A Comparative Analysis of PWM Methods of Z-Source Inverters Used for Photovoltaic System

Babita Panda, Bhagabat Panda and P.K. Hota

Abstract The photovoltaic cell produces pollution less electricity. It requires almost no maintenance and has long lifespan. Nowadays, the photovoltaic is one of the most promising markets in the world because of these advantages. This paper demonstrates the dynamic model of single-stage three-phase impedance source inverter or Z-source inverter connected to grid. Here ZSI connected to PV is analyzed and designed. As the output of the PV array is very low, in order to commercialize and utilize this, the output voltage must be increased. So to boost up the voltage, Z-source inverter (ZSI) is used instead of VSI or CSI. Different pulse width modulation (PWM) techniques are used to provide pulses for PV connected Z-source converter (ZSI). After this, the final model is simulated using MATLAB/SIMULINK, and THD related to different output waveforms are analyzed for different parameters used.

Keywords PV system · Multidevice boost circuit (MDBC) · Z-source inverter (ZSI) · PWM techniques · MATLAB/Simulink software

1 Introduction

Non-conventional power plants constitute around 27.80% of total installed capacity and the remaining 72.20% is constituted by nonrenewable power plants. India produced around 967 TWh (967,150.32 GWh) of electricity (not including electricity generated from captive power plants and renewable plants) for 2013–2014

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period. On March 2013, the per capita consumption of electricity in India was 917.2 kWh. Renewable energy connected to grid capacity in India has reached 29.9 GW, of which wind constitutes 68.9%, while solar PV produces around 4.59% of the renewable energy installed capacity in India.

Dense population and high solar insolation are the two factors that provide a good compounding for generation of solar power in India. As majority regions of the country are not grid connected, the first program of solar power is water pumping. The photovoltaic cell produces pollution less electricity. It requires almost no maintenance and has long lifespan. Nowadays, the photovoltaic is one of the most promising markets in the world because of these advantages. Nevertheless, PV power is quite costly, and the reduction of cost of PV systems is contingent on wide research. From the standpoint of power electronics, this target can be reached by boosting up the output energy of a given PV array. This can be done by Impedance Source Inverter or Z-source inverter. Section 2 of this paper describes solar PV module, Sect. 3 describes about ZSI and its modes of operation. Section 4 describes about the different PWM techniques. Section 5 describes about Simulation model for different techniques and their results. Section 6 states about Conclusion of my work.

2 Solar PV System

Solar cells are the basic constituents of photovoltaic panels. Maximum solar cells are manufactured using silicon also other materials are employed. Solar cells have property of photoelectric effect: where some semiconductors have capability of changing electromagnetic radiation precisely to electrical current. The charged particles produced using incident radiation is distinguished smoothly to develop an electrical current by using suitable layout of the solar cell. The electricity generated by solar cell depends on the intensity of sunlight. When the incidence of sunlight is perpendicular to the front side of PV cell, the power generated by the solar cell is optimum. The large number of solar cells is combined in series and parallel to form PV array. A single solar cell can be modeled can using a diode, two resistor, and current source named as a single diode model of solar cell. Figure 1 represents the equivalent circuit diagram of photovoltaic system.

Fig. 1 Single diode model of a solar cell
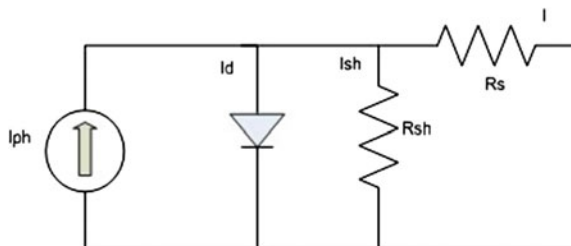
$$I_{PV} = N_P * I_{PH} - N_P * I_O * [\exp\{q * \frac{V + I_{PV} * Rs}{N_S * A * k * T}\} - 1])\tag{1}$$

$$I_O = I_{RS} * (\frac{T}{Tr})^3 * [\exp\{q * E_G * \frac{\frac{1}{T_R} - \frac{1}{T}}{A * k}\}]\tag{2}$$

$$I_{PH} = I_{SCR} + K_I * (T - T_R) * \frac{S}{1000}\tag{3}$$

$$I_{RS} = I_{SCR}/[\exp(q * V_{OC}/N_S * A * k * T) - 1]\tag{4}$$

where I_{Ph} is the light generated Current, I_d is the diode current, I_{sh} is the current through shunt resistance, R_s and R_{sh} represents series and shunt resistance, respectively. I_{pv} is the current at the output terminal, I_o is the reverse saturation current of diode, N_s is number of cells connected in series, N_P represents number of cells connected in series, q is the electron charge, k Boltzmann's constant and a the ideality factor modified, S represents the Irradiance. In MATLAB/SIMULINK the PV array is modeled by using these equations [1, 2].

The KC200GT solar is being chosen for modeling and simulation using MATLAB (Table 1) [3].

3 ZSI and Its Control Techniques

Impedance source inverter or Z-source inverter or Z-source converter is taken into consideration to overcome the limitations and barriers of traditional voltage source Inverters and Current Source Inverters [4]. The impedance network of ZSI couples the converter main circuit to power source, inverter or load of the circuit. It can perform both buck and boost operation. So it can be implemented for different forms of power conversions, i.e., from AC-to-AC, AC-to-DC, DC-to-AC, and DC-to-DC. The impedance network consists of two inductors L_1 and L_2 and two capacitors C_1 and C_2 and they are connected in X-shape [5]. This feature in case of inverter gives boosting of voltages. As the traditional VSIs and CSIs, it also have

Table 1 Specifications of PV Panel		
Temperature	25 °C
V_{OC}	32.9 V
I_{SC}	8.21 A
V_{MPP}	26.3 V
I_{MPP}	7.61 A
Maximum power, MPP	200.143 W
Temperature coefficient of I_{SC}	0.0032 A/K
Temperature coefficient of V_{OC}	−0.1230 V/K
N_s	54

six active states and two zero states, but it has seven more states known as shoot-through states which causes when both the upper and lower leg of a phase or more than one phase get shorted. ZSI operates in two states: shoot-through state and non-shoot-through state [6, 7]. This causes the buck or boost operation of the converter. In this paper, the ZSI is integrated with the PV array to get boosting of voltage from low input voltage (Fig. 2).

The boosting of voltages is carried out with the formula;

$$\hat{v}_s = M * B * V_{IN}$$
$$B = \frac{1}{1 - 2D_s} \tag{5}$$

where

B = boosting factor
D_s = shoot-through duty ratio
M = modulation index

The ZSI has three control methods [8] known as

(a) simple boost control
(b) constant boost control
(c) maximum boost control

In simple boost control, some part of the total zero state is converted into shoot-through state for voltage boost up. In case of maximum boost control the total zero state of the states are converted into shoot-through state which gives a result of maximum boosting of input voltage to the inverter [9].

The formulas followed for maximum boost controls are given below:

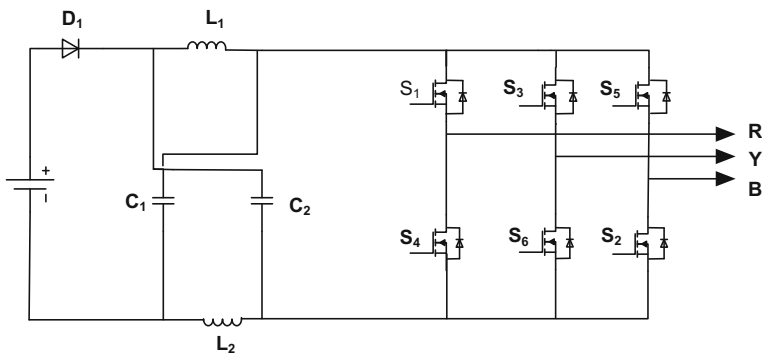For space vector analysis,

$$D_{sh} = 1 - \frac{2\sqrt{3}M}{\Pi} \tag{6}$$

Fig. 2 Impedance source inverter

For carrier-based analysis,

$$D_{sh} = 1 - \frac{3\sqrt{3}M}{2\Pi}$$

$$B = \frac{\Pi}{(3\sqrt{3}M) - \Pi}$$

$$(7)$$

In this paper, all the operations are done in maximum boost control as it gives better boost up than the simple boost control.

4 PWM Techniques

Following are some PWM techniques, which are carried out in maximum boost control for ZSI. Here both carrier-based PWM as well as space vector-based PWM techniques are discussed and also both conventional and some Advanced PWM techniques are implemented in both the cases [4, 10].

4.1 Carrier Based PWM Techniques

In carrier-based PWM techniques, for all the techniques, the carrier signal is a triangular signal and it is of a very high frequency compared to the modulating signal. The modulating signal is always a sine wave that has to be compared with the carrier signal to generate desired pulse, which is having the frequency same as fundamental frequency. The modulating signal gets changed by different carrier based techniques added with it at different modulation index. In this way, we get different desired PWM gate pulses from this technique. Below, some numbers of carrier-based techniques are discussed. They are as follows:

4.1.1 Sine-Triangle PWM (ST PWM)

In this type of PWM technique, the modulating signal is a sine wave and it gets compared with the carrier signal to generate pulse.

4.1.2 Third Harmonic Injected PWM (THI PWM)

Here the modulating signal or sinusoid signal is injected with another sinusoid signal which is called third harmonic injection and this signal is having frequency

exactly three times of it and having amplitude generally of one-sixth of it. Then the new modulating signal is compared with the carrier signal to get pulse [10].

4.1.3 Triplen-Injected PWM

Here the sinusoid modulating signal is injected with repeating signal which has different magnitude and time period according to the selection. This technique is somehow similar with the third Harmonic injected PWM technique.

4.1.4 Bus-Clamping 30° PWM and Bus-Clamping 60° PWM (BC 30° and 60° PWM)

Here each phase of the modulating sinusoid signal is clamped to one-one leg of DC bus terminal for a period of 30° and 60°, respectively, to create the desired modulated pulse. Then these new generated signals are compared with carrier signals and gate pulses are generated.

4.2 Space Vector-Based PWM Techniques

4.2.1 Conventional Space Vector PWM (CSVPWM)

In CSVPWM, the six active vectors are placed in such a way that they form a hexagon and they are apart from each other on 60° interval from the center. Two zero vectors are placed at the center. The area bounded by any two vectors is known as sector. They form six sectors. The reference vector is created from any two adjacent vectors applied for a particular time period. The switching sequence stars here from (0127-7210) for the first sector and likewise next sectors follow. In this way this technique works.

4.2.2 Bus-Clamping 30° and 60° PWM (BC 30° PWM and BC 60° PWM)

In Space Vector approach, the bus-clamping technique [10] is carried out as every phase of the inverter is clamped to one of the DC bus terminal for a duration of 30° and 60° for BC 30° and BC 60° PWM, respectively. In both the cases, each sector is divided into two subsectors. Thus, we get 12 numbers of subsectors. The switching sequence of these techniques are (012-210) and (721-127) for 30° and 60° clamping, respectively. Thus these techniques work accordingly.

5 Analysis of Simulation Result

Simulation studies are performed on PV ZSI implemented with all proposed PWM techniques in MATLAB/Simulink. The results obtained from the simulations are taken with some specific values of the parameters taken. Here the input voltage from the PV cell to the inverter is 100 V. For ZSI, the DC side inductors L1 and L2 are 37.5 µH, the capacitors values are as C1 = C2 = 470 µF and the AC-side three-phase load resistors are 200 Ω and inductors are 300 µH. In this topology the results from the experimental studies are taken as 0.8 modulation index for both carrier-based and space vector-based PWM techniques. Figure 3 shows the block diagram of the proposed system.

5.1 Simulink Block Diagram

The figure shows simulink block diagram of the proposed system. PV system is connected to Voltage source inverter through MDBC impedance source network. The RL load is connected at the output. A comparative analysis is made by using different PWM techniques to the voltage source inverter. The system is modeled in MATLAB/simulink environment (Fig. 4).

5.2 Wave Forms

Figures 5 and 6 show the line current and voltage waveforms of the proposed system when conventional space vector PWM technique is applied.
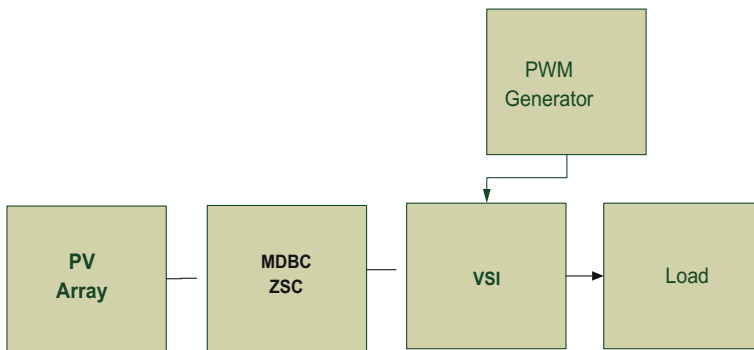

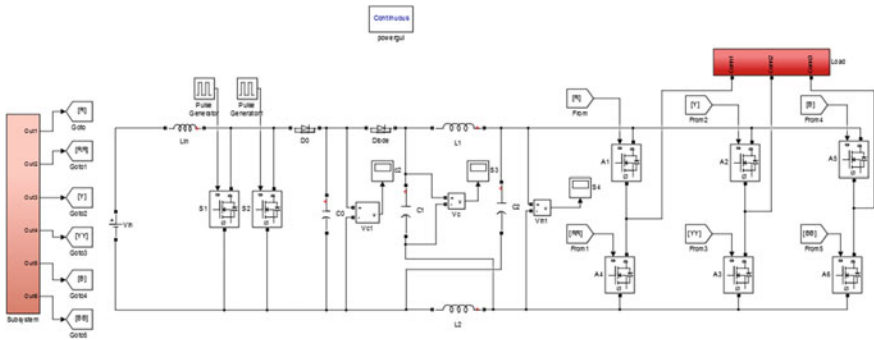**Fig. 3** Block diagram of the proposed system

Fig. 4 Simulink block diagram
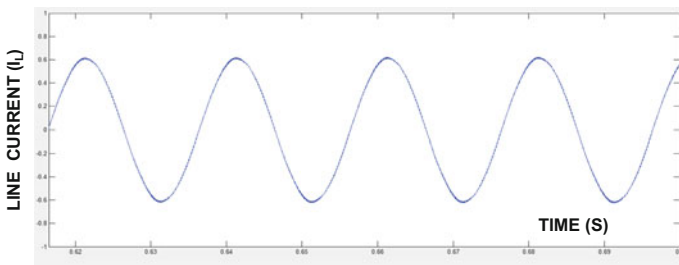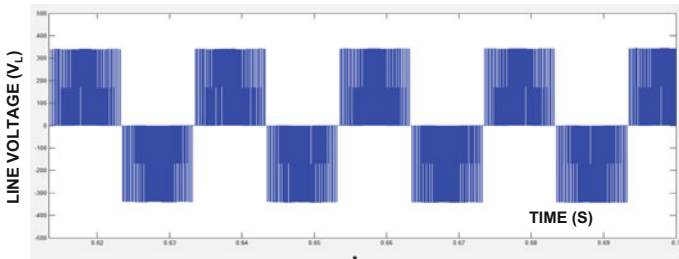

Fig. 5 Line current of ZSI with CSVPWM

Fig. 6 Line voltage of ZSI with CSVPWM

5.3 Summary

The THD analysis is made for different line voltage and current across the load for a particular modulating index, when PV is integrated with ZSI. It is observed that the proposed system gives less THD than the other system discussed by the authors [10]. Table 2 gives summarize report about the THD analysis.

Table 2 PV Array integrated space vector-based simulation results of conventional ZSI

	C-ZSI (Maximum boost control)			
Ma = 0.8	I_L (A)	THD (%)	V_L (V)	THD (%)
ST	0.627	0.57	240.2	71
THI	0.635	0.53	241.3	69.5
TRIPLEN	0.637	0.525	241.6	69.4
BC-30°	0.693	0.505	273	63.48
BC-60°	0.671	0.51	270.1	65.41
CSVPWM	0.625	0.61	240.7	75.2
BC-30°	0.66	0.55	255.4	68.8
BC-60°	0.642	0.58	0.58	71.6

6 Conclusion

In this paper, the ZSI is integrated with the PV array to get boosting of voltage from low input voltage. In all the cases the bus-clamping techniques are giving better results. In carrier-based techniques, the triplen-injected harmonic PWM and BC-30° and BC-60° PWM techniques are giving less THD compared to others. Among BC 30° and BC 60°, BC 30° gives better result. In case of space vector-based PWM techniques, the bus clamping 30° is giving the best output and less THD among the three proposed PWM techniques.

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