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Development of cell selection framework for second-life cells with homogeneous properties

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ABSTRACT

The used battery packs with inhomogeneous cells suffer from energy loss and poor state of charge (SOC) estimation accuracy. In order to reduce the cell-to-cell variations by minimizing the energy loss and SOC estimation error, they need to be reconfigured. In this paper, a framework for cell selection method is developed. To describe the cell characteristics, the first-order RC model is selected. Then, the cell testing profile with static capacity and dynamic parameter test is proposed. By means of the linear squares estimation, the cell parameters such as nominal capacity and dynamic parameters are obtained. Lastly, a screening algorithm minimizes the cell-to-cell variations with respect to both nominal capacity and dynamic parameters. Thereby, the optimal combination of selection parameters (σ-range for nominal capacity and weighting factors for dynamic parameters) is studied customized to the design requirements (number of packs and number of cells within pack). The results of case study imply that the developed framework reduces the maximum cell-to-cell variation by 60–70%. The reconfigured second-life packs can be offered with lower price compared to new battery packs by guaranteeing reliable energy supply. Therefore, they are the cost-effective and reliable energy storage solution for stationary power applications.

1. Introduction

Reduced maintenance cost, smoother driving performance, better fuel economy, and improvement of local air quality: these are the major advantages of electric vehicles over conventional vehicles [1]. Attracted by these aspects, more and more customers will transit from conventional to electrified technologies like plug–in hybrid electric vehicles or battery electric vehicles, as predicted by Bloomberg New Energy Finance [1] and International Energy Agency [2].

The increasing demand for electric vehicles simultaneously means a growing need for Li–ion cells. Since the performance of these cells degrades with operation time and applied load profile [3], the available driving range gradually drops. In order to provide the initially guaranteed driving range, the original equipment manufacturers provide a warranty for battery pack replacement after a certain operation time and distance driven (usually 8 years and 100,000 miles driven). After this warranty period, the residual capacity varies between 70% and 90% of the initial capacity [4]. Depending on the forecast scenarios, the number of post-vehicle cells will range between 1.4 and 6.8 million by 2035 [5]. For these replaced cells, there exist two rehabilitation strategies: Recycling to extract the raw materials and repurposing as second–life cells [6].

The common recycling process is conducted pyrometallurgically [7]. The main purpose of recycling is to extract valuable raw materials like cobalt and nickel [8]. Since the profitability is not guaranteed in Li-ion cell recycling [5,9], the idea of repurposing the used cells is often considered as a promising alternative. The main idea of repurposing is to generate additional revenue by extending the service life of battery cells used in vehicular application [10]. One promising market for second-life cells is the stationary power application, where the battery energy storage system (BESS) is used for storing the renewable power. For this application, however, the high cost of new Li-ion cells is considered as the major barrier [11]. By means of the repurposed cells, the energy storage cost could be reduced from $300–$400/kWh to

Abbreviations: AC, alternating current; BESS, battery energy storage system; BMS, battery management system; C, graphite; CCCV, constant current constant voltage; DC, direct current; ECM, equivalent circuit model; EIS, electrochemical impedance spectroscopy; LCO, lithium cobalt oxide ($LiCoO_2$); LFP, lithium iron phosphate ($LiFePO_4$); LS, least squares; NMC, nickel manganese cobalt ($LiNiMnCoO_2$); OCV, open circuit voltage; RMSE, root-mean-square error; SOC, state of charge; SOH, state of health; WF, weighting factor

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Nomenclature

C_d	diffusion capacitance in F
I_{cell}	cell terminal current in A
Q_N	nominal capacity in Ah
R_Ω	ohmic resistance in Ω
R_d	diffusion resistance in Ω
T_s	sampling time in s
V_{cell}	cell terminal voltage in V
V_{error}	error voltage within the pack in V
V_{oc}	open circuit voltage in V
t_f	final time step in s
t_i	initial time step in s
τ_d	time constant of RC-chain in s

$50–$130/kWh [12,13]. For this reason, diverse economical and environmental impacts of second-life cells on stationary application are discussed in [14–18]. The general performance and degradation process of second-life cells within stationary power system are studied in [19,20] and the usability of second-life cells for stationary system is verified by experimental tests presented in [21–23].

With respect to the repurposing strategy, there are two approaches to realize the second-life application, namely direct re-use and a reconfiguration approach. The direct re-use approach employs the original battery pack configuration without any complex cell selection or reconfiguration process. The reconfiguration approach, in contrast, includes procedures like dismounting the battery pack into the module or cell level, and selecting the most homogeneous modules or cells for second-life application.

These two approaches, direct re-use and reconfiguration, are investigated by Casals et al. with respect to the economical feasibility [24]. They conclude that the reconfiguration approach requires around 40–70% more labor time compared to the direct re–use approach. This time increase is mainly caused by the dismounting and reassembly of battery pack. For worst case, the prolonged labor time can rise the cost of second-life battery pack by 94% compared to direct re-use case (from 122 €/kWh to 237 €/kWh). For this conclusion, however, they either simplify the production process for direct re-use approach or completely neglect the demerit the direct re-use approach inherently faces. These aspects are pointed out in the following.

In order to increase the overall capacity of BESS, multiple modules or cells are connected together. Based on direct re-use approach, the battery packs in original form have to be connected to each other. In order to implement a BMS for overall BESS, it has to be guaranteed that each pack has a common communication interface. Within the study conducted by Casals et al., it is assumed that such a interface is given disregarding the manufacturer of battery pack [14]. If, however, such a common communication interface is not given, the labor time and the overall product cost will increase, which decreases the economical competiveness versus reconfiguration approach.

Furthermore, the direct re-use approach inherently faces a problem by using a battery pack, which contains inhomogeneous cells. During the manufacturing process, there are plenty of uncertainties (like grain size of active material, electrode thickness, formation procedure, etc.) that cannot be perfectly controlled [25]. All of those factors contribute to the inhomogeneous characteristics of produced cells even in brand-new status. This intrinsic inhomogeneity is further expanded during cell operation. Depending on the cell location within battery pack and the design of cooling system, each cell experiences different aging process [26–28]. Within literatures listed in Table 1, the real measurement data are presented that prove the inhomogeneity among cells. It shows the cell-to-cell variation occurs disregarding the cathode chemistry, cell shape, or aging status.

By utilizing the battery pack directly after first use, the weakest cell within the battery pack determines the overall capacity and performance [27,29,32]. That is, the inhomogeneity within the battery pack impedes the full utilization of the installed second–life cells as visualized in Fig. 1. This aspect is experimentally validated by Tong et al., who examine the feasibility of installing a second-life battery pack in an off-grid photovoltaic vehicle charging system [13,35]. For this purpose, an energy storage system is constructed based on used modules with capacities ranging from 23 to 36 Ah. Although a BMS with a passive balancing algorithm is implemented, the state of charge (SOC) among the modules cannot be completely equalized. This leads to the energy loss among the battery modules and the total loss is diagnosed to be between 6 and 10%. Furthermore, the inhomogeneity deteriorates the cycle lifetime of entire battery pack. Gogoana et al. state in their study that a 20% mismatch of internal resistance can lead to an approximately 40% reduction in cycle lifetime [36]. By establishing homogeneity within the battery pack, the utilization degree of installed capacity can be maximized and the lifetime of the battery pack can be prolonged.

Lastly, the homogeneity within the battery pack guarantees more precise SOC estimation. In order to monitor the SOC of the battery pack, a model-based extended Kalman filter is widely used [38–40]. Kim et al. investigate the estimation precision depending on the homogeneity within battery pack [41]. For this purpose, two battery packs are constructed. The first one consists of screened cells with homogeneous properties. The second pack is constructed by using unscreened cells. Although the same extended Kalman filter based algorithm is applied, the estimation performance is found to depend heavily on the homogeneity degree within the pack. That is, the more homogeneous the cells comprising the battery pack are, the more precise is the model describing the overall pack behavior. This finally results in higher precision of SOC estimation.

Considering these aspects, the advantages of the reconfiguration approach overweigh that of the direct re-use approach. In order to create a second-life battery pack based on the reconfiguration approach, a cell selection framework is necessary that guarantees homogeneity within battery pack. Thereby, the screening algorithm can be applied on the cell- or module-level. By conducting the screening process within the cell-level, higher degree of homogeneity can be achieved. In cases, however, the dismounting of modules into cells is economically not attractive or risks damaging the cells, the screening has to be conducted within the module-level. The proposed screening algorithm can be applied both on cell- and module-level. Furthermore, it will increase the homogeneity degree disregarding the shape or cell chemistry, whereby the cell model and parameter identification technique may need to be adjusted to given chemistry.

The main contribution of this paper is to develop a cell selection

Table 1
Literature list, which provides real measurement data for inhomogeneous cell properties.

Cathode/ Anode	Shape	C_N in Ah	Status	No. of cells	Ref.
LCO/C	Cylindrical (AAA)	0.3	New	100	[29]
LFP/C	Cylindrical (18650)	1.35	Aged in PHEV	840	[22]
NMC/C	Cylindrical (18650)	1.95	New/Aged in BEV	484/954	[30]
NMC/C	Cylindrical (18650)	2.7	New	138	[31]
LFP/C	Cylindrical (26650)	3	New	1100	[32]
NMC/C	Prismatic	5	Aged in lab	700	[26]
LFP/C	Prismatic	15	Aged in BEV	60	[33]
LFP/C	Prismatic	40	Aged in BEV	135	[34]