



# Article Lithium-Ion Polymer Battery for 12-Voltage Applications: Experiment, Modelling, and Validation

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Abstract: Modelling, simulation, and validation of the 12-volt battery pack using a 20 Ah lithium-nickel-manganese-cobalt-oxide cell is presented in this paper. The cell characteristics influenced by thermal effects are also considered in the modelling. The parameters normalized directly from a single cell experiment are foundations of the model. This approach provides a systematic integration of actual cell monitoring with a module model that contains four cells connected in series. The validated battery module model then is utilized to form a high fidelity 80 Ah 12-volt battery pack with 14.4 V nominal voltage. The battery cell thermal effectiveness and battery module management system functions are constructed in the MATLAB/Simulink platform. The experimental tests are carried out in an industry-scale setup with cycler unit, temperature control chamber, and computer-controlled software for battery testing. As the 12-volt lithium-ion battery packs might be ready for mainstream adoption in automotive starting-lighting-ignition (SLI), stop-start engine idling elimination, and stationary energy storage applications, this paper investigates the influence of ambient temperature and charging/discharging currents on the battery performance in terms of discharging voltage and usable capacity. The proposed simulation model provides design guidelines for lithium-ion polymer batteries in electrified vehicles and stationary electric energy storage applications.

**Keywords:** battery modelling and simulation; battery testing cycler; battery thermal model; lithium-ion polymer battery; SLI battery

# 1. Introduction

Lead–acid-based batteries have a long-term historical usage in the automotive and stationary standby power market, ranging from 12-volt high-power such as automotive starting–lighting–ignition (SLI) applications, low-power applications such as emergency lighting or uninterruptible power supplies (UPSs) for individual computers, to high-power, high-voltage electric energy storage in renewable energy systems or UPSs telecommunications facilities. Typical lead–acid batteries have several problems including high self-discharge rate, relatively heavy and large, and shallow depth of discharge (DOD). For the past decades, lithium-ion batteries have been widely used in portable electronics due to their features of high energy density, high discharge power, and long cycle life. The emerging applications of the lithium-ion batteries to electric-drive vehicles and large-scale energy storage systems for renewable energy make them a promising solution for challenges of environmental preservation and resource conservation [1,2]. The lithium-ion battery is also a suitable replacement for the conventional 12-volt SLI lead–acid battery; for example, Porsche offers an option of a lithium-ion SLI battery [3], and some medium-duty truck manufacturers use a lithium-ion battery for 12/24 V electrical systems [4,5]. The lithium-ion polymer battery uses a high conductivity semisolid (gel) polymer electrolyte instead of a liquid electrolyte. The battery cell voltage depends on the electrode material

chemistries. The lithium–metal–oxide-based (such as LiCoO<sub>2</sub>) cell has 2.5–2.8 V fully discharged voltage and 4.2 V fully charged voltage, while the lithium–iron–phosphate-based (such as LiFePO<sub>4</sub>) cell has 1.8–2.0 V fully discharged voltage and 3.6–3.8 V fully charged [6,7]. The lithium polymer battery has higher specific energy than do other lithium-based batteries [6]. The polymer electrolyte gives the lithium polymer battery more stable performance under vibration conditions. These two features have led to the promotion of lithium polymer batteries in electric-drive vehicle applications.

The lithium-ion batteries, however, still encounter some roadblocks that complicate their applications. One of the major roadblocks is temperature influence on the operation of lithium-ion batteries. The operating temperature of a battery is the result of ambient temperature augmented by the heat generated by an electrochemical reaction. Operating temperatures from -20 °C to 60 °C is a typically acceptable range for lithium-ion batteries [8]. Pesaran et al. [9] presented that the optimal temperature range for lithium-ion batteries is from 15 °C to 35 °C, which is similarly comfortable for humans. To avoid a severe temperature gradient that might lead to different degradation rates and unbalanced cells, 5 °C should be set as the maximum temperature difference from cell to cell within a module [9,10]. The impacts of temperature can generally be considered as low and high temperature effects [11]. At low operating temperatures, the lithium-ion batteries experience slow chemical reaction and charged transfer-rate, which decrease ionic conductivity and diffusivity [12,13]. Therefore, the battery energy capacity and power are reduced at low temperatures. At high temperatures, the energy capacity and power are degraded, respectively, due to loss of the reduction of active materials and increase of internal resistance [14]. Self-ignition and even explosion caused by thermal runaway may happen if the temperature is too high. The effects caused by low battery temperature mostly occur during low ambient temperatures, while the effects induced by high battery temperature could occur either in low or high ambient temperatures. For an example, the battery temperature could highly increase at a large discharging current even in a low ambient temperature environment. The ambient temperature dominates in low temperature effects, and the battery internal temperature during operations plays a more important (than ambient temperature) role in high temperature effects.

The battery cell characteristics are determined by the electrode materials, electrolyte materials, cell size and shape, as well as the operating conditions including temperature, charging, discharging current, etc. The cell characteristics are essential parameters in battery pack design, thermal management system design, and battery management control. The battery cell characteristics typically are acquired through a series of charging and discharging experimental tests, which are time-consuming and require several pieces of equipment, such as a cycler, temperature chamber, and device for data acquisition. Analytical approach uses certain numbers of cell parameters gathered from less experimental tests to form a mathematical model. The battery model is also helpful for predicting parameters that cannot be directly measured by any sensors, such as state of charge (SOC), state of health (SOH), and state of life (SOL). Model-based estimation algorithms are usually used to compute or estimate theses parameters [15,16]. Nevertheless, a high-fidelity battery model is required to obtain accurate simulation results. Many battery models have been developed ranging from simple models with a few parameters to complex models having a large number of parameters [17–27]. The common battery modelling approaches are electrochemical, mathematical or analytical, and electric circuit-based model [28,29].

This paper describes the development and validation of an electric circuit-based Simulink model of the lithium–nickel–manganese–cobalt–oxide (LiNiMnCoO2)-based cell with 3.6 V nominal voltage and 20 Ah capacity. The thermal effects on cell characteristics are also considered in the model. The experiments apply several charging and discharging currents to the battery cell and module that are enclosed in a chamber with controlled temperatures of -20 °C, -10 °C, 0 °C, 20 °C, and 50 °C as the ambient temperatures. The experimental data are used to calibrate the model parameters. A 12-volt battery pack (14.4 V, 80 Ah) model is built based on validated simulation models of a battery cell and module. This SLI-type pack has four parallel-connected modules where each module (14.4 V, 20 Ah) consists of four cells connected in series. As the 12-volt lithium-ion battery packs might be ready for mainstream adoption in automotive SLI, micro-hybrid (or stop–start engine idling elimination), and

UPS applications, this paper investigates the ambient temperature effect on the battery performance in terms of discharging voltage and usable capacity. The proposed simulation model provides design guidelines for lithium-ion polymer batteries in electric-drive vehicle and stationary UPS applications.

#### 2. Battery Modelling from Cell to Pack

A high-fidelity single cell model is a foundation to form a reliable battery module and pack with statistical confidence. The equivalent circuit technique is commonly used for electrochemical impedance characterizations in a cell model. This study uses parameters normalized directly from single cell experiments, which provide a systematic integration of actual cell monitoring with a module model. The approach begins with single cell model development and validation. A module with four cells connected in series is also validated. A high fidelity SLI battery pack model is then achieved.

#### 2.1. An Enhanced Equivalent Electric Circuit Cell Model

The equivalent electric circuit approach has been adopted by many researchers to model battery cells ranging from lead-acid to lithium-ion batteries. The most commonly used equivalent electric circuit models are the Thevenin-based model [17–19], impedance-based model [20–22], and the runtime-based model [23,24]. The Thevenin-based model can predict battery response to the transient load at a certain SOC due to a series resistor and resistor-capacitor parallel network in the model. An impedance-based model is formed by an AC-equivalent impedance model in the frequency domain and the electrochemical impedance spectroscopy method. The runtime-based model utilizes a capacitor and controllable current source to predict battery capacity, SOC, runtime, and open circuit voltage (OCV). The battery operation time and DC voltage response under a constant discharge C-rate also can be simulated by the runtime-based model. The advantages of the runtime-based model and Thevenin-based model are combined in a model presented by [26], as shown in Figure 1. Based on [27], an equivalent electric circuit model with improved features is presented in this paper. In the developed Simulink model shown in Figure 2, three inputs (discharging current, initial SOC ranging from 0 to 1, and battery capacity) replace the battery runtime model. Since the initial SOC is an input variable, the developed model can simulate batteries that are not fully-charged. The OCV is calculated according to real-time SOC, which is predicted from three inputs to the model. Subtracting both voltages of the resistor-capacitor (RC) parallel networks and series resistor ( $R_S$ ) from the OCV gives the cell terminal voltage (Vt), which is an output of the developed model. The real-time SOC, OCV, RC value, RC parallel network voltages, and series resistor voltage are calculated by five developed submodels.



Figure 1. Thevenin with runtime-based model.



Figure 2. Developed cell model with three inputs.

Equation (1) calculates the real-time SOC, in which SOC<sub>0</sub> denotes the initial SOC, *I* denotes the discharging current, and *UC* denotes the usable capacity. A submodel calculating SOC is presented in Figure 3a, in which three inputs are  $SOC_0$ , *I*, and *UC* and output is real time SOC. Equation (2) is derived from numbers of experimental discharging curves using the method presented in [26] that provides relationship between the SOC and OCV. The interpolation–extrapolation lookup method is applied to calculate and determine the most suitable RC values, as a submodel presented in Figure 3b. The transient response of the battery cell voltage in the developed model is computed by the voltages of RC parallel networks. Equation (3) calculates the voltages of RC parallel networks in the s-domain, as a submodel shown in Figure 3c. For a typical lithium–metal–oxide polymer cell, the series resistor is 0–0.01 ohms in the 20%–100% SOC range, and 0.01–0.06 ohms within the 0%–20% SOC range [26]. Therefore, the developed model uses 0.001 ohms for 20%–100% SOC and 0.03 ohms for 0%–20% SOC in all discharging currents. The voltage on the series resistor (*V*<sub>S</sub>) is calculated by Equation (4) where *R*<sub>S</sub> is the series resistor resistance, and a submodel is presented in the Figure 3d. Equation (5) calculates the terminal voltage (*V*<sub>t</sub>) of the battery cell. A more detail description of the submodels and their paraments is presented in [30].

$$SOC = SOC_0 - \int \frac{I}{UC \times 3600} dt$$
 (1)

$$OCV = -1.031e^{-35\times SOC} + 3.685 + 0.2156 \times SOC - 0.1178 \times SOC^{2} + 0.3201 \times SOC^{3}$$
(2)

$$V = \left(\frac{1}{s}\right) \left[\frac{I}{C} - \frac{V}{RC}\right]$$
(3)

$$V_{\rm S} = I \times R_{\rm S} \tag{4}$$

$$V_t = OCV - V_1 - V_2 - V_S$$
 (5)



**Figure 3.** Simulink submodels for developed cell model: (a) Calculation of R and C value; (b) Calculation of SOG; (c) Calculation of RC parallel voltage; (d) Calculation of  $V_S$ .

#### 2.2. Cell Thermal Model

The lithium-ion polymer cell thermal model was built in the Simulink battery block platform, which implemented similar equations as those discussed in Section 2.1 with thermal effects. In the discharge model (i\* > 0), Equations (6)–(11) are implemented to represent the temperature effect on the battery model parameters [31]. The temperature tab requires several parameters, which are determined by battery discharging test under 20 °C ambient temperature. The initial cell temperature is set to the ambient temperature because each cell is cooled down or warmed up to the ambient temperature before starting the discharging test. The "nominal ambient temperature T1 (°C)" parameter is the ambient temperature during nominal operations. It is assumed that all parameters in the parameters tab are obtained at 20 °C ambient temperature. The procedures of establishing the cell thermal model in the Simulink platform are presented in [32]. Figure 4 shows the Simulink battery cell discharging model considering ambient temperature effects.

$$f_{1}(it, i*, i, T, T_{a}) = E_{0}(T) - K(T) \cdot \frac{Q(T_{a})}{Q(T_{a}) - it} \cdot (i* + it) + A \cdot \exp(-B \cdot it) - C \cdot it$$
(6)

$$V_{batt}(T) = f_1(it, i*, i, T, T_a) - R(T) \cdot i$$
(7)

$$E_0(T) = E_0 \Big|_{T_{ref}} + \frac{\partial E}{\partial T} (T - T_{ref})$$
(8)

$$K(T) = K \left|_{T_{ref}} \cdot \exp\left[\alpha \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]$$
(9)

$$Q(T_a) = Q \Big|_{T_a} + \frac{\Delta Q}{\Delta T} \cdot (T_a - T_{ref})$$
(10)

where:  $T_{ref}$  (K) nominal ambient temperature, T (K) cell or internal temperature,  $T_a$  (K) ambient temperature, E/T (V/K) reversible voltage temperature coefficient,  $\alpha$  Arrhenius rate constant for the polarization resistance,  $\beta$  Arrhenius rate constant for the internal resistance, (Ah/K) maximum capacity temperature coefficient, C $\Delta$ Q/ $\Delta$ T (V/Ah) nominal discharge curve slope.



Figure 4. Battery cell thermal model in Simulink.

## 2.3. Battery Module and Pack Model

A battery module model containing four cells connected in series was created in the Simulink platform, as shown in Figure 5. The controlled current source, four battery cells, breakers with control algorithms to perform the battery management system (BMS) function, and voltage measurement with scopes are the four submodels in the module model. The charging and discharging current to each cell model are generated by the controlled current source sub-model, which has two parameters, namely DC source type and zero initial amplitude (A). The controlled current source block is connected to a constant block for generating a continuously constant charging or discharging current. A value in the constant block is the constant charging/discharging current. The pulse generator block is applied to generate a pulse charging/discharging current. Cell breaker, bypass breaker, cell voltage tag, and cell control tag form a BMS submodel for each cell. When the cell is charged to a voltage higher than 4.3 V or discharged to a voltage lower than 2.3 V, the control tag opens the cell breaker and closes the bypass breaker to prevent the cell from becoming over-charged or over-discharged. Each submodel contains one pair of tags for the breakers. Figure 5 shows only one pair of tags for a better display. Each cell voltage curve is shown in its scope and a terminal voltage is displayed in total voltage scope. All the parameters in this model are determined from the continuous and pulse discharge tests. A more detail description of the submodels and their paraments is presented in [33].



Figure 5. A Simulink battery module model consisting of four series-connected cells.

## 3. Experiment and Model Validation

used EiG ePLB C020 The lithium-ion polymer cells in this study were lithium-nickel-manganese-cobalt-oxide-based cathode and graphite-based anode with 3.6 V nominal voltage and 20 Ah capacity. Figure 6 shows the test equipment using in this study, namely a Digatron charge/discharge cycler, a computer with Digatron Battery Manager 4 (BM4) software (Battery Manager 4.0, Digatron Power Electronics Inc., Shelton, CT, USA) [34], and an Envirotronics temperature chamber. A fixture was designed to restrain the battery cells and cycler output cables inside the chamber. Three experimental procedures included calibration of battery cell model parameters, validation of the four series-connected battery module, and validation of the battery cell thermal model.



Figure 6. Battery experimental test setup: (a) Cycler and chamber; (b) cell testing; (c) module testing.

#### 3.1. Battery Cell Model Calibration and Validation

An initial battery performance evaluation test was conducted on 27 cells disassembled from a hybrid electric vehicle battery pack. Each cell was charged to 4.17 V and then fully discharged to 2.46 V using 1 C rate in the initial evaluation test. The cell model parameter determination, correlation, and validation utilized six cells with best performance in the initial evaluation test. Figure 7a shows an experimental curve generated by averaging curve data for each testing case (1/3, 1/2, 1, 1.5, and 2 C discharging current). These tests were used to calibrate the cell model parameters. The determination

of cell model parameters is presented in [30]. Examples of simulated and experimental discharging curves are shown in Figure 7b. A 7% or less discrepancy between simulations and experiments existed in the 0% to 80% DOD range during constant current discharge.



**Figure 7.** Examples of simulated and experimental discharging curves: (**a**) Averaged constant current discharging curves from tests; (**b**) simulated and test constant current discharging curves; (**c**) simulated and test constant current discharging curves; (**d**) simulated and test pulse discharging.

#### 3.2. Cell Thermal Experiment and Validation

To ensure the battery cell completely cooled down or warmed up to a specific ambient temperature, the battery cell was kept charging by a small current to sustain its voltage in the neighbor of 4.17 V. The temperature chamber was then set to a specific temperature for 15 minutes before applying the discharging current. The validation process consisted of 12 discharging tests, which were 10 A, 20 A, and 40 A constant discharging currents, and each discharging test was conducted under 4 different ambient temperatures (-20, -10, 0, 20, and 50°C). The simulated discharging curves from each discharging current with specified ambient temperature were compared to corresponding experimental discharging curves. Examples of comparisons between simulated and experimental discharging curves using constant currents, 10 A, 20 A, and 40 A, under four different ambient temperatures are shown in Figure 8. A full comparison results is shown in [32]. In each discharging test, the experimental and the simulated discharging curves matched well in the range from 0% to 80% DOD (assuming 100% DOD at 2.5 V). The discrepancy between each comparison was under 7%. From the range of 80% to 100% DOD, the discrepancy became much larger. This large discrepancy might be due to the fact that battery model parameters were acquired in the nominal voltage of 3.6 V. The accuracy of the model was acceptable because most of the batteries only used up to 80% DOD. The experimental and simulated discharging time to reach 2.5 V were correlated in most test cases. Under higher ambient temperature (50 °C), the battery usable capacity increased so the total discharging time was longer than 1 hour for the one C-rate (20 A) discharging test. A similar phenomenon occurred in the one-half C-rate (10 A) test, which showed more than two hours discharging time. However, the Simulink model could not simulate the increase of battery usable capacity under high ambient temperature. Table 1 summarizes two

correlated data under different ambient temperatures and discharging currents; discharging voltage at 50% DOD (assuming 100% DOD at 2.5 V) and total discharging time to reach 2.5 V are compared.



**Figure 8.** Examples of comparisons between simulated and experimental 20A discharging curves in battery module: (**a**)  $0 \degree$ C; (**b**)  $50 \degree$ C.

	Discharging Current					
	10 A		20 A		40 A	
Ambient	Experiment	Simulation	Experiment	Simulation	Experiment	Simulation
Temp (°C)	V (50% DOD) Dis. time (s)		V (50% DOD) Dis. time (s)		V (50% DOD) Dis. time (s)	
-20	3.15; 4200	3.15; 4000	3.05; 2072	3.07; 2010	2.95; 1076	3.02; 1020
-10	3.17; 4955	3.22; 4945	3.14; 2410	3.16; 2319	3.07; 1220	3.12; 1235
0	3.32; 5660	3.37; 5893	3.38; 2835	3.32; 2856	3.17; 1427	3.26; 1436
20	3.56; 7143	3.57; 7193	3.54; 3533	3.54; 3595	3.45; 1712	3.46; 1788
50	3.71; 7602	3.80; 7175	3.62; 3701	3.76; 3600	3.52; 1745	3.68; 1799

Table 1. Summary of comparisons between experimental and simulation results.

#### 3.3. Battery Module Experiment and Validation

For the module testing, four series-connected cells formed a battery module, where the four cells were numbered from #1 to #4. This section was abstracted from [33]. The inconsistency of the cells was taken into account in the experiments and analytical models. All tests were conducted at a constant temperature of 25 °C in the chamber. Figure 6c shows the assembled-module experimental setup in the cycler. The four cells selected for the experiments had slightly different aging, internal resistance, and voltage, although they performed very similarly to each other (voltage variation between four cells was smaller than 0.08 V) under loads, as the example shows in Figure 9a. At any specific time, the difference between the highest and lowest voltage among the four cells was always no larger than 0.08 V. Figure 9b indicates that the module terminal voltage measured by the cycler was higher than the summation value of each cell terminal voltage (measured by individual voltmeter) during continuous charging. This phenonium might be due to internal resistances existing in the connecting wires between cells. The difference between cycler measurement and summation voltage became larger as the charging current increased (0.04 V for 10 A, 0.1 V for 20 A, 0.25 V for 30 A, and 0.5 V for 40 A). In continuously constant current discharge tests, each cell had very similar 10 A and 20 A discharging voltage curves. At any timeframe, the difference between the highest and lowest voltage among the four cells was always no larger than 0.15 V, as the example shows in Figure 9c. The internal resistances in the connecting wires between cells resulted in that module voltage measured by the cycler always being lower than the summation value of each cell terminal voltage measured by each individual voltmeter. As the discharging current increased, the voltage difference between the cycler measurement and summation became larger (0.05 V for 10 A, 0.2 V for 20 A, 0.3 V for 30 A, and 0.5 V for 40 A). This discrepancy was clearly observed during the 40 A discharging test shown in Figure 9d.



**Figure 9.** Examples of cell and module charging/discharging curves from tests: (**a**) Individual cell voltage in 20 A charging; (**b**) module voltage in 20 A charging; (**c**) individual cell voltage in 40 A discharging; (**d**) module voltage in 40 A discharging.

Comparing the simulated module voltage curves with experimental voltage curves generated by the summation of four individual cells was conducted for module model validation. The module voltage curve measured by the cycler was not used for comparison because it was affected by the resistance of the connecting wires. Figure 10a–d shows that all the simulated curves matched well with the experimental ones during continuous charging and discharging. An up to 9% discrepancy occurred at the end of each charging and discharging cycle. Figure 10e and f indicate that simulated pulse charging and discharging curves matched with the experimental ones, particularly in the beginning of the cycle. The largest discrepancy was 7.8%, which occurred at the end of the 30 A pulse discharge curve. The validation of the developed battery module model presented an acceptable discrepancy.

The BMS function was simulated in the battery module model with predefined initial conditions. In one example of 25 A continuous charge current to the model, Cell #4 reached 4.3 V earlier than other cells because Cell #4 had a higher initial voltage. Therefore, the BMS opened the cell breaker and closed the bypass breaker to prevent Cell #4 from being overcharged. The voltage of Cell #4 then dropped to 4.08 V, as shown in Figure 11a. In the other example of 35 A continuous discharge current, Cell #4 reached 2.3 V first because it had a lower initial voltage. The BMS opened the cell breaker and closed the bypass breaker to prevent Cell #4 from being overdischarged. The Cell #4 voltage then increased back to 2.8 V.



**Figure 10.** Comparisons of module simulated and experimental charging/discharging curves: (a) Simulated and test of 20 A charging in module; (b) simulated and test of 20 A discharging in module; (c) simulated and test of 40 A charging in module; (d) simulated and test of 40 A discharging in module; (e) simulated and test of 20A pulse charge in module; (f) simulated and test of 30A pulse discharge in module.



**Figure 11.** Demonstration of BMS functions: (a) 25 A continuous charging; (b) 35 A continuous discharging.

# 4. Twelve-Volt Battery Pack Model

The new designed or future vehicle needs an SLI battery with a higher capacity to support increasing vehicle accessory or auxiliary loads [35,36]. Additionally, the 12-volt battery pack could become a building module to form a high-voltage battery pack (such as 48-volts or higher) used in

electrified vehicle and stationary electric energy storage for renewable energy. An 80 Ah SLT-type battery pack with 14.4 V nominal voltage is proposed in this study. This battery pack contains four modules connected in parallel where each module (14.4 V, 20 Ah) has four ePLB-C020 cells connected in series. A Simulink model of the proposed battery pack is shown in Figure 12.



Figure 12. Simulink model of an 80 Ah SLI-type battery pack.

The model scope displays the battery pack voltage, which is a summation of each module voltage. Both simulated battery pack and module have the same shapes of constant current charging/discharging voltage curves. Obviously, the pack has four times charging/discharging durations of the module. The pack voltage curves have large fluctuations in each pulse during 20 A pulse charge simulation (180 seconds charge, 120 seconds pause, and repeat) and 30 A pulse discharge simulation (180 seconds discharge, 120 seconds pause, and repeat), as indicated in Figure 13. Figure 14 shows the simulated discharging curves of a 14.4 V 80 Ah SLI battery with one C-rate (20 A) and two C-rate (40 A) under five ambient temperatures.



**Figure 13.** Voltage curves of the 80 Ah SLI battery pack during pulse charging and discharging simulations: (a) Charging; (b) discharging.



**Figure 14.** Simulated discharging curves of a 14.4 V 80 Ah SLI battery under five ambient temperatures: (a) One C-rate (20 A); (b) two C-rate (40 A).

# 5. Conclusions

Modelling, simulation, and validation of SLT-type 12-volt lithium-ion polymer battery are presented in this paper. The MATLAB/Simulink-based modelling starts from using parameters deduced directly from single cell experiments, which provide convenient integration with actual cell monitoring, to a module containing four cells connected in series. A validated module model is utilized to model a high fidelity 80 Ah SLI-type battery pack with 14.4 V nominal voltage. The battery cell thermal effectiveness and battery management system functions are also considered. The experimental tests are carried out in an industry-scale setup with a charge/discharge cycler, temperature chamber, and computer-controlled software for battery testing.

In the cell-level model validation, either with or without thermal effectiveness, the experimental and the simulated discharging curves match well in the range from 0% to 80% DOD (assuming 100% DOD at 2.5 V). The discrepancy between each comparison is under 7%. From the range of 80% to 100% DOD, the discrepancy becomes much larger. The module model validation indicates a 9% or less discrepancy in all continuous and pulse charge/discharge simulation results. An 80 Ah SLI-type battery pack model with 14.4 V nominal voltage then can be achieved with statistical confidence.

The 12-volt lithium-ion battery packs might be ready for mainstream adoption in automotive SLI, stop–start engine idling elimination, and UPS applications. Additionally, the 12-volt battery pack could become a building module to form a high-voltage battery pack (such as 48-volts or higher) used in electrified vehicle and stationary electric energy storage for renewable energy. The proposed simulation model provides design guidelines for lithium-ion polymer batteries in electric-drive vehicle and stationary energy storage applications.

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