Study and Development of Mixed Repurposing EV Battery System for Stationary Energy Storage Applications

Y.C. Fong, D.H. Wang, J. Mei, S. Raghu Raman and K.W.E. Cheng
Power Electronics Research Centre, Department of Electrical Engineering
The Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong
E-mail: yc-chi.fong@connect.polyu.hk

Abstract – This paper presents a case study of developing a stationary battery energy storage system (ESS) with a combination of used batteries from different electric vehicles (EVs). The batteries having nonidentical specifications, dismantled from two models of retired EVs with varied conditions, have been characterized. The state of health and the expected electrical performance of these repurposed batteries from EVs are analyzed and compared. A modular battery ESS with dual feed configuration is developed to strike a balance between reliability, performance and the cost of implementation. The modular approach allows flexibility in capacity and voltage level manipulation, as well as mitigates the efforts of battery replacement. The construction and key components in the systems are illustrated and explained. A simulation study has been performed which explores the effects of varied battery profiles and combinations to system performance. This work provides insights on designing and operating sustainable stationary ESS with mixed repurposed cells.

Keywords: Second life battery, batter recycling, electric vehicle, Battery repurposing.

I. Introduction

The penetration of electric vehicles (EVs) has been rapidly grown since last decade. From 2014 to 2019, the accumulative number of EVs produced in the world is over 4.5 million [1]. At present, over 500 GWh of EV batteries have been deployed worldwide, and the total capacity produced in each year are projected with a compound annual growth rate of about 25% in the coming decades [1]. In general, the lifespan of a battery EV is mainly limited by the battery cells, which normally last for about 8 to 15 years depending on the usage profile and battery technology. On one hand, the EVs offers an alternative transportation solution with zero road emission; on the other hand, the production and disposal of the batteries creates extra burden to the environment. Currently, the EV batteries are dominated by the Li-ion technology which provides sufficient power and energy density for traction power and driving range. Although the toxic metal content is lower compared to other battery technologies such as the lead-acid and nickel-cadmium based, without a proper treatment, cobalt, nickel, and other kinds of metals in the disposed lithium batteries would contaminate the ecosystem. In view of the increasing number of EVs retiring from the road, tackling of end-of-life EV batteries has become an emerging matter for both industry and authority. As a buffer to economically well-established recycling system, as well as to maximize the life-cycle value of the high-performance EV batteries, repurposing them into other applications is considered a promising way to relief the environmental impact of the end-of-life EV batteries. pack design.

Having about 60 to 80% state-of-health in general, the used EV batteries may no longer be suitable for automobiles, but still be capable of serving stationary energy storage for utilities, as well as other commercial and residential applications. For example, [2] presents a community energy storage system which provides grid ancillary services to local area; [3] and [4] demonstrates the feasibility of used EV batteries in both off-grid and grid-tied renewable systems.

Along with the battery technology development, there are variety of battery chemistries available in the market as well as deployed to different EVs. A second-life application capable of mixed batteries would greatly improve the availability and sustainability for the deployment of used EV batteries. This works presents the use of mixed repurposing EV battery into a back-up power supply for building applications. A battery energy storage system (BESS) with two types of used EV batteries is developed. A case study on different system composition is also conducted, which explores the design consideration of a mixed BESS.

II. Overview of the Proposed System

A battery energy storage system has been developed employing two different models of used EV batteries. The system configuration of the BESS is depicted in Fig. 1. The BESS consists of two strings of battery modules connected in-series via blocking diodes. The battery strings are constituted by series and parallel combinations of battery modules to form the desired capacity and voltage. Each of the modules is rated at 30 V and formed by eight sorted Li-ion battery cells connected in-series. With a 6S module configuration, the BESS has a total DC bus voltage rated at 180 V. The BESS has dedicated ports for charging and discharging. The charging port is connected to a charger integrating PV generation and utility mains; the discharging port is supplying to AC loads at 50 Hz 380 V through an inverter. With this configuration, the parallel strings provide additional redundancy in case of battery failure. Besides, the modular structure makes the replacement of battery much easier comparing to a single-pack design.

The system is constituted by the used batteries dismantled from Mitsubishi i-MiEV and Renault Fluence Z.E. (Fig. 2).

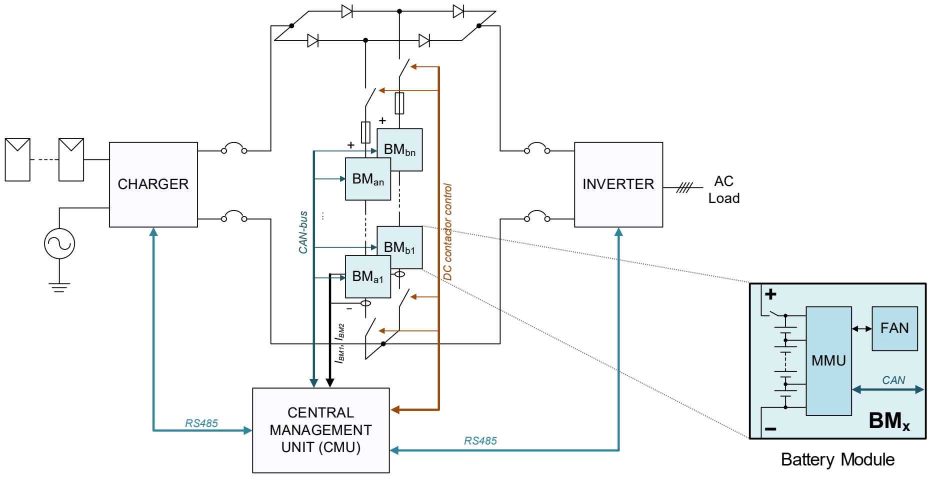


Fig. 1: The proposed energy storage system based on mixed repurposed EV batteries.

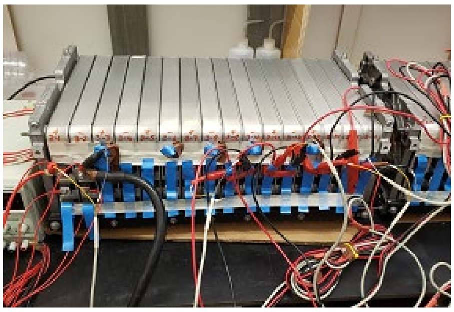


Fig. 2: The used EV batteries dismantled from a Renault Fluence Z.E. and placed on a test bench for measurement.

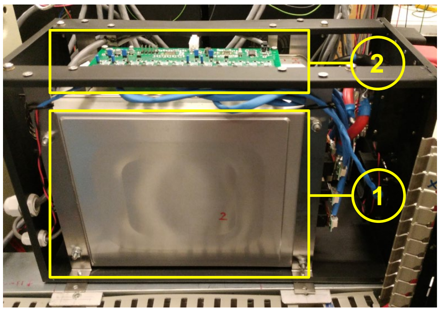


Fig. 3: Side view of an open-up battery modules; (1) the battery cells; (2) the module management unit (MMU).

A picture of the battery module prototype is depicted in Fig. 3 and 4. In each battery module, there is a manual switch accessible on the exterior of the chassis. When handling or replacing the battery module, the switches on the upper and lower, as well as the handling modules are opened to ensure that the circuit is cut-off. This improves the safety of battery installation and maintenance. Each of the modules is conditioned by a module management unit (MMU) which measures the voltage across each cell and the temperature of the cell terminals. The passive balancing switches in the MMU are controlled based on the cell voltage threshold and measured cell voltage difference. The cooling fans installed in the modules are also managed by the MMU based on the thermal condition. The voltage and temperature measurements, thresholds, as well as the operating status of the MMU are communicated to the central management unit (CMU) via an isolated Controller Area Network-bus (CAN-bus). The CMU collects the operating status of the battery modules via the CAN-bus, and controls the DC contactors of the battery strings accordingly. The CMU also monitors the voltage, current and insulation of the DC bus. Meanwhiles, the CMU coordinates with the charger and inverter to monitor and manages the charge and discharge status of the BESS.

III. Measurements and Analysis of Used EV Batteries

In this study, the used batteries from two models of EVs are examined. After visual inspection on any signs of visible damage or cell failure such as electrolyte leakage and obvious swell. The terminal voltage of each cell under idle

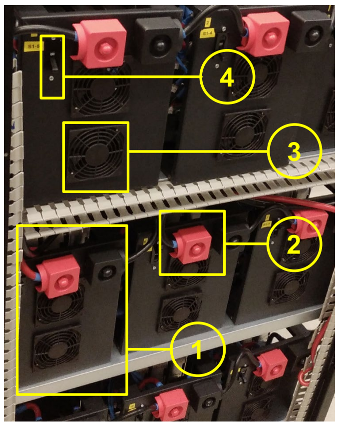
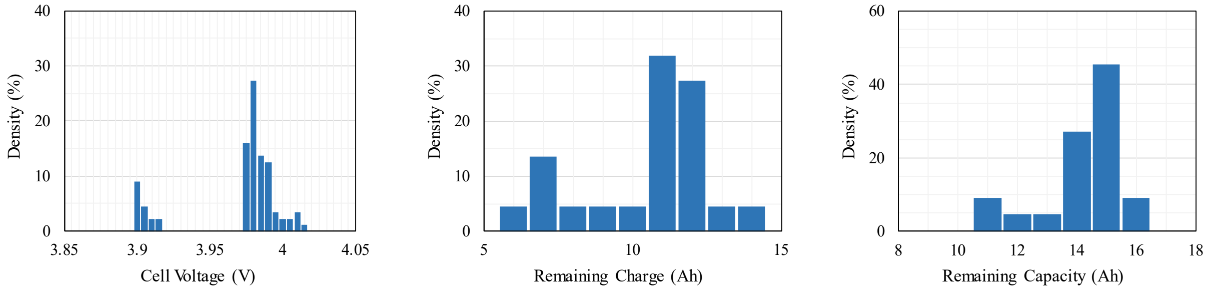


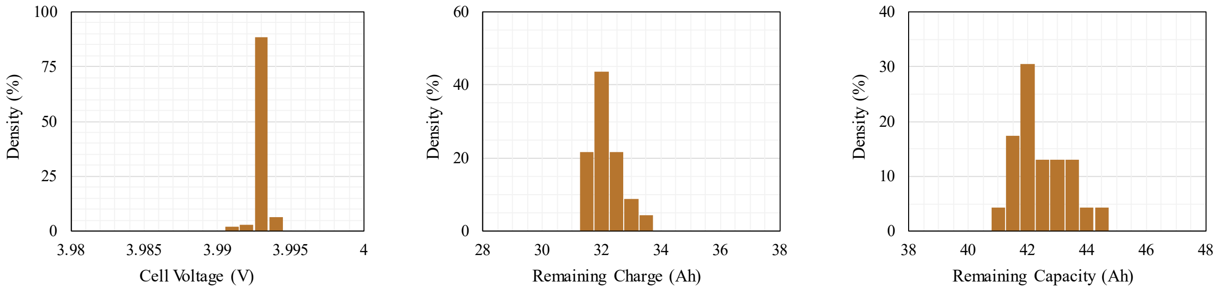
Fig. 4: A photo of the prototype; (1) a battery module; (2) module connection terminals; (3) cooling fan; (4) switch.

state was measured, followed by a full discharge test at 0.2 C of the rated capacity to measure the residual charge. These tests help screening unusable cells quickly at an early stage. After screening, the cells are sorted based on the analyzed results of the remaining capacity and the internal resistance. The measurements of the used battery dismantled from a retired Mitsubishi i-MiEV are shown in Fig. 5. The vehicle has been made full use of in its service for over 7 years with a total mileage of about 75,000 km. The battery cells inside the i-MiEV were LEV50 NMC [5] cells, with a rated capacity of 50 Ah, developed by GS-Yuasa. The measured terminal voltage of the cells when arrived was about 3.97 V with a range of around 100 mV. The remaining capacity of the used LEV50 cells with a charging constant voltage setting of 4.1 V and discharging



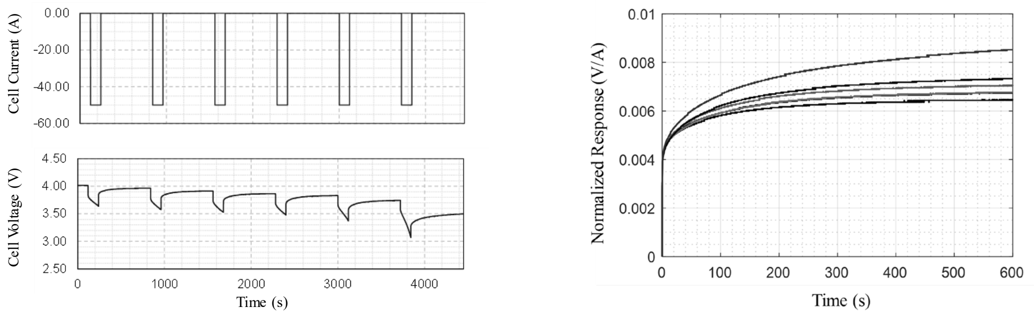
(a) (b) (c)

Fig. 5: Measurements and distribution of the used battery samples of LEV50 dismantled from a retired Mitsubishi i-MiEV. (a) Open-circuit voltage of the cells when arrived; (b) the residual charge in each of the cells; (c) the remaining available capacity.



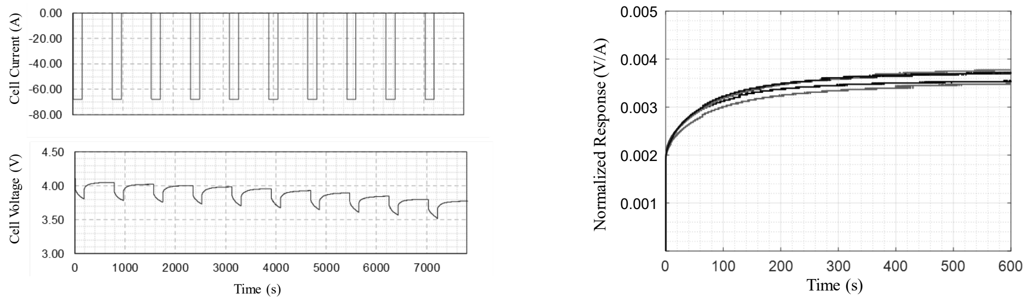
(a) (b) (c)

Fig. 6: Measurements and distribution of the battery samples from an end-of-service Renault Fluence Z.E. (a) Open-circuit voltage of the cells when arrived; (b) the residual charge in each of the cells; (c) the remaining available capacity.



(a) (b)

Fig. 7: The terminal voltage measurements of the used LEV50 cells under load current steps and the dynamic voltage response. (a) Measurements of cell voltage along with the load current steps; (b) the normalized dynamic cell voltage response to unit current step at different SOC.



(a) (b)

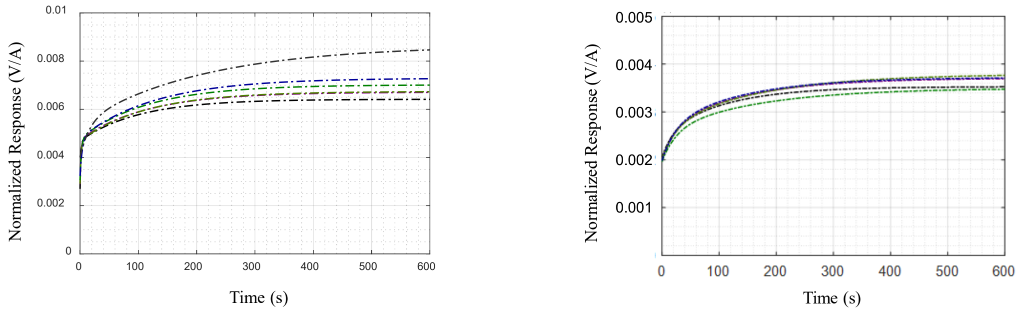
Fig. 8: The terminal voltage measurements of the used LMO cells from Fluence Z.E. under load current steps and the dynamic voltage response. (a) Measurements of cell voltage along with the load current steps; (b) the normalized dynamic cell voltage response to unit current step at different SOC.

cutoff voltage of 2.75 V was approximately 14 Ah. This is equivalent to 28 % state-of-health.

Similarly, the used LMO [6] cells from an end-of-service Renault Fluence Z.E. were examined. The cells dismantled form the Fluence Z.E. were at a healthier condition and uniformity. As depicted in Fig. 6, the cells terminal voltage was about 3.99 V having a total difference of within 5 mV. The average residual charge and capacity were approximately 32 Ah and 42 Ah, respectively. This is equivalent to an average SOH of 62% compared to the rated capacity of 68 Ah.

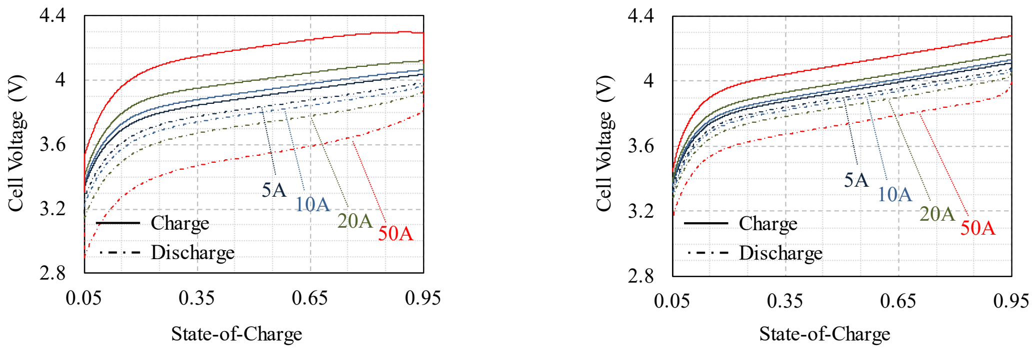
Table 1: Fitted circuit parameters of the used cells under different SOC

Mitsubishi i-MiEV					
	Resistance (Ω)			Capacitance (F)	
SOC	R_0	R_1	R_2	C_1	C_2
0.80	0.00270	0.00199	0.00173	682	58496
0.66	0.00289	0.00185	0.00197	938	57687
0.52	0.00291	0.00179	0.00205	1037	55951
0.38	0.00306	0.00172	0.00224	1349	51611
0.24	0.00324	0.00156	0.00250	2433	51498
Renault Fluence Z.E.					
SOC	R_0	R_1	R_2	C_1	C_2
0.79	0.00204	0.00050	0.00099	36414	109669
0.63	0.00199	0.00065	0.00107	34497	127377
0.49	0.00202	0.00065	0.00113	38119	145466
0.31	0.00196	0.00062	0.00091	38760	177689
0.15	0.00198	0.00070	0.00104	34246	131444



(a) (b)

Fig. 9: Emulated step response of the used battery cells at different SOC values using the fitted electrical parameters. (a) the used LEV50 cell; (b) the LMO cells from used Fluence Z.E.



(a) (b)

Fig. 10: Emulated charge-discharge characteristic of the used battery cells at different current. (a) the used LEV50 cell; (b) the LMO cells from used Fluence Z.E.

The electrical characteristic of the used cells was analyzed according to the measured voltage response to the applied load current step (Fig. 7 and 8). The dynamic responses of the cell voltage at different state-of-charge are normalized and modelled by a second order equivalent circuit model (1).

$$V_B = V_{OCV} + I_B[R_0 + R_1(1-e^{\frac{-t}{R_1C_1}}) + R_2(1-e^{\frac{-t}{R_2C_2}})] \qquad (1)$$

where V_B and I_B are the terminal voltage and current of the cell, respectively. V_{OCV} is the internal cell voltage represented by an ideal SOC-dependent voltage source. R and C are the equivalent internal circuit parameters representing voltage drop loss and time constant.

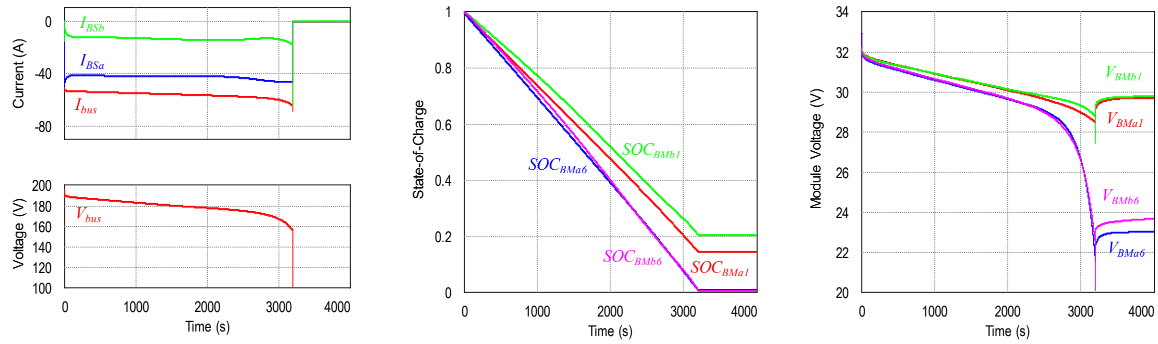
The measurements of the responses of the used battery cells could be fitted with the parameters shown in Table 1, which gives emulated responses of as depicted in Fig. 9. By putting the fitted parameters into the emulated battery models, the charge-discharge profiles of the two types of used battery under constant current charging and discharging at different current values are derived as Fig. 10. This gives an estimation on the cycle energy efficiency ranging from 84.3% at 50 A to 98.2% at 5 A for the used LEV50 cells of 28% SOH; and 91.1% to 99.1% in the same current range for the used cell from Renault Fluence Z.E.

Table 2: Modules available for deployment in the simulated mixed BESS

Mitsubishi i-MiEV		Renault Fluence Z.E.	
Module	SOH	Module	SOH
BM_{M1}	0.30	BM_{R1}	0.65
BM_{M2}	0.28	BM_{R2}	0.63
BM_{M3}	0.26	BM_{R3}	0.61
BM_{M4}	0.26	BM_{R4}	0.61
BM_{M5}	0.25	BM_{R5}	0.58
BM_{M6}	0.24	BM_{R6}	0.56
BM_{M7}	0.23	BM_{R7}	0.53
BM_{M8}	0.21	BM_{R8}	0.50

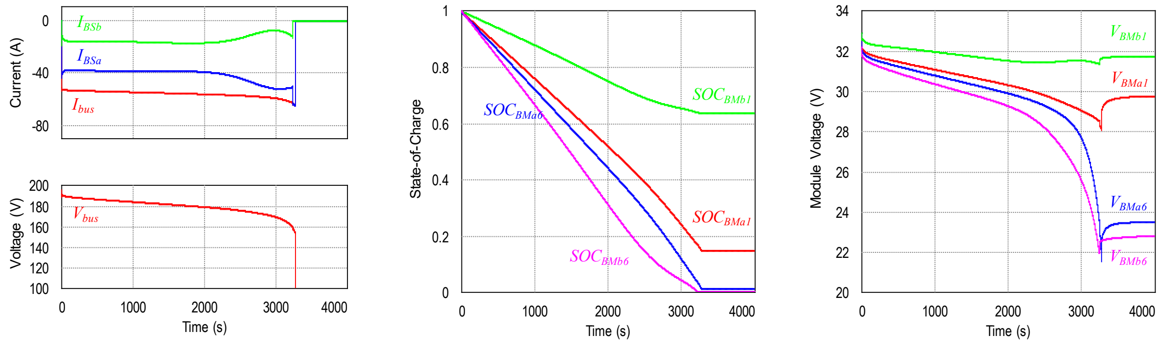
Table 3: Combinations of battery modules in different cases

Case-1	
String-A	String-B
BM_{R1}, BM_{R2}, BM_{R3}, BM_{R4}, BM_{R5}, BM_{R6}	BM_{M1}, BM_{M2}, BM_{M3}, BM_{M4}, BM_{M5}, BM_{M6}
Case-2	
BM_{R1}, BM_{R2}, BM_{R3}, BM_{R4}, BM_{R5}, BM_{R6}	BM_{R7}, BM_{R8}, BM_{M1}, BM_{M2}, BM_{M3}, BM_{M4}
Case-3	
BM_{R1}, BM_{R2}, BM_{R3}, BM_{R4}, BM_{R5}, BM_{R6}	BM_{R7}, BM_{R8}, $BM_{M1} \parallel BM_{M8}$, $BM_{M2} \parallel BM_{M7}$, $BM_{M3} \parallel BM_{M6}$, $BM_{M4} \parallel BM_{M5}$,



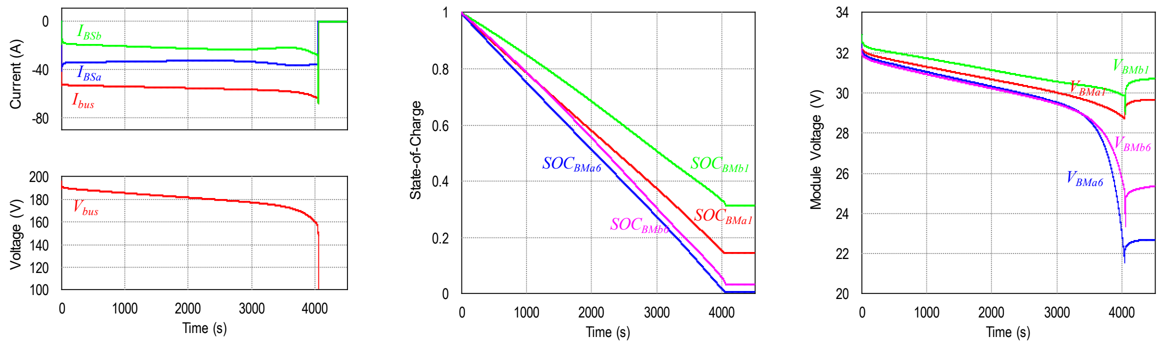
(a) (b) (c)

Fig. 11: Simulated discharge waveforms with the combination of Case-1. (a) Discharge voltage and current; (b) SOC; (c) module voltages.



(a) (b) (c)

Fig. 12: Case-2. (a) Discharge voltage and current; (b) SOC; (c) module voltages.



(a) (b) (c)

Fig. 13: Case-3. (a) Discharge voltage and current; (b) SOC; (c) module voltages.

IV. Simulation Study

A case study on the effect of the variations in battery profiles and the combination of batteries in the mixed BESS has been performed with numerical simulation. The simulation settings and parameters were designed referring to the system setting and the measured statistic on the used batteries. Based on the capacity measurements on the repurposing battery modules, the case study would be derived based on the available modules listed in Table 2. There are in total 16 modules, 8 modules with SOH ranged from 0.21 to 0.30 from the i-MiEV and eight modules with SOH of 0.50 to 0.65 from the Fluence Z.E., available for building the two battery strings, String-A and String-B. The module combinations in different cases are shown in Table 3. In Case-1, the best six modules from the respective Fluence Z.E. and i-MiEV would be selected to form the two strings while the remaining are severed as spares for future replacement; in Case-2, all modules formed from Fluence Z.E. cells would be used, and the rest are filled by the i-MiEV modules with highest SOH; in Case-3, all modules are used, the i-MiEV modules with the highest and lowest SOH would be connected in parallel to form a capacity comparable to the Fluence Z.E. modules. In the simulation model, the battery strings were connected together via blocking diodes to discharge to a 10-kW constant power load. All battery modules were fully charged initially. The corresponding battery string would be switched-out when one of the corresponding cells touch the cut-off voltage of 2.75 V. The discharge operation of the BESS ends if the DC contactors of both battery strings are opened.

The simulated results are illustrated in Fig. 11 to 13. The DC bus voltage, V_{bus}, as well as the bus current, I_{bus}, and the respective string currents, I_{BSa} and I_{BSb}, are shown. Throughout the discharge operation, the DC bus voltage decreased from an initial value of 196.8 V to a minimum value of about 148.8 V, and the maximum bus current was 67.2 A. The initial dynamic load current was distributed among the two strings majorly dependent on the corresponding internal impedance. Then, both the capacity and voltage characteristic have significant on the current sharing. In Case-1, approximately 75% of the load current was allocated to the String-A with Fluence Z.E. cells. While in Case-3, the parallel i-MiEV modules effectively reduced the impedance and increased the capacity of String-B, the load current allocated to String-A was drop to 60%. Besides, the module voltages as well as the SOC of the highest and lowest SOH modules in the respective battery strings are captured. Due to a comparatively large difference in the SOH or the remaining capacities, both the charge and battery voltage diverged along with discharging. The imbalance was more distinct in Case-2 where the Fluence Z.E. and i-MiEV modules with significant capacity difference were mixed used in String-B. At the end of discharging operation, the Fluence Z.E. modules in String-B had roughly 64% of unused charge. The total available discharging capacity in this case was limited by the i-MiEV modules with lower SOH. In these three cases, the discharging operation ended at about 3200 s, 3272 s and 4050 s, respectively. This would be corresponding to total discharging capacity of 8.89 kWh, 9.09 kWh and 11.25 kWh with efficiency of 95.75%, 95.85% and 96.46% for Case-1, Case-2 and Case-3, respectively.

The case study suggests that parallel two low SOH modules in a mixed BESS could improve the overall available capacity and performance of the system. This provides insight in the operation design and replacement schedule. For example, the used battery cells with better condition could be allocated to String-A. While the modules in String-A are further aged, the old modules can be used in parallel in String-B when a new batch of retired EV battery is available. The proposed replace schedule could make best use of the second-life EV batteries.

V. Summary

This paper presents a case study on the development of the back-up power supply with mixed repurposing EV batteries for building applications. The spent batteries from Mitsubishi i-MiEV and Renault Fluence Z.E. with different conditions are deployed to the system. The measurements showed that the used NMC cells from the i-MiEV have SOH of about 30% while the SOH of the LMO cells dismantled from the Fluence Z.E. was around 60%. The batteries are considered thoroughly used in their first-life in EVs, while still able to delivery power at fair efficiency in their second-life in stationary applications. A simulation of various cases of combining mixed battery modules in different ways has been conducted. By designing a module composition such that the capacity of the series modules and the impedance among the parallel strings are sorted the performance of the mixed BESS can be optimized and the second-life of the EV batteries can be fully utilized with a two-tier operation arrangement. This offers a repurposing EV battery application with improved availability and sustainability.

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