Energy Proceedings
Vol 27, 2022
ISSN 2004-2965

State-of-charge estimation of series-parallel battery packs based on fusion models for electric vehicles

Aihua Tang[1], Yukun Huang[1], Jianming Li[2], Quanqing Yu [2*]

1 School of Vehicle Engineering, Chongqing University of Technology, Chongqing, 400054, China.

2 School of Automotive Engineering, Harbin Institute of Technology, Weihai, 264209, China.
Corresponding Author：Quanqing Yu(E-mail: qqyu@hit.edu.cn)

ABSTRACT

Estimating the state-of-charge of battery packs is more important than that of single cells in electric vehicles. This paper proposes a battery pack model to estimate the SOC of a series-parallel battery pack for electric vehicles, which integrates the difference model and the mean model. To verify the performance of the model, we use the model to estimate the SOC of a 12-series-3-parallel (12S3P) battery pack under dynamic conditions, the results show that the maximum error of the battery pack SOC estimation is 0.005.

Keywords: series-parallel battery pack, state-of-charge, difference model, mean model

1. INTRODUCTION

In order to meet the dual demand for high voltage and high capacity in electric vehicles, lithium-ion power batteries need to be used in series and parallel combinations[1]. As the batteries will have differences in the production process, when these batteries are used in groups, the differences between individual batteries will further increase[2]. Although this problem can be improved by selecting individual cells with good consistency for use in groups[3], the consistency gradually deteriorates as the cells age and large errors can occur due to differences in the use environment and operating conditions[4]. Battery inconsistency has a significant impact on the safety of electric vehicles[5, 6].

To overcome the problem of battery pack state estimation, a number of methods have been proposed to estimate the battery pack SOC. Zheng et al. [7] developed a mean difference model (MDM) which takes into account the inconsistency of SOC and internal resistance. The accuracy of the model was verified experimentally on a battery pack with 12 cells connected in series. Hu et al. [8] also considered the inconsistency of SOC and internal resistance, a fuzzy system they designed to improve the accuracy and adaptability of SOC estimation under cell inconsistency. Jiang et al.[9] proposed an extension method for cell-to-cell state estimation based on a multilayer difference model to achieve joint estimation of the state of charge (SOC) and capacity of a series-connected battery pack.

Most of the current studies only consider series-connected packs or parallel-connected packs[10], while the SOC estimation of series-parallel batteries is less studied. Therefore, this paper proposes a fusion model to implement the state estimation of series-parallel battery packs.

The remainder of this paper is organized as follows. Section 2 describes the development of the fusion model, the accuracy of the model estimation is verified with the designed battery pack in section 3, and the final section provides some conclusions and summaries.

2. BATTERY PACK SOC ESTIMATION METHOD

In order to establish a battery pack state estimation model that describes both the battery pack state and the individual cell states, a difference model is first established to describe the individual cell states in each series branch, and then an average model is established to represent the battery pack state for a battery pack that is first connected in series and then in parallel.

2.1 The difference model

There are many inconsistency factors among cells, such as SOC, internal resistance, capacity, coulombic efficiency (CE), etc.[11] In order to reduce the computational burden on the battery management system (BMS) and to ensure the accuracy of the estimation, only SOC differences are considered in this paper.

First, one cell in the battery pack is selected for parameter identification and SOC estimation using the double extended Kalman filter algorithm (DEKF)[12], and this cell is noted as the reference cell (*r*-th cell), then the difference between the SOC of the remaining cells in the battery pack and the SOC of the reference electricity can be expressed as:

$$\Delta SOC_{k,m}^{i} = SOC_{k,m}^{i} - SOC_{k}^{r} \tag{1}$$

where $\Delta SOC_{k,m}^{i}$ is the difference between the *i*-th cell of the *m*-th branch and the reference cell; $SOC_{k,m}^{i}$ is the SOC of the *i*-th cell of the *m*-th branch; SOC_{k}^{r} is the SOC of the reference cell.

The terminal voltage of the *i*-th cell can be expressed as:

$$U_{k,m}^{i} = U_{oc}(SOC_{k,m}^{i}) - U_{p,k}^{r} - R_{o,k}^{r} I_{k,m} \tag{2}$$

where $U_{k,m}^{i}$ is the terminal voltage of the *i*-th cell of the *m*-th branch; $U_{oc}(SOC_{k,m}^{i})$ is the open-circuit voltage of the *i*-th cell of the *m*-th branch; $U_{p,k}^{r}$ is the polarization voltage of the reference cell; $R_{o,k}^{r}$ is the ohmic internal resistance of the reference cell; $I_{k,m}$ is the current in the *m*-th branch.

take (1) into (2):

$$U_{k,m}^{i} = U_{oc}(SOC_{k}^{r} + \Delta SOC_{k,m}^{i}) - U_{p,k}^{i} - R_{o,k}^{r} I_{k,m} \tag{3}$$

The state space expression of the difference model can be established by (1) and (3), considering that the change of $\Delta SOC_{k-1,m}^{i}$ in the same cell at the former moment and $\Delta SOC_{k,m}^{i}$ at the latter moment is small and negligible, so we assume that $\Delta SOC_{k-1,m}^{i} \approx \Delta SOC_{k,m}^{i}$,the state space equations are as follows:

$$\begin{cases} x_{\Delta \mathrm{SOC}_k} \approx x_{\Delta \mathrm{SOC}_{k-n}} \\ y = g\left(x_{\Delta \mathrm{SOC},k}\right) = \begin{bmatrix} U_{\mathrm{oc}}\left(SOC_{k,m}^{1}\right) - U_{\mathrm{p},k,m}^{1} - R_{\mathrm{o},k}^{r} I_{k,m} \\ \cdots \\ U_{\mathrm{oc}}\left(SOC_{k,m}^{i}\right) - U_{\mathrm{p},k,m}^{i} - R_{\mathrm{o},k}^{r} I_{k,m} \\ \cdots \\ U_{\mathrm{oc}}\left(SOC_{k,m}^{N}\right) - U_{\mathrm{p},k,m}^{N} - R_{\mathrm{o},k}^{r} I_{k,m} \end{bmatrix} \end{cases} \tag{4}$$

where $y_{\Delta \mathrm{SOC},k} = \left[U_{k,m}^{1}, \ldots, U_{k,m}^{i}, \ldots, U_{k,m}^{N}\right]^{\mathrm{T}}$ is the system output equation; $x_{\Delta \mathrm{SOC}_k} = \left[\Delta \mathrm{SOC}_{k,m}^{1}, \ldots, \Delta \mathrm{SOC}_{k,m}^{i}, \ldots, \Delta \mathrm{SOC}_{k,m}^{N}\right]^{\mathrm{T}}$ is the system state equation; m is the total number of series branches; N is the total number of individual cells.

The EKF algorithm is used to estimate the difference between individual cells, the SOC of the *i*-th individual cell can be expressed as:

$$\mathrm{S\hat{O}C}_{k,m}^{i} = \Delta \mathrm{S\hat{O}C}_{k,m}^{i} + \mathrm{SOC}_{k}^{r} \tag{5}$$

$$C_{\mathrm{m}} = \min_{1 \le i \le N}\left\{\mathrm{SOC}_{m}^{i} \times C_{\mathrm{m}}^{i}\right\} + \min_{1 \le j \le N}\left\{\left(1 - \mathrm{SOC}_{m}^{j}\right) \times C_{\mathrm{m}}^{j}\right\} \tag{6}$$

$$SOC_{k,m} = \min_{1 \le i \le N}(SOC_{k,m}^{i}) \tag{7}$$

Where C_{m} is the capacity of the *m*-th series branch; $SOC_{k,m}$ is the SOC value of the *m*-th branch; *n* is the total number of cells in a series branch circuit.

2.2 The mean model

Unlike the conventional averaging model, after estimating the SOC of each series branch using the difference model, we take the average of the SOC of the individual series branches as the battery pack SOC, which is implemented as follows.

First, for each series branch, the cell with the lowest SOC value is taken as the SOC of that branch, noted as $SOC_{k,m,f}^{i}$. Then the SOC of the battery pack and the capacity are calculated by the following equation:

$$SOC_{k}^{PACK} = \frac{1}{M}\sum_{m=1}^{M} SOC_{k,m,f}^{i} \tag{8}$$

$$C^{PACK} = \sum_{m=1}^{M} C_{m} \tag{9}$$

Where *M* is the total number of series branches.

3. RESULTS AND DISCUSSION

In this paper, a 12S3P battery pack is used to verify the accuracy of the constructed model as shown in Figure 1. Since the OCV-SOC relationship of the battery is constant, the OCV-SOC relationship of the reference battery is obtained through open circuit voltage experiments at different temperatures and the OCV-SOC relationship of the reference battery is used as the OCV-SOC relationship of all the cells in the battery pack as shown in Figure 2.

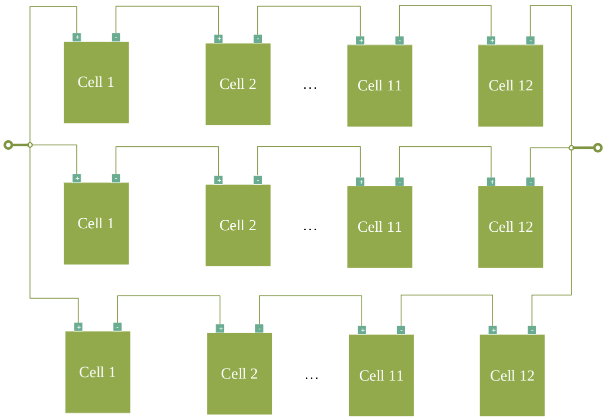


Fig. 1 Battery pack formation type

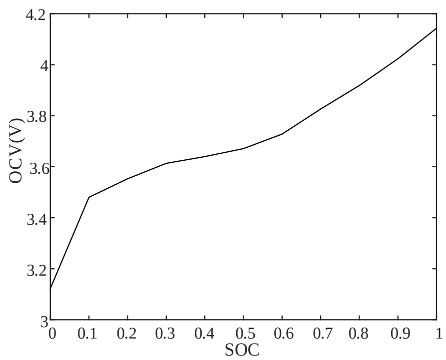
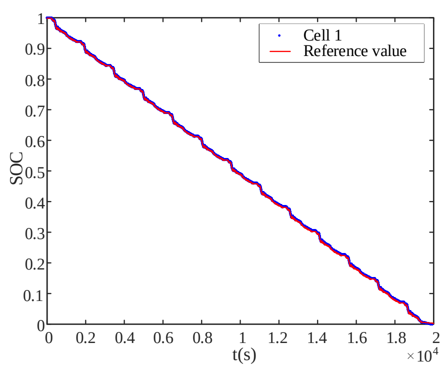
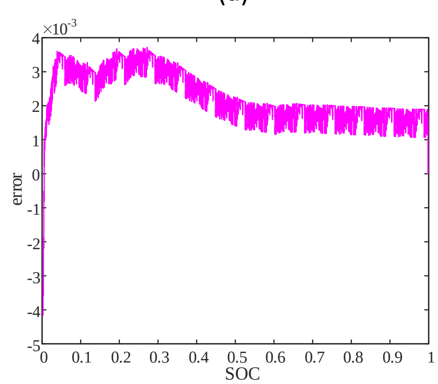


Fig. 2 OCV-SOC relationship

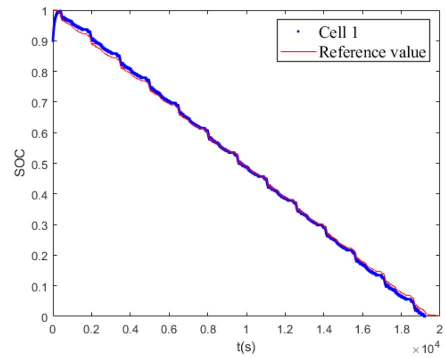
To validate the accuracy of the proposed model under UDDS operating conditions, the DEKF was used to estimate the reference cell SOC, as shown in Figure 3.



(a)

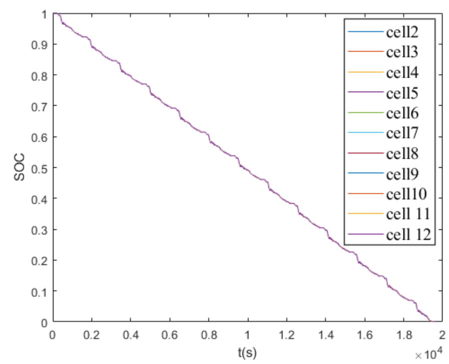


(b)

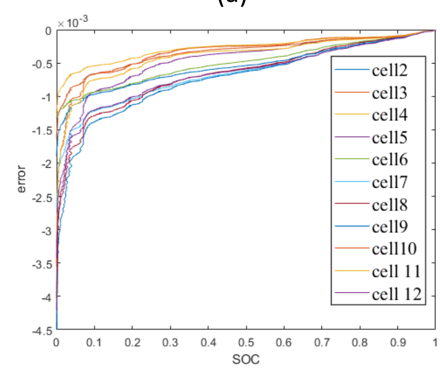


(c)

Fig. 3 (a) *the estimation results of the reference cell;* (b) *estimation error*



(a)



(b)

Fig. 4 (a) *the results of SOC estimation for the remaining 11 individual cells in series branch 1;* (b) *estimation error*

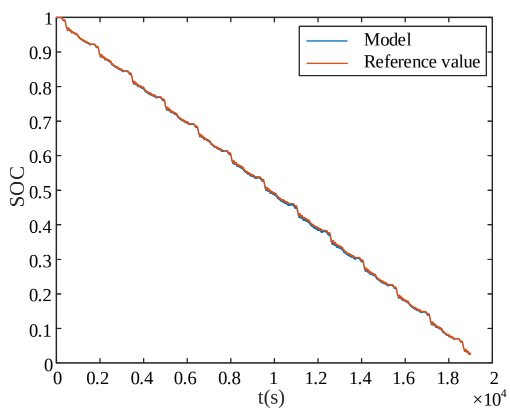
Figure 3 (a) shows the estimation results of the reference cell and Figure 3 (b) shows the SOC estimation error. The DEKF was used to estimate the SOC of single cell No. 1 to be able to meet its accuracy requirements and the error was maintained at 0.002, Figure 3(c) shows that the algorithm can converge to the true value within 500 seconds when the initial SOC value is inaccurate, so it can be considered that the estimation accuracy of single cell No. 1 is high enough to be used as a reference cell.

The battery pack SOC is then estimated by the fusion model proposed in this paper, and the results are shown in Figures 4, 5.

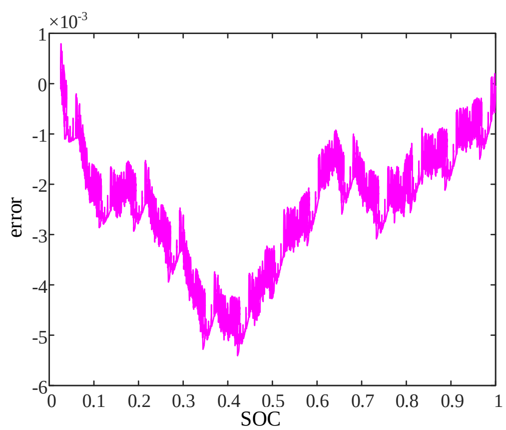
Figure 4(a) shows the results of SOC estimation for the remaining 11 individual cells in series branch 1.

Figure 4(b) shows the estimation error, and it can be seen that the maximum estimation error is 0.0045, and the maximum error is 0.001 when the SOC is in the 20%-100% interval, thus verifying the accuracy of the modified model.

Figure 5(a) shows the results estimated using this fusion model, and Figure 5(b) shows the fusion model estimation error, which can be based on a maximum error of 0.005 using the EKF algorithm, with the maximum error occurring at a SOC of 40%, due to the fact that this difference model does not take into account the differences caused by differences in internal battery resistance and Coulomb efficiency, but is also satisfactory for use in real vehicles.



(a)



(b)

Fig. 5 (a) *the results estimated using this fusion model;* (b) *estimation error*

4. CONCLUSION

In this paper, we proposed a fusion model to estimate the SOC of series-parallel battery pack for electric vehicles. Using the EKF in conjunction with this model, the results show that the modified model can not only estimate the SOC of the battery pack, but also achieve the estimation of the SOC of each individual cell in the battery pack, significantly improving the accuracy of the battery pack SOC estimation.

ACKNOWLEDGEMENT

This work was jointly supported by the Natural Science Foundation of Chongqing, China (Grant No. cstc2021jcyj-msxmX0464), Natural Science Program of Shandong Province (ZR2020ME209) and National Natural Science Foundation of China (Grant No. 52177210).

REFERENCE

[1] Bruen T, Marco J. Modelling and experimental evaluation of parallel connected lithium ion cells for an electric vehicle battery system[J]. Journal of Power Sources 2016, 310: 91-101.

[2] Rumpf K, Naumann M, Jossen A. Experimental investigation of parametric cell-to-cell variation and correlation based on 1100 commercial lithium-ion cells[J]. Journal of Energy Storage 2017, 14: 224-243.

[3] Xiong R, Sun FC, Gong XZ, et al. Adaptive state of charge estimator for lithium-ion cells series battery pack in electric vehicles[J]. Journal of Power Sources 2013, 242: 699-713.

[4] Song Z, Yang XG, Yang NK, et al. A study of cell-to-cell variation of capacity in parallel-connected lithium-ion battery cells[J]. Etransportation 2021, 7: 11.

[5] Su TL, Lyu N, Zhao ZX, et al. Safety warning of lithium-ion battery energy storage station via venting acoustic signal detection for grid application[J]. Journal of Energy Storage 2021, 38: 10.

[6] Fan XY, Zhang WG, Sun BX, et al. Battery pack consistency modeling based on generative adversarial networks[J]. Energy 2022, 239: 13.

[7] Zheng YJ, Gao WK, Ouyang MG, et al. State-of-charge inconsistency estimation of lithium-ion battery pack using mean-difference model and extended Kalman filter[J]. Journal of Power Sources 2018, 383: 50-58.

[8] Hu L, Hu XS, Che YH, et al. Reliable state of charge estimation of battery packs using fuzzy adaptive federated filtering[J]. Applied Energy 2020, 262: 15.

[9] Jiang B, Dai H, Wei X. A cell-to-pack state estimation extension method based on a multilayer difference model for series-connected battery packs[J]. IEEE Transactions on Transportation Electrification 2021: 1-1.

[10] Wang SL, Fernandez C, Shang LP, et al. Online state of charge estimation for the aerial lithium-ion battery packs based on the improved extended Kalman filter method[J]. Journal of Energy Storage 2017, 9: 69-83.

[11] Dong HN, Huang W, Zhao YX. Low complexity state-of-charge estimation for lithium-ion battery pack considering cell inconsistency[J]. Journal of Power Sources 2021, 515: 11.

[12] Sepasi S, Ghorbani R, Liaw BY. Improved extended Kalman filter for state of charge estimation of battery pack[J]. Journal of Power Sources 2014, 255: 368-376.