Battery Testing and Equivalent-Circuit Model Parameterization

Wenlin Zhang

Centre of Mechatronics & Hybrid Technologies

October 27, 2022

1. Introduction:

This document serves as a guide to how to perform standard time-domain battery tests, including capacity test, OCV-SOC test, pulse discharge test, and drive cycle test, and fit a n^{th} order equivalent circuit model (ECM) to the obtained data. Section 2 describes each of the tests. Figures in this section are generated using the accompanying data. Section 3 discusses ECM parameterization techniques. Section 4 describes the accompanying data and scripts which can be used to parameterize a ECM for the cell tested. Section 5 provides a summary of this tutorial. The reader is referred to [1] for details on frequency domain testing and model fitting technique utilizing the electrochemical impedance spectroscopy (EIS).

2. Battery Testing Methods:

2.1. Charge

The battery needs to be fully charged before any other tests can be performed. The CC/CV protocol is usually used, where a constant current is applied to the cell until the it reaches the maximum voltage specified by the datasheet. The current is then continuously lowered until it reaches the cut-off current while maintaining the voltage at the maximum voltage. Fig. 1 shows an example charging profile. The values of the charge and cut-off current should be specified in the datasheet. If this information is not available, a charging current of 0.5C and cut-off current threshold of 0.02C can serve as a starting point.

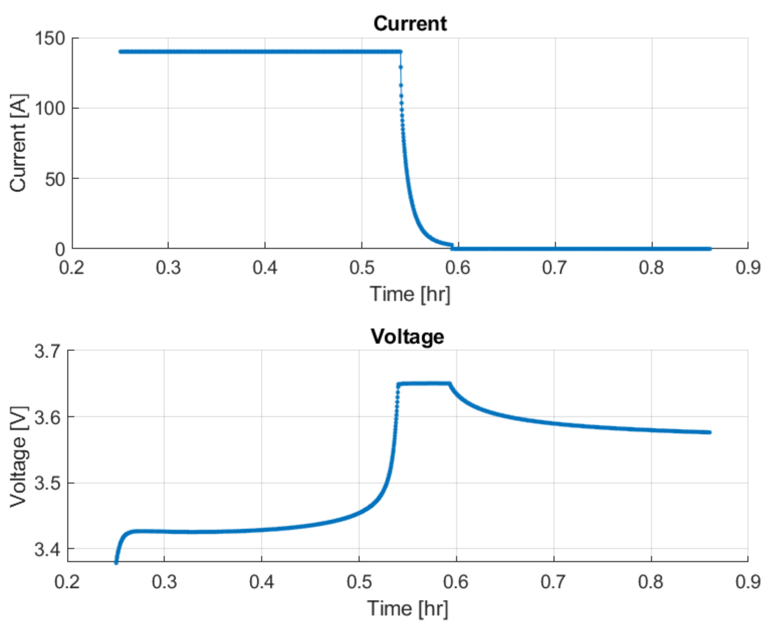


Figure 1 Example of the current and voltage profiles during charging.

2.2. Capacity test:

Capacity tests should be performed on a new cell, as well as regularly throughout the cell's life, to determine the cell's actual capacity, which will differ from the nominal value due to manufacturing inconsistencies, calendar aging, and cycle aging. The test is performed by discharging the cell at a constant current rate until it reaches the minimum voltage. Fig. 2 shows an example of a capacity test. The measured capacity also depends on the ambient temperature and current rate. Standard temperature and current rate to perform the capacity test at should be specified by the manufacturer. If this information is not available, a discharge current of 1C and ambient temperature of 25 °C can serve as a starting point. The cell capacity can then be calculated using Coulomb counting.

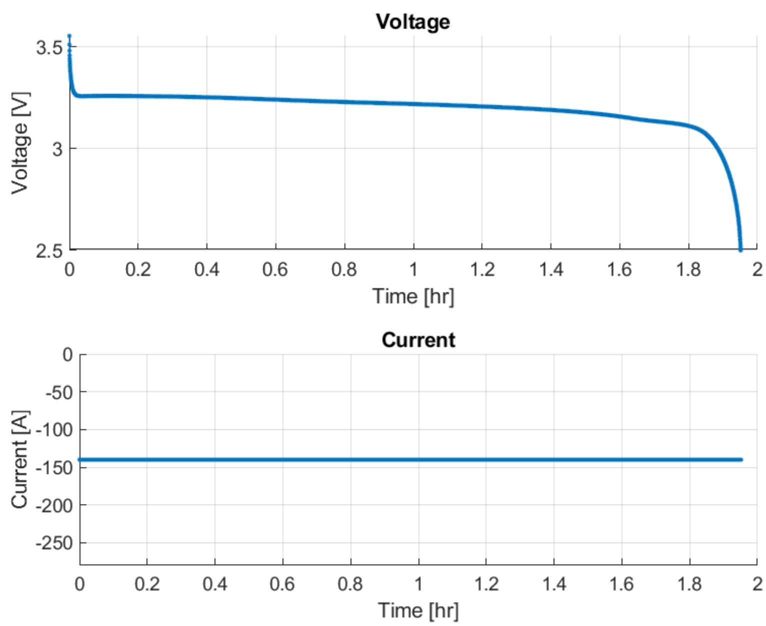


Figure 2 Example of the current and voltage profiles during capacity test.

2.3. OCV-SOC test:

The open-circuit voltage (OCV) of a battery refers to the cell's voltage when no load is applied to it. The OCV has a one-to-one relationship with the cell's state of charge (SOC). To obtain the OCV-SOC relationship, a very low current (C/20 or below) is applied to the cell and the obtained terminal voltage is regarded the cell's OCV. The lower the C rate, the closer the terminal voltage is to the cell's true OCV. Fig. 3 shows an example of the OCV-SOC relationship obtained using this method. The OCV-SOC relationship is slightly different during charge and discharge, known as the hysteresis effect, and can be compensated for if necessary [2].

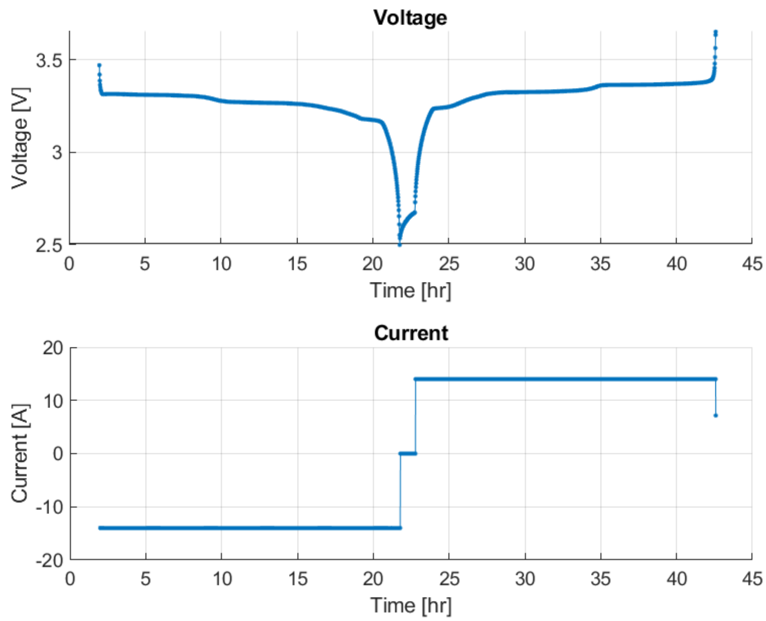


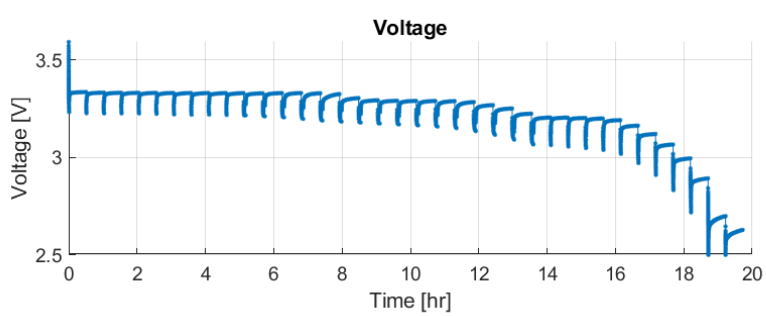
Figure 3 Example of the current and voltage profiles during OCV-SOC test.

2.4. Pulse discharge test:

The pulse discharge test can be used to obtain the cell characteristics at each SOC. A series of current pulses are applied to the cell with rests in between, until the cell reaches its minimum voltage. The duration of the current pulses can be calculated based on the C rate and cell capacity as shown in Eq. 1, where Δt is the length of the discharge pulse in seconds, Q is the cell's actual capacity in Ah determined from the capacity test, ΔSOC is the desired SOC interval to be discharged, and I is the discharge current in ampere. The magnitude of the current can be determined based on application and the rest lengths is usually between 30 minutes to 1 hour, although other rest lengths have been used [3].

$$\Delta t = \frac{(Q * 3600) * \Delta SOC}{I} \tag{1}$$

Fig. 4 shows an example of a pulse discharge test with 30 minutes rest in between.



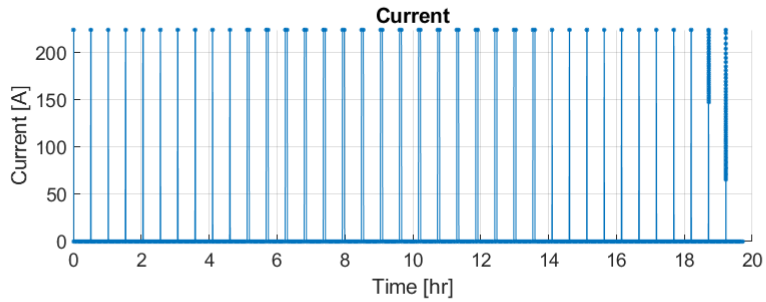


Figure 4 Example of the current and voltage profiles during pulse discharge test.

2.5. Drive cycle test:

Drive cycle tests are dynamic cell tests with realistic current profiles. Common drive cycle profiles can be found at [4]. A vehicle model is required to convert the driving speed to current drawn from the battery pack. The pack current can then be scaled down to the current drawn from an individual cell based on the pack configuration. The cycle is then repeated until the cell reaches its minimum voltage. The drive cycle tests can be used to obtain ECM parameters themselves as well as to validate the parameters obtained from the pulse discharge test as discussed later in Section 3. Fig. 5 shows an example of the UDDS drive cycle performed on a 280 Ah cell.

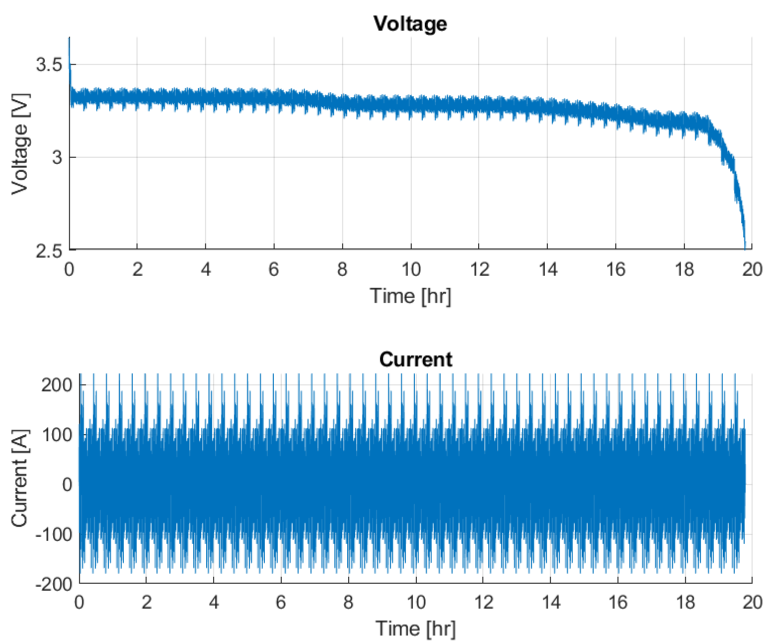


Figure 5 Example of the current and voltage profiles during UDDS drive cycle test.

3. Parameter Identification

The equivalent-circuit model (Fig. 6) is the most popular battery model used in battery management systems (BMS) for they provide a good compromise between accuracy and computational cost. It represents internal battery processes with RC branches of different time constant. The number of RC branches are referred to as the order of the ECM and can be used to balance the modelling accuracy and computational cost. Details on the variations of ECMs and their performances are discussed in [5].

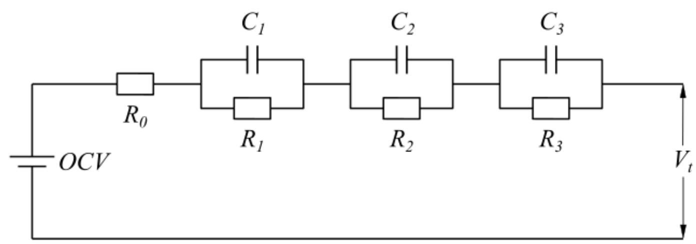


Figure 6 Example of a third-order equivalent-circuit model.

The terminal voltage of the third order ECM is given in Eq. 2, where $v_{[k]}$ is the terminal voltage at time k in volts,$OCV_{(z_k)}$ is the cell's open circuit voltage when $SOC = z_k$, $i_{[k]}$ is the input current at time k and $i_{i[k]}$ is the current through each RC branch at time k. This formula assumes that discharge current is positive and charge current is negative.

$$v_{[k]} = OCV_{(z_k)} - R_0 i_{[k]} - R_1 i_{1[k]} - R_2 i_{2[k]} - R_3 i_{3[k]} \qquad (2)$$

The current through each RC branch is given in Eq. 3, where Δt is the sampling time in seconds and $\tau_i = R_i C_i$ is the time constant of the RC branch in seconds.

$$i_{i\,[k+1]} = exp(-\frac{\Delta t}{R_i C_i}) * i_{i\,[k]} + (1 - exp(-\frac{\Delta t}{R_i C_i})) * i_{[k]} \qquad (3)$$

In order to obtain the parameters of an ECM, optimization algorithms need to be used to fit the model to the data. The mean squared error (MSE) between the measured and simulated terminal voltages can be used as the objective function to be minimized. The particle swarm optimization (PSO) method is used in this tutorial as an example for they provide good ability to search past the local minima, but other methods, such as the non-linear least squares optimization and genetic algorithm (GA) can also be used.

Since the battery parameters depend on the SOC, the experimental data can be divided into smaller segments by the SOC to be optimized separately. This results in parameter look-up tables where a set of parameters is found at each SOC level.

The initial guesses of the parameters are usually set based on trial and error, although the time constants should be sufficiently (about a decade) apart for them to be meaningful, since two RC branches with similar time constants can simply be merged as a single branch. The initial ohmic resistance can be determined by observing the amount of instantaneous voltage drop when a current is applied, and calculated using Ohm's law. The upper and lower search bounds constraint the values of the parameters during the optimization process. The larger the range, the longer it may take for the optimization to converge. [6] proposed a method to set the initial values of the parameters based on knowledge about the electrical circuit, and is referred to in this tutorial as the semi-analytical method. Fig. 7 shows an example of the model parameters obtained using the semi-analytical method from a pulse discharge test with discharge currents of 0.8C and rest period of 30 minutes.

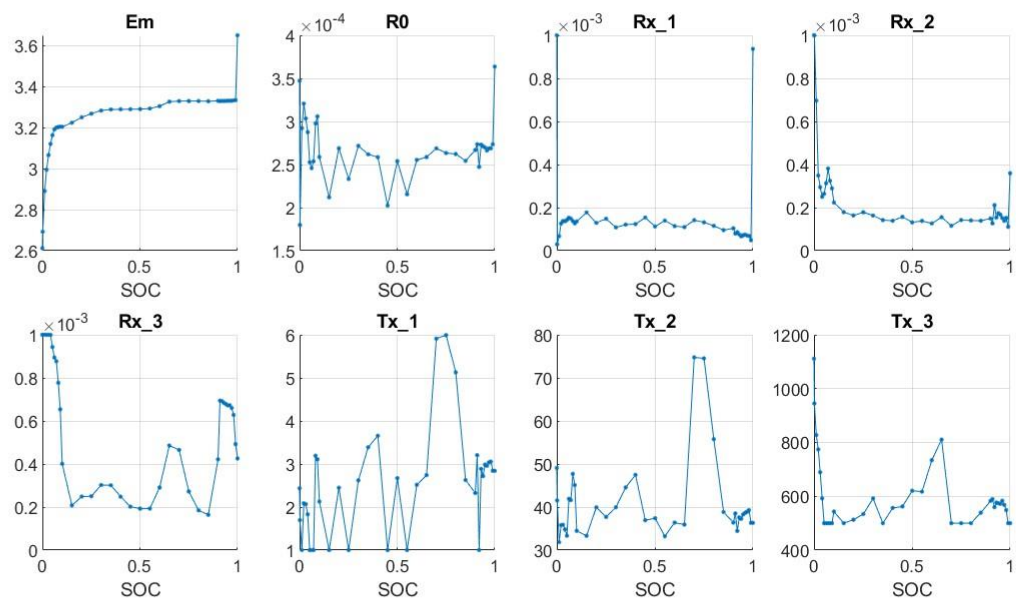


Figure 7 Model parameters obtained using the semi-analytical method from a pulse discharge test with discharge currents of 0.8C and rest period of 30 minutes

The obtained parameters need to be validated on an independent test that has not been used during the optimization process. Drive cycle tests, such as the UDDS and US06 profiles, are commonly used for validation since they represent the battery use during real driving situations. Fig. 8 shows a comparison between the terminal voltage simulated with parameters in Fig. 7 and the actual voltage measured during a US06 drive cycle test. The root mean squared error (RMSE) between the simulated and measured voltage in this case is 19.26 mV and the maximum error is 265.3 mV.

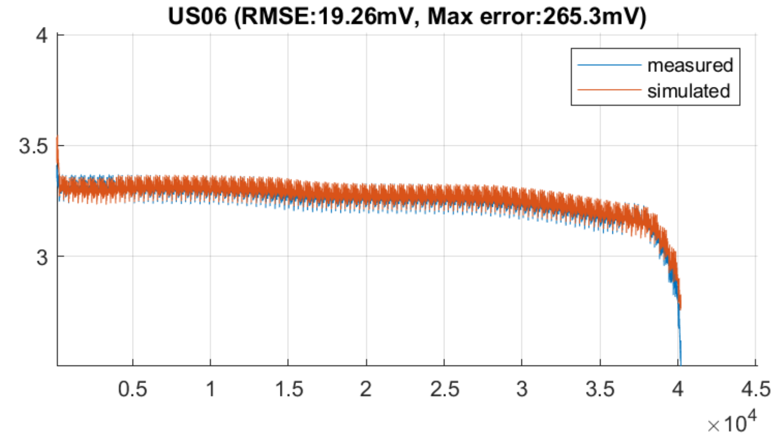


Figure 8 Comparison between the measured and simulated terminal voltage using parameters in Fig. 7.

4. Accompanying Data and Scripts

The accompanying scripts provides two methods to parameterize an ECM and are stored in folder "\scripts". The first method is referred to as the direct method, where the test data is divided into segments by the SOC and optimized directly from a user-defined initial condition. It can be used on any type of tests, although some may yield more accurate model than others. The second method is referred to as the semi-analytical method and is only applicable to pulse discharge tests. Details on these methods can be found in [3]. Table 1 provides a list each script and function file accompanying this tutorial with a short description.

Table 1 A list of scripts and functions accompanying the tutorial.

Filename	Description
parameterization_direct.m	Parameterizes the ECM using the direct method.
parameterization_analytical.m	Parameterizes the ECM using the semi-analytical method.
batterymodel_run.m	Runs the battery model to validate the input parameters.
ecm.m	Function that calculates the battery terminal voltage with a given set of parameters and current input.
format_opt_param.m	Function that manipulates the format of the model parameters for use with different scripts.
parameter_initialization.m	Function that sets the initial conditions and the bounds for optimization.
parameterization_Objective.m	Function that calculates the value of the objective functions.
parameterization_Optimize.m	Function that sets the optimization method and optimization parameters.

Example data are also provided with the tutorial stored in folder “\data”. The data are obtained from an EVE 280 LFP battery cell, whose datasheet is also included in this tutorial package.

All tests are collection at 25 °C after a full charge. The constant current capacity test is performed at 0.5C. Pulse tests (PUL) are performed with various rest lengths from 1 minute to 60 minutes. Drive cycle test profiles include UDDS, US06, HWFET, NEDC and a MIX profile combining UDDS, US06 and HWFET profiles. All these tests are performed with the maximum current scaled to 0.8C, except for the capacity test and “PUL_25degC_0p1_60min.mat” where the maximum current is scaled to 0.1C.

The parameters obtained after optimization are stored in folder “\results” by default. Some example results are provided in the folder for reference.

5. Conclusion

This tutorial and the accompanying data and scripts provide an introduction to the time domain parameterization techniques of battery ECMs. The different battery tests, including charging, capacity test, OCV-SOC test, pulse discharge test, and drive cycle tests are explained in Section 2. An example of each of the test profile is also provided with discussion on how the test parameters can be set. Section 3 provides descriptions of the methods used to obtain ECM parameters from the test data with example parameters provided. Finally, a description of the accompanying data and scripts are given in Section 4.

6. References

[1] M. Messing, “Case Study: EIS Model Fitting and Analysis – HEVPD&D-CREATE,” Aug. 2019. http://hevpdd.ca/publications-and-case-studies/eis-model-fitting-and-analysis/ (accessed Oct. 24, 2022).

[2] G. Plett, Battery Management Systems, Volume I: Battery Modeling. Norwood, UNITED STATES: Artech House, 2015. Accessed: Oct. 24, 2022. [Online]. Available: http://ebookcentral.proquest.com/lib/mcmu/detail.action?docID=4821261

[3] W. Zhang, R. Ahmed, and S. Habibi, “The Effects of Test Profile on Lithium-ion Battery Equivalent-Circuit Model Parameterization Accuracy,” in 2022 IEEE Transportation Electrification Conference & Expo (ITEC), Jun. 2022, pp. 119–124. doi: 10.1109/ITEC53557.2022.9814019.

[4] US Environmental Protection Agency, “Dynamometer Drive Schedules,” Sep. 16, 2015. https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules (accessed Dec. 10, 2021).

[5] X. Hu, S. Li, and H. Peng, “A comparative study of equivalent circuit models for Li-ion batteries,” Journal of Power Sources, vol. 198, pp. 359–367, Jan. 2012, doi: 10.1016/j.jpowsour.2011.10.013.

[6] R. Ahmed et al., “Model-Based Parameter Identification of Healthy and Aged Li-ion Batteries for Electric Vehicle Applications,” SAE International Journal of Alternative Powertrains, vol. 4, no. 2, pp. 233–247, 2015.