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Quasi-Z-Source Inverter with Enhanced Voltage Gain for Photovoltaic Power Generation

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Abstract— A quasi-Z-source inverter with a novel carrier based pulse width modulation (PWM) scheme is proposed for photovoltaic power generation systems. In this new technique, a high frequency sine wave is employed as carrier waveform instead of the conventional triangular wave in the simple boost technique. This increasess the shoot-through duty cycle for the given modulation index and hence the voltage gain. This paper manifests that the quasi-Z-source inverter employing this new PWM can boost DC voltage to the desired level and working as a power conditioning system to achieve the maximum power from photovoltaic array. The proposed control scheme is analyzed to exhibit the novelty of features. The control algorithm is affirmed by simulation and experimental results.

Index Terms— MPPT, Photovoltaic, Pulse Width Modulation, Quasi-Z-source Inverter, Shoot-through, Sine Carrier, Total Harmonic Distortion.

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1 Introduction

THE evolution of renewable energy is being increased because of the increasing price of fossil fuels and the growing problem of global warming and other environmental issues. With greater research, alternative renewable energy sources such as wind, water, bio-mass, geothermal and solar energy have been explored for electric power generation. Among the renewable energy sources, the solar energy is being widely utilized because of the free fuel, abundance, little maintenance and sustainability of solar radiant energy. Electrical energy is directly generated from the solar energy through the photovoltaic (PV) cells. In PV based power conditioning systems, the interface converter system acts as a key component. The voltage source inverter (VSI) is employed as the interfacing converter conventionally. But there are several drawbacks 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 necessitated to incur the desired AC output. This additional boost converter raises the cost and reduces the overall efficiency of the system. b) The two switches from the same leg of the inverter cannot be turned on simultaneously. Otherwise, a short circuit will destroy the devices. c) Dead-time must be employed, which will cause output current distortion [1], [2].

Both Z-source inverter (ZSI) and quasi-Z-source inverter (QZSI) overcome these drawbacks; by utilizing several shoot-through zero states, in which two switches in the same leg are gated on simultaneously to boost the output voltage. Sustaining the six permissible active switching states of a VSI, the zero states can be partially or completely replaced by the shoot-through states depending on the desired voltage boost.The QZSI circuit differs from that of a conventional ZSI in the LC impedance network interface between the source and inverter. QZSIs acquire all the advantages of traditional Z-source inverter. Fig.1 shows the basic topology of QZSI. The QZSI extends several advantages over the ZSI such as continuous input current, reduced component ratings, and enhanced reliability [3], [4]. These advantages make the QZSIs suitable for power conditioning in renewable energy systems.

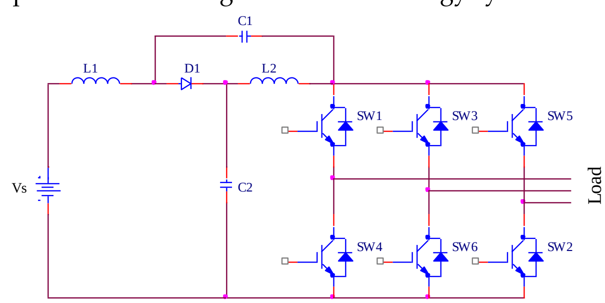

Fig. 1. Quasi-Z-source inverter

Like ZSIs, QZSIs have shoot-through and non-shoot-through modes of operation. In the non-shoot through mode, the switching pattern for the QZSI is similar to that of a VSI. The inverter bridge, viewed from the DC side is equivalent to a current source. In the shoot through mode, switches of the same phase in the inverter bridge are switched on simultaneously for a very short duration. The source however does not get short circuited when attempted to do so because of the presence LC network while boosting the output voltage. In the active states, the input dc voltage is available as DC link voltage input to the inverter, which makes the QZSI behave similar to a VSI. During the shoot through states, the DC link voltage is boosted by a boost factor, whose value depends on the shoot through duty ratio for a given modulation index.

The output voltage and frequency are controlled by the pulse width modulation (PWM) techniques in inverters. Many PWM control methods have been developed and used for the traditional three phase voltage source inverter. The conventional 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

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devices. The combinations of these active and zero vectors have spawned many PWM control schemes [5], [6]. On the other hand, QZSIs have additional zero vectors or shoot-through switching states that are forbidden in the traditional VSI, upper and lower 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 QZSI advantageously utilizes the shoot through state to boost the dc bus voltage by turning 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 [7]. This increases the reliability of the inverter greatly because unintentional shoot through due to misgating can no longer destroy the circuit. Thus it renders a high efficiency, low-cost, and reliable single stage structure for buck and boost power conversion.

2 Traditional PWM Techniques

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/QZSI [8], [9], [10], [11], [12]. There are three traditional PWM control strategies for ZSI/QZSI. They are simple boost control, maximum boost control, and maximum constant boost control methods.

2.1 Simple Boost PWM

This is the simplest technique in QZSIs, employing 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 sine PWM. Whenever the high frequency triangular carrier is greater than the upper straight line envelope or lesser than the lower straight line envelope the circuit is applied the shoot-through states. This technique has the drawback of high voltage stress across the switches, which restrain the obtainable voltage gain because of the limitation of device voltage rating. Further, all switches remain ON during shoot through time period, switching losses are high [1].

2.2 Maximum Boost PWM

The maximum boost control is quite similar to the normal carrier-based PWM control method, but turns all zero states into shoot through zero states without the six active 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 [9]. 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.

2.3 Maximum Constant Boost PWM

Here, 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 [10]. 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.

3 Proposed Sine Carrier PWM

A PWM control technique for QZSI, with modified carrier for active and shoot through states is presented. While the zero states of traditional VSI are replaced by shoot through states, the active states should remain unaltered, for the shape of output voltage waveform to be preserved. This technique uses output frequency sine wave reference and a high frequency sine wave as carrier. The simple boost control method used here employs two constant voltage envelopes which are compared with the sine carrier wave. Whenever the magnitude of sine carrier wave becomes greater than or equal to the positive constant magnitude envelope (or) lesser than or equal to the negative constant magnitude envelope, pulses are generated and they control the shoot through duty ratio D_o. These pulses, combined with the pulses generated by sine carrier sinusoidal PWM, serves as firing signals for the switches in the inverter. Fig. 2 illustrates the arrangement of sine carrier PWM. The dc-link (peak) voltage across the inverter bridge is boosted by a factor B during shoot through state.

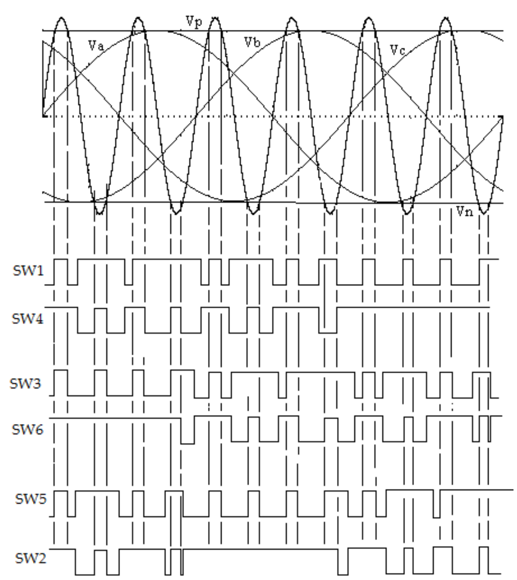

Fig. 2. Illustration of sine carrier PWM

Therefore the voltage gain G of QZSI is given by,

$$G = \frac{\text{Output peak AC voltage}}{\text{DC link voltage}} \quad (1)$$

$$V_{link} = \frac{V_s}{2} \quad (2)$$

$$V_{ac} = MB\frac{V_s}{2} \quad (3)$$

Where V_{link} is the DC link voltage of inverter

V_{ac} is the peak ac output voltage, B is the boost factor and M is modulation index

The boost factor is given by,

$$B = \frac{T}{T_1 - T_0} = \frac{1}{1 - 2\frac{T_0}{T}} = \frac{1}{1 - 2D_0} \quad (4)$$

where D_o is the shoot through duty ratio of QZSI T_o is the shoot through interval T is the switching cycle.

When a triangular carrier is employed, the shoot through duty ratio, boost factor and voltage gain are given as

$$D_o = 1 - M \quad (5)$$

$$B = \frac{1}{2M - 1} \quad (6)$$

$$G = \frac{M}{2M - 1} \quad (7)$$

It can be seen that improvement in duty ratio can be achieved only by reduction in M, which limits the gain and leads to more voltage stress on the switch. By implementing sine carrier PWM, the shoot through ratio, the boost factor and voltage gain of QZSI are derived as

$$D_o = \frac{T_0}{T} = 1 - \frac{2}{\pi}\sin^{-1} M \quad (8)$$

$$B = \frac{\pi}{4\sin^{-1} M - \pi} \quad (9)$$

$$G = \frac{\pi M}{4\sin^{-1} M - \pi} \quad (10)$$

It is observed that sine carrier PWM gives high shoot through duty ratio compared to triangular carrier, for the same modulation index, which reduces the voltage stress on the device and gives high peak output voltage. The comparison of voltage gain of all the PWM methods is illustrated in Fig. 3. The simple boost control method has shoot through states spread uniformly which makes output free of low frequency ripples. The use of sine carrier wave has also resulted in reduction of THD in output voltage, improved fundamental component.

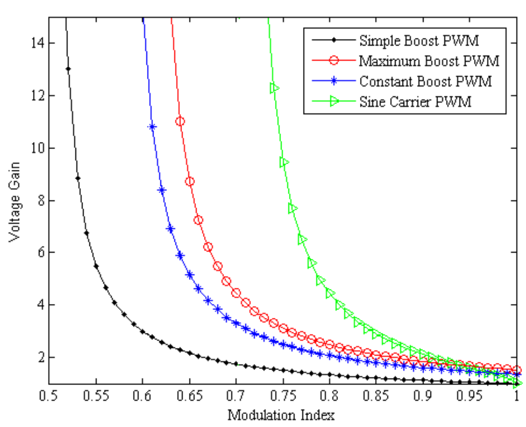

Fig. 3. Voltage gain vs modulation index

4 Photovoltaic Array and MPPT Algorithm

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 [13]. The simplest equivalent circuit of a PV cell consists of a photo current (Ip), a diode (Dj), 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. 4.

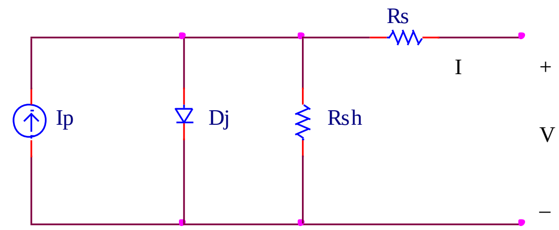

Fig. 4. Equivalent circuit of a PV cell

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. 5 which vary with the radiant intensity and cell temperature.

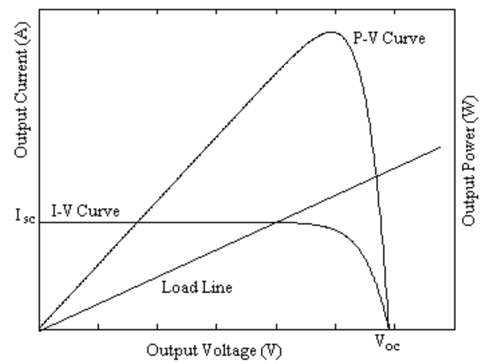

Fig. 5. Typical I-V and P-V characteristics of PV

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

$$I = N_p I_p - N_p I_s (\exp\left[q\left(\frac{\frac{V}{N_s} + \frac{IR_s}{N_p}}{kT_c A} \right) \right] - 1) - \left(\frac{\frac{N_p V}{N_s} + IR_s}{R_{sh}} \right) \quad (11)$$

where I_p is the photocurrent, I_s is the saturation current of photovoltaic cell N_p is the number of cells connected in parallel, N_s is the number of cells connected in series, q is the charge of an electron, R_s is series resistance, R_{sh} is the shunt resistance, k is Boltzmann's constant, T_c is the cell's working temperature, and A is diode ideality factor.

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

$$I_p = [I_{sc} + K_i (T_c - T_{ref})]\lambda \quad (12)$$

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where I_{sc} is the short circuit current of photovoltaic cell, K_i is the cell's short circuit temperature coefficient, T_{ref} is the cell's reference temperature and λ is the solar irradiation.
The cell's saturation current varies with cell temperature is described as

$$I_s = I_{rs}\left(\frac{T_c}{T_{ref}}\right)^3 \exp\left[\frac{qE_G\left(\frac{1}{T_{ref}}-\frac{1}{T_c}\right)}{kA}\right] \quad (13)$$

where E_G is the band-gap energy of the semiconductor.

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 [14], [15], [16], [17]. Here the simple perturbation and observation method of MPP tracking shown in Fig. 6 is applied.

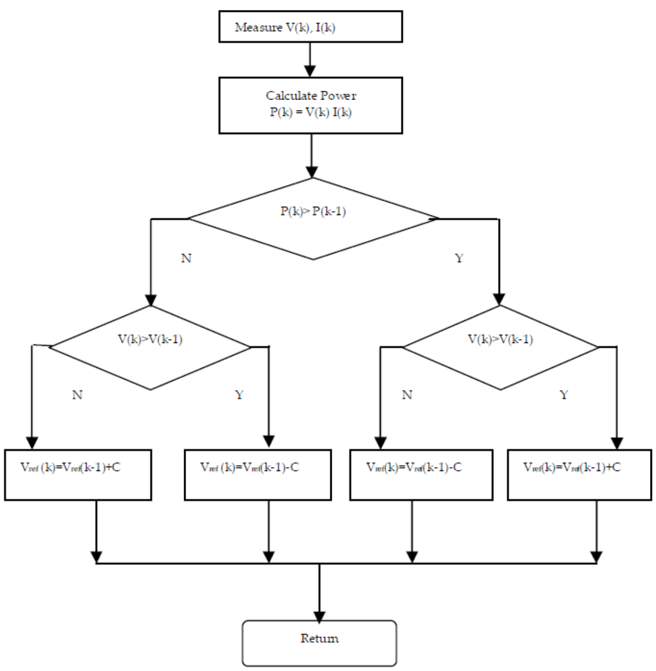

Fig 6: Flow chart of MPPT algorithm

5 Results And Discussion

The Solkar PV module is chosen for modeling, simulation and implementation, because this module is well suited to traditional photovoltaic applications. The Solkar PV module provides 37W of nominal maximum power, and has 36 series connected monocrystalline silicon cells. The key specifications are shown in Table 1. The model of the photovoltaic module is implemented using Matlab/Simulink. The model parameters are evaluated based on the Shockley diode equation listed on the previous section. The developed model takes solar irradiation and cell temperature as input parameters and outputs the I-V and P-V characteristics under various conditions. Fig. 7 and Fig. 8 show I-V and P-V characteristics of the photovoltaic module with various solar irradiation and temperature.

TABLE 1

Specifications of PV Module

Characteristics	Variable	Specification
Maximum power	P_m	37.08W
Voltage at maximum power	V_m	16.56 V
Current at maximum power	I_m	2.25 A
Short circuit current	I_{sc}	2.25 A
Open circuit voltage	V_{oc}	21.24 V
Series resistance	R_s	0.47 Ω
Shunt resistance	R_{sh}	145.62 Ω
Diode ideality factor	A	1.5

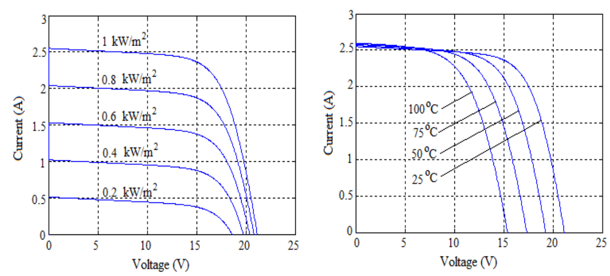

Fig. 7. I-V output characteristics of PV module with different (a) solar irradiation (b) temperature

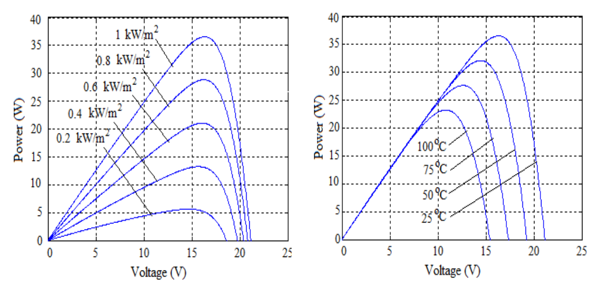

Fig. 8. P-V output characteristics of PV module with different (a) solar irradiation (b) temperature

The photovoltaic output voltage changes mainly with temperature, while the photovoltaic output current changes mainly with insolation. When the temperature rises, the photovoltaic output power decreases with a constant irradiation. With constant temperature specified, the photovoltaic output power increases when the insolation increases. Thus the main function of the interfacing the QZSI is to extract the maximum power out of the photovoltaic at any given temperature and irradiation. In QZSIs, 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 QZSI interfacing the photovoltaic is developed in Matlab/Simulink.

In this model four numbers of Solkar PV modules are connected in series to make a photovoltaic array, which acts as the DC source to the QZSI. Thus a maximum power of 148W can be obtained from this array under standard conditions. 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. For both simulation and experiments, the impedance network elements are designed with the following values: $L_1=L_2=3mH$ and $C_1=C_2=1000\mu F$ [18]. 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 load current waveforms and corresponding harmonic profiles are shown in Fig. 9 to Fig. 11. Harmonic analysis on the output voltage is performed and the total harmonic distortion is calculated as 1.32%.

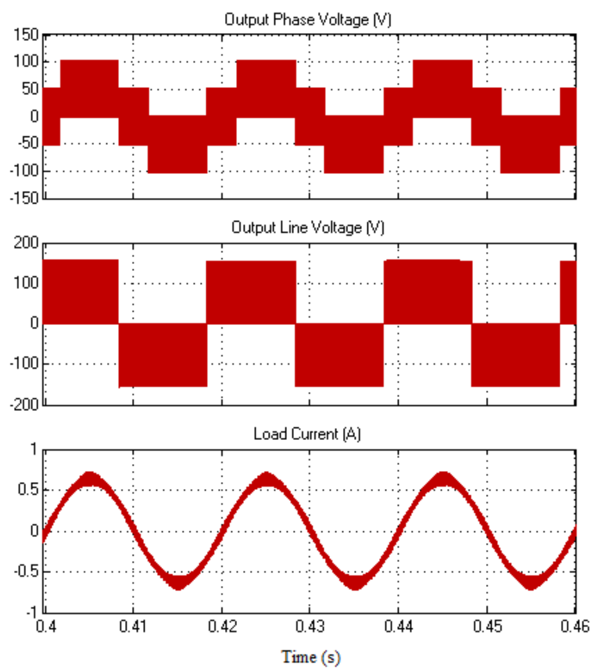

Fig.9. Simulation waveforms

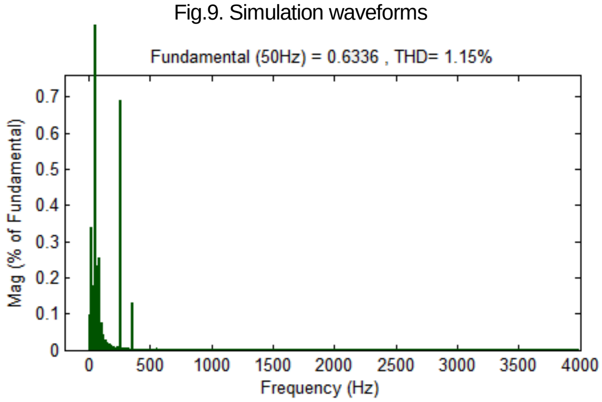

Fig.10. Harmonic spectrum of load current

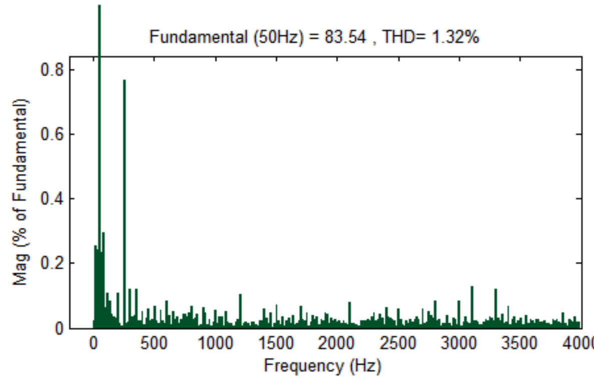

Fig.11. Harmonic spectrum of output line voltage

A laboratory model of QZSI is built and interfaced with PV panel as shown in Fig. 12. The same parameters used in simulation are used. Fig. 13 and Fig. 14 show experimental results. The firing pulses for the two switches in one phase leg of the Z-source inverter are shown in Fig. 13. The output line-to-line voltage is shown in Fig. 14.


Fig.12. Experimental setup

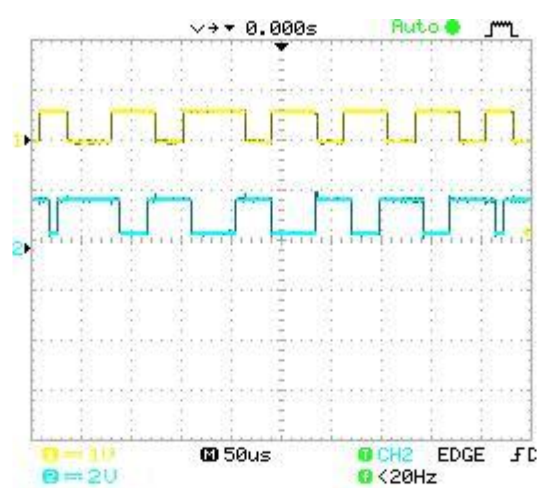

Fig.13. Switching pulses

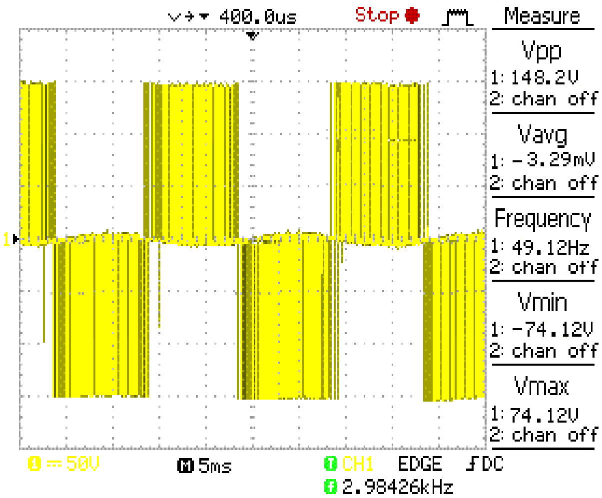

Fig.14. Experimental waveform of output line voltage

It is discernible that when sine carrier is employed, there is a significant reduction in the contribution of 5th, 7th, 11th order harmonics. The higher order harmonic contributions are also found to be less. There is also a noticeable reduction in the total harmonic distortion with good improvement in the fundamental voltage profile.

6 Conclusion

A Quasi-Z-source inverter based PV power conditioning system with perturb and observe MPPT algorithm is carried out. QZSI with a new carrier based PWM technique utilizing sine voltage as carrier waveform in simple boost PWM control is invoked. This new PWM gives high boost factor and hence high peak output voltage compared to other triangular carrier based PWM techniques. So the proposed system actualizes the boost and DC-AC inversion in single stage with maximum power tracking and minimum harmonic distortion. Simulation results presented verifies the analysis of the control method. The QZSI is capable of handling a wide range of input voltage fluctuations. It requires no additional converter, features low component rating and cost, and is more reliable. QZSI is best suited interface for photovoltaic power generation system and could prove to be highly efficient, when implemented with the improved control techniques proposed.

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