A Single-Phase Hybrid Multi-Level Converter with Less Number of Components

Ki-Mok Kim and Gun-Woo Moon
School of Electrical Engineering, KAIST

Abstract

This paper presents a new hybrid multilevel converter topology, which consists of a combination of the series connected switched capacitor units with boost ability, and an H-bridge with T-type bidirectional switches. The proposed converter boosts the input voltage without any bulky inductors, and has the small number of components, which can make the size and cost of a power converter greatly reduced. The output filter size and harmonics are also reduced by the high quality multilevel output. In addition, there is no need for complicated methods to balance the capacitor voltage. Simulation and experimental results with a *nine*-level converter system are presented to validate the proposed topology and modulation method.

Keywords: multilevel inverter, switched capacitor, T-type bidirectional switch, boost converter

1. Introduction

Recently, multilevel convers (MLCs) are considered as one of the most popular solutions for distributed generation (DG) systems based on renewable energy sources, and electric vehicles (EVs), etc. These multilevel converters can generate a staircase output voltage with high quality. The desired output voltage is synthesized by appropriate switching of several dc-voltage links, which can reduce the voltage stress of switches and total harmonic distortion (THD) [1], [2]. In general, there are mainly three types of multilevel converter topologies: Cascade H-bridge Multilevel Converter (CHB-MLC), Neutral-Point-Clamped Multilevel Converter (NPC-MLC), and Flying Capacitor Multilevel Converter (FC-MLC) [2]. As the number of voltage level increases, the number of clamping diodes in NPC-MLC, flying capacitors in FC-MLC, and the isolated dc sources in CHB-MLC also increase significantly.

In order to solve these problems, many researchers have developed the new types of the multilevel topology with reduced number of main components, such as number of switches, power sources, capacitors, and so on. One of the most particular schemes of them is the switched-capacitor multilevel converter (SC-MLC) [3]. This converter can produce more output voltage levels with boost ability and less number of components by connecting the capacitors and DC sources in series and in parallel. However, basically it has a structure with one power source, so it is difficult to use where more than one power source is needed. Also, as one of variations of SC-MLC, the new type of the multilevel inverter with multi-input function was proposed in [4]. However, in this structure the fundamental switching method can be only used for modulating the converter, which results in increasing the output filter size and harmonic components.

In this paper, a new hybrid multilevel converter topology (HB-MLC) is proposed. It consists of a combination of the series connected switched capacitor units with boost ability, and an H-bridge with T-type bidirectional switches. The switched capacitor unit generates a boosted output voltage in a single-stage by connecting the capacitors and DC sources in series without having any inductors and transformers that make the system large and heavy. In case the H-bridge with T-type switches is combined with the switched capacitor topology, it can contribute in reducing the number of components and conduction loss. The newly developed modulation method can solve the problem of capacitor voltage balancing by controlling each capacitor to be regulated to the value equal to one of the input source voltage every cycle. In addition, because the proposed modulation method can use both the low frequency and high frequency, output filter size and harmonic components can be significantly reduced.

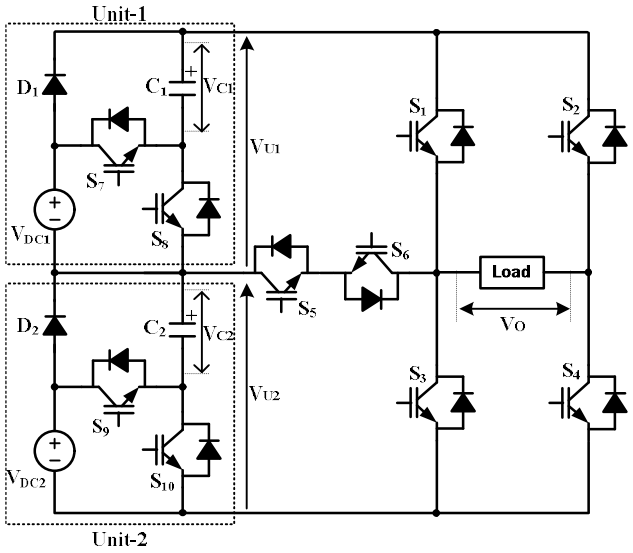

Fig. 1. The proposed *nine*-level hybrid multilevel converter.

2. The Proposed Multilevel Converter

A. Comparison of Device Number

Table I shows comparison of the device number for multilevel converter configurations: NPC-MLC, FC-MLC, CHB-MLC, and proposed HB-MLC. It can be seen that the total devices including power switches, diodes, and capacitors used in the proposed converter configuration are significantly reduced compared with three conventional multilevel converters.

TABLE I
COMPARISON OF DEVICE NUMBER FOR THE *NINE-LEVEL* CONVERTERS

Devices	NPC-MLC	FC-MLC	CHB-MLC	Proposed HB-MLC
Main Switches	16	16	16	**10**
Main Diodes	16	16	16	**12**
Clamp Diodes	56	0	0	**0**
DC-Bus Capacitors	8	8	4	**2**
Flying Capacitors	0	28	0	**0**
Total Devices	96	68	36	**24**

B. Operating Principle

The main circuit configuration of the proposed hybrid multilevel converter is shown in Fig. 1. The proposed topology consists of a combination of two switched capacitor units connected in series

and an H-bridge with T-type bidirectional switches. One switched capacitor unit (Unit-1 as an example) contains one dc power source(V_{DC1}), one capacitor(C_1), one passive power diode(D_1), and two active power switches(S_7,S_8). Photovoltaic (PV) cells, batteries, and fuel cells can be used as a power source in this structure. Switches S_7 and S_8 are used in series and parallel conversions, respectively. When the switch S_8 becomes ON, the capacitor C_1 is charged to V_{DC1} and when the switch S_7 turns ON, the diode becomes reverse biased and capacitor is discharged. In this mode, the power supply's energy and stored energy of C_1 are transferred to the output. It is obvious that, this unit does not need any extra charge balancing control circuits and complicated commutation methods, which is considered as a great merit of this structure. Also, it is remarkable that, the internal resistance of power diode and capacitor can damp the unequal voltage between capacitor and dc-voltage source during the charging operation, which leads to introduce an effective and practical power circuit. T-type bidirectional switches, S5 and S6 are connected between the neutral point and the output, which only need to block half of the sum of Unit-1 and Unit-2 voltages. Hence, it is possible to use the power devices with a lower voltage rating, and the conduction loss is considerably reduced compared to that of the NPC topology. H-bridge with switches S_1-S_4 is used to produce negative voltage levels. Switches S1 and S3, S2 and S4, S1 and S6, S3 and S5, S7 and S8, and S9 and S10, must be operated in a complementary way, respectively.

Assuming V_{DC1}=V_{C1} and V_{DC2}=V_{C2}, Unit-1 and Unit-2 can produce $2V_{DC1}$ and $2V_{DC2}$, respectively. Also, the maximum output voltage that can be produced is equal to the sum of Unit-1 and Unit-2 maximum output voltages, which is as follows:

$$V_{o,max} = 2(V_{DC1} + V_{DC2}) \quad (1)$$

The total sinusoidal output voltage of the proposed converter at fundamental frequency are given by

$$v_o = M \cdot V_{o,max} \cdot \sin(\omega t) \quad (2)$$

where M is the modulation index, and ω is angular frequency.

With switching states, the relationship between DC-source and capacitor voltages and output voltage is listed in Table Ⅱ.

TABLE Ⅱ

SWITCHING PATTERN OF THE PROPOSED CONVERTER

	No.	On Switches	V_O
Switching States	1	S_1, S_4, S_7, S_9	$V_{DC2}+V_{C2}+V_{DC1}+V_{C1}$
	2	S_1, S_4, S_8, S_9	$V_{DC2}+V_{C2}+V_{DC1}$
	3	S_4, S_5, S_8, S_9	$V_{DC2}+V_{C2}$
	4	S_4, S_5, S_8, S_{10}	V_{DC2}
	5	S_3, S_4, S_8, S_{10}	0
		S_1, S_2, S_8, S_{10}	0
	6	S_2, S_6, S_8, S_{10}	$-V_{DC1}$
	7	S_2, S_6, S_7, S_{10}	$-V_{DC1}-V_{C1}$
	8	S_2, S_3, S_7, S_{10}	$-V_{DC1}-V_{C1}-V_{DC2}$
	9	S_2, S_3, S_7, S_9	$-V_{DC1}-V_{C1}-V_{DC2}-V_{C2}$

C. Modulation Method

The Phase Disposition Sub-Harmonic PWM (PDSH-PWM) is proposed for modulating the proposed multilevel converter as shown in Fig. 2. The proposed PWM method uses eight triangular carrier signals along with only one modulation reference per phase to control the converter. The eight triangular carriers of the same frequency with the same peak-to-peak amplitude are disposed, so that the bands they occupy are contiguous. The zero reference is placed in the middle of the carrier set. At every instant each carrier is compared with the reference signal. When the reference signals are greater than the triangular carriers, the devices are switched on, and vice versa.

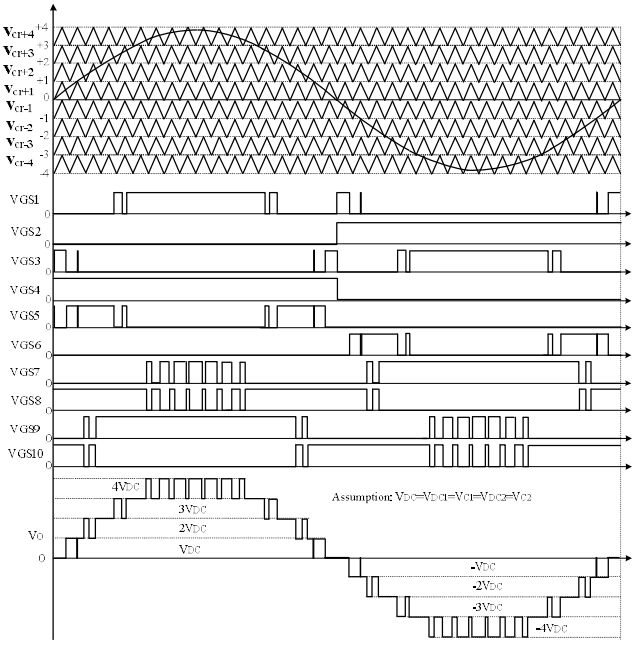

Fig. 2. Modulation method of the proposed multilevel converter (M=0.9).

TABLE Ⅲ

CONVERTER PARAMETERS IN THE SIMULATION AND EXPERIMENT

Parameter	Value
Output Fundamental Frequency	50Hz
Output Peak Voltage	96V
DC-source voltages: V_{DC1}/ V_{DC2}	24V / 24V
Switching Frequency	4.8kHz
Output Filter Inductance	5mH
Load Resistance	50Ω
Capacitors: C_1/ C_2	3300uF / 3300uF

3. Simulation and Experimental Results

In order to verify the proposed system and its modulation method, the simulations are performed by using PSIM software. A single-phase *nine*-level converter is built for simulation. The circuit parameters for the simulation system are listed in Table Ⅲ.

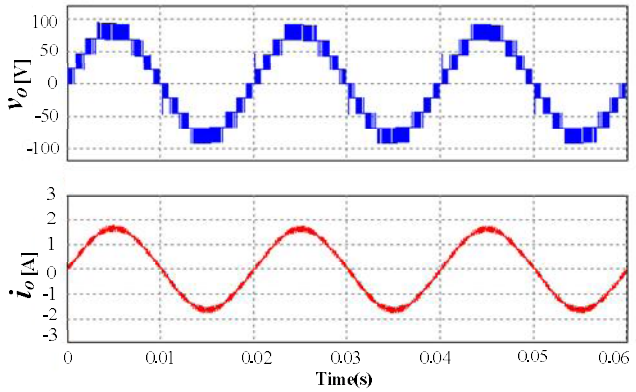

Fig. 3. Simulated output voltage and current waveforms of the proposed multilevel converter (Modulation index: M=0.9).

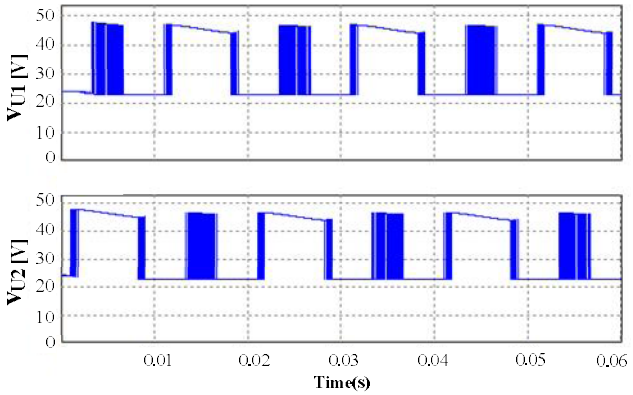

Fig. 4. Simulation results: a) Output voltage (V_{U1}) of Unit-1 and a) Output voltage (V_{U2}) of Unit-2 (M=0.9).

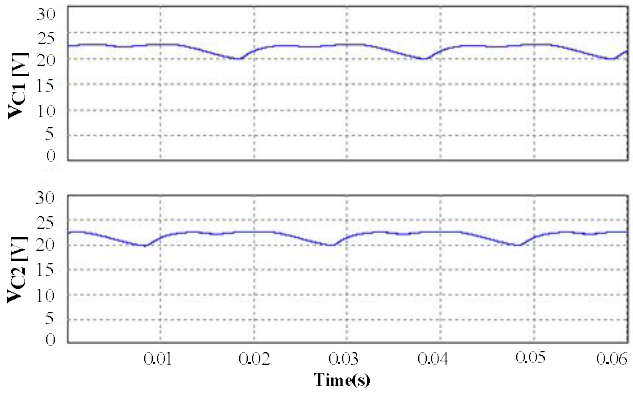

Fig. 5. Simulated C_1 and C_2 voltages of the proposed multilevel converter (M=0.9).

Fig. 3 shows the output voltage and current of the proposed single-phase nine-level converter at modulation index: M=0.9. When V_{DC1} and V_{DC2} are 24V, the peak output voltage and current are about $96V_P$ (24Vx4) and $1.7A_P$, respectively. As can be seen in Fig. 4, each of Unit-1 and Unit-2 generates 24V and 48V (24V+24V), periodically. Voltages of capacitors C_1 and C_2 are well controlled at the same value as the DC source voltage (24V) by the new modulation method as shown in Fig. 5.

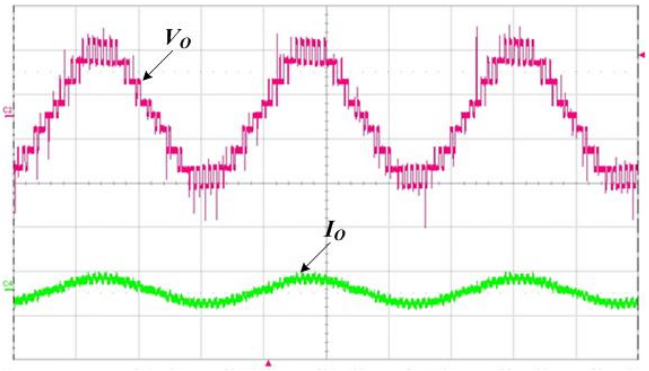

Fig. 6. Experimental output waveforms of the proposed multilevel converter (M=0.9): (a) Output voltage (100V/div), (b) Output current (2A/div).

Based on a digital experimental system platform combining DSP and FPGA, a prototype single-phase converter system has been built in the laboratory. The experimental parameters are the same as those of the simulation listed in Table Ⅲ. The sinusoidal peak output voltage and current of the experimental system are $93V_P$ and $1.7A_P$ at M=0.9 respectively, as shown in Fig. 6, which are approximately the same as those of the simulation results. The experimental and simulation results are well consistent with the theoretical results.

3. Conclusion

This paper has presented a new hybrid multilevel converter topology. The main features of the proposed converter are as follows:

- The number of components can be greatly reduced, which makes the size and cost of a power converter reduced.
- It can boost the output voltage in a single-stage by connecting the capacitors and DC sources in series without having any inductors and transformers that make the system large and heavy.
- High efficiency can be achieved by reducing switching loss and conduction loss with using a low frequency and low voltage switching devices.
- Output filter size and harmonic components can be significantly reduced.

Simulation and experimental results was presented to validate the proposed topology and modulation method, which is well consistent with theoretical analysis. It is expected that the proposed topology will be used as a competitive alternative for high power density, high efficiency, and low cost systems.

Acknowledgment

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