An Interface Converter with Reduced VA Ratings for Battery-Supercapacitor Mixed Systems

Giuseppe Guidi*, Tore M. Undeland*, Yoichi Hori**
* Norwegian University of Science and Technology (NTNU), Norway
** The University of Tokyo, Japan

Abstract—**This paper presents a converter topology used to interface a bank of Supercapacitors (SC) to a stiff DC-Link, like the one constituted by a typical battery. Main feature of the proposed converter is the reduced ratings of the power electronics switches compared to standard topologies. The capabilities of the proposed system in terms of energy storage and controllability of the power flow in and out the SC bank are identical to those of a conventional system, making the solution very attractive in terms of cost and efficiency in a wide number of applications. Theoretical principles underlying the converter operation are given, along with an experimental evaluation of the proposed solution, showing its practical feasibility.**

***Index Terms* — EDLC, Energy Management, Power Electronics, Supercapacitor.**

I. INTRODUCTION

Vehicles and traction systems in general are characterized by large peak-to-average power ratios, making them an ideal candidate for deployment of mixed battery-Supercapacitor (SC) energy storage systems [1-3]. In fact, while batteries tend to have a higher energy density than SC, the latter are able to handle high power peaks with no detrimental effect on their performance, durability and efficiency. It is therefore very desirable to let SC providing (or absorbing) the power peaks while the battery supplies the bulk average power to the load, as shown in Fig.1.

How to assemble and operate such a mixed system has been subject of extensive research, with special emphasis on how to control the power flow between the different components [4-6]. In [7], several bidirectional Power Electronics converters of different topologies have been analyzed and compared in order to determine the most suitable alternative, in terms of cost, efficiency and volume, concluding that the very simple half-bridge topology shown in Fig.2-a is the one to be preferred in most applications. This converter allows for bidirectional power flow, provided the SC voltage is kept lower than the battery voltage. Therefore, the voltage of the SC bank, who is widely dependent on the State Of Charge (SOC), is allowed to vary between the nominal voltage of the battery pack and a fraction of it (normally 50%). In general, the lower the voltage allowed on the SC side, the higher will be the VA ratings of the semiconductor switches used in the converter [8], making it uneconomical to go below 50%, corresponding to a VA ratings of each switch roughly equal to twice the power ratings of the converter, plus a margin needed for safe commutation.

In principle, it would be possible to reverse the approach by connecting the SC bank on the high voltage side of the DC/DC converter, as shown in Fig.2-b; in that case the SC bank voltage will be allowed to vary between a minimum bound given by the battery voltage and a maximum bound selectable by design. If the latter is taken as 200% of the battery voltage, the VA ratings of the switches in the DC/DC converter will still be the same as in the conventional case of Fig. 2-a (twice the power ratings of the converter). However, this solution is normally regarded as inconvenient, due to the following reasons. First, SC banks are made up of series connection of individual modules having each very low voltage ratings (typically 2.5V); higher block voltage rating means therefore a larger number of individual cells to be connected in series, making the problem of voltage

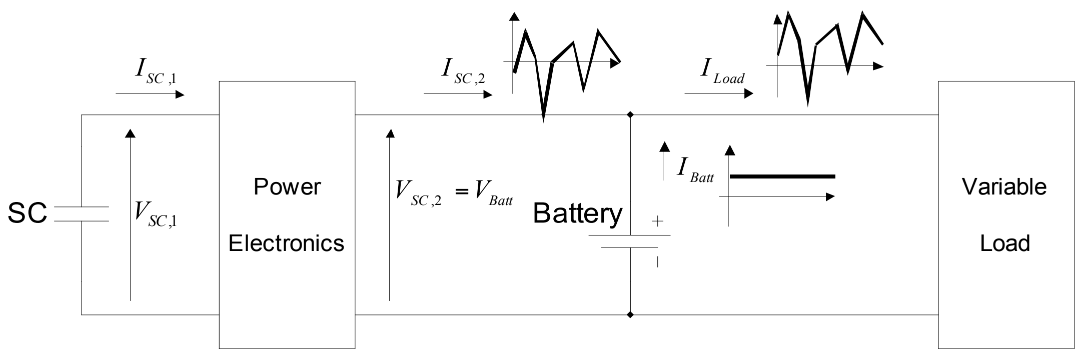
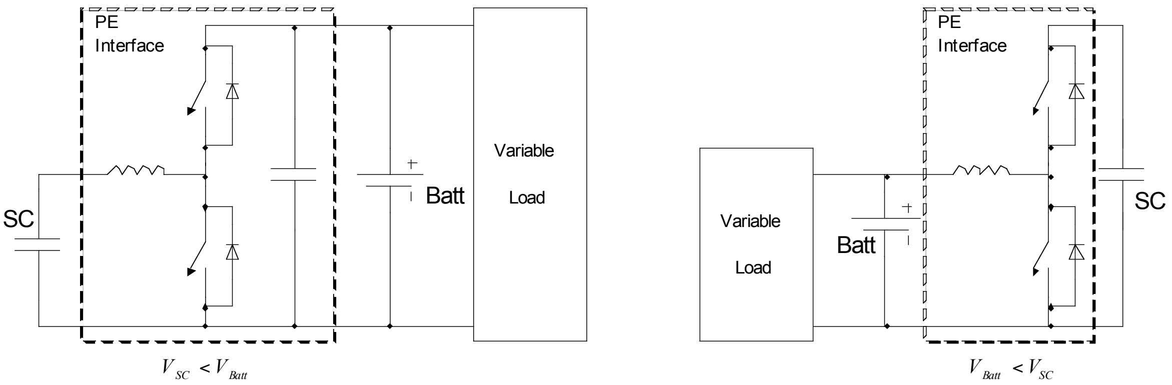


Fig.1 – Basic SC-Battery Mixed System with Power Electronics Interface



(a) – Conventional topology (b) – Reversed topology (not used in practice)

Fig.2 – Power Electronics interfaces based on Half-Bridge topology

sharing more severe, and increasing system complexity. Moreover, if SC bank is on the high voltage side of the converter, there will be some difficulties due to the inrush current that would result when connecting a discharged SC bank to the battery pack through the converter.

In spite of the disadvantages listed above, this paper will show how this reversed approach, if properly modified, can lead to a substantial reduction of the VA ratings of the semiconductor switches that may not be apparent at first glance, while retaining full control over the power flow and optimal utilization of the energy stored in the SC bank.

II. HALF CONTROLLED CASCADED CONVERTER

The starting point of the concept is the assumption that the battery voltage is a relatively stiff one, varying only very little with the battery SOC. Therefore, the output voltage of the converter interfacing the SC bank to the battery does not need to be controlled over the full range, in order to control the power flow. In other words, it is possible to have an uncontrolled offset voltage added to the converter output and control only the difference between such an offset voltage and the battery voltage. This can be achieved by the topology shown in Fig. 3.

In the converter shown above, if we assume that the energy stored in the filter inductor L is negligible (as it is most likely the case), the output voltage of the whole converter V_{out} will always have to be equal to the stiff battery voltage V_{batt}. As a consequence:

$$V_{bridge} = V_{out} - V_{SC,0} = V_{batt} - V_{SC,0} \quad (1)$$

where $V_{SC,0}$ is the voltage across the uncontrolled SC bank. From (1), we can now evaluate the output voltage capabilities needed for the bridge.

At first, the maximum voltage allowed for the uncontrolled block is fixed to:

$$V_{SC,0,Max} = V_{batt,\min} \quad (2)$$

The bound in (2) is selected so to ensure that when the uncontrolled SC block is fully charged, it will naturally be in equilibrium with the lowest possible battery voltage, with no contribution from the controlled block, who should be fully charged, too, as it will be explained in a following section.

Another design choice is to allow for maximum 50% discharge of the SC blocks:

$$V_{SC,0,\min} = \frac{V_{SC,0,Max}}{2} = \frac{V_{batt,\min}}{2} \quad (3)$$

As a consequence, the highest output voltage required from the H-Bridge will be:

$$V_{bridge,Max} = V_{batt,Max} - V_{SC,0,\min} = V_{batt,Max} - \frac{V_{batt,\min}}{2} \quad (4)$$

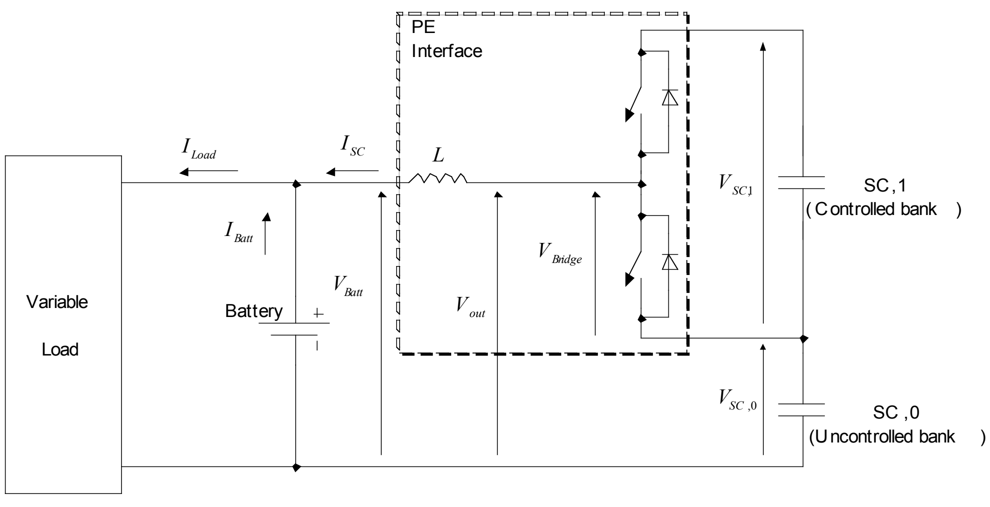


Fig. 3 – Half Controlled Cascaded Converter

The minimum DC voltage behind the bridge necessary to satisfy (4) is then:

$$V_{SC,1,\min} = V_{bridge,Max} = V_{batt,Max} - \frac{V_{batt,\min}}{2} \tag{5}$$

Applying the same principle of 50% maximum discharge also to the controlled SC bank, we get:

$$V_{SC,1,Max} = 2 \cdot V_{SC,1,\min} = 2 \cdot V_{batt,Max} - V_{batt,\min} \tag{6}$$

The voltage in (4) is also the rated voltage of the switches in the bridge, once a proper margin necessary for safe commutation is added. Since the current rating of the switches in Fig. 3 is equal to the maximum output current of the bridge, we can conclude that the VA rating of each switch P_{SW} is:

$$\begin{aligned} P_{SW} &= V_{SC,1,Max} \cdot I_{out,Max} = \left(2 \cdot V_{batt,Max} - V_{batt,\min}\right) \cdot I_{out,Max} \\ &\approx V_{batt} \cdot I_{out,Max} \end{aligned} \tag{7}$$

where the last approximation is valid in case of stiff battery voltage ($V_{batt,\min} \approx V_{batt,Max} \approx V_{batt}$).

From (7), it is evident that the series connection of an uncontrolled SC block and a controlled one has the very favorable effect of lowering the switches VA rating of about half, when compared to the standard converters in Fig. 2.

III. Charge Balancing

Series connection of an uncontrolled SC block with a controlled one only makes sense if it remains possible to make use of all the energy available in the system. In the conventional systems of Fig. 2, it is clear that the SC charge/discharge is completely controllable by the power electronics interface; the same is not very obvious in case of the half controlled converter in Fig.3.

In order to have optimal utilization of the two SC banks, they should reach the top charged ("full") state simultaneously, and do the same for the bottom discharged ("empty") state, independently of the load current requirements, which are unknown a priori.

The uncontrolled SC block will charge/discharge according to the following law:

$$\begin{aligned} \Delta V_{SC,0}(t) &= V_{SC,0}(t) - V_{SC,0}(0) \\ &= \frac{1}{C_{SC,0}} \cdot \int_0^t I_{out}(\tau) \cdot d\tau = \frac{1}{C_{SC,0}} \cdot \Delta Q_{SC,0}(t) \end{aligned} \tag{8}$$

Due to the voltage constraint (1), the bridge output voltage is determined at each time, and can be expressed in terms of the duty cycle D of each switch:

$$V_{bridge}(t) = D(t) \cdot V_{SC,1}(t) = V_{batt} - V_{SC,0}(t) \tag{9}$$

Average current flowing through the controlled SC bank over a switching period is also related to the same duty cycle by:

$$I_{SC,1}(t) = D(t) \cdot I_{out}(t) \tag{10}$$

Combining (9) and (10), it is possible to express the charge/discharge of the controlled SC block:

$$V_{SC,1}(t) = V_{SC,1}(0) + \frac{1}{C_{SC,1}} \cdot \int_0^t \frac{V_{batt} - V_{SC,0}(\tau)}{V_{SC,1}(\tau)} \cdot I_{out}(\tau) \cdot d\tau \tag{11}$$

leading to the non-linear differential equation:

$$V_{SC,1}(t) \cdot dV_{SC,1} = \frac{1}{C_{SC,1}} \cdot \left(V_{batt} - V_{SC,0}(t)\right) \cdot I_{out}(t) \cdot dt \tag{12}$$

After substituting (8) into (12), the equation can be solved as:

$$\begin{aligned} &V_{SC,1}(t) = \\ &\sqrt{V_{SC,1}{}^2(0) + \frac{C_{SC,0}}{C_{SC,1}}\left(2\left(V_{batt} - V_{SC,0}(0)\right) \cdot \Delta V_{SC,0}(t) - \Delta V_{SC,0}{}^2(t)\right)} \end{aligned} \tag{13}$$

The most remarkable aspect of (13) is that the voltage (or, which is equivalent, the SOC) of the controlled SC bank is a function of the SOC of the uncontrolled bank, and such a function does not depend on the particular shape of the converter output current. This fact allows us to design the system so that the two SC blocks reach their "empty" and "full" states at the same time, resulting in optimal utilization of the system capacitance.

As a design example, let us assume the design principle of 50% discharge for both SC banks, stated in the first equality of (3) and (6). From (13), we can calculate the capacitance required for the controlled SC bank, in order to satisfy the 50% discharge criterion:

$$\frac{C_{SC,1}}{C_{SC,0}} = \frac{\left(V_{SC,0,Max} - V_{SC,0,\min}\right)\left(2V_{batt} - V_{SC,0,Max} - V_{SC,0,\min}\right)}{V_{SC,1,Max}{}^2 - V_{SC,1,\min}{}^2} \tag{14}$$

Selection of the bank capacitances according to (14) will automatically ensure optimal use of the system energy. The bridge can then be operated in current control mode, as in conventional applications, in order to optimize the SC/Battery mixed system performance.

IV. Simulation Results

The system in Fig. 3 has been simulated in Simulink, using the Power System Blockset. The load current profile has been chosen so that the SC bank undergoes a complete discharge cycle, followed by a complete charge. The battery voltage is fixed to 150 V. The capacitance of the controlled and uncontrolled banks is selected as 200 mF and 600 mF, respectively, in accordance to the 50% discharge criterion and (14). Both banks are initially "full", meaning that their voltage is at the maximum bound selected by design, equal to the battery voltage (150 V).

Results show how the two bank discharges following different voltage trajectories but, as predicted by our analysis, they reach the "empty" state, corresponding to a voltage equal to half the battery voltage, at the same time.

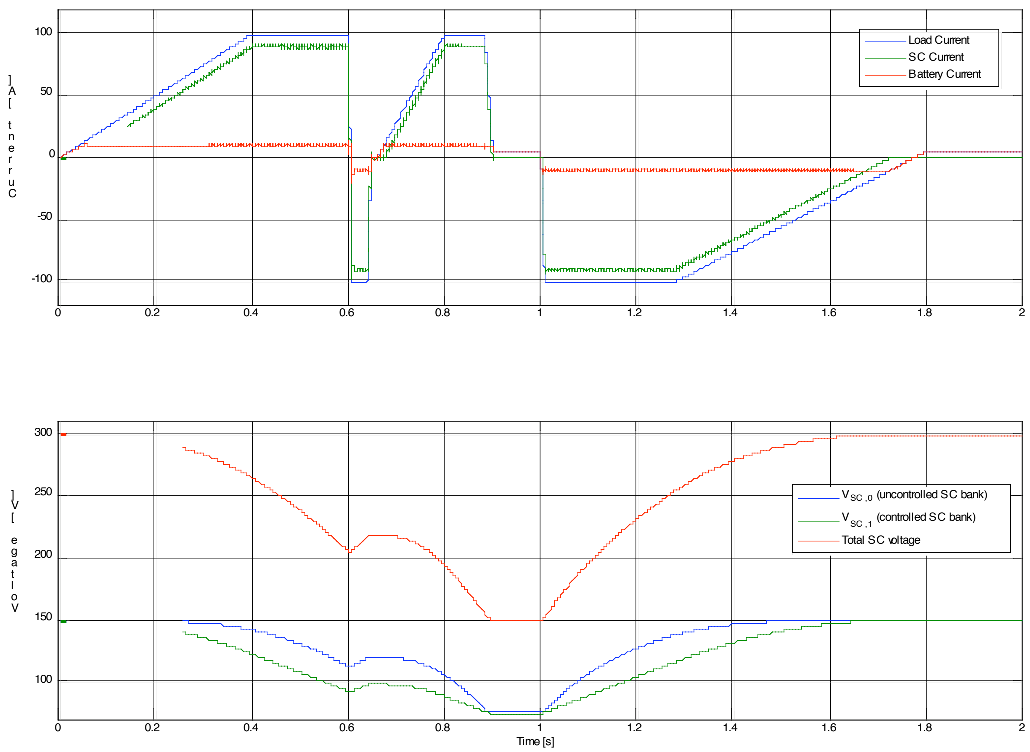


Fig. 4 – Simulation of charge/discharge cycle with the proposed Half-Controlled Converter.

The process is then reversed and the SC banks are charged with a different load current waveform; again, they reach the "full" state simultaneously. In synthesis, the two SC blocks behave exactly like a single SC block being charged and discharged between the selected "empty" and "full" states, as it would be in any of the standard topologies in Fig. 2. The only difference being that the result is achieved with a power electronics converter rated about half of the conventional.

V. Practical Realization

In order to validate the proposed concept, a reduced-scale system has been built, whose specifications are given in Table 1.

The two SC banks are made up of arrays of nominally identical elementary cells, as shown in the table; within each bank, passive voltage sharing is achieved by connecting a small resistance across each cell.

Compared to the basic system in Fig. 3, the practical implementation features a means for lossless dynamic voltage sharing between the two SC banks, as proposed in [9] and shown in Fig. 5. Dynamic balancing is responsible for keeping the voltage of the two banks in the theoretical relationship defined by (13), in spite of the several non-idealities of the real system. Some of the factors that would cause the voltages to deviate from (13) are unmodeled losses in the various components (battery, SCs, inductor, switches), quite high tolerance in the capacitance value of the SC cells, deviation of the battery voltage from its nominal value. Since the balancing circuit only has to take care of system non-idealities, its current capabilities can be very small compared to the main current flowing into the SC banks.

A relatively large capacitor with low ESR is connected

TABLE I
MAIN SPECIFICATIONS OF THE EXPERIMENTAL SETUP

Battery	Sealed lead Acid 12V, 10Ah $R_{int} \approx 80m\Omega$
SuperCapacitor elementary cell	Maxwell BCAP 350F $(\pm 20\%)$, 2.5V $ESR_{DC} = 3.2m\Omega\ (\pm 25\%)$
Uncontrolled SC bank	6 series by 3 parallel array of cells 175F, 15V $ESR_{DC} \approx 6.4m\Omega$
Controlled SC bank	6 series array of cells 58.3F, 15V $ESR_{DC} \approx 20.4m\Omega$

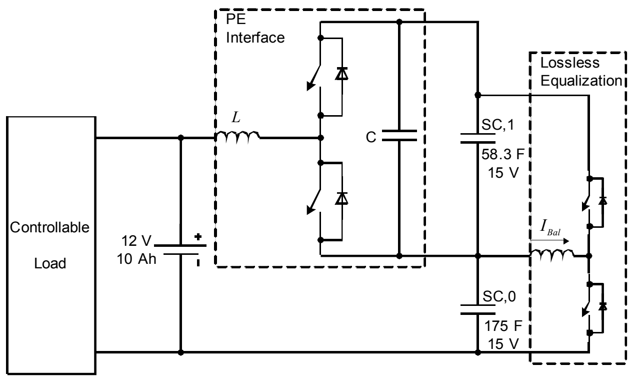


Fig. 5 – Experimental Setup.

in parallel with the controlled SC bank, in order to reduce losses due to the highly distorted current resulting from PWM switching of the converter. Notice that the presence of such a capacitor is not a prerogative of the proposed topology, since the same device is present in the conventional converter of Fig. 2(a) in parallel with the battery.

VI. Experimental Results

Fig. 6 shows experimental charge-discharge cycles of the system with arbitrary load current. Similarly to what was done in simulations, the share of the load current taken by the battery is limited to $\pm 2A$, with the SC bank providing or accepting all the rest. The system is designed to charge and discharge between lower and upper limits of $6.375V$ and $12.75V$, respectively, as indicated by the dashed lines in the figure.

It is observed that in spite of the non-stiff battery voltage and of all the other non ideal components, the SC banks follow the predicted voltage trajectory, hitting the lower and upper voltage limits simultaneously. This is achieved with very little current flowing through the lossless balancing circuit. From a system point of view, the two SC banks are behaving like a single bank being cycled between the voltage limits imposed by the design.

During very quick charge-discharge with large current flowing into the SC bank, the individual bank voltages may temporarily deviate from (13), as shown in Fig. 7. However, proper balancing is soon regained thanks to the control action of the lossless active balancing circuit. In all the experiments, the balancing current is limited to $1A$, which is less than one tenth of the peak value of the main charging-discharging current.

Fig. 7 also shows what happens if discharge is not stopped when the voltage reaches the lower limit. In this case, discharge is limited by the topology itself due to the presence of the clamping diodes which effectively prevent the sum of the SC bank voltages from going below the battery voltage. Obviously, all the power required by the load has to be given by the battery, after the SC banks are fully depleted. If, following an excessive discharge with very large load current, the latter is abruptly decreased (see Fig. 7), the battery voltage rises sharply due to the battery internal resistance. There is then a transient situation in which the battery voltage is higher than the total SC voltage, causing the clamping diodes in the topology to naturally charge the SC bank. Even though this inrush current cannot be controlled by the switching devices, it does not represent a real danger to the converter. In fact, if the current rises, the battery voltage will decrease due to the internal resistance, and it will eventually overcome the SC voltage; at this point, control over the current is regained. After a short transient, the system will reach a stable state of equilibrium

VII. Conclusion

An unconventional method for interfacing a Supercapacitor bank with a battery based on a half controlled power electronics converter has been proposed. Main advantage of the method is that the converter can be built using switches with almost half VA rating as compared to conventional half-bridge topologies. It has been shown that ideal utilization of the energy storage

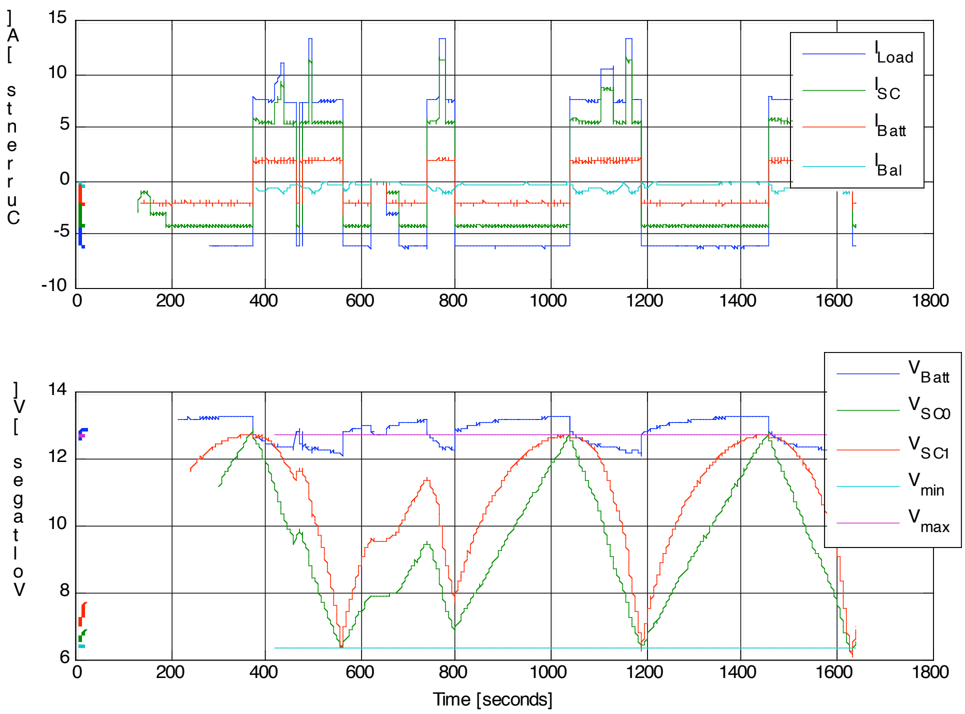
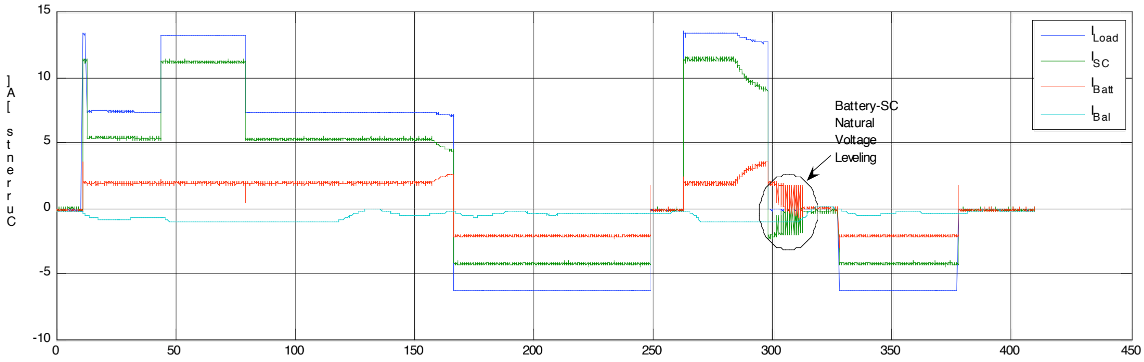


Fig. 6 – Experimental Results; Charge/Discharge cycles with arbitrary load current waveform.



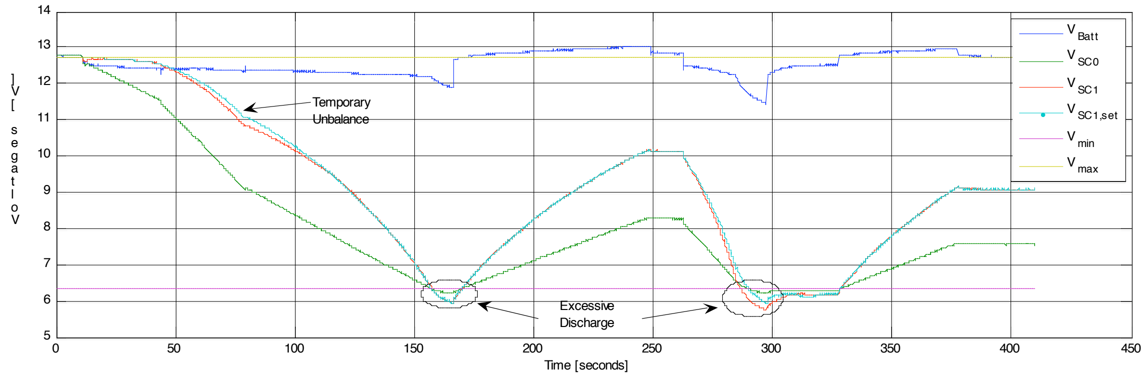


Fig. 7 – Experimental Results; Quick Discharge and natural recovery after excessive discharge.

capacity of the SC bank is still possible, even if the current flowing in one of the two SC banks of the proposed system is uncontrolled. Experimental results validate the principle. It is believed that the proposed converter can be of interest in a wide variety of applications, due to its potential for cost saving and volume reduction.

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