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Analysis of Different Multilevel Converter Topologies for Photovoltaic Applications

N.Das Jaya Raj[1] | P.Bala Krishna[2] | K.Manoz Kumar Reddy[3]

[1]PG Scholar, Department of EEE, Aditya College of Engineering, Surampalem, Andhra Pradesh, India.
[2]Assistant Professor, Department of EEE, Aditya College of Engineering, Surampalem, Andhra Pradesh, India.
[3]Professor & Head, Department of EEE, Aditya College of Engineering, Surampalem, Andhra Pradesh, India.

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ABSTRACT

This project deals with the different topology of multilevel converters, which are suitable for use in medium and high power photovoltaic (PV) applications. Multilevel converters offer several advantages compared to conventional types. These converters will achieve lower total harmonic distortion and better efficiency. Multilevel converters provide high quality output while using the low switching frequency which affects the switching losses, harmonic filters and size of semiconductor switches. 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: *Multilevel Converter Topology, Photovoltaic Applications, power quality, THD, Efficiency*

I. INTRODUCTION

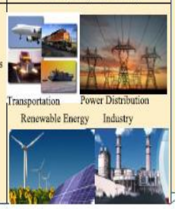
Multilevel inverters have been under research and development for more than three decades and have found successful industrial applications. However, this is still a technology under development, and many new contributions and new commercial topologies have been reported in the last few years. The aim of this dissertation is to group and review recent contributions, in order to establish the current state of the art and trends of the technology to provide readers with a comprehensive and insightful review of where multilevel converter technology stands and is heading. This chapter first presents a brief overview of well-established multilevel inverters strongly oriented to their current state in industrial applications and then centers the discussion on the new multilevel inverters that have made their way into the industry. Multilevel inverters have been attracting increasing interest recently the main reasons are; increased power ratings, improved harmonic performance, and reduced electromagnetic interference (EMI) emission that can be archived with multiple dc levels that are synthesis of the output voltage waveform. In particular multilevel inverters have abundant demand in applications such as medium voltage industrial drives, electric vehicles, and grid connected photovoltaic systems. The present work provides a solution to design an efficient multilevel topology which is suited for medium and high power applications. In the subsequent sections the research background is discussed in detailed. Motivation and objectives are clearly outlined.

Medium and High Power Inverters

There are different power converter topologies and control strategies used in inverter designs. Different design approaches address various issues that may be more or less important depending on the way that the converter is intended to be used. The issue of waveform quality is one the important concern and it can be addressed in many ways. In practice capacitors and inductors can be used to filter the waveform [1-2]. If the design includes a transformer, filtering can be applied to the primary or the secondary side of the transformer or to both sides. Low-pass filters are applied to allow the fundamental component of the waveform to pass to the output while limiting the passage of the harmonic components. Thus quality of waveform can be adjusted. Note that, normal inverters always generate very low quality output waveforms. To make the output waveform qualitative, low pass (LC filter) are often added in the circuit. Thus, at this point of time readers might have a question that, why the quality of converter output is low? And why Low pass filter are frequently added in the circuit. Further, what kinds of solutions are available to increase quality of output waveform without losing its efficiency? All this are open problems associated with present day inverters. However, eventually all this will be addressed in this thesis. But at first we try to figure out the converter applications from low power to high power and then we summarize the requirements to meet the high power demand. Finally we try to present the problems and solutions available to meet the high power demand.

Consider Table 1.1, which presents the important applications from low power to high power range. From Table 1.1 it is quite predictable that, power inverters are an enabling technology. They are potentially useful for a wide range of applications like; low power devices, home appliances, electric vehicles, photovoltaic, transport (train traction, ship propulsion, and automotive applications), and energy conversion, manufacturing, mining, and petrochemical applications. The inverters mentioned in Table 1.1 are available in a wide range. Note that, either it may be suited for DC or AC. But, at present industries are in chase of finding new type of power converter for medium to high power range, moreover it seems to be challenging issues for present generation researchers.

TABLE 1.1
Summary of Power Inverters

	Low Power	Medium Power	High Power
Power Range	Up to 2 KW	2-500 KW	More Than 500 KW
Usual Converter Topologies	ac/dc, dc/dc	ac/dc, dc/dc, dc/ac	ac/dc, dc/ac
Typical Power Semiconductors	MOSFET	MOSFET, IGBT	IGBT, IGCT, Thyristor
Technology Trend	High Power Density, High Efficiency	Small Volume and Weight Low Cost and High Efficiency	High Nominal Power of the Converter high Power Quality and Stability
Typical Applications	 Lower-Power Devices, Home Appliances	 Electric Vehicles, Roof PV	 Transportation, Power Distribution, Renewable Energy, Industry

Although research pioneers have built a numerous power inverters, but still researchers are in look for a new sort of architecture which can produce high quality waveform with less number of components. In other terms improving power quality is the greatest requirement. By considering above aspects, let us make an outline regarding the demanding aspects of power inverters, particular in Medium and high power range.

II. Multilevel Inverters

Multilevel inverter includes an array of power semiconductor devices and capacitors voltage sources, the output of which generates voltages with stepped waveforms [14-15]. The commutation of the switches permits the addition of the capacitor voltages to obtain high- voltage at the output, while the power semiconductors have to withstand only reduced voltages.

Fig.2.1 shows a schematic diagram of one phase leg of inverters with different numbers of levels, for which the action of power semiconductors is represented by an ideal switch with several positions. Form Fig.2.2, we can observe a two level inverter generates an output voltage with two values (levels) with respect to negative terminal of the capacitor. While the three level inverter generates three voltages, and a nine-level inverter generates a nine level output voltages. In all this cases devices are not arranged in series but they are arranged in such way that, they gain the capability to generate such kind of voltages. Herein, we should remember one important thing i.e. as the number of steps increases in the output waveforms; harmonic content comes down [16]. Thus power quality of such waveforms will increase drastically. However, in order to generate step kind of waveforms in output side, different *Multilevel* based archetypes are successfully built and verified. But general principle

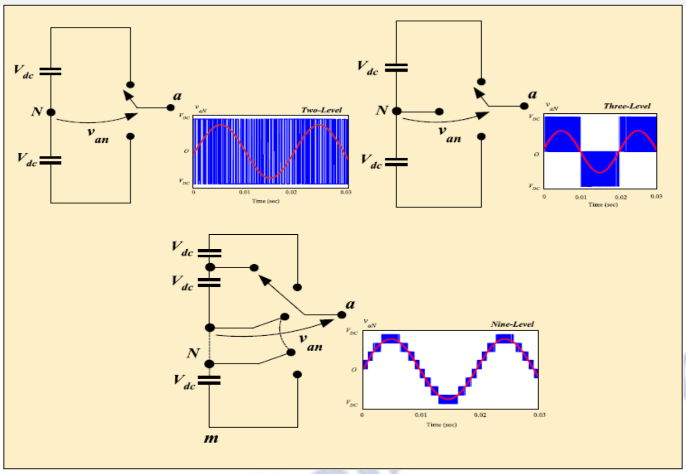


Fig.2.1 Converter output voltage waveforms a) two level b) three level c) nine level

of multilevel inverters is the synthesis of the ac voltage from several different voltage levels on the dc bus. As the number of voltage levels on the input dc side increases, the output voltage adds more steps [17-19], which approach the sinusoidal wave. However, from above thought, to present a general idea about the steps in the output waveform, consider m to be the number of steps of the phase voltage with respect to the negative terminal of the inverter, and then the number of steps in the voltage between two phases of the load K is given by equation A and B:

$K = 2m+1$ (1.1)

And the number of steps P in the phase voltage of a three phase load in wye connection is

$P = 2k - 1$ (1.2)

The term multilevel starts with the three-level inverter introduced by the Nabae et al.[15]. However topologically, multilevel inverters are largely divided into many configurations. The most common multilevel converter topologies are the neutral-point-clamped converter (NPC) [15], flying capacitor converter (FC) [18], and Cascade H-Bridge (CHB).

At present these inverters are highly visible in all Medium voltage drives, grid connected systems and FACTS devices. An extensive survey has been done on the multilevel inverters; these are addressed in the next chapter. However, at this point of time it is clear that, multilevel inverters are one of the best option for Medium and high power applications [19]. Now a question may arise; are there any other inverters which are competitive to multilevel inverters? Obviously the answer is yes. Any how to resolve this question and for a better idea, a complete list of high-power inverters are demonstrated in Fig.2.2. However, the main competitors of multilevel technology are: the cycloconverter and load commutated inverters (LCIs).

Other high-power converter topologies like current source and matrix inverters are also observed in the classification. Although they are capable of meeting high power demand, but they are less preferred because of their limited merits. However, some of which have recently found practical application and this content is not discussed in this dissertation as it is mentioned that, study is confined to only multilevel structures. Operating principles, multilevel waveform generation, special characteristics, modulation schemes, and other information related to the NPC, FC, and CHB are demonstrated subsequently.

III. Results and Discussion

3.1 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 25oc and a three phase resistive load of R=10 Ω.

Three level NPC PV source inverter

Fig.3.1 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.4.2.

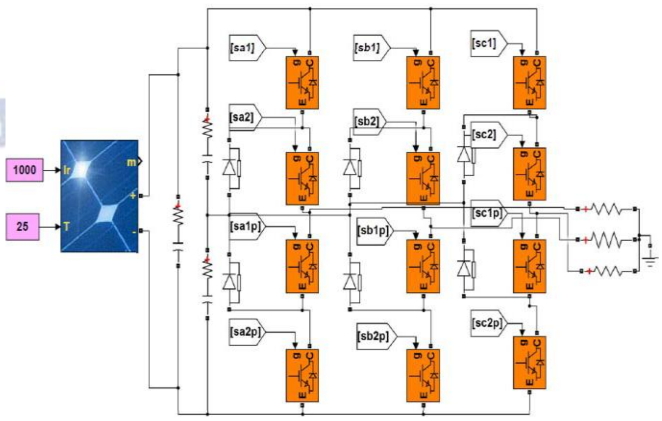


Fig.3.1:. Three level NPC, PV source model in Matlab/Simulink.

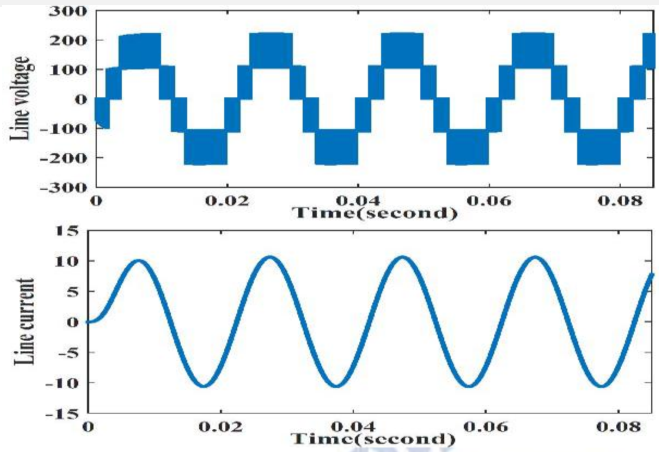


Fig.3.2. Three level NPC inverter voltage and current waveforms.

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

Capacitor clamped three level PV source inverter

Three level capacitor clamped PV source inverter model is shown in Fig.3.3. Capacitor values are 1000µF. The voltage and current waveforms of this simulation are shown in Fig.3.3. THD line voltage is 49.89% for this inverter topology; and the efficiency is calculated as η = 98.65%.

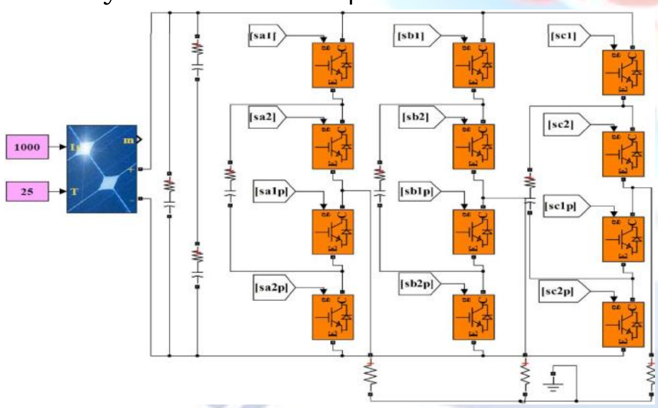


Fig. 3.3. Three level Capacitor clamped, PV source model in Matlab/Simulink

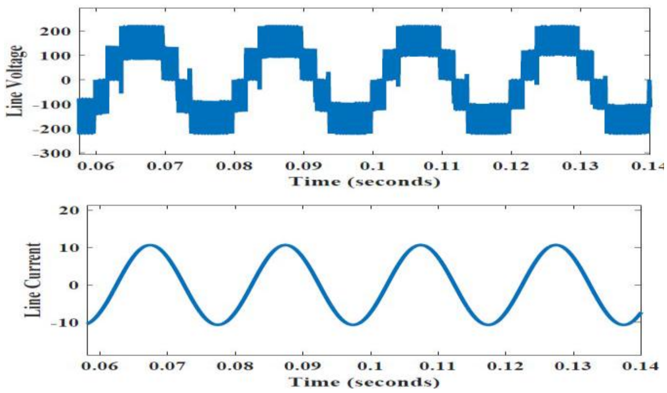


Fig. 3.4. Three level Capacitor clamped voltage and current waveforms.

Three level Cascaded PV source inverter

Fig.3.5 represents a three level cascaded PV source inverter model in Matlab, and its voltage and current waveforms are depicted in Fig.4.6. THD line voltage is obtained 47.18% for this model; and the efficiency is calculated as η = 83.33%.

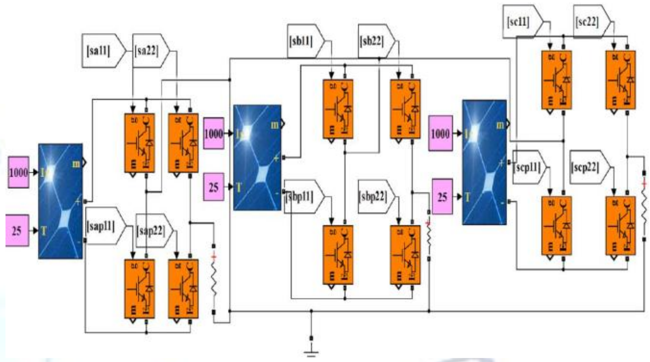


Fig. 3.5. Three level Cascaded PV source model in matlab/simulink.

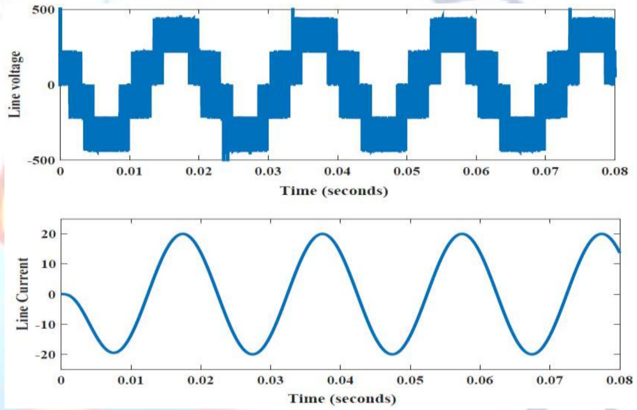


Fig. 3.6. Voltage and current waveforms of three level cascaded inverter.

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.4.7 and 4.8. 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%.

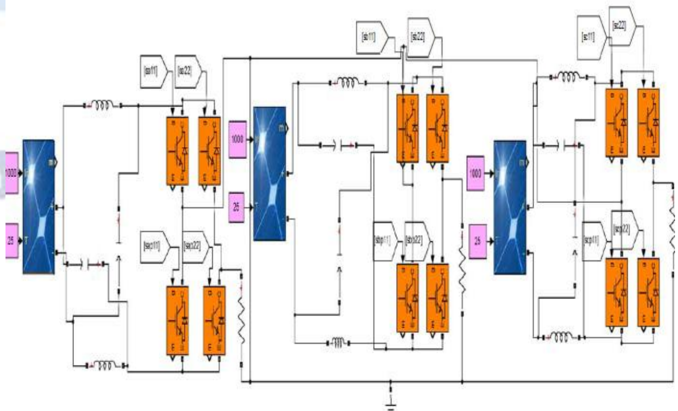


Fig. 3.7. Three level Z-source PV connected inverter in matlab/simulink.

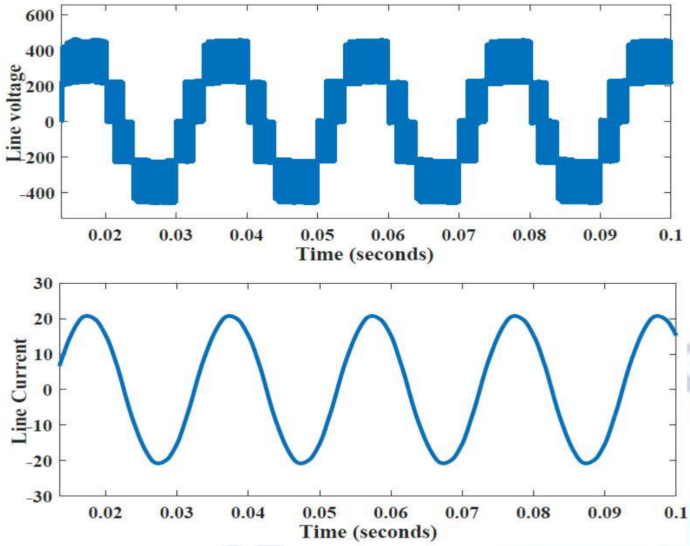


Fig. 3.8. Voltage and current waveforms of three level Z source inverter.

Three level Quasi-Z source PV source inverter

The Quasi-Z source model is done according to Fig.3.9, and its output waveforms are shown in Fig.3.10. 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.

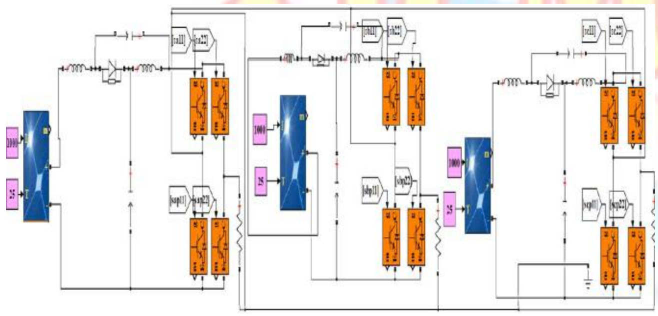


Fig. 3.9. Three level Quasi Z source PV connected model in matlab/simulink.

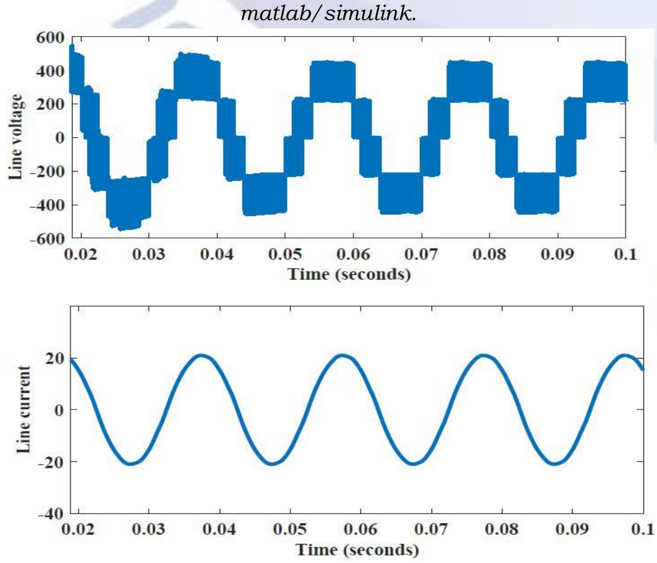


Fig. 3.10. Voltage and current waveforms of three level Quasi Z source.

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.3.11 and 3.12, 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.

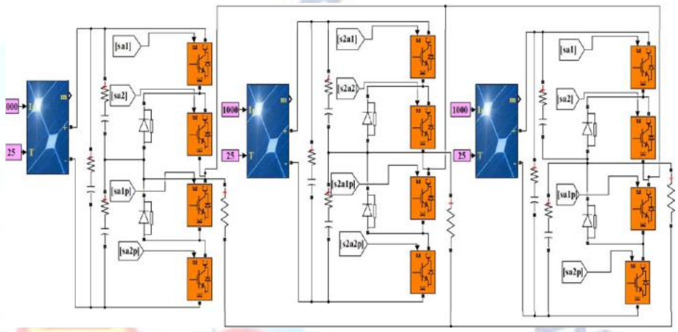


Fig. 3.11. Three level Hybrid PV source inverter in matlab/simulink.

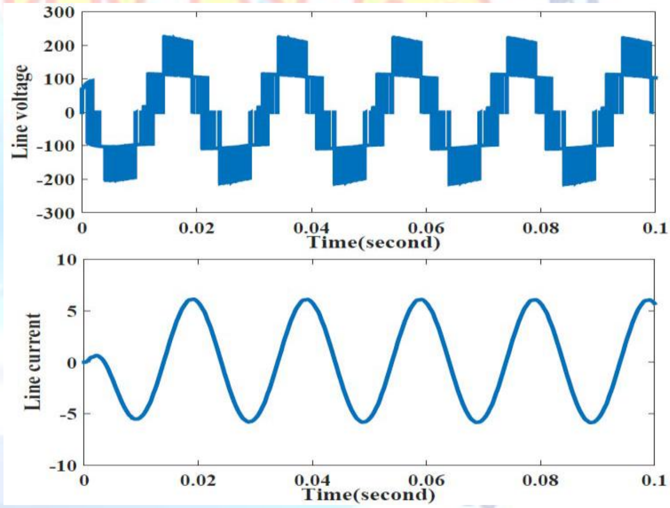


Fig. 3.12. Voltage and current waveforms of three level hybrid model.

3.2 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 Zsource 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.

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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