MinNE (Minimal Network Element) Project

CSD Course, Fall 2009

Draft report:

Measuring a Circuit Prototype for Balancing the Voltage between Supercapacitors

(Version 0.2)

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Abstract

In this draft report we will present some measurements that we have performed on a balancing circuit implemented by Robert Olsson. The purpose of this circuit is to balance the voltage between two super-capacitors and thus protect them from overvoltage. Before we proceed to the actual circuit and the experiments that we performed, we present the overall design of the power system, so that the reader can understand the purpose of this circuit. After taking the measurements, we evaluate the results and draw some conclusions.

1. Overall Design of the Power System

As stated in our Project Plan [1], we will investigate the use of solar panels and super-capacitors for the power supply and energy storage of our router. The use of super-capacitors will prove to be feasible if we manage to get the power consumption of the overall router configuration below 10W. The general design of the power system that includes solar panels and super-capacitors is depicted in Figure 1.

Solar panels will be the power source of our system. They will provide a DC voltage (12, 24 or 48V possibly) when there is sunlight. A DC-DC step down converter will follow the solar panels so that it decreases the voltage to a suitable value for the super-capacitors, since in most cases the voltage that a super-capacitor operates is around 2.5V. Larger voltages can damage the dielectric between the capacitor's plates. Following the DC-DC step-down converter will be the capacitor tank, which will include a number of super-capacitors, connected in parallel, for energy storage. When there is sunlight, the super-capacitors will get charged and then remain fully charged. After the sun goes down, the solar panel will stop providing power and the super-capacitors will discharge and give their stored electric energy to the system. A diode will be used between the step-down converter and the super-capacitor tank in order to avoid power leakage backwards. Since the voltage of the capacitors is relatively low compared to the system's voltage, a DC-DC step-up (boost) converter is also needed for increasing the voltage to an acceptable level for the system to work (12V).

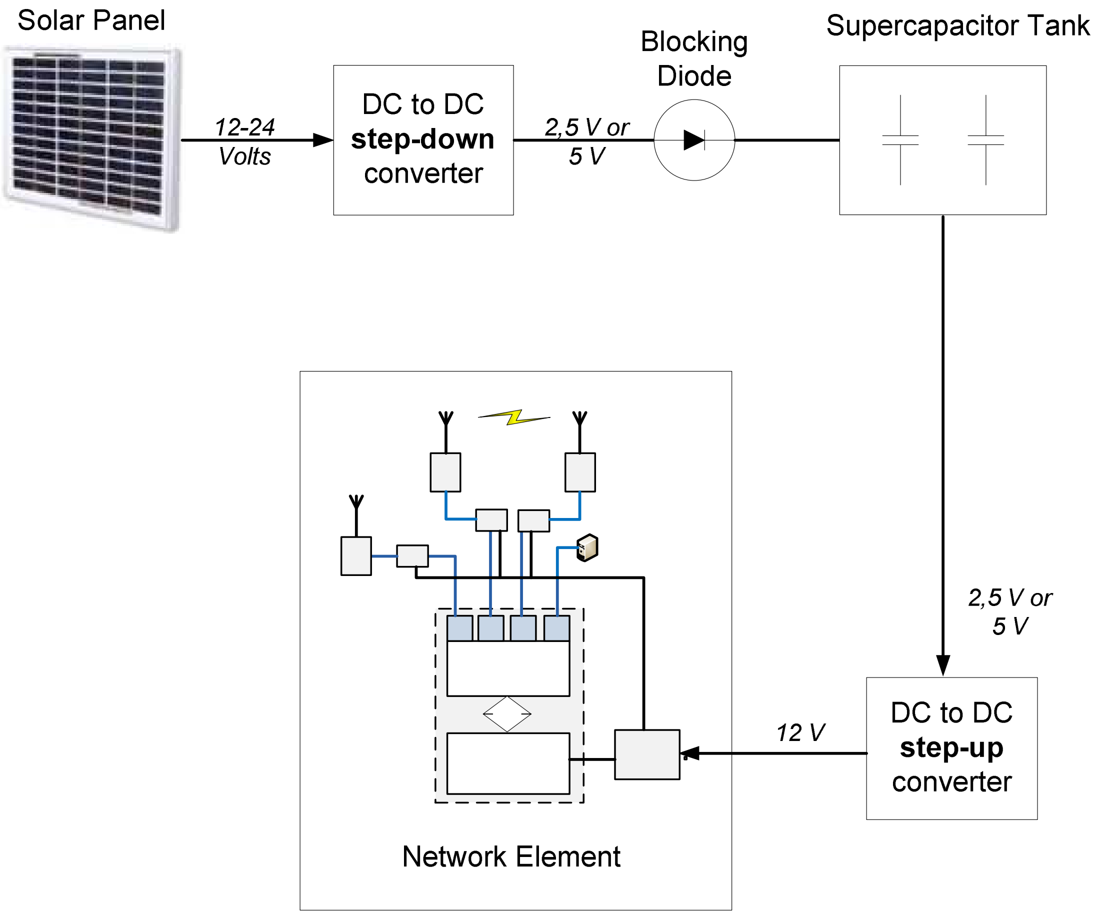

Figure 1: Overall design of the power system with solar panels and super-capacitors

The DC-DC step-up conversion becomes challenging when the input voltage is very low. For example, a super-capacitor has a voltage around 2.5V when fully charged but its voltage drops rapidly while it discharges. In order to be able to utilize as much energy of the super-capacitor as possible, we will have to use it down to the point where its voltage becomes low (for example down to 1V). Implementing a boost converter with an input voltage of 1V is extremely difficult, since it will demand a voltage gain of 12 in order to reach 12V. A solution could be to put two boost converters in series, for example a first one with a gain of 3 and a second one with a gain of 4. The drawback of this technique is the decrease in efficiency of the system, since the overall efficiency factor will be the product of the efficiency factors for each converter.

The problem described above can be mitigated if instead of having single capacitors connected in parallel we have pairs or triples of capacitors connected in series that are in turn connected in parallel. In this way, the voltage of the capacitor tank will double (or triple) and the step up conversion will be made easier, since the input voltage of the step-up converter will be higher.

On the other hand, when having two or more capacitors connected in series, there is no guarantee that the voltage of each one is the same. For example, when having two capacitors in series, the total voltage of 5V may not be equally split and one capacitor can have 3.5 V and the other 1.5 V. This will mean that one capacitor will operate under a voltage larger than its nominal voltage and may be damaged. As a result, there is a need for a way to control and balance the voltage between each capacitor that is connected in series. A balancing circuit implemented by Robert Olsson and based on [2] is described in the following section.

2. Balancing circuit

The balancing circuit that we tested is shown in Figure 2 (design) and Figure 3 (photo), where the main specs of each component are also provided. This circuit also includes two super-capacitors connected in series and a resistor (R_L), which acts as a load.

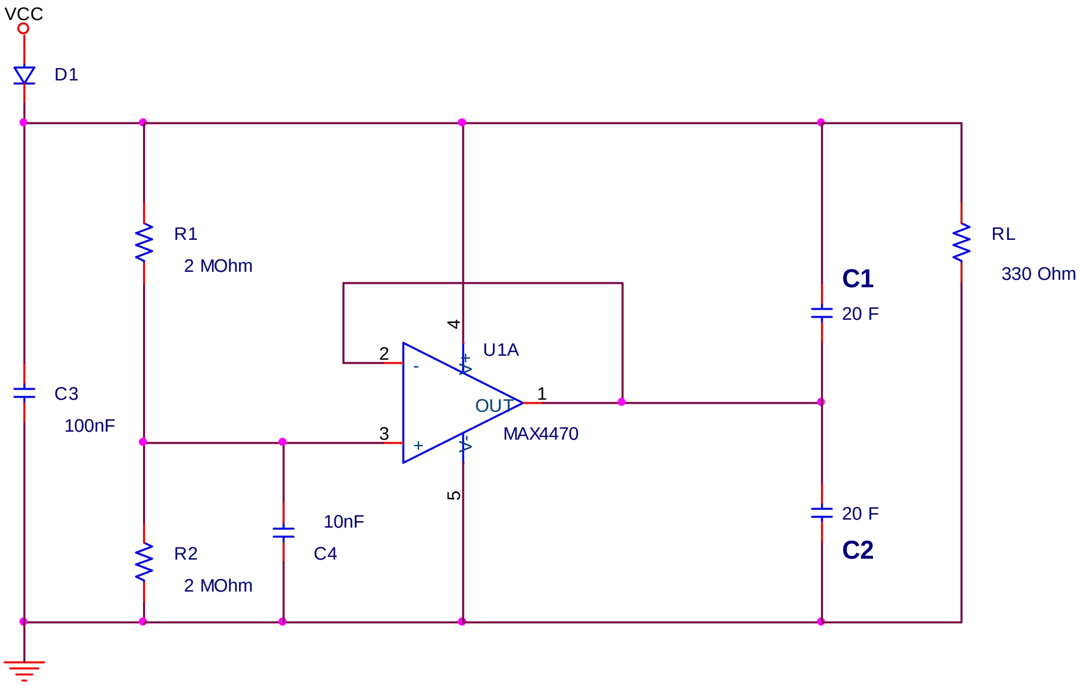

Figure 2: Design of balancing circuit

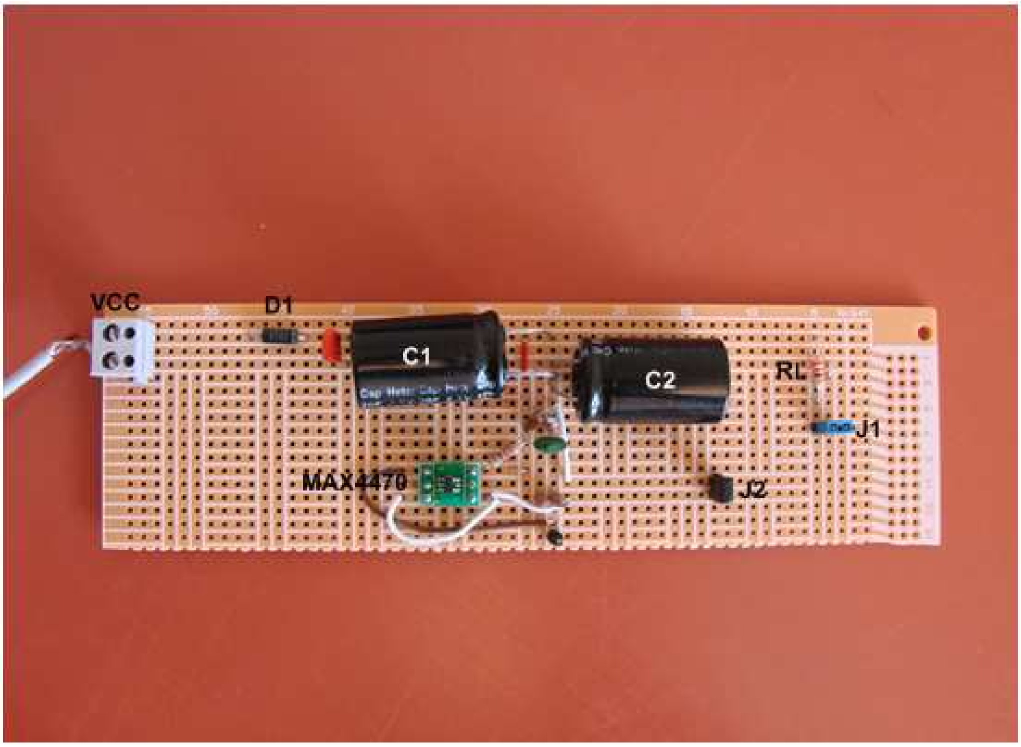

Figure 3: Photo of the supercapacitor balancing prototype, with main elements identified

The main element of this circuit that is responsible for balancing the voltage between the two capacitors is the operational amplifier MAX4470. It is an ultra-low power component that needs less than 1uA supply current [3] and can source or sink current to bring the two capacitors into balance. Since its power consumption is very low, it is ideal for use in our case where low power consumption is crucial.

For supplying power we used a 5V AC/DC adapter. While the adapter is connected, the 2 20F super-capacitors are being charged and then remain fully charged. There is also a load (a 330 ohms resistor) that can be connected/disconnected by jumper J1. The voltage of the load is the voltage of the pair of super-capacitors connected in series. The operational amplifier can be connected/disconnected by jumper J2. The Schottky diode D1 is placed just after the power supply terminals in order to prevent power leakage backwards when the DC power supply is disconnected and also to protect the capacitors from reverse polarity.

This circuit is a scaled-down version of the real case one since the capacitance of the super-capacitors used (20F) is lower than the capacitance of the super-capacitors that we are planning to use (some 1500 or 3000F). This scaled-down experiment will allow us to perform our measurements in a controlled way, draw some conclusions and extend them to meet the actual configuration.

3. Measurements

Before applying such a balancing circuit in our power supply module, we would like to test and measure some of its characteristics. Specifically we will measure the following:

- The voltage drop of a capacitor against time when operating under load. These measurements will give us the discharge curve of the capacitor, which will allow us to calculate the energy provided by the capacitor and compare it to the theoretical one.
- The rebalancing current that the operational amplifier provides and the voltage of one capacitor after an imbalance has been inserted between the voltages of the two capacitors.
- The voltage drop due to power leakage under no-load conditions.

All the above measurements are performed with the external charger disconnected.

3.1. Discharge curve under load

For measuring the balancing current we followed these steps:

1. Charging to maximum (2.5 V per capacitor).
2. Disconnect the charger.
3. Connecting jumper J1 to connect the load RL.
4. Measure voltage on C1 every 30 seconds.

In Figure 4 we depict the measured voltage values.

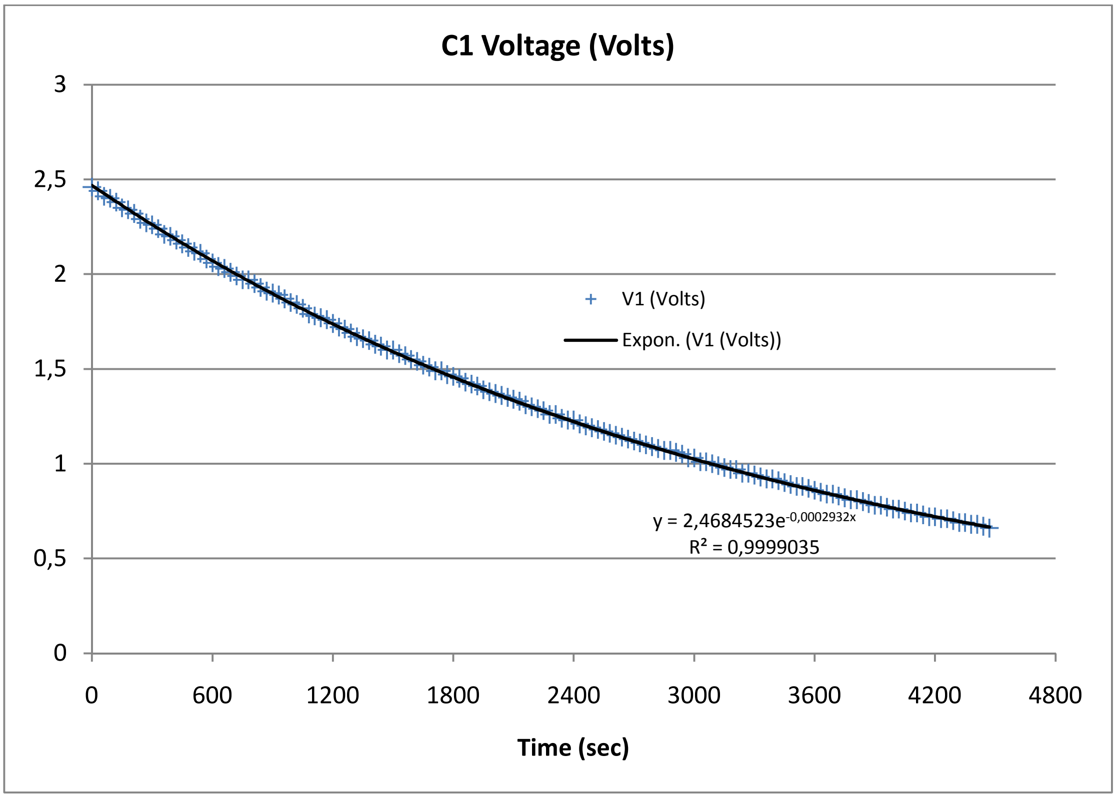

Figure 4: Voltage on super-capacitor C1

The mathematical function that seemed to match the data most was the exponential with an equation calculated from Microsoft Excel (with the Minimum Mean Square Method), as shown in Figure 4.

Following, we calculated the instant power consumed on the load resistor RL, as given by:

$$P = {V_L}^2 R_L = (2V_1)^2 R_L \ ,$$

as we have assumed that the voltage is the same on both C1 and C2.

In Figure 5 we depict the calculated values.

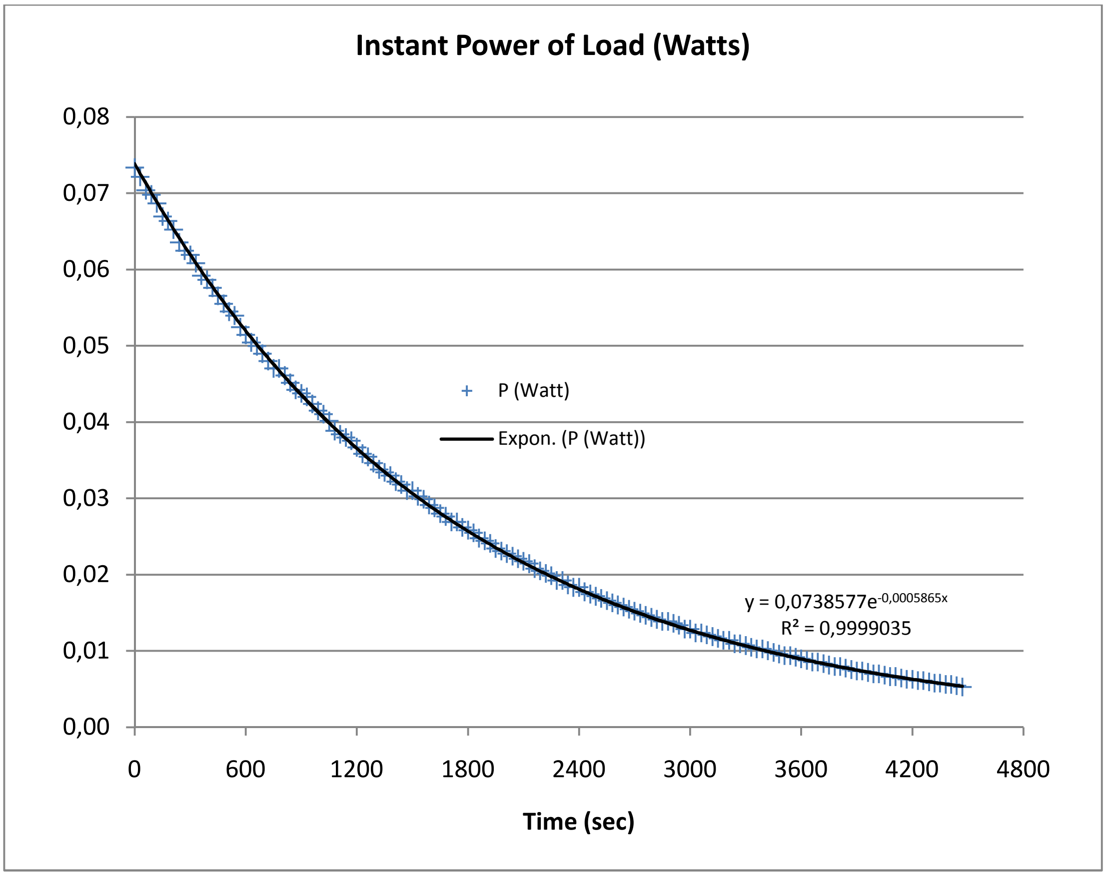

Figure 5: Instant power consumed by RL

Again the curve that best approximates the data is the exponential. By integrating the power (as given by the equation in Figure 5) between the initial time and the time that the voltage dropped to 1 Volt (at 3090 secs), we can calculate the energy consumed on the resistor. The 1 Volt limit is selected because for voltages lower than this it will be difficult to take advantage of the energy, due to the step-up conversion limitations.

$$E_{RL} = \int_0^{3090} 0{,}0738577 e^{-0{,}0005865t} dt = 105{,}37 \text{ J} = \ 0{,}0293 \text{ Wh}$$

The theoretical energy given by one capacitor at the same time is calculated by:

$$\begin{aligned} E_C &= E_C^{t0} - E_C^{t1} = \\ &= {}^1\!/_2\, C1 (V_1^{t0})^2 - {}^1\!/_2\, (C1)(V_1^{t1})^2 = \frac{(V_1^{t0})^2 - (V_1^{t1})^2}{2} \cdot C1 \\ &= \frac{(2{,}46V)^2 - (1V)^2}{2} \cdot 20F = \ 50{,}516 \text{ J} = 0{,}01403\text{Wh} \end{aligned}$$

The total energy given by both capacitors is:

$$E_{C,TOT} = 2E_C = [(V_1^{t0})^2 - (V_1^{t1})^2]C1$$
$$= 101.032\ \mathrm{J} = 0.02806\ \mathrm{Wh}$$

We can see that the theoretical value is very close to the measured one, although the energy of the capacitors should be higher than the one consumed by the resistor. This could have happened due to measurement errors.

By scaling the measured power for 3000 F capacitors (3000*(E_{RL}/20)), we can see that an exploitable energy of about 4,5 Wh is possible.

The following figure shows the percentage of energy utilized versus the voltage of a capacitor that has a nominal voltage of 2.7 V. The interpretation of this curve is as follows: If we make use of the capacitor's energy down to the point where the capacitor has voltage V, then the percentage of the total energy of the capacitor (1/2C$V_{nominal}^2$) that has been utilized is shown by the value on the horizontal axis. This curve can be used for any capacitor that has a nominal voltage of 2.7 V independently of its capacitance.

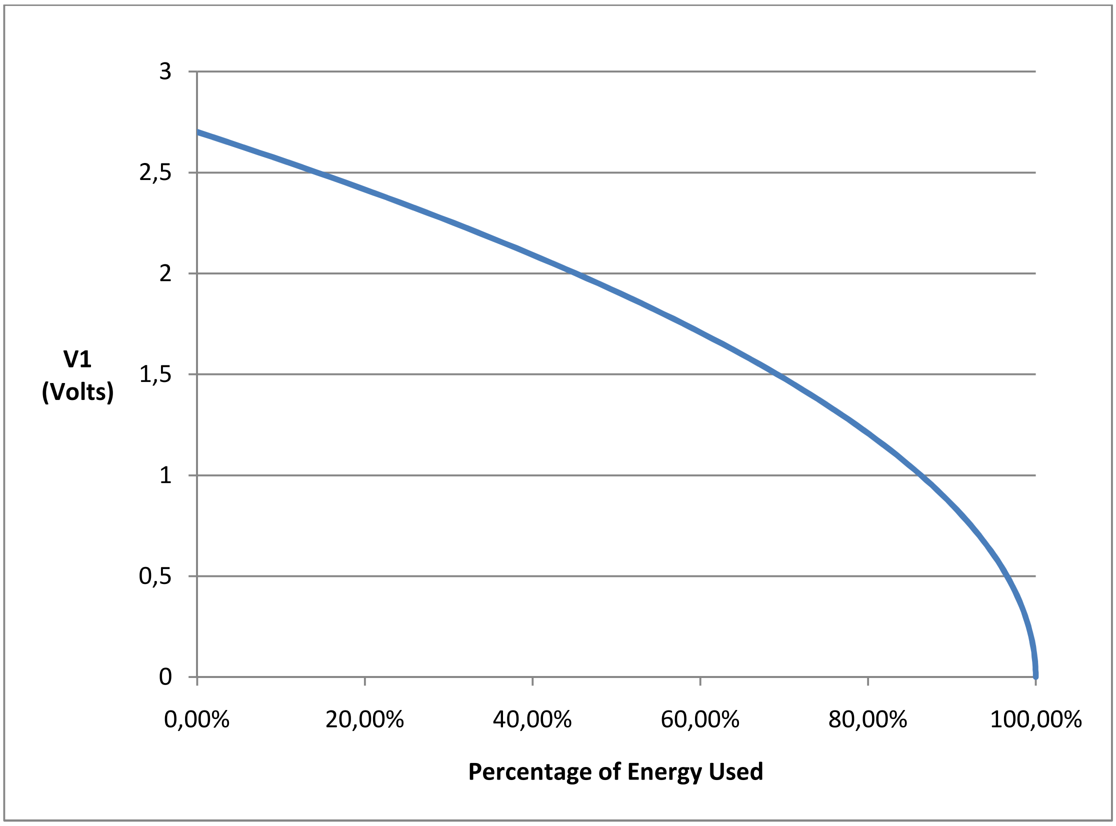

Figure 6: Percentage of energy utilized versus the voltage of a capacitor

3.2. Balancing current and voltage recovery

For measuring the balancing current we followed these steps:

1. Disconnect load resistor RL by opening jumper J1.
2. Charging to maximum (2.5 V per capacitor).
3. Disconnect the charger.

4. Measuring Initial voltage of each cap: C1: 2.45 V, C2: 2.44 V.
5. Disconnect the op-amp.
6. Short-circuit C1.
7. New voltage after unbalance C1: 1.43 V. C2: 2.44 V.
8. Connect the multi-meter to jumper J2 which reconnects the op-amp to the supercapacitors circuit.
9. Measure the balancing current every 30 seconds.
10. Stop after the current drops to zero.

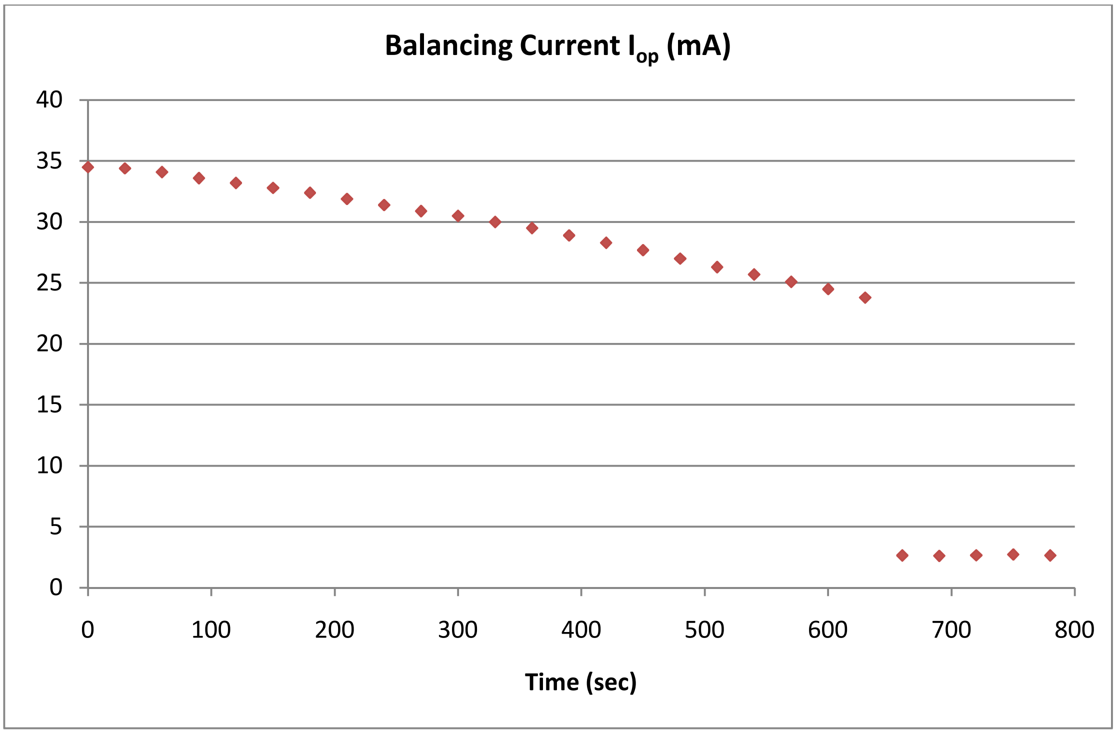

Figure 7: Balancing current produced by the op-amp

The current started at 34,5 mA and dropped almost linearly, until a certain time (630 secs). At that point, almost instantly, it dropped to zero.

We also measured the voltages on the capacitors during the balancing by the op-amp. To do that, we repeated the previous experiment by trying to achieve the same voltage as before, when we short-circuited capacitor C1. So the steps we followed were:

1. Disconnect load resistor RL by opening jumper J1.
2. Charging to maximum (2.5 V per capacitor).
3. Disconnect the charger.
4. Measure the initial voltage of each cap: C1: 2.45 V, C2: 2.45 V.
5. Disconnect the op-amp.
6. Short-circuit C1.
7. New voltage after unbalance C1: 1,38 V, C2: 2,25 V.
8. Measure the voltage on C1 every 30 secs.
9. Stop after it remains steady.
10. Measure final voltage C1: 1,42, C2: 1,41.

We chose to measure only the voltage on the capacitor with the higher initial voltage value (C2 here), since we observed that the balancing happened mostly due to the decrease of its voltage, rather than due to the increase of the voltage on the capacitor with the low initial voltage. To measure the voltage difference between C1 and C2, we just subtracted all the values measured on C2 from the respective voltages of C1. We calculated the C1 voltages using linear interpolation from the initial (1,38 V) and final value (1,42 V).

Below are the graphs of the respective measurements.

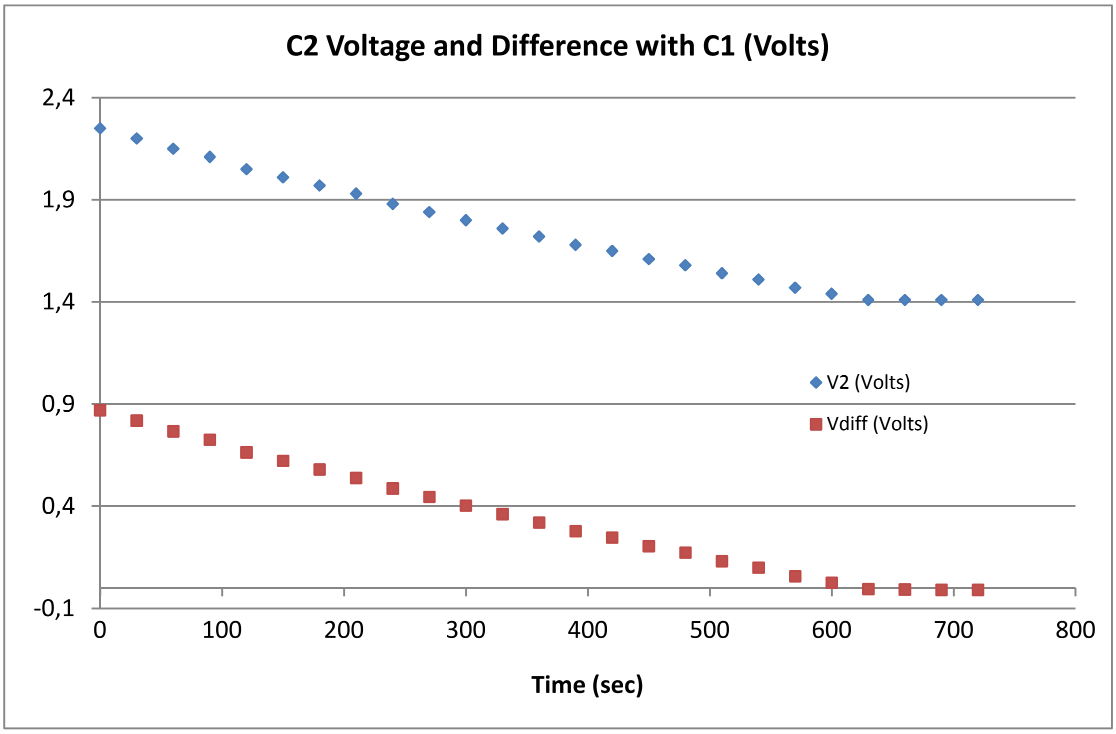

Figure 8: Voltage on capacitor C2 and voltage difference between C1 and C2

We can see that at 630 seconds the voltage difference roughly becomes zero, which explains the balancing current instant drop at the same time point. We should mention though, that these were different experiments with roughly the same initial conditions.

3.3. Energy leakage including balancing

The methodology was the following:

1. Disconnect load resistor RL.
2. Charging to maximum (2.5 V per capacitor).
3. Disconnect the charger.
4. Measure the voltage of each capacitor on various points during the day.

In Figure 9 we present the measurements on both C1 and C2.

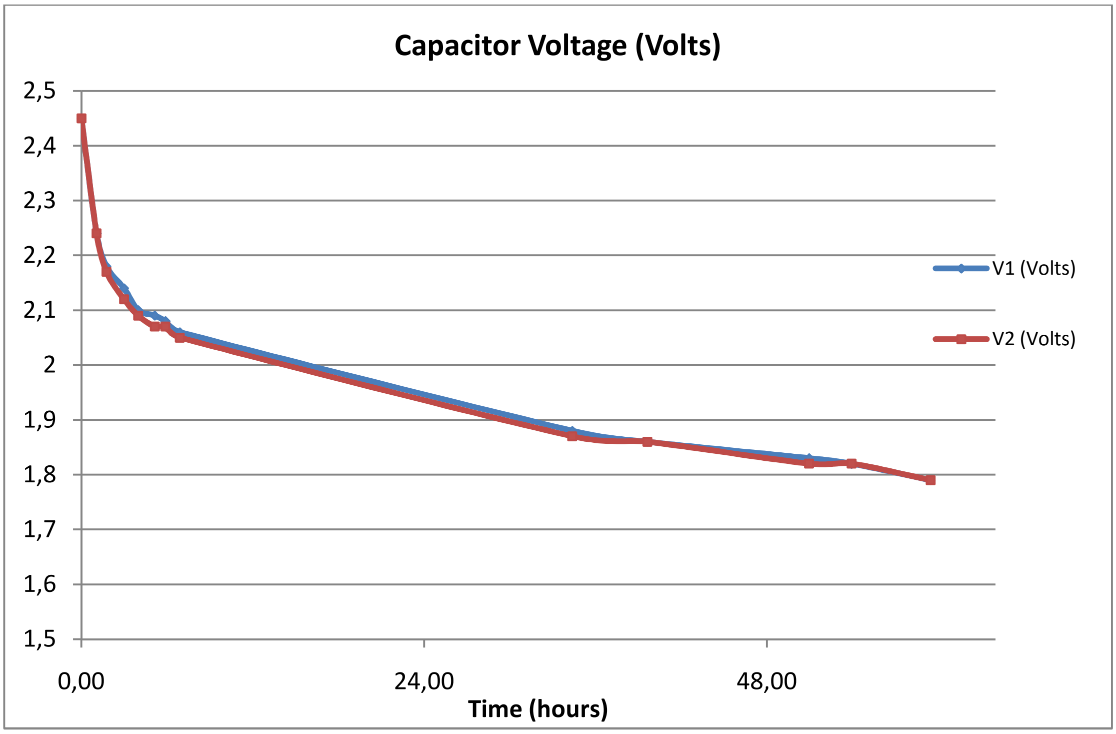

Figure 9: Voltage on both capacitors C1 and C2

We can see that the voltage drop at the beginning is very steep, but then it gets quite steady. On average the voltage drop was calculated at 0,03 Volts per hour. It is also obvious that the voltage drop is equal on both capacitors, also because the op-amp was connected throughout the whole measurement.

References

[1] http://www.tslab.ssvl.kth.se/csd/projects/0921191/

[2] http://www.cap-xx.com/resources/docs/CAP-XX_WP_0804_Good%20Vibrations.pdf

[3 http://datasheets.maxim-ic.com/en/ds/MAX4464-MAX4474.pdf