Unmanned Aerial Systems Techology (RMUAST) Spring 2017
University of Southern Denmark

Jesper Bogh Poder, Petr Batek and Bjarki Pall Sigursson, group 3

Module 2: Battery technology

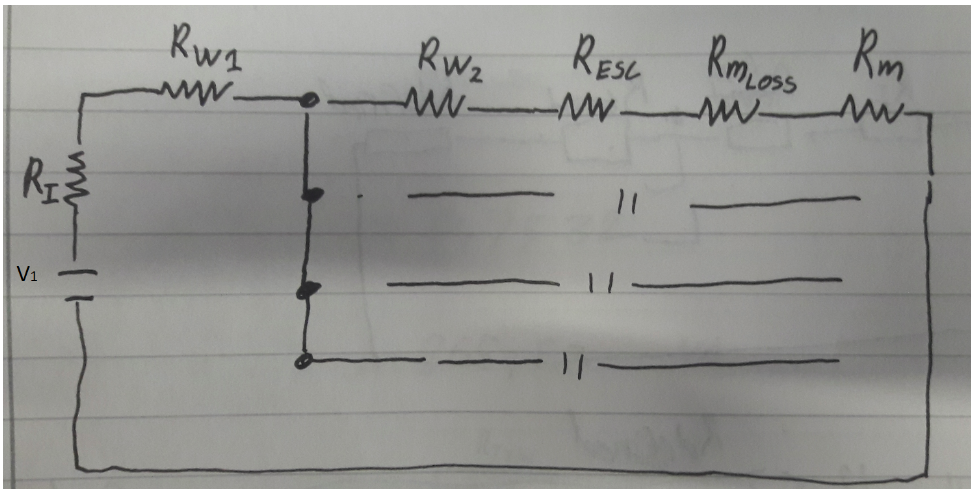
1 Exercises

1.1 Electric powertrain

1.1.1 Choosing the correct wires

Choose the two different cross section areas of the copper wires going from the battery to the center of the drone and from the center of the drone to the ESCs. Remember to take the efficiency of the motor and the ESCs into account.
ANSWER:

Figure 1 shows a diagram of our power system. For simplicity we create a equivalent resistor for the motors and their control system: $R_{eq1} = R_{ESC} + R_{Mloss} + R_m$. We know that this resistor will consume 129 W. Next we want to find the wires for the system and their resistance. Since we find those based on their current ratings, we want to estimate the current in our system. We do this by making a quick assumption saying that $R_I = 0$, $R_{W1} = 0$ and $R_{W2} = 0$ and we thereby get V_1 over R_{eq1}. This is naturally not correct, but by this assumption we get a bit higher current, which just keeps us on the safe side when choosing wires. We calculate the current running through R_{W2} to be 10.75 A and the current running through R_{W1} to be 43 A. Therefore, we choose a cross section of 1 mm^2 for R_{W2} and 10 mm^2 for R_{W1}. These values are chosen from http://kaizerpowerelectronics.dk/theory/wire-size-table/. When we know that the wires are made of copper, the specified length of the



Figur 1: Diagram illustrating the power system. We have four motors including their wires and motor controllers. Furthermore we have a wire, which draws the current for all four motors, R_{W1}, and and internal resistance R_I. We know from the assignment that after the ESC we need 129 W of electrical energy to make 100 W of mechanical energy.

wires should be multiplied by two and that the wires are operating at 60 degrees celsius, we can calculate the resistance with the following formulas:

$$
\begin{aligned}
\rho &= \texttt{resistivity coefficient}\\
L &= \texttt{length of wire}\\
A &= \texttt{cross section area of wire}\\
R_{res} &= \frac{\rho L}{A}\\
\alpha &= \texttt{temperature coefficient}\\
T &= \texttt{Operating temperature}\\
dR &= \alpha * (T - 20) * R_{res}\\
R_{total} &= R_{res} + dR
\end{aligned}
$$

We thereby get the following results:

$$
\begin{aligned}
R_{W1} &= 0.0012\Omega\\
R_{W2} &= 0.0081\Omega
\end{aligned}
$$

1.1.2 Estimating the efficiency

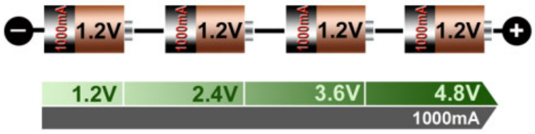
Calculate the total efficiency of the drone by using the applied effect from the battery and the effect converted to mechanical energy.
Answer:
We use the same assumption from earlier to calculate a resistance for R_{eq1} with the 129 W and 12 V, which results in $R_{eq1} = 1.12\Omega$. We know want to calculate the voltage in the node between R_{W1} and R_{W2}. Therefore, we create $R_{eq2} = 0.2820\Omega$ which corresponds to the four R_{W2} and R_{EQ1} in parallel. A simple voltage divider shows that the voltage across R_{W1} and R_I is 0.2987 V(from now called V_2), which corresponds to an effect of 12.3943 W given the previous values for R_{W1} and R_I. Next we want to calculate the effect in each R_{W2}, so we take into account V_2 and we thereby have 11.7013 V in the node between R_{W1} and R_{W2}. A voltage divider reveals that we have 0.0840 V across R_{W2}, which corresponds to an effect of 3.4859 W, when adding the four contributions together for R_{W2}. Thereby, we get a effiency of:

$$
efficiency = \frac{129 * 4 + 3.4859 + 12.3943}{400} = 0.7532
$$

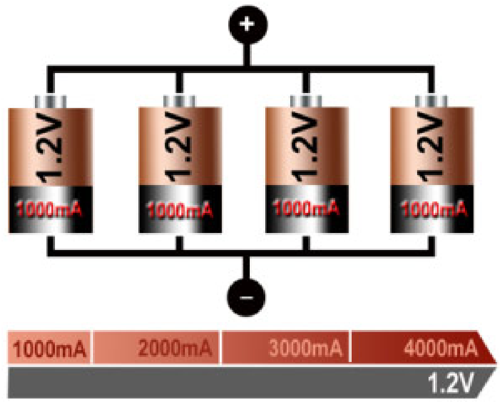
1.2 Batteries

1. How is a battery configuration described?
   ANSWER:
   Battery cells can be combined into packs in series, parallel or in combination of two previous. Connecting cells in series results in adding of their voltage and keeping of nominal charge capacity (in reality the weakest cell in series determines the useful capacity of pack). When connected in parallel the pack retains nominal voltage of cells but adds up charge capacities. Weak or defective cell doesn't have significant influence on the pack voltage, however it drains current from other healthy cells thus resulting to decreased runtime and overall capacity of the pack. When creating the pack, one needs to carefully choose individual cells and keep them matched. This can be done by choosing cells of the same type from the same manufacturer. Battery pack configuration is described in term `xSyP`, where S stands for no. of cells in series and P is for no. of parallel branches. E.g. 4S2P stands for a pack which contains from 2 parallel chains each composed of 4 cells in series.

2. Explain the difference between open circuit voltage (OSV) and terminal voltage.
   ANSWER:
   OSV is voltage over the source when it is not connected to any load. Voltage source in this case is disconnected from the circuit and thus doesn't form a complete closed circuit. OSV is related to EMF (ElectroMotive Force) and describes difference in source potential. Terminal voltage is



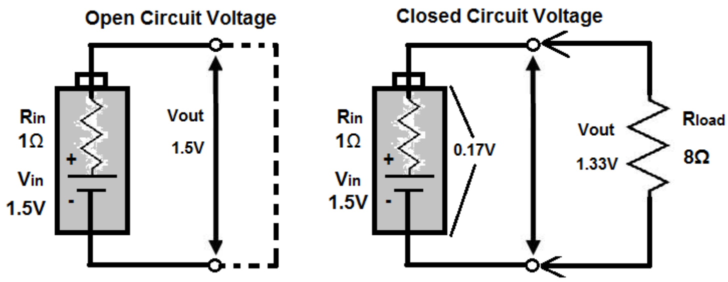
(a) Series cell configuration



(b) Parallel cell configuration

Figur 2: 2 main cells configurations (taken from: http://batteryuniversity.com)

measure across the battery when the circuit is closed. Because of voltage drop over the load in the circuit terminal voltage is lower than OSV. Terminal voltage is sometimes called a closed circuit voltage.



Figur 3: OCV vs. Terminal Voltage (taken from: http://www.learningaboutelectronics.com)
Because the left circuit isn't closed, there is no current and so no voltage drop from the OCV. On the other hand, the circuit on the right is closed and therefore current of $I = \frac{V}{R} = \frac{1.5}{1+8} = 0.17A$ flows through. Terminal voltage can be calculated by: $V_{term} = I * R_{in} = 0.17V$.

3. Explain what is SOH and SOC, and which parameters are used to describe it.
   ANSWER:
   SOC (State Of Charge) describes current battery level. Units are percents. 100% implies fully charged battery whereas 0% means empty battery. For a LiPo battery cells 0% marks the critical level (Cut-off voltage) of 3V and 100% signify level of 4.2. When the SOC gets below 0% the battery is destroyed. When working with pack of batteries these levels have to be multiplied accordingly to number of cells in series.
   SOH (State Of Health) describes a condition of a battery compared to its ideal condition. SOH is described in percentage. 100% signify that a battery meets its specification. This can be (but not necessarily) at the time of manufacture. SOH then decrease over time and battery use.

4. Explain what is c-rate and write an equation for calculating the minimum c-rate using the parameters maximum continuous current and nominal capacity.
   The C-rate is a normalization of the depletion current with respect to the battery's total capacity. nC is defined as the amount of continuous current which would deplete the battery n times in one hour. The maximum C rate is given by

$$maximum\ C\text{-}rate = \frac{maximum\ continuous\ current}{nominal\ capacity}.$$

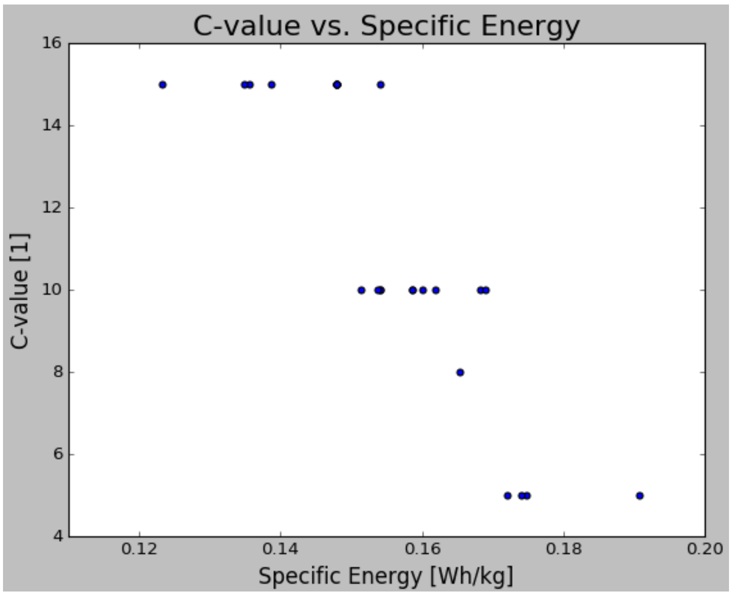
5. Write an equation for a battery specific energy using the data normally available for batteries.
   ANSWER:
   Battery Specific Energy is the ration of energy stored in a battery to its weight. It describes how

much energy could be stored in a battery of weight of 1kg. Approximate relationship to estimate battery specific energy is:

$$E_{spec} = \frac{(V_{nom} \cdot Ah)}{m} \quad ,$$

where V_{nom} is nominal voltage of the battery. Ah is battery total capacity described in Ampere-hours and m is the mass of battery active material.

6. Show on a graph the correlation (if existing) between C-value and Specific Energy. Use min. 25 of Melastas *High Drain Type Prismatic Li-polymer Battery* cells with various c-rate and capacities as test data. http://www.melasta.com/product2.asp
The graph is given on figure 4 and shows that there seems to be at least some linear correlation between the two parameters.



Figur 4: Scatter plot of C-value vs. Specific Energy.

7. Assuming the drone from exercise 1 is using 50 W pr. motor on average during a flight and we want to keep the drone flying for 30 min on a full charge. Calculate the minimum capacity and c-rate of the battery. Answer:
By the efficiency calculated in exercise one we get that, we should use 255.36 W to power the four motors. Given a voltage of 12 V we find that we should have 21.28 A to provide this effect. Since we need to fly for 30 minutes then we need 10.64 Ah and a C-rate of 2.

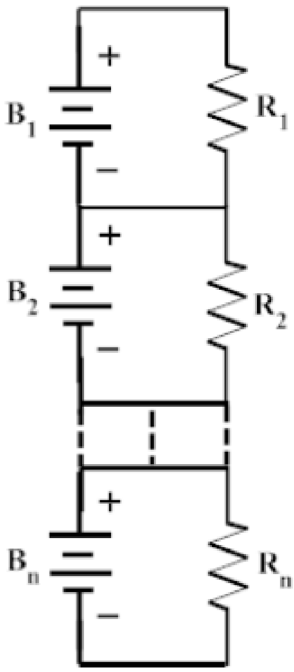
1.3 Charging and balancing

1. Why is balancing necessary?
Without balancing, the individual cell voltages will drift apart over time, the capacity of the pack as a whole will decrease more quickly during operation and the battery will fail prematurely.

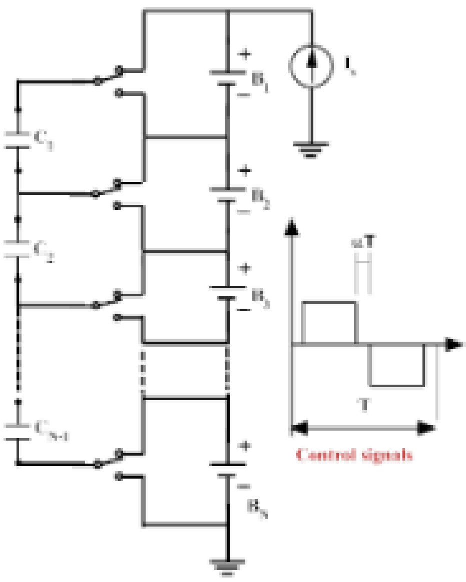
2. What are the three main states in charging a battery?
The first state is that of constant current. In this state the current supplied is kept at a constant value for fast charging up to a specified voltage.
The second state is that of constant voltage. Upon reaching the threshold voltage from the previous state, it is kept constant. In this state the charging slows down due to the limitation of the current, allowing safe charging up to the battery's maximum voltage.
The last state is a floating one in which the battery's voltage is kept at 100% SOC.

3. Sketch diagrams and briefly describe 3 types of balancing circuits that can be used for lithium based batteries.

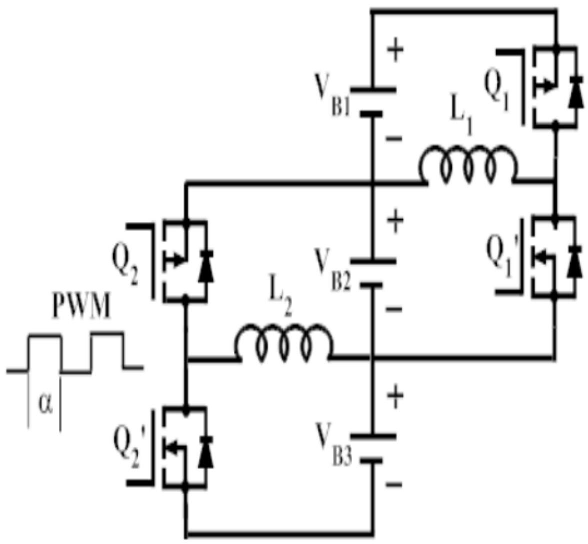
Balancing circuits are formed by adding an impedance in between battery cells to bypass excess current from the highest voltage cells to the lower ones. The differences in the following balancing circuits lie in the nature and configuration of the components used to provide this impedance.
The first type uses resistors as shown in figure 5. This circuit provides continuous, passive balancing but only works for battery cells which can be safely overcharged.
The second type uses (one or more) capacitors as shown in figure 6. This is an active balancing circuit as it requires a control signal to control the switches connecting the capacitors to their corresponding cells. This configuration provides simple balancing but faster topologies exist.
The third type uses (one or more) inductors and is shown in figure 7. This is also an active balancing circuit. Inductive components provide a high balancing current but require a high switching frequency and incur a relatively high cost. (Daowd et al., 2011)



Figur 5: Resistor balancing circuit.



Figur 6: Capacitor balancing circuit.

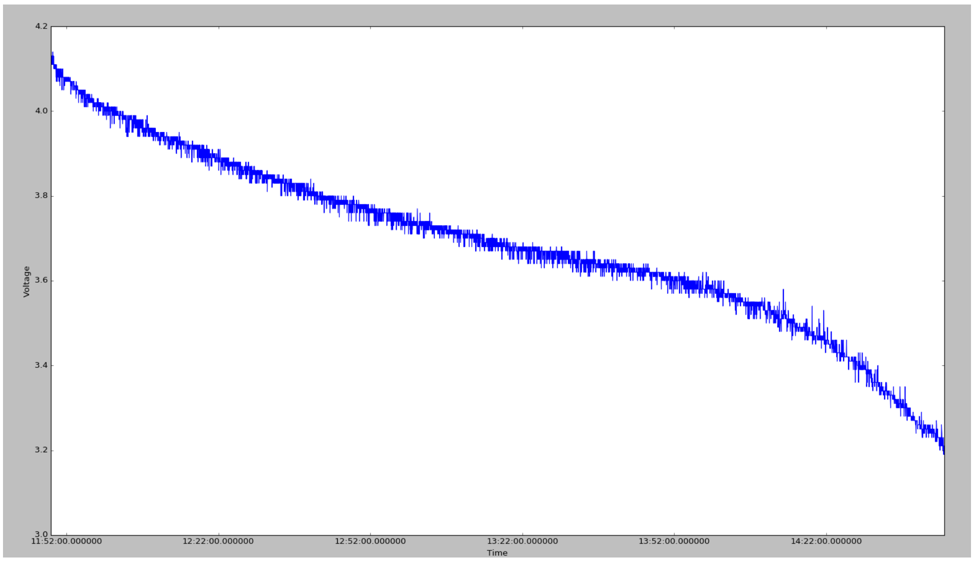


Figur 7: Inductor balancing circuit.

1.4 SOC estimation

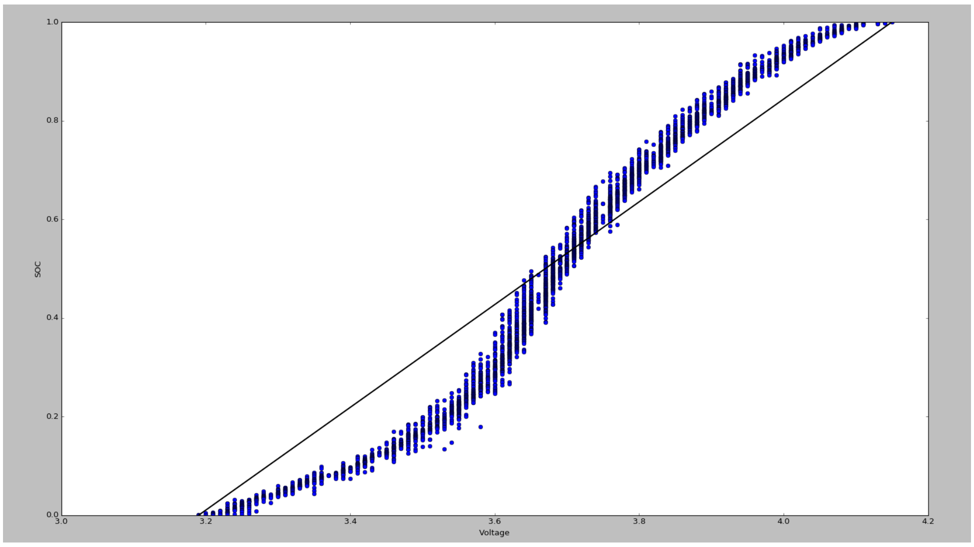
State of charge (SOC) is often handled by Coulomb count, but it can also be calculated directly from the OCV when current has not been drain from the battery for some time. Another estimation could be to measure the terminal voltage if the battery is drained with a constant current. In the file "log-2016-01-14.txt" column 12 are measurements of the voltage measured from a battery discharged at a constant current. The log file consist of battery voltage at 100 to 0 % SOC.

1. Make an xy-plot showing the discharge curve of the battery voltage according to the GNSS time (column 5)



Figur 8: A plot showing the voltage versus time

2. Create a function taking the voltage as input and the SOC as output.



Figur 9: A plot showing the SOC vs. voltage