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

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Keywords: EDLC, DC-DC converter, ultracapacitor, energy management system

Vehicles and traction systems in general are characterized by large peak-to-average power ratios, making them an ideal candidate for deployment of hybrid battery-supercapacitor (SC) energy storage systems. Control of the bidirectional power flow between the SC buffer and the load is usually achieved by a simple half-bridge converter. Voltage ratio of the converter depends essentially on the State Of Charge of the SC buffer, since the battery voltage can be assumed to be almost constant. It is common practice to let the SC voltage vary between the rated voltage and 50% of the rated voltage, thus achieving 75% utilization of the energy stored in the buffer. This leads to a maximum voltage ratio of 2 in the converter, meaning that the power electronics switches used to build the half bridge must have a Volt-Ampere rating equal to at least twice the rated power that the SC buffer is designed to supply (or absorb).

In this paper, the converter in Fig. 1 is proposed, based on series connection of two SC banks and a half bridge across one of them. It is shown that such a converter can be built with switching devices having Volt-Ampere rating equal to the power rating of the SC buffer; that is half of what would be necessary if a standard half bridge topology is used. The 50% reduction of semiconductor rating is achieved without compromising the ability to control the bidirectional power flow and allowing for the same 75% utilization of the energy stored in the supercapacitors.

It is demonstrated that in the ideal case of lossless components, the voltage sharing between the series connected SC banks is determined by the topology itself, and does not depend on the particular shape of the load current:

\[ V_{SC1} = \sqrt{V_{SC1}^2 + \frac{C_{SC0}}{C_{SC1}} \left(2(V_{batt} - V_{SC0}(0)) \cdot \Delta V_{SC0} - \Delta V_{SC1}^2\right)} \]

This fact allows us to select the capacitance ratio so that both SC banks reach simultaneously the “fully charged” and “fully discharged” states, resulting in optimal energy utilization. In particular, by using a capacitance ratio:

\[ \frac{C_{SC0}}{C_{SC1}} = 3 \]

Both SC banks will charge and discharge between the rated voltage (selected equal to the battery voltage) and half of it.

Simulation results are reported to verify the validity of the approach.

In the practical implementation, losses in the components will cause the voltage sharing between the series connected SC banks to deviate from the ideal relationship. It is therefore necessary to use an auxiliary circuit to dynamically ensure the ideal sharing; such a circuit is made out of virtually lossless components and must be able to handle a tiny fraction of the power being exchanged between the load and the SC bank, since it only has to compensate for losses. Therefore, the balancing circuit does not significantly add to the overall system cost.

Experimental results (Fig. 2) are in very good agreement with the theory and with simulations. Thanks to the addition of a small, lossless equalization circuit, the SC banks are charged and discharged following a close to ideal voltage trajectory, achieving optimal utilization of the energy stored in the SC buffer, in spite of non-idealities like equivalent series resistance of SC cells, battery and inductor, on state resistance of switches and non stiff battery voltage.

The proposed topology is a valid alternative to standard half bridge, due to reduced converter cost and size (smaller devices, smaller inductor), and increased converter efficiency.

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Fig. 1. The proposed converter with reduced Volt-Ampere rating

Fig. 2. Experimental results of charge/discharge with arbitrary load current
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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.

Keywords: EDLC, DC-DC converter, ultracapacitor, energy management system

1. 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. 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. In Ref. (7), several types of bidirectional Power Electronics converters 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 kind of converter allows for bidirectional power flow, provided the SC voltage is kept lower than the battery voltage. In order to limit the current flowing into the switches of the converter, the voltage across the SC bank, who is widely dependent on the State Of Charge (SOC), is allowed to vary between the 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 Volt-Ampere rating of the semiconductor switches used in the converter, making it uneconomical to go below 50%, corresponding to 75% energy utilization and leading to a VA rating of each switch roughly equal to twice the power rating 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), and the energy extraction capabilities will also be the same. However, this solution is normally regarded as inconvenient, due to the following reasons. First, SC banks are made up of series connection of individual cells having each very low voltage rating (typically 2.5 V); higher voltage rating for the SC bank means therefore a larger number of individual cells to be connected in series, making the problem of voltage sharing more severe, and increasing system complexity. Moreover, if the SC bank is on the high voltage side of the converter, there will be some difficulties due to the inrush current that would

Based on “An Interface Converter with Reduced Volt-Ampere Ratings for Battery-Supercapacitor Mixed Systems” by Giuseppe Guidi, Tore M. Undeland and Yoichi Hori which appeared in the proceedings of the 2007 Power Conversion Conference—Nagoya. ©2007 IEEE.

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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 rating of the semiconductor switches that may not be apparent at first glance, while retaining full control over the power flow and achieving the same utilization of the energy stored in the SC bank.

2. 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 order to establish the operating principle of the converter, we start writing the mesh voltage balance in Fig. 3:

\[ V_{\text{batt}} = V_L + V_{\text{bridge}} + V_{SC,0} \]

(1)

If we assume that the energy stored in the filter inductor \( L \) is very small in comparison to the energy stored in the SC banks (as it is most likely the case), the short term average voltage across the inductor is zero, since the circuit is always in the dynamic steady state, as defined in Ref. (8). As a consequence:

\[ V_{\text{batt}} = V_{\text{bridge}} + V_{SC,0} \]

(2)

From Eq. (2), we can now evaluate the output voltage capabilities needed for the bridge.

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

\[ V_{SC,0,\text{Max}} = V_{\text{batt,Min}} \]

(3)

The bound in Eq. (3) is selected so to ensure that when the uncontrolled SC bank is fully charged, it will naturally be in equilibrium with the lowest possible battery voltage, with no contribution from the controlled bank, who should be fully charged, too, as it will be explained in a following section.

An additional design choice is to allow for maximum 50% discharge of the uncontrolled SC bank:

\[ V_{SC,0,\text{Min}} = \frac{V_{SC,0,\text{Max}}}{2} = \frac{V_{\text{batt,Min}}}{2} \]

(4)

As a consequence, the highest output voltage required from the bridge will be:
The voltage in Eq. (7) 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 Fig. 3 is equal to the maximum output current of the bridge, we can conclude that the VA rating of each switch 

\[ S_{SWHC} = V_{SC1, Max} \cdot I_{conv, Max} = 2 \cdot V_{batt, Max} - V_{batt, min} \]

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

For the sake of comparison, let us consider the half-bridge converter topology in Fig. 2(a), and let us assume that the battery voltage is stiff and has the same value as in the case of the proposed converter. In this condition, the voltage that the switches have to withstand is given by:

\[ V_{SWHB} = V_{batt} \]

It is well known that the energy stored in a capacitive device like an SC bank is given by:

\[ E_{SC} = \frac{1}{2} C_{SC} \cdot V_{SC}^2 \]

In order to minimize the needed capacitance for a given amount of energy storage capability, it is convenient to select the SC bank rated voltage equal to the battery voltage.

If we assume the converter to be lossless, then in steady state the power flowing at the AC side must be equal to the power flowing at the battery side:

\[ P_{SC, HB} = P_{HB, HB} \Rightarrow V_{SC} \cdot I_{SC} = V_{batt} \cdot I_{conv} \]

As a consequence of Eq. (10), in order to be able to transfer at least 75% of the total energy stored in the SC bank to the load, the voltage of the SC bank must be allowed to vary from its rated value to half of it. Applying Eq. (11) to this minimum voltage yields:

\[ I_{SC, Max} = \frac{V_{batt} \cdot I_{conv, Max}}{V_{SC, Min}} = 2 \cdot I_{conv, Max} \]

The current above is also the maximum current that must flow into the switches of the half-bridge. Therefore, combining Eq. (11) and Eq. (12), we get the required VA rating of the switches:

\[ S_{SWHB} = V_{batt} \cdot I_{SC, Max} = 2 \cdot V_{batt} \cdot I_{conv, Max} \]

Direct comparison of Eq. (13) with Eq. (8) shows a 50% lower VA rating for the switches of the proposed converter for the same power output. Following a similar approach, it can be proven that the converter in Fig. 2(b) has switches with the same VA rating as the one in Fig. 2(a).

3. Charge Balancing

Series connection of an uncontrolled SC bank 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 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 two SC banks will charge/discharge according to the well known law:

\[ V_{SC,x}(t) = V_{SC,x}(0) + \frac{1}{C_{SC,x}} \cdot \int_0^t I_{SC,x}(\tau) \, d\tau \quad x = 0, 1 \]

Due to the voltage constraint Eq. (2), the bridge output voltage is determined at each time, and can be expressed in terms of the duty cycle \( D \) of each switch:

\[ V_{bridge}(t) = D(t) \cdot V_{SC,1}(t) = V_{batt} - V_{SC,0}(t) \]

The current flowing through the uncontrolled SC bank is always equal to the inductor current, due to the series connection:

\[ I_{SC,0}(t) = I_{conv}(t) \]

On the other hand, average current flowing through the controlled SC bank over a switching period is related to the duty cycle of the bridge:

\[ I_{SC,1}(t) = D(t) \cdot I_{conv}(t) \]

Substituting Eq. (15)~(17) into Eq. (14), we can derive the differential equation relating the voltages across the two SC banks:

\[ V_{SC,1}(t) = \frac{C_{SC,0}}{C_{SC,1}} \cdot (V_{batt} - V_{SC,0}(t)) \cdot dV_{SC,0} \]

Such equation can be solved for any given set of initial conditions \( V_{SC,0}(0) \) and \( V_{SC,1}(0) \):

\[ V_{SC,1}(t) = \sqrt{V_{SC,1}(0)^2 + \frac{C_{SC,0}}{C_{SC,1}} \left(2(V_{batt} - V_{SC,0}(0)) \cdot \Delta V_{SC,0}(t) - \Delta V_{SC,0}^2(t)\right)} \]

with \( \Delta V_{SC,0}(t) = V_{SC,0}(t) - V_{SC,0}(0) \).
The most remarkable aspect of Eq. (19) is that the voltage (or, which is equivalent, the SOC) of the controlled SC bank is a function of the voltage across 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 banks 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 Eq. (4) and Eq. (7). From Eq. (19), we can calculate the capacitance required for the controlled SC bank, in order to satisfy the 50% discharge criterion:

\[
\frac{C_{SC,1}}{C_{SC,0}} = \frac{(V_{SC,0,Max} - V_{SC,0,min})(2V_{batt} - V_{SC,0,Max} - V_{SC,0,min})}{V_{SC,1,Max}^2 - V_{SC,1,min}^2} \]  

Selection of the bank capacitances according to Eq. (20) 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.

4. 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 Eq. (20). 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 in Fig. 4 show how the two banks discharge 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. The process is then reversed and the SC banks are charged with a different load current profile; again, they reach the “full” state simultaneously. In synthesis, the two SC banks behave exactly like a single SC bank 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 remarkable difference being that the result is achieved with a power electronics converter rated about half of the conventional.

5. 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 Ref. (9) and shown in Fig. 5. Dynamic balancing is responsible for keeping the voltage of the two banks in the theoretical relationship defined by Eq. (19), in spite of the several non-idealities of the real system. Some of the factors that would cause the voltages to deviate from Eq. (19) 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 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
6. Experimental Results

Figure 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 within ±2 A, with the SC bank providing or accepting all the rest. The system is designed to charge and discharge between lower and upper limits of 6.375 V and 12.75 V, 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 Eq. (19), 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 within ±1 A, which is less than one tenth of the peak value of the main charging-discharging current.

Figure 7 also shows what happens if discharge is not stopped when the voltage reaches the lower limit defined by the design. 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 supplied 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 tends to be 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, the phenomenon is self-limiting and 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; hence, during this voltage-balancing process, there is a dynamic equilibrium, as shown in Fig. 7.

7. 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 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.

(Manuscript received May 10, 2007, revised Oct. 18, 2007)

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