Energy Feeding With Sequential Storage: Properties Of The Fast Energy Transfer Between Supercapacitive Tanks

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Abstract:

Supercapacitors are new and powerful components for energy storage. Compared with batteries, the amount of energy they can store is low. But, as power sources they have the property to be re-loadable in a few seconds [1][2][3]. In that case, the needed instantaneous power can reach very huge values, sometime not compatible with the power that a power network or an energy source can provide [4][5]. To solve those power constraints, some solutions have been proposed which consist of using an intermediary supercapacitive tank, as exposed in [6] as a feeder for an electric bus with supercapacitors. Experimental results are presented, defining the profile of the instantaneous power-level, which is controlled in order to achieve a fast energy transfer.

Energy feeding with sequential storage

A new concept for energy-feeding of an electric bus has been earlier presented [4] [6], based on the use of supercapacitor storage and periodic refilling, allowing the suppression of overhead lines (Fig. 1).
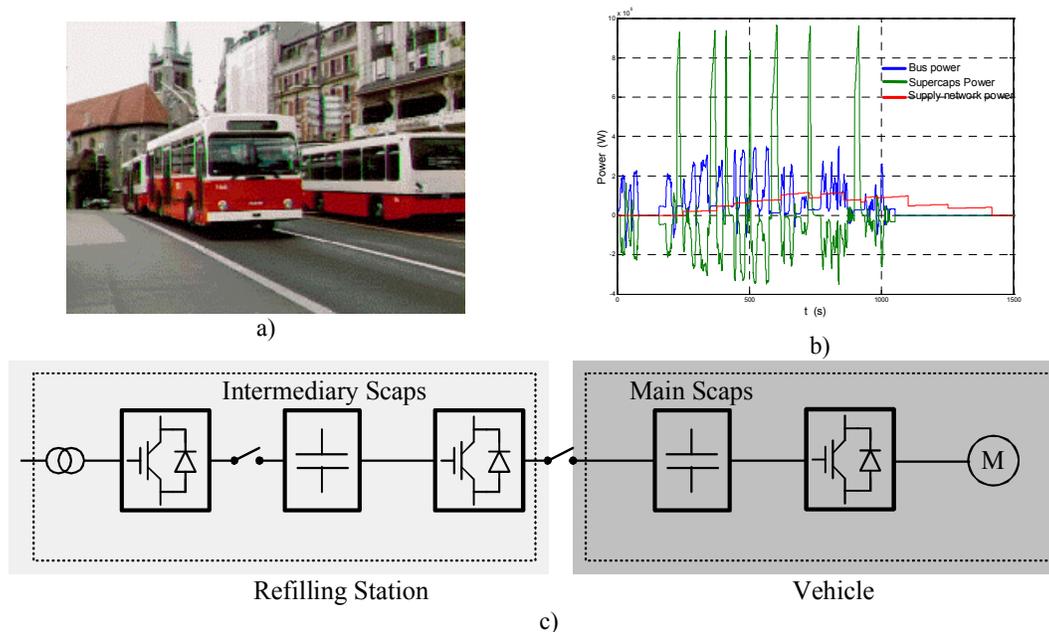

a)

b)

c)

Fig. 1 : Energy feeding with sequential storage

a)   A bus with classical overhead-lines
b)   Power profile of the propulsion system, of the on-board energy storage-tank inclusing the refilling-peaks, together with the sollicitation of the primary distribution system
c)   Power-conversion topology for the fast exchange between fix and mobile storage tanks

In that future-oriented concept, a sequential transfer to the bus from a distribution network occurs via intermediary storage-tanks placed at specific refill-stations. In this system, a low-power recharge of the fixed supercapacitors is done while busses are on the track, which means a relative long charging time equal to the time interval between two busses. When arriving at the refill station, the bus system is connected to the refill station, and a reload operation occurs during the reduced stop time of the vehicle, as an energy transfer impulse. When the refilling of the stations represents a low power solicitation of the primary distribution system, the transfer from the fix or intermediary tank to the main storage tank inside the bus is

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characterised by a special very high power profile, that must be current controlled in order to limit the poor efficiency of such an energy exchange.

The aim is to store firstly the needed energy in that tank with a low current and, as a consequence, by means of a reduced instantaneous power peak. Then, the main supercapacitors are loaded from the intermediary supercapacitors, thanks to a fast energy transfer between those two supercapacitive tanks. The main point is that the high magnitude power peak needed for loading energy into the main supercapacitors is no more supported by the power network, or the energy source.

In this paper, one of various solutions is presented to manage a fast energy transfer between supercapacitive tanks. First, topologies of power converters will be introduced for the interface-function between two supercapacitive tanks. A first scheme is presented in Fig. 2, realised with the help of two inverter-legs that are interconnected via a constant-voltage DC-link. Because of the energy transfer is defined only in one direction, the legs are realised as non-reversible set-up and step-down converters, comprising only one transistor and one single free-wheeling diode per leg. The connection between the capacitive tanks and the converter input and output are realised by the means of decoupling and smoothing inductors. The main advantages of this type of converters is that it allows an energy-transfer in both possible situations of the voltage ratio between the intermediary and the main capacitor tank, corresponding to the beginning situation of the transfer where the intermediary-tank is full and the bus-tank is empty, as well as to the final status of the transfer where the bus tank is full and the intermediary tank is discharged. Additionally, the converter topology can achieve a non-discontinuous current in both storage tanks.
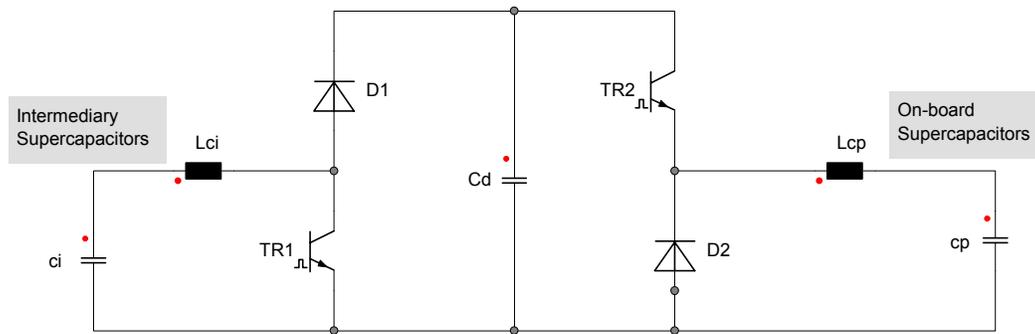

Fig. 2 : Power converters to interface two supercapacitive tanks

Profile of the exchanged power

Various power profiles for the energy-exchange have to be defined, formalised and compared, in order to optimise the number of supercapacitors of the intermediary tank side and the time needed for the energy transfer. As an example, one possible power profile is presented, called "Triangular Power Profile", obtained with the first experimental studies actually under way (Fig.3).
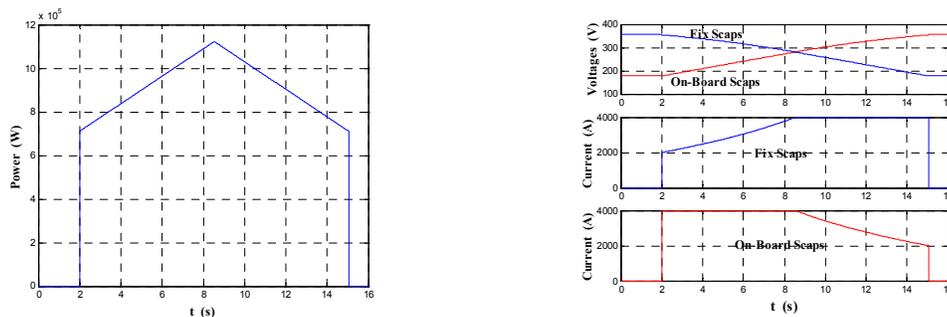

Fig. 3 : Triangular Power Profile

The conditions that are defining the triangular power-profile are determined mainly by the design of the current capability of the semiconductors in the power converters used for managing the energy transfer. As a main assumption, this design as of the limiting conditions, but is also adapted to the current capability of the supercapacitors themselves. This current capability is then influencing the power capability indirectly, because of the defined voltage conditions of the tanks, illustrating their state of charge. So at the beginning of the energy exchange, the "receiver-tank" has a low voltage, defining the power-level of the transfer,

while the "sender" is in a situation where it could provide more power. At the end of the transfer, when the sender is discharged, it is becoming the limiting power element. Of course the receiver is then characterised by a larger power capability.

Then the aim of such an energy transfer controller is to start the exchange with a constant current on the main supercapacitors side (the receiver). Because their voltage increases linearly, the exchange power increases also linearly. As the intermediary supercapacitors voltage decreases (sender-side), their current increases strongly. When it reaches a given limit, this current is kept to a constant value. From that point of view, as the voltage decreases linearly, the exchange power decreases also linearly [6]. This particular profile of the power transfer is shown on the left frame of Fig.3.

On the right frame of Fig.3 the voltage of the supercapacitive tanks are presented, together with their currents.

It is of course needed to identify the time needed for that profile of energy exchange, in order to be sure that the duration of the energy exchange is compatible with the duration of the stop time of the vehicle at the refill station. The duration for the energy exchange is then defined by the following equations :

$$T_{ex} = C_e \frac{U_M}{I_{e2}} \left[-\frac{d_2}{100} + K \left(1 + \frac{N_{s2}}{N_{s1}} \right) - Q \right]$$

$$\text{where} \begin{cases} Q = \frac{1}{N_{s1} + N_{s2}} \sqrt{(N_{s1} + N_{s2}) \frac{N_{s2}}{N_{s1}} \left[K^2 (N_{s1} + N_{s2}) + N_{s2} \left(-1 + \left(\frac{d_2}{100} \right)^2 \right) \right]} \\ K = \frac{1}{(N_{s1} + N_{s2})} \sqrt{\frac{N_{s1}}{N_{s2}} \left[\left(N_{s1} + \frac{d_2}{100} N_{s2} \right)^2 + \left(1 - \frac{d_2}{100} \right)^2 N_{s1} N_{s2} \right]} \end{cases}$$

Regarding the power profiles defined in Fig. 1, established for 7 re-filling stops on a 5 km run, the numerical integration of the bus power gives the needed energy for going from one re-filling stop to the next one. In that case, the needed energy that has to be stored in the bus is 17MJ (4.72kW.h). With a discharge voltage ration d of 70% [6], it is needed to have 5926 supercapacitors on-board. Other choices can be made for different ratio d, and for different number of re-filling stops. The results are given in Table 1, where the parameters d_2 and N_{s2} are respectively the considered voltage discharge ratio, and the associated number of on-board supercapacitors for the number of re-filling stops that are considered.

Then, we consider only the cases where the number of fix supercapacitors can be minimised. That is obtain by the choice of d_1=50% for all the cases. The results are also shown in Table 1, where the parameters d_1 and N_{s1} are respectively the considered voltage discharge ratio, and the associated number of fix supercapacitors for the number of re-filling stops that are considered.

This type of energy transfer leads to a strongly reduced total number of supercapacitors, compared to other solutions [6]. The most performing choice is 9 loading stations, 12MJ of usable energy, with a 50% of discharge voltage ration for both the fix and the on-board tanks. However, the reduced number of components on-board and in the loading stations leads to a lower exchange power. The result is an increased the time for the energy exchange compared to other solutions. But this energy exchange duration is still compatible with the time allowed for a bus stop in a town.

Usable energy		10MJ (11 loading)			12MJ (9 loading)			17MJ (7 loading)		
On-board Supercaps	d_2	50%	60%	70%	50%	60%	70%	50%	60%	70%
	N_{s2}	2371	2778	3486	2845	3334	4184	4030	4723	5926
Fix Supercaps	d_1	50%	50%	50%	50%	50%	50%	50%	50%	50%
	N_{s1}	2371	2371	2371	2845	2845	2845	4030	4030	4030
Time for energy transfer (s)		13.07	11.77	11.25	13.07	11.77	11.25	13.07	11.77	11.25
Total number of Supercaps for one bus		28452	28859	29567	28450	28939	29789	32240	32933	34136

Table 1 : Various possible sizing for on-board and fix supercapacitors, regarding the power profiles in Fig.1-b

Dedicated control strategy for the triangular profile

From the structural diagram given in figure 3, the open-loop and closed-loop control circuits can be shown. At both sides of the converter, this means at the sender-side and at the receiver-side, the currents must be controlled individually with a fast controller, assuming a well defined value of the current in the power-semiconductor devices and also in the interconnected circuits.
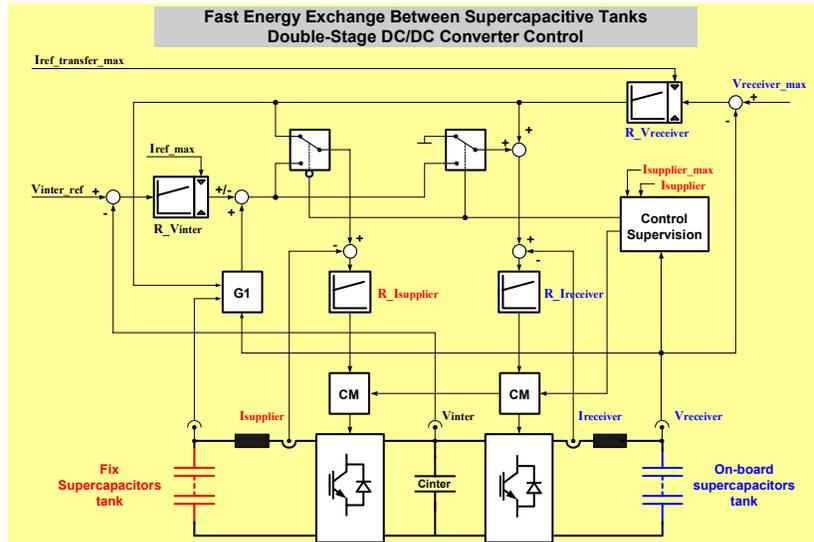

Figure 4: Control strategy for the reliable and triangular-shaped power-profile

At the level of the intermediary DC-circuit corresponding to the classical capacitor placed between the two boost and buck circuits, the voltage must be stabilised on a constant value which must be kept above the value of both the sender-tank value and also the receiver-tank voltage-value. For that purpose, a DC-voltage controller is used, which output quantity is injected at the level of the sender-side current control.

For the control of the power-flow from the intermediary tank to the main tank, the set-values of both current controllers are influenced. At the side of the sender, the current set-value is influenced by the limitation of the value given to the receiver-tank current-controller, which comes from the superimposed control of the voltage value of the intermediary DC-circuit.

Experimental results of the triangular power profile

Figure 5 gives an illustration of the experimental set-up used for the development and tests of the control strategy, and for first experimentation with the technique of fast energy transfer. This power-electronic system has been integrated in the model train experimentation system of LEI. The upper part of the picture shows the supercapacitors fed locomotive with a modified motor-and-gear, allowing regenerative breaking. Following the locomotive, a car with the dedicated converter for driving the motor in 4-quadrant mode, as well as a voltage stabilising booster between the supercapacitive tank and the propulsion circuit. The train has additionally a radio-control link allowing also a wireless monitoring of the quantities in the locomotive.

The lower part of the picture shows the converter needed for the fast energy transfer between the fix supercapacitor tank and the on-board tank.

Figure 5: Experimental set-up for testing the strategy of the fast energy transfer

The curves presented in figure 6 show a controlled energy transfer between two supercapacitive tanks of reduced size. On the right curve, the triangular profile is shown, for both sides of the system. The upper curve is the power provided by the intermediary supercapacitors. The second curve is the power absorbed by the main supercapacitors. It should be noticed that the difference between those two powers is related to the efficiency of the power converter that interfaces the two supercapacitive banks. It is evident that the efficiency of the scaled model cannot be a good illustration for this principle, due to the extremely low voltage-level of the experimentation set-up, related to the real voltage-drop of the used IGBT transistors. More realistic is the result concerning the profile of the voltages and currents of the tanks shown at the left side of the picture.
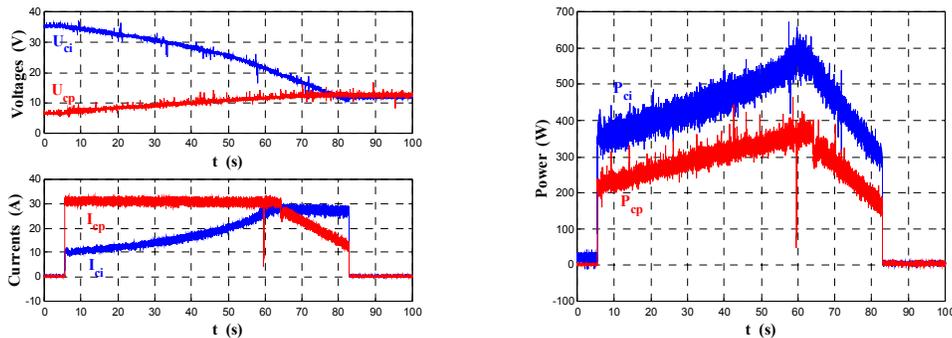

Figure 6: Experimental curves of the fast energy exchange with triangular profile.

The relation to the efficiency
In the defined triangular profile of the transferred instantaneous power, the losses in the storage tanks can be evaluated, due to the dissipation on the internal resistor. It is clear that the losses or the efficiency for loading and unloading the supercapacitors are dependant on the current value [2]. An interesting alternative to the strategy of keeping the current as constant as allowed in the converter and in the supercapacitor tank is to consider an exchange with constant power. First experimentation has been done on a theoretic base, setting in evidence the main properties of such a strategy. The behaviour of a supercapacitive component is shown on figure 7, where the trajectory of the current is represented, in dependency of the status of the capacitor voltage. Several operation conditions are represented, corresponding to different power levels. Another parameter is shown on the diagram, which is the calculated efficiency of the discharge under this specific condition, for a discharge from the maximum voltage value of a supercapacitor (typically 2.5V), to the minimum voltage value that can be reached under the condition of a discharge under a constant power.
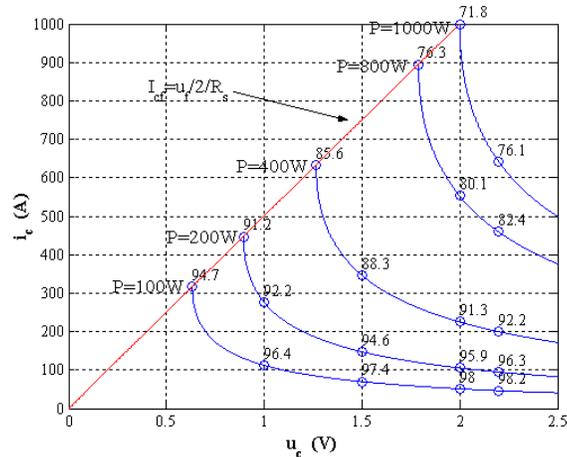
Figure. 7: Discharge of a supercapacitor under a constant power

Further studies and experimentations are currently under way at LEI, also with operation at better efficiency conditions of the power converters, using better adapted technologies. Results will be presented soon.

Conclusions

An innovative feeding concept based on double-stage supercapacitive storage has been proposed for electrical buses in cities without use of a over-head lines supply. In that sequential feeding, the energy transfer from a fix refill-station to the on-board storage tank must be done with the help of controlled converters, and with specific power-profiles. A power-electronic converter with intermediary circuit has been studied, with consideration on the power limiting conditions. A specific control scheme has been used, assuming the well defined current conditions in both the input and the output circuits. In addition, the stabilising of the intermediary voltage is necessary, with the problematic of choosing the correct intervention-side for the control quantity issued from the corresponding DC-voltage controller.

Experimental results have been presented regarding the following of an adapted power-profile, and the corresponding currents in the sender and in the receiver storage-tank.

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