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Design and Control of Switched-Inductor Quasi-Z-Source Inverter for Photovoltaic Applications

Dr.R.Seyezhai*, K.Arthi**, J.Bhavani** , A.Archana** & M. Deepa**
** Associate Professor, Renewable Energy Conversion Lab, Department of EEE, SSN College of Engineering, Chennai & ** UG Students, Department of EEE, SSN College of Engineering, Chennai.*

Abstract:- The conventional Z-Source Inverter (ZSI) used for photovoltaic applications has certain shortcomings such as high stress across the passive components and low boost factor. This paper presents the design and analysis of three phase switched inductor quasi Z-source inverter (SL-QZSI) for photovoltaic (PV) applications. The wide voltage gain and the compensation for dead time effect of SL-QZSI with the help of shoot-through states makes it suitable for PV application. Modulation strategies such as Simple boost, Maximum boost and Constant maximum boost control methods are investigated for the operation and control of SL-QZSI. PV source is modeled in MATLAB and incremental & conductance MPPT algorithm is implemented .Simulation of the SL-QZSI circuit powered by PV source is carried out by implementing maximum boost control method and the performance parameters are discussed.

Keywords:- SL-QZSI, Maximum Boost Control, PV, MPPT & Boost factor.

I. INTRODUCTION

A new topology called Z-source inverters have been developed to overcome the problems of the traditional voltage source and current source inverters wherein a Z shaped impedance network is included between the source and the power circuit. Z-source inverter can boost dc input voltage without requiring dc-dc boost converter or step up transformer, hence overcoming output voltage limitation of traditional voltage source inverter[1]. The inclusion of the shoot through state makes this topology superior and reliable and the extension of this inverter is quasi Z-source inverter (QZSI)[2-3].QZSI topology comprises of passive components such as inductors, capacitors, diodes and a three phase inverter with six switching devices. The voltage gain ratio of QZSI has wide range and the current drawn from the source is constant[4]. In addition to this, the reliability of this topology is high due to the presence of shoot through state. So, QZSI topology is better compared to Z source inverter. But it encounters a heavy in rush current during startup and has small boost factor. Thus, for efficient power production, we need to use a special type of Z source inverter called the switched inductor quasi Z source inverter[5].

The newer member in the family of QZSI topology is three phase switched inductor quasi Z-source inverter (SL-QZSI) which limits the ratings of the inductors and capacitors used in the Z- network to a greater extent. The impedance network of SL-QZSI is designed such that the boost factor of the inverter is increased to a considerable extent. Moreover, the stress on the passive devices are also deceased thereby enhancing the efficiency of this inverter and reduces the startup inrush current. On the same time a wide range of voltage gain can be achieved to fulfill the applications which require a large gain range, especially for renewable energy systems. As the PV cells are sensitive to temperature and solar radiation, they do not produce a constant power output. It is observed that SL-QZSI draws a constant current from the source which is most suited for Photovoltaic (PV) applications[6]. Therefore, this paper presents the modeling of PV with MPPT algorithm and then interfaced with the proposed Z-source inverter. Maximum constant boost control technique is employed for the proposed inverter which helps in introducing shoot through state. MATLAB/SIMULINK is used for carrying out the simulation studies. Performance parameters of the SLQZSI is investigated and the results are discussed.

II. SWITCHED INDUCTOR QUASI Z-SOURCE INVERTER

The proposed topology differs from the old quasi-Z-source inverters by the impedance network. The SL-QZSI topology has a passive network and an inverter bridge with six switches (S_1, S_2, S_3, S_4, S_5, S_6)[7-8]. The passive network has inductors (L_1, L_2, L_3), capacitors (C_1 and C_2) and diodes(D_1, D_2, D_3 and D_{in}) are arranged as shown in Fig.1.

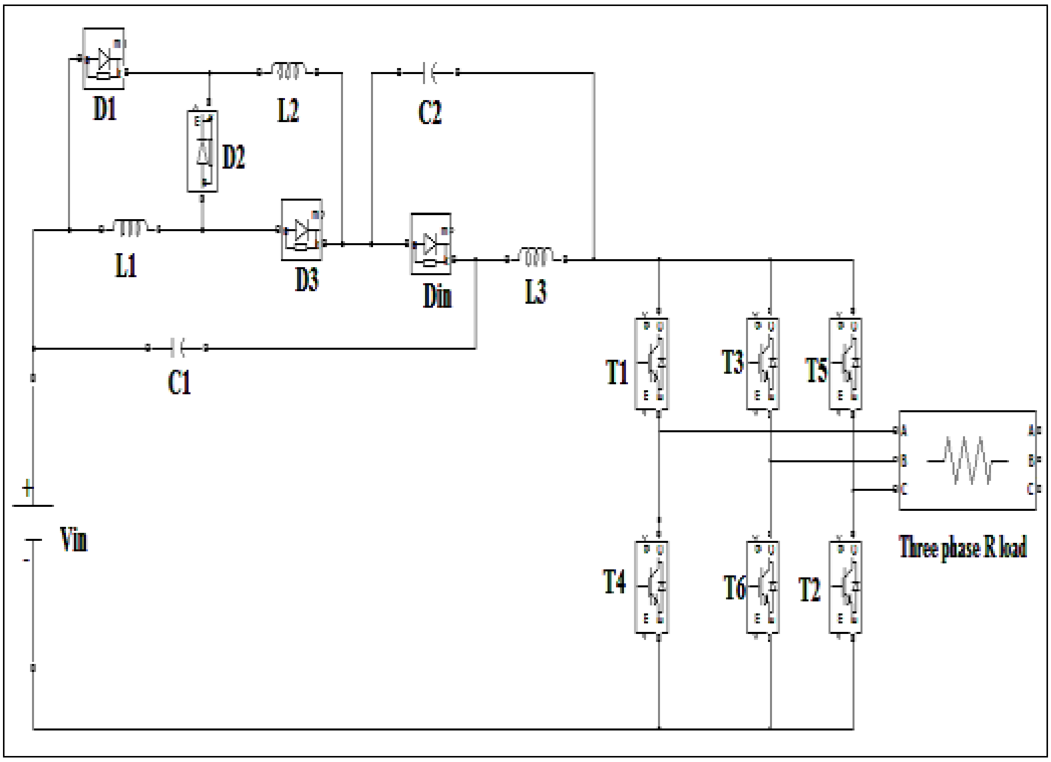

Fig.1 Circuit diagram of SL-QZSI

The operation of SL-QZSI can be explained with the help of two states (shoot through state and non shoot through state).In shoot through state, the switches belonging to the same phase leg is switched on or all the switches are switched on for a very short duration. During the shoot through state in SL-QZSI, the diodes D_{in} and D_2 are off, while the diodes D_1 and D_3 are on. The inductors L_1 and L_2 are now connected in parallel. The capacitors C_1 and C_2 are discharged, while inductors L_1, L_2, and L_3 store energy in this mode.

In this mode the relation between the input voltage, capacitor voltage and the inductance voltage can be presented by the following equations.

$$V_{L3} = V_{in} + V_{C1} \qquad (1)$$

$$V_{L1} = V_{L2} = V_{in} + V_{C2} \qquad (2)$$

During the non-shoot-through state, Din and D2 are on, while D1 and D3 are off. L1 and L2 are connected in series. The capacitors C1 and C2 are charged, while the inductors L1, L2, L3 transfer energy from the dc voltage source to the main circuit. In this mode the relation between the input voltage, capacitor voltage, the inductance voltage and the input DC voltage of the inverter can be presented by the following equations[9].

$$V_{in} = V_{dc} - V_{C1} + V_{L3} \qquad (3)$$

$$V_{L3} = -V_{C2} \qquad (4)$$

$$V_{L1} = V_{L2} = -1/2\, V_{C1} \qquad (5)$$

$$V_{dc} = V_{in} + V_{C1} + V_{C2} \qquad (6)$$

The following equations are used to design the impedance network of switched inductor quasi z source inverter. By applying the volt-second balance principle to the inductor voltage V_{L3} presented in (1) and (3) the following expression is obtained.

$$V_{C1} = (1 - D)V_{dc} - V_{in} \tag{7}$$

By applying volt-second balance to the inductor voltage V_{L1} which is presented in (2) and (5), the following expression is obtained.

$$V_{c2} = \frac{(1 - D)V_{dc} - (1 + D)V_{in}}{1 + D} \tag{8}$$

From (7) & (8) the following expressed is obtained

Table 1: Conduction table for switches of inverter during shoot through and non shoot through state

SWITCHING STATE	SWITCHES					
	T1	T2	T3	T4	T5	T6
ZERO STATES	ON	×	ON	×	ON	×
	×	ON	×	ON	×	ON
	ON	×	×	ON	×	×
	×	×	ON	×	×	ON
	×	ON	×	×	ON	×
	ON	ON	ON	ON	×	×
	×	×	ON	ON	ON	ON
	ON	ON	×	×	ON	ON
	ON	ON	ON	ON	ON	ON
NON SHOOT THROUGH STATE	ON	×	×	×	×	ON
	ON	ON	×	×	×	×
	×	ON	ON	×	×	×
	×	×	ON	ON	×	×
	×	×	×	ON	ON	×
	×	×	×	×	ON	ON

shoot through state

$$V_{dc} = \frac{1 + D}{1 - 2D - D^2} V_{in} \tag{9}$$

Thus the boost factor of the SL QZSI impedance B is expressed as follows,

$$\frac{1 + D}{1 - 2D - D^2} \tag{10}$$

The peak dc-link voltage across the inverter main circuit is expressed as,

$$V_{PN} = BV_{dc} \tag{11}$$

For simulation purposes, the value of inductor is chosen as 1mH and the value of capacitor as 1000µF.

III. MODULATION STRATEGIES FOR QZSI

The modulation technique adopted for the switched inductor quasi Z-source inverter is different from the conventional VSI because of the additional zero state called the shoot through state. Modifications are carried out in the traditional PWM technique so as to include the shoot through states. This can be achieved with the help of an additional constant line called the shoot through line whose magnitude is responsible for the three modulation strategies namely simple boost, maximum boost and maximum constant boost control[10-12]. This section discusses about the modulation methods employed for the proposed QZSI topology.

(i) SIMPLE BOOST CONTROL

The simple boost PWM technique uses three phase sinusoidal waves with a phase difference of 120 degrees. In this technique, a high frequency triangular wave is used as the carrier signal. Two straight lines are employed to realize the shoot through state. The amplitude of the shoot through line should be greater than or equal to the reference sine wave. Whenever the triangular carrier signal is higher than the positive straight line or lower than the negative straight line, the inverter will be operated in shoot through mode. Whenever the magnitude of each sine wave is found to be greater than the carrier wave, the corresponding switching device in the three upper limbs is switched on. Its complement is given to the lower limb devices. The pulse pattern of this control strategy is shown in Fig.2.

The boost factor and modulation index for simple boost control is given by,

$$B = \frac{1}{(2ma - 1)} \qquad (1)$$

$$ma = \frac{(B + 1)}{2B} \qquad (2)$$

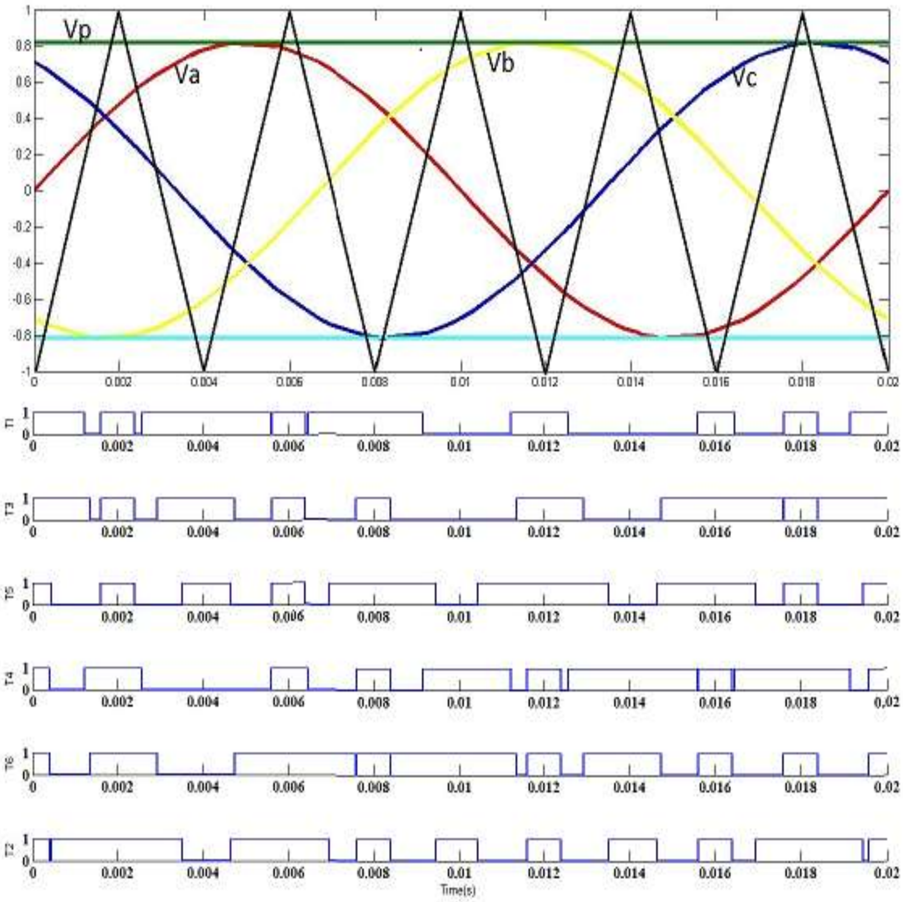

Fig. 2 Pulse pattern by simple boost control technique

(ii) MAXIMUM BOOST CONTROL

Similar to simple boost technique, triangular wave is used as carrier and three phase sinusoidal wave is used as reference wave in this technique. Maximum boost control method converts all traditional zero states to shoot through state. The shoot through state is obtained by comparing the maximum and the minimum values of the sinusoidal reference with the triangular wave. Whenever the maximum is lower than the triangular or the minimum is higher than the triangular, the inverter generates shoot-through. Otherwise, it is operated in the traditional PWM mode. The pulse pattern of maximum boost control strategy is shown in Fig.3. The maximum boost control technique is widely used because it reduces the voltage stress across the switch.

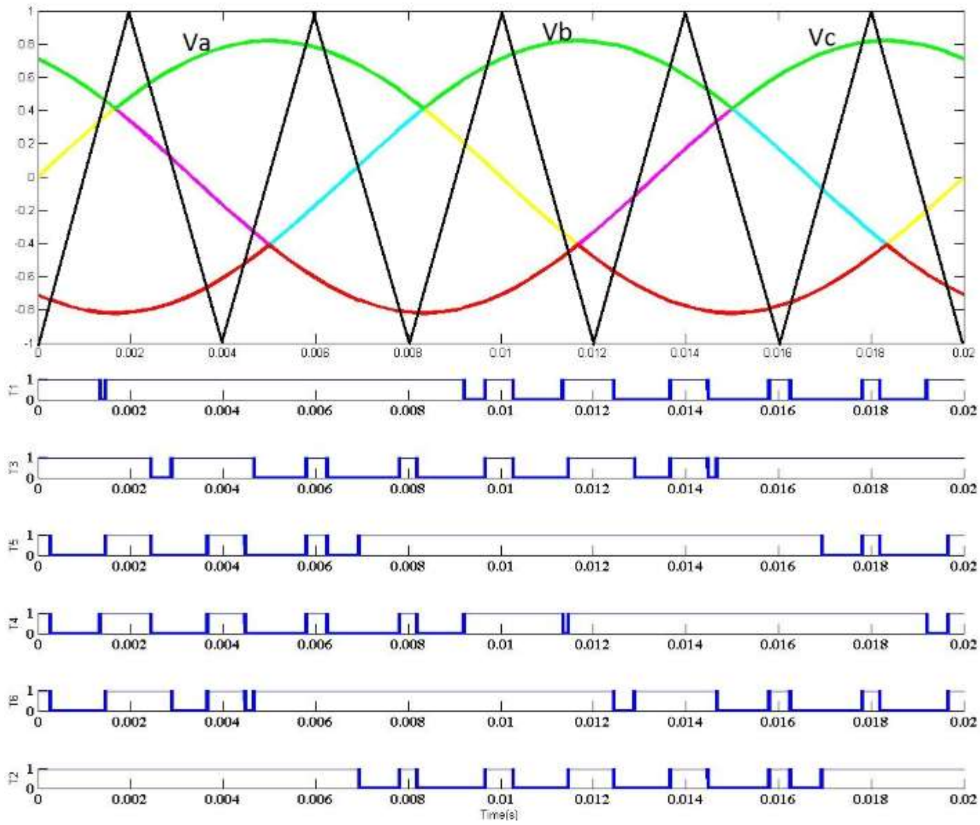

Fig.3 Pulse pattern by maximum boost control technique

The boost factor for this control strategy is given by,

$$B = \frac{\pi}{(3\sqrt{3}\,ma - \pi)} \quad (3)$$

$$ma = \frac{\pi(B+1)}{(3\sqrt{3}B)} \quad (4)$$

(iii) MAXIMUM CONSTANT BOOST CONTROL

In maximum constant boost control, the shoot through duty cycle should be maintained constant. In order to maintain constant duty cycle, the upper and lower shoot through values should be periodical. This control strategy consists of three phase sinusoidal reference signal and a high frequency triangular carrier wave. It also includes two shoot through envelopes V_p and V_n[13]. The amplitude of the shoot through envelope should be equal to the amplitude of the reference sine wave. When the carrier triangle wave is higher than the upper shoot-through envelope V_p or lower than the bottom shoot-through envelope V_n, the shoot through state is generated in the inverter. Whenever the reference wave is greater than the carrier wave, the corresponding switch in the upper leg is turned on and the inverted output is given to the lower leg of the same phase. The pulse pattern generated by this modulation technique is shown in Fig.4.This technique reduces the voltage stress across the components to a greater extent. For a desired modulation index, it can be seen that the boost factor of this method is greater than the simple boost control but is lower than that of maximum boost control.

The boost factor for maximum constant boost control strategy is given by,

$$B = \frac{1}{(\sqrt{3}ma - 1)} \tag{5}$$

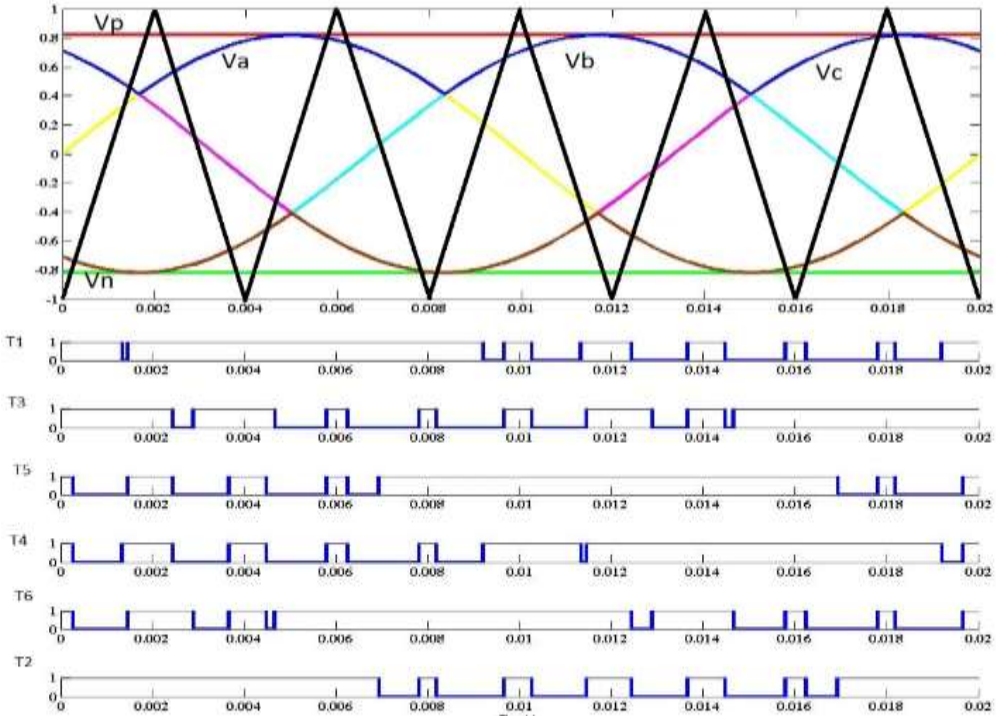

Fig.4 Pulse pattern by maximum constant boost control technique.

IV. SIMULATION RESULTS

The simulation of switched inductor quasi Z source inverter using the three different modulation strategies is carried out in MATLAB/SIMULINK. All components are assumed to be ideal in character. The initial voltage for capacitor is 0 V. The various parameters required for the simulation of SL - QZSI are listed in table 2.

Table: 2 Simulation Parameters for QZSI

Input Voltage(V_{dc})	48V
Modulation Index(ma)	0.82
Three phase resistive load	10Ω/phase
Inductor (L1,L2,L3)	1mH
Capacitor(C1,C2)	1000µF
Switching Frequency	10KHz
Inductor (for filter) , L_f	4mH
Capacitor(for filter) , C_f	33µF

The proposed switched inductor quasi z source inverter is simulated in MATLAB/SIMULINK. The six switches in the inverter is turned on using simple boost modulation strategy. The output phase voltage is shown in Fig.5 and the line to line voltage waveform is shown in Fig.6.

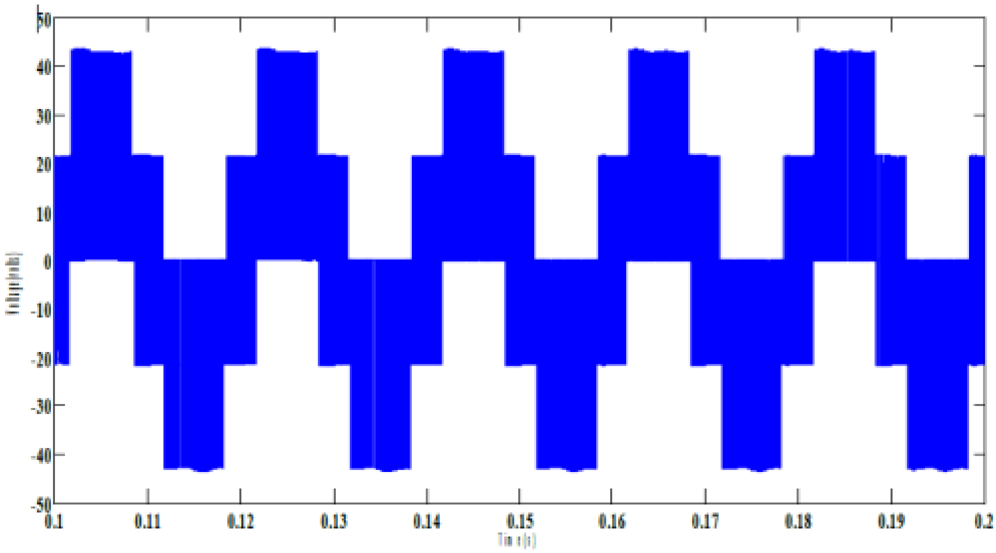

Fig.5 Phase output voltage waveform for simple boost control

From the simulation results, it is observed that the fundamental value of phase voltage is 32.46V and the peak value of phase voltage is about 38.2205V

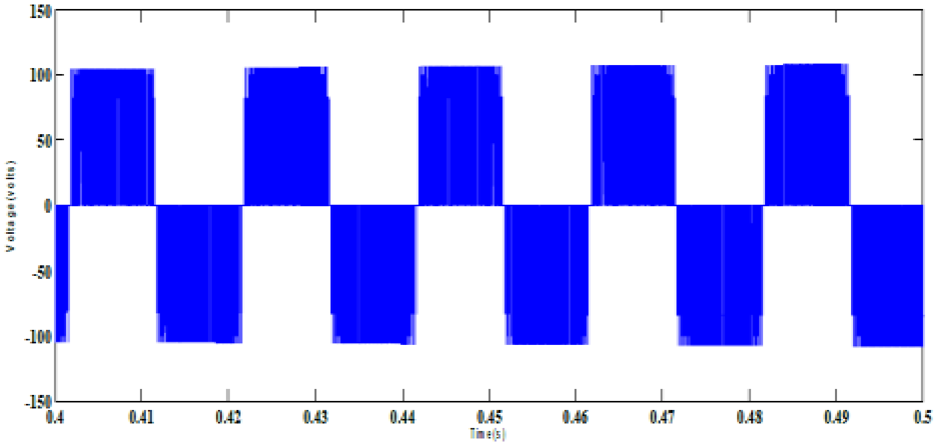

Fig.6. Line to line output voltage waveform for simple boost control

The output phase voltage and the line to line voltage waveform for maximum boost control technique is shown in Figs.7 &8.

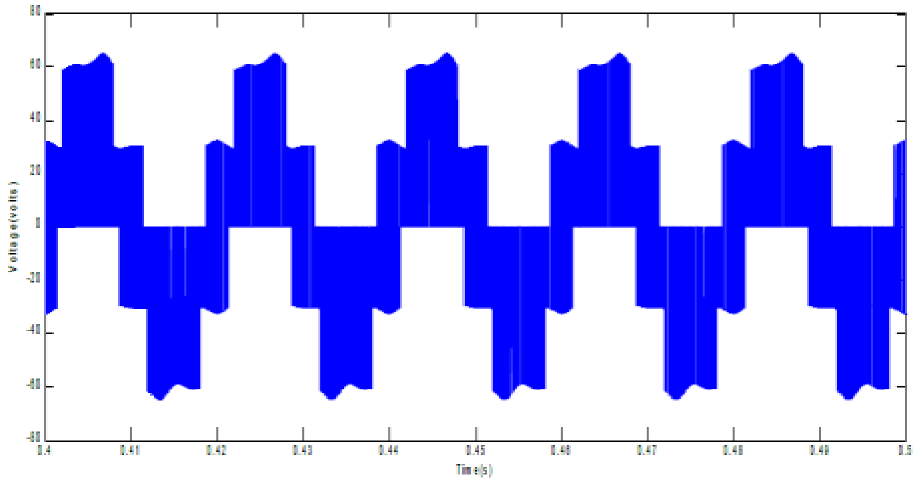

Fig.7 Phase output voltage waveform for maximum boost control

From the simulation, the fundamental value of phase voltage is 7.4V.Vdc=48V, m=0.82, D=0.3219, B=5.2315 and the peak value of phase voltage is about 102.95V.

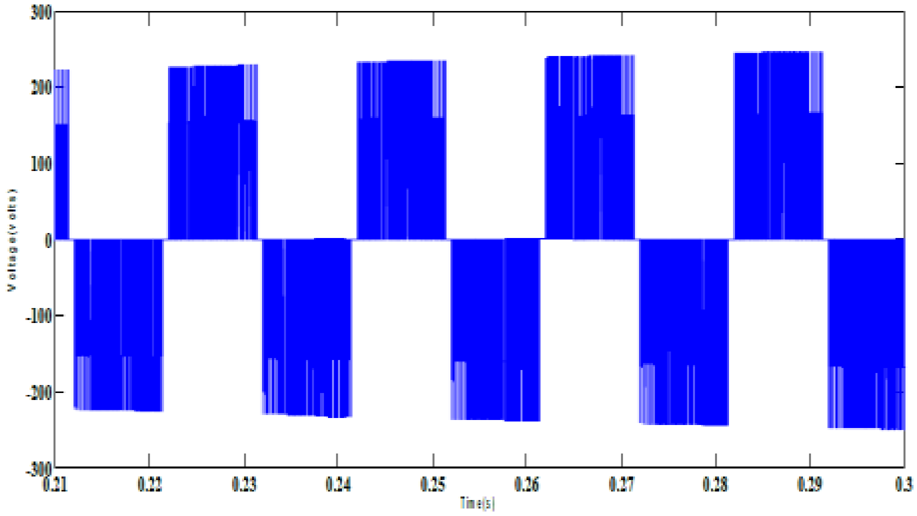

Fig.8 Line to line output voltage waveform for maximum boost control

The output phase voltage and the line to line voltage waveform for maximum constant boost control technique is shown in Figs.9 & 10.

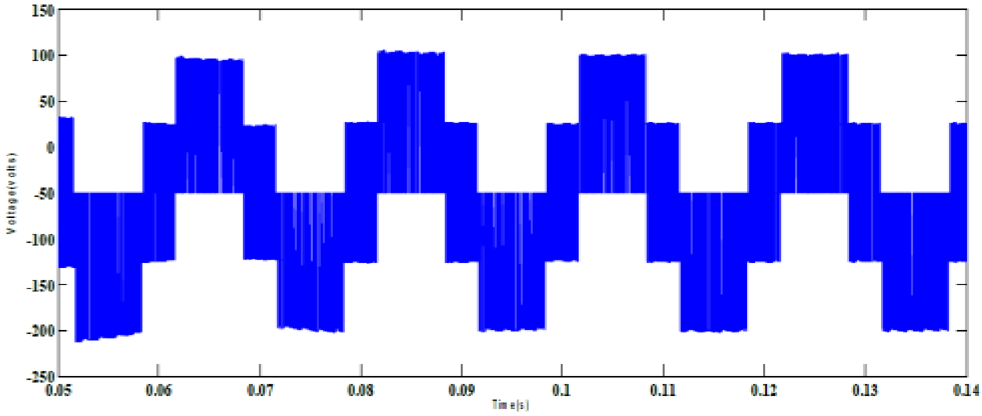

Fig.9 Phase output voltage waveform for maximum constant boost control

From simulation, fundamental value of phase voltage is 77.62V.Vdc=48V, m=0.82, D=0.2899, B=3.8372 and the peak value of phase voltage is about 75.51V.

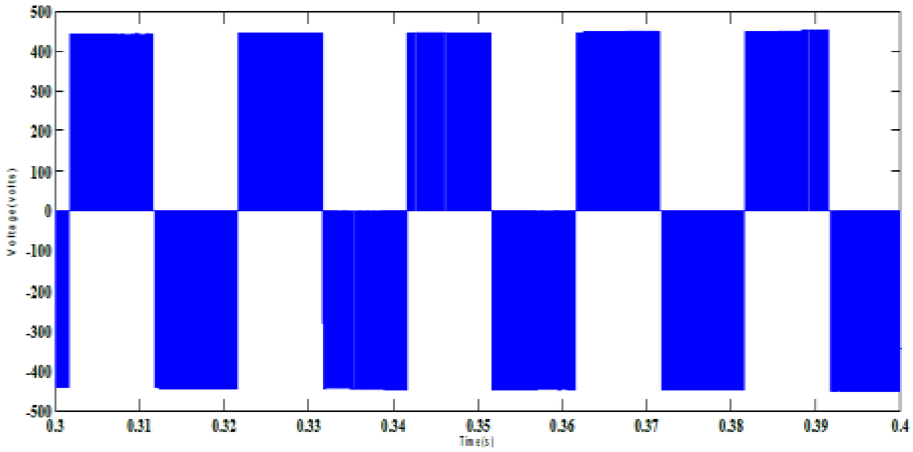

Fig.10 Line to line output voltage waveform for maximum constant boost control

V. PERFORMANCE PARAMETERS OF SL-QZSI

The performance of three phase switched inductor quasi z source inverter is found to be far superior to its ancestors. The various parameters such as boost factor, duty ratio, gain, voltage across the capacitors are calculated [] for different values of modulation index and the THD spectrum is plotted for all the three different modulation strategies. The comparison of the above mentioned three different modulation strategies are performed and it is found that the maximum constant boost technique is more suited for the implementation of SL-QZSI for photovoltaic applications with the chosen modulation index as 0.82.Fig.11 depicts the THD for various modulation index.

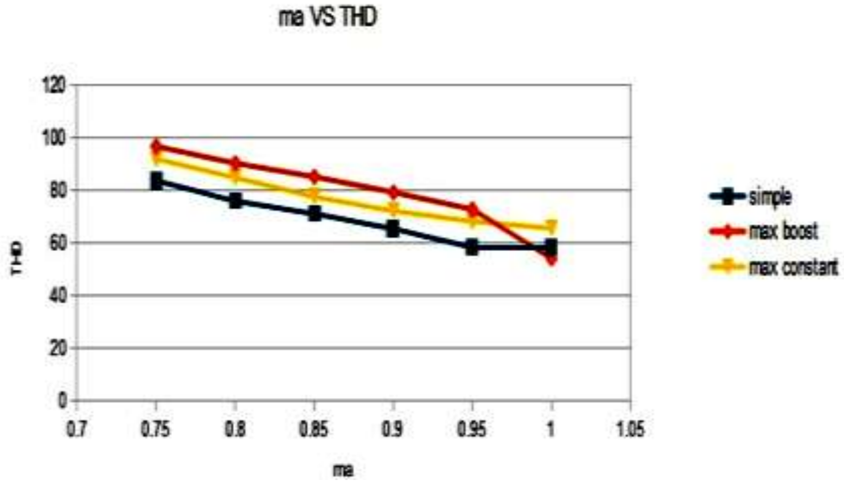

Fig.11 Plot showing the relationship between THD and modulation index for Different modulation strategies

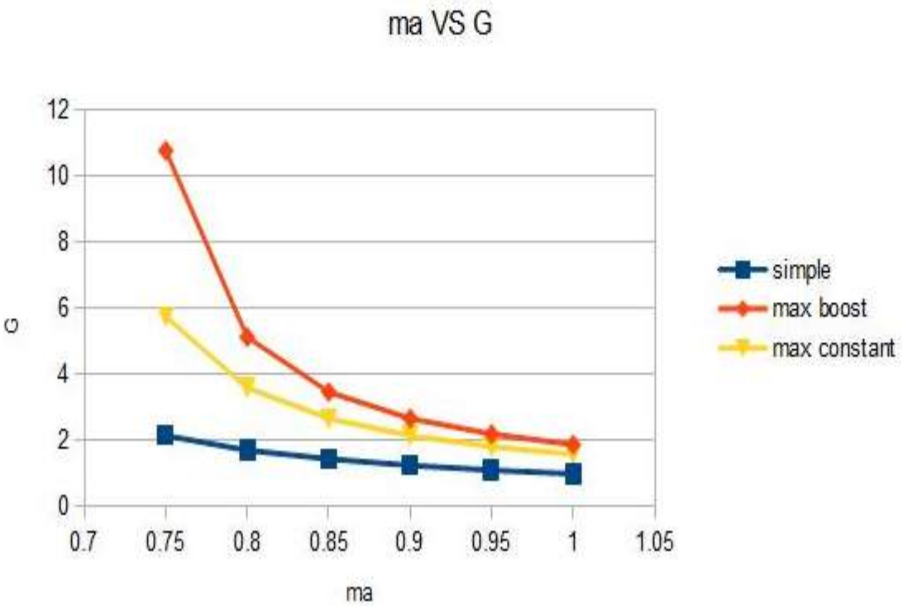

Fig.12 Plot showing the relationship between gain and modulation Index for different modulation strategies

Fig.12 illustrates the variation of gain with varying modulation index. With the increasing values of modulation index ,the gain decreases gradually as it approaches to unity. Hence the modulation index can be chosen less than 0.85 to have a better performance.

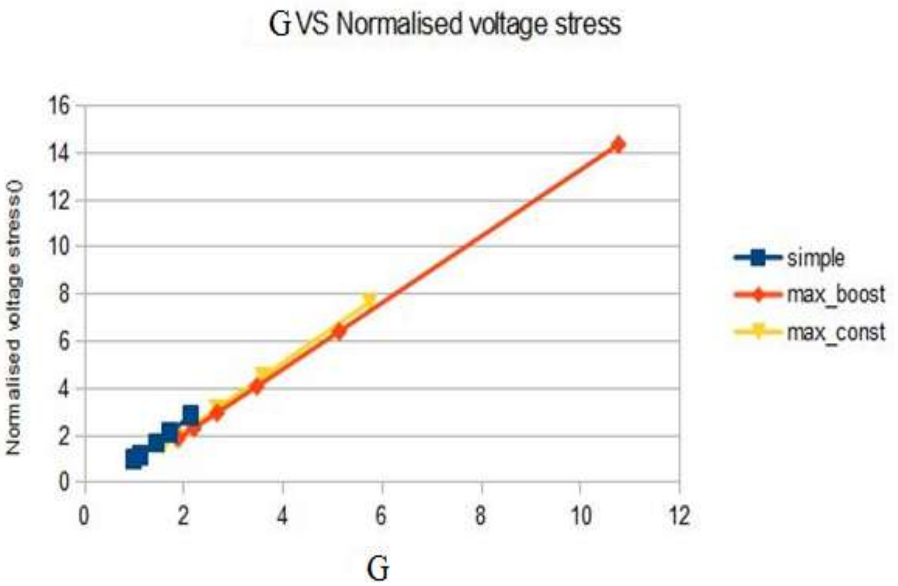

Fig.13 Plot showing the relationship between normalized voltage stress and gain for Different modulation strategies

Fig.13 shows the relationship between gain and normalised voltage stress for the various modulation strategies. It can be observed that the voltage stress is more for simple boost control when compared to the other two modulation strategies for the same voltage gain. When maximum constant boost technique is employed, the voltage stresses across the inverter's devices are reduced to a greater extent.

VI. APPLICATION OF SWITCHED INDUCTOR QZSI FOR PV SYSTEM

(i) Modeling of PV

A photovoltaic array (PV system) is a interconnection of modules which in turn is made up of many PV cells in series or parallel. The connection of the modules in an array is same as that of cells in a module. In general the output of photovoltaic system directly depends on the solar irradiance and cell temperature. In order to increase the capability of overall PV systems, the cells should be configured in series and parallel features. If we consider N_p as the number of cells connected in parallel and N_s as the number of cells connected in series, the output current I_{pv} can be determined as shown below,

$$I_{pv} = N_p I_{ph} - N_p I_o \left[\exp\left(\frac{q(V_{pv} + I_{pv}R_s)}{N_s AKT_k}\right) - 1\right] \tag{6}$$

where I_{ph} is the solar generated current which is affected by solar irradiance and temperature, I_o is the diode saturation current, V_{pv} is the output voltage of PV array R_s is the series resistance, A is the diode ideality factor. The average value assumed during the determination of unknown parameters in the photovoltaic system is usually 1.3, q is the electron charge and its value is 1.602* 10^{-19} C and K is the Boltzmann constant and its value is 1.3806503*10^{-23}J/K.The solar generated current I_{ph} is calculated by the expression given below[14]:

$$I_{ph} = (I_{scr} + K_i T_{dif})\frac{G}{G_r} \tag{7}$$

where I_{scr} is the solar generated current at the nominal condition (25^{o}C and 1000W/m), K_i is known as the cell short-circuit temperature/current coefficient,G is illumination in which the PV is operating on the design surface,G_r is the PV cell's nominal irradiance which is normally considered as 1000 W/m^{2,}T_{dif} is defined as the difference between current PV cell temperature(T_k) and reference temperature(T_{ref}) which is normally 298K (T_{dif} = T_k-T_{ref}).The diode saturation current, Io can be calculated by using the expression in equation below:

$$I_o = I_{rs}\left(\left(\frac{T_k}{T_{ref}}\right)^3 \exp\left[\frac{qE_{go}}{AK}\left(\frac{T_{dif}}{T_{ref}T_k}\right)\right]\right) \tag{8}$$

ii) MAXIMUM POWER POINT TRACKING ALGORITHM

The maximum power point tracking algorithm is used to obtain maximum power from the PV array. The voltage at which PV module can produce maximum power is called, 'maximum power point' (or peak power voltage).Maximum power varies with solar radiation, ambient temperature and solar cell temperature. The different MPPT algorithms to maximize the output power are as follows : Incremental conductance, perturb and observe, parasitic capacitance, voltage based peak power tracking and current based peak power tracking[15]. In incremental conductance method, the PV array terminal voltage is always adjusted according to the maximum power point(MPP) voltage which is based on the incremental and instantaneous conductance of the PV module. The basic concept of Incremental conductance on a PV curve of a solar module is shown in Fig.14. The slope of the P-V curve is zero at the maximum power point, increasing on the left of the maximum power point and decreasing on the right hand of the maximum power point.

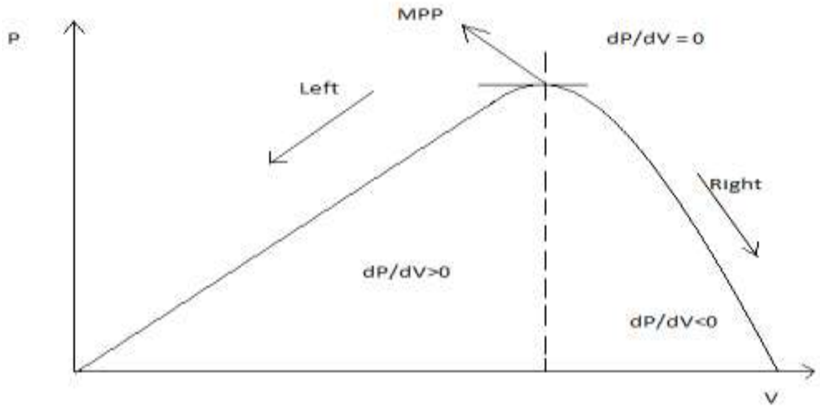

Fig.14 P-V curve of a photovoltaic array

By using equations (6)-(8), pv array is simulated in MATLAB and then MPPT algorithm is implemented to obtain maximum output power. Table 3 provides details about the parameters used for the simulation of PV array.

Table 3 PV array parameters

Number of cells in series, N_s	**36**
Number of cells in parallel, N_p	1
Cell temperature, T	25^0C
Open circuit voltage, V_{oc}	21.1V
Short circuit current, I_{sc}	3.8A
Charge of an electron, q	$1.6*10^{-19}$
Boltzmann's constant, k	$1.36*10^{-23}$

The photovoltaic array is simulated in MATLAB/SIMULINK with the parameters specified in table 3. The generalized PV array model is shown in Fig.15.

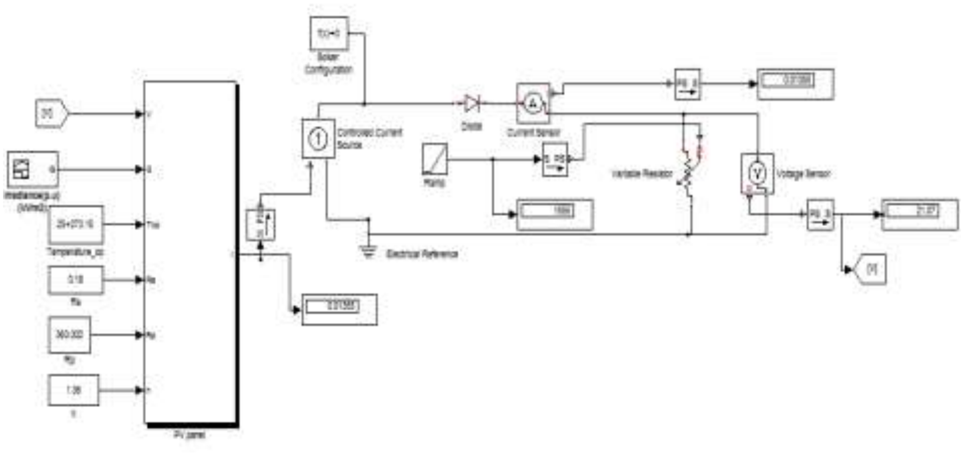

Fig.15 Model of PV array

The V-I characteristics and the P-V characteristics of the simulated PV array is shown in Figs.16& 17. respectively.

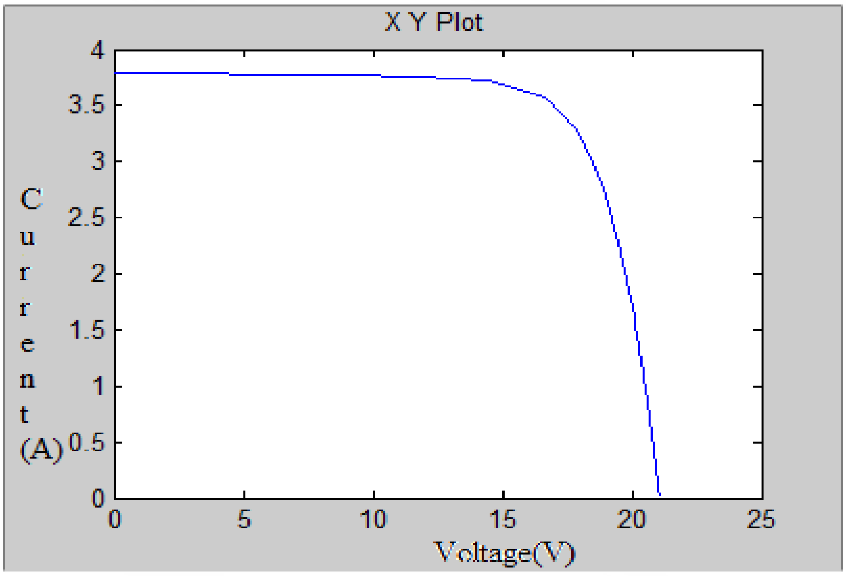

Fig.16. V-I characteristics of PV array

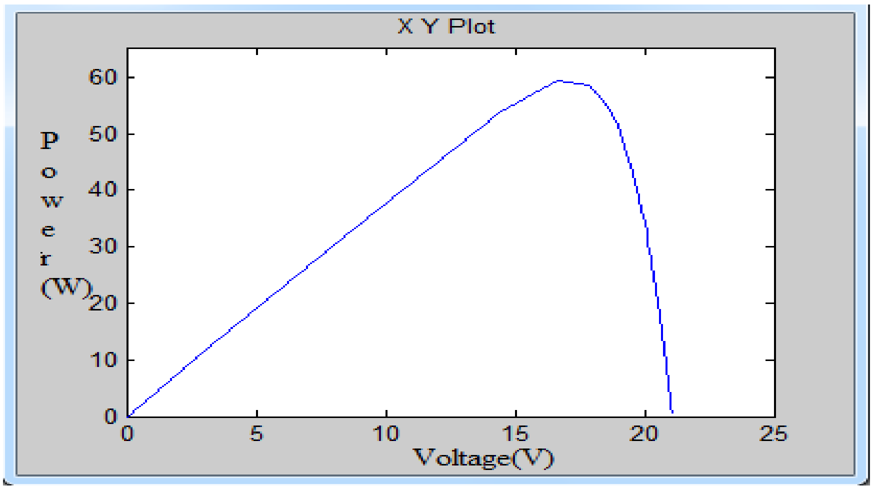

Fig.17 P-V characteristics of PV array

The simulation of MPPT which is carried out in MATLAB/SIMULINK is shown in Fig.18. The voltage and current values for the simulation is obtained from the output of PV array.

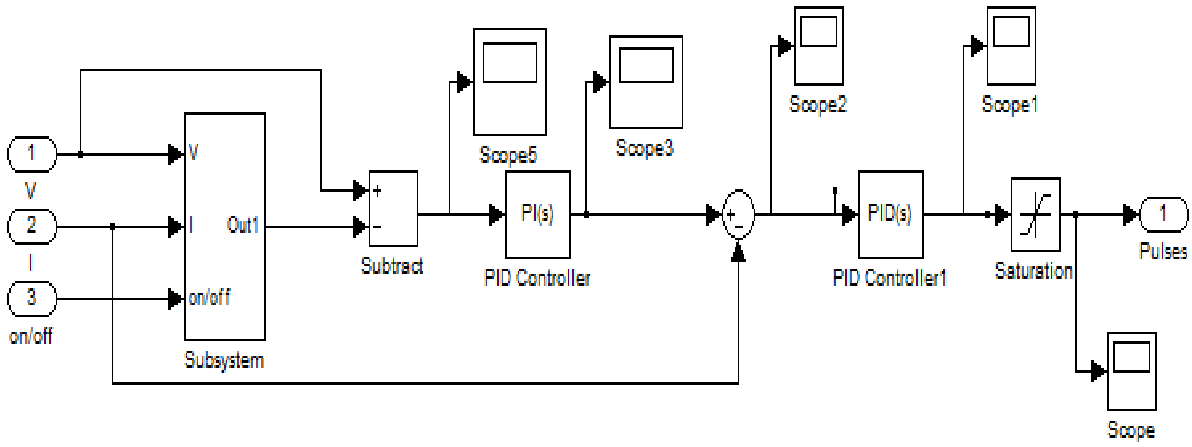

Fig.18 Simulation model of MPPT

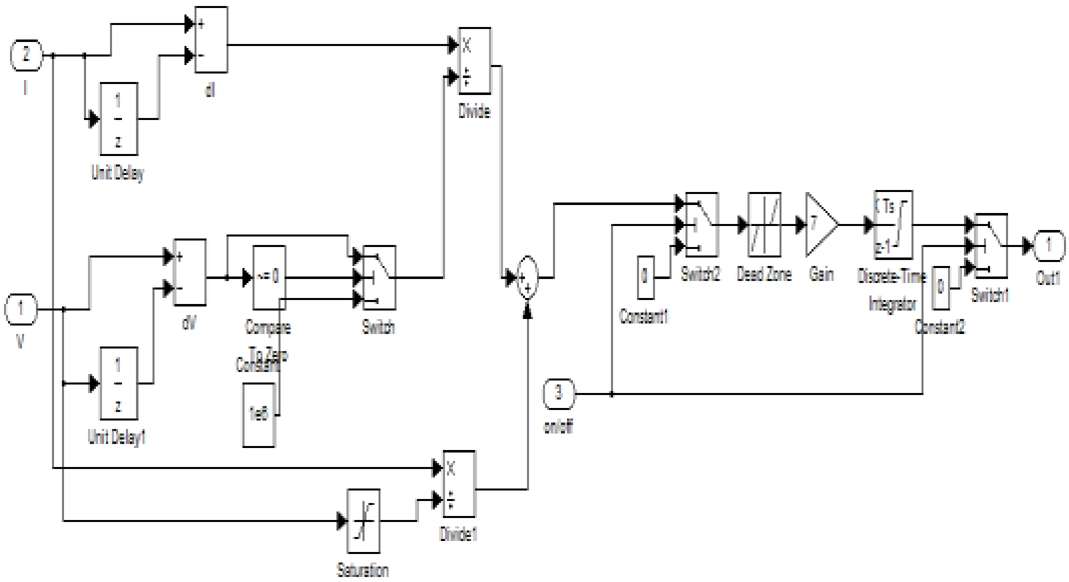

Fig.19 Simulation of incremental conductance

The PV array along with MPPT algorithm is interfaced with the proposed SL-QZSI to vary the shoot through state and the line to line voltage is shown in Fig.20.

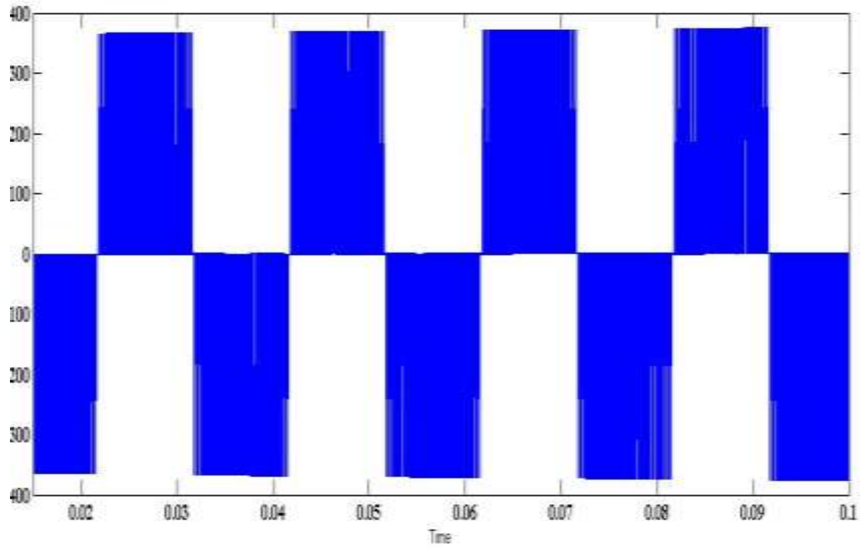

Fig.20 Output line to line voltage waveform of SL-QZSI

The output of MPPT varies the shoot through duty ratio of the inverter. Therefore, SL-QZSI topology is a valid candidate for photovoltaic applications as it avoids the use of bulky intermediate DC-DC converter.

VII. CONCLUSION

The three phase switched inductor quasi Z-source inverter with a resistive load has been simulated with modulation strategies namely simple boost, maximum boost and maximum constant boost control. A comparison has been drawn between these control strategies and the performance parameters of the inverter has been investigated. PV array has been simulated and incremental conductance algorithm has been used to track the maximum power point. The output of MPPT also varies the shoot through duty ratio of the inverter. SL-QZSI topology is a valid candidate for photovoltaic applications as it has wide range of gain. Furthermore, the proposed SL-QZSI has advantages of high boost voltage inversion ability, reduced source stress, and lower component ratings when compared to the traditional ZSI.

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