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Comparison of the Different Circuits Used for Balancing the Voltage of Supercapacitors: Studying Performance and Lifetime of Supercapacitors

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Abstract—The main disadvantage of using supercapacitors in the field of energy storage systems is their limited voltage due to technology limits. To resolve this problem, these components are usually applied in series to reach the suitable voltage. However the tolerance in these components' characteristics leads to imbalanced voltage during the charge-discharge cycle. This may influence adversely the supercapacitors lifetime. To avoid this phenomenon, balancing circuits have to be employed. This turned out to be very useful in improving the performance and extending the lifetime of supercapacitors and the reliability of energy storage system as a whole.

Keywords: Supercapacitor, overvoltage, balancing circuits, temperature, manufacturing tolerance, aging behavior, life expectancy, efficiency.

I. INTRODUCTION

Supercapacitors offer interesting electrical characterizations and high lifetime cycling compared to that of batteries. They appear well suited to automotive advanced applications to boost the battery especially in a hybrid electric vehicle: They allow to provide the necessary power for acceleration and to recuperate the braking energy.

Due to decomposition voltage of the organic electrolyte of approximately 3V, the maximum cell-voltage of supercapacitors is limited. A supercapacitor module is formed by several serial cells in series to obtain voltages suitable for applications. For different reasons, the internal parameters of supercapacitors (capacitance, ESR, and self-discharge rate) of a module may vary. These variations give raise to unequal voltage distribution during charge-discharge cycles and overvoltage may appear on cells. The causes of supercapacitors parameters tolerances and

balancing circuits will be analyzed in detail, in addition to the performance and lifetime of supercapacitors [1, 2, 3].

II. CAUSES OF SUPERCAPACITORS NON IDENTICAL PARAMETRES

The internal parameters of supercapacitors (ESR, capacitance and self-discharge rate) vary in accordance with the following conditions:

A. Manufacturing dispersion in supercapacitors parameters:

Parameters dispersion of supercapacitors produced by the same manufacturer can reach $\pm 20\%$ for capacitance and $\pm 25\%$ for ESR. A study was conducted on four components which belong to a series manufacturing (Maxwell 2600F 2.5V), tolerances were appeared on capacitance (5%) and on ESR (3%). Figure 1 shows these dispersions on Nyquist plan [2, 3].

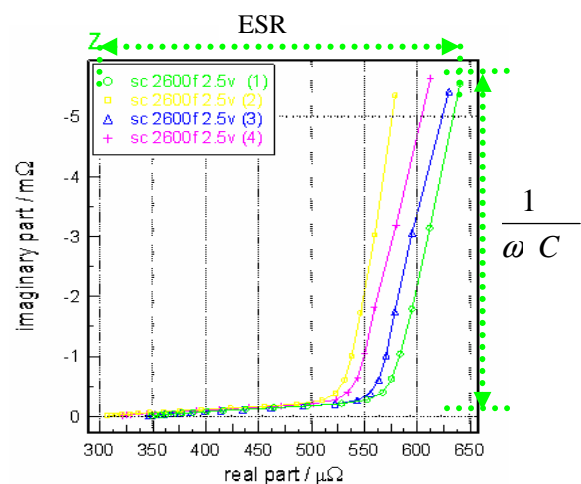


Fig. 1: Supercapacitors parameters manufacturing tolerances

The dispersion of supercapacitors self-discharge rate can influence the cells-voltage distribution especially in applications with low duty-cycle. Figure 2 shows that the four aforementioned components did not have the same self-discharge

rate, consequently a difference in the cells-voltage has appeared.

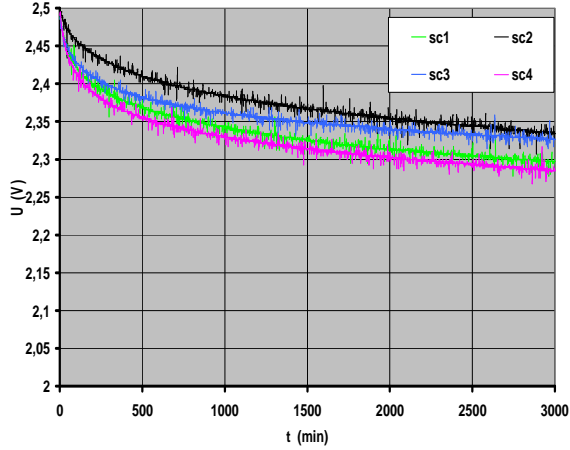


Fig. 2 : Self-discharge of supercapacitors

B. Temperature influence

The ambient temperature has an effect on the supercapacitor behavior: the increase of ambient temperature causes slight increase in the supercapacitor capacitance, huge decrease in ESR as depicted in figure 3, and decrease in the self-discharge rate [1, 4].

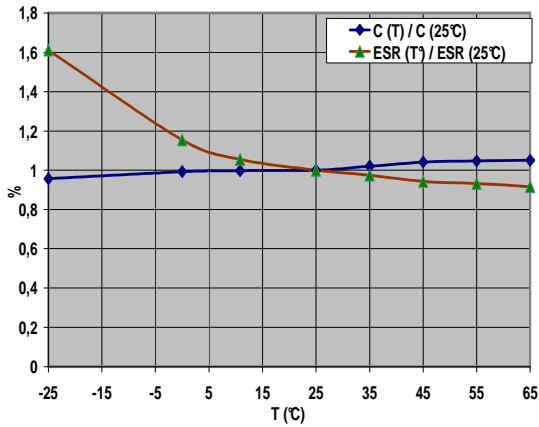


Fig. 3: Variation of supercapacitor parameters with temperature

C. Ageing behaviour

The supercapacitor aging mechanisms result from electrical, mechanical or environmental stresses. Maximum operating voltage and temperature are therefore important factors on aging behavior of supercapacitors. At higher temperature, the aging processes are accelerated by the higher reactivity of the chemical components. At higher voltage impurities undergo a redox reaction. In addition, organic electrolyte starts to decompose, producing gas product, which can lead to the component destruction. This phenomenon may decrease the capacitance by 20%, and increase ESR by 100% and self-discharge rate [3, 5].

III. ESTIMATE OF LIFE EXPECTANCY OF SUPERCAPACITORS

Operating voltage and ambient temperature largely influence the life expectancy of the supercapacitors. Therefore the life expectancy can be estimated by an exponential function of these variables (operating voltage and ambient temperature) as given by equation 1 according to figure 4 [3].

$$T_{\text{exp}}(U, \theta) = C_1 \cdot e^{\left(\frac{U}{C_2} + \frac{\theta}{C_3}\right)} \quad (1)$$

where U and θ are the cell voltage and the cell temperature, respectively. The constant parameters C_1 to C_3 are derived from the relationship given in figure 4.

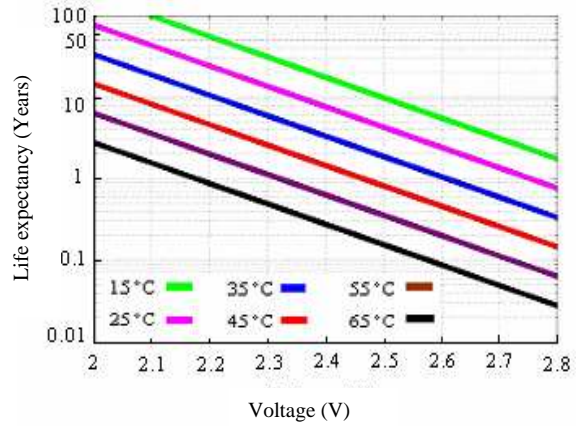


Fig. 4: Life expectancy of a supercapacitor in function of operating voltage and temperature

The average life expectancy can be estimated by the accumulated useful life (wear) of a supercapacitor in function of a dynamic voltage profile ($u(t)$). As given by equation 2 t_0 and t_1 are the starting and end time respectively.

$$T_{\text{av}}(u(t), \theta) = \frac{t_1 - t_0}{\int_{t_0}^{t_1} \frac{1}{T_{\text{exp}}(u(t), \theta)} dt} \quad (2)$$

IV. SUPERCAPACITOR MODEL AND EFFICIENCY OF VOLTAGE BALANCING CIRCUITS

To get appropriate simulations a suitable model of supercapacitor was used. This model was selected because it can be trade-off between the precision and the simplicity of the conducted simulations. This model consists of the immediate and the delayed branches as well as the self-

discharge components. They include the leakage current (Rf_1) and redox reaction (Rf_2), as depicted in figure 5 [6, 7].

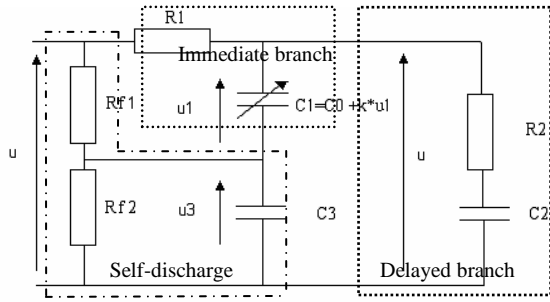


Fig.5: Equivalent circuit model for a supercapacitor Maxwell 2600 F 2.5 V: $R_1 = 0.47 \text{ m}\Omega$, $R_2 = 1.96 \Omega$, $C_2 = 176 \text{ F}$, $C_3 = 88.7 \text{ KF}$, $Rf_1 = 1.12 \text{ k}\Omega$, $Rf_2 = 42.9 \Omega$, $C_1 (\text{F}) = 1749 + 573 U_1$

In order to compare the performance of voltage balancing circuits, the efficiency of module is defined as given by equation 3.

$$\eta = \frac{W_{sc} - W_{eq}}{W_{sc}} \quad (3)$$

with W_{sc} is energy stored in supercapacitors and W_{eq} is energy dissipated in voltage equalization circuits.

V. BALANCING CIRCUITS

In order to simplify the study two supercapacitors in series were employed with a capacity tolerance of (ΔC) 20%:

$$C_{1sc1} (\text{F}) = 1749 + 573.U_1$$

$$C_{1sc2} (\text{F}) = 1399 + 458.U_2$$

We proposed periodical charge-discharge cycle in following settings: constant current $I = 400 \text{ A}$ for charge and discharge, interval between charge-discharge 20 ks see figure 6. The charge was to reach an overvoltage value on the supercapacitor SC_2 (lower capacitance) of 2.8 V. This last is the surge voltage of the conducted supercapacitor given by the manufacture.

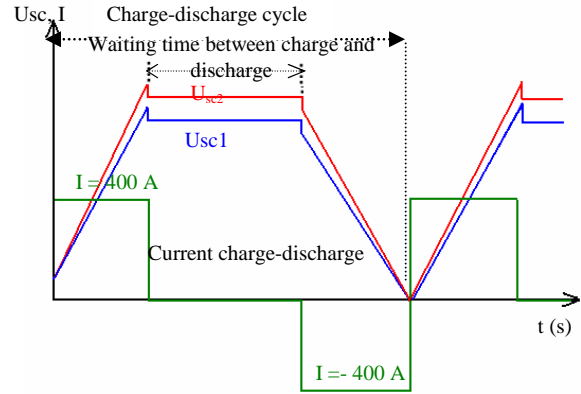


Fig.6 : Cells-voltage with switched balancing circuits

The tolerance of the supercapacitors parameters distributes cells-voltage unequally during charge-discharge cycles. An overvoltage may appear on the component SC_2 . To redistribute and equalize the cells-voltage, various voltage equalization circuits were employed, which are based on two main concepts: dissipative and non-dissipative [3, 8]:

V.1 DISSIPATIVE BALANCING CIRCUITS

A. Passive balancing circuits

A resistor is connected in parallel with each supercapacitor as shown in figure 7.a [3, 8]. It allows balancing cell-voltage by dissipating the supercapacitor energy manifested as overvoltage on supercapacitor (SC_2) by thermal effect. Equation 4 represents the estimate of resistor value for passive balancing circuits depending on maximum voltage U_{scmax} and leakage current of supercapacitor $I_{leakage}$ (their corresponding values are $U_{scmax} = 2.8 \text{ V}$, $I_{leakage} = 5 \text{ mA}$).

$$280 \Omega = \frac{U_{SCmax}}{2I_{leakage}} > R (\Omega) > \frac{U_{SCmax}}{10I_{leakage}} \approx 50 \Omega \quad (4)$$

The value of the balancing resistors was chosen as 50Ω in order to balance between the efficiency and the good balancing dynamic of voltage. But it can not equalize the cell-voltage quickly: it takes more than 5 ks to reach to the operating voltage 2.5 V (see figure 8).

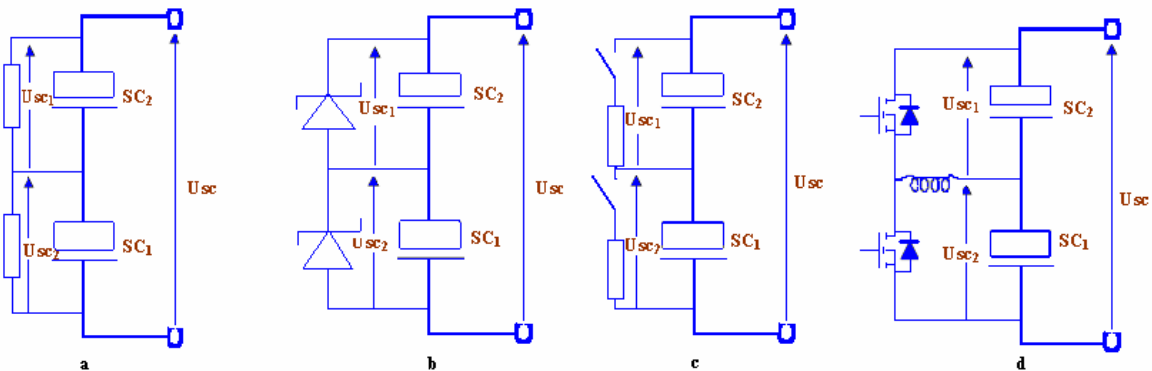


Fig.7: Cell balancing circuits a) resistor, b) Zener diodes, c) switched-resistor, d) DC/DC converter

Balancing circuit	Without balancing circuits		Passive Balancing circuits with R=50Ω		Switched-resistor balancing circuits with R=1Ω		DC/DC converters balancing circuits	
Component	SC ₁	SC ₂	SC ₁	SC ₂	SC ₁	SC ₂	SC ₁	SC ₂
Average life expectancy (years)	17	1.4	37	3.5	16	6.0	6.2	6.0
Average life expectancy of module (years)	1.4		3.5		6.0		6.0	
η %	100	100	79	76	100	83		
η module %	100		77		91		93	

Tab. 1 : Performance of balancing circuits

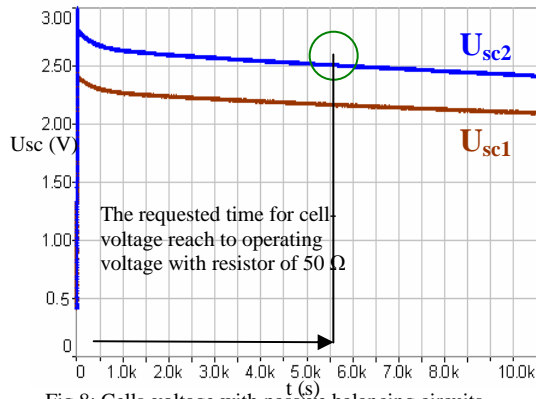


Fig.8: Cells-voltage with passive balancing circuits

This type of balancing reduces the efficiency of the module depending on the value of the resistor and the applied current profile because of continuous leakage current in resistors. For value of low balancing resistor the efficiency can fall to the value of ten percents [9]. On the other hand, this solution can improve lightly the life expectancy of supercapacitors as shown in table 1 [3].

B. Switched-resistors balancing circuits

The general concept depends on adding a controlled switch to an equalization resistor to limit the energy dissipation as shown in figure 7.c. The switch turns on when cell-voltage goes beyond operating voltage and turns off when the level is lower than this voltage. Figure 9 shows that the cell-voltage (U_{sc2}) takes a few minutes to reach to operating voltage (2.5 V) for a value of resistor 1 Ω and there isn't any more thermal loss in the other cell (SC_1) [1, 3, 8].

The efficiency of this solution rises largely more than the solutions mentioned above. Life expectancy of supercapacitors increases according to the value of the equalization resistor as shown in table 1. However the using of these circuits adds extra costs due to the requirement of electronic components.

To obtain a more effective balancing dynamic, we need to use value of resistors less than 1 Ω

without important decrease in efficiency. The last is almost independent of the value of the balancing resistor and current profile.

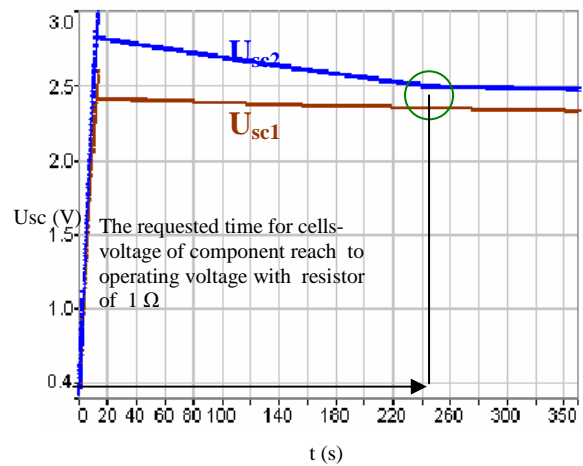


Fig.9: Cells-voltage with switched-resistors balancing circuits

There is another dissipative balancing circuit uses the Zener diodes as shown in figure 7.b. This circuit equalizes cells-voltage according to Zener-voltage by dissipating the extra energy in thermal effect [3, 8, 9]. Therefore we could not find voltage and current of the Zener diodes suitable for our application.

V.2 NON-DISSIPATIVE BALANCING CIRCUITS

All the solutions mentioned above dissipate the energy in order to equalize the cells-voltage. Another type of voltage balancing circuits has been proposed, which employ buck-boost structures with/without transformer. These circuits transfer instantaneously the exceeding energy of cells-overvoltage to other cells in order to equalize cells-voltage [8, 9].

A. Indirect balancing: current diverter using buck-boost converters

The equivalent circuit is given in figure 7.d. It equalizes the cells-voltage locally by two consecutive supercapacitors, using a structure of buck-boost converter for each pair of supercapacitors. The balancing is realized as soon

as a difference of cells-voltage appears: the extra energy of supercapacitor SC_2 is stored firstly in the inductor ($L = 0.5 \mu H$), then transferred to supercapacitor SC_1 using a switch with frequency ($f=10 \text{ kHz}$) and duty cycle (50%) as shown in figure 10. An important balancing current (60 A) had to be chosen to carry out the equalization of voltages in accordance with charging process.

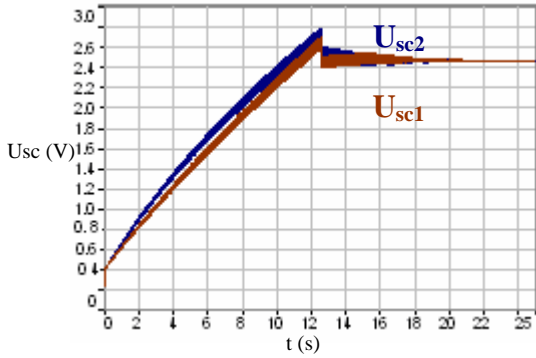


Fig. 10: Cells-voltage with buck-boost converters for balancing current 60 A, switched frequency 10kHz, inductor 0.5 μH and duty cycle 50%

The instantaneous transfer of energy related to overvoltage from SC_2 to SC_1 leads to higher efficiency and life expectancy than other solutions as pointed out in table 1. The main disadvantage of these balancing circuits resides in the indirect energy transmission especially for the applications with a huge number of supercapacitors in series. This lowers both efficiency and the lifetime. Although the concept of this circuit is non-dissipated, some losses may occur in the electronic components. In addition the use of converters (buck-boost) balancing circuits is costly [9, 10].

B. Direct balancing: flyback converters with distributed secondary

The aim of using a transformer is to transfer directly the energy: the switch T turns on to allow storing some energy in primary of transformer, and then this energy is transferred to distributed secondary, via the diodes as shown in figure 11. Most of this energy is provided to cells-lowest voltage.

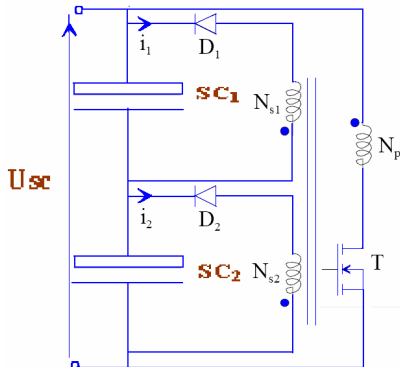


Fig. 11: Balancing circuits: flyback converters with distributed secondary

C. Direct balancing: current diverter using forward converters

This solution depends on the direct transmission of energy: the transistor T_2 is switched on as soon as the voltage U_{sc2} starts to be higher than U_{sc1} as shown in figure 12. This allows transferring some energy from SC_2 to SC_1 .

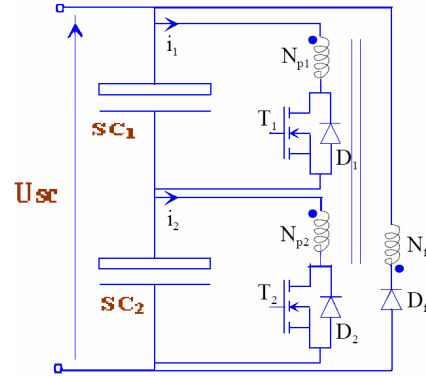


Fig. 12: Balancing circuits current diverter using forward converters

Both of the previous balancing circuits equalize instantaneously the cells-voltage (see figure 13). For the selected model with two supercapacitors in series, we found the performance and the life expectancy of supercapacitors are close to the solution A (current diverter using buck-boost converters). This result was obtained for ideal transformers, but the use of real transformer causes losses in addition to those of the electronics components. This also means a lower efficiency and lower life expectancy [9, 10].

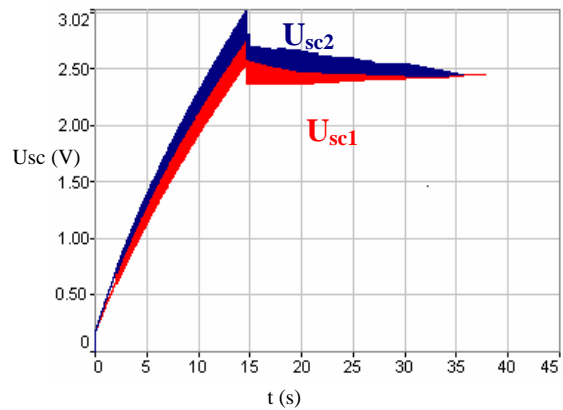


Fig. 13 : Cells-voltage with flyback converter with distributed secondary

VI. CONCLUSION AND PERSPECTIVES

Experiments and simulations were conducted to estimate the performance and the reliability of supercapacitors. Differences of supercapacitors parameters may appear, they may give raise to potential overvoltages. Several voltage balancing

circuits are employed to solve this problem: resistance, switched-resistors and static converters. Experimental results show that these circuits differ by their efficiency and their life expectancy: The balancing circuits with simple resistance improve lightly the life expectancy of the supercapacitors, but decrease their efficiency. Switched-resistors allow limiting the energy dissipation and improve significantly the life expectancy. The DC/DC converters balances circuits equalize instantaneously cells-voltage by redistributing the stored energy. This in turn increases the efficiency as well as life expectancy of supercapacitors.

The estimation of the tolerance caused by the aging behaviour is underway with an explanation to the aging processes. The used equation estimates the life expectancy of supercapacitors depending on two main factors; the ambient temperature and the cells-voltage taking into account that the current effect was neglected. The direct effect of these factors is not clear on the aging processes but it may make the temperature of the components higher than the surrounding ambience. We envisage tacking into account the current in the equation in order to achieve a better precision. We will realize this, in addition to a complete validation of the results obtained for balancing circuits in the near future.

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