Real Time Condition Monitoring in Li-Ion Batteries via Battery Impulse Response

Anahita Banaei
Department of Electrical Engineering
University of Texas at Arlington
416 Yates street, Arlington, TX 76019
anahita.banaei@mavs.uta.edu

Babak Fahimi
Department of Electrical Engineering
University of Texas at Arlington
416 Yates street, Arlington, TX 76019
fahimi@uta.edu

***Abstract*— Li-Ion batteries are suitable rechargeable choices for electric and hybrid electric vehicle (EV/HEV) applications due to their relatively high level of energy and power density. Development of an efficient method for monitoring their online state-of-charge (SOC) and state-of-health (SOH) is of high importance for vehicular applications. The methods used for SOH estimation are mostly based on discharge tests or ohmic techniques which are time consuming and inaccurate for real time usage. The present paper reports on a new method for estimating the SOH of a Li-Ion battery using its impulse response. Having the impulse response of a healthy battery, the proposed method predicts the terminal voltage of a battery using the terminal current measurement. Online comparison of the predicted and measured voltages provides information about the condition of the battery. The proposed method provides a tool to distinguish among the possible faults which may have occurred in the battery.**

Keywords-Battery; Li-Ion Battery; State-of-Health (SOH); Impulse Response.

I. Introduction

Electric and Hybrid Electric Vehicles (EV/HEV) are getting significant attention lately due to increase in gas prices and concerns about pollution and climate change. Having a reliable, durable, and efficient energy storage system is a necessity for these technologies to be successful. Li-Ion batteries seem to be a competitive choice as an energy storage system due to their unique abilities such as high power density, high energy density, low self-discharge, fast charging and durability.

One of the important issues in automotive batteries is to monitor their online state-of-charge (SOC) and state-of-health (SOH) due to problems caused in part by poor battery maintenance. During lifetime of the battery, its performance or health deteriorates due to irreversible physical and chemical changes which are caused by battery usage. Deep discharging, overcharging and using the battery in high temperature are examples of misusage of the batteries which affects the health of the battery. Some of the chemical and physical changes made inside a faulty battery include; (a) accumulation of a film of electrolyte decomposition products on the surface of the cathode which results in particle isolation and increasing the internal impedance of the battery and (b)chemical reactions in cathode (cathode decomposition) which isolates active materials in the cathode and formation of passive surface films on both electrodes. As a result of all these changes the amount of available active materials or in other hand the capacity of the battery is reduced. So, the battery can not deliver its maximum capacity even though it is fully charged.

Several studies have been done on SOH estimation and the parameters affecting health status of Li-Ion batteries over the past few years [1-4]. A common battery monitoring method is full or partial discharge test. However this method is expensive and takes a very long time. It also damages the battery, since routine and deep battery discharge (in case of full discharge) can reduce the life of the battery. Also in partial discharge test the accuracy of the technique depends on the depth of discharge [5, 6].

Another method which is used for SOH estimation of lead acid batteries uses a phenomenon referred as *coup de fouet,* which means producing a large voltage drop in the early minutes of battery discharge. As a result of aging the battery encounters a loss of active material utilization. This is caused by various processes such as sulfation and change in pore structure which causes decrease in active surface area and increase in local resistances. As a result of these changes the amount of available capacity decreases and the *coup de fouet* voltage is lowered [6]. Although this is a quick and simple technique for estimating SOH of the battery, it cannot be done online and it needs a constant load for performing the discharge test.

Ohmic techniques including impedance, resistance and conductance measurements are among other options for SOH estimation. However, these techniques are not precise [7-11]. Measuring the internal resistance of the battery is very sensitive to measurement error. The accuracy of the measurement depends highly on the way the contact is made between the battery terminals and the lead of the ohmic meter. Besides, none of the methods are efficient for real time estimation of

978-1-4244-8218-4/10/$26.00 ©2010 IEEE

SOH while the battery is under load. These methods require making measurements which are not always available in a general application.

The present paper proposes a new method of online SOH estimation of Li-Ion batteries using the concept of battery impulse response and can be generalized for other types of batteries.

II. Fundamentals of Li-ion Battery, Battery Modeling Methods

A. Lithium-Ion Batteries

Lithium-ion batteries represent a type of rechargeable battery in which a lithium ion moves between anode and cathode during charge and discharge. Electrolyte consists of lithium salts such as $LiPF_6$, $LiBF_6$ or $LIClO_4$ to act as a carrier, conducting lithium ions between anode and cathode. A variety of materials can be used for anode and cathode, but anode most of the times is made of graphite and cathode is made of a lithium oxides such as $LiCoO_2$ and $LiMn_2O_4$. The typical reaction taking place in cathode is as follows:

$$LiCoO_2 \Leftrightarrow Li_{1-x}CoO_2 + xLi^+ + xe^- \quad (1)$$

the reaction in anode can be shown as below:

$$xLi^+ + xe^- + 6C \Leftrightarrow Li_xC_6 \quad (2)$$

One of the characteristics of Li-Ion batteries which makes them superior among other types of batteries is that they hold their charge better. A Li-Ion battery loses a small percentage of its charge comparing to other types of batteries. They are generally lighter than other types of batteries of the same size and they don't have memory effect, which means there is no need to discharge them completely before recharging. All these advantages make them an excellent choice for electric and hybrid electric vehicles (EV/HEV).

It must be noted that Li-Ion batteries are sensitive to deep discharge or overcharge and these states of extremely high or too low SOC can lead to irreversible damage in the battery.

B. Impulse Response Concept

The convolution of two functions such as f and g is denoted by $f * g$ and the basic definition is given by the integral of one function at t multiplied by another function at $t-\tau$ (over the entire domain of the independent variable, i.e. time). This operation is shown below:

$$(f*g)(t) = \int_{-\infty}^{+\infty} f(\tau).g(t-\tau)d\tau = \int_{-\infty}^{+\infty} f(t-\tau).g(\tau)d\tau \quad (3)$$

The convolution in discrete domain is represented as follows:

$$(f*g)[n] = \sum_{k=-\infty}^{+\infty} f[k].g[n-k] = \sum_{k=-\infty}^{+\infty} f[n-k].g[k] \quad (4)$$

Another point to be made is that convolution is commutative, which means it does not matter which function is taken first.

From the linear system theory the output of a linear time invariant (LTI) system for an arbitrary input can be determined using its impulse response as shown below:

$$y[k] = x[k] * h[k] \quad (5)$$

where $x[k]$, $h[k]$ and $y[k]$ are the input, impulse response and output of the system. In other words, the convolution of the input to the system with its impulse response gives the output of the system.

In order to determine the impulse response of a battery a sufficiently narrow pulse of current (with a unitary area) is applied to the battery and the output voltage is monitored as shown in Figure 1.

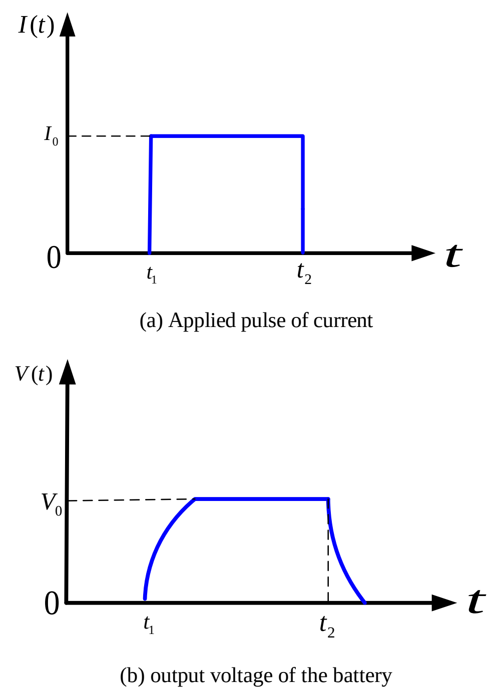


Figure 1. Impulse response demonstration

The impulse response of a battery can be used as a battery model and be used to calculate the output voltage. Having the impulse response of the battery and convolving it with any arbitrary input current, the output voltage can be calculated. It can be shown as follows:

$$v[k] = i[k] * h[k] \quad (6)$$

where $i[k]$, $h[k]$ and $v[k]$ are the battery terminal current, impulse response of the battery and the terminal voltage respectively.

C. ARMAX Modeling

Autoregressive moving average models (ARMAX) can be used to express the impulse response of a discrete time LTI system numerically. For a single-input/single-output system (SISO), the ARMAX polynomial model structure is given by:

$$A(q)y(t) = B(q)u(t) + C(q)e(t) \quad (7)$$

where $y(t)$ represents the output at time t , $u(t)$ represents the input at time t , $e(t)$ is the white-noise disturbance and q^{-1} is the back-shift operator. Also:

$$A(q) = 1 + a_1 q^{-1} + ... + a_n q^{-n} \quad (8)$$

$$B(q) = b_1 + b_2 q^{-1} + ... + b_m q^{-m} \quad (9)$$

$$C(q) = 1 + c_1 q^{-1} + ... + a_r q^{-r} \quad (10)$$

where n , m and r are the orders of the polynomials, respectively [12, 13]. The appropriate model orders should be determined in order to estimate the ARMAX model. Having the specified model, the input current of the battery can be used as the input of the model ($u(t)$) and by using the polynomials, the output voltage can be calculated ($y(t)$).

D. Equivalent Circuit Modeling

The battery equivalent circuit is a commonly used method for modeling of a battery. It provides a model to explain the voltage waveforms and to quantify the results into four circuit parameters which represent various parts of the battery. Figure 2 shows the equivalent circuit of a rechargeable battery.

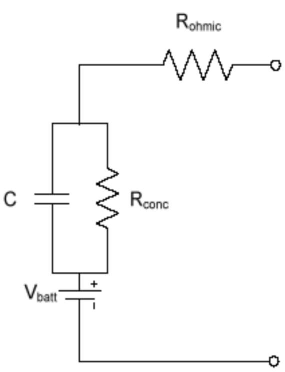


Figure 2. Equivalent circuit of a rechargeable battery

R_{ohmic} represents the electrode and packaging resistance of the battery, R_{conc} represents the battery's internal resistance, which defines the maximum current a battery can deliver and accounts for charging and discharging losses. C is the capacity of a battery which is formed by series connection of the double layer capacitance formed by each pair of battery cells and is indicative of the finite amount of electric charge stored inside the battery. V_{batt} represents the battery's rated voltage at no-load (open circuit) condition. To obtain various parameters of the model some charging and discharging tests need to be made [14].

III. Method Description

The method used in this paper for modeling a Li-Ion battery is based on the impulse response of the battery. The impulse response is dependent upon the amount of charge left in the battery (SOC) and also the health status of the battery (SOH). Different levels of SOC and various faults imply different impulse responses. It must be noted that the term impulse inherently suggests that the duration of the current pulse is significantly smaller than the smallest time constant in the system.

A family of impulse responses for various levels of SOC for a healthy battery are recorded and used such that the whole available range of the SOC of the battery is being presented by " n " individual values corresponding to a specific impulse response ($h_n[k]$). The impulse responses corresponding to different SOCs are formatted into an ARMAX model and the corresponding coefficients are stored in a look up table. Measuring the SOC of the battery using SOC estimator block, the impulse response of the battery corresponding to the specific SOC is determined and used for convolution by the arbitrary input current to calculate the output voltage. Figure 3 shows the block diagram of this algorithm.

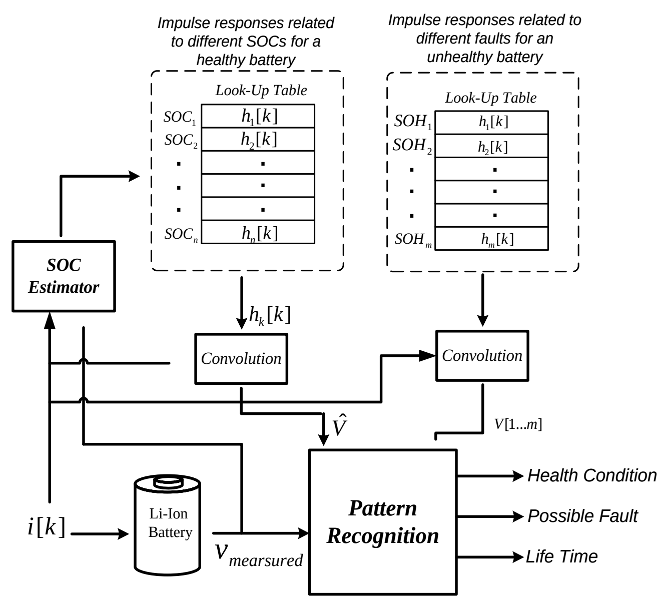


Figure 3. State-of-Health estimation algorithm

The impulse responses corresponding to different fault situations are also stored in a look up table. The applied current to the battery is convolved with all these impulse responses and a set of output voltages are calculated. The measured output voltage from terminals of the battery and the calculated output voltage using the specific impulse response corresponding to the battery State-of-Charge are used by a pattern recognition method to determine the health condition, possible fault occurred and the lifetime of the battery.

IV. Experimental Results

In this paper a new 26650 Li-Ion battery has been used for experimental results. The capacity of the battery is 3.0Ah and the experiments have been done in room temperature, $25\,^{o}C$. The idea has been verified by simulation results using Battery Design Studio software V13.6 and the model of 18650 Li-Ion battery with the capacity of 2.2Ah. Figure 4 shows the effect of electrolyte decomposition and reducing cathode active area on impulse response of the battery. A charging current of 1A is applied to the 18650 Li-Ion battery model using Battery Design Studio software while the SOC of the battery is 80%. It is shown that the output voltage response varies regarding to the amount of active area reduction.

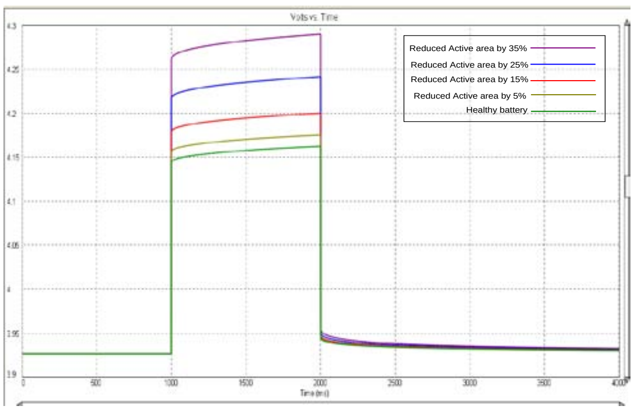


Figure 4. Effect of electrolyte decomposition and reducing cathode active area on impulse response of the battery: charging current of 1A for 1s, SOC = 80%

It must be noted that the impulse response is also related to the magnitude of current applied to the battery in each level of SOC. So, for estimating the impulse response a specific current pulse is chosen for all different state of charges. Figure 5 shows voltage responses to different current values of 0.5A, 1A and 1.5A while SOC = 80%.

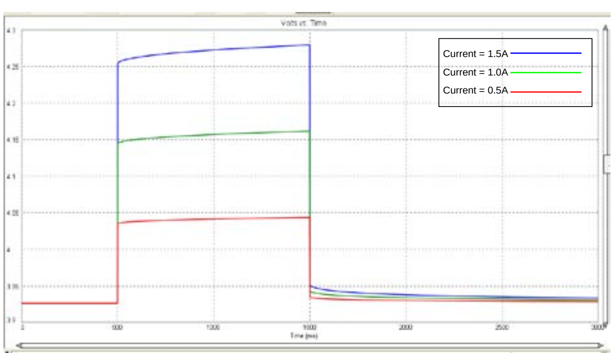
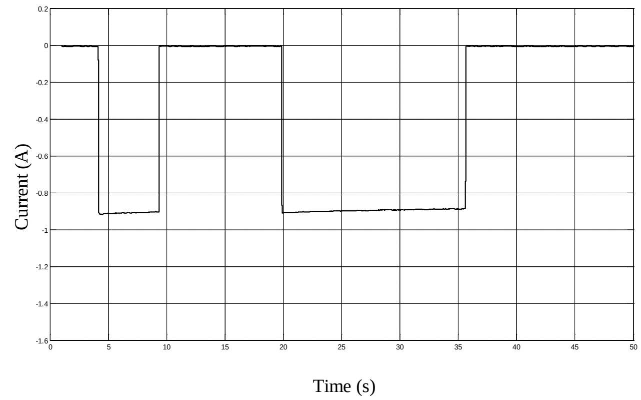
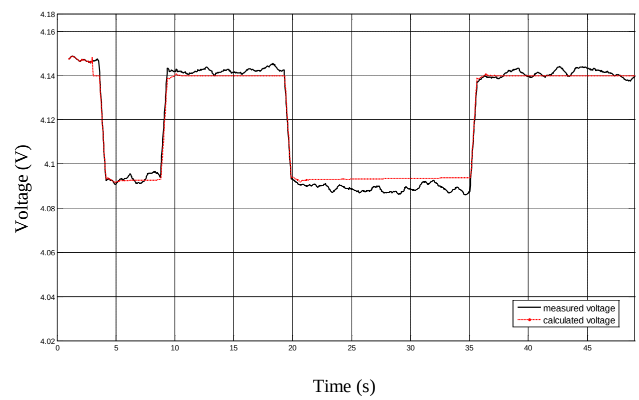


Figure 5. Charging pulse of 1sec for different currents of: 0.5A, 1A and 1.5A, SOC = 80%

Using a specific discharging pulse, the impulse response of the battery with a specific State-of-Charge is identified and stored in the form of ARMAX model. For this reason the System Identification Toolbox from MATLAB® is used. The calculated impulse responses can be used as the battery model to calculate the output voltage of the battery. Figure 6 compares the measured voltage of battery terminals with the calculated voltage using impulse response of the cell. Two charging current pulses with the magnitude of about 1A and various lengths have been applied to the battery and also are used to calculate the output voltage using the battery impulse response. It can be observed that the error between the calculated and the measured voltages is less than 0.5%.



(a) applied current



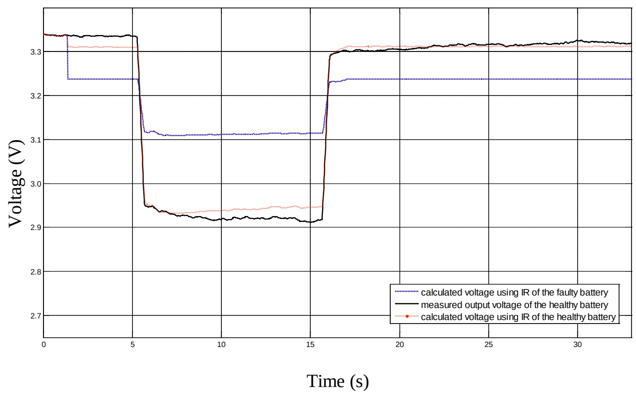
(b) output voltages

Figure 6. Comparison between measured voltage and calculated voltage using the battery impulse response, SOC = 100%

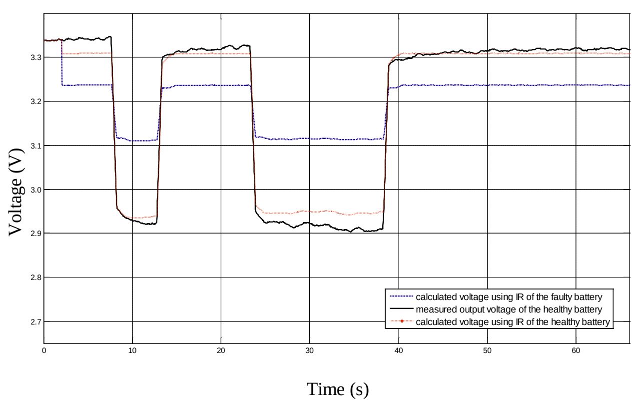
To verify the proposed method, two new (healthy) and aged 26650 Li-Ion batteries are selected. The health status of the aged battery is determined by discharge test. The impulse responses corresponding to both batteries are calculated and stored in the form of ARMAX coefficients. Then, by applying any specific current waveform to these impulse responses the expected voltage is achieved.

Figure 7 shows the comparison of calculated output voltages for both healthy and faulty batteries. A specific current waveform is applied to the healthy battery, and then the same current waveform is applied to both impulse responses of the healthy and aged batteries. The calculated output voltages using impulse responses are compared to the measured voltage from terminals of the battery. It can be noted that the voltage calculated by the impulse response of the healthy battery fits the measured voltage better than the one calculated by the impulse response of the faulty battery. The test has been done for two various current waveforms, the first one has one discharging pulse of about 10 seconds (Figure 7(a)) and second one contains two discharging pulses of 5 and 15 seconds (Figure 7(b)).

The same comparison is performed in Figure 8, this time for the faulty battery. As it is shown in this figure the voltage calculated by the impulse response of the faulty battery has better match to the measured voltage comparing to the calculated voltage of the healthy battery.

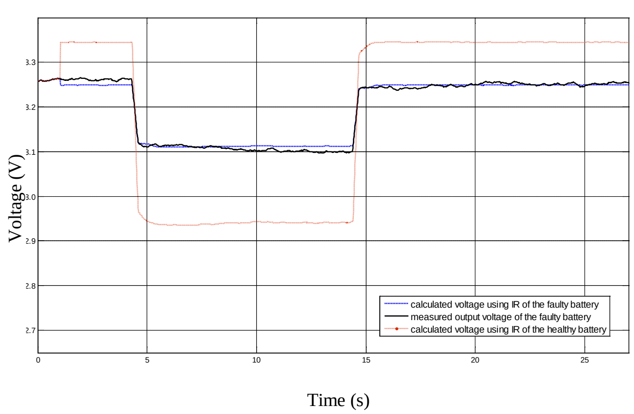


(a) voltage comparison for pulse length of 10s

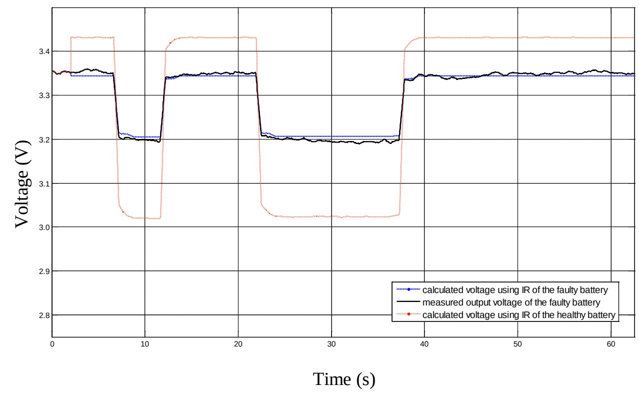


(b) voltage comparison for two pulses

Figure 7. Comparison of the measured output voltage of the healthy battery and the calculated voltages of the faulty and healthy batteries using the impulse responses, SOC = 100%



(a) voltage comparison for pulse length of 10s



(b) voltage comparison for two pulses

Figure 8. Comparison of the measured output voltage of the faulty battery and the calculated voltages of the faulty and healthy batteries using the impulse responses, SOC = 100%

CONCLUSIONS

A new method for online estimation of State-of-Health (SOH) in Li-Ion batteries is presented in this paper. The method is based on impulse responses of healthy and faulty batteries. The simulation and experimental results shown herein verify the claims of the proposed method. It can be used as a key step in battery management systems for automotive applications. This unit along with a SOC detector is able to update the health status of the battery continuously. The proposed method can be modified for other types of batteries.

REFERENCES

[1] M. Keralu, J. Reimer, E. Cairns, “Layered nickel oxide-based cathodes for lithium cells: Analysis of performance loss mechanisms”, *J. Electrochem. Soc.*, Vol. 152, No. 8, pp. A1629-A1632, 2005.

[2] J. Christensen, J. Newman, “A mathematical model for the Lithium-ion negative electrode solid electrolyte interphase”, *J. Electrochem. Soc.*, Vol. 151, No. 11, pp. A1977-A1988, 2004.

[3] J. P. Christophersen, C. D. Ho, C. G. Motloch, D. Howell, H. L. Hess, “Effects of reference performance testing during aging using commercial Lithium-ion cells”, *J. Electrochem. Soc.*, Vol. 153, No. 7, 2006.

[4] P. Ramadass, B. Haran, P. M. Gomadam, R. White, B. N. Popov, “Development of first principles capacity fade model for Li-ion cells”, *J. Electrochem. Soc.*, Vol. 151, No. 2, pp. A196-A203, 2004.

[5] V. Pop, H. J. Bergveld, P. P. L. Regtien, J. H. G. Veld, D. Danilov, P. H. L. Notten, “Battery aging and its influence on the electromotive force”, *J. Electrochem. Soc.*, Vol. 154, No. 8, pp. A744-A750, 2007.

[6] C. S. C. Bose, F. C. Laman, “Battery state of health estimation through Coup De Fouet”, *IEEE The 2nd Annual of Telecommunications Energy Conference, INTELLEC’00*, pp. 597-601, 2000.

[7] F. Olivier, M. Didier, “Testing battery state of health with portable metering devices?”, *IEEE The 9th Annual of Telecommunications Energy Conference, INTELLEC’07*, pp. 203-209, 2007.

[8] S. Brown, N. Mellgren, M. Vynnycky and G. Lindbergha, **“**Impedance as a tool for investigating aging in Lithium-ion porous electrodes, II. Positive electrode examination”, *J. Electrochem. Soc.*, Vol. 155, 2008.

[9] M. Keralu, R. Kostecki, “Interfacial impedance study of Li-ion composite cathodes during aging at elevated temperatures”, *J. Electrochem. Soc.*, Vol. 153, No. 9, pp. A1644-A1648, 2006.

[10] F. Huet, “A review of impedance measurements for determination of the state-of-charge or state of health of secondary batteries”, *J. Power Sources*, Vol. 70, pp. 59-69, 1998.

[11] C. S. C. Bose, D. Wilkins, S. McCluer, M. J. Model, “Lessons learned in using ohmic techniques for battery monitoring”, *IEEE The 6th Battery Conference on Applications and Advantages*, pp. 99-104, 2001.

[12] H. Yang, C. M. Huang, C.L.Huang, “Identification of ARMAX Model for Short Term Load Forecasting:An Evolutionary Programming Approach”, *Power Systems, IEEE Transactions on*, Volume 11, No. 1, pp. 403-408, 1996.

[13] A. Banaei, A. Khoobroo, B. Fahimi, “Online detection of terminal voltage in Li-ion batteries via battery impulse response”, *IEEE International Conference on Vehicle Power and Propulsion, VPPC’09,* pp. 1-6, 2009.

[14] M. Ragsdale, J. Brunet, B. Fahimi, “A Novel Battery Identification Method Based on Pattern Recognition”, *IEEE International Conference on Vehicle Power and Propulsion, VPPC’08,* pp. 1-6, 2008.