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Cascaded Multilevel Converter Using Five-Level Power Cells

[1]Morteza Farsadi, [1]Ali Vafamehr, [2]Mohammad Farhadi Kangarlu

[1]Department of Electrical Engineering, Faculty of Engineering, Urmia University, Urmia, Iran
[2]Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran

Abstract: Multilevel converters have many advantageous features over the conventional two-level topologies including capability of handling high-voltage high-power, improved output voltage quality etc. In this paper, a new cascaded multilevel converter is proposed. The proposed multilevel converter is based on a 5-level regenerative converter. In the proposed multilevel converter, the number of active switching devices are reduced in both inverter and rectifier sides resulting in a cost-effective topology. Also, as the active rectifier is used rather than the passive one, the power flow direction can be reverse to make a regenerative topology. As the proposed topology similar 5-level cells, it has good modularity and can be extended to any number of voltage levels. The simulation results of a 9-level converter based on the proposed topology are presented to verify its operation and control.

Key words: Multilevel converter, reduced switch topology, regenerative

INTRODUCTION

Multilevel converters as a popular sort of power-electronic converters have been widely investigated in recent years. A typical multilevel converter uses power-electronic switches and dc voltage sources to generate a multilevel output voltage. In this way, the output voltage can be a better approximation of the desired waveform. Also, the switching occurs between two voltage levels that are adjacent. These characteristics lead in higher quality output voltage, reduced electromagnetic interference (EMI) and noise problems, lower switching stresses and reduced losses in comparison with a two-level converter. Moreover, as the nominal voltage of the converter is distributed in the switches, low-voltage switches can be used for medium-voltage applications. In other words, the multilevel converters can operate in higher voltage and power levels using low-voltage semiconductor switches. However, the number of semiconductor devices in a multilevel converter increases considerably making it complicated to implement and control.

Conventionally, three main topologies of multilevel converters are recognized in the literature (Rodriguez, J., *et al*. 2002; Lai, J.S. and F.Z. Peng, 1996; Malinowski, M., *et al*., 2010; Rodriguez, J., *et al*., 2010): the neutral-point-clamped (NPC), the flying-capacitor (FC) and the cascaded H-bridge (CHB) multilevel converters. Among these inverter topologies, cascaded multilevel inverter reaches the higher output voltage and power levels (13.8 kV, 30 MVA) and the higher reliability due to its modular topology. Cascaded multilevel inverters are based on a series connection of several single-phase inverters. This structure is capable of reaching medium output voltage levels using only standard low-voltage mature technology components (Malinowski, M., *et al*., 2010).

The CHB multilevel converters have received increased attention due to modularity and ease of extending to higher number of voltage levels. One of the main disadvantages of the multilevel converters is to use high number of power electronic components which leads in complicated control and performance. Moreover, the CHB multilevel converters need several independent dc voltage sources.

The back to back CHB multilevel converters are possibly the most applied topologies for high power applications. Such an application has been investigated for high-power high-voltage motors (Tolbert, L.M., *et al*., 1999; Rodriguez, J., *et al*., 2005; Lezana, P., *et al*., 2007; Rodriguez, J., *et al*., 2007). The CHB multilevel converters have also been applied in the flexible ac transmission systems (FACTS) (Barrena, J.A., *et al*., 2008; Liu, Y., *et al*., 2009; Flores, P., *et al*., 2009), power quality compensators (Massoud, A.M., *et al*., 2010; Babaei, E. and M. Farhadi Kangarlu, 2011), traction applications (Aquila, A.D., *et al*., 2003; Du, Z., *et al*., 2009) and renewable energy interface applications (Carrasco, J.M., *et al*., 2006; Villanueva, E., *et al*., 2009; Cecati, C., *et al*., 2010).

Beside the conventional CHB multilevel converters, new cascaded topologies have been presented for multilevel converters (Farhadi Kangarlu, M. and E. Babaei, 2013; Hinago, Y. and H. Koizumi, 2010; Ebrahimi, J., *et al*., 2011; Farhadi Kangarlu, M., *et al*., 2012). These topologies though reduce the number of switches effectively; they lose some good features of multilevel converters. For instance, they use switches with wide variety of voltage ratings and also need high-voltage switches. Also, their back to back operation becomes very difficult and complicated.

A regenerative back to back multilevel converter has been presented in (Lezana, P., *et al*., 2008). This topology is as the same as the conventional CHB multilevel converter in its inverter side. However, it uses

Corresponding Author: Morteza Farsadi, Department of Electrical Engineering, Faculty of Engineering, Urmia University, Urmia, Iran

different rectifier side converter. The converter used in the rectifier side of this topology uses two switches per cell instead of four switches. Therefore, this topology halves the number of switches in its rectifier side. A simplified topology for multilevel inverter has been presented in (Cegila, A., *et al*., 2006). This topology is a 5-level topology and uses fixed dc voltage sources.

In this paper, a new back to back cascaded multilevel converter is proposed. The proposed topology uses 5-level cells with regenerative capability. In both rectifier and inverter stages, the topology effectively reduces the number of switches. The 5-level cell is described in the next section. The proposed cascaded topology is presented in section III. Finally, the simulation results of the 9-level converter based on the proposed topology are presented in section IV to verify its operation.

Proposed Five-Level Power Cell:

The performance of a multilevel inverter has a great deal with its DC-link voltage's structure. It can be a simple battery, fuel cell, PV, etc. But for high power application it is better to use a structure on dc link that is controllable. One of the simple structures for providing controllable dc voltage is to use a diode rectifier which is shown in Fig. 1. This topology has some drawbacks. For example it needs a complex input transformer in order to reduce low order harmonics and foremost being non-regenerative characteristic which cannot reverse the power flow from load to the ac supply, if it is needed. So to overcome these drawbacks, controllable rectifier which is shown in Fig. 2 has been presented. The most important advantage of this topology rather than diode rectifiers is being regenerative. Although it is a good solution for regenerative applications, it has its own defects. The main drawback of this cell is that the dc link presents ripple at double the input voltage frequency. Other drawback is that the conventional structure uses large number of switches.

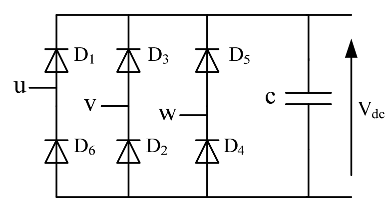

Fig. 1: Three-phase diode rectifier

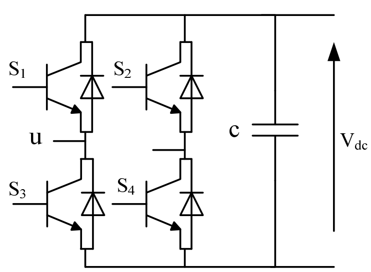

Fig. 2: Single phase active rectifier

Due to mentioned drawbacks, a new topology has been presented in (Lezana, P., *et al*., 2008) which reduces the number of switches comparing to conventional one. It uses only two switches (instead of four switches) and two capacitors. A simple application of this active rectifier has been presented for a cascade multilevel inverter which is shown in Fig. 3. If the rectifier cell shown in Fig. 3 is used in a back to back cascaded multilevel converter, the inverter stage will be the conventional CHB topology. For example to produce the five-level output voltage, 8 switching devices in the inverter stage and 4 switching devices in the rectifier stage should be use. In order to further simplify the multilevel converter, a new 5-level regenerative topology is proposed here which is shown in Fig. 4. The proposed 5-level topology consists of a rectifier stage with two switches and a 5-level inverter stage which uses only 6 switching devices. Therefore, it reduces the number of switches in both rectifier and inverter stages.

The switching combinations of the proposed 5-level cell which is required to generate the 5 level output waveform is shown in Table I.

Table I: switching combinations of the proposed 5-level converter

	Output Voltage Level					
Switches	2E	E	0	0	-E	-2E
S_1	1	0	1	0	0	0
S_2	0	0	1	0	1	1
S_3	0	0	0	1	0	1
S_4	1	1	0	1	0	0
S_5	0	1	0	0	0	0
S_6	0	0	0	0	1	0

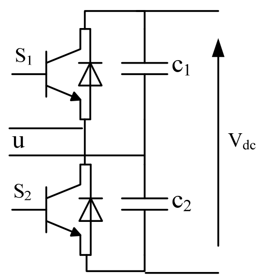

Fig. 3: Reduced switch active rectifier circuit

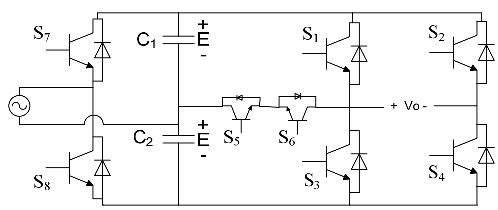

Fig. 4: The proposed 5-level regenerative multilevel converter

This structure not only reduces the number of switches comparing to other methods such as diode-clamped, capacitor–clamped etc, but also has other advantages .For instance it reduces the number of diodes and capacitors comparing to diode-clamped inverters and it reduces the number of capacitors, comparing to capacitor-clamped inverters.

The rectifier and inverter stage of the proposed 5-level power cell are controlled separately. The block diagram of the rectifier stage control is shown in Fig. 5 (Lezana, P., *et al*., 2008). As the figure shows, the measured dc link voltage is filtered by a band-stop filter to eliminate its oscillating component with twice the main frequency. The output of the filter is subtracted from the reference value of the dc link voltage. Through a PI controller the error between the measured and the reference value of the dc link voltage specifies the magnitude of the rectifier input current. However, in order to balance the voltage of the two capacitors used in the dc link (C_1, C_2) the error between their voltage is given to another PI controller the output of which is added to the control system a feed-forward control. Finally, a resonant controller is used to provide the switching pulses of the rectifier stage. The inverter part can be controlled by a simple multicarrier modulation scheme.

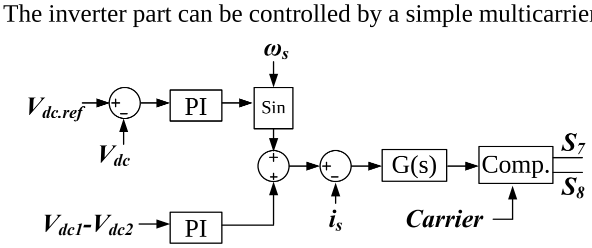

Fig. 5: Control circuit of rectifier part

The Proposed Cascaded Multilevel Converter:

In order to produce higher number of voltage levels, multiple proposed 5-level converters can be cascaded to form a cascaded multilevel converter. Fig. 6 shows the proposed cascaded multilevel converter based on the 5-level converter. It consists of k cascaded 5-level cells. Each 5-level cell should be supplied independently in the rectifier stage. In order to provide independent supply of the cascaded cells, a transformer is needed per cell. However, a multiple secondary transformer can also be used. It is important to know that if a transformer is used at the output of each inverter cell, one common rectifier stage will be enough. In this paper, each cell has its own rectifier supplied from a multiple secondary transformer. For the proposed cascaded multilevel converter, the following equations can be written:

$$N_L = 4k + 1 \tag{1}$$

$$N_{switch} = 8k \tag{2}$$

where, N_L and N_{switch} are the number of voltage levels and number of switches, respectively. using (1) and (2), the number of switches in terms of number of voltage levels can be written as follows:

$$N_{switch} = 2(N_L - 1) \tag{3}$$

The rectifier of each cell is controlled independently which has been described in the previous section. To control the inverter stage, the carriers of the cascaded cells should have proper phase shifts based on the number of cascaded cells.

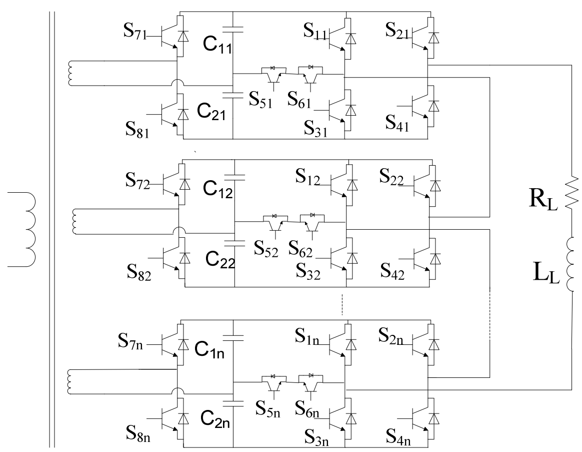

Fig. 6: The proposed 5-level regenerative multilevel converter

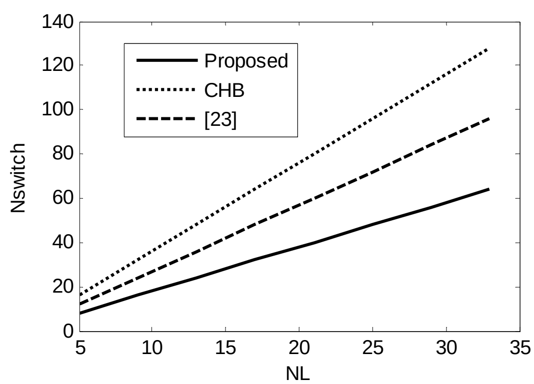

Fig. 7: Comparison of number of switches versus number of voltage levels

To have a better view, the number of switches required in the proposed topology along with that of the topology presented in (Lezana, P., *et al*., 2008) and also conventional CHB based scheme is shown in Fig. 7 as a function of number of levels. The figure clearly indicates that the proposed scheme uses lower number of switches for any specific number of voltage levels.

Simulation Results:

In order to verify the operation of the proposed multilevel converter, a two-cell 9-level converter based on the proposed topology has been simulated in the PSCAD environment. The simulated 9-level converter is shown in Fig. 8. The converter supplies a series R-L load with the values of 15 ohm and 10 mH. The system frequency is considered to be 50Hz and the switching frequency is 1.5 kHz. The rms value of input ac voltage of the rectifiers is 400V.

The output voltage of rectifier is shown in Fig. 9. This voltage is the sum of capacitors voltages and has a ripple at the frequency of 100 Hz (double the source frequency). It is important to note that the value of the dc link voltage is twice the rms value of the source voltage. Fig. 10 shows the voltage of the capacitors in dc link. As it is clear, the capacitors' voltages are equal to the source voltage and their ac component have 180 degrees phase shift. This phase shift makes the 100 Hz fluctuation of total dc link voltage.

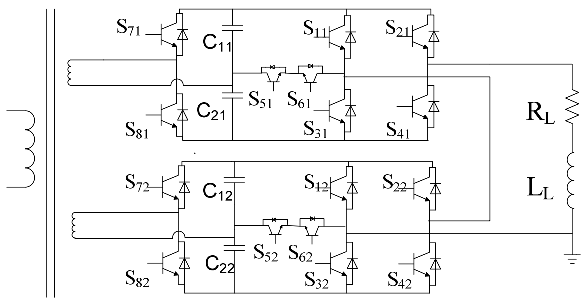

Fig. 8: simulated circuit

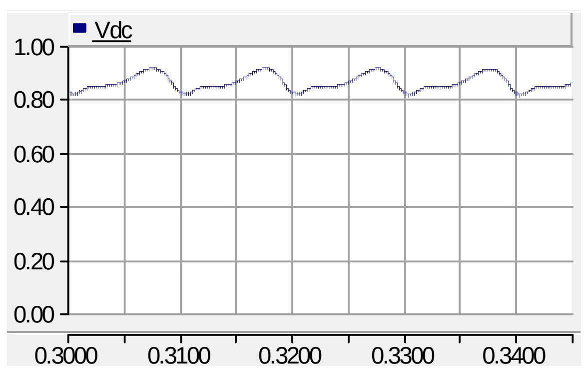

Fig. 9: Voltage of DC link

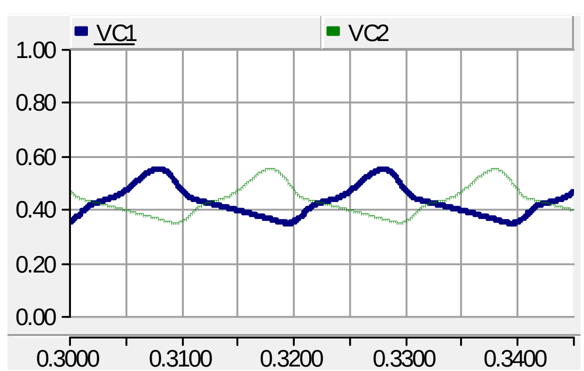

Fig. 10: Voltages of DC link capacitors

Considering the dc link voltage of Fig. 9 as the input voltage of inverter side, each cell generates a 5-level PWM voltage that their sum finally leads to a 9-level output voltage in the proposed structure. The output voltage of the first and second cell is represented in Fig. 11 and 12, respectively. The total output voltage of the proposed 9-level inverter is shown in Fig. 13.

The load current is shown in Fig. 14. This current is an almost sinusoidal waveform with negligible distortion because of the filtering characteristic of the RL load.

To illustrate the harmonic distortion of output voltage and load current, their frequency spectra up to the 31st harmonic of base frequency are presented in Figs. 15(a) and 15(b), respectively. According to these figures only the odd-order harmonics exist and total harmonic distortion (THD) for output voltage and load current are 5.73% and 4.3%, respectively.

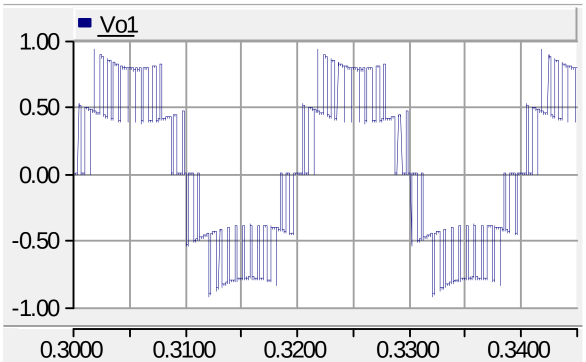

Fig. 11: Voltage of cell 1

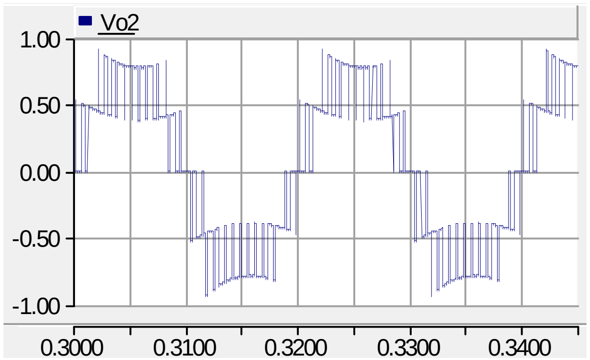

Fig. 12: Voltage of cell 2

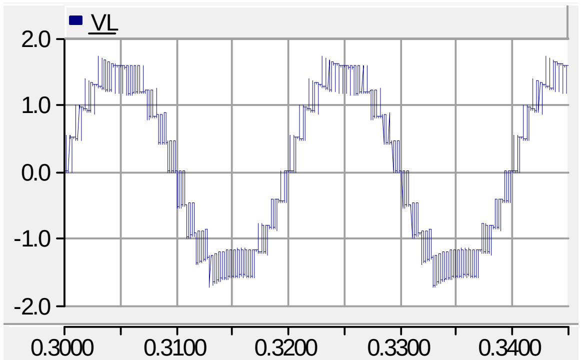

Fig. 13: Output voltage in proposed converter

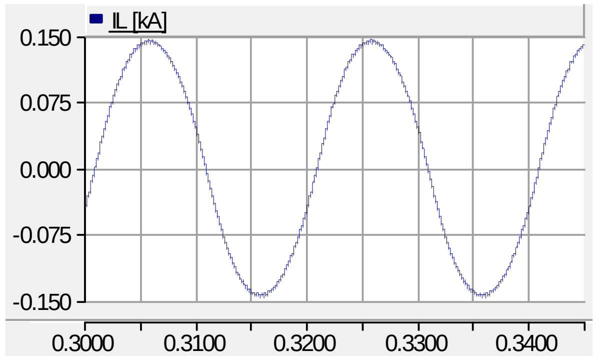

Fig. 14: Load current

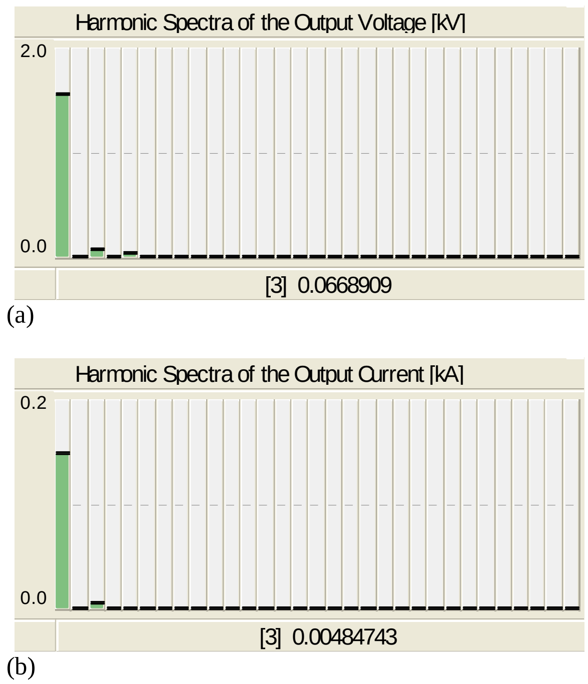

Fig. 15: Frequency spectrum of (a) output voltage and (b) load current

Conclusion:

The cascaded multilevel converter based on 5-level cells is presented in this paper. The proposed topology uses lower number of switching devices in both rectifier and inverter side. In the rectifier side, the number of switches is halved in comparison with the classic H-bridge topology. Also, in the inverter side, each 5-level cascaded cell uses six switches which are lower than that of the 5-level H-bridge topology (that uses eight switches). The simulation results of a two-cell 9-level converter based on the proposed topology show its satisfactory operation. The sum of the switches in rectifier and inverter side of the 9-level converter based on the proposed topology is 16. However, the classic H-bridge based topology uses 32 switches for the same operation. On the other hand, the topology presented in (Lezana, P., *et al*., 2008) uses 24 switches for the same number of voltage levels.

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