ME 597 Project 3 Report

Grant Gottlieb

Analysis of Battery Performance

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1. Introduction

This project aims to model and analyze the performance of a lithium-ion battery system using an equivalent circuit model in Simulink. The focus is on evaluating battery round-trip efficiency through 3 separate cycles by measuring the voltage, current, power, and state of charge (SOC). The results are compared to an assumed baseline efficiency of 80% used in earlier models. The model highlights the effects of C-rate on battery efficiency, while considering internal losses and transient dynamics using circuit-based modeling techniques

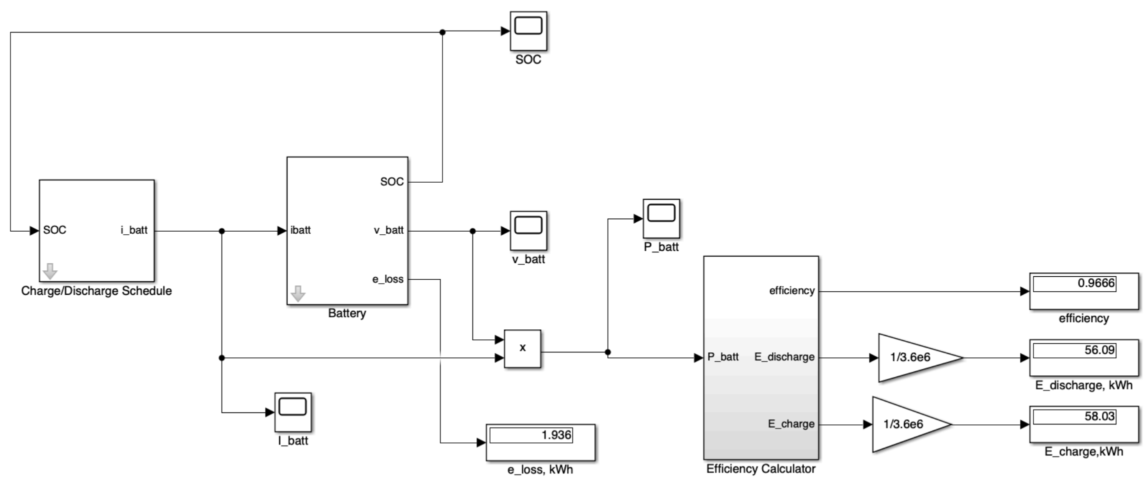


Figure 1: System Overview

2. Model Description

The battery model consists of a first-order equivalent circuit per cell. A Coulomb-counting method is used to estimate the state of charge (SOC), and the open-circuit voltage is extracted using a lookup table as a function of SOC. The battery pack is composed of 6 parallel strings, each consisting of 100 series cells, yielding a nominal pack capacity of 186 Ah and voltage of 370 V.

The top-level system includes:

- Charge/discharge schedule block
- Battery equivalent circuit block
- SOC estimator
- Table-based OCV block
- Efficiency Calculator

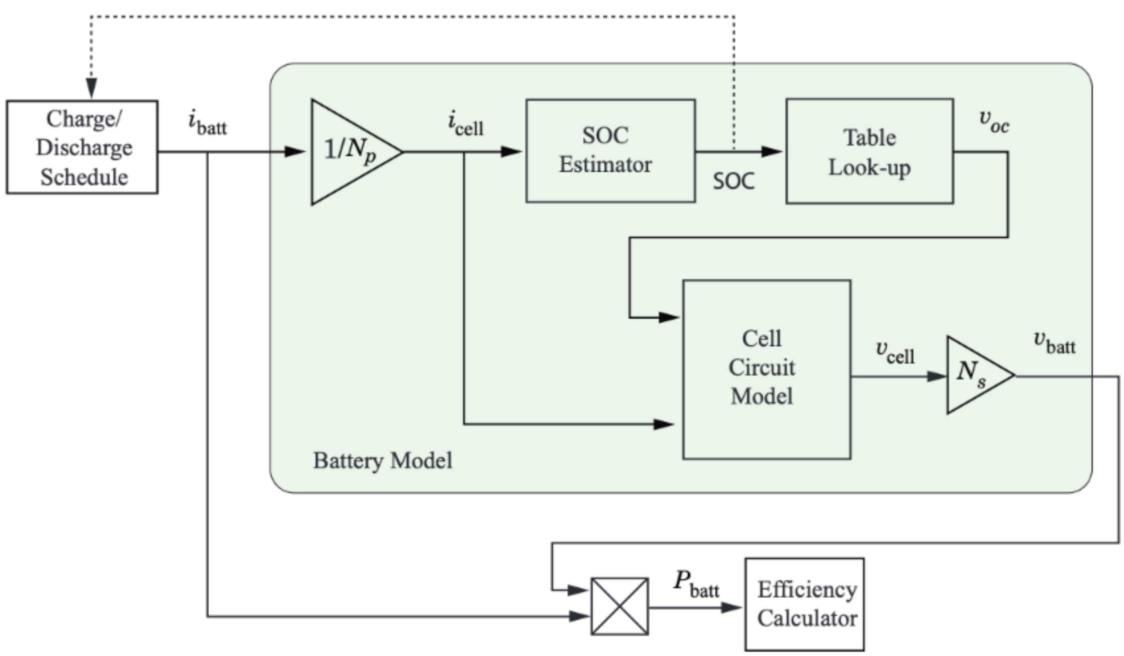


Figure 2: Top Level Block Diagram

3. Simulation Setup

Each simulation cycle involves setting initial SOC, defining C-rates for charging and discharging, and ensuring SOC remains between 0.2 and 1.0. Three test cases were considered:

1. Slow charge and discharge (0.2C in both directions)
2. Fast charge (2C) and slow discharge (0.2C)
3. Fast charge and discharge (2C in both directions)

Simulink outputs include battery voltage, current, power, and SOC over time. MATLAB was used for initialization and can be seen in Appendix C.

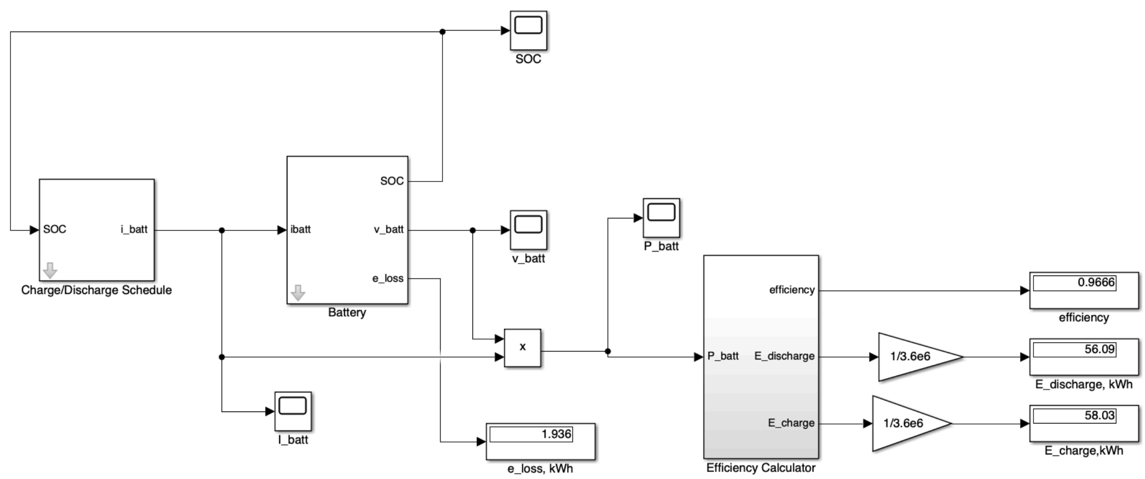


Figure 3: Simulink Model

4. Results & Discussion

4.1 Cycle 1 – Slow Charge/Discharge (0.2C)

Cycle 1 has a slow charge and discharge of 0.2C. The initial state of charge is 0.2 before peaking at 1.0, and then discharging back down to 0.2. This cycle is expected to yield high efficiency with minimal losses.

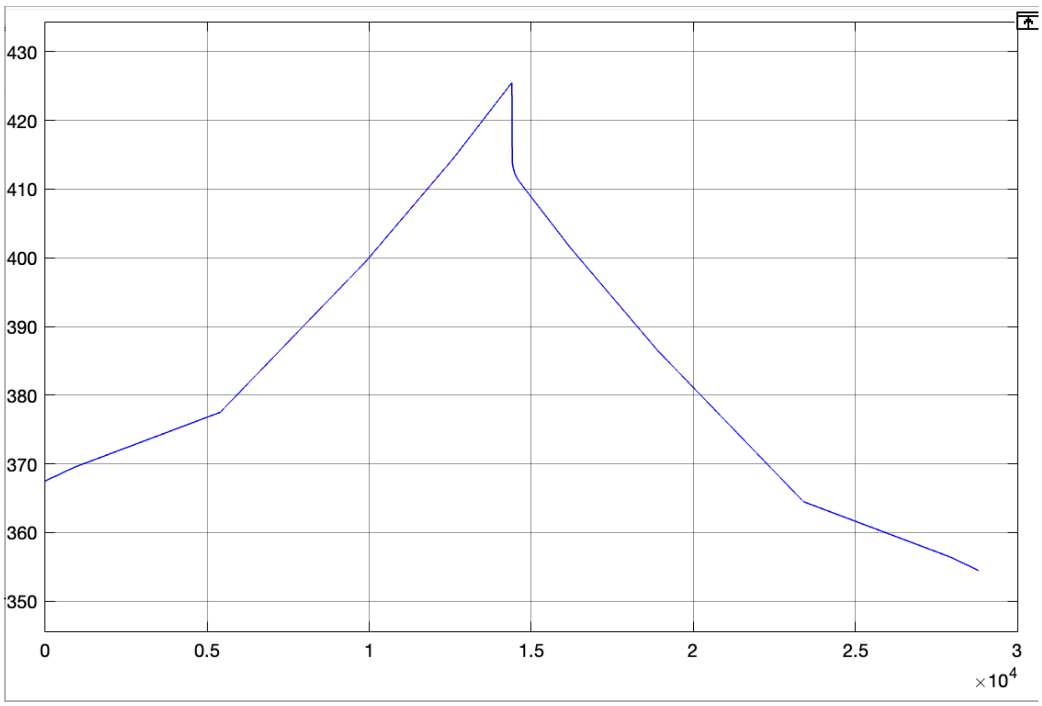


Figure 4: V_batt vs Time (s)

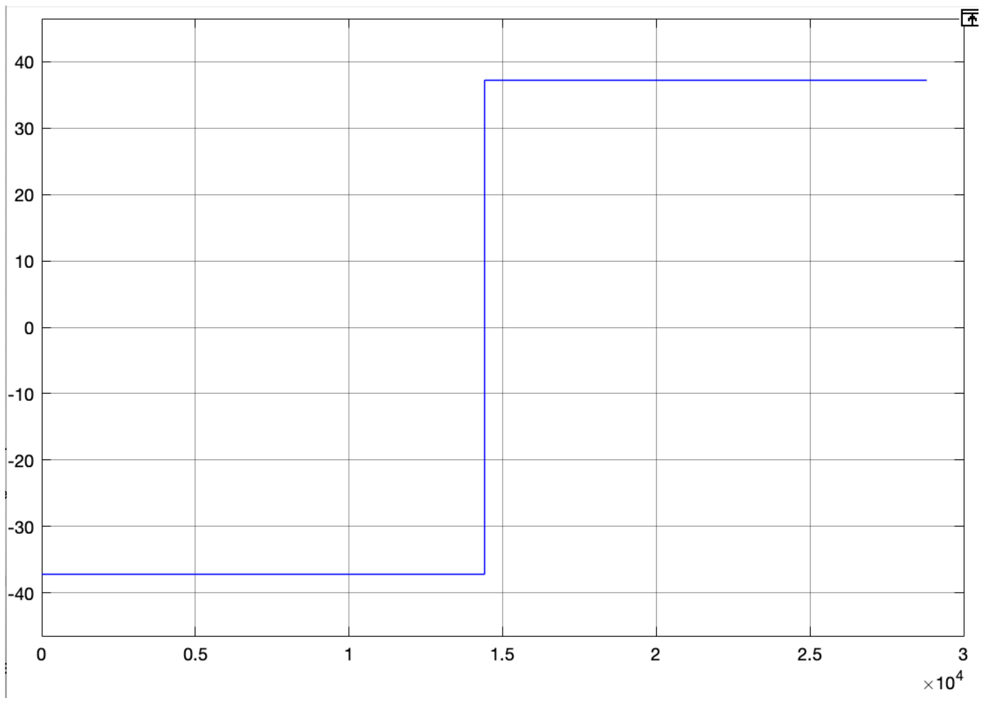


Figure 5: I_batt vs Time (s)

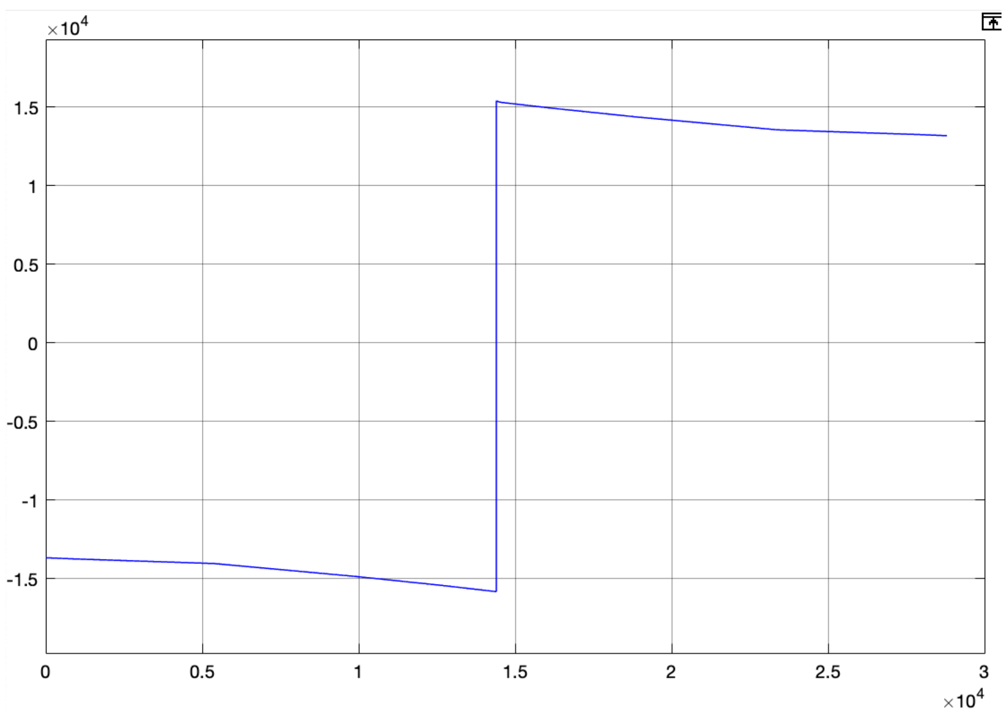


Figure 6: P_batt vs Time (s)

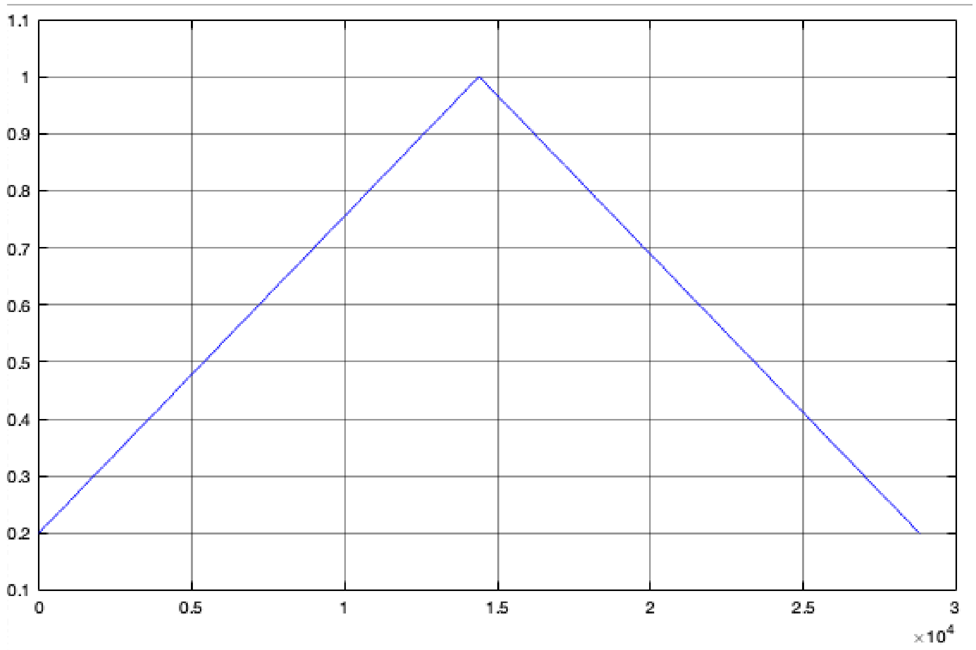


Figure 7: SOC vs Time (s)

Metric	Value
E_charge	58.03 kWh
E_discharge	56.09 kWh
E_loss	1.94 kWh
Efficiency (%)	96.66%
Cell Voltage Max/Min Violated?	Max-Yes, Min-No
Time to Charge/Discharge	Charge - 14,400s (4 hrs), Discharge - 14400s (4hrs)

Table 1: Cycle 1 Results

The graph depicting the current with respect to time (Figure 5) shows that the current is negative while the battery charges and is positive while discharging. The voltage plot (Figure 4) on the other hand, shows an increasing, positive voltage during charging and a decreasing, positive voltage while discharging. Battery power is the product of the current and voltage, indicating that the power should be negative during charging, and positive during discharging.

Our plot depicts this as expected in Figure 6. This makes sense because when the battery is using “negative” power, it is technically adding more power and charging.

In Figure 7, it can be seen that the battery state of charge increases at a constant rate before suddenly decreasing at a constant rate. This state of charge trend is good and promotes a healthy battery life.

4.2 Cycle 2 – Fast Charge (2C), Slow Discharge (0.2C)

Cycle 2 has a fast charge of 2C and a slow discharge of 0.2C. The initial state of charge is 0.2 before peaking at 1.0 quickly, and then slowly discharging back down to 0.2. This cycle is not expected to perform with as high efficiency as cycle 1.

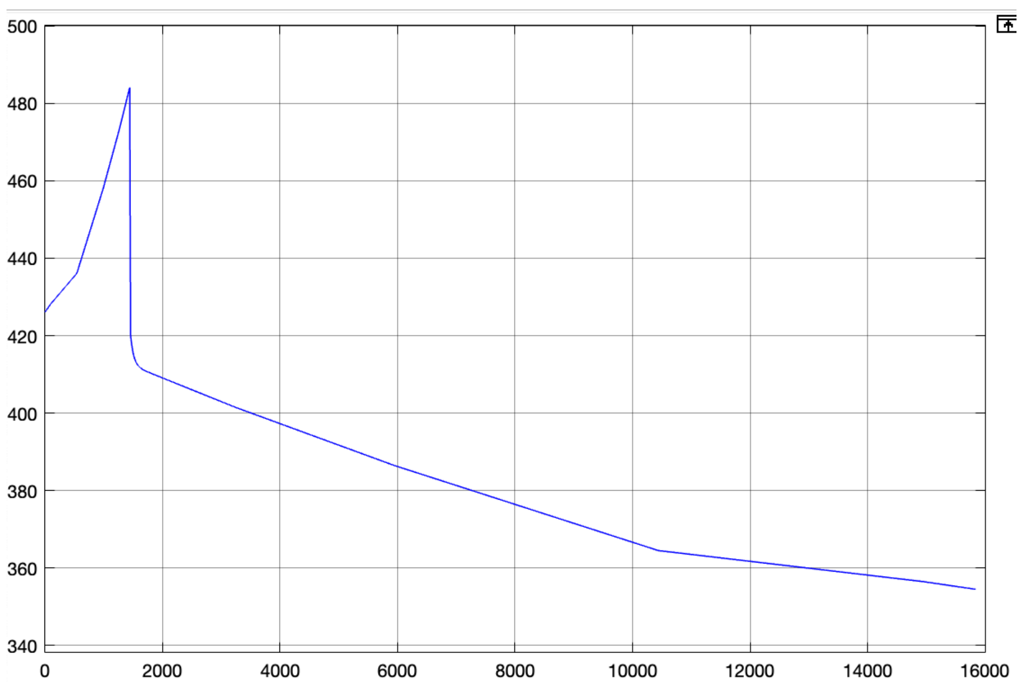


Figure 8: V_batt vs Time (s)

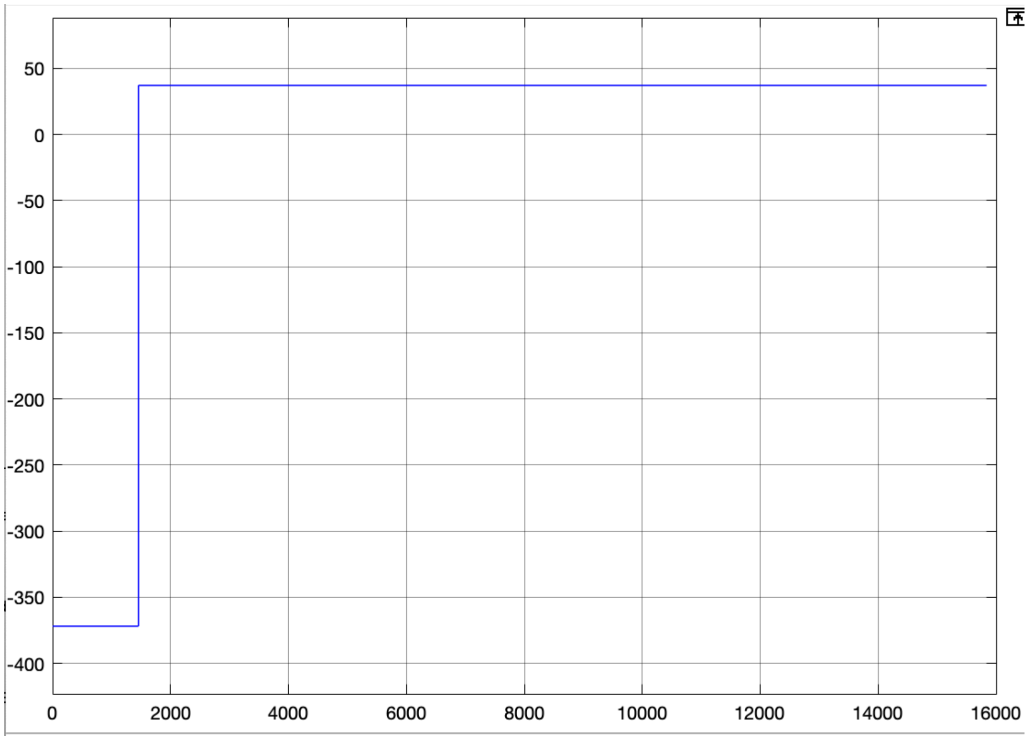


Figure 9: I_batt vs Time (s)

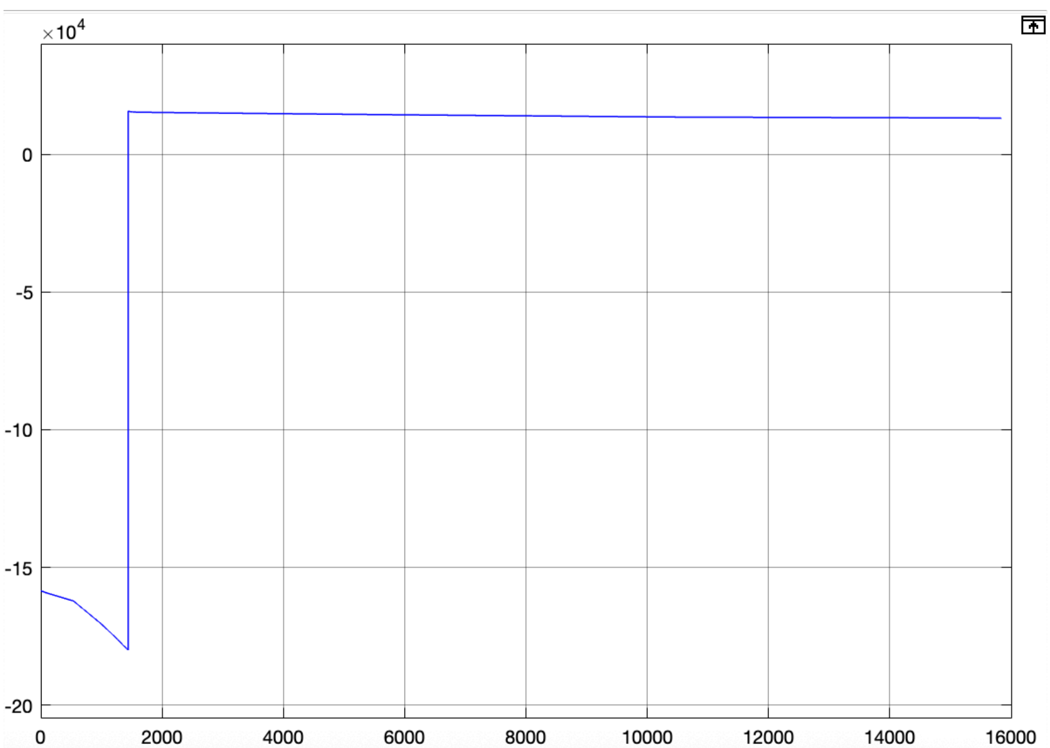


Figure 10: P_batt vs Time (s)

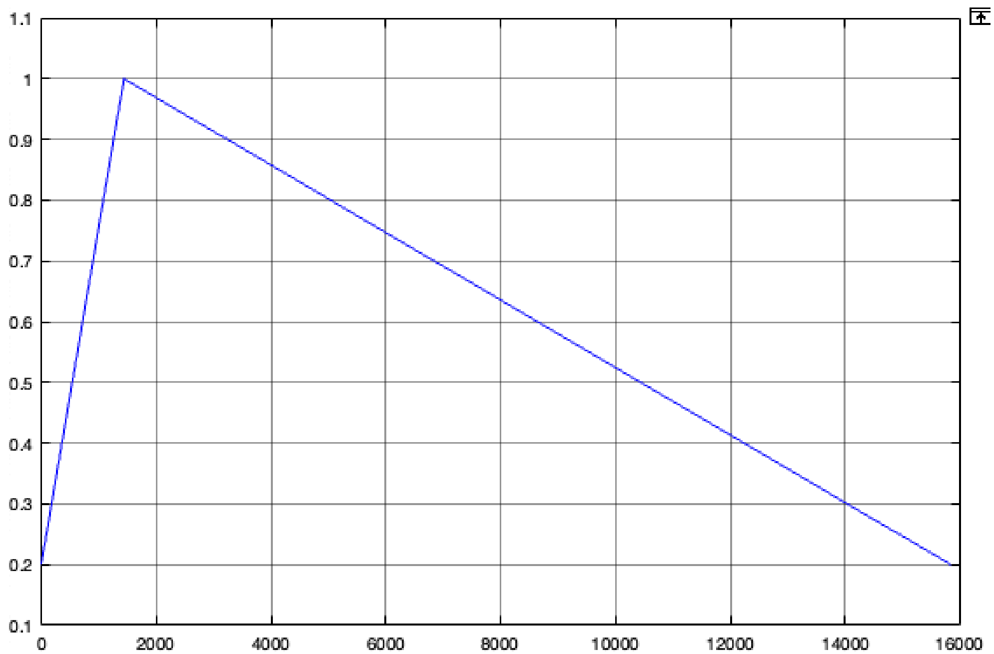


Figure 11: SOC vs Time (s)

Metric	Value
E_charge	66.75 kWh
E_discharge	56.1 kWh
E_loss	10.65 kWh
Efficiency (%)	84.04%
Cell Voltage Max/Min Violated?	Max-Yes, Min-No
Time to Charge/Discharge	Charge - 1,446s (0.4 hrs), Discharge - 14,383s (3.99 hrs)

Table 2: Cycle 2 Results

The graph depicting the current with respect to time (Figure 9) shows that the current is negative while the battery charges and is positive while discharging. The voltage plot (Figure 8) shows an increasing voltage during charging and a decreasing voltage while discharging. It is important to note that the voltage remains positive throughout the entire cycle. Our plot depicts the battery power as expected in Figure 10, with negative power as charging and positive while discharging. In Figure 11, it can be seen that the battery state of charge increases at a quick rate before suddenly decreasing at a slower rate due to the nature of this cycle.

4.3 Cycle 3 – Fast Charge/Discharge (2C)

Cycle 3 has a fast charge and discharge of 2C. The initial state of charge is 0.5 before peaking at 0.55 quickly, and then quickly discharging back down to 0.5. This cycle is expected to perform as the most inefficient of the 3 cycles.

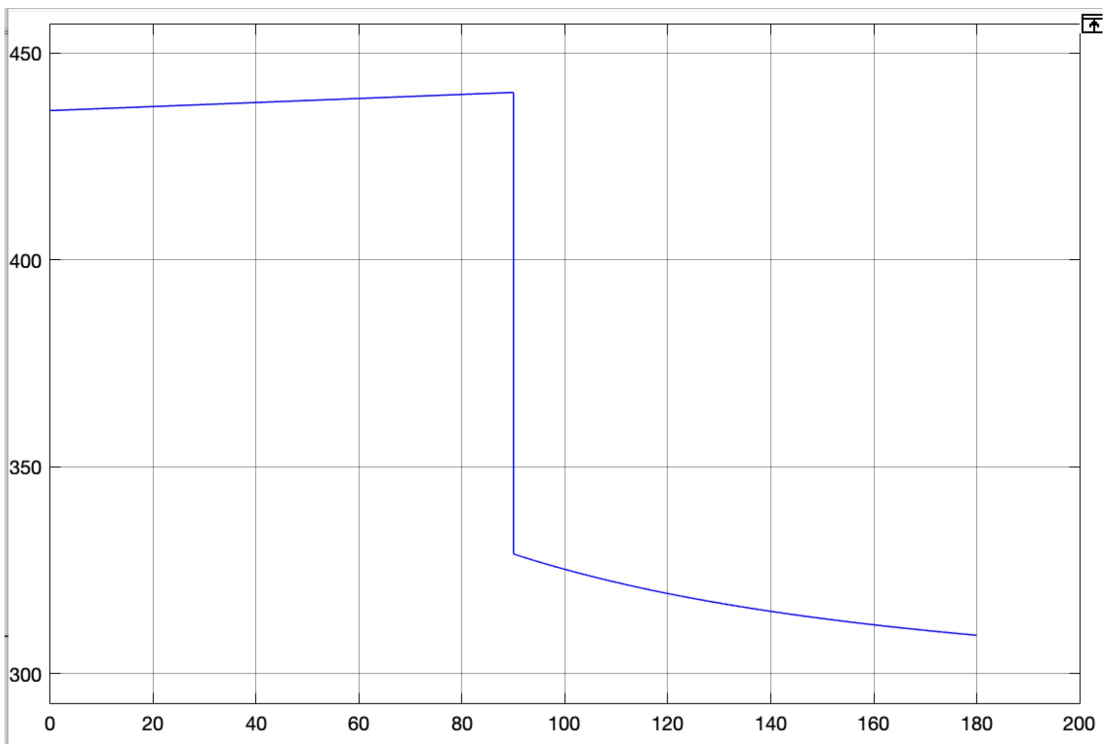


Figure 12: V_batt vs Time (s)

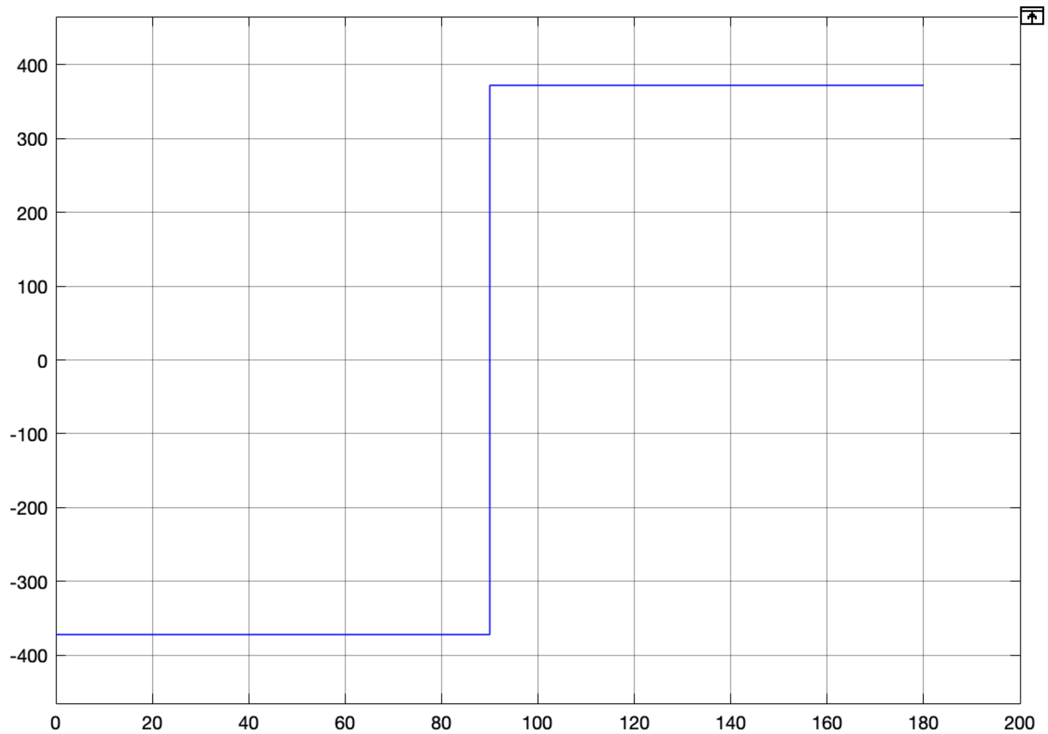


Figure 13: I_batt vs Time (s)

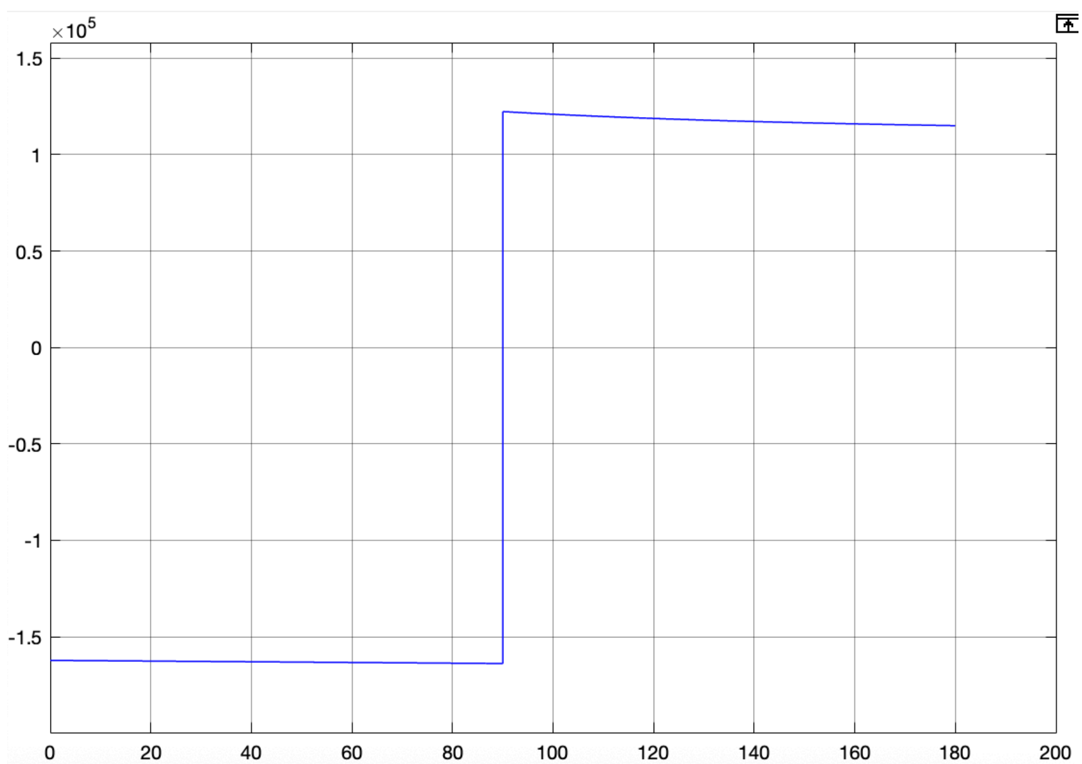


Figure 14: P_batt vs Time (s)

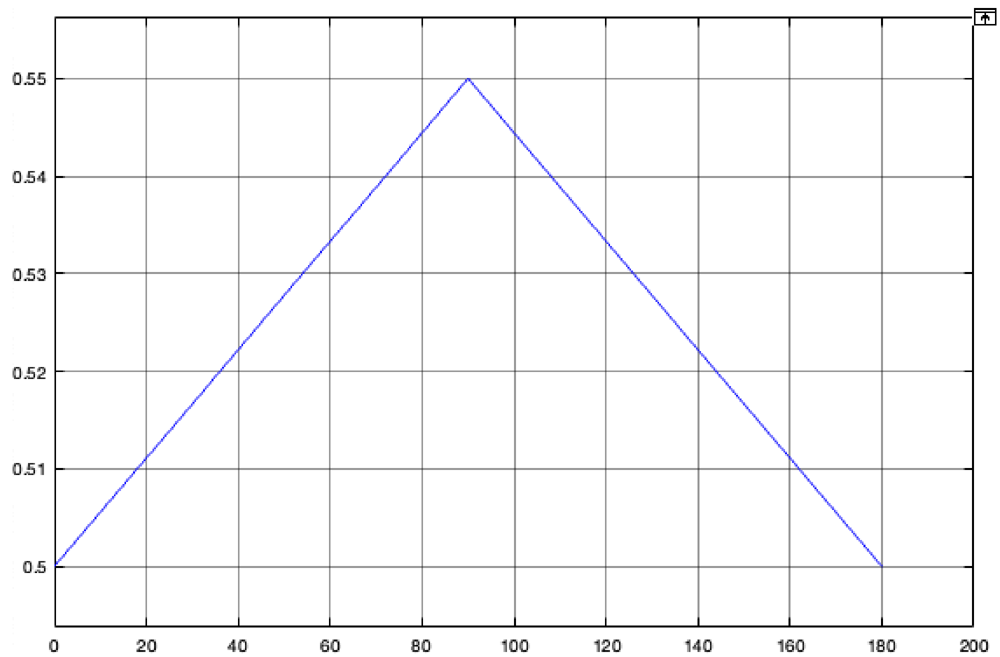


Figure 15: SOC vs Time (s)

Metric	Value
E_charge	4.076 kWh
E_discharge	2.948 kWh
E_loss	1.128 kWh
Efficiency (%)	72.32%
Cell Voltage Max/Min Violated?	Max-Yes, Min-No
Time to Charge/Discharge	Charge - 90s (0.025 hrs), Discharge - 90s (0.025 hrs)

Table 3: Cycle 3 Results

The graphs for this cycle depict all of the same trends as seen in the previous 2 cycles. The major difference in this data is that the SOC has a smaller range and the charge and discharge rate are both fast. Because of this, the efficiency of this cycle is the worst at 72.32%. The cycle is inefficient because of the high current both ways and the short cycle amplifying the loss.

4.4 Comparison of All Cycles

Across the three cycles, Cycle 1 had the highest efficiency (~96.7%) due to slow charging and discharging at 0.2C. Cycle 2, with fast 2C charging and slow discharging, showed reduced efficiency (~84.0%) from higher current losses. Cycle 3 had the worst efficiency (~72.3%). Cycle 3 had fast charging and discharging at 2C which contributed to the inefficiency due to the internal losses being amplified and the shorter cycle. From these results, it is safe to conclude that lower C-rates and longer cycles are more favorable when trying to have maximum battery efficiency.

5. Bonus

The bonus task asked to simulate the US06 drive cycles to determine total energy supplied by the battery, energy to fully recharge at 0.2 and 2.0 C-rate, travel time, and total distance traveled.

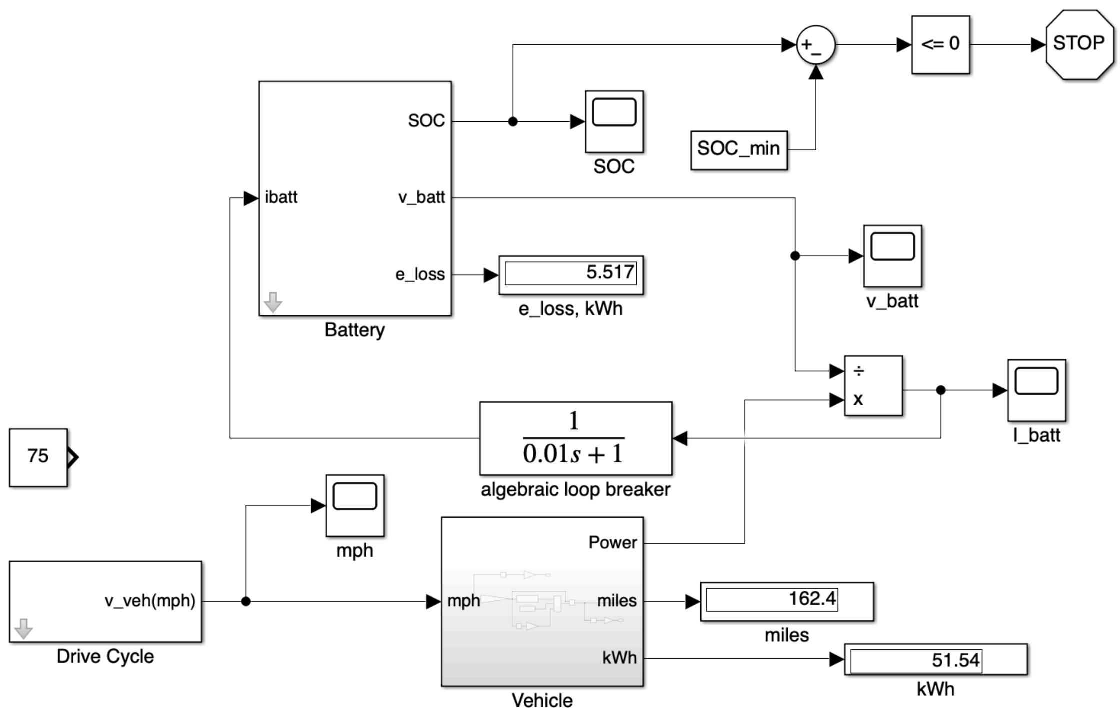


Figure 16: Bonus Simulink Model

Metric	Value
Total Energy Used	51.54 kWh
Distance Traveled	162.4 miles
Time Taken	12,240.99 seconds (~3.4 hours)
Energy to Recharge at 0.2 C Rate	58.03 kWh
Energy to Recharge at 2 C Rate	66.75 kWh

Table 4: US06 Drive Cycle Results

In the bonus simulation, the battery delivered 51.54 kWh of energy over 162.4 miles before reaching the minimum SOC. The simulation had a drive time of approximately 3.4 hours. Recharging this energy required 58.03 kWh at a 0.2C rate and 66.75 kWh at a 2C rate, which validates our previous conclusion that there are greater losses associated with faster charging.

6. Appendix

Appendix A: Cell Parameters at 40C

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

Appendix B: Cell Specification

Kokam™ *Global Leader in Power Solution*

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

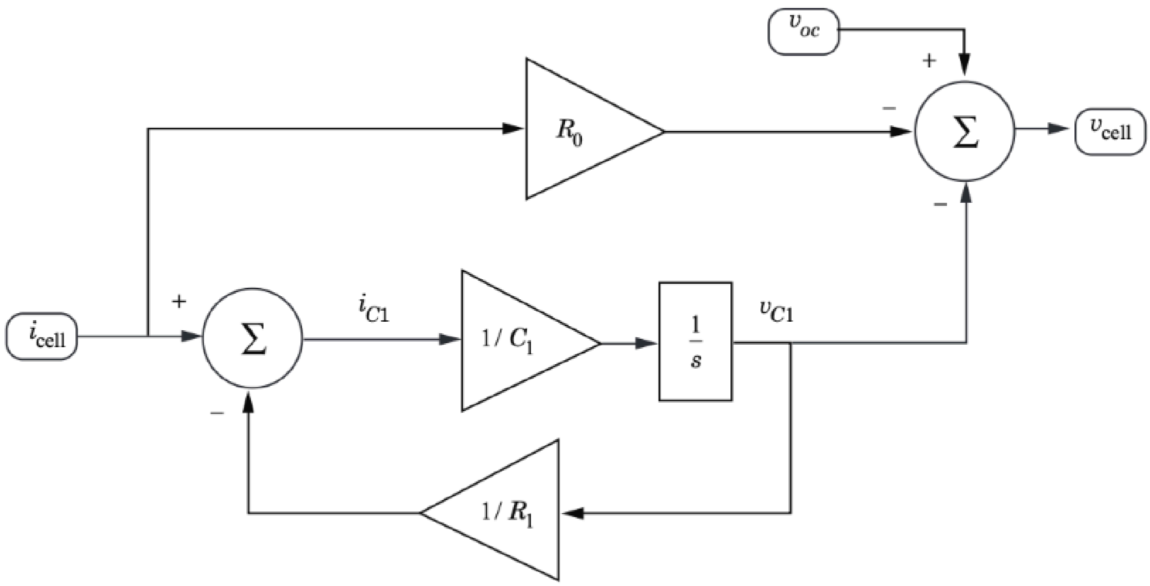
1) Typical Capacity : 0.5C, 4.2~2.7V @25°C
2) Voltage range : 4.15V ~ 3.40V

Appendix C: MATLAB initialization code

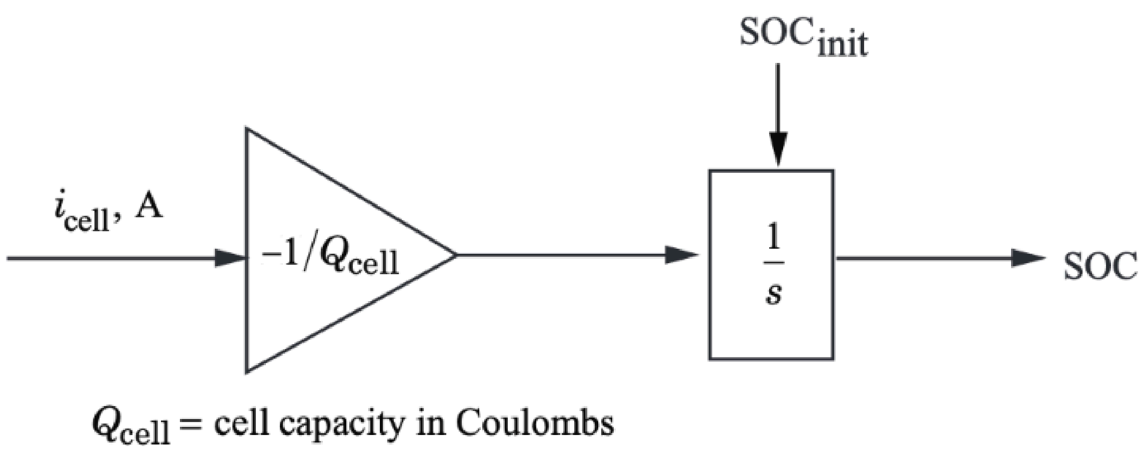
```
clearvars;

%load drive schedules

load us06.mat

load udds.mat

M_glider = 1746;  % glider mass, kg

M_passengers = 180; % passengers mass kg

C_D = 0.35;     % drag coefficient

C_0 = 0.015;    % rolling resistance coefficient

A_F = 1.93;     % frontal area, m^2

M_batt = 600;% battery mass in kg

M_veh = M_glider + M_passengers + M_batt;

% physical constants

rho = 1.225; % density of air, kg/m^3

g = 9.81; % acceleration due to gravity,  m/s^2

% unit conversions

meters_to_mi = 1/1609; % meters to miles

grams_per_hr_to_gal_per_s = 9.778e-8;  % g/hr to gal/s

mi_per_hr_to_m_per_s = 0.44704; % mi/hr to m/s

% Cell parameters

Capacity = 31; % Ampere-hours

Q_cell = Capacity*3600; % cell capacity in Coulombs

% R0 resistance

R0 = 0.009;

% R1 Resistance

R1 = 0.0015; %Ohms
```

```
% C1 Capacitance

C1 = 3.5e4; %Farads

Ns = 100;  % Number of series cells

Np = 6;   % Number of parallel cells

SOC_min = 0.2;
```

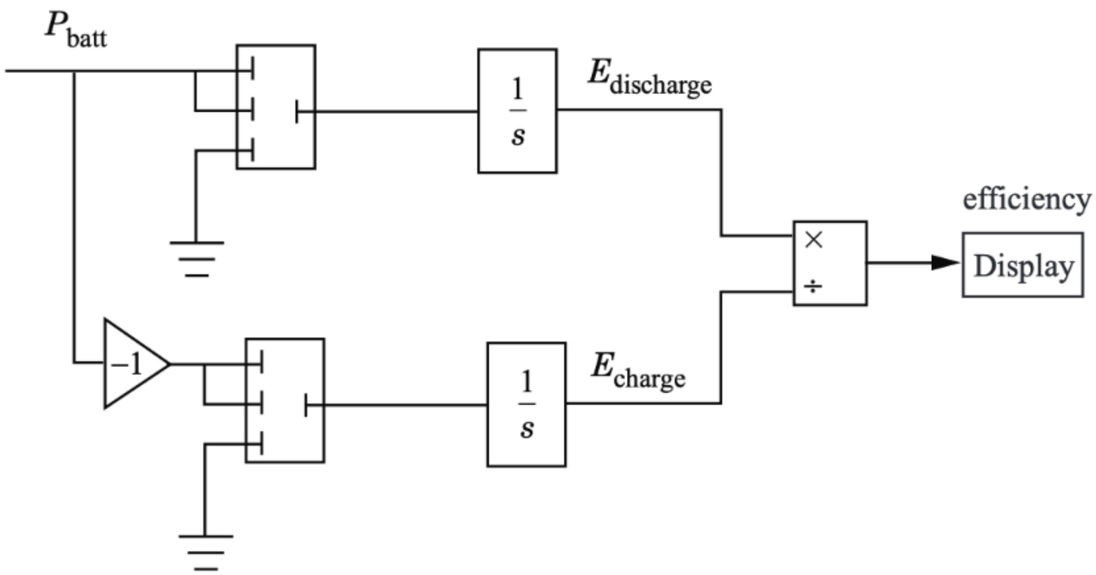
Appendix D: Simulink Subsystems



1. Cell Subsystem Model



2. SOC Calculation in Single Cell



3. Efficiency Calculator