Created in COMSOL Multiphysics 6.1

Lithium-Ion Battery Internal Resistance

Introduction

This application investigates the rate capability of a battery further and shows how the Lithium-Ion Battery interface is an excellent modeling tool for this.

The rate capability is studied in terms of polarization (voltage loss) or the internal resistance causing this loss. A typical high current pulse test, a Hybrid Pulse Power Characterization (HPPC) test, is simulated here for this purpose. Primarily, the first 10 s discharge and the subsequent relaxation at are looked upon.

The Lithium-Ion Battery interface takes into account many physical battery properties of which some can be pinned down as design parameters directly affecting rate capability. These are (Ref. 1 and Ref. 2):

- thickness of electrodes and separator,
- porosity of electrodes and separator,
- active material particle size,
- choice of active electrode material,
- other material choices, for example, electrolyte and electronic conductor, and
- the state-of-charge (SOC) of the electrode material; several material properties being SOC dependent.

Properties that decrease the internal resistance are normally thin battery domains, high porosities, and small active material particles. A battery with the opposite design features has high internal resistance, but can due to large active material particles and thick packed electrodes be able to store a lot capacity (energy). This explains why a battery cannot have both high energy and power output; that is, the battery is either power-optimized or energy-optimized.

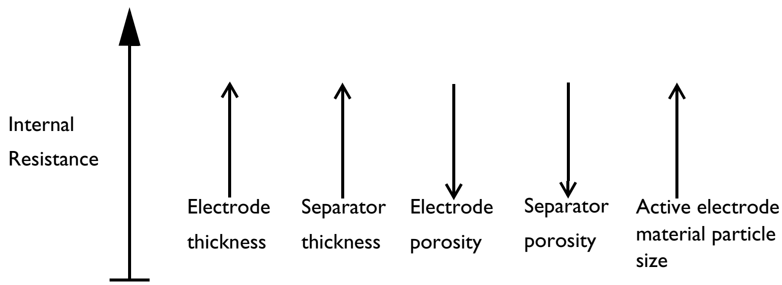


Figure 1: Selection of design parameters in cell with separator and their relation to increased internal resistance. Upward pointing arrows indicate increase, downward pointing decrease. For example, the internal resistance increases with decreased porosity and increased particle size.

The choice of active materials are important as well. Some materials are able to shift their lithium concentration efficiently even at high current loads. Additionally, the electrolyte is also important; for example, polymer batteries are seldom power-optimized since these contain a nonliquid electrolyte with poor lithium-ion transport properties.

Three parameters are varied in the application: The state-of-charge (SOC) of the cell (which in turn dictates the SOC of each electrode), the porosity of the positive electrode, and the particle size of the positive active electrode material. Thus, together with the original design, four cases are compared.

More battery parameters and additional variable definitions used here are found in the Lithium-Ion Battery Seed application.

Model Definition

The model is set up for a graphite/LMO battery cell. The materials are available from the Battery Material Library and mainly default settings are selected. The model domains consist of:

- Negative porous electrode: Graphite (MCMB Li_xC_6) active material and electronic conductor.
- Separator.

- Positive porous electrode: LMO ($LiMn_2O_4$) active material, electronic conductor, and filler.
- Electrolyte: 1.0 M $LiPF_6$ in EC:DEC (1:1 by weight).

This battery cell assembly gives a cell voltage around 4 V, depending on the state-of-charge (SOC) of the cell.

The Lithium-Ion Battery interface accounts for:

- electronic conduction in the electrodes,
- ionic charge transport in the electrodes and electrolyte/separator,
- material transport in the electrolyte, allowing for the introduction of the effects of concentration on ionic conductivity and concentration overpotential, and
- material transport within the spherical particles that form the electrodes, and
- Butler-Volmer electrode kinetics using experimentally measured discharge curves for the equilibrium potential.

The current pulse is charge neutral and contains 10 s of 10C discharge, 10 s relaxation, and 10 s of 10C charge. In Figure 2 the pulse is displayed.

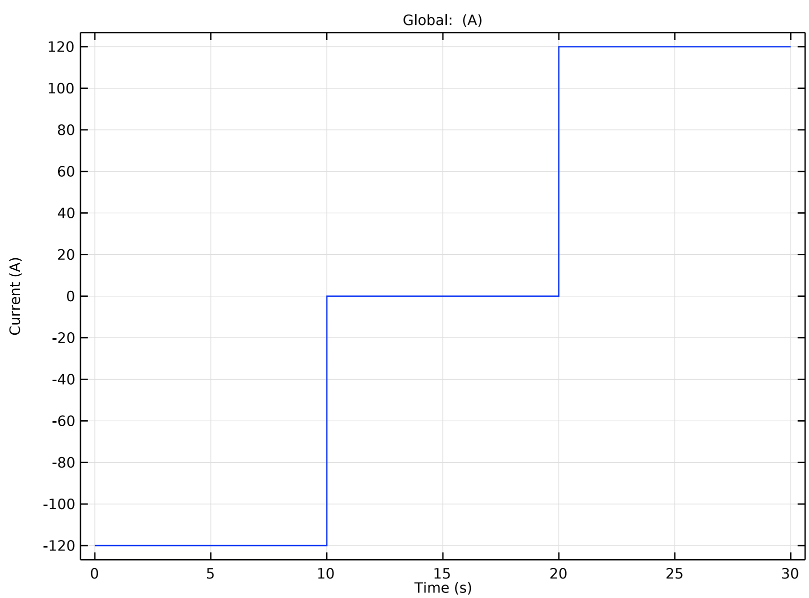


Figure 2: Charge neutral high current pulse used in model.

Additionally, the model calculates the energy efficiency of the pulse as the ratio between the energy output, W_{out}, and input, W_{in}.

$$\eta_e = \frac{W_{\text{out}}}{W_{\text{in}}} = \frac{\int_{t_{\text{out},1}}^{t_{\text{out},2}} (I \cdot E_{\text{cell}}) dt}{\int_{t_{\text{in},1}}^{t_{\text{in},2}} (I \cdot E_{\text{cell}}) dt} \tag{1}$$

The nominator and denominator in Equation 1 are solved with Global ODEs and DAEs.

The initial cell SOC is set to 0.6, using the Initial Cell Charge Distribution feature.

Results and Discussion

The cell voltage during the first 10 s 10C discharge and 10 s relaxation is shown in Figure 3. Compared to the open-circuit cell voltage, polarization is present in all four cases.

In Figure 3, it is shown that the lowered initial cell SOC (40%) lowers the voltage all through the pulse. The material properties affected by the cell SOC are the open-circuit potentials (OCP) of the electrodes and the electrochemical reaction rate in this model.

However, the changes seem to be mainly due to the OCPs, since the magnitude of the OCPs differ significantly between 40% and 60% cell SOC.

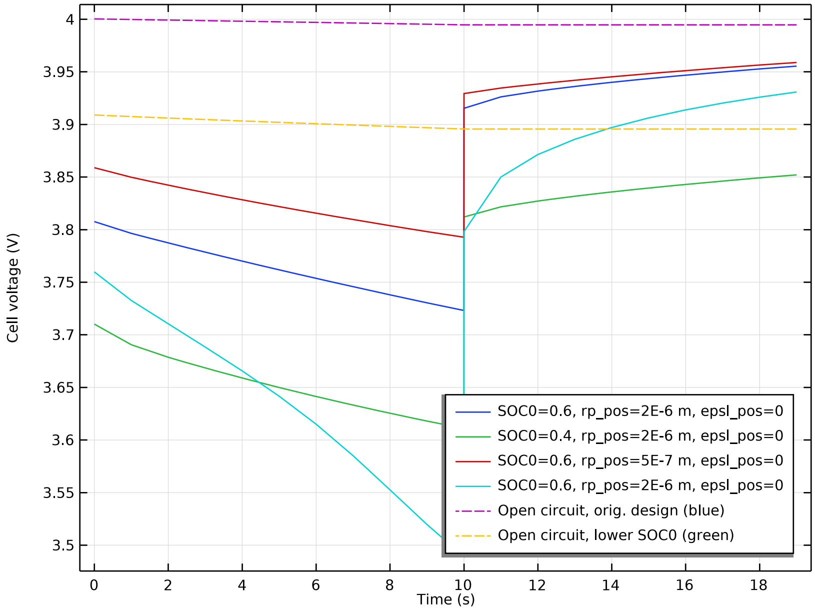


Figure 3: Cell voltage behavior for the different designs during the first 20 s of the pulse. (SOC0 equals initial cell SOC.)

The cell voltage increases considerably when the positive active material particle size is decreased, showing that a major part of the internal resistance originates from there in the original design. In contrast, the lowered porosity in the positive electrode shows that the electrolyte part of the positive electrode requires a quite high porosity (0.4) to efficiently transport lithium ions.

In Figure 4, the total polarization, which is equal to the difference between the cell voltage and open-circuit voltage, is shown. The polarization seems to depend on both instantaneous and time-dependent internal resistances. The former gives an immediate voltage drop when the current is turned on or off, the latter increases the drop more slowly, and is the only resistance that is observed during the relaxation period. The instantaneous behavior has to do mainly with ohmic resistances, such as conductivity, and the time-dependent one with slow mass transport processes, for example, diffusion, in the electrolyte and the active materials. The calculated internal resistance is calculated from Ohm's law at the end of the 10C discharge, as shown in Equation 2.

$$R = \left. \frac{E_{\mathrm{OCV,\ cell}}(\mathrm{SOC}) - E_{\mathrm{cell}}}{-I} \right|_{t\ =\ 10s} \tag{2}$$

The resistances calculated for the different cases are (in the order presented in the plot legends, top down): 2.0 m·Ω. 2.1 m·Ω., 1.4 m·Ω., and 4.1 m·Ω.

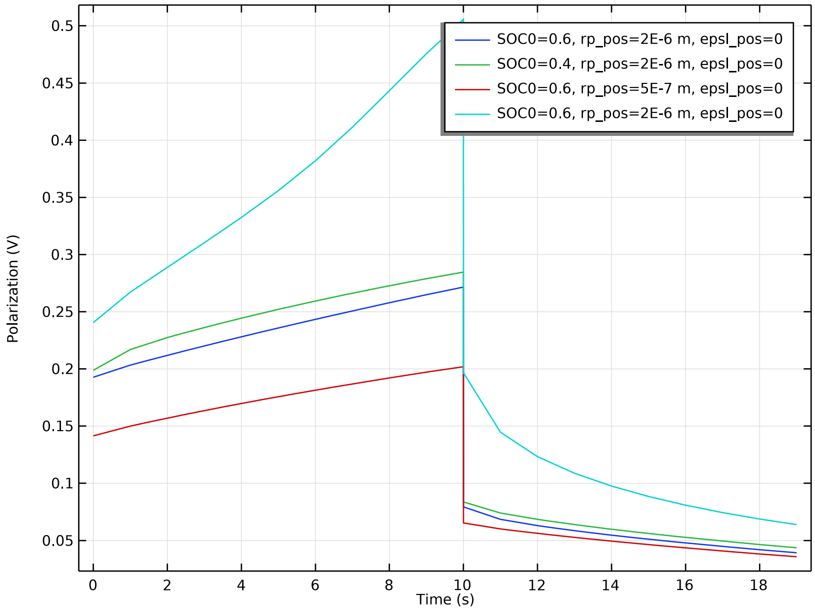


Figure 4: Total polarization (EOCV,cell-Ecell) in the different designs during the first 20 s of the pulse.

In Figure 5 and Figure 6, the potentials and OCPs are shown for the two electrodes. The internal resistance in both electrodes is almost the same. The polarization, given by the difference in potential and open-circuit potential, is approximately 10 mV in both electrodes.

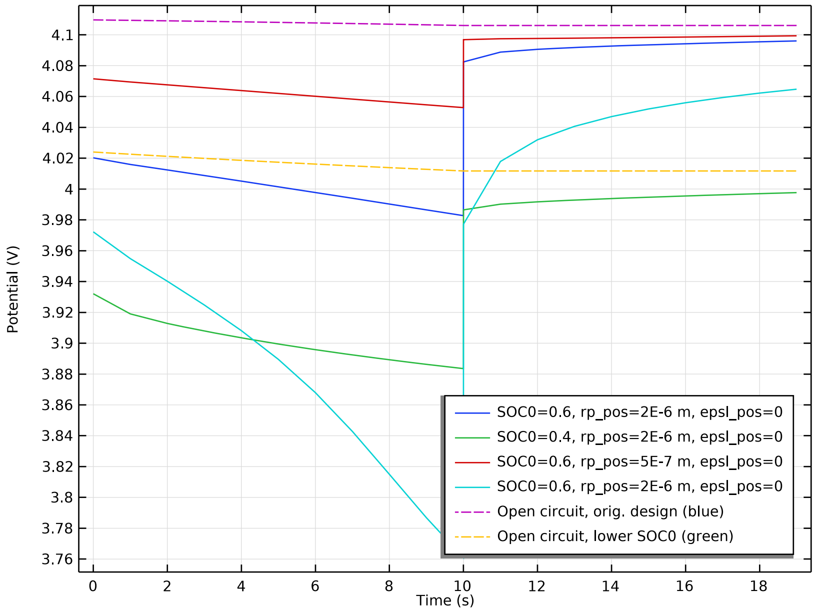


Figure 5: Positive electrode potential during the first 20 s of the pulse.

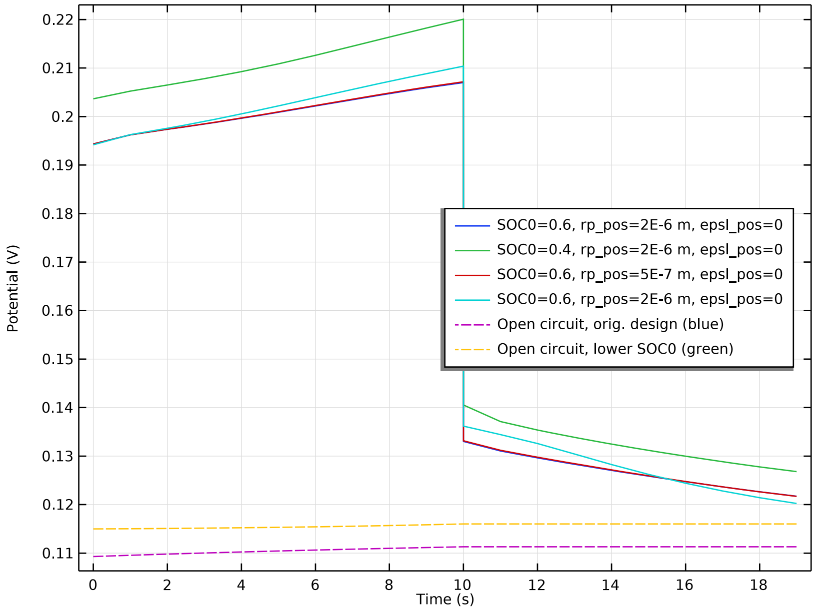


Figure 6: Negative electrode potential during the first 20 s of the pulse.

The energy efficiency of the battery during the pulse should be considerably less than 100% due to the polarization. Both the discharge and charge give considerable polarization, as shown in Figure 7. The energy efficiency is calculated from Equation 1 and becomes (in the order presented in the plot legends, top down): 90.8 %, 89.9 %, 93.4 % and 87.8 %.

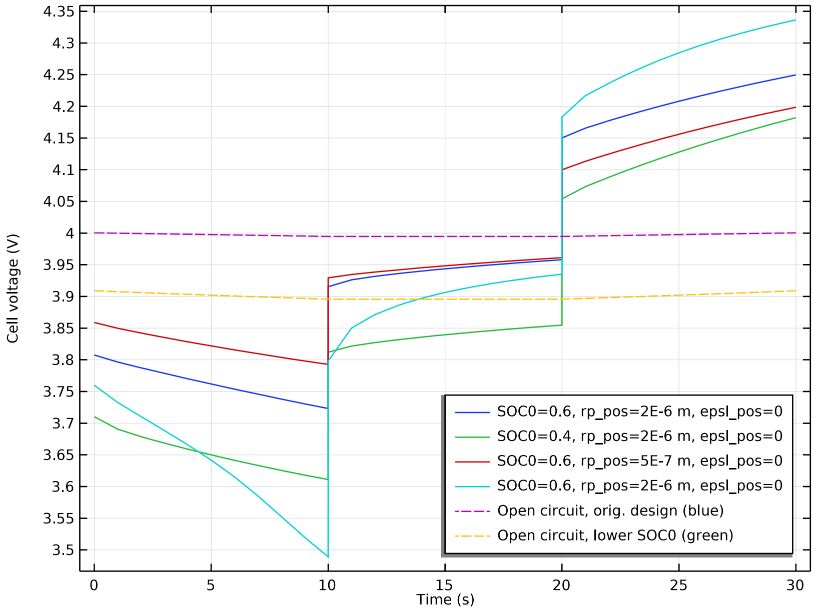


Figure 7: Cell voltage behavior for the different battery designs during the whole pulse.

Reference

1. M. Doyle, J. Newman, A.S. Gozdz, C.N. Schmutz, and J.M. Tarascon, "Comparison of Modeling Predictions with Experimental Data from Plastic Lithium Ion Cells," *J. Electrochem. Soc.*, vol. 143, no. 6, pp. 1890–1903, 1996.

2. A. Nyman, T. G. Zavalis, R. Elger, M. Behm, and G. Lindbergh, "Analysis of the Polarization in Li-Ion Battery Cell by Numerical Simulations," *J. Electrochem. Soc.*, vol. 157, no. 11, pp. A1236–A1246, 2010.

Application Library path: `Battery_Design_Module/Batteries,_Lithium-Ion/li_battery_internal_resistance`

APPLICATION LIBRARIES

1. From the **File** menu, choose **Application Libraries**.
2. In the **Application Libraries** window, select **Battery Design Module>Batteries, Lithium-Ion>li_battery_seed** in the tree.
3. Click **Open**.

GLOBAL DEFINITIONS

The rate capability of three battery parameters are tested: the initial cell state-of-charge (SOC), the porosity, and particle size of the positive electrode. These are added to the global parameters to enable parameter variation. Replace the initial cell voltage to initial cell state-of-charge, since the former is no longer needed.

Parameters 1

1. In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2. In the **Settings** window for **Parameters**, locate the **Parameters** section.
3. In the table, enter the following settings:

Name	Expression	Value	Description
SOCcell_init	0.6	0.6	Initial cell state-of-charge
rp_pos	2e-6[m]	2E-6 m	Particle size positive electrode
epsl_pos	0.4	0.4	Porosity positive electrode
smooth	1e-3	0.001	Rectangle pulse smoothing factor

DEFINITIONS (COMP1)

Load the variables from a text file.

Variables 1

1. In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions** node.
2. Right-click **Component 1 (comp1)>Definitions** and choose **Variables**.
3. In the **Settings** window for **Variables**, locate the **Variables** section.
4. Click **Load from File**.
5. Browse to the model's Application Libraries folder and double-click the file `li_battery_management_variables.txt`.

Piecewise 1 (pw1)

Set up the pulse with a Piecewise function. The pulse is 10 s of discharge, followed by 10 s of relaxation, and 10 s of charge.

1 In the **Home** toolbar, click f(X) **Functions** and choose **Local>Piecewise**.

2 In the **Settings** window for **Piecewise**, type `pulse` in the **Function name** text field.

3 Locate the **Definition** section. From the **Smoothing** list, choose **Continuous function**.

4 From the **Transition zone** list, choose **Absolute size**.

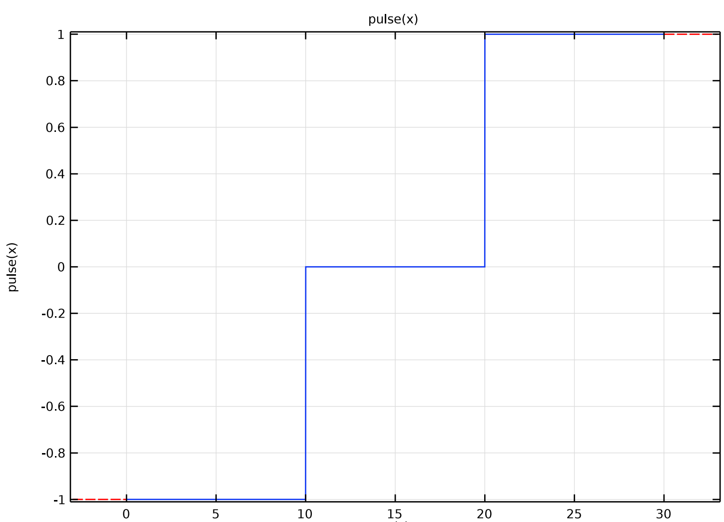
5 In the **Size of transition zone** text field, type `smooth`.

6 Find the **Intervals** subsection. In the table, enter the following settings:

Start	End	Function
0	10	-1
10	20	0
20	30	1

7 Locate the **Units** section. In the **Arguments** text field, type `s`.

8 Click **Plot**.



Variables 1

Set up the current pulse in the variable list.

1 In the **Model Builder** window, click **Variables 1**.

2 In the **Settings** window for **Variables**, locate the **Variables** section.

3 In the table, enter the following settings:

Name	Expression	Unit	Description
I_pulse	10*liion.I_1C*pulse(t)	A	10 C pulse test

LITHIUM-ION BATTERY (LIION)

Electrode Current -Current Load Rates

1 In the **Model Builder** window, under **Component 1 (comp1)>Lithium-Ion Battery (liion)** click **Electrode Current 1**.

2 In the **Settings** window for **Electrode Current**, type `Electrode Current -Current Load Rates` in the **Label** text field.

3 Locate the **Electrode Current** section. In the $I_{\mathrm{s,total}}$ text field, type `I_pulse`.

Porous Electrode 1

In the **Particle Intercalation** nodes of the **Porous Electrode** features, it is useful to enable fast assembly in the particle dimension option. This option enables an alternative method for assembling of the diffusion equation in the particle dimension, that typically decreases computation time for 1D models. Note that the same diffusion equations are solved for regardless of assembly method. Additionally, specify the reference exchange current density for the electrode kinetics in the **Porous Electrode Reaction** nodes. Also, introduce the parameters that are to be varied, into the **Lithium-Ion Battery** interface.

Particle Intercalation 1

1 In the **Model Builder** window, expand the **Porous Electrode 1** node, then click **Particle Intercalation 1**.

2 In the **Settings** window for **Particle Intercalation**, click to expand the **Particle Discretization** section.

3 Select the **Fast assembly in particle dimension** check box.

Porous Electrode Reaction 1

1 In the **Model Builder** window, click **Porous Electrode Reaction 1**.

2 In the **Settings** window for **Porous Electrode Reaction**, locate the **Electrode Kinetics** section.

3 In the $i_{0,\mathrm{ref}}(T)$ text field, type `i0ref_neg`.

Porous Electrode 2

1 In the **Model Builder** window, under **Component 1 (comp1)>Lithium-Ion Battery (liion)** click **Porous Electrode 2**.

2 In the **Settings** window for **Porous Electrode**, locate the **Porous Matrix Properties** section.

3 In the ε_l text field, type `epsl_pos`.

Particle Intercalation 1

1 In the **Model Builder** window, expand the **Porous Electrode 2** node, then click **Particle Intercalation 1**.

2 In the **Settings** window for **Particle Intercalation**, locate the **Particle Transport Properties** section.

3 In the r_p text field, type `rp_pos`.

4 Locate the **Particle Discretization** section. Select the **Fast assembly in particle dimension** check box.

Porous Electrode Reaction 1

1 In the **Model Builder** window, click **Porous Electrode Reaction 1**.

2 In the **Settings** window for **Porous Electrode Reaction**, locate the **Electrode Kinetics** section.

3 In the $i_{0,\mathrm{ref}}(T)$ text field, type `i0ref_pos`.

Initial Cell Charge Distribution 1

Change the initial battery setting from initial cell voltage to cell state-of-charge and enter the `SOCcell_init` parameter that is investigated.

1 In the **Model Builder** window, under **Component 1 (comp1)>Lithium-Ion Battery (liion)** click **Initial Cell Charge Distribution 1**.

2 In the **Settings** window for **Initial Cell Charge Distribution**, locate the **Battery Cell Parameters** section.

3 From the **Initial battery cell setting** list, choose **Initial cell state-of-charge**.

4 In the $SOC_{\mathrm{cell},0}$ text field, type `SOCcell_init`.

COMPONENT 1 (COMP1)

The cumulative energy input and output is calculated with a Global equation.

From the **Home** menu, choose **Add Physics**.

ADD PHYSICS

1 Go to the **Add Physics** window.

2 In the tree, select **Mathematics>ODE and DAE Interfaces>Global ODEs and DAEs (ge)**.

3 Click **Add to Component 1** in the window toolbar.

4 From the **Home** menu, choose **Add Physics**.

CUMULATIVE ENERGY OUTPUT AND INPUT

In the **Settings** window for **Global ODEs and DAEs**, type `Cumulative Energy Output and Input` in the **Label** text field.

Global Equations 1

1 In the **Model Builder** window, expand the **Initial Cell Charge Distribution 1** node, then click **Component 1 (comp1)>Cumulative Energy Output and Input (ge)> Global Equations 1**.

2 In the **Settings** window for **Global Equations**, locate the **Global Equations** section.

3 In the table, enter the following settings:

Name	f(u,ut,utt,t) (1)	Initial value (u_0) (1)	Initial value (u_t0) (1/s)	Description
Wout	Woutt-abs(pos_cc(I_pulse))*Ecell*(pos_cc(I_pulse)<0)	0	0	
Win	Wint-abs(pos_cc(I_pulse))*Ecell*(pos_cc(I_pulse)>0)	0	0	

4 Locate the **Units** section. Click **Define Dependent Variable Unit**.

5 In the **Dependent variable quantity** table, enter the following settings:

Dependent variable quantity	Unit
Custom unit	A*V*s

6 Click **Define Source Term Unit**.

7 In the **Source term quantity** table, enter the following settings:

Source term quantity	Unit
Custom unit	A*V

STUDY 1

1 In the **Model Builder** window, click **Study 1**.

2 In the **Settings** window for **Study**, locate the **Study Settings** section.

3 Clear the **Generate default plots** check box.

4 Clear the **Generate convergence plots** check box.

Step 1: Current Distribution Initialization

Shut off solving for the Cumulative Energy Density in the first study step.

1 In the **Model Builder** window, expand the **Study 1** node, then click **Step 1: Current Distribution Initialization**.

2 In the **Settings** window for **Current Distribution Initialization**, locate the **Physics and Variables Selection** section.

3 In the table, clear the **Solve for** check box for **Cumulative Energy Output and Input (ge)**.

Step 2: Time Dependent

Specify the times of interest to store in the solution in the times list.

1 In the **Model Builder** window, click **Step 2: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 In the **Output times** text field, type `range(0,1,9) 9.999 10 10.001 range(11,1,19) 19.999 20 20.001 range(21,1,30)`.

4 From the **Tolerance** list, choose **User controlled**.

5 In the **Relative tolerance** text field, type `1e-3`.

Parametric Sweep

The polarization in the pulse gives an indication of the rate capability of the battery cell. Set a parametric sweep to vary the three parameters.

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
SOCcell_init (Initial cell state-of-charge)	0.60 0.40 0.60 0.60	

5 Click **Add**.

6 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
rp_pos (Particle size positive electrode)	2e-6 2e-6 5e-7 2e-6	m

7 Click **Add**.

8 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
epsl_pos (Porosity positive electrode)	0.40 0.40 0.40 0.10	

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node, then click **Time-Dependent Solver 1**.

3 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Absolute Tolerance** section.

4 From the **Tolerance method** list, choose **Manual**.

Strict time stepping improves convergence for this model.

5 Click to expand the **Time Stepping** section. From the **Steps taken by solver** list, choose **Strict**.

6 In the **Study** toolbar, click **Compute**.

High Current Pulse

1 In the **Model Builder** window, under **Study 1>Solver Configurations** click **Parametric Solutions 1 (sol3)**.

2 In the **Settings** window for **Solution**, type `High Current Pulse` in the **Label** text field.

RESULTS

Current

Plot the current profile of the pulse.

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Current` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/High Current Pulse (sol3)**.

4 From the **Parameter selection (SOCcell_init, rp_pos, epsl_pos)** list, choose **First**.

5 Locate the **Plot Settings** section.

6 Select the **x-axis label** check box. In the associated text field, type `Time (s)`.

7 Select the **y-axis label** check box. In the associated text field, type `Current (A)`.

Global 1

1 Right-click **Current** and choose **Global**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>I_pulse - 10 C pulse test - A**.

3 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
I_pulse	A	

4 Click to expand the **Legends** section. Clear the **Show legends** check box.

5 In the **Current** toolbar, click **Plot**.

Cell voltage during discharge pulse

Evaluate the polarization in the 10 s discharge period in the following plots.

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Cell voltage during discharge pulse` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/High Current Pulse (sol3)**.

4 From the **Time selection** list, choose **From list**. In the **Times (s)** list, choose all times from **0** to **19.999**.

5 Click to expand the **Title** section. From the **Title type** list, choose **None**.

6 Locate the **Plot Settings** section.

7 Select the **x-axis label** check box. In the associated text field, type `Time (s)`.

8 Select the **y-axis label** check box. In the associated text field, type `Cell voltage (V)`.

Global 1

1 Right-click **Cell voltage during discharge pulse** and choose **Global**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>Ecell - Battery cell voltage - V**.

3 Locate the **Legends** section. From the **Legends** list, choose **Evaluated**.

4 In the **Legend** text field, type `SOC0=eval(SOCcell_init), rp_pos=eval(rp_pos) m, epsl_pos=eval(epsl_pos)`.

Global 2

1 Right-click **Global 1** and choose **Duplicate**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/High Current Pulse (sol3)**.

4 From the **Parameter selection (SOCcell_init, rp_pos, epsl_pos)** list, choose **From list**.

5 In the **Parameter values (SOCcell_init,rp_pos (m),epsl_pos)** list, choose **1: SOCcell_init=0.6, rp_pos=2E-6 m, epsl_pos=0.4** and **2: SOCcell_init=0.4, rp_pos=2E-6 m, epsl_pos=0.4**.

6 From the **Time selection** list, choose **From list**. In the **Times (s)** list, choose all times from **0** to **19.999**.

7 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>EOCVcell - Open-circuit cell voltage, coulombic - V**.

8 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

9 Locate the **Legends** section. From the **Legends** list, choose **Manual**.

10 In the table, enter the following settings:

Legends
`Open circuit, orig. design (blue)`
`Open circuit, lower SOC0 (green)`

Cell voltage during discharge pulse

1 In the **Model Builder** window, click **Cell voltage during discharge pulse**.

2 In the **Settings** window for **1D Plot Group**, locate the **Legend** section.

3 From the **Position** list, choose **Lower right**.

4 In the **Cell voltage during discharge pulse** toolbar, click **Plot**.

Positive potential during discharge pulse

1 Right-click **Cell voltage during discharge pulse** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Positive potential during discharge pulse` in the **Label** text field.

3 Locate the **Plot Settings** section. In the **y-axis label** text field, type `Potential (V)`.

Global 1

1. In the **Model Builder** window, expand the **Positive potential during discharge pulse** node, then click **Global 1**.
2. In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>Epos - Positive electrode potential - V**.

Global 2

1. In the **Model Builder** window, click **Global 2**.
2. In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>EOCPpos - Open-circuit potential in positive electrode, coulombic - V**.
3. In the **Positive potential during discharge pulse** toolbar, click **Plot**.

Negative potential during discharge pulse

1. In the **Model Builder** window, right-click **Positive potential during discharge pulse** and choose **Duplicate**.
2. In the **Settings** window for **1D Plot Group**, type `Negative potential during discharge pulse` in the **Label** text field.

Global 1

1. In the **Model Builder** window, expand the **Negative potential during discharge pulse** node, then click **Global 1**.
2. In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>Eneg - Negative electrode potential - V**.

Global 2

1. In the **Model Builder** window, click **Global 2**.
2. In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>EOCPneg - Open-circuit potential in negative electrode, coulombic - V**.

Negative potential during discharge pulse

1. In the **Model Builder** window, click **Negative potential during discharge pulse**.
2. In the **Settings** window for **1D Plot Group**, locate the **Legend** section.
3. From the **Position** list, choose **Middle right**.
4. In the **Negative potential during discharge pulse** toolbar, click **Plot**.

Polarization during discharge pulse

1 In the **Model Builder** window, right-click **Cell voltage during discharge pulse** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Polarization during discharge pulse` in the **Label** text field.

3 Locate the **Plot Settings** section. In the **y-axis label** text field, type `Polarization (V)`.

Global 1

1 In the **Model Builder** window, expand the **Polarization during discharge pulse** node, then click **Global 1**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>Total_polarization - Total battery cell polarization - V**.

Global 2

In the **Model Builder** window, right-click **Global 2** and choose **Disable**.

Polarization during discharge pulse

1 In the **Model Builder** window, click **Polarization during discharge pulse**.

2 In the **Settings** window for **1D Plot Group**, locate the **Legend** section.

3 From the **Position** list, choose **Upper right**.

4 In the **Polarization during discharge pulse** toolbar, click **Plot**.

Internal resistance

Calculate the internal resistance in the different battery designs at the end of the 10 s 10C discharge.

1 In the **Results** toolbar, click 8.5 **Global Evaluation**.

2 In the **Settings** window for **Global Evaluation**, type `Internal resistance` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/High Current Pulse (sol3)**.

4 From the **Time selection** list, choose **From list**.

5 In the **Times (s)** list, select **10**.

6 Locate the **Expressions** section. Click **Clear Table**.

7 In the table, enter the following settings:

Expression	Unit	Description
`Total_polarization/(abs(I_pulse))`	Ω	

8 Click **Evaluate**.

Cell voltage during discharge pulse

Investigate the charge neutral pulse.

Cell voltage during pulse

1 In the **Model Builder** window, right-click **Cell voltage during discharge pulse** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Cell voltage during pulse` in the **Label** text field.

3 Locate the **Data** section. From the **Time selection** list, choose **All**.

Global 2

1 In the **Model Builder** window, expand the **Cell voltage during pulse** node, then click **Global 2**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Time selection** list, choose **All**.

Cell voltage during pulse

1 In the **Model Builder** window, click **Cell voltage during pulse**.

2 In the **Cell voltage during pulse** toolbar, click **Plot**.

Energy efficiency

Calculate the energy efficiency.

1 In the **Results** toolbar, click **Global Evaluation**.

2 In the **Settings** window for **Global Evaluation**, type `Energy efficiency` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/High Current Pulse (sol3)**.

4 From the **Time selection** list, choose **Last**.

5 From the **Table columns** list, choose **Outer solutions**.

6 Locate the **Expressions** section. Click **Clear Table**.

7 In the table, enter the following settings:

Expression	Unit	Description
`Wout/Win`	1	

8 Click **Evaluate**.