PROJECT 4 REPORT

HYBRID ELECTRIC VEHICLES

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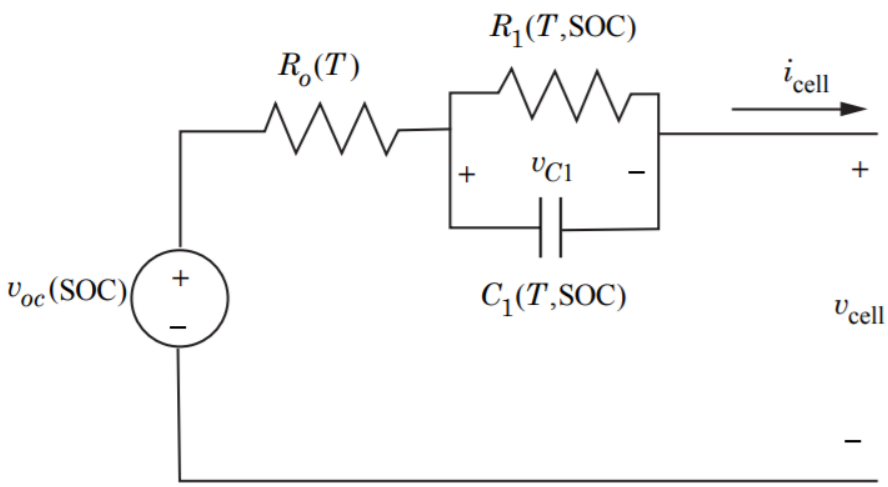
ABSTRACT

The primary objective of this project is to introduce a more sophisticated battery model to predict the battery round-trip efficiency. A commonly used equivalent-circuit model of the battery is shown in figure. Note that with the sign convention used, a positive current discharge the battery while negative current charges the battery. Voc represents the open circuit voltage (OCV) of the battery, R0 represents the battery internal impedance, and R1 and C1 represent the transient response of the battery under load. These parameters can be related to electrochemical processes taking place inside the cell: R0 represents the bulk resistance and solid electrolyte interface (SEI) layer impedance of the battery while R1 and C1 capture the dynamics of the lithium ions moving through the electrolyte.



EQUIVALENT CIRCUIT MODEL OF THE BATTERY

INTRODUCTION

An accurate forecast of the remaining driving range of an electric vehicle (EV) is crucial to avoid range anxiety. Drivers need to know how much further they would travel before their vehicle batteries require a recharge. In addition, the battery management system should predict when batteries need replacement. The remaining charge calculation must be precise to utilize the battery's full capability. The state of charge (SOC) of a battery or pack of batteries is analogous to a fuel gauge of a conventional vehicle.

Accurate run-time SOC estimation techniques are also needed by the battery management system (BMS) for cell balancing of battery packs in vehicles with electrified powertrains. The SOC estimation must be accurate under all vehicle operating conditions, and account for changes in temperature, different rates of current, and cell aging. Elevated temperatures, broad SOC operation ranges, and strenuous load profiles accelerate cell aging. Coulomb counting (i.e. integration of the current) is a simple technique for estimating the SOC by integrating the measured current with time.

In this project, we will examine several charge-discharge cycles to examine the effects on losses and round-trip efficiency. To achieve these goals, we develop a new Simulink battery model that accepts battery current versus time 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. The goal of this project is to calculate the SOC versus time and the round-trip efficiency of the battery, and maintain the SOC so that it does not fall below 0.2 or exceed 0.8.

CIRCUIT

The battery pack is assumed to consist of Np parallel-connected battery modules with each module consisting of Ns series-connected cells. The parameters of an individual cell are provided in Table 1 corresponding to a temperature of 40-degree Celsius. The open-circuit voltage Voc versus SOC at T = 40-degree Celsius is provided in Table 2. Although each of the circuit parameters in the battery model are, in general, a function of the SOC, we neglect this dependence except for the dependence of Voc on SOC. The battery is assumed to be charged or discharged at a constant current. A C-rate of 1 means that the 31 Ah capacity of the cell is discharged in 1 hour (i.e. icell = 31 A); a C-rate of 0.2 means that the 31 Ah capacity of the cell is discharged in 5 hours (i.e. icell = 31/5 A). Some useful equation are given below.

$$P_{\text{batt}} = N_s N_p v_{\text{cell}} i_{\text{cell}}$$

$$v_{\text{cell}} - v_{oc} + v_{R0} + v_{C1} = 0$$

$$i_{R1} + i_{C1} = i_{\text{batt}}$$

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

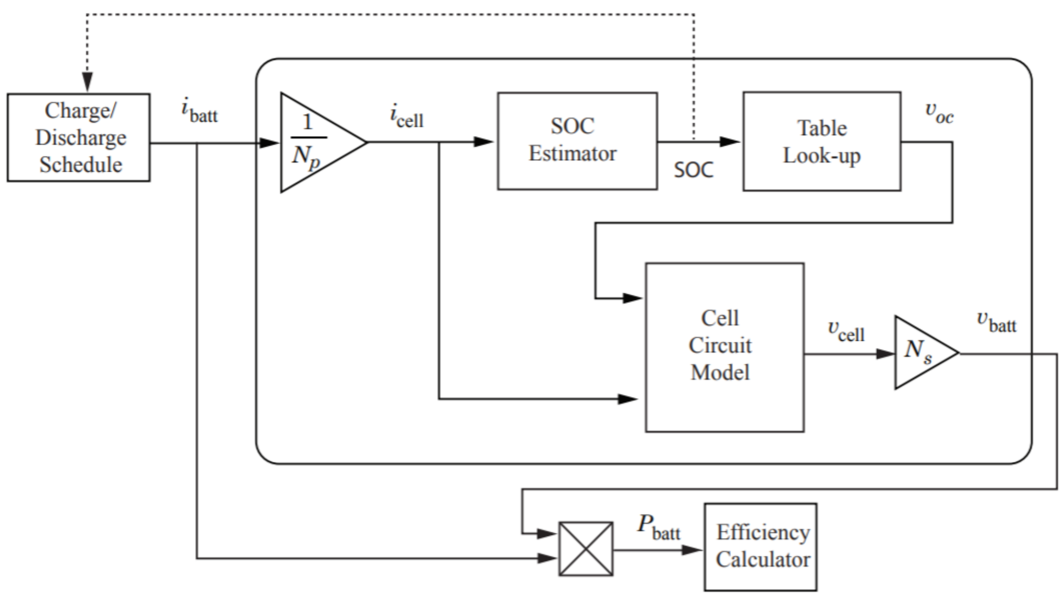
Table 1: Cell Parameters at 40° C

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

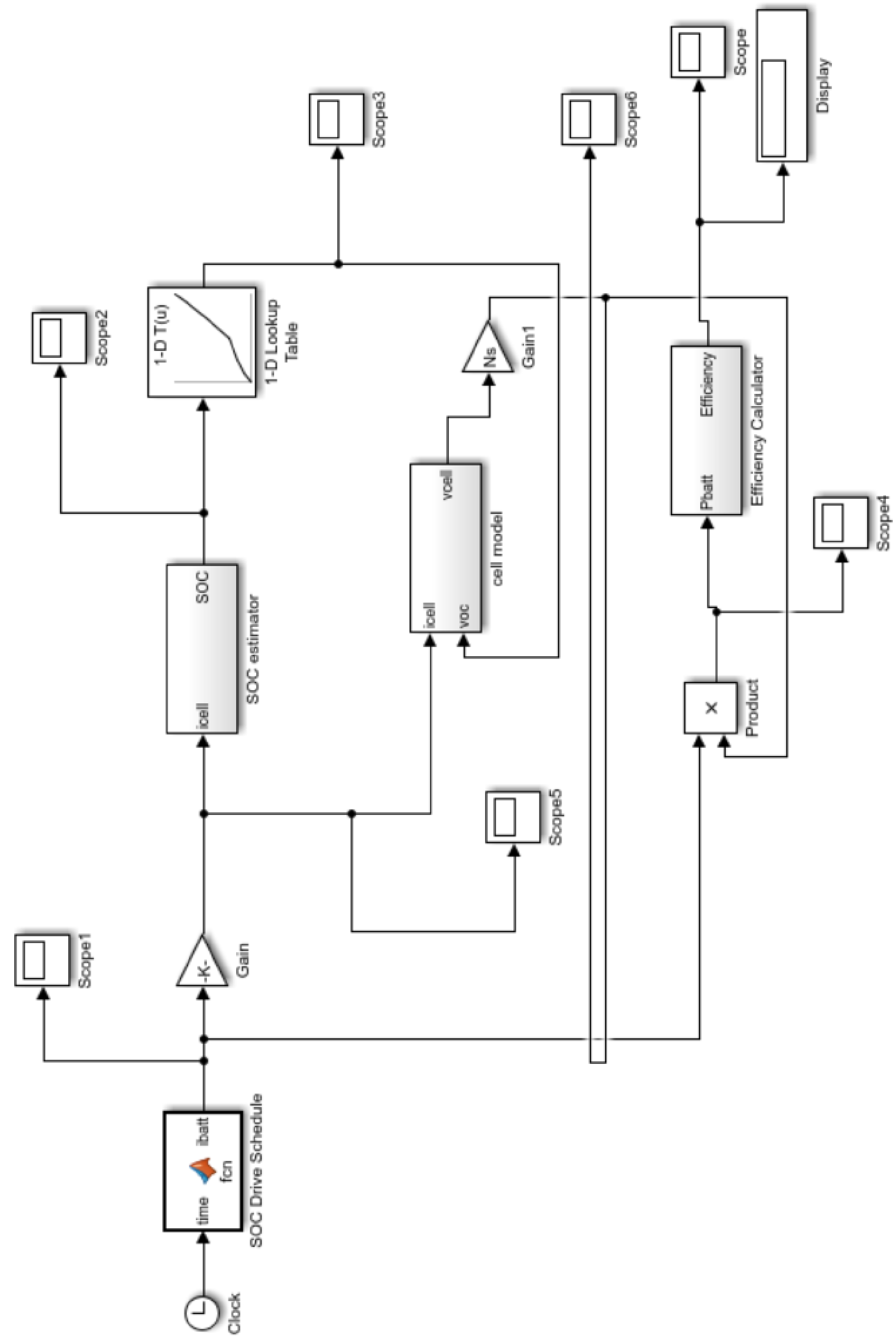
SOC	Open-Circuit Voltage, V
0	3.51
0.1	3.57
0.25	3.63
0.5	3.71
0.75	3.93
0.9	4.08
1	4.19

The block/circuit diagram of the battery circuit that needs to be simulated is provided below.



BATTERY MODEL TOP LEVEL DIAGRAM

In the circuit model of a cell, assume the initial condition of vC1 = 0, vcell = voc, and icell = 0. The charge-discharge schedules are described later. The battery cell data is for a 31 Ampere hour cell. We assume that the battery consists of Np parallel-connected modules and each module includes Ns series-connected cells. Ns is selected to give a nominal battery voltage of approximately 300 V. Then Np is selected so that the energy capacity exceeds that of the battery from Project 1 (approximately 1.7 kWh). The Ns we have selected is 70 and the Np we have selected is 1. The Simulink implementation of the battery is given below.



SIMULINK REPRESENTATION

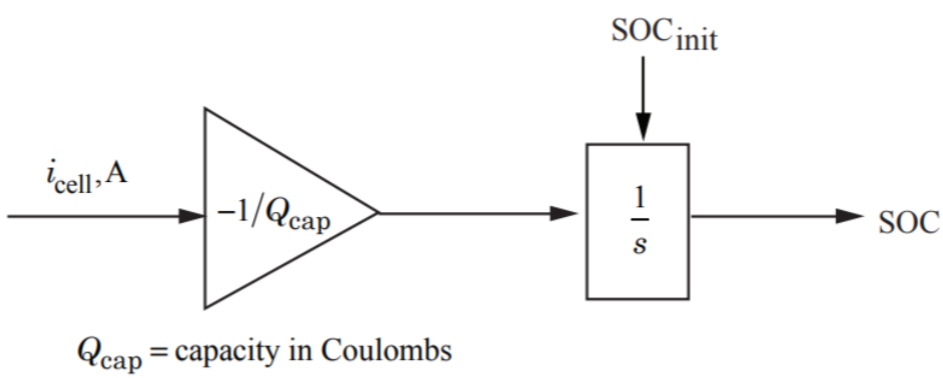
The main parts in the circuit are:

1. SOC estimator
2. Cell circuit model
3. Efficiency Calculator
4. Charge/Discharge cycle

They explained in detailed below.

State of Charge Estimator

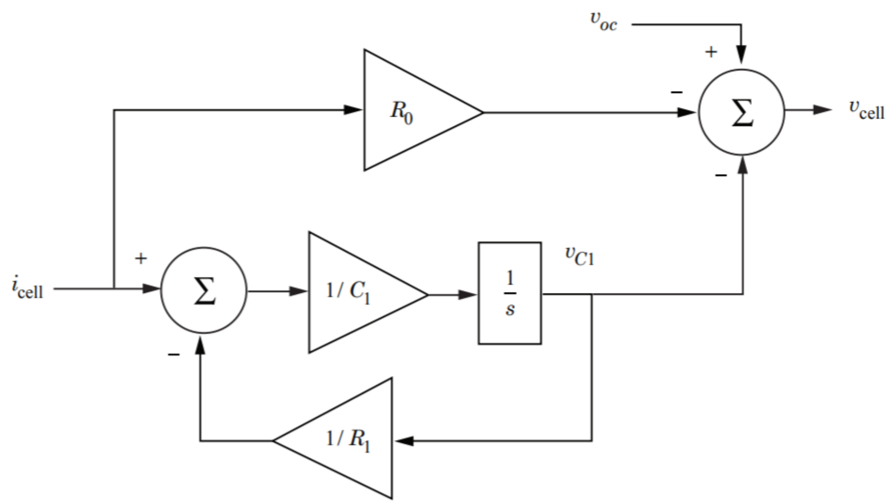
The SOC estimator is the model used for the calculation of the SOC of the battery unit. It uses the coulomb charge method where the cell current is divided by the cell capacity in coulombs and integrated over time to give the value of SOC. The initial value of the SOC is also fed into the integrator. The SOC estimator takes in the cell current as the input and gives out the SOC as the output.



SOC ESTIMATION CIRCUIT

Cell Circuit Model

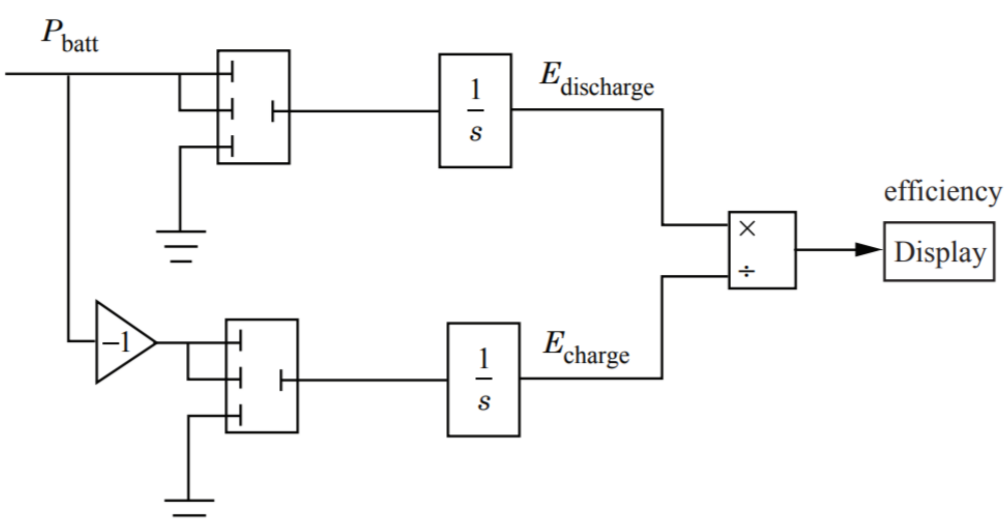
The cell circuit model takes in the open circuit voltage and cell current as the inputs and provides the cell voltage as the output. The cell current undergoes a series of gaining and integration and is then subtracted from the open circuit voltage to give out cell voltage. The model is given below.



CELL CIRCUIT MODEL

Efficiency Calculator

The efficiency calculator is used to calculate the efficiency of the battery. It takes in the battery power as the input and calculates the charging and discharging energies. Then it compares them both to calculate efficiency in percentage. The circuit diagram of the efficiency calculator is provided below.



EFFICIENCY CALCULATOR

Charge/Discharge Cycles

This is just a user generated function block which gives out the battery current as the output with time and SOC as the inputs. The code for the function is provided below.

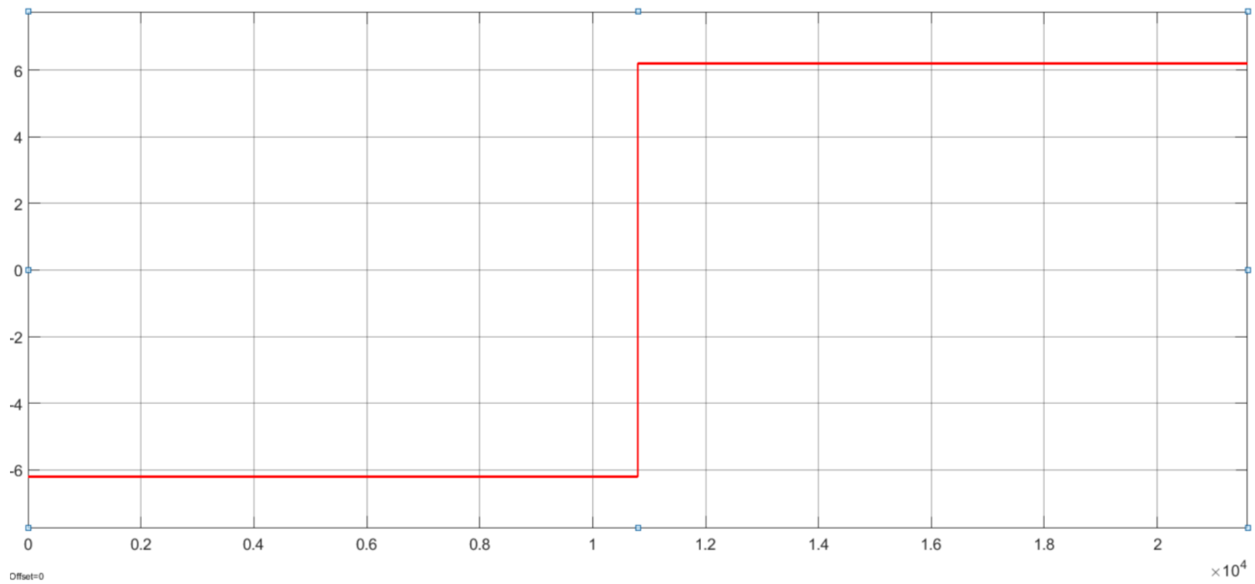
```
function ibatt = fcn(time)
C_rate1 = 5;
C_rate2 = 5;
cell_capacity = 31;
SOC_init = 0.6;
SOC_final = 0.6;
SOC_max = 0.7;

criticaltime = ((SOC_max - SOC_init)/C_rate1)*3600;
finaltime = (criticaltime) + ((SOC_max -
SOC_final)/C_rate2)*3600;
if(time < criticaltime)
     ibatt = -cell_capacity*C_rate1;

elseif ((criticaltime < time) && (time < finaltime))
    ibatt = cell_capacity*C_rate2;
else
    ibatt = 0;
end
return
```

Case 1. Slow charge and Discharge

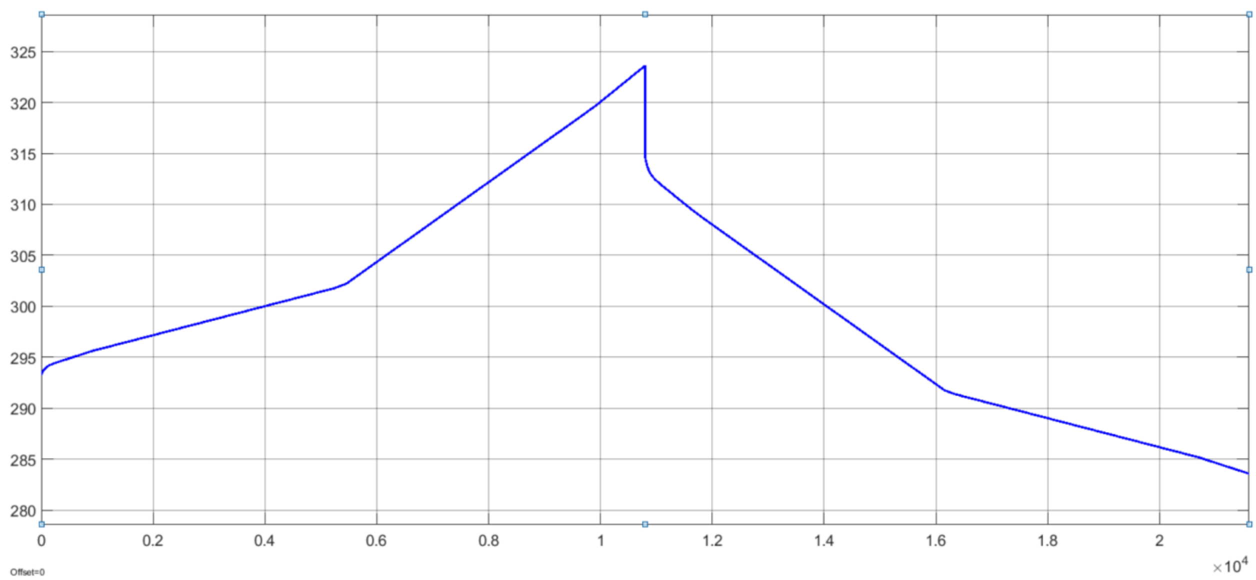
The battery starts at SOC initial = 0.2. It is charged at a C-rate of 0.2 to SOC maximum = 0.8. Then, it is discharged at a C-rate of 0.2 to SOC final = 0.2.

This is a case of slow charge and discharge. With a slow charge rate of 0.2 the battery would require the battery 3 hours to charge from 0.2 to 0.8 SOC and 3 hours to discharge from 0.8 to 0.2 SOC. Since its slow charge and discharge there will be less loss and the efficiency have a very high value of 96.86%. The plots of battery current, voltage power and SOC are provided below.

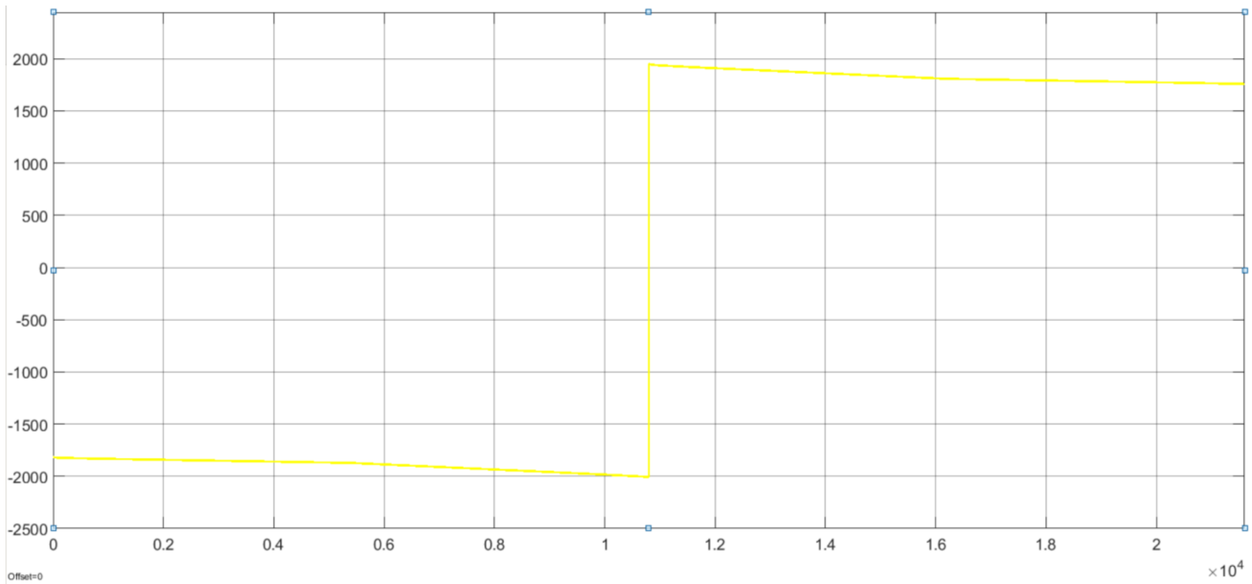
The battery current lies between -6 to 6 Amperes during charging and discharging. The battery voltage lies between 285 to 325 volts which is in the specified cell safety requirements. The battery power lies -2 to 2 kilowatts.



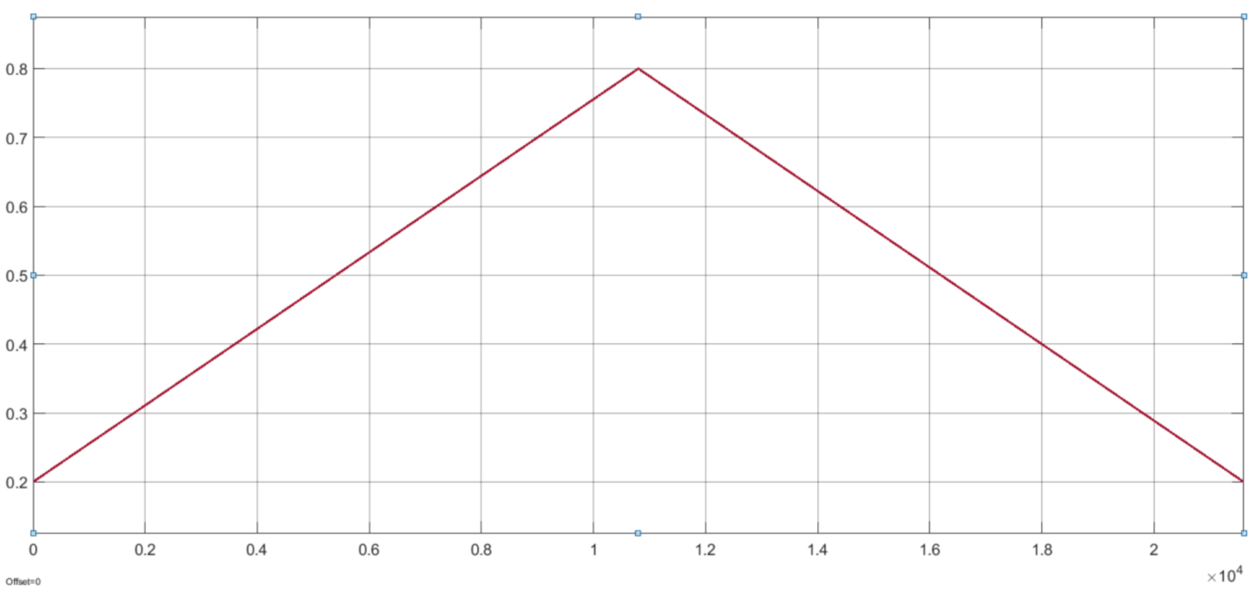
BATTERY CURRENT IN AMPERES VS TIME IN SECONDS



BATTERY VOLTAGE IN VOLTS VS TIME IN SECONDS



BATTERY POWER IN WATTS VS TIME IN SECONDS



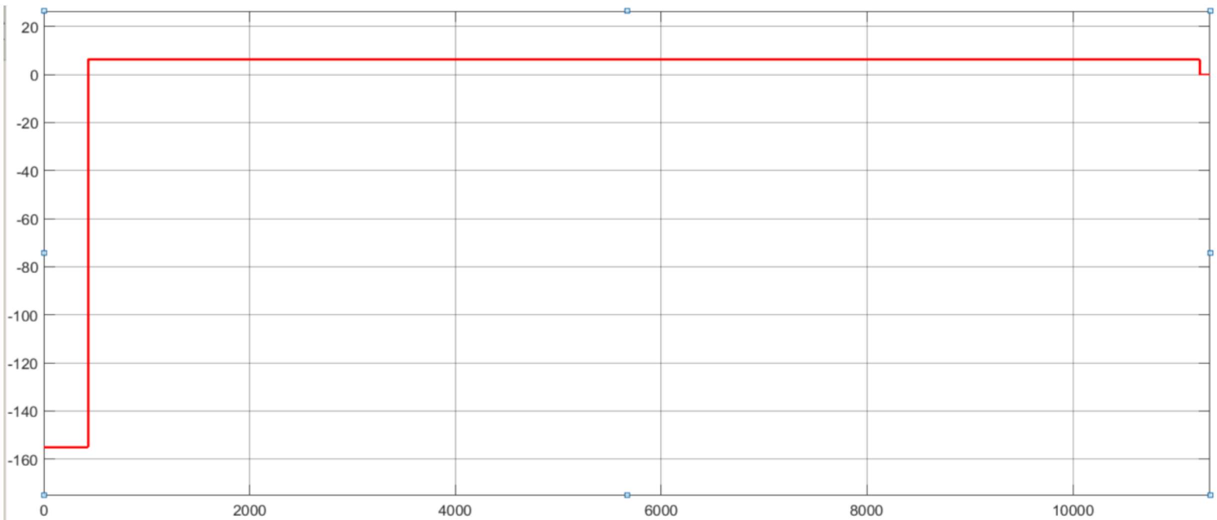
BATTERY SOC VS TIME IN SECONDS

Case 2. Fast charge and Slow Discharge

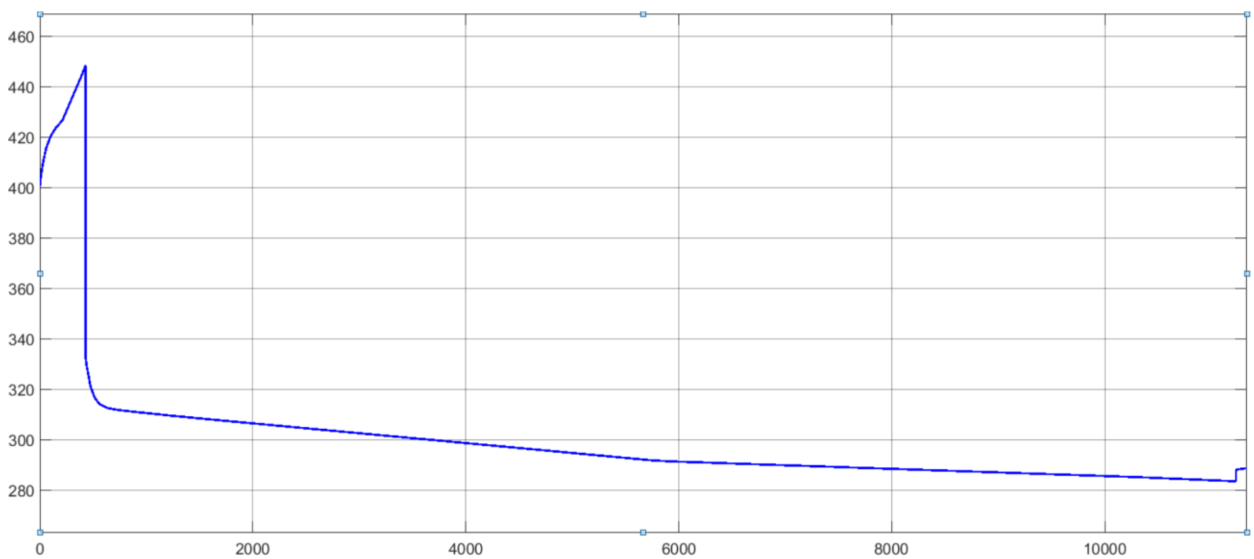
The battery starts at SOC initial = 0.2. It is charged at a C-rate of 5 to SOC maximum = 0.8. Then, it is discharged at C-rate = 0.2 to SOC final = 0.2.

This is a case of fast charge and slow discharge. With a slow discharge rate of 0.2 the battery would require the battery 3 hours to discharge from 0.8 to 0.2 SOC and with a charge rate of 5 the battery would need just 432 seconds to charge from 0.2 to 0.8 SOC. Since its got fast charge and slow discharge there will be some loss, and the efficiency has a value of 68.96%. The plots of battery current, voltage power and SOC are provided below.

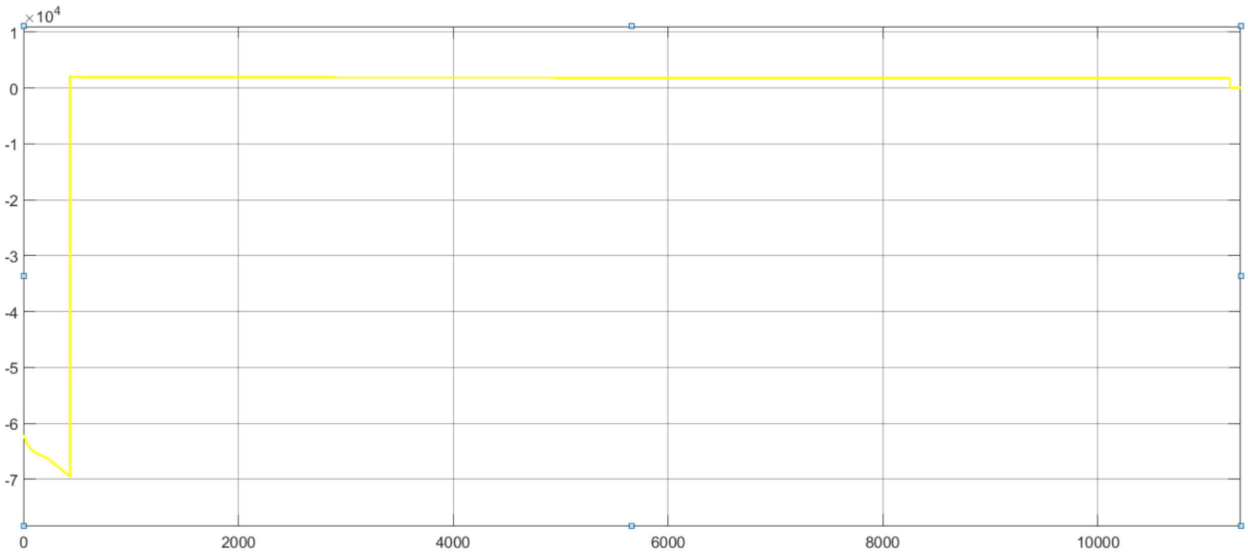
The battery current lies between -160 to 6 Amperes during charging and discharging. The battery voltage lies between 285 to 440 volts which is not in the specified cell safety requirements. Hence, it's not advised to operate model under these conditions. The battery power lies -7 to 0.2 kilowatts.



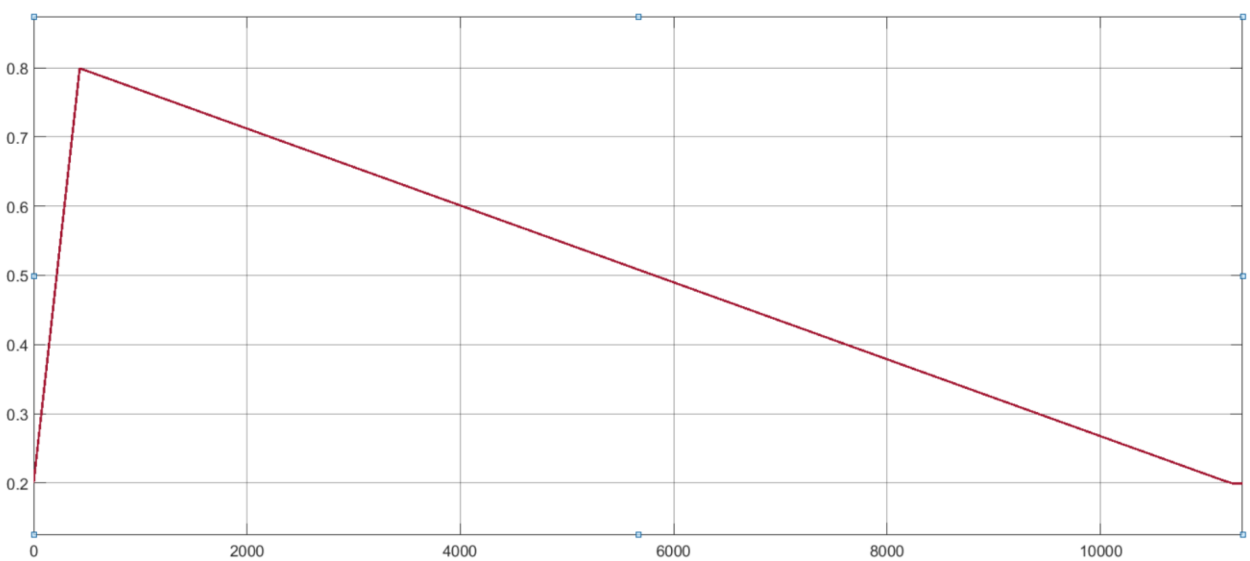
BATTERY CURRENT IN AMPERES VS TIME IN SECONDS



BATTERY VOLTAGE IN VOLTS VS TIME IN SECONDS



BATTERY POWER IN KILOWATTS VS TIME IN SECONDS



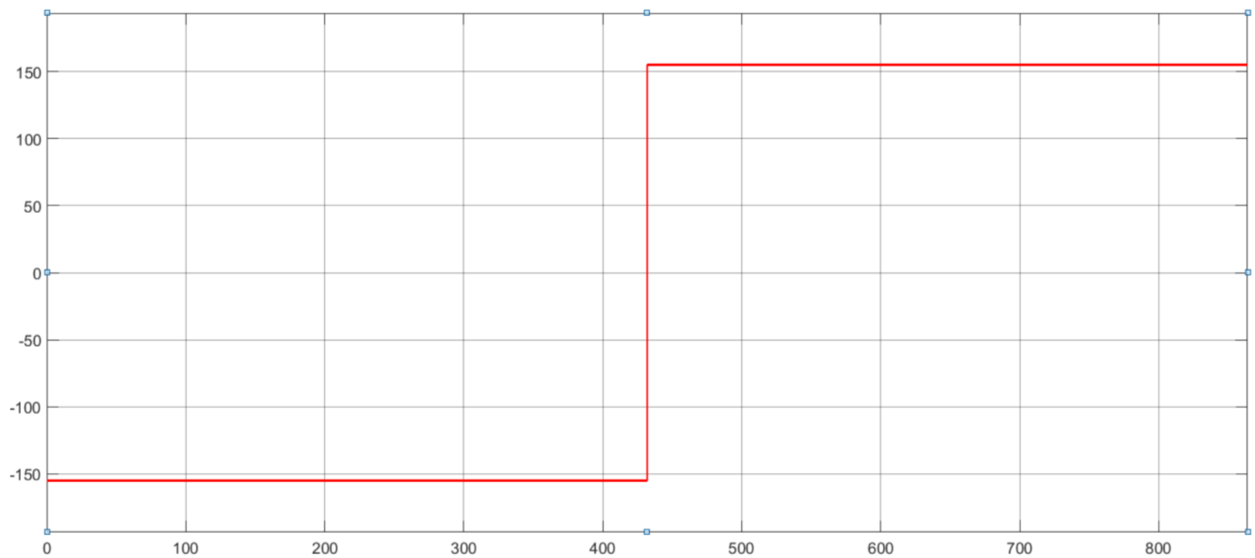
BATTERY SOC VS TIME IN SECONDS

Case 3. Fast charge and Discharge

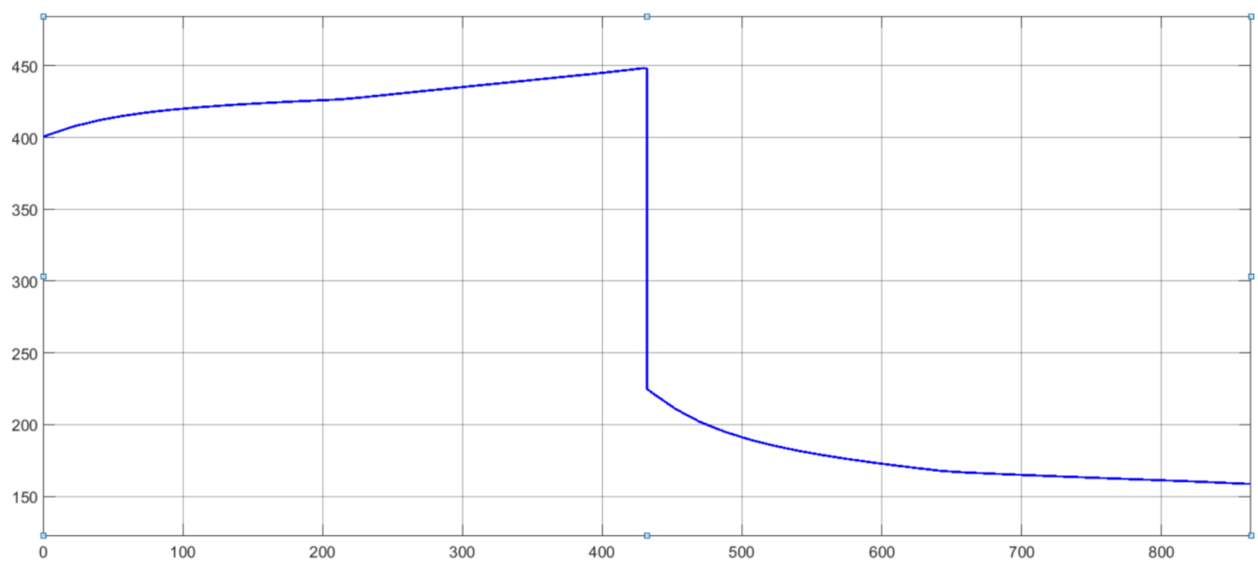
The battery starts at SOC initial = 0.2. It is charged at a C-rate of 5.0 to SOC maximum = 0.8. Then, it is discharged at C-rate = 5.0 to SOC final = 0.2.

This is a case of fast charge and discharge. With a fast charge rate of 5 the battery would require the battery 432 seconds to charge from 0.2 to 0.8 SOC and 432 seconds to discharge from 0.8 to 0.2 SOC. Since, its fast charge and discharge there will be a very high loss and the efficiency has a low value of 40.8%. The plots of battery current, voltage power and SOC are provided below.

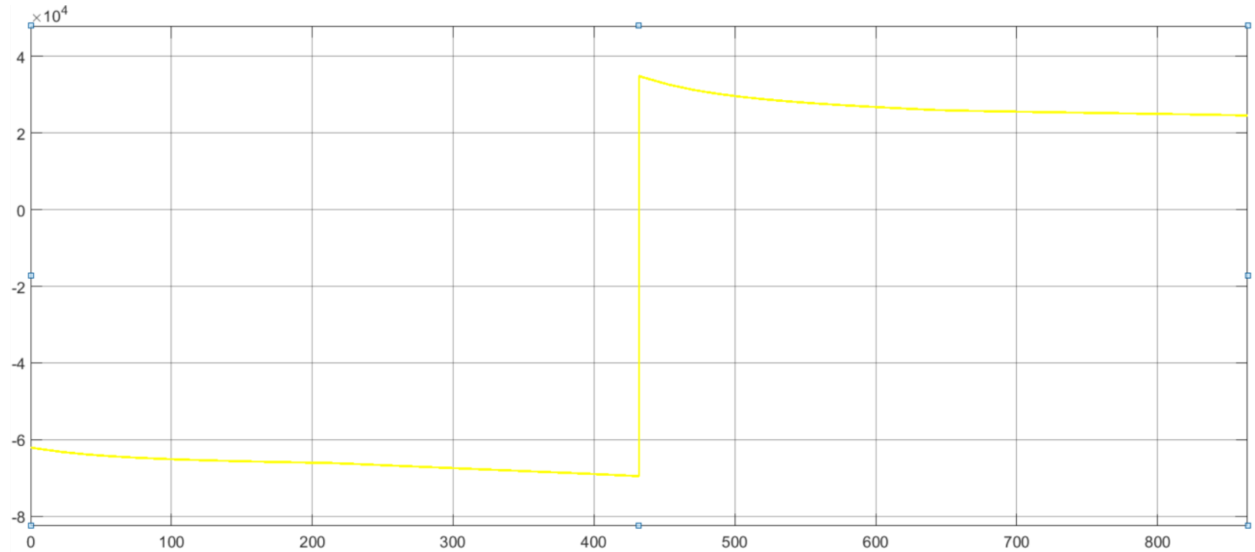
The battery current lies between -150 to 150 Amperes during charging and discharging. The battery voltage lies between 150 to 440 volts which is not in the specified cell safety requirements. Hence, it's not advised to operate model under these conditions. The battery power lies -7 to 4 kilowatts.



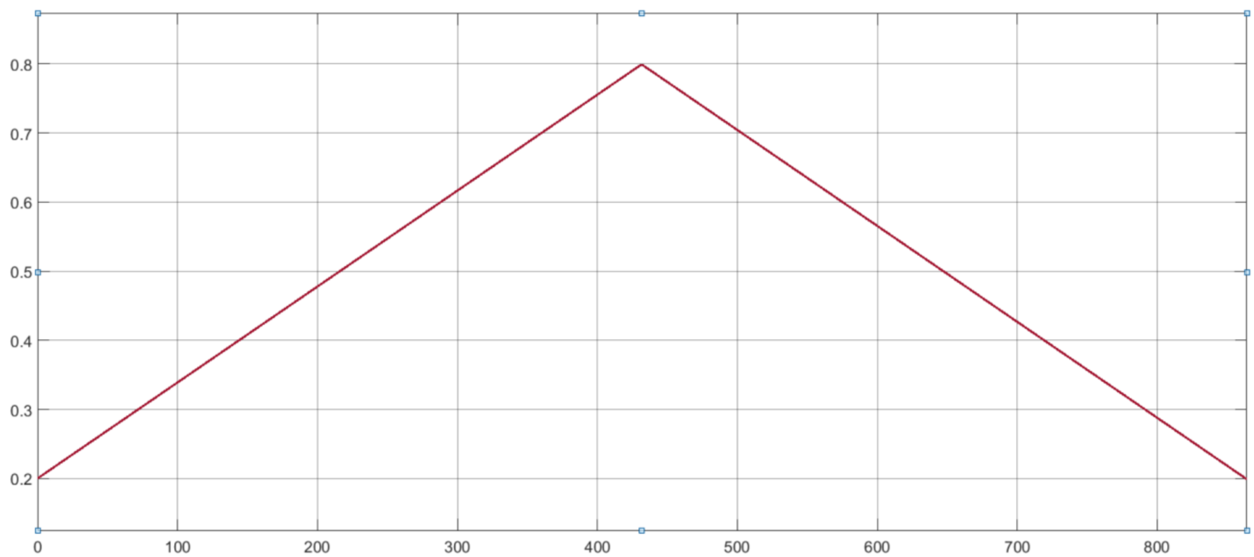
BATTERY CURRENT IN AMPERES VS TIME IN SECONDS



BATTERY VOLTAGE IN VOLTS VS TIME IN SECONDS



BATTERY POWER IN KILOWATTS VS TIME IN SECONDS



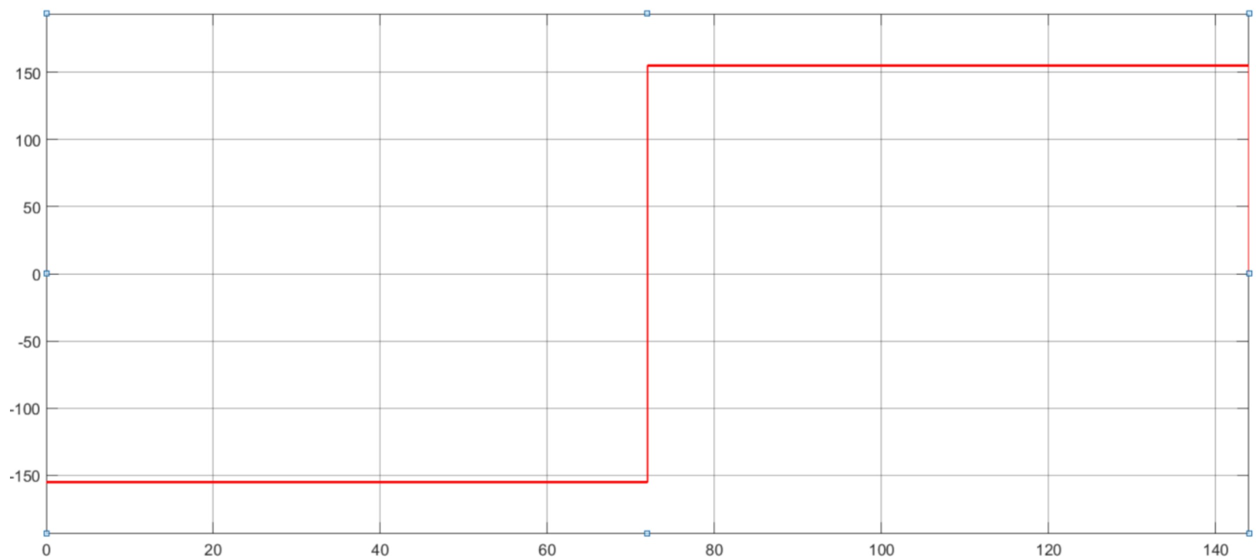
BATTERY SOC VS TIME IN SECONDS

Case 4. Fast charge and Discharge (relatively short-term storage)

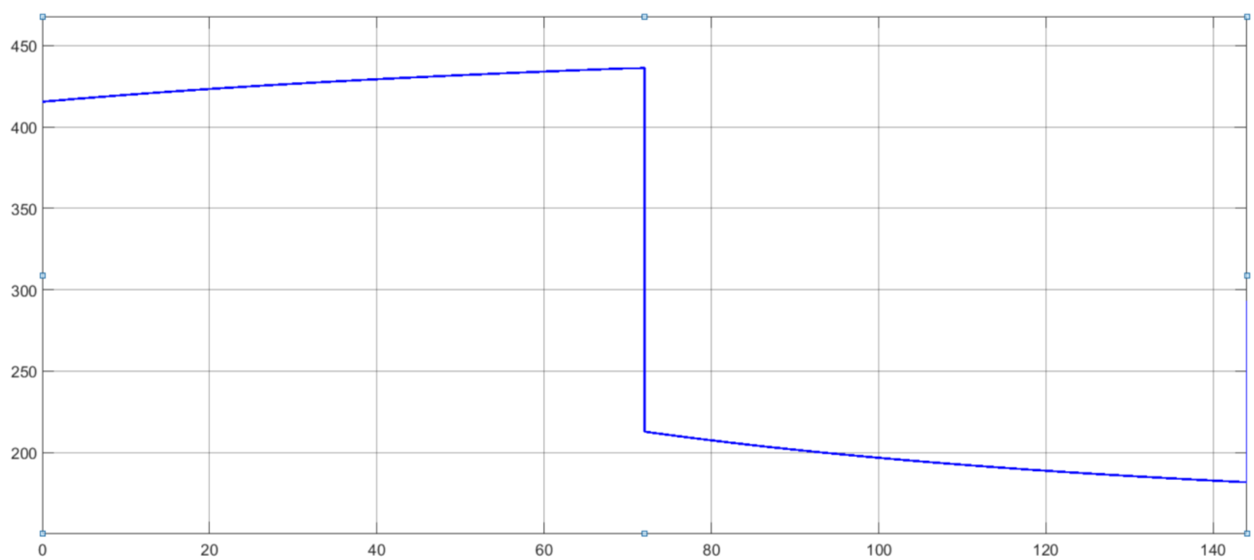
The battery starts at SOC initial = 0.6. It is charged at a C-rate of 5.0 to SOC maximum = 0.7. Then, it is discharged at C-rate = 5.0 to SOC final = 0.6.

This is a case of fast charge and discharge. With a fast charge rate of 5 the battery would require the battery 72 seconds to charge from 0.6 to 0.7 SOC and 72 seconds to discharge from 0.7 to 0.6 SOC. Since, its fast charge and discharge there will be a very high loss and the efficiency has a low value of 45.81%. The plots of battery current, voltage power and SOC are provided below.

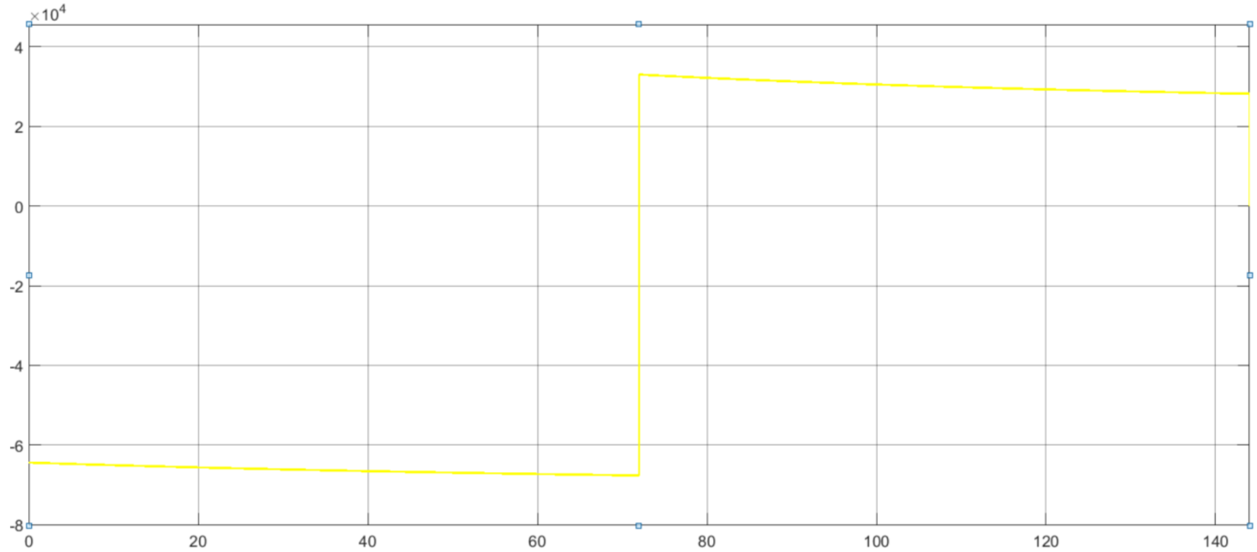
The battery current lies between -150 to 150 Amperes during charging and discharging. The battery voltage lies between 170 to 440 volts which is not in the specified cell safety requirements. Hence, it’s not advised to operate model under these conditions. The battery power lies -7 to 3 kilowatts.



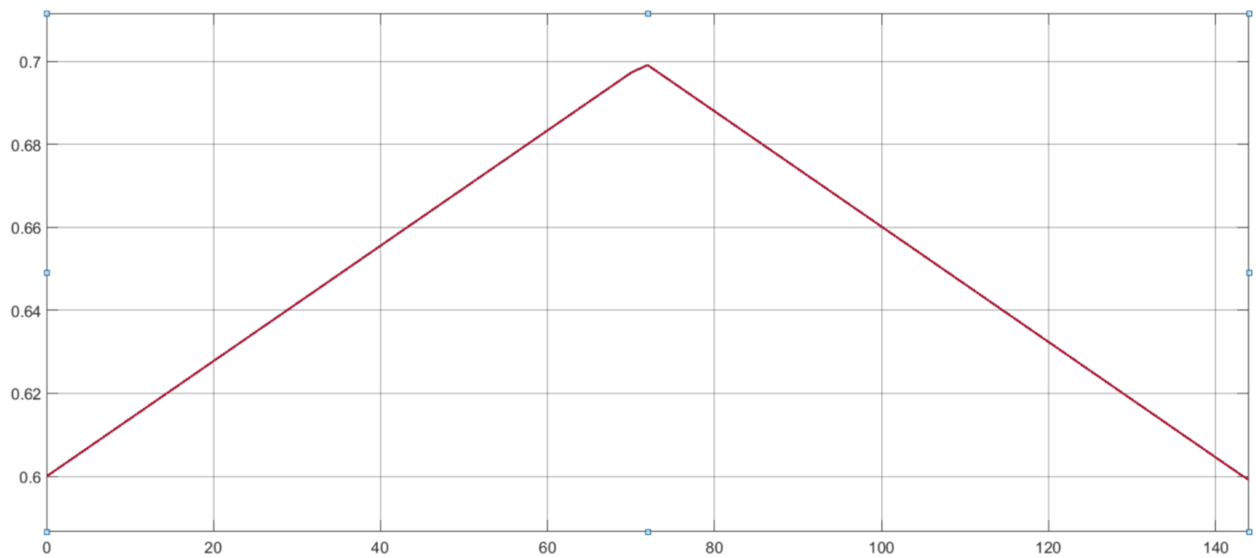
BATTERY CURRENT IN AMPERES VS TIME IN SECONDS



BATTERY VOLTAGE IN VOLTS VS TIME IN SECONDS



BATTERY POWER IN KILOWATTS VS TIME IN SECONDS



BATTERY SOC VS TIME IN SECONDS

Tabular Comparison

Cases	Battery Current	Battery Voltage	Battery Power	Efficiency	Losses
Slow Charge and Discharge	-6 to 6 Amperes	285-325 volts	-2 to 2 kilowatts	96.86%	0.7 Mega Joules
Fast Charge and Slow Discharge	-160 to 6 Amperes	285-440 volts	-70 to 2 kilowatts	68.96%	8 Mega Joules
Fast Charge and Discharge	-150 to 150 Amperes	150-440 volts	-70 to 40 kilowatts	40.8%	16.9 Mega Joules
Fast Charge and Discharge(short-term)	-150 to 150 Amperes	170-440 volts	-70 to 30 kilowatts	45.81%	2.5 Mega Joules

We can observe that slow charge and discharge has the highest efficiency and the least losses. This means that it requires lesser power and operates at a safer voltage and current range. The fast charge and slow discharge has a mediocre efficiency which is due to the slow discharge rate of 0.2. This battery is not particularly built to withstand the fast charge rate of 5. Hence every cycle involving either fast charging or discharging will have high losses and a weak efficiency. In this situation case 3 which involves fast charging and discharging for an extended period has the least efficiency of 40.8%. This means that it has the highest losses and operates at dangerous voltage and current ranges.

Conclusion

The Simulink model of the battery circuit was replicated, and the required results were calculated and plotted.