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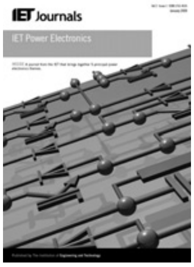

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Bi-directional power management and fault tolerant feature in a 5-kW multilevel dc–dc converter with modular architecture

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Abstract: A 5-kW multilevel modular capacitor-clamped dc–dc converter (MMCCC) with bi-directional power management and real-time fault bypassing capability will be presented in this study. The modular structure of the MMCCC topology was utilised to build this 5-kW converter with necessary redundancy and hot swap feature for industrial and automotive applications including a future plug-in hybrid or fuel-cell powered all electric vehicles. Moreover, the circuit has flexible conversion ratio that leads to establish bi-directional power management for automotive applications mitigating the boost voltage for the fuel-cell or dual battery architecture. In addition, the MMCCC exhibits better component utilisation compared to many capacitor-clamped or classical dc–dc converters based on inductive energy transfer mechanism. Thus, the MMCCC circuit can be made more compact and reliable compared to many other dc–dc converters for high-power applications.

1 Introduction

The use of power electronic converters has gained momentum in industrial and automotive applications especially in future plug-in hybrid or all-electric automotive research. Recent developments in high-temperature semiconductors including high-temperature switching devices [1, 2] and gate drives [3] facilitate the design of various high-temperature dc–dc converters, inverters and other power electronic converters suitable for future automobiles. The robustness of wide band-gap semiconductors [4] and high-temperature tolerant ancillary circuits permits the use of more power electronic converters for various applications inside future automobiles. Therefore a great propensity of using higher numbered power electronic converters has already begun inside present day's vehicles to mitigate the need for an ever-increasing number of electronic appliances (essential and luxury components) [5, 6]. As a result, the present vehicle electrical power system has to provide power to a plethora of modern appliances, and it is anticipated that the standard 14-V bus will require some alternative and sustainable solutions to generate high power for additional dc loads in the near future [5, 6].

A 42-V/14-V bus system named as '42V Power Net' was proposed several years ago [6]. In this architecture, there will be two voltage buses in the electrical system of a vehicle. Some electrical loads will be connected to the 42-V bus, and some of the existing electrical loads will remain connected to the 14-V bus. This system might have one or two sets of batteries; one for 14-V and one for 42-V bus. In both cases, there will be a bi-directional converter that will manage power flow between the two voltage buses. In this way, loads connected at the 42-V bus can be powered from the battery connected on the same bus or from the 14-V bus [7–9]. This is also true for the loads connected at the 14-V bus.

The development of a compact, high-efficiency dc–dc converter can introduce several modifications and advancements to the overall automobile design. The overall performance of the bi-directional dc–dc converter will be a large factor in determining if the 42 V/14 V dual bus system will be a successful and cost effective solution for future automobiles. Especially in automotive applications where high ambient temperature (∼150°C) under hood is present, conventional dc–dc converters with magnetic elements can be very inefficient, and dc–dc converters with bulky inductors can suffer from limited space issue [10].

The other criterion that needs to be fulfiled from this bi-directional converter is high efficiency even in partial loads. Classical dc–dc converters based on inductive energy transfer method (IETM) suffer from limited efficiency at partial loads, and the maximum efficiency is achieved at full load. Thereby, a new dc–dc converter having an operating principle other than IETM converters could be advantageous. Several capacitor-clamped multilevel dc–dc converters with isolated and non-isolated architecture [7–20] can be considered as a solution to meet this criterion to achieve high efficiency operation and bi-directional power handling capability.

Bi-directional power management is an important attribute of a dc–dc converter used in several applications. In a future plug-in hybrid or fuel-cell automobile, there are various electrical loads that may be grouped into two main categories depending on the voltages they use. Fig. 1 shows the typical arrangement of the power electronic modules in a fuel-cell vehicle [21]. The main traction motor is powered from the high-voltage (HV) bus (around 500 V). There are also low-voltage (LV) loads that need to be powered from a LV source in the range of 40–50 V. The LV source could be a battery or a stepped down voltage from the HV battery pack or any other source. When the HV source is a fuel cell, the LV source is normally a battery pack. During the start up time of the vehicle, the LV battery pack delivers power to the fuel-cell system (for auxiliary fans and pumps) and to the main motor, and the LV loads in the vehicle [21]; the dc–dc converter works in the up conversion mode. Once the fuel cell is ready, it provides power to the main motor and LV loads. The LV battery is also charged from the fuel cell if required. During this time, the dc–dc converter works in the down conversion mode. Thus, a dc–dc converter used in the system must have the capability to deliver power in both directions depending on the state of the fuel-cell or the battery voltage.

There are several existing topologies of capacitor-clamped multilevel dc–dc converters [7–20]. Many of them have semi-modular structure, and some of them can be operated at very high efficiencies. However, the converter presented in [22] was a new topology that combines the favourable aspects of many capacitor-clamped converters. The multilevel modular capacitor-clamped dc–dc converter (MMCCC) presented in [22] has been modified to meet the load requirement in future hybrid and fuel-cell vehicles. The present paper will introduce a 5-kW MMCCC circuit

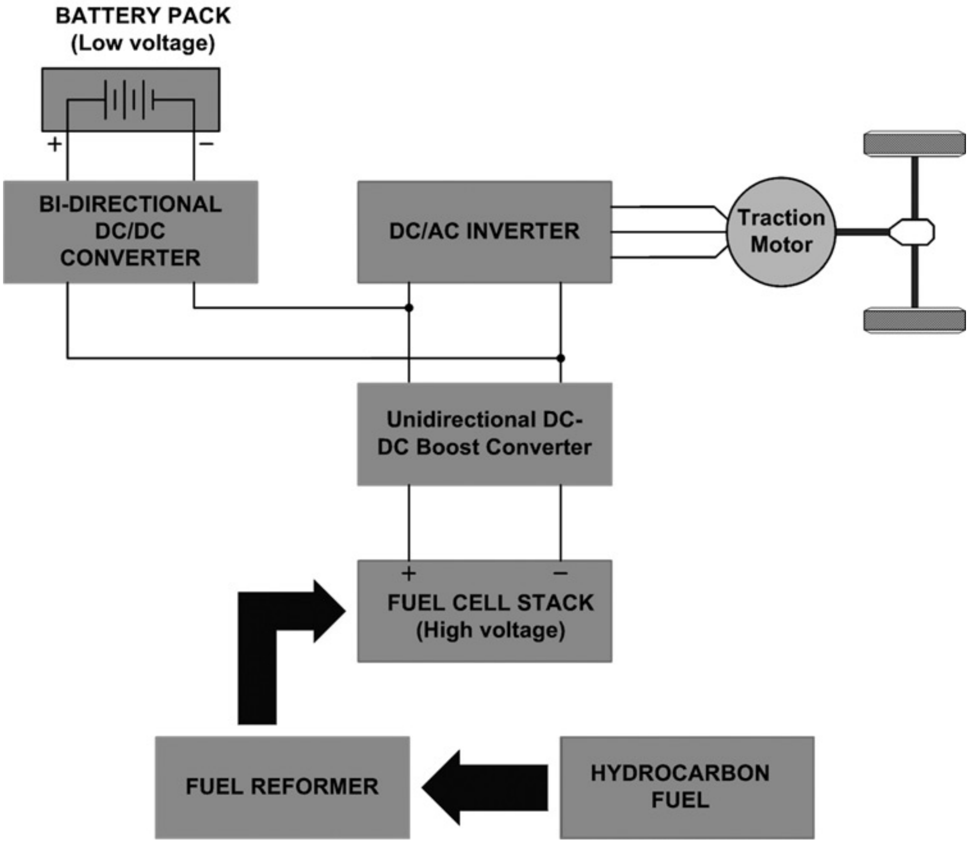

Figure 1 *Block diagram of the various components in a typical fuel-cell vehicle [21]*

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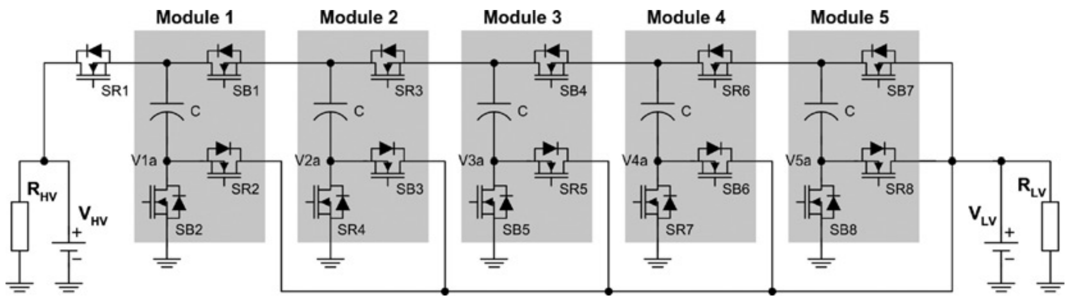

Figure 2 *Schematic diagram of a six-level MMCCC with 5 modules*

with several additional features. The six-level MMCCC topology shown in Fig. 2 has a modular structure with six (6) modules, and this 5-kW prototype can establish a bi-directional power management system for future hybrid electric and fuel-cell vehicular drive train. Using all six (6) modules in active state, a maximum conversion ratio (CR) of seven (7) can be achieved from the circuit. This proof of concept converter described in this paper could be used to establish power management between a 250 and 50-V dual bus system, which leads to build the circuit with a CR of 5 for normal operation.

2 Bi-directional power management

One unique feature of the MMCCC topology is its modularity, and any of the active modules used in the circuit can be bypassed. When transistor SB1 in Fig. 3 is continuously on and the other two transistors are continuously off, the module works as a bypass module. In this situation, the module does not participate in the operation of the converter and simply bypasses the current through itself. During the normal operation that is defined as the active state, all three transistors in a module are controlled by the proper gate-driving signals. Thus, any module can be operated in either an active state or a bypass state by activating appropriate control signals in a module. In this way, it is possible to increase or decrease the number of levels and thereby the CR. Using this feature, any fault inside the converter can be localised and the corresponding module can be bypassed. Thus, an uninterrupted operation is possible during a fault condition. Depending on the application, some modules can be operated in bypass state to bring some redundancy into the system. This eventually brings the fault tolerant feature and on-line fault bypass capability into the application.

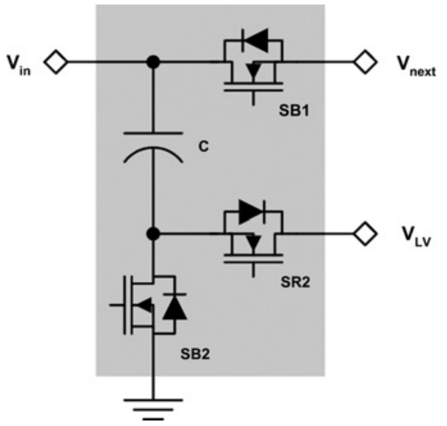

Figure 3 *Schematic of 1 module inside the MMCCC converter*

For a dual bus system, the bi-directional converter can transfer power from HV bus to the LV bus or vice-versa. The CR of the converter depends upon the number of active modules and the duty ratio of the gate-driving signal. Two different gate drive signals are fed to each of the modules in the MMCCC circuit, and this pair of signals is common to all modules. When the number of active modules is even such as 4, these two signals have durations of 0.6 and $0.4T$, where T is the time period of the gate-driving signals. The signal with duty ratio 0.6 is fed to the transistors with the suffix SRX (such as SR1, SR2 etc.). On the other hand, SBX transistors are controlled by the signal that has a duty ratio of 0.4. For an odd number of active modules, each of the signals has a duration of $0.5T$. Thus, when 4 modules are active, the CR is 5; and the CR is 6 for 5 active modules in the system. The detailed relationship of CR and duty ratio can be found in [22, 23].

For any number of active modules, if the duty ratios of the two gate-driving signals are reduced, the CR increases from the previous value, and it is no longer an integer value. Thus, for 4 active modules, if the two signals' durations are reduced from their original value of 0.6 and $0.4T$, a non-integer CR of more than 5 is obtained. This feature of obtaining fractional CR can be used to control the power flow in both directions. When a multilevel converter is used to transfer power between two voltage sources, the direction of power flow is governed by the ratio of the voltage sources (RVS) and the CR. Unlike the RVS, the CR is usually an integer value for capacitor-clamped converters, and when the CR is greater than the RVS, the LV source transfers power to the HV side. On the other hand, a CR smaller than the RVS will force the converter to transfer power from the HV side to the LV side. However, depending on the source voltages, RVS may change; and for a fixed CR, the power flow may change its direction, even if it is not desired [23]. In this situation, a variable CR is needed, and in the MMCCC circuit, the CR value can be changed by adding or subtracting a level in the system. Thus, a six-level converter can be operated in either a five- or a six-level configuration. This operation is explained in Fig. 4.

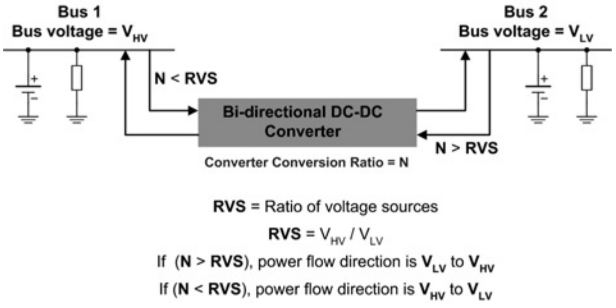

Figure 4 *Bi-directional power transfer mechanism in a two-source dc–dc converter system*

The bi-directional power management of the MMCCC can be explained by using a specific example as shown in Fig. 5. Fig. 5*a* shows an operation when the HV source is feeding power to the LV side. During this time, the CR was 6, and the RVS was 6.16. When V_1 is reduced to 65 V, RVS drops to 5.33, and the direction of power flow is reversed. This is shown in Fig. 5*b*. To maintain the same current to the LV side, the CR of the circuit needs to be less than 5.33, and this is done by bypassing a level, and changing the duty ratio of the gate drive signals. This operation is shown in Fig. 5*c*. If the gate-drive signal is not controlled, 4 active modules will produce a CR of 5, and the LV side current will be very high. Thus, by reducing

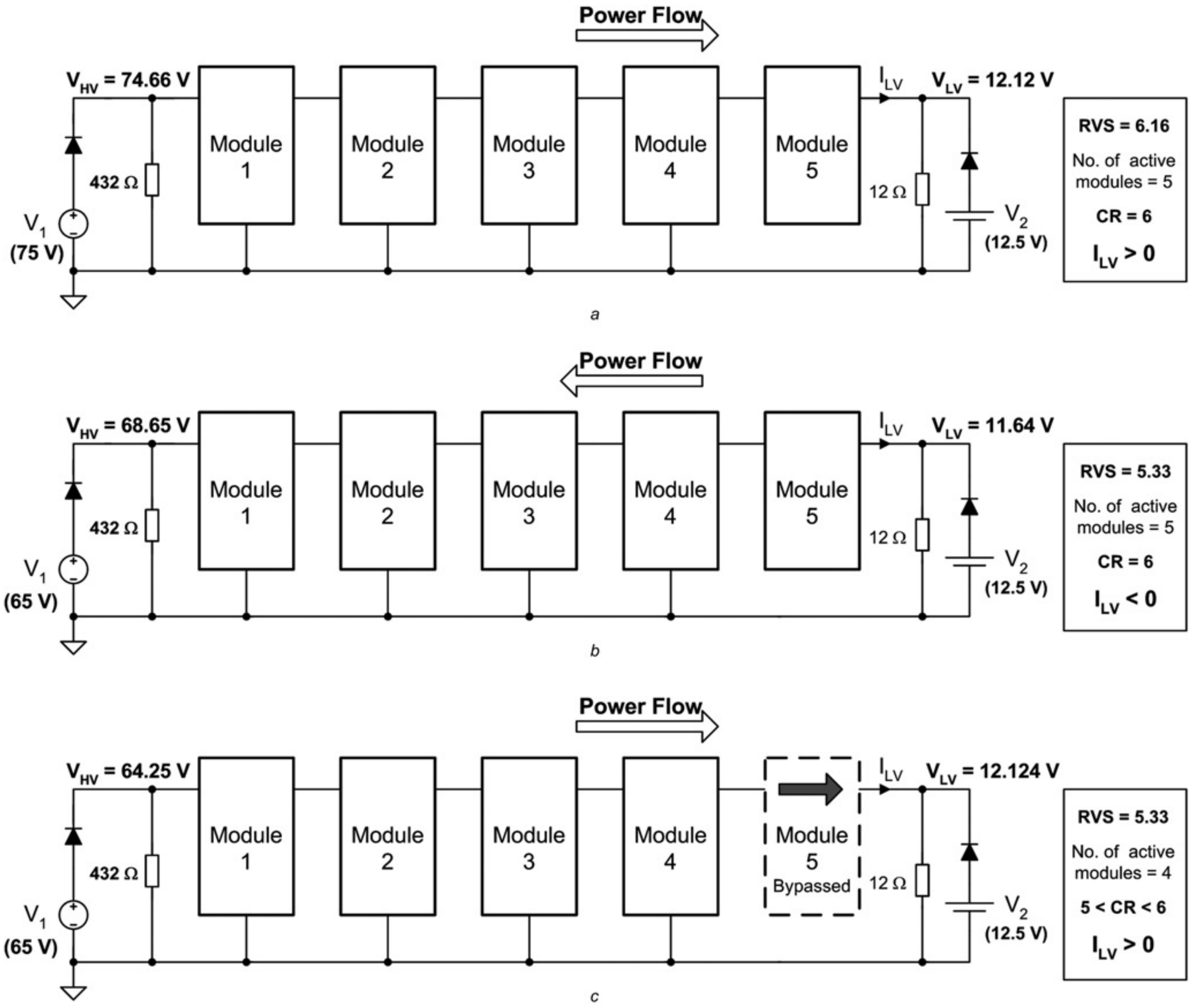

Figure 5 *Bi-directional power management operation*

a V_1 is feeding power to LV side using 5 active modules
b V_1 has decreased, power flow direction has been reversed, and I_{LV} has become negative; V_2 is feeding power to HV side
c Module 1 has been bypassed and a CR less than 6 is achieved using 4 active modules

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the duty ratio of the gate drive signals, a CR of 5.33 is obtained, and the LV side current can be controlled.

3 Simulation results

To examine the bi-directional power management capability of the MMCCC, a five-level circuit was simulated in PSIM. The HV side of the converter was connected to a 220-V battery, and the LV side to a 42-V battery. Fig. 6 shows the simulation results of the bi-directional power management operation of the converter. These results demonstrate the variable CR of the MMCCC topology, and shows how this attribute can be used to control the power in any direction regardless of the end node voltages. Fig. 6*a* shows the charging current to the LV side battery; it had an average value close to 17 A. During this time, RVS was 5.24 and CR was 5. So, power flowed from the HV side to the LV side.

To investigate the circuit's behaviour when the RVS is changed, the HV side battery voltage was reduced from 220 to 200 V. Thereby, the RVS drops to 4.76 and becomes less than the CR of the converter (5). According to the power flow direction shown in Fig. 4, power is transferred from the LV side to HV side and the LV side current becomes negative. In Fig. 6*b*, the charging current to the LV side battery is shown. This current has a negative average value meaning that the LV side battery is actually charging the HV side battery. The LV side battery is now being discharged at a rate of approximately 17 A. Because the HV side voltage is reduced, the power flow direction has been reversed; however, it is required to keep the power flow direction as before. To implement that, CR must be smaller than RVS. Now the CR of the circuit is reduced from 5 to 4 by bypassing one level. However, the present RVS is 4.76, and it is much higher than the CR (4). This condition causes a very high current flow from the HV side to the LV side. To avoid that, the duty ratio of the MMCCC's clock circuit is reduced to 3% for both SRX and SBX, and thus a CR higher than 4 but lower than 5 is obtained.

Fig. 6*c* shows the charging current to the LV side battery after reducing the CR from 5 to 4 by bypassing a level and reducing the duty ratio. In Fig. 6*c*, the charging current still has an average of approximately 16.28 A, which is close to the original value (17 A). Because the new duty ratio is quite small, the charging current has a high peak value that is close to 40 A for this setup. The flexible CR of the MMCCC is the key factor responsible for the bi-directional power management.

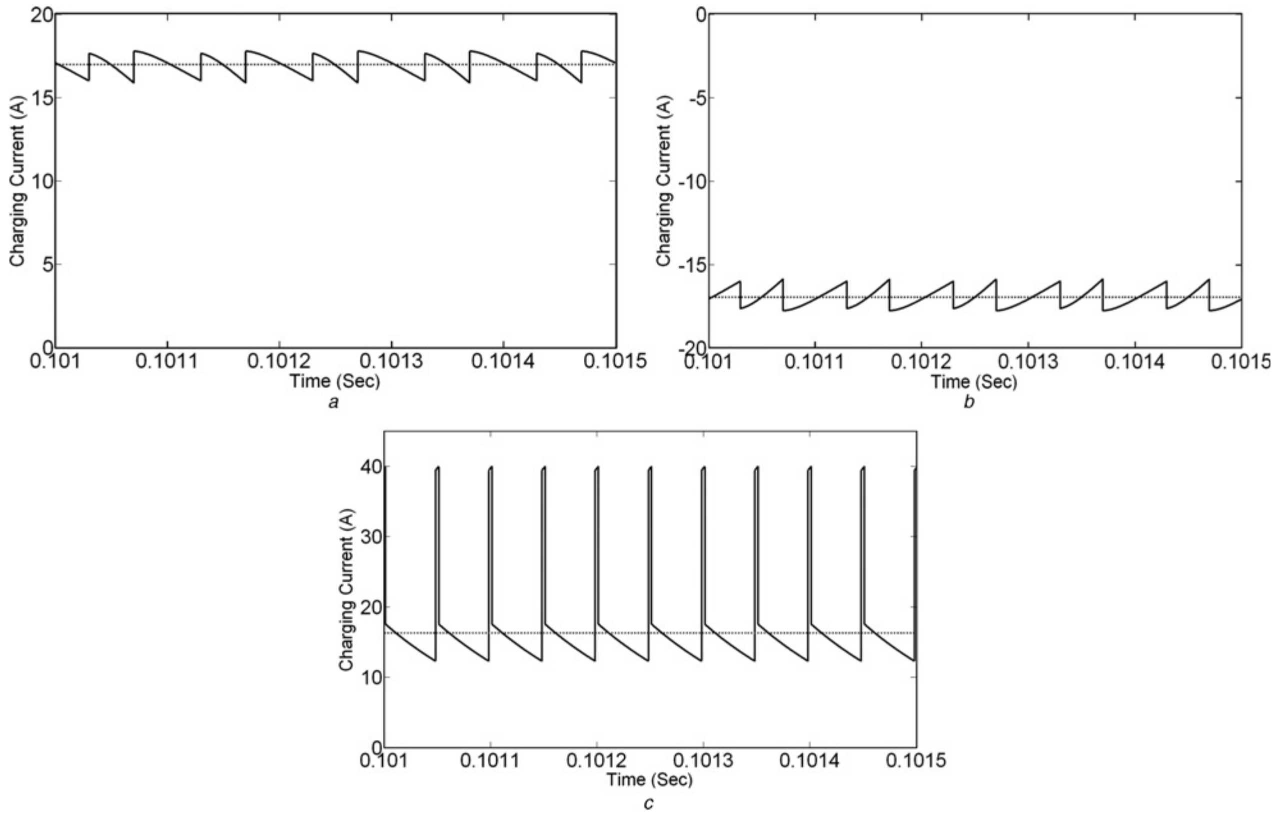

Figure 6 *Simulation results of the bi-directional power transfer mechanism of the MMCCC. Current going to the LV side battery when*

a Charged by the HV side battery
b Discharged to the HV side battery
c Charged by the HV side battery after level reduction and duty cycle control

4 Experimental results

Fig. 7 shows the prototype of a 5-kW MMCCC that has been fabricated to verify various features of the converter. This converter is designed to achieve any CR up to 7 without controlling the duty cycle of the two-phase clock circuit of the MMCCC. Thus, the converter has 6 modules, and each module has its own gate drive circuit on board. A control circuit using Parallax Stamp BS2P40 has been programmed to generate the proper gate signals for the various transistors in each module. Each module has three pairs of MOSFETs to be used as SB1, SB2 and SR2 in Fig. 3, and they are used in pair to enhance the current handling capability. For normal operation with a CR of 5, the last two modules from the right are used as bypass modules. As explained earlier, to implement the bi-directional power management, one additional module is required. In addition, to introduce some level redundancy and fault bypass capability in the system, 1 module is used as reserve. This is why the converter was fabricated with 6 modules. The operating frequency of the converter is 10 kHz.

4.1 Bi-directional power management

To test the bi-directional power management of the converter, the arrangement shown in Fig. 5 was followed, and the MMCCC circuit was connected between two dc power supplies at LV and HV sides. Two sets of loads were also connected at HV and LV sides. The HV side voltage was kept at 75 V and the LV side voltage was 12.5 V. Initially the CR was 6, and for this CR, the HV side source was sending power to the LV side loads. The LV side load current generated by the HV side is shown in Fig. 8*a*. In this figure, V_{HV} is sending power to the LV side, and the average I_{LV} was 1 A. When V_{HV} is reduced to 65 V, I_{LV} becomes negative, and V_{LV} feeds power to the HV side as the power flow direction has changed. This is shown in Fig. 8*b*. To maintain the same current to the LV side, module 5 is bypassed, and the gate signal duty ratio is changed. Thus I_{LV} becomes positive again, and this is shown in Fig. 8*c*.

4.2 Performance analysis of the MMCCC

To test the efficiency and performance of the 5-kW converter, it was connected to resistive loads at different voltage levels, and the circuit was configured for various CR. To take these measurements, the MMCCC circuit was operated in down conversion mode. Fig. 9*a* shows the LV side voltage after connecting a resistive load of 1.76 Ω at the LV side and a 250-V source at the HV side. For this configuration, the output power was 1984.8 W, the output voltage was 59.2 V and the circuit was running at CR = 4. As a next step, the circuit's CR was increased to 5 by bypassing 2 modules because 4 active modules generate a CR of 5. During this time, the HV side voltage was 275 V, and the LV side voltage was 52.4 V. At this operating point, the output load consumed 1556.5 W, and the corresponding output voltage is shown in Fig. 9*b*. In the last step, the circuit's CR was increased to 6, and the average dc voltage found was 44.07 V. During this time, the power consumption of the load connected at the LV side was 1100.8 W.

The second part of the experiment was to measure the efficiency of the converter at different input voltages while having a fixed load connected to the circuit. As the first step, the CR was set to 4, a fixed load of 1.76 Ω was connected to the LV side, and the input (HV side) voltage was varied from 0 to 250 V. The input and output power of the converter was measured using a Yokogawa PZ4000 power analyser, and the efficiency was calculated. Thus for varying input voltage, the corresponding efficiency of a four-level converter is shown in Fig. 10*a*. Fig. 10*b* shows the efficiency of the MMCCC in a five-level configuration, and Fig. 10*c* shows it for a six-level configuration. After observing these three figures, two conclusions can be made: (a) the converter has almost flat efficiency characteristics which means that the efficiency is very high even at zero or partial loads, (b) the best possible efficiency is achieved when the CR is high. Thus, when the converter operates in a six-level configuration, the efficiency is higher than a four or five-level configuration for the same output power.

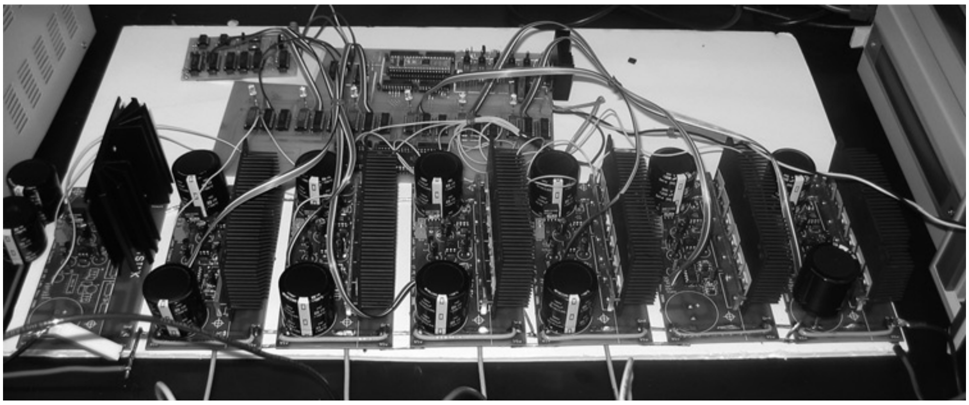

Figure 7 *5-kW prototype of the MMCCC*

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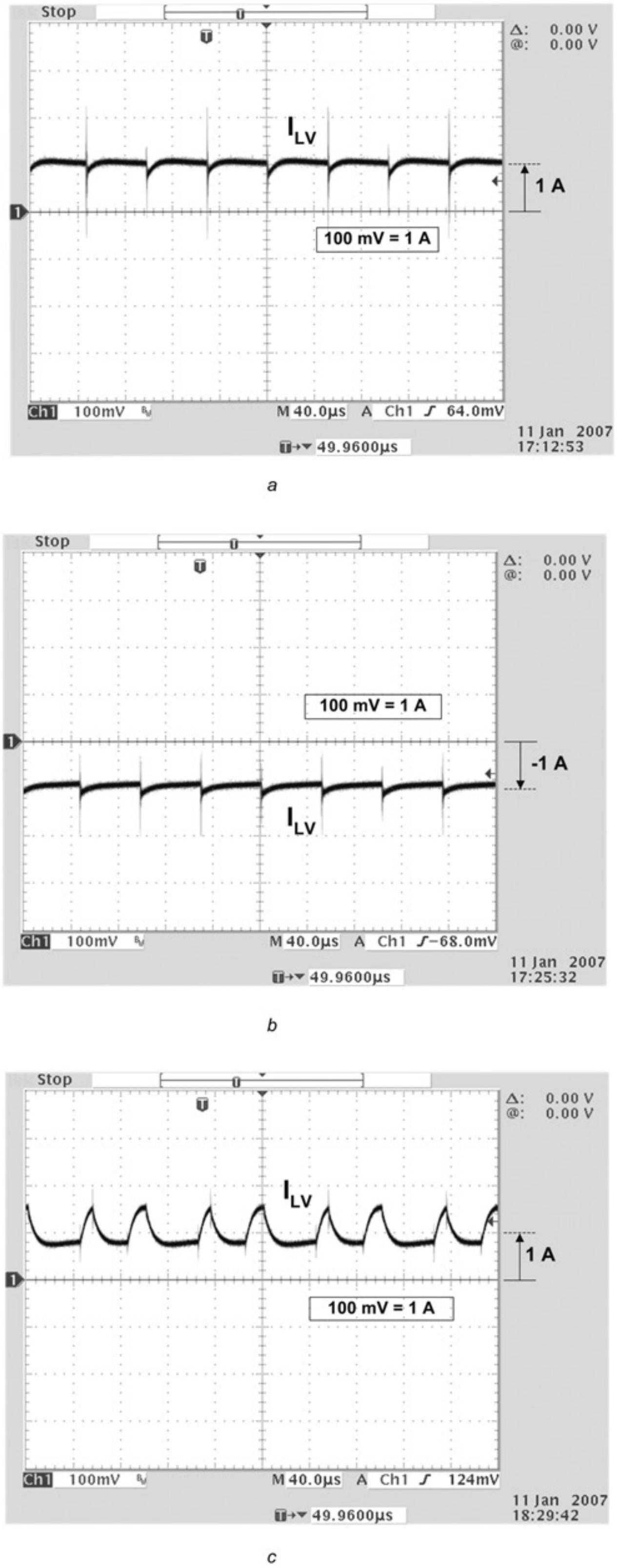


Figure 8 *Experimental results of the bi-directional power transfer mechanism of the MMCCC. Current going to the LV side battery when*

a Charged by the HV side battery
b Discharged to the HV side battery
c Charged by the HV side battery after level reduction and duty cycle control

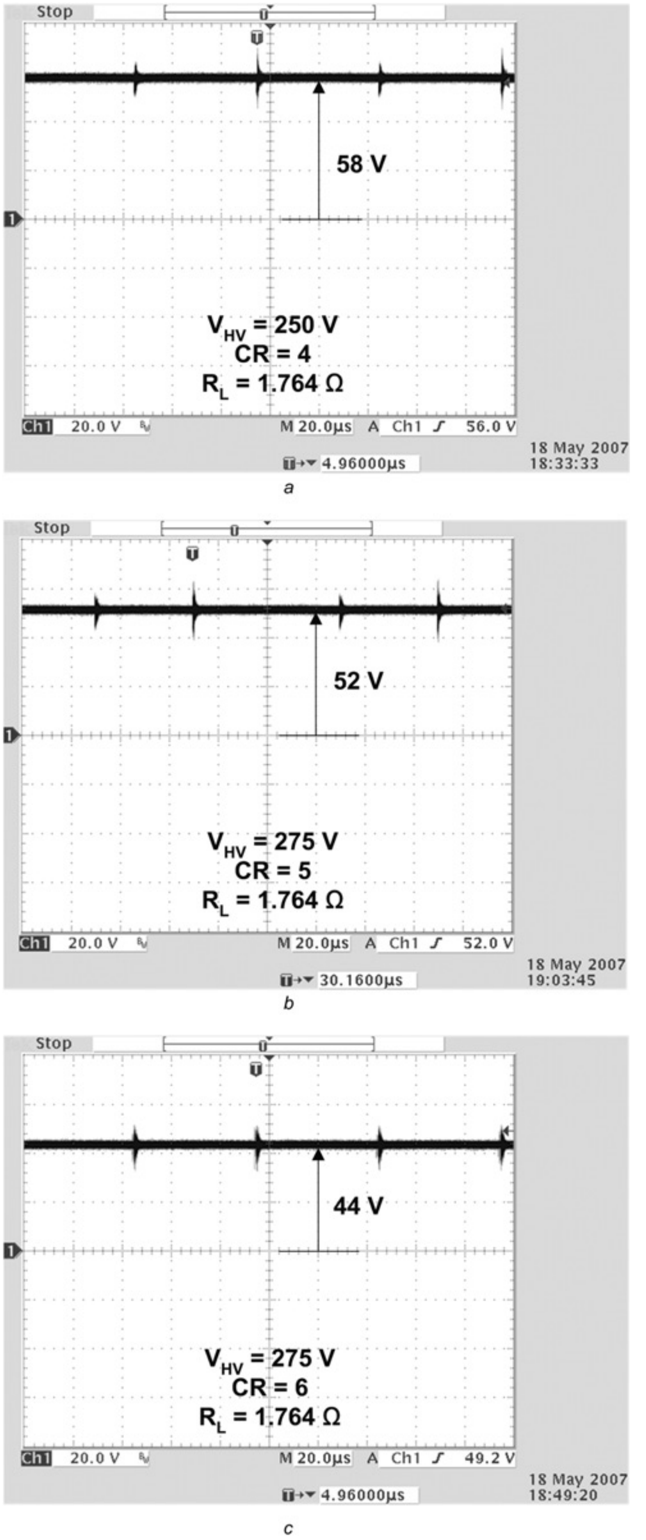
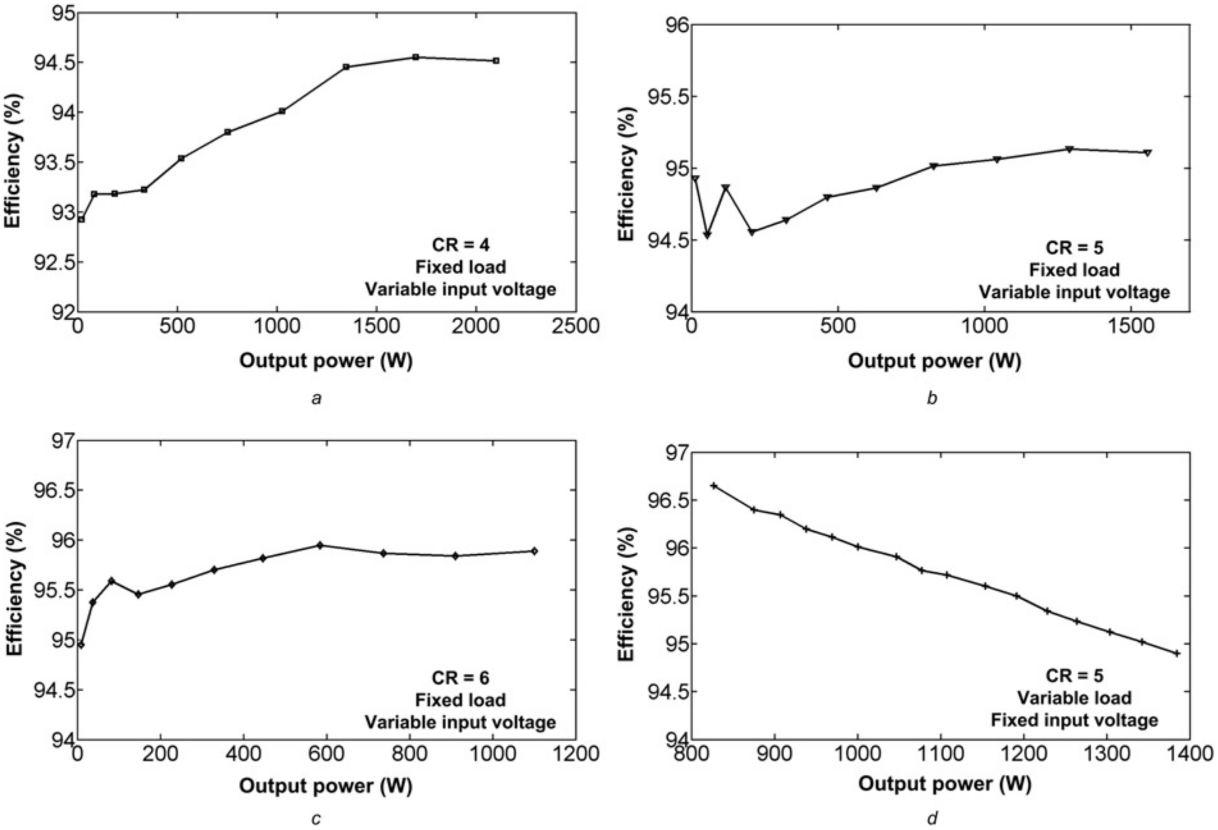


Figure 9 *Output voltages of the MMCCC at various CR. The converter is operating in down conversion mode*

The third part of the performance analysis was to measure the efficiency of the converter with varying load and for a fixed input voltage. In this step, the converter was operated at a five-level configuration, and the input voltage was set at 250 V. Then the LV side load was varied using a



a

b

c

d

Figure 10 *Performance analysis of the MMCCC. Efficiency of the converter at constant load and variable input voltage for*

a Four-level configuration
b Five-level configuration
c Six-level configuration
d Efficiency of the converter for fixed input voltage and variable loading condition for a five-level configuration. The converter is operating in down-conversion mode

programmable load bank and the efficiency was measured for variable load conditions. The efficiency at different loading conditions is shown in Fig. 10*d*. In this step, the load connected at the LV side was varied in the range of 827.4–1384.8 W. It was found that when the input voltage is fixed, efficiency drops slightly with increasing output power or the load current. On the other hand, for a fixed load and varying input voltage, the efficiency increases with output power that can be seen in Fig. 10*b* for a five-level configuration.

It can be easily shown how Figs. 10*b* and 10*d* are consistent. In Fig. 10*d*, when the input of the five-level converter is fixed at 250 V and the load is varied, at around 1300 W output, the efficiency of the converter is around 95%. On the other had when the converter has a fixed load of 1.76 Ω and the input voltage is varied, at 250 V input, the converter produces 1289 W output and the corresponding efficiency is 95.1%. This can be found in Fig. 10*b*. In this way, the performance of the MMCCC under variable load and variable voltage can be correlated using the test results.

The reason behind the lower efficiency at lower CR can be explained using the schematic diagrams shown in Figs. 2 and 3. The 5-kW MMCCC prototype has six (6) modules and the number of bypassed modules are three (3), two (2) and one (1) for CRs of four (4), five (5) and six (6), respectively. Each module experiences a constant conduction loss because of the constantly 'ON' MOSFET when the module works in bypass mode. This constant loss in each bypassed module contributes to the total loss of the converter, and it increases with increased load current. As a result, a six-level converter achieves higher efficiency compared to a four-level configuration for two reasons: (a) less number of bypassed modules, thereby lower conduction loss, (b) load voltage at the LV side is lower compared to a four-level configuration, and it initiates a lower load current that eventually reduces the losses across the switching devices.

5 Improved component utilisation in MMCCC

One of the major advantages of the MMCCC circuit is the improved component utilisation over the existing topologies of capacitor-clamped dc–dc converters. This ongoing discussion will compare the component utilisation of the

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MMCCC with the flying capacitor multilevel dc–dc converter (FCMDC) discussed in [7–9, 22]. For a five-level MMCCC and FCMDC, the power rating is assumed to be 1000 W, and the high side and low side voltages are considered to be 100 and 20 V, respectively. For this case, the converter is assumed to operate in down conversion mode. The load connected at the LV side will have 50 A current through it.

5.1 MMCCC

For a five-level MMCCC, 13 transistors are required to establish a CR of 5 [20]. Of these 13 transistors, 3 transistors (the top transistor in modules 1, 2 and 3; as an example, S_{B1} in Fig. 3) will experience a voltage stress of $2V_{HV}/N$, during off time where N is the CR, and V_{HV} is the HV side voltage. Thus, the voltage stress of these three transistors would be 40 V for this example, and for the other transistors, the voltage stress is $V_{HV}/N = 20$ V.

The operational diagram of a five-level MMCCC was explained in [22], and it was shown that the current flows from the HV side to the LV side in three parallel circuits during the first sub-interval. These parallel paths include only the SRX transistors. During the second sub-interval, the current flows through two parallel paths and thereby the current flows through the SBX transistors only. Thus, the peak volt–ampere (VA) stress of the 13 transistors used in the circuit is

$$\left(40\,\mathrm{V}\times\frac{50\,\mathrm{A}}{3}\times 1\right)+\left(40\,\mathrm{V}\times\frac{50\,\mathrm{A}}{2}\times 2\right)+\left(20\,\mathrm{V}\times\frac{50\,\mathrm{A}}{3}\times 6\right)+\left(20\,\mathrm{V}\times\frac{50\,\mathrm{A}}{2}\times 4\right)=6400\,\mathrm{VA} \tag{1}$$

As each transistor operates for 50% of the total time period, the total average VA rating of the installed transistors would be 3200 VA.

5.2 FCMDC

The five-level FCMDC circuit shown in [22] has ten transistors, and each of them experiences a voltage stress of 20 V. The circuit has five sub-intervals, and during each sub-interval, the load current flows through several transistors connected in series. Thus, there is no parallel operation like the MMCCC that could take place in the FCMDC circuit. The total peak VA rating of the ten transistors used in the circuit would be

$$(20\,\mathrm{V}\times 50\,\mathrm{A}\times 10)=10\,000\,\mathrm{VA} \tag{2}$$

Of these ten transistors, five transistors work for 80% of the total time period and five transistors work for 20% of the total time period. Thus, on average, each transistor is operated for 50% of the total time. So, the total average VA rating of the installed transistors would be 5000 VA.

The comparison presented here shows that although the MMCCC circuit uses three more transistors, the installed power switching capacity (peak VA stress) of the circuit (6400 VA) is 36% less than that is required for the FCMDC circuit (10 000 VA). Thus it is possible to build the MMCCC circuit having the same power rating from smaller size components. This advantage of the MMCCC is achieved by virtue of the higher component utilisation of the circuit topology.

6 Conclusions

A five-level 5-kW MMCCC prototype has been demonstrated, and the bi-directional power management capability has been explained. The origin and need for bi-directional power management in several key applications have been presented and explained. Through the experimental results it was shown that the MMCCC topology has very good efficiency at partial or no-load condition. This 5-kW converter was tested up to 2 kW, and the efficiency was higher than 95% for that power range. In addition, various other favourable features of a capacitor-clamped converter have been preserved in this 5-kW prototype, and it was explained how the MMCCC can achieve improved component utilisation compared to other capacitor-clamped converters such as the well-known FCMDC circuit. Better component utilisation from the MMCCC can yield a 36% saving in transistor VA sizing that has been verified through the analytical computation in this paper. This advantageous feature eventually leads to smaller form factor of the MMCCC circuit compared to other capacitor-clamped converters.

Especially the bi-directional power management and superior efficiency at partial loading condition of a converter can yield a great propensity in future plug-in hybrid or fuel-cell automobiles, and the MMCCC circuit can be considered a potential candidate for those applications. The use of ultra capacitors and wide band-gap semiconductors such as SiC can bring many other interesting and useful features into the converter including compact design, minimum heat sink requirement and reduced switching loss. All these efforts along with the MMCCC topology will work as a synergy towards the future of hybrid electric vehicle power-train architecture mitigating various power conversion needs.

7 Acknowledgment

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