Control of supercapacitor energy storage systems for DC grids

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Abstract

This dissertation aims to analyse and develop a voltage balancing system for the operation of storage technologies of storage of electrical energy in supercapacitors. For this, an electric supercapacitor model is analysed. The accuracy of this model is evaluated experimentally. The obtained simulated result was very similar to that observed experimentally. Generally supercapacitors withstand very low voltages, between 2 to 3 volts. Supercapacitor storage systems use dozens or hundreds of supercapacitors connected in series. Being connected in series, the smallest variations of its properties (capacity, leakage currents) lead to unbalance of the voltages in the supercapacitors of the series. In order to solve this issue, load management systems are developed, that is, the terminal voltage of the supercapacitors of the series taking into account costs, performance, size and efficiency. The simplest balance systems of the voltages in the supercapacitors to implemented and to design are the passive balance systems. However, these systems compromise the useful energy to be supplied by the supercapacitors. For this reason, active equilibrium systems are studied and analysed. Obtaining a satisfactory active balance system, the respective prototype is developed, being a Power Converter with active balance of the supercapacitors voltages. The prototype allowed to validate the corresponding models and simulations, and the only electromagnetic effect left to consider was the skin effect.
Keywords: supercapacitors, dynamic model, load management system, active balance system, prototype.

1. Introduction

1.1. Motivation

Supercapacitor and ultracapacitor are registered names (by NEC and Maxwell, respectively) which denominate double-layer capacitors. Unlike batteries, which produce and store energy through chemical reactions the supercapacitors store energy by an electric field. This mechanism grant the supercapacitors a high density power, over a million cycles without performance loss and high resistance to shocks and vibrations. Energy storage technologies have been the subject of successive technological advances, in order to follow up with the growing demand of energy by the human being. Along with the increase of energy consumption and a higher dependency to renewable energy sources and electrical systems poses challenges to storage technologies, like the ability to supply or store a high amount of energy in a short time space. Supercapacitors currently support voltages of the order of 2-3V. To achieve the required 300-500V voltages in many applications, it is necessary to arrange in series a large number of supercapacitors. This series of supercapacitors can be charged to a certain current, obtaining in all supercapacitors of the series the same voltage, if they were strictly all the same. In practice the parameter values which characterize a supercapacitor, including the value of an equivalent capacity, vary from the order of -10 % to + 20 % due to tolerances of the manufacturing processes. Consequently, supercapacitors of different capacities will present different voltages for the same charge, which is the main problem to solve in this dissertation.

1.2. Objectives

This dissertation aims to analyse and develop a voltage balancing system for the operation of storage technologies of storage of electrical energy in supercapacitors. So, there were established the following steps:

- Understand and identify solutions for balance management systems for supercapacitors, revision of the state of the art;
- Design new topological structures for balance management systems for supercapacitors;
- Obtain control systems for a scalable modular structure,
- Obtain and discuss experimental and simulated results of the dynamic supercapacitor model used in the laboratory and for the balance management systems.

2. Theoretical Study

2.1. Dynamic supercapacitor model

The electrical model of the supercapacitor should be as simple as possible to describe the voltage to the terminals of the supercapacitor during a time interval of 10m, with a considerably higher accuracy than the RC series model. The parameters of the equivalent model should only be obtained with the voltage to the terminals of the supercapacitor and with equipment of low spectral resolution, such as the oscilloscope, a device generally of 8 bits.

The method was introduced by Luís Zubieta in his dissertation [3], in 1997, to obtain the master degree in Electrical and Computer Engineering in the Toronto University.

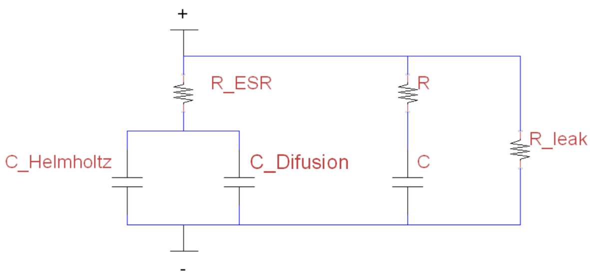

Figure 1: Dynamic model of the supercapacitor

The identification of the first branch parameters is based on the charge up to the rated voltage with high curent and the continuous measurement of the terminal voltage. When the terminal voltage reaches the rated value, the current source is turned off and an internal charge distribution process among the RC branch begins. Continuous voltage measurement during that charge distribution is used to identify the RC equivalent circuit parameters.

The leakage resistence is identified using a capacitor whose voltage is equal across all the internal equivalent capacitances. In other words, no charge distribution process is occuring inside the device. Under this condition, the charge in terminal voltage is only a result of the equivalent model leakage resistence.

Charging a supercapacitor with a constant current until the nominal voltage is reached, it's then possible to obtain the parameters of the electrical model.

The nomenclature is the following: $C_{Helmholtz}$ *to* C_h , $C_{Difusion}$ *to* $C_d \cdot V$, R *to* R_r and C *to* C_r.

Defining C_k as the ration between the total charge delivered to the suprcapacitors by the voltage V:

$$C_k = \frac{Q}{V} = \frac{C_h \cdot V + \frac{C_d}{2} \cdot V^2}{V} = C_h + \frac{C_d}{2} \cdot V \quad (1)$$

The following points are defined. t1 when the current source starts operating. t2 a value right after t1. t3 when the supercapacitor reaches the nominal voltage. t4 right after the current source is turned off. And t5 reflects the instant after 600 seconds $(3 \cdot \tau)$ the current source is turned off. The relevant formulas are the following:

$$R_{ESR} = \frac{V(t_1) - V(t_0)}{I} \quad (2)$$

$$C_h = \frac{I \cdot (t2 - t1)}{V(t_2) - V(t_1)} \quad (3)$$

$$C_d = \frac{2 \cdot \left(\frac{I \cdot (t_3 - t_1)}{V(t_3) - V(t_1)} - C_h\right)}{V(t_3) - V(t_1)} \quad (4)$$

$$C_r = \frac{V_C(t_4) \cdot C_{eq}(t_4) - V_C(t5) \cdot C_{eq}(t_5)}{V_C(t_5)} \quad (5)$$

$$R_r = \frac{\tau}{C_r} = \frac{200}{C_r} \quad (6)$$

$$\begin{cases} V_C(t) = V_0 \cdot e^{-(\frac{t}{R_{leak} \cdot C})} \\ C = C_h + C_d \cdot V_0 + C_r \end{cases} \quad (7)$$

2.2. Energy Management System

2.2.1. Passive equilibrium

Passive equilibrium is very attractive since the cost of a passive equilibrium is negligible compared with the costs of the supercapacitors, but since there is a loss of energy it is necessary to study and analyse the losses. It was simulated and analysed the switched passive equilibrium systems in figure 2.

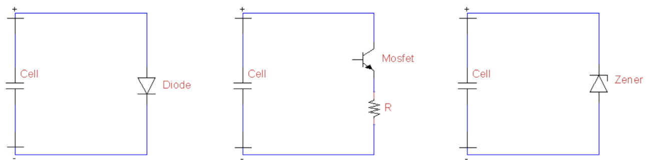

Figure 2: Passive topologies

2.2.2. Active equilibrium

It was simulated and developed the following active topologies:

- Active topology with one inductor,
- Active topology with multiple inductors.

As a first analysis it's turned to the active equilibrium topology introduced in the national patent of invention n.º 106681 [2], figure 3. Subsequently the topology is slightly modified to increase efficiency. figure 4.

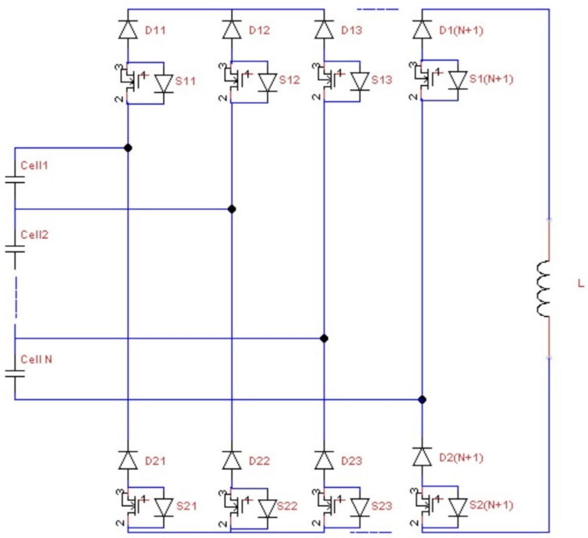

Figure 3: Single inductor topology - national patent n.º 106681

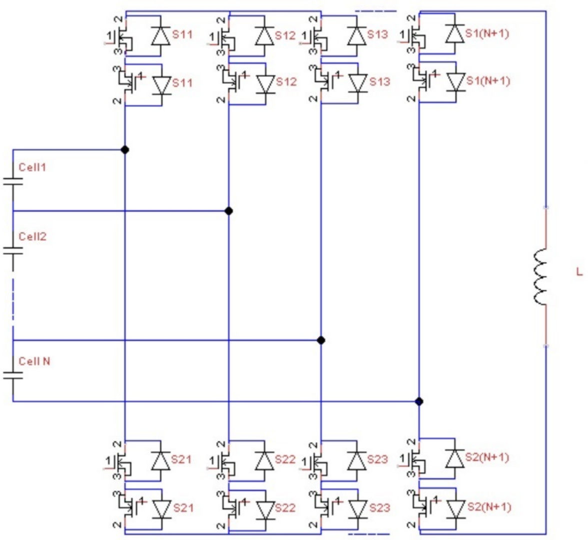

Figure 4: Single inductor topology - modified

In the equilibrium system with multiple inductors, figure 5, the semiconductors and the inductors support the voltage of only one supercapacitor. With applied voltages in the equilibrium components inferior than the topology with one inductor, the losses in the equilibrium system and the costs of the components are inferior.

The equilibrium system with multiple inductors have less semiconductors but more inductors, and the cost of the inductors are superior in relation to the costs of the semiconductors, however, designing the system to have an elevated switching frequency (kHz), the inductance decreases in such way that the costs of the inductors equals the costs of the semiconductors.

Thus the equilibrium system with multiple inductors emerge to reduce the cost of the equilibrium system.

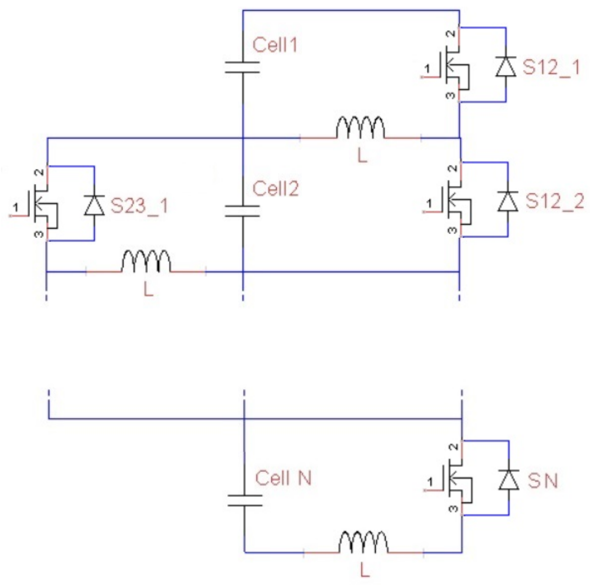

Figure 5: Topology with multiple inductors

The approaches to the topology control system of the figure 6 were two. It was first an open loop controller (without current control) and subsequently a non linear current controller.

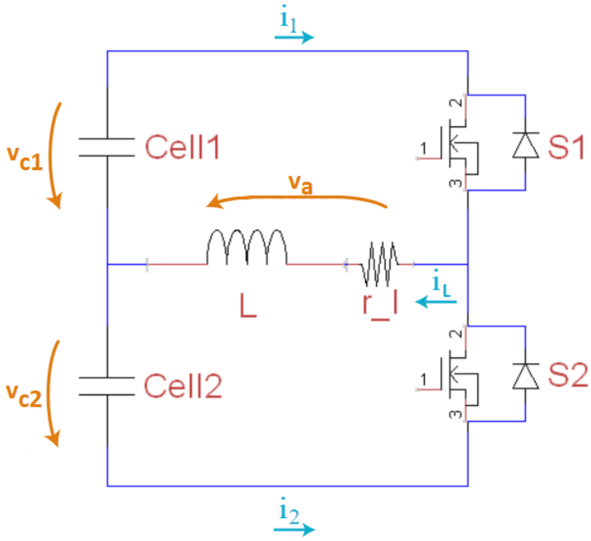

Figure 6: Denotation used in the equilibrium system of multiple inductors

Controller without current control

With the analyses of the circuit in the figure 6 and knowing that the average value of the inductor voltage is null, the duty cycle, δ, is given by the expression in the equation 8.

$$\delta = \frac{V_{c2}}{V_{c1} + V_{c2}} \quad (8)$$

With the duty cycle of 50% the equilibrium current increments or decrements in function of the voltage difference between the supercapacitors and in permanent regime the pair of supercapacitors equilibrates:

$$\Delta I = \frac{(v_{c_i} - (r_L + r_{ON}) \cdot i_L) \cdot T}{L} \quad (9)$$

Placing the duty cycle of 50% in function of the voltage difference between the pair of supercapacitors the equilibrium velocity increases, equation 10. In the permanent regime the duty cycle tends to 50%.

$$\delta = 0.5 + \alpha \cdot (v_{c1} - v_{c2}) \quad (10)$$

Controller with non linear current control

The expression to estimate the current in the inductor is given by the equation 11. It's considered that the initial current is zero and the variable γ represents the MOSFETS driving signal (1 if S1 is activated or 0 if S2 is activated).

$$i_L = \frac{1}{L} \int \gamma v_{c1} - (1-\gamma) v_{c2} - (r_{ON} + r_L) \cdot i_L \ \partial t \quad (11)$$

The reference inductor current, equation 12, is obtained with the stability control Lyapunov theorem, it's is considered that the average inductor current is null and that the capacity in both supercapacitors are more less identical.

$$i_{L_{ref}} = k \cdot C \cdot (v_{c1} - v_{c2}) \quad (12)$$

The constants K and C are obtained defining the value of the maximum current when a certain voltage difference between the supercapacitors occurs:

$$k \cdot C = \frac{(v_{c1} - v_{c2})}{i_{L_{max}}} \quad (13)$$

3. Simulation

3.1. Dynamic supercapacitor model

Analysing the laboratorial experience of charging the ELNA 200F supercapacitor from discharged to it's nominal voltage of 2.5 volts, 3.1 were obtained the following parameters for the dynamic supercapacitor model, table 3.1.

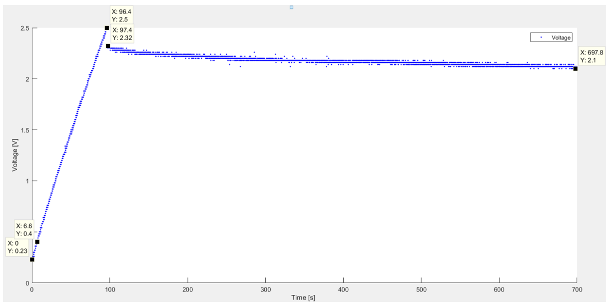

Figure 7: Graph of the voltage with the points of time and voltage noted for the obtation of the parameters

Table 1: Dynamic supercapacitor model - obtained parameters

Parameter	Value
R_{ESR}	$43 m\Omega$
C_h	$194\ F$
C_d	$11\ F/V$
C_r	$21\ F$
R_r	$10\ \Omega$
R_{leak}	$2.5\ k\Omega$

To validate the obtained parameters it's simulated within Simulink the supercapacitor dynamic model with the obtained parameters and compared with the laboratorial results. The results are as expected, figure 8.

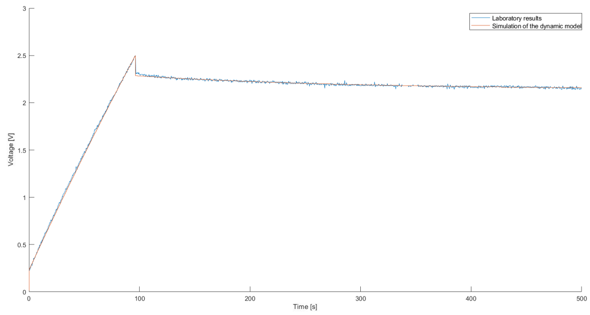

Figure 8: Simulation: dynamic supercapacitor model

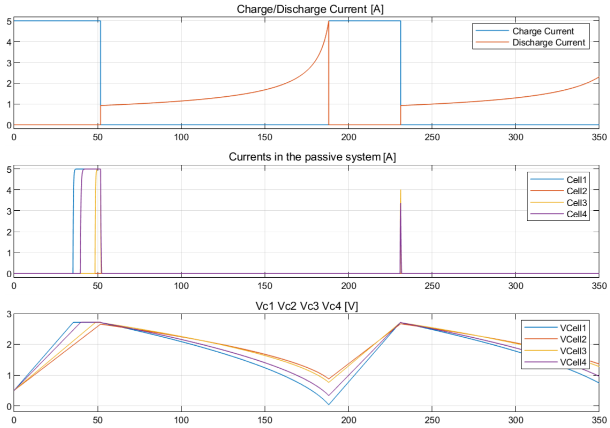

Figure 9: Simulation of the passive equilibrium system with Diodes

3.2. Energy Management System

The efficiency is obtained within Simulink and differently, according if the balance system is passive, equation 14, or active, equation 15.

$$\eta = \frac{P_{OUT}}{P_{IN}} = \frac{P_U - P_{Losses}}{P_U} \tag{14}$$

$$\eta = \frac{E_f}{E_0} \cdot 100 = \frac{E_f}{E_0} \cdot 100 \quad [\%] \tag{15}$$

The supercapacitors energy can be obtained with the following equation:

$$E(t) = \sum_{i=1}^{N} \frac{1}{2} \cdot C_{cell_i} \cdot V_{cell_i}^2(t) \tag{16}$$

In order to compare the topologies the simulation conditions are the same. The simulation consists of successive charge and discharge tests of four supercapacitors in series.

The supercapacitor under study is made by Maxwell with 100 Farads [1], a nominal voltage of 2.7V and a resistance of $12m\Omega$, R_{ESR}. The maximum deviation in reference to the nominal capacity is ± 20 %. The capacities are the following: $C_1 = 80F$, $C_2 = 120F$, $C_3 = 110F$ e $C_4 = 90F$.

3.3. Passive equilibrium

The performance between the passive equilibrium system with Diodes, figure 9, is identical with the passive system with Mosfets.

In passive equilibrium system the useful energy of the supercapacitors are compromised by 3% to 12% of the total energy. The system operates in the beginning and afterwards when a new disequilibrium between the supercapacitors occurs.

In the simulation with the Zener passive equilibrium system the maximum current supported by the Zener, 0.36 amps, is surpassed.

3.4. Active equilibrium

3.4.1. Topology with a single inductor

As the voltage drop in the Diode is superior than in the Mosfet the active equilibrium system with current blockage Mosfet-Mosfet allows the balance system to start with lower supercapacitors voltages. However the results obtained are similar, figure 10, differing essentially in the efficiency, figure 11.

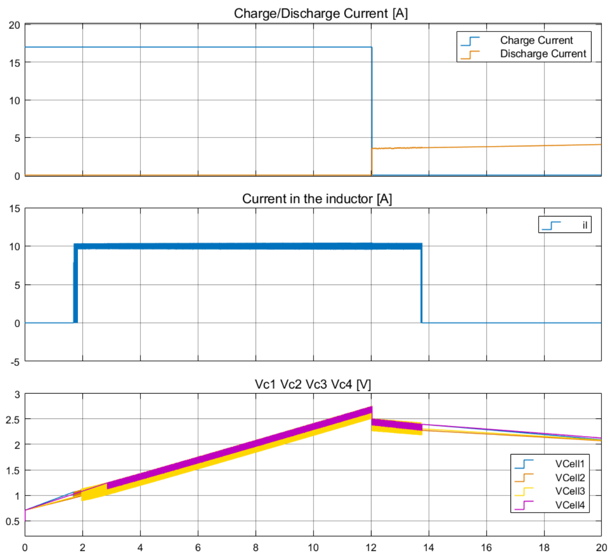

Figure 10: Simulation: single inductor topology with Mosfet-Mosfet current blockage

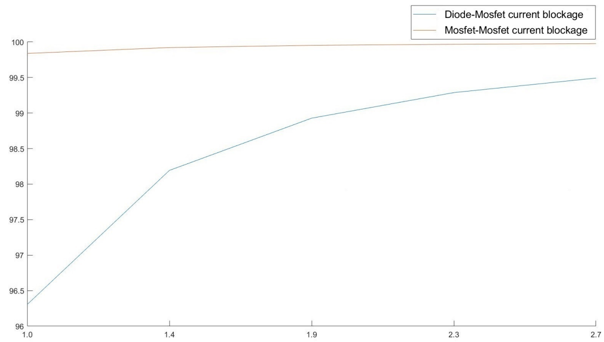

Figure 11: Single Inductor system efficiencies

Despite the high efficiency with the topology with Mosfet-Mosfet current blockage the implementation requires a high amount of semiconductors (related to size) and twice the maximum voltage in series of the supercapacitors (related to the cost). The topology that follows, with multiple inductors, arises in order to reduce the cost and size of the balancing system.

3.4.2. Topology with multiple inductors

The results of the equilibrium system with the 50% duty cycle were satisfactory, figure 12. The voltages of the supercapacitors were kept below the maximum voltage and the currents in the active system are in accordance with the most accessible Mosfets, 10 amperes.

With the dynamic duty cycle, where α is defined as 0.2, the results are in accordance with the expected, figure 13. The current growth rate is higher than the active system with 50% duty cycle.

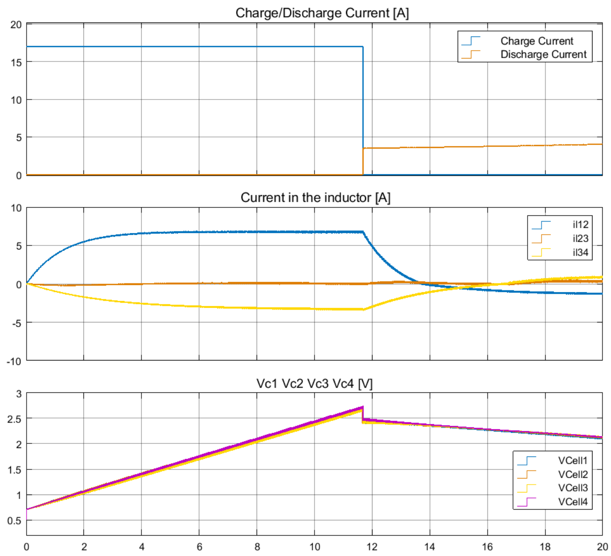

Figure 13: Simulation: dynamic duty cycle, $\delta = 0.5 + 0.2 \cdot (v_{c_i} - v_{c_{i+1}})$

With the non linear controller the operating time of the equilibrium system is lower, figure 14, which reflects in a higher efficiency, figure 15.

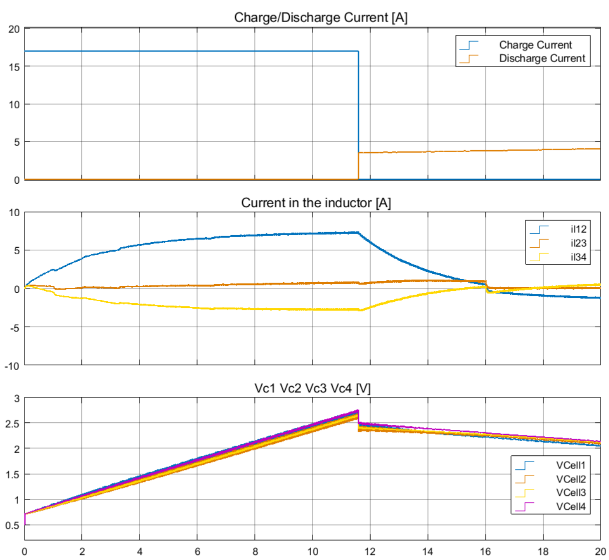

Figure 12: Simulation: 50% duty cycle

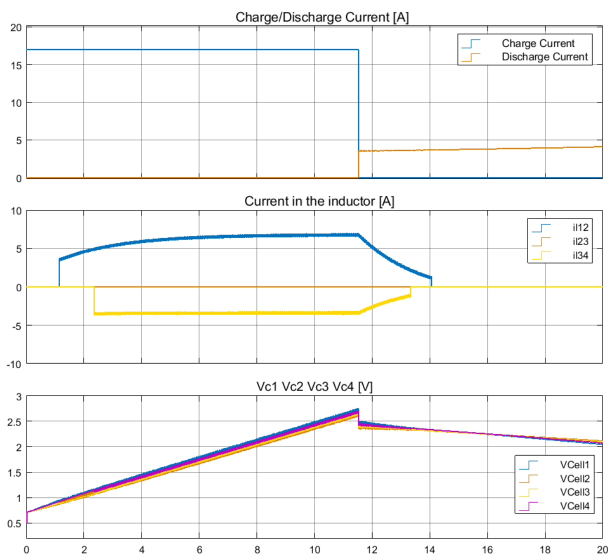

Figure 14: Simulation: Non linear current control

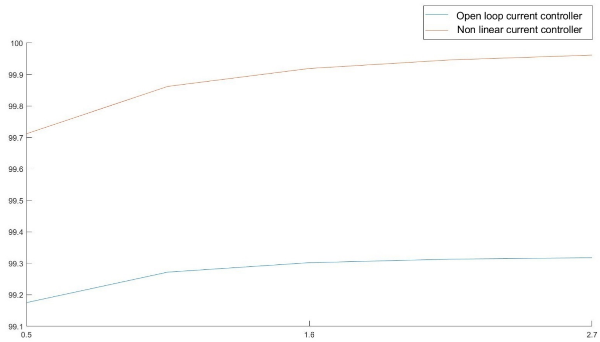

Figure 15: Multiple Inductor system efficiencies

4. Balance management system prototype for supercapacitors

A prototype was made in order to evaluate the theoretical analyses. It was developed a prototype for the topology with multiple inductors with active balance system, for 50% duty cycle and non linear current control. The PWM signal was generated with a PIC microcontroller and it was used two supercapacitors with a nominal capacity of 200 farads each. With experimental results the capacity values of C_1 and C_2 are 205.7F and 204.8F.

4.1. 50% duty cycle

The supercapacitors voltages are $v_{c_1} = 2V$ e $v_{c_2} = 1.12V$, the inductor has 39uH with an equivalent resistance of $14m\Omega$ and the commutation frequency is 10kHz. Due to the skin effect the equivalent resistance at 10kHz is higher. Simulating the following experimental results it's obtained the same simulated results for an additional resistance of 0.64Ω for a switching frequency of 15kHz:

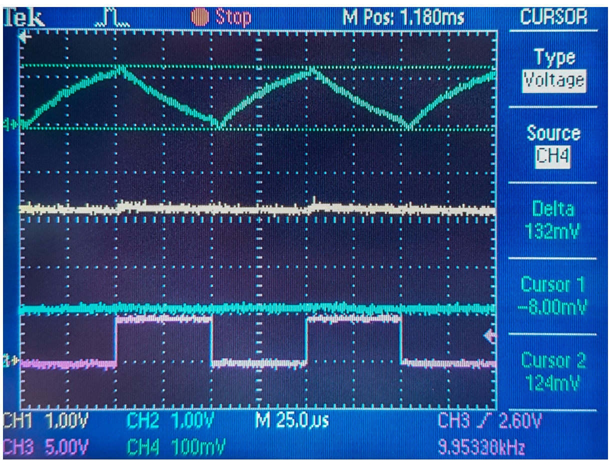

Figure 16: Laboratorial result: 50% duty cycle

4.2. Non linear current control

The supercapacitors voltages are $v_{c_1} = 1.10V$ e $v_{c_2} = 1.14V$ and the inductor has 270mH. Short circuiting the lower Mosfet is obtained the combined circuit resistance, of the MOSFET and the inductor, of 1.26Ω. The results were the following:

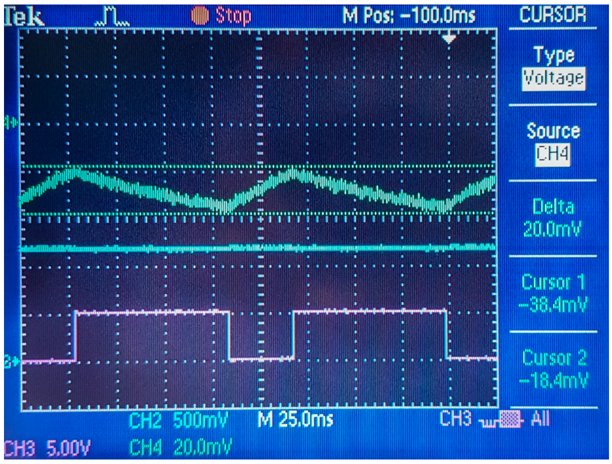

Figure 17: Laboratorial result: Non linear current control

Simulating the PIC operations in Simulink is obtained identical results.

5. Conclusions

The behaviour of the supercapacitor can be modelled with a model containing capacitors and resistances. However, the complexity and difficulty to obtaining the model parameters is correlated with the required accuracy. But, in order to analyse and develop the balancing system in supercapacitors, it's enough to use the RC linear model. Although the model is less accurate it reflects the implications of the capacities being slightly different between supercapacitors with the same reference.

The passive equilibrium system compromises the useful energy to be supplied by the supercapacitors. In the active equilibrium the currents in the balancing system are attenuated relative to the operating current of the supercapacitors and the useful energy to be supplied to the load is maximized.

In the passive equilibrium the balancing system only acts if the leakage currents are different and when there is a distinct degradation in the supercapacitors, either in the equivalent resistance or in the capacity. In the active equilibrium it is constantly being triggered but as the efficiency is approximately to a ideal system, without lossless, the energy received to the supercapacitors and the energy supplied to the load is equivalent to a system in which the supercapacitors are ideal, which does not require a balance management system.

In the elaboration of the prototype of the active balance system of the supercapacitor voltages was observed that the systems are subject to the skin effect. With the increase of the switching frequency the equivalent impedance of the inductor increases, differing greatly from the values announced in the datasheet.

Acknowledgements

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