BEHAVIORAL SPICE MODELS OF LITHIUM ION BATTERIES IN THE CHARGE STAGE

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The computer behavioral macromodels are proposed in the paper describing single cell lithium ion batteries in the charge stage. The voltage and current dependencies on the time v(t) and i(t) are modeled using the elements from the Analog Behavioral Library of the general-purpose circuit analysis programs. In addition, the capacity performance curve C(t,N) is analytically described, where N is the cycle times. The analytical expression gives the ability for parametric analysis for obtaining the dependence C(N). This information is useful as an input parameter for a behavioral battery discharge model. The proposed behavioral macromodel is parameterized. The parameterized model description is presented in accordance with the input language of the OrCAD PSpice simulator.

1. INTRODUCTION

More and more attention is paid recently on modeling the processes in charge and discharge stages of lithium ion batteries during the design process. The *Spice*-like simulators are very useful and powerful environment for modeling at behavioral and circuit levels. Battery discharge process models are widely used [1]. They are applicable when the discharge processes in lithium ion batteries are investigated. They are used in co-simulation at system level in the power management systems design (Fig 1). This leads to decreased measurement and verification time. These models help designers to predict the system behavior in different modes of operation, and provide the state of charge status before the discharge process. In the present paper a behavioral computer model is proposed, for modeling the charge stage processes of a single cell lithium-ion battery. The model describes the following specific characteristics in the charge stage: charge voltage, charge current, and battery capacity. The dependence of capacity versus the

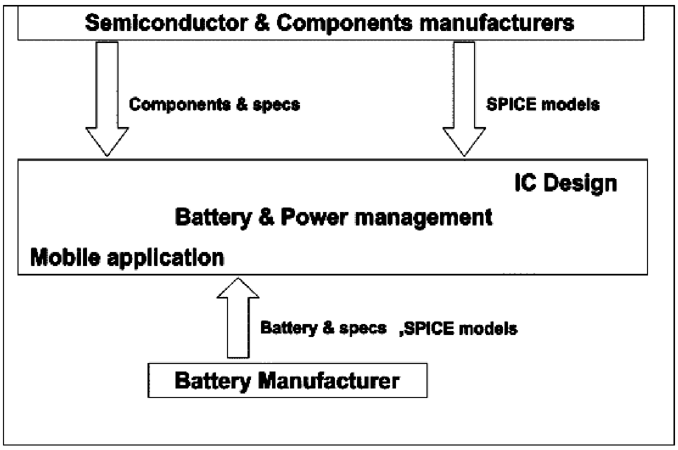

Fig. 1

number of full cycles, the temperature dependences, and other critycal charcteristics can be obtained using this behavioral model. The realization of the proposed model is based on datasheet of typical lithium ion batteries. The characteristic graphics and curves are used for modeling of the charge current, charge voltage, and capacity in the charge stage. The models are parameterized and universal. They allow capacity determination for a given number of cycles, compared to the nominal capacity. Models are proposed for three different charge modes.

1.1 Input data for model development

The datasheet characteristic graphics and curves are used for model construction of lithium ion battery. The behavior of the parameters: charge current $I_{ch}(t)$, charge voltage $U_{ch}(t)$, as well as capacity $C(t)$ in the charge stage are modeled. These characteristics are presented in Fig. 2.

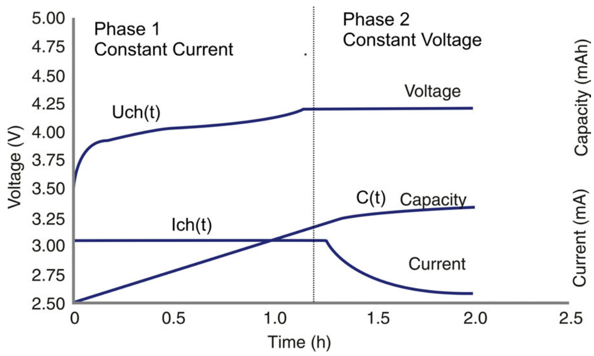

Fig. 2

A specific feature is the existence of two regions of the characteristic. The capacity increases linearly with the time in the first region. This region is characterized by a constant charge current and fast battery charging. During the second phase, the capacity reaches its nominal value, but the process is slower compared with the first phase. The capacity dependence on the work cycles is presented in Fig 3. It is approximated in the model and used for capacity determination for a given cycle number.

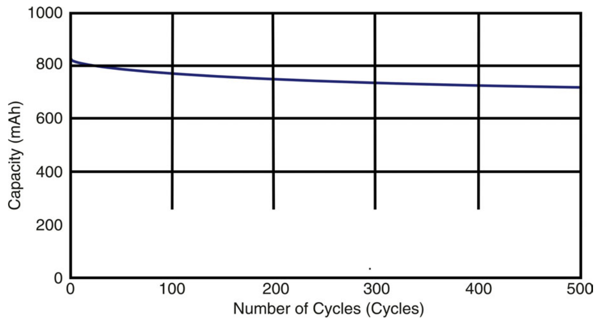

Fig. 3

2. PSPICE BEHAVIORAL MODEL

The proposed macromodel is constructed in accordance with the input language of the *OrCAD PSpice* simulator. The elements from the behavioral modeling library *ABM.lib*, as well as from the libraries *Source.lib* and *Breakout.lib*, are used.

2.1 Behavioral model parameters

The advantage of this model is its parameterization. All model parameters are defined by the **.param** statement. Table 1 references the used parameters.

The charge voltage, current and capacity parameters can be obtained from a battery datasheet. The cycle coefficient can be obtained by linear first order polynomial model of the characteristic given in Fig. 3.

2.1 Behavioral model description

The computer *PSpice* model is constructed using voltage controlled voltage source (VCVS) of **Evalue** type, tabular defined voltage sources of **Etable** type for the describing the battery behavior: voltage $U_{ch}(t)$ and capacity $C(t)$.

Table 1

Parameter	Description	Dimension
voltage_lo	Charge voltage low reference value	[V]
voltage_hi	Charge voltage high reference value	[V]
current_hi	Charge current low reference value	[A]
current_lo	Charge current high reference value	[A]
capacity_hi	Battery nominal capacity	[Ah]
capacity_lo	Battery capacity low reference value	[Ah]
cycles	Number of work cycles (charge/discharge)	–
kn	Cycle coefficient	–
ku#	Charge voltage polynomial coefficient	–
ki#	Charge current polynomial coefficient	–
cap#	Battery capacity polynomial coefficient	–

The charge current $I_{ch}(t)$ is modeled using dependent sources of **Gvalue** and **Gtable** type. The voltage controlled switches are modeled using the **Vswitch** model.

*Charge voltage model.*Two phases are defined in the voltage behavior. In the first phase the voltage is characterized by a nonlinear dependence and the current is constant. When the voltage reaches the **voltage_hi** it is limited to that value. The charge voltage value is used to control the **Vswitch** model. When the voltage reaches a specified maximal value, the sources describing the current and capacity behavior, are switched by voltage controlled switches. Three dependent voltage sources of **Evalue** type (e1, e2 and e3) are used for the charge voltage modeling. This voltage source network shown in Fig. 4 enables the full parameterization of the charge voltage $U_{ch}(t)$, by scaling the data.

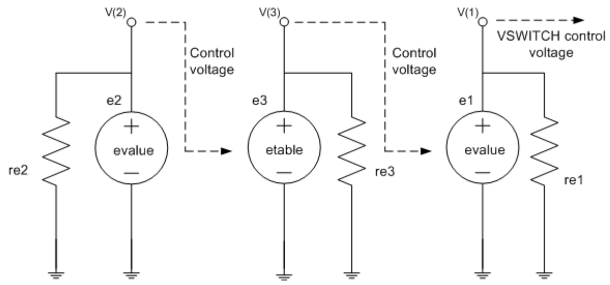

Fig. 4

*Battery capacity model.*The capacity behavior is modeled in two phases. The first phase is characterized by a constant current. The capacity is modeled by a source with a linear dependence on the time. The transfer from the first charging phase to the second – constant voltage – is realized using an ideal switch, controlled by the voltage $U_{ch}(t)$. The capacity model in this phase uses the parameters **capacity_hi** and **capacity_lo**. For the full parameterization, three sources are used with a linear dependence of time. The capacity modeling network is shown in Fig. 5. The capacity value is modified by the correction coefficient obtained from the dependence shown in Fig. 3.

Voltage controlled switch model. The voltage controlled switches use the **Vswitch** model. They are represented by resistance values for **on** and **off** state and threshold voltages **Von** and **Voff**.

The control voltage for this switches is $U_{ch}(t)$. The switches **S_se1a** and **S_se2a** are used to separate the two-phase charge process. Initially **S_se1a** is **on**. It remains on until the voltage reaches the **Von** value. **S_se2a** has the opposite behavior to **S_se1a.**

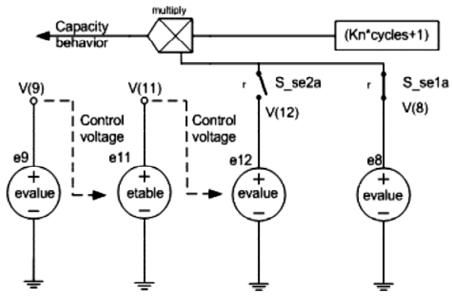

Fig. 5

Charge current model. In the second phase, the voltage is constant and the current is characterized by a nonlinear dependence on the time. The charge current modeling is achieved using two current sources. The battery current depends on the battery voltage in the given time point. The current is constant when $U_{ch}(t_n) < voltage\_hi$. In this phase the current is modeled by an independent current source – **i1**. Its value is defined by the model parameter **current_hi**. When the charge voltage reaches its maximal value **voltage_hi,** the constant current source is switched off, and a current source *g3* of **gvalue** type is applied to the output. It models the nonlinear charge current behavior using a polynomial of order 3. The model is presented in Fig. 6.

2.2 Behavioral model implementation

The voltage, capacity and current behavior is modeled by polynomial expressions with argument time and limiter elements. Datasheets for a number of lithium ion batteries are used to obtain the polynomial coefficients. The characteristic curves for the current, voltage and capacity, as well as the dependence $C(cycles, t)$ are analyzed and approximated using the MATLAB™ Curve Fitting Toolbox™ [3]. Data sets are generated using 4 to 6 data points from the datasheet performance curves. The polynomials are in the form:

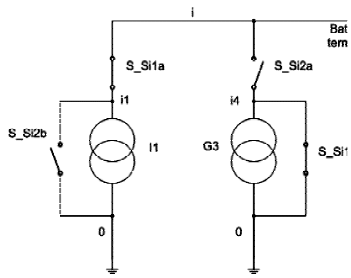

Fig. 6

$$y = \sum_{i=1}^{n+1} p_i x^{n+1-1} \qquad (1)$$

where n is the order of the polynomial. Polynomials of order 3 give the optimal results in this case.

Charge mode 1C. The data fit for the charge voltage is shown in Fig 7. The fitted data polynomial is obtained in the form:

$$U_{ch}(t) = p_1 t^3 + p_2 t^2 + p_3 t + p_4\,; \quad p_1 = 0{,}5431; p_2 = -1{,}064; p_3 = 0{,}9329, p_4 = 3{,}748 \quad (2)$$

The fitted data polynomial coefficients are given as parameters $ku\#$ in the model. The voltage source **e2** in Fig.4 is modeled with the polynomial equation (2). The capacity sources **e8** and **e9** in Fig. 5 are modeled with first order polynomials. The battery capacity curve is linear in the first charge phase (constant current) and can be accepted for linear in the second charge phase (constant voltage). The capacity polynomials are obtained in the form:

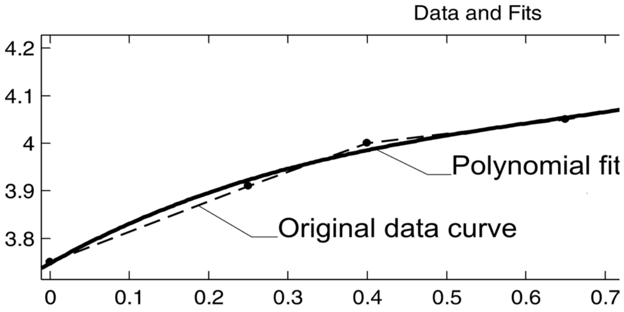

Fig. 7

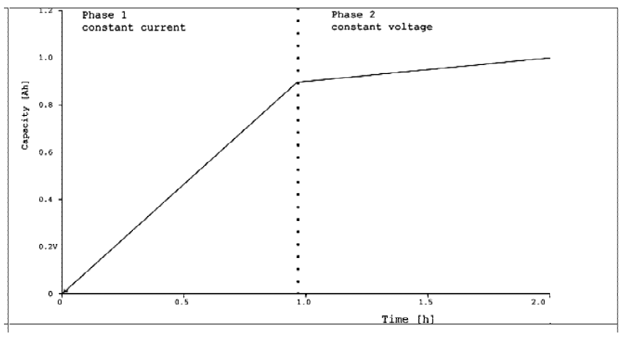

Fig. 8

$C_{e8}(t) = p_1 t$; $p_1 = 0{,}93$, $C_{e9}(t) = p_1 t + p_2$; $p_1 = 0{,}1$; $p_2 = 0{,}8$

The simulation results are represented in Fig.8.The fitted data polynomial coefficients are given as parameters *cap#* in the model.

The charge current sources **i1** and **g3** (Fig. 6) model the current behavior. The source **i1** is a constant current source of value **current_hi**. The source **g3** is a polynomial of order 3:

$$I_{ch}(t) = p_1 t^3 + p_2 t^2 + p_3 t + p_4 \quad ; \quad p_1 = -0{,}256; p_2 = 1{,}781; p_3 = -4{,}273; p_4 = 3{,}565$$

The simulation results are represented in Fig.9.

An approach is used where the current voltage and capacity values are scaled to the range [0,1]. After limiting block, the signal is recovered to the original limits **voltage_hi, voltage_lo, current_hi, current_lo, capacity_hi** and **capacity_lo**. In this way, a parametrization of the limit block is achieved. The approach is illustrated in the following model fragment, describing the charge voltage behavior:

```
e2 2 0 value={(ku3*time*time*time+ku2*time*time+ku1*time+ku0)}
e3 3 0 table {(V(2)-vlo)/(vhi-vlo)} (0 0) (1 1)
e1 1 0 value={V(3)*(vhi-vlo)+vlo}
```

3. SIMULATION RESULTS

The model is simulated in the *PSpice* simulator. The *Probe* waveforms for the charge current, the charge voltage and capacity behavior for different work cycles, are represented in Fig. 10, Fig. 11 and Fig. 12 correspondingly.

3.1 Model Simulations

Fig. 12 presents the modeling of capacity versus cycles. The capacity curves for 0, 250 and 500 cycles are shown in the picture. The error estimation is performed by the analysis of the provided data and fitted model. The relative error is $\varepsilon_y = \left|1 - \hat{y}/y\right|.100$, where y is the response value and $\hat{y}$ is the predicted response value. The obtained maximal relative error is $0{,}1\%$.

The R-square estimation is also obtained in the form: $R_{square} = 1 - SSE/SST$, where $SSE = \sum_{i=1}^{n} w_i (y_i - \hat{y}_i)^2$; $SST = \sum_{i=1}^{n} w_i (y_i - \overline{y})^2$, w_i are weighting coefficients and $\overline{y}$ is the mean value.

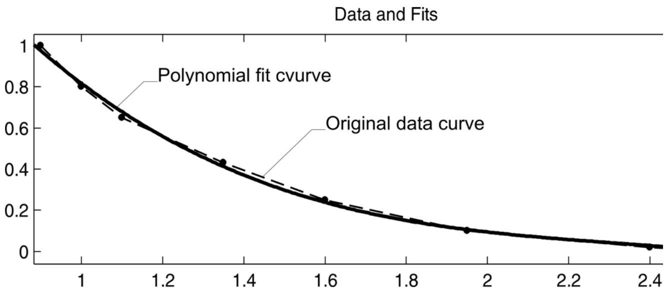

Fig. 9

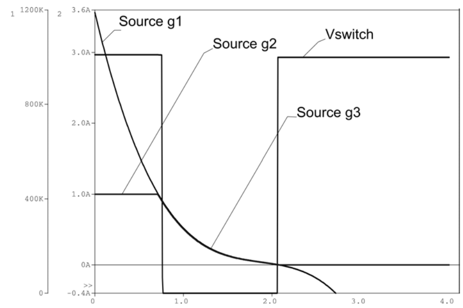

Fig. 10

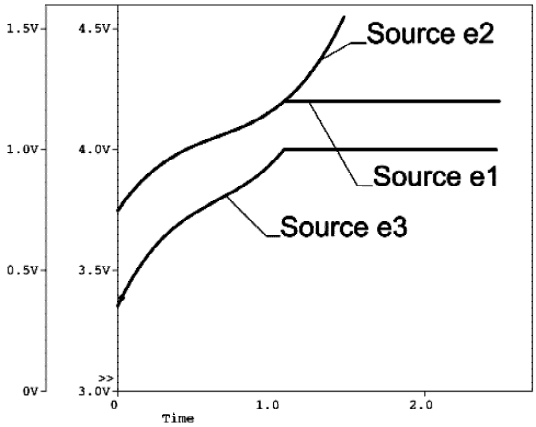

Fig. 11

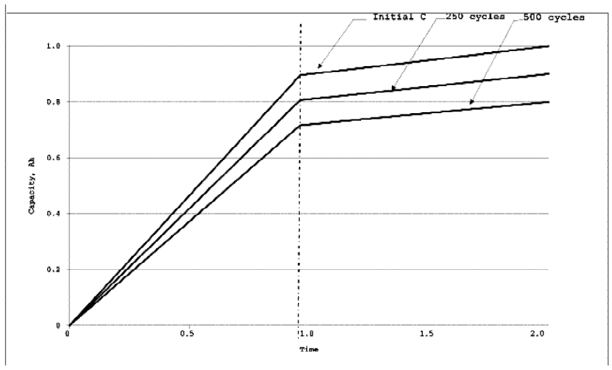

Fig. 12

The *R-square* measure is between 0 and 1. The value closer to 1 indicates a better fit. The obtained results for *R-square* and *SSE* are represented in Table 2.

Table 2

Parameter	SSE	R-sqare
Charge voltage	0.00040381	0.99683
Charge current	0.0023198	0.99768

4. CONCLUSION

The proposed macromodel can be used in simulation of power management systems or battery status monitor systems. The proper charge curve modeling allows the problem detection in such systems. The model accuracy in respect with the input data and battery characteristics is investigated. The relative errors are in the range of 1%. The macromodel gives the ability to share data with such discharge model and to close the work cycle investigation of the lithium ion battery. Other important battery performance characteristics can be modeled like capacity versus time and temperature dependence of the charge process. The only requirement is an accurate datasheet data provided from the manufacturers.

REFERENCES

[1] F. Hans, *Compact models (SPICE) of Li-ion(-polymer) batteries from First Principles*, Philips research presentation, 1998.

[2] Buchmann I., *Batteries in a portable world*, online edition http://www.buchmann.ca.

[3] *Curve Fitting Toolbox User Guide*, MathWorks