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Performance assessment of retired EV battery modules for echelon use

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ABSTRACT

The performance of retired EV battery modules was tested in order to learn their attenuation states and different capacity test protocols of retired modules are compared in order to strike a balance between calibration accuracy and test time. The results show that most modules have no serious capacity fading while a minority of modules whose capacity is less than 80% SOH will bring about the capacity of the whole battery system down to below 80% SOH. Echelon use of EV battery from aspect of modules has more value than that from aspect of packs. The capacity fading of Pack 2 is more than that of Pack 1 due to a rise in temperature because the cold air enters the side of Pack 1 and exits from the side of Pack 2. High capacity is not always related to small resistance, showing that different modules have experienced different ageing processes. The retired modules still have good discharge ability at 25%–200% of rated power, implying that a retired battery energy storage system can be employed to satisfy power demand of electricity grid. The capacity test protocol of 1/3 C constant current process without constant voltage process is proposed for retired modules.

1. Introduction

The scarcity of fossil energy resources and the increase of pollutant emission are relevant challenges to the transportation field [1]. The electric vehicle (EV) powered by renewable energy is a possible solution to these challenges [2]. Although EVs are promising substitutes for oil-fueled cars, the expensive batteries in EVs are still one of major obstacles that hinder the widespread use of EVs. Attempts are being made to resolve the problem of affordable EVs, such as building more efficient battery production plants [3], developing new low-cost battery materials of high energy density [4] and increasing additional values of EVs by feeding networks of vehicle to grid (V2G) [5]. Besides, the echelon use of retired EV batteries is considered as one of the most promising ways to reduce battery cost by extending their service life. Back in 2010, Neubauer et al. [6] believed that the second use strategies had the potential to become a common part of the future automotive battery lifecycle.

There are many works in the literatures devoted to the second use of retired EV batteries. Tong et al. [7] verified the feasibility of the retired vehicle batteries used in an off-grid photovoltaic vehicle charging systems and clarified the capacity decay trend of cells. The result showed that the testing cells possessed another 1400 cycles life while they were charged/discharged at 1C and 80% depth of discharge (DOD). Casals et al. believed that battery reuse enlarged their lifespan by 40% and their participation in energy storage service was profitable in secondary electricity markets [8]. Although it is generally viewed that the application of decommissioned batteries to grid energy storage is a good idea, there are a lot of key technical issues that need to be resolved, such as the precise and rapid estimation of retired battery remaining capacity, the degradation behavior during secondary utilization. Jiang et al. estimated the second-life battery remaining capacity by three types of regression methods and concluded that the correlation-based feature selection method was feasible and the estimation error was within 3% [9]. Omar et al. [10] studied the degradation

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performance of two $LiFePO_4$ (LFP) cells in a laboratory test environment. The cells were firstly cycled in the condition of 1C charge/discharge and 100% DOD until their state of health (SOH) was lower than 80%. Then, the cells were simulated for a second use and their results showed that these batteries below 80% SOH had more than another 1000 cycles life while they were charged at 1C and discharge at 2C in the 80% DOD range. Schuster et al. assessed the correlation between capacity and impedance of lithium-ion cells during calendar life as a base for capacity quick tests and found that SOH quick test must be parameterized with aging data close to actual use [11]. Lai et al. proposed a rapid screening approach based on neural networks for large-scale retired lithium-ion cells in second-use applications, illustrating that the capacity estimation error was less than 4% using this approach [12]. Viswanathan et al. [13] studied the battery performance in their reusing life and concluded that those retired batteries had another 15 years in the gird regulation use although a few batteries were required to be replaced in the operation time. There are also many literatures reporting the economic benefits of retired batteries. Han et al. [14] thought that the economy of the second-use battery energy storage system was related to the purchase, operation and maintenance costs of the energy storage system. Song et al. [15] considered that reusing batteries were not worthwhile for the studied wind farm but might be advantageous if the wind energy price decreased fast.

Despite all that, many previous researches of battery reuse focused on cells. The study of battery reuse in the aspect of modules or packs is still relatively few and the ageing performance of retired battery modules or packs is still seldom reported. Besides, capacity calibration is very vital for the reuse of EV batteries. The international organizations and associations for standardization have provided basic test standards and analytical methods for capacity calibration, such as ISO 12405−4 (2018) [16], IEC 62660−1 (2018) [17] and SAE-J1798 (2008) [18]. And much work has been done in detail to test and assess the capacity of new batteries. However, the effectiveness of these analytical methods on retired batteries still needs to be verified. It is admitted that the vantage of retired battery reuse lies in low cost while capacity calibration of retired battery consumes considerable time. There is probably a balance between calibration accuracy and the time spent on calibration. Hence, capacity test methods for retired batteries is worth exploring for the future reuse industrialization.

This paper presents a detailed description of performance characterization for 24 modules of retired LFP batteries after they are employed in an electric vehicle for three years. In addition, six kinds of capacity test protocols are discussed in order to seek a balance between calibration accuracy and the time spent on calibration and an optimal capacity test protocol is proposed. The results will be helpful to the strategies for echelon use of retired EV batteries.

2. Experimental

2.1. Configuration of the battery module testing platform

The testing platform for the retired battery modules is displayed in Fig. 1, and it is composed of the central control computer (Lenovo YangtianT4900v-00, China), physical control switch (Bull Electric GN-216, China), battery testing machine (Bitrode FTV1-300-100, USA), battery modules (Tianjin Bic Battery Co., Ltd., China), battery management system (Shanghai Qiansai electronics Co., Ltd., China), data line (Blekin Co., Ltd., China) and data converter machine (Netgear JFS524, USA). The central control computer is used for the programming and operating command of charge-discharge protocols, the record and storage of test data. The physical control switch is in charge of the on-off state of power supply. The battery testing machine (Bitrode FTV 1-300-100, USA) is provided for the charge-discharge of battery modules. The battery management system monitors battery status such as temperature, voltage and so on. The data line and data converter machine controls data transmission. Battery modules are the subjects for study.

2.2. Battery modules

The battery modules were retired from a Chery S18 EV after three years usage, which was manufactured by one of the largest auto manufacturers in China in 2010. The total driving distance of the EV was not less than 50000 kms and the cycle count of its battery system was not less than 1000 cycles before the EV was retired. The research work of the retired battery modules started from 2017. Therefore, the retired battery modules had at least a calendar life of 8 years. Fifteen cylindrical 26650-type $LiFePO_4$ cells were firstly connected in parallel as a 15P1S module. Then four or six 15P1S modules were connected in series as a 15P4S or 15P6S module and every pack consisted of eleven 15P4S modules and one 15P6S module in series. Finally, the whole EV battery system was comprised of two packs in series (showed in Fig. 2). The rated voltage and capacity of the single cell in the module was 3.2 V and 2.69 Ah while the whole EV battery system had a nominal voltage of 320 V and a nominal capacity of 40 Ah. The total energy capacity of the EV battery system is 12.8 kWh.

2.3. Test methods

The capacity of retired battery modules was characterized using a module battery tester, with the procedure referred to as the standard entitled “Technical specifications of performance test for smart grid energy storage batteries” (DB31/T817-2014, China) [19]. The retired module was discharged with a constant current (CC) of 1/3 C (C_3) until the working voltage of the whole module dropped to 2.7 $\times$ n V or the working voltage of one cell in the module dropped to 2.5 V, in which the symbol n stands for the amount of series. After a 1-h rest, it was charged with C_3 until the working voltage of the whole module climbed to 3.65 $\times$ n V, then switched to a constant voltage (CV) phase until the current was less than 1/20 C (C_{20}). If the working voltage of one cell in the module climbed to 3.75 V, the charging step should be stopped immediately and go to the next step. After 1-h break, it was discharged with C_3 until the working voltage of the whole module dropped to 2.7 $\times$ n V or the working voltage of one cell in the module dropped to 2.5 V. Other charge/discharge protocols of capacity tests were also considered. The first kind of protocols included CC and CV procedures, but the charge/discharge rates were 1 C (C_1) [20], 1/5 C (C_5) [21] and 1/10 C (C_{10}) [22], respectively. The second kind of protocols had the same charge/discharge rates as C_3 and the same upper and lower cutoff voltages, in which one protocol implemented CC procedure without CV procedure until the upper and lower cutoff voltages of the whole module or one cell; another protocol finished CC and CV procedures only at the upper and lower cutoff voltages of the whole module. The comparison among different protocols of capacity tests helps to find out the suitable protocol for retired battery, which can balance the accuracy of measured capacity against the duration of measurement.

The direct current (DC) internal resistance referred to the hybrid pulse power characterization (HPPC) in the standard entitled “FreedomCAR battery test manual for power-assist hybrid electric vehicles” (DOE/ID -11069, USA) [23]. The test modules were first charged to 50% state of charge (SOC) and then rested for 2 h. After that, the test modules were discharged at the pulse current of C_1 for 10 s, rested for 40 s, and then charged at the pulse current of 1/2 C (C_2) for 10 s. As for the calculation of DC internal resistance, referred

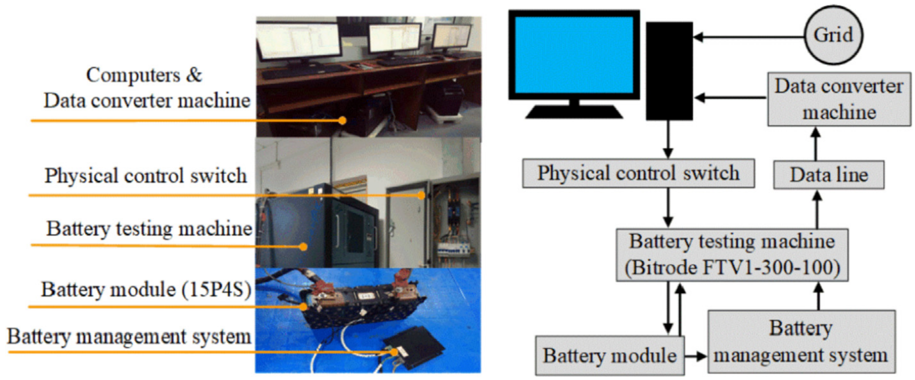

Fig. 1. Testing platform of the battery module from Chery S18 EV.

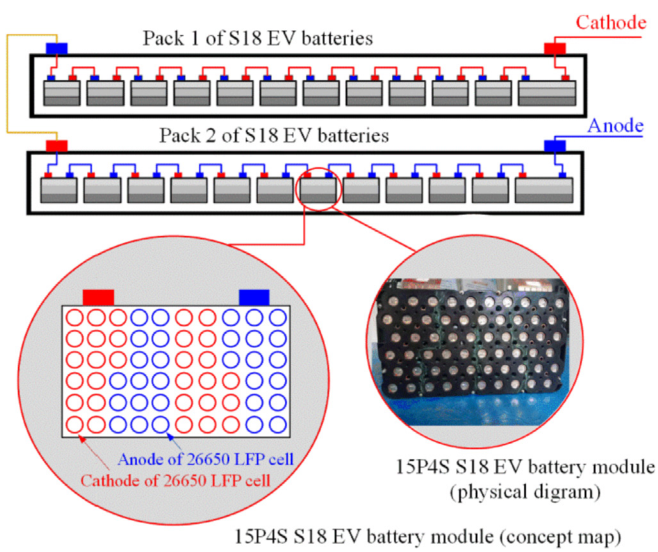

Fig. 2. Arrangement of the Chery S18 EV battery module.

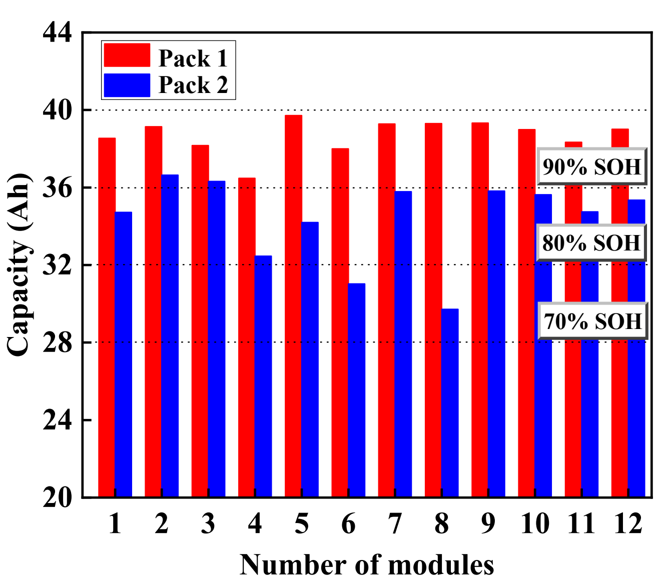

Fig. 3. Scatter diagrams of actual capacities of all retired modules from the EV battery system.

to the literature [24].

The power characteristics of retired batteries is a very important parameter if they are used to provide ancillary services for the electricity market after being manufactured as a battery energy storage system. The power characteristics test was performed at different constant power in order to inspect the continuous discharge ability of the retired battery modules. The rated capacity of the retired battery modules was set as 90% of the rated capacity of the new battery modules, i.e. 36 Ah. So the rated power P_r of the retired battery modules was set as 0.461 kW (P_r = 36 Ah × 3.2 V × 4/1000 = 0.461 kW). The retired battery modules were first charged at a constant power of 33.3% P_r (0.154 kW) until the working voltage of the whole module climbed to 3.65 × n V or the working voltage of one cell in the module climbed to 3.75 V, rested for 1 h, then discharged at different constant power such as 50%, 75%, 100%, 125%, 150%, 175% and 200% of the rated power of the retired battery modules, respectively, until the working voltage of the whole module dropped to 2.7 × n V or the working voltage of one cell in the module dropped to 2.5 V.

The performance of all the disassembled battery modules was tested and assessed at 25 ± 2 °C in our lab.

3. Results and discussion

3.1. Basic performances of retired battery modules

3.1.1. Capacity characteristic

After having been disassembled from packs, all the retired modules underwent basic capacity calibration. Fig. 3 illustrates scatter diagrams of actual capacities of all retired modules from the EV battery system and Table 1 shows statistical results of battery module capacity. Capacities of the red bars belong to the modules in Pack 1 while the blue ones stand for the capacities of the modules in Pack 2 in Fig. 3. It can be seen from Fig. 3 that the capacities of the twelve modules in Pack 1 are all larger than 36 Ah (90% SOH) and ten of them have more capacity than 38 Ah, indicating that the modules in Pack 1 have small capacity fading. By comparison, the modules in Pack 2 have larger capacity fading. There are two modules whose capacity is between 36 and 38 Ah (more than 90% SOH), eight modules whose capacity is between 32 and 36 Ah (80%–90% SOH) and two modules have the capacity of 28–32 Ah (70%–80% SOH), suggesting that there are only two modules whose SOH is less than 80% in Pack 2. Although most modules in the EV battery system have no serious capacity fading as the whole, one or two modules whose capacity is less than 80% SOH will bring about the capacity of the whole battery system down to below 80% SOH. It suggests that echelon use of EV battery from aspect of modules has more value than that from aspect of packs. In addition, the Chery

Table 1
Statistical results of battery module capacity.

Item	Pack 1	Pack 2	The whole battery system
Maximum (Ah)	39.72	36.64	39.72
Minimum (Ah)	36.48	29.72	29.72
Mean (Ah)	38.69	34.37	36.53
Standard deviation (Ah)	0.835	2.089	2.683
The module number (SOH < 80%)	0	2	2
The module number (SOH ≥ 80%)	12	10	22

Table 2
Statistical results of DC internal resistance of battery modules.

Item	Pack 1	Pack 2	The whole battery system
Maximum (mΩ)	19.50	21.75	21.75
Minimum (mΩ)	14.50	14.25	14.50
Mean (mΩ)	16.67	18.75	17.71
Standard deviation (mΩ)	1.556	1.934	2.401
The module number (<18 mΩ)	10	4	14
The module number (> 18 mΩ)	2	8	10

S18 EV battery system is air-cooled by serial ventilation mode. The cold air enters the side of Pack 1 and exits from the side of Pack 2. The temperature of battery packs ascends in turn from Pack 1 to Pack 2 because of heated air in the flow process, so the cooling effect of air on Pack 2 is inferior to that on Pack 1, resulting in more capacity fading of Pack 2 than that of Pack 1. It is very necessary to optimize wind cooling modes of battery packs in order to reduce battery attenuation.

3.1.2. Internal resistance characteristic

Scatter plots of DC internal resistance of battery modules with their capacity is shown in Fig. 4. Red points stand for the data from Pack 1 while blue ones represent for the data from Pack 2. There is a reasonable phenomenon that battery modules with high capacity have small resistance from the general trend in Fig. 4. However, big capacity is not always related to small resistance. There is still high capacity in some battery modules with small resistance while some battery modules with high (low) capacity have big (small) resistance, suggesting that different modules have experienced different ageing processes. Table 2 is statistical results of DC internal resistance of battery modules. The resistance consistency among modules in Pack 2 is worse than that in Pack 1. Moreover, the proportion of modules with small resistance in Pack 1 is higher than that in Pack 2. The mean resistance value of all 24 battery modules is 17.71 mΩ. If the mean resistance value of 18 mΩ in the whole battery system is regarded as a boundary line between good or poor modules, there are 10 good modules in a total of 12 modules of Pack 1 while only 4 good modules are selected from a total of 12 modules of Pack 2. In short, modules in Pack 1 are better than those in Pack 2 no matter either from capacity or resistance.

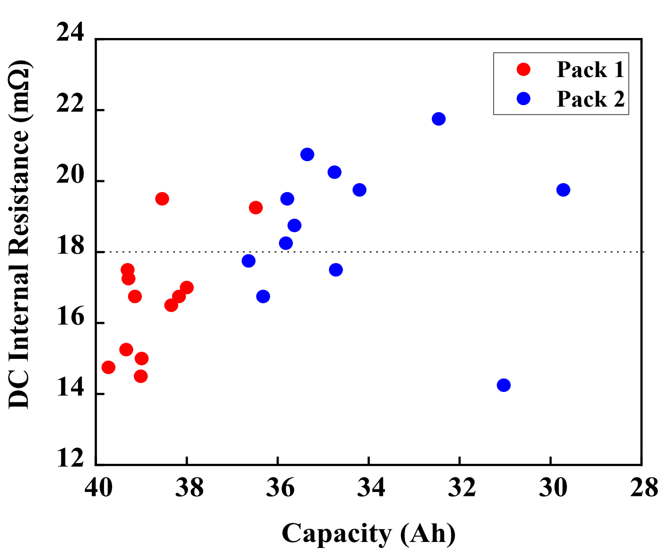

Fig. 4. Scatter plots of DC internal resistance of battery modules with their capacity.

3.1.3. Power characteristic

Frequency regulation [25] and power smoothing [26] are two important auxiliary services of a battery energy storage system for power regulation of electricity grid. The power characteristic of retired batteries is very important but has yet to be verified if they are manufactured into energy storage system. Therefore, four retired modules with approximate capacity (38.06 Ah, 38.22 Ah, 38.35 Ah and 38.51 Ah) are tested for understanding their power characteristic in one, two or four series, respectively. Fig. 5 shows power characteristic curve of the retired battery modules in different series, reflecting the effective discharging period of the retired module under specified discharge power. The power rate on the vertical axis in Fig. 5 means the ratio of the specified discharge power to the rated power in percentage.

It can be seen from Fig. 5(a) that the effective discharge time is 59 min when the discharging power is equal to the rated power of 0.461 kW, indicating that the discharge time of this module is close to that of the new one. The effective discharge time decreases with the increase of the power rate when the power rate is more than 100%, but it is still very close to the nominal discharging time at the corresponding power rate. For example, when the power rate is 200%, the effective discharge time is 28 min and very close to the nominal discharging time of 30 min. On the other hand, the effective discharge time is a little more than the nominal discharging time at the corresponding power rate when the power rate is less than 100%. Fig. 5(b) and (c) both show the similar rules when the retired modules are connected in two or four series. Fig. 5 illustrates that the retired modules in different series still have good discharge ability at 25%–200% of rated power, suggesting that it is feasible to satisfy power demand of electricity grid using a retired battery energy storage system. It is universal in scenes of energy storage applications for power demand such as power smoothing and frequency regulation. The employment of retired batteries will reduce markedly the cost of energy storage applications.

3.2. Optimization for capacity test protocols of retired modules

3.2.1. Capacity test protocols

Capacity test is one of the most important steps for understanding the decay of retired batteries. China has released a standard entitled “Recycling of traction battery used in electric vehicle—test of residual capacity” (GB/T 34015–2017, China) and set a small constant charge/discharge current at C_5 rate for the capacity test in 2017 [21]. Some papers have also used other protocols such as the smaller constant current of C_{10} to analyze the retired batteries [22]. Of course, small constant charge/discharge currents are favorable for the accuracy of residual capacity of retired batteries. However, both protocols have the same drawback that the test protocols are time consuming for large scale industrial use. In order to weigh the test accuracy against the test time, other protocols which employ higher testing currents are also provided for comparison. In addition, the impact of different cutoff voltage limits on capacity accuracy is also discussed.

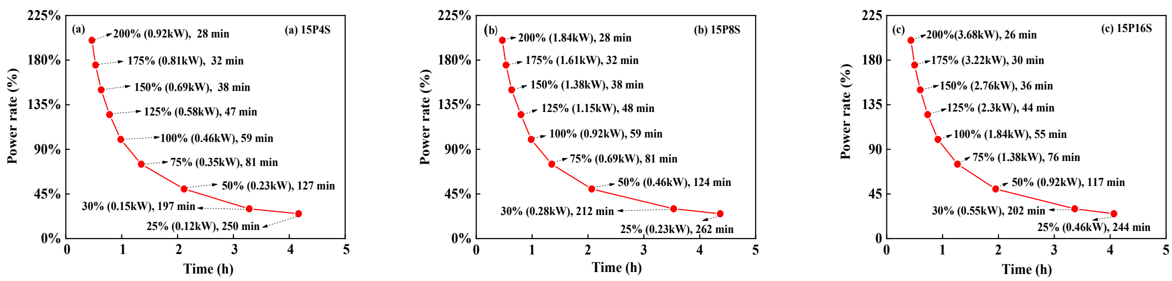

Fig. 5. Power characteristic curve of the retired battery modules in different series.

Table 3 presents six kinds of capacity test protocols for retired 15P4S modules. Protocol 1 refers to the standard entitled "Lithium-ion traction battery pack and system for electric vehicles (GB/T 31486—2015, China)" [20] and "FreedomCAR battery test manual (DOE/ID-11069, America)" [27]. Protocol 2 is based on "Electric vehicle battery test procedures manual (SAND 99—0497, America)" [28], and it is also used by the State Key Laboratory of Automotive Safety and Energy in China [29], and the National Active Distribution Network Technology Research Center in China [30]. Protocols 3 and 4 both include CC and CV procedures, but the charge/discharge rates are C_5 [21] and C_{10} [22], respectively. Protocols 5 and 6 have the same charge/discharge rates as those of Protocol 2 and the same upper and lower cutoff voltages of module. Protocol 5 implements CC procedure without CV procedure until the upper and lower cutoff voltages of the whole module. The difference between Protocols 6 and 2 is only that Protocol 6 fails to set the upper and lower cutoff voltages of one cell. Five retired modules with the SOH values of 93.00%, 89.38%, 83.03%, 74.20% and 71.38% are selected for exploring the optimal capacity test protocol of retired modules and these modules are marked as #1, #2, #3, #4 and #5 in order, respectively. Table 4 presents the charge capacity (C_{charge}) and discharge capacity ($C_{discharge}$) of all five modules by different capacity test protocols, showing that C_{charge} of every module is very similar to its $C_{discharge}$ by a specific capacity test protocol. Therefore, we can adopt C_{charge} instead of $C_{discharge}$ to analyze the influence of different charge-discharge protocols on the capacity calibration of retired modules.

3.2.2. Optimization for capacity test protocols

Fig. 6 shows the C_{charge} of modules #1, #2, #3, #4 and #5 by different capacity test protocols. It can be seen from Fig. 6 (a) that the C_{charge} of Module #1 increases obviously with the decrease of charge/discharge rate from Protocols 1 to 4, and the C_{charge} of Module #3 declines directly while the C_{charge} values of the other three modules rise slightly firstly and then go down. It may be caused due to good or poor consistency among cells in one module. C_{CC} means charge capacity during CC process while C_{CV} means charge capacity during CV process. C_{charge} is the sum of C_{CC} and C_{CV}. C_{CC} and C_{CV} of modules #1, #2, #3, #4 and #5 by different capacity test protocols are presented in Fig. 6 (b) and Fig. 6 (c), respectively. Fig. 6 (b) displays that C_{CC} of other four modules except Module #1 increases firstly and then decline slightly with the decrease of charge rate from Protocols 1 to 4 while that of Module #1 climbs substantially. Although the capacity test by Protocol 1 takes far less time than that by Protocols 2, 3 and 4, C_{CC} of every module by Protocol 1 has a gap more than 1.0 Ah compared with that by Protocols 2, 3 and 4 for Modules #2, #3, #4 and #5. The C_{CC} values of each module by Protocols 2, 3 and 4 are closer and have a gap less than 0.5 Ah for Modules #2, #3, #4 and #5, but the testing time by Protocols 3 and 4 is much longer than that by Protocol 2. Therefore, Protocol 2 is thought to be an optimal protocol for the capacity test of retired modules among Protocols 1, 2, 3 and 4 after weighing between measuring accuracy and test time. Fig. 6 (c) illustrates that C_{CV} of five modules all goes down with the diminution of charge rate from Protocols 1 to 4. Moreover, the smaller the SOH of modules, the less the proportion of C_{CV} to C_{charge}, suggesting that the CV process of capacity test can be neglectable for most retired modules.

The common ground of Protocols 2, 5 and 6 is the same charge/discharge rate as C_3. It can be shown in Fig. 6 (a) that the capacity of each module in Protocol 6 is the biggest among Protocols 2, 5 and 6, but the inconsistency of cells in modules will lead to the dangerous over-charging of certain poor cells when the cutoff condition is only set as the cutoff charge rate of C_{20}. Moreover, the difference of C_{CC} of every module between Protocol 5 and Protocols 2 or 6 is not wide and less than 0.5 Ah while the difference of C_{CV} of every module for Modules #1, #2 and #3 between Protocol 5 and Protocols 2 or 6 is more than 1.0 Ah. The C_{CC} of each module has micro-close values in Protocols 2, 5 and 6 for these five modules. It is reasonable that capacity test of retired batteries is done only by CC process without CV process.

Fig. 7 shows the degradation performance of another retired battery module (#6) from the capacity of 37.88 Ah (94.7% SOH) to 26 Ah (65.0% SOH). Fig. 7 (a) is the discharge capacity $C_{discharge}$ of Module #6 according to four kinds of capacity test protocols when it ages at a 2C charge-discharge rate from the SOC of 80% 30% for 3000 cycles while Fig. 7 (b) is the corresponding coulomb efficiency. Fig. 7(a) shows that the smaller the charge-discharge rate,

Table 3
Six kinds of capacity test protocols for retired 15P4S modules.

Protocol	Charge rate	CV charge voltages (V)	CV charge	Lower cutoff charge rate or upper cutoff voltage (V)	Rest time	Discharge rate	Lower cutoff voltages (V)
1	C_1	14.60 (Module) or 3.75 (Cell)	✓	C_{20} (Module) or 3.75 (Cell)	1 h	C_1	10.80 (Module) or 2.5 (Cell)
2	C_3	14.60 (Module) or 3.75 (Cell)	✓	C_{20} (Module) or 3.75 (Cell)	1 h	C_3	10.80 (Module) or 2.5 (Cell)
3	C_5	14.60 (Module) or 3.75 (Cell)	✓	C_{20} (Module) or 3.75 (Cell)	1 h	C_5	10.80 (Module) or 2.5 (Cell)
4	C_{10}	14.60 (Module) or 3.75 (Cell)	✓	C_{20} (Module) or 3.75 (Cell)	1 h	C_{10}	10.80 (Module) or 2.5 (Cell)
5	C_3	14.60 (Module) or 3.75 (Cell)	×	14.60 (Module)	1 h	C_3	10.80 (Module)
6	C_3	14.60 (Module) or 3.75 (Cell)	✓	C_{20}	1 h	C_3	10.80 (Module)

Table 4
The charge capacity (C_{charge}) and discharge capacity ($C_{discharge}$) of all five modules by different capacity test protocols (Ah).

Protocol	Module #1		Module #2		Module #3		Module #4		Module #5	
	C_{charge}	$C_{discharge}$	C_{charge}	$C_{discharge}$	C_{charge}	$C_{discharge}$	C_{charge}	$C_{discharge}$	C_{charge}	$C_{discharge}$
1	35.30	35.31	35.31	35.38	33.30	33.35	29.17	29.24	28.25	28.26
2	37.21	37.20	35.71	35.75	33.21	33.21	29.69	29.68	28.57	28.55
3	37.98	37.93	35.33	35.36	32.81	32.78	30.07	30.05	28.70	28.66
4	39.26	39.20	34.18	34.02	31.38	31.66	29.94	29.83	28.50	28.35
5	35.39	35.08	33.60	33.37	31.64	31.43	29.89	29.70	28.54	28.36
6	37.61	37.39	35.82	35.79	34.14	34.17	32.47	32.51	30.58	30.63

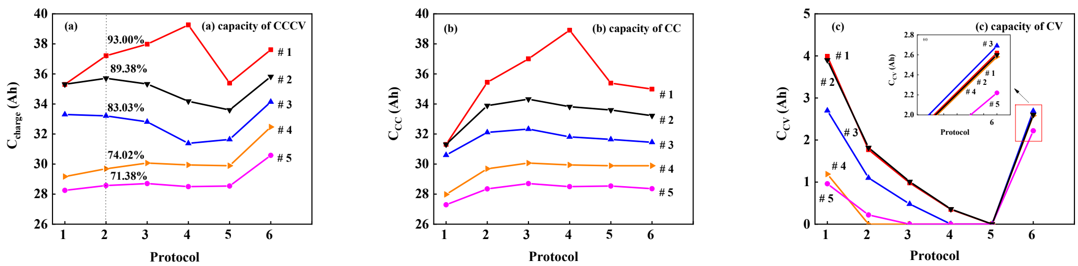

Fig. 6. Charge capacity of modules #1, #2, #3, #4 and #5 by different capacity test protocols.

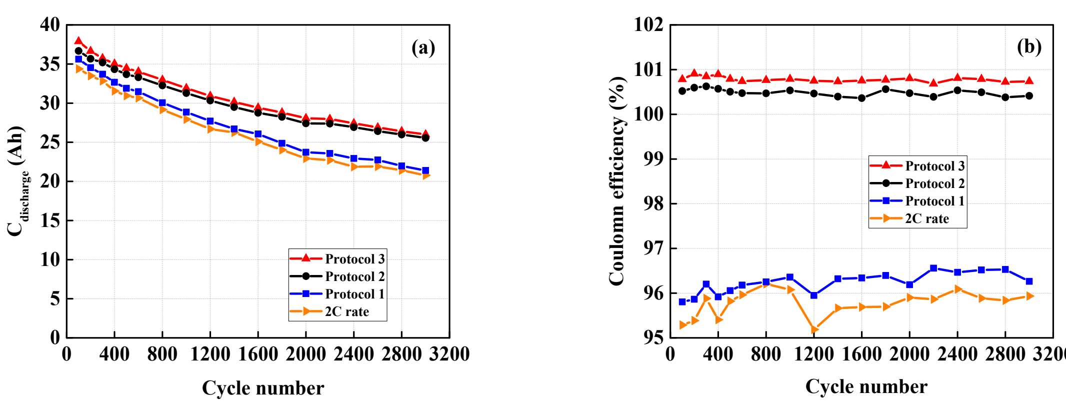

Fig. 7. Discharge capacity and coulomb efficiency of Module #6 with cycle number using four kinds of capacity test protocols.

the larger the discharge capacity. Fig. 7(b) displays that the coulomb efficiencies of the module are a little bigger than 100% using Protocols 2 and 3 and smaller than 100% using Protocol 1 and 2C charge-discharge rate, respectively. Moreover, the coulomb efficiency of Protocol 2 is the closest to 100% among all the four protocols. Fig. 8 reveals the C_{charge}, C_{CC} and C_{CV} of Module #6 with cycle number according to four kinds of capacity test protocols, indicating that C_{charge} and C_{CC} values using Protocols 2 and 3 are nearly equal at a certain cycle number while C_{CV} values using Protocols 2 and 3 are equal to 0 Ah after about 400 cycles. It suggests that Protocols 2 is more advantageous than Protocols 3 on the premise of the same capacity accuracy because of the shorter test duration of the former. Moreover, Protocols 5 is better than Protocols 2 because Protocols 5 does away with the CV process while

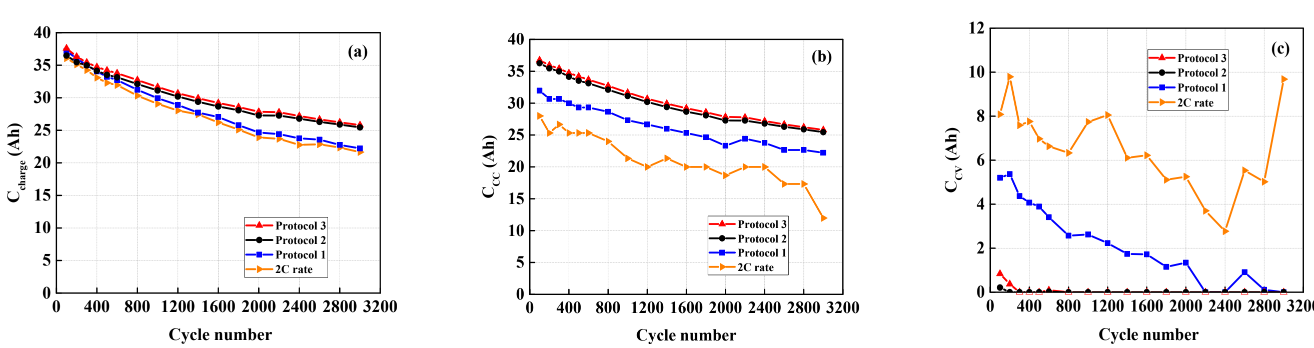

Fig. 8. C_{charge}, C_{CC} and C_{CV} of Module #6 with cycle number using four kinds of capacity test protocols.

C_{CV} values in Protocols 2 are almost 0 Ah. Therefore, Protocols 5 is optimal among all five protocols proposed for the capacity test of retired battery modules.

4. Conclusions

(1) Most modules in the EV battery system have no serious capacity fading as the whole. A handful of modules whose capacity is less than 80% SOH will bring about the capacity of the whole battery system down to below 80% SOH. Echelon use of EV battery from aspect of modules has more value than that from aspect of packs.
(2) Battery modules with high capacity have small resistance from the general trend. However, big capacity is not always related to small resistance, showing that different modules have experienced different ageing processes.
(3) The retired modules still have good discharge ability at 25%–200% of rated power, implying that it is feasible for a retired battery energy storage system to be employed to satisfy power demand of electricity grid.
(4) It is reasonable that capacity test of retired batteries is done only by CC process of C_3 without CV process after a proper balance is struck between measuring accuracy and test duration.

Declaration of competing interest

There is no competing interest regarding the publication of this paper.

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Nomenclature

Symbols

C_1: 1 C
C_2: 1/2 C
C_3: 1/3 C
C_5: 1/5 C
C_{10}: 1/10 C
C_{20}: 1/20 C
C_{charge}: charge capacity
$C_{discharge}$: discharge capacity
C_{CC}: charge capacity during CC process

C_{CV}: charge capacity during CV process
kW: kilowatt

Abbreviations

CC: constant current
CV: constant voltage
DC: direct current
DOD: depth of discharge
EV: electric vehicle
HPPC: hybrid pulse power characterization
LFP: $LiFePO_4$
P_r: rated power
SOC: state of charge
SOH: state of health
V2G: vehicle to grid