Modeling a Lithium-Ion Cell using PLECS®

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1 Introduction

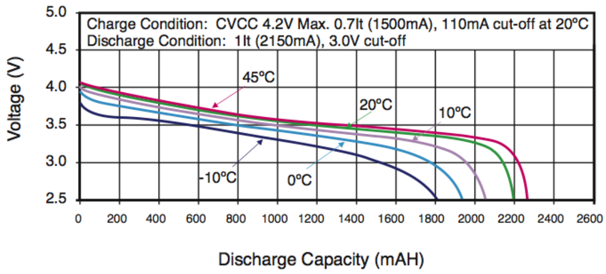
Lithium-ion cells have become a ubiquitous technology in portable electronic devices and electric vehicles due to their high energy density and low maintenance requirements.

A lithium-ion cell exhibits a range of electrical changes that are observable over a time range from seconds to years. Short-term effects that occur in the order of milliseconds to seconds are typically voltage and current transients due to a step change in load. In this time frame, the internal cell voltage and operating temperature can be assumed to be constant.

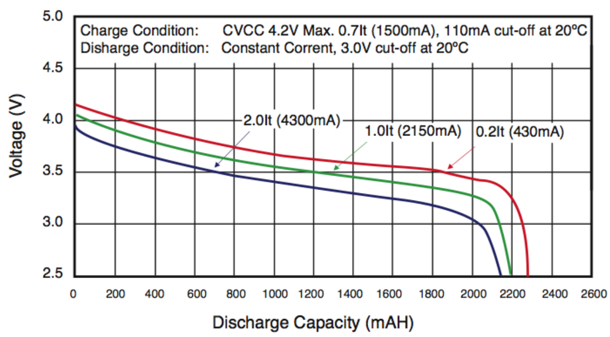
In the medium-term time range of seconds to hours, the dependence of cell voltage on state of discharge (SOD) and temperature can be observed. In the long-term time range that extends from days to years, the effect of storage temperature and cycling on the cell lifetime is important.

In this report, an electrical and thermal model of a lithium-ion cell that models medium-term effects is presented. An example simulation model that is based on a CGR18650CG 3.6V 2250mAh Panasonic cell is derived. The medium-term effects are directly observable from the manufacturer's datasheet, making derivation of the model a straightforward process. The behavior of the CGR18650CG cell is depicted in Fig. 1. It can be seen when the battery is fully charged, the output voltage is approximately $4.1\ \mathrm{V}$. During discharge, the output voltage decreases in an approximately linear fashion until the energy has been depleted. At this point the output voltage sharply declines. Below $3.0\ \mathrm{V}$, the cell can be assumed to be empty and must be recharged.

Fig. 1(a) shows that temperature changes have two effects. One effect is to decrease the final discharge capacity and the other is to decrease the cell output voltage. Discharge rate effects, shown in Fig. 1(b), show that increasing the discharge rate decreases the discharge capacity or final SOD. The output voltage differences on this graph are due to the voltage drop across the internal resistance of the cell.



(a) Effect of temperature on cell output voltage and final capacity.



(b) Effect of load current on cell capacity (final SOD).

Fig. 1: CGR18650CG lithium-ion cell discharge curves. (Source: Panasonic Data Sheet, December 2008)

2 Lithium-Ion Cell Model

The PLECS lithium-ion cell model is similar to the behavioral model of a lithium-ion cell presented in [1]. A reference internal voltage is modeled for a fixed temperature and discharge rate and correction factors are applied to account for the influence

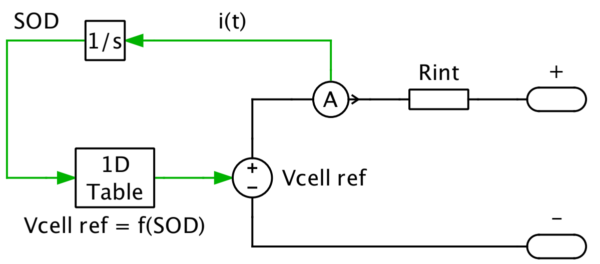


Fig. 2: Lithium-ion conceptual model.

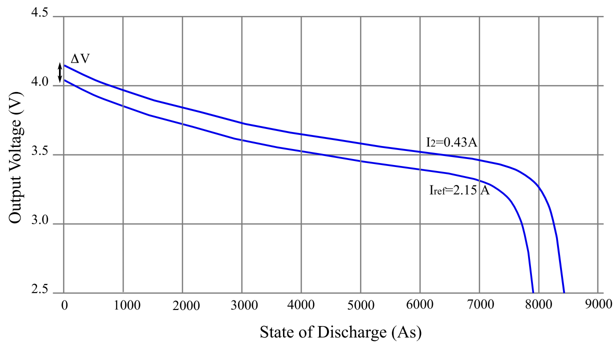


Fig. 3: Method for calculating of initial internal resistance, R_{int}, from datasheet output voltage curves.

of temperature and discharge rate.

2.1 Model concept

The concept of the lithium-ion cell model is to model the cell using an internal voltage and internal resistance, as shown in Fig. 2. The reference internal cell voltage is a non-linear function of the state of discharge,

$$V_{cell\,ref} = f(SOD) \tag{1}$$

and the state of discharge is calculated by integrating the cell output current,

$$SOD = \int_0^t i(t)\,dt \tag{2}$$

The data for modeling $V_{cell\,ref}$ is based on the output voltage curve measured at $T = 20°C$ and $i(t) = 2.15A$. This curve, referred to as $V_{out\,ref}$, can be seen in Fig. 1(b).

2.2 Internal resistance

To calculate $V_{cell\,ref}$ from $V_{out\,ref}$, the cell internal resistance must be calculated. The initial internal resistance is calculated from the manufacturers voltage curves using:

$$R_{int}\big|_{SOD=0} = \frac{\Delta V}{I_{ref} - I_2}, \tag{3}$$

as depicted in Fig. 3. The resultant value is $0.07\ \Omega$. In many instances it can be assumed that R_{int} is constant because variations tend to be small and the actual value is typically much smaller than the effective load resistance.

2.3 Internal cell voltage

The reference internal cell voltage is calculated by adding a constant internal voltage drop to the reference output voltage curve:

$$V_{cell\,ref} = V_{out\,ref} + I_{ref} R_{int} \tag{4}$$

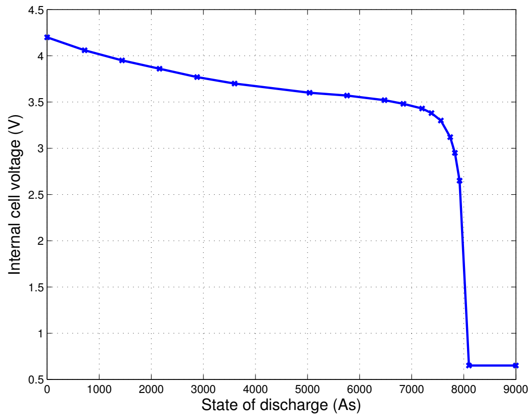


Fig. 4: Data points for modeling reference internal cell voltage, $V_{cell\,ref}$, as a non-linear function of SOD. Reference operating point is $T = 20°C$ and $i(t) = 2.15A$.

The result is a non-linear function $V_{cell\,ref} = f(SOD)$, as shown in Fig. 4. Modeled in PLECS as a one-dimensional lookup table, the function uses linear interpolation to calculate the values for $V_{cell\,ref}$ between the recorded data points.

2.4 Accounting for capacity change

The capacity or final SOD of the cell is affected by changes in discharge current and temperature. The effect of these changes can be modeled by multiplying $i(t)$ in Eq. (2) by a current-dependent rate factor, $k1$, and a temperature-dependent rate factor, $k2$:

$$SOD = \int_0^t k1[i(t)].k2[T(t)].i(t)\,dt$$

The discharge rate factor, $k1$, is calculated from Fig. 1(b) using the final SOD of each output voltage curve:

$$k1[I_n] = \frac{SOD\,final(I_{ref})}{SOD\,final(I_n)} \tag{5}$$

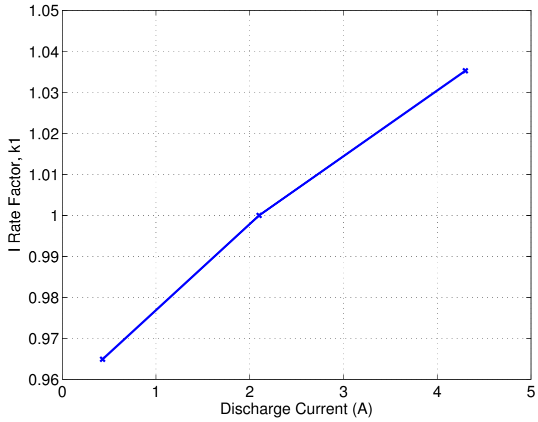


Fig. 5: Discharge rate factor $k1$ vs. output current.

The complete set of results for $k1$ is shown in Fig. 5. The temperature rate factor $k2$ is calculated in a similar fashion from the set of output voltage curves in Fig. 1(a). Since $k1$ and $k2$ are not constant but are dependent on the output current and temperature respectively, they use a lookup table implementation.

2.5 Modeling internal voltage changes

A decrease in temperature not only decreases the capacity, but also decreases the cell voltage. Temperature-dependent voltage changes can be accounted for by adding a temperature-dependent correction factor, $k3$, to the internal voltage.

Thus,

$$V_{cell}(t) = V_{cell\,ref}(t) + k3[T(t)] \tag{6}$$

The voltage correction factor $k3$ is calculated directly from Fig. 1(a) by subtracting the initial voltage of each output voltage curve from the initial voltage of the reference curve:

$$k3[T_n] = V_n(0) - V_{ref}(0) \tag{7}$$

3 Cell Output Interface

The lithium-ion cell voltage calculated in Eq. (6) is converted into a current source that supplies an output capacitor. The current source is calculated using:

$$I_{cell} = \frac{V_{cell} - V_o}{R_{int}} \tag{8}$$

The complete lithium-ion model, shown in Fig. 6, is implemented as a subsystem in PLECS. The output capacitor eliminates state dependency of the current source on the output current, preventing an algebraic loop. The lithium-ion model supports:

- Supply of constant current and constant power loads without the creation of an algebraic loop.
- Direct connection with voltage or current source converters.

The model also supports the implementation of a variable internal resistance for situations where more accuracy is required. The variable internal resistance is dependent on the SOD and should be derived from experimental measurements.

4 Thermal Model

The thermal characteristics of the cell are modeled using the thermal domain modeling capabilities of PLECS. The case is represented with a heat sink and the thermal power flows through an impedance between the case and the environment. The losses collected by the case are due to the power dissipated in the internal resistance. These losses are calculated as follows:

$$P_{int} = \frac{(V_{cell} - V_o)^2}{R_{int}} \tag{9}$$

The top level of the lithium-ion model, depicted in Fig. 7, shows the thermal model of the cell. Multiple terminals can be added to the heat sink to model multiple thermal paths that would be present in battery pack applications.

5 Model Parameters

The model parameters box is shown in Fig. 8. The parameters are described as follows:

- `Cout`: Output capacitance of the lithium-ion cell. This must be greater than zero to allow the connection of constant current and constant power loads to the cell.
- `Vout init`: The initial voltage across the output capacitor.
- Internal resistance, `Rint`: Represented by the vector pair, `SOD, R` and `Rint`. For the fixed resistance model just a single value for `Rint` is required.
- Discharge rate factor, `k1`: Represented by the vector pair, `Irate, xval` and `Irate, k1`.
- Discharge rate factor, `k2`: Represented by the vector pair, `Trate, xval` and `Trate, k2`.
- Voltage correction factor, `k3`: Represented by the vector pair, `Trate, xval` and `Voffset, k3`.

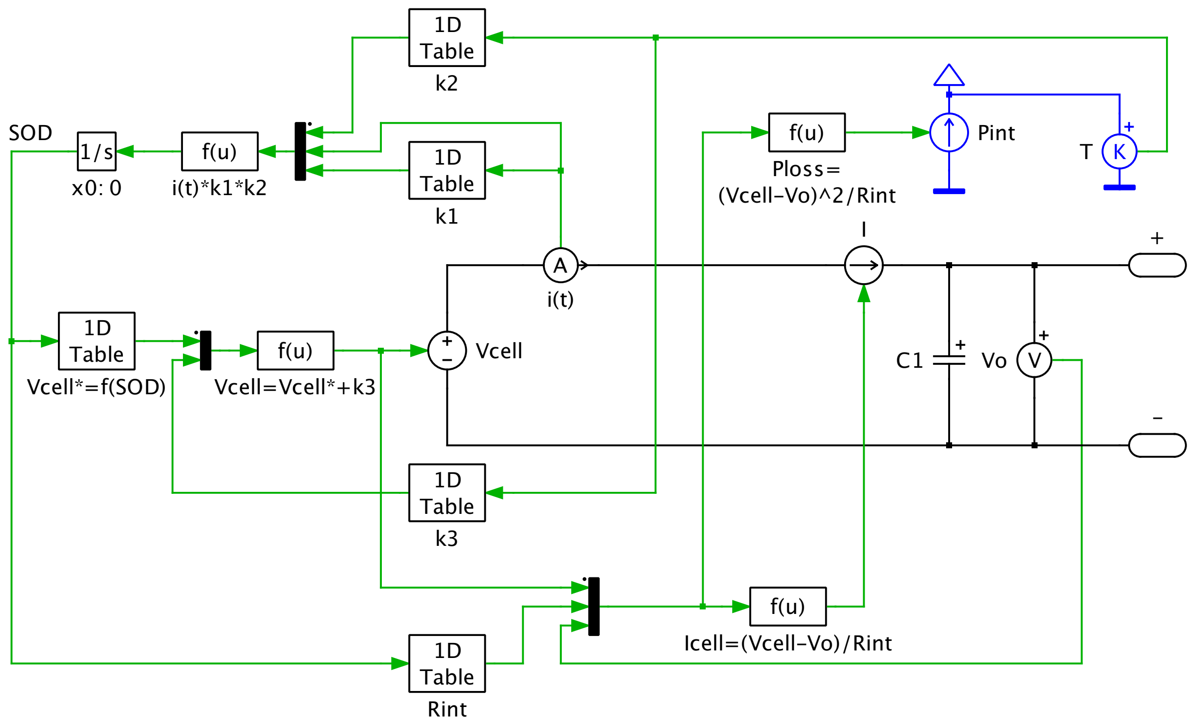


Fig. 6: Complete lithium-ion cell model. Internal losses, P_{int}, are automatically injected into the cell case.

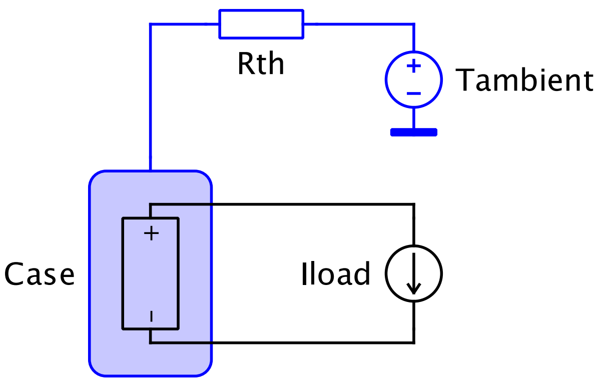


Fig. 7: Thermal circuit showing the heat flow path between the case (heat sink) and environment (Tambient). Multiple terminals can be added to the heat sink for modeling multiple thermal paths in battery pack applications.

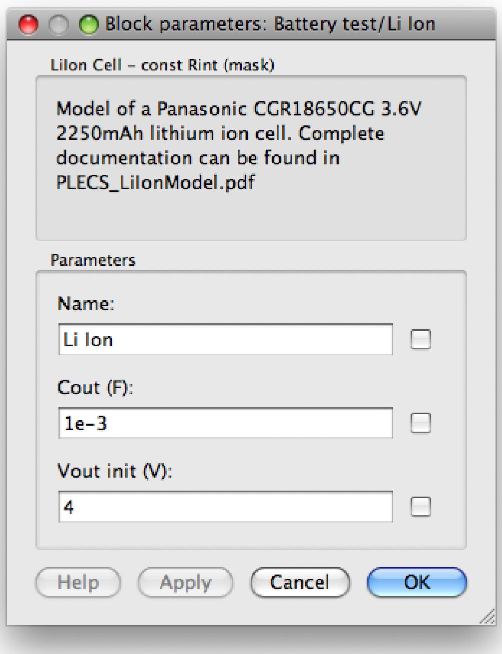


Fig. 8: Lithium-ion model parameters box.

Appendices

A Simulation Files - PLECS Blockset

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

- *Lithium_ion_variable_R.mdl*: The full cell model described in this report with variable internal resistance and the thermal circuit included.
- *Lithium_ion_constant_R.mdl*: A cell model with constant internal resistance and the thermal circuit included. This can be used when the effect of variable resistance is unimportant.
- *Lithium_ion_constant_T.mdl*: A cell model with constant internal resistance and ambient temperature. The thermal circuit of the cell case is not modeled. This model is suitable for straightforward models where just the electrical voltage vs. SOD characteristics are important.
- *CGR18650CG_data.mat*: The matrices containing the data for the CGR18650CG 3.6V 2250mAh Panasonic cell, as provided by the datasheet.
- *plot_CGR18650CG_data.m*: The various plots provided in this report can be visualized by running this function in MATLAB.

B Simulation Files - PLECS Standalone

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

- *Lithium_ion_variable_R.*plecs: The full cell model described in this report with variable internal resistance and the thermal circuit included.
- *Lithium_ion_constant_R.*plecs: A cell model with constant internal resistance and the thermal circuit included. This can be used when the effect of variable resistance is unimportant.
- *Lithium_ion_constant_T.*plecs: A cell model with constant internal resistance and ambient temperature. The thermal circuit of the cell case is not modeled. This model is suitable for straightforward models where just the electrical voltage vs. SOD characteristics are important.
- *CGR18650CG_data.mat*: The matrices containing the data for the CGR18650CG 3.6V 2250mAh Panasonic cell, as provided by the datasheet.

References

[1] L. Gao, S. Liu, and R. Dougal, “Dynamic lithium-ion battery model for system simulation,” *IEEE Transactions on Components and Packaging Technologies*, vol. 25, pp. 495–505, September 2002.