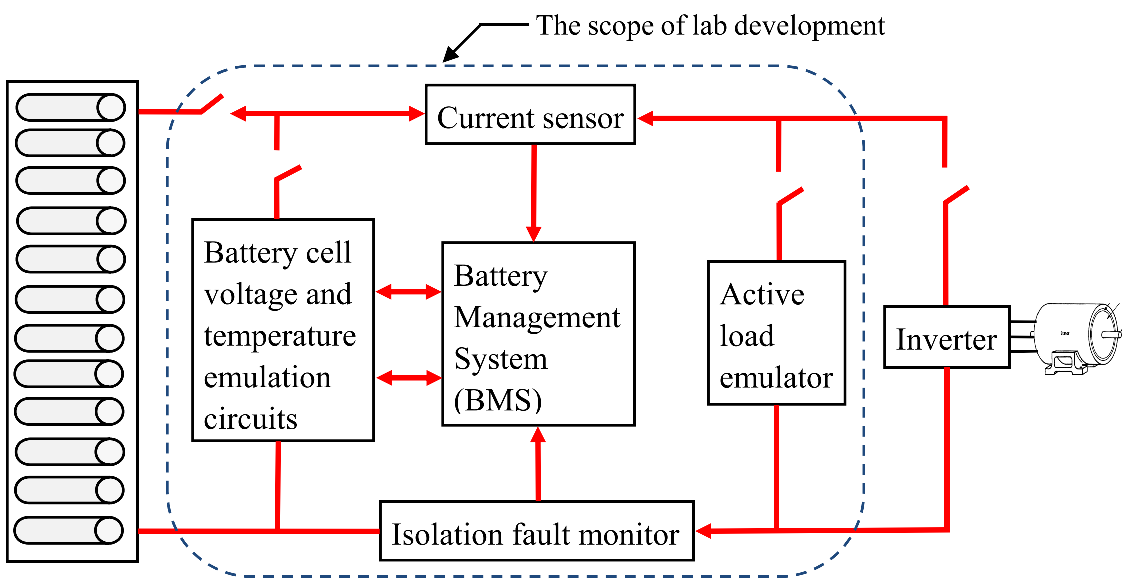

Figure 2. Layout of the learning tool

3.1 Software Integration

From the graphic user interface on PC, the student can perform several battery management functions, such as reading voltage of individual cell and module, identifying circuit faulty conditions, changing voltage thresholds, and discharging individual cell for cell balancing purpose. The student has the opportunity to key-in the commands to the computer and control each function. In a real BMS operation, these functions will be operated by a pre-programmed microprocessor and data can be transmitted to other controllers. The graphic user interface provides the following eight operating functions as illustrated in Fig. 4.

(1) Set board address
(2) Read configuration
(3) Program cell voltage monitoring thresholds
(4) Write configuration
(5) Read cell voltages
(6) Read temperatures
(7) Discharge cells
(8) Read fault flags and warning messages

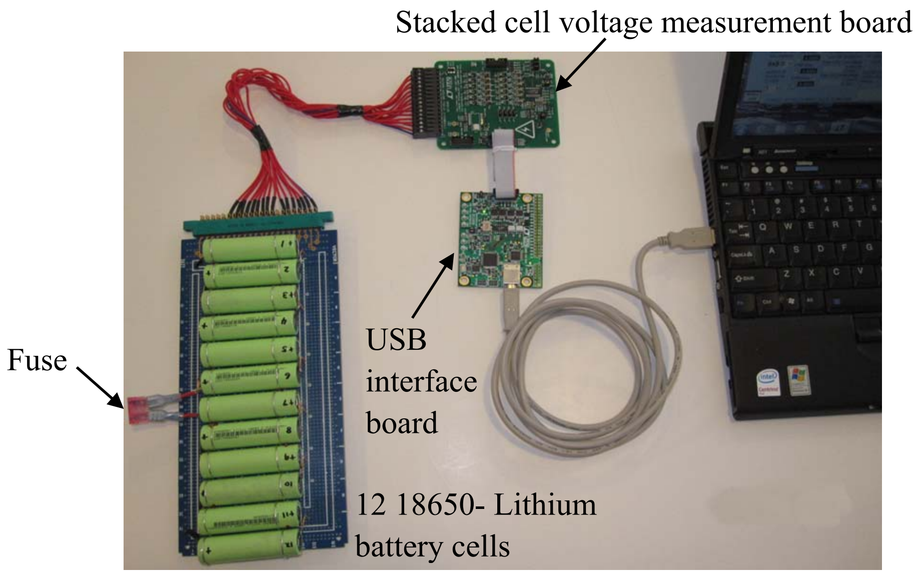

Figure 3. The developed learning tool for BMS

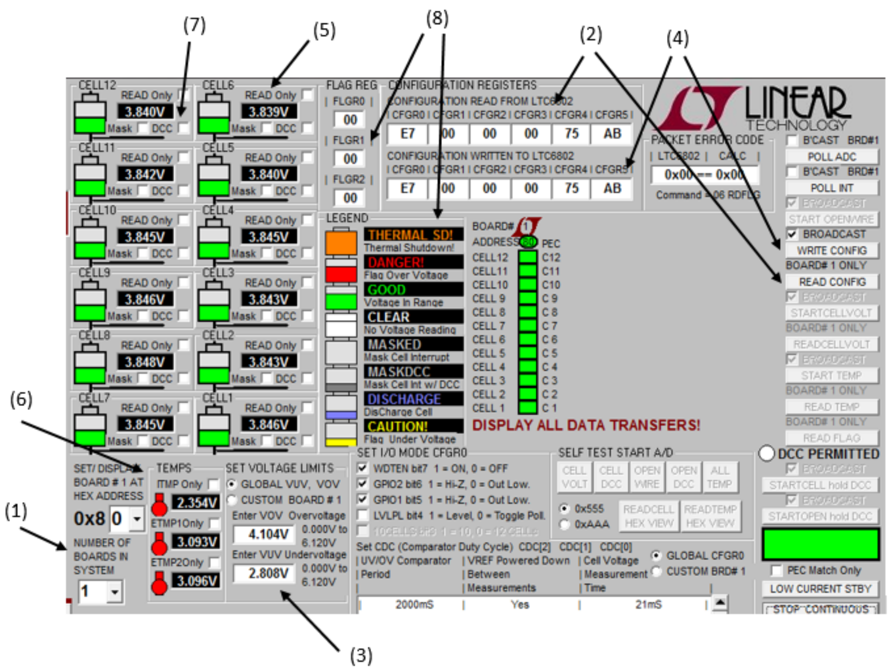

Figure 4. Indication of eight operating functions

3.2 Hardware Interface Setup

This section describes the hardware specifications and the installation procedure.

(1) Connect computer to DC590B USB Interface Board
(2) Connect a ribbon cable from DC590 to the Main connector of DC1393B
(3) Set jumpers on DC1393B to the default positions indicated in Table 1
(4) Install a DC590 driver before running the DC1393 GUI. To do this, install the Quick Eval Software[11]. After installation, close the DC590 driver program and launch the GUI control program. When the DC590 board recognizes the String ID code from the DC1393B board, the program will display the control screen. The program will not operate unless the DC590 is connected to the computer as well as the DC1393B board.
(5) Connect the cells which are to be monitored to the cells connector J1. This connector is in two pieces. The setscrew piece can be unplugged to make it easier to attach a wiring harness from the number 4 to 12 cells battery stack. The LTC6802-2 is intended to measure from the number 4 to 12 individual cells for a total stack voltage of 10V to 60V. If fewer than 12 cells are to be monitored, the bottom cell of the stack should always be connected as Cell-1 between terminals J1-5 (cell positive contact) and J1-4 (cell negative contact). Terminals J1-4 and J1-1 are the ground reference points for the battery cell stack and the DC1393B board.
(6) Inserting the setscrew piece into connector J1 will apply power to the board from the battery cell stack.

Table 1. Default indicator on DC1393B

JUMPER	FUNCTION	DEFAULT POSITION	"1" POSITION	"0" POSITION
JP1	Two Jumper Block to Select Voltage or Current Mode for Bottom SPI Port	Voltage Mode	Labeled "V" on board. Sets bottom port for voltage mode SPI communication.	Labeled "I" on board. Sets Top and Bottom ports for Current Mode SPI communication using external daisy-chain current source circuitry.
JP6,JP7,JP8,JP9	SPI Daisy Chain Configuration Jumpers: **(All Four Jumpers Must be Moved Together)**	1, 1, 1, 1 Top of Stack (TOS) Setting	For V Mode communication to all boards set all four jumpers to the 1 position. For SPI daisy chain communication this setting is required for only the board at the top of a cell stack. These settings connect the top daisy chain current source transistors to the top cell at the top of the cell stack.	For SPI daisy-chain communication set all four jumpers to the 0 setting. This enables the top port on each board for current mode communication up the stack. Use these settings also for the bottom board in a daisy chain stack which should be set to V mode (JP1) for the bottom port communication to a system controller.
JP2,JP3,JP4,JP5	Board Address Setting (0000 to 1111) JP2 is MSB JP5 is LSB	0, 0, 0, 0 (for address 0000)	Logic '1' setting	Logic '0' setting

4. Integration of an Ad Hoc Learning Tool

The department offers several battery related courses, ETT4150 (Fundamentals of Hybrid and Electric Vehicles), ETT4310 (Energy Storage Systems for Hybrid and Electric Vehicles), and ETT4410 (Advance Energy Storage Systems). There is no formal laboratory associated with these

3-credit hour courses due to considerable amount of lecture materials to be delivered in the classroom. Two of the courses have utilized this ad hoc learning tool which provides students with practical, hands-on experiences and encouraging students to 'learn by doing.' The descriptions of the courses are listed in this section. In ETT4310, the electrochemistry topic is an introduction-level subject which normally needs two classes time (six hours). To utilize the developed ad hoc learning tool, the lecture hours of the electrochemistry is reduced to four hours with less detail covered. Such that students have two hours using the tool for laboratory exercise. Similarly, the lecture topic of hydrogen electrochemical cells was removed in order to free two hours to using ad hoc laboratory in EET4410.

4.1 Course short descriptions

ETT4310 Energy Storage Systems for Hybrid and Electric Vehicles
Comprehend hybrid vehicle battery systems development and design, including electric system packaging, mechanical structure, thermal management, performance, volume/size, and safety issues. Battery technologies including lead acid, nickel metal hydride, and lithium ion batteries will be provided together with their applications to vehicle hybridization and electrification. Vehicle on-board energy storage system principles, including cells, batteries, chemistries, cycling, specifications and performance requirements, high voltage battery system design, control, and management will be presented.

ETT4410 Advance Energy Storage Systems
This course provides brief coverage of energy storage for automotive and renewable energy. The necessity for efficient energy storage; storage in automotive, consumer, nuclear and green industries; battery technologies including primary and secondary electrochemical cells; lead acid, nickel based, Li-ion batteries; advanced battery systems and hydrogen electrochemical cells; mechanical energy storage; thermal and chemical storage; inductive storage based on superconducting magnetic field; social and economic aspects of storage technology, specific new developments in storage.

4.2 Assessment of learning outcomes

The impact of the developed ad hoc learning tool on students was assessed through evaluation of Student Outcomes at WSU as part of the normal Accreditation Board for Engineering and Technology (ABET) assessment process. The standard evaluation was carried out in the form of end-of-semester student surveys in which students were asked to rate if they agreed that they had mastered the learning outcomes specified in the courses. The results of the surveys are shown in Table 2. Students indicated their response by selecting from five options: Strongly Agree, Agree, No Opinion, Disagree, or Strongly Disagree. Internally, the department has set a target of 75% of students being in the 'Agree' or 'Strongly Agree' categories as an indicator of success on achieving any given outcome. As can be seen in Table 2, the evaluations show that students met the desired level of performance in all the competency outcomes assessed.

Table 2. Course assessment results

Course	Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
ETT4310 Energy Storage Systems for Hybrid and Electric Vehicles					
Apply in-vehicle energy storage system principles in HEV battery system design, control, and management.	84%	16%			
Comprehend hybrid vehicle battery systems development and design, including electric system packaging, mechanical structure, thermal management, performance, volume/size, and safety issues.	80%	20%			
Apply knowledge on electrical system packaging and heat generation in solving battery thermal management issues	47%	43%		10%	
Determine failure mode avoidance and fail safe strategies for battery related systems	77%	23%			
ETT4410 Advance Energy Storage Systems					
Understand the fundamentals of energy and the latest development of sustainable energy	84%	16%			
Explain the energy conversion and the need for energy storage systems	80%	20%			
Understand the fundamentals of electrochemistry	47%	43%		10%	
Analyze pros and cons of various types of energy storage systems and their applications	77%	23%			
Analyze pros and cons of various types of electro-chemical energy storage and their applications	52%	36%		7%	5%

5. Conclusions

The developed BMS learning tool is able to emulate the battery terminal voltage for up to 12 serially connected cells. It serves as hands-on experience workstations for students with multidisciplinary backgrounds who are enrolled in the battery related courses. The integrated system is computerized for measurement and control hence it is comprehensive and visualized for student doing the laboratory experiments. Therefore, the learning tool augments the students' knowledge on the BMS which performs important functions for the lithium-based battery systems. We also hope the hands-on experience would inspire students' interest in the green movement of transportation and renewable energy.

Acknowledgements

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