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REVIEW PAPER

A Review Analysis of Inverter Topologies for Solar PV Applications Focused on Power Quality

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Abstract This research article gives widespread review of non-isolated topologies for solar photovoltaic equipments. To relate with available elucidations of the said studied topological arrangement, some conditions have been imposed. The benchmark is based on harmonic distortion as well as power quality issues. Some of the selected solution have been designed and simulated for power quality issues. The best one has been discussed in the paper.

Keywords Transformer-less inverter · Power quality · Photovoltaic

Introduction

With the sharp rise in growth of population in urban rural, and suburban sectors, the basic needs of electricity is expected to increase. In order to meet this excess demand of energy, we need to explore renewable energy sources like solar, wind, biomass etc. [1]. Among these sources, solar energy is more preferred as it is available widely, whereas wind energy is confined to the coastal area. Also, solar power-driven systems can breed electricity by means of PV panels, or else thermal collectors. The trend today is to go with solar energy. Within the PV system, PV inverters are required which infuse the generated power to the AC grid. A gist of power pattern for photovoltaic system is obtainable in literature [2]. By tradition, central inverter systems were being passed down for solar farms. But, nowadays multi-string inverters or string inverters are being used with their bypass model and variation in control circuit which are copiously employed in utility-scale photovoltaic systems. Figure 1 depicts the block diagram for single stage topology and dual stage topology.

Research focused on module integrated converter (MIC) for residential applications such as DC–DC power converter, and AC module technology have been carried out earlier [3, 4]. AC module comprises of a grid coupled inverter also known as micro inverter which is affixed to the photovoltaic panel. The leading advantage of micro inverter based system involved authorising an easy escalation of the equipped power and modularity. With extension to it [5], maximum power point is enforced for each and every photovoltaic module, panel mismatching, partial shading problems were diminished, leading to improved energy harvesting capability. The main challenges were in designing of the PV inverter with the further improvements within the efficacy as well as increment in the trustworthy operation of inverter. Various topologies for AC module equipments are stated in earlier work [6, 7]. Use of transformers based system have been increased in numbers because of high voltage boost requirement which relates to low output voltage of the PV module. Survey of commercially viable PV inverter topologies were carried out by Rahim and Selvaraj [8] in terms of volume, weight, and maximum efficiency. Therefore, non-isolated topologies are lighter, highly proficient, less costly but not bulky as compared to isolated inverters. Sahan et al. [9] discussed main concerns of grounding and leakage current for the non-isolated inverters which can be handled by the solar panel parasitic capacitance. This paper contains a widespread

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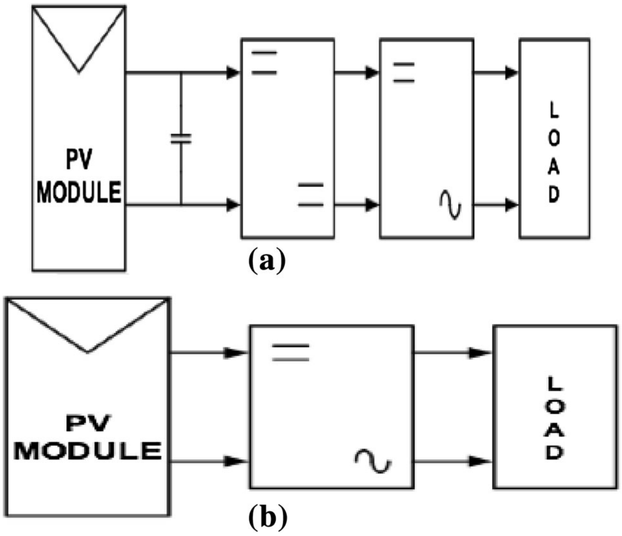


Fig. 1 **a** Two stage topology. **b** Single stage topology

analysis of transformer-less topologies which is appropriate for panel integration. Different topology has been reviewed for various specifications. Rating of semiconductors and passive components are nominated as elementary scheme to accomplish an overall contrast in view of cost and size. Photovoltaic inverters interface mutually with grid and PV module and are charged with two main responsibilities. It must confirm maximum accessible power at the PV side in the solar panel, on the other hand at grid side it must introduce the sinusoidal current into grid. Further grid requirements have been stated by Leon et al. [10].

Grid Requirements

The micro inverter which is attached with the module is said to be grid-tied inverter. Therefore, it should fulfil grid connection standards. Table 1 depicts the main code concerning the grid linking affairs of the photovoltaic system [11–14]. An expression of power quality, in addition to harmonics distortion of the inoculated current, a chief worry in the transformer-less topology, is inoculation of the DC current. The standard offers boundary of 1% or less than 1%, of the yield rate current, that point toward low values of current and escalation in control complexity. Due to safety reasons, both for electronics equipment and humans, the grid-tied inverters must identify islanding operation [15].

Grounding

Rahim and Selvaraj [8] reported that non-isolated topologies are extra lighters, lesser bulky, cheaper in price, high in efficiency as compared to detached inverters. As soon as the transformer is removed from circuitry, appropriate galvanic separation fades away among the grid and photovoltaic panels. Thus, ground leakage current comes into sight because of parasitic capacitance of solar panel in midst of grounded frame and cells, combined with common mode voltage variation [16]. Ground current's estimation is to be done for applied modulation techniques as well as for specific topology. To minimize leakage current novel topologies have been proposed in literature [17–19] due to the inspiration of the modulation technique in the full bridge inverter. In the view of the above mentioned principles, there is no intercontinental covenant related to ground current limitation. Still, protection of ground leakage current and monitoring are needed. Solar PV inverters with single phase, prompt demand power comprise of two times the line-frequency oscillation and a DC value. Power spawned by photovoltaic module is sterling DC, a local storing device, commonly a capacitor, is used to stabilise the power.

Single-Stage Topologies

In recent years, the penchant to lower the integer of power processing phase in order to surge in the whole efficacy and reliability of system as well as to cut down the tariff of rising power density. Present trend is integrating a single stage converter that consist of all the chosen functionalities advanced by the multi stage topologies. Numerous topology has been recommended based on the either buck-boost, boost or buck postulates. Single stage topologies that can operate either in boost, buck or boost-buck mode is in literature [1].

Some of the ethics that inverters for grid and PV applications must fulfil, addresses on system grounding, injection of dc currents into the grid, power quality and detection of islanding operation gives an outline on topologies of multilevel inverter and investigate their correctness for single-phase grid rope PV systems [2]. A number of transformer-less PV system combining multilevel converters are preferred regarding issues such as stress, component count, and system power rating. Calais and Agelidis [3] reported 11-level cascaded H-bridge inverter, used MPPT and PLL with disparate solar panels as DC sources to merge with power grid. A SPWM approach was conferred to deal with the lumpy power transferring feature of the customary SPWM modulation procedure but THD for output current is 7.8%, which is high according to IEEE 5147. Kumari et al. [4] reported transformative, computing based cascaded H-bridge multilevel inverter for PV system with simple PWM process to have the advantage of low switching frequency. Still the

Table 1 Summary of PV systems interconnection standards [11–14]

Issues	IEC 61727		IEEE 1547	
Nominal power	10 kW		30 kW	
Harmonic content	Order (h)	Limit (%)	Order (h)	Limit (%)
	3–9	4.0	3–9	4.0
	11–15	2.0	11–15	2.0
	17–21	1.5	17–21	1.5
	23–33	0.6	23–33	0.6
			>35	0.3
	Even harmonics are limited to 25% of the odd harmonics limit shown above			
	THD < 5%			
DC Current injection	Less than 1% of rated output current		Less than 0.5% of rated output current	
Voltage deviation	Range (%)	Time (s)	Range (%)	Time (s)
	V < 50	0.1	V < 50	0.16
	50 ≤ V ≤ 88	2	50 ≤ V ≤ 88	2
	110 ≤ V ≤ 120	2	110 ≤ V ≤ 120	1
	V ≥ 120	0.05	V ≥ 120	0.16
Frequency deviation	Range (Hz)	Time (s)	Range (Hz)	Time (s)
	49 < f< 51	0.2	59.3 < f < 60.5	0.16

output current THD and voltage THD with this modulation technique is 7.49 and 11.59% respectively. Fundamental frequency modulated diode clamped multilevel inverter fed from PV modules for standalone operation is reported by Monge et al. [5]. The maximum efficiency reported by the multilevel inverter is 98.5% and is also verified experimentally, which is higher than that of conventional inverter and also the output current THD and voltage THD with this modulation technique is 1.2% and 6.3% respectively. Modulation strategy for the interconnection of a set of photo voltaic arrays to a three phase diode clamped multilevel inverter and have considered the maximum power extraction issues under partial shades and in case of mismatched PVAs condition [6]. Five-level single-phase multi-string inverter for solar PV equipments is reported by Chen et al. [7]. A unique PWM control process having two reference signals and one carrier signal have been used to initiate the PWM switching signals. With this modulation technique, though the power quality has been improved to some extent but, it was unable to meet the required standard. For modulation index less than 0.5, current will inoculate from grid side to the inverter side. Also the efficiency of the five-level PV generation network is discussed. The topological assembly can resolve the leakage current complication in transformer-less PV network, which is lesser in cost and higher in efficiency. Sahan et al. [9] carried out analysis of possible modulation scheme incorporating carrier-based PWM and space vector modulation techniques for single-phase multilevel converters was also investigated. Leon et al. [10] have discussed about an active islanding detection methods. The first method consists of disturbance signal infusion in current at the interface converter side, while the second method consists of introducing zero time intervals in the current waveform. By introducing disturbances the response time become very slow with these methods.

Funabashi et al. [11] reported that the proposed topology is three phase single stage power conversion system where DC–DC converter is employed with the PV module because there could be MPP discrepancy losses due to mass production tolerances and no optimal conditions such as alignment in different angles or partial shading. So to shrink the number of conversion stages, a single stage topology is proposed. Module integrated control (MIC) notion execute power processing without ease of access to DC connections. This topology provides an output of some hundred volts. Electrolytic capacitors (ECs) many times absorb in MICs because of soaring energy density, but there could be a reason for critical point of foundering, also they have the terse lifespan amongst all power electronic apparatuses. When compared with efficacy, most recent heavy duty inverters reach 98%, whereas, the general efficacy of MIC devices typically spans around 90%. The CSI is known for high power drives and rectifiers. So the drawback of the topology is that the efficiency is less and can only be used for high power drives. Gonzalez et al. [12] reported that the topology comprises of H-bridge shown in Fig. 2 with recently developed AC bypass network composed of a switch with brace to the DC midpoint & a diode rectifier. The zero voltage state H-bridge rectifier (HB-

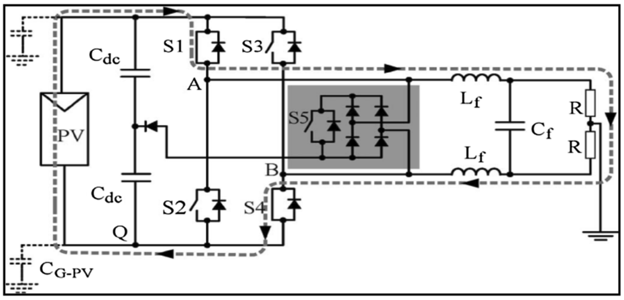


Fig. 2 HB-ZVR topology

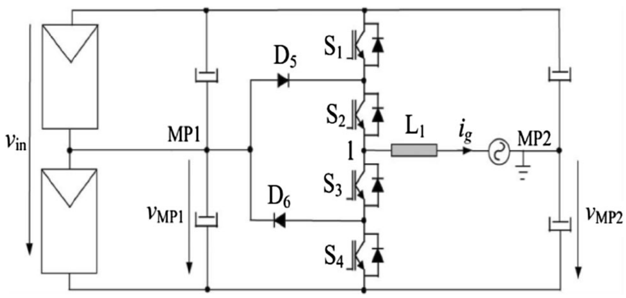
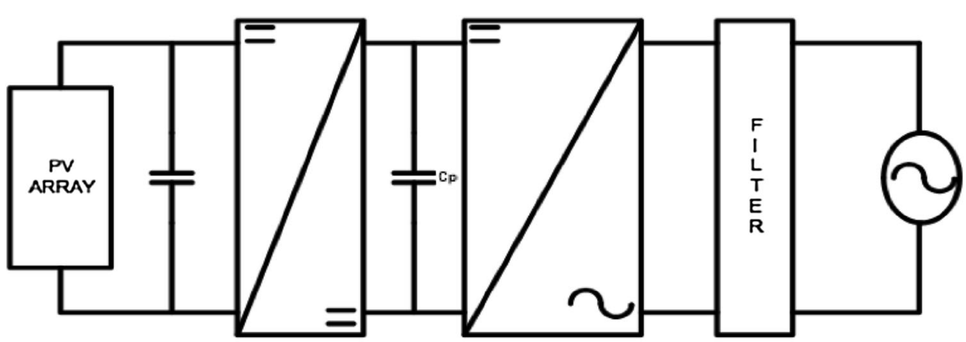


Fig. 3 Single phase three-level diode clamped inverter

ZVR) where the center point of the DC link is braced to the inverter only for the time of zero-state period by the help of switch & diode rectifier. Clarification for producing zero-voltage stage is achieved by making a use of bidirectional switch composed of an IGBT and a diode bridge. Figure 3, showing a bidirectional switch as an auxiliary section with a grey framework, in exposition of HB-ZVR, whatever polarity does the load current has, a track will be developed with the help of the bidirectional switch, which comprises of a switch and a diode bridge. The drawback HB-ZVR is it's lesser altering rate, due to auxiliary switch S5 which has the high frequency switching pattern. Proposed topology shown in Fig. 3, represents a three-level single phase diode clamped multilevel inverter which guarantees the non-injection of DC to the load [13]. The eradication of the yield transformer from load tie up PV network not only minimises the size, weight and cost of the transformation stage but also escalates the overall efficacy of the system. Safety requirements are met by means of extrinsic elements. It is fulfilled by ground fault detectors which disengage the inverter upon the perception of an isolation defect. The maximum achieved efficiency is 98.16%. Analysis of a single-phase step-up transformer-less inverters is acceptable for AC-module applications [14]. To collate the nearly viable resolutions of the assessed topologies, a reference is set. Criterion, found on classical AC-module application taking into account the demand for the grid and the solar panel. Both single stage and two stage conversion topology have been reviewed. The two stage topology block diagram shown in Fig. 4 boosts converter with NPC inverter. Dual stage topology, incorporating the interpretation with binate grounding capability that theoretically clears of the ground leakage currents are the preferable choice for the stick principle in which switching frequency for the DC–DC state is kept twice than for the DC–AC stage. The dual state blend of step-up DC–DC converter and a step-up inverter should be appraise. Early literature [15] suggests a widespread circuit topology of Voltage Source Inverter (VSI), that is based upon direct appendage of the three-level inverter to soaring level, and the circuit topology up to five-level. The accessible multilevel inverter can realise any level pulse width modulation program that leads to lowering in harmonics and issue full deployment of semiconductor devices such as GTO, chiefly in high power scale. Where soaring voltage could be functional, capacitor voltage footing problem is jagged out and a circuit therapy for such a complication is also given. Choi et al. [16] offered a widespread topology from which any type and any level of multilevel inverter can be assumed. It has a self-voltage balancing feature. It has a disadvantage too, that is for higher levels inverter, there is an increment in the cipher of devices used, which results in increments of face value of the system. So far, the discussion was about the overall structure, configuration, and power processing stages for the PV inverter. This part studies the structure and topology of the power conditioning unit employed in the grid-connected PV systems. PE inverter connects the utility grid with the PV source.

Fig. 4 Two stage topology



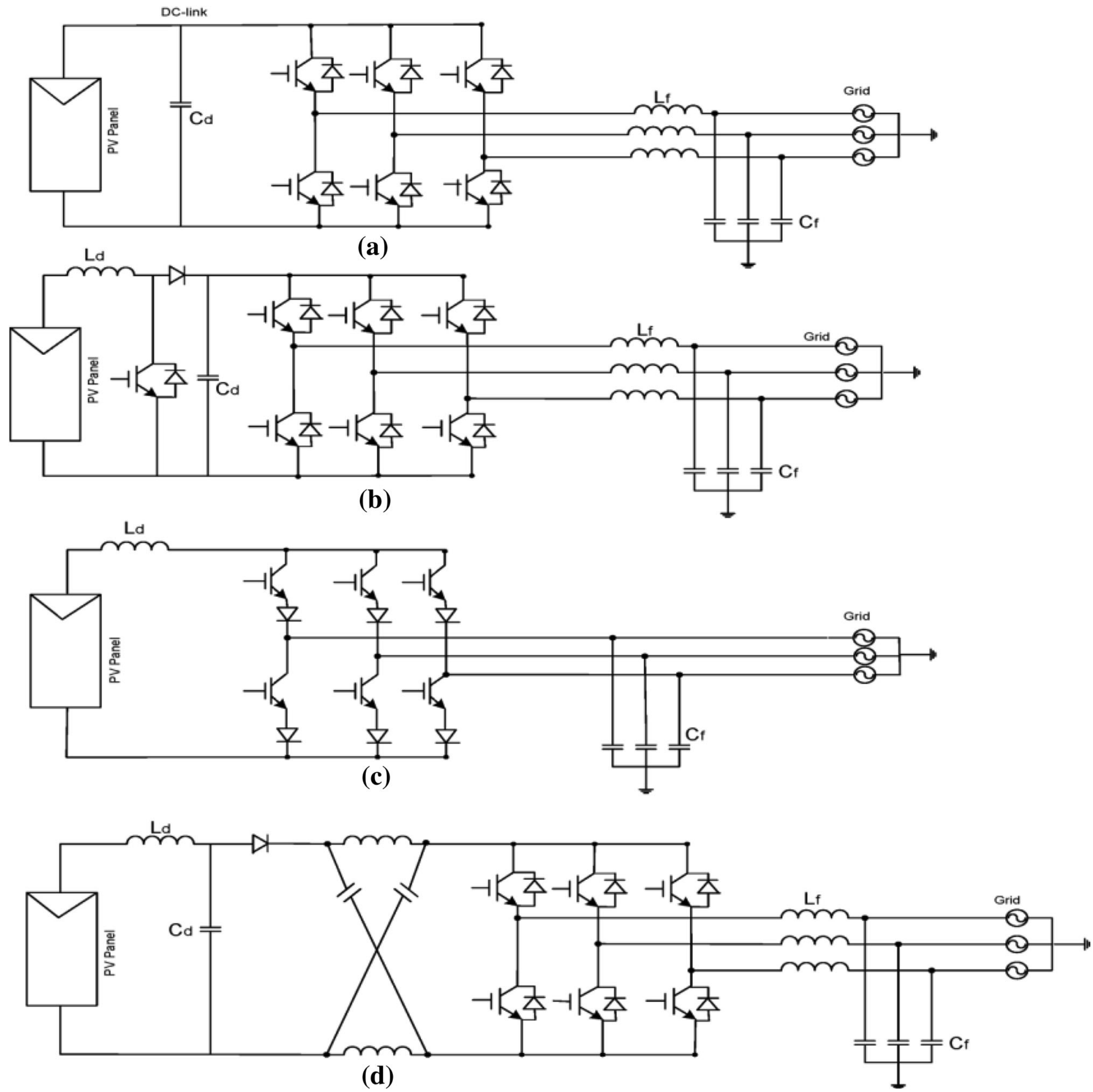


Fig. 5 PV grid interface topologies. **a** Voltage Source Inverter (VSI). **b** Voltage Source Inverter cascaded with a boost converter. **c** Current Source Inverter (CSI). **d** Z-source inverter

Moreover, selection of a proper PE interface topology can contribute towards reducing the number of stages, which in return reduces the face value of the whole unit. Since 1984, researchers have proposed a range of topologies for the power conditioning system. Earlier works [17, 18] reported surveys on the structure of power electronic interface used in three-phase grid-connected PV systems. The topology that has been thoroughly investigated and adopted for grid-connected PV inverter is VSI, which enjoys a simple and effective control scheme and well-established Pulse Width Modulation switching technique. Schematic diagram of VSI topology connected to 3-phase grid is presented in Fig. 5a. Literature is rich in information on the VSI topology, and the established proposed control and switching schemes and application in grid-connected systems [19, 20]. One major drawback of VSI is that, as a buck topology, it requires sufficiently high input voltage for proper functioning. Therefore, when the input voltage is low, another converter stage, usually a boost converter is employed in the middle of the DC source and VSI [21, 22].

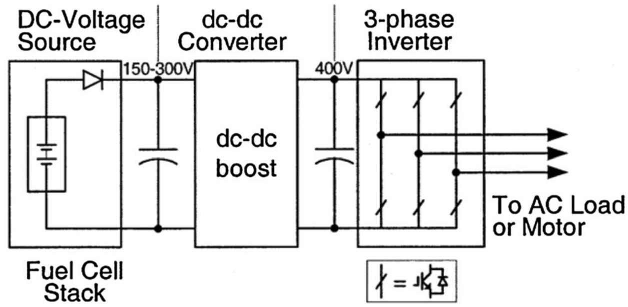


Fig. 6 Traditional two-stage power conversion for fuel-cell applications

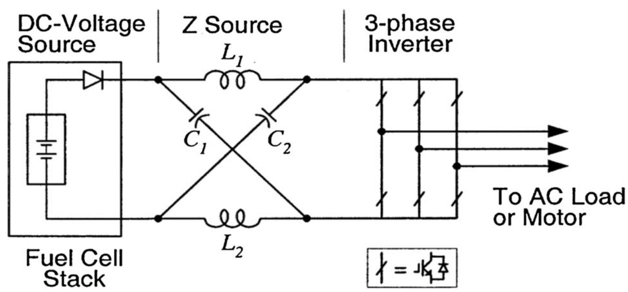


Fig. 7 Z-source inverter for fuel-cell applications

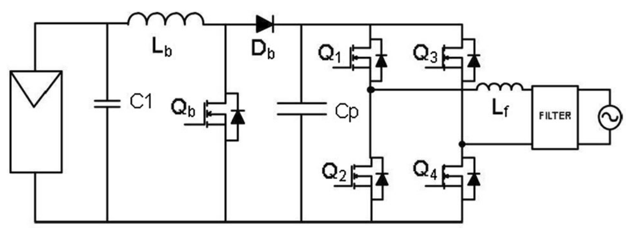


Fig. 8 Boost converter and full bridge inverter

A schematic diagram of a VSI cascaded with a boost converter is shown in Fig. 5b. Besides, the topology that has been less investigated and adopted when compared with VSI for grid-interface applications is Current Source Inverter (CSI) topology, shown in Fig. 5c. Recently, a new topology named "Impedance-Inverter" or Z-sourceinverter which enrolls an eccentric impedance network to pair the converter to the DC source has been adopted for interfacing DG. A schematic diagram of Z-source inverter is presented in Fig. 5d [23]. Earlier work [23] has presented the advantages and drawbacks of the new put in postulation of Z-source inverter. The leading benefit of this recently developed notion is the unbroken range of power conversion. The Z-source inverter is a buck-boost inverter with features that customary voltage source and current source cannot provide. It can be registered in applications where the input voltage alters widely. All accepted PWM stratagem can be used to command the Z-source inverter and their theoretical input–output relationship leads to cost reduction and increment in efficiency. With the shoot-through duty cycle and modulation index, any desired output AC voltage can be generated. Compensation methods need further investigation. The special feature of Z-source inverter is the theoretical barriers, conceptual barriers and restriction of the conventional VSI and CSI topologies can be overcomed. They are proficient of working in both boost and buck modes also eliminate the requirement of a bulky transformer. Application of Z-source inverter in the field of grid-connected PV system is at a very early stage. However, efforts have been made in [24] to interface PV module through Z-source inverter to single-phase and three-phase grid, respectively. Since the Z-source is competent of operating in both buck and boost mode, a comparative study between buck-boost inverter and Z-source inverter for PV applications is carried out. The experimental results of earlier work [25] shows that the efficiency of Z-source inverter drops more rapidly for high loads compared to that of buck-boost inverter. Though the Z-source inverter can operate both in step-down and step-up modes, it offers more structural complexity than a single-stage grid-connected PV system based on VSI or CSI. Considering that for PV and fuel cell applications as shown in Figs. 6 and 7, where the boosting feature is desired, a CSI is better than Z-source inverter as it lifts the requirement for the additional impedance requirement used in a Z-source inverter. Figure 8 represents a full bridge inverter with boost converter. Some work reports [26] impedance-fed or impedance-source power converter abridge as Z-source converter and its command procedure for executing DC–DC, DC–AC, DC–AC, and AC–AC power transformation. The Z-source converter deploys an eccentric impedance fretwork to pair the converter's focal loop to the power source, thus providing unrepeated factors that can't be acquired in the conventional voltage-source and current-source converters where capacitor and inductor are used, respectively. For VSI, capacitor acts as a filtering element and energy storage device, used to subdue the voltage ripples and an interim storage, for current source inverter. Thus inductor behaves as a filtering or storage element, also used to squash the current ripples and act as a non-permanent storage. Impedance source act as filter which is more capable of suppressing both the voltage and current ripples alone which a traditional inverter cannot do. Some works [27] have described five modes of operation of Z source inverter with the size of the inductor. The working modes are; Mode 1 is a shoot through zero state, diode is reverse biased. The voltage across the capacitor is greater than the input voltage. Since the capacitor voltage remains constant, the voltage across the inductor rises linearly. Mode 2 is a non-shoot through state. Due to the uniformity of the circuit, the current across the inductor and capacitor

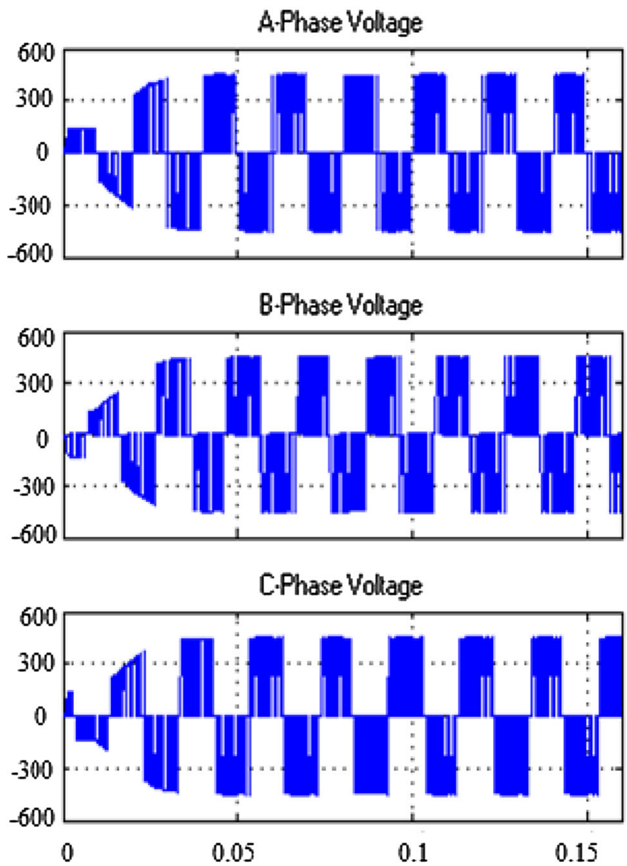


Fig. 9 Phase voltage waveforms

are equal. At this moment inductor is having negative voltage across it. Since the capacitor voltage is more than the input voltage during boost operation that is mode 1. Now the inductor current decreases linearly with time. With this mode 2 ends when diode current reaches to zero. Mode 3 states that the inductor current dies down to fifty percent of the inverter DC side current. When this condition occurs, input current becomes cipher and diode is reverse biased. In Mode 4 diode stops to conduct, and inverter behaves as an open circuit. The inductor current becomes zero and remains zero until next switching. In Mode 5, mode 1 stands accurate and inductor current rises in uniformity. Mode 5 continues until the inductor current rises to fifty percent of the DC side. Since small inductor can reduce face value, weight and volume but at the same time will lead to current stress to the switches. The voltage is no longer constant during active states, which might cause unexpected harmonics. Badin et al. [28] have discussed about three different pulse width modulation control; Traditional pulse width modulation, Simple boost pulse width modulation, Modified reference pulse width modulation. It is an open loop system. Simple boost pulse width modulation has been used to control the shoot-through duty ratio. Modified reference pulse width modulation uses four different reference signals for four different switches. Modified reference pulse width modulation is a better pulse width modulation control method

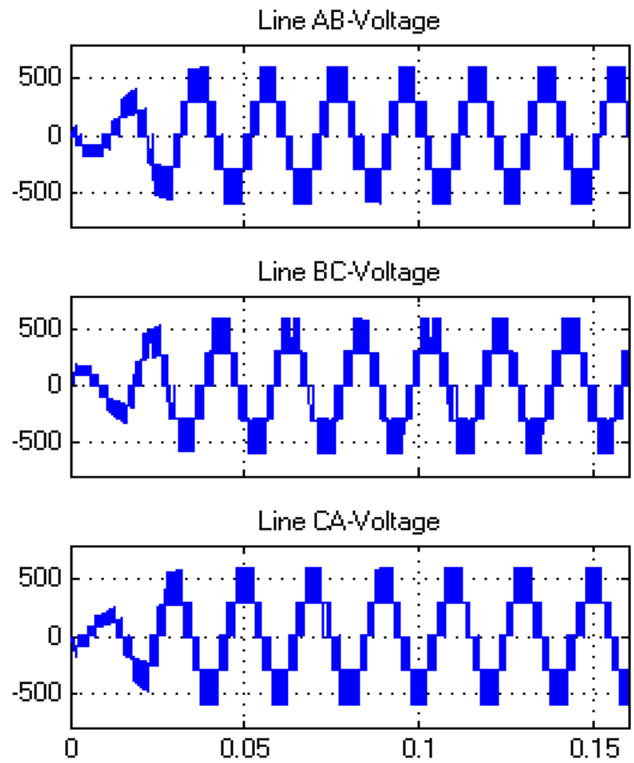


Fig. 10 Line voltage waveforms

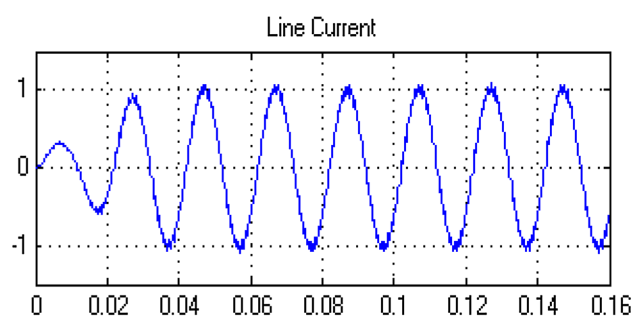


Fig. 11 Line current waveform

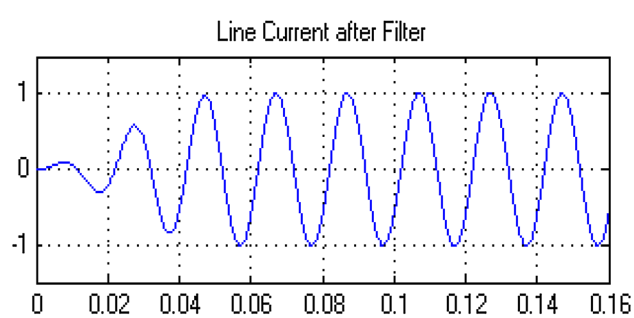


Fig. 12 Line current after filtering waveform

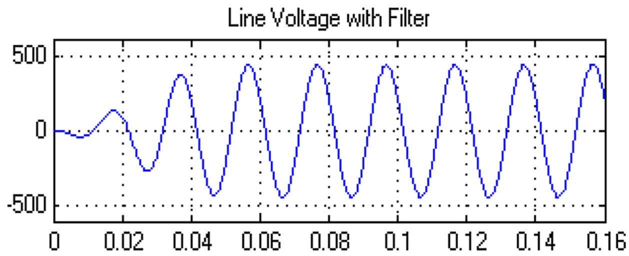


Fig. 13 Line voltage with filter waveform

because it is gives total harmonic distortion in the permissible limit. Since in the proposed pulse width modulation scheme, four different signals are generated for four different switches, it leads to complexity in the circuitry, increase in the cost of the system and reduction in reliability. Alaas and Wang [29] presented a topology which is a blend of cascaded basic unit and H-bridge unit. The basic unit comprises of one Z-source, one DC voltage source and two switches generating two voltage levels. Power quality issue is the main concern and hence it is pointed out in this research paper. Dynamic voltage restorer has been used to cope up with the problem of power quality. Since the system is transformer based and its output THD is not in the permissible limit according to IEEE standard, it needs further investigation for the reduction total harmonic distortion. Florescu et al. [30] reported various multi-carrier PWM procedure like Phase Opposition Disposition (POD), Phase Shifted (PS), Alternative Phase Opposition Disposition (APOD), Phase Disposition (PD) are presented for five level three phase diode clamped multilevel Z-source inverter THD for 3Level DCMLI with traditional PWM technique is 34.59%. THD for 3Level DCMLI with Phase disposition PWM technique is 26.85%. THD for 3Level DCMLI with Phase opposition disposition PWM technique is 26.48%. THD for 5level DCMLI with Alternate phase opposition disposition PWM technique is 26.47%. THD for 5level DCMLI with Phase shifted PWM technique is 22.20%. From the above work it is clear that THD is best among the Phase shifted PWM technique. Therefore attract attention for further research to lower down the THD. Results achieved during simulation of transformer-less three phase inverter are stated. Figure 9 states the phase voltage waveforms. Figure 10 shows stepped waveform of line voltages. Figures 11, 12 and 13 depict the line current waveform with and without filtering.

Conclusion

This research paper gives a complete analysis of transformer-less inverters for AC module running devices. Individually the grid connection and the solar panel requirements are analysed emphasising on power quality and THD. When compared to transformer based system, it was found that transformer-less system has higher sensitivity, lower noise immunity and distortion. Transformer-less system puts forward superior efficacy when juxtapose with inverters which are transformer based. A transformer-less topology has been studied and verified in MATLAB simulink environment for power quality issues such as DC current injection into grid. Therefore, these type of systems are lesser in size and offer reduction in the cost of the filter.

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