Closed Loop Current Control of Three Phase Photovoltaic Grid Connected System

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Abstract

The paper presents a closed loop current control technique of three phase grid connected systems with a renewable energy source. The proposal optimizes the system design, permitting reduction of system losses and harmonics for the three phase grid connected system. The performance of the proposed controller of grid connected PV array with DC-DC converter and multilevel inverter is evaluated through MATLAB-Simulation. The results obtained with the proposed method are compared with those obtained when using without current controller for three-phase photovoltaic multilevel inverter in terms of THD and switching frequency. Experimental works were carried out with the PV module WAREE WS 100, which has a power rating of 10 W, 17 V output voltages and 1000 W/m^2 ir-radiance. The test results show that the proposed design exhibits a good performance.

Keywords : Photovoltaic (PV), renewable energy systems, power electronic converters, PLL, SVPWM, THD.

1 Introduction

In the current global climate, demand for a renewable energy system has increased due to environmental issues and limited fossil resources. There are many advantages of the application of photovoltaic systems: no cost of energy, no pollution, no rotating parts and long lifetime. Various types of DC-DC converters have been utilized to provide grid connected renewable energy systems. In PV applications, boost converter is required to adjust the variable and low quality output voltage of the PV panels [1]-[3].

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In response to the growing demand for medium and high power applications, multilevel inverters have been attracting growing consideration in PV systems recently. Multilevel inverters enable the output voltage to be increased without increasing the voltage rating of switching components, so that they offer the direct connection of renewable energy systems to the grid voltage without using the expensive, bulky and heavy transformers. In addition, multilevel inverters synthesis stair case output voltage which is closer to sinusoidal voltage using DC link voltages compared with two level inverters. Synthesizing a stepped output voltage allows reduction in harmonic content of voltage and current wave forms and eventually size of the output filter. Among the different types of multilevel converters diode clamped converter is widely used in transformer-less grid connected systems due to its minimum number of active power components and shared DC link voltage.

The Space Vector Pulse Width Modulation (SVPWM) method is an advanced, computation intensive PWM method and possibly the best among all the PWM techniques for variable frequency drive application [4]-[6]. A control algorithm with standard Perturbation and Observation (P&O) is proposed to achieve commanded values of DC voltages necessary for Maximum Power Point Tracking (MPPT) of PV panels. Besides the power generation the system can function as an active filter, with the additional capabilities of load balancing, harmonics compensation and reactive power injection.

Because the inverter is used in a PV system, a Proportional Integral Derivative (PID) current control scheme and Phase Locked Loop (PLL) scheme are employed to keep the output current sinusoidal and to have high dynamic performance under rapidly changing atmospheric conditions and to maintain proximate unity at the power factor. Simulation results are presented to validate the proposed configuration [7]-[9]. The inverter offers a lower total harmonics distortion (THD), an improved step response and a quality of power.

2 System Configuration

The configuration of the PV energy conversion system together with its general control structure is depicted in Fig.1. The system connected with a utility power is mainly composed of PV modules, a high step-up converter, a three phase diode clamped multilevel inverter, and a system controller. Due to the photo-voltaic effect, the voltage of a PV cell is not very high. In order to satisfy the requirement of high-voltage demand, a DC-DC converter with high voltage gain is one of the essential mechanisms in the grid-connected PV generation system [13].

Since the SVPWM controlled multilevel inverter is expected to produce an output current in phase with the utility voltage for obtaining a unity PF, a system controller [25] is introduced by the way of switching the four power semiconductors in each leg of this multilevel inverter to maintain an output current with a higher PF and lesser variation under load changes.

2.1 Photovoltaic Cell Modeling

An ideal solar cell can be considered as a current source wherein the current produced by the solar cell is proportional to the solar irradiation falling on it. Though the practical behavior of a cell

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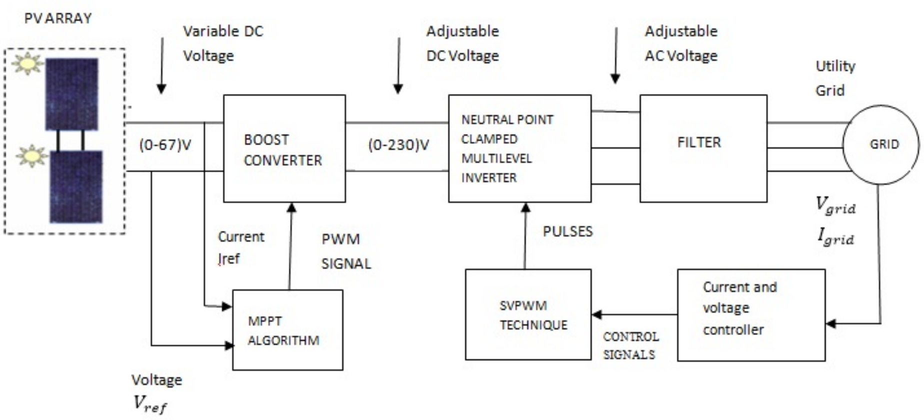

Figure 1: Grid-Connected PV Energy Conversion System and the Associated Closed Loop Control Structure

is deviated from ideal due to the optical and the electrical losses, in order to develop an electrical equivalent circuit model for solar cell, appropriate components should be added with ideal current source. An electrical circuit representing a solar cell is shown in Fig.2. The optical loss is represented by the current source itself, where the generated current Iph is proportional to the light input. The recombination losses are represented by the diode connected parallel to the current source, but in the reverse direction. The ohmic losses in the cell occur due to the series and shunt resistance denoted by R_s and R_{sh} respectively [1],[15].

Applying Kirchoffs law to the node where an I_{ph}, a diode, an R_p and an R_s meet, we get:

$$I_{ph} = ID + IR_P + I \tag{1}$$

We get the following equation for the photovoltaic current:

$$I = I_{ph} - I_D - IR_P \tag{2}$$

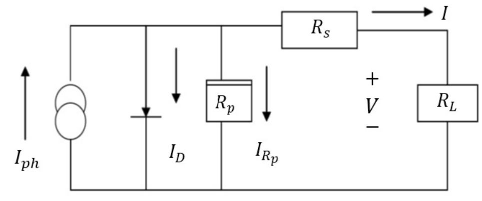

Figure 2: Simplified-Equivalent Circuit of Photovoltaic Cell

$$I = I_{ph} - I_o\left(exp\left(\frac{V + IR_s}{V_T}\right) - 1\right) - \left(\frac{V + IR_s}{R_p}\right) \tag{3}$$

where, I_{ph} is the Insolation Current, I is the Cell Current, I_o is the Reverse Saturation Current, V is the Cell Voltage, R_s is the Series Resistance, R_p is the Parallel Resistance, V_T is the Thermal Voltage (kt/q), K is the Boltzman Constant, T is the Temperature in Kelvin and q is the Charge of the electron.

2.2 Boost Converter

Boost converters are the kinds of high frequency converters which convert unregulated DC power to regulated DC power. Since the output voltage of renewable energy systems is basically unregulated DC voltage, as shown in Fig.3, the boost converters are necessary to adjust the DC voltage for different applications. In these converters the output voltage is a function of the duty cycle of switch (S) which can be defined by a proper modulation technique. When the switch is on, the inductor can be charged by the current flowing through it. However, in the next sub-interval when the switch is turned off, the capacitor will be charged by the inductor current. Second order LC filter in this configuration can regulate the output voltage and remove the high frequency harmonics [7],[12].

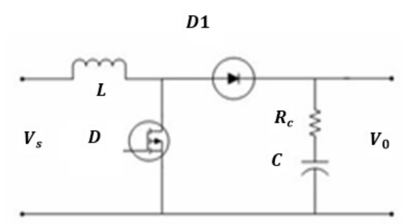

Figure 3: Schematic Configuration of a DC-DC Boost Converter

The conversion ratio is given by the following expression:

$$\frac{V_0}{V_s} = \frac{I_s}{I_0} = \frac{1}{1-d} \tag{4}$$

d = T_{on}/T where I_s is the input current of the converter and T = T_{on} + T_{off}, with its range $1 \geq d \geq 0$. By knowing the V_s and I_s, we can find the input resistance R_{in} of the converter. It is given by:

$$R_{in} = \frac{V_s}{I_s} = R_0(1-d)^2 \tag{5}$$

Here, R_{in} varies from R_0 to 0 and d varies from 0 to 1.

2.3 MPPT Algorithm

As the ir-radiance level is inconsistent throughout the day, the amount of electric power generated by the solar modules is always changing with weather conditions. To overcome this problem, Maximum Power Point Tracking (MPPT) is used. The most popular algorithm is the Perturb and Observe (hill climbing) method and its flow chart is shown in Fig.4. The Perturb and Observe (P&O) algorithm is used to extract the maximum power from the PV panel.

It is applied by perturbing the duty cycle D at regular intervals and by recording the resulting array current and voltage values, thereby obtaining the power. Once the power is known, a check for the slope of the PV curve or the operating region is carried out and then the change in D is effected in a direction so that the operating point approaches MPP on the power voltage characteristic [1].

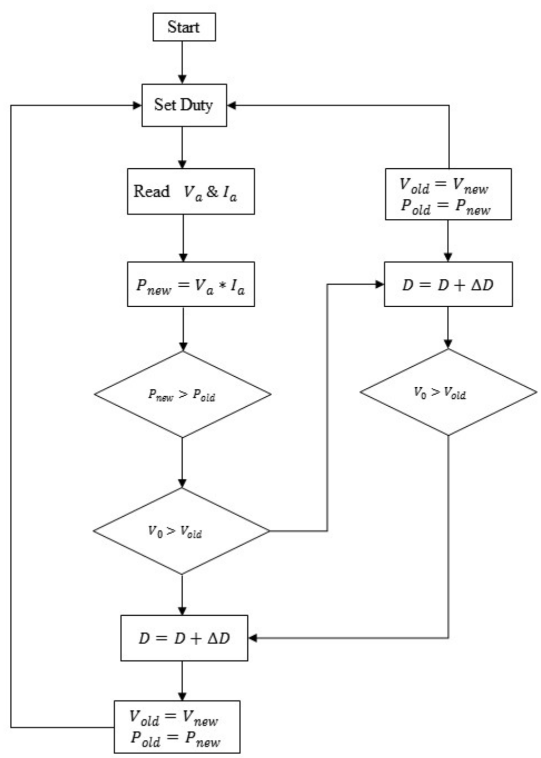

Figure 4: Flow Chart

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2.4 Diode Clamped Inverter

In this configuration the input source is a voltage which is stored in DC link capacitor. This converter chops the input DC voltage and generates an AC voltage with desired magnitude and frequency with respect to the pulse patterns and modulation techniques. Different current and voltage control methods have been proposed to generate a high voltage high current rectangular waveform based on the reference voltage characteristics [11]-[13].

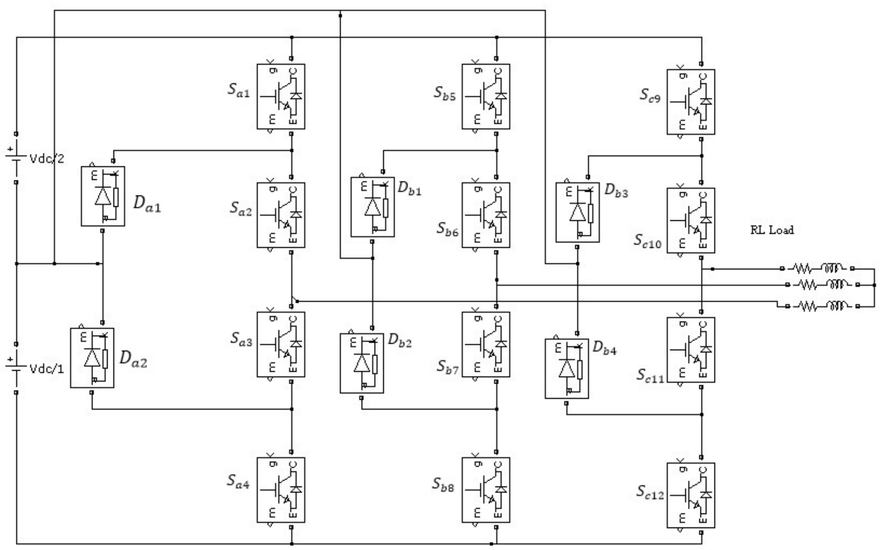

Figure 5: Three Level Diode Clamped Multilevel Inverter

Concept of the diode clamped topology was proposed by Nabae (Nabae et al. 1981). This topology has found wide acceptance for its capability of high voltage and high efficiency operation. Three phase three level diode clamped inverter is shown in Fig.5. A diode clamped multilevel inverter is employed to generate desired voltage and frequency for the grid connection [10].

In one leg consist of two pair of switches & two diodes. Each pair works in complimentary mode & the diodes are used to provide access to midpoint voltage. The DC bus voltage is split into three voltage levels by using two series connection of DC capacitors, C_1 and C_2. Each capacitor is supposed to have an equal DC voltage. Each voltage stress will be limited to one capacitor level through clamping diodes (D_{a1} & D_{a2}). If assumed that total DC link is V_{dc} and mid-point is regulated at half of the DC link voltage, the voltage across each capacitor is $V_{dc}/2$ ($V_{c1} = V_{c2} = V_{dc}/2$). Based on the structure of the diode clamped converter, there are three different possible switching states which apply the staircase voltage on output voltage relating to DC link capacitor voltage rate. Switching states for phase A of three level converters are summarized in Table 1.

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Table 1: Switching States for Phase A

V_{ao}	S_{a1}	S_{a2}	$S_{a2}^{'}$	$S_{a1}^{'}$	S_a
$+V_{dc}/2$	ON	ON	OFF	OFF	2
0	OFF	ON	ON	OFF	1
$-V_{dc}/2$	OFF	OFF	ON	ON	0

3 Control Technique of a Three Level Inverter

The process of switching the power devices in power converter topologies from one state to another is called modulation. A space vector PWM is used, which is one of the most efficient methods. The modulation index m is maintained between 0 to 1.

The SVPWM technique is very popular for industrial converters [2]-[6]. The principle of SVPWM method is that the command voltage vector is approximately calculated by using three adjacent vectors. The duration of each voltage vectors obtained by vector calculations:

$$T_1V_1 + T_2V_2 + T_3V_3 = T_sV_s \tag{6}$$

$$T_1 + T_2 + T_3 = T_s \tag{7}$$

where V_1, V_2 and V_3 are vectors that define the triangle region in which V_s is located. T_1, T_2 and T_3 are the corresponding vector durations and T_s is the sampling time[6].

If the output voltages are pure sinusoids, then:

$$V_{ref} = me^{jwt} \tag{8}$$

where m is the modulation index which varies from $0 < m < 1, \omega$ is the output frequency and V_{ref} is locus of circle. The ideal trajectory for V_{ref} should be a circle and should rotate at a uniform angular velocity. The instantaneous values of the line-to-line voltages of the inverter are as follows:

$$V_{an} = V_m Sin\ \omega t \tag{9}$$

$$V_{bn} = V_m Sin\ (\omega t - 120^o) \tag{10}$$

$$V_{cn} = V_m Sin\ (\omega t + 120^o) \tag{11}$$

It is assumed that the three phase system is balanced then:

$$V_{an} + V_{bn} + V_{cn} = 0 \tag{12}$$

When the three phase voltages are applied to the AC machine a rotating flux is created. This flux is represented as one rotating voltage vector. To implement the space vector PWM, the voltage equations in the abc reference frame can be transformed into the stationary dq reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Fig. 6. The reference voltage can then be expressed:

$$V_{ref} = V_{an} + V_{bn}e^{\frac{j2\pi}{3}} + V_{cn}e^{\frac{-j2\pi}{3}} \tag{13}$$

$$\overrightarrow{V_{ref}} = \frac{3}{2}V_m[Sin\ \omega t - jCos\ \omega t] \tag{14}$$

$\overrightarrow{V_{ref}}$ is a vector having a magnitude of $\frac{3}{2}V_m$ and rotates in space at ω rad/sec.

$$V_{ref} = V_d + jV_q \tag{15}$$

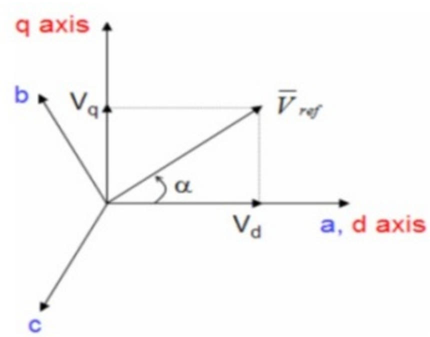

Figure 6: Voltage Space Vector and its Components in (d, q)

$$V_d = V_{an} - \frac{1}{2}[V_{bn} + V_{cn}] = \frac{3}{2}V_{an} \tag{16}$$

$$V_q = \frac{\sqrt{3}}{2}[V_{bn} - V_{cn}] \tag{17}$$

The voltage vectors on the V_d and V_q axes can then be described as:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

$$\mid \overrightarrow{V_{ref}} \mid = \sqrt{V_d^2 + V_b^2} \tag{18}$$

$$\alpha = tan^{-1}\frac{V_d}{V_q} \tag{19}$$

Having calculated V_d, V_q, V_s and the reference angle, the first step is taken. The next step is to calculate the duration time for each vector $V_1 - V_6$. There are 27 Switching States are used and each vector for $T/6$ period. The space vector diagram a for three level inverter is shown in Fig.7. They correspond to 19 voltage vectors (V_0 to V_{18}) whose positions are fixed. The space vector magnitude depends on V/F requirement. The frequency is equal to the time taken by the space vector to complete one complete rotation. If space vector lies in between any two active vectors, then these two active vectors and zero vectors are used to synthesize V_s.

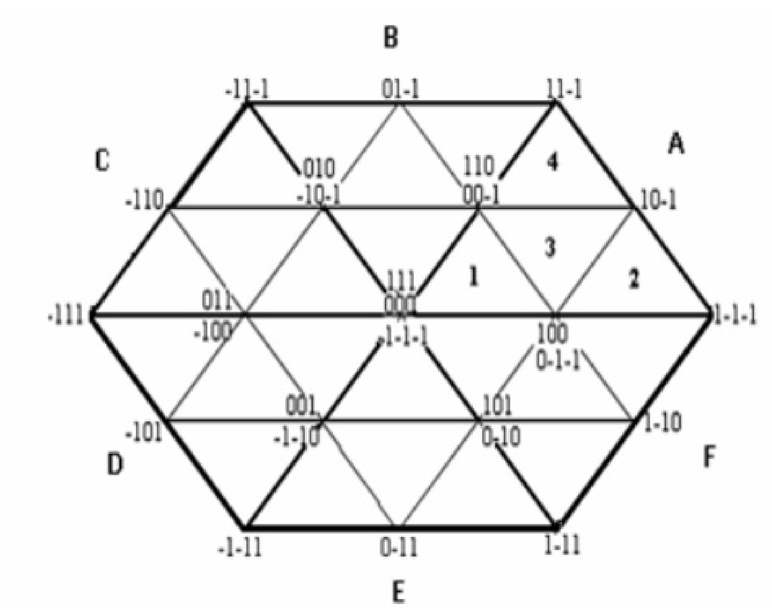

Figure 7: Space Vector Diagram of a Three Level Inverter

4 Current Controller of the Grid Connected System

The aim of the controller is to transfer the power produced by the renewable energy source to the utility system. The controller has an inner current control loop and an outer voltage control loop. The current controller minimizes the error between the reference current and the measured output current. The output of the current controller is the reference voltage for the inverter. This reference voltage is fed to a Space Vector Pulse Width Modulation (SVPWM) unit. The SVPWM unit determines the duty cycles of the multilevel inverters switches. The switching frequency components in the current are attenuated by the LC filter inserted between the multilevel inverter and the utility grid.

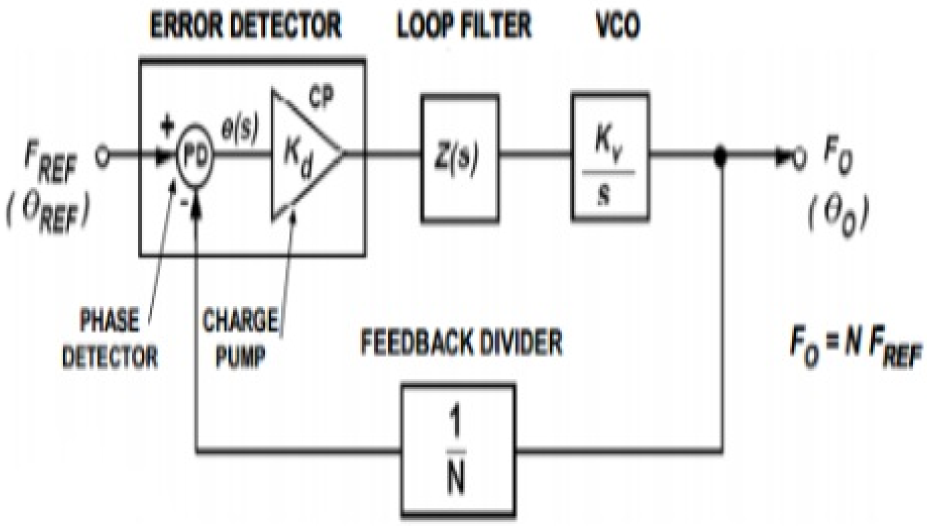

Figure 8: Phase Locked Loop

A phase-locked loop is a feedback system combining a Voltage Controlled Oscillator (VCO) and a phase comparator. The oscillator maintains a constant phase angle relative to a reference signal is shown in Fig.8. Phase-Locked Loops can be used to generate the stable output high frequency signals from a fixed low-frequency signal. The error detector compares the signals at both inputs. When the two signal inputs are equal in phase and frequency, the error will be constant and the loop is said to be in a locked condition.

5 Simulation Results

The proposed system was performed by using MATLAB Simulink software. PV array is an energy source and the power of PV source depends on the load, ir-radiance and temperature. The principle characteristic of WAREE WS 100PV module is summarized in Table 2.

The simulated PV has 6 series connected photovoltaic cells. It produces a maximum power point voltage of about 110 V for the reference operation conditions of ir-radiance $1000W/m^2$ and the temperature 25^0 C that satisfy the condition imposed in (Equation 1). Fig.9 shows the voltage-power relationship of PV array.

Table 2: PV Module Specifications of WAREE WS 100

Parameters	Values
Maximum Power (P_{max})	10 W
Voltage at maximum Power (V_{mp})	17 V
Current at max Power (I_{mp})	0.59 A
Open Circuit Voltage	21 V
Short Circuit Current	0.62 A
Tolerance	5 %
Power Measured at Standard Test Load	1000 W/m^2, $25c, AM1.5$
Temperature Co-efficient of Power	-0.47 % I K
Temperature Co-efficient of Voltage	-0.123 V/K
Operation Temperature	40° C to 85° C
Nominal operating Cell temp	48°C
Maximum System Voltage	1000 VDC

The output of the PV array is 110 V and the voltage is applied to the boost converter from PV array. The output of the boost converter is 230 V and the outputs of the inverter are 230 V and 50 Hz for voltage and frequency respectively. Fig.10 shows the PWM signal of the boost converter, which is generated by MPPT algorithm.

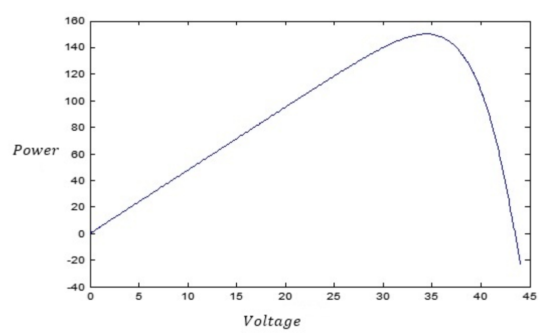

Figure 9: Voltage Power Waveform of PV

The closed loop current controller output is shown in Fig. 11. The grid voltage and the current waveform is almost a pure sine wave as shown in Fig. 12 and Fig. 13 respectively.

The utility grid was assumed to be a purely sinusoidal source with amplitude of 400 V and a frequency of 50 Hz. The grid current is variable one, which depend upon the load. Fig.12 and Fig.13 show the grid current and the voltage waveform of a closed loop system.

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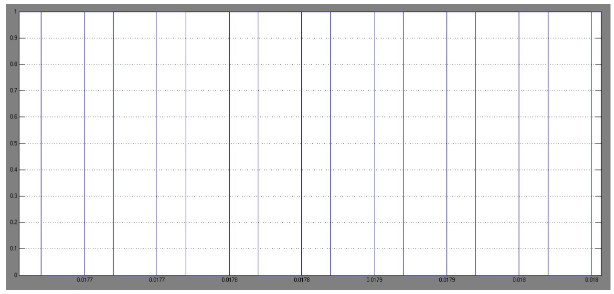

Figure 10: Switching Frequency of the Boost Converter

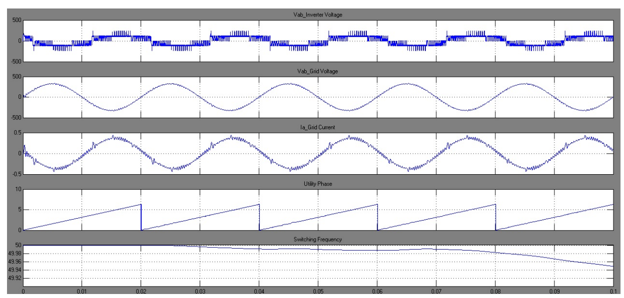

Figure 11: Inverter Voltage, Utility Voltage, Grid Current, Utility Phase Angle and Switching Frequency

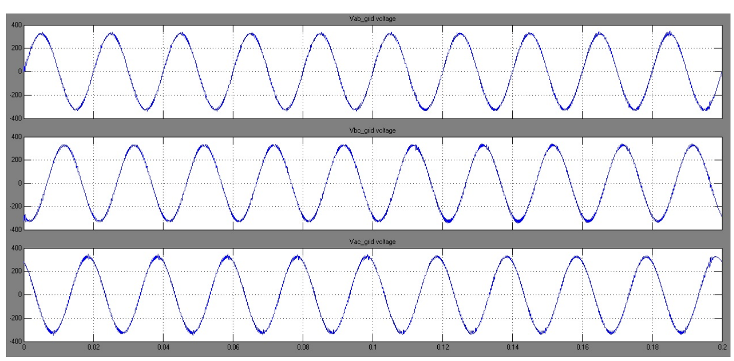

Figure 12: Grid Voltage Waveform of Current Controller

The sampling frequency is 3 KHz. The simulation was carried out to observe the improvements in the line voltage THD and the line current THD for a grid connected system by using FFT analysis and its shown in Fig. 14.

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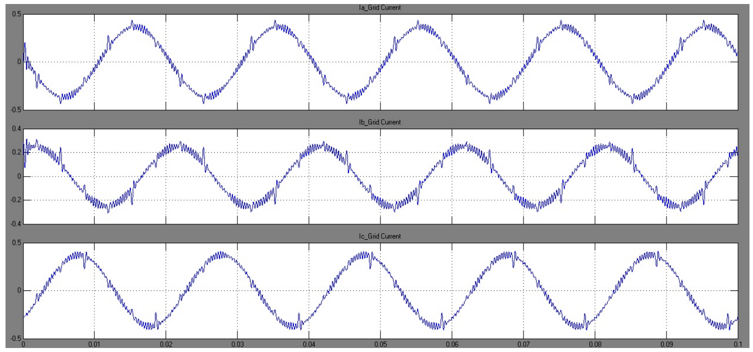

Figure 13: Grid Current Waveform of Current Controller

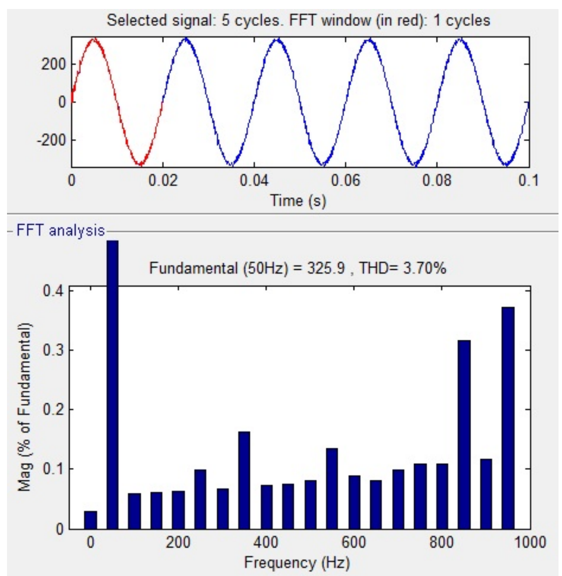

Figure 14: THD Waveform of Current Controller

The comparison of two level and three level voltage and current THD with and without current controller is given in Table 3.

Table 3: Comparison of THD

Sr. No.	Configuration	Without Current Controller		With Current Controller	
		Voltage	Current	Voltage	Current
1.	Two Level	68.39 %	5.78 %	10.20 %	4.38 %
2.	Three Level	45.42 %	2.08 %	3.70 %	2.01 %

6 Conclusion

In this paper the simulation method for a control verification of the power electronic converters in the grid connected systems with the energy generated from the photovoltaic sources is proposed. The photovoltaic models, operation of proposed inverter topology, control system, MPPT algorithm, modulation technique and simulation results were analyzed. Furthermore, since the DC output voltage of PV systems are not very high, this topology is a suitable candidate for these systems as it can boost the low and unregulated input voltage for a transformer less grid connection based on the multilevel topology. The current controller results in constant switching frequency and limited harmonic content and is suitable for a Photovoltaic system. To verify the operation of this topology, with and without current controller methods, they have been compared through simulation results.

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