Journal of Power Sources 278 (2015) 668–674

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

# Sampling based State of Health estimation methodology for Li-ion batteries

Fatih Camci [a, *], Celil Ozkurt [b], Onur Toker [c], Vepa Atamuradov [a]

[a] *Antalya International University, Industrial Engineering Department, Antalya, Turkey*
[b] *Karadeniz Teknik University, Trabzon, Turkey*
[c] *Fatih University, Electrical and Electronics Engineering Department, Istanbul, Turkey*

## HIGHLIGHTS

- A new circuit design has been presented for SoH estimation of the Li-ion batteries.
- The battery cells can be separated into two groups when SoH estimation is needed.
- Simple SoH estimation is performed using the test battery.
- The micro-chip performing the idea has been produced.
- Preliminary results of SoH estimation is very promising.

## ARTICLE INFO

*Article history:*
Received 10 September 2014
Received in revised form
21 December 2014
Accepted 23 December 2014
Available online 24 December 2014

*Keywords:*
Battery management system
State of Health estimation
Remaining useful life
Li-ion batteries

## ABSTRACT

Storage and management of energy is becoming a more and more important problem every day, especially for electric and hybrid vehicle applications. Li-ion battery is one of the most important technological alternatives for high capacity energy storage and related industrial applications. State of Health (SoH) of Li-ion batteries plays a critical role in their deployment from economic, safety, and availability aspects. Most, if not all, of the studies related to SoH estimation focus on the measurement of a new parameter/physical phenomena related to SoH, or development of new statistical/computational methods using several parameters. This paper presents a new approach for SoH estimation for Li-ion battery systems with multiple battery cells: The main idea is a new circuit topology which enables separation of battery cells into two groups, main and test batteries, whenever a SoH related measurement is to be conducted. All battery cells will be connected to the main battery during the normal mode of operation. When a measurement is needed for SoH estimation, some of the cells will be separated from the main battery, and SoH estimation related measurements will be performed on these units. Compared to classical SoH measurement methods which deal with whole battery system, the proposed method estimates the SoH of the system by separating a small but representative set of cells. While SoH measurements are conducted on these isolated cells, remaining cells in the main battery continue to function in normal mode, albeit in slightly reduced performance levels. Preliminary experimental results are quite promising, and validate the feasibility of the proposed approach. Technical details of the proposed circuit architecture are also summarized in the paper.



## 1. Introduction

Importance of portable energy storage technologies has been increasing dramatically in the last decades not only for low power applications such as cell phones but also for high power applications such as Electric Vehicles (EVs) and Unmanned Air Vehicles (UAVs). Li-ion batteries are one of the most popular alternatives for high capacity energy storage applications. As the number of cells increase, complexity of the battery management system (BMS), which is responsible for condition monitoring of individual cells, maintaining their operational limits, protecting them from out-of-tolerance conditions, cell voltage balancing, estimation of battery state of charge (SoC), State of Health (SoH),

* Corresponding author.
*E-mail address:* fatih.camci@antalya.edu.tr (F. Camci).

http://dx.doi.org/10.1016/j.jpowsour.2014.12.119

state of life (SoL), and optimum charging, does increase as well [1].

SoH of a battery system is a critical parameter for its effective usage throughout its life. Prediction of time to exhibit unsatisfactory performance levels can be estimated from SoH measurements [2]. Accurate real time estimation of SoH is crucial for reducing the through life ownership cost of the battery and increasing availability and safety of the overall battery system. In one hand, early disposal of the batteries increases the ownership cost of the batteries; on the other hand, unexpected failure of the battery leads to low availability, safety, and comfort. For example, the life cycle cost of a light armored vehicle will be reduced by 94.9 K $ if unnecessary battery replacement can be avoided [3]. We can also note two catastrophic battery failure examples: First, in 2000, landing gear of an aircraft did not work due to battery failure, which in turn led to crash of the aircraft [4]. Second, in 2006, Mars Global Surveyor has been lost in the space in due to a battery failure related problem [4].

The general definition of SoH is the ratio of the current energy storage capacity to the initial capacity. Even though internal resistance and self-discharge may affect the capacity this SoH definition will be used throughout this paper [5].

SoH estimation has been studied extensively in recent years. The basic approach in SoH estimation is the process of counting the discharged energy of a fully charged battery during a controlled constant load, which is known as the load test [6]. This approach requires a full discharge process under constant load just for the sake of SoH estimation. It is obvious that the time and labor required to apply this method is not very practical. This approach requires interrupting the normal operation of the battery system, and causes waste of significant amount of energy during tests. The main motivation of this paper is to find feasible alternatives to this problem. More precisely, to develop a system on which SoH can be estimated with minimum possible disturbance to the system, preferably without interrupting its normal mode of operation, and also with minimum possible energy consumption.

Another commonly used method for SoH estimation is measuring the charged and discharged energy during the normal usage of the battery, called Columb counting [7]. Even though this approach removes the impracticality of the load test, measurement errors may accumulate and lead to significant estimation errors [8]. Periodic calibration is needed to get accurate results [7], and researchers continue to work on several different improvements [9–11].

Another approach for SoH estimation is to utilize the look-up tables prepared by the battery manufacturer, and utilize the relationship between the open circuit voltage (OCV) and the SoC. These tables might be used to estimate the SoH indirectly. However, its accuracy is not quite high since the environmental conditions for OCV/SoC tables may not be the same as the actual usage environment of the battery [12]. Furthermore, this technique requires very high accuracy OCV measurements, causing this method to be not so practical as well [13].

Temperature is an important parameter, and is used for SoH estimation together with other parameters [14]. Internal resistance of the battery, which is difficult to measure directly, is another parameter closely related to the SoH. Various different battery models can be used to estimate the internal resistance of a battery. There are basically two types of battery models: circuit and electrochemical models. Electrochemical models are good for design of electro–chemical interactions within electrodes and electrolyte, however it is difficult to build and time consuming [5,15]. There are several circuit models such as Thevenin, Randles, and Lumped Parameter battery models [5,16]. Even though these models may estimate the internal impedance, these estimations are not often sufficient to obtain the SoH accurately.

Electrochemical impedance spectroscopy (EIS) is a special technique to understand the effects of chemical reactions in the battery, which cannot be measured through simple sensors. It is shown that there exist a close relationship between SoH and EIS measurements at specific frequencies [17]. However, EIS measurement is a difficult and expensive process requiring special tools and equipment [7]. The size and the cost of the required equipments make EIS measurements not very practical, especially for online applications. For example, it may not be feasible to install an EIS system on an electric/hybrid vehicle for SoH measurement.

As seen from the discussions given above, measurement of a single parameter is not sufficient for effective SoH estimation. Thus, alternative complex statistical and/or computational methods based on various different parameter measurements, have been presented in the literature. For example, fuzzy logic, artificial neural networks, support vector machines, relevance vector machines, Kalman filters, and particle filters are some of the tools used for SoH estimation [7].

All of the studies mentioned above focus either on identification of a new measurement parameter or development of new statistical/computational methods for SoH estimation.

In this paper, a completely different approach to SoH estimation is presented. The proposed approach does not require interrupting the whole battery system for SoH measurement, instead it is based on separating a small but representative set of cells from the main system. While SoH measurement is performed on these isolated cells, remaining cells in the main battery system can continue to provide energy to outside, or can be charged all together. The model presented in this paper has a pending patent application.

This paper is organized as follows. In Section 2, the circuit model which can separate the battery cells into two groups is presented. In Section 3, we present results of various tests performed on the Li-ion batteries using a custom made microcontroller board, and professional battery test equipment. Finally, in Section 4 some concluding remarks are made.

## 2. Methodology

The proposed battery system is composed of parallel connection of several (Nc) column systems, where each column system is series connection of several (Nr) battery cells. Total number of battery cells should be selected according to design requirements of the main battery system. Fig. 1 displays "+" and "−" terminals of the main battery system used for charge, discharge, and possibly for parameter measurement of the whole battery system.

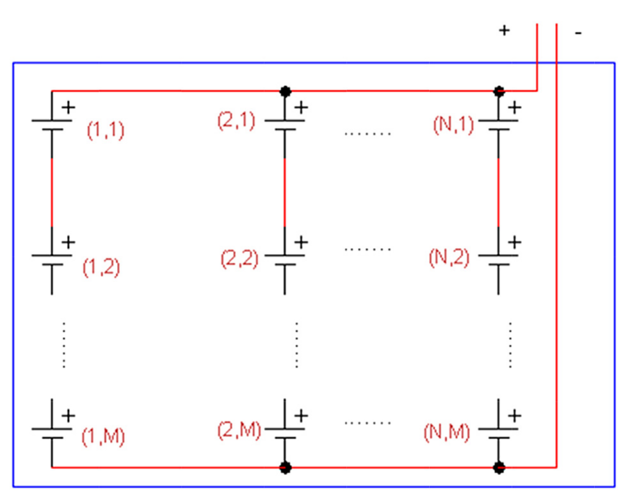


**Fig. 1.** Traditional battery system with single charge–discharge structure.

In this paper, we propose a new circuit organization such that, whenever needed battery cells can be divided into two groups which can be viewed as two independent batteries in practice. For each battery cell, we have two relays located next to it controlling where the battery cell will connect to, and an on board microcontroller is used to operate these relays for system configuration. One of the battery systems, called the main battery, will have most of the battery cells and will operate in an uninterrupted fashion. The other battery system, called the test battery, will have the remaining battery cells, which will be a small but representative portion of all of the battery cells. On this small set of battery cells, we measure the amount of energy stored by counting the discharged energy under constant load after the cell is fully charged. After this controlled discharge is performed and energy is counted, all battery cells will be connected together again as one battery. The separation process is done when a measurement for SoH estimation is needed. During the SoH measurement, the main battery continues to function at slightly reduced performance levels, whereas when SoH measurement is not necessary the main battery will function at full performance level.

The proposed approach is inspired from the sampling theory, i.e. a group of samples representing the whole population, commonly used in many industrial applications. For example, the quality of the products may be measured through selected samples instead of testing each and every product. Fig. 2 shows the organization of a traditional battery system, whereas Fig. 3 displays the organization proposed in this paper. Some of the cells, represented with a different pattern in the figure, are selected for testing, whereas the remaining majority will form the main battery. The proposed approach is based on the assumption that the sampled battery cells represent the whole battery system in terms of SoH. This approach removes the disadvantage of the load test (time, labor requirements and wasted energy), which is the basic and most effective method to measure the amount of stored energy. SoH measurements on these selected battery cells require less time, labor and result significantly reduced levels of wasted energy.

Fig. 4 displays the circuit architecture proposed in this work. This design divides the battery system, more precisely cells, into two groups called the "main battery" and the "test battery" when a SoH measurement is needed. The main battery consists of most of the battery cells and is used as a battery to operate the main load. The test battery on the other hand consists of a small portion of battery cells, and is used to measure the required parameters for

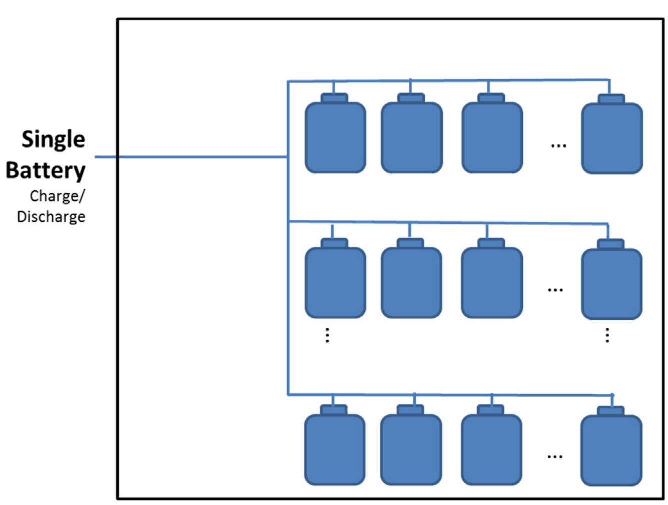


**Fig. 2.** Normal operation of the battery system.

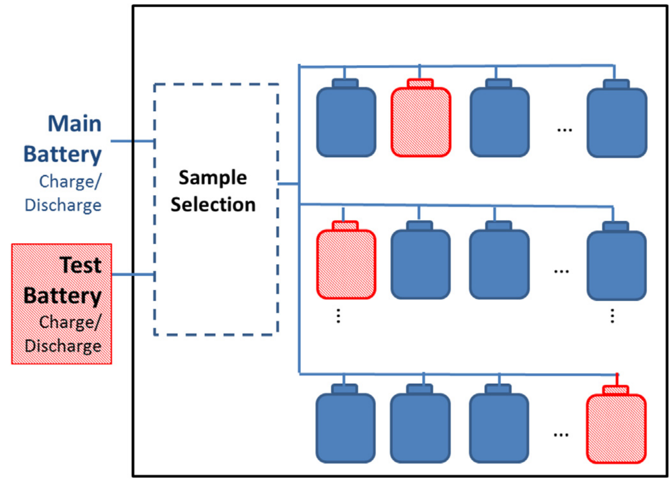


**Fig. 3.** Cell selection concept for testing.

SoH estimation. Selection methodology of these battery cells can be random or based on a specific algorithm. A battery cell is either connected to the main battery or to the test battery, and this is accomplished by using a pair of relays (Relay 1 and Relay 2) for each battery cell. The output of the proposed battery system includes two "+" and two "−" terminals, one of which is for main battery, the other for test battery. The test battery is formed and used only when a SoH related measurement is needed. The battery cell selection algorithm is programmed on a desktop PC, which is connected to a microcontroller system operating all of the on board relays. Depending on the messages received from the desktop PC, the microcontroller operating these on board relays can separate selected cells from the main battery system, re-organize these selected cells as the test battery, and the remaining cells as the main battery. Whenever the SoH measurement is over, the microcontroller system can reconfigure all of the cells as a single main battery system.

All the battery cells are connected to the main battery in the normal usage of the battery system. When a test or a measurement is needed, selected battery cells based on the selection algorithm are separated from the main battery and connected to the test battery. The main and test batteries are independent and one can be charged while the other is being discharged. The test battery is fully charged with a charge mechanism and then discharged with constant load for SoH measurement.

The charge and discharge for the test battery can be performed under controlled parameters without affecting the normal usage of the main battery. The measurement results are obtained in a short time since the test battery consists of a small number of battery cells. We propose the use of these measurements to estimate the SoH of the whole battery system. The normal usage of the battery will not be affected by these SoH measurements, since the main battery continues to operate at slightly reduced performance levels while SoH measurement is being conducted on the test battery. In this way, the sampled battery cells are used to measure the SoH, and the rest continues to function as a battery to operate the main load. After the test is completed, the whole system can continue to work together at full performance level.

One can consider two alternative approaches. In the first one, the number of battery cells is selected so that when all of the cells are used in the main battery, performance requirements are satisfied, but when a test battery is formed system should be able to tolerate reduced performance levels. For example, if 100 battery cells are required to satisfy full performance requirements, and 10

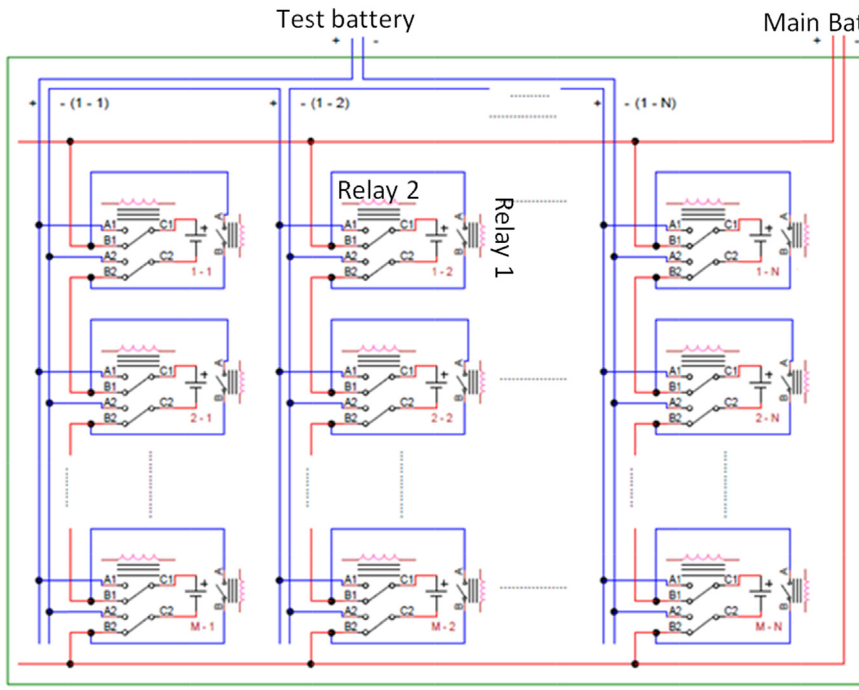


**Fig. 4.** Proposed battery system to work as two batteries when needed.

cells are separated for test, the remaining 90 battery cells will provide a slightly reduced performance level. Thus, either performance reduction should be accepted or the battery should not be used during the test. For example, the test can be performed during the park position of an electric/hybrid vehicle or reduced speed/acceleration should be tolerated during test periods.

The other alternative is installation of redundant battery cells, i.e. more cells than necessary. For example, if the system requires 100 battery cells and 10 cells will be used for the test whenever a SoH measurement will be conducted; then in this alternative we propose the use of 110 battery cells in the system. The redundant 10 battery cells will be randomly (or based on an algorithm) left idle during the normal operation, i.e. when a SoH measurement is NOT being conducted.

Let NL represent the average number of charge/discharge cycles that can be performed on a Li-ion battery cell during its lifetime. We propose a sampling based SoH measurement on Ns cells among total Nt cells. Selection can be according to some pseudorandom selection algorithm, but sampling and SoH measurement of selected cells will be done with a relative frequency of F, i.e. (F-1) times all cells in the battery will be used for the main system charge/discharge, and after that Ns number of the total Nt cells will be isolated from the main system, and a SoH measurement will be conducted on these separated cells. During this time, the remaining Nt-Ns cells will be in the main battery and provide uninterrupted services, possibly at slightly reduced performance levels. Therefore, we require.

$F >> 1$, i.e. do not measure SoH very frequently.

$Nt/Ns >> 1$, i.e. each time a relatively small set of cells is selected.

to minimize effects of SoH measurement, however we also require

$$Nx = (NL/F) * Ns/Nt >> 1$$

so that each cell is selected several times (Nx on the average if random selection is used) for SoH measurement throughout the entire life of the battery system. For example, if $NL = 2000$, then $F = 10$ and $Ns/Nt = 1/10$ will result $Nx = 20$, i.e. each cell will be monitored on the average $Nx = 20$ times during the expected lifetime.

The key idea of the proposed architecture is that the circuit topology of the battery connections can be changed by using the relays next to the battery cells. These relays are operated by an on board microcontroller, which in turn gets its commands from a desktop PC running a Windows.NET application.

The proposed battery system has the following benefits:

- Battery SoH will be estimated without interrupting the function of the main battery.
- The abnormal degradation in some of the battery cells compared to other will be detected.
- The battery related failures and accidents will be detected and prevented.
- The time that the battery will reach to its end of life will be effectively estimated based on the estimated SoH. This will lead to effective usage of the battery life reducing unnecessary battery replacement and risk of battery failures.

## 3. Results and discussion

A microcontroller based electronic system, which is able to separate the selected cells from the main battery system and combine them back again after the test, has been developed. In other words, the microcontroller based system enables the battery cells to be divided into two groups, each behaving as a separate battery when desired. The developed board can control 32 battery cells (8 serially connected in 4 parallel rows). In our lab experiments 16 battery cells (8 serially connected in a row with 2 rows) are used and one of the battery cells has been separated as for test (sampling ratio of 1/16). Fig. 5 displays the developed microcontroller based electronic board. This system can communicate with a desktop PC, also called as the host or the host PC, via custom designed protocol over a USB connection. The electronic board is recognized as an HID device by the host PC, and will not require special USB drivers to be developed for system operation. On the host PC, a NET application is developed which is used for management of the battery system.

The standard AA sized Li-ion batteries (Cathode: $LiFePO_4$, Anode: $TiO_2$/graphene, 3.2 V 600 mAh, 0.6 A Rate, 2.22 Wh) have been used as battery cells. The board has two layers, the top one has the microcontroller system, and the bottom one has battery cell sockets, pairs of relays for each cell, and necessary driving electronics.

The battery system has been degraded through 960 charge–discharge cycles. The charge discharge cycle has been performed with 1 Ah between 28 V and 20 V. 30 min waiting time between each cycle has been set. The battery system has worked as a whole during the normal charge–discharge cycles. Test battery has been activated by separating selected battery cells from the main battery and connecting them to the test battery in every 30 cycles. Each time, a selection process has been performed randomly among previously unselected cells. In the first test, a battery cell has been selected randomly among 16 cells. In second test, battery cell has been selected among remaining unselected 15 cells. Thus, we forced selection process to test all cells at the end of 16 tests (480 cycles = 30 cycles per test × 16 tests). All battery cells have been selected twice in 960 cycles. This process may be completely random (random selection among all cells in every test) for systems with higher number of cells. Fig. 6 displays the experimental setup.

State of Health (SoH) is calculated as the ratio of the capacity measured at a given time to the maximum capacity measured in initial tests. Fig. 7 displays the capacities of the test batteries: The y-axis represents the capacity and the x-axis is the cycle number. A test has been performed once every 30 cycles, which leads to 32 measurements in 960 cycles.

As seen from the Fig. 7, there exists a trend representing the degradation of the battery system. However, the capacity variation in the selected battery cells in different tests leads to inconsistencies such as in 30th, 60th, and 360th cycles. The results of these tests conflict with the degradation path and the results of the others. Results of these tests have been removed from the analysis assuming to be outliers. The degradation of the batteries without these outlier data has been presented in Fig. 8. A logarithmic function that better represents the degradation of Li-ion batteries is obtained as seen in this figure.

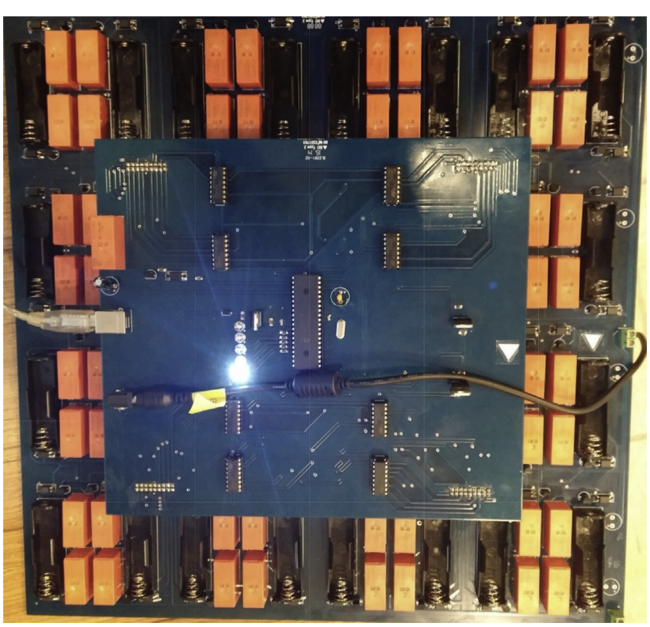

**Fig. 5.** Custom developed electronic circuit board.

The representation capability of the selected cells for the whole battery system in term of State of Health (SoH) is crucial for the effectiveness of the presented approach. The capacity of the selected battery cells has been measured through the Columb counting during the discharge with constant load following a full charge. The ideal way to measure the SoH of the whole battery system is to measure the capacity of each individual battery cell separately, test each cell as a standalone single battery unit, through discharge with constant load after a full charge. The impracticality of this approach is obvious due to the time required for serial charge and discharge of all battery cells. However, to assess representation capability of the proposed sampling method, this has been performed after 480th and 960th cycles. Note that all battery cells will be selected for test at the end of every 480 cycle, since the random selection has been performed among unselected cells (30 cycles per test × 16 cells = 480 cycles). Thus, representation capability has been obtained at two points (480th and 960th cycles).

Table 1 presents the SoH values of the whole battery system obtained via sampling, and then via full cell measurements, i.e. no sampling. In the case of full cell measurements, we proposed two different metrics: In the first one, the average of all cell SoH values is defined as the system SoH. It is also possible to consider the least healthy battery cell (i.e. the one with minimum SoH) as the system SoH, which is our second proposed metric. Both options are presented in Table 1 with error values. As seen from the table, the estimation error is higher when the system SoH is assumed to be the minimum of SoH's of all battery cells. The distance of selected samples from a distribution to a number in the far tail of the distribution is expected to be higher than the average of the distribution.

Fig. 9 displays box plot of SoH of all battery cells obtained at 480th and 960th cycles. The thin line inside box is the median value; the lower and upper edges of the boxes give the 25th and 75th percentiles; all other data points that are not considered outliers are captured with the dashed vertical lines below and above the boxes; and outliers are given as distinct points. The horizontal dashed thick lines are the sampled SoH values. The degradation of all battery cells from 480th to 960th cycles and representation capability of the selected samples can be seen from this figure.

Since we have system SoH values for only two cycles, the evaluation of the representation capability of the selected cells to the whole battery system in other cycles has been performed by comparing the SoH of the selected cells with the SoH trend. This interpolation like approach is used because of the difficulty of testing each battery cell's SoH individually at the end of each cycle. The system SoH is identified as the value of y-axis on the trended line shown in Fig. 8 given the corresponding cycle (x-axis). Table 2 gives the SoH of the battery system, which is estimated using the trended line, and SoH of sampled cells with the errors. Maximum, minimum, average, and median values of the errors have been given in the table.

One of the discussion points of the proposed methodology is the potential side effects of the test procedure. Since the test procedure involves separation of the battery cells into two groups, the effects to each side should be discussed differently. In the ideal case, after the test procedure is completed; there should not be any difference in the degradation of all cells in both groups. However, this may not

**Fig. 6.** Experimental setup.

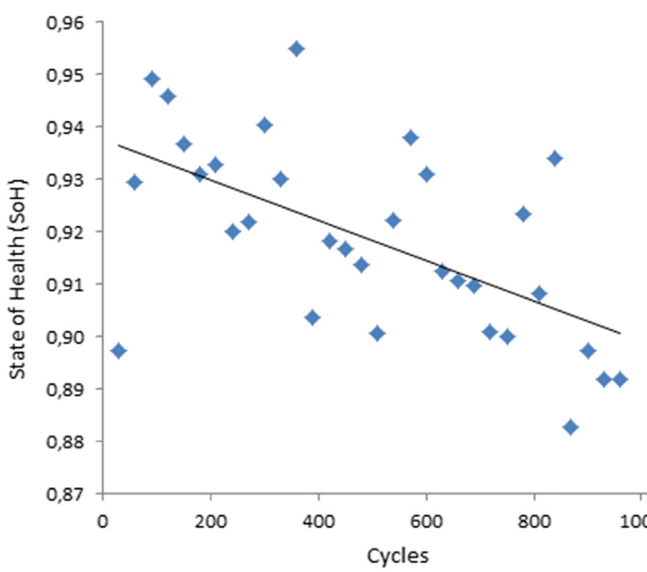


**Fig. 7.** Capacity of the test battery.

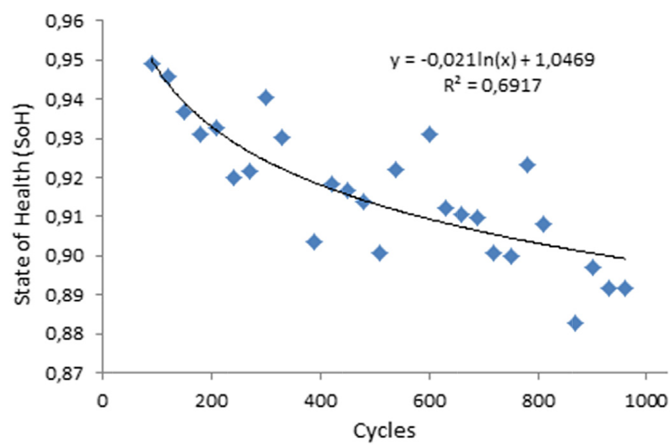


**Fig. 8.** Degradation after removal of the outlier data.

**Table 1**
Sampled SoH vs System SoH at 480th and 960th Cycles.

| Cycle | Sampled SoH % | Measured system SoH % | | Error | |
|---|---|---|---|---|---|
| | | Cell average method | Cell min method | Cell average | Cell minimum |
| 480 | 91.37 | 92.14 | 89.28 | −0.77 | 2.09 |
| 960 | 89.18 | 90.22 | 87.05 | −1.04 | 2.13 |

be true in the reality. The degradation of each group will be discussed below.

The degradation due to the discharge of the selected cells for test can be ignored since the test is performed under constant load. The SoH calculation with Columb counting requires a test procedure that affects the SoH the least for accurate estimation. High environmental and load variability will lead to bad estimations. In addition, any variance in the degradation due to selected cells will be eliminated due to the random selection process in the long run. In other words, all battery cells will be selected in the long run and they will have the same degradation effect in the long run. However, we do not yet have sufficient data to support this claim about the effect of the selection process on the battery degradation. It is worthwhile to analyze it experimentally which we consider as a potential future research problem.

The degradation of the battery cells in the main battery during the test procedure is a critical issue if the main battery is used

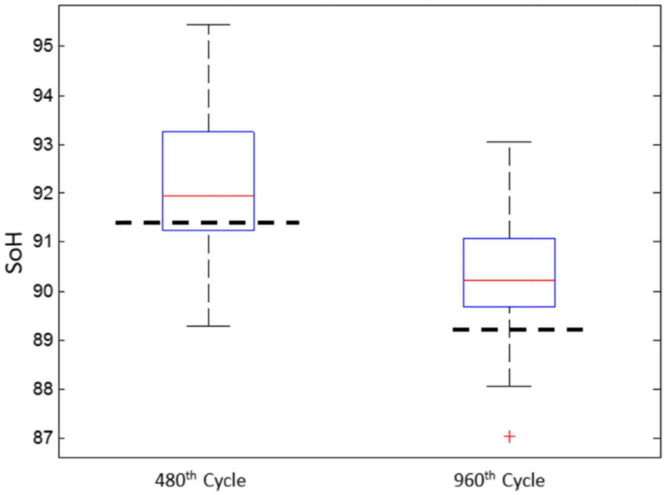


**Fig. 9.** Box plot of SoH values of all battery cells and sampled SoH.

**Table 2**
Sampled SoH vs System SoH (Estimated).

| Cycle | Sampled SoH % | Measured system SoH | Error | Cycle | Sampled SoH % | Measured system SoH | Error |
|---|---|---|---|---|---|---|---|
| 30 | 89.71 | 97.55 | −7.84 | 510 | 90.06 | 91.60 | −1.54 |
| 60 | 92.94 | 96.09 | −3.15 | 540 | 92.22 | 91.48 | 0.74 |
| 90 | 94.92 | 95.24 | −0.32 | 570 | 93.80 | 91.36 | 2.44 |
| 120 | 94.58 | 94.64 | −0.05 | 600 | 93.09 | 91.26 | 1.84 |
| 150 | 93.66 | 94.17 | −0.51 | 630 | 91.23 | 91.15 | 0.08 |
| 180 | 93.11 | 93.78 | −0.68 | 660 | 91.06 | 91.06 | 0.01 |
| 210 | 93.26 | 93.46 | −0.20 | 690 | 90.97 | 90.96 | 0.01 |
| 240 | 91.98 | 93.18 | −1.20 | 720 | 90.09 | 90.87 | −0.78 |
| 270 | 92.17 | 92.93 | −0.76 | 750 | 90.00 | 90.79 | −0.79 |
| 300 | 94.05 | 92.71 | 1.33 | 780 | 92.34 | 90.71 | 1.63 |
| 330 | 93.02 | 92.51 | 0.50 | 810 | 90.80 | 90.63 | 0.17 |
| 360 | 95.51 | 92.33 | 3.18 | 840 | 93.38 | 90.55 | 2.83 |
| 390 | 90.37 | 92.16 | −1.79 | 870 | 88.28 | 90.48 | −2.20 |
| 420 | 91.83 | 92.01 | −0.17 | 900 | 89.72 | 90.40 | −0.68 |
| 450 | 91.66 | 91.86 | −0.20 | 930 | 89.17 | 90.34 | −1.17 |
| 480 | 91.37 | 91.73 | −0.36 | 960 | 89.18 | 90.27 | −1.08 |
| Ave: | 1.26 | Max: | 7.84 | Median: | 0.77 | Min: | 0.01 |

during the test. If the system does not involve redundant battery cells as discussed in the previous chapter, then the overload on the battery cells may lead to faster degradation, which leads to increased unbalanced SoH values for the battery cells. The analysis and quantification of the effect of overload on unselected cells during the test have been stated as future work.

The preliminary results shown above reveal the potential of the presented methodology for the estimation of SoH. Further analysis is needed to identify the SoH measurement variations of the test battery in each test moment.

## 4. Conclusion

A new circuit design has been presented in this paper to enable the battery cells to be separated into two groups when needed. During the normal operation of the battery, all battery cells will be connected to the main battery. When a test for SoH estimation is needed, some of the battery cells are separated from the main battery and connected to the test battery. A simple SoH estimation technique is applied to the test battery without interrupting the operation of the main battery. It is assumed that the SoH obtained through the sampling will represent the SoH of the whole battery system, i.e. system SoH. The preliminary results show a clear trend with some variation in different tests. Further analysis is needed about the analysis of the variation, best sample size, and effects of the test procedure to the SoH of selected and unselected cells.

## Acknowledgment

This research was supported by The Scientific and Technological Research Council of Turkey (TUBITAK) under project number 113M093.

## References

[1] B. Pattipati, C. Sankavaram, K. Pattipati, System identification and estimation framework for pivotal automotive battery management system characteristics, IEEE Trans. Syst. Man. Cybern. Part C. Appl. Rev. 41 (2011) 869–884, http://dx.doi.org/10.1109/TSMCC.2010.2089979.
[2] Z. Guo, X. Qiu, G. Hou, B.Y. Liaw, C. Zhang, State of health estimation for lithium ion batteries based on charging curves, J. Power Sources 249 (2014) 457–462, http://dx.doi.org/10.1016/j.jpowsour.2013.10.114.
[3] B. Sun, S. Zeng, R. Kang, M.G. Pecht, Benefits and challenges of system prognostics, IEEE Trans. Reliab 61 (2012) 323–335.
[4] W. He, N. Williard, M. Osterman, M. Pecht, Prognostics of lithium-ion batteries based on Dempster–Shafer theory and the Bayesian Monte Carlo method, J. Power Sources 196 (2011) 10314–10321, http://dx.doi.org/10.1016/j.jpowsour.2011.08.040.
[5] B. Pattipati, C. Sankavaram, K. Pattipati, System identification and estimation framework for pivotal automotive battery management system characteristics, IEEE Trans. Syst. Man. Cybern. Part C. Appl. Rev. 41 (2011) 869–884, http://dx.doi.org/10.1109/TSMCC.2010.2089979.
[6] R.S. Robinson, R. Bank, On-line battery testing: a reliable method for determining battery health, in: Telecommun. Energy Conf. 1996. INTELEC'96., 18th Int, 1996, pp. 654–661.
[7] J. Zhang, J. Lee, A review on prognostics and health monitoring of Li-ion battery, J. Power Sources 196 (2011) 6007–6014, http://dx.doi.org/10.1016/j.jpowsour.2011.03.101.
[8] M.V. Micea, L. Ungurean, G.N. Cârstoiu, V. Groza, Online State-of-Health Assessment for Battery Management Systems, vol. 60, 2011, pp. 1997–2006.
[9] K.-S. Ng, Y.-F. Huang, C.-S. Moo, Y.-C. Hsieh, An enhanced coulomb counting method for estimating state-of-charge and state-of-health of lead-acid batteries, in: INTELEC 2009-31st Int. Telecommun. Energy Conf, 2009, pp. 1–5, http://dx.doi.org/10.1109/INTLEC.2009.5351796.
[10] F. Codecà, S.M. Savaresi, V. Manzoni, The Mix Estimation Algorithm for Battery State-of-Charge Estimator – Analysis of the Sensitivity to Measurement Errors, 2009, pp. 8083–8088.
[11] F. Codecà, S.M. Savaresi, G. Rizzoni, M. Piazza, On Battery State of Charge Estimation: a New Mixed Algorithm, 2008, pp. 102–107.
[12] S.J. Lee, J.H. Kim, J.M. Lee, B.H. Cho, The state and parameter estimation of an Li-ion battery using a new OCV-SOC concept, in: 2007 IEEE Power Electron. Spec. Conf, 2007, pp. 2799–2803, http://dx.doi.org/10.1109/PESC.2007.4342462.
[13] K.-H. Chao, J.-W. Chen, State-of-health estimator based-on extension theory with a learning mechanism for lead-acid batteries, Expert Syst. Appl. 38 (2011) 15183–15193, http://dx.doi.org/10.1016/j.eswa.2011.05.084.
[14] M. Dubarry, C. Truchot, B.Y. Liaw, Synthesize battery degradation modes via a diagnostic and prognostic model, J. Power Sources 219 (2012) 204–216, http://dx.doi.org/10.1016/j.jpowsour.2012.07.016.
[15] S.R. Raman, B. Saritha, V. John, Computationally efficient and accurate modeling of Li-ion battery, in: 2013 IEEE Innov. Smart Grid Technol. (ISGT Asia, 2013, pp. 1–6, http://dx.doi.org/10.1109/ISGT-Asia.2013.6698734.
[16] M. Daowd, N. Omar, B. Verbrugge, P. Van Den Bossche, J. Van Mierlo, Battery Models Parameter Estimation Based on Matlab/Simulink®, vol. 2, 2010.
[17] H. Blanke, O. Bohlen, S. Buller, R.W. De Doncker, B. Fricke, A. Hammouche, et al., Impedance measurements on lead–acid batteries for state-of-charge, state-of-health and cranking capability prognosis in electric and hybrid electric vehicles, J. Power Sources 144 (2005) 418–425, http://dx.doi.org/10.1016/j.jpowsour.2004.10.028.