Homework 3 on Prof. Krein’s Lecture on Batteries and Oliver Gross’ Lecture on Battery Hazards and Safety

Date due: Friday, March 4, 2022

In the solution of problems 1 – 4, ignore battery losses with the implication that those losses are considered to be part of the grid losses. A more thorough approach is to assume a battery round-trip efficiency in the 85 % to 95 % to get a more concrete idea. However, for the purposes of this course, that level of detail is not required.

1. An $EV$ has been equipped with a $Li$-ion battery pack with a 100 % state of charge ($s.o.c.$) rating of 80 kWh. The $EV$ requires about 200 $Wh/mi$ for city driving and 250 $Wh/mi$ for modest-speed highway cruising. We wish to analyze the functionality with respect to the US average round-trip commute distance of 32 miles.
   a. For a commute in an urban setting, determine the amount of energy that needs to be recovered at work during the day or at night at home. You need to consider the scenarios in which charging is either available or not available at one of the two locations.
   b. Given a specified $C/5$ recharge rate, calculate the charge time needed for a one-way commute or for the full round-trip commute. Comment on the results if the charger is limited to 1.4 $kW$ output.
   c. In the event that the user seeks to refill to at least 80-% $s.o.c.$ over a short time after a daily commute, is daily fast charging required? If so, determine in terms of the $C$ multiple rate required to recover to the 80-% $s.o.c.$ in 10 minutes.

2. A large truck is equipped with a 700 kWh battery pack and consumes about 2,500 $Wh/mi$ for highway cruising. Truck drivers must take breaks of at least 30-min duration after driving a maximum of 8 $h$. Moreover, they are allowed to drive only 11 $h$ during a 14-$h$ total shift. The driver must then be off-duty for the remaining 10 $h$ in a 24-$h$ day.
a. **Determine** the distance this truck travel between breaks, given that all of the following constraints must not be violated:
   - 8 h maximum continuous operation
   - 70 mph maximum speed
   - keep s.o.c. at or above 20%

Which of these constraints is the most restrictive and is met ahead of either of the other two constraints and becomes binding?

b. **Compute** the charge rate required to recover all of the energy use if charging is possible for all 3 hours of the required breaks?

c. Subject to the constraints in part (a), **determine** the charge rate required to make use of all the downtime and restore full range every 24 hours?

3. *Li-ion* battery range, in effect, the energy capability, at 0 °C is about 60 % of the value at 25 °C. This temperature impacts the effective battery pack capability and also affects the C rate: a cold battery needs to be charged more slowly than a warm one. Repeat the problem 1. above for a low-temperature commute with the same *EV*. However, assume that the cabin heat load requires an additional 50 Wh/mi for the commute.

4. A hypothetical battery offers double both the energy density and the power density compared to a widely available *Li-ion*-cell-based battery pack. Based on your analysis and results in the solution of the problems above, comment on the impacts of such a technology. Carry out your analysis under the assumption that the costs per kWh of the technology is double that of *Li-ion* technology.

5. Consider an *EV* battery pack made up of 108 prismatic can *Li-ion* cells connected in series. Each cell has the characteristics given in the table below. **Determine** both the cell and pack power, given that the fully charged pack is short circuited with a resistance equal to the pack resistance, *i.e.*, assume that the voltage is halved.
6. **Evaluate** the discharge current for the pack under the assumption that there is a 10-s discharge. **Determine** the equivalent C-rate.

7. **Calculate** the heating power generated by that cell, under that condition.

8. **Compute** the amount of heat energy generated in one cell in 10s under the assumption of a constant current during that time.

9. **Estimate** the temperature rise that occurs in the cell under adiabatic conditions

10. Consider a discharge with an initial temperature of 35 °C, which was calculated based on the pulse temperature at the end of the discharge. **Determine** the likely cause of the cell failure.

11. **Repeat** for the case the cell is short circuited to 0.9 V. **Compute** the heat generation and expected temperature rise of the cell. **Identify** the cause of the cell failure.

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<table>
<thead>
<tr>
<th>feature</th>
<th>value and unit</th>
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</thead>
<tbody>
<tr>
<td>rated discharge capacity</td>
<td>140 Ah</td>
</tr>
<tr>
<td>maximum voltage at full charge</td>
<td>4.2 V</td>
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<tr>
<td>nominal discharge voltage</td>
<td>3.7 V</td>
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<tr>
<td>nominal discharge resistance</td>
<td>0.5 mohm</td>
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<tr>
<td>cell mass</td>
<td>2.11 kg</td>
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<tr>
<td>cell dimensions (t x w x h)</td>
<td>31 mm x 230 mm x 91 mm</td>
</tr>
<tr>
<td>cell specific heat capacity</td>
<td>1 kJ/kg*K</td>
</tr>
</tbody>
</table>
12. We are told that a 140-Ah cell combusts. **Determine** the maximum additional amount of energy expected to be released from the anode alone.

13. Assume the cell skin reaches a maximum temperature of 600 °C. The two major cell faces (91mm x 230mm) are protected with a 2 mm thick piece of aerogel. **Calculate** the temperature at the end of 10 s seen by these two adjacent cells.

14. Assume the pack had been engineered to use a 600-A-rated thermal fuse. Use the plots below to **determine** whether the fuse would have activated within the 10 s, 2.1-V short circuit event and, if so, at what time. An additional bonus question is to **determine** the pack safe discharge power limit, given the 600-A fuse, so that the fuse would not activate over the life of the pack.