Md Nazmuzzaman Khan
ECE 51018 project 4

Problem Description:

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 are to develop a Simulink battery model that accepts I_{batt} 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. For the following charge/discharge cycles, plot v_{batt}, i_{batt}, P_{batt}, and SOC. 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.

Consider the following charge/discharge cycles.

(1) The battery starts at $SOC_{init} = 0.2$. It is charged at a C-rate of 0.2 to SOC = 1.0. Then, it is 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 $SOC_{max} = 1.0$. Then, it is discharged at C-rate = 0.2 to $SOC_{final} = 0.2$. (fast charge, slow discharge).
(3) The battery starts at $SOC_{init} = 0.2$. It is charged at a C-rate of 2.0 to SOC = 1.0. Then, it is discharged at C-rate = 2.0 to $SOC_{final} = 0.2$. (fast charge, fast discharge).
(4) The battery starts at $SOC_{init} = 0.5$. It is charged at a C-rate of 5.0 to $SOC_{max} = 0.6$. Then, it is discharged at C-rate = 5.0 to $SOC_{final} = 0.5$. (fast charge, fast discharge, relatively short-term storage).

Battery model in Simulink:

Following parameters are considered for the model. The parameters of an individual cell corresponding to a temperature of 40deg C. Although each of the circuit parameters in the battery model are, in general, a function of the SOC, we will neglect this dependence with the exception of the dependence of voc on SOC.

```
% Lookup Table Breakpoints
clearvars;

% Cell capacity
Capacity = 31; % Ampere*hours

Q = Capacity*3600; % cell capacity in Coulombs

% Terminal Resistance Properties

% R0 resistance vs SOC rows
R0 = 0.009;

% R1 Resistance vs SOC rows and T columns
R1 = 0.0015; %Ohms

% C1 Capacitance vs SOC rows and T columns
C1 = 3.5e4; %Farads

Ns = 80; % Number of cells in series
Np = 1;  % Number of celss in parallel

Q_batt = Q * Ns * Np; % net battery capacity
```

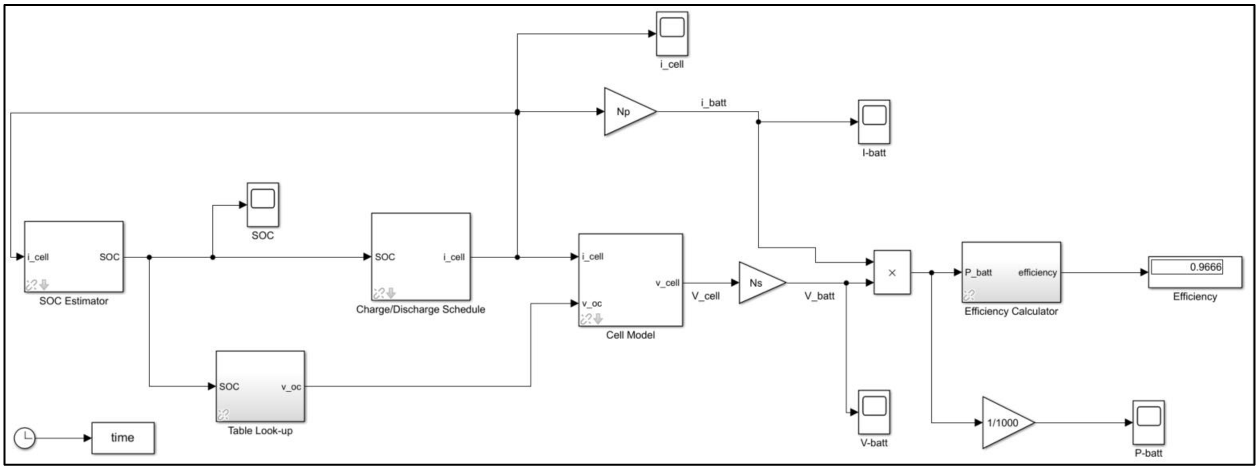

Fig 1: Overall battery model.

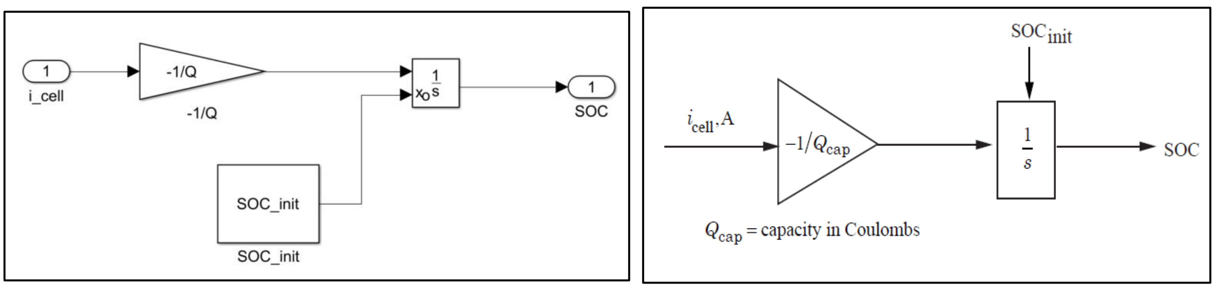

Fig 2: SOC calculation in a single cell using columb counting method. Simulink 'SOC Estimator' sub-block, and block diagram.

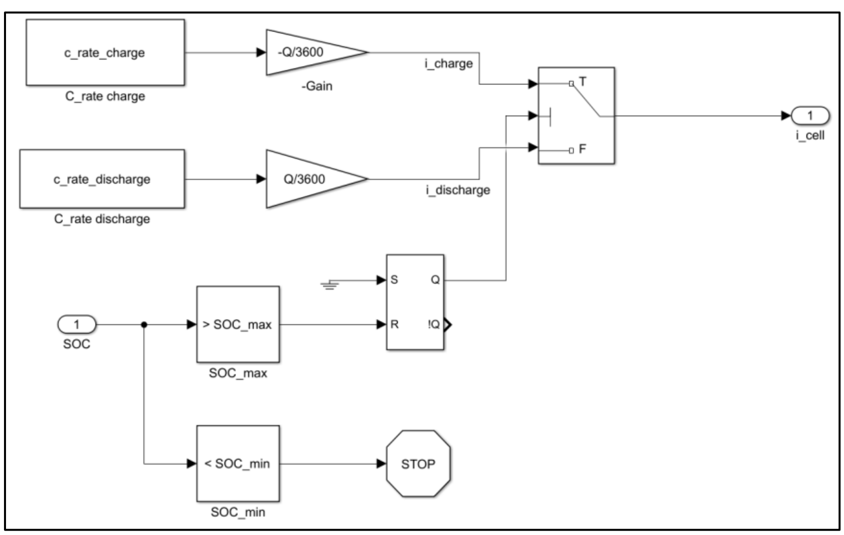

Fig 3: 'Charge/Discharge schedule' Simulink block. Simulation time is set at 'inf' because simulation is set to stop when battery SOC goes below SOC_{min}.

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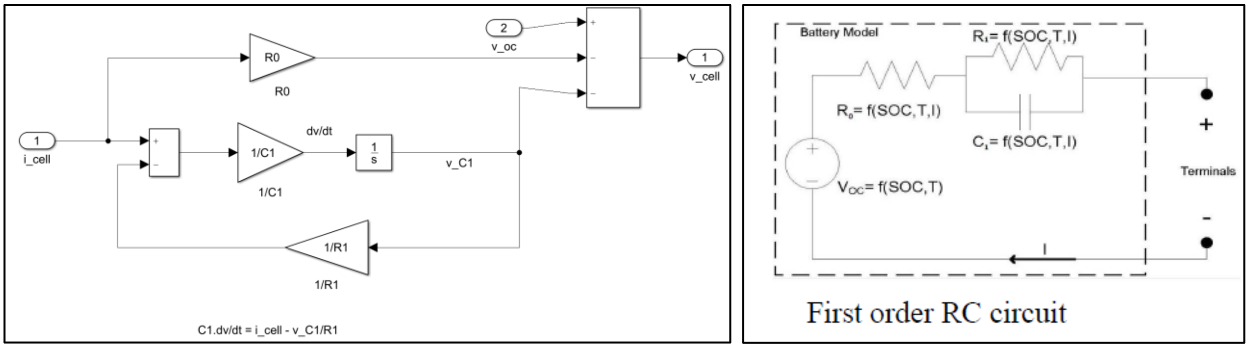

Fig 4: First-order Simulink battery model and block diagram. R0 is responsible for the instantaneous voltage drop of the input response. R1 and C1 are responsible for time constant of the input response. The sign convention used, a positive current discharge the battery while a negative current charge the battery. v_{oc} represents the open circuit voltage (OCV) of the battery, R_0 represents the battery internal impedance, and R_1 and C_1 represent the transient response of the battery under load. These parameters can be related to electrochemical processes taking place inside the cell: R_0 represents the bulk resistance and solid electrolyte interface (SEI) layer impedance of the battery while R_1 and C_1 capture the dynamics of the lithium ions moving through the electrolyte.

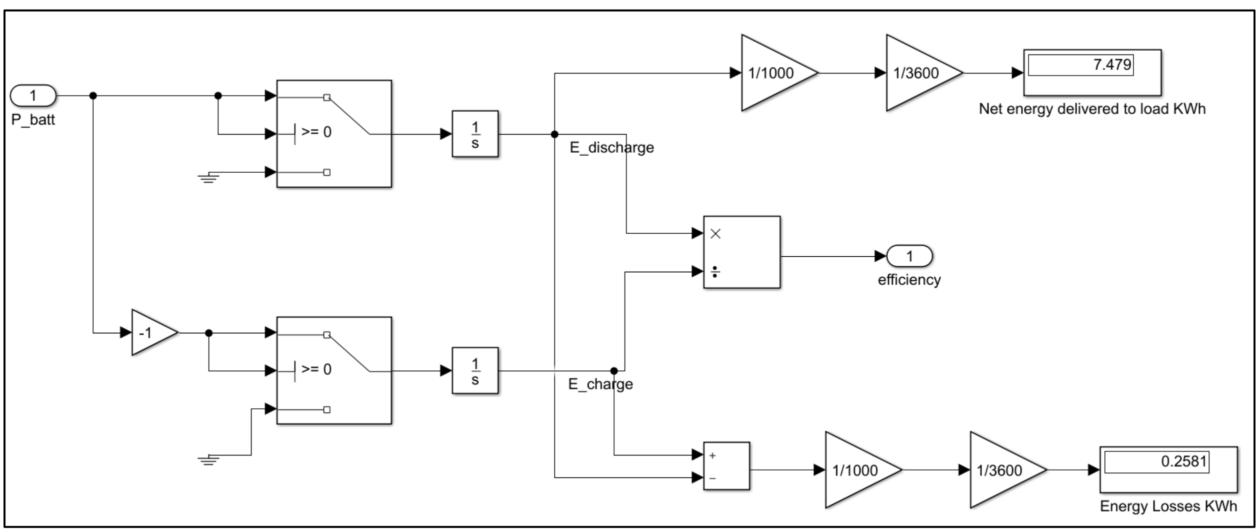

Fig 5: ‘Efficiency calculator’ Simulink block. Also, net energy delivered to load is calculated from discharge energy. Energy loss is calculated from energy charge and energy discharge. Positive battery power is integrated to obtain discharge energy and negative battery power is integrated to obtain charge energy. Round-trip efficiency is defined as the ratio of discharge energy to charge energy.

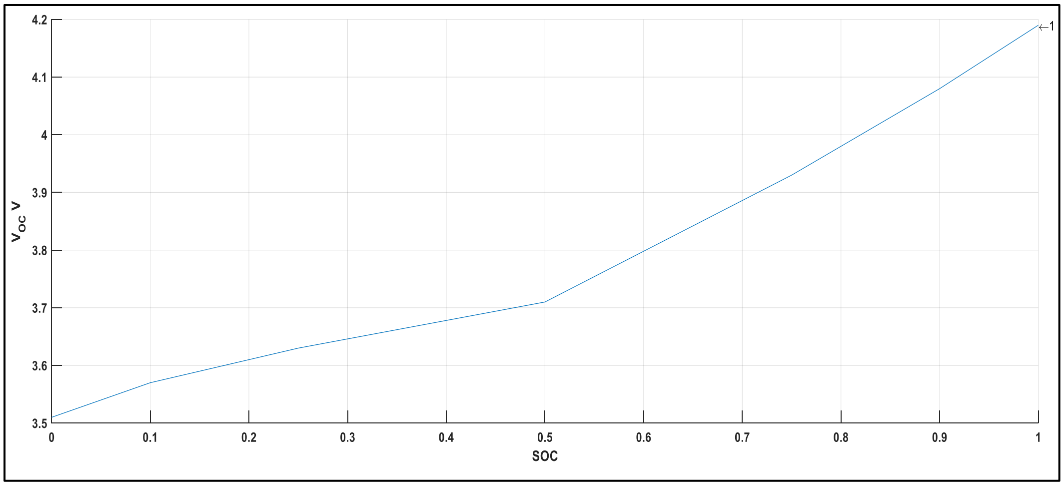

Fig 6: How open circuit voltage changing with SOC at T = 40 deg C. 'Table Look-up' block in Simulink.

Results:

Table 1: Net loss, Net energy delivered to load and round-trip efficiency of battery for 4 charge-discharge cycles.

charge/discharge cycles	Net losses (kWh)	Net energy delivered to the load (kWh)	Round-trip efficiency
Case-1: slow charge and discharge	***0.258***	***7.78***	***0.967***
Case-2: fast charge, slow discharge	***1.413***	***7.48***	***0.841***
Case-3: fast charge, fast discharge	***2.56***	***6.33***	***0.712***
Case-4: fast charge, fast discharge, relatively short-term storage	***0.721***	***0.582***	***0.447***

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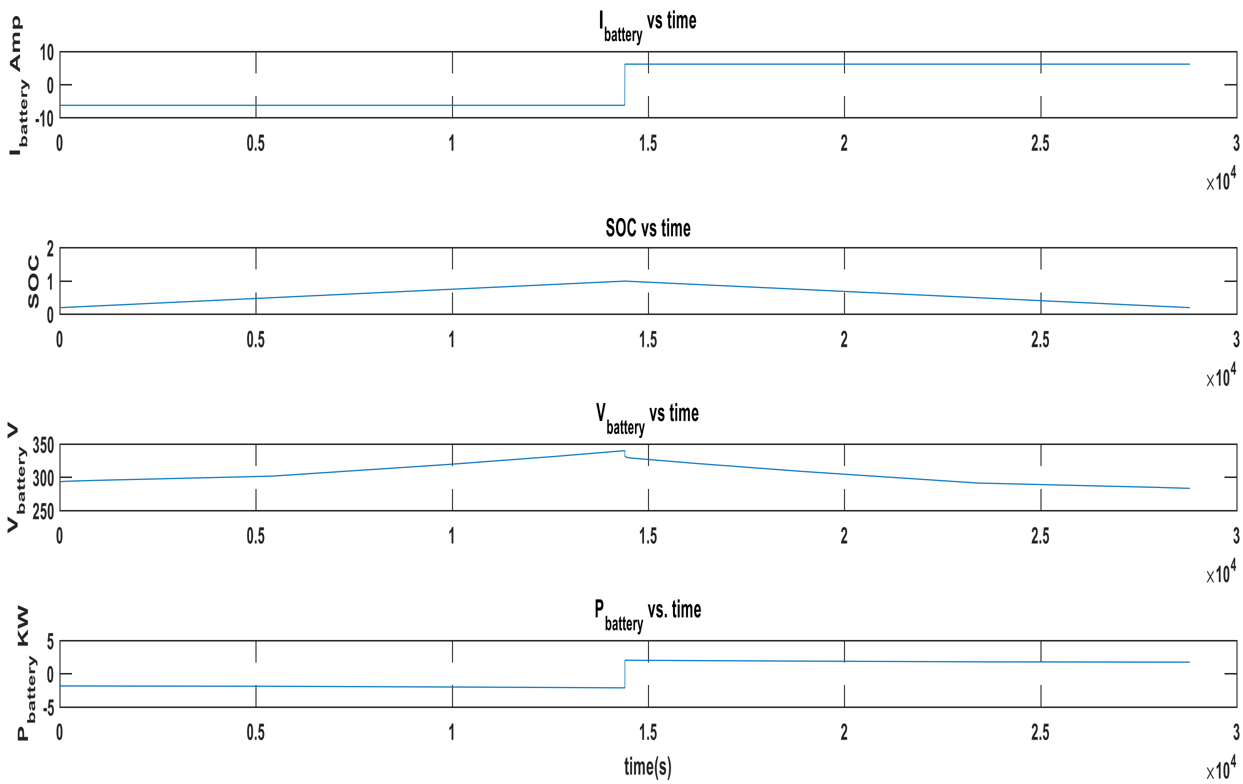

Fig 7: Charge/discharge cycle 1 (The battery starts at SOC_{init} = 0:2. It is charged at a C-rate of 0.2 to SOC = 1:0. Then, it is discharged at a C-rate of 0.2 to SOC = 0:2. (slow charge and discharge)). Plot for vbatt, ibatt, Pbatt, and SOC vs. time. $P_{battery}$ changes from -1.9 KW to 1.9 KW. $V_{battery}$ changes from 340 V to 285 V. $I_{battery}$ changes from -6.2 Amp to 6.2 Amp.

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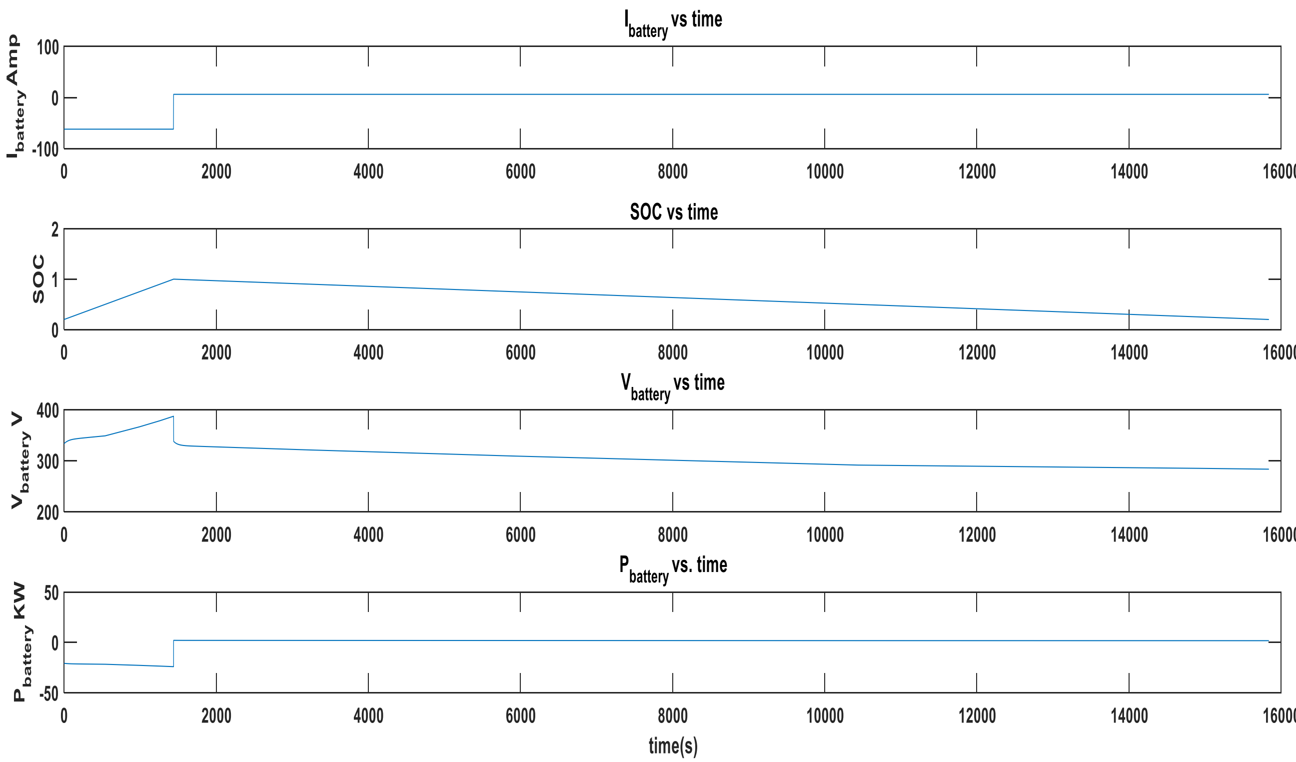

Fig 8: Charge/discharge cycle 2 (The battery starts at SOC_{init} = 0:2. It is charged at a C-rate of 2 to SOC = 1:0. Then, it is discharged at a C-rate of 0.2 to SOC = 0:2. (fast charge slow discharge)). Plot for vbatt, ibatt, Pbatt, and SOC vs. time. Due to fast charge, charge time is only 1440 s and discharge time is 14390 s. $P_{battery}$ changes from -24 KW to 1.98 KW. $V_{battery}$ changes from 387 V to 285 V. $I_{battery}$ changes from -62 Amp to 6.2 Amp.

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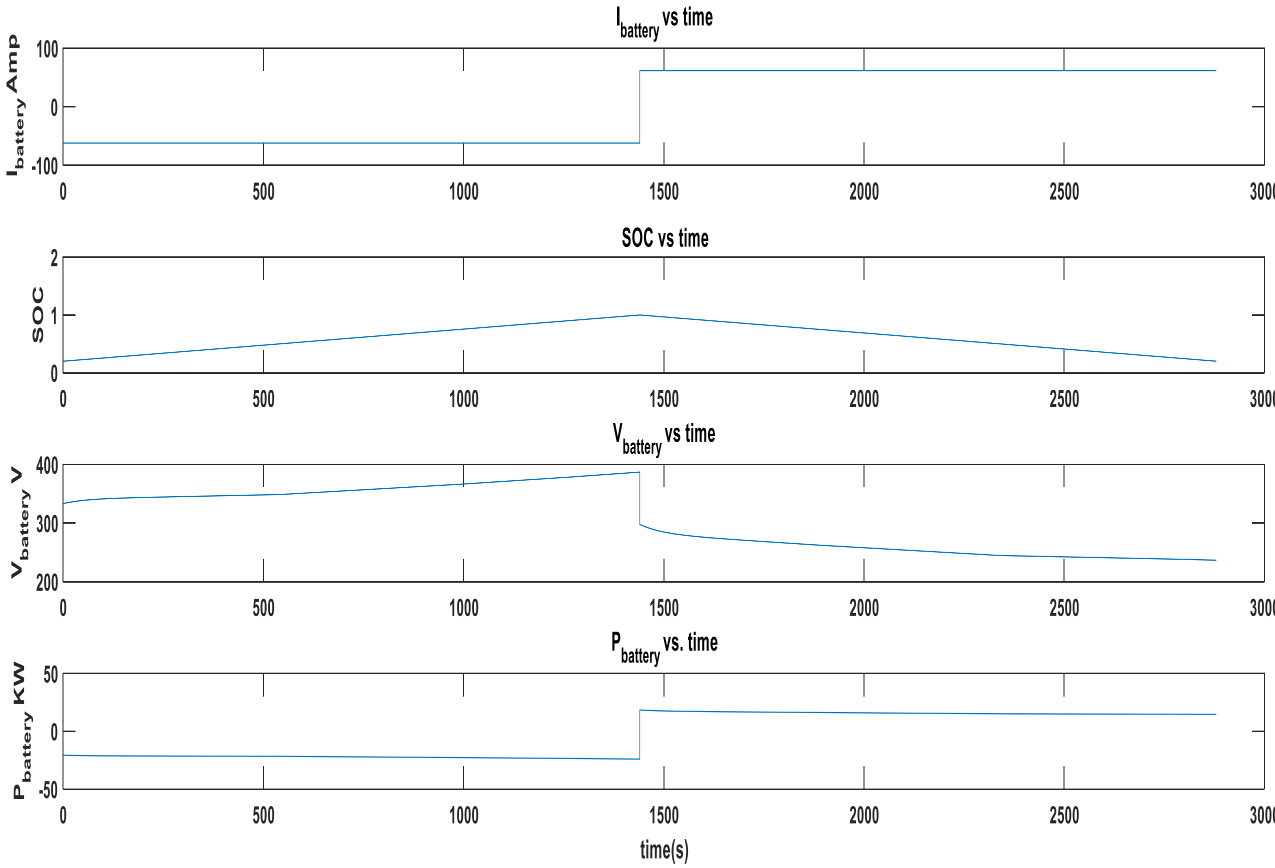

Fig 9: Charge/discharge cycle 3 (The battery starts at SOC_{init} = 0:2. It is charged at a C-rate of 2 to SOC = 1:0. Then, it is discharged at a C-rate of 2 to SOC = 0:2. (fast charge fast discharge)). Plot for vbatt, ibatt, Pbatt, and SOC vs. time. $P_{battery}$ changes from -22 KW to 15 KW. $V_{battery}$ changes from 386 V to 240 V. $I_{battery}$ changes from -62 Amp to 62 Amp.

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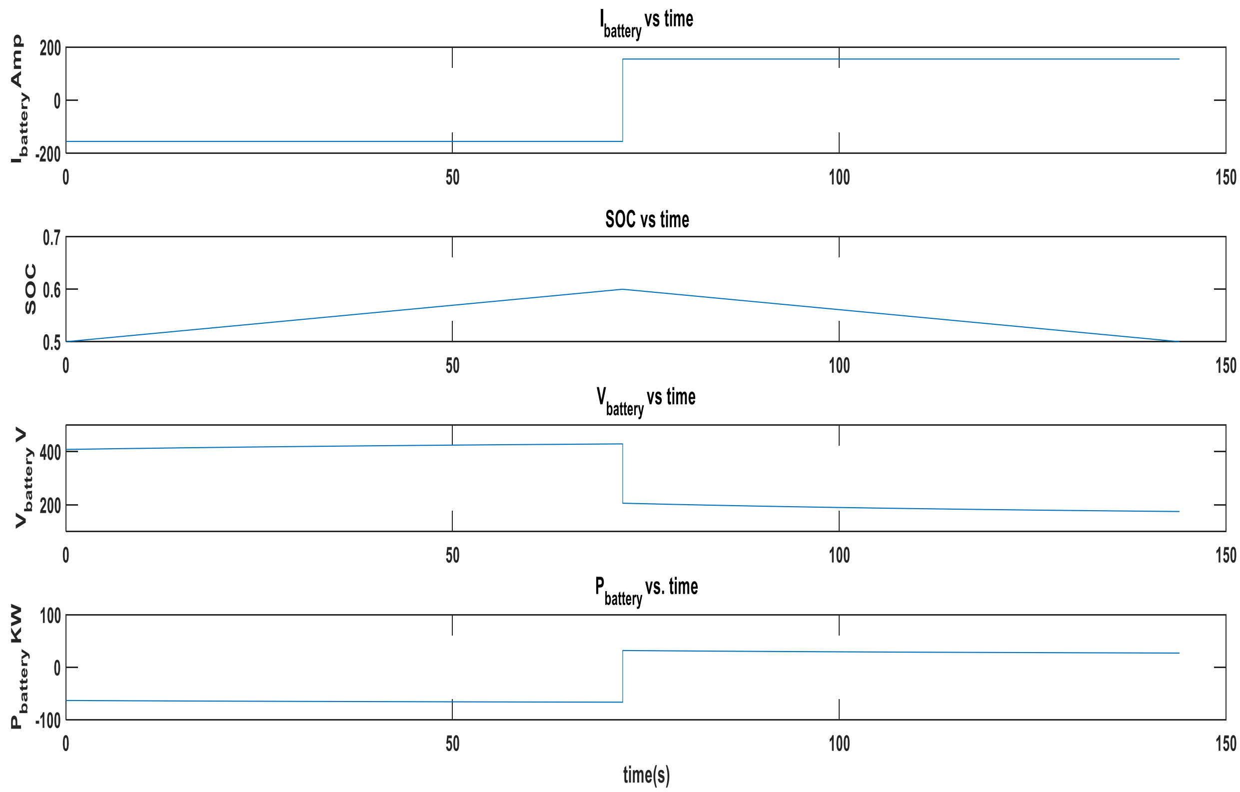

Fig 10: Charge/discharge cycle 4 (The battery starts at SOCinit = 0:5. It is charged at a C-rate of 5 to SOC = 0:6. Then, it is discharged at a C-rate of 5 to SOC = 0:5. (fast charge fast discharge, relatively short-term storage)). Plot for Vbatt, Ibatt, Pbatt, and SOC vs. time. Time needed is very short (140s). $P_{battery}$ changes from -65 KW to 29.6 KW. $V_{battery}$ changes from 426 V to 192 V. $I_{battery}$ changes from -155 Amp to 155 Amp.

Conclusions:

1) Slow charge-discharge (case-1) has the highest efficiency. Fast-charge-discharge (case-3) has the lower efficiency. Ridiculous fast charge-discharge (case-4) has lowest efficiency. Which shows slow charge-discharge is good for battery health and performance (if we need longer range from EV).
2) Increasing charge-rate increases the current flow through battery. This increases the energy loss and decreases efficiency.
3) Battery is drawing more power during charge cycle (higher negative value) than delivering during discharge cycle (lower positive value). Remaining power (or energy) is lost through Ro and R1 ($P = I^2R$). Higher the amount of current, higher the loss. Case-4 has the highest amount of net losses compared to net energy delivered.
4) $I_{battery}$ during charge and $I_{battery}$ during discharge remains constant. During charge, as SOC goes towards 1, $V_{battery}$ increases . Maximum, $V_{battery}$ and $P_{battery}$ (power needed to charge) at SOC = 1. This indicated, may be fully charging the battery is not always a good idea. Charging upto 90-95% SOC is better in terms of power consumption and battery health. But round-trip efficiency goes down if we charge upto SOC 0.95 instead of 1. So, there is a tradeoff.

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5) For SOC between 0.2 and 1, the variation in open-circuit will be between 3.6 V and 4.2 V. With 80 cells in series, the variation in open-circuit battery (V_{oc}) voltage will be between 288 V and 336 V. However, the cell "terminal" voltage during charge or discharge ($V_{battery}$ in Fig 7-10) will be different due to the voltage drops across R_0 and R_1. The range in cell (hence battery) terminal voltage will be substantially greater than range in "open-circuit" voltage. $V_{cell} = V_{oc} – V_{R0} - V_{C1}$. But, we are within manufacturer-supplied limits in all charge/discharge cycles considered except for case-4.