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Modelling and Simulation of Z-Source Inverter for PV Based Stand-alone System

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Abstract
Z-source inverters are recent inverter topologies that can perform both buck and boost functions in a single unit. Z-source inverter is connected to PV array with MPPT incremental method. This inverter operates in three modes. They are active mode in which inverter output is generated, null mode in which inverter output is shorted the load and shoot through control method in which the inverter output is zero and the inverter input is boosted with shoot through pulses. By using shoot through control methods Z-source components (L&C) where calculated for designing.

The inverter is controlled with two different PWM control techniques. They are simple boost PWM (SBPWM) control method and third harmonic injected maximum constant boost PWM (THIMCB) control method. For the desired output LC filter component where calculated and incorporated in circuit. The output is connected to standalone RL load. This modelling is prepared in MATLAB Simulink model and tested and it’s simulation results are discussed.

1. Introduction

Conventional converter topologies such as voltage source inverter (VSI) and current source inverter (CSI) are commonly used as power electronics circuits for power conversion purposes. The VSI produces an ac output (after filtering it) which is limited below the dc input voltage, which means that VSI is buck type converter. The buck operation nature of the VSI limit its operation to power conversion applications and ac drive circuits. An additional dc-dc unit is connected to the dc input of the converter in order to further increase the dc input voltage, which leads to an increase in the ac output voltage. As a result; the additional dc-dc boost converter increases the system cost, control complexity and reduces the efficiency. Furthermore, any misgating for the inverter bridge switches cause short circuit and destroys the power switching devices. For that, a dead-time is set between the upper and the lower switching devices at the same leg in order to avoid short circuit occurrences.

On the other hand, for CSI type of converter, the output voltage is always greater than the input voltage. In order to have an output voltage which is less than the input an additional dc-dc buck converter is installed at the input of the CSI. Which increase the cost, control complexity and reduces the overall efficiency.

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Besides the fact that the lower and the upper switches should be turned-on simultaneously, if not; an open circuit for the dc input source cause huge current flow and destroys the power switching devices.

The idea of impedance-source converter (ZSI) was originally developed due to the limitation in VSIs and CSIs. The conceptual and theoretical limitations in the conventional converters types limited their application and complicate their control methods. While the ZSI great advantage can be seen as: it can operate as VSI inverter (buck type) or as CSI inverter (boost type) depending on the application. Where the output voltage can ideally ranges from zero to infinity.

2. MODELLING OF PV CELL

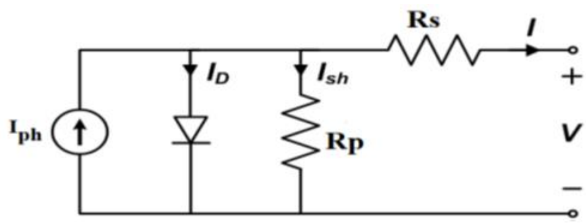

Figure 1: Modeling of PV cell

Rs is the intrinsic series resistance whose value is very small.

Rp is the equivalent shunt resistance which has a very high value.

Applying KCL then

$$I_{ph} = I_D + I_{sh} + I$$

………… (1)

PV current

$$I = I_{ph} - I_D - I_{sh}$$

……….. (2)

$$I = I_{ph} - I_0\left[\exp(\frac{V + IR_s}{V_T}) - 1\right] - \left[\left(\frac{V + IR_s}{R_p}\right)\right]$$

……… (3)

Where Iph is the Isolation current, I is the Cell current, I0 is the saturation current, V is the Cell voltage, Rs is the Series resistance, Rp is the Parallel resistance, VT is the Thermal voltage (KT/q) K is the Boltzmann constant (1.38×10^{-23} J/K), T is the Temperature in Kelvin, q is the Charge of an electron (1.6×10^{-19} C).

Simplified Model for an ideal PV cell (no series loss and no leakage to ground, i.e., RS = 0 and Rp = ∞, respectively).

$$I = Iph - I0\left[\exp\left(\frac{q}{KTA} * \frac{V}{Ns}\right) - 1\right]$$

………… (4)

The photo current I**ph** depends on the solar radiation(S) and cell temperature (Tr) as follows

$$I_{ph} = [I_{sc} + K_i(T - T_r)]\frac{S}{1000}$$

…...... (5)

Where Isc is the cell short-circuit current at reference temperature and radiation, K**i** is the short circuit current temperature coefficient

The cell saturation current varies with the cell temperature, which is described as

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$$I_0 = I_{RS}\left[\frac{T}{T_r}\right]^3 \exp\left[qE_G \frac{\left[\frac{1}{T_r} - \frac{1}{T}\right]}{KA}\right]$$

……… (6)

Where IRS is the cell reverse saturation current at reference temperature and solar radiation EG is the band-gap energy of the semiconductor used in the cell.

The reverse saturation current at reference temperature can be approximately obtained as

$$I_{RS} = \frac{I_{SC}}{\exp\left[\frac{qV_0}{NsKAT}\right] - 1}$$

………… (7)

2.1 MODELLING OF PV MODULE AND ARRAY

Since a PV cell produces very low power, the cells should be arranged in series-parallel configuration on a module to produce enough power. As mentioned earlier, PV array is a group of PV modules which are connected in series and parallel circuit configurations to generate the required current and voltage. The equivalent circuit for a PV module arranged in N_P parallel and N_S series cells.

$$I = N_P I_{ph} - N_P I_0\left[\exp\left[\frac{\frac{V}{N_s} + \frac{IR_s}{N_P}}{V_T}\right] - 1\right] - \left[\frac{\frac{V}{N_S} + \frac{IR_s}{N_P}}{R_P}\right]$$

…….(8)

The PV mathematical model used to simplify our PV array is represented by the equation where NS = NP = 1 for a PV cell, NS and NP are the series-parallel number for a PV array.

$$I = n_p I_{ph} - n_p I_0\left[\exp\left[\frac{q}{KTA} * \frac{V}{n_s}\right] - 1\right]$$

……. (9)

Where

I is the PV array output current

V is the PV array output voltage

Ns is the number of modules in series

Np is the number of modules in parallel

A is the p-n junction ideality factor

T is the cell temperature (K)

I0 is the cell saturation current.

The factor A in equation determines the cell deviation from the ideal p-n junction characteristics; it ranges between 1-5 for our case A=2.46

The power can be calculated using equation as follows

$$P = IV = n_p I_{ph} - n_p I_0 V\left[\exp\left(\frac{q}{KTA} * \frac{V}{n_s}\right) - 1\right]$$

…………… (10)

3. Z–SOURCE INVERTER

A traditional inverter (VSI or CSI) if connected directly to PV module would require a higher maximum power point MPP voltage because of a module manufacturing tolerance.

A traditional VSI and CSI technology has advanced to the new Z-source inverter (ZSI) with a built-in impedance network. It can be seen that there is no need for DC boost converter if ZSI is used without any change in the objective of PV system.

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Three phase ZSI is as shown in figure. ZSI can be controlled by PWM technique.

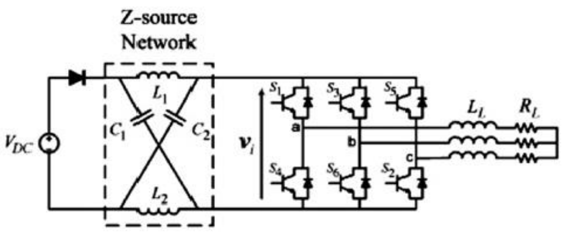


Figure 2: ZSI circuit

A Z-source inverter based drives can:

- Produce any desired output a voltage, even greater than the line voltage, regardless of the input voltage, thus reducing motor ratings.
- Provide ride-through during voltage sags without any additional circuits.
- Improve power factor reduces harmonic current and common – mode voltage.

3.1 OPERATION OF Z-SOURCE INVERTER

Z-source inverter has 3 possible switching states

- Active states(six)
- Zero (Null) states(two)
- Shoot through states(seven)

In active states one switch in each arm (upper switch in first leg and lower switch in second leg or vice versa) will conduct thus a finite output will appear across load. In zero state the switches in upper arm or switches in lower arm will conduct. There will be zero voltage across the load.

In shoot-through state the load terminals are shorted through both the upper and lower switches of any one leg or both the legs.

In shoot through mode a diode placed at the input side is reversed biased and the capacitor charge the inductor and voltage across the inductor is

$V_{L1} = V_{C1}$ and $V_{L2} = V_{C2}$ ……………… (11)

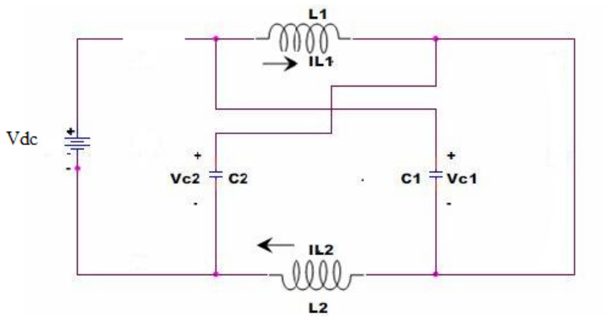


Figure 3: Shoot through mode

It is assumed that the impedance network is a symmetric network $(C_1 = C_2 = C)$ and $(L_1 = L_2 = L)$ it can be observed that

$V_{L1} = V_{L2} = V_L$ and $I_{L1} = I_{L2} = I_L$

The DC link voltage across the inverter bridge during shoot through interval is

$V_i = 0$ …………………. (12)

The inductor voltage in two modes

Shoot through mode $V_L = V_C$ ……………………… (13)

$V_{dc} = 2V_C$

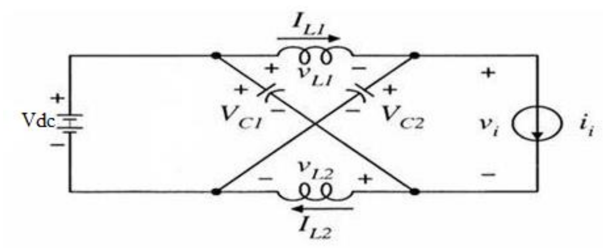


Figure 4: Non-shoot through mode

Non -shoot through mode $V_L = V_{dc} - V_C$ ……………………… (14)

The average inductor voltage over one switching period is zero.

$$V_L = \frac{T_0 * V_C + T_1 * (V_{dc} - V_C)}{T} = 0$$

…………………………………… (15)

$$\frac{V_C}{V_{dc}} = \frac{T_1}{T_1 - T_0}$$

…………...................................... (16)

Where

V_L - Inductor Voltage

V_C - Capacitor Voltage

V_{dc} - Input DC Voltage

T_1 - Non-Shoot through period

T_0 - Shoot through period

T - Total switching period = $T_0 + T_1$

Capacitor voltage of Z-source network is given as

$$V_C = \frac{T - T_0}{T - T_0 - T_0} V_{dc}$$

………………………… (17)

$$V_C = \frac{1 - \frac{T_0}{T}}{1 - 2\frac{T_0}{T}} V_{dc}$$

………………………….. (18)

$$V_C = \frac{1-D}{1-2D} V_{dc}$$

…………………………. (19)

D (Duty Cycle) $= \frac{T_0}{T}$

Peak dc voltage V_i appearing across inverter input is

$$V_i = V_C - V_L = V_C - V_{dc} + V_C = 2V_C - V_{dc}$$

$$= 2\left(\frac{T_1}{T_1 - T_0}\right) V_{dc} - V_{dc}$$

$$= \frac{T}{T_1 - T_0} V_{dc}$$

$$\Rightarrow V_i = BV_{dc}$$

………………………… (20)

B- Boost factor of inverter

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 non-shoot through states of the PWM inverter.

The shoot-through zero state does not affect PWM control of the inverter. Because, it equivalently produces the same zero voltage to the load terminal, the available shoot- through period is limited by the modulation index.

$$B = \frac{T}{T_1 - T_0} = \frac{1}{\frac{T_1 - T_0}{T}} = \frac{1}{\frac{T - T_0 - T_0}{T}} = \frac{1}{1 - 2\frac{T_0}{T}} \geq 1$$

…………… (21)

From above equation $\frac{T_0}{T} = \frac{B-1}{2B}$

From equation (3.8) $V_C = \frac{B+1}{2} V_{dc}$

$$V_i = BV_{dc} = B * \frac{2V_C}{B+1} = \frac{2B}{B+1} V_C$$

………. (23)

The output peak phase voltage from the inverter can be expressed as

$$\hat{V}_{AC} = \frac{MV_i}{2} = \frac{MBV_{dc}}{2}$$ ………. (24)

Where M is the modulation index (M≤1).

Z-network components design

Inductor design

Inductor value is calculated using

$$L = \left[\frac{V * T_0}{\Delta I_L}\right]$$ …………. (25)

Where $\Delta I_L = \hat{I}_L - \breve{I}_L$

T_0 is the ST period per switching cycle and can be calculated using

$$B = \frac{T}{T_1 - T_0} = \frac{1}{1 - 2\frac{T_0}{T}}$$

T=1/Switching frequency, F

Capacitor design

The capacitor value can be roughly calculated using

$$C = \frac{I_L * T_0}{\Delta V_C}$$ ………… (26)

Where T_0 is the ST period per switching cycle, IL is the average current through the inductor and $\Delta V_C = V * 3\%$.

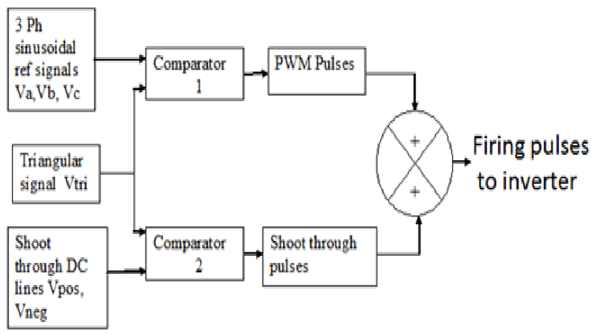
4. ZSI CONTROLLING METHODS

There are a few control methods that have been proposed: simple, maximum boost and maximum constant boost control. Unlike the traditional inverters, the ZSIs have an extra ST state during which the output voltage to the load terminal is zero. In order to maintain the sinusoidal output, the active state duty ratio remains unchanged and all or some of the zero states are turned into ST states.

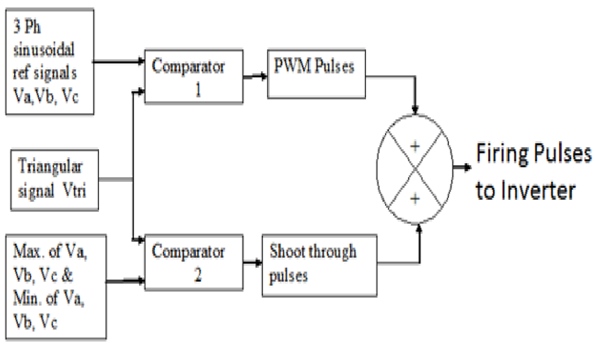
4.1 Types of PWM control methods

1. Simple Boost control (SBPWM)
2. Maximum Boost control (MBPWM)
3. Third harmonic injection maximum constant boost control (THIMCBPWM)

Simple Boost control Algorithm



Maximum Boost Control Algorithm



Third Harmonic Injection Maximum constant boost control Algorithm

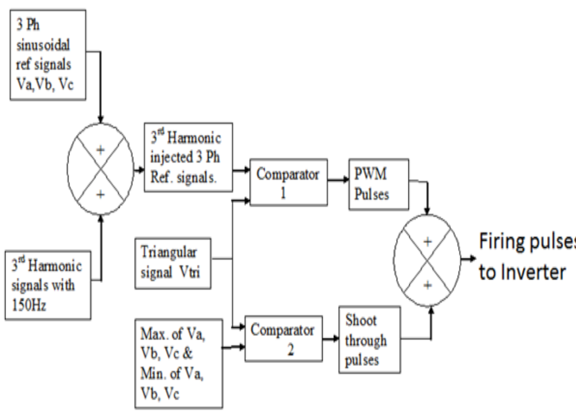


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Table 1: Parameters of ZSI with different PWM control

PWM control Algorithm	Shoot Through Duty Ratio (d)	Boost factor (B)	Voltage Gain (G)	Voltage Stress (Vstress)
SBPWM	$1-M$	$\frac{1}{2M-1}$	$\frac{M}{2M-1}$	$\frac{1}{2M-1}V_B$
MBPWM	$\frac{2\Pi-3\sqrt{3}M}{2\Pi}$	$\frac{\Pi}{3\sqrt{3}M-\Pi}$	$\frac{\Pi M}{3\sqrt{3}M-\Pi}$	$\frac{\Pi}{3\sqrt{3}M-\Pi}V_B$
THIMCB PWM	$1-\frac{\sqrt{3}M}{2}$	$\frac{1}{\sqrt{3}M-1}$	$\frac{M}{\sqrt{3}M-1}$	$\frac{1}{\sqrt{3}M-1}V_B$

Table 2: Required Passive components values for ZSI circuit

PWM controls	Modulation Index (M)	Boost Factor (B)	Z-source components		LC filter components	
			L (mH)	C (µF)	Lf (mH)	Cf (µF)
SBPWM	0.7	2.5	51.5	97.11	45.51	55.71
THIMCBPWM	0.7	4.708	110.25	78.16	85.71	29.58

5. SIMULATION RESULTS AND DISCUSSION

The modeling and simulation is performed in MATLAB Simulink model. ZSI control with shoot through mode has developed for stand-alone with PV array based input. In shoot through control mode, Simple boost control technique and Third harmonic injection maximum control boost techniques used. In these techniques modulation index is taken as 0.7 and switching frequency is 1 KHz. With the PV array input parameters ZSI components were calculated for both the control techniques.

5.1 Input Data for PV Array

Table 3: PV Array parameters

Parameters	Symbol	Value
Open circuit voltage (V)	Voc	686.4
Short circuit current (A)	Isc	10.84
Maximum power point voltage (V)	V_{MPP}	598.4
Maximum power point current (A)	I_{MPP}	10.17
Maximum power point power (W)	P_{MPP}	6085
STC operating temperature (^{0}C)	T	25
STC operating irradiance (W/m^2)	G	1000

Z-source Inverter assumed parameters values

Modulation index (M) taken as 0.7

Switching frequency (Fsw) taken as 1 KHz

Z-source Inverter parameters calculated values

Simple Boost PWM Control Method

Boost factor (B) = 2.5

Shoot through time per cycle (T0) = 300µs

Third Harmonic Injected Maximum Constant Boost PWM Control Method

Boost factor (B) = 4.708

Shoot through time per cycle (T0) = 393.8µs

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5.2 Simple Boost PWM control Simulink Model

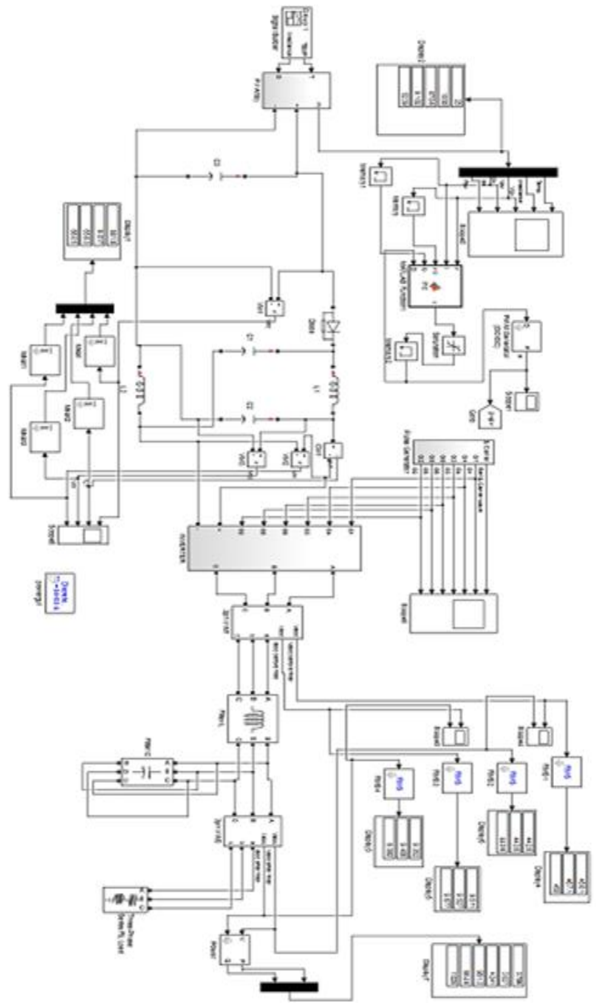

Figure 5: SBPWM Simulink Model

Output Voltages and Current at Load Side for SBPWM Technique

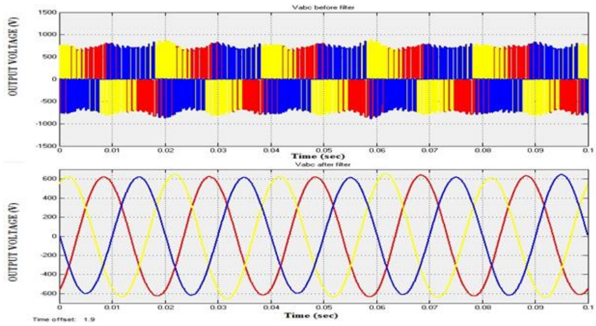

Figure 6: Vabc output wave forms before and after filter.

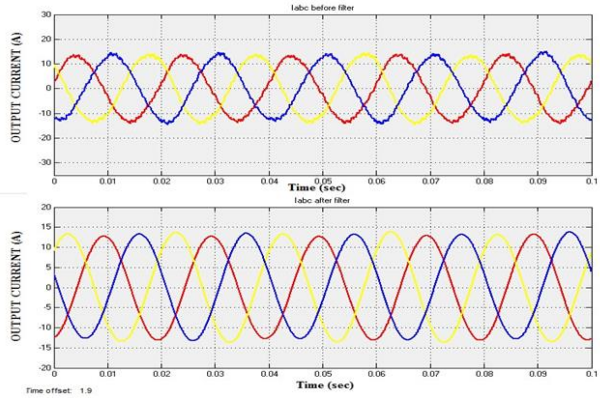

Figure 7: Iabc output wave forms before and after filter

5.3 THIMCB PWM control Simulink Model

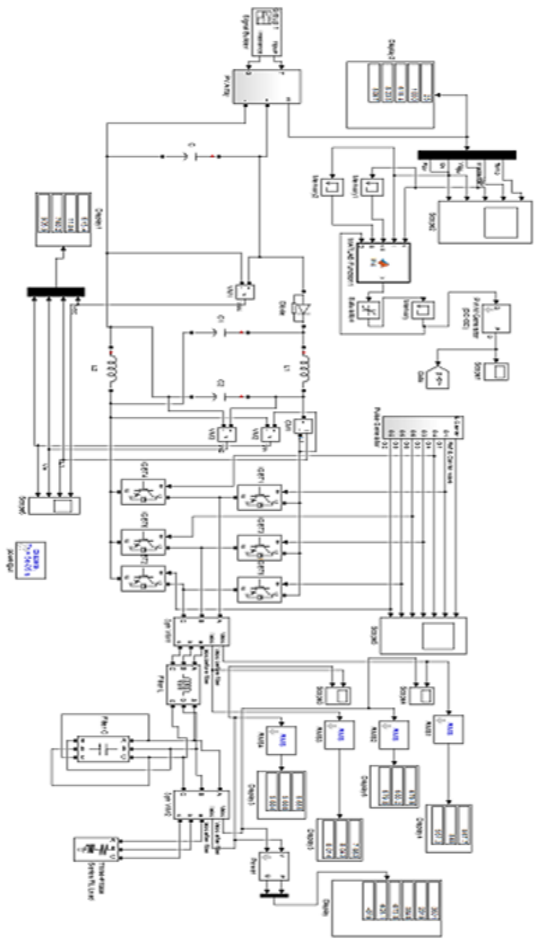

Figure 8: THIMCB PWM control Simulink Model

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Output Voltages and Current at Load Side for THIMCB PWM Technique

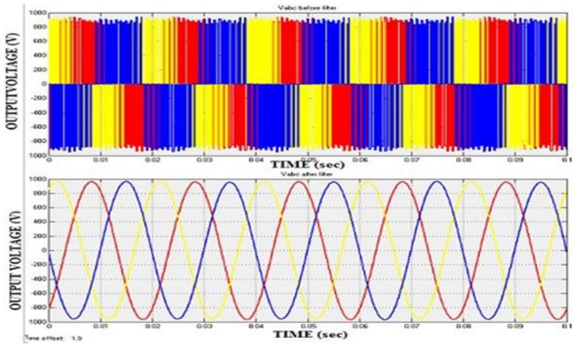

Figure 9: Vabc output wave forms before and after filter.

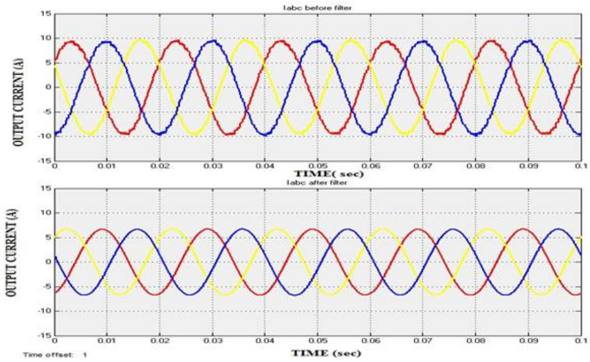

Figure 10: Iabc output wave forms before and after filter.

Table 4: Output Values of PV Model and ZSI

Parameters	Symbol	Value	
		SBPWM	THIMCB
PV OUTPUT VOLTAGE (V)	V_{PV}	5	615
PV OUTPUT CURRENT (A)	I_{PV}	9.18	8.23
PV OUTPUT POWER (W)	P_{PV}	5239	5067
ZSI OUTPUT VOLTAGE BEFORE FILTER [Ph-Ph] (V)	V_{abc}	458	565
ZSI OUTPUT CURRENT BEFORE FILTER (A)	I_{abc}	9.52	8.0
ZSI OUTPUT VOLTAGE AFTER FILTER [Ph-Ph] (V)	V_{ABC}	443.6	679.9
ZSI OUTPUT CURRENT AFTER FILTER (A)	I_{ABC}	9.38	5.68
ZSI OUTPUT POWER [/Ph] (W)	P_O	3027	2819

6. CONCLUSION

A brief discussion has given regarding the photovoltaic system like operation and types of solar panels. PV array has been designed in mathematical modeling method in MATLAB Simulink model and its graphs observed. PV system MPPT incremental conductance method discussed. A comprehensive comparison of the three inverter system has been performed. The comparison shows that the z-source inverter can increase inverter conversion efficiency by 1% over the two existing inverter topologies. The z-source inverter topology can minimize stresses and size of the PV system and increase output power greatly. The existing two inverter systems suffer the shoot through reliability problem.

Shoot through PWM techniques has been developed for the PV array based ZSI with standalone load has developed. In the shoot through control method Simple Boost control PWM technique and Third harmonic injection maximum constant boost control PWM techniques used. Modulation index verses other parameters graph developed for easy comparison. With shoot through state PWM control the ZSI components and LC filter components calculated. The ST PWM control algorithms developed in MATLAB Simulink model and connected it to PV based ZSI and simulated. The output values and wave forms observed.

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