The primary objective of this project is to introduce a more appropriate battery model (compared with that used in Project 1) in order to predict its round-trip efficiency. A central part of the overall battery model is the model of an individual cell. A first-order equivalent-circuit model of an individual cell is shown in Figure 1. Note that with the sign convention used, a positive current discharges the cell while a negative current charges the cell. Here, v_{oc} represents the open circuit voltage (OCV) of the cell, R_0 and R_1 represent the internal losses, and C_1 represents the transient response under load changes. These parameters can be related to electrochemical processes taking place inside the cell. For example, R_0 represents the bulk resistance and solid electrolyte interface (SEI) layer impedance while R_1 and C_1 capture the losses and dynamics of the lithium ions moving through the electrolyte. The battery is assumed to consist of N_p parallel-connected strings, each with N_s series connected cells.

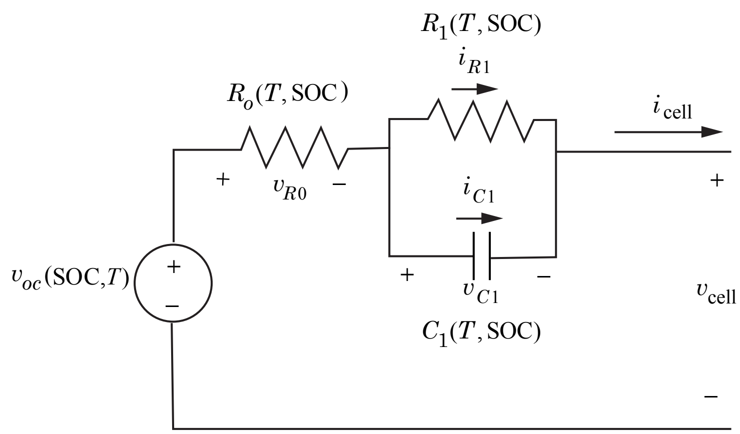

Figure 1: Equivalent-circuit cell model.

1 Problem Statement

In this project, we will examine several charge-discharge cycles to examine the effects on losses and round-trip efficiency. To achieve these goals, you will be provided with a Simulink battery model that accepts i_{batt} as an input and outputs battery terminal voltage. The current will be used to determine the state of charge (SOC) of the battery using the Coulomb-counting method as described later. The goal of this project is to (i) calculate the SOC versus time and the round trip efficiency of the battery, and (ii) compare the results with the assumed efficiency (80%) of the simplified battery/electric machine/converter model used in Project 1. The SOC should not fall below 0.2 or exceed 1.0.

2 Implementation

A top-level block diagram of the system model is shown in Fig. 2. The battery model consists of cell model, an SOC estimator, and a table look up that determines the open circuit voltage as a function of the SOC. These models are described further in the following paragraphs.

In the circuit model of a cell, assume the initial condition of $v_{C1} = 0$, $v_{\mathrm{cell}} = v_{oc}$, and $i_{\mathrm{cell}} = 0$. Some useful equations are given below. From Kirchhoff's voltage law (KVL) applied to the circuit of Fig. 1,

$$v_{\mathrm{cell}} - v_{oc} + v_{R0} + v_{C1} = 0 \tag{2.1}$$

Kirchhoff's current law (KCL) applied to the same circuit yields

$$i_{R1} + i_{C1} = i_{\mathrm{cell}} \tag{2.2}$$

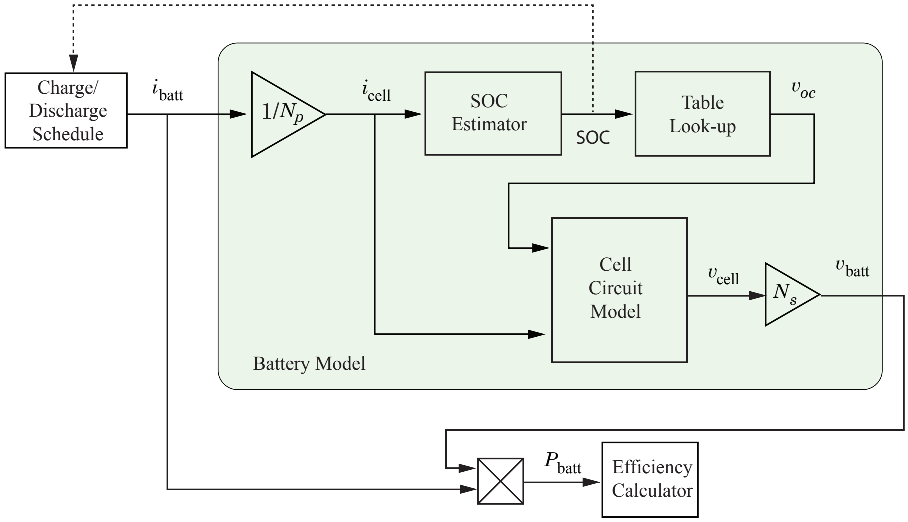

Figure 2: Top-level block diagram.

Finally, the dynamic relationship between capacitor current and voltage may be expressed

$$v_{C1} = \frac{1}{C_1} \int i_{C1} \, \mathrm{d}t \tag{2.3}$$

The preceding equations may be depicted in block-diagram form as shown in Fig. 3.

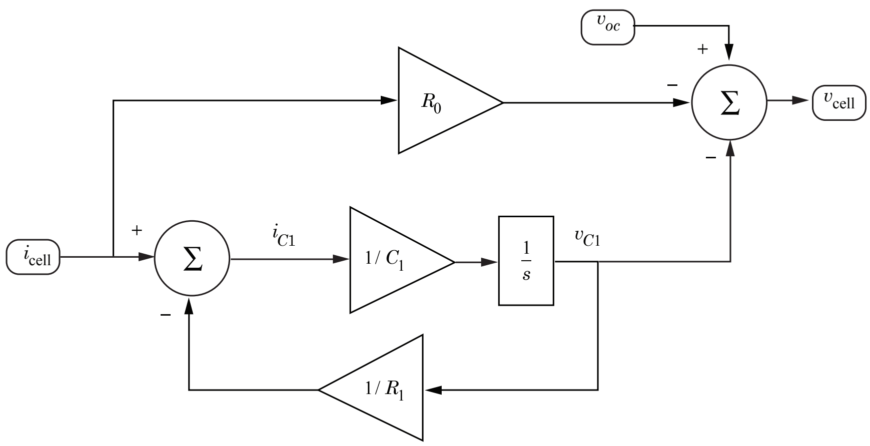

Figure 3: Cell subsystem model.

The parameters of an individual cell are provided in Table 1 corresponding to a temperature of 40° C. The open-circuit voltage v_{oc} versus SOC at $T = 40°$ C is provided in Table 2. Although each of the circuit parameters in the cell model are, in general, a function of the SOC, we will neglect this dependence with the exception of the dependence of v_{oc} on SOC.

Table 1: Cell Parameters at 40° C

Variable	Value	Unit
R_0	0.009	Ω
R_1	0.0015	Ω
C_1	3.5×10^4	F

Table 2: Open-Circuit Voltage vs SOC

SOC	Open-Circuit Voltage, V
0	3.51
0.1	3.57
0.25	3.63
0.5	3.71
0.75	3.93
0.9	4.08
1	4.19

The SOC of the cell is estimated using the Coulomb counting method as shown in Fig. 4. Therein, Q_{cell} is the cell capacity in Coulombs. In practice, the effective cell capacity will be a function of temperature and SOC; however, in this project we will assume it to be fixed and equal to the nominal capacity of 31 Ah. The dependence on temperature and/or SOC can be represented using table-look-up tables.

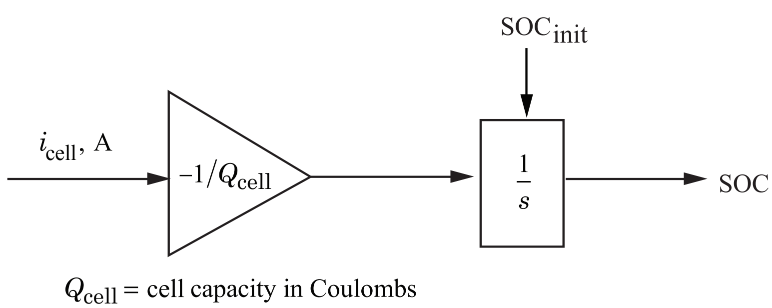

Figure 4: SOC calculation in a single cell.

The round-trip efficiency may be calculated as shown in Fig. 5. Therein, positive battery power is integrated to obtain discharge energy and negative battery power is integrated to obtain charge energy. Round-trip efficiency is defined as the ratio of discharge energy to charge energy. Battery losses may be calculated by subtracting discharge energy from charge energy, or by integrating i^2R power losses in R_0 and R_1.

Please note that the cell data is for a 31 Ah cell[1]. For convenience, the manufacturer's data sheet for the cell is provided at the end of this document. We will assume that the battery consists of 6 parallel strings ($N_p = 6$) of 100 series-connected cells ($N_s = 100$) for a nominal battery voltage of 370 V and battery capacity of 186 Ah (68.8 kWh).

Consider the following charge/discharge cycles.

1. The battery starts at $\mathrm{SOC}_{\mathrm{init}} = 0.2$. It is charged at a C-rate of 0.2 to SOC = 1. Then, it is

[1] Huria, T.; Ceraolo, M.; Gazzarri, J.; Jackey, R.; , "High Fidelity Electrical Model with Thermal Dependence for Characterization and Simulation of High Power Lithium Battery Cells," *2012 IEEE International Electric Vehicle Conference (IEVC)*, pp. 1-8, March 4-8, 2012.

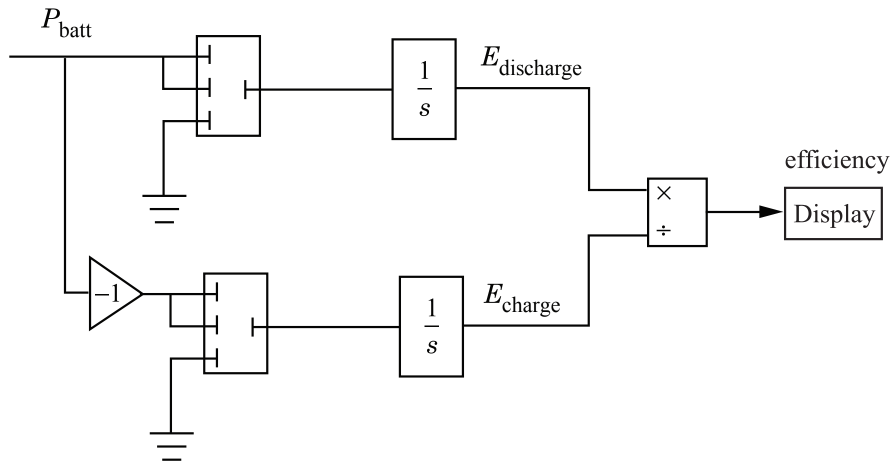

Figure 5: Efficiency calculator.

discharged at a C-rate of 0.2 to SOC = 0.2. (slow charge and discharge).

2. The battery starts at $SOC_{init} = 0.2$. It is charged at a C-rate of 2 to $SOC_{max} = 1$. Then, it is discharged at C-rate = 0.2 to $SOC_{final} = 0.2$. (fast charge, slow discharge).

3. The battery starts at $SOC_{init} = 0.5$. It is charged at a C-rate of 2.0 to $SOC_{max} = 0.55$. Then, it is discharged at C-rate = 2.0 to $SOC_{final} = 0.5$. (fast charge, fast discharge over short time interval).

In each case, plot v_{batt}, i_{batt}, P_{batt}, and SOC. Determine whether the cell voltage exceeds the maximum or falls below the minimum (cut-in) voltage. If so, when and why does this occur. Determine the net energy delivered to the load, the net losses (in kWh), and the round-trip efficiency. Summarize the results in table form. Draw appropriate conclusions.

Grading will be based upon the following criteria: documentation, results, discussion, and supporting analysis. Documentation should be sufficient to allow someone else to duplicate all results based upon information in your report. Each plot (figure) should be labelled and numbered. Each figure should include a discussion to describe its content and any conclusions derived therefrom. Supporting analysis should verify simulated values of battery voltage at a few selected instants of time (e.g. at the beginning and end of the charge and discharge intervals). Verify first law at end of each charge/discharge cycle ($E_{out} + E_{loss} = E_{in}$)

3 Bonus (2 points)

Consider the tractive power requirements established in Project 1 for the US06 cycle. Using the Simulink model provided, calculate the total energy supplied by the battery as the vehicle travels repeated US06 cycles starting from $SOC_{init} = 1$ until SOC hits 0.2. Compare this number to the energy used to fully charge the battery at 0.2C and 2C rates starting with $SOC_{init} = 0.2$. What is the travel time in hours and how far does the vehicle go during this trip (in miles).

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Cell Specification

Typical Capacity[1]		31.0 Ah
Nominal Voltage		3.7 V
Charge Condition	Max. Current	62.0 A
	Voltage	4.2V ± 0.03 V
Discharge Condition	Continuous Current	155.0 A
	Peak Current	310.0 A
	Cut-off Voltage	2.7 V
Cycle Life [@ 80% DOD] [2]		> 800 Cycles
Operating Temp.	Charge	0 ~ 40 ℃
	Discharge	-20 ~ 60 ℃
Dimension	Thickness (mm)	8.4 ± 0.5
	Width (mm)	215 ± 2.0
	Length (mm)	220 ± 2.0
Weight (g)		860 ± 40

1) Typical Capacity : 0.5C, 4.2~2.7V @25°C
2) Voltage range : 4.15V ~ 3.40V