The use of Supercapacitors in electrical vehicle: modeling, sizing and control

M. Y. Ayad, M. Becherif, S. AitCheikh and M. Wack

Abstract. In a traditionally embarked system the management of embarked electrical energy needs a storage device for peak load shaving, in order to compensate for the intrinsic limitations of the main energy source. The use of supercapacitors for this storage system is quite suitable, especially in regard to their energetic properties: appropriate characteristics, direct storage, and easy control by power electronic conversion. This paper deals with the use of supercapacitors as a storage device in electrical and hybrid vehicle. The different supercapacitors models will be given, the mathematical calculation for sizing this device and an example of their control will also be presented.

Index terms— supercapacitor, power electronics, power supplies, power system control, electrical vehicle.

I. INTRODUCTION

The classic storage element in electric vehicle consists of accumulators, which allow a relatively high autonomy, but their power capability is moderately compromised. On the other hand, the capacitors have high power capability and they can hence only be considered for applications which require little energy. There was thus a lack, in means of storage energy for high power applications, between the batteries and capacitors that supercapacitors (SCs) try to minimize.

SCs were initially developed by Japanese companies towards the end of the seventies, for signal electronics applications. The ideas of applications for power electronics equipment not only appeared in Japan but also in the United States and in Europe, in the middle of the eighties. In actuality, devices of thousands of farads, with an ability to deliver hundreds of amps are available. Therefore, these new components form an energy storing device, the performances of which fills the gap between the electrolytic capacitors and conventional batteries, and thus, offer large perspectives concerning management of embarked electrical power, by achieving a hybrid power source.

These sources are based on the use of SCs as an auxiliary power source, as supplement to the main source. In their principle, they associate advantages of both energy storage technologies:

- Firstly, a huge specific energy,
- Secondly, a great specific power available on quite long duration.

In particular, they allow dissociating mean power sizing from peak transient power sizing, the aim being to reduce volume and weight [1, 2].

This article concerns the integration of SCs in embarked systems with traditional storage elements such as batteries or a new power source such as fuel cells. The conception of this hybrid source, the sizing of the SCs bench and the interface converter associating the storage element to the DC link, are presented in this paper. Different results on the studied hybrid source have also been given in this work.

II. ELECTRIC DOUBLE-LAYER SUPERCAPACITORS

A. Principle

The basic principle of electric double-layer capacitors lies in capacitive properties of the interface between a solid electronic conductor and a liquid ionic conductor. These properties discovered by Helmholtz in 1853 lead to the possibility to store energy at solid/liquid interface [3, 4]. This effect is called electric double-layer, and its thickness is limited to some nanometers. Energy storage is of electrostatic origin, and not of electrochemical origin as in the case of accumulators. So, SCs are therefore capacities, for most of marketed devices. This gives them a potentially high specific power, which is typically only one order of magnitude lower than that of classical electrolytic capacitors. In SCs, the dielectric function is performed by the electric double-layer, which comprises solvent molecules. Then, the difference with mainly electrolytic capacitors, are first a high surface capacitance (10-30 $\mu F.cm^{-2}$) and second a low rated voltage limited by solvent decomposition (2.5 V to 2.7 V for organic solvent). Then to take advantage of electric double-layer potentialities, it is necessary to increase the contact surface area between electrode and electrolyte, without increasing the total volume of the whole. The most widespread technology is based on activated carbons to obtain porous electrodes with high specific surface areas (1000-3000 $m^2.g^{-1}$). This allows obtaining several hundred of farads by elementary cell.

B. State of the art and potential application

Developed at the end of the seventies for signal applications (for memory back-up for example) SCs, at that time, presented a capacitance of some farads and specific energy of about 0.5 $Wh.kg^{-1}$. High power SCs appeared during the nineties and brought components of capacitance of thousand of farads and specific energy and power of several $Wh.kg^{-1}$ and $kW.kg^{-1}$ to high power applications.

In the energy-power plan, electric double layer SCs are situated between accumulators and traditional capacitors,

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and can therefore carry out the following two main functions [3, 4]:

- The function "source of energy", where SCs replace electrochemical accumulators, the main interest being an increase in reliability,
- The function "source of power", for which SCs come in complement with accumulators (or any other source limited in power), for a decrease in volume and weight of the whole system.

The hybrid source studied in this paper concerns this second function.

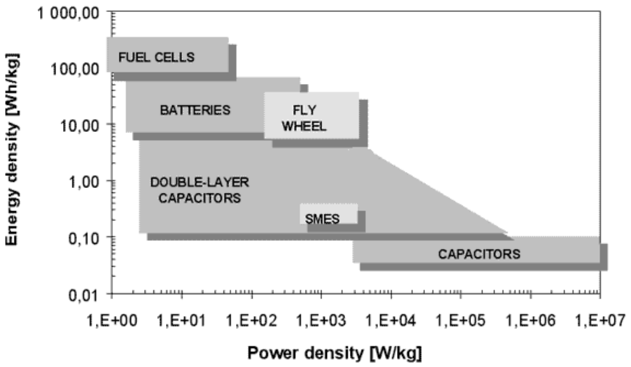

Fig. 1. Comparison between capacitors, supercapacitors, batteries and Fuel cell

III. HYBRID DC SOURCE USING SUPERCAPACITORS AS POWER SOURCE

A. Structure of the hybrid source

As shown in Fig. 2, the studied system comprises a DC link directly supplied by batteries (or any other power source: fuel cell, solar panel….etc.), and a supercapacitive storage device [5-11], which is connected to the DC link through a current reversible DC-DC converter. The function of permanent source is to supply mean power to the load, whereas the storage device is used as a power source: it supplies and absorbs peak loads required during acceleration and braking.

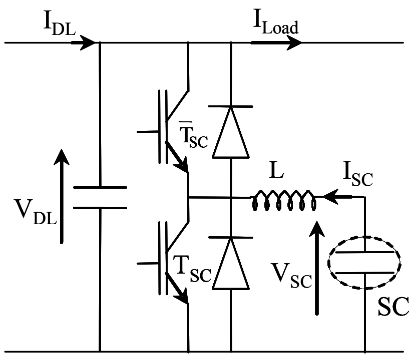

Fig.2. Structure of the hybrid source

In order to manage energy exchanges between the DC link and the storage device, three operating modes can be found:

- Charge mode, in which the main source supplies energy to the storage device,
- Discharge mode, in which the storage device supplies energy to the load,
- Recovery mode, in which the load supplies energy to the storage device.

Another function falling on the interface converter, that the levels voltage adaptation DC link (appreciably constant voltage value) and the storage element (voltage essentially variable).

We will choose here an analytical dimensioning procedure of the hybrid source, which will be carried out with respect to the mode of discharge. The dimensioning is detailed in reference [12]. It is initially advisable to give it an extreme mode of energy provided to the load, that is to say, if we suppose the voltage V_{DL} to remain constant, a profile of current $I_{Load}(t)$ on a duration Δt. We then evaluate easily the minimum capacity of the storage device, capacity obtained for a conversion without losses. In the second place, we determine the law of temporal variation of the discharge current I_{SC}, which makes it possible to quantify the losses in the storage device and the converter. We can then readjust the value of the capacity, and calculate the size of the storage device and the converter. It then remains to dimension the principal source in maximum power.

Two significant parameters intervene in the dimensioning of the hybrid source, namely of the energy provided by the principal source during the in put of power, and the state of full charge of the storage device. The voltage V_{DL} being supposed constant, we will describe the first in relation to the energy required at the load by the report/ratio of the electric charges:

$$\eta = \frac{\int_0^{\Delta t} I_{DL}(t) \cdot dt}{\int_0^{\Delta t} I_{Load}(t) \cdot dt} \tag{1}$$

As for the second, which we will also suppose the initial voltage being V_{20} at the boundaries of the storage device, it will be represented by a dimensioned parameter x_0 definite as follows:

$$x_0 = \frac{V_{SC0}}{V_{DL}} \tag{2}$$

B. Capacity minimum

The capacity minimum of the storage device is obtained for a transfer without losses. That is to say C_{SCMIN} this capacity and V_{SCF} the voltage at the end of the discharge. If the losses are neglected, the basic relation characterizing the transfer of energy considered is written:

$$\frac{1}{2} \cdot C_{SCMIN} \cdot \left(V_{SC0}^2 - V_{SCF}^2\right) = V_{DL} \cdot \int_0^{\Delta t} \left(I_{Load}(t) - I_{DL}(t)\right) \cdot dt \tag{3}$$

There by noting the depth of discharge of the storage element, that is to say thus:

$$y = \frac{V_{SC}}{V_{SC0}} \tag{4}$$

and y_F the value of there of fine of discharge, it comes for C_{SCMIN} according to η and x_0:

$$C_{SCMIN} = \frac{2 \cdot (1-\eta) \cdot \int_0^{\Delta t} I_{Load}(t) \cdot dt}{x_0^2 \cdot \left(1 - y_F^2\right) \cdot V_{DL}} \tag{5}$$

We give a representation figure 3 of it, according to the relative level of initial voltage x_0, it for a maximum depth of discharge of 50%.

The transfer being supposed without losses, the mass and volume associated with this capacity minimum depend only on the energy provided by the storage element and on the energy characteristics on the supercapacitive element used.

Mass and volume thus evolve/move in a linearly decreasing way according to η, and independently of x_0.

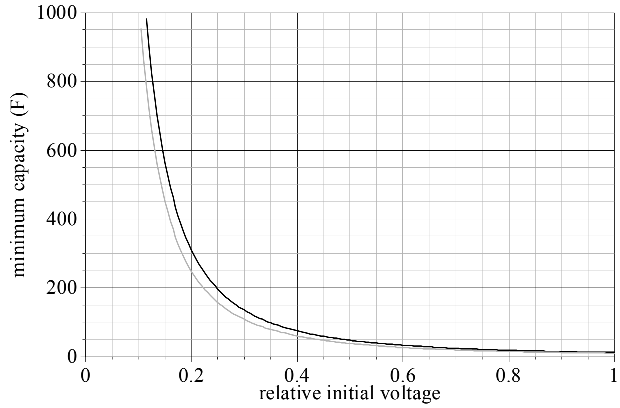

Fig.3. Capacity minimum of the storage device (y_F = 50%)

If one takes again like reference element 3500 F of the Saft company (held in voltage of 2.5 V, masses of 0.65 kg, volume of 0.5 L), we obtain for the supercapacitive elements with $\eta = 0$ mass minimum of 79.2 kg and a minimum volume of 61 L, to balance by $1-\eta$ if the principal source takes part in the in put of power, and to increase by 30% to evaluate the size of the storage element [12].

C. Current in the storage device

The knowledge of the I_{SC} current in the storage element is necessary to evaluate the losses and the size of the converter. An assessment of power, in the ideal case, makes it possible to write:

$$I_{SC}(t) = \frac{(I_{Load}(t) - I_{DL}(t))/x_0}{y(t)} \qquad (6)$$

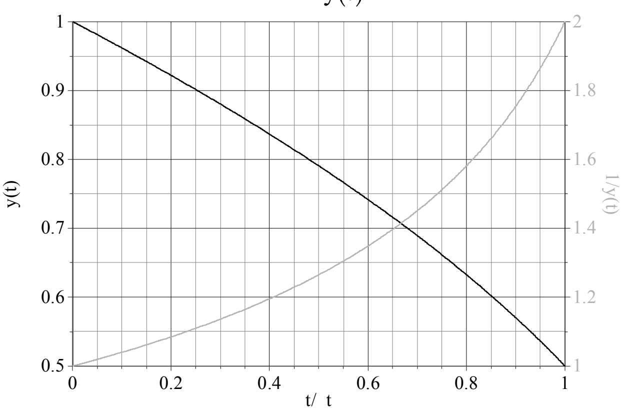

Fig.4. Functions y and 1/y (y_F = 50%, constant I_{CH} and I_1)

As for the temporal evolution law of the function y, we establish it by means of the conservation equation of the energy (equation of the type that is given in relation (3)), written in the ideal case at the moment t and Δt. We obtain:

$$y(t) = \sqrt{1 + (y_F^2 - 1)\cdot \frac{\int_0^t (I_{Load}(u) - I_{DL}(u))\cdot du}{(1-\eta)\cdot \int_0^{\Delta t} I_{Load}(u)\cdot du}} \qquad (7)$$

We present in figure 4, the evolution curves of the y and 1/y functions, functions representative of V_{SC} and I_{SC} respectively. The currents I_{Load} and I_{DL} are supposed to be constant, so that the expression (7) is reduced to:

$$y(t) = \sqrt{1 + (y_F^2 - 1)\cdot \frac{t}{\Delta t}} \qquad (8)$$

D. losses and capacity sizing

The criterion of the losses doesn't plead in favor of the low voltages: the various losses are indeed as well as possible, independent of the initial level voltage of the storage element, if not the decreasing functions of the level [12]. We present for this reason, figure 5, the assessment of the losses relative with W_{st} according to the relative initial voltage level for an inductance with core iron-silicon. It should be noted that in this relative assessment, only the term associated with the losses in inductance depends of it, and still very slightly, of the parameter η.

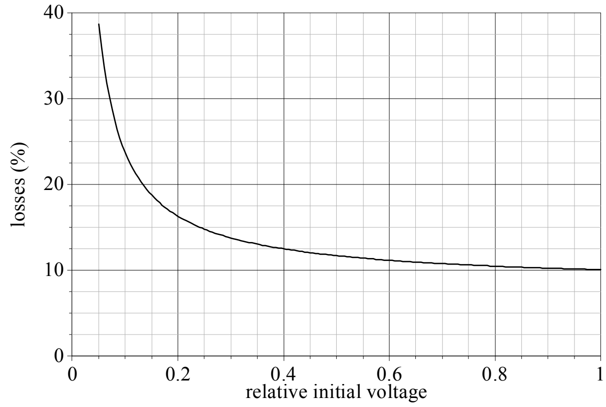

Fig.5. Assessment of the losses (y_F = 50%, f = 10 kHz, η_L = 10%)

The capacity minimum C_{MIN} of the storage element corresponds to an ideal energy transfer. The real capacity that we will denote as C, must take account of the losses on translation. An approximate evaluation of this capacity can be obtained via the following energy balance:

$$\frac{1}{2}\cdot C_{SC}\cdot (V_{SC0}^2 - V_{SCF}^2) = \begin{cases} V_{DL}\cdot \int_0^{\Delta t} (I_{Load}(t) - I_{DL}(t))\cdot dt \\ + W_{Jst} + W_T + W_D + W_L \end{cases} \qquad (9)$$

With

W_{Jst} Losses in the storage device, W_T Losses in transistor, W_D Losses in the diode and W_L Losses in the inductance

Assessment which makes it possible to write:

$$C_{SC} = (1+\chi)\cdot C_{MIN} \qquad (10)$$

χ is the total losses brought back to the energy provided to the load by the storage element:

$$\chi = \frac{W_{Jst} + W_T + W_D + W_L}{(1-\eta)\cdot V_{DL}\cdot \int_0^{\Delta t} I_{Load}(t)\cdot dt} \qquad (11)$$

We give in figure 3, a chart of the storage capacity thus evaluated, according to the level relating of initial voltage to the storage element.

Let us note however that in the absolute, the energy assessment (9) is inaccurate, insofar as the procedure of the losses calculation rests basically on a relation (in fact the law (7) giving the evolution of the function y) established under cover of the assumption of an ideal energy conversion. Consequently, this procedure whose, essential merit is to be analytic to an undervaluation of the real losses and thus of the energy ratio χ and storage capacity C.

We place for example at $\eta = 0$ and $x_0 = 0.5$. The capacity minimum of the storage element is worth 42.7 F, and the loss ratio χ 11.7%, either a corrected capacity 47.6 F With these parameters, a simulation by Saber environment led to a discharge depth of 0.479 (or $V_{2F} = 119.7$ V), and to a dissipated energy of 147.8 kJ instead of the 116.8 kJ envisaged. A supplement of 0.9 F is enough to reach the 50% of discharge depth. The loss ratio χ is worth 13.8% [12].

Let us finally underline that dimensioning effected, energy nature dimensioning, can be insufficient in terms of power. Indeed, nothing in the procedure guarantees that the storage element is able to provide the required instantaneous power.

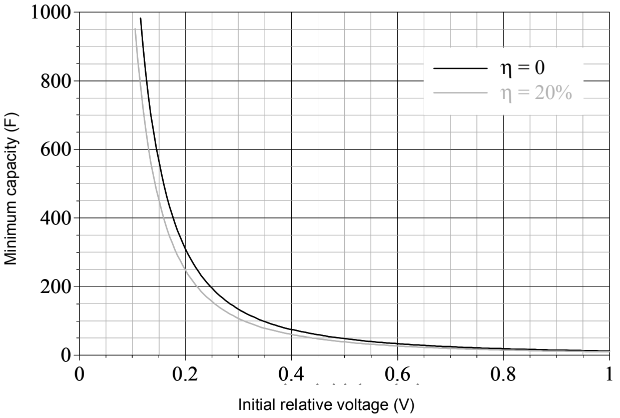

Fig.6. Capacity of the storage element ($y_F = 50\%$ f = 10 kHz, inductance with core Fe-Si, $\eta_L = 10\%$)

E. Mass and volume

The loss ratio χ is also the factor of increase in the storage element size, relative with the results obtained in the ideal case. By taking again like reference the supercapacitive element 3500 F of the company Saft, one obtains for the mass (expressed in kg) and the volume (expressed in L) of the bench of supercapacities according to η and χ:

$$\begin{cases} M_{st} = 1{,}3 \cdot (1-\eta) \cdot (1+\chi) \cdot 79{,}238 \\ V_{st} = 1{,}3 \cdot (1-\eta) \cdot (1+\chi) \cdot 60{,}952 \end{cases} \quad (12)$$

Expressions in which suppose a maximum discharge depth of 50% [12]. We present it on figure 7, according to the initial voltage level of the storage element. The currents I_{Load} and I_{DL} associated with this representation are constant.

The size of the storage element is a criterion supporting the initial high levels voltage. But it is advisable to relativize the problem, being given the not very sloping behaviour of the curves of mass and volume to high voltage. For example, with $\eta = 0$, the gain in size between $x_0 = 0.5$ and $x_0 = 1$ is only 1.5%.

As for the parameter η, which recall quantifies the participation of the principal source in the in put of power, its influence on the size of the hybrid source being complex. In fact, the size of the principal source being an increasing function of η, those of the storage element and inductance being decreasing functions of η, we can obtain for the unity a strict monotony, or an evolution presenting an extremum. We give an example of it in figure 8, example obtained for $x_0 = 0.75$ by supposing constant I_{load} and I_1. It should be noted that the points $\eta = 1$ correspond to a solution without storage system.

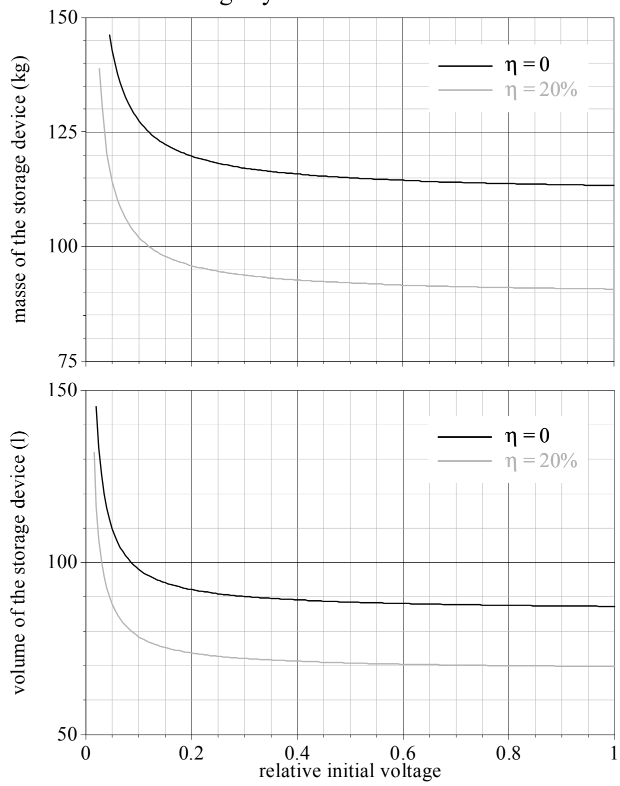

Fig.7. Mass and volume of the storage element (inductance with core iron-silicon, $y_F = 50\%$, f = 10 kHz, $\eta_L = 10\%$)

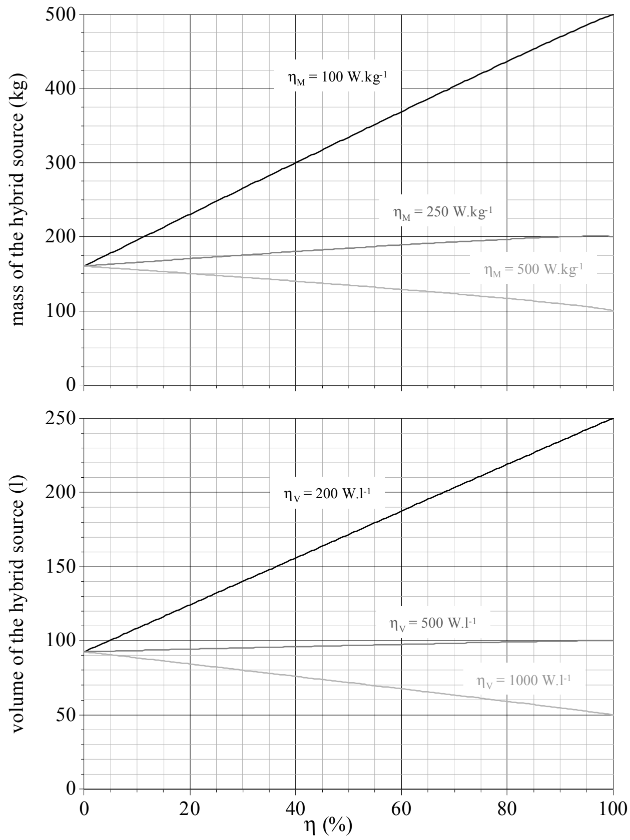

Fig.8. Size of the hybrid source for $x_0 = 0.75$ (except converter, inductance with iron-silicon core, $y_F = 50\%$, f = 10 kHz, $\eta_L = 10\%$)

C. Principal source

The principal energy source provides a share of the in put of power. If we suppose the constant currents I_{Load} and I_{DL}, dimensioning in maximum capacity led to a mass and a volume given by:

$$\begin{cases} M_{SP} = \dfrac{\eta \cdot I_{Load} \cdot V_{DL}}{\eta_M} \\ V_{SP} = \dfrac{\eta \cdot I_{Load} \cdot V_{DL}}{\eta_V} \end{cases} \quad (13)$$

η_M and η_V being powers specific and voluminal of the principal source.

D. Supercpacitors Model

In taking account of electrochemical phenomena, the distribution of charge, the ion moving, the ion sizing…., the supecpacitor can be presented with a multi connection of resistance (R) in serial with variable or constant capacitor (C). A many models have been developed with this principal. L. Zubieta et R. Bonert propose a SC model based on double connection of serial RC, presenting low charge distribution, with serial RC, presenting fast charge distribution. F. Belhachemi proposes a model with multi RC connection. In this article, we use the RC supercapacitor model based on the similarity between the behavior of the supercapacitor and electrolytic capacitor [13]. The SC is then modeled by:

$$\begin{cases} \dfrac{dV_0}{dt} = \dfrac{1}{C_0 + kV_0} I_2 \\ V_2 = R_{sc} I_2 + V_0 \end{cases} \quad (14)$$

Where $C_0 + kV_0 > 0$

The differential capacitance is represented by two capacitors: a constant capacitor C_0 and a linear voltage dependent capacitor kV_0. Where k is a constant corresponding to the slope voltage.

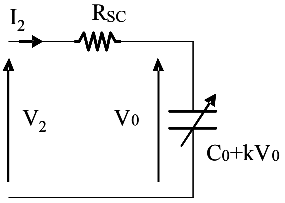

Fig. 9 Supercapacitor electrical model

IV. REGULATION OF THE SCS SUPPLYING SOURCE, RESULTS AND DISCUSSIONS

Many control techniques can be applied to SCs. Since SCs can give all its storage energy in few second, it can not supply by only itself the load. SCs are mainly used to absorb and supply the transient peaks power; they are then hybridized with other energy sources. The main source (other then SCs) have generally the task to regulate the DC Bus voltage during all the working period, a voltage control loop is then recommended for these sources. In the other hand, SCs have the task to regulate the power, and consequently the current. Hence, a current control loop is generally recommended for the SCs. Combination between current and voltage loops (could be as internal and external loops) can be found.

Then, any current control technique can be applied to SCs.

As an example, we use in this paper a combination between a current control loop to match the load power flow and a voltage control loop. The two objectives have their weighting gains (k_1 and k_2) allowing to define a priority for loops.

The chosen control technique is a sliding mode control for the SCs DC-DC adapter converter. The main source is supposed to maintain a constant DC link voltage and the SCs are used to absorb or to supply the transitory power. Thus, we define a sliding surface S as a function of the DC link voltage V_{DL}, its reference V_{DL}^*, the SCs voltage V_{SC}, and the SCs current I_{SC}:

$$S = k_1\left(V_{DL} - V_{DL}^*\right) + k_2 \cdot \left(I_{SC} - I\right) \quad (15)$$

The reference current I depends on the load power and the state of charge of the SCs:

$$I = \frac{V_{DL} . I_{Load}}{V_{SC}} \quad (16)$$

k_1 and k_2 are the coefficients of proportionality, which ensure that the sliding surface equals zero by tracking the SC currents to its reference I when the supercapacitors controller can't ensure V_{DL} tracks V_{DL}^*.

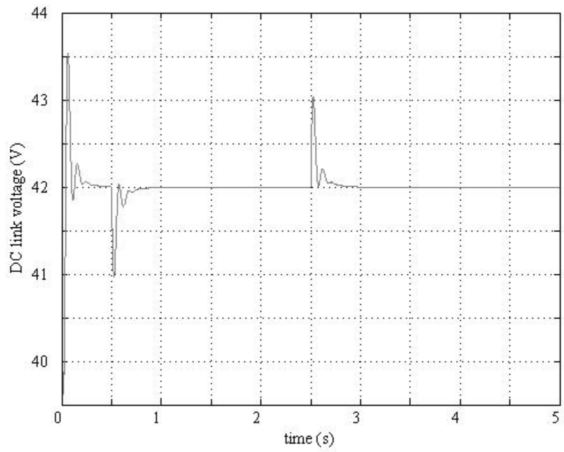

Fig 10: DC Link voltage

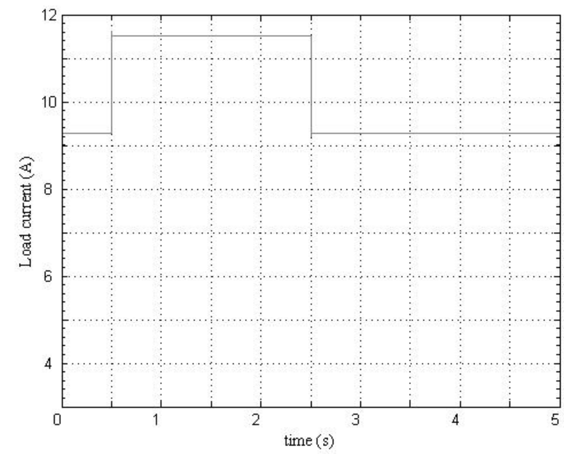

Fig 11: load current variations

In steady state condition, the SCs converter ensures that the first term of the sliding surface is null, Then, imposing S=0 leads to $I_{SC} = 0$, as far as the boost converter output current I_{Load} is not limited. So that, the storage element supplies energy only during power transient and I_{Load} limitation.

The waves forms presented on figure 10, 11 and 12 are obtained by connecting the proposed source in figure 2 to an active load. These waves present the behavior of the DC link voltage V_{DL}, the load currents I_{Load}, and the supercapacitor current I_{SC} for large load variation. The storage device supplies the load current at the starting of the system and during the transient state. These results show the goodness of the DC Link regulation at 42V by applying the control law (15).

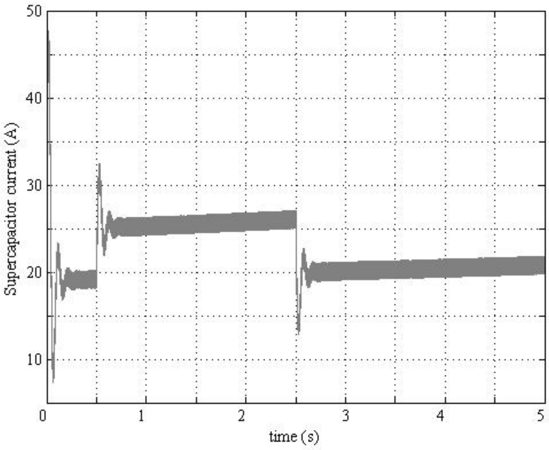

Fig 12: Supercapacitors current

VI. Conclusion

In this work, the sizing, modelling and control of hybrid source based on supercapacitors and permanent source has been presented.

The sizing of the supercapacitors depends on the level of voltage, load current and the source component losses.

A SC model based on the transitory temperature phenomena will be presented in the final article.

A results based on sliding mode control is presented and discussed.

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