State-of-health Indication Method for Li-Ion Batteries

Zhiyong Xia, *Student Member*, *IEEE*, Jaber A. Abu Qahouq, *Senior Member, IEEE*

The University of Alabama
Department of Electrical and Computer Engineering
Tuscaloosa, Alabama 35487, USA

Abstract— **This paper presents a state-of-health indication (SOH-I) method based on the online measurement of the impedance phase. Experimental measurement on 18650-2600 Li-Ion battery showed a relationship between the age increase of the battery and the increase of the frequency value at which the complex impedance phase is equal to zero. This relationship is utilized in this paper to present a preliminary method and controller to adjust the value of the initially assumed battery's available capacity as a function of an impedance phase based SOH-I preliminary equation. This SOH-I can also be used as an indicator for the need to replace the battery. The presented method is evaluated based on preliminary experimental results measured from a preliminary proof-of-concept laboratory prototype.**

Index Terms — Battery, energy storage, battery management system (BMS), battery capacity, electrochemical impedance spectrum (EIS), state of health, DC-DC, power converter.

I. Introduction

The determination or estimation of State-Of-Health (SOH) of batteries is important for the performance, reliability, and safety of many related applications [1-5]. As a Li-Ion battery goes through more charge/discharge cycles, part of its capacity fades which makes the available capacity of the battery lower [6-18]. This is one of the factors, among others, that results in lower SOH for a Li-Ion battery.

Integrating SOH estimation functionality as a part of a Battery Management System (BMS) is desirable. This is in order to enable safe and efficient operation of the battery system and the application it is used with.

Several SOH estimation methods have been presented in the literature [6-12]. Most of these methods have one of more of the following characteristics: they require the collection and analysis of large amount of historical data, they are too complicated or not suitable for online monitoring, and/or they require a relatively long time to respond to SOH change.

The electrochemical impedance of the battery is an important parameter that can be used to evaluate the condition of a battery [13-15]. References [13-15] show how the online complex impedance or impedance spectrum of a battery can be obtained by controlling one or more power converters.

This paper presents an SOH indication (SOH-I) method and controller which is based on the phase value of the complex impedance of Li-ion battery. Experimental measurement on 18650-2600 Li-Ion battery showed a relationship between the age increase of the battery and the increase of the frequency value at which the complex impedance phase is equal to zero. This relationship is utilized in this paper to present a preliminary method and controller to adjust the value of the initially assumed battery's available capacity as a function of an impedance phase based SOH-I preliminary equation. This SOH-I can also be used as an indicator for the need to replace the battery. The SOH-I equation presented in this paper is preliminary and future work includes but is not limited to developing better SOH-I equations that utilize the phase of the online electromechanical impedance.

Section II of this paper discusses the principles of the proposed SOH indication method, and Section III presents some preliminary experimental results for evaluation. The conclusion is given in Section V.

II. Principle of the SOH Indication Method and System

The frequency at which the complex impedance phase is zero increases as the li-ion battery health degrades. This is based on preliminary experimental measurements which part of it is presented in this paper (Fig. 1). Fig. 1 shows this trend based on experimental measurements for the phase of the impedance of a relatively new battery and the phase of the impedance of a less healthy battery (with larger capacity fading). This zero-phase behavior can be explored to develop new SOH indicators, estimators, and/or monitoring methods or improve the accuracy and speed of some of the exiting methods. In this paper, a preliminary relationship for an SOH indicator (SOH-I) algorithm is presented in order to illustrate the concept of impedance phase based SOH monitoring. Future work includes but is not limited to investigating and developing improved relationships/equations based on the same concept.

The preliminary SOH-I, β, is defined as in Equation (1), where α is a correction factor which can be used to adjust the relationship between zero crossing frequency of battery impedance phase and SOH status, $f_{initial}$ is the frequency value at which the battery impedance phase becomes zero for a 100% healthy battery or for a reference battery before additional aging process starts, f_z is the current/updated value of zero-phase frequency which is measured as the battery becomes less healthy and/or with larger capacity fading, and n is a factor that is selected to describe more accurately any nonlinearity in the preliminary SOH-I equation for a given battery type. The range of SOH-I (β) is between 0 and 1 (or 0% and 100%). Smaller β value indicates a less healthy battery and vice versa.

The total available capacity of a battery can be adjusted or estimated based on the SOH indicator β as shown in Equation (2), where $Q_{adjust\_available}$ is the capacity of battery after the adjustment, and $Q_{new\_available}$ is the capacity of the reference or new battery before the capacity starts to fade or the battery health starts to degrade. By using the available capacity adjustment method of this paper, a more accurate available capacity value can be obtained. To verify the accuracy of SOH-I method, sample batteries with different health conditions are discharged and their capacity values are calculated and recorded.

$$SOH_i = \beta = \alpha \times \left(\frac{f_{initial}}{f_z}\right)^n \quad (1)$$

$$Q_{adjust\_available} = \beta \times Q_{new\_available} \quad (2)$$

$$SOC = \frac{Q_{adjust\_available} - \sum I_{batt}\Delta t}{Q_{new\_available}} \quad (3)$$

The SOC value of each sample battery is calculated based on Equation (3), where I_{batt} is battery current and Δt is the time interval during which the battery current is equal to I_{batt}.

Fig. 2 illustrates the block diagram of the presented battery system with SOH monitoring for available capacity update controller using the zero-phase frequency concept. The DC-DC converter has two functions in this system: the first is to regulate the output voltage to a desired value, and the second is to perform online electrochemical impedance spectroscopy (EIS) measurement. The battery impedance spectrum can be measured based on the methods presented in [13-15]. For example, the impedance can be measured at odd and even harmonics of perturbation frequency by adding a pulse waveform perturbation to output voltage reference of DC-DC power converter. The diagram of the DC-DC converter system for the battery impedance spectrum measurement is illustrated in Fig. 3.

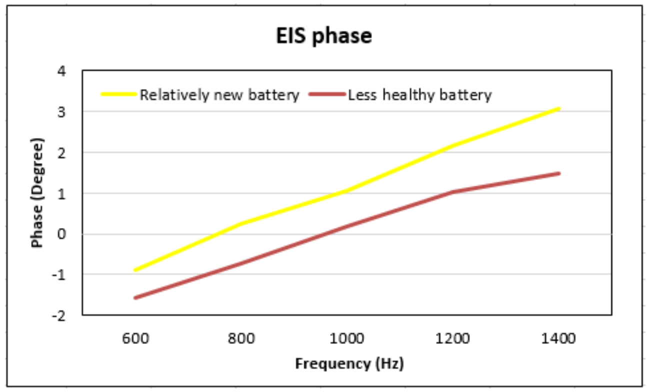


Fig. 1. Battery impedance phase measurement results for two Li-Ion batteries with different SOH conditions.

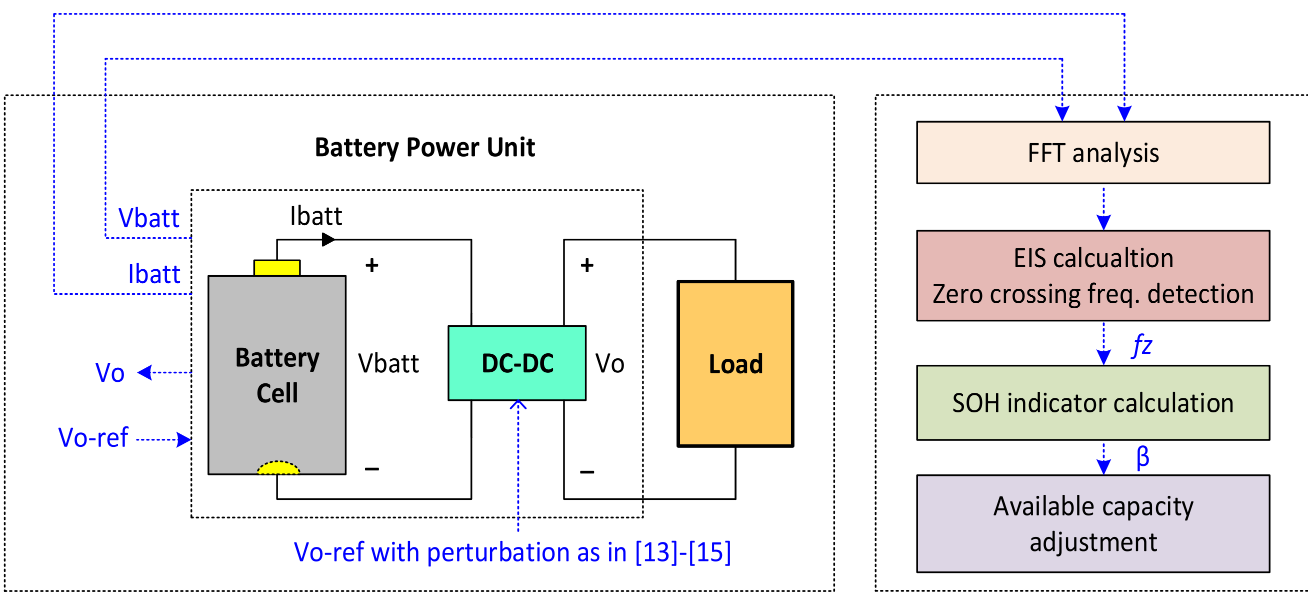


Fig. 2. Block diagram of the presented system and controller for battery SOH indication.

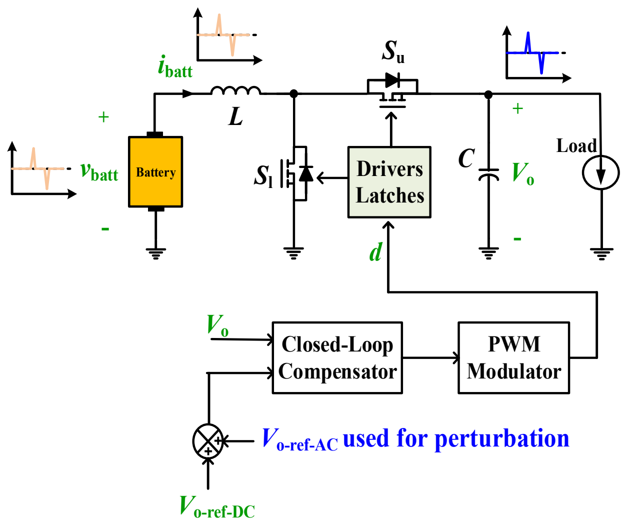


Fig. 3. Diagram of the DC-DC converter connected with battery cell [20, 21].

III. PRELIMINARY EXPERIMENT RESULT

In order to obtain a preliminary evaluation for the presented SOH indication concept, an experimental prototype is built in the laboratory. In this prototype, the battery is connected to the input of a DC-DC power converter as illustrated in Fig. 2 and Fig. 3. The battery used is Tenergy ICR 18650-2600. The main parameters of interest for the DC-DC boost power converter are: 120 µH inductor, 120 µF input and output capacitors, 100 kHz switching frequency, and 8V output voltage. The presented controller is realized using TI microcontroller TMS320F28335 [16].

A relatively new battery (battery 1) and a less healthy battery (battery 2) are selected for the experiments. The results of the impedance phase measurements for these two batteries are shown in the Fig. 1. Table 1 shows a list for the zero-phase frequency values for the two batteries when the experiments were conducted.

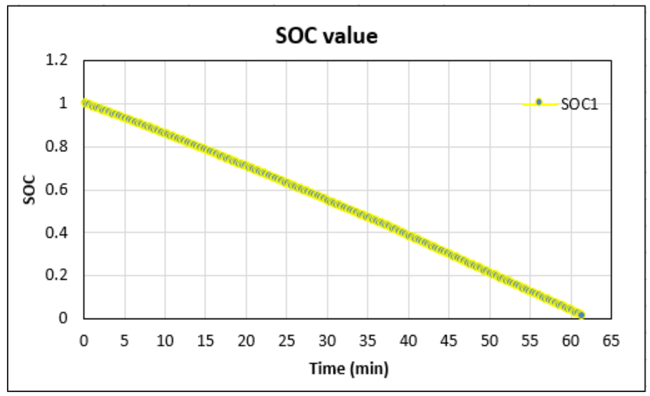
TABLE I. ZERO-PHASE FREQUENCY VALUES

Battery	Zero-phase frequency (Hz)
Battery 1	800
Battery 2	1000

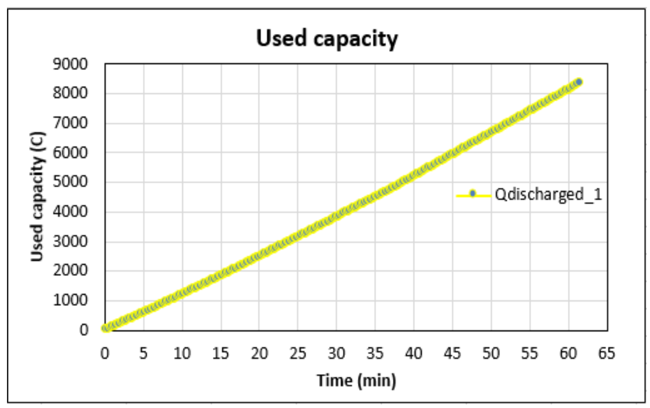
In this experiment, the value of α is set to one (α = 1). Based on the data collected from the battery under different SOH conditions, n = 2.5 is found to be suitable value that yields an SOH-I or β values with good accuracy. The α = 1 and n = 2.5 values are used in Equation (1). The value of $f_{initial}$ in Equation (1) is set to 800 Hz based on the results shown in Fig. 1 and Table I. Based on Equation (1), this yields β_1= 1 for battery 1 and β_2= 0.5724 for battery 2.

The value of $Q_{new\_available}$ is measured by using 2.3A discharging current to discharge battery 1 and found to be equal to 8437 Coulombs. Based on Equation (2), the estimated available capacity value for battery 2 is 4829 Coulombs.

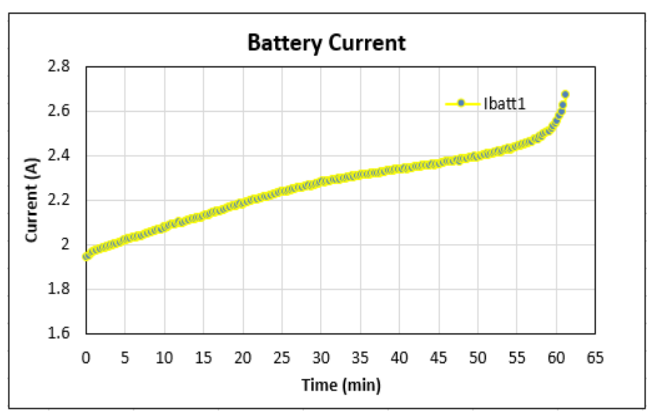
Two discharging experiments are run using the battery system as illustrated in Fig. 2, one with battery 1 and another for battery 2. The start of each experiment is with a fully charged battery and the discharging in each experiment is terminated when the terminal voltage of the battery reaches 2.8 V as specified by the battery manufacturer.



(a)

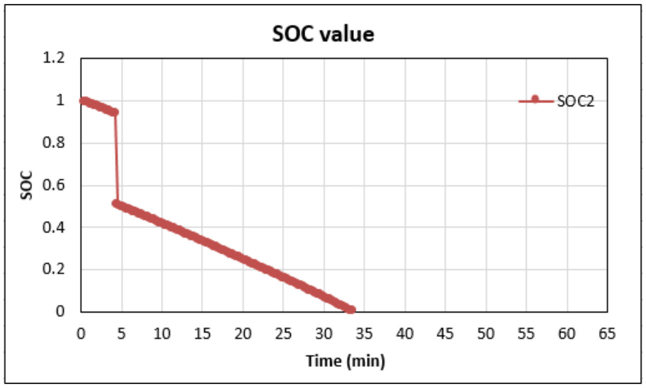


(b)

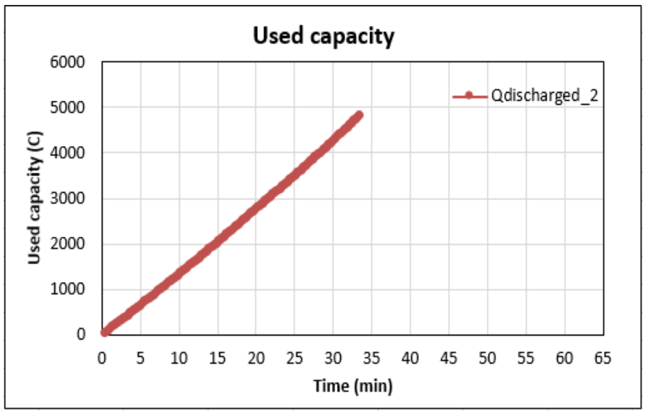


(c)

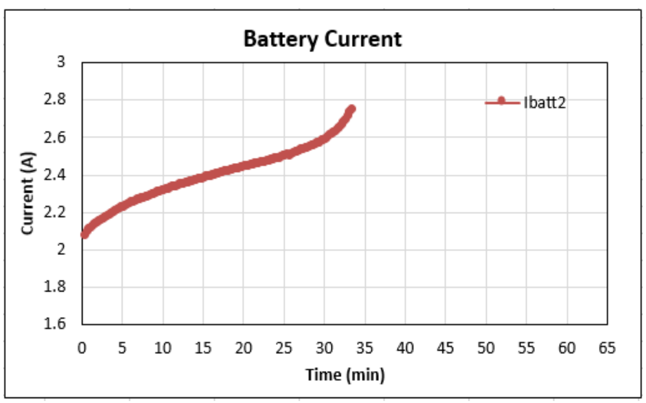
Fig. 4. The SOC, used capacity and battery current values for battery 1 during discharging.



(a)



(b)



(c)

Fig. 5. The SOC, used capacity and battery current values for battery 2 during discharging.

Fig. 4 and Fig. 5 show the discharging results for battery 1 and battery 2, respectively. Each figure shows the SOC, used capacity, and current values as a function of time of the battery during discharging. The SOH-I controller is activated after 5 minutes of the start of the discharging operation (before this time SOH-I controller was not activated). Once the SOH-I controller is activated, the SOC of battery 2 is corrected taking into account its health condition. This resulted in reaching a zero SOC value for battery 2 approximately at the same time the terminal voltage of the battery becomes equal to 2.8V. This is because the available capacity of battery 2 was corrected based on its health condition by using the zero-phase frequency concept and controller of this paper. When the SOH-I controller is not used, the end of discharge voltage of 2.8V is reached much earlier than when the assumed SOC value reaches zero. From Fig. 5(b), the total discharged/used capacity is equal to 4798 Coulombs, which is close to the estimated value of 4829 Coulombs.

The SOC value of battery 1 did not change after activating the SOH-I controller which is expected because it is the healthier reference battery with 100% SOH-I value. From Fig. 4, battery 1 reached a zero SOC value approximately the same time the terminal voltage of the battery becomes equal to 2.8V. From Fig. 4(b), the total discharged/used capacity is equal to 8338 Coulombs, which is close to the estimated value of 8437 Coulombs.

IV. Conclusion

This paper presents a state-of-health indication (SOH-I) method based on the online measurement of the impedance phase. Experimental measurement on a Li-Ion battery showed a relationship between the age increase of the battery and the increase of the frequency value at which the complex impedance phase is equal to zero. This relationship is utilized in this paper to present a preliminary method and controller to adjust the value of the initially assumed battery's available capacity as a function of an impedance phase SOH-I preliminary equation. The preliminary results presented in this paper showed that the impedance zero-phase frequency based SOH-I concept has a potential for developing BMS systems that can account for the degradation of the batteries. When combined with online impedance measurement methods such as those presented in [13-15], the potential result is battery systems with fast, real-time, and online accounting for the SOH of the battery. Future work includes but is not limited to developing better SOH-I equations that utilize the phase of the online electromechanical impedance.

Acknowledgement

This material is based upon work supported in part by the National Science Foundation under Grant No.1509824. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

References

[1] H. R. Eichi, U. Ojha, F. Baronti, and M. Y. Chow, "Battery management system: an overview of its application in the smart grid and electric vehicles," *IEEE Industrial Electronics Magazine*, vol. 7, no. 2, pp. 4-16, June 2013.

[2] B. Pattipati, C. Sankavaram, and K. R. Pattipati, “System identification and estimation framework for pivotal automotive battery management system characteristics,” *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 41, no. 6, November 2011.

[3] W. Huang and J. A. Abu Qahouq, “Energy sharing control scheme for state-of-charge balancing of distributed battery energy storage system,” *IEEE Transactions on Industrial Electronics*, vol. 62, no. 5, pp. 2764-2776, May 2015.

[4] F. Huet, “A review of impedance measurements for determination of the state-of-charge or state-of-health of secondary batteries,” *Journal of Power Sources*, vol. 70, no. 1, pp. 59–69, January 1998.

[5] Z. Xia, J. A. Abu Qahouq, E. Phillips, and R. Gentry, “A simple and upgradable autonomous battery aging evaluation and test system with capacity fading and AC impedance spectroscopy measurement,” in *APEC*, pp. 951-958, March 2017.

[6] H. Chaoui and C. Ibe-Ekeocha, “State of charge and state of health estimation for lithium batteries using recurrent neural networks,” *IEEE Transactions on Vehicular Technology*, vol. 66, no. 10, pp. 8773-8783, October 2017.

[7] J. Yu, “Health degradation detection and monitoring of lithium-ion battery based on adaptive learning method,” *IEEE Transactions on Instrumentation and Measurement*, vol. 63, no. 7, July 2014.

[8] X. Hu, J. Jiang, D. Cao, and B. Egardt, “Battery health prognosis for electric vehicles using sample entropy and sparse Bayesian predictive modeling,” *IEEE Transactions on Industrial Electronics*, vol. 63, no. 4, pp. 2645-2656, April 2016.

[9] C. Weng, J. Sun, and H. Peng, “Model parametrization and adaptation based on the invariance of support vectors with applications to battery state-of-health monitoring,” *IEEE Transactions on Vehicular Technology*, vol. 64, no. 9, pp. 3908-3917, September 2015.

[10] H. Chaoui, N. Golbon, I. Hmouz, R. Souissi, and S. Tahar, “Lyapunov-based adaptive state of charge and state of health estimation for lithium-ion batteries,” *IEEE Transactions on Industrial Electronics*, vol. 62, no. 3, pp. 1610-1618, March 2015.

[11] J. Remmlinger, M. Buchholz, M. Meiler, P. Bernreuter, and K. Dietmayer, “State-of-health monitoring of lithium-ion batteries in electric vehicles by on-board internal resistance estimation,” *Journal of Power Sources*, vol. 196, no. 12, pp. 5357-5363, June 2011.

[12] H. Lin, T. Liang, and S. Chen, “Estimation of battery state of health using probabilistic neural network,” *IEEE Transactions on Industrial Informatics*, vol. 9, no. 2, pp. 679-685, May 2013.

[13] W. Huang and J. A. Abu Qahouq. “An online battery impedance measurement method using DC–DC power converter control,” *IEEE Transactions on Industrial Electronics*, vol. 61, no. 11, pp. 5987-5995, Jun. 2014.

[14] J. A. Abu Qahouq and Z. Xia, “Single-perturbation-cycle online battery impedance spectrum measurement method with closed-loop control of power converter,” *IEEE Transactions on Industrial Electronics*, vol. 64, no. 9, pp. 7019-7029, September 2017.

[15] Z. Xia and J. A. Abu Qahouq, “An online battery impedance spectrum measurement method with high frequency resolution,” in *APEC*, March 2018.

[16] Texas Instruments Inc., Datasheet of TMS320F28335 microcontroller, http://www.ti.com/ [Online], last accessed June 24, 2016.