Essential Testing and Stepwise Evaluation of Lithium-Ion Battery Packs for Electric Vehicles

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ABSTRACT

The evaluation of electric vehicle (EV) battery packs through essential testing is critical to prevent safety risks that may endanger technicians, users, and the battery itself, as well as to avoid undetected performance degradation. This paper presents a set of indispensable tests for assessing lithium-ion battery packs before their integration into EV systems. The important tests and their corresponding standards are summarized to stress the need for systematic evaluation and provide clear criteria for interpreting test results. A testing process is also proposed, beginning with the preparation and verification of battery management system data, which includes the acquisition and analysis of key parameters for the initial evaluation of potential faults. Electrical tests are then carried out, including open-circuit voltage measurement, short circuit inspection, insulation resistance testing, withstand voltage testing, and internal resistance measurement, all aimed at verifying the safety and detecting possible defects. This is followed by discharging and charging tests to record characteristic behaviour and to validate capacity, state of charge, and state of health for performance assessment. Finally, the proposed procedure is demonstrated on a 33.6-kWh-100S1P LiFePO4 battery pack, using industrial-grade electrical testing equipment and a 150-kW programmable power supplies, providing a practical reference for test engineers.

Keywords: Electric vehicle, lithium-ion battery pack, battery pack testing, safety and performance

1. INTRODUCTION

The rapid growth of electric vehicles (EVs) has accelerated the demand for reliable and high-performance battery systems, particularly lithium-ion battery packs, which serve as the core energy source [1]. As EV technology advances and adoption expands globally, the safety and performance of battery packs have become critical considerations for manufacturers, engineers, and users alike. Before a battery pack is integrated into an EV system, thorough testing is necessary to ensure that it meets safety standards, functions properly under expected conditions, and delivers the required performance throughout its service life [2]. Without proper evaluation, the risk of malfunction increases significantly, potentially resulting in hazardous incidents, shortened battery life, or costly failures in the field.

Many of the critical failures observed in EV battery systems can be traced back to incomplete or improperly conducted testing [3]. When essential safety tests are omitted, risks such as thermal runaway, insulation breakdown, or short circuits may go undetected [4], [5]. For example, skipping insulation resistance or withstand voltage testing could allow latent electrical faults to persist, posing serious hazards during operation. Likewise, defect-related issues such as abnormal internal resistance or undetected cell imbalance can lead to uneven aging, cell damage, or unexpected shutdowns [6]. These can often be identified through proper defect detection tests, including open-circuit voltage checks and internal resistance measurements. In terms of performance, omitting controlled discharging and charging tests may result in incorrect assessment of the battery's capacity, state of charge (SOC), and state of health (SOH), which are key indicators for determining whether the battery can reliably support the vehicle's power demands [7]. Industry standards exist to guide each of these tests, but failure to adhere to them undermines their purpose and leaves the battery system vulnerable to failure [5], [8-16].

Equally important as the tests themselves is the procedure by which they are carried out. Faults during testing can arise not only from poor battery condition but also from errors in test execution, such as incorrect equipment settings, unsafe connections, or misinterpretation of battery management system (BMS) data [17]. These mistakes can harm the battery pack, damage via controller area network (CAN) test equipment, or endanger personnel conducting the tests. A clearly defined and standardized procedure helps eliminate these risks by ensuring consistency, accuracy, and safety throughout the evaluation process. It also improves repeatability, allowing different engineers or facilities to arrive at the same conclusions under the same conditions [18].

To address these challenges, this paper proposes a complete testing procedure for lithium-ion battery packs before EV integration. The procedure includes safety evaluations, defect detection, and performance assessments based on relevant standards. It begins with BMS data verification, followed by a sequence of

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electrical and thermal tests. The method is demonstrated using a 33.6 kWh, 100S1P $LiFePO_4$ battery pack and industrial-grade testing equipment. This work aims to support safe and effective battery validation and provide a practical reference for test engineers.

2. ESSENTIAL TESTS AND STANDARDS FOR BATTERY PACK EVALUATION

The essential tests for evaluating the battery pack are classified into three stages: initial assessment via BMS data, safety and diagnostic evaluation through electrical testing, and performance evaluation using charging and discharging tests, as illustrated in Fig. 1. This section explains the purpose and core principles of each test, along with the diagnostic insights they provide. All evaluations are interpreted within the context of relevant industry standards or original equipment manufacturer (OEM) specifications to ensure safety, reliability, and functional integrity.

***Table 1**: Important BMS Real-Time Parameters.*

BMS Parameters	
▪ Maximum cell voltage	▪ Cell voltages
▪ Minimum cell voltage	▪ Battery pack voltage
▪ Maximum cell temperature	▪ Battery pack current
▪ Minimum cell temperature	▪ SOC

2.1 CAN Bus Data Analysis for Initial Evaluation of Battery Packs

CAN bus communication, based on the ISO 11898 standard, is widely used in EVs due to its reduced wiring complexity, real-time capability, robustness, and support for modular systems [19]. EV subsystems exchange messages and commands over the CAN interface using either classical CAN (ISO 11898-1) or CAN FD (ISO 11898-7), depending on system complexity and data requirements. As expected, the BMS also communicates via the CAN bus, continuously broadcasting key battery pack parameters. Accordingly, BMS data analysis via CAN communication serves as the first step in battery pack evaluation, providing a rapid, non-intrusive overview of system status.

Before initiating the evaluation stage, data extraction from the BMS is required. Raw CAN signals are transmitted through the CAN-high and CAN-low differential physical layers, as illustrated in Fig. 2. However, this data is encoded in hexadecimal (HEX) format, making it difficult to interpret directly. To convert the data into a human-readable format, the raw CAN messages must be transmitted to a PC using a CAN interface adapter and processed through dedicated logging software. Crucially, a database CAN (DBC) file is needed to decode the BMS data correctly. This file defines the structure, scaling, and interpretation rules for each message ID and signal. It is important to note that for commercial battery packs, the DBC file is typically provided by the manufacturer; however, in the case of custom-developed BMS units, this file must be manually defined or generated by the developer. For clarity, the structure and an example of the DBC file will be discussed in the following section.

In the evaluation stage, key parameters extracted from the BMS are summarized in Table 1. This begins with the analysis of individual cell voltages, denoted as $V_{cell,1}, V_{cell,2}, V_{cell,3}, ..., V_{cell,n}$, where n represents the total number of series-connected cells. These values are assessed to ensure they fall within the manufacturer's specified voltage range. From these, the maximum cell voltage ($V_{cell,\max}$) and the minimum cell voltage ($V_{cell,\min}$), are determined using the expressions:

$$V_{cell,\max} = \max(V_{cell,1}, V_{cell,2}, V_{cell,3}, ..., V_{cell,n}),$$
$$V_{cell,\min} = \min(V_{cell,1}, V_{cell,2}, V_{cell,3}, ..., V_{cell,n}). \quad (1)$$

And the maximum cell voltage difference is defined as

$$\Delta V_{cell} = V_{cell,\max} - V_{cell,\min}. \quad (2)$$

These values are used to evaluate cell imbalance and to verify compliance with the manufacturer's specified range. If any cell falls outside this range, it must be immediately inspected for potential defects.

Similarly, the maximum cell temperature ($T_{cell,\max}$) and the minimum cell temperatures ($T_{cell,\min}$), measured by integrated thermal sensors, are analysed to verify compliance with the specified thermal operating range. The maximum cell temperature difference is defined as

$$\Delta T_{cell} = T_{cell,\max} - T_{cell,\min}. \quad (3)$$

ΔT_{cell} is used to assess thermal distribution across the battery pack. If this parameter exceeds the acceptable threshold, it may indicate a defective cell or a malfunction in the thermal management system.

Additional critical parameters include the battery pack voltage and current, defined as $V_{batt,bms}$ and $I_{batt,bms}$, which are checked against defined operational limits. Finally, SOC is extracted and recorded for use in capacity assessment during performance testing. Importantly, all BMS parameters also serve as boundary conditions in subsequent tests to prevent unintended faults such as overcharging or overdischarging.

2.2 Electrical Testing for Safety and Diagnostic Evaluation of Battery Packs

Electrical testing follows the initial evaluation to assess safety and detect defects. This stage includes insulation and fault detection tests, offering essential diagnostic insights. Each test verifies electrical integrity under standard conditions, ensuring compliance with safety specifications and identifying faults before further testing.

The open-circuit voltage (OCV) of individual cells and the total battery pack is a key diagnostic parameter, recorded alongside the SOC from the BMS. It serves

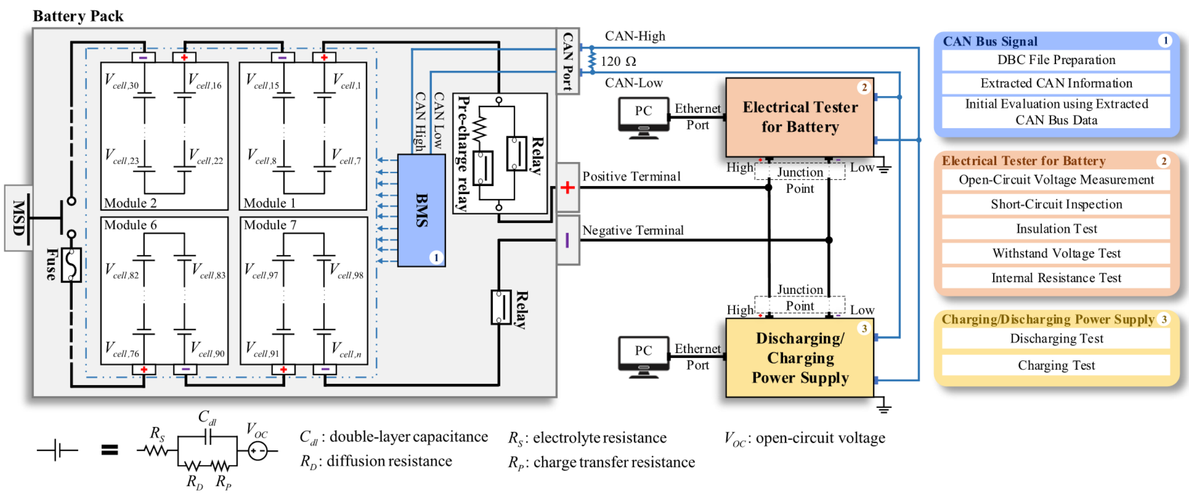


Fig. 1: *Battery pack testing configuration.*

Table 2: *Essential Tests, Criteria Evaluation, and Standards.*

Types	Test Items	Testing Equipment	Acceptance Criteria	OEM or Int Standards
Initial evaluation	Analysis of BMS messages via CAN bus	Logger software	▪ All key real-time BMS parameters are within the acceptable range.	Manufacturer
Electrical testing	OCV measurement	Digital multimeter Logger software	▪ No deviation between measured OCV and BMS value. ▪ No excessive cell voltage difference detected.	Manufacturer
	Short circuit test	Digital multimeter	▪ Overload (OL) = No short circuit.	Manufacturer
	Insulation test	Insulation withstand voltage tester	▪ $R_{ins} \geq 100\ \Omega / \mathrm{V}$. ▪ $R_{ins} \geq 100\ \mathrm{M\Omega}$.	ISO 6469-1, GB 18384 Manufacturer
	Withstand voltage test	Insulation withstand voltage tester	▪ No leakage current. ▪ No breakdown during the test.	UL 2580
	AC Internal resistance test	Battery impedance tester	▪ $R_{int} \leq 10\ \mathrm{m\Omega}$ for the battery cell. ▪ $R_{int} \leq 200\ \mathrm{m\Omega}$ for the battery pack.	Manufacturer
Performance testing	Discharging and charging test	Discharging/charging tester	▪ -20°C to 60°C for discharging, 0°C to 45°C for charging. ▪ $\Delta T_{cell} \leq 5$ °C. ▪ $\Delta V_{cell} \leq 50$ mV. ▪ SOH > 80%.	IEC 62619 Manufacturer Manufacturer Manufacturer

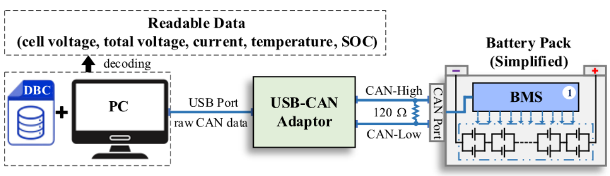


Fig. 2: *Extraction of BMS data via CAN bus.*

to detect cell imbalance and ensure voltage deviations remain within manufacturer-specified limits. OCV also defines the usable voltage range for EVs, typically constrained to a SOC window of 25% – 95% to prevent overcharge or deep discharge [20].

OCV measurement is conducted by applying a one-way charge or discharge current pulse corresponding to 5% of the battery's capacity, followed by a 30-minute rest period to achieve electrochemical equilibrium prior to voltage recording [21]. This process is repeated incrementally until the battery reaches full charge or discharge. The OCV of each cell is extracted from BMS data, while the total pack voltage (V_{batt}) is measured across the battery terminals using a digital multimeter, as shown in Fig. 3. The measured OCV of total pack values

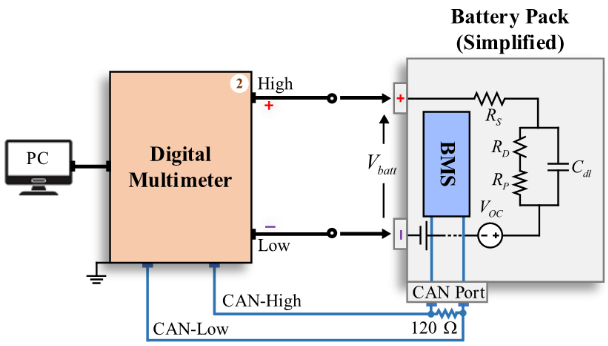


Fig. 3: *Circuit diagram for OCV measurement.*

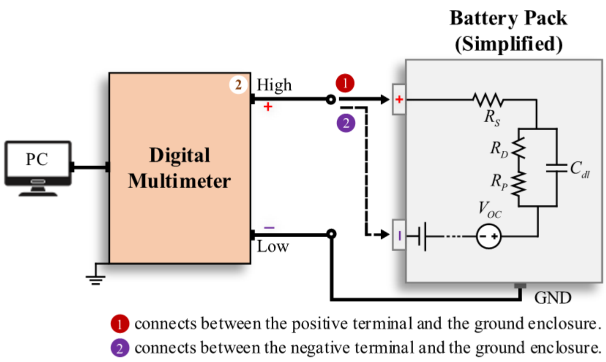


Fig. 4: *Circuit diagram for short-circuit inspection.*

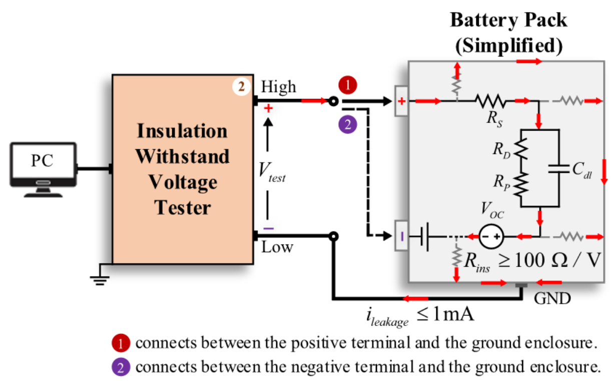


Fig. 5: *Circuit diagram for insulation and withstand voltage tests.*

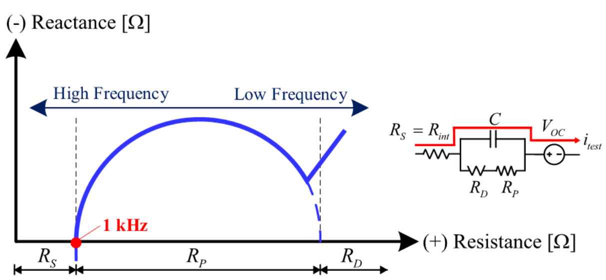


Fig. 6: *Principle of AC internal resistance measurement.*

should correspond with the BMS-reported voltages via CAN bus, with cell-to-cell voltage differences maintained

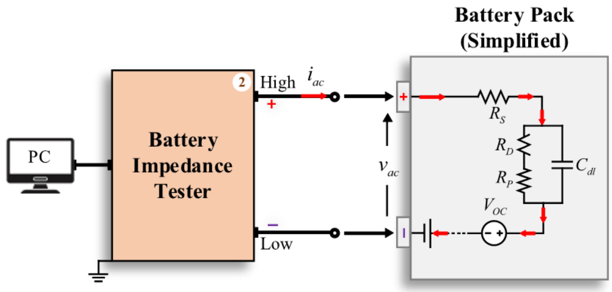


Fig. 7: *Circuit diagram for AC internal resistance test.*

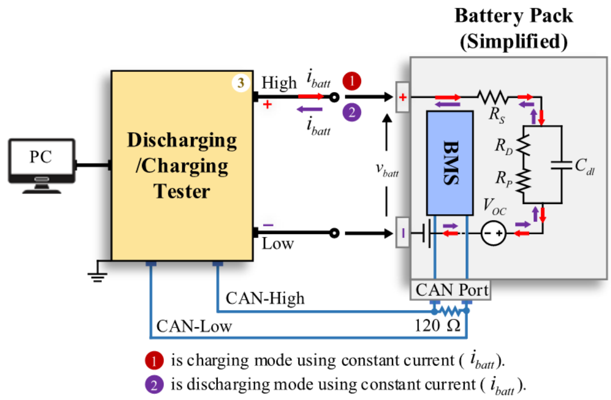


Fig. 8: *Circuit diagram for charging and discharging tests.*

within 50 mV [18]. If any cell exhibits significant deviation, it should be individually inspected, and the BMS balancing function should be verified.

- Short-circuit inspection

The most of the key safety concerns in battery systems is the risk of a short circuit between the terminals and the battery's insulation, which can lead to dangerous outcomes such as fire or even explosion. To prevent such hazards, it is imperative to check for any unintended connection between the battery's terminals and its enclosure.

This is typically done using a digital multimeter set to resistance mode, as shown in Fig. 4. The inspection

Table 3: *Battery Pack Parameters.*

Parameter	Value
Battery configuration	100 series-cell $n = 100$
Type of battery cell	LFP
Cell voltage range	2.5 – 3.65 V
Nominal cell voltage	3.2 V
Battery pack voltage range	250 – 365 V
Nominal battery pack voltage	320 V
Capacity	105 Ah
Energy capacity	33.6 kWh
BMS configuration	Modular
Cooling system	Air cooling

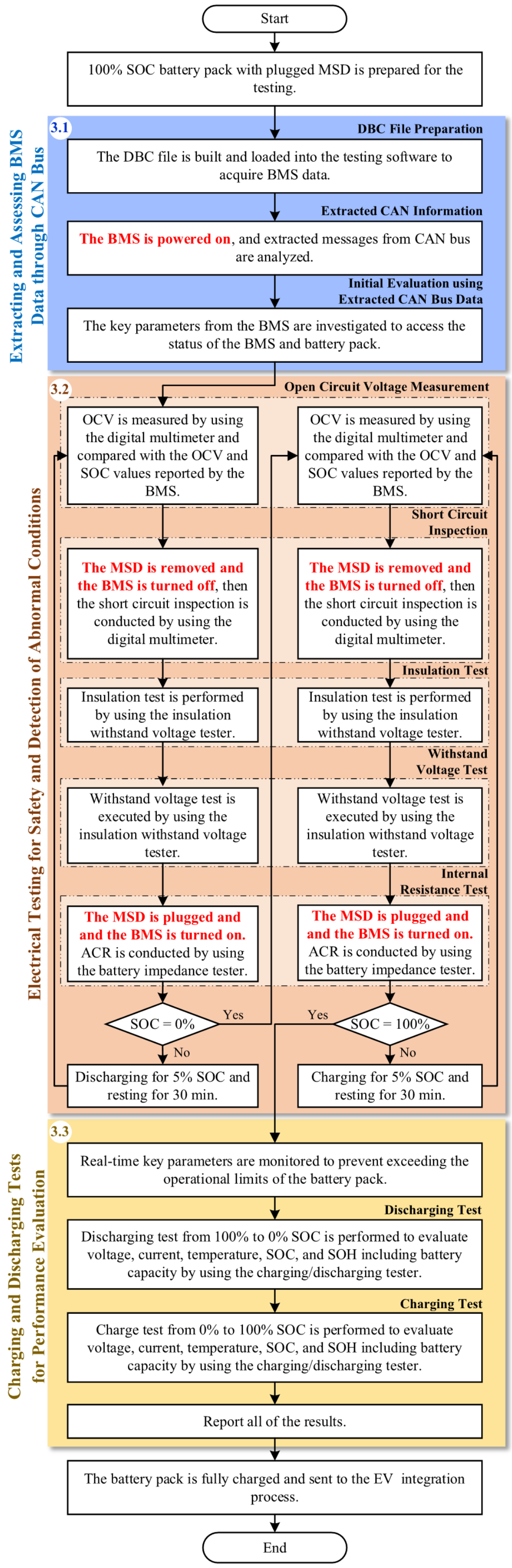


Fig. 9: *Testing guideline for battery pack evaluation.*

involves measuring the resistance between the positive terminal and the battery enclosure, and then between the negative terminal and the enclosure. A proper result should show an overload or infinite resistance, indicating that no short circuit is present.

- Insulation test

The insulation test is conducted to detect defects in the battery pack by measuring its insulation resistance, which can be affected by internal short circuits, moisture, or surface contamination. This test is usually performed before the withstand voltage test to verify that the insulation integrity has not degraded.

As shown in Fig. 5, a DC high voltage (V_{test}), typically 500 volts or 1000 volts, is applied using test equipment suitable for high voltage battery systems. The insulation resistance (R_{ins}) is measured between the positive terminal and the battery enclosure, and then between the negative terminal and the enclosure, using an insulation voltage withstand tester. A small leakage current is detected and used to calculate the insulation resistance value. According to international standards such as ISO 6469-1 [8] and GB 18384-2020 [9], the insulation resistance should not be less than 100 Ω/V of the battery's nominal voltage. Some equipment manufacturers alternatively recommend a minimum insulation resistance of 1 MΩ.

- Withstand voltage test

The purpose of the withstand voltage test is to verify the insulation strength of the battery by evaluating its ability to resist breakdown under high-voltage conditions, especially at potential weak points during hazardous events such as switching, arcing, or instantaneous voltage.

Again, as expressed in Fig. 5, the test is conducted by applying a high DC voltage, greater than the nominal voltage of the battery pack, based on requirements specified in standards such as IEC 60664, ISO 6469-3, and other relevant international standards [10-12]. The applied test voltage is defined as follows:

$$V_{test} = 1.414 * (2V_{batt,\max} + 1000). \qquad (4)$$

where $V_{batt,\max}$ is the maximum operating voltage of the battery pack. The leakage current ($i_{leakage}$) is measured between the positive terminal and the battery enclosure, and subsequently between the negative terminal and the enclosure, using an insulation voltage withstand tester. According to standard criteria, the leakage current should remain below 1 mA and must not exceed 2 mA under worst-case conditions [22]. UL 2580 further specifies that no breakdown or measurable leakage current should occur during the test [5].

- AC internal resistance test

Internal resistance testing is a critical method for evaluating battery defects and assessing aging-related degradation. To ensure reliable performance, this evaluation should be conducted across the entire battery pack, including the individual cells or modules [23].

Among AC measurement techniques, electrochemical impedance spectroscopy is widely used in laboratory settings to analyze a battery's impedance response by injecting an alternating current over a broad frequency range, typically from 1 mHz to 10 MHz [24]. In contrast, AC internal resistance measurement is a faster and more practical method. It applies a single frequency AC signal, typically at 1 kHz for 1 to 5 seconds, based on several international standards [13-16]. Thus, it is suitable for final inspection testing in manufacturing. As shown in Fig. 6, Nyquist plot based on the Randles Ershler equivalent circuit model is used, which represents the fundamental electrochemical processes under high frequency excitation [24]. The resistance of the electrolyte, influenced by the movement of lithium ions, is reflected as the internal resistance (R_{int}) of the battery pack [25]. This internal resistance is measured between the battery terminals, using an impedance tester, as shown in Fig. 7 and is calculated as follows.

$$R_{\text{int}} = \text{Re}\left[V_{ac}/I_{ac}\right]. \tag{5}$$

where V_{ac} is the alternating RMS voltage. I_{ac} is the alternating RMS current. For the acceptable criteria, it is typically less than 1 mΩ for a battery cell and 200 mΩ for a battery pack, or within limits specified by the manufacturer [25].

2.3 Discharging and Charging Tests for Performance Evaluation of Battery Packs

To verify that the battery pack delivers its intended capacity and operates without irregularities under standard operating conditions, discharging and charging tests using a programmable power supply are conducted as the final stage of performance evaluation, as shown in Fig. 8. These tests typically employ constant current control to cycle the battery across its full usable range, from 0% to 100% SOC, enabling accurate capacity measurement. During the test, key parameters provided by the BMS, as presented in Section 2.1, are continuously monitored to ensure that operation remains within the specified safety and performance limits. The key metric derived from this process is SOH, defined as

$$\text{SOH}\ (\%) = Q_m[\text{Ah}]/Q_{nom}[\text{Ah}] \times 100. \tag{6}$$

where Q_m is the current maximum capacity and Q_{nom} is the nominal capacity specified by the manufacturer. SOH reflects the battery's capacity degradation and is a direct indicator of long-term performance. A value above 80% is generally considered acceptable for continued use [26].

In addition to capacity measurement, these tests monitor voltage, current, and SOC to detect operational irregularities. Special attention is given to cell voltage and temperature differences, which should not exceed 50 mV and 5 °C, respectively [18], [27]. Deviations may indicate imbalance or thermal issues, requiring further investigation to ensure safe and reliable operation.

Finally, the essential tests, evaluation criteria, and applicable standards are summarized in Table 2. However, it is important to note that additional tests, such as mechanical testing, discharging under real-profile loads, and charging with commercial on-board and off-board chargers, are recommended to enhance the robustness and reliability of the battery pack.

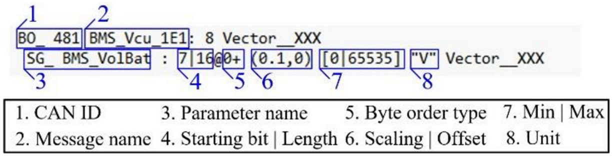


***Fig. 10**: Structure of a DBC file used to decode raw CAN bus data.*

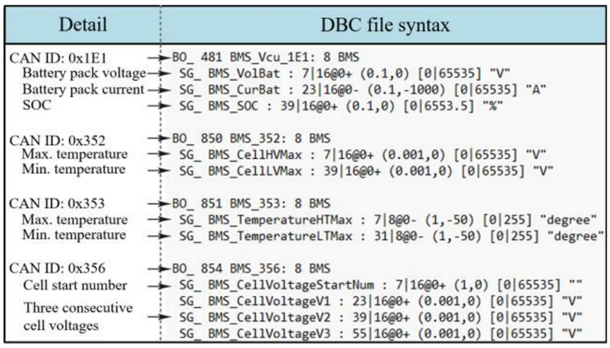

<table>
<tr><th>Detail</th><th>DBC file syntax</th></tr>
<tr><td>CAN ID: 0x1E1</td><td>BO_ 481 BMS_Vcu_1E1: 8 BMS</td></tr>
<tr><td>Battery pack voltage</td><td>SG_ BMS_VolBat : 7|16@0+ (0.1,0) [0|65535] "V"</td></tr>
<tr><td>Battery pack current</td><td>SG_ BMS_CurBat : 23|16@0- (0.1,-1000) [0|65535] "A"</td></tr>
<tr><td>SOC</td><td>SG_ BMS_SOC : 39|16@0+ (0.1,0) [0|6553.5] "%"</td></tr>
<tr><td>CAN ID: 0x352</td><td>BO_ 850 BMS_352: 8 BMS</td></tr>
<tr><td>Max. temperature</td><td>SG_ BMS_CellHVMax : 7|16@0+ (0.001,0) [0|65535] "V"</td></tr>
<tr><td>Min. temperature</td><td>SG_ BMS_CellLVMax : 39|16@0+ (0.001,0) [0|65535] "V"</td></tr>
<tr><td>CAN ID: 0x353</td><td>BO_ 851 BMS_353: 8 BMS</td></tr>
<tr><td>Max. temperature</td><td>SG_ BMS_TemperatureHTMax : 7|8@0- (1,-50) [0|255] "degree"</td></tr>
<tr><td>Min. temperature</td><td>SG_ BMS_TemperatureLTMax : 31|8@0- (1,-50) [0|255] "degree"</td></tr>
<tr><td>CAN ID: 0x356</td><td>BO_ 854 BMS_356: 8 BMS</td></tr>
<tr><td>Cell start number</td><td>SG_ BMS_CellVoltageStartNum : 7|16@0+ (1,0) [0|65535] ""</td></tr>
<tr><td>Three consecutive cell voltages</td><td>SG_ BMS_CellVoltageV1 : 23|16@0+ (0.001,0) [0|65535] "V"
SG_ BMS_CellVoltageV2 : 39|16@0+ (0.001,0) [0|65535] "V"
SG_ BMS_CellVoltageV3 : 55|16@0+ (0.001,0) [0|65535] "V"</td></tr>
</table>

***Fig. 11**: Example details of DBC file preparation.*

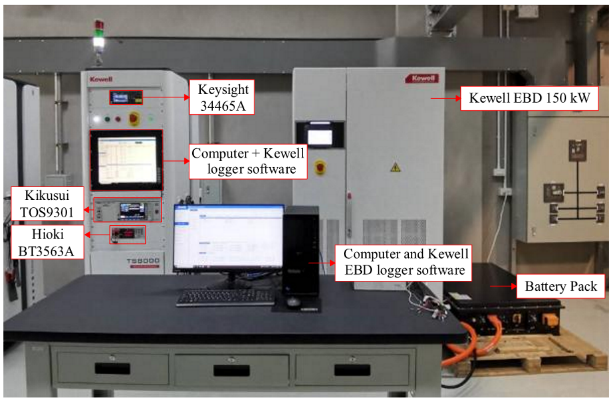
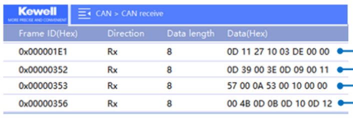


***Fig. 12**: Experimental setup for battery pack testing.*

3. PROPOSED TEST PROCEDURE FOR BATTERY PACK

To ensure the battery pack is tested comprehensively and without failure due to procedural errors, the proposed test procedure is conducted in a progressive sequence. It begins with preliminary preparation and assessment via BMS data, followed by safety inspections through electrical testing, and concludes with performance evaluation using charging and discharging tests. The overall guideline for this procedure is illustrated in Fig. 9.



Parameter	Start bit	Length (bit)	HEX data	DEC data	Scaling	Offset	Readable data
Battery pack voltage	8	16	0D 11	3345	0.1	0	334.5 V
Battery pack current	24	16	27 10	10000	0.1	-1000	0 A
SOC	40	16	03 DE	990	0.1	0	99.0 %
Maximum cell voltage	8	16	0D 39	3385	0.001	0	3.385 V
Minimum cell voltage	40	16	0D 09	3337	0.001	0	3.337 V
Maximum cell temperature	0	8	57	87	1	-50	37 °C
Minimum cell temperature	24	8	53	83	1	-50	33 °C
Cell voltage start number	8	16	00 4B	75	1	0	75th
Three consecutive cell voltages	24	16	0D 0B	3339	0.001	0	3.339 V
	40	16	0D 10	3344	0.001	0	3.344 V
	56	16	0D 12	3346	0.001	0	3.346 V

***Fig. 13**: Extracted BMS parameters via CAN bus.*

3.1 Extracting and Assessing BMS Data through CAN Bus Procedure

In the first stage, the fully charged battery pack with the manual service disconnect (MSD) installed, as shown in Fig. 1, must be inspected through key BMS parameters described in Section 2.1. To decode the raw CAN data, the appropriate DBC file must be loaded onto the PC. Fig. 10 illustrates the DBC file structure, which comprises eight parts. First, the CAN ID uniquely identifies the message on the network. Second, the message name provides a readable label for reference. Third, each message includes parameter names representing specific signals. Fourth, the starting bit and bit length define the signal's position and size within the data payload. Fifth, the byte order format (0 for Motorola, 1 for Intel) and sign (+ for unsigned, − for signed) are specified. Sixth, the scaling factor and offset convert raw values into physical units. Seventh, minimum and maximum limits define valid data ranges. Finally, the unit denotes the measurement unit. These elements enable accurate decoding of CAN messages into readable engineering values for monitoring and diagnostics.

To inspect the key BMS parameters referenced in Section 2.1, an example of the corresponding DBC file used for data extraction is shown in Fig. 11, based on the standard DBC file syntax structure. Once the DBC file is prepared, a 12 V supply is applied to power the BMS, the analysis is then performed using the decoded output.

3.2 Electrical Testing Procedure

Electrical tests are performed once no defects are identified during the BMS data inspection. All test items described in Section 2.2 are conducted sequentially. These tests are at 5% SOC intervals during both discharging (from 100% to 0%) and charging (from 0% to 100%), with a recommended 30-minute rest period before each step to allow the battery to reach electrochemical equilibrium. This approach ensures safe test execution and enhances the likelihood of detecting underlying defects across different SOC levels.

It is important to note that, prior to performing insulation and withstand voltage tests, the MSD must be removed and the 12 V power supply to the BMS disconnected. Failure to do so may result in serious damage to the BMS due to high-voltage exposure. After completing these tests, the MSD must be reinstalled to enable detection of all cell voltages, and the 12 V supply must be restored before proceeding with the ACR test.

3.3 Discharging and Charging Tests Procedure

If the electrical tests confirm that there are no defects or safety risks, discharging and charging tests are subsequently performed to evaluate the performance of the battery pack. These tests are conducted to assess the characteristics described in Section 2.3. Before initiating the discharging or charging processes, BMS parameters must again be verified to ensure they are actively broadcasted. Continuous monitoring of these parameters is essential to protect the battery pack during testing, particularly if any values exceed the specified limits set by industry standards or the OEM.

The discharging is firstly performed from 100% to 0% SOC to capture the main parameter to evaluate the performance. After resting the battery pack, charging test is then operated from 0% to 100 % SOC. If there is no faults or underqualified capacity, the battery pack with all report test is ready to be sent to the EV integration.

4. EXPERIMENTAL DEMONSTRATION RESULTS

To demonstrate the outcome of the practical testing of the battery pack, this section presents the results from a full assessment based on the principles in Section 2 and the procedure described in Section 3. The experimental setup used for the tests is shown in Fig. 12. The specifications of the battery pack are provided in Table 3, and the equipment configuration, test parameters, and cases for the three test groups are summarized in Table 4.

Based on the first test stage, which involves initial BMS data evaluation via CAN bus under no-load conditions, Fig. 13 shows raw extracted CAN data for four CAN IDs related to key BMS parameters. The data were captured using Keywell logger software and decoded using a mapped DBC file. Initially transmitted in HEX format, the logger uses the DBC to locate each signal from its starting bit and length, convert values to decimal

***Table 4**: Equipment Configuration, Test Parameters, and Cases.*

Test		Testing Equipment	Test Parameter and Mode	Test Cases
Extracting and assessing BMS data		Kewell logger software	Motorola-format CAN frame at 250 kbps baud rate	▪ Open circuit test
Electrical test	OCV Measurement	Keysight 34465A and Kewell logger software	Voltage measurement mode	▪ Open circuit test
	Short circuit test	Keysight 34465A	Resistance measurement mode	▪ + to GND test ▪ - to GND test
	Insulation test	Kikusui TOS9301	Performed at $V_{dc} = 500\,\text{V}$ for 3 s	▪ + to GND test ▪ - to GND test
	Withstand voltage test	Kikusui TOS9301	Performed at $V_{dc} = 500\,\text{V}$ for 3 s	▪ + to GND test ▪ - to GND test
	AC Internal resistance test	Hioki BT3563A	Performed at $I_{ac} = 100\,\text{mA}$, $f = 1$ kHz for 5 s.	▪ Open circuit test
Charging and discharging tests		Kewell EBD 150 kW	Cycling at 0.2C in CC mode under room temperature conditions	▪ Charging from 0% to 100% SOC ▪ Discharging from 0% to 100% SOC

+ and - are the positive and negative terminal of the battery pack, respectively. GND is ground enclosure.

(DEC) format, apply scaling and offset, and present them as readable engineering values.

CAN ID 0x1E1 includes battery pack voltage $V_{batt,bms}$, current $I_{batt,bms}$, and SOC, measured at 334.5 V, 0 A, and 99%, all within normal operating limits. CAN ID 0x352 provides $V_{cell,\max}$ and $V_{cell,\min}$, measured at 3.385 V and 3.337 V, with a maximum cell voltage difference ΔV_{cell} of 48 mV, within the manufacturer's tolerance, indicating no cell imbalance. CAN ID 0x353 contains $T_{cell,\max}$ and $T_{cell,\min}$, measured at 37°C and 33°C, resulting in a 4°C maximum cell temperature difference ΔT_{cell}, which confirms good thermal distribution. Finally, CAN ID 0x356 broadcasts the starting cell number and three consecutive cell voltages. In this case, cell voltages 75 to 77, denoted as $V_{cell,75}$, $V_{cell,76}$, and $V_{cell,77}$, were transmitted with voltages of 3.339 V, 3.344 V, and 3.346 V, all within normal range. The data in this CAN ID updates every 0.5 seconds to transmit the next group of three cell voltages. This approach is a result of the modular BMS architecture, which limits the ability to broadcast all cell voltages simultaneously due to CAN bus bandwidth constraints.

The electrical test results are discussed next. As guided by the procedure in Fig. 9, the tests were conducted sequentially at 5 % SOC intervals during both discharging and charging, with a recommended 30-minute rest period before each step to evaluate the OCV characteristics, safety, and potential defects of the battery pack.

Fig. 14 presents the OCV characteristics of the 100 cells and the total battery pack voltage. Fig. 14(a) shows the cell OCV values, extracted from CAN bus after a 30-minute rest following discharge. All cell voltages fall within 2.8 V to 3.55 V across 0 to 100 % SOC, confirming compliance with manufacturer specifications and no cell defects. However, the voltage difference exceeds 50 mV below 5 % and above 95 % SOC, indicating these regions should be avoided to prevent imbalance. As expected, Fig. 14(b) shows the OCV results after charging under the same conditions. All values remain within the acceptable range, and the recommended operating window is between 5 and 95 % SOC to ensure cell balance. Fig. 14(c) shows the OCV of the battery pack after both discharging and charging. The measured pack voltage V_{batt} is plotted against SOC and compared with the BMS-reported voltage $V_{batt,bms}$. Two key observations can be made. First, the close alignment between the measured and BMS-reported voltages confirms the reliability of both data sources. Second, the OCV is consistently higher after charging than after discharging at the same SOC, attributed to electrochemical potential. These findings support a recommended SOC window of 5 to 95 %, where voltage deviation remains minimal.

Next, safety and defect evaluations are presented. Short circuit inspection results, measured using a digital multimeter, consistently showed overload values, indicating no direct electrical path between the battery electrodes and the enclosure. Then, safety and defect assessments are shown in Fig. 15, which presents the results of insulation resistance, leakage current, and internal resistance measurements after both discharging and charging, using two terminal-pair test configurations, as shown in Figs. 15(a)-(c). The insulation resistance is approximately 10 GΩ, and the leakage current is around 2 μA across the SOC range, confirming compliance with safety standards and the overall integrity of the battery pack. Furthermore, the internal resistance ranges between 170 and 180 mΩ, indicating that the battery pack remains within the acceptable threshold for a healthy, defect-free condition.

The final part of the analysis focuses on performance

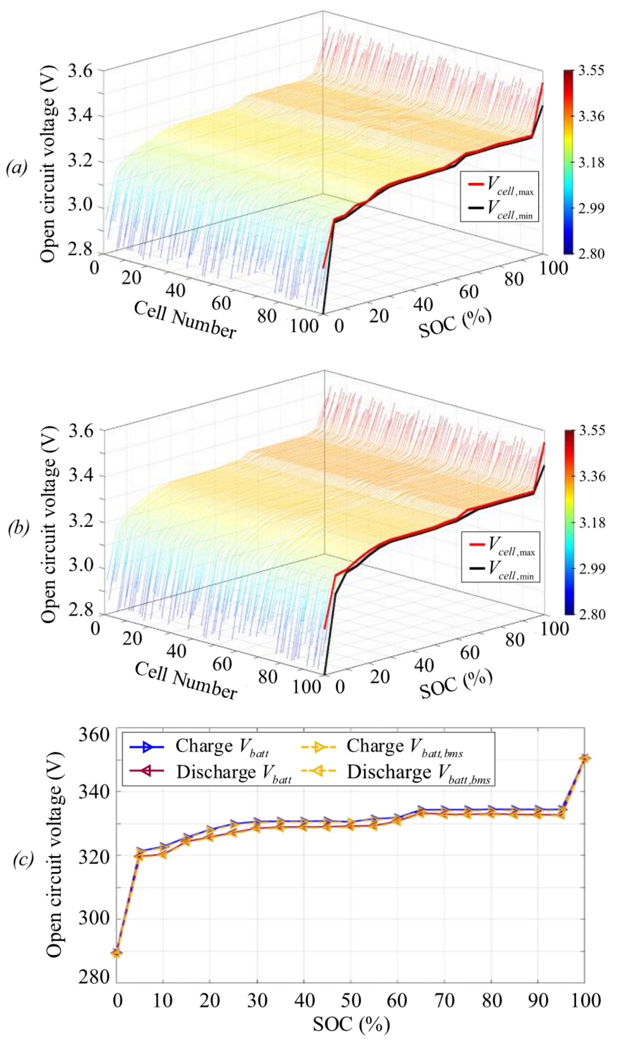


***Fig. 14**: OCV characteristics. (a) 100-cell voltages after discharging. (b)100-cell voltages after charging. (c) Battery pack voltage after the charge–discharge process.*

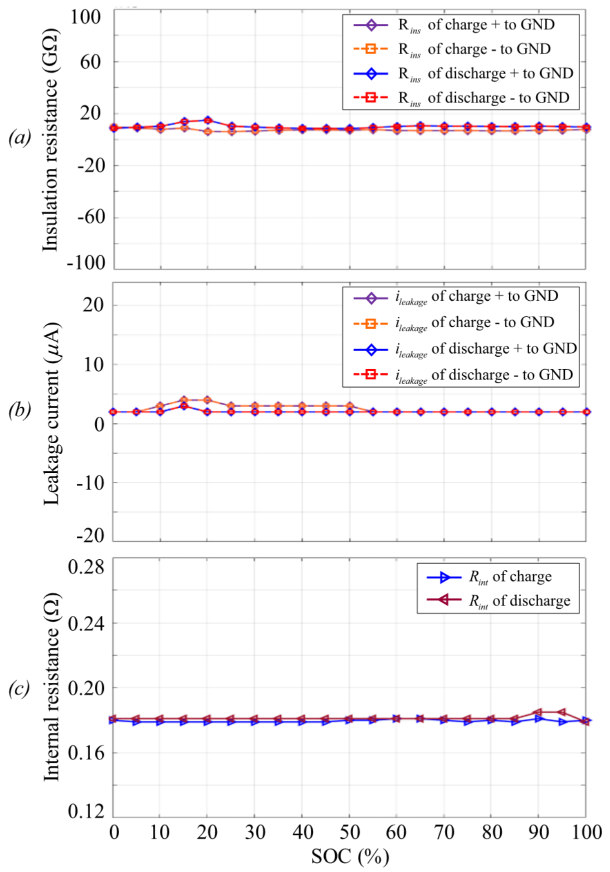


***Fig. 15**: Abnormal detection results. (a) Insulation test. (b) Withstand voltage test. (c) Internal resistance test.*

evaluation through discharging and charging tests. Fig. 16 illustrates the discharging behavior of the battery pack at a constant current of 0.2 C (21 A). In Fig. 16(a), both capacity and SOC decrease linearly, with discharging capacity reaching -104.8 Ah at 18,000 seconds or 5 hours, indicating a full discharge. Based on this result, the SOH is calculated using (**??**) as 99.8%, reflecting the strong performance of the battery pack. Figs. 16(b) and 16(c) show the voltage, current, and temperature behavior during discharge. In Fig. 16(b), battery pack voltage gradually decreases from 330 V to 300 V, while current remains stable near −21 A, confirming consistent discharge within the operational voltage range. Fig. 16(c) shows cell voltages remain within safe limits, and cell temperature rises moderately to a peak of 40 °C, indicating safe thermal performance.

Fig. 17 shows the battery pack's charging behavior. In Fig. 17(a), capacity and SOC increase linearly, reaching 105 Ah and 100% SOC at 5 hours, indicating an SOH of 100% and confirming that the battery is in good condition. Fig. 17(b) shows the pack voltage rising from 310 V to 340 V within the operational range, while the charging current remains steady at 21 A. This ensures the operational capability of the battery pack during charging. 17(c) shows that cell voltages stay within safe limits, and the temperature gradually rises to a peak of 41 °C, indicating stable thermal behavior. However, deviations between maximum and minimum cell voltages and temperatures can exceed acceptable limits, suggesting that operation at very low or high SOC should be avoided.

The testing results and observations provide further insight into the practicality and broader applicability of the proposed method. The testing approach presented in this study differs from conventional practices in both industry and academic research. Industrial procedures typically emphasize functional checks or end-of-line tests, whereas the method described here offers a more structured and comprehensive evaluation, incorporating safety, electrical integrity, and performance metrics in accordance with established standards. In academic research, the focus is frequently limited to individual cell testing under controlled laboratory conditions, which may not fully capture the operational complexity at the battery pack level. This study addresses that limitation by presenting a complete and practical testing protocol

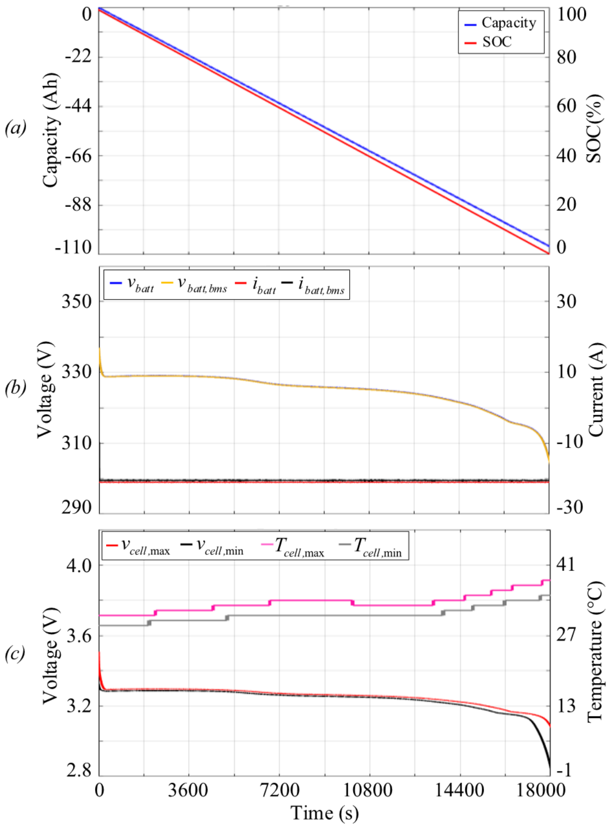


Fig. 16: Discharging characteristics of battery pack. (a) Capacity and SOC. (b) Battery pack voltage and current. (c) Cell voltage and operating temperature.

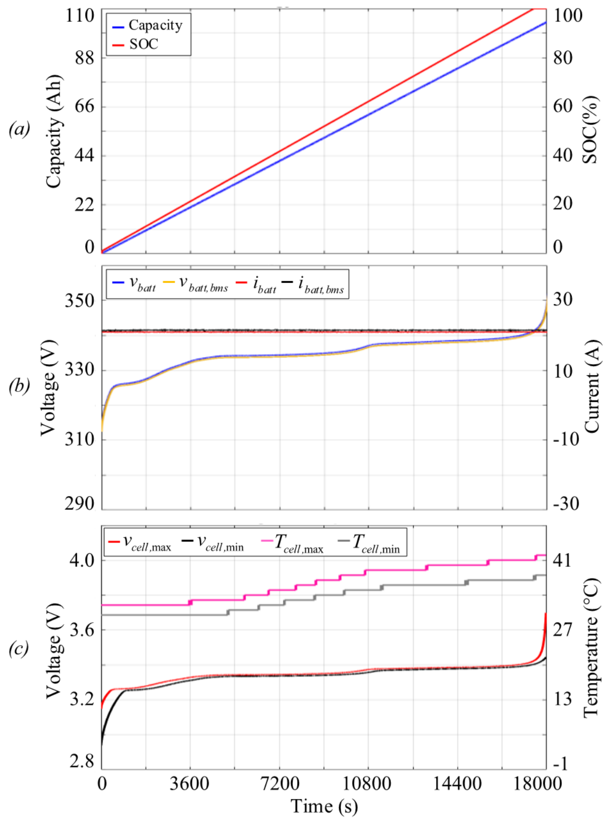


Fig. 17: Charging characteristics of battery pack. (a) Capacity and SOC. (b) Battery pack voltage and current. (c) Cell voltage and operating temperature.

designed for pack-level validation prior to real-world deployment. During the test process, the surface temperature of the battery pack reached a maximum of 41°C under ambient indoor conditions without the use of active cooling. Temperature was continuously monitored throughout to ensure safe operation. While no thermal issues were observed under the given test conditions, external cooling measures, such as forced air or heat dissipation systems, may be required in scenarios involving higher current loads or extended testing durations.

5. CONCLUSION

This paper concludes the essential tests required to evaluate lithium-ion battery packs in accordance with relevant standards. A complete testing procedure is proposed to ensure the battery is assessed properly in terms of safety, fault detection, and performance. The process is designed to eliminate the possibility of errors caused by the test itself. The method was applied to a 33.6 kWh, 100S1P LiFePO4 battery pack using industrial testing equipment. The results are reported in detail, with clear explanations of each step and measurement. The findings help determine the condition of the battery pack before it is delivered for integration into an electric vehicle. The procedure provides a reliable way to assess battery status and supports its use as a standard practice in testing and inspection before deployment.

Although the demonstration in this study was conducted using a new LiFePO4 battery pack, the proposed testing procedure is designed to detect signs of cell degradation, including elevated internal resistance, reduced capacity, and abnormal state of health values. These diagnostic indicators are part of the evaluation process and can be used to assess second-life or aged battery packs. Future work will involve applying the procedure to degraded packs, either naturally aged or artificially conditioned, to further confirm its effectiveness in identifying performance deterioration and safety concerns.

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