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An Equivalent Circuit Model for a Nickel–Metal Hydride Battery

Introduction

Equivalent circuits models are commonly employed for modeling electrochemical devices. This simulation approach relies on a lumped approach for representing the underlying electrochemical processes using electrical circuit elements, without a detailed description of the electrode materials, geometry configuration, and physical processes. Despite their simplicity, equivalent circuit models are capable of qualitatively capturing transient or steady-state voltage and current characteristics of electrochemical devices. The parameters in each circuit element are typically obtained by fitting the model to experimental data. However, the individual parameter values may be difficult to correlate to specific parts of, or phenomena occurring in, the electrochemical cell.

This tutorial defines an equivalent circuit model for a nickel–metal hydride (Ni–MH) battery. The same modeling approach can be used to model other battery chemistries.

Model Definition

The 0D model simulates a nickel–metal hydride battery using an equivalent circuit model. The model consists of two resistors, a capacitor, a current source, and a voltage source depending on the battery state of charge (SOC). Various charge-discharge cycles at different C-rates are simulated using a parametric sweep.

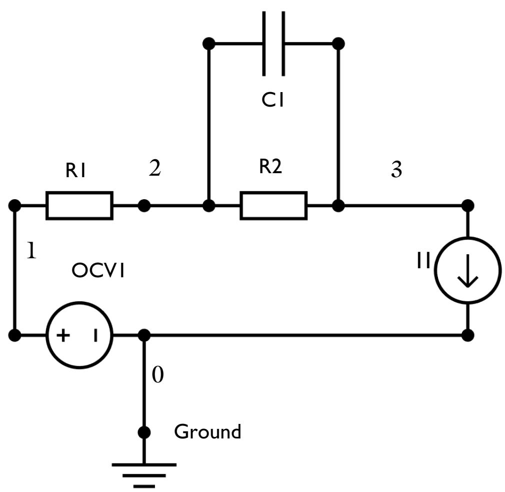

Figure 1: Equivalent Circuit diagram used for modeling the Ni-MH battery. The numbers denote the node numbers in the Battery Equivalent Circuit interface.

The circuit is based on the Newman-Ong (Ref. 1) approach for modeling electrochemical systems.

Figure 1 represents the equivalent circuit used in this simulation. The series resistance (R1) represents the ohmic resistance and the RC couple (a resistor-R2 and capacitor-C1 connected in parallel) represents the charge transfer polarization process. The time constant for the RC couple is assumed to be 15 s. The Battery Open Circuit Voltage node (OCV1) requires battery open circuit voltage data, E_{OCV} (V), as function of state of charge. Initial battery capacity and state of charge are also required as inputs for the Battery Open Circuit Voltage node.

The load cycle is represented through a current source (I1) connected in series with the Battery Open Circuit Voltage node.

The fundamental equations solved for in the Battery Equivalent Circuit interface are Kirchhoff's current and voltage laws. A current balance for each branch node (see Figure 1) is defined as:

$$I + I_{R2} + I_{C1} = 0$$

By summing the voltage around resistors R1 and R2, we get:

$$V = E_{\mathrm{OCV}} - IR_1 + I_{R2}R_2$$

By summing the voltage around capacitor C1, we get:

$$V = E_{\mathrm{OCV}} - IR_1 + \frac{Q}{C}$$

Using a time-dependent study, charge-discharge cycles for various C-rates are modeled.

Results and Discussion

Figure 2 shows the computed node voltage at node 3, during charge and discharge for different C-rates.

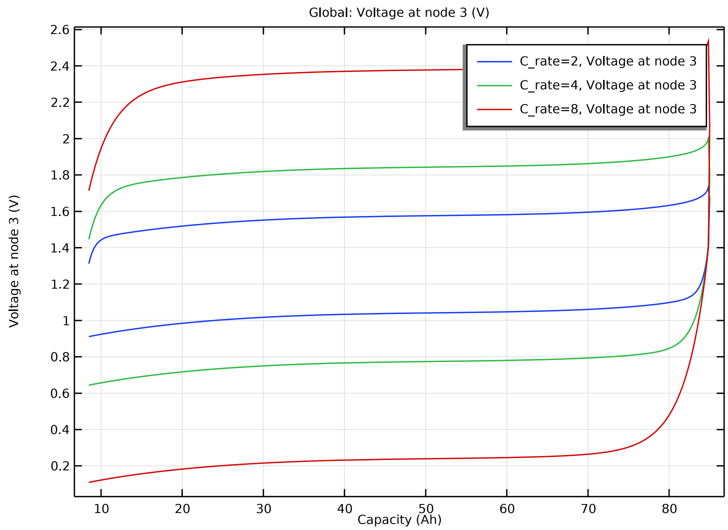

Figure 2: Voltage at node 3 for different C-rates.

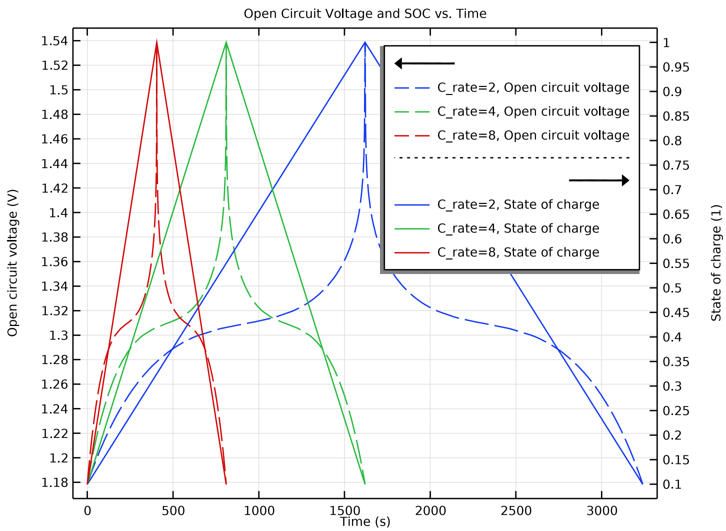

Figure 3: Open circuit potential and state of charge for different C-rates.

Figure 3 shows the open circuit potential and state of charge for various C-rates. The model is able to capture the charge-discharge characteristics of NiMH batteries.

Notes About the COMSOL Implementation

E_{OCV} for the intercalation electrodes is calculated via following equation (Ref. 2):

$$E_{\mathrm{OCV}} = \left(U_0(\mathrm{discharge}) + \sum_{j=1} (\upsilon_{j,\,\mathrm{discharge}})(\mathrm{SOC})^j + \frac{RT}{nF}\ln\left(\frac{\mathrm{SOC}}{1-\mathrm{SOC}}\right)\right)$$

where SOC is the state of charge and $\nu_{j,\mathrm{discharge}}$ are the coefficients used to determine the open circuit cell potential. The values of the coefficients are given in Table 1.

TABLE 1: PARAMETERS DESCRIBING OPEN CIRCUIT CELL POTENTIAL.

PARAMETER	UNIT	FOR DISCHARGE
ν_j	1	3
U_0	V	1.779
ν_1(V)	V	0.6845
ν_2(V)	V	-1.1779
ν_3(V)	V	0.6127

References

1. I.J. Ong and J. Newman, "Double Layer Capacitance in a Dual Lithium Ion Insertion Cell," *J. Electrochem. Soc.*, vol. 146, no. 12, pp. 4360–4365, 1999.

2. M.W. Verbrugge and R.S. Conell, "Electrochemical and Thermal Characterization of Battery Design Modules Commensurate with Electric Vehicle Integration," *J. Electrochem. Soc.*, vol. 149, no. 1, pp. A45–A53, 2002.

Application Library path: `Battery_Design_Module/Batteries,_General/nimh_equivalent_circuit_battery`

Modeling Instructions

This tutorial demonstrates how to build an equivalent circuit battery model and run a time-dependent simulation for a charge/discharge load cycle.

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **0D**.

2 In the **Select Physics** tree, select **Electrochemistry>Batteries>Battery Equivalent Circuit (cir)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies>Time Dependent**.

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

Import the model parameters from a text file.

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

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

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `nimh_equivalent_circuit_battery_parameters.txt`.

Step 1 (step1)

In the **Home** toolbar, click **Functions** and choose **Global>Step**.

DEFINITIONS

Variables 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Definitions** and choose **Variables**.

The battery charging and discharging variables are set up as follows:

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

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `nimh_equivalent_circuit_battery_variables.txt`.

ELECTRICAL CIRCUIT (CIR)

Set up the equivalent circuit for the battery.

Resistor 1 (R1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Electrical Circuit (cir)** click **Resistor 1 (R1)**.

2 In the **Settings** window for **Resistor**, locate the **Device Parameters** section.

3 In the R text field, type `R1`.

Battery Open Circuit Voltage 1 (OCV1)

Information about the battery characteristics is provided as an input to the Battery Open Circuit Voltage node. Next, import the open circuit potential versus state of charge data for nickel metal hydride (Ni-MH) battery.

1 In the **Model Builder** window, click **Battery Open Circuit Voltage 1 (OCV1)**.

2 In the **Settings** window for **Battery Open Circuit Voltage**, locate the **Capacity and Initial State of Charge** section.

3 In the $Q_{\mathrm{cell},0}$ text field, type `Q0`.

4 In the $\mathrm{SOC}_{\mathrm{cell},0}$ text field, type `SOC_0`.

5 Locate the **Open Circuit Voltage** section. Click **Clear Table**.

6 Click **Load from File**.

7 Browse to the model's Application Libraries folder and double-click the file `nimh_equivalent_circuit_battery_E_OCP_data.txt`.

Current Source 1 (I1)

Set up the battery load.

1 In the **Model Builder** window, click **Current Source 1 (I1)**.

2 In the **Settings** window for **Current Source**, locate the **Device Parameters** section.

3 In the i_{src} text field, type `i_load`.

Resistor-Capacitor Couple 1 (RC1)

Next, define the RC couple in the circuit to represent polarization.

1 In the **Model Builder** window, click **Resistor-Capacitor Couple 1 (RC1)**.

2 In the **Settings** window for **Resistor-Capacitor Couple**, locate the **Device Parameters** section.

3 From the list, choose **Resistance and capacitance**.

4 In the R text field, type `R2`.

5 In the C text field, type `C1`.

STUDY 1

Set up a time-dependent study and a parametric sweep for various charge/discharge C-rates.

Parametric Sweep

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
C_rate (C-rate)	2 4 8	1

Step 1: Time Dependent

1 In the **Model Builder** window, click **Step 1: 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,t_cycle/1000,t_cycle)`.

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

RESULTS

Plot the currents, voltage, and state of charge resulting from the simulation.

Load Cycle Voltage

1. In the **Model Builder** window, expand the **Results** node.
2. Right-click **Results** and choose **1D Plot Group**.
3. In the **Settings** window for **1D Plot Group**, type `Load Cycle Voltage` in the **Label** text field.
4. Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.

Global 1

1. Right-click **Load Cycle Voltage** 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)> Electrical Circuit>Node voltages>cir.v_3 - Voltage at node 3 - V**.
3. Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
4. In the **Expression** text field, type `Q0*comp1.cir.OCV1_SOC`.
5. From the **Unit** list, choose **Ah**.
6. Select the **Description** check box. In the associated text field, type `Capacity`.
7. In the **Load Cycle Voltage** toolbar, click **Plot**.
8. Click the **Zoom Extents** button in the **Graphics** toolbar.

Load Cycle Voltage

In the **Model Builder** window, right-click **Load Cycle Voltage** and choose **Duplicate**.

Open Circuit Voltage and SOC vs. Time

1. In the **Model Builder** window, under **Results** click **Load Cycle Voltage 1**.
2. In the **Settings** window for **1D Plot Group**, type `Open Circuit Voltage and SOC vs. Time` in the **Label** text field.
3. Click to expand the **Title** section. From the **Title type** list, choose **Label**.
4. Locate the **Plot Settings** section. Select the **Two y-axes** check box.

Open Circuit Voltage

1. In the **Model Builder** window, expand the **Open Circuit Voltage and SOC vs. Time** 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)> Electrical Circuit>cir.OCV1.E_OCV - Open circuit voltage - V**.

3 In the **Label** text field, type `Open Circuit Voltage`.

4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Time**.

5 In the **Open Circuit Voltage and SOC vs. Time** toolbar, click **Plot**.

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

Cell State of Charge

1 In the **Model Builder** window, right-click **Open Circuit Voltage and SOC vs. Time** 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)> Electrical Circuit>cir.OCV1.SOC - State of charge - 1**.

3 In the **Label** text field, type `Cell State of Charge`.

4 Locate the **y-Axis** section. Select the **Plot on secondary y-axis** check box.

5 Locate the **Coloring and Style** section. From the **Color** list, choose **Cycle (reset)**.

6 In the **Open Circuit Voltage and SOC vs. Time** toolbar, click **Plot**.

7 Click the **Zoom Extents** button in the **Graphics** toolbar.