The New Family of High Step Ratio Modular Multilevel DC-DC Converters

Xiaotian Zhang* and Timothy C Green*

*Department of Electrical Engineering

Imperial College London, U.K. SW7 2BT

Email: xiaotian.zhang@imperial.ac.uk; t.green@imperial.ac.uk

Abstract—This paper presents a family of modular multilevel converters (MMCs) for high step ratio dc-dc conversion. The modular multilevel unidirectional step-down dc-dc converter topologies are presented. The high step-up ratio bidirectional modular multilevel dc-dc converter is also provided. Operation principle and analysis of the bidirectional dc-dc converter are shown, and verified by experimental results with a conversion ratio of 1 : 10. The proposed converters achieve high voltage step ratio depending on the number of sub-modules and the charging ratio.

I. INTRODUCTION

Multilevel converter schemes for dc-dc conversion are becoming popular [1] in renewable energy applications following the success of this type approach in dc-ac conversion. There are many different types of multilevel converters developed [2], [3], which can be directly or indirectly used as step-up dc-dc converters. However, none of these multilevel topologies is found to have more attractive features than the modular multilevel converter [4]. Diode clamped converters have a large number of diodes required, which will make the system impractical to implement [3]. Conventional flying capacitor converters [5] require many capacitors connected in series. Generalized multilevel converters can be used for step-up dc-dc conversion [6], [7], but the topology results in a large size when the step ratio is high. Other topologies such as input-parallel-output-series (IPOS) converters [8] have been proposed for step-up dc-dc conversion. The IPOS converters use resonant sub-modules to achieve high power conversion and efficiency [9], but the main disadvantage is the requirement of a large number of isolation transformers each with a high potential difference between the windings. The balancing control is complicated and the converter becomes less reliable when the number of sub-modules is very large.

Modular multilevel converters (MMCs) used for dc-dc conversion in medium and high voltage applications are emerging technologies [1], [10]. These converters based on conventional MMCs [11]–[15] require a complicated balancing control scheme to maintain the voltage levels. However, the MMCs provide more than two levels which depends on the number of modular cells. Cells with fault can be bypassed while keeping the system operational. The MMCs are characterized by high modularity and redundancy.

Until now there has been no prototype of large step ratio resonant dc-dc converter using the MMC approach. This

Fig. 1. Single switches and active clamping sub-modules.

paper presents a new family of modular multilevel bidirectional dc-dc converter with a high voltage step ratio. The idea comes from conventional dc-dc switching converters but is implemented with modular multilevel arrangements. The unidirectional dc-dc step-down converter topologies are presented. Furthermore, based on the modular concept, the bidirectional step-up topologies (with and without isolation) are proposed. They have the feature of modularity, simplicity and flexibility. The configuration of the circuit and operation principle are presented, and verified by experimental results from a downscaled prototype.

II. MMC DC-DC CONVERTERS WITH ACTIVELY CLAMPED SWITCHES

Fig. 1 shows capacitor clamped single switches. Single IGBT, diode, and IGBT with anti-parallel diode can all be clamped by a dc capacitor with an active switch. This gives the possibility of clamping the voltage on the single switch to the capacitor voltage when the single switch is off. When a stack of switches are connected in series to share the switch voltage stress, each switch can be clamped as in Fig. 1. Therefore, the switch voltage stress when the switch is turned off is clamped by the capacitor. This guarantees a good voltage sharing between switches if the capacitor voltages are well balanced.

Two-level converters with series connected IGBTs had been used in high voltage applications. The active clamping applied to the two-level converter with series connected switches gives the generation of MMC topologies.

This active clamping idea also applies to two-level dc-dc converters. Fig. 2 shows the modular multilevel step-down dc-dc converters derived from conventional step-down converters. The first modular converter in Fig. 2 (a) comes from the buck converter. Its modular topology allows the switches to share the high off-state voltage. However, the high voltage input and low voltage output have a common ground. The

Fig. 2. Actively clamped step-down dc-dc converters with modular multilevel arrangements. (a) Buck. (b) Buck-boost. (c) Flyback. (d) Full bridge flyback.

Fig. 3. Bidirectional dc-dc converters. (a) Conventional two-level dc-dc converter. (b) Novel modular multilevel dc-dc converter.

second modular step-down converter topology in Fig. 2 (b) is based on buck-boost converter with a reversed polarity on output side. The flyback converter can be used to reform its modular multilevel step-down version (see Fig. 2 (c)). This converter achieves galvanic isolation between input and output. However, this converter with single diode rectifier results in higher current stress and has no advantage compared to its variation with full bridge rectifier in [10] (see Fig. 2 (d)). The latter, can also achieve full wave resonant conversion. The cell capacitor voltages are naturally balanced in these converters with phase-shifted PWM control. These converters have quite a reliable cell capacitor voltage distribution even without a balancing control.

III. BIDIRECTIONAL STEP-UP MMC DC-DC CONVERTERS

Following the development of previous MMC step-down dc-dc converters, this section presents the bidirectional modular multilevel step-up dc-dc converter. The concept is based on the conventional boost converter.

A. System Configuration

The classic bidirectional boost converter is shown in Fig. 3. It consists of an inductor on low voltage side, two IGBTs with

Fig. 4. Unidirectional step-up dc-dc converters. (a) Conventional boost converter. (b) Proposed modular multilevel step-up dc-dc converter.

anti-parallel diodes and capacitors on dc voltage sides. Replacing all the switches by series connected actively clamped sub-modules, the bidirectional boost converter becomes the modular multilevel step-up dc-dc converter shown in Fig. 3. To smooth the sudden change of cell capacitor voltages when switching, a small inductor is added in series with the upper sub-modules.

The configuration of the step-up conversion is provided to demonstrate the concept. The most commonly used boost converter topology with a single IGBT and a single diode is shown in Fig. 4(a). The IGBT in the lower position is used for charging the input inductor L . The diode in the upper position of the circuit is automatically commutated on when the inductor discharging current to the high voltage capacitor C_H . Applying active clamping (see Fig. 1) to the two switches, the modular multilevel unidirectional step-up converter with two stacks of sub-modules is obtained as shown in Fig. 4(b). The number of the half-bridge (clamped

Fig. 5. Unidirectional step-down dc-dc converters. (a) Conventional buck converter. (b) Proposed modular multilevel dc-dc converter.

IGBT) sub-modules in the lower position is M . The number of the chopper (clamped diode) sub-modules in the upper position is N . The output (high-side) voltage is approximately equal to the sum of capacitor voltages of the stack of sub-modules once duty-cycles are accounted for. There will be small differences between the instantaneous voltage across the stack (as sub-modules switch) and the voltage across C_H and this is accommodated by including the small inductor L_S . A large capacitor C_L would normally be present at the input (low voltage) side. The step-down conversion is configured using the similar concept. The circuit of the proposed converter for step-down operation is shown in Fig. 5.

Furthermore, the proposed modular multilevel dc-dc converter can be modified to adapt isolation requirement. Fig. 6 shows the circuit diagram of the proposed step-up converter with and without isolation. It can be seen in Fig. 6 that the isolation is achieved by using an isolation transformer. The isolation transformer can also bring further step-ratio into the converter, giving the converter an ability of reaching higher step-up ratios. The operation of the isolated modular multilevel dc-dc converter is the same as that of the non-isolated converter. Therefore, this converter will be demonstrated in detail in the paper.

B. Operation Principle

Phase-shifted PWM is used to control the modular multilevel step-up dc-dc converter. Phase-shifted PWM is arranged with a high duty-cycle such that only one sub-module capacitor at a time is out of the series connection and thus the step-up ratio of the circuit becomes dependent on the number of upper cells N . The effective frequency of this excitation is much higher than the frequency of switching of an individual cell.

To demonstrate the principle of operation, a converter with four upper sub-modules is considered ($N = 4$). To ensure that

Fig. 6. Unidirectional step-up dc-dc converters. (a) The basic modular multilevel dc-dc converter. (b) The modular multilevel dc-dc converter with isolation.

Fig. 7. Time domain key waveforms of the proposed dc-dc converter..

either four or three sub-modules are injecting voltage at any time, each must be operated with a duty-cycle above 75%. For illustration, 90% is used. The system will be illustrated with two sub-modules in the lower position operating at twice the frequency of the upper sub-modules and with interleaved pulses. Assuming the sub-module capacitor voltages to be constant, the key waveforms of the sub-module voltages are shown in Fig. 7.

The proposed converter is aimed at high step-up ratio dc-dc conversion. The analysis of operation and conversion ratio will proceed by examining one equivalent cycle T_e in Fig. 7. Fig. 8 shows the detailed circuit diagrams with current paths highlighted for the two modes of the circuit. Mode 1 starts

when the IGBT in Cell 4 is switched on and ends when the IGBT in Cell 1 switches off (see Fig. 8(a)). The IGBT in Cell 1 switches off when the lower IGBT in Cell 5 switches off and this defines the beginning of Mode 2, Fig. 8(b). Mode 2 ends when the IGBT of Cell 1 is switched on again. Modes 1 and 2 are analogous to the on- and off-states of the simple boost converter but with the difference that current can flow in both paths in both modes. The current flowing through the input inductor, upper cells (clamped diodes) and lower cells (clamped IGBTs) are defined as i_L , i_N and i_M , respectively.

In Mode 1, the current i_L of inductor L is directly charged by the low-side (input) voltage v_L via the IGBTs in Cell 5 and Cell 6. The capacitors C_1 , C_2 , C_3 , and C_4 are in series with the inductor L_s and the high-side (output) capacitor C_H and together they form a resonant tank. Because C_H is large and the cell capacitors are smaller and placed in series, the resonance is dominated by the cell capacitors and C_H can be ignored. Therefore, the resonant frequency is

$$f_r = \frac{1}{2\pi\sqrt{L_s C/N}}. \quad (1)$$

In the case of $N = 4$, $f_r = 1/\pi\sqrt{L_s C}$. When the converter enters Mode 2 from Mode 1, capacitor C_5 is connected into the circuit while capacitor C_1 is out of series connection. The capacitors C_2 , C_3 , C_4 , and C_5 are in resonant tank with L_s and C_H . As the inductor L is relatively large, the current i_L is considered as from a current source. Therefore, the resonant frequency in Mode 2 is also dependent on four series connected capacitors and the series inductor L_s . When the lower (clamped IGBT) cells and the upper (clamped diode) cells use the same capacitors, the resonant frequency in Mode 2 is the same as that in Mode 1.

From Fig. 8(b) it can be seen that the current i_N can not be negative in Mode 2 because one cell (Cell 1 in the figure) is acting as a diode. If the actual resonant frequency is slightly higher than f_e , by the end of Mode 2 the current i_N reaches zero and the circuit operates in discontinuous conduction mode (DCM).

When Mode 1 begins, the current i_L is charged directly by the low-side voltage source. Meanwhile, the current i_N starts to resonate (starting from zero) with the frequency of f_r . The current i_M is i_L minus i_N . When the circuit enters Mode 2 from Mode 1, since v_{C5} is higher than v_L , the inductor current i_L reduces. As the circuit operates in DCM, before the end of the equivalent operating cycle, the current i_N falls to zero and the current i_M is equal to i_L until a new cycle begins.

C. High Step-up Ratio

To obtain the voltage conversion ratio, the charging ratio d is defined as the time duration of Mode 1 relative to the period, T_e of the equivalent operating cycle. In steady-state, the increase and decrease of i_L over a equivalent cycle T_e should be the same, hence,

$$\frac{v_L T_e d}{L} = \frac{(v_{Cj} - v_L) T_e (1 - d)}{L} \quad (2)$$

Fig. 9. General control for output voltage.

TABLE I
PARAMETERS OF THE EXPERIMENTAL SYSTEM

Symbol	Quantity	Value
V_L	Nominal low dc voltage	30 V
V_H	Nominal high dc voltage	300 V
T_e	Equivalent operating cycle	250 μ s
L	Low voltage side inductor	821 μ H
L_s	Series inductor	120 μ H
C_1	Cell 1 capacitor	48.9 μ F
C_2	Cell 2 capacitor	49.1 μ F
C_3	Cell 3 capacitor	48.2 μ F
C_4	Cell 4 capacitor	48.7 μ F
C_5	Cell 5 capacitor	48.8 μ F
C_6	Cell 6 capacitor	49.3 μ F
C_L	Low voltage side capacitor	470 μ F
C_H	High voltage side capacitor	180 μ F
R_L	Low voltage side load	18 Ω
R_H	High voltage side load	1070 Ω

with $j = 5$ or $j = 6$. The capacitor voltages of the lower sub-modules is $v_{Cj} = v_L/(1 - d)$.

The sum of average stack voltages v_N and v_M should be equal to the high-side voltage, V_H , which yields

$$v_H = \frac{N - 1 + d}{N} \sum_{j=1}^N v_{Cj} + \frac{1 - d}{M} \sum_{j=N+1}^{N+M} v_{Cj}. \quad (3)$$

Ideally, the capacitor voltages are balanced and equal to $\bar{v}_C$. The voltage conversion ratio can be derived as

$$\frac{v_H}{v_L} = \frac{N}{1 - d}. \quad (4)$$

It can be seen that without increasing d , the conversion ratio can be increased by using higher numbers of N . In the case with $N = 4$ and $d = 0.6$, the conversion ratio is 1 : 10.

The general output voltage feedback control for all sub-modules is shown in Fig. 9. The voltage regulator is represented by $H_v(z)$, usually an anti-windup proportional-integral (PI) controller or a phase lead controller. The gain in this controller for sub-modules in lower position is doubled compared to that in upper position because of the duty-cycle differences (see Fig. 7). The pulse generated by the lower sub-modules is almost complementary to that of upper sub-modules.

The step-down operation has the similar relationship compared with the step-up operation. Due to the page limit, the step-down operation is demonstrated but not explained in detail.

IV. EXPERIMENTAL RESULTS

A downscaled experimental prototype with four upper cells and two lower cells was constructed based on the proposed circuit in Fig. 3(b) for verification. As the experimental operating voltage level is much lower than that of the application

Fig. 8. Step-up operation modes in the first equivalent operating cycle (a) Mode 1. (b) Mode 2.

example, the IGBT voltage drop and diode forward voltage drop become very significant and the results are expected to show a lower step-up ratio. The dc capacitors on the low-side and the high-side were $470 \mu\text{F}$ and $180 \mu\text{F}$, respectively. The inductors on the low-side and high-side were $821 \mu\text{H}$ and $120 \mu\text{H}$, respectively. The sub-modules were implemented using capacitors with a nominal capacitance value of $50 \mu\text{F}$. As a result, the resonant frequency was expected to be approximately 4.1 kHz . The switching frequency for upper cells and lower cells were fixed as 1 kHz and 2 kHz , respectively, giving an effective operational frequency of 4 kHz which is slightly less than the resonant frequency. The detailed circuit parameters are listed in Table I.

A. Open-loop Results

The open-loop step-up tests used a fixed charging ratio of $d = 0.6$. The input voltage is 30 V and the output voltage

is expected to be 300 V . Fig. 10 shows the experimental waveforms. When the current i_N is negative in Mode 1, the voltage drop on diodes is positive compared to v_N . When the current i_N changes to positive, the voltage drop on transistors becomes negative compared to v_N . Because in this mode the inductor L is charging and the capacitor C_H is discharging, the rising of current i_N is suppressed until the end of this mode. When Mode 2 begins, the inductor L is discharging current to the high voltage side and the current i_N keeps resonating until it reaches zero or the end of the equivalent operating cycle.

Fig. 11 shows how the output (high-side) voltage varies as the input (low-side) voltage is changed for a fixed charging ratio of $d = 0.6$ (that is, open-loop operation) and also the characteristic of an ideal transformer. The circuit shows a linear relation between output and input voltages but with an offset compared to the ideal case. This offset is caused by

Fig. 10. Experimental waveforms of the proposed converter for step-up conversion (X-axis: Time, 50 $\mu\text{s}/\text{div}$). (a) Currents (2 A/div). (d) Voltages (100 V/div).

Fig. 11. Experimentally measured step-up linearity.

the conduction voltage drops of the IGBTs and diodes of the sub-modules. The relatively low sub-module voltage means that IGBT conduction losses are significant in this downscaled prototype.

The step-down operation of the proposed modular multilevel dc-dc converter can be achieved by redirecting the current directions. The controller for step-down operation is quite similar to that for the step-up operation. For step-down operation, the input high voltage was set to 300 V. The output low voltage is expected to be 30 V. However, as there are voltage drops in the real switches, the output voltage may be lower than

Fig. 12. Experimental waveforms of the proposed converter for step-down conversion (X-axis: Time, 50 $\mu\text{s}/\text{div}$). (a) Currents (2 A/div). (d) Voltages (100 V/div).

expected. Fig. 12(a) and (b) show the simulated step-down current and voltage waveforms with 1 V voltage drop in each switch. In contrast, the experimental step-down current and voltage waveforms in Fig. 12(c) and (d) are quite similar to the relevant simulation results. The inductor L is charging in Mode 1 and discharging in Mode 2. The lower stack current is zero during this mode. The currents i_L and i_N should increase linearly in Mode 1 and i_L equals i_N . In Mode 2, the current i_L start to decrease linearly. All the cell capacitors in the upper stack are in series with the inductor L_s , forming a resonant tank for i_N to discharge. This verifies the operation analysis of the proposed converter. The output high voltage is around 25 V with $v_H = 300$ V under open-loop control. The output voltage is lower than the expected value due to the voltage drop across the IGBTs.

B. Closed-loop Results

The closed-loop control was implemented by adjusting the effective charging ratio. The step-up conversion ratio of 1 : 10 from input to output is achieved such that the high voltage v_H is almost 300 V. Fig. 13 shows the experimental current and voltage waveforms of the closed-loop controlled step-up conversion. The input low voltage was fixed as $v_L = 30$ V. Compared to the waveforms under open-loop control with $d = 0.6$ (see Fig. 10), it can be seen that the charging ratio d in the closed-loop curve has been raised by the controller. Moreover, the currents in the converter with the closed-loop controller are higher than those with the open-loop controller and the

Fig. 13. Experimental waveforms of the closed-loop control step-up conversion (X-axis: Time, 50 μ s/div). (a) Experimental currents (Y-axis: Magnitude of current, 2 A/div). (b) Experimental voltages (Y-axis: Magnitude of voltage, 100 V/div).

Fig. 14. Experimentally measured step-up voltages with closed-loop control.

peak voltage of v_N is higher as well. As a result, the step-up conversion ratio of 10 : 1 is achieved such that the high voltage v_H is almost 300 V. Fig. 14 shows the experimentally measured step-up voltages under closed-loop control. It can be observed that the closed-loop controller is effective that the high voltage is always controlled around the rated value 300 V.

V. CONCLUSION

This paper has presented a new family of MMC dc-dc converters generated from conventional dc-dc converters. Con-

Fig. 15. Experimental waveforms of the closed-loop control step-down conversion (X-axis: Time, 50 μ s/div). (a) Experimental currents (Y-axis: Magnitude of current, 2 A/div). (b) Experimental voltages (Y-axis: Magnitude of voltage, 100 V/div).

verters with two generic operation purposes are introduced: the step-up conversion and the step-down conversion. The operation of the non-isolated modular multilevel step-up dc-dc converter is demonstrated. The experimental results show that the converter can achieve large step-up conversion ratio without the use of transformers. This converter is capable of operating under open-loop control as a dc transformer with good linearity. It has the feature of modularity, scalability and simplicity and these may make it attractive in some high voltage applications.

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