A Multilevel Boost Converter Based on a Switched-Capacitor Structure

Seyed Hossein Hosseini[1,2], Amirreza Zarrin Gharehkoushan[1], and Hadi Tarzamni[1]

[1] University of Tabriz, Tabriz, Iran
[2]Engineering Faculty, Near East University, 99138 Nicosia, North Cyprus, Mersin 10, Turkey
hosseini@tabrizu.ac.ir
Zarrin.gharehkoushan@gmail.com
hadi_tarzamni@yahoo.com

Abstract

In this paper, a new circuit for multilevel boost converter based on DC-DC switched-capacitor structure is presented. This DC-AC converter increases the input voltage for the output terminal, so it's suitable for photovoltaic applications. The proposed multilevel converter is compared with other recently suggested structures in terms of power electronic components and voltage boosting capability. Based on the comparison results, the proposed topology utilizes least number of power switches, diodes and capacitors. Also, the proposed multilevel converter overcomes the disadvantage of conventional multilevel converters which were suffering from voltage imbalance of the capacitors. These advantages decrease the costs, reduce the size of the converter and prevent the control circuit from being more complicated. Finally, for verifying the performance of the proposed structure, experimental results are provided.

1. Introduction

Nowadays, multilevel converters, including DC voltage sources, power switches, diodes, and capacitors, are playing an important role in power electronic applications like renewable energy systems, hybrid electrical vehicles, industrial drives and reactive power compensation [1,2].

In this case, some structures have been presented as multilevel topologies in other literature, where diode-clamped converters (DCCs), flying-capacitor converters (FCCs) and cascade H-bridge converters (CHBCs) are the first ones [3]. Suffering from voltage imbalance of the input DC-link capacitors, large number of DC-link capacitors, clamping diodes, flying capacitors can be called as some of the disadvantages of the conventional DCCs and FCCs. Although in CHBCs, diodes and capacitors are not used; large numbers of DC voltage sources are employed in these converters.

In previous years, several multilevel structures have been presented, due to the above mentioned limitations of classical multilevel converter topologies, however, these multilevel topologies utilize more number of DC voltage sources.To overcome the mentioned restriction of classical multilevel converters, new topologies have been presented in recent years, which can be divided into three main groups as follows:

1.1. Buck multilevel converters [4]

In these topologies, the amplitude of output voltage waveform is less than the sum of all utilized DC voltage sources in the structures. In this division, DCCs and FCCs, belong to this group. These multilevel converters can produce high number of output voltage levels with less number of required power electronic components. On the other hand, reducing the amplitude of input DC voltage sources at the output voltage terminal, leads to restricted applications of them.

1.2. Unity voltage gain multilevel converters [5,6]

These topologies can't change the amplitude of input DC voltage sources at output voltage terminal. So, the maximum value of output voltage waveform is equal to the sum of all utilized DC voltage sources in these structures. In this division, CHBCs belongs to this group. This group is divided into two sections, which are named symmetric and asymmetric topologies. In symmetric topologies, the magnitudes of all DC sources are equal. On the contrary, in asymmetric type of converters, the values of DC voltage sources are different, so various algorithms have been proposed for determination of DC voltage sources. Furthermore, it is notable that the asymmetric topologies can produce higher number of levels at output voltage waveform in comparison with the symmetric structures with the same number of power electronic components.

1.3. Boost multilevel converters [7]

These multilevel converters can increase the amplitude of input DC voltage sources at the output voltage terminal, so the maximum value of output voltage waveform is more than the sum of all input DC voltage sources. Mainly, the operation of these topologies is based on charging and discharging of capacitors. These multilevel converters are applicable in renewable energy systems like photovoltaic applications, since the generated voltage by PV panel in photovoltaic systems needs to be boosted. However, for producing higher number of output voltage levels and increasing the voltage gain, these topologies utilize a large number of power electronic components, like power switches, diodes and capacitors. So, having voltage boosting capability and utilizing minimum number of DC voltage sources, make these converters more suitable than other topologies. However, high values of standing voltages on switches along with using a large number of power electronic components are disadvantages of boost multilevel converter structures.

In this paper, a new switched-capacitor multilevel topology is presented. Then, the proposed topology is compared with other suggested topologies in the recent years. Finally, to prove the performance of the proposed topology, simulation works along with experimental results are provided.

2. Proposed DC-DC Switched-Capacitor Unit

The proposed DC-DC switched-capacitor unit is shown in Fig. 1. As presented in this figure, the proposed DC-DC switched-capacitor unit consists of two capacitors and two power diodes. Also, two different types of power switches are used in the proposed DC-DC switched-capacitor unit, where S_1 and S_2 switches are both unidirectional power switches with anti-parallel body diodes and K is a unidirectional switch for current and bidirectional for voltage. The K switch consists of a diode in series with a unidirectional switch.

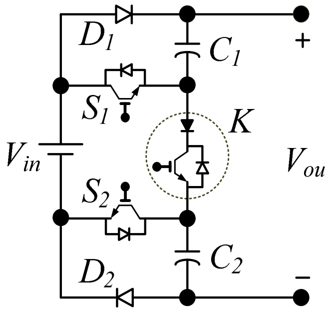
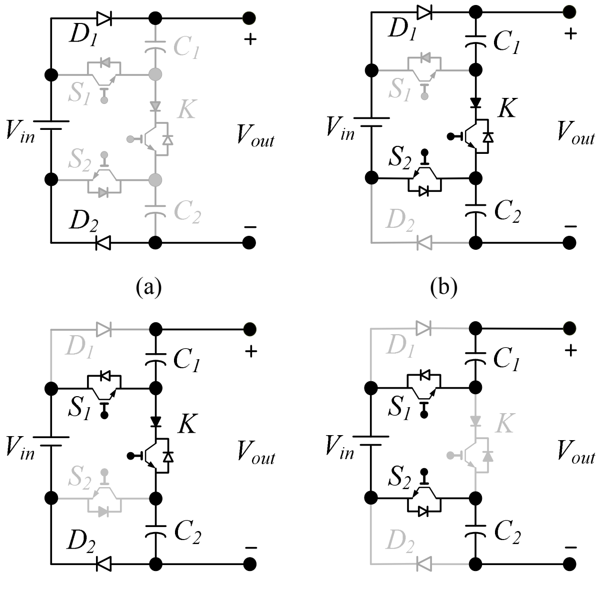


Fig. 1. Proposed DC-DC switched capacitor unit

The proposed structure in Fig. 1, can generate three levels at output voltage waveform which are $+V_{in}$, $+2V_{in}$ and $+3V_{in}$. The current flow path of each level is separately shown in Fig. 2.



(a) (b)

(c) (d)

Fig. 2. Operational modes of proposed DC-DC switched-capacitor topology. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4.

3. Proposed Switched-Capacitor Multilevel Topology

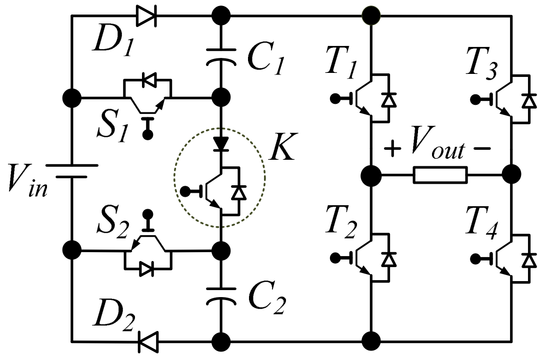


Fig. 3. The structure of proposed switched-capacitor multilevel.

The structure of the proposed multilevel includes proposed DC-DC switched-capacitor topology, available in Fig. 2, along with an H-bridge inverter. The conventional H-bridge topology consists of four unidirectional switches that are similar to the power switches S_1 and S_2. As mentioned, the proposed DC-DC Connecting a conventional H-bridge inverter to the DC-DC switched-capacitor topology, the proposed switched-capacitor multilevel unit can generate both positive, negative, and zero levels as 0, $\pm V_{in}$, $\pm 2V_{in}$, $\pm 3V_{in}$ at the output voltage waveform (V_{out}). The switching states of the proposed switched-capacitor multilevel structure are indicated in Table 1.

Table 1. Switching states of the proposed switched-capacitor multilevel structure.

V_{out}	S_1	S_2	K	T_1	T_2	T_3	T_4
$+3V_{in}$	on	on	off	on	off	off	on
$+2V_{in}$	off	on	on	on	off	off	on
	on	off	on	on	off	off	on
$+V_{in}$	off	off	off	on	off	off	on
0	off	on	on	on	off	on	off
	on	off	on	on	off	on	off
$-V_{in}$	off	off	off	off	on	on	off
$-2V_{in}$	on	off	on	off	on	on	off
	off	on	on	off	on	on	off
$-3V_{in}$	on	on	off	off	on	on	off

Switched-capacitor topology can generate three levels of $+V_{in}$, $+2V_{in}$ and $+3V_{in}$ in the output voltage waveform. Therefore, by Standing voltage on switches (SVS) is another important factor in multilevel converters, which is equal to the maximum value of applied voltage on the switch in its OFF-state. In the proposed multilevel topology, the total standing voltage on the switches (TSVS) is equal to

$$TSVS = \sum_{j=1}^{4} SVS_{T_j} + \sum_{i=1}^{2} SVS_{S_i} + SVS_K \tag{2}$$

Where SVS_{T_j} is the standing voltage on the T_j switch in the j^{th} switch of H-bridge converter for j=1, 2, 3 and 4. The value of SVS_{T_j} is equal to $3V_{in}$. SVS_{S_i} is the standing voltage on the switch S_i in the i^{th} switch of the DC-DC switched-capacitor unit (i=1, 2,). The value of standing voltage on the switch S_i (SVS_{S_i}) is equal to V_{in}. Similarly, the value of standing voltage on the switch K (SVS_K) is equal to V_{in}. Therefore,

$$\sum_{j=1}^{4} SVS_{T_j} = 12V_{in} \qquad (3)$$

$$\sum_{i=1}^{2} SVS_{S_i} = 2V_{in} \qquad (4)$$

$$SVS_K = V_{in} \qquad (5)$$

With Substitution of (3-5) in (2), TSVS of the proposed topology is defined as:

$$TSVS = 15V_{in} \qquad (6)$$

4. Comparison Study

In this section, the proposed multilevel structure is compared with three other switched-capacitor multilevel converters, with only one DC voltage source as an input power supply [7-9]. Table 2 indicates the comparison results. In this table, the comparison is provided in terms of the number of utilized power electronic components along with the voltage boosting capability. This procedure is performed by evaluating the amounts of proportion of output voltage levels number over number of required components.

Table 2. Comparison among proposed multilevel converter and other suggested structures.

Topology	[7]	[8]	[9]	Proposed multilevel
N_{Level}	7	5	7	7
$\frac{N_{Level}}{N_{IGBT}}$	1	0.83	1	1
$\frac{N_{Level}}{N_{Diode}}$	1.75	2.5	1.75	3.5
$\frac{N_{Level}}{N_{Capacitor}}$	2.33	2.5	3.5	3.5
Voltage boosting capability	Yes	No	Yes	Yes

Power electronic components like IGBTs, drivers, diodes and capacitors are the most important elements in multilevel converters in which they increase the cost and control complexity of the system. Moreover, it is clear that the proposed switched-capacitor multilevel structure utilizes minimum number of power electronic components. Note that, the capacity of utilized inductance load of the suggested multilevel converters in [7-9] is restricted. Also, this restriction exists in the proposed switched-capacitor multilevel structure, however, it can be solved by replacing the power diodes D_1 and D_2 by two number of unidirectional power switches. İf the above mentioned replacement accurs, the topology could supply the pure inductive load. This time the topolgy is compared with those structures which do not have the previous restriction for inductive loads. As shown in Table 3. The proposed converter for pure inductive load (PIL) applications utilizes the least number of power electronic components. Being usable for inductive load applications is an important issue in the industry.

Moreover, as indicated in Table 2 and 3, recommended structures in [8], [10] and [11] lack voltage boosting capability, however, the proposed topology can overcome this limitation. Finally, the mentioned topology in [12] utilizes two numbers of DC voltage sources which makes the structure expensive and bulky.

Table 3. Comparison among proposed multilevel converter and other suggested structures.

Topology	[10]	[11]	[12]	Proposed Multilevel For PIL applications
N_{Level}	7	7	7	7
$\frac{N_{Level}}{N_{IGBT}}$	0.35	1.17	0.58	0.78
$\frac{N_{Level}}{N_{Diode}}$	0.35	0.87	-	-
$\frac{N_{Level}}{N_{Capacitor}}$	0.78	1.75	3.5	3.5
Voltage boosting capability	No	No	Yes	Yes

5. Simulation Results

For verifying the validity of the proposed switched-capacitor multilevel converter in the generation of output voltage levels, a single-phase 7-level converter is simulated. The PSCAD/EMTDC Simulink software is used for simulation. The parameters selected for simulation are: (a) L=50mH, (b) R=100Ω, (c) C_i=2200uF (d) The input voltage of 100V. The output voltage and current waveforms of simulated 7-level converter are shown in Fig.4. Moreover. Fig. 5. İndicates the current waveform of the capacitors. As indicated in Fig. 5 when the converter is used for resistive load applications, there are alternative spike waves with high amplitude for charging the capacitors. This is the inrush current which could be avoided just by putting some small resistance in series with the capacitors. However, in the following it will be shown that the above mentioned inrush current will be eliminated as the capacity of inductance load increases.

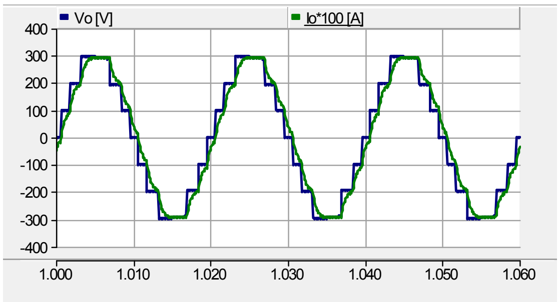
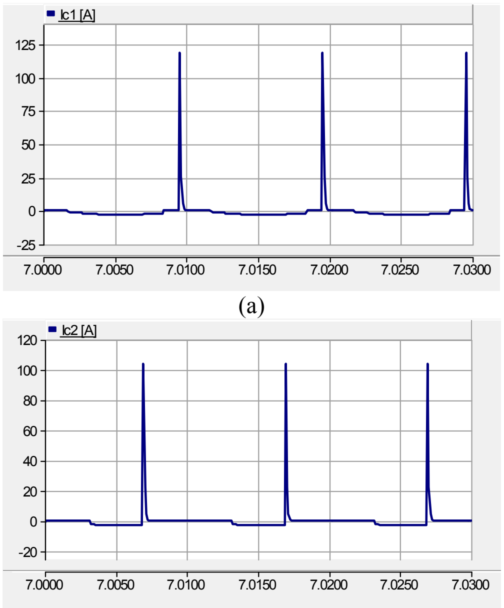


Fig. 4. Waveforms of output voltage (blue) and output current (red).

Second time, simulation results are analyzed for the inductive load application (L=500mH, R=50Ω). The output voltage and current waveforms of simulated 7-level converter are shown in Fig.6. Fig. 7. depicts the current waveform of the capacitors. As indicated in this figure, for inductive load applications, the capacitors in the proposed converter tolerate low amount of current spikes.



(a)

(b)

Fig. 5. Current waveforms of the capacitors.

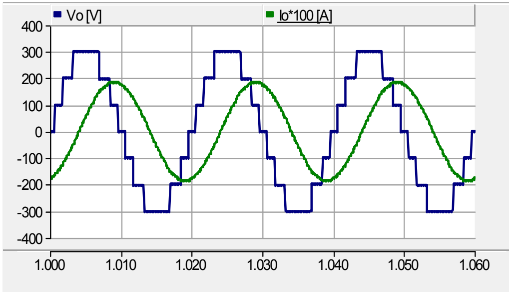
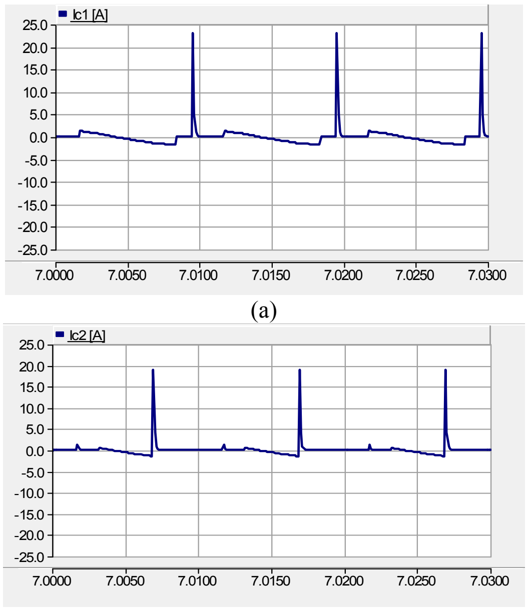


Fig. 6. Waveforms of output voltage (blue) and output current (red).



(a)

(b)

Fig. 7. Current waveforms of the capacitors.

For the last one, simulation results are analyzed for the pure inductive load application (L=500mH, R=1). As indicated in Fig. 9, for pure inductive load applications, there is no current spikes which damage the capacitors. Therefore, the proposed multilevel converter topology could easily interchange the reactive power and has convenient performance in that applications. Finally, this kind of converter is suitable for applications like STATCOMs which is used for power factor correction (PFC).

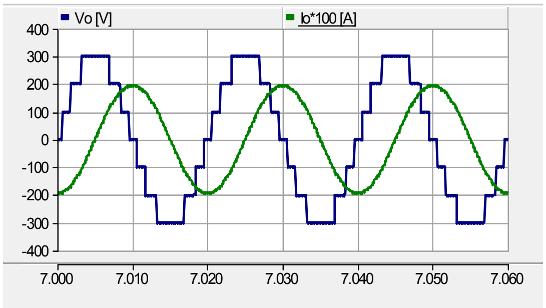
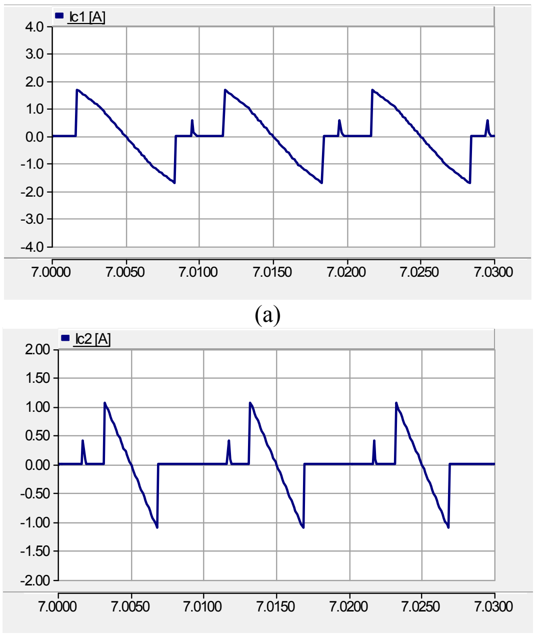


Fig. 8. Waveforms of output voltage (blue) and output current (red).



(a)

(b)

Fig. 9. Current waveforms of the capacitors.

5. Experimental Works

In this section, the experimental results are provided for verifying the accuracy of the proposed switched-capacitor multilevel converter in generating output voltage levels and demonstrating the voltage boosting capability. In the presented experimental work, IRF power MOSFETS driven by TLP250 along with capacitors with the values of 2200μF have been used. Also, LPC1768 ARM microcontroller is used to apply the controlling pulses to the switch drivers. For the proposed topology, fundamental frequency switching technique is used to produce switching pulses Moreover, for the proposed experimented switched-capacitor topology the values of inductance and resistance of the load are selected as 50mH and 100Ω, respectively. Finally, the amplitude of the DC voltage source as an input power supply is selected as 100V.

The waveforms of output voltage and current based on the experimental results are shown in Fig. 10. From this figure, it is clear that the maximum level at the output voltage waveform is equal to 300V. Also, Fig. 11 depicts the voltage waveforms of capacitors in the experimented topology. Based on this figure, it is obvious that the amplitude of voltages on the capacitors are equal to 100V and they are well-balanced.

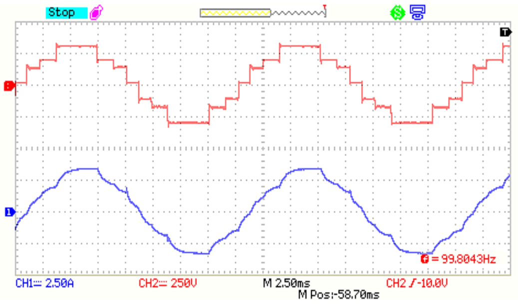
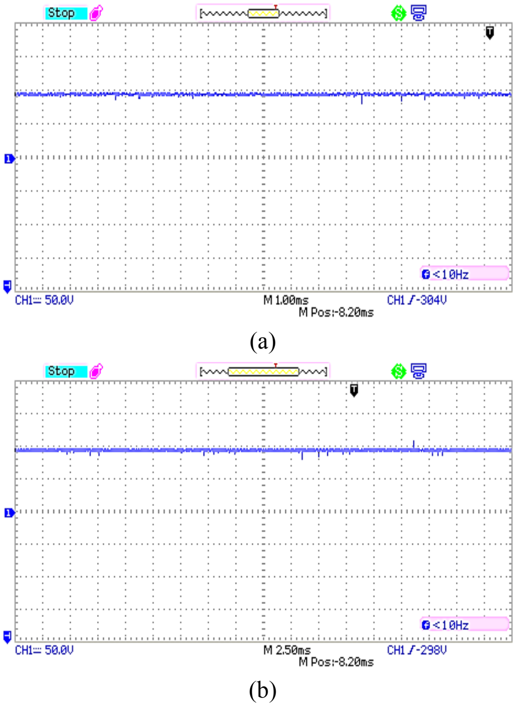


Fig. 10. Waveforms of output voltage (upper) and output current (down).



(a)

(b)

Fig. 11. Capacitor voltages. (a) C_1 voltage. (b) C_2 voltage.

6. Conclusions

In this paper, a new structure for multilevel boost converter was presented. When it is compared to the recommended multilevel converters in other literature, the proposed topology utilizes minimum number of power electronic components. It was shown that the proposed structure increases the input DC voltage to the output voltage without using any transformers. Also, in the proposed switched-capacitor multilevel converter, voltages of capacitors are charged well as self-balancing and without utilizing any auxiliary control circuits. It is clear that these benefits lead to the reduction of costs, circuit size, installation area and simplify the control unit. Finally, In order to verify the performance of proposed topology, simulation results along with experimental works were provided.

7. References

[1] J. Chavarria, D. Biel, F. Guinjoan, C. Meza, and J.J. Negroni, "Energy balance control of PV cascaded multilevel grid-connected inverters under level-shifted and phase-shifted PWMs," IEEE Trans. Ind. Electron. vol. 60, no. 1, pp. 98–111, Jan. 2013.

[2] Nami, J. Liang, F. Dijkhuizen, and G.D. Demetriades, "Modular Multilevel Converters for HVDC Applications: Review on Converter Cells and Functionalities," IEEE Trans. Power. Electron. vol. 30, no. 1, pp. 18–36, Jan. 2015.

[3] J. Rodríguez, J-S. Lai and F.Z. Peng, "Multilevel Inverters: A Survey of Topologies, Controls, and Applications", IEEE Trans. Ind. Electron., vol. 49, no. 4, pp. 724-738, 2002.

[4] E. Babaei, S. Alilu, and S. Laali, "A new general topology for cascaded multilevel inverters with reduced number of components based on developed H-bridge," *IEEE Trans. Ind. Electron.*, vol. 61, no. 8, pp. 3932-3939, Aug. 2014.

[5] E. Babaei, S. Laali, and Z. Bayat, "Single-Phase Cascaded Multilevel Inverter Based on a New Basic Unit With Reduced Number of Power Switches," IEEE Trans. Ind. Electron., Vol. 62, No. 2, pp. 922–929, Feb 2015.

[6] R. Shalchi Alishah, D. Nazarpour, S. H. Hosseini and M. Sabahi, "Reduction of Power Electronic Elements in Multilevel Converters Using a New Cascade Structure," in *IEEE Transactions on Industrial Electronics*, vol. 62, no. 1, pp. 256-269, Jan. 2015.

[7] Axelrod, Y. Berkovich, and A. Ioinovici, "A Cascade Boost-Switched-Capacitor-Converter –Two Level Inverter With an Optimized Multilevel Output Waveform," IEEE Trans. Circuits Syst., vol. 52, no. 12, pp. 2763–2770, Dec. 2005.

[8] G. Buticchi, E. Lorenzani, and G. Franceschini, "A Five-Level Single-Phase Grid-Connected Converter for Renewable Distributed Systems," IEEE Trans. Ind. Electron., vol. 60, no. 3, pp. 6672–6680, Mar. 2013.

[9] Y. Ye, K.W.E. Cheng, J. Liu, and K. Ding, "A Step-Up Switched-Capacitor Multilevel Inverter With Self-Voltage Balancing," IEEE Trans. Ind. Electron., vol. 61, no. 12, pp. 6672–6680, Dec. 2014.

[10] J. Zhao, Y. Han, X. He, C. Tan, J. Cheng, and R. Zhao, "Multilevel Circuit Topologies Based on the Switched-Capacitor Converter and Diode-Clamped Converter," IEEE Trans. power Electron., vol. 26, no. 8, pp. 2127-2136, Aug. 2011.

[11] J. arzegarkhoo R, Zamiri E, Vosoughi N, Madadi Kojabadi H, Chang L. "Cascaded multilevel inverter using series connection of novel capacitor-based units with minimum switch count." IET Power Electron 2016, pp. 6887-6895.

[12] Xiaofeng Sun, Baocheng Wang, Yue Zhou, Wei Wang, Huiyuan Du, and Zhigang Lu, "A Single DC Source Cascaded Seven-Level Inverter Integrating Switched-Capacitor Techniques," IEEE Trans. Ind. Electron., vol. 63, No. 11, pp. 7184–7194, Nov. 2016.