Performance Evaluation of Retired Lithium-ion Batteries for Echelon Utilization

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***Abstract*—With the rapid growth of the electric vehicle (EV) market, the number of Lithium-ion (Li-ion) batteries that reach their end of life (EOL) is increasing rapidly. Given the stringent capacity fading threshold of EV batteries, tools are required for better understanding and evaluating the health condition of large volume EV batteries that have reached EOL. In this paper, four modules from the same battery pack of a hybrid electric vehicle have been evaluated in terms of their current capacity and performance of the cells within each module. The results have been analyzed to find an affordable method for performance assessment of the retired batteries for echelon utilization. Electrochemical impedance spectroscopy (EIS) as an accurate and powerful technique has been used as a benchmark for the measurement to show the reliability of the tests. Experimental results are obtained from different test approaches on both modules and cell levels and show a different ageing degradation pattern for the cells inside the modules. The result shows that even for the modules with the same range of state of health, any non-uniformity of the cells inside the modules will affect the reliability of the modules for a second life. We also show there is a meaningful dependency between the voltage monitoring of the cells and other test approaches to determine the uniformity of a module.**

Keywords— Battery, Electric Vehicles, Echelon Utilization, Retired Batteries, Second Life Batteries, SOH

I. INTRODUCTION

Energy is one of the most important factors in the growth and development of different countries. Renewable energy is a key to having a CO_2-free energy supply, and it is necessary to accelerate the energy transition that is essential to mitigate the complications created by climate change and global warming. Fortunately moving toward using low-carbon sources is happening very fast, especially it is going very well in European countries e.g. Sweden, Norway, and Denmark are the top 3 countries in the world based on the latest Energy Transition Index (ETI) on the world economic forum [1].

Batteries are an important puzzle part of the acceleration of the energy transition. Li-ion batteries due to their remarkable characteristics e.g. high energy density, high power density, low self-discharge rate, and capability to drain high current for high power applications, are the most favourable batteries, especially for EVs [2] [3]. The growth of the EV market is very fast and passenger EV sales had a big jump from 450,000 in 2015 to 2.1 million in 2019[4]. According to Bloomberg's prediction, more than 50% of the passenger cars that will be sold in 2040 will be electric [5]. The global battery electric vehicle stock based on the data from the international energy agency (IEA) has been shown in Fig. 1.

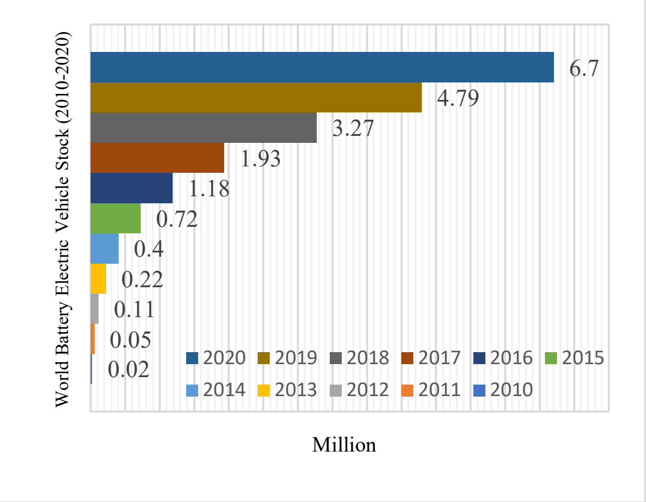

Fig. 1: Global battery electric vehicle stock from 2010 till 2020 adapted from [4]. The growth is a factor of 6 in 4 years.

While the progression of vehicle electrification is good news, on the other hand like any other new technology it will bring its own problems and challenges, especially related to the batteries. High/low temperature, over/under voltage, charge/discharge C_{rate} and time are the most important stress factors that affect the degradation of the Li-ion batteries by loss of active material, increase of internal impedance and loss of lithium inventory (LLI) [6] [7].

The battery state of health (SOH) characterizes the ageing condition of the battery and indicates the current capacity of the battery compared to the fresh battery [8]. Normally, the EV manufacturers define a specific SOH for the battery EOL to avoid the failure threshold. This threshold is normally defined when the battery capacity fades by 20-30%, which is reaching 70-80% of SOH [9]. When the battery reaches its EOL in an EV, it means that the battery is rendered unsuitable for the harsh operating conditions related to automotive applications. However, it is possible to use the battery in less demanding applications in terms of charge/discharge operating condition e.g. stationary energy storage systems [10].

Based on different feasibility and techno-economic analyses it indeed has been proved that reusing the batteries in both energy and power application is economically viable [11] [12]. Performance assessment is the most important technical challenge to be performed on retired batteries from EVs [13]. It is crucial to determine the health condition of the battery pack to evaluate the eligibility of the battery pack/module/cell for second use. The SOH of the modules need to be known and the modules with a similar health condition can be combined into a new battery configuration to reduce the failure rate of the battery. This further extends the battery lifetime which will lead to more economically viable second-life battery (SLB) use [11] [14]. One common method for performance assessment of SLBs is the capacity measurement of the battery. In this method, after fully charging the battery, a resting period related to the relaxation time is applied subsequently capacity measurement takes place, and the battery will be fully discharged based on the cut-off condition of the battery, which takes multiple hours. Besides the time-consuming nature of the capacity test that increases the labour cost for SLBs, it is also energy-consuming during the discharge process. In recent years, researchers are working on fast assessment methods to meet the requirement of fast verification of the large scale retired batteries that the EV market will face in the near future [15]. The rapid evaluation techniques assess the evaluation of health factors or parameters of the battery that reflect the SOH of the battery. Incremental capacity analysis, open-circuit voltage, incremental voltage differences based technique, differential thermal analysis, etc are the most common techniques that have been used to show the health condition of the battery.

This paper focuses on the performance characteristics of retired Li-ion battery modules and is organized as follows. Section II discusses the main principles of the evaluation process in terms of the main characteristics of the retired modules, experimental setup and the methodology for performing the measurement with the test procedures. In section III the results from the voltage monitoring test, DC internal resistance test, temperature monitoring of the cells inside the modules and finally the electrochemical impedance spectroscopy (EIS) are analysed. Finally, section IV draws some conclusions.

II. EVALUATION PROCESS

In this study, four modules of a battery pack from a hybrid electric vehicle (HEV) have been evaluated based on the performance of the cells inside the modules during normal operation condition. Each module contains 8 prismatic Lithium Manganese Dioxide (LiMnO2) cells that are connected in series. The modules have been used for 8 years in an HEV, and apparently with a significant number of charging/discharging cycles as the battery pack reached 70% of its initial capacity. As a first step, capacity test for each module has been performed. The general procedure in this test is straightforward by measuring the energy and capacity that has been stored within the battery in different temperatures and C_{rate}. Table I shows the main characteristics of the modules under test in this paper.

Table I. Key data from the battery modules, as obtained from the datasheet and from capacity tests on each module.

Parameter	Unit	Value
Cell chemistry	-	LiMnO2
Nominal capacity	Ah	40
Nominal voltage	V	30
Operation voltage range	V	22-32.8
Max continues charge current	A	125
Max continues discharge current	A	300
State of health $(SOH)_m$	Module 1	73.75%
	Module 2	72%
	Module 3	70.5%
	Module 4	73%

During the evaluation process, a comprehensive analysis based on different measurement approaches is performed at the module and cell levels. All measurable parameters of the modules and individual cells inside the modules are analysed to check for consistency of capacity and SOH.

A. Experimental Setup

The general objective of the experimental setup is to have a working measurement setup to test modules/cells that have been disassembled from an HEV battery pack. Charging/discharging the modules and measuring the power, energy, and capacity. further, it is capable of data logging, this is performed by using a data acquisition system.

A photograph of the measurement setup has been illustrated in Fig. 2.

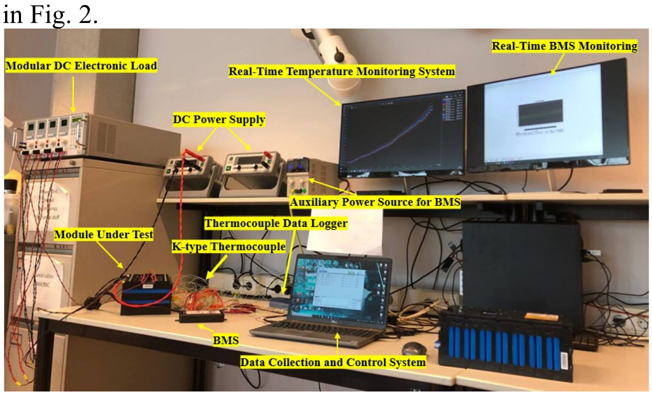

Fig. 2: Test setup for charge-discharge, measurement, monitoring and data acquisition of the cells and modules under test.

The measurement setup includes programmable DC power supplies and load modules to conduct battery charge and discharge test at different C_{rate}. To protect the module from abnormal conditions and guarantee safe charging and discharging characteristics each module has been tailored with an Orion Jr.2 BMS. Cell balancing, battery SOC and SOH estimation, cell and pack voltage, current, temperature monitoring and finally cell and pack protection from overcharge and under discharge are the main functions of the BMS in this setup. For temperature measurement of each cell and data acquisition, an 8-channel TC-08 thermocouple with ±0.75% error of measurement system has been used with a thermal camera to monitor the temperature distribution on the surface of the module under test. A schematic diagram of the test setup is given in Fig. 3.

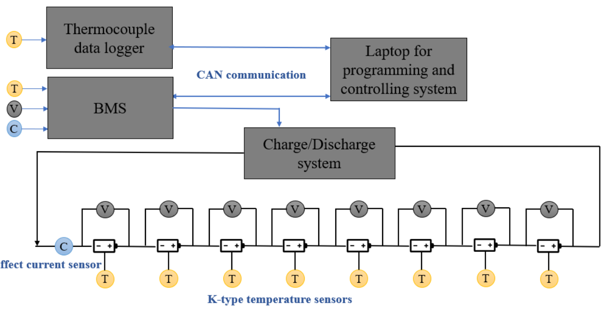

Fig. 3: Block diagram of the battery test system showing the interconnection between the cells, measurement sensors, BMS, charge/discharge system, etc.

B. Experimental Methodology

The assessment of retired modules from an HEV has been done based on the following steps on each module to evaluate performance of each module based on the health condition of the modules in terms of the uniformity of the cells inside each module.

- Step 1: Disassemble four modules from an HEV.
- Step 2: Mount Orion Jr. 2 BMS to protect the modules from abnormal situations.
- Step 3: Charge and discharge the modules according to the manufacturer's defined cycle.
- Step 4: Measure the current capacity of each module and compare it with the initial capacity of the modules.
- Step 5: Measure voltage of each individual cell within the modules and analyse the behaviour of the cells in terms of their voltage changes.
- Step 6: Measure and analyse the temperature changes of the cells.
- Step 7: Measure DC internal resistance for the cells.
- Step 8: Perform EIS measurement as a powerful technique for determining cell impedance and use this method as a benchmark for measurement validity.

III. RESULT AND DISCUSSION

During the charge and discharge process, the battery capacity test is performed to identify the SOH for each module and the results of the capacity test have been shown in Table I. The voltage of the module under test and also the voltage of each cell have been measured during the charge/discharge. Fig. 4 exhibits the voltage curves of the cells within the modules during discharge to show how the voltage response of the cells are behaving at the end of their first life in an HEV.

To narrow down the behaviour of each cell without any external influence, the cell balancing function of the passive BMS has been disabled to avoid dissipating power in the balancing resistors. The balancing function of the BMS will override the natural behaviour of the cells in order to maintain the integrity of the state of charge (SOC) among the cells. Hence it is important for second life assessment of cells to bypass the BMS and measure accurately each cell's parameters. In order to ascertain safety during the discharge process, it was necessary to define a cut-off voltage (2.8 V) condition for the cells in order to prevent deep discharge and hence the acceleration of health degradation.

Fig. 4 presents the voltage as a function of time during the discharge process of one module. It shows that the voltage of the cells is very similar during the normal discharging process and the significant difference between the characteristics of the cells only happens when the module reaches the end of discharge, after the cut-off voltage limitation. Actually, it can be considered a critical point for the cells based on their behaviour at the end of discharge.

The voltage of the cells after disconnecting the load and during the relaxation period has been measured while the cell voltage is rising to reach an equilibrium condition.

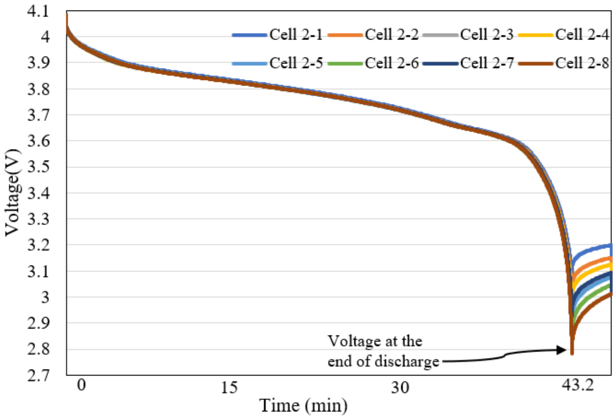

Fig. 4: Measured voltage of each individual cell within the module 2 during discharge without the BMS to observe its behaviour in order to voltage uniformity.

As illustrated in Fig. 5, the behaviour of the various cells within the four modules in terms of their voltage is different when they are reaching the cut-off discharge voltage and also the voltage rise at the end of discharge is different for the cells inside the modules.

To gain further insight into the cell properties, the DC internal resistance (DCIR) of each cell inside the modules has been calculated based on instantaneous voltage dropping based on applied current pulse approach according to [17]. The results are shown in Fig. 6 and also the deviation between the cells in terms of DCIR has been calculated in Table II. Module 1 has the lowest standard deviation (σ = 0.007 mΩ) which means there is more uniformity in terms of the DCIR between the cells in this module while module 3 has the highest standard deviation (σ =0.066 mΩ).

All modules and cells also have been evaluated based on their temperature changes during the charge and discharge process. The first challenge to measure the temperature of each individual cell was to find the best location to install the K-type thermocouple to monitor the surface temperature of each cell within the module under test. To find the location it has been decided to use a temperature camera to monitor the temperature distribution of the module surface and find the hot spots of the cells. Fig.7 shows a captured thermographic image of a module under test.

Based on the results from the thermal camera the hot spot for the placement of the temperature sensors is verified as the middle of each cell.

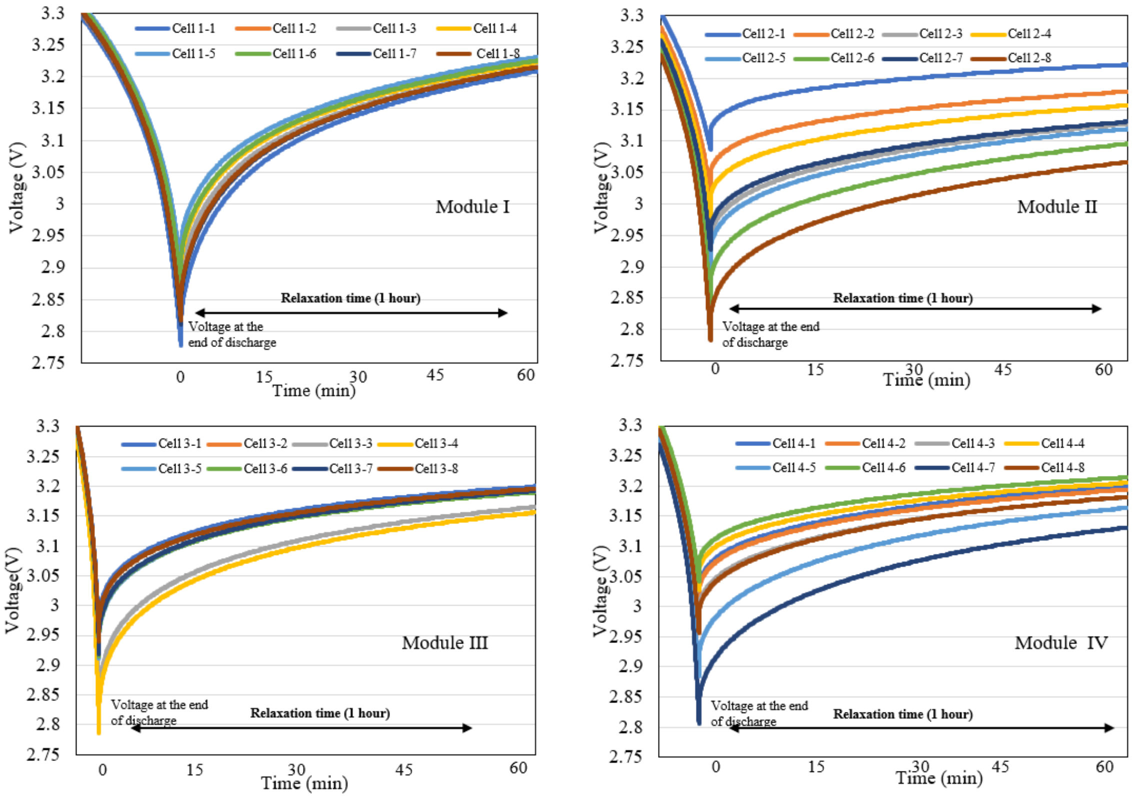

Fig. 5: Measured voltage of the individual cell within the 4 modules during the discharging process zoomed into the end of discharge and relaxation time of 1hour. Module 1 has cells that show very consistent and similar behaviour in terms of voltage characteristics of the cells.

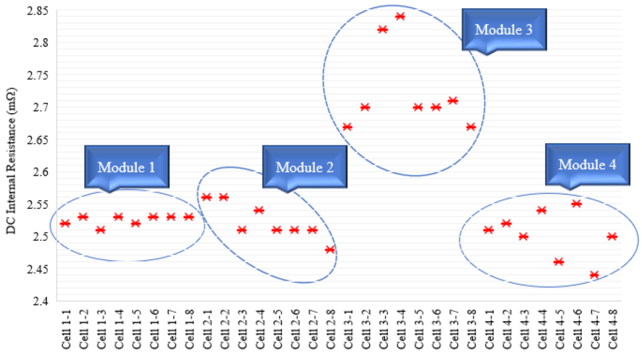

Fig. 6: DCIR calculated for each individual cell based on the current pulse approach at 1C.

The temperature changes during the discharging process are more significant than during charging due to the fact that the discharge process happens in constant current (CC) mode during the whole process but the charging process of the battery happens in constant current-constant voltage mode (CC-CV).

This means that during the charging of the battery when the battery voltage reached a pre-defined voltage limit (4.2 V), the charging current will start to decrease in a constant voltage mode. Fig. 8 illustrates the temperature changes on the surface of each cell within the modules during discharge at 1C.

Table II. Average DCIR of each module and the standard deviation between the cells inside each module.

	Average DCIR (mΩ)	Standard deviation (mΩ)
Module 1	2.525	0.007
Module 2	2.523	0.028
Module 3	2.726	0.066
Module 4	2.502	0.037

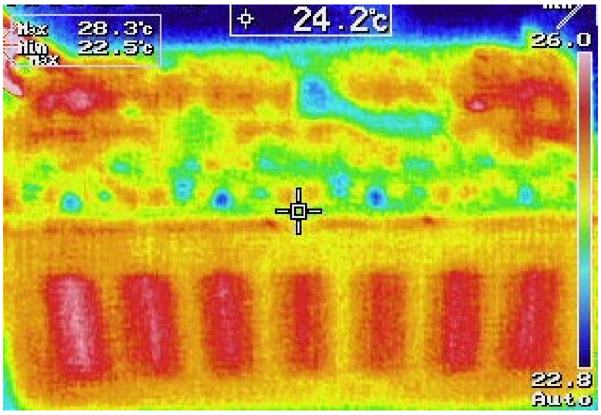

Fig. 7: Captured IR image from a module during charging, to monitor the temperature distribution on the surface of each cell.

It is clear from Fig. 8 that the behaviour of cells in terms of their temperature is quite different between the modules.

In module 1, the behaviour of cells in terms of temperature is uniform for all cells inside the module but for the other modules while the battery reached the end of discharge and its maximum temperature the discrepancy between the cells' temperatures is increasing. Since the cells are connected inside the module closely it is also important to mention that the temperature of one cell can affect the temperature of the adjacent cell. Temperature monitoring of the cells within a module can be used as an index for the module uniformity and discrepancy between the cells can be a sign of mismatching between the cells but uncertainties related to the position of the cells inside the module/pack or the position of the module itself can affect the measurement reliability.

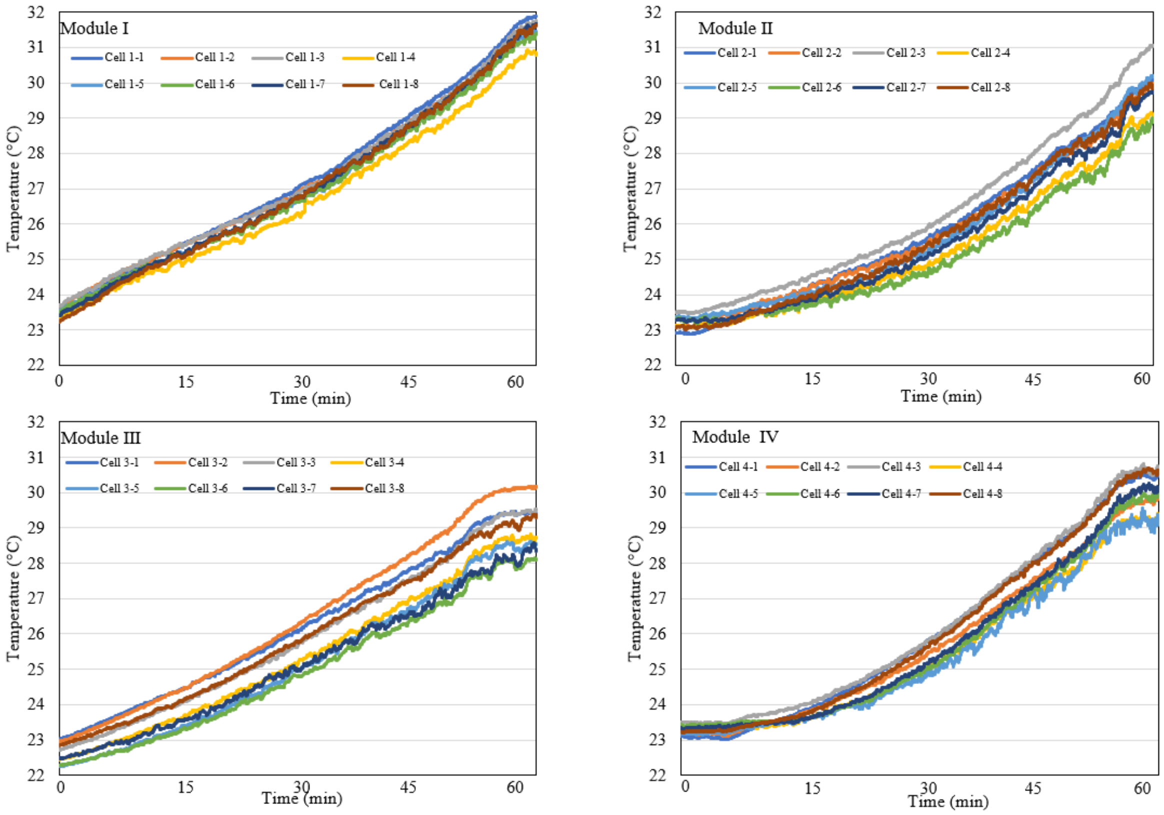

Fig. 8: Temperature behaviour of the cells within the modules during the discharge without the BMS regarding their surface temperature changes in 1 hour.

Electrochemical impedance spectroscopy (EIS) is a powerful diagnostic technique in battery measurement. In this method, an AC sweep signal is applied to the battery and from the response signal the impedance is determined. The EIS can be performed in two different ways, in the first method the injected signal is a voltage and the measured parameter is current (potentiostatic) while the complementary method is with the current signal injected into the battery and its voltage response measured (galvanostatic).Application of EIS on Li-ion batteries has been investigated comprehensively in [16]. Due to the ability to measure impedance over a wide range of frequencies results in a more accurate battery parameter determination related to other techniques such as voltage monitoring, DCIR, and battery thermography, EIS method can be used as a benchmark for battery measurement with different methods. Fig. 9 presents the EIS measurement results for the cells within module number 1. Solartron EchemLab [17] is used to perform EIS measurement on cell level of each module with a frequency range of 0.1 Hz to 5 kHz with an impedance accuracy of ~0.2%.

In comparison with other modules, module 1 had the best uniformity based on the cell's performance and internal parameters. Fig.10 shows the EIS measurement results for module 3 which had the highest discrepancy in terms of voltage and DCIR. The discrepancy between the cells in module 3 is conspicuous based on the EIS results.

Generally, the EIS data can be presented by a Nyquist plot or Bode plot. To compare the magnitude of the measured impedance in different frequencies, the Bode plot is more usable. It can be seen from the Bode plot based on EIS measurement for module 1 in Fig. 9 that the results based on voltage monitoring, DCIR and temperature changes show a good uniformity for the cells inside this module, and have a good correlation with EIS measurement.

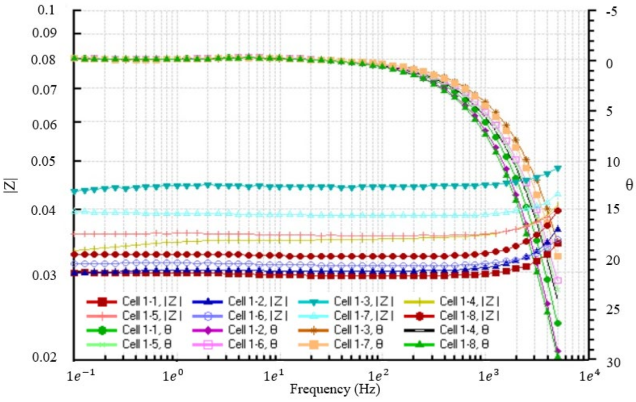

Fig. 9: Bode plot of the impedance characteristics of the cells within module 1.

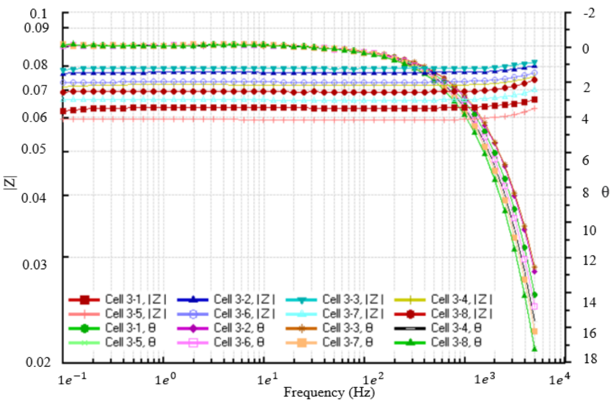

Fig. 10: Bode plot of the impedance characteristics of the cells within module 3.

IV. CONCLUSION

A comprehensive performance assessment to evaluate the eligibility criteria for SLBs is the core emphasis of the current work. This paper also highlighted the need for appropriate assessment criteria beyond the capacity based SOH estimation of modules, going all the way to cells. It is observed practically that the SOH of modules does not correlate directly to all cells. The reliability of a battery pack is a function of the reliability of individual cells and as a corollary, it is important to note that the SOH of the module is a function of the SOH of cells. To decrease the failure rate / increase the reliability of the SLBs, performance evaluation needs multi-level assessment criteria to analyze the uniformity of the cells inside the modules.

The results from DCIR measurements, voltage monitoring, temperature monitoring and EIS measurements, show there is a discrepancy between the SOH, DCIR, temperature and EIS measurements of cells in different modules from the same battery pack.

For module number 1 with 73.75% of SOH and an average impedance magnitude of 0.03 mΩ based on EIS measurement, the results show a quite homogeneous behaviour for all cells in terms of measurement criteria that have been applied in this work. The result shows that this module apparently has been aged uniformly since the standard deviation for the cells in terms of DCIR is very low indicating the DCIR of all 8 cells is very close to the mean (σ =0.007 mΩ). This uniformity was also found in the cell behaviour in their voltage changes, temperature changes (σ =0.32 °C) and also the EIS Bode plot. For the other modules, there is more inhomogeneity within the cells that will affect the module performance and lifetime in its second life. Module 3, with the lowest SOH (70.5%), has the highest standard deviation among these 4 modules in terms of DCIR (σ =0.066 mΩ) and also highest discrepancy between the lowest and highest DCIR of the cells inside the module (6% from the average DCIR), standard deviation in terms of temperature at the end of discharge (σ =0.7 °C) and voltage monitoring at this point. The behaviour of the cells based on voltage and temperature monitoring and also the EIS plot with an average impedance magnitude of 0.06 mΩ can prove it. This seems to further indicate a correlation between SOH and other consistent battery parameters.

Between the different measurement approaches that have been done on each module in this study, there is a meaningful dependency between the voltage monitoring of the cells and EIS measurement which means that voltage monitoring at the end of discharge is the most critical for assessment of uniformity between the cells of each module. It has been observed that temperature monitoring of the cells due to the fact that can be affected by the temperature of the adjacent cells in a module suffered from the uncertainties related to the position of the cell and also the position of the module inside the pack.

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