Modeling Lithium-ion Battery Chargers in PLECS®

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1 Introduction

Lithium-ion (Li-ion) batteries play an integral part in electrical systems such as those in electric vehicles, cordless power tools, and energy storage systems. During the design phase of these systems, engineers develop, tune, and benchmark the performance of different control strategies and circuits in a simulation environment like PLECS. Li-ion batteries are often modeled as ideal constant voltage sources in these circuits. However, as the battery is charged and discharged, the current and voltage (I-V) of the battery changes. These effects are not reflected in the models with a constant voltage source. To optimize the overall system performance, the I-V characteristics of the battery must be considered [1]. Further, these models can be used to benchmark different charging and State of Charge (SOC) estimation algorithms at the system level.

This report describes two circuit-based Li-ion cell models. The models' advantages and limitations are explored. A battery pack is developed using the cell model and connected to the output of a buck converter. An average model of the buck converter is then developed, and the advantages and disadvantages are investigated. Finally, simulation results for a buck converter charging a Li-ion battery pack with a constant current, constant voltage (CCCV) charging algorithm are shown.

2 Li-ion Models

The battery's voltage varies as it is charged and discharged, exhibiting a nonlinear relationship with the battery's SOC. Thus it is important that the model reflects the voltage change as the battery SOC also varies.

Li-ion battery models can be divided into three main categories: electrochemical, mathematical, and electrical. Electrochemical models consist of solving large systems of partial differential equations. These models are very accurate and primarily utilized when designing the battery packaging. However, simulation of these models can be quite time consuming, as it requires solving a complex set of equations [2].

An alternative modeling type is based on empirical formulas or stochastic approaches. These mathematical models can be used to predict battery run time, efficiency or capacity. However, they can not provide the I-V characteristics that are critical for design and optimization of power electronic systems [2].

Circuit-based or electrical models, are capable of accurately exhibiting the I-V characteristics of the Li-ion batteries while maintaining simulation efficiency. These models are based on resistors and capacitors connected to controlled voltage sources. Two such models are discussed below:

2.1 RC-chain-based Li-ion model

The voltage as a function of SOC of a Li-ion battery exhibits the characteristics in Fig. 1. This characteristic can be captured using controlled voltage sources where the voltage is determined as a function of SOC.

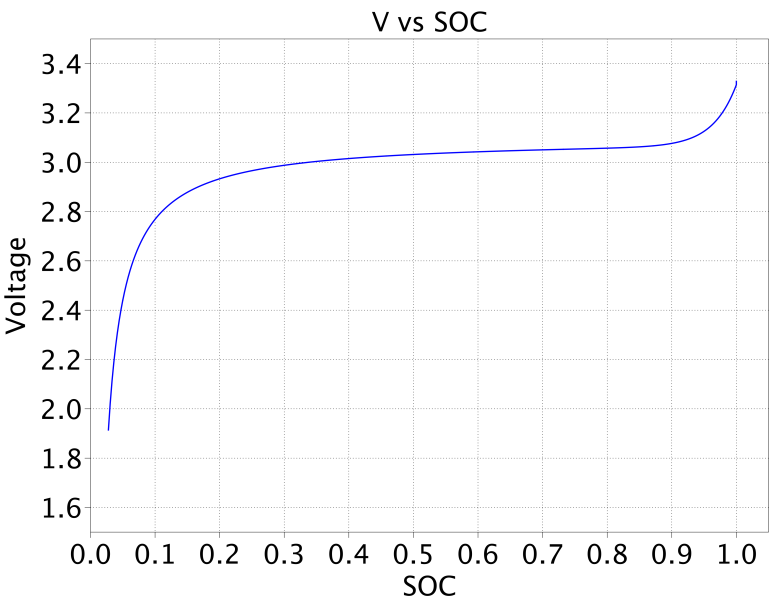

Fig. 1: Voltage as a function of SOC.

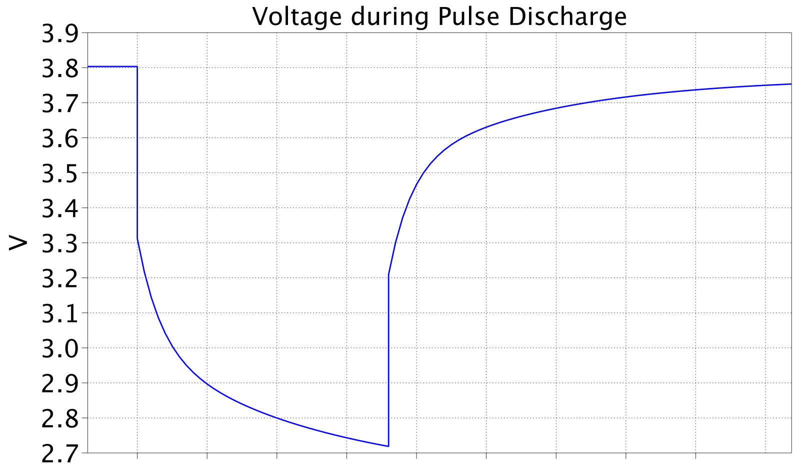

Fig. 2: Transient response to a step change in load current (Fig. 3(e) in [2]).

Additionally, studies show that for a load step in current, the battery exhibits an instantaneous voltage drop and a transient with both slow and fast time constants, as in Fig. 2. These characteristics are related to the electrochemical properties of the battery and can be modeled using two RC-chain networks to capture the slow and fast time constants. A series-connected resistor captures the instantaneous voltage drop.

The Li-ion electrical model proposed in [2] consists of a SOC-dependent electrical circuit, as shown in Fig. 3. The two RC-chain models provides a good balance between simulation accuracy and model complexity [3]. Additional RC chains can be used to improve the accuracy, however, this adds to the model's complexity and adversely affects the simulation speed.

2.1.1 Li-ion cell

The circuit parameters are related to their respective electrochemical processes [4].

- R1: Bulk resistance of the cell accounting for the electrolyte, separator, and electrodes.
- RC1: Resistance and capacitance of the surface film layer of the electrodes; represents the high-frequency impedance.

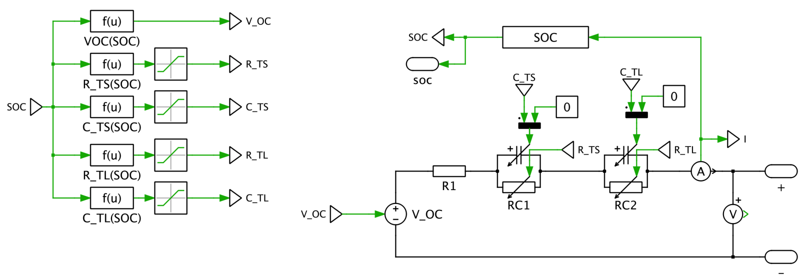

Fig. 3: RC-chain-based electrical Li-ion cell model.

- RC2: Resistance due to the low diffusion rate and capacitance because of the Li-ion cell's double layer capacitance.
- V_{OC}: Open circuit cell voltage.

The parameters for the electrical circuit change as a function of SOC. Variable resistances and capacitances along with a controlled voltage source, are used, along with equations 2 - 7 in [2], to model a one polymer Li-ion cell.

2.1.2 Advantages and disadvantages

The RC chains enable battery transient behavior modeling during load current step change. However, to determine the SOC-dependent parameters (V_{OC}, R1, RC1 and RC2), extensive tests must be conducted on the battery of interest.

Chapter 2 in [5] describes the experimental setup and tests conducted to obtain data for an A123 APR19650m1 LiFePO4 battery with a nominal capacity of 1.1 Ah. These experiments can be expensive and time consuming. After the data is gathered, the author in [5] used the Matlab Simulink Design Optimization toolbox to extract the parameters for the model. Once the parameters are determined as a function of the SOC, look-up tables may be used. However, care must be taken as these look-up tables may introduce numerical instability when simulating electrical circuits. The approach taken in [2] to fit continuous functions to the parameters ensures the parameters are smooth, continuously differential functions of SOC, reducing the occurrence of numerical instabilities due to the battery.

Additionally, when used in system level simulation of power electronic systems, this implementation contributes its time constants to the overall system. The system may become extremely stiff and overall simulation speed may decrease. Finally, the model assumes the following:

- Battery capacity is unchanged (no Peukert effect).
- Temperature has no effect on the model's behavior.
- Self-discharge of the battery is not considered.
- The battery has no memory.

Further extensions must be made to capture the effects above. However, this increases model complexity and results in slow simulation speeds.

2.1.3 Li-ion battery pack model

The cell model described above can be used as a basic building block for a larger battery pack. One way to implement a battery module is to connect multiple cells in series and parallel in the desired configuration. However, packs consist of hundreds of cells and this configuration can result in extremely slow simulation without adding much value overall.

An alternative is to use the implementation in Fig. 4. It assumes the cells in the pack are evenly charged and discharged during simulation. Battery terminal current is measured and scaled down by the number of parallel branches in the pack to determine the current through each cell. Cell terminal voltage is then scaled by the number of series cells in the pack to determine the pack terminal voltage. Metallic contact resistance is represented by a simple resistance and is assumed to be constant.

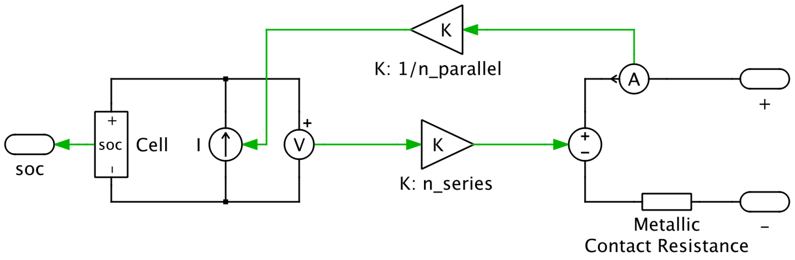

Fig. 4: Li-ion pack model for RC-chain based cell model.

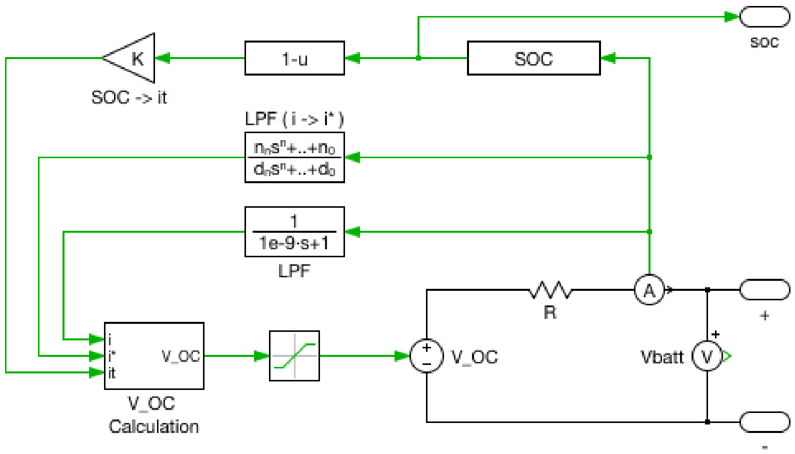

Fig. 5: R-only based electrical Li-ion cell model.

The implementation of this model requires detailed extraction of the battery parameters. For this study, the one-polymer Li-ion cell model proposed in [2] is implemented. To model another battery, the user must obtain the parameters over a wide range of SOC by gathering experimental data or from the manufacturer. Fitting functions must then be derived for each parameter to be reflect changes in these parameters as battery SOC changes.

2.2 R-only Li-ion model

The RC-chain-based battery model provides an electrical model that can be used to accurately reflect battery transient behavior with a current load step. However, there remain a number of challenges associated with this model. A major issue is the extraction of the parameters using experimental or manufacturer data, which may not be available. An R-only based model proposed in [6] and extended in [7], uses information on battery data sheets to implement the non-linear I-V relationship exhibited by Li-ion batteries.

The model proposed in [6] implements a Li-ion electrical circuit where V_{OC} is derived as a function of SOC. However, this representation is only valid with constant current; it exhibits inaccuracies when battery current varies. In [7] the model was further extended to accurately reflect battery behavior with variable current. Fig. 5 illustrates the R-only electrical circuit model for Li-ion cells where V_{OC} is derived as described in [7]. V_{OC} is determined as a function of SOC and filtered current. A second low-pass filter with a faster transient is also used to avoid an algebraic loop while at the same time indicating whether the battery is charging or discharging.

2.2.1 Li-ion cell

The equation governing battery V_{OC} during discharge is:

$$V_{OC,discharge} = E_0 - K * (\frac{Q}{Q-it}) * it - K * (\frac{Q}{Q-it}) * i^* + A * e^{-B*it}$$

During the charging process, V_{OC} is given by:

$V_{OC,charge} = E_0 - K * (\frac{Q}{Q-it}) * it - K * (\frac{Q}{it-0.1*Q}) * i^* + A * e^{-B*it}$, where the terms are:

- $V_{OC,charge/discharge}$ - no load voltage [V].
- E_0 - battery constant voltage [V].
- K - polarizing voltage/resistance factor [V].
- Q - battery capacity [Ah].
- it - actual battery charge [Ah].
- i^* - filtered battery current [A].
- A - exponential zone voltage amplitude [V].
- B - exponential zone time constant inverse [Ah]$^{-1}$.

The R-only model can be derived using three points on the V as a function of Charge curve. These points are taken when the battery is fully charged, where the exponential, and nominal zones end (see Fig. 1 in [7]). The factors of interest and their values for an A123 Li-Iron-Phosphate ANR26650M1B are:

- V_{full} - fully charged voltage ($3.3\ V$).
- V_{exp} - voltage at end of exponential zone ($3.05\ V$).
- Q_{exp} - charge depleted at end of exponential zone ($0.25\ Ah$).
- V_{norm} - voltage at end of nominal zone ($2.9\ V$).
- Q_{norm} - charge depleted at end of nominal zone ($2.1\ Ah$).

The resultant curve for discharge at $1\ C$ rate is shown in Fig. 6. The factors K, A, B, and E_0 used in determining V_{OC} are:

- $A = V_{full} - V_{exp}$
- $B = \frac{3}{Q_{exp}}$
- $K = \frac{(V_{full} - V_{norm} + A*(e^{-B*Q_{norm}} - 1)*(Q - Q_{norm})}{Q_{norm}}$
- $E_0 = V_{full} + K + R * i_{1C-rate} - A$

2.2.2 Advantages and disadvantages

The R-only model does not consider the short and long transient time constants associated with the step in load current, in contrast with the RC-chain-based implementation. Additionally, it assumes the following [6] :

- The internal resistance is constant during charge and discharge.
- Battery capacity is unchanged (no Peukert effect).
- Temperature has no effect on the model's behavior.
- Self-discharge of the battery is not considered.
- The battery has no memory.

Further extensions need to be made to capture the effects above. They contribute to a more complex model and adversely affect simulation speed. However, the R-only implementation can accurately reflect the macro-level *I*-*V* [7] characteristics that are important for system level simulations. The great advantage of this model is the ease of implementing the Li-ion battery of interest using information on the battery data sheet. This avoids the need to obtain data from manufacturers or in the lab. The R-only implementation results in faster simulation speeds as it doesn't contribute the time constants associated with the RC chains.

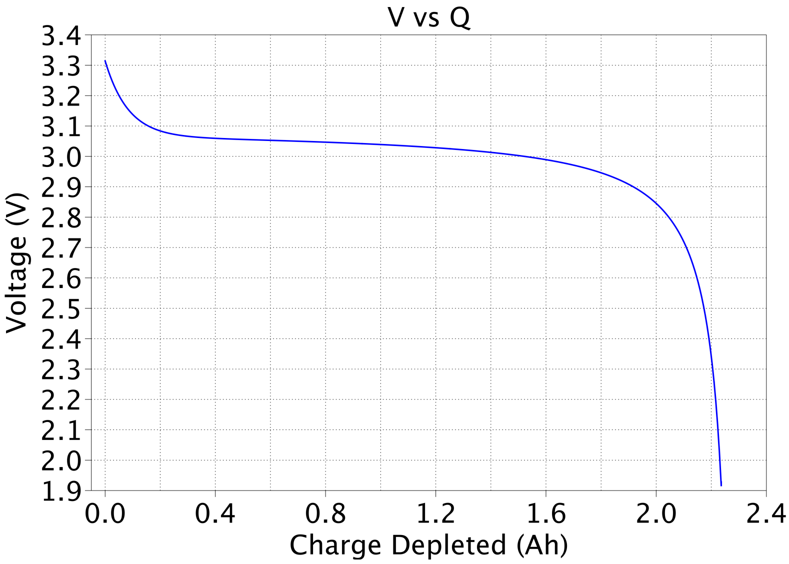

Fig. 6: Voltage as a function of depleted charge.

2.2.3 Li-ion battery pack model

The R-only model can be extended to model a battery pack by scaling the quantities as follows:

- $V_{OC,pack} = N_{series} * V_{OC,cell}$
- $V_{norm,pack} = N_{series} * V_{norm,cell}$
- $V_{exp,pack} = N_{series} * V_{exp,cell}$
- $R_{pack} = \frac{N_{series}}{N_{parallel}} * R_{cell}$
- $Q_{capacity,pack} = N_{parallel} * Q_{capacity,cell}$
- $Q_{norm,pack} = N_{parallel} * Q_{norm,cell}$
- $Q_{exp,pack} = N_{parallel} * Q_{exp,cell}$

This pack model again assumes the cells are evenly charged and discharged.

3 Converter Modeling

Li-ion batteries are connected to converters operated at switching frequencies ranging from a few kilohertz to a few hundred kilohertz. Depending on the charge/discharge current and the battery pack capacity, the battery may need to be charged for hours (simulation time). To simulate these systems for an hour of simulation time, with full switching and digital controls, will result in several hours of real-time simulation. The solver will be forced to take time steps that are even smaller than the switching period, often in the μs scale. By using averaged models of the converter and continuous controls, the same simulation can be run in seconds.

In this study a buck converter is used to step down a $60\ V$ input to charge the battery with a CCCV charging algorithm. The averaged model of the buck converter was derived as:

$\overline{I_L} = \int \frac{D*V_{in}-V_{out}}{L}\,\mathrm{d}t$

$I_{out} = \overline{I_L}$

$I_{in} = D * I_{out}$

The PLECS model to implement an averaged buck converter is shown in Fig. 7. The implementation is realized using voltage measurements and injecting currents with controllable current sources. The converter also includes the effects of a resistor connected in series to the inductor in the buck converter.

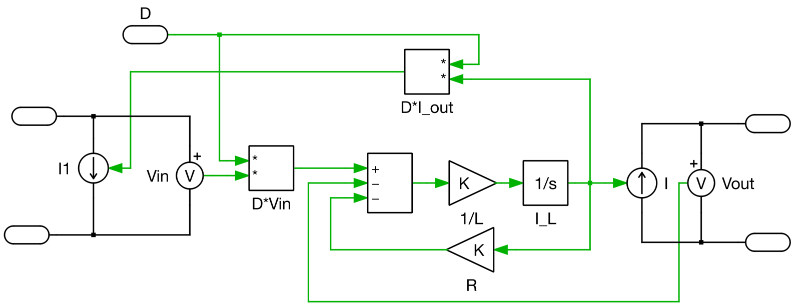

Fig. 7: Average model implementation for a buck converter.

The averaged model of the converter allows fast simulation of the charging circuit. However, it is severely limited as switching effects are no longer captured. Additionally, continuous controls must be adopted to maintain the simulation speed. The addition of digital control strategies would introduce sampling times based on execution frequency of the control loops. The averaged modeling of converters is useful when developing high level algorithms (such as SOC estimation). However, fully switched models are needed when system losses and component sizing are of interest.

4 Simulation Results

Two simulation models are provided. Both models implement a buck converter with closed-loop control using a CCCV charging algorithm. Additionally, both simulations include a battery pack to model a 10 series and 10 parallel cell system. One of the models implements the RC-chain-based Li-ion model proposed in [2]. The other implements the R-only Li-ion model for an A123 Li-Iron-Phosphate ANR26650M1B. Further, each model can be operated either in fully switched mode with digital controls or with an averaged model for the buck converter and continuous controls.

The simulation is configured to operate for 3 seconds in fully switched mode with digital controls by setting the SimSetup variable to 0, in the Initialization tab. Running the R-only model, the battery SOC increases slightly over this time. The battery is charged at a constant current of about $13.8\ A$ for the 3 seconds. This 3 second simulation takes 25 seconds in real time. The same operating mode is available for the RC model. In this case, the 3 second simulation takes 47 seconds in real time. The added complexity from the two RC chains contributes to the longer simulation time.

The simulation is configured to operate for 4.5 hours of simulation time with continuous control and the averaged model implementation of the buck converter by setting the SimSetup variable to 1, in the Initialization tab. In both models, the CCCV charging algorithm is demonstrated. The battery is initially charged using constant current as battery voltage slowly increases. At a certain point, the constant charging voltage limit is reached and charging current is slowly decreased to maintain battery terminal voltage at the constant voltage. After the battery reaches 90% SOC, the charger is turned off by setting the controller duty cycle to zero. The 4.5 hour simulation is completed in less than 0.5 seconds in real time for both the R-only and RC models. Fig. 8 shows the simulation result for the R-only Li-ion model with the averaged model of a buck converter and continuous controls.

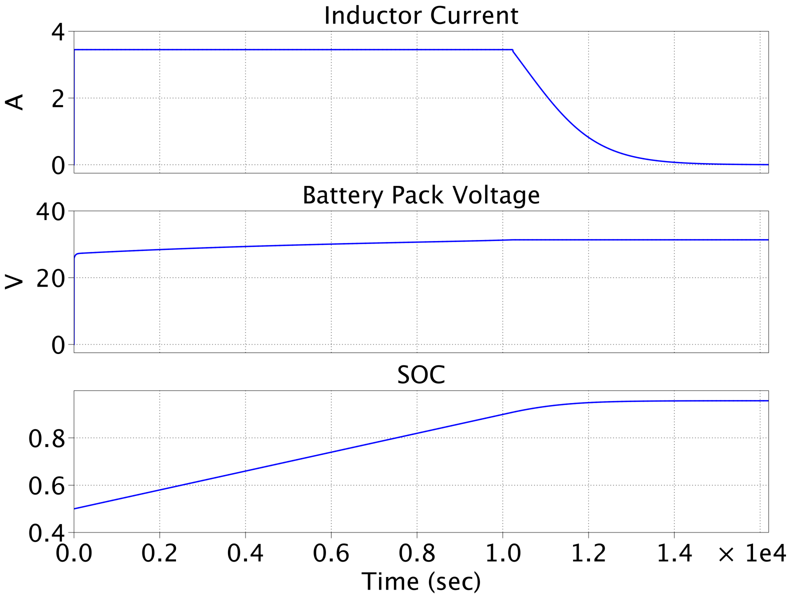

Fig. 8: Simulation results for CCCV charging of Li-ion battery pack. The averaged model of a buck converter with a continuous controller is used on an R-only Li-ion model.

Appendices

A Simulation Files - PLECS Blockset

Example files used for simulating different battery cell models in PLECS Blockset accompany this application note:

Li_ion_RCModel.mdl: This demonstration shows the CCCV charging of a Li-ion battery pack modeled with an RC chain. The simulation is designed to be run either in fully-switched mode by setting the SimSetup variable in the Initialization tab to zero, or average switched mode by setting the SimSetup variable to 1.

Li_ion_RCModel_init.m: This final initializes the parameter values for the above model.

Li_ion_RonlyModel.mdl: This demonstration shows the CCCV charging of a resistor-only Li-ion battery pack model. The simulation is designed to be run either in fully-switched mode by setting the SimSetup variable in the Initialization tab to zero, or average switched mode by setting the SimSetup variable to 1.

Li_ion_RonlyModel_init.m: This final initializes the parameter values for the above model.

B Simulation Files - PLECS Standalone

Example files used for simulating different battery cell models in PLECS Standalone accompany this application note:

Li_ion_RCModel.plecs: This demonstration shows the CCCV charging of a Li-ion battery pack modeled with an RC chain. The simulation is designed to be run either in fully-switched mode by setting the SimSetup variable in the Initialization tab to zero, or average switched mode by setting the SimSetup variable to 1.

Li_ion_RonlyModel.plecs: This demonstration shows the CCCV charging of a resistor-only Li-ion battery pack model. The simulation is designed to be run either in fully-switched mode by setting the SimSetup variable in the Initialization tab to zero, or average switched mode by setting the SimSetup variable to 1.

References

[1] L. Benini, G. Castelli, A. Macii, E. Macii, M. Poncino, and R. Scarsi, “Discrete-time battery models for system-level low-power design,” *IEEE Transaction on Very Large Scale Integration (VLSI) Systems*, 2001.

[2] C. Min and G. Rincon-Mora, “Accurate electrical battery model capable of predicting runtime and i-v performance,” *IEEE Transactions on Energy Conversion*, vol. 21, no. 2, pp. 504 – 511, June 2006.

[3] H. Zhang and M.-Y. Chow, “Comprehensive dynamic battery modeling for phev applications,” *2010 IEEE Power and Energy Society General Meeting*, 2010.

[4] L. Lam, P. Bauer, and E. Kelder, “A practical circuit-based model for li-ion battery cells in electric vehicle applications,” *IEEE 33rd Int. Telecommun. Energy Conf. (INTELEC)*, pp. 1–9, 2011.

[5] J. Issac, “Modeling and state of charge estimation of li-ion batteries for vehicular applications,” Master’s thesis, Purdue University, 2013.

[6] O. Tremblay, L.-A. Dessaint, and A.-I. Dekkiche, “A generic battery model for the dynamic simulation of hybrid electric vehicles,” *Vehicle Power and Propulsion Conference*, 2007.

[7] O. Tremblay and L.-A. Dessaint, “Experimental validation of a battery dynamic model for ev applications,” *World Electric Vehicle Journal*, 2009.