Whitepaper

AN1002

Supercapacitor Cell Balancing

Background

CAP-XX highly recommends some form of cell balancing for any series connected supercapacitor module. This white paper will discuss the reason behind it as well as various cell balancing options.

Supercapacitor Cell balancing

Why Balance?

Leakage current for a supercapacitor cell is complex function of voltage, time and temperature. Supercapacitors with multiple cells in series require a balancing circuit to ensure all cells have approximately equal voltage. This is because the leakage current of different supercapacitor cells will differ over time, temperature and voltage. Furthermore, even if different cells could be matched by leakage current during production, there is no guarantee that the cells will age identically, so their leakage current functions will diverge over time, or, in operation, one cell may be at a different operating temperature to the other (e.g. closer to a heat source such as a power amplifier.) Since leakage current is very sensitive to temperature, the cells will then have different leakage currents irrespective of how well matched they are.

Fig 1 illustrates the variation in leakage current of a population of GS203 cells at room temperature. Note how over the first 40hrs, the leakage current is much greater than the equilibrium value that the cells will eventually reach. This early phase is known as diffusion current, when even though the cell has reached its final voltage, it is still taking charge which is used in migrating ions further into the pores of the activated carbon. It is for this reason that the Y axis of Fig 1 is labelled “Input Current” rather than “Leakage Current”.

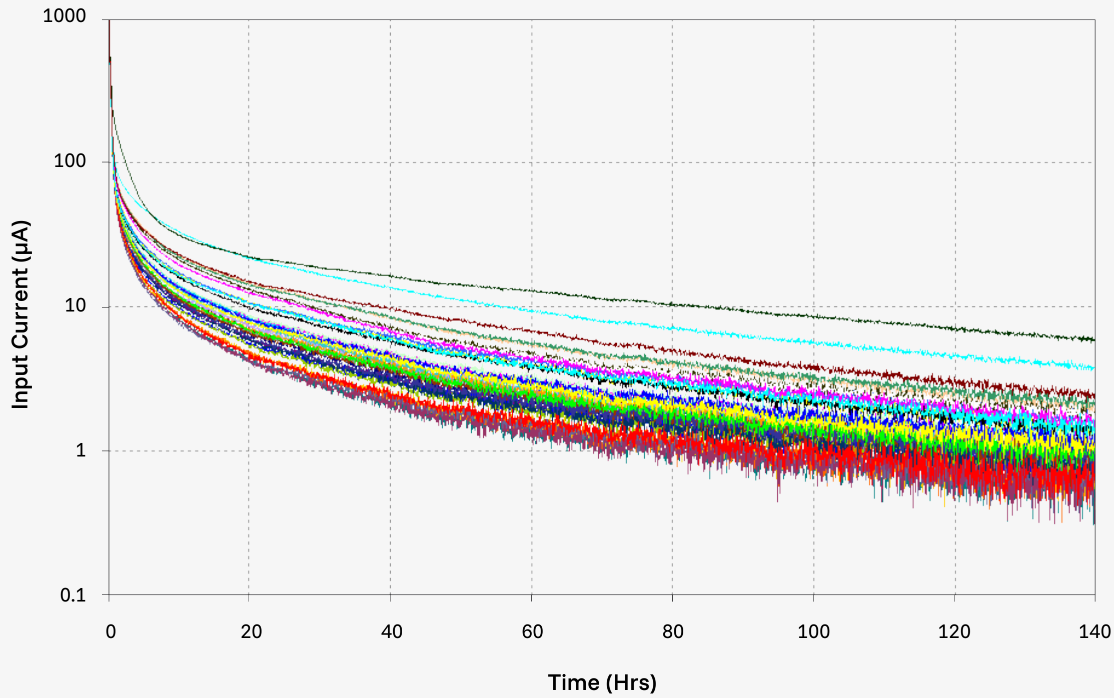

Fig 1: Diffusion + Leakage current for GS103 cells

Consider a dual cell supercapacitor with 2 cells in series. Since they are in series their Diffusion + Leakage currents with no balancing circuit must settle to the same value. In order to achieve this equilibrium condition, the cell voltages will adjust so their leakage currents become equal. Without a balancing circuit, this may mean that one cell will be subjected to over-voltage and become damaged. This is illustrated in Fig 2.

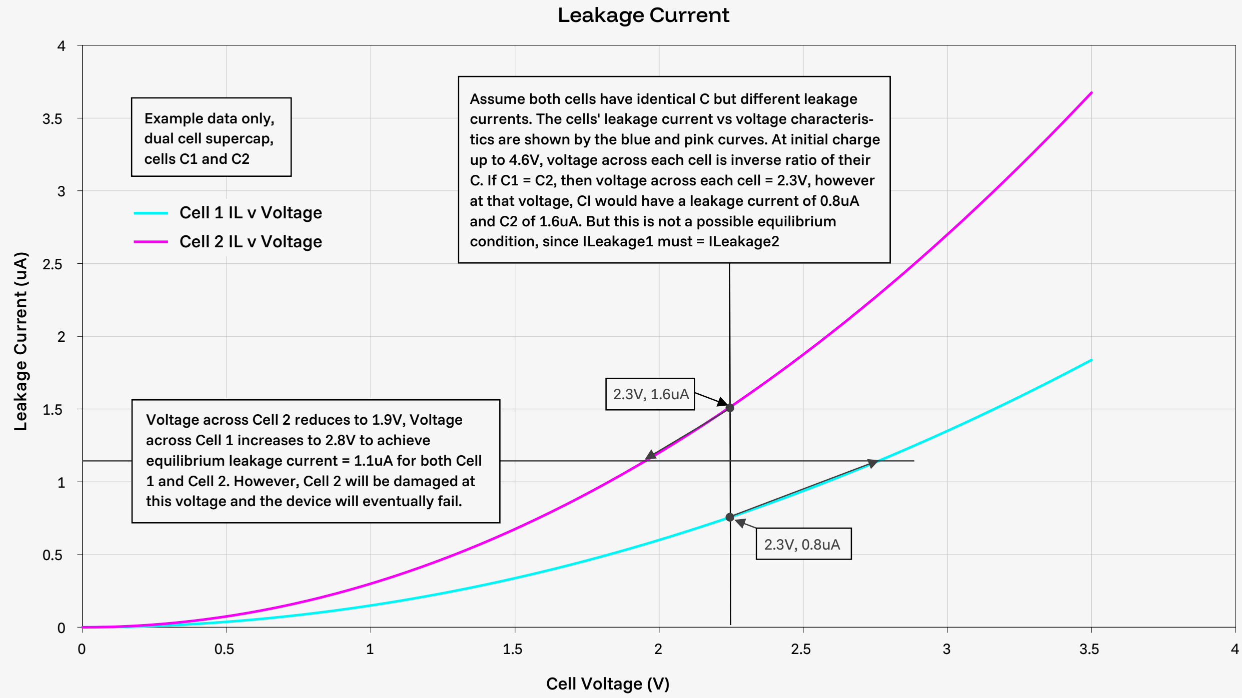

Fig 2: Explanation of Cell over-voltage due to leakage current imbalance with no voltage balancing circuit.

In Fig 2, the magenta and cyan curves represent the Voltage vs Leakage current curves for 2 cells in series. If the 2 cells have the same C, and are rapidly charged, they will initially have the same voltage. However, since the two cells are in series, they must settle to have the same leakage current. The cell with the lower leakage current (cyan curve) increases its voltage while the cell with the higher leakage current (magenta curve) decreases voltage until their leakage currents are the same. The cell with the cyan curve is now at risk of going over voltage and ageing prematurely with increased ESR and C loss.

In order to prevent the scenario shown in Fig 2, a balancing circuit is required. The balancing circuit will source or sink current from the midpoint between the 2 cells so the current flowing in each cell is equal. This application white paper will now consider some different balancing circuits.

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CAP-XX Cell Matching in Dual Cell Supercapacitors

When 2 cells in series are first charged, their voltage distributes as V1:V2 = C2:C1. If CAP-XX just used the standard ±20% production tolerance when assembling 2 cells to make a dual cell supercapacitor, then in the worst case one cell would be nominal C + 20% and the other cell nominal C – 20%. If two such cells were paired together, and charged to 5.5V (e.g. CAP-XX H series dual cell supercapacitor such as an HS230) then one cell would charge to 3.3V and the other to 2.2V. The cell charged to 3.3V may suffer some accelerated aging before the cell balance circuit can correct its voltage. To prevent this, CAP-XX matches capacitance of the 2 cells used to make a dual cell supercapacitor to within ±4% so in the worst case, when charged to 5.5V, one cell will initially charge to 2.86V and the other to 2.64V after which the balancing circuit will correct the cell voltages to 2.75V each.

Note that even if the cell voltage in a dual cell supercapacitor circuit << rated voltage, balancing is still required. Consider the case above where the 2 cells have been matched by capacitance to within ±4% and the supercapacitor has been placed across a 3.6V battery. One might assume that since the cell rated voltage = 2.75V, and the cell voltage in this application = 1.8V, there is sufficient headroom between the nominal cell voltage and rated cell voltage so balancing is not required. In this case the 2 cells will distribute voltage between them so the cell at nominal C - 4% has 1.87V across it while the cell at nominal C + 4% has 1.73V across it. The cell with 1.87V across it will age (lose C) at a slightly faster rate than the cell with 1.73V across it. The cell that loses capacitance at a greater rate will have even more voltage across it, and the other cell less voltage. This exacerbates the difference in ageing rates between the 2 cells accelerating the loss of C in the lower C cell in a runaway situation until the part fails. For this reason, cell balancing is always required for long term reliable operation of 2 or more cells in series, even if the nominal cell voltage << rated cell voltage.

Further, cell balancing should have true balance, where all cells are at the same voltage, rather than over voltage protection circuits across each cell, where one cell may be at the max rated cell voltage but other cells are at lower voltages, see Application White Paper '***Over Voltage Protection vs True Balancing***'.

Over Voltage Protection vs True Balancing

Balancing Resistors

The simplest balancing circuit is a pair of balancing resistors as shown in Fig 3.

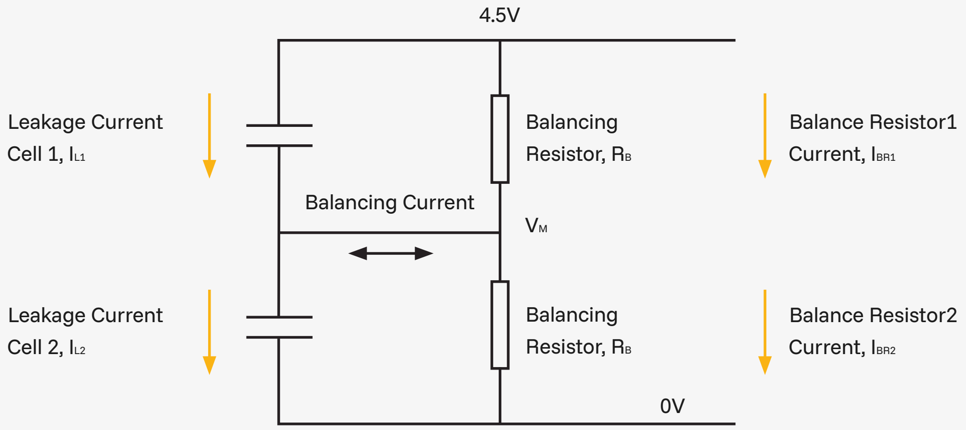

Fig 3: Balancing resistor circuit

The purpose of the circuit in Fig 3 is to maintain V_M close to 4.5V/2 = 2.25V.

$V_M = R_B \times I_{BR2} = R_B \times (I_{BR1}$ – Balancing Current).

For the circuit in Fig 3 to work, Balancing Current must be << I_{BR1}, I_{BR2}.
V_M must be prevented from going >> 2.25V or <<2.25V for any significant length of time.

To determine the value of balancing resistor to use, model each supercapacitor cell as a resistor drawing the same leakage current as the cell. Choose a balancing resistor that is approximately 1/10 this value.

Leakage current will decay over time—refer Fig 1. How fast it decays depends on operating temperature, the higher the temperature, the faster the rate of decay. The value to which leakage current decays to depends on the nature of the supercapacitor's carbon coating and the operating temperature.

For CAP-XX supercapacitors, you can use an approximation of 1µA/F as the leakage current a CAP-XX supercapacitor decays to after >120hrs at cell rated cell voltage at room temperature. **At 70°C, the long-term leakage current is approximately 5–10µA/F.**

The simplest solution is to choose a very low value balance resistor, however, this wastes energy and drains power. The difficulty is in choosing the maximum value of balance resistor to maintain voltage balance during expected operating conditions when leakage currents decay to their equilibrium values but low enough to avoid excessive voltage excursions during the early diffusion current phase.

Cell voltages take time to adjust to equalize cell leakage currents as per Fig 2, but during that time the leakage currents decay as per Fig 1, enabling the balancing resistor currents to start dominating the value of midpoint voltage. This typically results in cell voltages over time as shown in Fig 4 for two supercapacitors, where the initial cell voltages are determined by the ratio of C1/C2, the cell voltages then start to drift apart as the diffusion currents are greater than the balance resistor currents, and then as the diffusion/leakage current decays, the balance resistor currents start to dominate the value of the midpoint voltage and the cell voltages converge. In Fig 4 this occurs after~3hrs.

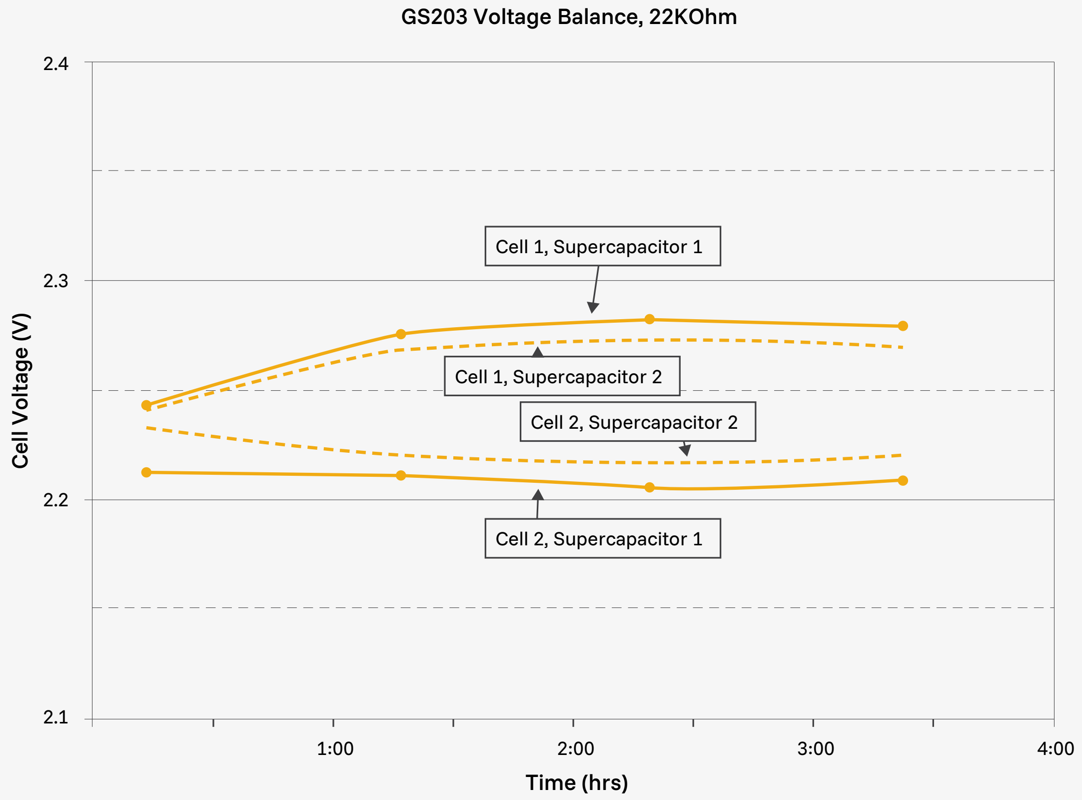

Fig 4: Cell Voltages, balanced by 22KΩ resistors, initially diverge then converge over time

Since there is no simple equation for leakage current as a function of time, temperature and voltage, this optimum value of balancing resistor is best determined by experiment. CAP-XX recommends a balancing resistor value of 10KΩ for most applications and supercapacitors. However, it is best if you consult with CAP-XX to select the optimum value for your application taking
into consideration factors such as:

- Operating temperature and how it varies over time
- Operating voltage
- Whether the supercapacitor is always on voltage or periodically charged and discharged

To be safe, **the highest value balancing resistor CAP-XX normally recommends is 39KΩ where operating temperature is ≤ 50°C.** However, we have done experiments where 100KΩ appeared to be sufficient.

Fig 5 shows a population of 45 x GS203 supercapacitors, 250mF, at 4.5V balanced with 100KΩ resistors. It shows that during the initial high leakage current phase, in the first 20hrs, the supercapacitors go out of balance but as the leakage current decays the balancing current supplied by the resistors dominates and forces the midpoint voltage to its correct value. Fig 6 shows that these brief excursions have not affected cell performance with ESR unaffected.

If it is desired to use a value of balancing resistor higher than 39KΩ at temperatures up to 50°C or values higher than 10KΩ for temperatures up to 70°C, then it is recommended to run an experiment with a population of the supercapacitors and balancing resistors intended to be used at the most severe temperature and voltage they will endure to verify performance will be acceptable.

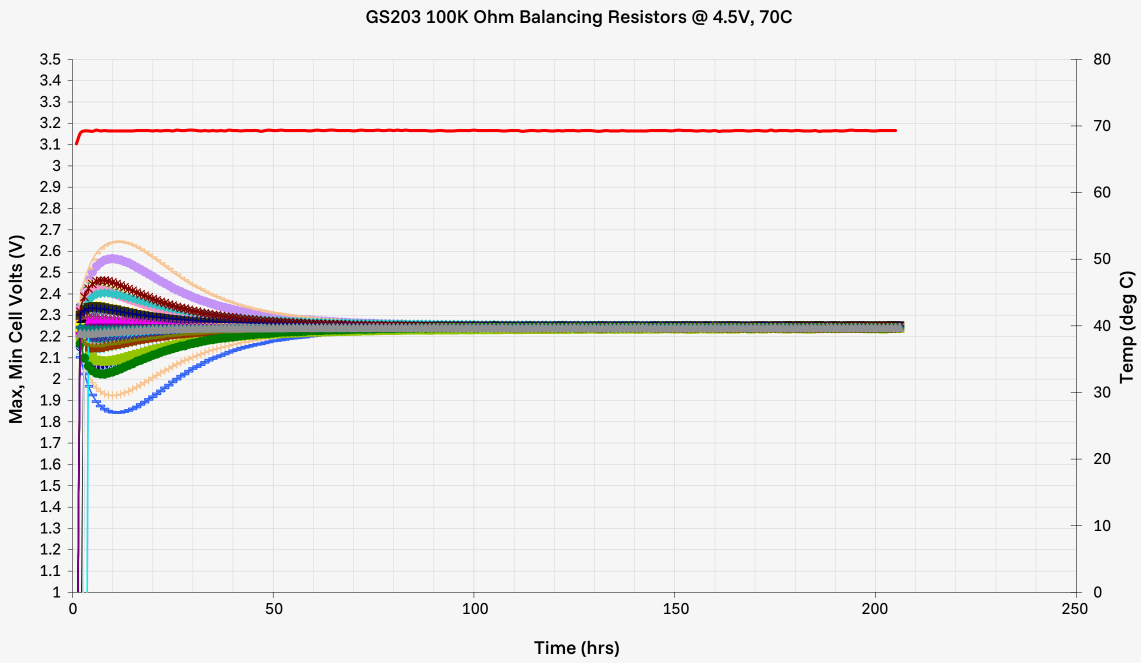

Fig 5: Dual cell supercapacitors balanced with 100KΩ balance resistors at 4.5V, 70°C

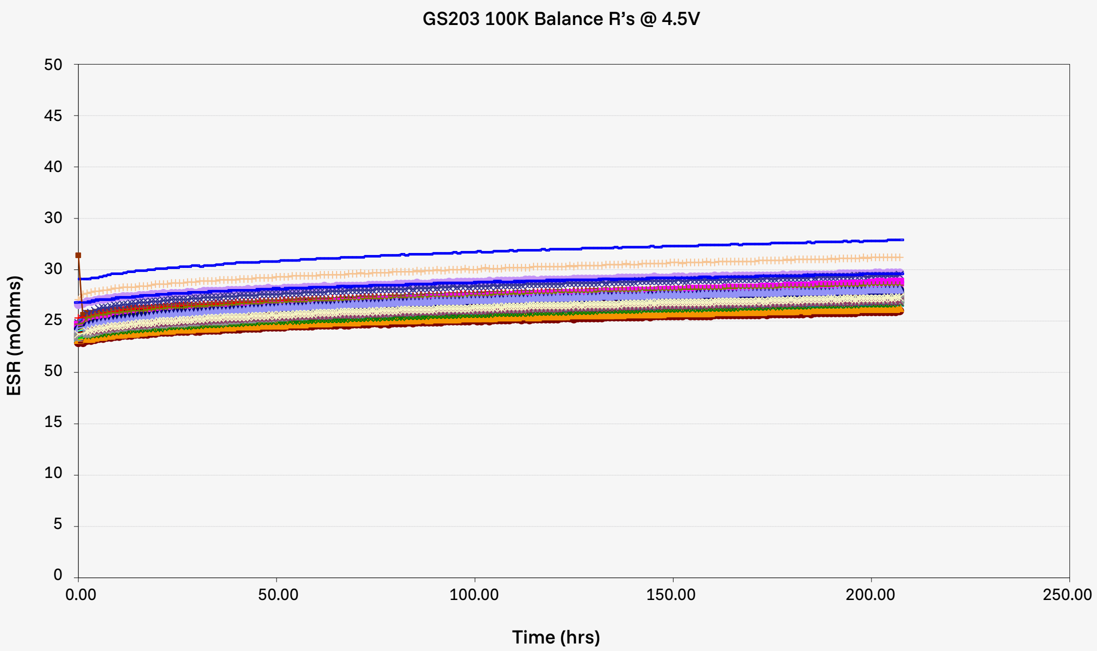

Fig 6: ESR for the supercapacitors shown in Fig 5

Even though balancing resistors are the simplest lowest cost solution, it wastes power and energy. Consider a pair of 39KΩ resistors used across a dual cell supercapacitor charged to 3.6V. The current flowing through the balancing resistors= 1.8V/39KΩ = 46μA. In many applications this is unacceptably high.

If the supercapacitor was being charged with a small indoor solar cell providing ~1mW, then if the charger IC was 80% efficient, this would be 222μA at 3.6V. In this case, the balancing circuit would be wasting 46/222 = 20% of the available power. If the supercapacitor was connected across a 3.6V primary battery to provide peak pulse power, the balancing resistor current drain represents 404mAh over 1 year. Even with a 100KΩ resistor, the current drain = 18μA, which would be an 8% loss in the 1mW solar cell example, and 158mAh drain from a 3.6V battery over 1 year.

Operational Amplifier Balancing Circuit

A simple low current balancing circuit, shown in Fig 7, uses an operational amplifier as a voltage follower, with the reference voltage set at the supercapacitor midpoint voltage.

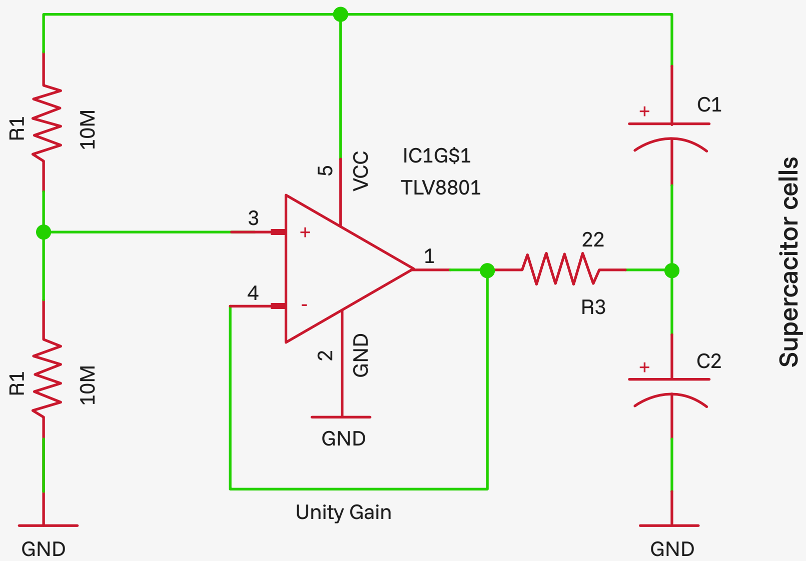

Fig 7: Micro-power active balance circuit with Op Amp

The TLV8801 was chosen because it is low cost, has low supply current, typical 500nA, very low input bias current, typical ±0.1pA, allowing high value resistors to set the midpoint voltage reference, operates rail—rail, and will start operating when the supercapacitor is only charged to 1.8V.

The amplifier operates in voltage-follower mode with its reference voltage = 1/2 of the supply voltage set by R1 & R2. The values of the resistors in the divider network are selected as high as possible, but need to be sufficiently low that the bias current drawn by the amplifier will not cause a significant error. The typical bias current for the TLV8801 = ±0.1pA, so the typical error using 10MΩ resistors to set the reference = ±0.1pA x 10MΩ = ±1μV. If the supply voltage = 5V then the resistive divider network would only draw 250nA.

The amplifier will source or sink current from the junction of the supercapacitor cells to ensure the cells are at equal voltage. The value of R3 at the output of the amplifier determines how quickly an imbalance will be corrected. The value of 22Ω was chosen to limit the Op Amp's output current during normal operation and offer some protection against a supercapacitor cell short circuit. A fusible resistor could be used at R3 to protect the circuit from shorts. The amplifier needs to be chosen so that it can source or sink sufficient current to quickly balance the 2 cells—the TLV8801 can source or sink 4.7mA continuously.

This design will draw minimum current until a voltage imbalance begins to occur between the supercapacitor cells. The increased current that subsequently flows will be only that required to maintain voltage balance making this is an optimal design to minimising the current drawn from the supply.

The estimated current consumption of this circuit at 5V is:

Voltage reference resistor ladder:	250nA
Operational amplifier:	480nA (typical)
Supercapacitor leakage current:	1μA (typical)
Total	**~1.7μA**

Fig 8 shows experimental results for the above circuit, balancing an HW207 @ 5.5V, 23°C. In the experimental circuit, the supercapacitor cells, C1 and C2 are 1.1F each and R1 & R2 were 10MΩ. The legend has the following meanings:

- Bot I: leakage current in the bottom cell (C16)
- Top I: leakage current in the top cell (C15)
- |Bal I|: absolute value of balancing current sourced/sunk by the Op Amp. Absolute value is used so the value is always positive to enable a log graph.
- Amp I: supply current drawn by the Op Amp
- Total I: total leakage current drawn by the supercapacitor + active balance circuit
- Bot V: voltage across the bottom cell (C16). Should ideally be 2.75V
- Top V: voltage across the top cell (C15). Should ideally be 2.75V

In Fig 8, the total current (green) after 100,000 secs (or ~28hrs) is ~4μA, and after 600,000 secs (or~1 week) is ~1.5μA, including the leakage current of the supercapacitor. Referring to the examples given in the section on resistor balancing, this would only represent 0.7% loss if the supercapacitor was being charged by a small solar cell at 1mW to 3.6V through an 80% efficient charger, or would drain only 13mAh from a primary battery over 1 year.

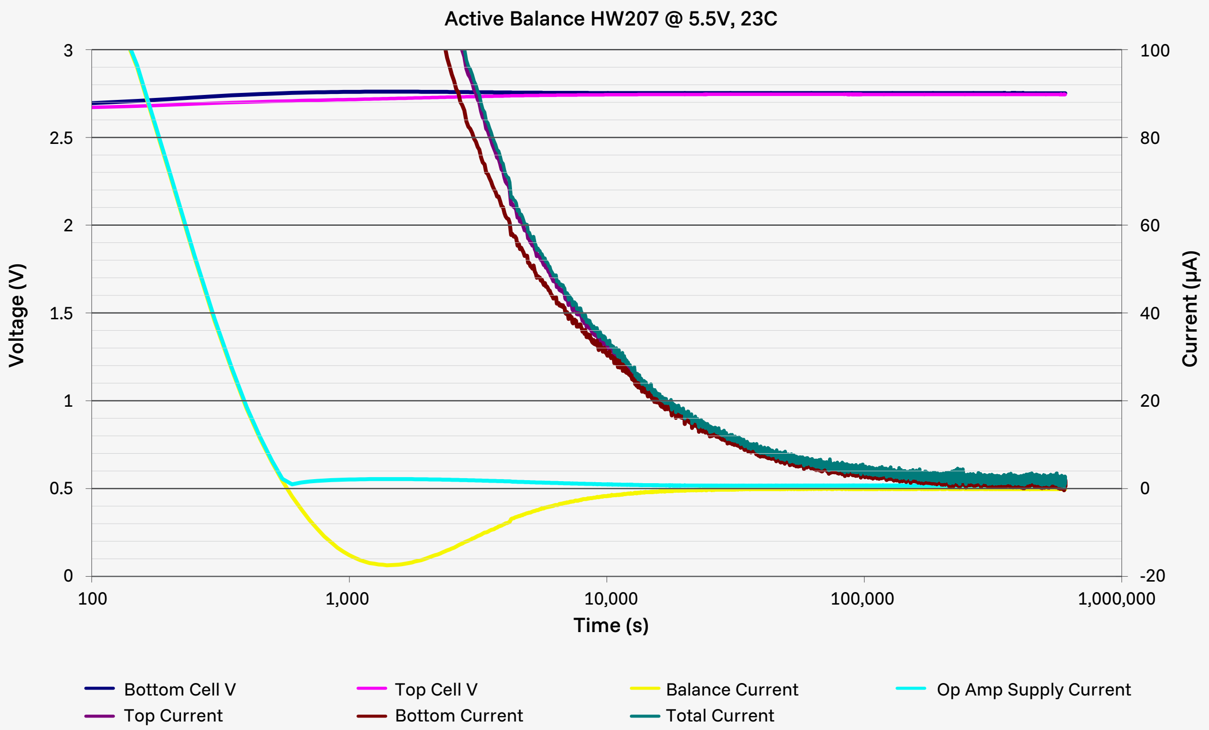

Fig 8: OP AMP active balance circuit results

Supercapacitor Auto Balancing (SAB) MOSFETs

Another very simple circuit to balance cells with minimum current is to use SAB MOSFETs with one across each cell. These MOSFETs have very accurate V_{GS}. Select MOSFETs with V_{GS}=target cell voltage, for example, if balancing 2 cells across 5V, select MOSFETs with V_{GS} = 2.5V.

These MOSFETs have part number ALD8100xx which has 4 MOSFETs (can balance up to 4 supercapacitor cells in series) and ALD9100xx which has 2 MOSFETs (suitable to balance a dual cell supercapacitor) where xx is the V_{GS}, so to balance a dual cell supercapacitor at 5V use an ALD910025. This solution will only draw the leakage current of the cell which has the higher leakage current of the 2 cells.

The configuration for balancing 2 cells is shown in Fig 9. When V_{GS} is at its nominal value, I_{OUT} shown in Fig 9=1μA. For every 0.1V that a cell is above/below nominal V_{GS} I_{OUT} increases/decreases by a factor of ~10. Therefore, if a cell starts drifting above its target midpoint voltage, the SAB MOSFET will draw more current from it, returning it to balance.

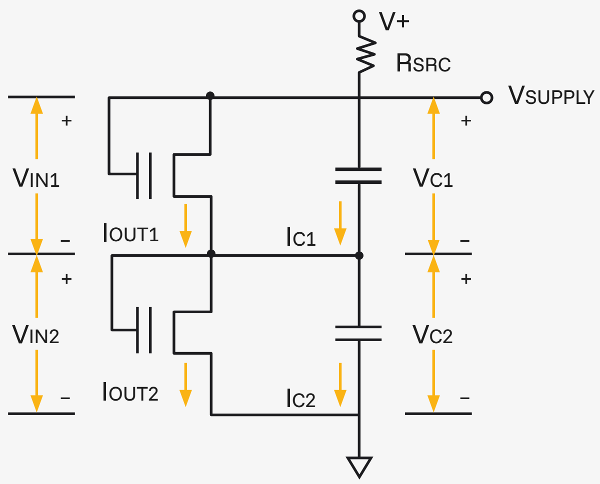

Fig 9: Use of SAB MOSFETs to balance supercapacitor cells

CAP-XX tested this circuit by balancing a population of GS208 supercapacitors at 4.5V using an ALD910023. The GS208 consists of 2 x 1.8F cells in series making a supercapacitor that is 0.9F, 28mΩ ESR. Fig 10 shows the leakage current and balancing current for one of these cells.

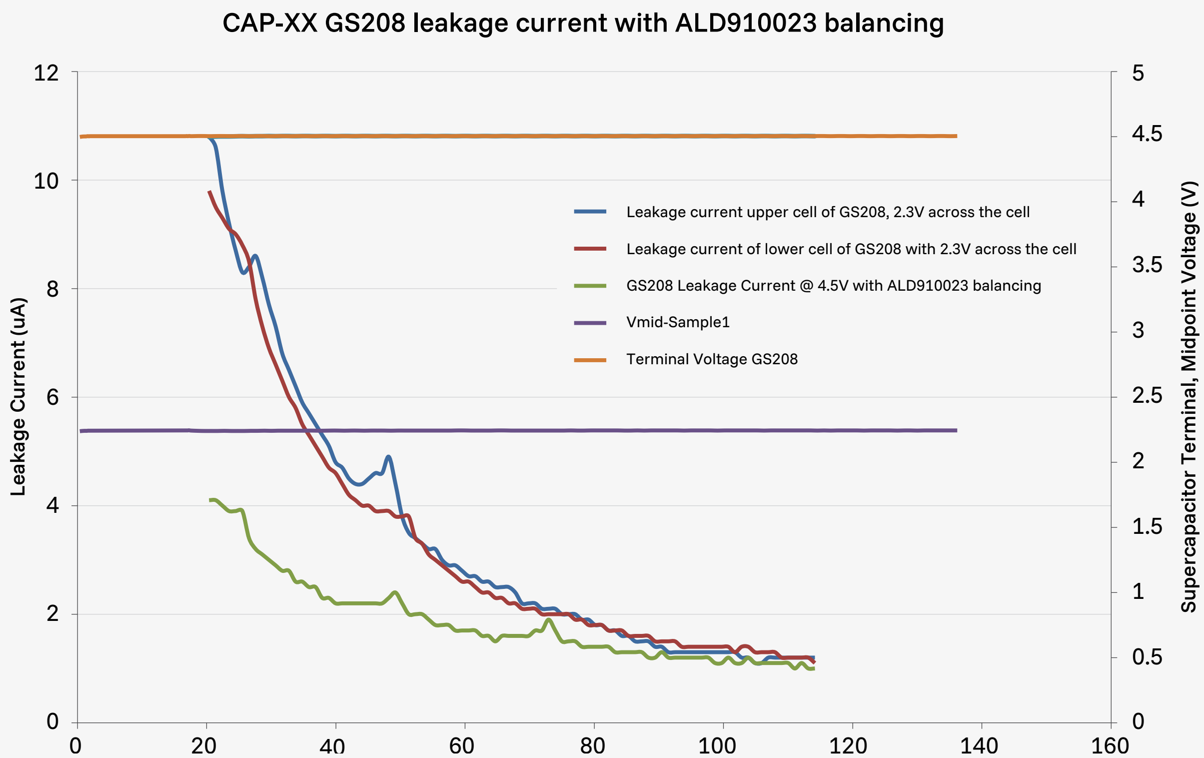

Fig 10: Balancing a GS208 with a SAB MOSFET

The blue and brown curves are the leakage currents for the 2 individual cells charged to 2.3V. The cells were held short circuit for 24hrs and then each independently charged so these leakage current curves are the worst case following a deep discharge. After ~110hrs the leakage current of both cells had settled to ~1μA. The GS208 was then deeply discharged again and charged to 4.5V as a dual cell module with an ALD910023 used to balance voltage of the 2 cells. This is the green curve.

The fact that the green curve does not have the same starting leakage current is due to the fact that the GS208 was not as deeply discharged as the 2 individual cells prior to charging. The key point however, is that the total current for the solution is the same as the leakage current of the individual cells. The tan curve shows the supercapacitor terminal voltage = 4.50V and the purple curve shows the midpoint voltage which the ALD910023 has balance at 2.244V, confirming this as an excellent low current balancing solution.

Balancing More Than 2 Cells in Series

In the section, CAP-XX Cell Matching in Dual Cell Supercapacitors, above it was explained that by matching the 2 cells used in our dual cell supercapacitors by capacitance, CAP-XX has made the task of cell balancing much easier by ensuring good initial voltage balance. However, when balancing 3 or more cells in a series string, normal production tolerances mean cells could be mismatched by up to ±20%. This means the balancing circuit must be able to quickly redress any initial imbalance due to the maldistribution of voltages resulting from mismatched capacitances, where for cells: **1 … N, V_1:V_2:V_3 … V_N = 1/C_1:1/C_2:1/C_3 … 1/C_N.**

Resistor Balancing

The simplest, lowest cost solution. CAP-XX recommends using the lowest value balancing resistors possible. This inevitably increases the leakage current draw from the supercapacitor bank. Same as mentioned above, the balancing resistor should draw >10x the leakage current spec of the cell to ensure sufficient balancing ability.

SAB MOSFET Balancing

Another simple solution is to use the ALD8100xx for up to 4 cells, and cascading ALD8100xx and ALD9100xx for more than 4 cells. The current drawn from a cell to reduce its voltage increases proportionally to the square of the cell over voltage, so this solution reduces imbalance rapidly.

General Purpose Evaluation Board

CAP-XX has available a general purpose evaluation board with various current limit options and dual cell balancing options using resistors or the TLV8801 op amp to accelerate development of your supercapacitor circuit, refer to User Manual for APPEB1002 Supercapacitor Eval Board. It can be purchased from the CAP-XX website.

Further Information

CAP-XX will be pleased to provide further information on the applications described here, and on the use of supercapacitors in any application.
Please use the contact details provided on the CAP-XX web site cap-xx.com.
This application white paper is available on the CAP-XX web site.

On the web site you may also find product bulletins, datasheets, SPICE models, application white papers, application briefs and design-aid calculators.

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