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Multilevel Modular DC/DC Converter for Regenerative Braking Using Supercapacitors

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Abstract: Regenerative braking is presented in many electric traction applications such as electric and hybrid vehicles, lifts and railway. The regenerated energy can be stored for future use, increasing the efficiency of the system. This paper outlines the benefits of the MMC (modular multilevel converter) in front of the cascaded or series connection of converters to achieve high voltage from low voltage storage elements such as supercapacitors. The paper compares three different solutions and shows that the MMC can benefit from weight and volume reduction of the output inductance when shifted switching modulation strategy is used. Using this modulation strategy, not only the output frequency is increased, but also the magnitude of the inductor applied voltage is reduced, reducing inductor size and volume.

Key words: Multilevel converters, power converters for EV, power converters for HEV, supercapacitors.

1. Introduction

The main advantage of using electric traction is that the motor that uses the energy is reversible. The braking energy can be stored for future use, instead of being dissipated in heat as in traditional mechanical braking systems. Regenerative braking is presented in many applications, such as battery or hybrid power cars and bikes [1], railway [2], lifts [3, 4] and many others.

Batteries are mainly used in mobile applications as energy storage devices instead of flywheels and superconductive magnetic storage systems because there are no moving components [5], whilst for high energy dynamics (or high power), as in regenerative braking applications, SC (supercapacitors) are preferred to batteries because of their higher power density and reliability [5, 6].

In battery powered applications, hybridization with supercapacitors is a choice in order to not degrade battery life and increase energy efficiency [7, 8]. Supercapacitors provide instant power while batteries provide constant energy. However, direct parallelization of supercapacitor and batteries has many drawbacks. To start with, there is no control on where the energy is being drawn as it depends on the resistance of the cables connecting one storage system to the other and to the regenerative power system. Also, as the batteries have a constant voltage, the supercapacitors will be kept at the same voltage level and, thus, without being able to store neither use the energy stored they have. To achieve higher energy management capabilities, a converter must be interfaced between supercapacitors and batteries in order to control the energy flux [9].

The regenerative system would be connected on the DC bus side before the inverter that drives the electric motor and would store the energy while maintaining the DC voltage constant.

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In regenerative braking applications, the connection of SC to the DC bus has to be studied and several possibilities can be taken into consideration.

SC are low voltage devices. To achieve the high voltages needed in traction applications, a large number of elements must be connected in series as depicted in Fig. 1. Moreover, with the direct series connection of SC cells depicted in Fig. 1, constant voltage at input stage of traction inverter is not achieved, and there is no capability of energy management in SC. Direct series connection of SC of different capacitance value can lead to voltage unbalances between cells because of the common series current. These voltage unbalances can produce overvoltage and destruction of cells. Passive and active, power electronics based, devices have been proposed in the literature to balance these voltages [10-13].

To reduce the number of serialized elements and to increase energy management capabilities, a two quadrant, bidirectional in current, converter can be placed between the traction converter and the SC as depicted in Fig. 2. By using this topology, less number of series connected SC is needed, there is control on the charge and discharge of the SC and the voltage at the DC bus can be kept constant [9].

However, this converter needs a big inductor in order to reduce current ripple at the SC side.

Higher efficiency can be obtained using an interleaved converter topology as depicted in Fig. 3 [14, 15]. This solution is widely implemented for low voltage high-current applications, but for traction applications, where high voltages are needed, cascaded DC/DC converters can be used [6, 16, 17].

This paper presents the comparison and design of a MMC (multilevel modular converter) for regenerative applications using supercapacitors. The proposed converter is compared in terms of inductor weight and size with two cascaded converters. Using MMC with shifted switching strategy significantly reduces inductor size and weight.

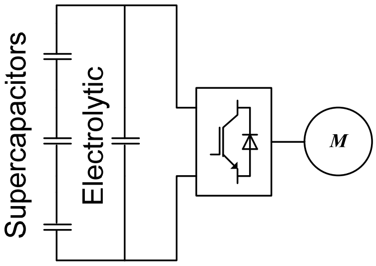

Fig. 1 Direct connection of supercapacitors to the high voltage DC link.

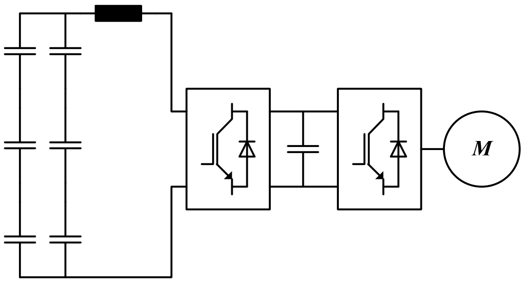

Fig. 2 Use of a boost converter to interface supercapacitors and the high voltage DC link.

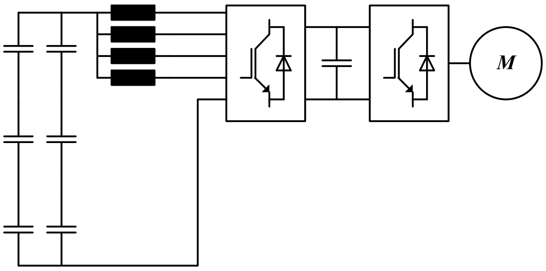

Fig. 3 Use of interleaved boost to interface SC and the high voltage DC link.

2. Cascaded and MMC Converters

Cascaded DC/DC converters split the power source in small parts, allowing multiple low voltage inputs and giving high voltage output. The energy management can be improved, because it can be independent for each energy source [7]. Cascaded buck and cascaded boost connection are depicted in Figs. 4 and 5, respectively, for the connection of three cells.

2.1 Cascaded Buck Converter (CBk)

In the cascaded buck the SC are placed on the high voltage side (U_{11}, U_{12} and U_{13}), while the SC bus is on the low side U_2. The operation of this converter is the same as for one of each cells that it holds, a half bridge buck converter, in which its output is controlled by the

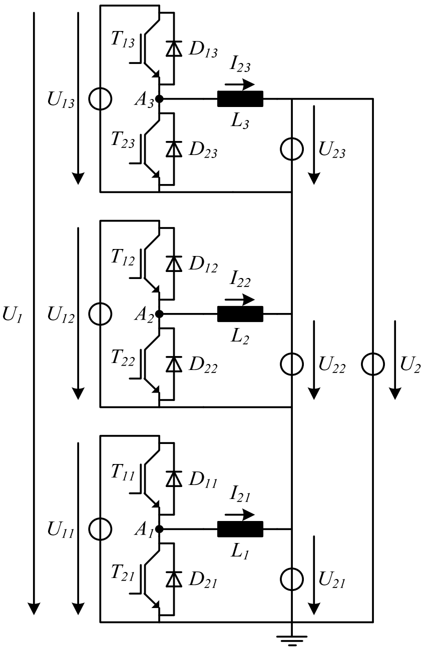

Fig. 4 3-cell cascaded buck.

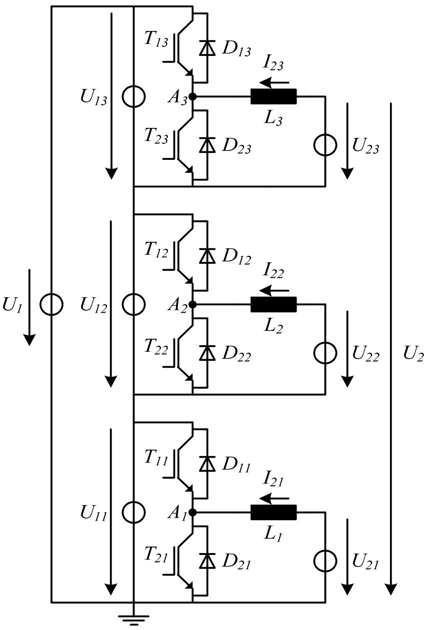

Fig. 5 3-cell cascaded boost.

duty cycles imposed. The whole converter output is the sum of every cell output voltages, allowing several redundancies that make this topology reliable and robust. However, if it is compared to a one cell converter of the same power, it can be seen that even if the inductance has been split in several inductances, the total weight and volume is the same if the switching frequency and ripple are equal. Thus, the benefits of this topology are the modularity and the high voltage achieved.

2.2 Cascaded Boost Converter (CBt)

In the cascaded boost, the SC are placed on the low voltage side (U_{21}, U_{22} and U_{23}), whilst the DC bus is on the high side U_1. Each cell of this converter is a half bridge boost converter that varies its output voltage depending on the duty cycle applied to its transistors. The whole converter output voltage is the sum of each cell output voltage.

To achieve the same DC voltage and power, in this converter double current is needed in contrast to CBk, and half the voltage in the SC. However, if it is compared to a one cell equivalent converter, as done with CBk, the total inductance will be the same, and the benefits of multiple cascaded cells are the same as before.

2.3 MMC (Multilevel Modular Converter)

The multilevel buck converter is the series connection of half bridge cells as depicted in Fig. 6. The SC are connected on the high voltage side (U_{11}, U_{12} and U_{13}) while the DC bus is on the low voltage side U_2. The output voltage can be synthesized as the addition of the output voltage of each cell, but in this case a modulation strategy can be used in order to increase the output frequency.

Using shifted switching modulation strategy [18], the frequency of the voltage applied to the inductor is multiplied by the number of series connected converters, reducing inductors' size.

Every triangular carrier of each one of the comparators is delayed 360°/N respect the cell before, where N is the number of cells. Thus, at the output of the converter it can be seen a frequency of $N \times F_s$ (F_s is the switching frequency). Its behaviour can be seen in Fig. 7.

The output inductance can be computed as:

$$L = \frac{(U_{max} - U_{min})(1 - D_{eqmax})D_{eqmax}}{\Delta I_2 \times F_{eq}} \quad (1)$$

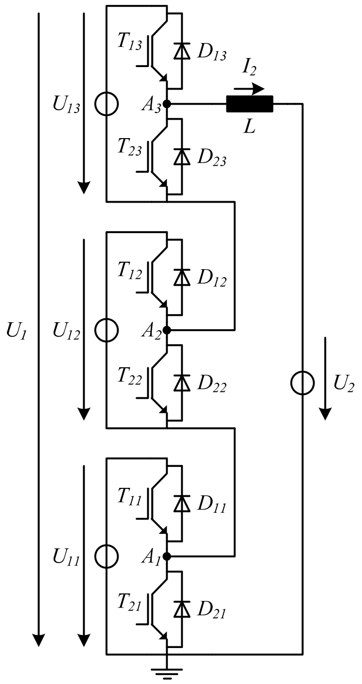

Fig. 6 3-cell multilevel buck.

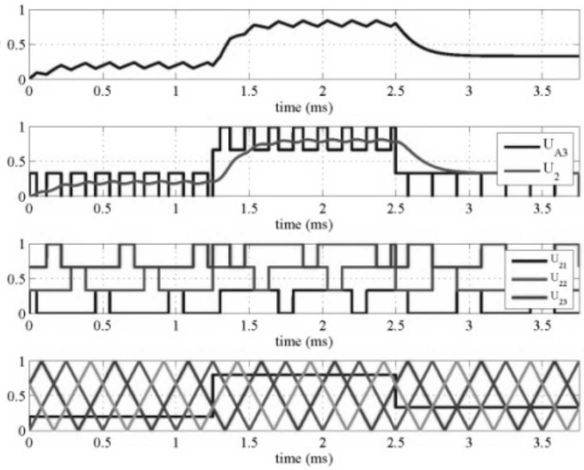

Fig. 7 Voltages, currents and switching signals for a three cells converter.

where, $D_{eqmax} = 0.5$ is the equivalent duty cycle where the maximum ripple occurs, ΔI_2 is the outputinductor ripple and $F_{eq} = N \times F_s$. U_{max} and U_{min} are defined as:

$$U_{max} = N \times U_{1N} \left(D - Dmod \frac{1}{N} + \frac{1}{N} \right) \quad (2)$$

$$U_{min} = N \times U_{1N} \left(D - Dmod \frac{1}{N} \right) \quad (3)$$

$U_{1N} = \frac{U_1}{N}$ is the one converter input voltage and D is the duty cycle.

As seen in these equations and in Fig. 7, increasing the number of series connected converters reduces the voltage across the inductor and increases the frequency, for a fixed switching frequency and inductor ripple.

That reduces the needed inductor value for a fixed inductor current ripple.

2.4 Converter Input Current Filter

The cascaded buck and the multilevel buck topologies presented in this paper have the drawback that the input current, i.e. the SC current, has a high frequency harmonic content due to switching.

SC degrade its capacity performance for frequencies above 100 Hz, where the capacity value is near zero, and behaves as a resistor, producing only loses, reducing its lifetime [9]. To reduce these harmonic currents, an input LC (series inductor, parallel capacitor) filter must be added as depicted in Fig. 8. This LC filter reduced voltage and current ripple in SC, but increased the magnetic elements of the topology, increasing weight and size [19].

The size of the capacitor and the inductor of the filter have to be chosen in dependence to the switching frequency. A cut-off frequency five times smaller is a good start. In Fig. 9 the pairs LC for a switching frequency of 20 kHz can be seen. The smaller the frequency, the bigger the value of both elements is.

It has to be noticed that the filter capacitor will have to support the current ripple, so the limitation of this filter may be this element, but in order to set a reference value, a inductance of 1% the value of the equivalent one cell converter will be chosen, and the capacitor to obtain a cut-off frequency below $F_s/5$.

3. Topology Comparison

To determine the proper number of series connected cells, the total magnetic energy needed in the inductor for the three topologies can be compared.

The three topologies are compared assuming constant inductor current ripple, constant frequency, and supposing a filter inductor value of 1% of the one cell output inductor.

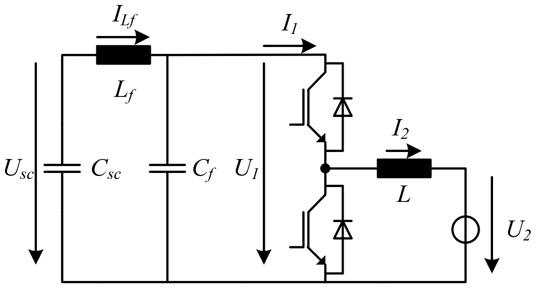

Fig. 8 LC input current filter to reduce current harmonic content in supercapacitors.

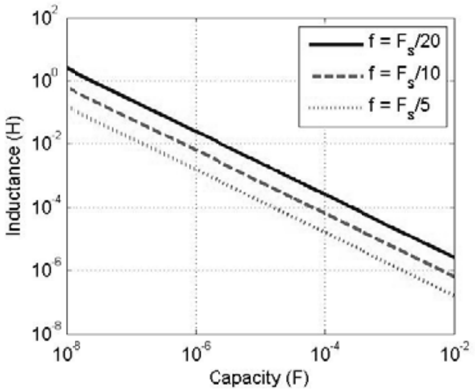

Fig. 9 L and C pairs in function of the cut-off frequency.

The base value for the comparison is the total magnetic energy stored for the equivalent half bridge converter (HB), where the inductance value is calculated by:

$$L_{HB} = \frac{U_1(1-D)D}{\Delta I_2 F_s} \tag{4}$$

And the total energy stored by:

$$E_{HB} = \frac{1}{2} L I_2^2 \tag{5}$$

Supposing that the switching frequency and the output current are maintained constant, the total inductance for the cascaded buck converter (CBk) can be computed as the addition of the output inductance of each converter and the inductance of each input filter as shown when $U_1 = 2U_2$ $(D = 0.5)$.

$$L_{CBk} \propto \frac{1}{N} N + 0.01N \tag{6}$$

$$E_{CBk} \propto 1 + 0.01N \tag{7}$$

Each cell inductor is reduced 1/*N*, but because there are *N* series connected converters, the total inductance is the same, plus the filter inductance. The needed inductance is only divided in small parts.

For the cascaded boost converter (CBt) the total inductance can be computed as:

$$L_{CBt} \propto \frac{1}{4N} N \tag{8}$$

$$E_{CBt} \propto 1 \tag{9}$$

Because the voltage is the half of the buck derived topologies but the current is doubled, and there is no filter needed for the SC. ($U_1' = 2U_2'$ but now U_1' is the DC bus that was U_2 in the CBk and $I_2' = 2I_2$.)

For the multilevel buck, the inductance can be computed as:

$$L_{MBk} \propto \frac{1}{N^2} + 0.01N \tag{10}$$

$$E_{MBk} \propto \frac{1}{N^2} + 0.01N \tag{11}$$

Here, the reduction is higher as increasing the number of series connected converters, because the reduction is due to lower voltage, but also higher frequency. Fig. 10 shows the total inductance as a function of the number of series connected converters.

As it can be seen, the total inductance for the cascaded buck converters increases as the number of series connected converters increase because the input filter inductance is increased. On the other hand, the total inductance of the cascaded boost remains constant and its value is the same as for the HB for one channel because there is no need of input filter inductance, and the voltage across the inductors is the half. It must be said that for the boost topology, the current in the inductor will be higher than for the buck derived topologies, thus, considering constant power the amount of copper will be bigger but the amount of ferrite will be smaller. In average, the mass and volume will be approximately the same as in the HB inductance.

As it can be seen in Fig. 10, the minimum for the total inductance is achieved by the multilevel buck topology for a six cell converter.

4. Verification

In order to show the important differences between the size and volume of one inductor in the case of one

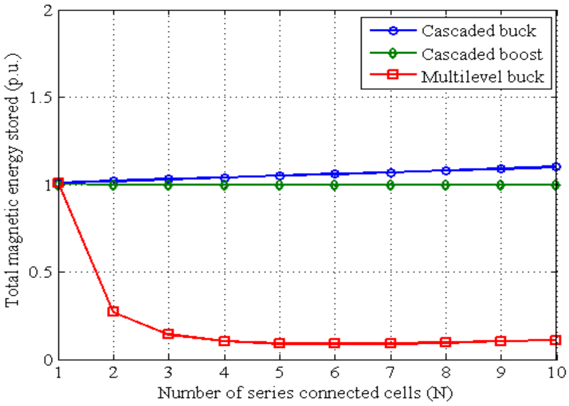

Fig. 10 **Magnetic energy as a function of series connected cells for the three proposed topologies.**

cell converter and the inductor needed for a six cell multilevel buck converter, both inductances have been sized and calculated for a converter working between $U_1 = 97.2$ V and $U_2 = 42$ V with a nominal current of $I_2 = 5$ A.

For the one cell, half bridge converter (HB) the inductance value can be computed assuming a ripple of the 15% of the nominal current and a switching frequency of 20 kHz.

$$L = \frac{U_1(1-D)D}{\Delta I_2 F_s} = 1.26\,mH \qquad (12)$$

On the other hand, for the six cell multilevel buck (MBk) the value needed is depicted by:

$$L = \frac{U_1(1-D)D}{\mathrm{N}^2 \Delta I_2 F_s} = 45\,\mu H \qquad (13)$$

The number of turns needed in the inductor with a saturation current of 6 A can be obtained with:

$$N = \left\lceil \frac{L\, I_{sat}}{B_{sat} A_e} \right\rceil \qquad (14)$$

For the HB, 58 turns are needed if E55/28/21 ferrite core is used, but for the MBk eight turns are needed if the RM10/ILP ferrite core is used. Computing the amount of copper wire needed, Table 1 can be obtained.

The mass of copper has been calculated supposing a current density of 5 A/mm^2 and four wires of 0.25 mm^2 for each turn, with copper density and the average perimeter stated in the cores datasheet.

The RM10 inductor is 13 times lighter and needs 19 times less volume than the needed for E55. As seen in Fig. 10, the relationship between 1 and 0.088(which is the value at 6-cell MBk) is kept by the relationship between the two ferrite masses, which is 0.079.

Table 1 **Comparison between inductors.**

Model	N (turns)	v (mm^3)	m_{Fe} (g)	m_{Cu} (g)
RM10	8	4,247	17	3.72
E55	58	81,670	216	60.15

5. Conclusions

This paper shows that multilevel converters can be used in mobile DC/DC applications not only to increase the efficiency of the power electronics system itself, but to reduce the weigh and volume of the system. The paper presents and compares three topologies in terms of magnetic energy, which is directly related with the volume of the magnetic components. This comparison shows that the best topology is the multilevel buck converters, because it beneficiates not only from voltage reduction, but also from frequency increase if shifted switching strategy is used.

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