TSFS19 Battery Systems

Laboratory Compendium

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Contents

Lab 1

Modeling of Li-ion cells

The first part of the lab is to determine the open circuit voltage (V_{ocv}) of a Li-ion cell as a function of the state of charge (SOC). The second part of the lab is to model the cell using equivalent circuit models (ECM).

1.1 Determining OCV as a function of SOC

A constant low current charge and discharge is performed on the cell to determine the OCV as a function of SOC. Figure 1.1 shows the measured cell voltage, current, and step-index as a function of time during the low current charge and discharge test of a Li-ion cell. The cell is an INR18650-20R 2000 mAh LiNiMnCo/Graphite cell and the test data is taken from Maryland University. The test was performed at an ambient temperature of 25°C. The sections in Figure 1.1 where the cell is charged and discharged with a low current are highlighted in green. The sections where the cell is at rest or CV charge are highlighted in orange. The step-index shown in Figure 1.1c is used to identify the different stages of the test. When the step index is 1, the cell is charged at a constant current of 1 A (0.5 C), when the step index is 2, the cell is CV charged to the cut-off, and so on.

SOC has several definitions, but the one used here is the ratio of the remaining capacity to the full capacity of the cell, i.e.,

$$z_{\mathrm{c}}(t) = \frac{Q_{\mathrm{c}}(t)}{Q_{\mathrm{full}}}, \tag{1.1}$$

where $z_{\mathrm{c}}(t)$ and $Q_{\mathrm{c}}(t)$ are the instantaneous state of charge and capacity of the cell at time t, respectively, and Q_{full} is the full Furthermore, $Q_{\mathrm{c}}(t)$ is the integral of the current over time, i.e.,

$$Q_{\mathrm{c}}(t) = \int_0^T I_{\mathrm{c}}(t)\, dt, \tag{1.2}$$

where $I_{\mathrm{c}}(t)$ is the instantaneous cell current at time t.

Note

Feel free to use any definition of SOC, but be consistent with the definition used in the lab.

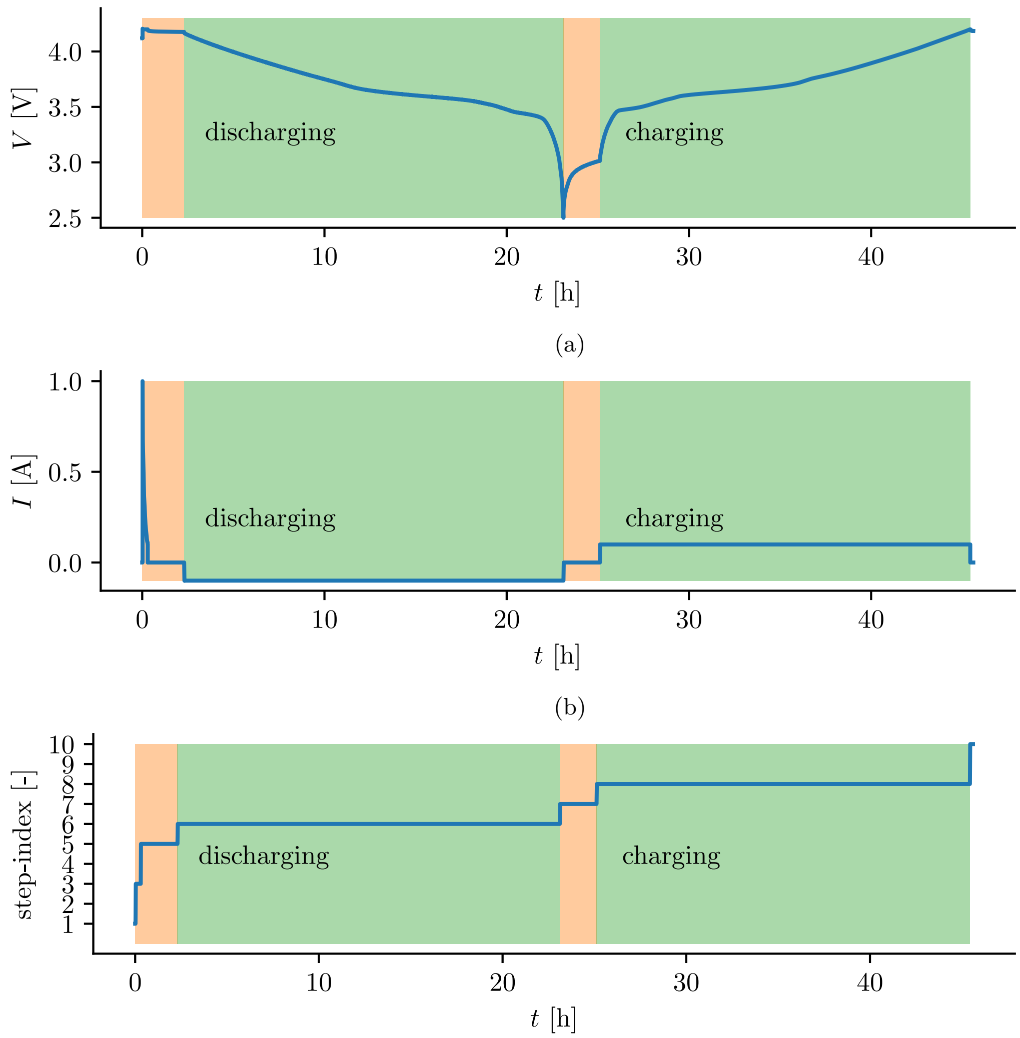
Task 1: Determining Q_{full}

To get the SOC, the full capacity of the cell, Q_{full}, needs to be determined. The test data shown in Figure 1.1 is used to determine the full capacity of the cell. Use the step-index data to identify the sections where the cell is charged and discharged. When step index = 6, the cell is discharged at a constant current of 0.1 A (0.05 C). The discharge capacity (Q_{dis}) is the integral of the current over time.

Q 1.1) Determine the discharge capacity of the cell, Q_{dis}, in Ah.

A 1.1)

The charge capacity (Q_{ch}) is the integral of the current over time when the cell is charged. When step-index = 8, the cell is charged at a constant current of 0.1 A (0.05 C).



(a)

(b)

(c)

Figure 1.1: Low current constant current charge and discharge of a Li-ion cell. (a) Cell voltage as a function of time, (b) cell current as a function of time, and (c) step index as a function of time.

Q 1.2) Determine the charge capacity of the cell, Q_{ch}, in Ah.

A 1.2)

Q 1.3) Comment on the difference between the charge and discharge capacities, if any.

A 1.3)

Q 1.4) Determine the full capacity of the cell, Q_{full}, in Ah.

A 1.4)

Task 2: Determining the terminal voltages (V_t) as a function of SOC

Since the cell is discharged and charged at a low current, the terminal voltage and the OCV are approximately the same, or are they? In this task, the terminal voltage of the cell during charge (step index = 8) and discharge (step index = 6) are determined.

Q 2.1) Is the terminal voltage during charge and discharge the same? If not, why?

A 2.1)

Q 2.2) Plot the terminal voltage of the cell during charge and discharge as a function of SOC.

Task 3: Determining the OCV curve

The V_{ocv} (OCV or open circuit voltage) of the cell as a function of SOC is called the OCV curve. The OCV curve is determined by using the measured terminal voltages during charge and discharge and over the full range of SOC (0 to 100%). From the previous tasks, it is clear that neither the terminal voltages nor the SOC are the same during charge and discharge. Therefore, to determine the OCV curve, two cases are considered:

Case 1: Using the terminal voltages during charge and discharge

Q 3.1) Complete the equation (1.3).

In this case, the terminal voltages from the charge and discharge data are used to determine the OCV curve, i.e.,

$$V_{\text{ocv}} = \tag{1.3}$$

where $V_{\text{t(ch)}}$ and $V_{\text{t(dis)}}$ are the terminal voltages during charge and discharge, respectively.

Case 2: Using the terminal voltages during discharge

Q 3.2) Complete the equation (1.4).

In this case, the terminal voltage from discharge data is used to determine the OCV curve, i.e.,

$$R_{\text{cell}} = \tag{1.4a}$$

$$V_{\text{ocv}} = \tag{1.4b}$$

where $V_{\text{t(ch)}}$ and $V_{\text{t(dis)}}$ are the terminal voltages during charge and discharge, respectively, and I_{c} is the current during charge or discharge.

Note

- ‘`vt_charge`‘ and ‘`vt_discharge`‘ are cubic spline interpolation functions created using the ‘`CubicSpline`‘ class from the ‘`scipy.interpolate`‘ module. These functions are used to interpolate the voltage values for given SOC values during charging and discharging, respectively.
- These interpolation functions can be used to estimate voltage values for any SOC value within the range of the provided data.

For example,

```python
# Interpolated voltage during charging at a specific SOC
voltage_at_soc = vt_charge(soc_value)
# Interpolated voltage during discharging at a specific SOC
voltage_at_soc = vt_discharge(soc_value)
```

where ‘`soc_value`‘ is the SOC value for which you want to estimate the voltage.

Q 3.3) Plot the OCV curve.

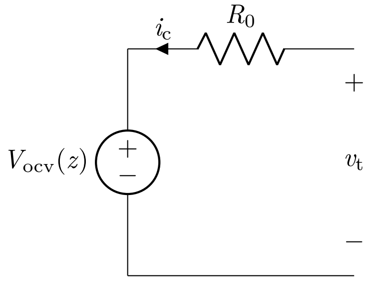


Figure 1.2: Thevenin equivalent circuit of a Li-ion cell.

1.2 Estimating the parameters of the Thevenin equivalent circuit model of a Li-ion cell

The Thevenin equivalent circuit model of a Li-ion cell is shown in Figure 1.2. The model consists of a voltage source, which corresponds to the open circuit voltage (V_{ocv}) and the Thevenin equivalent resistance (R_0) in series. The terminal voltage of the cell is denoted by V_t.

Task 4: Determining the Thevenin equivalent resistance (R_0) of a Li-ion cell

Like the V_{ocv}, R_0 is a function of the state of charge (SOC).

Q 4.1) What is the average Thevenin equivalent resistance (R_0) of a Li-ion cell over the entire state of charge range?

A 4.1)

Q 4.2) Plot the Thevenin equivalent resistance (R_0) as a function of the state of charge (SOC).

Task 5: Modeling the Li-ion cell using the Thevenin equivalent circuit model

To simulate and analyze the behavior of a Li-ion cell, the Thevenin equivalent circuit model can be used.

Q 5.1) Complete (1.5) by writing the differential equations for the Thevenin equivalent circuit model.

The equivalent circuit model is shown in Figure 1.2 can be written as a set of differential-algebraic equations (DAEs) as follows:

$$\dot{z} = \tag{1.5a}$$

$$v_{\mathrm{t}}(t) = \tag{1.5b}$$

where z is the state of charge, Q_{full} is the full capacity of the cell, i_{c} is the instantaneous cell current, and v_{t} is the instantaneous terminal voltage of the cell.

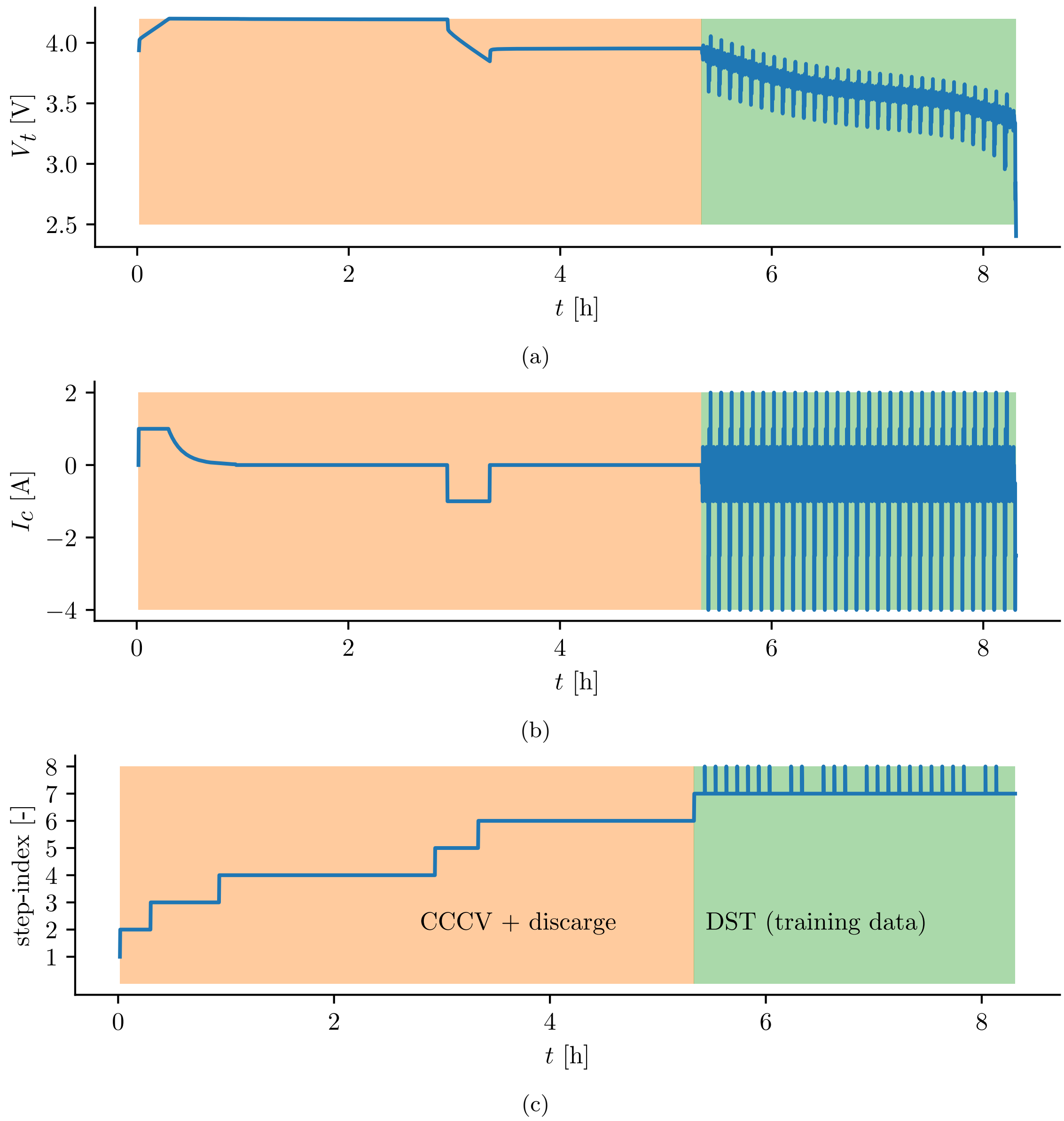


Figure 1.3: Dynamic stress test data (training data) for the Li-ion cell. (a) Terminal voltage (V_t), (b) Cell current (I_c), and (c) Step index.

Task 6: Fitting the Thevinin equivalent circuit model to experimental data

In this task, you will fit the Thevenin equivalent circuit model to experimental data. The test is referred to as a dynamic stress test (DST) and is performed by applying a current pulse to the cell and measuring the terminal voltage response. Figure 1.3 shows the DST data collected for the Li-ion cell. The section of the training data highlighted in orange corresponds to the CC-CV charging phase and a CC discharging phase, which is not used for the model fitting. However, the section of the training data highlighted in green is used for the model fitting. Implement the model (1.5) in your code and fit the model to the training data shown in Figure 1.3.

For model fitting, the best value of the Thevenin equivalent resistance (R_0) and the initial SOC (z_0) is determined by minimizing the root mean square error (RMSE) between the measured terminal voltage and the predicted terminal voltage using the Thevenin equivalent circuit model.

Q 6.1) What is the value of the thevenin equivalent resistance (R_0) of the Li-ion cell?

A 6.1)

Q 6.2) Is the Thevenin equivalent resistance (R_0) different from the average value you calculated in **task 5**? If so, why?

A 6.2)

Q 6.3) Compare the terminal voltage (V_t) predicted by the Thevenin equivalent circuit model with the measured terminal voltage. Where and why are the discrepancies between the model predictions and the measurements largest?

A 6.3)

Q 6.4) How can the Thevenin equivalent circuit model be improved to better predict the terminal voltage of the Li-ion cell?

A 6.4)

Task 7: Evaluating the Thevenin equivalent circuit model to experimental data

In this task, you will evaluate the Thevenin equivalent circuit model using several test data sets. The test data sets are as follows:

Test dataset 1 This test is a `FUDS` drive cycle test at 25°C ambient temperature and the test begins at 50% state of charge.

Test dataset 2 This test is a `UDDS` drive cycle test at 25°C ambient temperature and the test begins at 80% state of charge.

Test dataset 3 This test is a `FUDS` drive cycle test at 0°C ambient temperature and the test begins at 80% state of charge.

To quantify the performance of the model, you will calculate the norm between the measured terminal voltage and the predicted terminal voltage using the Thevenin equivalent circuit model, i.e., the root mean square error (RMSE) defined as:

$$\mathrm{RMSE} = \| \tilde{V}_{\mathrm{t(model)}} - V_{\mathrm{t(meas)}} \|, \tag{1.6}$$

where $\tilde{V}_{\mathrm{t(model)}}$ is the predicted terminal voltage using the Thevenin equivalent circuit model and $V_{\mathrm{t(meas)}}$ is the measured terminal voltage.

Q 7.1) Fill in the table below with the RMSE values for the test data sets.

A 7.1)

Test dataset	**RMSE [V]**
Test dataset 1	
Test dataset 2	
Test dataset 3	

Q 7.2) Which dataset has the largest discrepancies between the model predictions and the measurements and why?

A 7.2)

Q 7.3) How can the Thevenin equivalent circuit model be improved to better predict the terminal voltage of the Li-ion cell?

A 7.3)

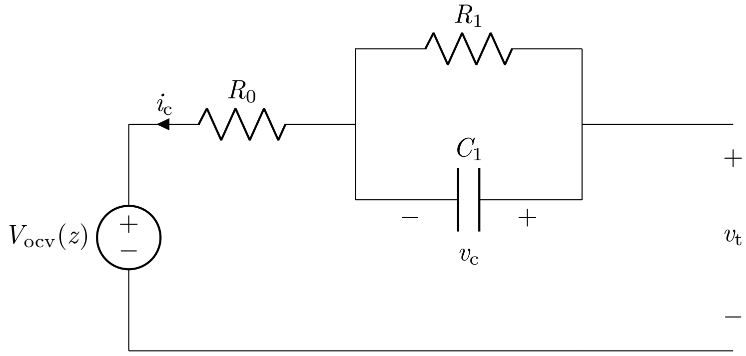


Figure 1.4: RC equivalent circuit model of a Li-ion cell.

1.3 Estimating the parameters of the RC equivalent circuit model of a Li-ion cell

The RC equivalent circuit model of a Li-ion cell is shown in Figure 1.4. The model consists of a voltage source, which corresponds to the open circuit voltage (V_{ocv}) and a series connection of a resistor (R_0) and a parallel RC network with resistance R_1 and capacitance C_1. The voltage across the capacitor is denoted by V_c and the terminal voltage of the cell is denoted by V_t.

Task 8: Modeling the Li-ion cell using the RC equivalent circuit model

To simulate and analyze the behavior of a Li-ion cell, the RC equivalent circuit model can be used.

Q 8.1) Complete (1.7) by writing the differential equations for the RC equivalent circuit model.

The equivalent circuit model is shown in Figure 1.4 and can be written as a set of differential-algebraic equations (DAEs) as follows:

$$\begin{pmatrix} \dot{v}_c \\ \\ \dot{z} \end{pmatrix} = \begin{pmatrix} \quad\quad\quad\quad\quad\quad \\ \\ \end{pmatrix} \begin{pmatrix} v_c \\ \\ z \end{pmatrix} + \begin{pmatrix} \quad\quad\quad\quad\quad\quad \\ \\ \end{pmatrix} \tag{1.7a}$$

$$v_t(t) = \tag{1.7b}$$

where z is the state of charge, Q_{full} is the full capacity of the cell, v_c is the instantaneous voltage across the capacitor, i_c is the instantaneous cell current, and v_t is the instantaneous terminal voltage of the cell.

Q 8.2) Comment on the differences between the Thevenin equivalent circuit model and the RC equivalent circuit model.

A 8.4)

Task 9: Fitting the RC equivalent circuit model to experimental data

In this task, you will fit the Thevenin equivalent circuit model to experimental data. The dynamic stress test data set is used for this task (see Figure 1.3).

Q 9.1) What are the values of the parameters R_0, R_1, and C_1 of the RC equivalent circuit model?

A 9.1)

Q 9.2) Comment and compare the parameters for the RC equivalent circuit model with the Thevenin equivalent circuit model.

A 9.2)

Q 9.3) Where and why does the deviation between the model and the measurements occur?

A 9.3)

Q 9.4) How can the RC equivalent circuit model be improved to better fit the experimental data?

A 9.4)

Task 10: Evaluating the RC equivalent circuit model to experimental data

In this task, you will evaluate the RC equivalent circuit model using several test data sets. The test data sets are as follows:

Test dataset 1 This test is a `FUDS` drive cycle test at 25°C ambient temperature and the test begins at 50% state of charge.

Test dataset 2 This test is a `UDDS` drive cycle test at 25°C ambient temperature and the test begins at 80% state of charge.

Test dataset 3 This test is a `FUDS` drive cycle test at 0°C ambient temperature and the test begins at 80% state of charge.

To quantify the performance of the model, you will calculate the norm between the measured terminal voltage and the predicted terminal voltage using the RC equivalent circuit model, i.e., the root mean square error (RMSE) defined as:

$$\text{RMSE} = \| \tilde{V}_{\text{t(model)}} - V_{\text{t(meas)}} \|, \tag{1.8}$$

where $\tilde{V}_{\text{t(model)}}$ is the predicted terminal voltage using the RC equivalent circuit model and $V_{\text{t(meas)}}$ is the measured terminal voltage.

Q 10.1) Fill in the table below with the RMSE values for the test data sets.

A 10.1)

Test dataset	**RMSE [V]**
Test dataset 1	
Test dataset 2	
Test dataset 3	

Q 10.2) Does the Model fit the measurements better than the Thevenin equivalent circuit model and why?

A 10.2)

Q 10.3) Which dataset has the largest discrepancies between the model predictions and the measurements and why?

A 10.3)

Q 10.4) How can the RC equivalent circuit model be improved to better predict the terminal voltage of the Li-ion cell?

A 10.4)