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Three Level Z source Inverter Based Photovoltaic Power Conversion Systems

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***Abstract*— A Z-source inverter (ZSI) has a unique ability to achieve single stage voltage buck-boost operation for energy conversion. This paper presents a three level ZSI using a single impedance network for photovoltaic (PV) application. A single LC impedance network is used between DC voltage source and neutral-point-clamped (NPC) inverter to achieve the desired stepped-up and stepped-down output voltage level. Alternative phase opposition and disposition (APOD) modulation technique with proper triplen offset and appropriate addition of time delay/advance is used to achieve the required boost in DC link voltage. A traditional MPPT technique is used to introduce a shoot-through interval in switching waveform to extract the maximum power from the PV panel. Traditional MPPT technique does not allow to boost the Z-network capacitor voltage more than the maximum power point (MPP) voltage of the PV array. This paper also presents a unified voltage control technique to track the MPPT and also maintains the desired Z-source capacitor voltage level. The design, implementation and control of single impedance network based multilevel ZSI for photovoltaic application is discussed and their MATLAB/Simulink simulation and results are presented in the later section of the paper to validate proposed control scheme in PV application.**

Keywords— Z-Source Inverters, Neutral point clamped (NPC), MPPT algorithm, and Capacitor voltage control.

I. INTRODUCTION

The rapidly increasing demand of energy from all across globe has urged the society to go for alternative energy sources because of declining fossil fuel reserves, increasing global warming etc. Out of all available and feasible alternative energy sources, photovoltaic (PV) energy is the most popular and promising one [1]. Inverter topologies play a crucial role in PV generation system. Out of various techniques for power conversion system (PCS), the two stage converters are commonly used to boost up the DC output voltage of the PV panel up to the desired voltage level to meet the AC load demand [2]-[6]. A ZSI topology overcomes the limitations and disadvantages of most commonly used voltage source inverter (VSI) and current source inverter (CSI) [7]. The block diagram of a ZSI based DC to AC PCS is shown in Fig.1. Desired AC output voltage is maintained by boosting the input DC link voltage level using the shoot-through state, which is not permitted in the traditional inverters. In recent years multilevel inverters are gaining attention of researchers and manufactures because of their ability to produce better performance in terms of output waveforms, lesser total harmonic distortion (THD). Three level ZSIs provide a single stage voltage buck-boost operation based energy conversion while retaining all favorable advantages of traditional inverters. The power circuit of three phase ZSI for PV system using traditional shoot-through control is shown in Fig.2. Topology of a single impedance based NPC three level ZSI for buck-boost operation [8]-[10] is illustrated in Fig.3. APOD carrier based modulation technique with a proper triplen offset and appropriate addition of time delay/advance is used to control the single impedance based three level NPC-ZSI for PV system.

There are various methods to control the DC link voltage along with the AC output voltage of an inverter [11]-[13]. A simple power feedback based method is used to achieve MPPT in a single phase ZSI based PV system [14]. Generally, in a ZSI based PV system MPPT controller gives a duty ratio which is used to introduce the shoot-through state so as to maintain the PV output voltage at maximum power point (MPP). If the load power demands changes then the inverter DC link voltage level is adjusted accordingly to meet the load demand. To achieve this Z-network capacitor voltage of ZSI should be increased/decreased. A traditional MPPT controller is unable to boost the Z- network capacitor voltage beyond MPP. This paper also incorporates a unified voltage control technique to track the MPPT and also achieves the desired capacitor voltage control.

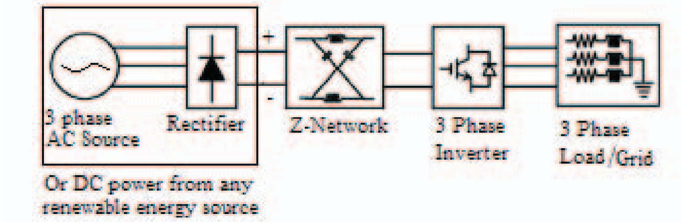

Fig.1. Block diagram of ZSI based PCS.

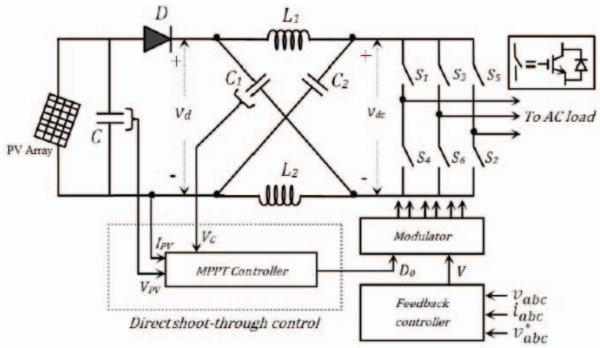

Fig.2. Three phase ZSI based photovoltaic PCS

II. OPERATION OF SINGLE IMPEDANCE NETWORK BASED THREE-LEVEL Z -SOURCE INVERTERS

Fig. 3 illustrates the topology of three level ZSI using a single impedance network, having two capacitors (C_1 and C_2) and two inductors (L_1 and L_2) connected between the input DC voltage source and NPC inverter.

To achieve the buck operation, the pole voltage of ZSI translates between the three distinct voltage levels of $+V_{dc}$, 0 V, $-V_{dc}$ similar to a traditional three phase three level inverter. In order to achieve the voltage boost operation shoot-through state is introduced in the switching sequences. A simple method of introducing the shoot-through state is to turn on all switches of a particular leg simultaneously (e.g., SA1, SA2, SA3, SA4 of phase leg A or SB1, SB2, SB3, SB4 of phase leg B in Fig. 3) which gives an equivalent circuit with diodes D1 and D2 open circuit as shown in Fig. 4(a). Thus ZSI inverter topology does not require dead-time delay for short circuit protection to protect the switches from longer duration of the short circuit current.

From the equivalent circuit representation as illustrated in Fig. 4(a) and for a symmetrical network it is assumed that that inductor voltages $v_{L1} = v_{L2} = v_L$ and capacitor voltages$V_{C1} = V_{C2} = V_C$, then the Z-network capacitor and inductor voltages during the shoot-through interval T_0 is expressed as:

$$v_L = V_c \tag{1}$$

And during a non-shoot-through interval (T_1), the equivalent illustrated in Fig. 3(b) comes in operation. During the non-shoot through state inverter circuit and load are treated as current source. From this equivalent circuit, the capacitor voltage and inductor voltage are given as

$$v_L = V_0 - V_C \tag{2}$$

Average of v_L for one complete switching cycle T gives

$$\frac{V_C}{V_0} = \frac{T_1}{T_1 - T_0} \tag{3}$$

Using equation (3), the DC link voltage (V_i) and the AC output voltage, Vx (x = A, B or C) of the inverter during a non-shoot-through state are given as:

$$V_i = V_C - v_L = 2V_C - V_0 = \frac{1}{1-\frac{2T_0}{T}} V_0 \tag{4}$$

$$Vx = M.\frac{V_i}{2} = M.B_f.\frac{V_0}{2}$$

Where, M is the modulation index and $B_f = \frac{T}{T_1 - T_0}$ is the boost factor.

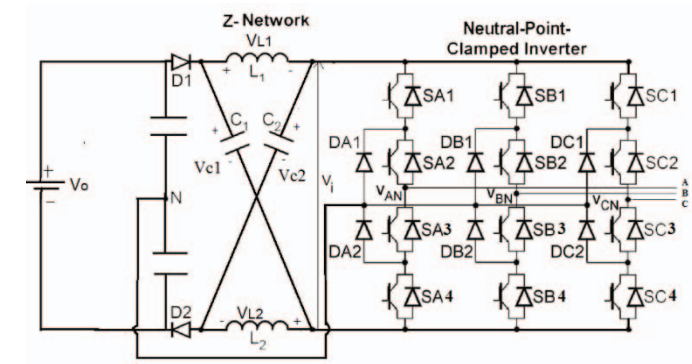

Fig.3. Three level NPC ZSI topology using only a single LC impedance network

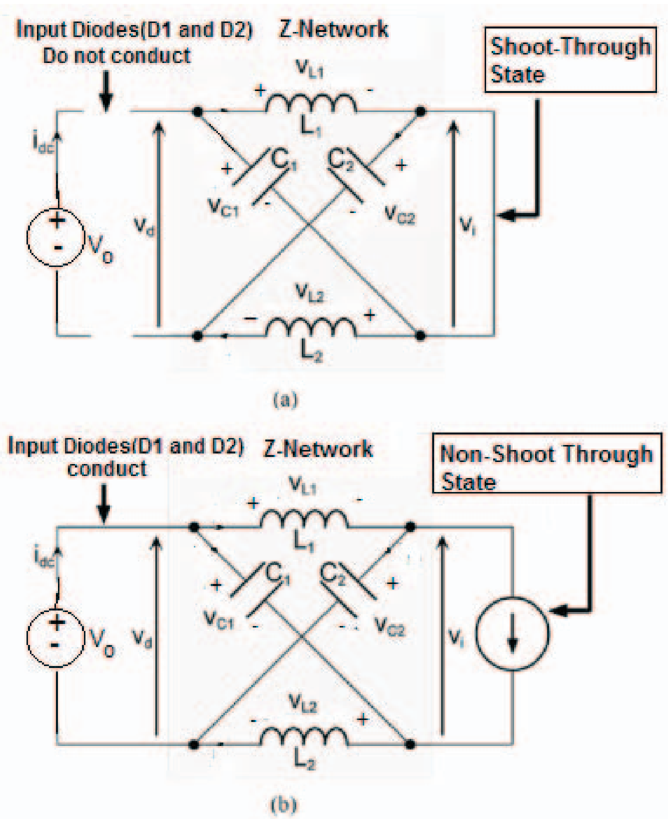

Fig.4. The Equivalent circuit representations of single impedance based ZSI during (a) shoot-through state and (b) non-shoot-through state.

III. MODULATION SCHEME

APOD based modulation technique for controlling the three level ZSI is discussed in [12]. To introduce the required shoot-through interval in the inverter switching state, it is ensured that in all switching instances correct volt-sec average is synthesized. Considering this criterion, the feasible state sequence to control a traditional three level inverter is illustrated in Fig.5. In this figure the two triangular carriers which are vertically disposed and have 180º phase shift are used to form the APOD carrier placement arrangements. In addition with two triangular carriers, three sinusoidal reference signals are also required to carry out the comparison of sinusoidal references with the

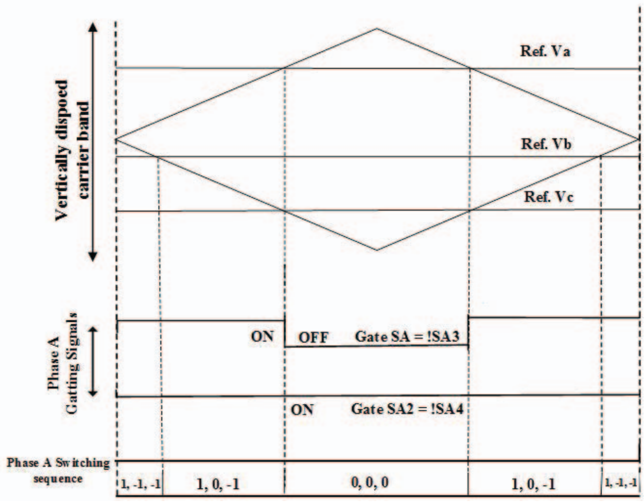

Fig.5 APOD modulation for traditional three-level inverters

triangular carriers to generate gating signals for two independent switches of a particular leg (SA1 and SA2 of phase leg A). While remaining Complementary switches of that particular leg (SA3 and SA4 of phase leg A) are driven by logically NOT signals, as it is reported in Fig.5. From the generated switching state sequence as reported in Fig.5, it can be observed that in APOD based three level NPC inverter, state{0,0,0} is always present in the switching state sequence. So partially replacing the zero state with the shoot-through state as illustrated in Fig.6 will provide the required boost in the DC link voltage of ZSI.

In Fig.5 it can be observed that the two reference signals $V_{a(SAU)}$ and $V_{c(SCL)}$), is used to insert the shoot-through state by modifying the switching on time of switches SA1 and SC4. The original reference signals V_a and V_c (renamed as $V_{a(SAL)}$ and $V_{c(SCU)}$, Fig.5) are used to control the termination of shoot-through state by turning off the switches SA3 and SC2. A vertical offset of T0/T is added to the reference V_a and same offset is subtracted from reference, V_c to generate the additional references $V_{a(SAU)}$ and $V_{c(SCL)}$.This reference generation process is generalized by subtracting the vertical

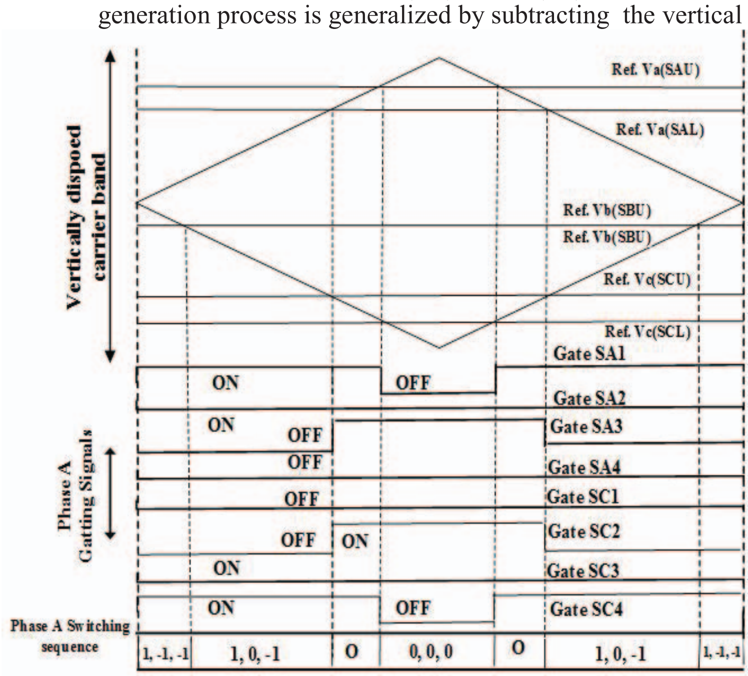

Fig.6 APOD modulation for three level ZSI

offset of T_0/T from the "minimum" reference (V_{min}= min(V_a,V_b,V_c) while adding the offset T_0/T to the "maximum" reference (V_{max}=max(V_a,V_b,V_a) to get the required references needed to control the ZSI. In this reference generation process (V_{mid} = mid(V_a,V_b,V_c)=) is not modified.

A triplen offset (V_{offset}) given by equation (5) is properly added to the required three original sinusoidal references, so that the resulting references are centered vertically within the disposed triangular carrier bands, thus give a synchronized gating signal for phase A and phase C. On adding offsets to all original sinusoidal references, the resulting set of required references to control the single impedance network based NPC three-level ZSI is given as:

$V_{max(SXU)} = V_{max} + V_{offset} + T_0/T$

$V_{max(SXL)} = V_{max} + V_{offset}$

$V_{mid(SXU)} = V_{mid} + V_{offset}$

$Vmid_{(SXL)} = Vmid + V_{offset}$

$Vmin_{(SXU)} = Vmin + V_{offset}$

$Vmin_{(SXL)} = Vmin + V_{offset} - T_0/T$

$V_{offset} = -0.5(\max(V_a,V_b,V_c) + \min(V_a,V_b,V_c))$ (5)

where X= A, B, or C; U= 1 and 2; L= 3 and 4 (6)

IV. UNIFIED VOLTAGE CONTROL TECHNIQUE

The PV array possesses a non-linear I-V and P-V characteristics as illustrated in Fig. 7. The PV output voltage and current varies with variation in environmental condition of irradiance and temperature [15]. To harness the maximum power from PV panel different types of MPPT techniques are available [16]-[18]. Fig. 8(a) illustrates the operating principle of a traditional MPPT controller for a Z-source inverter based PV power conversion system (PCS). In a traditional MPPT technique the MPPT controller directly controls the shoot-through interval and accordingly reference signals can be generated as per expression (5) and (6). The Z-network capacitor voltage level is boosted as per the generated shoot-through time period, calculated by the MPPT controller. It is not possible to increase capacitor voltage beyond MPP voltage of PV panel, as the generated shoot-through states can only track the MPP voltage. So, the traditional MPPT algorithms can not boost Capacitor voltage beyond MPP voltage value. Fig. 8 (b) shows a unified voltage control technique which tracks the MPPT and also achieves the desired capacitor voltage control. In this MPPT technique an extra shoot period, (T'_0) is generated to increase Z-network capacitor voltage beyond maximum power point voltage of PV panel. The extra generated shoot through interval (T'_0) is added to the MPPT generated shoot-through period (T_0) to obtain the total shoot through time period (T_{sh}). The flowchart of unified control technique is shown in Fig.9, which tracks the MPPT and also maintains the desired Z-network capacitor voltage.

A. MPPT Algorithm

There are two stages in the flowchart of the unified voltage control technique, shown in Fig. 9. The first stage of the flowchart generates the shoot through time period (T_0) to track the MPPT by boosting the capacitor voltage level to the MPP voltage level while the second stage of the flowchart generates extra shoot through time period to provide the required boost in the Z-network capacitor voltage beyond MPP voltage level, if required. By adjusting the shoot-through time period, the inverter DC link voltage can be maintained to the desired voltage level by controlling the Z-network capacitor voltage. Perturb and Observe (P&O) MPPT technique is employed to extract the maximum power from the PV panel [19] [20]. In P&O algorithm, the output power of PV panel is continuously measured and change in power is observed and accordingly shoot-through time period is adjusted to achieve the MPP voltage. The Z-network capacitor voltage is also updated accordingly till capacitor achieves the MPP voltage, (V^*_{PV}) and thus maximum power is extracted from the PV array

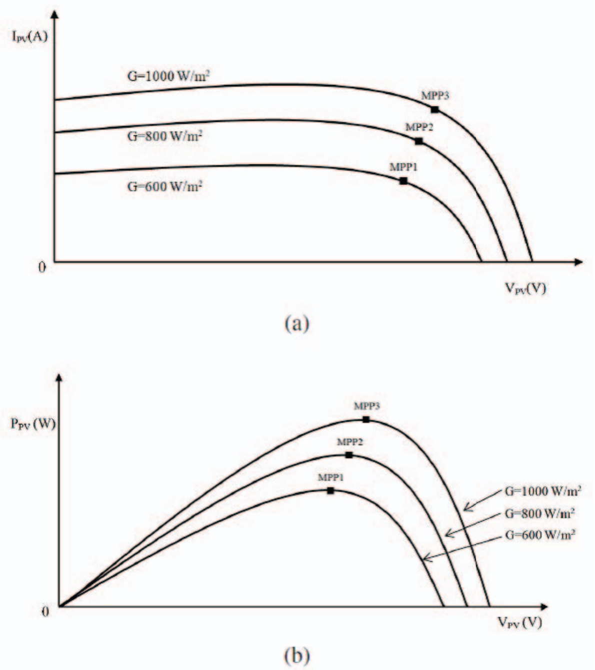

Fig. 7. The non-linear (a) I-V and (b)P-V characteristics of a PV array.

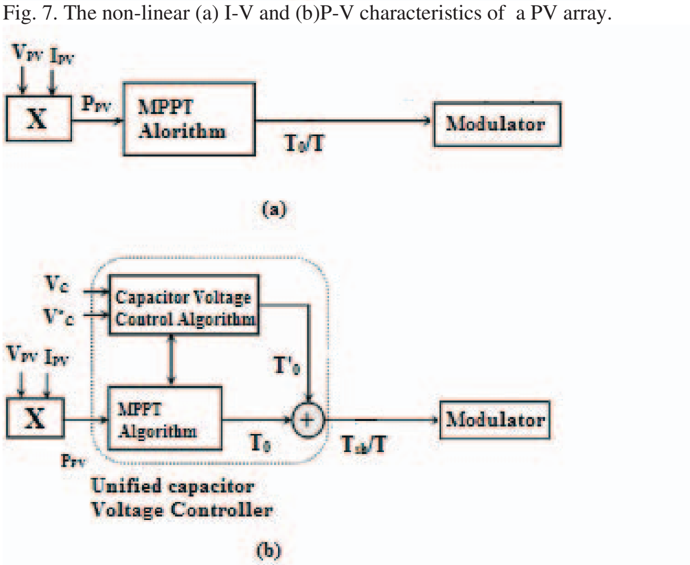

Fig.8. ZSI based PV-PCS capacitor voltage control mechanism (a) Traditional MPPT controller (b) Unified voltage controller.

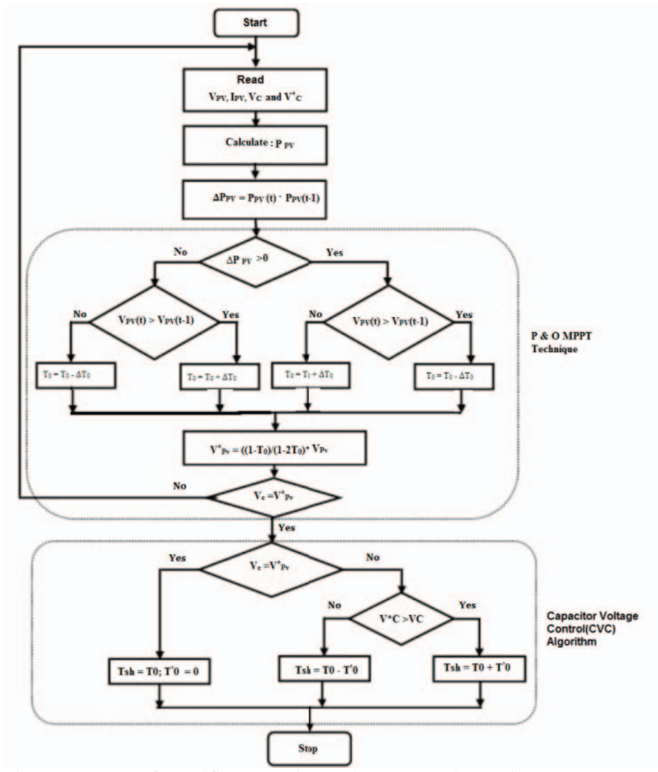

Fig.9. Flowchart for unified capacitor voltage control technique.

Equation (4) can be expressed as follow:

$$V_i = \frac{1}{1-\frac{2T_0}{T}} V_{PV} = V^*_{PV} \tag{7}$$

B. Capacitor voltage control (CVC) algorithm

Using MPPT technique Z-network capacitor voltage is raised to MPP voltage level. After achieving the MPP voltage the actual Z-network capacitor, (V_c) is compared with the desired/reference capacitor voltage, (V^*_C) which decides the ZSI DC link voltage level. If it is found that the reference capacitor voltage is same as the actual capacitor voltage (i.e. $V_c=V^*_C$) then no extra shoot-through period (T'0) is required. If MPP voltage is achieved but Z-network capacitor voltage requires further boost to achieve the desired voltage level (i.e. $V^*_C>V_C$), then an extra shoot-through time period (T'_0) is obtained shown in fig.9 which is added to the shoot-through time period T_0 , obtained from P&O MPPT algorithm. Similarly to step-down the Z-network capacitor voltage(i.e. $V^*_C<V_C$), then the extra shoot-through time period (T'_0) is subtracted from the MPPT generated shoot-through time period (T_0) and the required total shoot-through time period (T_{sh}) is obtained. Thus in this way total shoot-through time period (T_{sh}) achieves simultaneous control of the MPP voltage along with the Z-network capacitor voltage. The expression for the total shoot-through time period (T_{sh}) is as follow:

$$T_{sh} = T_0 \pm T'_0 \tag{8}$$

Where, T_0 gives MPP capacitor voltage (V^*_{PV}), and T'_0 controls the Z-network capacitor voltage (V_C) as per the reference capacitor voltage (V^*_C). The possible range of the total shoot-through time period T_{sh}, is given by:

$$T_{sh}/T \bullet (1-M) \tag{9}$$

The range of additionally required shoot-through duty ratio ($D'_0= T'_0/T$) is limited by the modulation index (M) and the

MPPT generated shoot-through duty ratio (D_0= T_0/T). By substituting equation (8) into (3) the average value of Z-network capacitor voltage and the ZSI DC link voltage are expressed as follows:

$$V_c = \frac{T-(\frac{T_0 \pm T'_0}{T})}{T-2(\frac{T_0 \pm T'_0}{T})} V^*_{PV} = \frac{T-(\frac{T_{sh}}{T})}{T-2(\frac{T_{sh}}{T})} V^*_{PV} = \frac{1-D_{sh}}{1-2D_{sh}} V^*_{PV} \quad (10)$$

The peak AC output voltage of the ZSI is expressed as:

$$V_{ac} = M\left(\frac{1-D_{Sh}}{1-2D_{Sh}}\right) V^*_{PV} = M.\frac{V_{pv}}{2} \quad (11)$$

V. RESULTS AND DISCUSSION

APOD based three level NPC ZSI using single impedance network is studied for grid connected photovoltaic application. The DC output voltage of PV panel is boosted to desired voltage level and converted into AC, so as to feed the generated power into the grid. By employing suitable inverter control power is feed into the grid at unity power factor. The effect of variation of irradiance and temperature is studied by carrying out the simulation work in the MATLAB/SIMULINK environment. Simulink model of NPC three level ZSI using single impedance network with a switching frequency of 5 kHz is presented in Fig. 10.

ZSI provides desired boosted DC link voltage to meet the required AC output voltage. From design consideration value of Z-network is chosen as L1=L2=0.02mH and C1=C2=1mF. The ZSI output voltage is again step to grid voltage level using suitable transformer. It is ensured that even if irradiance changes as shown in Fig.11 grid voltage is maintained constant(Fig.12 and 13). Current is feed into the grid at almost unity power factor, shown in voltage and current waveform of Fig.13. FFT analysis of steady state current shows a THD content of 2.80% which is acceptable (Fig.14).

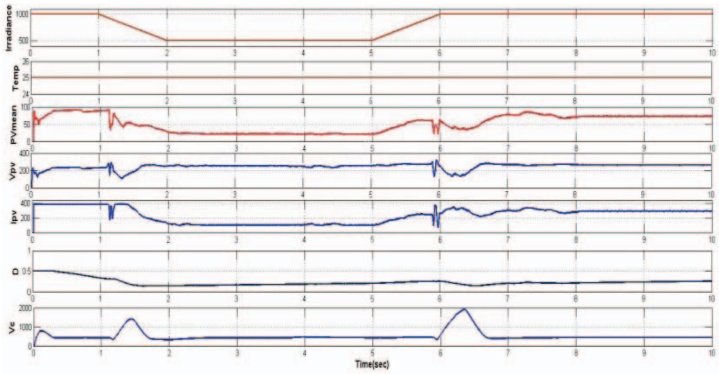

Fig.11 Signal variation of Irradiance(scale:500 W/m2/div.), Temperature(scale:25ºC/div.), $P_{mean\_}pv$(scale:50 kW/div.), Vpv(scale: 200 V/div.), I_{pv}(scale: 200 A/div.), D_0(scale: 0.5/div.), and Vc(scale: 1000 V/div.) (From top to bottom),Time(scale: 1sec/div.)

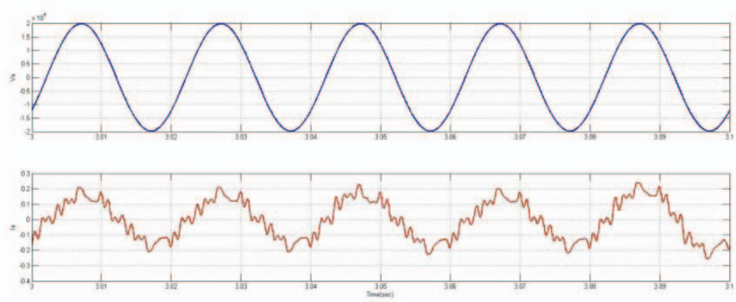

Fig.12 Voltage(scale: 10 kv/div) and current(scale: 0.5 A/div) waveform feeding into the grid when radiation is reduced to 500 W/m2 ,Time(scale: 0.01sec/div.)

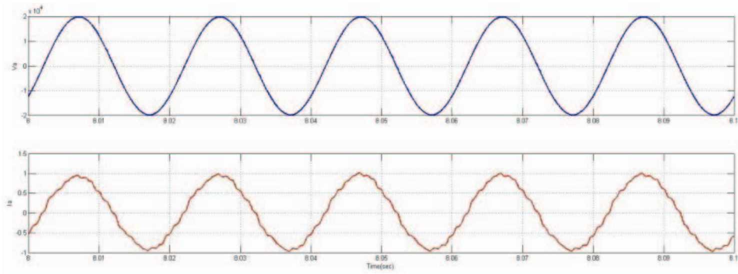

Fig.13 Steady State voltage (scale: 10 kv/div) and current (scale: 0.5A/div) (Radiation is 1000 W/m2), Time(scale: 0.01sec/div.)

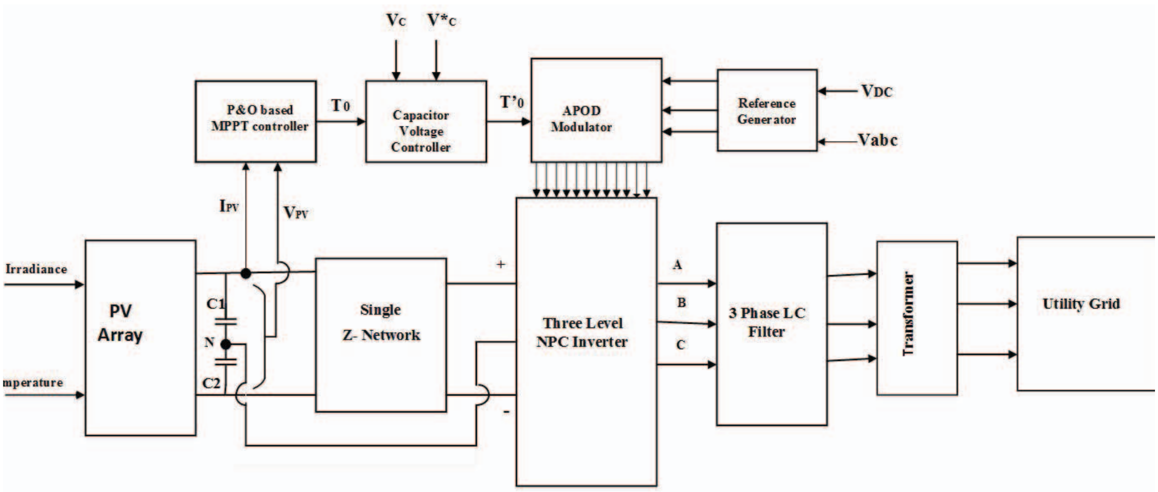

Fig.10. Block Diagram of Three Level ZSI using single impedance network based Grid

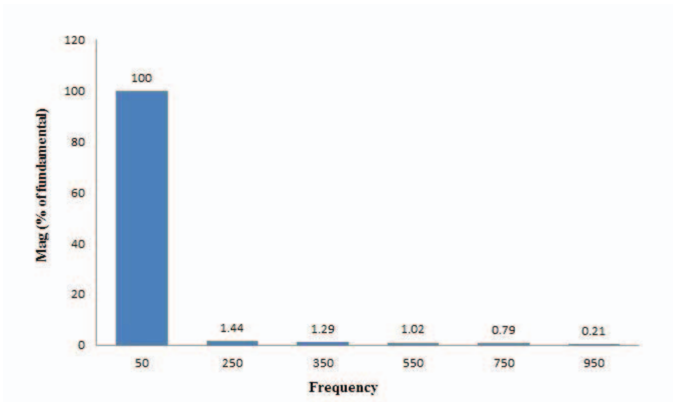

Fig.14 FFT analysis of steady state of current fed into grid

VI. CONCLUSION

A single impedance network based NPC three level ZSI for grid connected photovoltaic power conversion system is implemented by simulation. The usefulness of APOD modulation technique for photovoltaic application has been established by the detailed simulation work. Unified control technique provides control of MPP voltage and it also maintains Z-network capacitor voltage for hassle free operation of ZSI. For a grid connected system NPC three level ZSI gives better performance at reduced cost and complexity of hardware. Author is working for hardware results and it will be appended in the final submission.

References

[1] J. P. Benner and L. Kazmerski, "Photovoltaics gaining greater visibility,"IEEE Spectr., vol. 29, no. 9, pp. 34–42, Sep. 1999.

[2] Debnath, D.; Chatterjee, K. "Transformer coupled multi-input two stage standalone solar photovoltaic scheme for rural areas", Industrial Electronics Society, IECON 2013 - 39th Annual Conference of the IEEE, On page(s): 7028 – 7033

[3] Xue, Y., Chang, L., Baekhj, Kjaer, S., Bordonau, J.and Shimizu, T., "Topologies of single-phase inverters for small distributed power generators: an overview," IEEE Trans. on Power Electronics, vol 19, pp. 1305-1314, Sept. 2004

[4] M. Calais, J. Myrzik, T. Spooner and V. G. Agelidis, "Inverters for single-phase grid connected photovoltaic systems – an overview," Proc. IEEE Power Electronics Specialists Conference,PESC, 2002, pp. 1995-2000.

[5] S. B. Kjaer, J. K. Pedersen, F. Blaabjerg, " A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules" IEEE Trans. On Industry Applications, vol. 41, n° 5, September/October 2005

[6] R. O. Caceres, I. Barbi "A boost DC-AC converter, analysis, design and experimentation" IEEE Trans. On Power Electronics, vol.. 14, n° 1, January 1999.

[7] F. Z. Peng, "Z-source inverter," IEEE Trans. Ind. Applicat., Vol. 39, No.2, pp. 504-510, Mar./Apr. 2003.

[8] P. C. Loh, F. Blaabjerg, S. Y. Feng, and K. N. Soon, "Pulse-width modulated Z-source neutral-point-clamped inverter," in Proc. IEEE APEC'06, 2006, pp. 431–437.G. O. Young, "Synthetic structure of industrial plastics," in Plastics, 2nd ed., vol. 3, J. Peters, Ed. New York: McGraw-Hill, 1964, pp. 15-64.

[9] P. C. Loh, F. Blaabjerg, and C. P. Wong, "Comparative evaluation of pulse-width modulation strategies for Z-source neutral-point-clamped inverter," in Proc. IEEE PESC'06, 2006, pp. 1316–1322

[10] Z. Chen, X. Zhang, and J. Pan, "An integrated inverter for a single phase single-stage grid-connected PV system based on Z-source," Bull. Pol. Ac.: Tech., Vol. 55, No. 3, pp. 263-272, 2007.

[11] P. C. Loh, D. M. Vilathgamuwa, Y. S. Lai, G. T. Chua, and Y. W. Li, "Pulse width modulation of Z-source inverters," IEEE Trans. Power Electron., Vol. 20, No. 6, pp. 1346-1355, Nov. 2005.

[12] Poh Chiang Loh ; Sok Wei Lim ; Feng Gao ; Blaabjerg, F., "Three-Level Z-Source Inverters Using a Single LC Impedance Network," Power Electronics, IEEE Transactions on Volume: 22,Publication Year: 2007 ,Page(s): 706 - 711

[13] S. Yang, X. Ding, F. Z. Peng, and F. Z. Z. Qian, "Unified control technique for Z-source inverter," in Proc. IEEE–PESC, pp. 3236-3242, 2008

[14] Huang, Y., Shen, M., Peng, F. Z. and Wang, J., "Z-source inverter for residential photovoltaic systems", IEEE Trans. Power Electron., Vol. 21, No. 6, pp. 1776-1782, Nov. 2006.

[15] Desai H P, Patel H k. Maximum power point algorithm in PV generation: an overview[C]. In:7th International Conference on Power Electronics and Drive Systems. Bangkok, 2007:624-630

[16] V. Salas, E. Olias, A. Barrado, and A. Lazaro, "Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems," Solar Energy Materials & Solar Cells, Vol. 90, pp. 1555-1578, Jul. 2006

[17] Ishaque, K., Salam, Z., Taheri, H. Shamsudin, A. Maximum Power Point Tracking for PV system under partial shading condition via particle swarm optimization[C]. 2011 IEEE Applied Power Electronics Colloquium, 2011, pp. 5-9

[18] Lyden, S.; Haque, M.E.; Gargoom, A.; Negnevitsky, M. "Review of Maximum Power Point Tracking approaches suitable for PV systems under Partial Shading Conditions", Power Engineering Conference (AUPEC), 2013 Australasian Universities, On page(s): 1 – 6

[19] Villalva, M.G.; Gazoli, J.R.; Filho, E.R. "Analysis and simulationof the P&O MPPT algorithm using alinearized PV array model", Power Electronics Conference, 2009. COBEP '09. Brazilian, On page(s): 189 - 195

[20] L. Egiziano, N. Femia, D. Granozio, G. Petrone, G. Spagnuolo, and M. Vitelli, Photovoltaic inverters with Perturb & Observe MPPT technique and one-cycle control[C]. In: Proc. IEEE Int. Symp. Circuits Syst. 2006:3718-3721.