A 5 kW Bi-directional Multilevel Modular DC-DC Converter (MMCCC) Featuring Built in Power Management for Fuel Cell and Hybrid Electric Automobiles

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***Abstract*- A new capacitor clamped modular dc-dc converter with bi-directional power handling capability will be presented in this paper. This inductor-free design is modular, and it is possible to integrate multiple loads and sources simultaneously in the converter. Moreover, this 5 kW dc-dc converter can produce multiple ac outputs to feed power to ac loads or transformers to get further control over the conversion ratio of the circuit. This high efficiency modular converter has flexible conversion ratio, and it could be successfully used in a multi-bus power system by virtue of its inherent power management properties.**

I. INTRODUCTION

A bi-directional dc-dc converter is a key element in a fuel cell vehicle. A fuel cell has a slow dynamic response, and it suffers from a long startup time. For this reason, a fuel cell vehicle usually has two different voltage buses. The high voltage bus is connected to the fuel cell, and the low voltage bus is powered from a battery. During the startup or dynamic load changes, the low voltage side battery provides power to the high voltage side bus, and thereby to the inverter for the automobile power train. In steady state condition, the fuel cell feeds power to the drive train, and charges the battery at the low voltage side.

To accomplish this charge-discharge operation, a bi-directional dc-dc converter is an indispensable element in the fuel cell automobile power system. The overall performance of the fuel cell automobile greatly depends on the efficiency and reliability of the bi-directional dc-dc converter that seamlessly maintains the power balance between the fuel cell and the low voltage side battery. A schematic of a fuel cell power train is shown in Fig. 1 [1].

There are many existing topologies [2-8] that could be adopted to design this bi-directional converter. However, the list of expected attributes of this dc-dc converter would contain high efficiency operation, bi-directional power transfer capability, and high reliability. This paper will introduce a new multilevel modular capacitor clamped dc-dc converter (MMCCC) with its potential applications in fuel cell or future

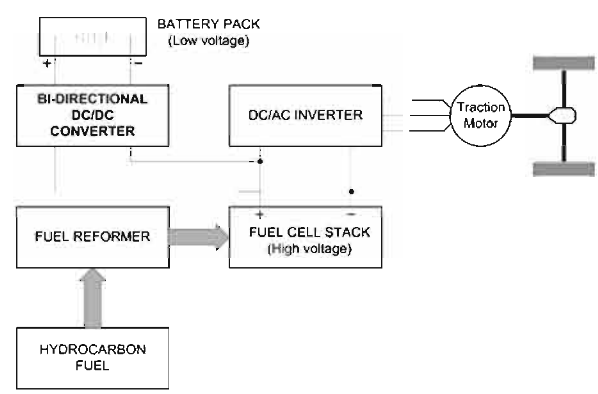


Fig. 1. Typical topological arrangement of a hybrid fuel cell vehicle drive train [1].

hybrid electric automobiles. The inductor-free design of the converter makes it very efficient, and the modular structure improves the reliability of the converter to a great extent. The modular nature of the converter also allows the integration of multiple loads and sources simultaneously considering it as a dc transformer having multiple taps [9]. Using these taps, the MMCCC circuit can also produce ac outputs to integrate ac loads or transformers to achieve an additional control over the conversion ratio of the circuit.

This 5 kW converter is the up-scaled version of the 500 W MMCCC converter presented in [9]. While designing the MMCCC for 5 kW, some additional attributes were achieved such as the integration of ac loads and sources. Thereby, the MMCCC converters can incorporate various kinds of loads and sources simultaneously.

II. MMCCC TOPOLOGY

Fig. 2 shows the schematic of a 6-level MMCCC circuit, and this circuit has 5 modules. Fig. 3 shows the schematic of one module, and each module has three transistors and one

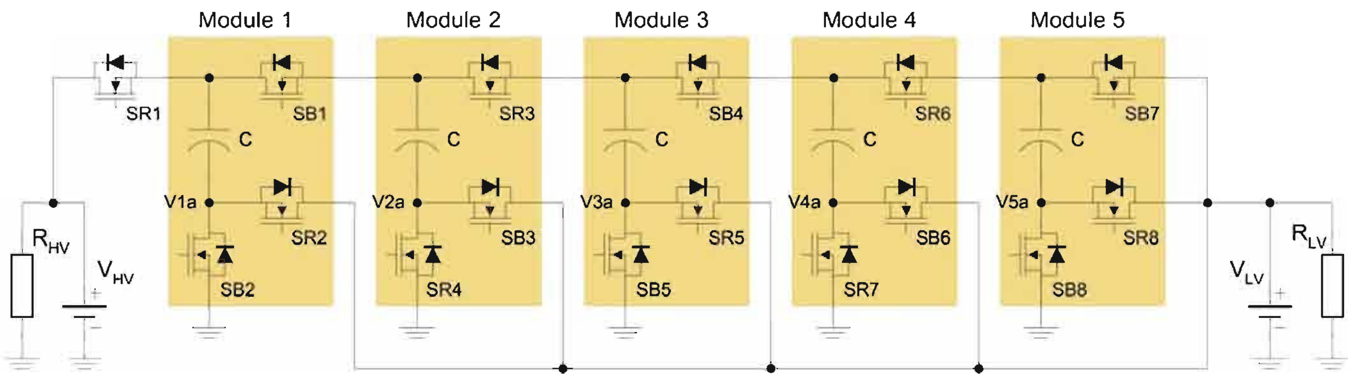


Fig. 2. The 6-level MMCCC circuit with 5 modules.

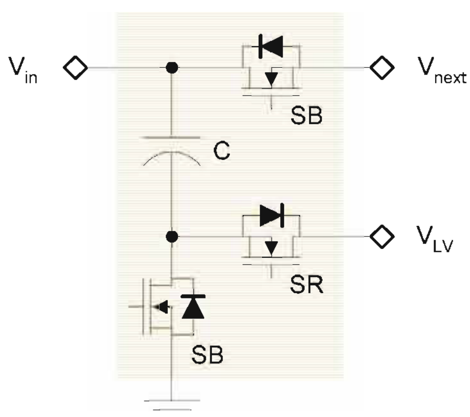


Fig. 3. One module of the MMCCC circuit.

capacitor to form a 3-terminal block. Thus connecting multiple blocks or modules in a cascade pattern, various conversion ratios can be achieved from the circuit. Five modules of the converter shown in Fig. 2 produce a conversion ratio 6. It means that the voltage ratio of V_{HV} and V_{LV} is 6, and power can flow either from the high voltage (HV) to low voltage (LV) side or vice-versa. The primary objective of the circuit is to manage power flow between the LV and HV buses and to the loads connected to these buses. The detailed operating principle of the converter can be found in [10].

The advantage of this circuit over the existing topologies is the redundancy and fault bypass capability [9]. Any module can be used in active state or bypass state. As an example, inside module 1 (shown in Fig. 2), if SB1 is permanently on and SR2 and SB2 are permanently off, then this module does not participate in the operation of the converter, and it works in bypass state. If all three transistors inside one module are operated with proper gate signals, it works in active state. Thus, it is possible to bypass any module during a fault, or to change the number or levels thereby the conversion ratio of the converter.

Another distinctive feature of the MMCCC structure is the modular construction. Because of the cascade connection of multiple modules, the circuit provides several intermediate voltage nodes that could be connected to multiple voltage sources or loads [9]. Fig. 4 shows the schematic of a 6-level MMCCC converter with the simulated voltages at different nodes of the converter. The application and significance of these node voltages will be analyzed in section IV and V.

III. Power Management Features of MMCCC

There are various architectures of power management systems in hybrid electric or fuel cell automobiles. A power management system basically organizes the power system platform that bridges various power sources, loads, and storage units for high efficiency and performance of the vehicle. A future fuel cell vehicle may have many different voltage buses (including both ac and dc), and there could be various ac and dc loads with operating voltages covering a wide range. A power management block (PMB) inside the vehicle will control the power flow from different sources to different loads; and to ensure that, the entire system will involve several power electronic converters [1]. Moreover, the PMB also involves battery chargers to extract regenerative energy and sends it to the battery. Depending on the architecture of the power system, there could be multiple dc voltage buses with separate batteries.

The 5 kW MMCCC converter presented in this paper has several features that make it a very good candidate to offer a power management system for fuel-cell or future hybrid electric vehicle. To integrate several sources and loads into the system, it takes dc-dc, ac-dc, and dc-ac converter circuits in addition to the main dc-dc converter or inverter in the power system of the vehicle. However, the MMCCC topology has several power management features that lead to one simplified solution without involving many converters in the system. The circuit can accept multiple dc and ac voltage sources at the same time. Also, it can provide power to ac and dc loads simultaneously.

The inherent nature of the modular structure of the MMCCC converter takes the shape of a dc transformer. As a result, various nodes of the converter produce dc voltages of different magnitudes. In addition, ac outputs of multiple values can be obtained from the MMCCC circuit. Thus, the MMCCC circuit could be connected to both ac and dc loads and sources.

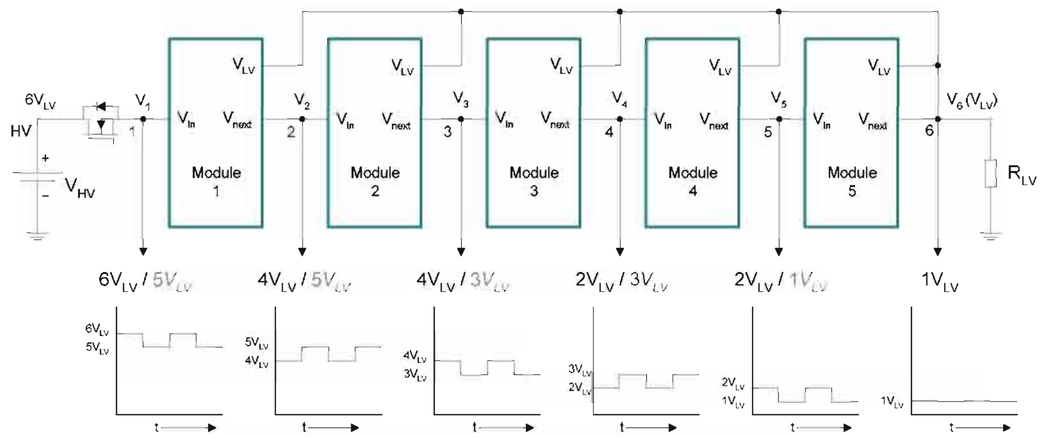


Fig. 4. The simulation results of the intermediate node voltages in a 6-level MMCCC circuit for dc load/source integration.

The detail of this load/source integration feature of the MMCCC converter will be discussed in the later sections.

IV. MULTIPLE DC LOAD-SOURCE INTEGRATION

Fig. 4 shows the simulation results of the various node voltages inside the 6-level MMCCC converter. In this figure, the voltages at nodes 1 to 5 are shown. These node voltages are also summarized in Table 1. These nodes are eventually the positive leads of the capacitors inside these modules. The modular nature of the MMCCC topology provides access to these ground referenced intermediate node voltages, and multiple voltage sources or loads can be connected at these terminals considering the converter as a dc transformer. Depending on the node voltages at these nodes, several voltage sources or loads can be connected at the same time. As an example, the voltage at node 2 is varying between 4 V_{LV} and 5 V_{LV}. Thus, if a voltage source of amplitude slightly greater than 4 V_{LV} is connected at this node, it will contribute power to the system during the time when the node voltage is 4 V_{LV}. However, when the node voltage becomes 5 V_{LV}, there will be no current flow from this source to the converter. The operational diagram of this feature is shown in Fig. 5.

Fig. 4 shows that node 1 and node 3 has a voltage difference of 2 V_{LV}, and this is true for nodes 3, 5 and nodes 2, 4. According to the simulation results, a voltage difference equal to 4 V_{LV} can be obtained by connecting a load between node 1 and 5. Thus, multiple dc loads can be connected at these node pairs, and the corresponding operational circuit diagram is shown in Fig. 5. In this figure, the converter is operating in down conversion mode, and various voltages such as 1 V_{LV}, 2 V_{LV}, 4 V_{LV} can be obtained at the same time. The dc load/source integration feature for a 500 W MMCCC converter has been shown in [9].

TABLE 1. TIME VARYING NODE VOLTAGES OF A 6-LEVEL MMCCC CIRCUIT.

State	Active Switches	V_1	V_2	V_3	V_4	V_5
1	S_{R1}-S_{R8}	$6V_{LV}$	$4V_{LV}$	$4V_{LV}$	$2V_{LV}$	$2V_{LV}$
2	S_{B1}-S_{B8}	$5V_{LV}$	$5V_{LV}$	$3V_{LV}$	$3V_{LV}$	$1V_{LV}$

V. PRODUCING AC OUTPUTS FROM MMCCC

Taking the advantage of the modular structure of the MMCCC topology, it is also possible to generate ac voltages (square waves at the converter switching frequency) from this dc-dc converter. This feature enables to connect ac loads or sources to the converter, and thus it creates the hybrid architecture. The ac operation of the circuit is mirror to the dc operation of the circuit. When multiple dc loads are connected to the MMCCC converter, they are connected across alternate nodes (shown in Fig. 5). However, MMCCC produces ac outputs across two adjacent nodes of the five nodes shown in Fig. 2 (V1a, V2a, V3a, V4a, and V5a, and these nodes are eventually the negative leads of the capacitors inside the modules in the MMCCC circuit.) Thus, when a load is connected across V1a and V2a, it experiences an ac voltage with amplitude of 1 V_{LV}. Acknowledging the mirror behavior, the ac voltage across two alternate nodes was found to be zero.

There is another difference between the ac and dc loading situations of the MMCCC circuit. From a 6-level MMCCC circuit, it is possible to achieve dc voltages having amplitudes of 2 V_{LV} and 4 V_{LV} by connecting loads appropriately (Fig. 5), and the amplitude of the load voltage depends upon the location of the taps where the load is connected. For this reason, the voltage across node 1 and 3 is 2 V_{LV}, and it is 4 V_{LV} across node 1 and 5. However, the amplitude of the ac output is always zero or 1 V_{LV}. Thus the voltage across node V1a and V2a is 1 V_{LV}, and this is the same for node V1a and V4a. However, the voltage across two alternate nodes such as V1a and V3a is always zero.

These ac outputs can be used to run ac loads, or transformers could be connected at these outputs to generate isolated ac or dc voltages (after rectification). In Fig. 2, the negative terminal of the capacitor in each module produces a time varying voltage, and the MMCCC circuit shown in this

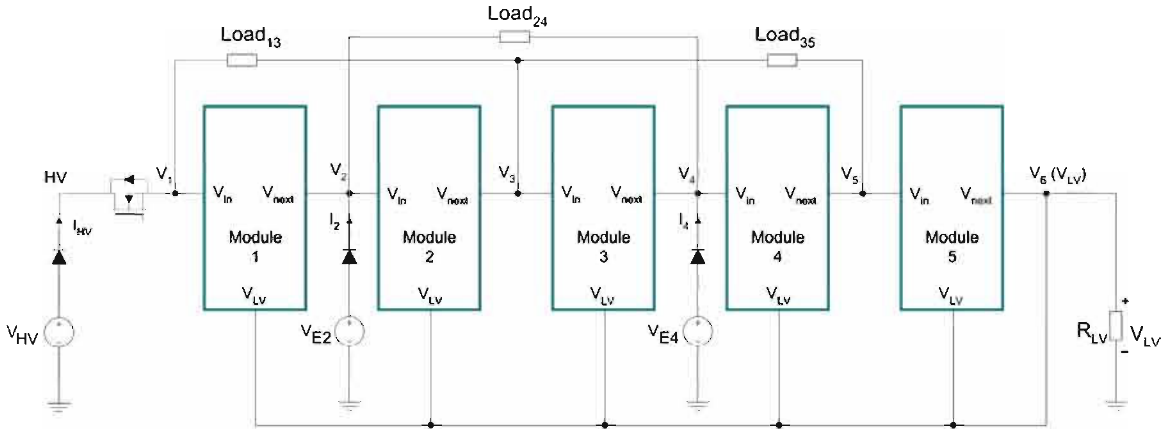


Fig. 5. Integration of multiple dc loads and sources in the MMCCC circuit.

figure has 5 of these nodes. In Fig. 6, the operational MMCCC circuit to obtain multiple ac outputs is shown.

VI. Bi-directional Power Management

The circuit has full flexibility of managing power in both directions. Unlike the existing flying capacitor topologies [2-4], the circuit can control the power flow direction irrespective of the voltages at HV or LV side. By changing the number of active modules, it is possible to increase or decrease the number of levels and thereby the conversion ratio (CR). 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 low voltage source transfers power to the high voltage source. On the other hand, a CR smaller than the RVS will force the converter to transfer power from the high voltage side to low voltage side. However, depending on the battery condition, RVS may change; and for a fixed CR, the power flow may change its direction, even if it is not desired. In this situation, a variable CR could solve this problem, and in the MMCCC topology, the CR value can be changed by adding or subtracting a level in the system. Thus, a 6-level converter can be operated at any CR up to 6, and true bi-directional power management can be established. For a finer control on the CR, duty ratio of the gate drive signal may be changed, and it becomes possible to get a more precise control of the current and CR.

VII. Simulation Results

A 6-level 5 kW MMCCC converter was simulated in PSIM to generate ac voltages across the loads connected to the converter. The operational diagram shown in Fig. 6 was followed to get the simulation and experimental results. Three 20 Ω resistors were used as R12, R23, and R14 and a 10 Ω resistor was used as R_{LV} in both simulation and experiment. This 5 kW converter was operated in down conversion (buck) mode at 10 kHz switching frequency, and the HV side was connected to a 240 V dc source. The simulation results are summarized in Fig. 7, and the experimental results are shown in Fig. 8.

Fig. 7(a) shows the dc output at the loaded LV node, and it shows that the output dc voltage is around 40 V, which is close

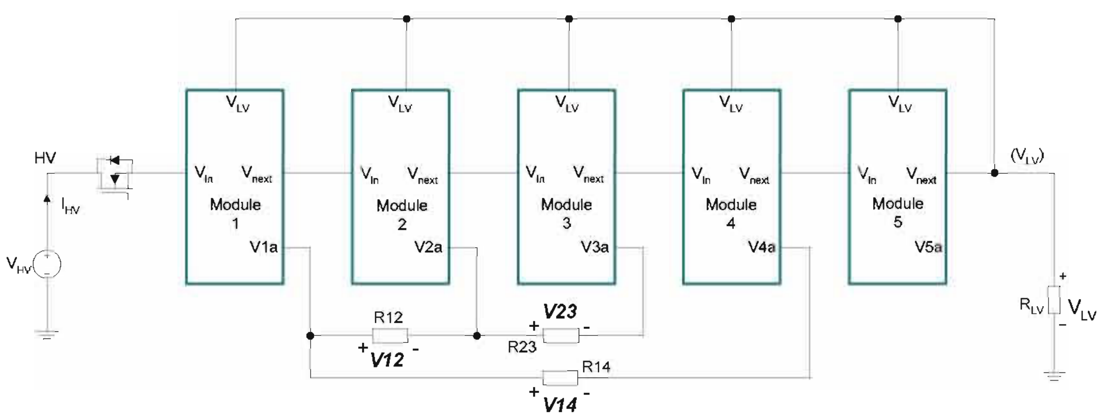


Fig. 6. The operational circuit to generate ac outputs from a 6-level MMCCC circuit.

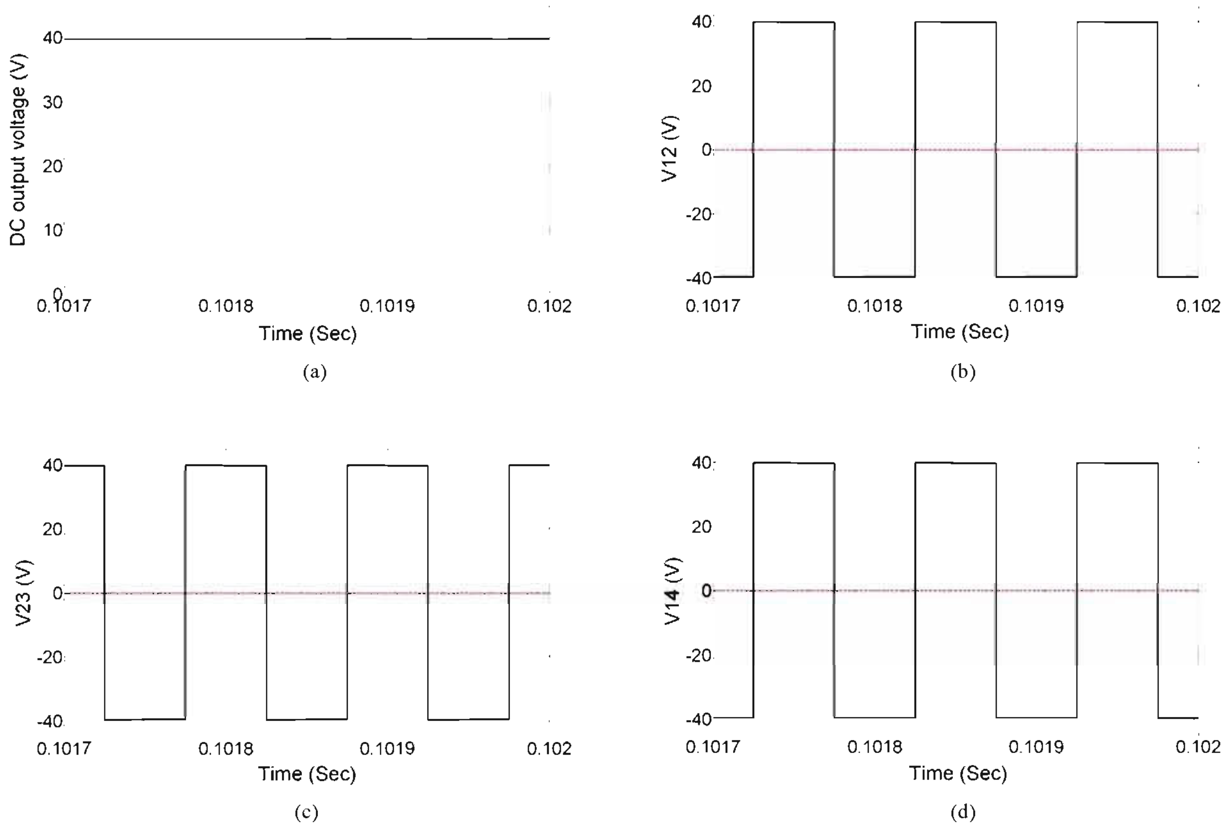


Fig. 7. The simulation results of the 5 kW MMCCC. (a) dc output at LV node, (b) V12, (c) V23, (d) V14.

to the theoretical value (240V/6). The ac output across R12 is shown in Fig. 7(b), and it shows that the amplitude of V12 is close to 40 V (1 V_{LV}). Fig. 7(c) shows the simulated voltage across R23, and Fig. 7(d) shows V14. It is found that V12 and V23 will have opposite phases; V12 and V14 are in phase. For this reason, when a load is connected across node V1a and V3a, the resultant voltage is zero.

VIII Experimental Results

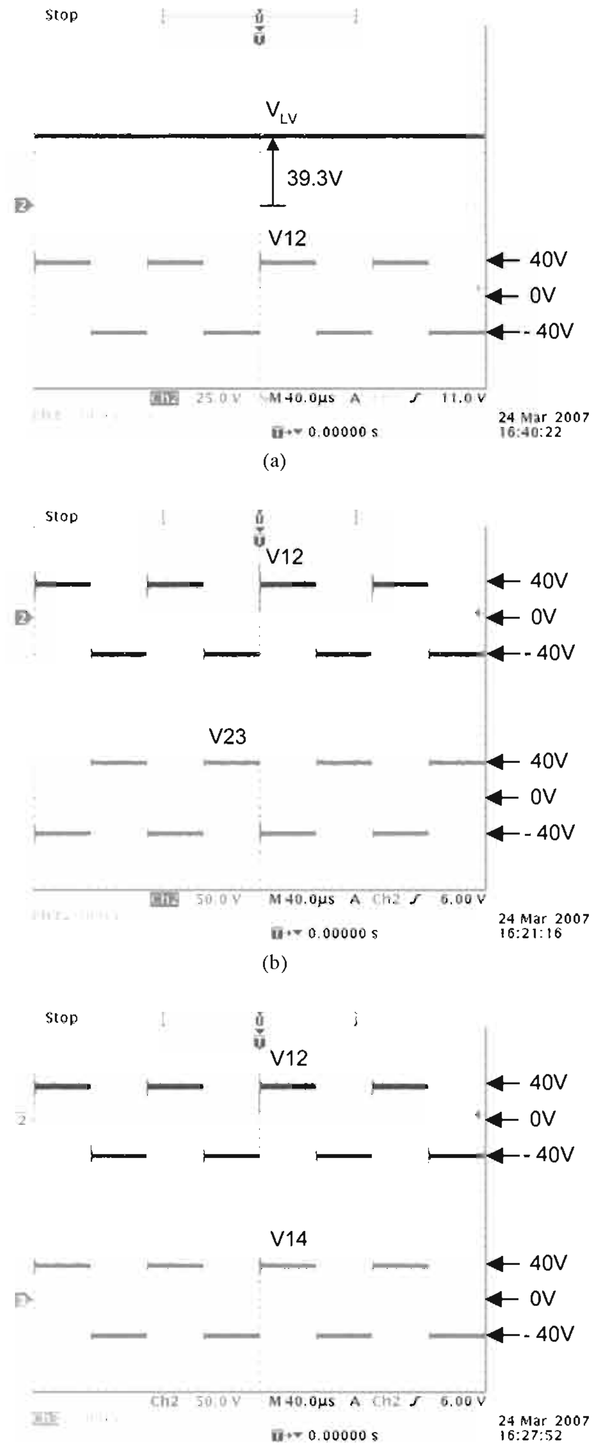
To complete the verification of the MMCCC features, a 5-level 5 kW MMCCC converter was constructed. This converter was designed to have 6 modules so that it has 2 redundant modules for fault bypass and bi-directional power transfer capability. Thus, without any fault, the converter may operate with a maximum CR 7. Inside the MMCCC, each module has 3 pairs of MOSFETs to be used as SB and SR transistors in Fig. 3, and they were used in pair to enhance the current handling capability. One pair of bootstrap gate drive circuits were used to drive these six transistors. Each module had one 1000 μF general purpose electrolytic capacitors as the energy transfer element.

A control circuit using Parallax Stamp BS2P40 has been programmed to generate the proper gate signals for the various transistors in each module. Using this microcontroller, it is possible to change the CR, or implement the automated fault bypass capability. In addition, it is also possible to control the modules to implement the bi-directional power management by activating or bypassing any module.

A. Generating AC Outputs

The same setup of the simulation was followed in the experiment. Three 20 Ω resistors were used as R12, R23 and R14, and a 10 Ω resistor was used as R_{LV}. The converter was operated in down conversion (buck) mode with a CR 6, and a 240 V dc source was connected at the HV side of the converter. Fig. 8(a) shows V_{LV} and V12 of the MMCCC circuit. For a 240 V dc input, the circuit produces the LV side dc voltage close to 40 V (actual value recorded was 39.3 V), and the V12 has an amplitude of close to 40 V also. Fig. 8(b) shows V12 and V23, and it shows that V12 is out of phase of V23. Fig. 8(c) shows the voltages V12 and V14, and it is found that they are in phase.

The experimental results indicate that the generated ac output has amplitude of 1 V_{LV}, and it is square wave. For isolation or to gain higher conversion ratio, transformers can be connected at these ac terminals. Moreover, the circuit can produce dc output (V_{LV}) simultaneously. Thus the MMCCC circuit could be considered as a common platform of different kinds of loads and sources.



(a)

(b)

(c)

Fig. 8. Experimental results of the ac outputs of the MMCCC converter. a) V_{LV} and V12, b) V12 and V23, c) V12 and V14.

B. Performance analysis of the 5 kW MMCCC converter

To test the efficiency and performance of the 5 kW converter, it was operated at different voltages and conversion ratios. The input and output power of the converter was measured using a Yokogawa PZ4000 power analyzer, and the efficiency was hand calculated. To take these measurements, the MMCCC circuit was operated in down conversion mode, and the performance analysis was made to measure the efficiency of the converter with varying load and for a fixed input voltage. In this step, the converter was operated at 5-level configuration, and the input voltage was set at 250 V. Then using load banks, the LV side load was varied and the efficiency was measured for variable load condition. The load connected at the LV side was varied in the range of 827.4 W to 1384.8 W, and the corresponding efficiencies at these operating conditions are shown in Fig. 9. During this test, it was found that when the input voltage is fixed, efficiency drops slightly with increasing output power or the load current. This happens because of the increasing on-state loss of the MOSFETs. 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 for a 5-level configuration.

In the second part, 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. Thus for varying input voltage, the corresponding efficiency of a 4-level converter is shown in Fig. 10(a). Fig. 10(b) shows the efficiency of the MMCCC in 5-level configuration, and Fig. 10(c) shows it for 6-level. After observing these three figures, two conclusions can be made: 1) the converter has almost flat efficiency characteristics which means that the efficiency is very high even at partial loads, 2) the best possible efficiency is achieved when the CR is high. Thus, when the converter operates in 6-level configuration, the efficiency is higher than 4 or 5-level configuration for the same output power.

It can be shown how Fig. 9 and Fig. 10 are consistent. In Fig. 9, when the input of the 5-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.

IX. Conclusions

A 5 kW MMCCC circuit and several of its functions have

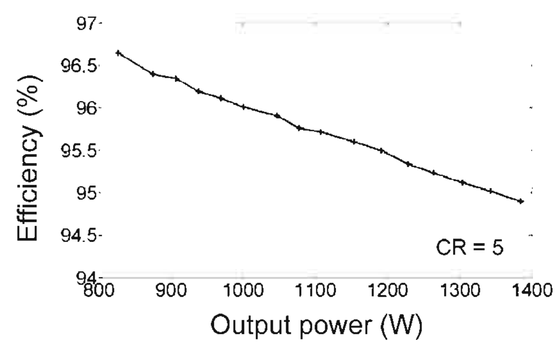


Fig. 9. Efficiency of a 5-level converter with constant input voltage and variable loading condition at the low voltage side.

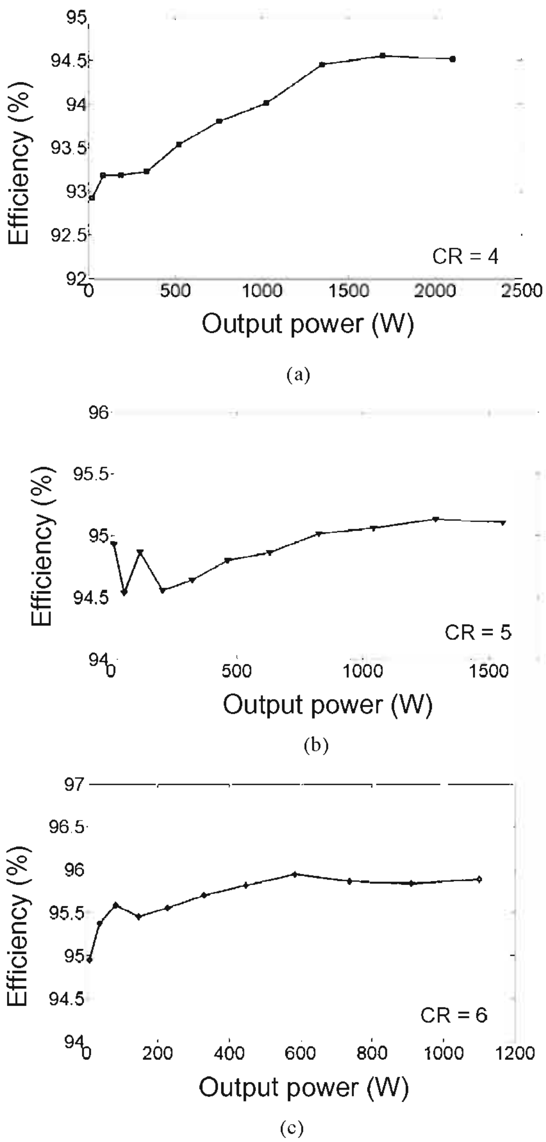


Fig. 10. The efficiency of the 5 kW MMCCC converter at different conversion ratio and output power. (a) the efficiency of a 4-level converter with constant load and variable input voltage, (b) the efficiency of a 5-level converter with constant load and variable input voltage, (c) the efficiency of a 6-level converter with constant load and variable input voltage.

been presented here. The simulation and experimental results show that the circuit can produce ac voltages which have an amplitude of 1 V_{LV}, and both ac and dc loads can be connected at the same time. In addition to V_{HV} and V_{LV}, the MMCCC circuit can be connected to other voltage sources (shown in Fig. 5). Thus, this converter can be successfully used in future hybrid or fuel cell vehicle where it can be integrated to multiple dc voltage sources and both dc and ac loads at the same time. Moreover, ac voltage sources could be connected to the MMCCC converter in the same way dc sources are connected. At this moment, this feature is considered as a future work.

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