Examination **EEN016 Lithium-ion battery systems for vehicles and large-scale energy storage**
Thursday January 16, 2020, 14:00
Lecturer: Torbjörn Thiringer
Help: Calculator Chalmers Approved Type
Solutions: Course Homepage
Mark list: Before Wednesday February 4 , 2020
Complaints: Friday February 7, 2020, Room Uno Lamms room , 12:30 - 13:00

The limit for a 3 on the exam is 20 p Grade 4 is 30p and grade 5 is 40p. Approved labs and project is also required.

Observe that the questions are not arranged in any kind of order. Assume T=20 °C (293K).

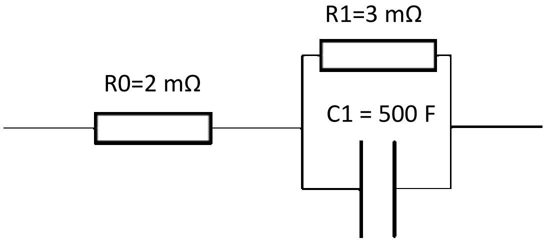
Observe that the numbering of the answer papers must be chronological, so do it just before you hand in the exam. Disordered numbering will lead to 0 points on the exam.

Motive your choices, purely writing answers or putting up final expressions without derivations gives 0 points.

Question 1 (7p)

a) What are the advantages and disadvantages of the ZARC and Randels models compared with the RC-link model? (1p)

b) Draw the EIS curve of the circuit below. (1p)



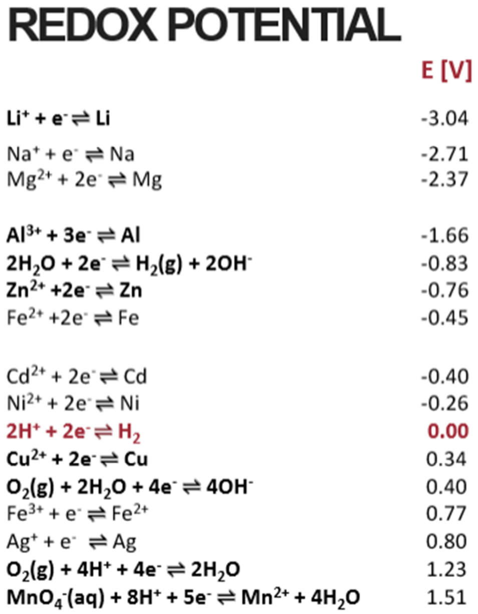
c) The circuit above is an equivalent circuit model of a 30 Ah battery cell and the open circuit voltage of the battery is 3V. Plot the voltage response of the battery when a 5A current step is applied for 20 seconds. Clearly mark the x-axis and y-axis. (2p)

d) Assume that the impedance trajectory for the RC-link in task b represents the charge transfer resistance in parallel with the double layer capacitance. If a real measurement is conducted, how would the trajectory rather look like compared to the theoretical one from task b ? What modification needs to be done to the circuit ? (2p)

e) How does the battery internal resistance change with temperature/SoC/SoH/current? (1p)

Question 2 (10p)

a) In iron ships, a sacrificial electrode is commonly used to protect iron against corrosion. Choose one material that can be used as the sacrificial electrode. Write the redox reactions that happen on each electrode and mark the anode and cathode. The redox potential of different materials vs standard hydrogen electrode (SHE) are shown in the table blow. (2p)



REDOX POTENTIAL

	E [V]
$Li^+ + e^- \rightleftharpoons Li$	-3.04
$Na^+ + e^- \rightleftharpoons Na$	-2.71
$Mg^{2+} + 2e^- \rightleftharpoons Mg$	-2.37
$Al^{3+} + 3e^- \rightleftharpoons Al$	-1.66
$2H_2O + 2e^- \rightleftharpoons H_2(g) + 2OH^-$	-0.83
$Zn^{2+} + 2e^- \rightleftharpoons Zn$	-0.76
$Fe^{2+} + 2e^- \rightleftharpoons Fe$	-0.45
$Cd^{2+} + 2e^- \rightleftharpoons Cd$	-0.40
$Ni^{2+} + 2e^- \rightleftharpoons Ni$	-0.26
$2H^+ + 2e^- \rightleftharpoons H_2$	**0.00**
$Cu^{2+} + 2e^- \rightleftharpoons Cu$	0.34
$O_2(g) + 2H_2O + 4e^- \rightleftharpoons 4OH^-$	0.40
$Fe^{3+} + e^- \rightleftharpoons Fe^{2+}$	0.77
$Ag^+ + e^- \rightleftharpoons Ag$	0.80
$O_2(g) + 4H^+ + 4e^- \rightleftharpoons 2H_2O$	1.23
$MnO_4^-(aq) + 8H^+ + 5e^- \rightleftharpoons Mn^{2+} + 4H_2O$	1.51

b) Based on the redox potential table, what is the potential of a fuel cell operating on hydrogen and oxygen? What can affect this potential? (2p)

c) What are the advantages and disadvantages of LTO as the negative electrode compared with graphite? (2p)

d) In a battery management system, what are the challenges to estimate the state of charge using voltage measurement? what are the challenges to estimate the state of charge using coulomb counting? (1p)

e) Once a battery fire has started, which is the way to extinguish it ? (1p)

f) Which materials in a Li-Ion battery is problematic from environmental and ethical point of views (2p)

Question 3 (15p)

A cell has a resistance value of 2 mΩ, and in the SOC interval 0-40 % SOC the entropy coefficient is -0.2 mV/K. for 40-100 % it is 0.1 mV/K. The OCV as function of SOC is shown in Figure 1. The upper voltage limit for the cell has been set to 3.75 V and the lower to 3.25 V. A 100s2p battery is now made up of the cells. The ambient temperature is 20 deg C and there is no cooling of the battery.

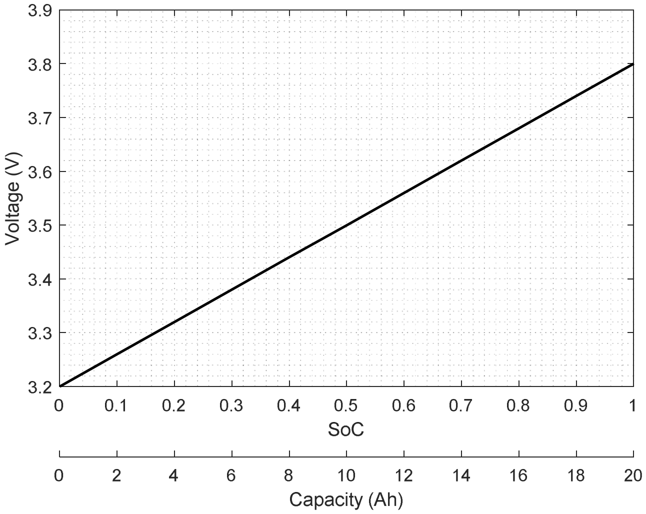


Figure 1. Open circuit voltage versus SoC.

a) Assume the battery is at rest and the cell voltage is 3.25 V. From this point it is charged with a 1C current, until the upper voltage limit is reached. How much charge will be put into the battery? (2p)

b) What will the total reversible and total irreversible energy loss be in the battery during the charging? (2p)

c) Assuming that the cell has a heat capacity of 900 J/K and a thermal resistance towards the surrounding of 0.1 K/W (the whole cell can be assumed to be a homogenous body): What is the temperature in the cell after 10 minutes of charging ? (3p)

d) The battery is now left to cool down and relax at 50 % SOC. Sketch the temperature development of the cell during a 4-hour sequence with continuous charging and discharging between 50 and 80 % SOC using a 1 C current, and mark the final value clearly as well as the value after 1 minute of charging (2p)

e) At what charging rates is the irreversible heat effect larger than the reversible for the SOC interval of 0-40 %? (2p)

f) The battery is now put into an electric vehicle, the strategy is to use the battery between 5 and 95 % SOC, the voltage of the battery output is thus allowed to go outside the previously mentioned voltage limitations. The maximum power both in motoring and generating mode of the electric machine is 80 kW. What is the voltage operation range that the inverter should be designed for? (4p)

Question 4 (8p)

Design a 5.5 V, 10 F supercapacitor, using sulfuric acid H_2SO_4 electrolyte (1.0 V maximum operating voltage). Use the same material for positive and negative electrodes.

a) How many unit cells do you intend to apply in your design? (1p)
b) What is the capacitance of the positive electrode in a unit cell in your design if the active materials mass ratio of positive to negative electrodes is 2:1? (4p)
c) What is the working potential range ratio of the two electrodes? (2p)
d) The capacitive potential range (CPR) of electrode materials has been measured in a three electrode system on two super capacitors, by conducting cyclic voltammogram (CV) scans, and the results are shown in the figure below. One of them is a LiIon supercapacitor. Motivate which one. (1p)

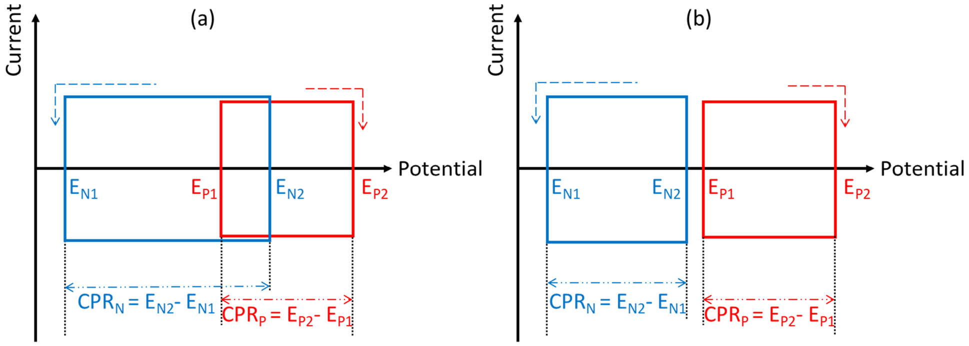
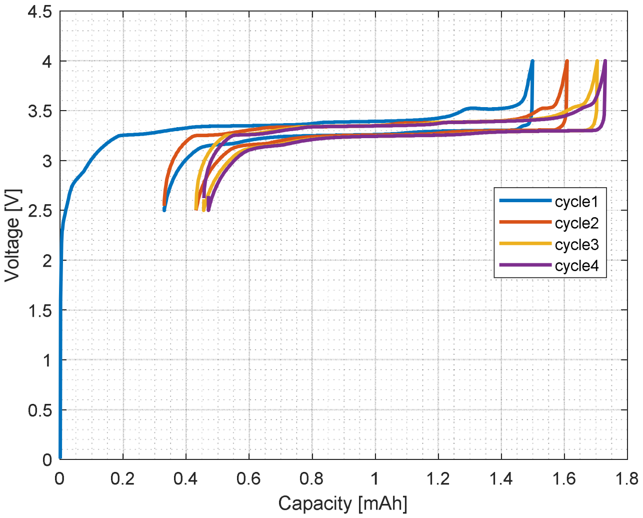


Figure 1. CPR ranges of the electrodes of the supercapactiors

Question 5 (4p)

The formatting data of a lithium ion battery cell is shown in the figure below. The positive electrode is LFP and the negative electrode is Graphite.



a) Calculate the columbic efficiency for the 4 cycles. (1p)
b) What is the expected columbic efficiency of a commercial Li-Ion cell? (1p)
c) What does N/P ratio mean? (1p)
d) Why is the N/P ratio normally higher than 1? (1p)

Question 6 (6p)

Design a 6 Ah Graphite//LFP cell and calculate the energy density (Wh/kg) of the cell (4p)

- Cathode: 94 wt% LFP (capacity 160 mAh/g, 5 mg LFP/cm2); 3 wt% PVdF, 3 wt% carbon black; 20 um Al foil (double-side coated)
- Anode: 90 wt% graphite (capacity 350 mAh/g); 5 wt% PVdF, 5 wt% carbon black; 20 um Cu foil (double-side coated)
- Electrolyte: 1 M $LiPF_6$ in 1:1 EC:DEC + 2% VC; 3 times excess
- Separator: Solupor 3P07A
- Electrode format and housing 5x5 cm: Pouch cell casing 6*6 cm, weight incl. tabs: 8.0 g
- N/P ratio: 1.3
- Cu density: 8.96 g/cm3
- Al density: 2.70 g/cm3
- Electrolyte density: 1.35 g/cm3
- Separator data: 3 g/m2; 20 um thick; 87 % porosity
- Cell voltage: 3.4 V

How many layers of aluminium and copper sheets are needed ? (2p)

Formula sheet for the final exam

Step response of a RC circuit

$$u(t) = iR\left(1 - e^{-\frac{t}{RC}}\right) + u(0)$$

RMS (root-mean-square) current

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2 dt}$$

The effective conductivity in a porous material

$$\sigma_{eff} = \sigma\frac{\Phi}{\tau} = \sigma\Phi^{\beta}$$

The effective diffusion coefficient in a porous material

$$D_{eff} = D\frac{\Phi}{\tau^2}$$

Active material specific capacity

$$Q = \frac{nF}{M_w}$$

Butler-Volmer relation

$i = i_0\left(exp\left(\frac{\alpha_a nF}{RT}\eta\right) - exp\left(-\frac{\alpha_c nF}{RT}\eta\right)\right)$ can for low currents be written as $i = i_0\left(\frac{nF}{RT}\eta\right)$

Constants:
Faradays constant 96485 Coulumb/mol
Avogadros number $6.02e^{23}$/mol
Bolzmans constant $1.38e^{-23}$ J/K
Gas constant: 8.31 J/mol/K

Volume of a sphere=$4/3\pi r^3$
Area of a sphere=$4\pi r^2$

a) What are the advantages and disadvantages of the ZARC and Randel model compared with the RC-link model?

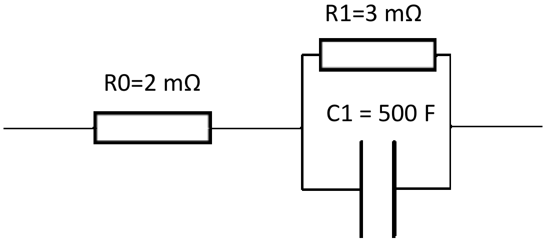
The ZARC and Randel models

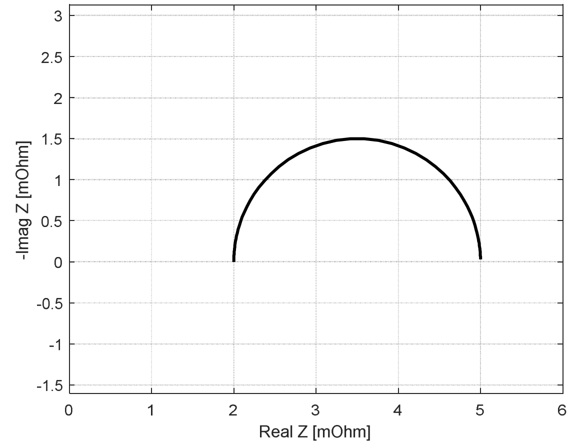
- Advantages: Can model the nonlinear behaviour. Each element has a physical meaning
- Disadvantages: Difficult to compute in time domain.

RC-link model

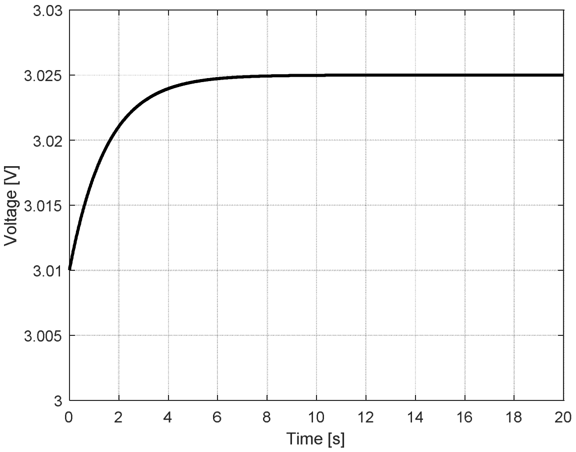
- Advantages: Easy to fit.
- Disadvantages: The elements cannot be explained with physical meanings.

b) Draw the EIS curve of the circuit below. (1p)





c) The circuit above is an equivalent circuit model of a 30 Ah battery cell and the open circuit voltage of the battery is 3V. Plot the voltage response of the battery when a 5A current step is applied for 20 seconds. Clearly mark the x-axis and y-axis.



d) Assume that the impedance trajectory for the RC-link in task b represents the charge transfer resistance in parallel with the double layer capacitance. If a real measurement is conducted, how would the trajectory rather look like compared to the theoretical one from task b ? What modification needs to be done to the circuit ? (2p)

The semicircle would be a bit lower. Instead of having a pure capacitor we need to replace the capacitor with a Constant Phase Element (CPE)

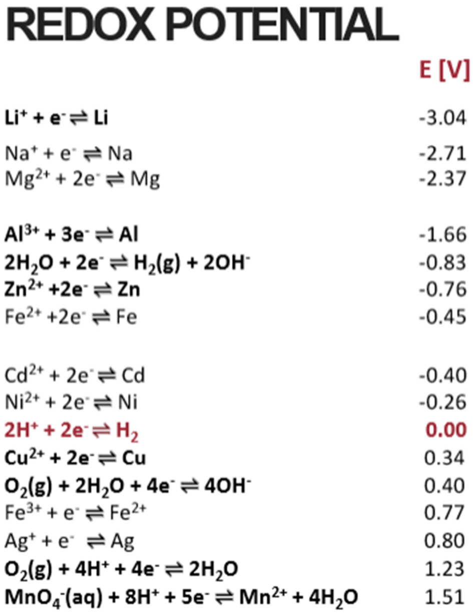
$$Z_{CPE} = \frac{1}{(j\omega)^{\alpha} C}$$

e) How does the battery internal resistance change with temperature/SoC/SoH/current?

The battery internal resistance is normally higher at low temperature, low SoC level, aged cell, and low current level.

Question 2 (10p)

a) In iron ships, a sacrificial electrode is commonly used to protect iron against corrosion. Choose one material that can be used as the sacrificial electrode. Write the redox reactions that happen on each electrode and mark the anode and cathode. The redox potential of different materials vs standard hydrogen electrode (SHE) are shown in the table blow. (2p)



REDOX POTENTIAL

	E [V]
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$Mg^{2+} + 2e^- \rightleftharpoons Mg$	-2.37
$Al^{3+} + 3e^- \rightleftharpoons Al$	-1.66
$2H_2O + 2e^- \rightleftharpoons H_2(g) + 2OH^-$	-0.83
$Zn^{2+} + 2e^- \rightleftharpoons Zn$	-0.76
$Fe^{2+} + 2e^- \rightleftharpoons Fe$	-0.45
$Cd^{2+} + 2e^- \rightleftharpoons Cd$	-0.40
$Ni^{2+} + 2e^- \rightleftharpoons Ni$	-0.26
$2H^+ + 2e^- \rightleftharpoons H_2$	0.00
$Cu^{2+} + 2e^- \rightleftharpoons Cu$	0.34
$O_2(g) + 2H_2O + 4e^- \rightleftharpoons 4OH^-$	0.40
$Fe^{3+} + e^- \rightleftharpoons Fe^{2+}$	0.77
$Ag^+ + e^- \rightleftharpoons Ag$	0.80
$O_2(g) + 4H^+ + 4e^- \rightleftharpoons 2H_2O$	1.23
$MnO_4^-(aq) + 8H^+ + 5e^- \rightleftharpoons Mn^{2+} + 4H_2O$	1.51

Answer: Mg, Al or Zn (Li or Na are reactive with water and cannot be used as the sacrificial anode)

Anode: $Mg \rightarrow Mg^{2+} + 2e^-$ (or Al, Zn)
Cathode: $Fe^{2+} + 2e^- \rightarrow Fe$

b) Based on the redox potential table, what is the potential of a fuel cell operating on hydrogen and oxygen? What can affect this potential? (2p)

Answer: 1.23V, affected by temperature and pressure of the oxygen and hydrogen.

c) What are the advantages and disadvantages of LTO as the negative electrode compared with graphite? (2p)

Answer: Advantages: More stable, less side reactions (longer lifetime).
Disadvantages: Low specific capacity, low cell voltage.

d) In a battery management system, what are the challenges to estimate the state of charge using voltage measurement? what are the challenges to estimate the state of charge using coulomb counting? (1p)

For the voltage estimation, some important problems are that the V_OCV(SOC)-characteristics can be very flat. In addition it takes a long time for the battery voltage to relax. For the columb counting, a problem is that it is an open integration so a slight error in the current measurement will continue to by integrated. In addition there is a leakage current that also impacts the quality of the coloumb counting.

e) Once a battery fire has started, which is the way to extinguish it ? (1p)

Water

f) Which materials in a Li-Ion battery is problematic from environmental and ethical point of views (2p)

Nickel and Cobalt are two examples of environmentally problematic materials. Cobalt in particular also has a great ethical problem due to the mining in some regions, like the peoples republic of Congo. Copper is a large pollution when being extracted from the ground as well.

Question 3 (15p)

A cell has a resistance value of 2 mΩ, and in the SOC interval 0-40 % SOC the entropy coefficient is -0.2 mV/K. for 40-100 % it is 0.1. The OCV as function of SOC is shown in Figure 1. The upper voltage limit for the cell has been set to 3.75 V and the lower to 3.25 V. A 100s2p battery is now made up of the cells. The ambient temperature is 20 deg C and there is no cooling of the battery.

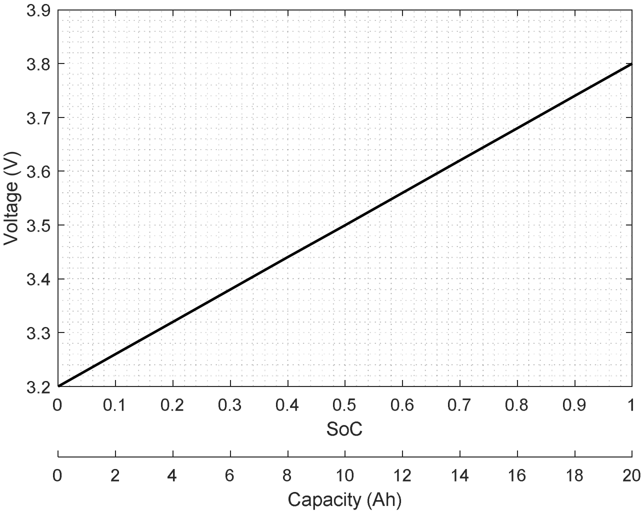


Figure 1. Open circuit voltage versus SoC.

Answer:
*So the battery is a 200 cell battery with a 40 Ah total current capacity and 320-380 V total range for 0 -100 % SOC, usable energy, the usable range is 8.3-91.7 %, i.e 0.83.3*40=33.3 Ah. OCV=3.20+SOC/100*0.6   or SOC=(OCV-3.20)*100/0.6*

Assume the battery is at rest and the cell voltage is 3.25 V. From this point it is charged with a 1C current, until the upper voltage limit is reached. How much charge will be put into the battery? (2p)

> *Answer: Charging with 1C rate, and just looking at one cell gives that the voltage drop will be DU=R*I=0.002*20=40 mV, so when the OCV has reaches 3.75-DU=3.71 V, the charging stops. 3,71 V gives a SOC of 85 %, starting from 8.3 %. Total charge to the battery cell is 76.7/100*20=15.34 Ah, and thus 30.68 Ah into the battery. The charging process takes 46 minutes.*

What will the total reversible and total irreversible energy loss be in the battery during the charging? (2p)

$$\dot{Q} = \dot{Q}_r + \dot{Q}_{irr} = I\big(V - U(OCV)\big) + IT\frac{\partial U}{dT}$$

I positive when charging

*Answer: The reversible loss is R*I*I, per cell it is 20*20*0.002=0.8 W. 160 W for the battery. The irreversible power is I*T*DU/dT, meaning for the low SOC interval the energy exchange is 20*293*(-0.0002)=-1.17W per cell, -234 W for the battery (i.e. the battery absorbs energy, i.e 74 W. For the high SOC level it is 20*293*(0.0001)=0.586 W per cell, i.e. 117 W for the battery. So the total loss is -74 W in the SOC interval 0-40 % and 277 W (1.385 W on cell level) for 40-100%.*
The first part with an power absorption level of 72W takes place between (40-8.3 % SOC), i.e. 1141 s, then from 40 to 85 % SOC, 277 W is emitted during 1620 seconds.
*Energyexchanged: 1620*277-74*1141 =448740 J (124.6 Wh) -84434 J(23.45 Wh)= 364306 J=101 Wh*

Assuming that the cell has a heat capacity of 900 J/K and a thermal resistance towards the surrounding of 0.1 k/W (the whole cell can be assumed to be a homogenous body): What is the temperature in the cell after 10 minutes of charging ? (3p)

The information given corresponds to a first order RC-LPN-model of the battery cell.

$\Delta T(t)=P\_loss*Rth*(1- \exp(-t/(CthRth))=P\_loss*Rth*(1- \exp(-t/\tau)$

the time constant τ =Cth*Rth=90 seconds. After 10 minutes, we are still in the low SOC interval and the temperature has reached its steady state so the simplified expression

$\Delta T(t)=P\_loss*Rth$

Can be used.

In the beginning 0.8-1.17 W=-0.37 W is absorbed by the cell

$\Delta T(t)=P\_loss*Rth=-0.37*0.1=0.037$ deg C. So, the temperature is 20-0.037=19.963 degrees, after 10 minutes

The battery is now left to cool down and relax at 50 % SOC. Sketch the temperature development of the cell during a 4-hour sequence with continuous charging and discharging between 50 and 80 % SOC using a 1 C current, and mark the final value clearly as well as the value after 1 minute of charging (2p)

In the 50-80 % SOC interval,

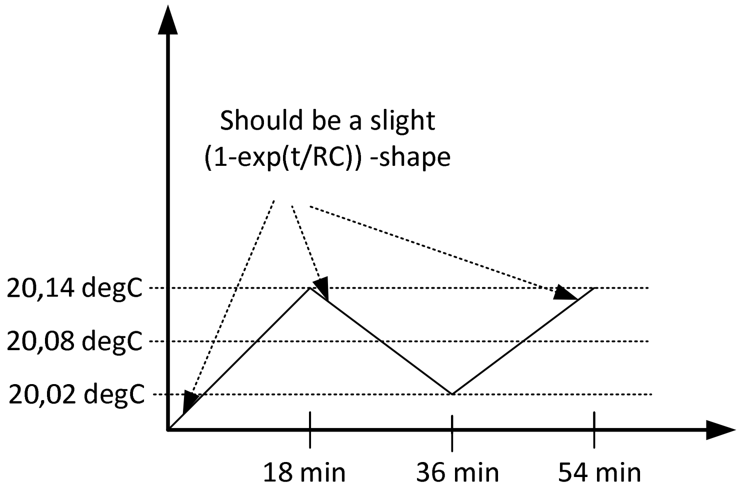
Ploss during charging is 1.385 W and during discharging (0.8-0.586W)=0.214 W.
The average loss is 0.8 W, and the loss swing is

A charge or discharge event covers a SOC range of 30 %, which takes 18 minutes, accordingly steady-state can be assumed.

So the average temperature increase is

$\Delta T\_increase(t)=P\_loss*Rth=-0.8*0.1=0.08$ deg C

The swing
$\Delta T\_swing(t)=P\_loss*Rth=-1.17*0.1=0.117$ deg C , or +-0.058 deg C



At what charging rates is the irreversible heat effect larger than the reversible for the SOC interval of 0-40 %? (2p)

> Answer: Looking on cell level, R*I^2=I*T*DU/dv => I=T/R*DU/dv=293/0.002*(-0.0002)=29.3 A

The battery is now put into an electric vehicle, the strategy is to use the battery between 5 and 95 % SOC, the voltage of the battery output is thus allowed to go outside the previously mentioned voltage limitations. The maximum power both in motoring and generating mode of the electric machine is 80 kW. What is the voltage operation range that the inverter should be designed for? (4p)

5 % SOC gives =U_OCV=3.23 V
95 % SOC gives =U_OCV=3.77 V

80 kW means 400 W per cell. We need to determine the battery voltage, but we wo not know the current, so we have two unknown:

U=U_ocv-R*I , P=U*I

P/I= U_ocv-R*I -> R*I^2-I*U_ocv+P=0 -> I=135 A at low SOC and 100 A at high SOC
U_high=100*(U_ocv+R*I)=100*(3.77+0.002*100)=397V
U_low=100*(U_ocv-R*I)=100*(3.23-0.002*135)=296V.

So, a suggestionis 290-400 V for the inverter.

Question 4 (8p)

> Design a 5.5 V, 10 F supercapacitor, using sulfuric acid H_2SO_4 electrolyte (1.0 V maximum operating voltage). Use the same material for positive and negative electrodes.

a) How many unit cells do you intend to apply in your design? (1p)

Since the maximum operating voltage is restricted to 1.0 V by the aqueous electrolyte, one has to connect multiple devices in series in order to achieve high voltage, namely bipolar design to keep the size of device small. At least 6 devices must be applied to achieve a 5.5 V rating using 1 V unit device.

b) What is the capacitance of the positive electrode in a unit cell in your design if the active materials mass ratio of positive to negative electrodes is 2:1? (4p)

In a series connection, the total capacitance C_T of the "pack" follows the relation

$$\frac{1}{C_T}=\sum_{i=1}^{6}\frac{1}{C_i}$$

where C_i represents the capacitance of each unit cell. The best design is to make unit cells identical, to gain the highest specific capacitance of the "pack", and also to avoid cell "imbalance" during operation. Hence, each unit cell should have a capacitance of 60 F to have a 6-cell pack rating at 10 F.
The positive and negative electrodes coordinate with each other during device operation through the following relation

$$m_+C_+E_+ = m_-C_-E_-$$

where m, C and E represent the mass (g), specific capacitance (F/g) and working potential range (V) of the electrodes, respectively, i.e. the charge flow through positive equals to that through negative.
Using the same material for both electrodes implies that the specific capacitances are similar. Knowing $m_+ = 2\times m_-$, the absolute capacitance of positive electrode is 2 times of negative, and then the value can be calculated via

$$\frac{1}{C_i}=\frac{1}{C_{positive}}+\frac{1}{C_{negative}}$$

$$\frac{1}{60\text{ F}}=\frac{1}{C_{positive}}+\frac{1}{0.5\times C_{positive}}$$

$$C_{positive}=180\text{ F}$$

c) What is the working potential range ratio of the two electrodes? (2p)

Knowing above information, the working potential range can be calculated through the charge flow balance equation, to be

$$E_+ : E_- = 1:2$$

d) The capacitive potential range (CPR) of electrode materials has been measured in a three electrode system on two super capcitors, by conducting cyclic voltammogram (CV) scans, and the results are shown in the figure below. One o f them is a LiIon supercapcitor. Motivate which one. (1p)

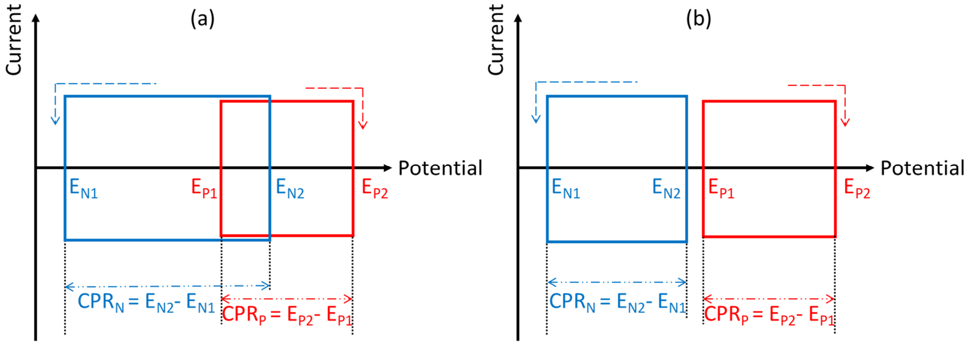
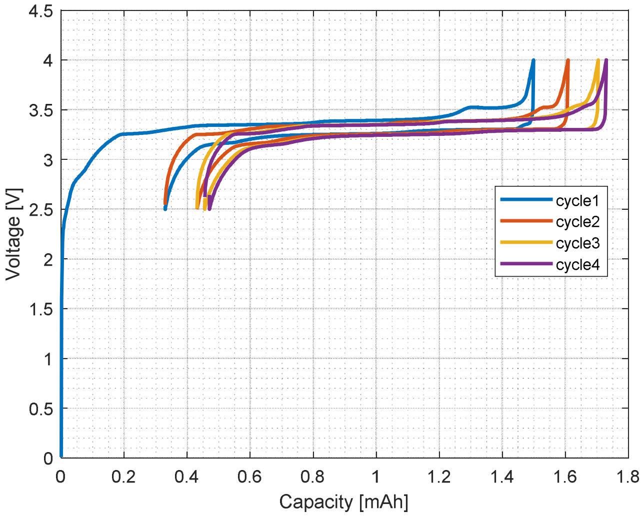


Figure 1. CPR ranges of the electrodes of the supercapactiors

The one without overlap

Question 5 (8p)

The formatting data of a lithium ion battery cell is shown in the figure below. The positive electrode is LFP and the negative electrode is Graphite.



e) Calculate the columbic efficiency for the 4 cycles.

$$\eta_{coulombic} = \frac{Q_{discharge}}{Q_{charge}}$$

$$\eta_{coulombic,1} = \frac{1.12\ mAh}{1.45\ mAh} \times 100\% = 77.24\%$$

$$\eta_{coulombic,2} = \frac{1.18\ mAh}{1.28\ mAh} \times 100\% = 92.19\%$$

$$\eta_{coulombic,3} = \frac{1.25\ mAh}{1.27\ mAh} \times 100\% = 98.43\%$$

$$\eta_{coulombic,4} = \frac{1.26\ mAh}{1.28\ mAh} \times 100\% = 98.44\%$$

f) What is the expected columbic efficiency of a commercial cell?

Up to 99.9%.

g) What does N/P ratio mean?

The capacity ratio of the negative electrode and the positive electrode.

h) Why is the N/P ratio normally higher than 1?

To avoid lithium plating at high SoC.

Question 6 (6p)

Design a 6 Ah Graphite//LFP cell and calculate the energy density (Wh/kg) of the cell (4p)

- Cathode: 94 wt% LFP (capacity 160 mAh/g, 5 mg LFP/cm2); 3 wt% PVdF, 3 wt% carbon black; 20 um Al foil (double-side coated)
- Anode: 90 wt% graphite (capacity 350 mAh/g); 5 wt% PVdF, 5 wt% carbon black; 20 um Cu foil (double-side coated)
- Electrolyte: 1 M LiPF6 in 1:1 EC:DEC + 2% VC; 3 times excess
- Separator: Solupor 3P07A
- Electrode format and housing 5x5 cm: Pouch cell casing 6*6 cm, weight incl. tabs: 8.0 g
- N/P ratio: 1.3
- Cu density: 8.96 g/cm3
- Al density: 2.70 g/cm3
- Electrolyte density: 1.35 g/cm3
- Separator data: 3 g/m2; 20 um thick; 87 % porosity
- Cell voltage: 3.4 V

a)
Electrodes:

$$m_{LFP} = \frac{Q_{cell}}{Q_{LFP}} = \frac{6}{0.160} = 37.5g$$

$$m_g = \frac{Q_{cell}}{Q_g} * N/P = \frac{6}{0.350} 1.3 = 22.28g$$

$$A = \frac{m_{LFP}}{5mgLFP/cm^2} = \frac{37.5}{0.005} = 7500cm^2$$

$$m_{Al} = \frac{\rho_{Al}L_{Al}A}{2} = \frac{2.7 * 0.002 * 7500}{2} = 20.25g$$

$$m_{Cu} = \frac{\rho_{Cu}L_{Cu}A}{2} = \frac{8.96 * 0.002 * 7500}{2} = 67.2g$$

$$m_{Cathode} = m_{Al} + m_{LFP} + m_{Additive} = 20.25 + \frac{37.5}{0.94} = 60.14g$$

$$m_{Anode} = m_{Cu} + m_g + m_{Additive} = 67.2 + \frac{22.28}{0.9} = 91.96g$$

Sep:

$$m_{Sep} = A * \rho_{Sep}(g/m^2) = 0.750 * 3 = 2.25g$$

Electrolyte:

$$V_l = 3V_{l,sep} = 3 * A * L_{Sep} * \varepsilon_l = 3 * 7500 * 0.002 * 0.87 = 39.15cm^3$$

$$m_l = V_l * \rho_l(g/m^3) = 39.15 * 1.35 = 52.85g$$

Cell mass:

$$m_{tot} = m_{Anode} + m_{Cathode} + m_{Sep} + m_l + m_{lcasing} = 91.96 + 60.14 + 2.25 + 52.85 + 8 = 215.2g$$

Energy density:

$$U = \frac{Q_{cell} * V_{cell,nom}}{m_{tot}} = \frac{6 * 3.4}{0.2152} = 94.8Wh/kg$$

How many layers of aluminium and copper sheets are needed ? (2p)

Using double coated current collectors: 7500/(5*5)/2=150 each