



Z-Source Micro-Inverter for Residential Photovoltaic Systems

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Abstract: This paper proposes a Z-source micro-inverter system for photovoltaic systems. The operation principle, control method, and characteristics of the system are presented. A comparison between the new and traditional system configurations is performed. Advantages and disadvantages of different topologies and other research work have also been undertaken. Facts and figures of Solar Energy installations in India and World have been taken into account while preparing this project. Simulation and experimentation done in MATLAB Simulink are also shown to verify the proposed circuit and analysis along with the results.

Index Terms: Micro inverter, MPPT, Photovoltaic (PV), power conditioning unit (PCU), Z-source inverter, ZSI.

I. INTRODUCTION

PV inverter will play an unprecedented role in the increasing market in near future. Due to environmental concerns, more effort is now being put into clean distributed power like geothermal, wind power, fuel cells, and photovoltaic (PV) that directly uses the energy from the sun to generate electricity. Energy from renewable sources, such as solar and wind, is gaining interest as the world's power demand increases and non-renewable resources are depleted. A large component of this demand is from industries and houses connected to the electrical grid. Because of this, attempts are made to raise the percentage of energy sourced from renewable sources into the grid. Photovoltaic (PV) energy sources increase the renewable content because of their ubiquitous nature and extended life time due to an absence of moving parts.

India is densely populated and has high solar insolation, an ideal combination for using solar power in India. With about 300 clear, sunny days in a year, India's theoretical solar power reception, on only its land area is about 5,000 trillion kilowatt (kWh) per year. By end September 2014, the installed grid connected solar power had increased to 2,766 MW, and India expects to install an additional 100,000 MWp or 100 GWp by 2022. Hence, India has tremendous opportunities for development of renewable energy resources especially solar energy.

This is a MATLAB based project for converting DC voltage generated by solar panels in suitable AC voltage for domestic purpose. A single PV and a micro-inverter form the ac module which feeds quality power from the solar. Our basic concept on making this project is based on Z-source inverter to obtain required AC voltage from DC voltage. It features a compact size, economical cost and compatibility with solar panels, which make this micro-inverter much useful and reliable than widely used technologies of central or string inverter. A low dc voltage from the PV panel is given as input to the micro inverter, like the small scale inverters these micro-inverters would transform this dc voltage to ac feeding it to the grid.

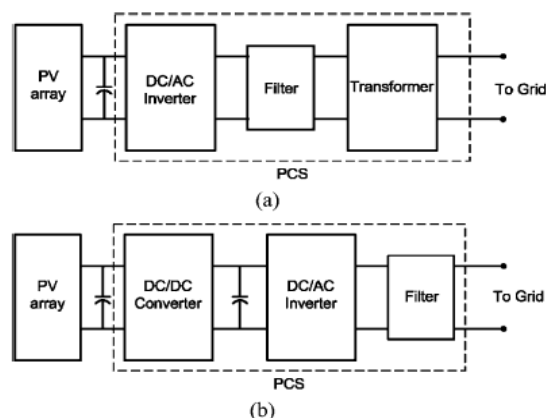


Fig. 1. Traditional PV system topologies: (a) dc-ac with step up transformer and (b) dc-ac with dc-dc boost. With this new topology, the proposed PCU offers the following advantages over the traditional

PCUs: 1) The dc-dc booster and the inverter have been combined into a single-stage power conversion; 2) the distortion of the ac output-voltage waveform is reduced in the absence of dead time in the PWM signals; and 3) the micro-system removes the possibility of low power generation due to the shading effect and due to presence of defective panels in the string.

II. BASICS OF PCU FOR RESIDENTIAL USE

A solar inverter, or PV inverter, or Solar converter, or Power Conditioning Unit (PCU) converts the variable direct current (DC) output of a photovoltaic (PV) solar panel into a utility frequency alternating current (AC) that can be fed into a commercial electrical grid or used by a local, off-grid electrical network. It is a critical component in a photovoltaic system, allowing the use of ordinary AC-powered equipment. Solar inverters have special functions adapted for use with photovoltaic arrays, including maximum power point tracking and anti-islanding protection. Thus the basic functions can be summed into the following:

- 1) To convert the dc voltage into ac voltage;
- 2) To boost the voltage, if the PV array voltage is lower than the grid voltage;
- 3) To insure maximum power utilization of the PV modular.

Fig. 1 presents the two very commonly used converter system configurations in practice. In Fig. 1(a), a transformer at line frequency is utilized to boost or step-up the voltage after the dc-ac inverter. Generally, a line frequency transformer is has huge size, loud acoustic noise, and high cost.

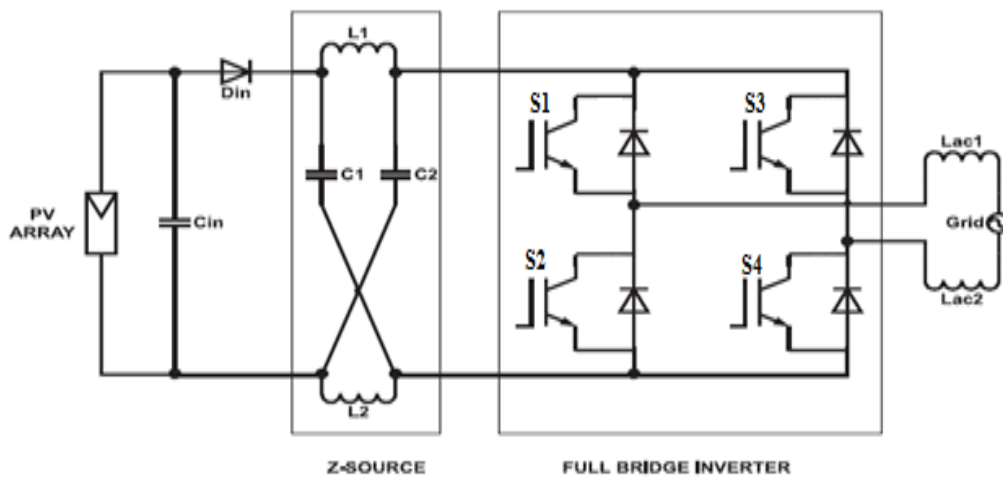


Fig. 2. Proposed Power Conditioning Unit (PCU) using Z-source for PV systems.

Furthermore the inverter has to be oversized to cope up with the wide PV array voltage change. The KVA rating of the inverter becomes twice if the PV voltage varies at a 1:2 range. So in order to eliminate the transformer and to keep the required KVA rating of the inverter low, in many applications, a high frequency dc-dc converter is used to boost or step-up the voltage to a constant value as shown in Fig. 1(b). Unfortunately, the switch in the dc-dc converter is very costly and an efficiency killer of the system.

III. CHOICE OF INVERTER

Solar micro-inverter is an inverter designed to operate with a single PV module. The micro-inverter converts the direct current output from each panel in to alternating current. Its design allows parallel connection of multiple, independent units in a modular way. Micro-inverter advantages reside mostly on single panel power optimization, independent operation of each panel, plug-and play installation, improved installation and fire safety, minimized costs with system design and stock minimization.

The Z-source converter (ZSC) is an alternative power conversion topology as shown in Fig. 2 that can both buck and boost the input voltage using passive components. It uses a unique LC impedance network with split inductor and capacitor connected in X shape, for coupling the converter main circuit to the power source, which provides a way of boosting the input voltage in a single stage, a condition that cannot be obtained in the traditional voltage source or current source inverters. With the impedance network, the Z-source inverter can advantageously use the shoot through states to boost the overall voltage. Additionally, with the ability to handle the shoot through state, the inverter system becomes more reliable and robust. The inductors and capacitors in the Z-source are both being energy storage devices, enable optimized designing to ensure small size and low cost. It also allows the use of the

shoot-through switching state, which removes the need for dead-times that are used in the traditional inverters to avoid the risk of damaging the inverter circuit.

IV. CLASSIFICATION OF SOLAR INVERTERS

The inverter which feeds the grid by receiving input from the PV module has a chief responsibility of feeding sinusoidal input to the grid. The technologies used to design such inverters are centralized inverters, string technology, and multi-string technologies. At present micro-inverter technology is gaining popularity.

A. Centralized Inverters

A large number of PV modules were interfaced to the grid in centralized inverters as shown in Fig. 3(a). The PV modules are in a form of string, which are series connections of modules. There is no need of amplification since each module generated sufficiently high voltage. Then higher power levels were reached by parallel connections of string through diodes. This topology has the following advantages:

- 1) Low capital price per watt,
- 2) High efficiency,
- 3) Comparative ease of installation – a single unit in some scenarios.

While the limitations are like:

- 1) DC cable losses,
- 2) PV modules mismatch,
- 3) Loss of power due to centralized MPPT,
- 4) Complexity in designing.

These increased the investment cost and decreased the efficiency. Alternate modules were developed to overcome these disadvantages.

B. String Inverters

A string inverter is the type most commonly used in home and commercial solar power systems. It is a large box that is often situated some distance away from the solar array. Depending on the size of the installation, there may be more than one string inverter present as shown in Fig. 3(b). Voltage amplification is not necessary since the input is high enough. Here there are no losses due to diodes, here the overall efficiency is increased and installation cost is reduced. However enlarging this system is complex due to its structure.

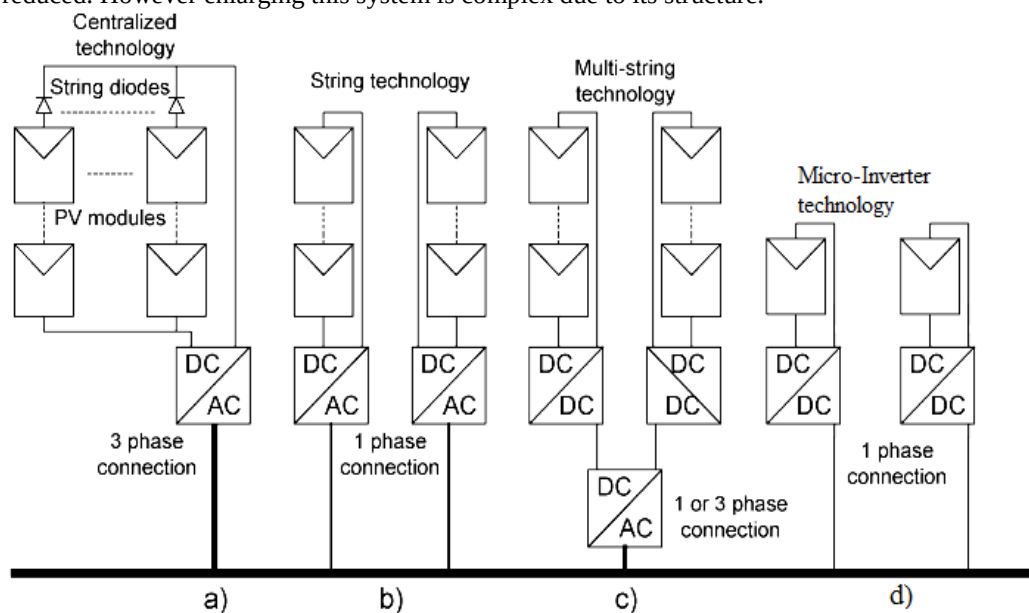


Fig. 3. Classification of inverters: (a) Centralized technology, (b) String technology, (c) Multi-string technology, (d) Micro-inverter technology

Advantages of string inverter can be summed as:

- 1) Allows for high design flexibility,
- 2) High efficiency & Robust,
- 3) 3 phase variations available,
- 4) Low cost and remote system monitoring capabilities.

Disadvantages can be summed as:

- 1) No panel level MPPT,

- 2) No panel level monitoring,
- 3) High voltage levels present a potential safety hazard.

C. Multi-string Inverters

Fig. 3(c) depicts the multi-string inverter. Here each string has its own converter all of which is connected to a common inverter. Here each string can be controlled individually. It is easy to expand the system by just plugging in dc-dc converter into existing plant. Efficiency is more and designing is also flexible. Pros of this topology can be elaborated as:

- 1) High design flexibility and easy expansion,
- 2) High efficiency,
- 3) High control

Cons of multi-string topology are:

- 1) High dc voltage levels present a potential safety hazard,
- 2) Complexity in design,
- 3) No panel level monitoring.

D. Micro-Inverters

Solar micro-inverter is a converter designed to operate with a single PV module. The micro-inverter converts the direct current output from each panel in to alternating current. Its design allows parallel connection of multiple, independent units in a modular way. A 2011 study at Appalachian State University states that individual integrated inverter setup yielded about 20% more power in un-shaded conditions and 27% more in shaded conditions compared to string connected setup using one inverter. Micro-inverter boons reside in:

- 1) Single panel power optimization,
- 2) Independent operation of each panel,
- 3) Plug-and play installation and easy expansion,
- 4) Improved installation and fire safety,
- 5) Minimized costs with system design and stock minimization.

While the disadvantages reside in:

- 1) Higher Complexity in design,
- 2) Lower life of inverter,
- 3) Heating problems with the inverter.

V. PRINCIPLE OF OPERATION OF PROPOSED CONVERTER

Compared with the topologies in Fig. 1, in the proposed system, there is neither bulky transformer nor a dc-dc converter to boost the voltage in the circuit. The size and cost are minimized. As no dead time is needed, the control accuracy and THD can also be improved. Additionally, the split-phase Z-source inverter naturally inherits all the advantages of the split-phase six-switch inverter. Compared with the direct inverter systems the ZSI has a minimum KVA requirement. For the inverter system with a PV voltage change of 1:2 range, a 10-kW PV system, needs a 20-kW inverter to cope with the voltage change. Using the proposed system of Fig. 2, the required KVA rating of the -source inverter remains the same 10 kW for a 10-kW PV system. Therefore, by utilizing the ZSI, the volume, the cost as well as the number of active switching devices are minimized.

Because of the single stage operation, the efficiency of the system can be greatly improved. In summary, the proposed system:

- 1) Has only one stage to realize inversion, boost, and maximum power tracking;
- 2) Has the minimized number of switching devices;
- 3) Needs no dead time;
- 4) Can have shoot through state in the inverter;
- 5) Inherits all the advantages of the six switch inverter system;
- 6) Has independent control of each panel and higher efficiency.

Operation of ZSI in continuous conduction mode (CCM) is based on two states:

- Shoot-through state
- Active state

Table I shows the nine switching states and their vector representations, where the switching function S_x ($x = 1, 2, 3$, or 4) is defined as 1 when switch S_x is on and as

0 when switch S_x is off. Thus, when two active vectors ({1 0}, {0 1}) are taken, the PV voltage is applied to the load through two inductances (L1 and L2); when two null vectors ({0 0}, {1 1}) are taken, the load terminal is shorted by either the upper or lower switches creating a shoot-through and known as shoot through zero states. During these periods of time, the output voltage of the inverter is zero, i.e., zero states.

For the Z-source inverter, the basic idea of control is to turn zero states into shoot through states and keep the active switching states unchanged, thus we can maintain the sinusoidal output and at the same time achieve voltage boost from the shoot through of the dc link. These zero vectors are present in the Z-source inverter, whereas they are forbidden in the voltage source inverter. Both unipolar and bipolar modulation is possible for inverter section. Unipolar technique is preferred, since it produces fewer harmonic compared with bipolar method. For the Z-source inverter, the unipolar technique permits higher modulation index with lower dc bus voltage.

TABLE I: SWITCHING STATES OF THE Z-SOURCE INVERTER

Switching States	S_1	S_2	S_3	S_4
Active {1 0}	1	0	0	1
Active {0 1}	0	1	1	0
null {0 0}	0	1	0	1
null {1 1}	1	0	1	0
Shoot through	1	1	0	1
Shoot through	1	1	1	0
Shoot through	0	1	1	1
Shoot through	1	0	1	1
Shoot through	1	1	1	1

Fig. 4 shows the boost control method of the ZSI. Phase legs are controlled by SPWM to synthesize ac output, and the shoot-through command, and are used to boost voltage as desired. When the carrier is greater than the modulated wave line, phase leg “1” goes to shoot through state, whereas phase leg “2” goes to shoot through state when the lower modulated wave line is greater than the carrier. The voltage boost of the ZSI is achieved by increasing the shoot-through duty ratio, while the ac output voltage is regulated according to the modulation index. However, there is a compromise between the shoot-through duty ratio and the modulation index: if a large modulation index is used, only a small shoot-through duty ratio can be utilized and vice-versa.

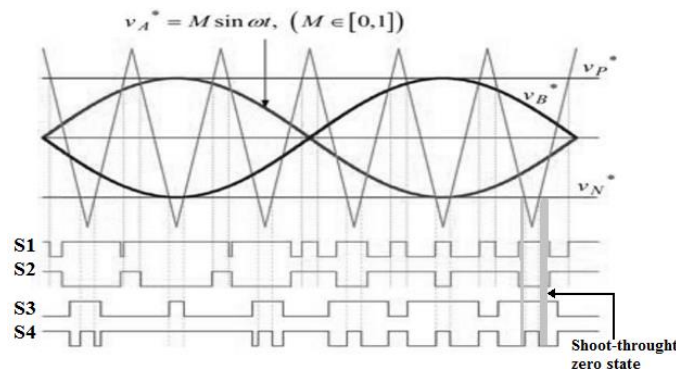


Fig. 4. Proposed method of simple boost control

VI. ANALYSIS OF IMPEDANCE (Z) NETWORK

The inductors which can be wound around the same core, have the same inductance, and the capacitors and have the same capacitance, assuming that the inductors L1 and L2 and capacitors C1 and C2 have the same inductance and capacitance respectively, the Z-source network become symmetrical. The relationship between the output ac voltage and input dc voltage is found as:

$$V_{out} = MB.V_o/2 \quad (1)$$

Where V_{out} is the output peak voltage, V_o is the PV output voltage, B is the boost factor, M is the modulation index of H-bridge inverter, which is defined by:

$$M = V_{peak}/V_{tri} \quad (2)$$

1.) Shoot through state:

From the symmetry and the equivalent circuits, we have:

$$\begin{aligned} L_1 &= L_2 \\ V_{C1} &= V_{C2} = V_C \\ V_{L1} &= V_{L2} = V_L \end{aligned} \quad (3)$$

Given that the inverter bridge is in the shoot-through zero state for an interval of T_o , during a switching cycle, T and from the equivalent circuit given in Fig. 5, one has:

$$\begin{aligned} V_C &= V_L \\ V_d &= 2V_C, V_i = 0; \end{aligned} \quad (4)$$

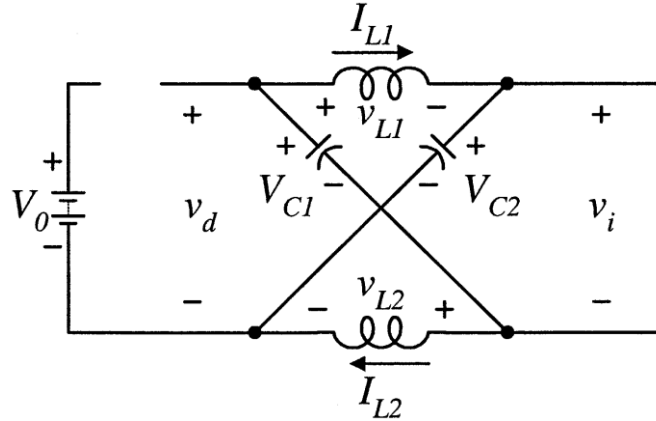


Fig. 5. Equivalent circuit of the Z-source inverter in shoot-through state

2.) Active or nonshoot-through state:

Consider that the inverter bridge is in one of the nonshoot-through states for an interval of T_1 , during the switching cycle. From the equivalent circuit, Fig. 6, one has:

$$V_L = V_o - V_C \quad (5)$$

$$V_d = V_o$$

$$V_i = V_C - V_L = V_C - (V_o - V_C)$$

$$V_i = 2V_C - V_o \quad (6)$$

Where V_o is the DC source voltage and:

$$T = T_o + T_1 \quad (7)$$

The average voltage of the inductor over one switching period should be zero in steady state, thus we have:

$$V_L = [\{T_o V_C + T_1 (V_o - V_C)\} / T] = 0$$

$$V_L = (T_1 V_o) / T + (T_o - T_1) V_C / T = 0$$

$$V_C / V_o = T_1 / (T_1 - T_o) \quad (8)$$

Similarly the average DC link voltage across the inverter bridge can be found as follows:

From equation 6:

$$V_i = (2V_C \cdot T_1 / T) - (T_1 V_o / T)$$

$$2V_C = V_o \quad (9)$$

From equation 8:

$$T_1 \cdot V_o / (T_1 - T_o) = 2V_C \cdot T_1 / (T_1 - T_o)$$

$$V_C = V_o \cdot T_1 / (T_1 - T_o) \quad (10)$$

The peak DC-link voltage across the inverter bridge is:

$$V_i = 2V_C - V_o = T / (T_1 - T_o) \cdot V_o = B \cdot V_o \quad (11)$$

Where B = Boost Factor:

$$B = T/(T_1 - T_0) \geq 1 \quad (12)$$

The output peak phase voltage from the inverter:

$$V_{out} = M.V_i/2 = M.B.V_o/2 \quad (13)$$

The output voltage can be stepped up and down by choosing an appropriate buck - boost factor (M.B) which varies from 0 to A. The boost factor B is determined by the modulation index M. The boost factor B can be controlled by duty cycle of the shoot-through zero state over the nonshoot through states of the PWM inverter. The shoot-through zero state does not affect PWM control of the inverter. Because, it produces the same zero voltage to the load terminal, the available shoot- through period is limited by the modulation index.

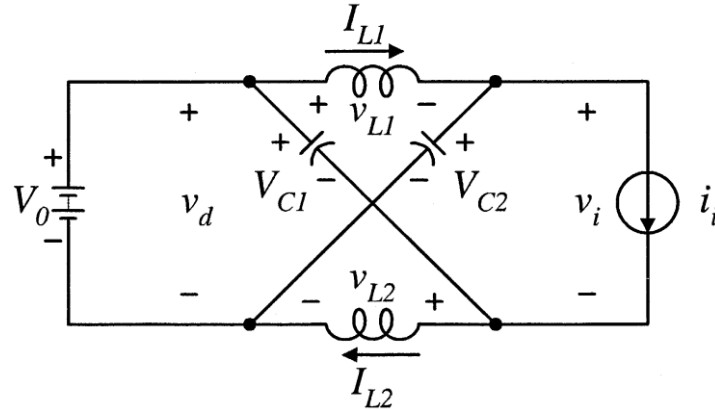


Fig. 6. Equivalent circuit of the Z-source inverter in nonshoot-through state

VII. SIMULATION AND RESULTS

The Z-source inverter can be operated in both boosts and buck operations depending on values of 'M'. If M is greater than 0.5 it acts as boost inverter, if M is less than 0.5 then it acts as buck inverter. The block diagram in fig 7 shows the SIMULINK implementation of Z – Source micro-inverter.

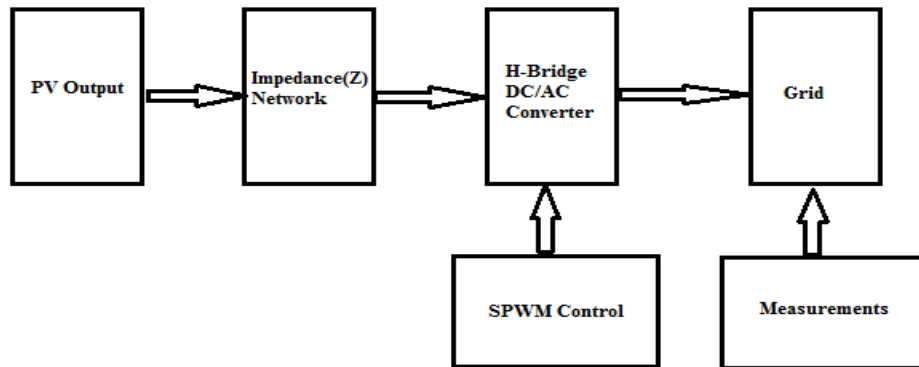


Fig. 7. Block diagram of the system

TABLE II : TOTAL HARMONIC DISTORTION (THD) Vs OVERLAP ANGLES

S. No.	Overlap Angle (in degree)	THD (%)	Peak Voltage (in Volts)
1	30	44.93	23.8
2	60	23.17	46.49
3	90	12.05	59.9
4	120	8.99	62.8
5	150	8.88	69.23
6	180	8.37	63.84

The table above lists the value of THD and peak voltage for different values of overlap angle. Overlap angle can be defined as the angle measure of the overlap of firing pulses for switch S_1 and S_3 . The fig. 9 depicts the firing circuit used in Simulink experiment, while fig. 8 gives experimental circuitry of the Z-Source Inverter.

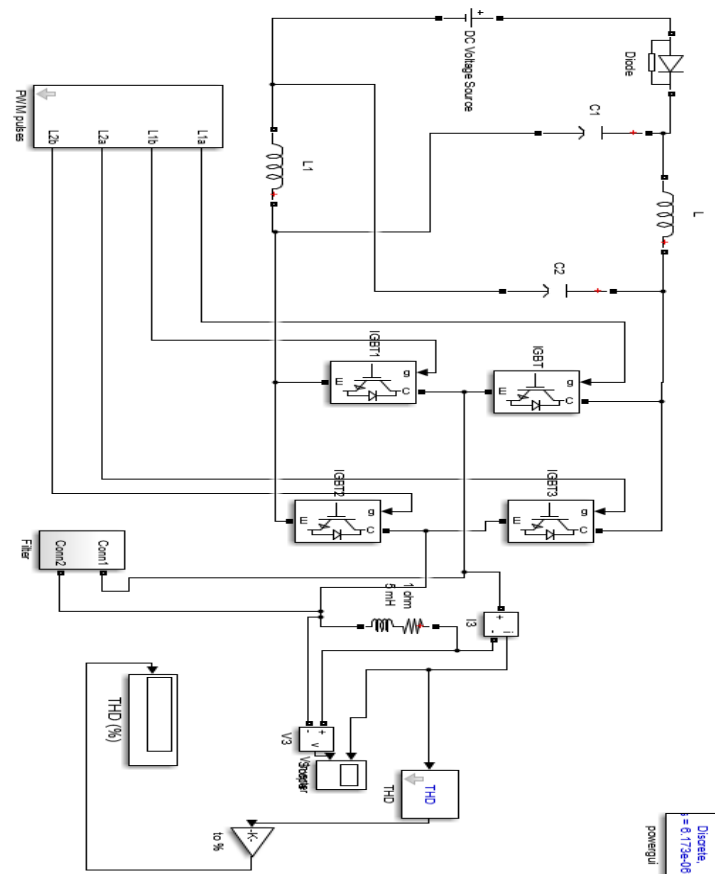


Fig. 8. Final Implementation Circuit

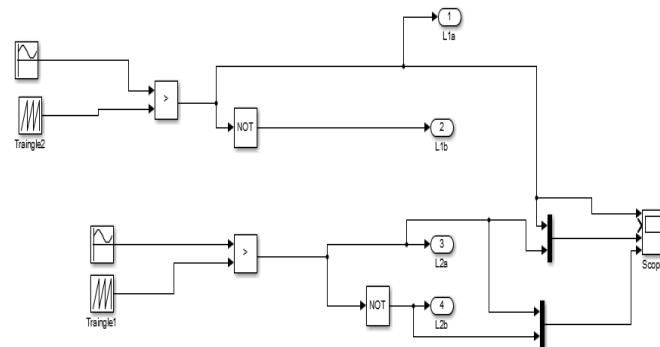


Fig. 9. Firing circuit of switches

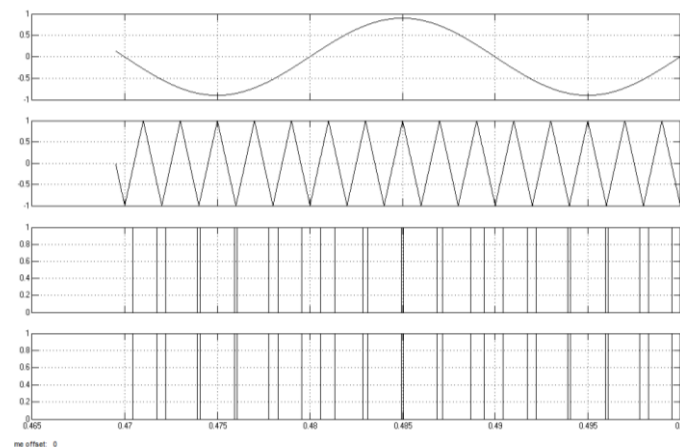


Fig. 10. Output for the circuit shown in fig 9.

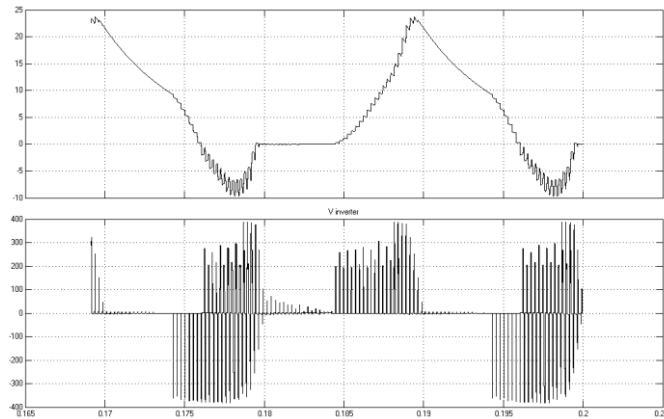


Fig. 11 Output with lower boost factor and higher harmonic content

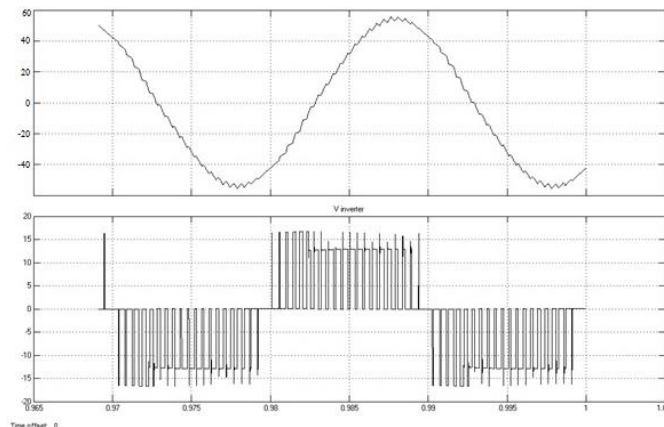


Fig. 12. Output waveform generated by the experimental circuitry with controlled boost factor and harmonic content.

VIII. CONCLUSION

In this paper, a new PV power conditioning unit (PCU) based on Z-source micro inverter is studied. The proposed system realizes the boost and inversion in one single power stage, thus minimizing the number of switching devices. The Z-source inverter employs a unique impedance network to couple the inverter main circuit to the PV source and thus providing unique feature. The control methods with the insertion of shoot-through states of Z-source micro inverter have been studied. Micro-inverter and other inverter technologies with its pros and cons have also been discussed. The proposed scheme under simple boost control is simulated with the help of MATLAB/ SIMULINK and the simulation results are obtained. From the results it has been observed from the outputs that 150° shoot through gave the highest boosted voltage level while the harmonic content was in acceptable limit by using proper filters.

By using the boost operations of Z-source micro inverters we got the increased voltage levels thus transformers and switching devices of lower ratings can be used which makes them cost effective for domestic and rooftop use in rural areas. Rather than using transformer and other equipment's to boost the voltage, we can have transformer less topologies by directly boosting the voltage to 230V AC with proper designing of Z-source inverter and filters for higher harmonic content. It seems that single stage micro inverter provides a good room for research as it reduces the cost as well as size and increases the reliability and life of the system. With the advanced features, the proposed system is very promising for future PV power conditioning applications.

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