Series Connection of Supercapacitors: Comparative Study of Solutions for the Active equalization of the Voltages

P. Barrade

Abstract—Because of their low voltage level, supercapacitors need arrangement with series connection in order to obtain voltage levels from few dozen to few hundred of volts. As for batteries, devices have then to be defined to balance the voltages across each series connected components. This paper presents the problematic of voltage sharing in a series connection of supercapacitors. It is generally described the way the balancing of the voltages can be obtained, with the main design rule. It is also introduced how the voltage balancing can be obtained easier with a coherent arrangement of the supercapacitors in their tank. Then, the main solutions for sharing the voltages with active devices are presented, detailed and compared, using a global modeling approach.

Index Terms—Capacitive energy storage, Power Conversion, Power System Modeling

I. INTRODUCTION

Because of their relatively high energy density, batteries are devices used in a lot of applications where energy storage is needed. However, the main disadvantage of those elements is their poor power density. This leads to important time for the loading, and the discharging power is often limited. To solve this limitation, new components, such as the supercapacitors, offer today a new alternative. The main property of the supercapacitors is to propose both a high energy density together with a high power density [1]. Even if this energy density is lower than that of one of batteries, and if the power density is lower than that of a conventional capacitor, the supercapacitors can be used in a lot of applications for energy storage and management. In particular, the main application for supercapacitors is to use them as energy buffers, to limit the power constraints on energy sources like batteries, fuel cells, or decentralized power networks [2][3][4].

As for batteries, the maximum energy that can be stored in one single supercapacitor is too low. The first step in the design of a supercapacitive tank is to identify the number of needed components. On another hand, the maximum voltage that can be applied across a supercapacitor is low (typically 2.5-2.7 volts). Even if the energy density of a supercapacitor is high, one single component is not enough for most of applications. The first step for the definition of a supercapacitive tank is then the determination of the needed number of supercapacitors. Two parameters have to be defined: the energy that has to be stored and used, and the instantaneous power that a supercapacitive tank must absorb during the refilling and provide during the discharge of the tank.

Knowing the usable energy $W_u$ needed for a given application, and for a voltage discharge ratio $d$ given (ratio between the voltage at the end of the discharge and the maximum voltage) [9], the number of needed supercapacitors $N_s$ can be obtained thanks to the following equation:

$$N_s = \frac{2W_u}{CU_M^2 \left(1 - \left(\frac{d}{100}\right)^2\right)}$$  (1)

It should be noticed that this number depends also on the capacitance $C$ of the supercapacitors, and of course on their maximum voltage $U_M$. 

II. SERIES CONNECTION OF SUPERCAPACITORS

A. Sizing of a supercapacitive tank

Today, manufacturers are able to propose supercapacitors with capacitances from few farads to few thousand farads. But, because of the technology that allows these high capacitances, the maximum voltage that can be applied across a supercapacitor is limited (typically 2.5-2.7 volts).

Even if the energy density of a supercapacitor is high, one single component is not enough for most of applications. The first step for the definition of a supercapacitive tank is then the determination of the needed number of supercapacitors. Two parameters have to be defined: the energy that has to be stored and used, and the instantaneous power that a supercapacitive tank must absorb during the refilling and provide during the discharge of the tank.

Knowing the usable energy $W_u$ needed for a given application, and for a voltage discharge ratio $d$ given (ratio between the voltage at the end of the discharge and the maximum voltage) [9], the number of needed supercapacitors $N_s$ can be obtained thanks to the following equation:

$$N_s = \frac{2W_u}{CU_M^2 \left(1 - \left(\frac{d}{100}\right)^2\right)}$$  (1)

It should be noticed that this number depends also on the capacitance $C$ of the supercapacitors, and of course on their maximum voltage $U_M$. 

Index Terms—Capacitive energy storage, Power Conversion, Power System Modeling
As an example, if the needed usable energy is 220KJ, and if d is 70%, then 77 supercapacitors will be needed.

Once the energy requirements have defined the minimum number of supercapacitors, it has to be identified if this number is compatible with the power requirements. Indeed, the energy efficiency of the supercapacitors is depending on the power they have to absorb/provide (the efficiency of a 1800F/2.5V supercapacitor is 86% with constant 200A current loading). In particular cases, the number of supercapacitors defined in (1) has to be increased, to reduce the charging and discharging current per supercapacitors, and increase the energy efficiency.

B. Unbalanced voltages

Because of the technology limits, the maximum voltage of a supercapacitor when charging is low, near 2.5V. As the supercapacitors are used for energy storage, the efficiency of the associated power electronic must be as high as possible. In order to reduce the power losses in the static converter when charging and discharging, a series connection of several supercapacitors is needed to increase the operating voltage and decrease the charging and discharging current.

Due to differences in the values of each supercapacitor, the total voltage over a series connection will not be equally distributed between the different supercapacitors. This can lead to an asymmetrical voltage share between the capacitors. If this effect is not compensated for, a local over-voltage could appear over one of several supercapacitors. There is then a risk of destruction of this component in the worst case, or a decrease of its lifetime in most cases.

As an example, we can consider two extreme cases. The first one is related to the series connection of two ideal supercapacitors (C1=C2=1000F). The second case is related to a series connection of two supercapacitors where the C2 capacitance is only 80% of C1 capacitance (C1=1000F and C2=800F). The results are given in Table I.

<table>
<thead>
<tr>
<th>Table I</th>
<th>Voltage Sharing and Stored Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C1=C2</td>
</tr>
<tr>
<td>Uf (V)</td>
<td>5</td>
</tr>
<tr>
<td>Uc1f (V)</td>
<td>2.5</td>
</tr>
<tr>
<td>Uc2f (V)</td>
<td>2.5</td>
</tr>
<tr>
<td>W (J)</td>
<td>6250</td>
</tr>
</tbody>
</table>

In the case of same values for each supercapacitor, the loading process is ended when the two supercapacitor reach their maximum voltage value (2.5V). The stored energy is 6.25kJ.

When C2≠C1, with no voltage sharing, the voltages across each supercapacitor are not equally distributed. In order to avoid any over-voltage across a supercapacitor, the charging process is ended as soon as one supercapacitor reaches maximum voltage (2.5V). In this case, the charging process is ended when C2 is 2.5V. The voltage across C1 is only 2V, and the total voltage is only 4.5V instead of 5V. As a result, the stored energy is 28% lower than the ideal case (C1=C2).

The third case takes into account a device, connected across each supercapacitor, which allows the balance of the two voltages. Even if the stored energy is still lower than 6.25kJ (because of C1 and C2 values), this energy is 20% higher than the case where C2≠C1 without any voltage sharing device. The main advantage of balancing the voltages is to keep the voltages across each supercapacitor on their nominal values with no over-voltage. The stored energy is in that case at its maximal possible value, taking into account the respective values of C1 and C2.

This example illustrates the reason why the balance of the voltages is needed in a supercapacitive tank: the first objective is to avoid any over-voltage on the supercapacitors, to increase their lifetime. The second advantage is to be able to store in a supercapacitive tank the maximum possible level of energy, taking into account the unavoidable difference of capacitances from one supercapacitor to the other.

III. EQUALIZATION OF THE VOLTAGES

A. Principle of the voltage balancing

In order to obtain the balance of each series connected supercapacitor voltages, it has first to be noticed that, as for batteries, the efficiency of the sharing voltage device has to be as high as possible. This does not allow the conventional solutions such as parallel resistor, or anti-parallel zener diode across each supercapacitor. It has then to be defined non dissipative equalization devices.

Such devices have already been described, for applications with batteries [5]. But new investigations have to be initiated for the special applications with supercapacitors. The main reason is that the time constants are reduced with supercapacitors (few second to few dozen of seconds) compared to batteries.

In a general way, two main solutions for the equalization of the supercapacitor voltages can be used. Their main working principles are illustrated in Fig. 1.

The principle of the so called “current diverter” is presented in the left side of Fig. 1. The aim of such a device is to take some energy on the supercapacitor that has the highest voltage. Then this energy is transferred on the supercapacitor that has a lowest voltage, by means of current sources. The principle is here a current deviation of the main charging current. The equalization device has to assume all the energy transfers from the most charged supercapacitors to those one that are at a lowest energy level.

The second proposed principle, on the right side of Fig. 1, is different from the second because a direct connection is made from the equalization device to the dc link that is used for the charging of the supercapacitors. With such a system, it is of course possible to transfer some energy from one supercapacitor to the others. It is also possible to take directly some energy from the dc source to inject it on the supercapacitors that are at a lowest energy level compared to the others. It is also possible to take some energy from the...
supercapacitors that are the most charged, to re-inject that energy on the dc source.

B. Main criteria for the voltage equalization

The reason why it is needed to investigate again the way identical voltages across some series connected supercapacitors can be obtained is directly linked to the specificities of the supercapacitors themselves, compared to the proposed solutions for batteries.

One of the supercapacitor interesting parameter is their power density. The typical currents for loading and unloading can reach 100A to 200A (10% to 20s for loading/unloading the supercapacitors). For that reason, the currents $I_{eq}$ (Fig. 1) needed for the equalization of the voltages can reach large values, in order to obtain a dynamic for the voltage equalization identical to the dynamic of the charging process. This criterion will be satisfied under the following condition:

$$I_{eq} = I \frac{d}{d_1 + 200}$$

This relation shows, for a typical charging current $I=100A$, that the sharing current should be $I_{eq}=9.1A$, for a typical capacitance dispersion $d_1=20%$. This leads to a first difficulty. The power converters, that will realize the general functions described in Fig. 1, will have to manage currents of large value, with the difficulty to obtain a high efficiency.

The second main difficulty is related to the number of series connected supercapacitors. In case of huge number of series connected components, it will be necessary to add an equivalent number of devices for the voltage equalization. This is a problem for the safety of the supercapacitive tank itself, and also a problem of cost for the whole system.

A simple way to avoid these disadvantages is to limit the number of series connected components, as it is illustrated in Fig. 2 for a supercapacitive tank made of 4 supercapacitors. Various arrangements are possible, but two only are shown. The arrangement on the left side of Fig. 2 is made of 4 series connected supercapacitors. Assuming that each current source is an elementary power converter, this arrangement needs 4 power converters. The needed current for the equalization of the voltages is then defined according (2), and is mainly a function of the tolerance defined for the capacitance of each supercapacitor.

Another possible arrangement is defined on the right side of Fig. 2. The number of supercapacitors is still the same. As a consequence, the power and the energy that such a supercapacitive tank is able to provide/absorb stay the same. But the first advantage is that the number of converters needed for the voltage equalization has been reduced by a factor two. On another hand, the tolerance on the capacitances for the equivalent supercapacitors made of $C_1$ and $C_2$ on one side, $C_3$ and $C_4$ on the other side, is reduced because of the averaging on the capacitance values when supercapacitors are paralleled. The consequence is that the dispersion factor $d_1$ in (2) is reduced, even when the respective values for the capacitances of $C_1$, $C_2$, $C_3$ and $C_4$ are still the same. Then the needed currents for the voltage equalization can be reduced. The constraints on the power converter modeled by the current sources are minimized.

It is so very interesting to design supercapacitive tank with a massive parallel connection of supercapacitors, instead of a massive series connection. An easier voltage equalization is allowed, with a reduced number of added components.

It is evident that the global voltage of such a supercapacitive tank will be low, with the difficulty to design an efficient power interface between the tank itself and its load if a high voltage is required. Various solutions are proposed to solve this problem, using power converters with middle frequency transformer intermediary stage [2].

IV. SOLUTIONS FOR NON-DISSIPATIVE VOLTAGE BALANCING
Once the main principle of voltage balancing has been defined, it is then needed to investigate how such functions can be implemented. Various solutions exist, that have been defined for series connection of batteries. It is necessary to make an examination of those solutions in the context of series connection of supercapacitors. In this section we propose three different devices for the equalization of the voltages in a series connection of supercapacitors. In order to make an easier comparison, we will use a global modeling approach, based on the Energetic Macroscopic Representation (EMR) [7]. This methodology has been developed for multi-converter analysis and control [8].

A. Centralized flyback dc-dc converter with distributed secondary

A first topology for the equalization of the voltages in a series connection of supercapacitors is defined in Fig. 3.

![Fig. 3. Equalization with a flyback converter with distributed secondary](image)

The aim of such a solution is to define a centralized equalizing converter. When a significant difference of voltage is detected across one or various supercapacitors, then the transistor T is switched on to store some energy into the magnetization inductor of the transformer. When the transistor T is switched off, this energy is transferred to the distributed secondary of the transformer, via the diodes. Most of this energy is provided to the supercapacitors that have the lowest voltages. Equal voltages across each supercapacitor correspond to identical conduction time of the diodes. The equalization process can be stopped.

The transistor T must be designed to support the total voltage of the supercapacitive tank, and the maximum value of the magnetizing current, defined by the switching frequency and the duty cycle of the control signal of T.

The diodes must be chosen to support, as reverse voltage, the sum of the maximum voltage across the supercapacitive tank plus the value of the voltage across their associated supercapacitor. During their on state, they have to support, in the worst case, the maximum value of the magnetizing current.

The model of such an equalization converter, using the EMR formalism, is described in Fig. 4, in order to identify the various energetic coupling in such a system.

This representation is presently useful to understand the main difficulty in the use of a flyback structure for the voltage equalization. Indeed, this model makes appear two main independent circuits: the first one is the series connection of the supercapacitors themselves, and the second one is the flyback converter. The coupling between these two elements is realized thanks to the transformer, which will distribute its magnetizing energy in the supercapacitors. The transformer has then to be designed with symmetrical leakage inductors, in order to have symmetrical balancing currents. Some asymmetrical leakage inductors can lead to unbalanced supercapacitors voltages, that the control of the flyback converter will not be able to compensate.

The macro-model in Fig. 4 shows also that this equalization solution is related to the principle defined in the left side of Fig. 1. In this case, some energy is taken from the dc current source, and distributed directly in each supercapacitor that need it.

B. Current diverter using the association of buck-boost dc-dc converters

The main principle of the previous solution was to store firstly some energy, to distribute it in some supercapacitors in a second time. An evolution of this solution is given in Fig. 5, for a structure with no transformer, using an association of buck-boost dc-dc converters [10]. The aim of such an association is to enable a voltage equalization of the voltages across two consecutive supercapacitors, by means of a current deviation. This behavior is related to the left side schematic in Fig. 1.

For each pair of supercapacitor is associated such a reversible buck-boost converter. Each converter allows an energy transfer between its two associated supercapacitors, independently from their respective voltages. The equalization of the voltages is made locally, by pairs of supercapacitors.

In order to optimize the efficiency of the voltage balancing device, each converter works in discontinuous conduction mode, to reduce the switching losses in the diodes. The maximum voltage that the switches (transistor and diodes) have to support is two times the maximum voltage across the supercapacitors (2 times 2.5V). Mos-Fets with reduced Rds-on losses have to be chosen to minimize the conduction losses.
Fig. 5. Voltage equalization by association of buck-boost dc-dc converters

The currents needed for a good balancing of the voltages are set thanks to the switching frequency of the converters, and their duty cycle. However, in many cases, the duty cycle is set constant to 50%, and the balancing currents are adjusted by the switching frequency. When all the voltages are identical, then all the converters are shut down.

The model of such an equalization converter, using the EMR formalism, is described in Fig. 6, in order to identify the various energetic coupling in such a system.

Fig. 6. Macro-model of the buck-boost converters voltage equalizers

This representation makes appear two different coupling. The first one is related to the series connection of the supercapacitors themselves. The second coupling is related to the coupling of two successive supercapacitors to a single buck-boost converter. It appears also the inductors, needed for each power converter. The signification is that when a supercapacitor is over-charged, some energy is taken from this component to be firstly stored into the inductor of the associated buck-boost converter. Then, this energy is transferred to the second supercapacitor associated to the same converter.

The second comment regarding Fig. 6 is dealing with the main disadvantage of this solution: in the case where some energy has to be transferred from the supercapacitor $C_1$ to the supercapacitor $C_2$, then the two power converters have to be used, and the supercapacitor $C_2$ has to be used to transmit the energy from the inductors $L_1$ to $L_2$. It is then impossible to have a direct transmission of energy from $C_1$ to $C_3$. The efficiency of such voltage equalization is then the product of the efficiency of the two power converters. This problem can be huge in a series connection of 120 supercapacitors, with energy transfer from the first to the last component.

But, as main advantage (deduced from Fig. 6), this solution offers a high modularity, because each buck-boost converter can work independently from the other.

C. Current diverter using forward dc-dc converters with distributed primaries

Another alternative is proposed in Fig. 7, where the main advantages of the two previous solutions are combined.

Fig. 7. Voltage equalization with a forward dc-dc converter with distributed primary

As it is in a general way described in the principle schematic on the right side in Fig. 1, the energy needed for the voltage balancing is not taken on the main dc supply. A power converter is associated to each supercapacitor. Then, energy will be taken on the supercapacitor that has the highest voltage, to be injected on the supercapacitors that have the lowest voltages.

As soon as one supercapacitor voltage has been detected to be higher than the other ones, then its associated transistor is switched on. Energy is transferred from this supercapacitor to the other ones, via the transformer and their respective diodes. There is no energy storage in the transformer, and the energy is directly transmitted. As for forward converts, a last winding has to be realized ($N_f$), for the demagnetization of the transformer.

The current needed for an efficient voltage balancing can be adjusted thanks to the switching frequency of the transistors, and their duty cycles. But it has also to be taken into account the time needed for a complete demagnetization of the transformer.

The model of such an equalization converter, using the EMR formalism, is described in Fig. 8, in order to identify the various energetic coupling in such a system.
This representation makes appear two different coupling. The first one is related to the series connection of the supercapacitors themselves. The second coupling is related to the transformer, via each power converters associated with the supercapacitors. Such a representation illustrates the main advantage, together with the main disadvantage of such a solution.

The advantage is that each supercapacitor is connected to the transformer. In this case, it is possible to have a direct energy transfer from $C_1$ to $C_3$, without the intermediary of $C_2$, as it is for the solution with buck-boost converters. Then the global efficiency of the voltage balancing process during a charge of the supercapacitive tank is increased.

The main disadvantage is that the state of each transistor is also coupled with the states of the others, still because of the transformer. A transistor cannot be triggered independently from the others, as it was possible in the solution in Fig. 5. The control process must first detect the supercapacitor that has the highest voltage, then can enable the switching of the associated transistor, while blocking the others.

If several supercapacitors have some too high voltage levels, the control signals for each concerned transistors have to be multiplexed in order to have one and only one transistor in the on-state at the same moment.

Despite this complexity in the control of this solution, the topology defined in Fig. 7 keeps as main advantage to transfer directly the energy from the most charged supercapacitors to the lowest ones without intermediary energy storage, with a self-adjustable injection of the energy on the supercapacitors that have the lowest voltages.

V. CONCLUSION

Because supercapacitors enable new developments and applications, it is important to study the way supercapacitive tank can be designed in an optimal way. For this reason, and because of the low voltage of these new components, the problem of the series connection of several supercapacitors has to be studied, and solved.

In this paper, the necessity of the equalization of the voltages in a series connection of supercapacitors has been introduced. It has been shown that the arrangement of the supercapacitors in their tank has a high influence on the efficiency of the voltage equalization, and on the constraints on the equalization devices.

Three solutions for the voltage equalization have been proposed, and compared using a global modeling approach. The final choice on a particular solution depends particularly on the application, regarding the number of supercapacitors to be series connected, and the needed efficiency.

VI. REFERENCES


VII. BIOGRAPHIES

Philippe Barrade was born in Cahors, France, on March 12, 1968. In 1997, he received the Ph.D. degree in Electrical Engineering from INP, Toulouse, France. In 1998, he was working at SAFT, in the field of power electronics, and energy management for UPS applications. Since 1999, he is First Assistant, Lecturer at Ecole Polytechnique Fédérale de Lausanne, Switzerland. His main research fields are power electronics applications, and the energy management and storage with supercapacitors.