Comparison of MLI and Z-Source Inverter for Transformerless Operation of Single-Phase Photovoltaic Systems

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Abstract

This paper presents a comparative analysis of single-phase transformer-less photovoltaic inverters and the topologies are compared in terms of efficiency, DC current injection and regulation. A model of cascaded multilevel inverter and Z-source inverter is built in MATLAB/SIMULINK and its performance is analyzed. Phase disposition control scheme is used for pulse generation for cascaded multilevel inverter and maximum boost control is used for Z-source inverter. The effects of intensity and modulation index on the output voltage are studied through simulation and prototypes of the inverters are implemented. The simulation, and the experimental results are presented in this paper.

Keywords: Multilevel Inverter, Z-source Inverter, Single-Phase Photovoltaic Inverter, Phase Disposition, Maximum Boost Control, Modulation Index (M).

1. Introduction

Nowadays, the high price of gasoline and increased demands on clean energy, renewable based generation are receiving more attention. Renewable energy sources (RES) include solar energy, wind energy, bio-fuel, geothermal energy, hydrogen and fuel cells. These sources are abundant and utilization of them creates zero emission. The power generated from the renewable energy systems are tied to the utility grid [1] and [2]. In remote places where there is less/no feasibility of utility grids, renewable energy systems provide electricity to the isolated region. These isolated renewable energy systems can be employed to power residential applications or low power industrial applications.

For renewable energy sources, the output voltage and power typically depends on a variety of uncontrollable factors, for example: radiation intensity determines the obtainable voltage and power output of a solar panel, wind speed determines the voltage and power of a wind electrical generator, and the output voltage and power of a fuel cell changes with operating temperature, fuel and air flow rates [3] to [5]. To obtain the required voltage output for varying input conditions, power conditioning systems (PCS) are introduced as an interfacing scheme with the renewable energy systems [6]. The conventional PCS uses a PWM inverter and a tap changing transformer to convert the low voltage DC power output of the PV modules into AC power of required voltage and frequency [7] and [8]. Use of a transformer increases the system cost and decreases the overall efficiency of the system. The existing power conversion topologies used in PCS consist of boost converter and a voltage source inverter. The boost converter enhances the low voltage output from the RES during low input conditions and the inverter converts the DC power into AC of required voltage and frequency.

A two stage conversion system also increases the system cost and decreases the efficiency of the system. To eliminate the boost conversion stage, multilevel inverter [MLI] topologies and Z-source inverter are proposed in the literature [9-10] and [20]. The advantages of MLI are well recognized for high power, medium voltage applications. Depending on the number of levels, filters can be avoided or filter effort is significantly reduced. For low power, low voltage applications, where switching frequency limits are not as restrictive, the higher number of switching devices for multilevel topologies has to be justified. Multilevel converters therefore have the potential to become an interesting alternative not only for high, but also low power applications [11-17]. The different multilevel inverter topologies are [9]:

- Cascaded multilevel inverter.
- Diode clamped multilevel inverter.
- Capacitor clamped multilevel inverter.

Among the three topologies, cascaded MLI is more suitable for PV inverter since the output of the each PV panel is connected to each bridge of the MLI. There are different modulation strategies for switching the multilevel inverters. Carrier-based pulse width modulation (CBPWM) methods are preferred due to the low harmonic distortion waveform characteristics [18-19]. CBPWM is based on the comparison of a reference input, which is usually a sinusoidal waveform, with some triangular waveforms. For an level inverter, n-1 triangular carrier waveforms are compared with sinusoidal reference waveform. Comparison among the n-1 carriers and reference waveforms by some special rules determine the switching of the voltage level to be attained.

In MLI, as the level increases, the firing circuit becomes complex and the cost of the system increases. The Z-source inverter can overcome the above problems. When the thyristors in the same leg are fired (shoot-through), energy is stored in the inductor, which is used to boost the input voltage during the non-shoot-through state. Therefore the inverter does both the buck and boost operation. Further, the shoot-through state caused by the electromagnetic interference will not destroy the circuit. Therefore a more reliable single stage power converter for both buck and boost operation is achieved. There are different firing schemes for Z-source inverter presented in [21]. A simple control for the Z-source inverter is discussed in [20]. The relation between voltage boost and modulation index is discussed in [22].

In this paper, a comparative study of the MLI and Z-source inverter topologies is considered. A MATLAB/SIMULINK of the topologies is developed. The voltage, current and power variations are studied for various solar intensities. The effects of modulation index are also analyzed. The performances of the schemes are compared in terms of output voltage, total harmonic distortion and efficiency, and the results are presented.

2. Cascaded Inverter

The single-phase n-level configuration of a cascaded multilevel topology is shown in Fig 1(a). The modular structure of the MLI leads to advantages in terms of manufacturing and flexibility of application. Applications and control techniques of this topology have been discussed in a number of papers [11-17]. Each inverter has a separate DC source (V_{dc}) for each individual inverter bridge. Each unit can generate a three-level output, $+V_{dc}$, 0 or -

V_{dc}. The multilevel inverter's output voltage V_{an} is equal to the sum of the output voltages of the individual inverter bridge units ($V_1, V_2, \ldots Vn$ in Fig1(a)) and can be controlled to produce a staircase sine waveform [Fig 1(b)].

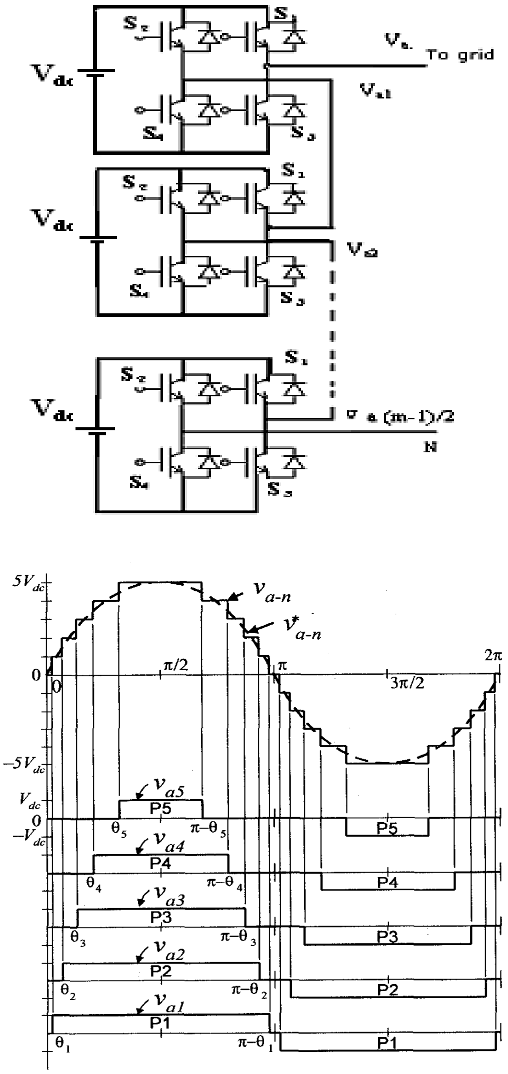


Fig. 1 (1a) Cascaded multilevel inverter topology **(1b)** Staircase sine output of cascade eleven level inverter.

The number of possible voltage levels at the output generally defines the multilevel inverter topologies. In the case of this cascaded topology, the staircase sine waveform in figure 1(b) represents an 11-level multilevel inverter with five FBI units in series and a line frequency of f=1/T. The switching phase angles θ_n (n=1, 2,…., 5) can be calculated offline for discrete values of the modulation index (MI) to minimize harmonics.

3. Z-Source Inverter

The Z-source inverter consists of a Z-impedance network along with the inverter circuit [21]. Fig. 2 shows the circuit diagram of Z-source inverter. The Z-impedance network consists of L and C components connected in an X fashion. The firing control of the Z-source inverter includes the shoot through states. The Z-source inverter advantageously utilizes the shoot-through state to boost the DC bus voltage by gating on both the upper and lower switches of a phase leg. Fig. 3 shows the Z-source network during the shoot-through state. The inductor is energized and the inductor voltage increases due to the increasing current. The capacitor is connected in parallel to the inductor and its voltage is boosted during this state.

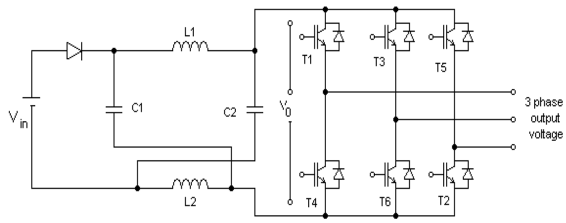


Fig. 2 Z - source inverter.

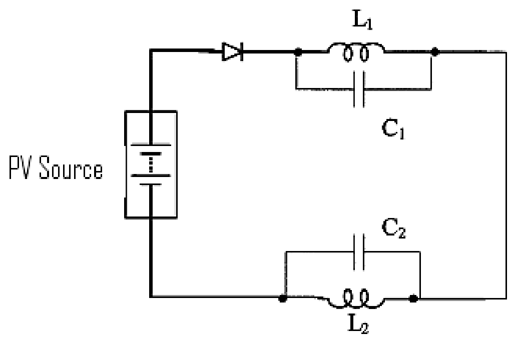


Fig. 3 Z-source network during the shoot through state.

During the non shoot through state this boosted voltage appears across the inverter.

The peak DC link voltage across the inverter bridge is expressed in (6):

$$Vi = B.Vo \tag{1}$$

where B is the boost factor which is given by (2)

$$B = \frac{T}{T1 - T0} = \frac{1}{1 - 2\frac{T0}{T}} \tag{2}$$

The boost factor is greater than or equal to 1.

The output peak phase voltage from the inverter is expressed in (3)

$$Vac = M.B.\frac{Vo}{2} \tag{3}$$

4. Firing Scheme

A. Multilevel inverter

There are several pulse width modulations [11] based on sine-triangular comparisons with voltage-shifted or time shifted carrier for a multilevel converter. For each technique the following parameters introduce degrees of freedom:

1) The frequency modulation index, M_f, with $M_f = f_c / f_0$, where f_c is the frequency of the carrier signal and f_0 is the frequency of the modulating signal.

2) The amplitude modulation index, M_a, with M_a defined for each modulation technique in Table 1, where A_0 is the amplitude of the modulating signal and A_{cpp}, is the peak to peak value of the carrier (triangular) signal.

Carrier disposition schemes, which include Alternative Phase Opposition Disposition (ADOP), in Phase Disposition (PD) and Phase Opposition Disposition (POD), are given in reference [18]. For n-level phase voltage, n-1 carrier waves are required in the carrier disposition scheme. The phase shift of each carrier wave is 180° alternately in the APOD scheme. But the carrier waves are all in phase in the PD scheme. For the POD scheme, carrier waves are in phase above and below the zero voltage. Fig. 4(a) - 4(d) shows the modulating signal and the carrier waves for the five-level inverter. Phase Shifted (PS) scheme, as shown in Fig. 4(d), shifts four carrier waves by 90° in order to provide five-level PWM pattern in each phase. Among the discussed techniques, the PD technique has less harmonic distortion on line voltages. The PD technique puts the harmonic energy directly into a common mode carrier component, so that the harmonics are cancelled in line voltages [19].

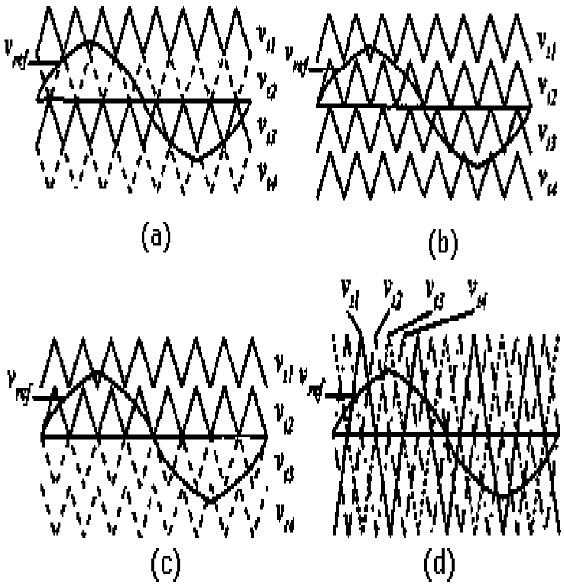


Fig. 4 The PWM Schemes for the multilevel inverter (4a) APOD scheme **(4b)** PD scheme **(4c)** POD scheme **(4d)** PS scheme.

Table 1 Amplitude modulation indices for the various multi-carrier modulation techniques.

	APOD	POD	PD	PS
Ma	$\frac{Ao}{\frac{(m-1)}{2}Acpp}$	$\frac{Ao}{\frac{(m-1)}{2}Acpp}$	$\frac{Ao}{\frac{(m-1)}{2}Acpp}$	$\frac{Ao}{Acpp}$

B. Z-source inverter

The various firing control techniques of the Z-source inverter are:

a. Simple Boost control technique

The simple control uses two straight lines to control the shoot through states as shown in Fig. 5. When the triangular waveform is greater than the upper envelope, Vp, or lower than the bottom envelope, Vn, the circuit turns into a shoot-through state. Otherwise it operates as traditional carrier based PWM. Some traditional zero states are not utilized in this control. The shoot through duty ratio obtained in this method decreases with increase of modulation index and the resulting voltage stress across the device is relatively high.

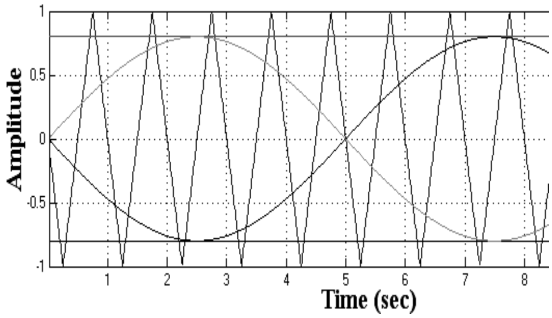


Fig. 5 Simple Control scheme.

The boost factor is given by (4):

$$B = \frac{1}{1 - 2To/T} = \frac{1}{2M - 1} \tag{4}$$

The voltage gain is given by (5):

$$\frac{Vac}{Vo/2} = MB = \frac{M}{2M - 1} \tag{5}$$

b. Maximum boost control

The maximum boost control fully utilizes the zero states and turns all traditional zero states into shoot-through states. Fig. 6 depicts the maximum boost control. Compared to the simple boost control, the possible operation region is much wider, and for any given voltage gain, a higher modulation index can be used, which means lower voltage stress across the switches.

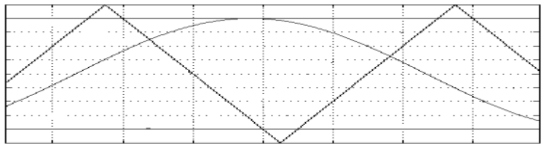


Fig. 6 Maximum Boost control strategy.

The boost factor is given by the equation (6):

$$B = \frac{1}{1 - 2To/T} = \frac{\pi}{3\sqrt{3}M - \pi} \tag{6}$$

The voltage gain is given by equation (7):

$$\frac{Vac}{Vo/2} = MB = \frac{\pi M}{3\sqrt{3}M - \pi} \tag{7}$$

5. Simulation Results

To study the performance of the cascaded multilevel inverter and Z source inverter, simulations were performed in MATLAB/SIMULINK with the configuretion shown in Fig. 1 to Fig. 2 with the following parameters: Modulation index= 0.3 to 1, switching frequency= 10kHz, Intensity=40 to 100mW/cm^2, output RMS voltage =230V and the load is 0.9 PF RL load. The simulation result for the Phase disposition (PD) technique for eleven levels is shown in Fig. 7 for an MI of 1. To produce a firing pulse for an eleven level inverter, ten carriers with a frequency of 10 KHz are compared with the sinusoidal reference waveform of 50 Hz. In this method, carriers are the same in frequency, amplitude and phases, but they are just different in DC offset to occupy continuous bands. Output voltage and current of a cascaded three level inverter is shown in Fig. 8. At the minimum intensity of 40 mW/cm^2, the rated output voltage of 230V is achieved for an MI of 0.93. As the intensity increases, the MI is decreased to maintain the output voltage constant.

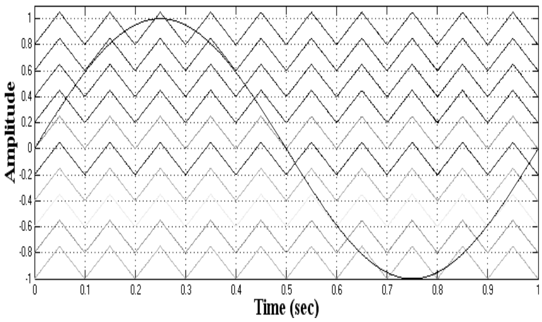


Fig. 7 Phase disposition scheme for eleven level inverter.

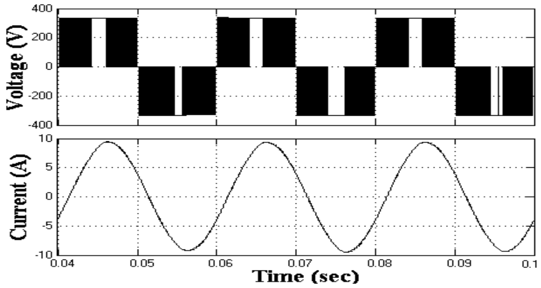


Fig. 8 Output voltage and current of cascaded three level inverter.

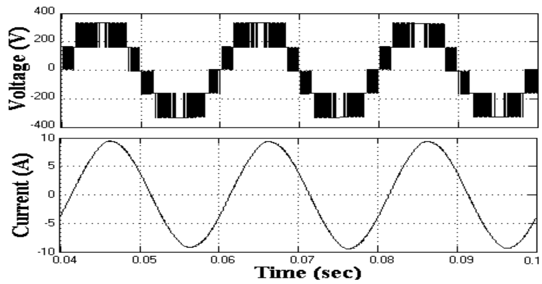


Fig. 9 Output voltage and current of cascaded five level inverter.

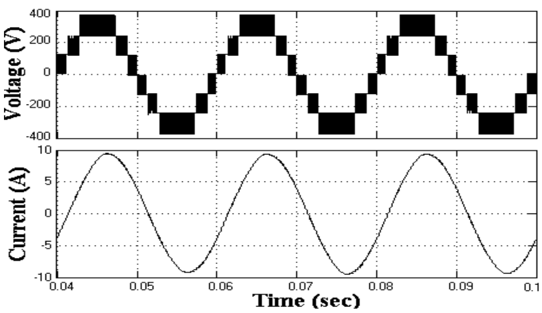


Fig. 10 Output voltage and current of cascaded seven level inverter.

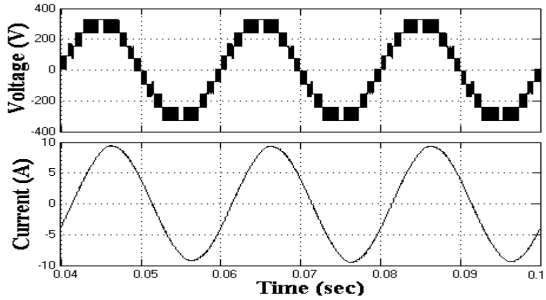


Fig. 11 Output voltage and current of cascaded nine level inverter.

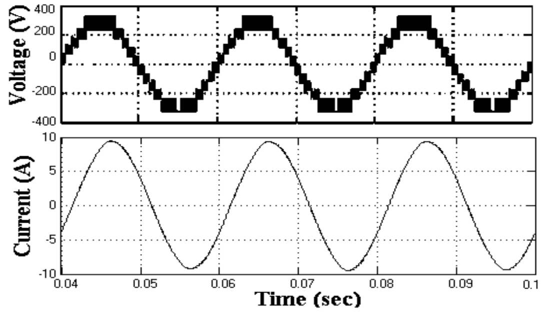


Fig. 12 Output voltage and current of cascaded eleven level inverter.

Table 2 Comparison of different levels of cascaded inverter at 40 mW/cm^2.

NUMBER OF LEVELS	OUTPUT RMS VOLTAGE (V)	FUNDAMENTAL RMS VOLTAGE (V)	THD (%)	MODULATION INDEX
3	264.1	227	59.34	0.93
5	238.3	228	30.75	0.95
7	233.4	229	20.55	0.96
9	232.1	230	15.34	0.971
11	231.4	229	12.42	0.98

Table 3 Comparison of different levels of cascaded inverter at 100 mW/cm^2.

NUMBER OF LEVELS	OUTPUT RMS VOLTAGE (V)	FUNDAMENTAL RMS VOLTAGE (V)	THD (%)	MODULATION INDEX
3	274	229	66	0.89
5	242.2	230	33.63	0.905
7	233.8	228	22.78	0.9
9	232.3	229	16.95	0.91
11	231.4	228	13.42	0.92

It is observed from Table 2, Table 3 and Fig.13 that the percentage of total harmonic distortion decreases with increase in the number of levels. The minimum THD of 20.93 % is achieved at eleven levels when compared to three levels.

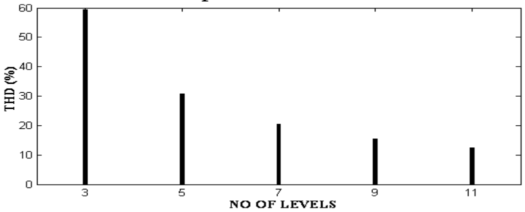


Fig. 13 THD (%) for different levels at minimum intensity of 40 mW/cm^2.

Firing pulses generated for Z-source inverter with the maximum boost firing scheme for an MI of 0.8 with boosting factor (B) of 2.47 is shown in Fig. 14. To produce the firing pulse for a Z-source inverter, a sine wave of frequency 50 Hz is compared with the triangular wave with the frequency of 10 KHz and two straight lines, and the pulses are given to the corresponding gates of the thyristors. The two straight lines are used to control the shoot through states.

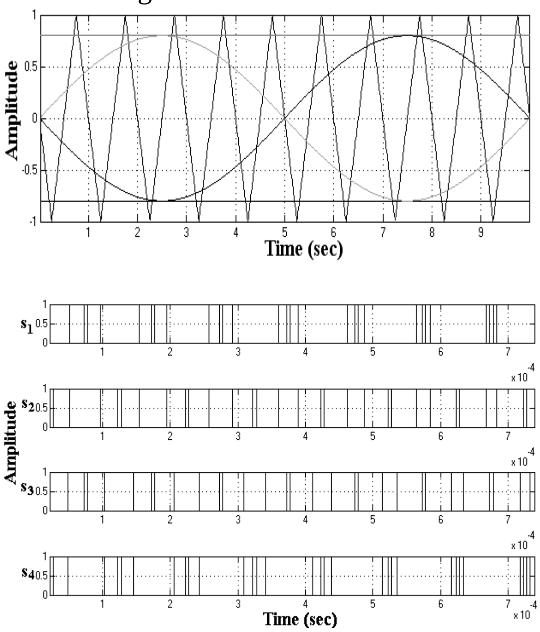


Fig. 14 (14a) Modulation Technique **(14b)** Firing pulse for Z-source Inverter.

The output voltage and current of Z-source inverter without filter and with filter of L=1mH, C=50µF is shown in Fig. 15 and Fig. 16 At the maximum intensity of 100 mW/cm^2, the rated output voltage of 230V is achieved for an MI of 0.75 with boosting factor (B) of 1.78.

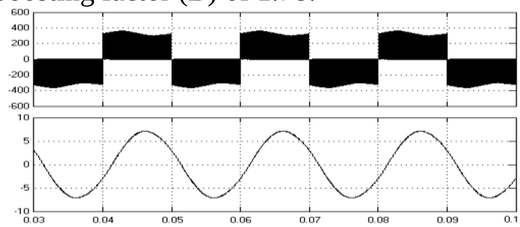


Fig. 15 Output voltage and current of Z-source inverter without filter.

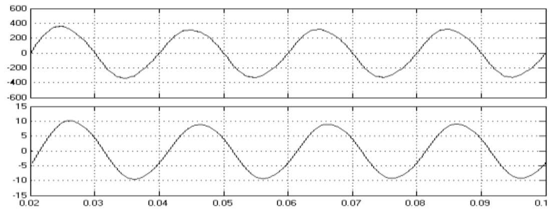


Fig. 16 Output voltage and current of Z-source inverter with filter.

The steady state results for minimum solar intensity of 40 mW/cm^2 of and the optimum MI of 0.69 to maintain the output voltage constant is shown in Table 4. From Table 4, the THD of Z-source inverter is reduced by using filter.

Table 4 Comparison of Z-source inver-ter with and without filter at 40 mW/cm^2 and 0.69 MI.

PARAMETERS	Z SOURCE INVERTER	
	WITHOUT FILTER	WITH FILTER
FUNDAMENTAL VOLTAGE (V)	177.7	229.8
OUTPUT RMS VOLTAGE (V)	228.5	229.9
THD (%)	80.81	3.239
CAPACITOR VOLTAGE (V)	250.6	328.2

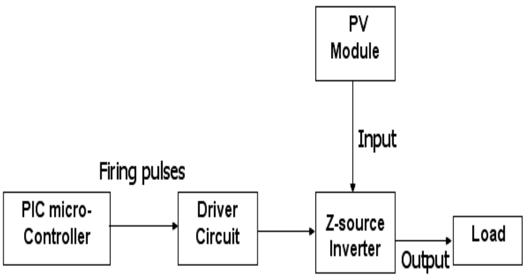
Table 5 Comparison of eleven level cascaded, eleven level diode clamped and Z-source inverter 0.9 PF, 1.5 kVA, 230V.

PARAMETERS	ELEVENLEVEL CASCADED INVERTER	Z SOURCE INVERTER WITH FILTER
FUNDAMENTAL VOLTAGE (V)	227.9	229.8
RMS VOLTAGE (V)	231.4	229.9
THD (%)	12.42	1.836
INTENSITY (mW/cm^2)	40	40
MODULATION INDEX	0.98	0.69
NO OF PV MODULES	34	20

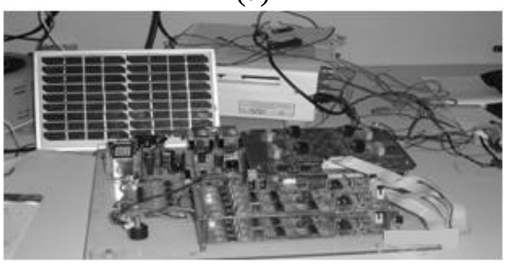
The comparison of cascaded MLI and Z-source inverter topology is shown in Table 5. From Table 5, the number of panels required to produce the output RMS voltage of 230V, 1.5 kVA for Z source inverter is less when compared to MLI inverter.

6. Experimental Results

A. Cascaded five level inverter



(a)



(b)

Fig. 17 (a) Block diagram (b) Experimental set up of cascaded five level inverter.

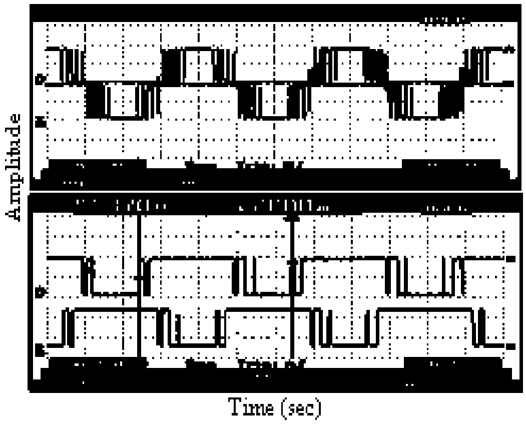
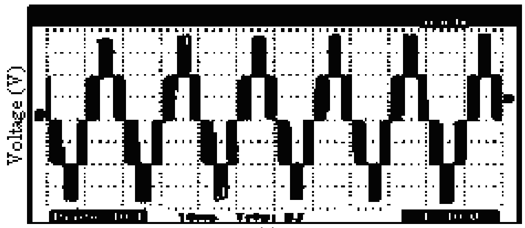
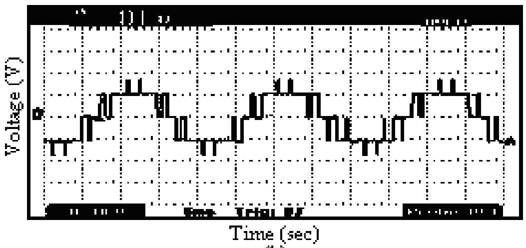


Fig. 18 Firing pulse of cascaded five level inverter.



(a)



(b)

Fig. 19 Cascaded five level inverter output voltage for MI of (a) 0.8 (b) 0.6.

B. Z-source inverter

CT60AM-18F IGBT is used in the single phase H bridge inverter.

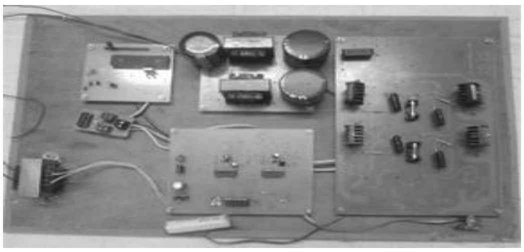


Fig. 20 Experimental set up of Z-source inverter.

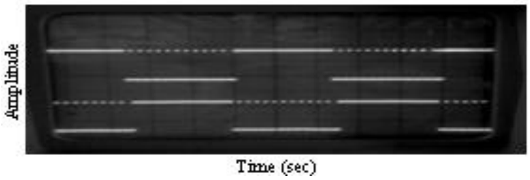


Fig. 21 Firing pulse of Z-source inverter.

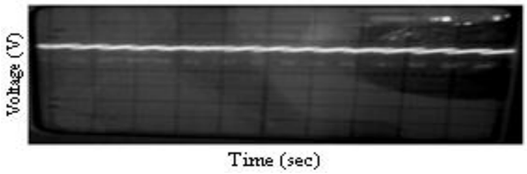


Fig. 22 Capacitor voltage of Z-source inverter.

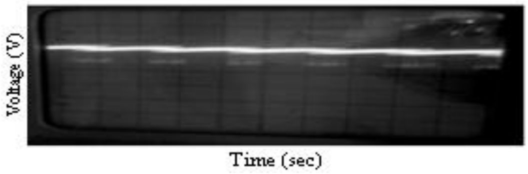


Fig. 23 DC link voltage of Z-source inverter.

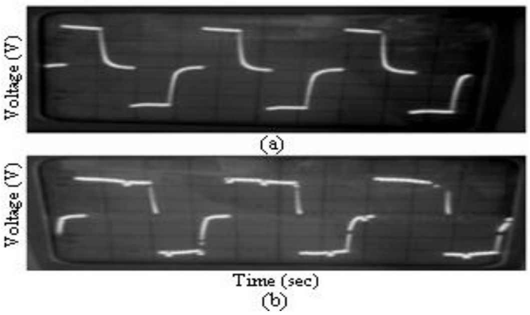


Fig. 24 Z-source Inverter output voltage for a shoot through state **(24a)** zero second **(24b)** 1.2 millisecond.

Experimental work on a cascaded five level inverter and a Z-source inverter was carried out and the experimental set-ups are shown in Fig. 17 and Fig. 20. The procedure is repeated for different voltage for five, seven, nine and eleven levels and the corresponding waveforms are shown in Fig. 9 to Fig. 12. The steady state results for varying solar intensity and optimum MI to maintain the output voltage constant is presented in Tables 2 and 3 and the total harmonic distortion for different levels of cascaded multilevel inverter is shown in Fig. 13. The firing pulses to the gate circuit of five level inverter are shown in Fig. 18. The output voltage of a five level inverter for the input of 40V at MIs of 0.8 and 0.6 are 26.1V and 24.8, respectively. The output waveforms are shown in Fig. 19. The Z-parameters used in Z-source inverter are L=3mH, 5A and C=470micro F, 600V. The firing pulses to the gate circuit of Z-source inverter are shown in Fig. 21. The capacitor voltage and DC link voltage for Vin=40V are 60V and 104V for a shoot-through period of 1.2ms and 0.214ms, respectively. The waveforms are shown in Fig. 22 and Fig. 23. The output voltage of Z-source inverter for the input of 40V at zero shoot-through state and the 1.2ms shoot through period are 24V(peak) and 100V(peak), Vrms=72V. The output waveforms are shown in Fig. 24.

7. Conclusion

Based on the simulation and experimental results, it is found that the Z-source inverter achieves better performance with a single inverter and reduced the number of panels, when compared to the cascaded MLI. Since the Z-source inverter boost, and inverts the input DC in a single stage, its firing circuit is simple. Therefore, the Z-source inverter is identified to be the best topology for a PV inverter.

8. Abbreviations

M = Modulation index
V_0 = Output Voltage in volts
n = Number of levels
rms = Root mean square
V_{DS}(max) = Maximum drain-source voltage
I_D(max) = Maximum drain current
$R_{DS\,(on)}$ = Drain–source resistance
t_r = Rising time in seconds
t_f = Falling time in seconds

V_{in} = Input voltage in volts
C = Capacitance (µF)
L = Inductance (mH)
RMS = Root Mean Square
PF = Power Factor
mW = milli watt
kVA= Kilo volt ampere
MLI =Multilevel Inverter
RL = Resistive Inductive load
kHz = kilo Hertz

9. Appendix

Specification of BP 380 Photovoltaic Module

Rated power	80watts
Current at load	4.6Amps
Voltage at load	17.3volts
Short circuit current	5Amps
Open circuit voltage	21.9volts
Efficiency at peak power	13.42%

10. References

[1] Doumbia, M.L., Agbossou, K., and Bose, T.K., Islanding Protection Evaluation of Inverter-Based Grid-Connected Hybrid Renewable Energy System, Electrical and Computer Engineering, Canadian Conference Vol. 2, Issue, 2-5 May 2004, pp. 1081-1084, 2004.

[2] Jih-Sheng Lai. Power Electronics Applications in Renewable Energy Systems, Industrial Electronics Society, IECON, 2003.

[3] Detrick, A. Kimber, and Mitchell, A. Performance Evaluation Standards for Photovoltaic Modules & Systems, Proceedings of the 31st IEEE Photovoltaic Specialists Conference, Lake Buena Vista, FL, 2005 (in press).

[4] Armenta-Deu, C., Prediction of Battery Behaviour in SAPV Spplications, Renewable Energy 28, pp. 1671-1684, 2003.

[5] De Souza, K.C.A., Gonçalves, O. H., and Martins, D.C., Study and Optimization of two DC-DC Power Structures Used in a Grid-Connected Photovoltaic System, Power Electronics Specialists Conference, PESC06, pp. 1–5, 2006.

[6] Huang-Jen Chiu, Chun-Jen Yao., and Yu-Kang Lo, A. DC/DC Topology for Renewable Energy Systems, International Journal of Circuit Theory and Applications, Dec., 2007.

[7] Kjaer, S.B., Pedersen, J.K. and Blaabjerg, F.A. Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules, IEEE Trans. Ind. Elecs, Vol. 41, Sep., 2005.

[8] Xue, Y., Chen, Y. and Kjaer S.B. Topologies of Single-Phase Inverters for Small Distributed Power Generators: An Overview, IEEE Trans. Power Electron., Vol. 19, No. 5, pp. 1305-1314, Sept., 2004.

[9] Rodriguez, J., Lai, S. and Peng, F.Z. Multilevel Inverters: A Survey of Topologies, Control, and Applications. IEEE Trams on Ind Elect, Vol. 49 No. 4, pp. 724-738, 2002.

[10] Lai, J.S. and F.Z. Peng, F.Z. Multilevel Converters-A new Breed of Power Converters, IEEE Trans. Ind. Applicat., Vol. 32, pp. 509-517, May 1996.

[11] Peng, F.Z. and Lai, J.S. A multilevel Voltage-Source Converter with Separate DC Sources for Static Var Generation, IEEE Trans. Ind. Applicat., Vol. 32, pp. 1130–1138, Sept.-Oct. 1996.

[12] Peng, F.Z. and Lai, J.S. Dynamic Performance and Control of a Static Var Generator Using Cascaded Multilevel Converters, IEEE Trans. Ind. Applicat., Vol. 33, pp. 748–755, May-June 1997.

[13] Joós, G., Huang, X. and Ooi, O.T. Direct-coupled Multilevel Cascaded Series Var Compensators, IEEE Trans. Ind. Applicat., Vol. 34, pp. 1156–1163, Sept.-Oct.,1998.

[14] Cheng, Y. and Ooi, B.T. STATCOM Based on Multimodules of Multilevel Converters Under Multiple Regulation Feedback Control. IEEE Trans. Power Electron., Vol. 14, pp. 959–965, Sept. 1999.

[15] Tolbert, L.M. and Peng, F.Z. Multilevel Converters for Large Electric Drives. in Proc. IEEE APEC'98, Vol. 2, Feb. 1998, pp. 530–536.

[16] Huang, F., Lim, P.I. and Goh, E.K. A Variable Amplitude Multilevel Voltage Source Converter Used for Transient Power Sag Compensation, in Proc. EMPD, Vol. 2, Mar., 1998, pp. 737–740.

[17] Calais, M. et al. A Transformer-less Five Level Cascaded Inverter Based Single Phase Photovoltaic System, in Proc. IEEE PESC, Vol. 3, Galway, Ireland, June 2000, pp. 1173–1178.

[18] Carrara, G., Gradella, S., Maechesoni, M., Salutari, R. and Sciutto, G. A New Multilevl PWM Method: A Theoretical Analysis, IEEE Trans. On Powerelectronics, Vol. 7, No. 3, July 1992, pp. 497-505.

[19] Grahame Holmes, D., and Thomas Lipo, A. Pulse Width Modulation for Power Converters, IEEE Press Series on Power Engineering, Wiley Interscience, 2004.

[20] Loh, P.C., Vilathgamuwa, D.M., Lai, Y. S., Chua, G.T. and Li, Y. W. Pulse-Width Modulation of Z-source inverters.-IEEE Trans. Power Electron., Vol. 20, No. 6, pp. 1346–1355, Nov. 2005.

[21] Peng, F. Z. Z-Source Inverter. IEEE Trans. Ind. Appl., Vol. 39, No. 2, pp. 504–510, Mar/Apr. 2003.

[22] Peng, F.Z., Miaosen Shen., and Zhaoming Qian., Maximum Boost Control of the Z-Source Inverter. IEEE Trans on Power Electron, Vol. 20, No. 4, July 2005.