Stanford | SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES

Midterm (120 points)

ENERGY 294 - Electrochemical Energy Storage Systems: Modeling and Estimation

Spring Quarter 2018

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Due May 11, 2018 at 12:01 PM (Electronic pdf copy in CANVAS and hard-copy to the TA)

The midterm must be conducted individually.

Instructions: All the steps must be thoroughly documented, commented, and quantitative answers must be reported while including all the plots and calculations. All plots must be readable, and multiple signals over a single plot must be distinguishable when printed in black and white. Indicate all the axes (with units) and legends.

Note 1: The final project of this course will leverage the outcome of this midterm.

This midterm is aimed at assessing your understanding of equivalent circuit battery models and parameter identification methods. Data sets from experiments conducted on an US18650VTC4 lithium-ion cell H4 will be utilized in this midterm. The cell technical specifications have been provided to you in Homework 2. The data sets provided to you are summarized below:

Data Set	**Temperature**	**Utilization**
1 C-rate capacity test in discharge	23°C	Problem 1
0.05 C-rate capacity test in discharge	23°C	Problem 1 and Problem 2
0.05 C-rate capacity test in discharge	45°C	Problem 1 and Problem 2
Hybrid Pulse Power Characterization (HPPC) test	23°C	Identification study in Problem 2
HPPC test	45°C	Identification study in Problem 2
US06 test	23°C	Validation study in Problem 2

Problem 1 (20 points)

1. Design and code in MATLAB the input current profile to perform a HPPC test at 23°C. Assume that you start the experiment from a fully charged battery. The following characteristics must be implemented while designing the profile:
   a) The test will begin when the cell is at 100% state-of-charge (SoC) and will be terminated when the cell is at 10% SoC.
   b) At every 10% SoC interval (i.e. 100%, 90%, etc.), the battery will be subjected to charge and discharge pulses of 4 C-rate in both directions. The duration of each pulse is 10 s long, and a rest period of 30 s must be provided at the end of each pulse event.

c) After the completion of the pulse events at each SoC interval, the battery must be discharged at 1 C-rate in 10% depth-of-discharge increments (i.e. 100% to 90%, 90% to 80%, etc.).

d) After each 10% SoC discharge, a rest period of one hour must be provided to the cell, before commencing the next set of pulse events.

e) Calculate the cell capacity at 1 C-rate of discharge.

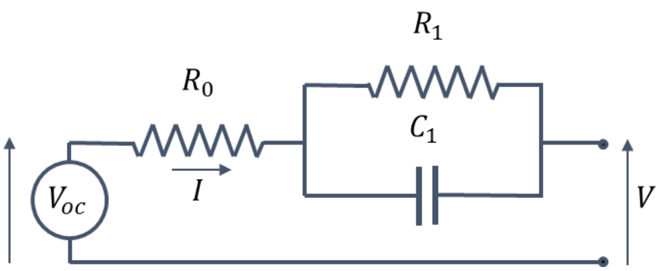
2. The open circuit voltage of a cell, V_{oc}, can be approximated as the cell voltage response from a 0.05 C-rate capacity test. Using the data provided, plot V_{oc} of the cell as a function of SoC for the $T = 23°C$ data set and the $T = 45°C$ data set. SoC is calculated as the integral of current I over time t normalized by battery capacity Q_{nom} (in units of Ah):

$$SoC(t) = SoC(0) - \frac{1}{3600 \cdot Q_{nom}(T)} \int_0^t I\, dt$$

Problem 2 (100 points)

<u>Parameter Identification</u>

The dynamic response of a battery can be described using a first-order Randles model (equivalent circuit model) as shown in the figure below.



Implement a first order equivalent circuit model in MATLAB/Simulink and identify the 3 parameters of this model, $\theta = [R_0, R_1, C_1]$, as a function of the cell SoC and temperature. A root mean square (RMS) error of less than 5% is expected to be achieved. The percentage RMS error must be calculated using the expression

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(V_{exp}(i) - V_{sim}(\theta; i)\right)^2} \cdot \frac{100 \cdot N}{\sum_{i=1}^{N} V_{exp}(i)},$$

where V_{exp} is the experimentally measured voltage response, V_{sim} is the model-predicted voltage response that is a function of θ, N is the total number of data samples, and i is the time index.

The portion of the identification profile that is relevant for this task begins at 100% SoC (just before the beginning of the first discharge) and terminates at the end of the test profile. For such a profile, the following tasks are to be conducted:

a) Use the graphical method studied in class to generate the initial guesses for the three parameters. Tabulate the initial guesses of the three parameters from the graphical method at each SoC and temperature.

b) Use the *fminsearch* algorithm to identify the elements of the vector θ as a function of the cell SoC and temperature. Tabulate the results obtained from this approach.

c) Use the *ga* algorithm to identify the elements of the vector θ as a function of the cell SoC and temperature. Tabulate the results obtained from this approach.

d) Provide a 3-D surface plot of the internal resistance R_0 as a function of SoC and temperature from the results obtained using the *fminsearch* algorithm.

e) Provide a 3-D surface plot of the internal resistance R_0 as a function of SoC and temperature from the results obtained using the *ga* algorithm.

f) Comment on the advantages and the limitations of the two approaches you have used for parameter identification.

g) Conduct a comparison analysis among these two approaches in terms of the overall achieved % RMS error.

h) Analyze the sensitivity of the model-predicted voltage using the identified values from the *ga* algorithm for a constant current discharge input of 2 A between the voltage range of 4.20 V and 2.50 V. This sensitivity analysis must be conducted for the following scenarios:

    i. A 5%, 10%, and 15% increase in R_0 while keeping R_1 and C_1 fixed.

    ii. A 5%, 10%, and 15% increase in R_1 while keeping R_0 and C_1 fixed.

    iii. A 5%, 10%, and 15% increase in C_1 while keeping R_0 and R_1 fixed.

    For each scenario, illustrate the voltage response for the baseline (original identified values), the 5% increase, the 10% increase, and the 15% increase on the same plot. Since the first order model has three parameters, a total of three plots must be generated (one corresponding to each parameter).

i) Comment on the results observed from the sensitivity studies.

Note 2: Extra points will be provided if Problem 2 part i) is answered correctly.

Model Validation

The identified model must be validated against the US06 driving cycle profile. Report the % RMS error obtained from model validation, and provide a plot comparing the experimental and the model-predicted voltage response. Only consider the US06 dynamic charge/discharge portion of the experimental data set when providing this plot. In addition, perform the following tasks:

1. Plot the overall variation of the cell SoC from the beginning to the end of the US06 cycle as a function of time.
2. Based on the overall variation of the cell SoC from the beginning to the end of the US06 cycle, what type of vehicle could this driving cycle have been obtained from? Explain your answer, if you can.

Note 3: Before beginning working on the midterm, please be familiar with the following materials:

a) Content covered in all the lectures so far.

b) Robyn Jackey, Michael Saginaw, Pravesh Sanghvi, Javier Gazzarri, Tarun Huria, and Massimo Ceraolo, "*Battery Model Parameter Estimation Using a Layered Technique: An Example Using a Lithium Iron Phosphate Cell*", SAE International 2013-01-1547.

Note 4: Submit all Matlab files pertaining to this midterm in a zipped folder. When we execute the code, there should be no need to make any modifications. If there are specific *.mat* or function files that must be retained in the same folder, please include them and mention them specifically.

Note 5: All the experiments are conducted using an Arbin BT-2000 tester, for which the current convention is positive during charge and negative during discharge. As mentioned in the slides, the general current convention is the opposite for charge and discharge.