A New Method of Balancing Supercapacitors in a Series Stack Using MOSFETs

Novel Circuit Design Offers Insight on Over-Voltage Problem that Jeopardizes Cell Life and Provides Solution on How to Implement Automatic Leakage Current Equalization

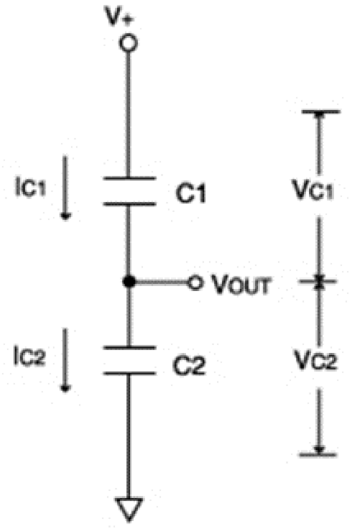
Supercapacitors are becoming increasingly useful in high-voltage applications as energy storage devices. When an application requires more voltage than a single 2.7 volt cell can provide, supercapacitors are stacked in series of two or more. An essential part of ensuring long operational life for these stacks is to balance each cell to prevent leakage current from causing damage to other cells through over-voltage.

Applications for these supercapacitor stacks are rapidly growing, but the problem of leakage current and over-voltage is not well known. However, since supercapacitor stacks in high-voltage energy storage applications represent the next-generation, designers need a clear path forward to address this significant problem.

By diagramming two supercapacitors in series and showing how Supercapacitor Auto Balancing (SAB^{TM}) MOSFETs manage the cells implemented in the series stack, a designer will gain insight on how to control leakage current of each cell and thus prolong the life of each supercapacitor.

How Do Supercapacitor Auto Balancing SAB^{TM} MOSFETs work?

FIGURE 1 - Two **supercapacitors** stacked in a series.



Scenario 1:

- *Power Supply V+ = 4.6V*
- *If* $I_{C1} = I_{C2}$
- $V_{OUT} = V+ / 2 = 2.30V$
- Each Supercapacitor = 2.7V max. rating

Scenario 2:

- *If* $I_{C1} > I_{C2}$
- V_{OUT} *rises until* $I_{C1} = I_{C2}$
- *If* $V_{C2} = V_{OUT} > 2.7V$*, then C2 is damaged due to over – voltage*

Scenario 3:

- *If* $I_{C2} > I_{C1}$
- V_{OUT} *drops until* $I_{C1} = I_{C2}$
- *If* V_{C1} $(V+ - V_{OUT}) > 2.7V$*, C1 is damaged due to over-voltage*
- *Total leakage current equals* I_{C2}

The figure above shows a pair of supercapacitors connected in series. Capacitor value C1 is equal to C2 in the first of three possible scenarios.

They are equal in value to each other but, bear in mind they are never exactly the same in real world applications. All the cells differ slightly and each one will have different capacitance values as well as different leakage currents levels.

C1 exhibits a leakage current value noted here as I_{C1} and C2 has leakage current of I_{C2}.

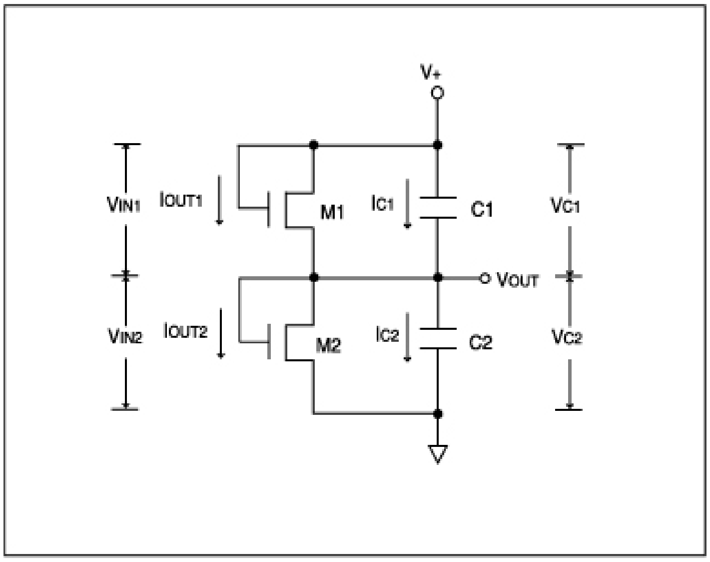
If the two leakage currents are exactly the same, ironically, the supercapacitors would be balanced. A supercapacitor manufacturer does not provide the exact specification required to balance the supercapacitor. The datasheet typically provides maximum leakage current, but the actual leakage can vary significantly, even for parts manufactured from the same lot and with the same part number. Additionally, over time, the temperature and leakage current values will change depending upon the actual material composition and construction of each supercapacitor.

In Scenario 2, I_{C1} is greater than I_{C2} and this causes the output voltage to rise until the two leakage currents balance. If the output voltage exceeds 2.7V, then C2 will eventually fail due to over-voltage.

In Scenario 3: If the leakage current of I_{C2} is greater than I_{C1}, then C1 would eventually fail because the voltage across it would exceed 2.7V.

Two Supercapacitors connected in series with SAB^{TM} MOSFET across each Supercapacitor as the auto-balancing element

FIGURE 2 - **Two supercapacitors stacked in series with MOSFETs.**



Total Leakage Current:

- *M1 connects across C1,*

  $V_{IN1} = V_{C1}$
- *M2 connects across C2,*

  $V_{IN2} = V_{C2}$
- $V+ = V_{IN1} + V_{IN2} = V_{C1} + V_{C2}$
- $I_{C1} + I_{OUT1} = I_{C2} + I_{OUT2}$

The above figure shows a pair of SAB MOSFETs placed across two supercapacitors. SAB MOSFET 1, or M1, is connected across C1, so input V_{IN1} of the SAB MOSFET is equal to supercapacitor voltage V_{C1}. M2 is across C2 so V_{IN2} is equal to V_{C2}.

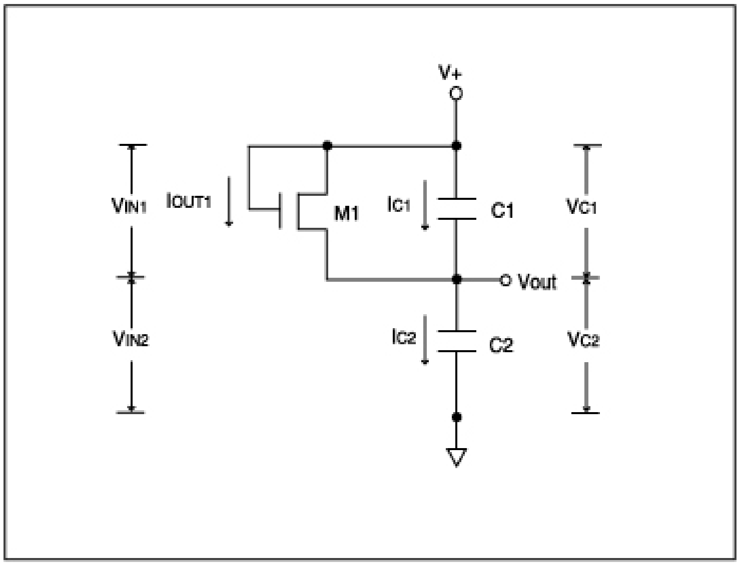
There is leakage current going through each one of the MOSFETs, referred to as I_{OUT1} for M1 and I_{OUT2} for M2.

Notice the equation, which states: V+ is equal to $V_{IN1} + V_{IN2} = V_{C1} + V_{C2}$. In other words, the two voltages across M1 and M2 are equal to the two voltages across both supercapacitors C1 and C2.

The total leakage current now becomes $I_{C1} + I_{OUT1} = I_{C2} + I_{OUT2}$.

First of Three Scenarios with two SAB^{TM} MOSFETs Across two Supercapacitors

FIGURE 3 - **Two supercapacitors connected in a series with M1 turned on**.



If $I_{C2} > I_{C1}$:

- *V_{OUT} drops until M1 is turned on*
- *M2 is turned off, I_{OUT2} is zero*
- *$I_{OUT1} + I_{C1} = I_{C2}$*
- *V_{OUT} ~= 2.25V for I_{C2} ~= 10 x I_{C1}*
- *Total leakage current equals I_{C2} at 2.25V*

Figure 3 above demonstrates how SAB MOSFETs work. If I_{C2} is greater than I_{C1}, then V_{OUT} voltage is going to drop a little bit until SAB MOSFET M1 is turned on. When M1 is turned on, the other MOSFET, M2, is turned off.

This changes the equation: I_{OUT1} of M1 + I_{C1} is equal to I_{C2}. The other MOSFET disappears because it is turned off exponentially, so I_{OUT2} ~= 0. V_{OUT} voltage can keep dropping until I_{OUT1} equals the difference between IC1 and IC2. Without I_{OUT1}, V_{OUT} can go down to 0.0 volt. That would kill the supercapacitor C1 in the series as the voltage across it exceeds 2.7V.

The unsaid condition is that the supercapacitor output voltage V_{OUT}, which is a mid-point between supercapacitors, can go as far as 0.0V or 4.6V. If it does, it will slowly destroy the next supercapacitor in the series.

In this case, if C2 is leaking more current than C1, the output voltage is going to keep going down. But as the output voltage keeps dropping, the voltage across C1 increases until the supercapacitor succumbs to over-voltage and fails.

If C2 is leaking despite a clamp down on voltage, then it will force more voltage across the good supercapacitor C1 until it bursts. When C1 bursts, it can cause a short circuit and sent 4.6V across C2, and eventually the cell will also fail. When C1 bursts, it can also result in an open circuit and render the supercapacitor network to be inoperative.

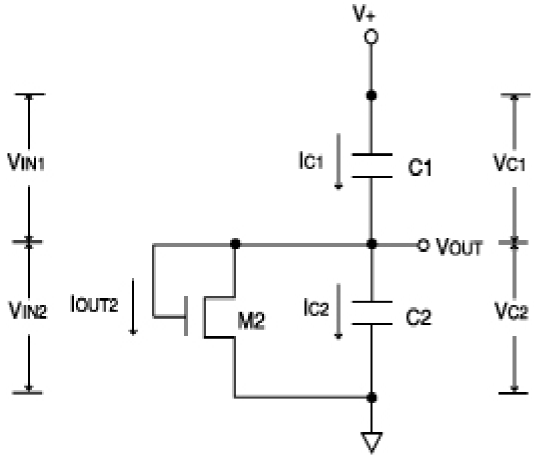
The SAB MOSFET can prevent this. It senses that the voltage wants to go down, so it starts leaking current very quickly, without allowing the voltage to go down much. Because it is exponential in nature and the current goes up, it will automatically float to a point where the SAB MOSFET current I_{OUT1}, plus the I_{C1} current would be equal to the leakage current of C2, which is I_{C2}.

There is a push-pull dynamic relationship. In other words, there are two supercapacitors and two SAB MOSFETS, but only one SAB MOSFET is turned on at any given time. Since there is no way to know which supercapacitor has higher leakage, placing the SAB MOSFET across both supercapacitors will balance the network automatically.

Second of Three Scenarios with two SAB^{TM} MOSFETs across two Supercapacitors

FIGURE 4 - Two supercapacitors connected in series with M2 turned on.

.



If $I_{C1} > I_{C2}$:

- *V_{OUT} rises until M2 is turned on*
- *M1 is turned off, I_{OUT1} is zero*
- *$I_{OUT2} + I_{C2} = I_{C1}$*
- *V_{OUT} ~= 2.35V for I_{C1} ~= 10 x I_{C2}*
- *Total leakage current equals I_{C1} at 2.25V.*

In Figure 4, C1 has a higher leakage, so the top MOSFET, M1, is actually turned off. This is the case where the top MOSFET “disappears” as only one of them is actually conducting at any time. The active MOSFET would be M2, but it would balance C1 with greater leakage.

Since the specific leakage of each supercapacitor is unknown, when there are two supercapacitors, the one that has the higher leakage would be automatically balanced by the SAB MOSFET.

When an SAB MOSFET is placed across a supercapacitor, it automatically balances the system, by equalizing whichever supercapacitor has the highest leakage current.

The MOSFET is able to turn itself off but both MOSFETs do not turn off simultaneously. Only one of them will turn off. In the case above, MOSFET M1 would turn itself off completely.

When the SAB MOSFET turns itself off, the total leakage current is only equal to the higher of I_{C1} or I_{C2}, whichever supercapacitor that has the highest leakage current in the stack.

Balancing with SAB MOSFETs is automatic, simple and elegant to implement. When connected across the supercapacitors, one MOSFET will turn itself on automatically to balance and the other one will turn itself off automatically to balance the stack. Depending on which way it goes, the balancing scheme is fully automated, hence “auto-balancing”. This auto-balancing scheme is scalable and stackable, extending to any number of supercapacitors connected in series without limitations on the number of cells the design requires. Another way to view the mechanism is that each SAB MOSFET automatically senses the voltage across it and turns itself off or turns itself on exponentially, based upon its rated design threshold voltage.

There is no way to tell which supercapacitor in a series has higher leakage current before they are linked together. It is also difficult to determine the exact leakage current in any supercapacitor, because time, environment and application can introduce unforeseen variables. It is, however, possible to test each supercapacitor for a max, rated leakage current before being connected to a series stack.

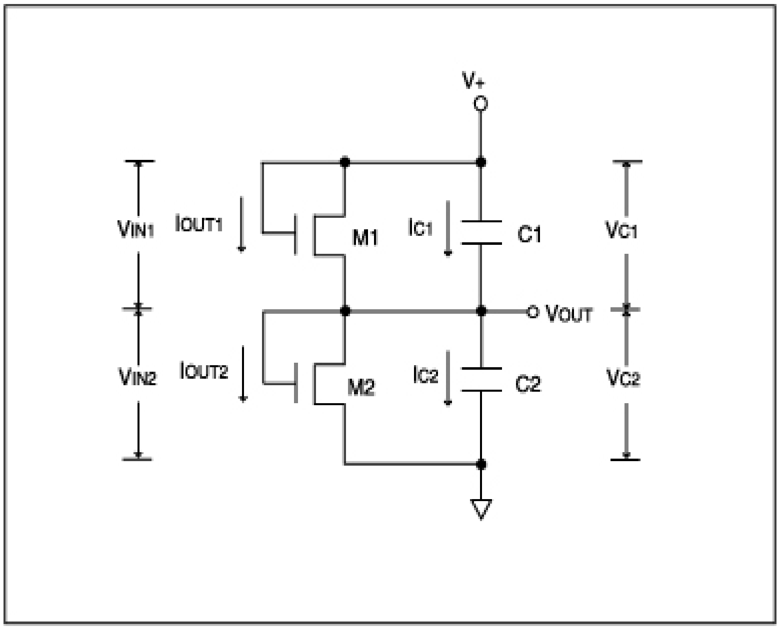
SAB MOSFET balancing adds only a negligible amount of leakage, compared to the max. rated supercapacitor leakage current. Balancing without adding leakage current is not possible with an op-amp solution. A quiescent current is required to power up the op-amp. It forces the voltage to a higher leakage point of the supercapacitor because it will only balance to the midpoint.

The SAB MOSFET solution while adding little or no leakage, does allow a lower voltage bias on the leakier supercapacitor, so that the actual total leakage of the series-connected supercapacitors can be potentially less than not balancing the circuit at all. As an example, if one supercapacitor is leaking 10 times that of the other one, the difference between the two supercapacitor voltages would be a total of 100 mV, its voltage could be off by as much as 50 mV from the mid-point. The other 50 mV would be added to the less leaky supercapacitor. The leakier supercapacitor would see a lower voltage bias than the mid-point, which is a favorable condition. The leakier the supercapacitor, the lower its voltage, which in turn lowers its leakage current. The other supercapacitor, however, would experience an increased voltage across it, but limited by the SAB MOSFET to the max.voltage at the leakage current level of the leakier supercapacitor.

But if the leakage current difference between supercapacitors is much less than 10 times, then the voltage difference could be off by less than 50 mV, as balancing is actually dependent upon adding just enough leakage current to balance the leakier of the supercapacitors in a series stack. The other MOSFET exponentially turns itself off to the extent that the leakage current becomes inconsequential.

Third Scenario with two SAB™ MOSFETs across two Supercapacitors

FIGURE 5 - Two supercapacitors connected in series with M1 and M2 both turned on.



If $I_{C1} = I_{C2}$:

- *V_{OUT} ~= 2.30V*
- *M2 is slightly turned on*
- *M1 is slightly turned on*
- *$I_{OUT1} + I_{C1} = I_{OUT2} + I_{C2}$*
- *Pick minimum I_{OUT1} value so that $I_{OUT1} << I_{C1}$*
- *Total leakage current equals ~ I_{C1}*

In figure 5 above, a third scenario is presented, where both supercapacitors are exactly balanced, which implies that they are exactly equal in leakage current However, in reality one leakage current is usually greater than the other. Even when only a small amount of leakage difference occurs the cells will still eventually fail although it may take several weeks or even months, postponing the inevitable. Without active balancing there is no mechanism to reverse the over-voltage excursions.

In balancing, we have a third case, where all the SAB MOSFETs are slightly turned on. The values have to be picked so that they will not burn power. Most of the time, when one MOSFET is turned on, the other MOSFET is turned off, as mentioned earlier. The exact amount of current they consume is a lot less than the leakage current. Leakage current will vary **tremendously** depending upon the leakage currents of each individual cell.

The second MOSFET will turn off and go “incognito,” but if you use it in a different stack of supercapacitors, there is no way to know which one is turning on because the individual leakage current situation is unknown. The voltages measured across the supercapacitors would confirm that auto-balancing is working.

To Summarize:

- SAB MOSFETs automatically balance supercapacitors
- They lower additional leakage currents to near zero levels
- They provide simple and yet elegant solution
- Scalable and stackable to any number of supercapacitors
- Completely automatic process
- Adjusts for changing environmental conditions and leakage currents

Selecting the right SAB MOSFET requires knowledge of the supercapacitor operating voltage and max. rated leakage current. This method limits leakage current better than any other method. SAB MOSFETs are stackable and scalable whether you use two or 100 supercapacitors in series.

SAB MOSFETs actively adjust to different temperature or supercapacitor chemistry changes. They adjust automatically - no change to the circuitry is needed. A designer can just pick the maximum operating voltage margin and the maximum Leakage current for the particular supercapacitor(s) and look up the correct SAB MOSFET part number. For more information, go to www.aldinc.com search: sab mosfet.

# # #