International Journal of Electrical Engineering.
ISSN 0974-2158 Volume 5, Number 5 (2012), pp. 587-601

http://www.irphouse.com

Z-Source Inverter with Minimization of Total Harmonic Distortion on Output Voltage for Photovoltaic Applications

U. Shajith Ali and V. Kamaraj

Department of EEE, SSN College of Engineering, Kalavakkam, Chennai-603 110, Tamil Nadu, India
E-mail: shajithali@ssn.edu.in, kamarajv@ssn.edu.in

Abstract

This paper proposes the use of Z-source inverter with a modified carrier based pulse width modulation technique for photovoltaic systems. In this modified technique, two carrier waves and three reference waves are used to produce the required switching pulses. This paper manifests that the Z-source inverter can boost DC voltage when needed, perform maximum tracking and minimum output distortion, and interface with photovoltaic system. The control method is analyzed to exhibit the novelty of features. The control algorithm is corroborated by simulation and experimental results. A comparison in harmonic distortion between the new and traditional pulse width modulation techniques is performed.

Keywords: Z-source inverter;Photovoltaic;Double Carrier PWM;Total harmonic distortion

Nomenclature

A	**:** Diode ideality factor
B	**:** Boost factor
d_s	**:** Shoot-through duty ratio
E_G	**:** Band-gap energy of the semiconductor
I	**:** Photovoltaic output current
I_p	**:** Photocurrent
I_s	**:** Saturation current of PV cell
I_{rs}	**:** Reverse saturation current

I_{sc}	: Short circuit current of PV cell
k	: Boltzmann's constant (=1.38x10^{-23}J/K)
K_i	: Cell's short circuit temperature coefficient
M	: Modulation index
N_p	: Number of cells connected in parallel
N_s	: Number of cells connected in series
q	: An electron charge (=1.6x10^{-19} C)
R_s	: Series resistance
R_{sh}	: Shunt resistance
THD	: Total harmonic distortion
T_o	: Shoot-through time period
T	: Switching time
T_c	: Cell's working temperature
T_{ref}	: Cell's reference temperature
V	: Photovoltaic output voltage
V_{ac}	: Output peak phase voltage
V_{oc}	: Open circuit voltage of PV cell
V_{off}	: DC offset voltage
V_t	: Peak of the carrier wave
V_s	: DC voltage across impedance network
VSI	: Voltage source inverter
ZSI	: Z-source inverter
λ	: Solar insolation

Introduction

The conventional fossil fuel energy sources such as petroleum, coal and natural gas which meet most of the world's energy demand today are being exhausted rapidly. The renewable energy sources are attracting more attention as an alternative energy. Among the renewable energy sources, the photovoltaic (PV) energy is being widely utilized because of the ubiquity, abundance and sustainability of solar radiant energy. These photovoltaic cells or solar cells directly use the energy from the sun to generate electricity. In PV based power conditioning systems, the interface converter system acts as a key component. Presently, the voltage source inverter (VSI) is employed as the interfacing converter. But there are several disadvantages of such an inverter: a) It is only a buck converter for DC-AC power conversion. When the PV array voltage is lower than the required AC voltage, an additional DC-DC boost converter is needed to obtain the desired AC output. The additional boost converter increases the system cost and reduces the overall efficiency. b) The two switches from the same arm of the inverter cannot be gated on simultaneously. Otherwise, a shoot-through will destroy the devices. c) Dead-time must be employed, which will cause output current distortion.

Z-source inverters (ZSI) have been recently proposed as an alternative power conversion concept, which overcome the above-mentioned disadvantages of voltage source inverter. Fig.1. shows the main circuit of the Z-source inverter. It employs a unique impedance network coupled between the power source and the converter circuit that consists of a split-inductor L_1 and L_2 and capacitors C_1 and C_2 connected in X shape. This unique impedance network allows the Z-source inverter to buck or boost its output voltage, and also provides it with unique features that cannot be achieved in voltage source inverters [1]-[2].

Many pulse-width modulation (PWM) control methods have been developed and used for the traditional three phase voltage source inverter. The traditional VSI has six active vectors when the dc voltage is impressed across the load and two zero vectors when the load terminals are shorted through either the lower or upper three devices. These total eight switching states and their combinations have spawned many PWM control schemes. On the other hand, Z source inverter has additional zero vectors or shoot-through switching states that are forbidden in the traditional VSI, both switches of any phase leg can never be gated on at the same time or a short circuit (shoot through) would occur and destroy the inverter. The new Z-source inverter (ZSI) advantageously utilizes the shoot through state to boost the dc bus voltage by gating on both upper and lower switches of a phase leg and produce a desired output voltage that is greater than the available dc bus voltage [3]. In addition the reliability of the inverter is greatly improved because the shoot through due to misgating can no longer destroy the circuit. Thus it provides a low-cost, reliable, and high efficiency single stage structure for buck and boost power conversion.

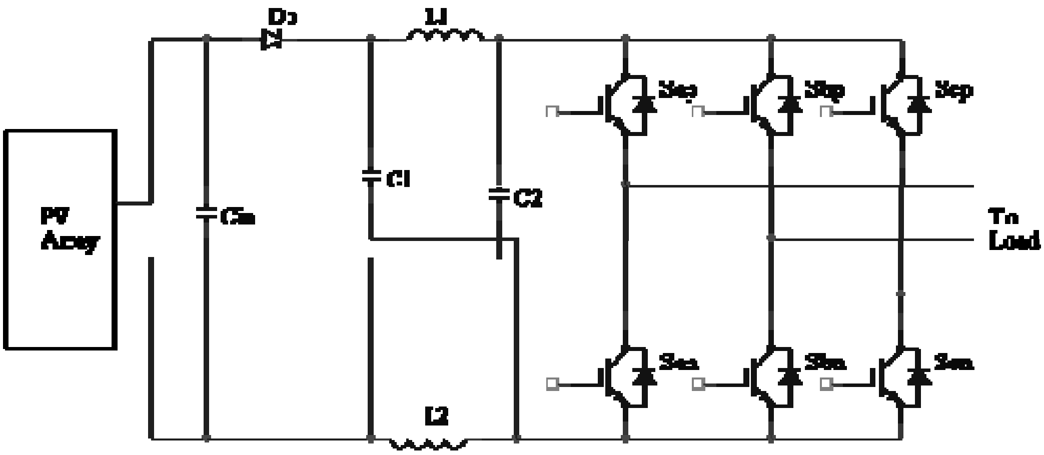

Figure 1: Z-Source inverter

In [1], the operation principle and the shoot through duty ratio control using simple boost control method have been described in detail. In this paper, a new carrier based PWM technique is proposed for the Z-source inverter which lowers the distortion in the output AC voltage.

Traditional PWM Techniques for Z-Source Inverter

For an output voltage boost to be obtained, a shoot-through state should always be followed by an active state, i.e., shoot through states should be incorporated without affecting the active states. Thus, minor modifications in the traditional three phase sinusoidal PWM technique will yield various PWM control strategies for the ZSI. There are three traditional PWM control strategies for ZSI. They are simple boost control, maximum boost control, and maximum constant boost control methods.

Simple Boost PWM

The simple boost control method employs two straight envelops equal to or greater than the peak value of the three phase sinusoidal reference signals to control shoot-through duty ratio in a traditional sinusoidal PWM. The circuit is in shoot through state when the high frequency triangular carrier is greater than the upper straight line envelope or lesser than the lower straight line envelope. In this method the voltage stress across the switches is quite high, which restrict the obtainable voltage gain because of the limitation of device voltage rating. As during shoot through all the switches are ON, switching losses are high.

Maximum Boost PWM

The maximum boost control is quite similar to the traditional carrier-based PWM control method, but this control method maintains the six active states unchanged and turns all zero states into shoot through zero states. The circuit is in shoot through state when the triangular carrier wave is greater than the maximum curve of the reference or lesser than the minimum curve of the reference. This method turns all the zero states into shoot through state thus minimizing the voltage stress across the switches. However it causes shoot through duty ratio to vary in each cycle, thus increasing the ripple content in inductor current. When the output frequency is low, the inductor ripple becomes significant and a large inductor is required. This increases the cost and size of the circuit [4].

Maximum Constant Boost PWM

In maximum constant boost control method the straight envelops of simple boost control method are replaced by two sinusoidal signals of three times the frequency of sinusoidal modulating signals. Thus this method involves three reference sinusoidal signals and two shoot through envelopes. The circuit enters shoot through state whenever the high frequency triangular wave is greater than the upper shoot-through envelope or lesser than the lower shoot-through envelope [5]. This method achieves maximum boost while keeping shoot through duty ratio constant all the time, thus reducing ripple content in inductor current compared to maximum boost control method.

Proposed Double Carrier PWM Technique

This method employs three phase sinusoidal reference signals, V_a, V_b, and V_c and two triangular waves of high frequency as carrier signals. One of the carrier wave is with zero dc offset value whereas the other carrier wave is up-shifted to certain dc offset voltage (V_{off}) to control shoot through duty ratio. Gating pulses which are obtained by comparing lower triangular wave (with zero dc offset) and reference wave is given to the upper leg devices of inverter circuit, whereas the pulses obtained by comparing upper triangular wave and reference wave is inverted and given to the lower leg devices of inverter circuit [6]. Fig.2. shows double carrier control waveforms.

In the other control methods modulation index has to be minimum to get maximum boost factor. But the voltage stress increases with minimum modulation index. This limitation is eliminated in the newly proposed double carrier control method.

This control method has the following features over the other traditional control methods

- Unlike other methods, the boost factor is made independent of the modulation index.
- Number of shoot through states per cycle of carrier wave is increased when compared to other methods.
- Switching loss is reduced as only one of the phase legs is gated during shoot through states.
- It involves alternative active state and shoot through state and no zero states. Hence, it reduces the ripple content in inductor current.
- The voltage stress across the switches is reduced as modulation index could be kept high.
- This method enhances the fundamental voltage by reducing the total harmonic distortion.

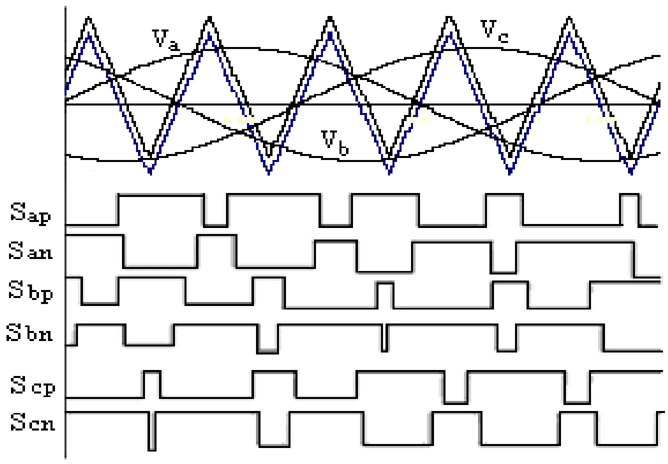

Figure 2: Double carrier PWM waveforms

Given its many benefits, this paper now examines the relationship of voltage boost and dc offset voltage.

As described in [1], the voltage gain of the Z-source inverter can be expressed as,

$$\frac{V_{ac}}{V_s/2} = MB \tag{1}$$

B is determined by

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

$T_o / T = d_s$ is the shoot through duty ratio.

In double carrier control method, shoot through duty ratio is varied by varying the dc offset voltage and is derived as

$$d_s = \frac{V_{off}}{V_t} \tag{3}$$

Unlike other traditional control methods, in double carrier control the duty ratio depends only on the dc offset voltage and hence completely independent of the modulation index. In this method of control to get finite voltage gain, d_s should be less than 0.5.

Photovoltaic Array and MPPT

PV cell is basically a p-n junction fabricated in a thin wafer or layer of semiconductor. The electromagnetic radiation of solar energy can be directly converted electricity through photovoltaic effect. The simplest equivalent circuit of a PV cell consists of a photo current (I_p), a diode (D_j), a parallel resistor (R_{sh}) expressing a leakage current, and a series resistor (R_s) describing an internal resistance to the current flow, is shown in Fig.3.

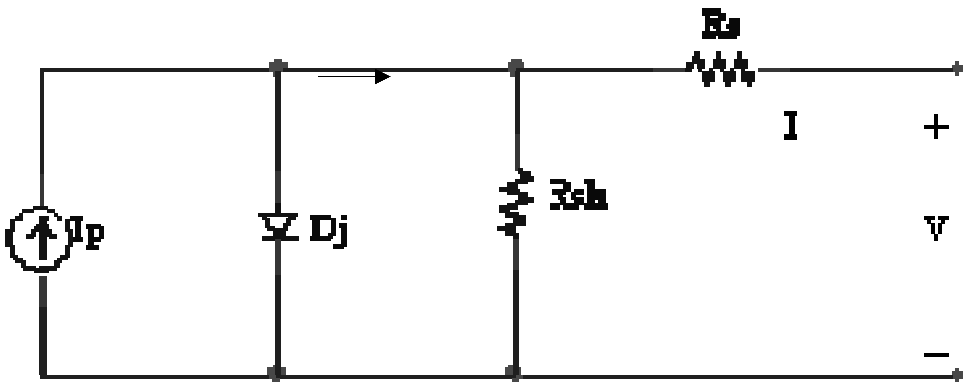

Figure 3: Equivalent circuit of a PV cell

Since a typical PV cell produces less than 2W at 0.5V approximately, the cells must be connected in series-parallel configuration on a module to produce enough high power. A PV array is a group of several PV modules which are electrically connected in series and parallel circuits to generate the required current and voltage. PV system naturally exhibits a non-linear I-V and P-V characteristics shown in Fig.4. which vary with the radiant intensity and cell temperature.

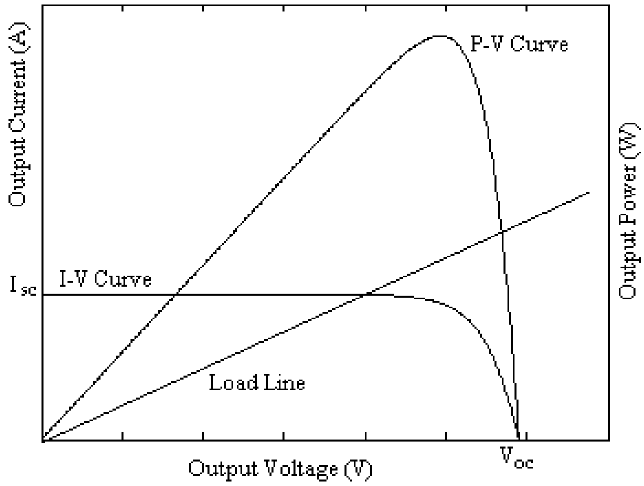

Figure 4: Typical I-V and P-V characteristics of PV

The voltage-current characteristic equation of the array becomes as follows:

$$I = N_p I_p - N_p I_s (\exp\left[q\left(\frac{\frac{V}{N_s}+\frac{IR_s}{N_p}}{kT_c A}\right)\right] - 1) - \left(\frac{\frac{N_p V}{N_s}+IR_s}{R_{sh}}\right) \tag{4}$$

The photo current mainly depends on the solar radiant intensity and cell's temperature, which is given as

$$I_p = [I_{sc} + K_i (T_c - T_{ref})]\lambda \tag{5}$$

The cell's saturation current varies with cell temperature is described as

$$I_s = I_{rs}\left(\frac{T_c}{T_{ref}}\right)^3 \exp\left[\frac{qE_G\left(\frac{1}{T_{ref}}-\frac{1}{T_c}\right)}{kA}\right] \tag{6}$$

Since the Z-source inverter based PV power system is directly connected to the load, the PV power system is controlled to transfer maximum power from the PV array to the load circuits continuously. Because of the non-linear characteristics of PV modules, the maximum power cannot be achieved by directly connecting the PV models. Tracking of the maximum power point (MPP) must be used to effectively get the maximum output power [7]-[9]. Here the simple perturbation and observation method of MPP tracking is used.

Simulation and Experimental Results

A typical 42W PV module is taken for modeling. The module has 36 series connected polycrystalline cells. The key specifications of the module at a reference temperature of 25^{o}C are listed in Table I.

Table 1: Specifications of PV module

Characteristics	**SPECIFICATION**
Open circuit voltage (V_{oc})	21.6 V
Short circuit current (I_{sc})	2.55 A
Voltage at Peak Power (V_{pp})	17.8V
Current at peak Power (I_{pp})	2.35A
Peak power (P_{max})	42W

The model of the PV module is implemented using a Matlab program. The developed model takes solar insolation and cell temperature as input parameters and outputs the I-V and P-V characteristics under various conditions. Fig.5. and Fig.6. show I-V and P-V characteristics of the PV module with various solar insolation and temperatures.

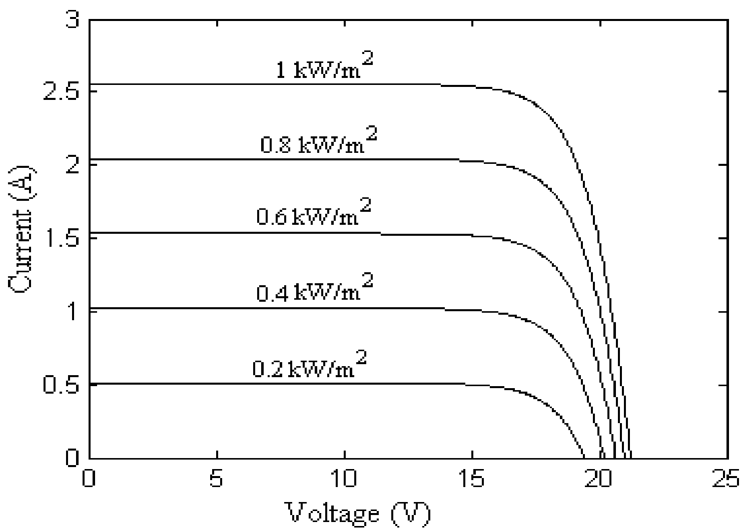

Figure 5 (a): I-V output characteristics of PV module with different solar insolation

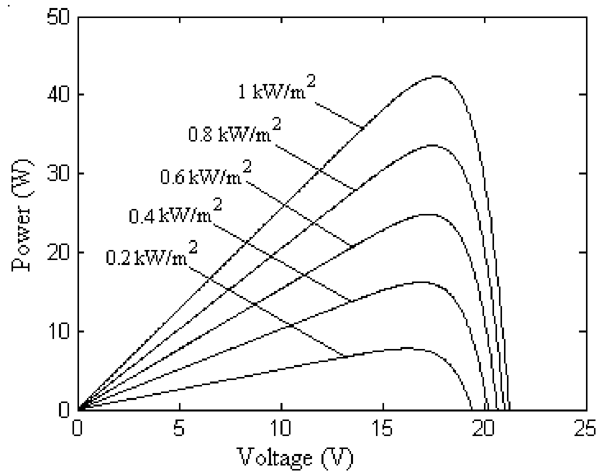

Figure 5(b): P-V output characteristics of PV module with different solar insolation

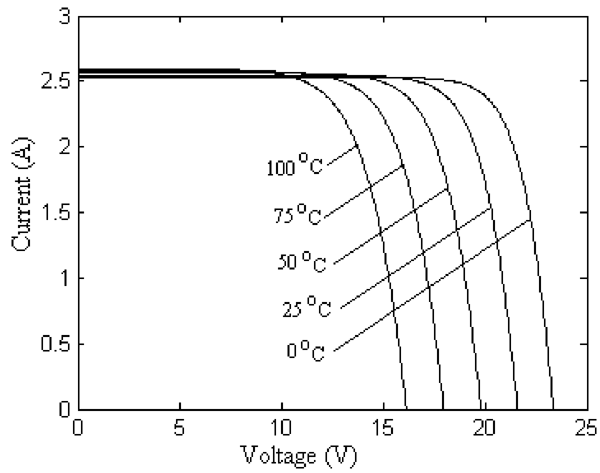

Figure 6(a): I-V output characteristics of PV module with different temperature

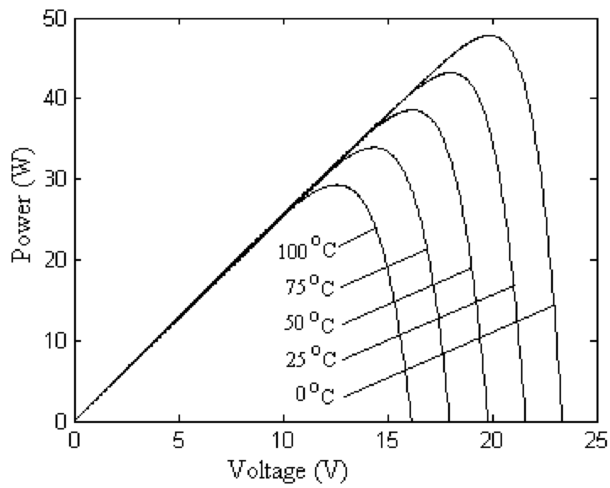

Figure 6(b): P-V output characteristics of PV module with different temperature

The photovoltaic output voltage changes mainly with temperature, while the photovoltaic output current changes mainly with insolation. When the temperature rises, the PV output power decreases with a constant insolation. With constant temperature specified, the PV output power increases when the insolation increases. Thus the main function of the interfacing the Z-source inverter is to extract the maximum power out of the PV at any given temperature and insolation. In the Z-source inverter, the output voltage can be controlled to the desired level by controlling the shoot-through time period. Thus the shoot-through state is used to control the MPPT.

The Z-source inverter interfacing the PV is developed in Matlab/Simulink. In this paper, four numbers of PV modules are connected in series to make a PV array, which acts as the DC source to the Z-source inverter. The inductors in the impedance network limit the current ripple through the devices during boost mode with shoot-through. The capacitors in the impedance network absorb the voltage ripple and maintain a reasonably constant voltage across the bridge [10]. For both simulation and experiments, the impedance network elements are designed with the following values: $L_1=L_2=3mH$ and $C_1=C_2=1000\mu F$. The switching frequency is 5 kHz and the fundamental frequency is 50Hz. The semiconductor devices in the inverter bridge are selected based on the current through them and the maximum voltage across them. Here IGBTs are taken as the switching devices. The complete system is simulated and the output voltage and current waveforms are shown in Fig.7.

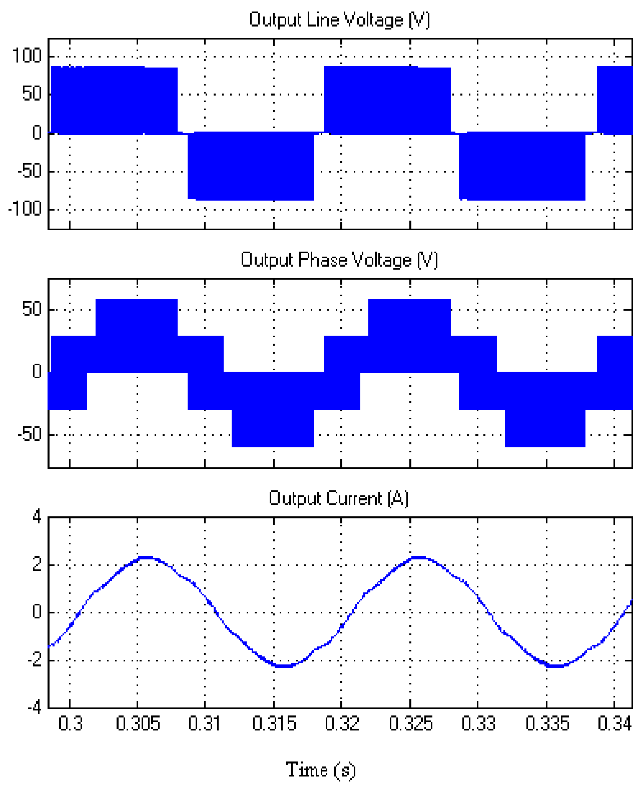

Figure 7: Simulation waveforms

Harmonic analysis on the output voltage is performed and the total harmonic distortion is calculated as 6.82%. Harmonic spectrum of output phase voltage is shown in Fig.8.

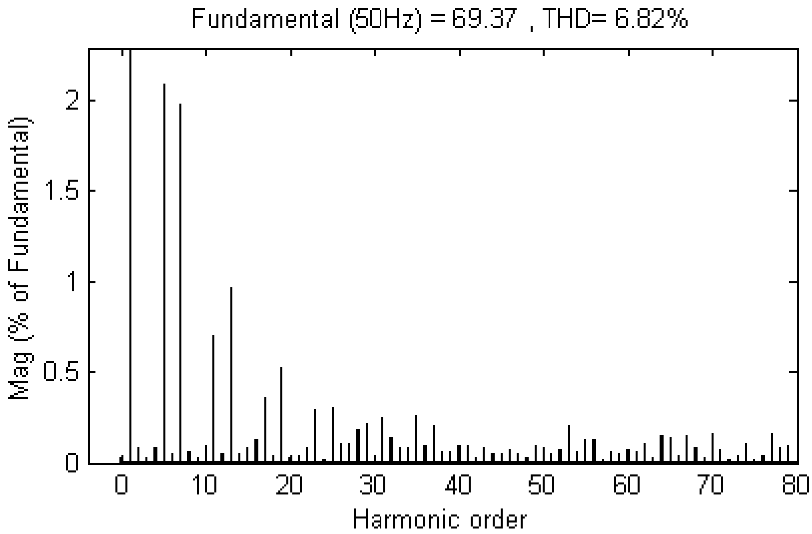

Figure 8: Harmonic spectrum of output phase voltage

A laboratory model of Z-source inverter is constructed (Fig.9.). The same parameters used in simulation are used. Fig.10. and Fig.11. show experimental results. The firing pulses for the two switches in one phase leg of the Z-source inverter are shown in Fig.10. The output line-to-line voltage is shown in Fig.11.

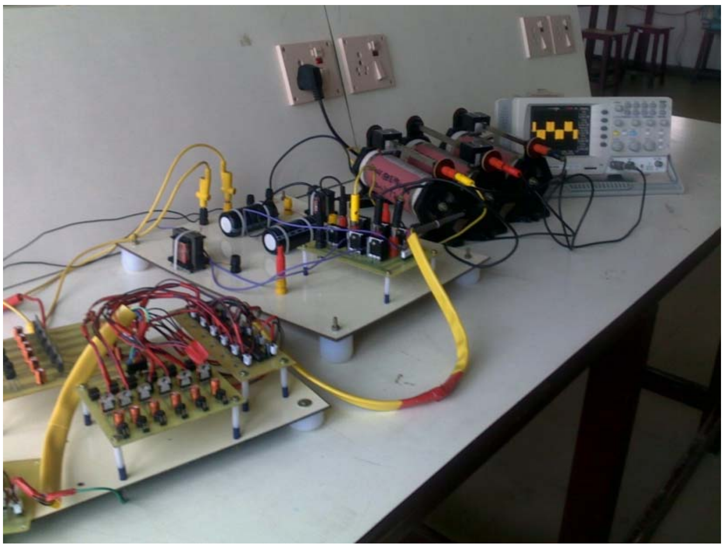

Figure 9: Experimental setup

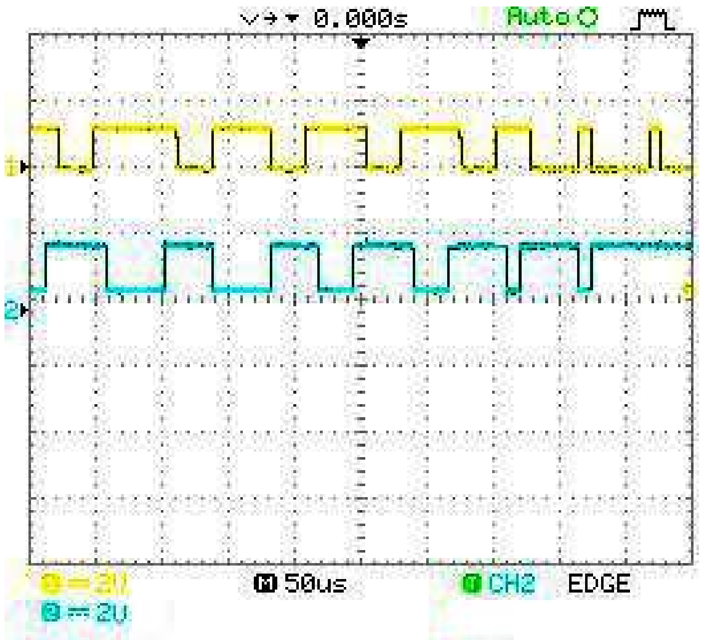

Figure 10: Switching pulses obtained in experiment

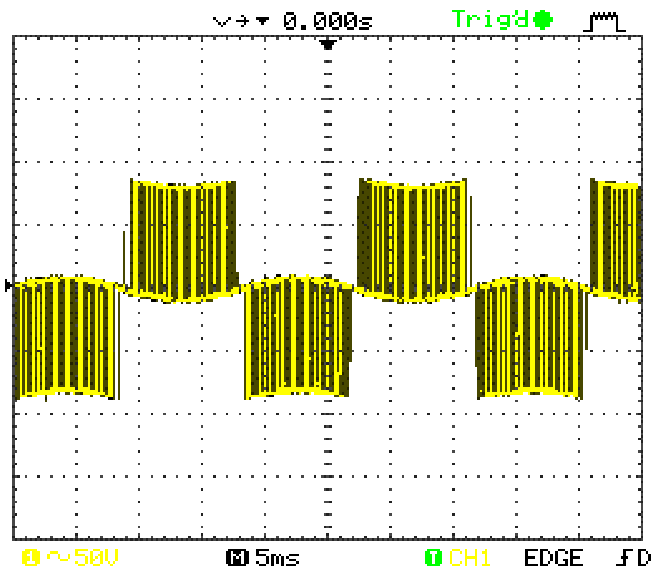

Figure 11: Experimental output line voltage waveform

Fig.12 shows the experimental harmonic spectrum of the output line voltage of the Z-source inverter.

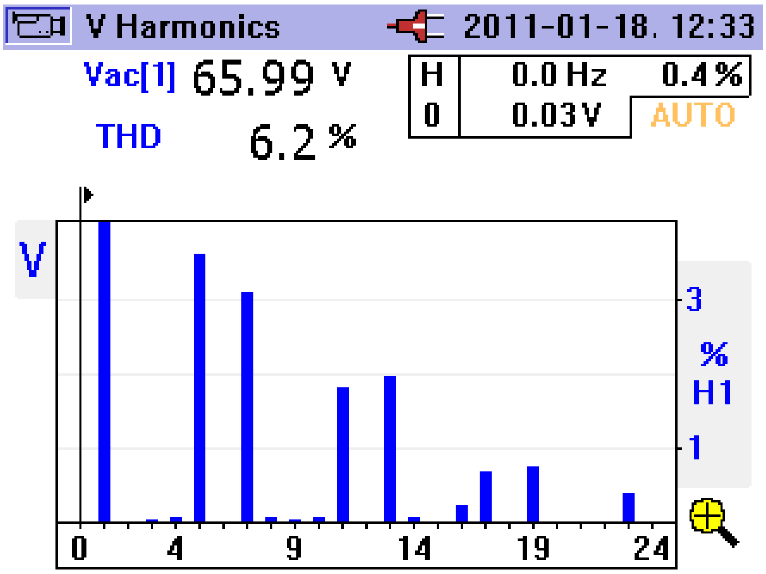

Figure 12: Harmonic spectrum of output phase voltage

In this double carrier PWM, there are six shoot-through states distributed in a switching cycle, whereas in other traditional PWM techniques only two shoot-through states are inserted in a switching cycle. So in the proposed PWM technique, the switching frequency viewed from the impedance network is very high. It reduces distortion in the output waveforms. The variation of THD on the output voltage with the voltage gain for the traditional and proposed PWM methods are analyzed. The comparison is shown in Fig.13. Since all the zero states are converted into shoot-through states, the high value of voltage gain can also be achieved.

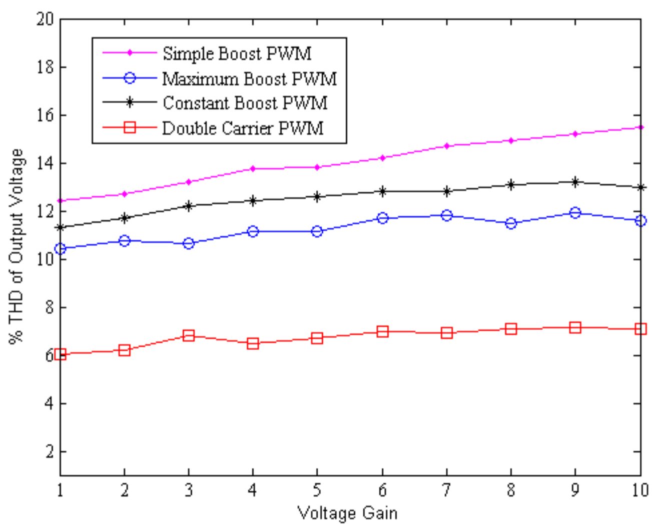

Figure 12: THD comparison of all PWM methods

Conclusion

Z-source inverter with a new modulation technique is proposed. In this new technique, more shoot-through states are inserted during the carrier wave period, and offer a better boost factor and lowers distortion. By controlling the DC offset voltage, the shoot-through duty cycle and hence the PV array output voltage is controlled and the maximum power point tracking is achieved. So the proposed system substantiates the boost and inversion in single stage with maximum power tracking and minimum harmonic distortion. Theoretical analysis and control algorithm are presented in this paper. The photovoltaic array is modeled and developed in the Simulink environment. Using Matlab/Simulink software package the Z-source inverter with the PV is simulated to verify the proposed algorithm. The frequency spectrum and the total harmonic distortion of the output voltages are obtained. Also the presented concepts are verified experimentally using a laboratory prototype. A comparison is made in the THD of the output voltage between the new control and traditional control methods. The results show that the new proposed double carrier PWM technique gives minimum THD. So the proposed control is very promising for photovoltaic applications.

References

[1] F. Z. Peng, 2003, “Z-Source Inverter,” IEEE Transactions on Industry Applications, 39(2), pp.504–510.
[2] Yi Huang, Miaosen Shen, F.Z.Peng and Jin Wang, 2006, “Z-Source Inverter for Residential Photovoltaic Systems,” IEEE Transactions on Power Electronics, 21(6), pp.1776-1781.
[3] Poh Chiang Loh, D. M. Vilathgamuwa, Y. S. Lai, G. T. Chua and Y. W.Li, 2005, “ Pulse-width modulation of Z-source inverters,” IEEE Transactions on Power Electronics, 20, pp. 1346-1355.
[4] Fang Zheng Peng, M. Miaosen Shen, Z. Qian,2005, “Maximum Boost Control of the Z-source Inverter,” IEEE Transactions on Power Electronics, 20(4), pp. 833–838.
[5] Miaosen Shen, Jin Wang, Alan Joseph, Fang Zheng Peng, Leon M.Tolbert, D.J.Adams, 2006, “Constant Boost Control of the Z-Source Inverter to Minimize Current Ripple and Voltage Stress,” IEEE Transactions on Industry Applications, 42(3), pp.770-778.
[6] U.Shajith Ali and V.Kamaraj, 2011, “Double Carrier Pulse Width Modulation Control of Z-Source Inverter,” European Journal of Scientific Research, 49(2), pp.168-176.
[7] Eftichios Koutroulis, Kostas Kalaitzakis, and Nicholas C. Voulgaris, 2001, “Development of a microcontroller-based, photovoltaic maximum power point tracking control system,” IEEE Transactions on Power Electronics, 16(1), pp. 46–54.

[8] Yeong-Chau Kuo, Tsorng-Juu Liang, and Jiann-Fuh Chen,2001, "Novel maximum-power-point tracking controller for photovoltaic energy conversion system," IEEE Transactions on Industrial Electronics, 48(3), pp. 594–601.

[9] Mummadi Veerachary, Tomonobu Senjyu, and Katsumi Uezato,2002, "Voltage-Based Maximum Power Point Tracking Control of PV Systems," IEEE Transactions on Aerospace and Electronic Systems, 38(1), pp.262-270.

[10] Sumedha Rajakaruna, and Laksumana Jayawickrama, 2010, "Steady-State Analysis and Designing Impedance Network of Z-Source Inverters," IEEE Transactions on Industrial Electronics. 57 (7) pp.2483-2491.

[11] Miaosen Shen, F.Z.Peng., 2008, "Operation Modes and Characteristics of the Z-source Inverter with small inductance or Low Power Factor," IEEE Transactions on Industrial Electronics, 55(1), pp.89-96