International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 11 (2015) pp. 29303-29319

http://www.ripublication.com

Analysis Of High Power Multifunctional Grid Connected PV System Using Multilevel Inverter

Jeyasudha.S, Ramya.S, and Geethalakshmi.B

Department of EEE, Pondicherry Engineering College, Tamil Nadu, 605 014, India.
E-mail: jeyasudha_s @rediffmail.com, ramya0303@pec.edu,
bgeethalakshmi@pec.edu

Abstract

The demand for clean energy is increasing day by day, and hence, grid connected PV systems are gaining more attention. One of the major problems faced by the grid connected systems is power quality as the usage of non-linear and unbalanced loads are increased. This paper employs a high power multifunctional PV system with high gain boost converter, diode clamped multilevel inverter connected to the grid through a 75kVA step up transformer. The multi functions are 1) wide range of input voltage supplied by the PV array to the grid and 2) compensation of harmonic and unbalanced currents due to non-linear loads. The control scheme of the proposed system includes MPPT control for high gain boost converter and current control loop in d-q-0 coordinate for the inverter to function as active power filter. Dynamic performance of the grid connected PV system is evaluated in the MATLAB/Simulink environment. The reported simulation results show that with the proposed high gain boost converter, cascaded multilevel inverter and control strategy used in grid connected PV system work satisfactorily under steady state and dynamic load condition.

Index Terms—Maximum Power Point Tracking (MPPT), Photovoltaic (PV), Active Power Filter (APF), Multilevel Inverter (MLI).

I. Introduction

Renewable energy resources are an alternative approach to the generation of clean energy and are augmented by the energy sector due to the global energy crisis [1]. Solar photovoltaic is one of the fastest growing technologies among various renewable energy resources. Photovoltaic power supplied to the utility grid is gaining more and more visibility, while the world's power demand is increasing [2]. The primary goal of these systems is to increase the energy injected to the grid by keeping track of the maximum power point (MPP) of the panel and by providing high reliability [3]. Besides, grid-connected PV systems offer advantages such as improvement in grid reliability by reducing stresses on transmission and distribution systems, possibility to inject the maximum available PV energy to the grid, and are cheaper than stand-alone PV systems [4]. However, their intermittent nature has introduced many technical issues including power quality, load management, stability and controls, reliability, and voltage regulation. With the advancement in power electronics technology, the power electronic interfaces can be effectively used to resolve some of the issues pointed above [5].

This paper proposes a multifunctional grid connected PV system using d-q-0 coordinate technique which functions as both PV inverter and active power filter. Since the PV module voltage has a low-voltage characteristic, the voltage should be stepped up to high dc voltage in order to deliver electric power to the grid. Thus, a dc–dc converter with high gain is needed [6]. The conventional boost converter can be used but it has drawbacks such as reverse recovery problems at high duty ratios, high sensitivity to duty ratios at extreme ends, and forcing the converter into an unstable region [6]. The high-gain boost converter (HGBC) topology proposed in [5] is employed in the present work. The DC – DC converter is then connected to an inverter and then to the grid through a step up transformer. Since the multilevel inverters have been proven to be one of the important enabling technologies in photovoltaic (PV) utilization, two stages of diode clamped multilevel inverter is considered in the present work [7].When compared with conventional inverters, multilevel inverters have an advantage, as it synthesizes staircase ac output voltage with low harmonic distortion the filter requirements is reduced [7].

II. BLOCK DIAGRAM DESCRIPTION OF THE GRID CONNECTED PV SYSTEM

The block diagram of the multifunctional grid connected PV system is shown in Fig.1.

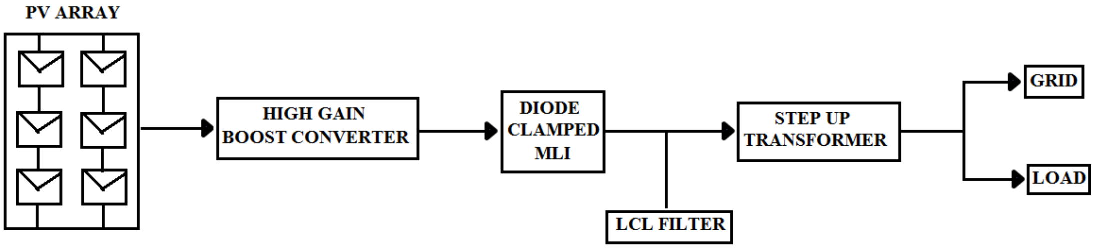

Fig.1. Block diagram of the multifunctional grid connected PV system

This system employs dual performances. The first stage is the boost converter that allows a wide input voltage range from PV arrays. The second stage is the paralleled diode clamped multilevel inverter, which injects the PV power and also perform the function of active power filter (APF). During the day the system supplies the PV active power to the grid, at the same time it compensates the harmonic, unbalanced, and reactive currents. In case of cloudy days or nights, the system performs just as an APF.

III. MODELING OF PHOTOVOLTAIC ARRAY

The main objective of modeling PV array is to find the parameters of the nonlinear *I-V* equation by adjusting the curve at three points: open circuit, maximum power, and short circuit [8]. The basic equation (1) of the elementary photovoltaic cell represents the I-V characteristic of a practical photovoltaic array.

$$I=I_{ph}-I_s\left[\exp\left(\frac{qV}{nkT}\right)-1\right] \tag{1}$$

where,

I_{ph} - Phase current (A)
I_d - Shockley diode current (A)
I_s - Reverse saturation or leakage current of the diode (A)
q - Electron charge
k - Boltzmann constant
T - Temperature in Kelvin of the p–n junction
n - Diode ideality constant.

Practical arrays are composed of several connected photovoltaic cells and the observation of the characteristics at the terminals of the photovoltaic array requires the inclusion of additional parameters to the basic equation (1) [9] and is obtained as

$$I=I_{ph}-I_s\left[\exp\left(\frac{V+R_sI}{V_tn}\right)-1\right]-\frac{V+R_sI}{R_p} \tag{2}$$

where,

V = N_skT/q - Thermal voltage of the array
N_s - Cells connected in series.
R_s - Series resistance
R_p - Parallel resistance

The input given to the array is temperature and irradiance. The parameters are given in Table-1. Equation (2) is realized using MATLAB/Simulink models and the corresponding PV and IV characteristics obtained are shown in Figs.2 and 3.

TABLE-1 PV ARRAY PARAMETERS

Parameters	Values
Temperature (T)	25°C
Irradiance (I_{r0})	1000 W/m^2
Electron charge (q)	1.6×10^{-19}C
Boltzmann constant (k)	1.38×10^{-23}
Series resistance (R_s)	0.18 Ω
Parallel resistance (R_p)	360.002 Ω
Duality constant (n)	1.36
Short circuit current (I_{sc})	3.8 A
Cells in module (c)	36
Array size	12 x 12

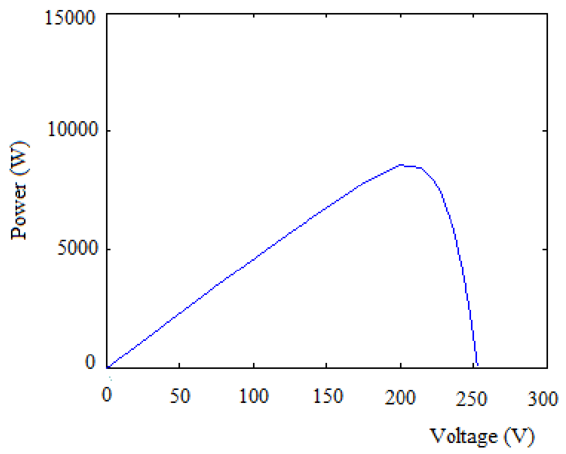

Fig.2 – Output waveform of P-V characteristics

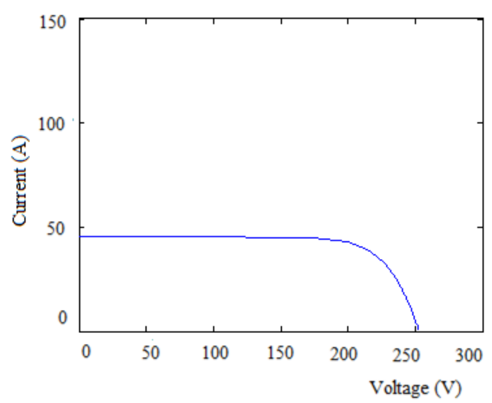

Fig.3 – Output waveform of I-V characteristics

IV. MAXIMUM POWER POINT TRACKING

Maximum power point tracking maximize the power output from a PV system for a given set of conditions, and therefore maximize the array efficiency and minimize the overall system cost. Among different MPPT algorithm perturb and observe algorithm is the classic method [10]. The algorithm takes the values of current and voltage as initial values from the solar photovoltaic module and calculates the power value.

An m.File program is created for tracking the maximum power point and the algorithm decides whether to increase or decrease the duty cycle. The reference voltage (V_{ref}) obtained from the MPPT algorithm is compared with a triangular carrier so as to generate the pulse for high gain boost converter as depicted in Figs.4 and 5.

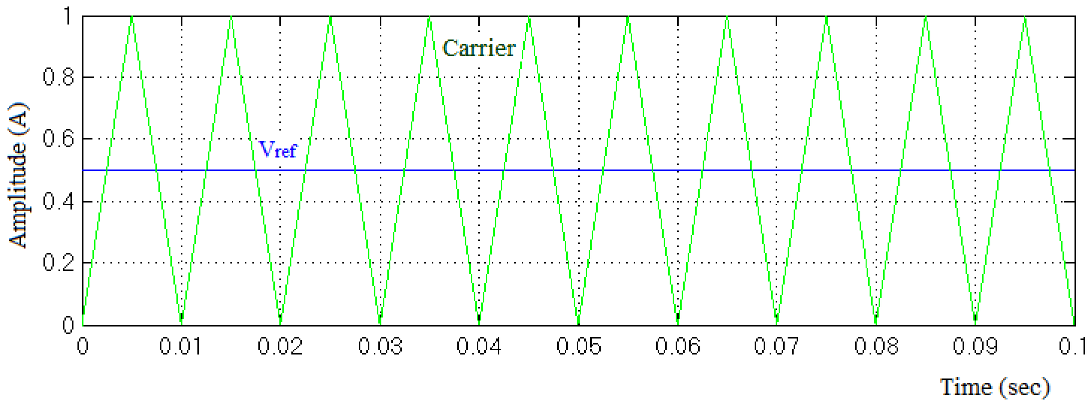

Fig.4 – Comparison of reference voltage with triangular carrier

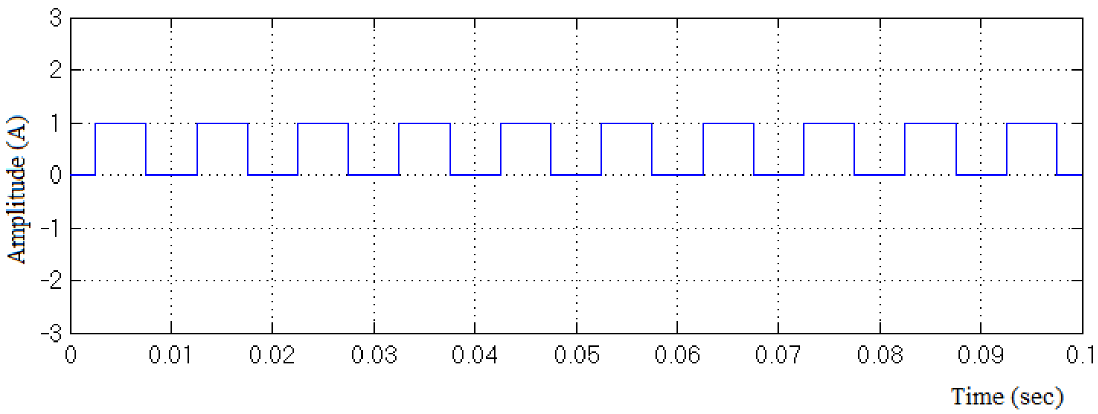

Fig.5 – Pulse applied to high gain boost converter

V. HIGH GAIN BOOST CONVERTER

In order to lift up the voltage of the PV array the high gain boost converter shown in Fig.6 is used. In conventional boost converters, the voltage gain is limited by the effect of the power switches, diodes and equivalent series resistance of the inductors and capacitors. Besides, the high duty ratio operation results in reverse recovery and electromagnetic interference problems [11]. In order to address these issues, an HGBC topology as used in [5] is chosen over the conventional boost converter topology.

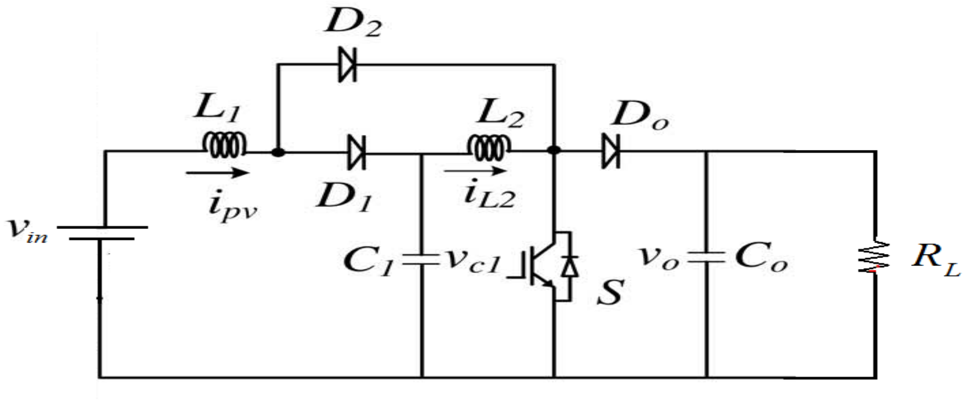

Fig.6 – High gain boost converter

The mathematical model of the HGBC topology (Fig.6) is given as follows:

$$V_{C1} = L_1 \frac{di_{pv}}{dt} + r_{L1} i_{pv} + V_0 + r_s i_{pv} \quad (3)$$

$$V_{C1} = r_2 i_{L2} + L_2 \frac{di_{L2}}{dt} + r_s i_{L2} + V_0 \quad (4)$$

$$i_{L2} = C_0 \frac{dV_0}{dt} + \frac{V_0}{R_1} \quad (5)$$

$$i_{L1} = \frac{V_0 - V_{c1}}{R_1} - C_1 \frac{dV_{c1}}{dt} \quad (6)$$

where,

V_{C0} - Voltage across capacitor 0
V_{C1} - Voltage across capacitor 1
V_{C2} - Voltage across capacitor 2
i_{L1} - Current across inductor 1
i_{L2} - Current across inductor 1
r_s - Parasitic resistance of switch
r_{L1} - Parasitic resistance of inductor L_1
r_{L2} - Parasitic resistance of inductor L_2
R_1 - Equivalent load resistance

The high gain boost converter is realized using MATLAB/Simulink and the simulation parameters are listed in Table – 2. In order to highlight the performance of HGBC with the conventional boost converter topology, the PV array output is employed to both the converters and their outputs are compared in Fig.7. For the operating conditions specified in Table – 1, the PV array in association with MPPT produces a maximum voltage of 253V as depicted in Fig.7(a) which is given as input to both the DC-DC converters considered. From Fig.7 (b) and (c), it is clear that the output of the HGBC is almost two times of the conventional boost converter.

Table-2 HGBC Parameters

Parameters	Values
Input voltage (V_{in})	253 V
Output voltage (V_{out})	990 V
Inductance 1 (L_1)	10mH
Inductance 2 (L_2)	6.9mH
Capacitance (C_0, C_1)	200µF

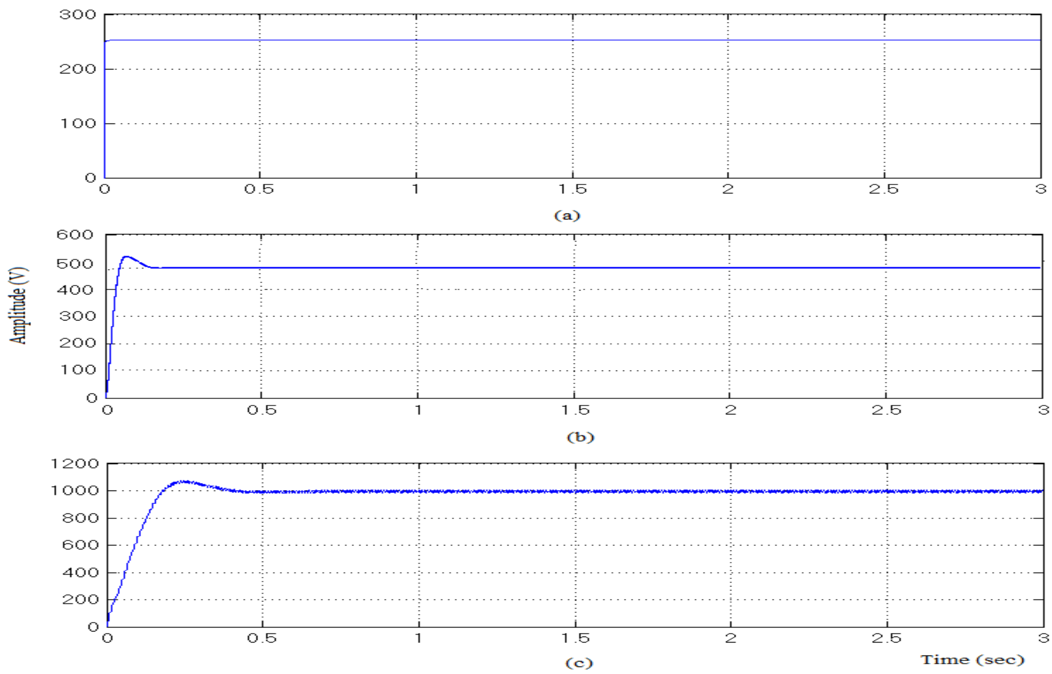

Fig.7 (a) – Input voltage to the DC – DC converter (b) Output voltage of boost converter (c) Output voltage of high gain boost converter

VI. PV MULTILEVEL INVERTER

Multilevel inverters have obtained more and more attention in recent years and new topologies with a wide variety of control strategies have been developed [7].

Cascaded H-bridge multilevel inverter is one of the mostly used inverter for PV power supply system in stand-alone and grid-connected operations [13]–[16]. However, H-bridge multilevel inverters require too many separate dc sources for each phase. Some of the proposed single-phase topologies also require string inverters and multiple stages or complex algorithms for grid-connected operations [7]. Hence to overcome the above issue diode-clamped multilevel inverters (DCMLIs) shown in Fig.8 is used. It shares a single dc level for each of the three phases and hence decreases dc cabling and losses on the dc side. A five level dc-to-ac diode clamped multilevel inverter for three-phase PV power supply system is presented in this paper. The interleaved structure with two five level multilevel inverters directly paralleled is adopted for high current consideration [17].

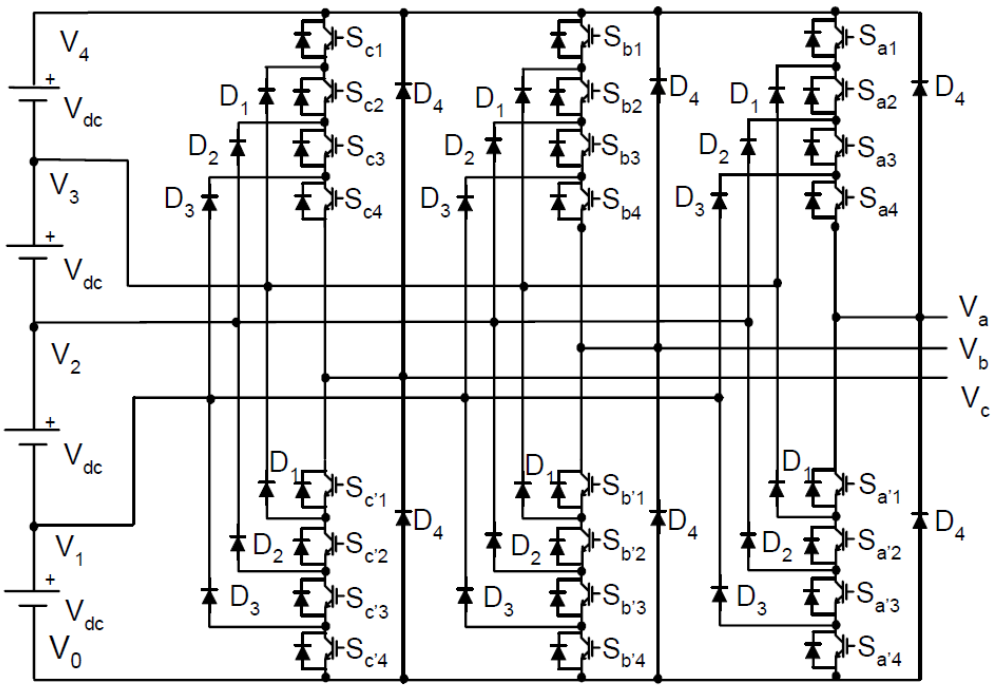

Fig.8 – Five level diode clamped multilevel inverter

VII. OPEN LOOP OPERATION OF THE GRID CONNECTED PV SYSTEM

The complete schematic of the PV system connected to the grid through the HGBC and diode clamped multilevel inverter is depicted in Fig.9. This system is realized in MATLAB/Simulink environment and the system parameters used for the simulation is given in Table-3. A single phase diode rectifier between phase and neutral and a three phase full converter are considered as non-linear loads for the purpose of simulation and are connected to the grid through a 75kVA step up transformer. Upon addition of non-linear load, distortions are produced in the line current which is shown in Fig.10. Harmonic distortion occurs when the harmonic currents flow through the finite output and transmission impedances of the power system and can extremely damage the loads and power transmission equipment, such as transformers. For this reason, THD guidelines have been established for to prevent improper operation of, or damage to, power-processing and power-consuming equipment.FFT analysis is shown in Fig.11which is undesirable. For the above reason, we go for a closed loop control scheme, which ensures a significant elimination of harmonic distortions irrespective of non-linear loads.

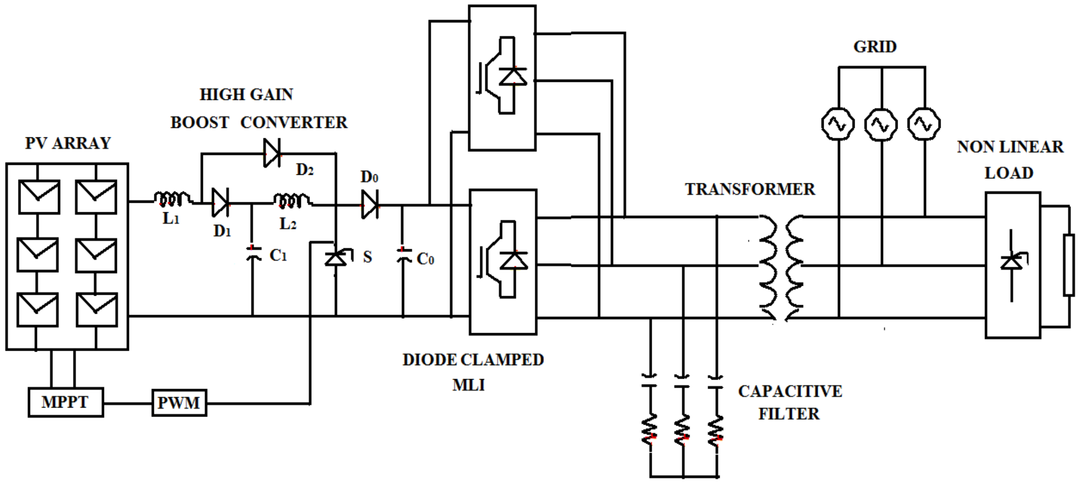

Fig.9- Open loop grid connected PV system

TABLE-3 DESIGN PARAMETERS

Parameters	**Values**
Grid voltage	380 V
Grid frequency	50 Hz
Capacitor of the filter (C)	50µF
Resistor of LCL filter (R)	0.15 Ω
Transformer rating	75 kVA

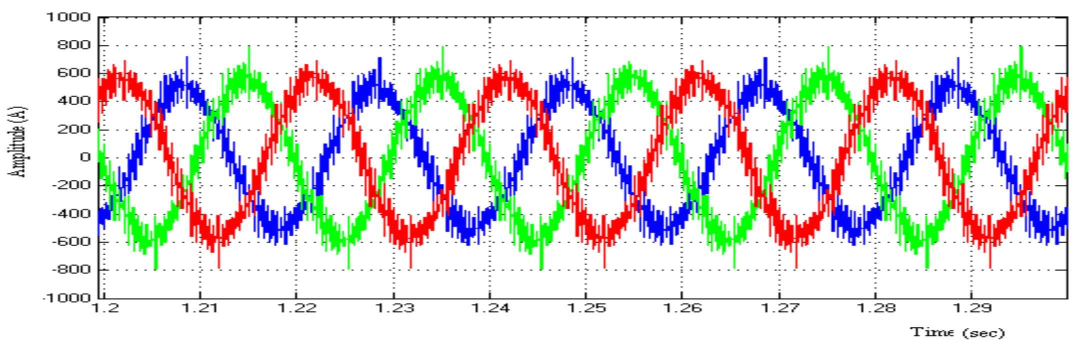

Fig.10 – Line current

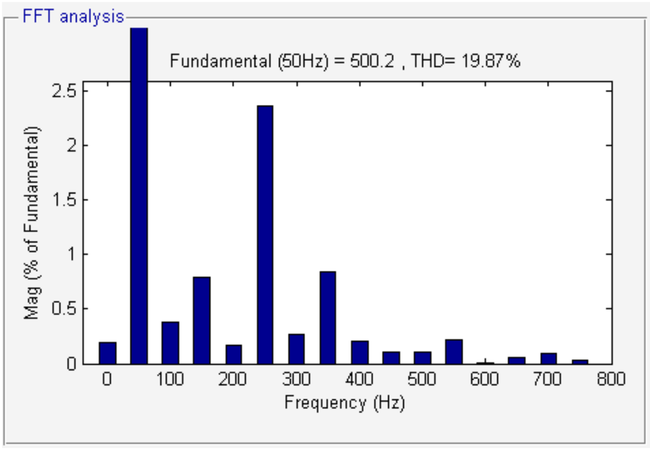

Fig.11 – FFT analysis of line current

VIII. CLOSED LOOP CONTROL

In closed loop, the system performs a dual function such as PV inverter and APF. The closed loop control of the system is done by using d-q-0 co-ordinate technique as shown in Fig.12.This control is a current control of PV inverter, realized by sensing the inverter current in order to maintain the system stability [18]. Here LCL filter is used in order to reduce the harmonic current around the switching frequency. Compared with the traditional *L* or *LC* filter, the *LCL* filter is more effective on harmonic currents attenuation at switching frequency [18]. The capacitors of LCL filter demand the reactive power and it is provided by the inverter. In this control mode, the inverter absorbs the active power from the PV arrays to maintain the dc-link voltage; when under APF mode, the inverter absorbs the active power from the grid to maintain the dc-link voltage. PI controller is applied here in order to ensure the stability of the system [17].

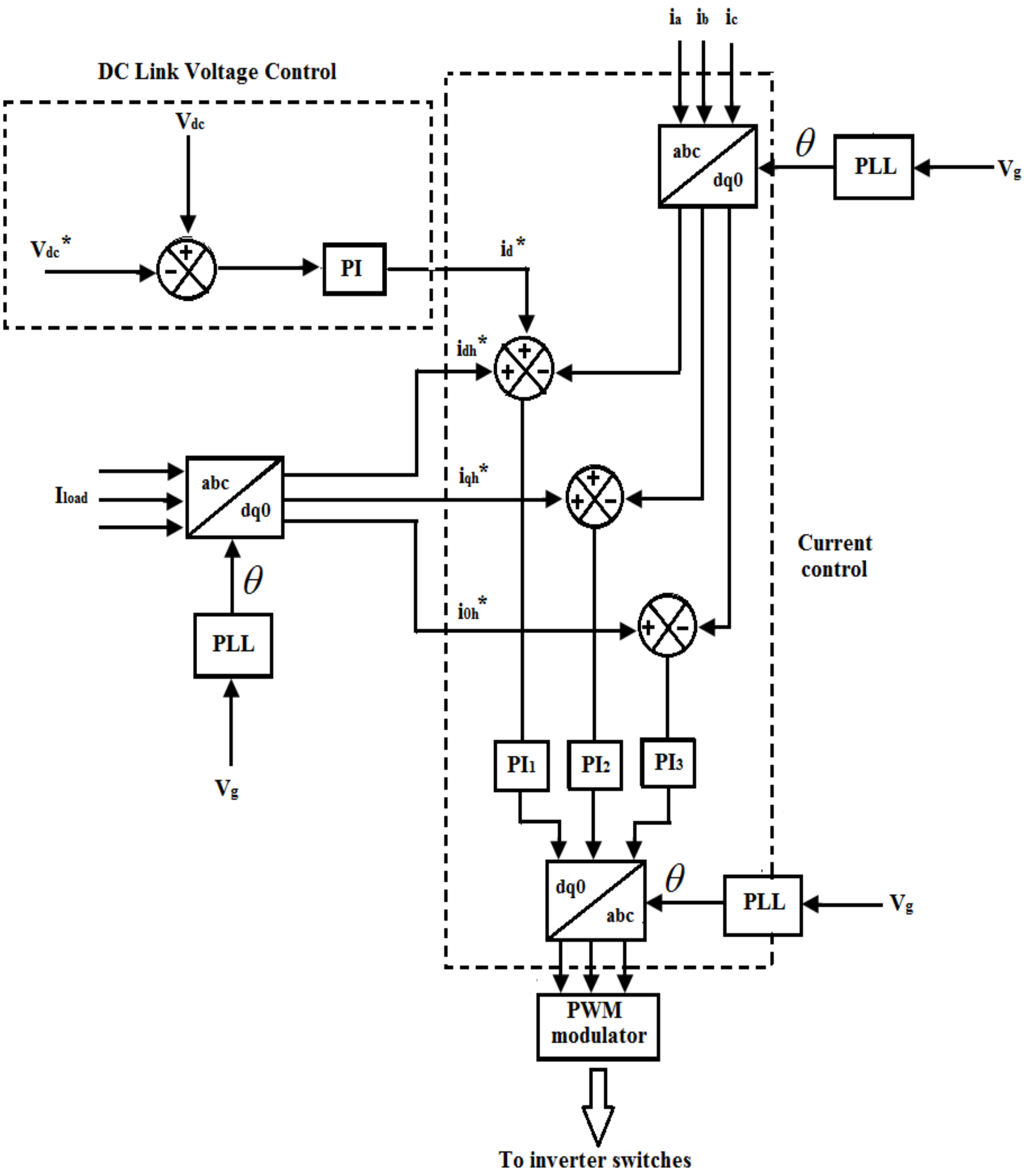

Fig.12 - d-q-0 Co-ordinate control

VIII. Simulation Results and Discussions

In this section the behavior of the multifunctional grid connected PV system is analyzed using MATLAB/Simulink. Thus in order to test the closed loop control scheme and the behavior of the system suitable case studies are carried out under steady state and dynamic operation.

Table-4 Design Parameters

Parameters	**PI**	**PI_1**	**PI_2**	**PI_3**
Proportional gain (K_p)	1	0.0001	0.0001	0.0001
Integral gain (K_i)	0.1	1	1	1

From Fig.12 it can be seen that the current reference consists of three parts: one is the fundamental active current references $i_d^*$the other one is the harmonic current references i_{dh}^*, $i_{qh}^*$and i_{0h}^*; the last one is capacitors reactive current reference i_{qcf}^*.The fundamental active references i_d^* is produced by comparing the DC link voltage V_{dc} and the reference V_{dc}^*. It controls the output active power and at the same time the harmonics, unbalanced and reactive currents are delivered.

The capacitors reactive current $i_{qcf}^*$is calculated from the branch impedance of capacitive filter and grid voltages and it is shown in Fig.13.

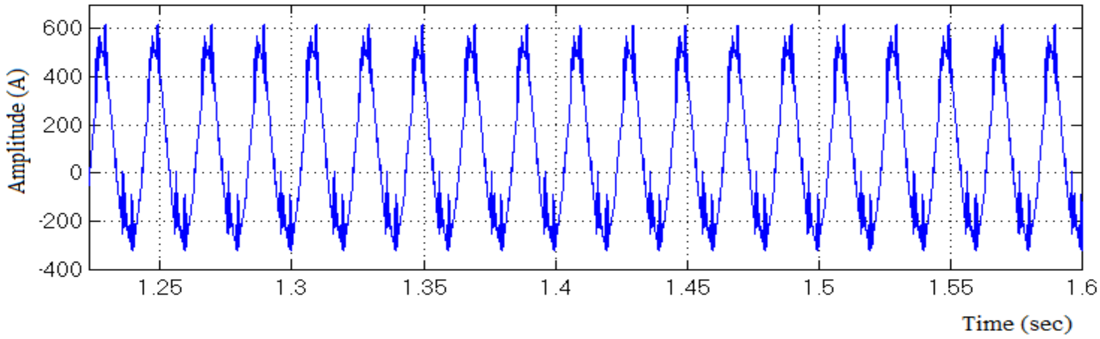

Fig.13 -Capacitors reactive current reference i_{qcf}^*

The harmonic currents i_{dh}^*, $i_{qh}^*$and i_{0h}^*shown in Figs.14, 15 and 16 are obtained by extracting the harmonic current from the load current and transforming it o d-q-0 co-ordinate. The extraction of harmonic current from the load current is done by subtracting the fundamental current from the load current.

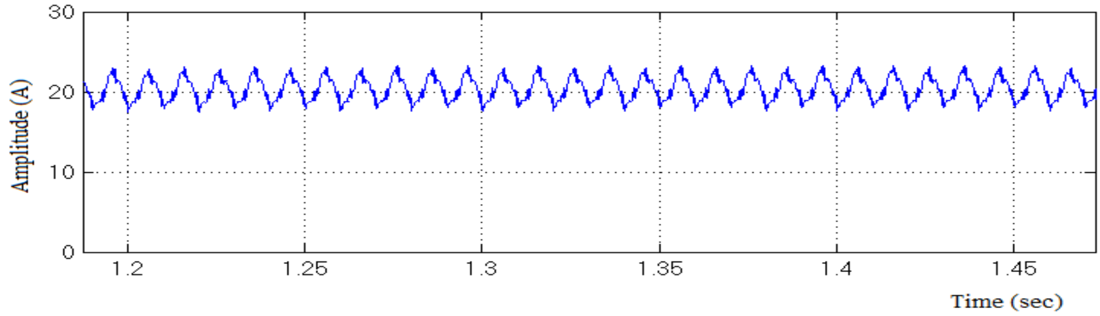

Fig.14 -Harmonic current reference i_{dh}^*

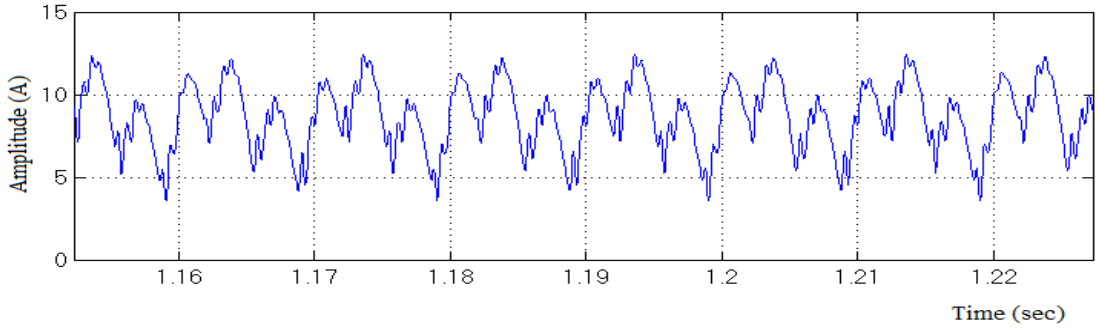

Fig.15- Harmonic current reference i_{qh}^{*}

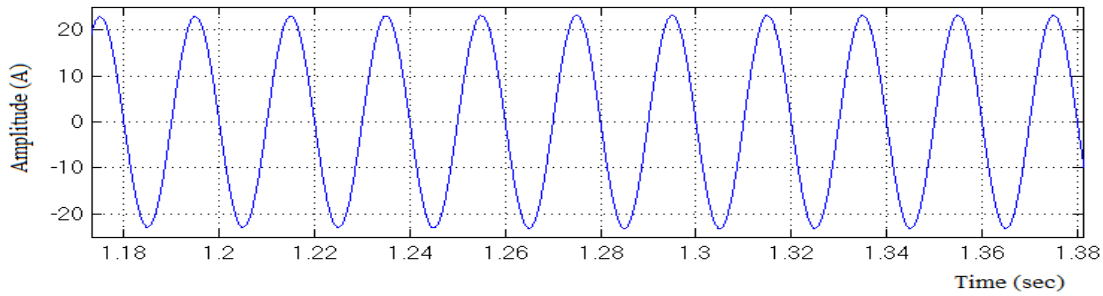

Fig.16 - Harmonic current reference i_{0h}^{*}

Now these above references are compared with the currents of inverter 1 and 2. The inverter 1 and 2 currents are transformed to d-q-0 axis. The harmonic current references i_{dh}^{*} added with active current reference i_{d}^{*}, i_{qh}^{*} added with capacitive reactive current i_{qcf}^{*} and i_{0h}^{*} are compared with inverter current and again transformed to abc axis. Hence the current produced is sinusoidal with less distortions and harmonics in coordinates shown in Fig.17 and Fig.18. These sinusoidal currents are given as reference to the diode clamp multilevel inverter.

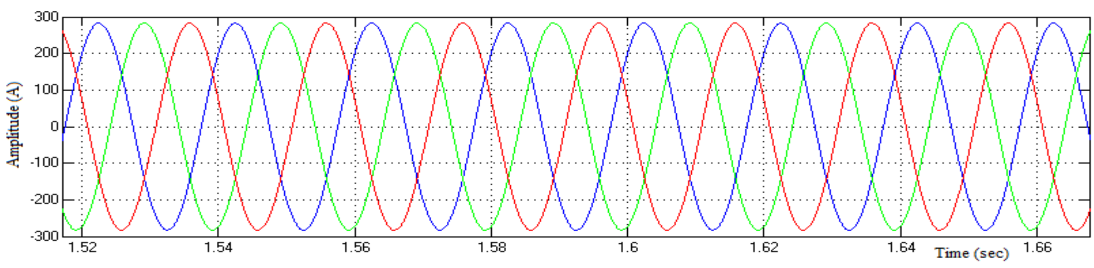

Fig.17 – Reference current given to inverter - 1

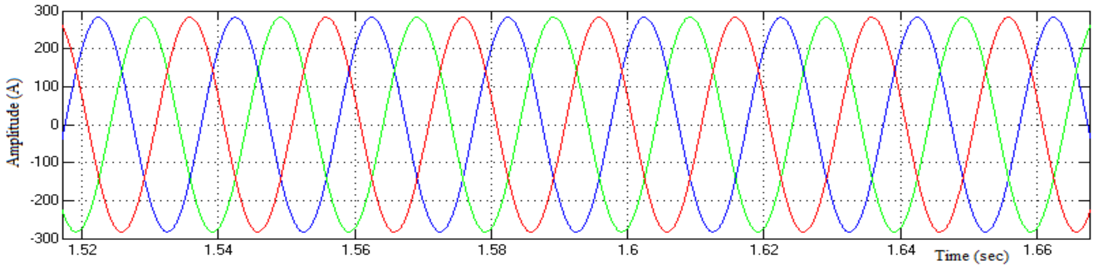

Fig.18 – Reference current given to inverter – 2

A. Steady state condition

A single phase diode rectifier is connected as non-linear load to the system considered. The distortion present in the line current which is depicted in Fig.10 has been eliminated significantly. The compensated line current is highlighted in Fig.19 and the corresponding reduction in THD is shown in Fig.20.

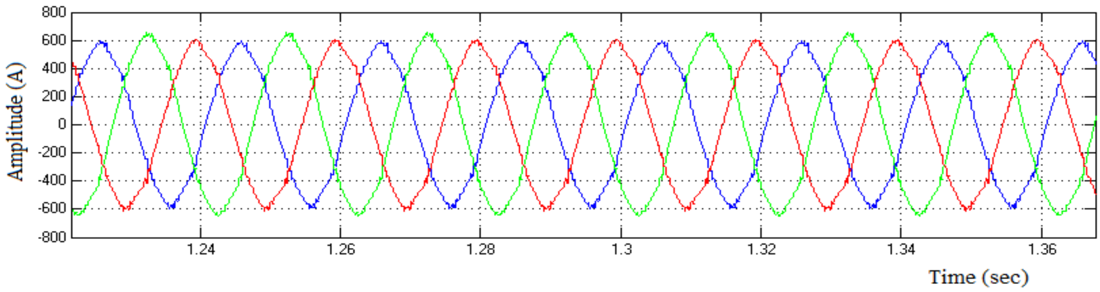

Fig.19 – Line current after compensation

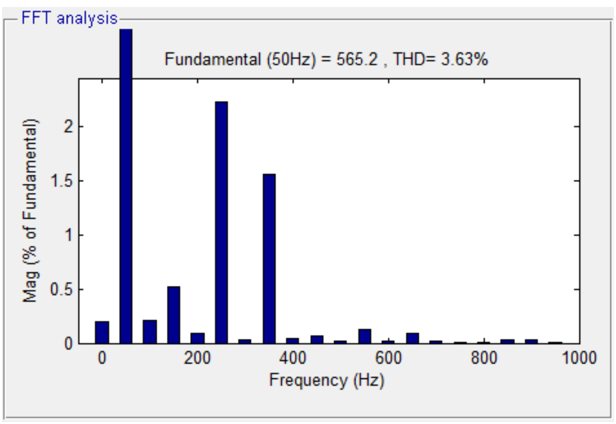

Fig.20 – FFT analysis of line current after compensation

B. Dynamic condition

The stability performance of the system is verified by switching the loads at different time periods. The single phase diode rectifier and a three phase full converter are used as non-linear loads. Initially the single phase diode rectifier is connected as load. Later at t = 0.7 sec the diode rectifier load is replaced with the three phase full converter. Then both the loads are connected from t = 1.1 sec to t = 1.5 sec.

The corresponding load current and line current waveform is shown in Figs.21 and 22. From the figures it is observed that irrespective of variations in the non-linear load the line current is maintained at the desired value with reduced THD.

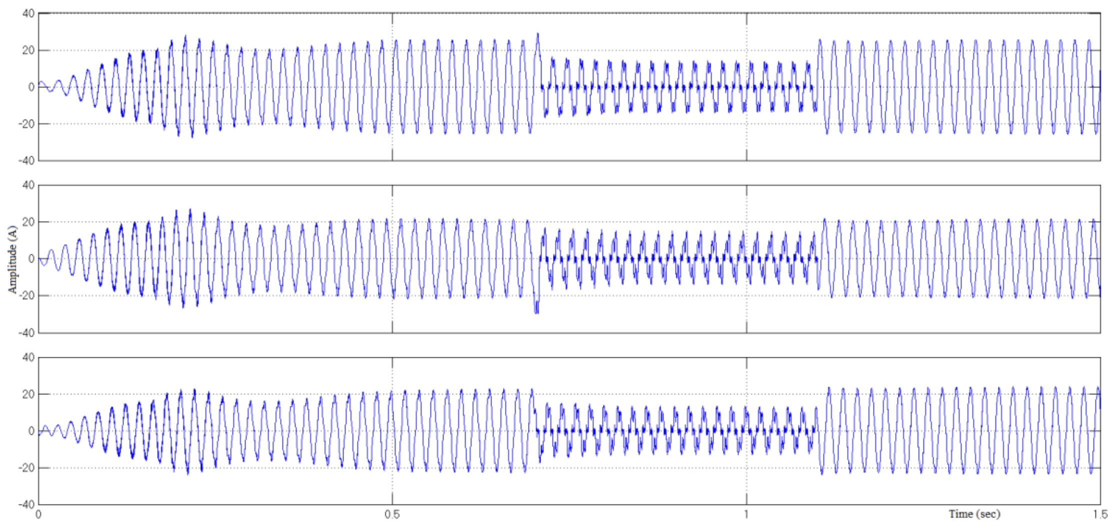

Fig.21 – Load current

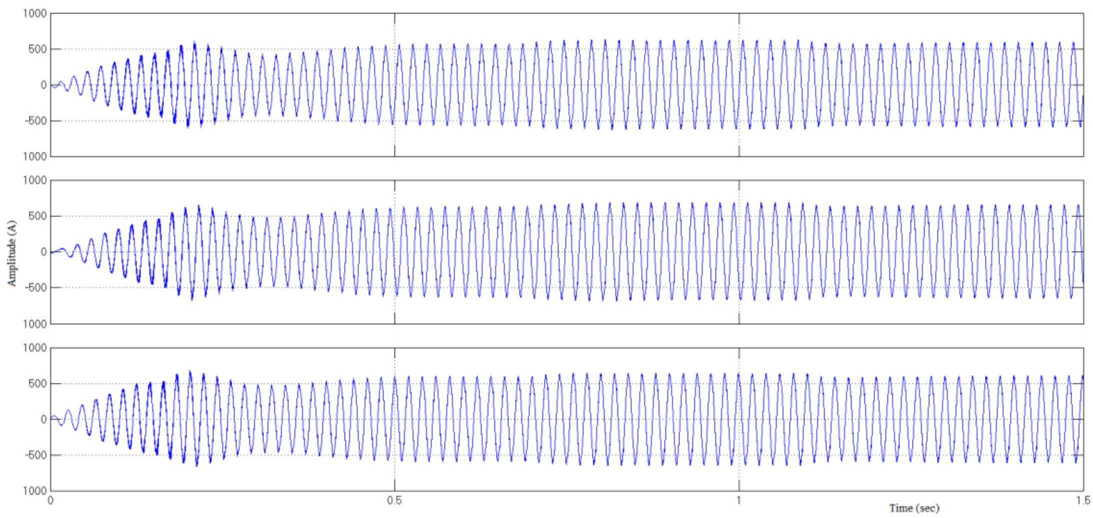

Fig.22 – Line current

IX. CONCLUSION

A dual-stage high power multifunctional grid-connected PV system has been proposed. The perturb and observe algorithm is used for MPPT which tracks the maximum power of the PV system. The high gain boost converter is coupled directly with two three phase diode clamp multilevel inverter configuration. This system is connected to the grid through 75 kVA step up transformer. The closed loop controller based on d-q-0 co-ordinates has been developed and found to be effective over a wide range of load variation. The PV system not only provides power to the grid but also compensates distortion in the line current. The behavior of the proposed system has been analyzed under steady state and dynamic operating conditions. The simulation results describe the ability of the control algorithm for successful operation of the proposed multifunctional grid connected PV system.

REFERENCES

[1] Nehrir, M., Wang, C., Strunz, K., Aki, H., Ramakumar, R., Bing, J., Miao, Z., and Salameh, Z., 2011, “A review of hybrid renewable/alternative energy systems for electric power generation: Configurations, control, and applications,” IEEE Trans. Sustain. Energy, vol. 2, no. 4, pp. 392–403,.

[2] Benner, J. P., and Kazmerski, L., 1999. “Photovoltaics gaining greater visibility”, *IEEE Spectr*, vol. 29, no. 9, pp. 34–42,.

[3] Elena Villanueva, Pablo Correa, Jose Rodríguez and Mario Pacas, 2009, “Control of a Single-Phase Cascaded H-Bridge Multilevel Inverter for Grid-Connected Photovoltaic Systems”, IEEE Transactions on Industrial Electronics, vol. 56, no. 11,.

[4] Negroni, J. J., Francesc Guinjoan, Carlos Meza, Domingo Biel, Pablo Sanchis, 2006 “Energy-Sampled Data Modeling of a Cascade H-Bridge Multilevel Converter for Grid-connected PV Systems”, CIEP,.

[5] Narsa, W. Y., Reddy Tummuru, Mahesh K. Mishra, 2014 “Multifunctional VSC Controlled Microgrid Using Instantaneous Symmetrical Components Theory”, IEEE Transactions on Sustainable Energy, Vol. 5, No. 1,.

[6] Choi, 2013 “High-efficiency dc–dc converter with fast dynamic response for low-voltage photovoltaic sources”, IEEE Trans. Power Electron., vol. 28, no. 2, pp.706–716,

[7] EnginOzdemir, SuleOzdemir, and Leon, M., Tolbert, 2009, “Fundamental-Frequency-Modulated Six-Level Diode-Clamped Multilevel Inverter for Three-Phase Stand-Alone Photovoltaic System”, IEEE Transactions on Industrial Electronics, vol. 56, no. 11,.

[8] Villalva, M. G., Gazoli, J. R., Ruppert, E. F., 2009 “Modeling and circuit-based Simulation of photovoltaic arrays”, Brazilian journal of Power Electronics, vol.14, no.1, pp 35-45 ISSN 1414-8862,.

[9] Marcelo Gradella Villalva, Jonas Rafael Gazoli, and Ernesto Ruppert Filho, “Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays”, IEEE Transactions on Power Electronics, vol. 24, No. 5,.

[10] Ioan Viorel Banu, Razvan Beniugă, Marcel Istrate, 2013. “Comparative Analysis of the Perturb-and-Observe and Incremental Conductance MPPT Methods”,advanced topics in electrical engineering,.
[11] Tofoli, F. L., de Souza Oliveira, D. R., Torrico-Bascope, P. and Alcazar, Y. J. A. “Novel non isolated high-voltage gain dc–dc converters based on 3SSC and VMC”, IEEE Trans. Power Electron., vol. 27, no. 9, pp. 3897–3907, ..
[12] Bibek Mishra, BibhuPrasanna Kar, 2012 “Matlab Based Modeling of Photovoltaic Array Characteristics”, National Institute of Technology, Rourkela,.
[13] Beig, A. R., Kumar, U. R. Y., and Ranganathan, V. T. , 2004 ,“A novel fifteen level inverter for photovoltaic power supply system,” in *Conf. Rec. 39th IEEEIAS Annu. Meeting*, Oct. 3–7, vol. 2, pp. 1165–1171.
[14] Kang, F. S.,Park, S. J., Cho, S. E., Kim, C., and Ise, T., 2005 “Multilevel PWM inverters suitable for the use of stand-alone photovoltaic power system”, *IEEE Trans. Energy Convers.,* vol. 20, no. 4, pp. 906–915,.
[15] Alonso, O., Sanchis, P., Gubia, E., and Marroyo, L., 2003 “Cascaded H-bridge multilevel converter for grid connected photovoltaic generators with independent maximum power point tracking of each solar array”, in *Proc.34th IEEE Annu. Power Electron.Spec. Conf.*, vol. 2,pp. 731–735.
[16] Valderrama-Blavi, H., Munoz-Ramirez, M., Maixe, J., Giral, R. and Calvente, J. 2005 “Low frequency multilevel inverters for renewable energy systems”, in *Proc. IEEE Int. Symp. Ind. Electron*, Jun. 20–23, 2005, vol. 3, pp. 1019–1024.
[17] Asiminoaei, L., Aeloiza, E., Enjeti, P. N., and Blaabjerg, F., 2008, “Shunt active power - filter topology based on parallel interleaved inverters”, *IEEE Trans. Ind. Electron.*, vol. 55, no. 3, pp. 1175–1189,.
[18] Xianwei Wang, Fang Zhuo, Jing Li, Lin Wang, and Song Ni, 2013 “Modeling and Control of Dual-Stage High Power Multifunctional PV System in *d–q–o* Coordinate”, IEEE Transactions On Industrial Electronics, vol. 60, No. 4,.