Modeling of Lithium-ion battery open-circuit voltage using incremental and low current test

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Abstract— *Accurate estimation of lithium-ion (Li-ion) cell state of charge (SOC) is critical for battery management systems (BMS) in electric vehicles (EV).*

Li-ion cell SOC is related to its open-circuit voltage (OCV) by a non-linear relationship; finding this relation that can accurately reflect cell behavior is favorable for increasing SOC estimate accuracy. This paper studies Li-Ion cell static behavior. The non-linear relation OCV- SOC is modeled by polynomial and Fourier functions for two cells subjected to tests "low-current OCV" and "incremental OCV". The goal is to find the common function that best fits both tests and over the largest area of SOC.

Keywords— *Li-ion batteries- static behavior- state of charge- open circuit voltage- model fitting*

I. Introduction

In recent years, the global energy problem and the deterioration of the environment have provided an opportunity for Electric vehicle (EVs) development [1].

The energy needed for the general operation of electric vehicles is stored in batteries (battery is a group of cells), which are the key to the development of EVs [2], vehicle's autonomy depends mainly on the electrical charging capacity of its battery [3].

The Li-ion battery is often viewed as the most favorable power source and is preferred by the majority of modern vehicle technologies considering the different advantages it offers over other technologies in terms of energy density range [2].

The battery's level of charge commonly termed a state of charge or SOC is an essential and necessary indicator for better management of the battery's reliable use [1].

Direct measurement of SOC on a battery is not reliable, hence estimation is used. Among the different approaches to estimating SOC, the model-based methods are common. [4, 5]. Open-circuit voltage (OCV) as a function of SOC must be precisely represented in models [1].

According to the literature, various nonlinear functions to characterize the OCV-SOC relationship have been proposed [1]; the functions are proposed to fit experimental data [5].

Hemi et al used a 2/4 rational polynomial to represent the OCV-SOC relationship of LiFePO4 cell at different temperatures [6], Baccouche et al used two exponential and a simple quadratic function to model the OCV of an NMC cell, the observed error between the model and the experimental data is 1 mV and the model has been validated for different temperatures and taking into account the hysteresis [7].

Yu et al presented a comparative study of 18 OCV models using two types of LiFePO4/graphite(LFP) and LiNiMnCoO2/graphite (NMC) batteries, the models' sensitivity to different temperatures, aging stages, data points, and different regions of the SOC were investigated. For NMC and LFP cells, the 9th order polynomial was recommended for describing OCV-SOC functional relations [1].

Yuan et al also recommended a 9th order polynomial [9]. Elmahdi et al used an 8th order polynomial to link OCV to SOC, the parameters of the polynomial were determined by the genetic algorithm [10]. To represent the OCV-SOC relationship, Zheng et al used the piecewise linear method [11], while Wang et al proposed a combined model of several functions (polynomial, polynomial rational, and logarithmic) [12].
Zhang et al proposed a model combining a real-power logarithmic function, a linear and an exponential function to cover the entire range of SOC, the identification of the model parameters was performed by a nonlinear algorithm [13].
Hu et al were tested five models of the OCV, a polynomial of six order was chosen to represent the OCV-SOC relation in the region (0.1-0.9) of SOC inducing an RMSE of 0.01053 [14].

Our concern in this work is to model the nonlinear Li-ion cell static behavior. The nonlinear relation OCV- SOC is modeled by polynomial and Fourier functions for two cells tested at "low-current OCV" and "incremental OCV". The goal is to find the common function that best fits both tests and over the largest area of SOC.

In this paper, the primary contribution is to use a common model that can combine both the OCV-SOC relationship for low current testing and incremental testing. The rest of this paper is organized as follows.

In section I, a static study of the cell is presented. In section II, we seek to find the best model OCV-SOC that captures fundamental electrochemical underpinnings in the largest SOC range. Results and discussion are given in section III.

II. EXPERIMENTATION AND TESTING

A. *Test cell's description*

The cell utilized in our study is a Lithium-ion INR 18650-20R, Nickel Manganese Cobalt oxide, NiMnCoO2/Graphite (NMC) cell, which is the most common type of cell in the field of electric vehicles [8].

A cell is a reversible Physico-chemical system that can convert chemical energy into electrical energy through redox reactions. The electric current is converted to chemical energy when the system is in charge mode and then released as electrical energy when it is in discharge mode.

During charging, Li-ions positively charged move from the cathode to the layered graphite structure of the anode via the separator where they are stored, the cell is charged. During discharge, Li-ions move from the anode via the separator to the cathode [8].

The reactions that occur inside the cell during the charging and discharging process are complex. A cell model is needed to describe the correspondence between these reactions that occur inside and the external characteristic parameters[11].

The cell's charge/discharge principle and equivalent circuit are summarized respectively in Fig1.(1-a, 1-b and 1-c) and specifications are given in TABLE1[4].

Cells were subjected to a set of tests, including a capacity test and two OCV tests to map the OCV-SOC relationship, The Low-current test and, the Incremental test, all of which were carried out at a temperature of 25°C.

The experimental data for the cells which include time, current through the cell, output voltage, and amount of charge/discharge are recorded at a 1seconde interval. The data was obtained from the website "Calce Battery Group".

B. *Capacity Test*

The capacity test is used to assess the cell's maximum capacity, which differs from its nominal capacity[15]. A fully charged cell's maximum capacity is the number of ampere-hours that can be removed before it is completely discharged. It consists of a full charge/discharge at a 1C rate.

The capacity's test determines a cell's maximum capacity and its Coulombic efficiency which is the ratio between the amount of discharge and the amount of charge. Fig.2 represents the curve deduced from the experimental data of the test capacity.

C. *Test Low-current OCV*

Low-current OCV test uses a small current amplitude, such that the voltage measured at the cell terminals is approximately equivalent to the cell's (OCV) [9].

First, the cell is charged to the upper Cut-off voltage (4.2V) with the CC-CV profile. (The CC-CV profile consists of charging the cell using a 1C-rate constant current until the voltage reached its upper Cut-off Value, The cell will then continue to charge at a steady

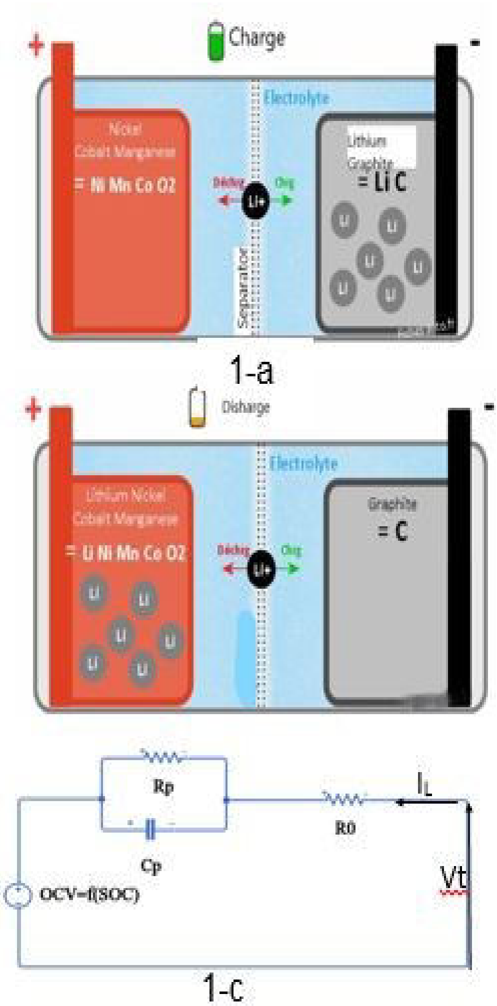

Fig. 1. (1-*a) – cell charge, (1-b)- cell discharge (1-c)- equivalent circuit*

TABLE1 SPÉCIFICATIONS OF THE LNMC/GRAPHITE CELL

LNMC/Graphite	
Parameters	***Specifications (Value)***
Nominal Capacity:	2Ah
Nominal Voltage:	3,6V
Courant Cut-off:	100mA
Standard charge	CCCV, 1A, 4.20 ± 0.05 V, 100mA cut-off
Upper/Lower Cutt off voltage	4.2V /2.5V

voltage until the current hits the 0.01C cut-off point., then we proceed to discharge the cell by applying a small negative current of 0.1A, the cell is slowly discharged until its terminals voltage reaches its lower cut-off of 2.5V, after a relaxation time of about 2h, we charge the cell by applying a positive current of the same rate as the discharge current until the cut-off upper voltage reached [9].

The cell's terminal voltage obtained with a low-current OCV profile reflects a near-equilibrium state [1]. The experimental data of the cell representing the current and terminal voltage of OCV- low-current test obtained at room temperature of 25°C is shown in Fig.3

D. *Incremental Test*

Incremental OCV test consists to discharge a fully charged cell by using a negative current pulse every 10 percent of SOC. When the cell voltage reaches the Lower cut-off value of 2.5V, the cell is recharged using a positive current pulse every 10pecent of SOC.

Cell's experimental data representing incremental test current and voltage obtained at room temperature of 25°C is shown in Fig.4

E. *Lithium-ion cell's OCV-SOC mapping.*

The relationship that relates OCV to SOC is crucial for enhancing the cell model's accuracy and SoC estimate [9].

Coulomb counting formulation is used to SOC calculate according to equation (1)

$$SOC(t) = SOC(t_0) - \frac{\int_{t_0}^{t} \eta_i \cdot i(\tau) d\tau}{C_{\max}} \qquad (1)$$

With SOC(t) is SOC's value at time t, SOC(t_0) is SOC's initial value, ηi is the Coulombic efficiency, ·i(τ) is the current at time τ, and Cmax is the maximum cell capacity.

To find the OCV-SOC relationship, a multi-point fit of the OCV test is performed, the error between experimental data and model fit value is quantified by the Root mean square measure (RMSE)[16].

I. *Polynomial fitting :*

A polynomial equation may be used to depict the cell's open-circuit voltage as a function of SOC.

$$f(x) = p_1 x^n + p_2 x^{n-1} + p_3 x^{n-2} + \ldots + p_n x + p_{n-1} \qquad (2)$$

Where f(x) represents the cell's OCV, x represents the SOC, coefficients of a polynomial function are represented by p_i i=1,2,.........n+1 which are calculated by a least-squares approach using Matlab toolbox 'curve fitting'

II. *Model Fourier:*

The model Fourier of n order is given by equation (3):

$$f(x) = a_0 + a_1 \cos(wx) + b_1 \sin(wx) + a_2 \cos(2wx) + b_2 \sin(2wx) + \ldots a_n \cos(nwx) + b_n \sin(nwx) \qquad (3)$$

Where f(x) represents the cell's OCV, x represents the *SOC,*

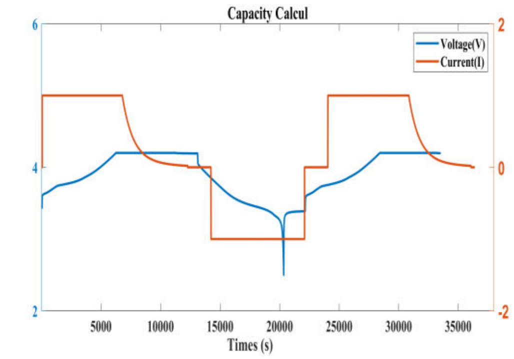

Fig. 2. Charge/Discharge at 1C rate

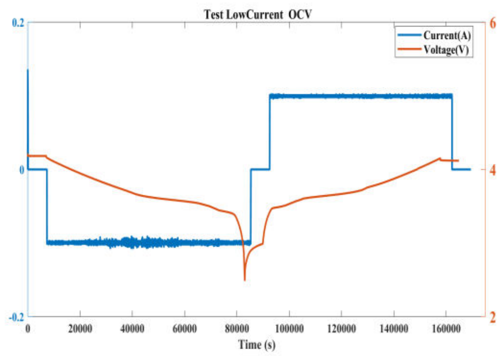

Fig. 3. Low Current Test

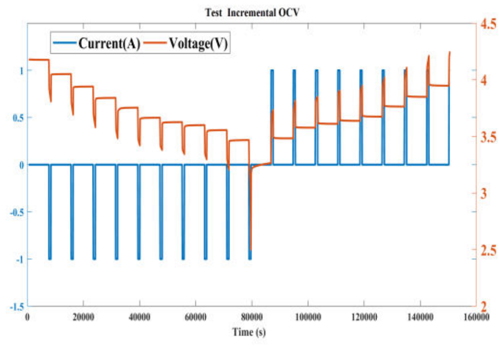

Fig. 4. Incremental test

Fourier model coefficients ai, bi for i=1,2,...n and w, are obtained by the Non-Linear least squares approach using Matlab toolbox 'curve fitting'

III. *Root Mean Squared*

The error expressed by RMSE is given by equation (4)

$$RMSE = \sqrt{\frac{1}{n} \sum \left(V_{est}^{i} - V_{\exp}^{i} \right)^2} \qquad (4)$$

V_{est}^{i} is the value of OCV estimated by the fitting function at index i, $V_{\exp}^{i}$ is the value of experimental OCV at index i, n is the number of points sampled.

III. RESULTS

The maximum capacity deduced from the charge/discharge curve of test capacity is 2.009 Ah and the Coulombic efficiency capacity is 0.86.

A- Cell's OCV-SOC curve

Experimental data of OCV low current and OCV incremental test along with SOC calculation allowed to plot the charge/discharge curves as a function of SOC, The curves show the existence of the hysteresis effect.

The most common methodology in the literature to deal with the hysteresis problem is to calculate the average between the charge voltage and the discharge voltage at different SOC levels. These average values will define the experimental curve to find the OCV-SOC relationship [1, 12]. Fig.5 and Fig.6 represent respectively the charge/discharge curves as well as their average of OCV low-current test and OCV incremental test.

TABLE 2 shows the average values voltage of both OCV tests at each 10 percent SOC.

I. -Polynomial fitting curve

Relationship OCV-SOC of NMC cell's low current test is represented using the 7th order polynomial model and the 9th order polynomial model.

TABLE 3 gives models' coefficients, Fig.7 and Fig.8 show respectively the 7th-order and 9th-order polynomial fitting curve and their residuals respectively

II. The Fit curve of Fourier model

the coefficients of the fifth-order and sixth-order Fourier models are given in TABLE 4.

Experimental data, the fit curve of the fifth-order and sixth-order Fourier model, and the residual between the experimental data and the fit model are displayed respectively in Fig.9 and Fig.10

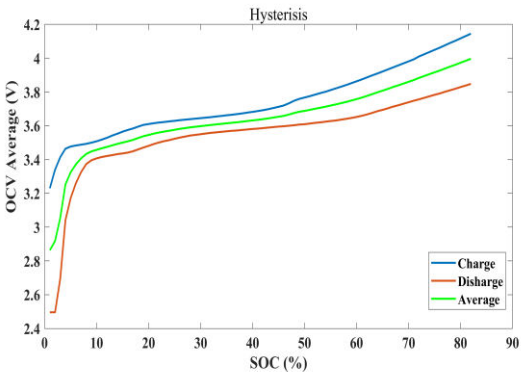

Fig. 5. Hysteresis Low current test

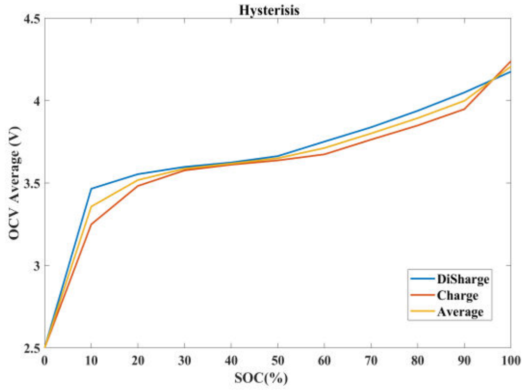

Fig. 6. Hysteresis Incremental test

TABLE2 Open Circuit Volatge Value

	LowCurrent OCV Test	*Incrémental OCV Test*
SOC(%)	***VOC(V)***	***VOC(V)***
10	3,50	3,36
20	3,58	3,52
30	3,61	3,55
40	3,65	3,60
50	3,71	3,62
60	3,80	3,65
70	3,91	3,71
80	4,02	3,80
90		3,89
100		3,99

B- PERFORMANCE OF THE OCV MODEL

I. Comparison of models

Fig.11. depicts the experimental data as well as the fitting curves for the previously determined low-current OCV test.

Fig.12 represents the residual of the fitting Models.

TABLE 3 Coefficients Polynomial functions

Coefficients	*7th order polynomial*	*9th order polynomial*
p_1	-0.002161	-0.0006031
p_2	0.002443	-0.0005711
P_3	0.01481	0.0015
P_4	-0.0241	0.005702
P_5	-0.01713	0.007505
P_6	0.08092	-0.0301
P_7	0.146	-0.01185
P_8	3.68	0.08482
P_9		0.145
P_{10}		3.679

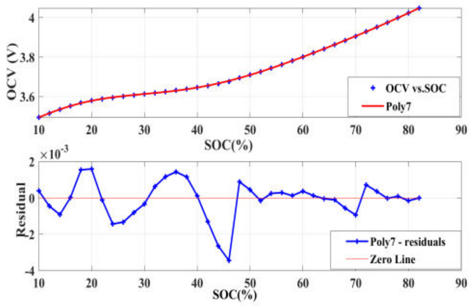

Fig.7 Curve fitting 7th order polynomial and residual,

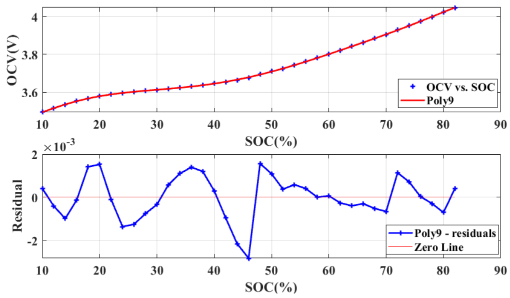

Fig.8 Curve fitting 9th order polynomial and residual

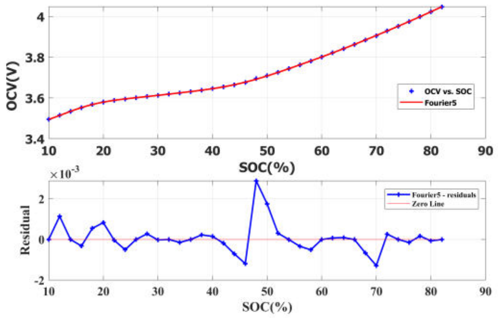

Fig.9 Curve fitting 5th order Fourier and residual,

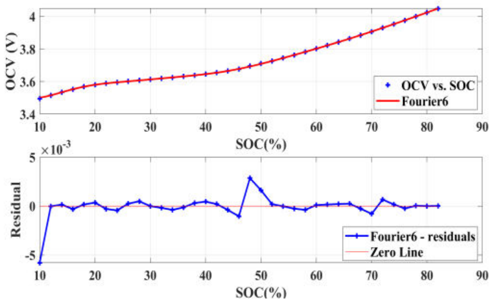

Fig.10 *curve fitting 6th order Fourier and residual,*

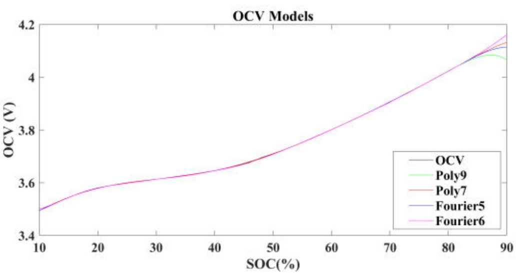

Fig11. *OCV models of Low-current test*

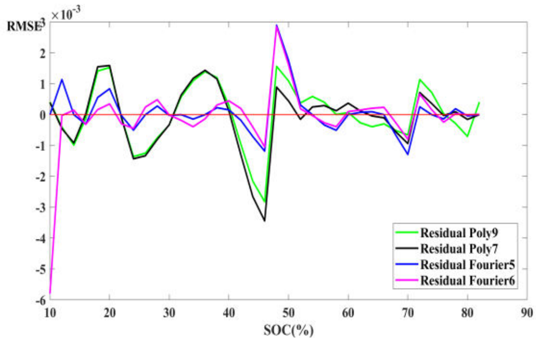

Fig12. Residual of fitting model

TABLE4 Coefficients Rationnel polynome

Coefficients	*5th order Fourier*	*6th order Fourier*
w	1.235	0.05359
a_0	3.76	3.833
a_1	-0.07982	0.01576
b_1	0.2363	-0.3147
a_2	0.01084	-0.06506
b_2	-0.1116	-0.124
a_3	-0.01874	-0.05629
b_3	0.05185	-0.06068
a_4	0.01002	-0.0318
b_4	-0.01694	-0.02088
a_5	-0.004269	-0.01406
b_5	0.003432	-0.004448
a_6		-0.00299
b_6		-0.001041

TABLE 5 RMSE Value

RMSE	*Polynomial order 9*	*Polynomial order 7*	*Fourier order5*	*Fourier order 6*
Parameter number	10	8	12	14
test Cell ‘S1’ NMC (lowcurrent	0,00116	0,00113	0,00069	0,00076
Cell S2 NMC (Lowcurrent)	0,00102	0,00108	0,00101	0,00082
Cell ‘S1’NMC (incremental Test)	0,00534	0,00976	0,00554	0,00478
Cell ‘S2’NMC (Current Test	0,00458	0,00802	0,00468	0,00415
Min (%)	0,102	0,108	0,069	0,076
Max(%)	0,534	0,976	0,554	0,478

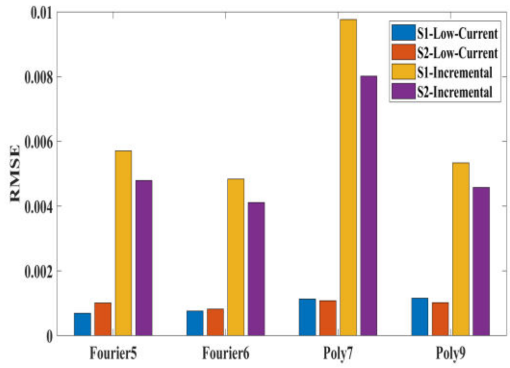

Fig13. Residual of fitting models

II. *Validation of models proposed*

The proposed OCV-SOC models are compared with the experimental data of the Incremental test of the same cell and also the experimental data of a second cell of the same type subjected to the same tests (low current OCV and incremental OCV). The RMSE results obtained for the cells are grouped in TABLE 5.

Fig.13 shows a histogram indicating the error between the experimental data and the fit function values for the test cell and the validation cells.

DISCUSSIONS

Our study focused on finding a model that relates OCV to SOC for an NMC cell which was subjected to Two OCV Tests; Low-current test and incremental test, OCV was modeled by a 9th order polynomial function, a 7th order polynomial function, a 5-term Fourier series, and a 6-term Fourier series. The models were tested over the operating range [10-80] % SOC.

According to the RMSE Values, the results showed that all functions can represent OCV-SOC, the error oscillates between 0.1% and 0.9% for polynomials functions and between 0.07% and 0.5% for Fourier functions, but comparing the results of the low-current test and the incremental test, we notice that the error is much smaller in the first test concerning the four models.

CONCLUSION

In this paper, we used four functions to characterize the relationship OCV- SOC over the operating range [10-80] % of SOC, models' parameters are determined by the least-square approach for polynomials functions and by the non-linear least square approach for Fourier models. The cells in our study were subjected to two OCV tests Low- current and incremental tests.

To compare the various models, the RMSE error between the experimental data of NMC cells and models was employed.

All of the four models that were utilized to express OCV-SOC gave satisfactory results, the model chosen remains a compromise between the model's accuracy and the parameters' number to be determined.

The focus of future research is the identification of the cell's electrical parameters, and we will expand to explain the behavior of the cell at various temperatures with the chosen model.

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