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A Comparative Study of Different Multilevel Converter Topologies for High Power Photovoltaic Applications

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Abstract— **This paper investigates the modern topology of multilevel converters, which are suitable for use in high power photovoltaic applications with the focus on achieving lower total harmonic distortion and better efficiency. Multilevel converters offer several advantages compared to conventional types. Multilevel converters provide high quality output while using the low switching frequency. It affects the switching losses, size of semiconductor switches and harmonic filters. This research investigates various topologies of multilevel converter for high power photovoltaic applications and compares their THD, efficiency, number of required semiconductors and other important characteristics. All topologies are simulated using MATLAB/Simulink in the same operating conditions. Finally, the more suitable multilevel topology is selected with respect to the simulation results.**

Keywords—photovoltaic; Multilevel converter; qualitative study; high power application

I. INTRODUCTION

Recent years have seen a growing trend for generating electric power from renewable energies sources [1,2]. At the same time, the increase in the power rating of wind turbines, photovoltaic power plants and other renewable equipment has been accelerated sharply [3,4]. In this context, high demand for medium and high power converters has made multilevel converters a timely and interesting subject in the field of power electronics [3,4,5]. Researchers strive to propose new multilevel topologies able to provide lower THD and higher efficiency [5], especially at high power level.

Conventional PV plant consisted of a large number of PV modules connected in series and parallel to form strings and sub-arrays, which are combined to feed the inverters. The inverters are then connected to the medium-voltage (MV) electric grid through a low-frequency (LF) transformer [5,6,7,8]. The trend in the industry is to design and utilize the higher inverter ratings since pricing analysis proves that the inverter cost per watt decreases by increasing the inverter power rating. Therefore, inverters with power ratings up to a few megawatts are now being offered on the market [5,6,7]. Also, designers prefer to use higher nominal voltages for both the DC and AC side of the inverter, which leads to reduce wire costs and power losses. These design choices also result in smaller cross-section cables, fewer generator connection boxes and less cabling at the DC end, which is important in balance-of-system costs [5,9]. Therefore, topologies for medium-voltage grid integration of megawatt-scale PV inverters are moving toward multilevel structures.

Researchers have recently proposed many different multilevel topologies for PV applications [2,5,9,11-14]. Neutral point Clamped converter (NPC) [1], cascaded H-bridge [10], Y-Connected Hybrid Cascaded [15], Capacitor Clamped [2], Z-source [16] and quasi Z-source [17] are important topologies, which are proposed to use with the PV modules. It is possible to investigate these topologies from different point of views. As this work is concerned, to find the most appropriate structure for the PV modules, our investigation is organized in two stages; dealing with quantitative and qualitative study respectively. Quantitative study investigates the output specification of the converter, which is analyzed using Matlab/Simulink. The important parameters, which should be evaluated, are line voltage and current, THD, losses and efficiency. Qualitative study verifies the characteristics, which are important to implement the converter. However; converter reliability, modularity, scalability and functionality are the important issues in qualitative study.

II. MULTILEVEL TOPOLOGY REVIEW

In this section, a brief review of the most common topologies is presented. The topologies considered in this paper are shown in Fig.1.

A. Diode-Clamped Topology (NPC)

According to records the first multi-level inverter was a cascaded one which was designed in 1975 with diodes blocking the source [12]; this inverter was later driven into the diode clamed multilevel inverter proposed in [1].This topology is shown in Figure 1(a). Each of the three-phase outputs of the inverter is connected to a common DC bus voltage divided into three levels over two DC bus capacitors. Existing A high number of clamping diodes results in high cost and different limitations for high-voltage level applications [18]. In addition, a special control is required to balance the capacitor voltages. Consequently, most of practical applications for a diode clamped multilevel inverter are limited to lower than five levels [12,19].

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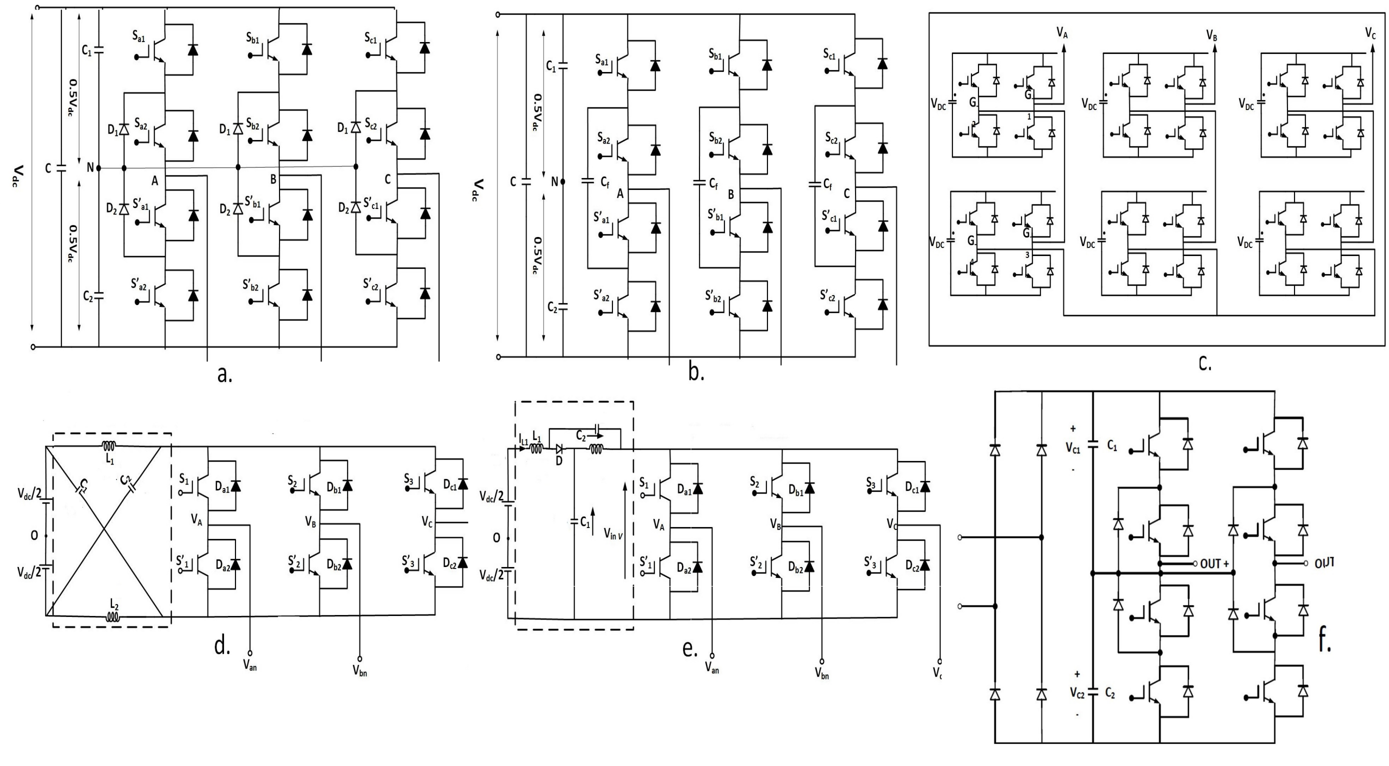

Fig 1: a) NPC b) Capacitor clamped c) Cascade d) Z-source e) Quasi Z-source f) Hybrid

B. *Capacitor Clamped Topology*

Another type of multi-level inverter which has similar topology to the NPCMLI topology is named the flying capacitor inverter or capacitor clamped multilevel inverter [2,14,18] as shown in Fig.1(b). However; instead of using clamping diodes it uses capacitors to keep the voltages to the favored values.[18] It is considered as a good substitute of NPC topology to dominate some of its shortcomings according to [20] and [21].

C. *Cascade H-Bridge Topology*

Cascaded Multi-Cell Inverter (CMCI), which is proposed in [10] is different in several ways from NPCMLI and CCMLI, especially in how to build the multilevel voltage waveform. It creates the step waveform by using cascaded full-bridge inverters with separate DC-sources, as shown in Fig.1(c) [22]. The cascade topology allows utilizing dc sources with dissimilar voltage values, and high-resolution multilevel waveforms can be reached with a fairly low number of components [23,24].

D. *Z-source Topology*

The impedance source or Z-source inverter was proposed for the first time by [16] and is shown in Fig.1(d). Z-source inverters distinguished themselves from other conventional types of inverters by providing voltage boost capability in common inverters. The conventional inverters are always buck converter; because of generating the output voltage lower than the DC input voltage [18]. In addition, the upper and lower power switch cannot conduct all together; if not, the DC source will short-circuit. Therefore, a dead band is provided purposefully between the switching on and switching off of the complimentary power switches of the identical leg, consequently some deformations in the output current are caused by this dead band. These deficiencies are overcome in the Z-source inverter [18]. Comprehensive discussions on the Z-source inverters are given in [25,26,28].

E. *Quasi Impedance Source or QZSI Topology*

Fig.1(e) presents the QZSI topology which was proposed in [17] as a derivative of the original Z-source inverter; so it contains all the benefits of the ZSI. The impedance source or Z-source inverter has the weakness of discontinuous input (DC) current during boost mode, high voltages across the capacitors, and higher stress on power switches [18, 26]. These limitations are overcome by QZSI [26,27]. Drawing continuous current from DC source, decreasing the voltage across the capacitor C2, lower elements count and therefore high reliability as well as putting lower voltage stress on the power switches are considered as the major advantages of a QZSI [18].

F. *Y-Connected Hybrid Cascaded Topology*

This kind of topology is obtained by substituting the conventional two-level leg in the H-bridge module of the CMI with diode clamped or capacitor clamped multilevel leg in order to diminish the number of separate DC sources. Each module of this topology can output three-level voltage and each phase contains a cascaded NPC-based H-bridge module [15, 19]. The number of switching devices in the conversion system will be reduced by taking hybrid topologies.

III. RESULTS DISCUSSION

A. Quantitative study

In this section, the most common topologies of multilevel converters, which are connected to PV array, are scrutinized in six case studies. By comparing their output wave forms and their characteristics, the most suitable inverter configuration is found. All scenarios have been done in identical situations using the same PV array source and loads while all switches are modeled as IGBT ones. The PV array module is called Canadian solar load CS5C90M with 40 parallel strings and 10 series connected modules per strings, with irradiation of rate 1000, temperature of 25^{oc} and a three phase resistive load of R=10(Ω).

a) Three level NPC PV source inverter

Fig.2 illustrates a three level NPC PV source inverter model in Matlab. The inverter is connected to the pre-defined PV array and load. The voltage and current wave forms of this simulation are shown in Fig.3.

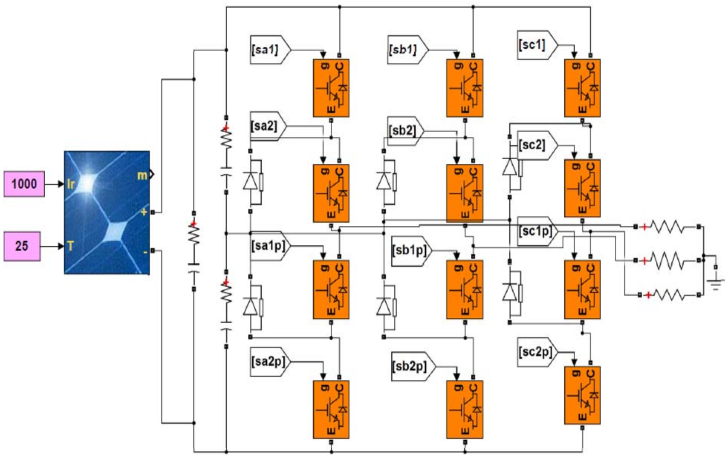

Fig.2:. Three level NPC, PV source model in Matlab/Simulink.

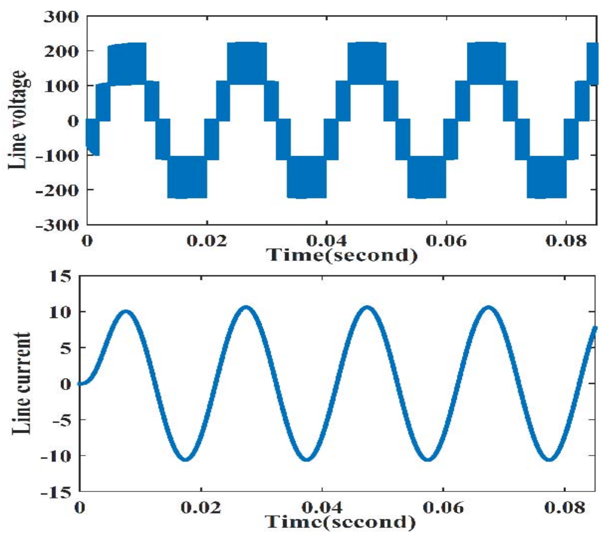

Fig.3. Three level NPC inverter voltage and current waveforms.

The total harmonic distortion (THD) value of each waveform is calculated by Matlab/Simulink. In this way the capacitor values are considered 2200μF while THD of line voltage is 36.22% for this case study; in addition, the efficiency of inverter is calculated as η = 98.93%

b) Capacitor clamped three level PV source inverter

Three level capacitor clamped PV source inverter model is shown in Fig.4. Capacitor values are 1000μF. The voltage and current waveforms of this simulation are shown in Fig.5. THD line voltage is 49.89% for this inverter topology; and the efficiency is calculated as η = 98.65%.

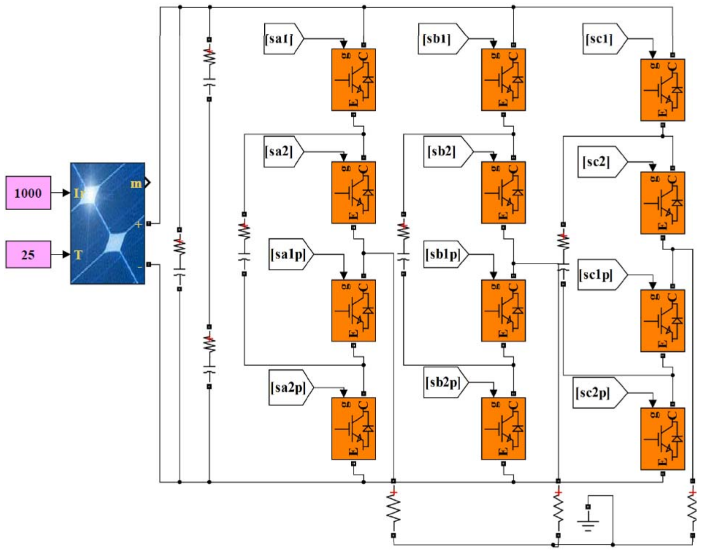

Fig. 4. Three level Capacitor clamped, PV source model in Matlab/Simulink.

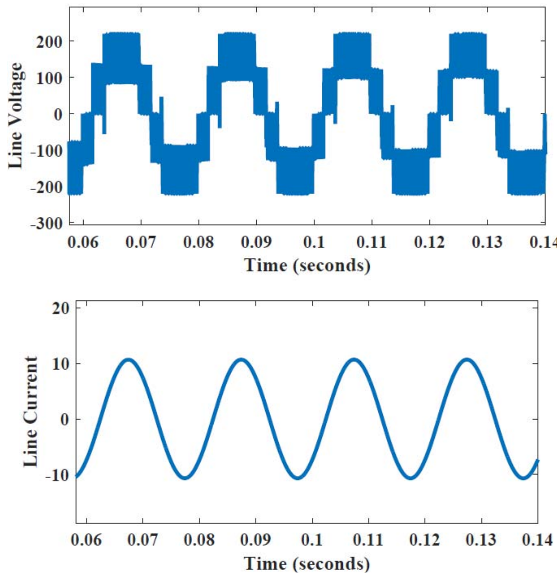

Fig. 5. Three level Capacitor clamped voltage and current waveforms.

c) Three level Cascaded PV source inverter

Fig.6 represents a three level cascaded PV source inverter model in Matlab, and its voltage and current waveforms are depicted in Fig.7. THD line voltage is obtained 47.18% for this model; and the efficiency is calculated as η = 83.33%.

d) Three level Z-source PV connected inverter

Three level Z-source PV connected inverter as well as its output wave forms are shown in Fig.8 and 9. The inductance values are assumed to be the same equal to 0.5mH as are the capacitor values 0.4mF. THD of this modeled is measured 42.19% and its efficiency is calculated as η=99.48%.

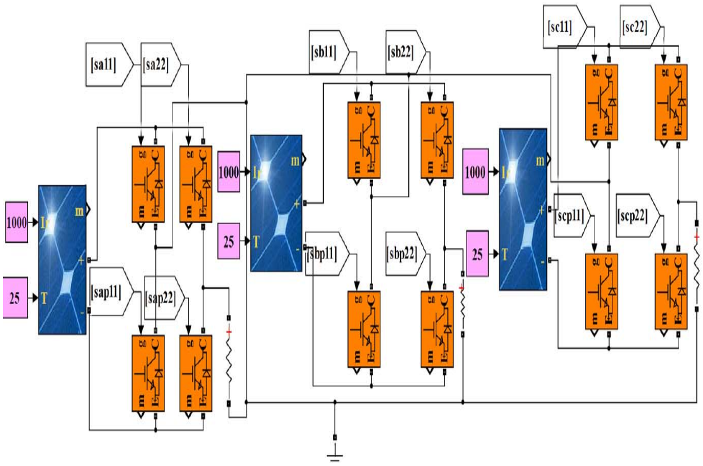

Fig. 6. Three level Cascaded PV source model in matlab/simulink.

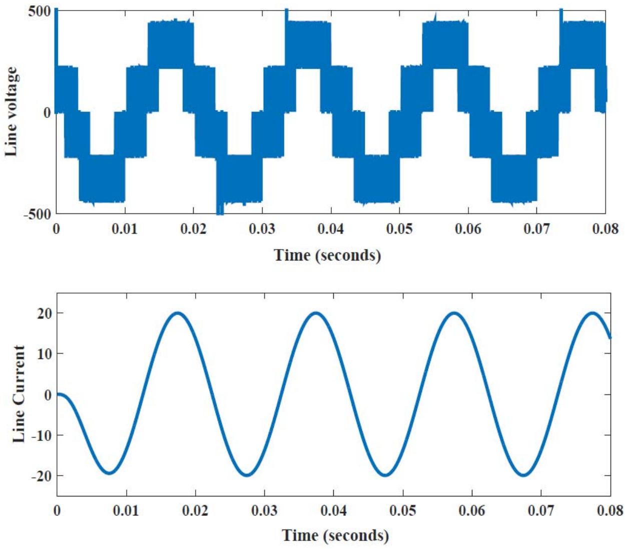

Fig. 7. Voltage and current waveforms of three level cascaded inverter.

e) Three level Quasi-Z source PV source inverter

The Quasi-Z source model is done according to Fig.10, and its output waveforms are shown in Fig.11. The inductance values are assumed to be the same equal to 0.5mH as are the capacitor values 0.4mF. Line voltage THD as well as efficiency for this model are 41.49% and η=98.95% respectively.

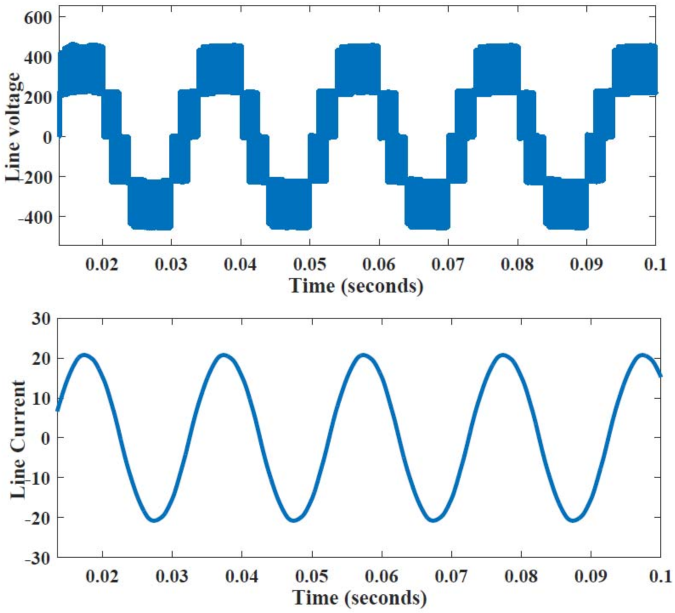

Fig. 9. Voltage and current waveforms of three level Z source inverter.

f) Y-Connected three level Hybrid Cascaded PV source inverter (CMI)

Three level hybrid cascaded NPC PV source inverter model as well as its voltage and current waveforms are shown in Fig.12 and 13, respectively. Capacitors values are 2200μF while THD is 37.57% and efficiency is η=81.8%. Normally hybrid topologies are used for creating high level output voltage. This concept was introduced in [19] by presenting 17-level CMI as the most suited for application to PV power generation. The simulation result of this topology confirms the low THD rate of this topology.

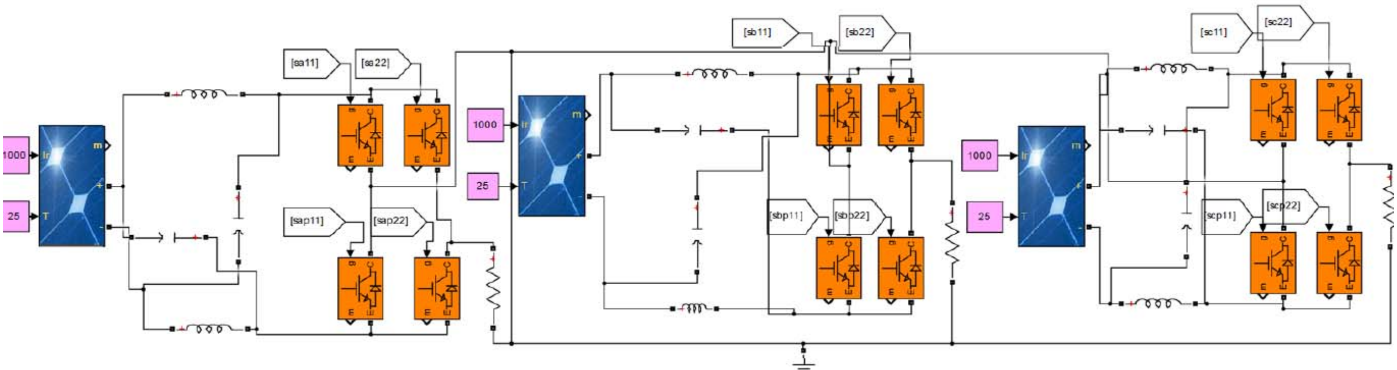

Fig. 8. Three level Z-source PV connected inverter in matlab/simulink.

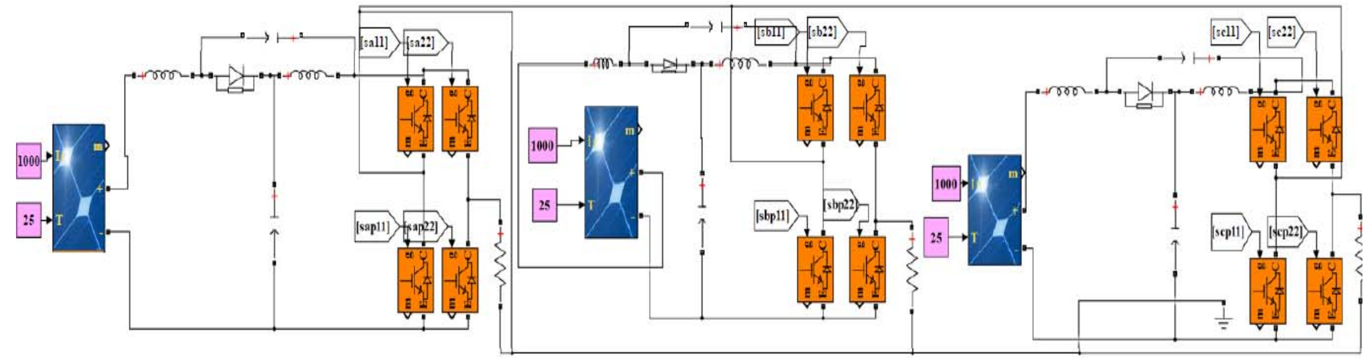

Fig. 10. Three level Quasi Z source PV connected model in matlab/simulink.

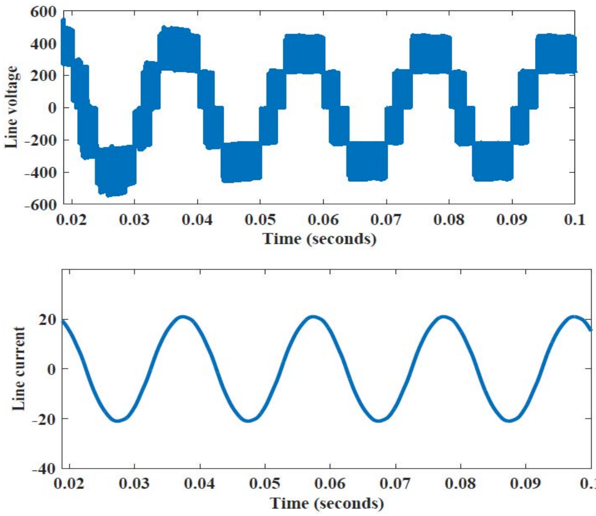

Fig. 11. Voltage and current waveforms of three level Quasi Z source.

B. *Qualitative Study*

Table I, represents quantitative results of case studies; in addition, the characteristics of different topologies are summarized in Table III in accordance with Table II .As it can be seen in Table II, a lot of clamping diodes in NPC topology make it very expensive and raise different issues in high-voltage level applications, Therefore, according to table III practical uses of diode clamped multilevel inverters are limited to lower than five levels [18].

The second inverter, which has a quite similar topology to the first one is the capacitor clamped topology. The major dissimilarity is the use of clamping capacitors in place of clamping diodes, and the number of switching combinations rises as capacitors do not block reverse voltages [17,18].

According to table III, both NPC and capacitor clamped topologies are single input inverters, however other types of topologies are modular so they reaches the higher reliability in comparison with NPC and capacitor clamped because of its modular topology [9].

Quasi-Z source inverter is introduced as a derivative of Z-source inverter by having the ability of solving some Z-Source topology problems such as high voltages across the capacitors, and higher stress on power switches [18] and therefore reaching a reduced value of THD. In addition the efficiency of Z source as well as Quasi-Z source inverters are superior among other types of multi-level inverters. Hybrid multi level inverter is also considered as a suitable case in THD rate according to Table I; however, its efficiency is lower than Z types.

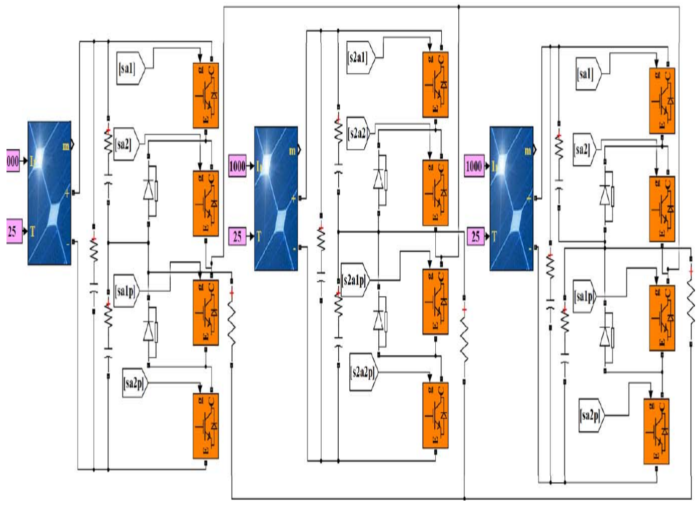

Fig. 12. Three level Hybrid PV source inverter in matlab/simulink.

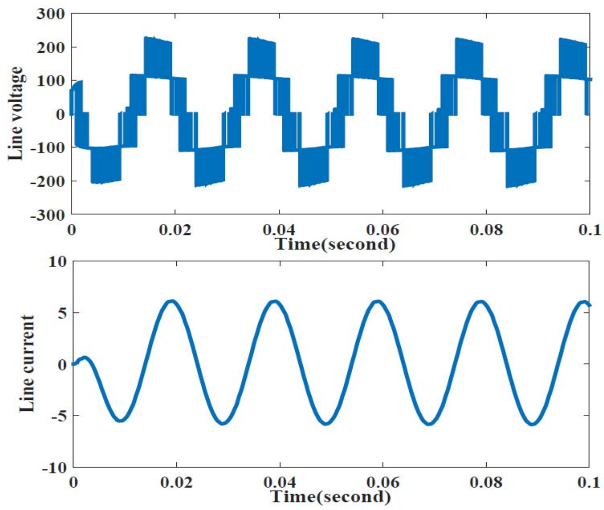

Fig. 13. Voltage and current waveforms of three level hybrid model.

TABLE I. THD AND EFFICIENCY OF DIFFERENT TOPOLOGIES

R	THD and Total Efficiency		
	Converter Topology (3level)	***Efficiency %***	***THD %***
1	NPC	98.93	36.22
2	Capacitor clamped	98.65	49.89
3	Cascaded	83.33	47.18
4	Hybrid	81.08	37.57
5	Z-source	99.48	42.19
6	Quasi Z source	98.95	41.49

TABLE II. TABLE STYLES

R	Parameter Identification	
	Id	***Inverter Characteristics***
1	M1	Number of power Switch
2	M2	Number of Capacitor
3	M3	Number of Inductance
4	M4	Number of Diode
5	M5	Single source input
6	M6	Suitable to implement high level voltage
7	M7	Reliability (Medium/High)
8	M8	Bidirectional (Yes/No)

TABLE III. DESIGN DATA AND PERFORMANCE

R	Parameters								
	Converter Topology (3level)	***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***
1	NPC	12	3	0	6	Y	N	M	Y
2	Capacitor clamped	12	6	0	0	Y	N	M	Y
3	Cascaded	12	0	0	0	N	Y	H	Y
4	Hybrid	12	9	0	6	N	Y	H	Y
5	Z-source	12	6	6	0	N	Y	H	Y
6	Quasi Z source	12	6	6	3	N	Y	H	Y

IV. CONCLUSION

The price analysis of the converter shows that multilevel converters are more economic than conventional types in the case of medium and high power applications. In This research, different multilevel converter topologies have been investigated and compared in order to find the most suitable topology, which is appropriate to use in the PV applications. Six multilevel topologies, which were proposed in the literature, have been investigated. The investigation was done via quantitative and qualitative study. In quantitative study, important output parameters of proposed multilevel topologies were evaluated using Matlab/Simulink at the same operating point. Also, a qualitative analysis has been performed to investigate some advantages and disadvantages of each topology, which cannot be considered in the simulation. The results prove that quasi Z-source converter has better performance in comparison with other types.

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