7 level Modular Multilevel DC/DC Converter

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Abstract: - Energy-storage systems (ESSs) play an important role in electric vehicle (EV) and hybrid EV (HEV) applications. In the system, supercapacitors are preferred for high power buffer and regenerative braking energy storage because it has the advantages of high power density, long life cycles, and high efficiency. While in the high-voltage application, the super capacitors are employed in series, and the voltage unbalance issue must be taken care of. This paper proposes a modular multilevel dc-dc converter using IGBT as the semiconductor device. The main advantage of this circuit is the reduced number of inductor components, compact size and reduced power losses. This circuit acts as a bi-directional power source or converter. It is shown that the modular multilevel dc-dc converter (MMC) can benefit from both reduced voltage and increased frequency across the inductor to reduce its weight and volume. The use of super-capacitor helps in balancing the voltage in the circuit. The simulation and experiment results validate the feasibility of the proposed equalization circuit.

I. INTRODUCTION:

SUPERCAPACITORS represent one of the latest innovations in the field of electrical energy storage, and will find their place in many applications where energy storage can help to smooth strong and short duration power solicitations of a distribution network. In comparison with conventional capacitors, these new components allow a much higher energy density, together with a high power density. Fig. 1 illustrates the amount of storable energy in an electrochemical double-layer (ECDL) super capacitor in comparison with a conventional electrolytic capacitor of similar size. Even if the energy density is not comparable to that of electrochemical accumulators, the possible amount of stored energy and storage time are compatible with many industrial requirements. In transportation systems, as a first example, the energy needed by the bus between two stops can easily be transferred from a fixed super capacitive storage tank to another one placed on the bus during passenger transfer time. It allows for the use of electrical propulsion without overhead lines (trolleys). Other complementary storage systems for a better sharing between energy and instantaneous power have also been described [1], as well as super capacitor tanks as boosters for fuel-cell powered passenger cars. This paper presents how super capacitors can be used for power smoothing in various applications or regenerative breaking.

Regenerative braking is not only present in electric vehicle (EV) or hybrid vehicle. A regenerative brake is an energy recovery mechanism which slows a vehicle or object down by converting its kinetic energy into another form, which can be either used immediately or stored until needed. Many electric traction applications such as elevators and railway can also benefit from regenerative braking. Regenerative braking in any type of mobility application (hybrid and EV cars, trams, buses, cranes, and forklifts) is one of the main applications. They can fit also in heavy diesel engines as a power sources when starting or in start/stop applications. In mobile applications, SCs are often paired with batteries in order not to degrade their life, to increase efficiency, and to provide instant power whenever it is demanded.

For mobile applications, a high-power dc/dc converter is a key element that interfaces ESS with the dc bus in the power train of the HEVs. Therefore, the dc system with
multiple dc/dc converters may play an important role in the future power train system. The topology design of dc/dc converters has been documented in many pieces of literature [2]. In addition, the design of high-power dc/dc converters and their controller play an important role to control power regulation particularly for a common dc bus. In this configuration, the super capacitor is connected to the dc bus or source through a boost converter, whereas the ESS is connected to the dc bus via a bidirectional dc/dc converter. It allows a desired level of dc voltage to be obtained. In high-power boost converters, the major design aspect is the selection of the boost inductor and the output capacitor.

In this paper, a multilevel buck-boost converter has been studied and analyzed to reduce the size and weight of the passive components, such as the inductor, capacitor, and input/output electromagnetic interference (EMI) filter. Meanwhile, the input current ripple and output voltage ripple can be minimized with high efficiency and reliability. Furthermore, the proposed multilevel converter will be compared to other dc/dc converter topologies to investigate its dynamic response. Simulation and experimental results are provided.

II. LITERATURE SURVEY


Power variations and energy criteria have been the main motivations for developing regenerative drive converters for elevators. A better performing solution for power smoothing can be easily found by using a supercapacitor-based storage device, connected to the intermediary circuit of a variable-speed-drive system. In this paper, power and energy considerations are being accounted for in the design of the storage tank and regarding the maximum power demand from the feeding network. For the power-conversion circuit, which is necessary to compensate the voltage variations of the supercapacitors during charge and discharge, a high-efficiency converter, topology is proposed, which allows the bidirectional energy flow under soft-commutation conditions. Additionally it offers a good flexibility for the optimal sizing of the supercapacitor voltage level. The typical behavior of the special converter is given, together with an analysis of the advantages related to the specific application.


This paper proposes a novel multidevice interleaved boost converter (MDIBC) that interfaces the fuel cell with the powertrain of hybrid electric vehicles. In this research, a multidevice structure with interleaved control is proposed to reduce the input current ripples, the output voltage ripples, and the size of passive components with high efficiency compared with the other topologies. In addition, low EMI and low stress in the switches are expected. The proposed dc/dc converter is compared to other converter topologies such as conventional boost converter (BC), multidevice boost converter (MDBC), and two-phase interleaved boost converter (IBC) to verify its dynamic performance. Furthermore, a generalized small-signal model is derived for these dc/dc converters, which has not been previously discussed. A digital dual-loop control is designed to achieve the proper regulator for the converters with fast transient response. The dc/dc converter topologies and their controller are designed and investigated by using MATLAB/Simulink. The simulation and experimental results have demonstrated that the proposed converter is more efficient than other dc/dc converter topologies in achieving high performance and reliability for high-power dc/dc converters.


Energy-storage systems (ESSs) play an important role in electric vehicle (EV) and hybrid EV (HEV) applications. In the system, an ultracapacitor is preferred for high power buffer and regenerative braking energy storage because it has the advantages of high power density, long life cycles, and high efficiency. While in the high-voltage application, the ultracapacitors are employed in series, and the voltage unbalance issue must be taken care of. This paper presents a novel circuit for equalizing a series ultracapacitor stack, which is based on a dc-dc converter. The proposed voltage-equalization circuit derives energy from the series ultracapacitor stack and transfers them to the weakest ultracapacitor cell. The equalizer balances the whole stack by sequentially compensating the weak ultracapacitor cells. Unlike previous methods for battery-storage systems, which include complex circuit detecting and comparing the voltages of capacitor cells, the novel equalizer can realize autonomic voltage equalization without voltage detection and comparison, and it is more efficient with the soft switching method, which is a benefit for high-power applications in EV/HEV. The simulation and experiment results validate the feasibility of the proposed equalization circuits.


Ultracapacitors have numerous advantages including remarkably high energy density as compared with conventional capacitors, long life cycle, temperature stability, and require no maintenance, which make them a good candidate to replace batteries as energy storage devices in renewable energy applications. However, ultracapacitors, just like conventional capacitors, inevitably suffer from constant voltage drop during discharging, which may limit their energy utilization, increase the voltage ripple of the DC bus across which the capacitors are connected and consequently increase the VA stresses of the subsequent converter stage. To alleviate the above limitations, parallel-series
ultracapacitor shift circuits are employed to improve the energy utilization and minimize the DC bus voltage ripple. Two generalized parallel-series ultracapacitor shift topologies are presented and analyzed, and some design considerations and optimization methods are discussed.


In the transportation field, the empty weight of the vehicle has to be as light as possible in order to have the highest energetic efficiency. For onboard storage electrical systems, DC/DC converters are usually used to control the power flows in the vehicle. This paper focuses on two different DC/DC converter applications: high current/low voltage on the one hand and low current/high voltage on the other hand. For all power mobile applications, a standard dc/dc converter is not realizable due to mass and volume constraints. As the inductor is usually the biggest and heaviest component in the system, it is important to develop a new structure allowing the reduction of its size and weight. The chosen technology is based on interleaved channels operating in discontinuous mode, also using reverse conduction of power MOSFET transistors. For both of the cases described above, a prototype has been built composed of 8 and 4 channels respectively. The first converter is used for power assistance (250 A/18 V) using the MOS reverse conduction property. In this particular case, efficiency is up to 96.3%. The second is developed for a mobile solar application (3.8 A/270 V). Efficiencies are up to 98.4%.


Interleaving technique is used in some applications due to its advantages regarding filter reduction, dynamic response, and power management. In dual battery system vehicles, the bidirectional dc-dc converter takes advantage of this technique using three-to-five paralleled buck stages. In this paper, we propose the use of a much higher number of phases in parallel together with digital control. It will be shown that this approach opens new possibilities since changes in the technology are possible. Thus, two 1000-W prototypes have been designed using surface mount technology devices (SO-8 transistors). An additional important feature is that due to the accuracy of the digital device [field-programmable gate array (FPGA)], current loops have been eliminated, greatly simplifying the implementation of the control stage.

Existing Circuitries and Limitations

Direct parallelization of SC and batteries as mentioned (for mobile applications) has many drawbacks. There is no control on where the energy is flowing from or to and also the voltage at which the capacitors are connected is almost constant. Therefore, SCs are not used as an energy source but as a powerful decoupling capacitor, which is not what it is intended for. To achieve energy management capabilities, a converter has to be placed to control the energy flow in an SC.

SCs are low-voltage devices. To achieve the high voltage needed in traction applications, a large number of cells have to be connected in series. This series connection can cause voltage imbalances due to the difference in capacitance of each SC cell because of common series current. These imbalances could cause premature failure of the SC or even destruction of cells. Commercially available SC banks reach voltages up to 200 V, but active voltage-balancing methods must be used.

Proposed Method

Fig. (1) PV Cell/fuel cells:

Fuel cells are electrochemical devices and are by nature more effective. There is a short chain of energy conversion: chemical energy of the fuel is directly converted into electrical energy without combustion. The chemical reactions of hydrogen and oxygen taking place in fuel cells in the presence of a catalyst lead to production of electric energy. Water is only a by-product of this action. Maximum efficiency of hydrogen fuel cells reaches 70% and is available at low power (0.15-0.30 of maximum power). High efficiency is achieved, because the fuel cell is not limited by temperature. This is a very advantageous characteristic enabling high exploitation of energy at small and medium loads of propulsion system – which is often the case in city traffic. The advantages of fuel cells are also their size, similar to that of combustion engines, and the possibility to function on different fuels (gasoline, hydrogen, methanol). Assuming that the current fuel distribution infrastructure should be maintained, it would be desirable to use petroleum-derived, liquid hydrocarbon fuels as a source of hydrogen for fuel cells.

Regenerative fuel cell offers advantages where long term storage is required such as standalone power supply system powered by solar energy or uninterruptible power supply systems (UPS). Eg: Super Capacitors.

DC to DC Converter:

The purpose of a DC-DC converter is to supply a regulated DC output voltage to a variable-load resistance from a fluctuating DC input voltage. DC-DC converters are also used to provide a regulated variable DC voltage.
for DC motor speed control applications. The output voltage in DC-DC converters is generally controlled using a switching concept. The converter is made from the series connection of HBs. It has only one inductor for the whole converter. That makes the converter as a unique converter, not the series connection of converters as in cascaded converters. MMCs are mainly used in HVDC systems because its modularity allows high voltage levels. In this paper IGBT is used as a switching element.

PWM Generation:
The modulating signal is a stepped wave. The stepped wave is not a sampled approximation to the sine wave. It is divided into specified intervals with each interval controlled individually to control the magnitude of the fundamental component and to eliminate specific harmonics. This type of control give low distortion, but higher fundamental amplitude compared with normal PWM control.

Controller Circuit:
The converter is aimed to store the regenerative braking energy in the SCs and release it when needed. This power flow can be easily controlled by controlling the current in the output inductor. Another control objective of the converter is to equalize the energy stored in the SCs. That can be done by controlling SC voltage to be the same value. Balancing is crucial to obtain constant current ripple at the output inductor. From the inductor current controller point of view, the modular multilevel dc/dc converter can be seen as a HB converter.

Voltage and Current Measurement:
The current and voltage measurement elements are placed at the output to measure the output current and voltage.

Load: Eg: Motors

CASCADED AND MMCS

Two quadrant dc/dc converter is needed in regenerative applications with energy storage in SCs. When braking, the energy flows into SCs, but when in the traction mode, the energy flows from SCs to the load. All the converters presented in this paper are based on the HB topology shown in Fig. Some authors propose the cascaded connection of multilevel neutral point clamped or flying capacitor converter to achieve higher number of levels at the output (4).

HB Converter:

Fig. 2(a) shows the HB converter topology. It is built with two transistors, with its antiparallel diodes, connected in series. This converter connects two voltages \( U_1 \) and \( U_2 \) by an inductor \( L \). The HB converter is irreversible in voltage, but bidirectional in current. The transfer functions that relate the two voltages and the two currents when the converter is working in the continuous conduction mode are

\[
U_2 = D \cdot U_1 \quad (1)
\]
\[
I_1 = D \cdot I_2 \quad (2)
\]

where \( U_1 \) and \( U_2 \) are the voltage levels in each side of the converter defined in Fig. 2(a), \( 0 \leq D \leq 1 \) is the duty cycle, and \( I_1 \) and \( I_2 \) are the two currents in each side of the converter.

![Fig 2 Topology and typical current waveforms for an HB converter](image_url)

As can be seen in Fig. 2(a), the condition \( U_1 \geq U_2 \) must be always satisfied for proper converter operation. For a given input voltage \( U_i \) and switching frequency \( F_s \), the maximum inductor current ripple \( \Delta I_L \) occurs for \( D = 0.5 \). Then, the value of the inductor can be calculated as [5]

\[
|L_{HB}| = \frac{U_1}{4 \Delta I_L F_s}.
\]

As can be seen in Fig. 2(b), the current waveform at voltage source \( U_i \) has severe ripple. The dc bus and the SCs can be connected either to \( U_1 \) or \( U_2 \). In regenerative braking applications, dc bus voltage is supposed constant, while SC voltage changes in order to store or release energy. In this paper, when the SCs are connected to \( U_1 \), the converter is said to work in the buck mode, because it reduces the SC voltage to the dc-bus voltage, and when connected to \( U_2 \), it is said that the converter works in the boost mode, because it elevates the SC voltage to the dc-bus voltage. SCs are normally operated between rated voltage and half of the rated voltage because within this voltage range, they deliver 75% of the energy stored [6]. For constant power operation, SC current is lower, increasing efficiency.

![Fig (3) Evolution of the voltages and duty cycle for the buck and boost mode converter when discharging the SC](image_url)

As shown in Fig. 3(a), when working in the buck mode, the SCs are fully charged at \( 2U_{DC} \). The initial converter
duty cycle is 0.5, but as the SCs are discharged, its voltage decreases, and the duty cycle increases up to the maximum value of 1. In this discharge process, the inductor current is maintained constant to \( I_{dc} = (I_2) = (I_{SC}) \) when the power level at the dc bus is maintained constant.

As shown in Fig. 3(b), when working in the boost mode, the initial full charge voltage of the SCs is the same as the dc-bus voltage. When SCs are discharged, its voltage is reduced to half of the dc-bus voltage, and the duty cycle is also decreased down to 0.5. In this discharge process, the average inductor current \( (I_2) = (I_{SC}) \) will become twice when the power level at the dc bus is maintained constant compared to the buck mode.

Cascaded and modular multilevel dc/dc converters split the converter into smaller modules or cells, allowing multiple input and output voltage and current levels, and switching frequencies. Each module can be operated independently. In these topologies, redundancy in combination with hot-swap capability of modules can be achieved. When splitting the power sources, the energy management can be improved because it can be independent for each energy source [7]. However, in this paper, equal modules are supposed. The cascaded and multilevel converters proposed here are the series connection of HB converters.

Depending on where the SCs are connected and how the HB converters are arranged in three topologies i.e: cascaded buck (CBk), cascaded boost (CBt), and the modular multilevel dc/dc converter (MMC). Here our focus is on modular multilevel dc/dc converter.

Modular Multilevel DC/DC Converter (MMC)

The modular multilevel dc/dc converter is shown in Fig. 4(c). The converter is made from the series connection of HBs. It has only one inductor for the whole converter. That makes the converter as a unique converter, not the series connection of converters as in cascaded converters. MMCs are mainly used in HVDC systems because its modularity allows high voltage levels [8]. In the proposed converter, the application to HVDC systems can be as an energy storage system.

In the modular multilevel dc/dc converter proposed in this paper, the SCs are connected in the high-voltage side \( U_1 \). The output converter voltage \( U_2 \) is the addition of each output voltage \( U_{AN} \) that depends on the switching state of each HB and modulation strategy used. Each HB has a \( U_{SCN} = U_{SC}/N \) voltage level.

Several modulation strategies exist for this type of converters. In this paper, phase shifting modulation is used because it offers several advantages over others. As can be seen in Fig. 4, using this modulation strategy, the triangular pulse-width-modulated (PWM) carriers are shifted \( 360°/N \) with respect to the next HB. The frequency seen by the inductor is \( N \) times the HB switching frequency, \( F_{eq} = N \cdot F_s \), and the applied inductor voltage is only \( U_{SCN} \) [10].

![Fig (4) Three level example of a MMC](image)

![Fig (5) Typical waveform of a multilevel dc/dc converter](image)

These are the main benefits of using this modulation strategy for the modular multilevel dc/dc converter. Because it is a buck-type converter, when the SCs are fully charged, \( \text{USCN} = 2U_{DC}/N \). Then, the inductance \( L_{MBkN} \) can be computed as \( L_{MBkN} = U_{DC} \cdot 2 \Delta I_{2FsN2} \). It has to be noted that the inductor value
reduction depends on the square of the number of series-connected HBs.

SC Considerations: Input Filter

As said previously, SCs can be connected in the high-voltage side $U_1$ or in the low-voltage side $U_2$. But as can be seen in Fig. 2(b), when connected to the low-voltage side $U_2$, the inductor and SC current ripple is smaller compared with when connected to the high-voltage side $U_1$. SCs cannot attenuate high-frequency currents. They behave as a resistor for frequencies above 100 Hz [11]. Therefore, when connected to the high-voltage side, filters must be installed [8]. LC filters are used because of low losses and simple design [11]. CBk and modular multilevel dc/dc converters need filters for SC current. Fig. 6 shows the LC filter used to filter input currents in SCs. An attenuation of approximately $-30$ dB can be easily obtained with an $L_f$ of 1% of the HB one-level converter inductor, and a filter capacitor $C_f$ for a cutoff frequency five times smaller than the switching frequency [12]. When using filter in the SCs in the CBk and modular multilevel dc/dc converter, losses in SCs are reduced by a factor of $D$ [12], but the inclusion of this filter can cause input disturbances to the controller [13].

CONVERTER CONTROL

The converter is aimed to store the regenerative braking energy in the SCs and release it when needed. This power flow can be easily controlled by controlling the current in the output inductor $I_L$. But this reference level for output current is fixed by a higher level control system that is out of the scope of this paper. Another control objective of the converter is to equalize the energy stored in the SCs. That can be done by controlling SC voltage to be the same value. Balancing is crucial to obtain constant current ripple at the output inductor. From the $I_L$ controller point of view, the modular multilevel dc/dc converter can be seen as a HB converter, as shown in Fig. 9. Common techniques can be used to design the controller $G_c$. The converter is a first-order RL system that can be defined as

$$G_c(s) = \frac{1}{1 + s \frac{L}{R}}.$$  

First-order systems can be controlled with zero steady-state error using a proportional-integral (PI) controller. Here, the controller is tuned using an indirect matrix converter method where $K_p$ and $K_i$ are selected as [1], [32]

$$K_p = \alpha \cdot L$$  \hspace{1cm} (17)  

$$K_i = \alpha \cdot RL$$  \hspace{1cm} (18)

where $\alpha$ is selected to fix the 10–90% rise time $t_r$ as

$$t_r = \frac{\ln 2}{\alpha}.$$  

Simulation Parameters

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<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>Value</th>
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<tbody>
<tr>
<td>$F_s$</td>
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<tr>
<td>$F_{exec}$</td>
<td>Control execution frequency</td>
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<td>$U_1$</td>
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<td>$U_2$</td>
<td>Output voltage</td>
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<tr>
<td>$C_{ac}$</td>
<td>SC capacity</td>
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<tr>
<td>$ESR_{ac}$</td>
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<td>IGBT On resistance</td>
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<td>$U_{drop}$</td>
<td>IGBT voltage drop</td>
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<tr>
<td>$t_r$</td>
<td>Rise time (controller)</td>
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Experimental Parameters

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<td>$ESR_{SC}$</td>
<td>SC ESR</td>
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Seven Level Modular Multilevel dc/dc Converter:

Model And Simulation results:
Advantages

The proposed circuitries reduce the output inductor size and weight and can achieve voltage balancing in SCs. A phase shift switching modulation strategy in modular multilevel dc/dc converters allows for lower voltage level and higher frequency voltage applied to the inductor, reducing its size and weight. Equal voltage module is a must in modular multilevel dc/dc converter to maintain current ripple when the phase shift switching modulation strategy is used. It is also needed to balance the stored energy in SCs. The voltage-balancing loop proposed here balances the voltage even when SCs are charging or discharging.

CONCLUSION

This paper has presented a modular multilevel dc/dc converter to be used in regenerative applications with SCs. The main objectives of reducing output inductor size and weight and achieving voltage balancing in SCs are accomplished.

REFERENCE


