Studies of voltage stabilization and balancing systems in energy storage modules based on supercapacitors

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Abstract. Supercapacitors come under different names and scientific nominations as Ultracapacitors (UCs) or double layer capacitors, or electrochemical capacitors, they are considered as promising technological devices used for storing energy in the field of energy storage systems. They are able to deliver high power and enable high load currents in addition their ability to bridge power gaps. As we will notice, they have fast yet complicated charging/discharging mechanism interpretations. This paper will provide an overview on different equivalent circuits of a supercapacitor, and will highlight the concept of unbalanced series of connected ultracapacitors and different options in rectifying such unbalance. The balancing of supercapacitors connected in series can come in different modes passive or active and maybe hybrid. A comparison between the different modes will be executed using MATLAB/Simulink and results will be shown based on the economical and performance perspectives.

1. Built-in supercapacitor model in MATLAB/Simulink
The software MATLAB /Simulink library contains different types of supercapacitors based on the different model and equivalent circuit proposal of the supercapacitor model. Our studies are based on the Zubieta-Bonert model having the shown below equivalent circuit:

![Figure 1. Zubieta-Bonert Supercapacitor Equivalent Model.](image)

The circuit model consists of three well distinct “RC” time constants differing from each other’s in more than an order of magnitude which will make the model easily measurable:
1- The immediate branch, consisting of the elements: $R_i$, $C_{i0}$, and $C_{i1}$ (where $C_{i1}$ is a voltage-dependent capacitor in F/V), has a time constant “RC” of seconds in response to the action of charge. It describes the immediate response of the first branch and reflects the behavior of the supercapacitor.

2- The second or as described by Zubieta-Bonert, the delayed branch, has the parameters $R_d$ and $C_d$, it describes the terminal behavior in the range of minutes.

3- The third or long-term branch, with parameters $R_l$ and $C_l$, describes the behavior for times much longer than 10 min.

The first branch is modeled as a voltage-dependent differential capacitor for the purpose to reflect the voltage dependence of the capacitance that exists in the Double Layer Capacitor (DLC) or supercapacitor.

As the DLC by its nature will encounter internal leakage, a parallel resistor $R_{lea}$ is added to the terminals of the model representing this self-discharge property.

It is worth to note the built-in model in MATLAB is not taken into consideration the inductor represented in the original Zubieta-Bonert model, therefore it is not being discussed.

Our design will be based on the measured and experimental measurements of Zubieta for a DLC of 470 Farads from Panasonic that is currently not in the range of production of Panasonic. Further studies are planned to be part of our works in later stages and will be based on real measurements and comparison of actual supercapacitors available in the market.

For the time being, the values of the equivalent circuit of our model based on Zubieta works are as follows:

| PARAMETERS | PANASONIC | MAXIMUM VALUE | MINIMUM VALUE |
|------------|-----------|----------------|---------------|
| $R_i$      | 2.5 mΩ    | 2.353 mΩ       | 2.251 mΩ      |
| $C_{i0}$   | 270 F     | 281 F          | 269 F         |
| $C_{i1}$   | 190 F/V   | 205 F/V        | 189 F/V       |
| $R_d$      | 0.9 Ω     | 0.925 Ω        | 0.842 Ω       |
| $C_d$      | 100 F     | 109 F          | 102 F         |
| $R_l$      | 5.2 Ω     | 5.252 Ω        | 4.951 Ω       |
| $C_l$      | 220 F     | 238 F          | 222 F         |

2. Unbalanced behavior of supercapacitors in series (3 supercapacitors model)

There are several types of ultracapacitors and ultracapacitor modules. The rated voltage of one supercapacitor is in general in the range of 2 to 5 volts. Due to the low operating voltage of supercapacitors, with the exception of rare cases, supercapacitors are usually used in series in a form of modules, to achieve a suitable operating voltage. Since the tolerance of the parameters of supercapacitors is usually from 10 to 20%, the voltage distribution between the supercapacitors in such a series connection will not be uniform. In this case, the voltage on one of the series-connected supercapacitors may exceed the rated voltage.

When this happens for an extended period of time, it may lead to a reduction in the service life of the supercapacitor and the occurrence of an electrical failure. To avoid this, in most applications that have modules of two or more series-connected supercapacitors, means of automatic control and adjustment of the charge balancing at maximum operating voltages becomes required. Ideally, when identical supercapacitors are placed in series, the voltage on each capacitor should be evenly distributed.
across the capacitors. This is not always the case due to changes in the leakage currents of supercapacitors and inside the module of supercapacitors itself. This is due to the different internal leakage currents in each specific cell. The leakage current of a supercapacitor is a variable function of many parameters, such as aging, the material of the electrodes and the design of the supercapacitor, its chemical composition, the values of the charging voltage and charging current and temperature, the operating temperature range, and the rate of change of these parameters. As noted previously, variations in the leakage current may cause some of the supercapacitors to have voltages across them that may exceed their nominal values. A simulation of this case is represented in Matlab/Simulink and a simulation of the unbalance behavior of a module constructed from 3 series-connected DLC’s is shown.

The simulation is controlled through the use of a Signal Builder Block considering a combined charging technique of currents and voltage charging.

![Simulation Diagram](image)

**Figure 2.** Unbalanced Module of Supercapacitors.
3. Balancing Supercapacitors using different balancing techniques

Exceeding the rated voltage of a supercapacitor will compromise the reliability of the supercapacitor and may lead to other serious and dangerous consequences. Therefore, it is important to avoid this situation in any application. Thus, the study of the methods of balancing the voltage of supercapacitors is an important task. In this case, the balancing of the voltage of the supercapacitor should take into account changing parameters affecting the magnitude of the leakage current.

So, the performing of balancing operation becomes necessary for:
- Achieving a voltage balance between cells.
- Accounting to the changes between the capacitances and leakage current.
- Reducing the voltage stress on a single cell.
- Increasing the overall reliability of individual cells.

In this case, balancing reduces the failure time of the module of supercapacitors and therefore the application in which it is used guarantees the maximum service life of each supercapacitor, protects the environment and saves money.

Various methods for stabilizing the voltage of supercapacitors are considered. We developed models of voltage stabilization systems using MATLAB / Simulink, allowing to explore passive or active methods of balancing. Cell balancing topologies vary in cost, size, complexity, management, implementation, and appropriate use. Each topology has its advantages and disadvantages.

Our simulation investigation will cover three balancing techniques: passive balancing, active balancing using N-Channel MOSFETS, and active (hybrid) balancing using Op-Amps and resistors.

3.1. Passive Balancing
This technique, shown in figure 5, uses one resistor in parallel to each supercapacitor. The resistors set in parallel to the DLC’s will work as a voltage divider and will limit the voltage of each capacitor to its nominal value ensuring that any capacitor will not bypass its nominal voltage. Because the response of passive balancing is slow, we had to use a balancing resistor of 5 Ohms in order to show the voltage conversion to the supercapacitor’s nominal voltage. Of course, this is not a practical value for the balancing case, and we end up with a power consumption of 8.7 W.h for a balancing period of 10000 sec.

Figure 4. Passive Balancing of a module of Supercapacitors.
3.2. N-Channel MOSFET Active Balancing
This topology uses N-Channel MOSFETS instead of the resistors in parallel to each supercapacitor as shown in figure 6, uses one resistor in parallel to each supercapacitor. The threshold voltage of MOSFET is used as $1/n$ of $V_S$ ("n" – number of series-connected supercapacitors in the module). According to Murata EDLC MOSFET balancing resources, small variation of threshold voltage and dynamic ON-state characteristics are necessary because they affect the accuracy of voltage balance.

Figure 5. Passive Balancing Output of a module of Supercapacitors.
Figure 6. N-Channel MOSFET Active Balancing of a Module of Supercapacitors.
3.3. Operational Amplifier and Resistors Active Balancing (Hybrid Balancing):
In this case the OpAmp plays a role of a voltage comparator leading the supercapacitors to equivalent voltages across them. OpAmps balancing technique shows a very fast response in the very beginning moment of the start of balancing and the value of the used resistors does not affect the balancing process. Consequently, we used in our study resistors with 10 KOhms value, leading to a power consumption of 0.0044 W.h

**Figure 7.** N-Channel MOSFET Active Balancing Output of a Module of Supercapacitors.
Figure 8. OpAmp Active (Hybrid) Balancing of a Module of Supercapacitors.
3.4. Comparison between the different balancing techniques:
There are a lot of other techniques that can be applied to establish balance between a set of series-connected supercapacitors in a module, this paper shows a comparison between three of these techniques. It has been established that passive balancing is cheap and easy to implement, when active balancing is more expensive and can be complicated in accordance with the implemented technology. However, the active balancing system has higher speed and accuracy.

4. Conclusion
Although passive balancing improves the voltage distribution on supercapacitors, however the balancing resistors established in parallel with the DLC’s fit the place of additional load in the system and the additional currents passing through them reduce the energy efficiency of supercapacitors used as energy storage devices. Therefore, this method is not recommended for applications requiring energy efficiency. For such applications, it is recommended to use circuits implementing active voltage balancing technology on supercapacitors that will drain less energy from the system. The active method uses semiconductors for balancing and is considered best for:

- High performance cycle.
- When efficiency and resistance to leakage losses are necessary.
- Maximum cell reliability.

In general, the choice of balancing method is a solution depending on the type of application used, taking into account all the various parameters that surround it.

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