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MODELING AND CONTROL OF A SINGLE-PHASE GRID CONNECTED PHOTOVOLTAIC SYSTEM

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ABSTRACT

This paper at first presents a control algorithm for a single-phase grid-connected photovoltaic system in which an inverter designed for grid-connected photovoltaic arrays can synchronize a sinusoidal current output with a voltage grid. This paper presents modeling, controller design, and simulation study of a grid connected PV system. The overall configuration of the grid connected PV system is present. The main points discussed here are the MPP tracking algorithm, the synchronization of the inverter and the connection to the grid. Tracking the dc voltage and current allows MPP calculation which gives the inverter to function efficiently. We apply the MPP equations to the PV array model and watch the inverter input and output. In order to synchronize the simulated inverter to the grid the waveforms from the grid are applied to the pulse width modulation (PWM) input and drive appropriately the inverter's IGBT's. A Matlab/Simulink based simulation model is developed for the system. A Simulation results are presented to show the overall system performance.

Keywords: *Grid connected PV systems, DC-DC boost converter, harmonic filter, MPPT.*

1. INTRODUCTION

In the past century, global surface temperatures have increased at a rate near 0.6 C/century because of the global warming taking place due to effluent gas emissions and increasing CO [1]-[2]. Problems with energy supplies and use are related not only to global warming but also to such environmental concerns as air pollution, acid precipitation, ozone depletion, forest destruction, and radioactive emissions. To prevent these effects, some potential solutions have evolved including energy conservation through improved energy efficiency, a reduction in fossil fuel use and an increase in environmentally friendly energy supplies. Recently, energy generated from clean, efficient and environmentally friendly sources has become one of the major challenges for engineers and scientists. Among them, photovoltaic (PV) application has received a great attention in research because it appears to be one of the most efficient and effective solutions to this environmental problem [3]-[4].

The conventional stand-alone photovoltaic systems have the advantages of simple system configuration and control scheme. However, in order to draw maximum power from PV arrays and store excess energy, battery banks are required in these systems. For high power systems, they will increase system cost and weight, and narrow the application areas. Therefore, grid-connected systems, which are designed to relieve this shortcoming, have become the primary researches in PV power supply applications, [5].

The solar cell array produces only a small amount of current and voltage. So, in order to meet a large load demand, the solar cell array has to be connected into modules and the modules connected into arrays. The output voltage from PV array is changeable with solar radiation and ambient temperature. So in order to connect the electrical grid the output voltage from PV array should be fixed and converted to AC voltage which can be done by an inverter. The PV converter and inverter have the task to guarantee safe and efficient operation, to track the maximum power of the PV solar cell array and controlling the power which is injected from the inverters to the electrical grid.

Grid-connected PV plants makes good economic sense to maximize the amount of power generated by PV arrays and thus transferred to the grid at all times. An important technique for achieving the

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above is called the maximum power point tracking (MPPT). In principle, this controls the output of a PV system to match with the grid for all atmospheric conditions. Hence, it results in the system operating at the maximum power point at all times.

The aim of this paper is to introduce a complete modeling and simulation of whole PV system connected to electrical grid under Matlab/Simulink software.

2. GLOBAL CONFIGURATION

In the distributed PV generation, many circuit configurations of topologies can be observed, [6]-[7].

The general conception can be illustrated in the Fig.1, where the PV generator and its controller (composed of dc-dc boost converter and the MPP tracker); associated to a dc-ac PWM converter followed by harmonic filter are given as block diagrams.

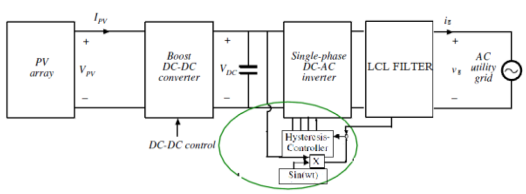

Fig. 1. PV grid connected block diagram overview

2.1. PV GENERATOR MODEL

A simple equivalent circuit of the PV array is shown below in Fig.2. this model is widely used and is called "four parameters model" which depicts the well-known equivalent circuit of the solar cell composed of a light generated current source, a diode representing the nonlinear impedance of the p-n junction, and series intrinsic resistance representing the internal electrical losses, The four parameters appearing in the IV equations are the light current *IL*, the series resistance *Rs*, and two diode characteristics *Io* and γ .

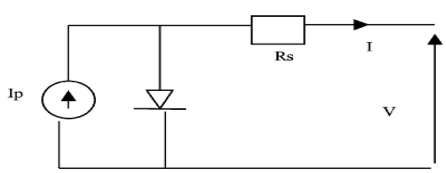

Fig. 2 Equivalent electric circuit of a P-V module

Applying Kirchoff's law of current, the terminal current of the cell is:

$$I = I_L - I_D$$

(1)

The light current is related to irradiance and temperature and the light current measured at some reference conditions:

$$I_L = \left(\frac{G}{G_{REF}}\right)\left(I_{L,REF} + \mu_{ISC}\left(T_C - T_{C,REF}\right)\right)$$

(2)

Where

$I_{L,REF}$ = Light current at reference conditions [A].

G, G_{REF} = Irradiance, actual and at reference condition [W/m²].

T, $T_{C,REF}$ = Cell temperature, actual and at reference condition [° K].

μ_{ISC} = Manufacturer supplied temperature coefficient of short circuit current [A/°K].

The diode current is given by Shockley equation:

$$ID = I_0\left[\exp\left(\frac{q(V + IR_s)}{\gamma k T_c}\right) - 1\right]$$

(3)

Where:

V = terminal voltage [V], I_0 = reverse saturation current [Amps], γ = shape factor.

R_s = series resistance [Ω], q = electron charge $1.602.10^{-19}$ C, k = Boltzman constant=$1.381.10^{-23}$ J/K.

Combining the eq. 1and 2 gives:

$$I_{pv} = I_L - I_0\left[\exp\left(\frac{q(V_{pv} + IR_s)}{\gamma k T_c}\right) - 1\right]$$

(4)

The expression of PV terminal voltage is then given by:

$$V_{pv} = \frac{\gamma k T_c}{q}\ln\left(\frac{I_L - 1}{I_0} + 1\right) - IR_s$$

(5)

The above eq. 5 is verified for certain values of temperature and solar irradiance. In case one of these variables differs, the output voltage and current of the P-V module varies from the MPP. In order to calculate the module voltage we have to multiply it by the number of the cells connected in series. The module current is the sum of the cells connected in parallel. When cell temperature or

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solar irradiance change the PV module is being affected, thus we calculate the output current and voltage from eq. 4, 5, ref. [7].

By implementing this mathematical model in Matlab for different conditions of temperature but in constant solar irradiance, we take the characteristics V-I curve of the pv-cell Fig. 3. In this figure we can see the voltage-current characteristics for constant irradiance but for different cell temperatures. As the temperature is rising the efficiency is falling. The blue line is at 0^0 C, the red at 25^0 C, the black at 50^0 C and the green at 75^0 C. The same behavior appears in many PV cells connected together in order to reach the required power.

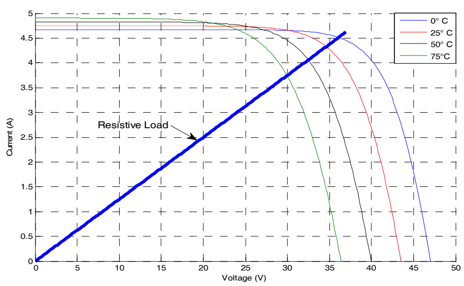

Fig. 3 I-V characteristics under different operating temperature

The straight line represents a simple resistive load. From this figure it is obvious that the power that is generated form this cell and for this load is near the MPP only at the lowest temperature and in the other scenarios there is an amount of energy that cannot be injected to this simple system due to the Ohm's Law and the I-V PV curve. Also we can see that this load is under different voltage and current at different cell temperatures. This indicates the necessity of voltage, or current regulation power electronic circuits, and a system to enable the maximization of the generated power.

2.2. MODEL OF THE BOOST DC-DC CONVERTER

For grid-connected PV applications, two hardware topologies for MPPT have been mostly studied worldwide, known as one-stage and two-stage PV systems. In this work, it was selected the second case, i.e. the two-stage PV energy conversion system, because it offers an additional degree of freedom in the operation of the system when compared with the one-stage configuration, in addition to decreasing the global efficiency of the combined system because of the connection of two cascade stages. Therefore, by including a dc-dc converter between the PV array and the inverter connected to the electric grid, various control objectives are possible to track concurrently with the PV system operation. The intermediate dc-dc converter is built with an (IGBT) as main power switch *Tb* in a standard unidirectional boost topology as shown in Fig.4. The converter is linked to the PV system with a filter capacitor *CA* for reducing the high frequency ripple generated by the transistor switchings. The dc-dc converter output is connected to the dc bus of the dc-ac converter as depicted in Fig. 4. The dc-dc converter produces a chopped output voltage and therefore controls the average dc voltage relation between its input and output aiming at continuously so the characteristic of the PV system and the dc-ac converter be matching. The steady-state voltage and current relations of the boost converter operating in continuous current mode are [8]:

$$V_D = \frac{V_{pv}}{1-D}$$

(6)

$$I_D = \eta_b (1-D) I_{pv}$$

(7)

Where:

ηb: Efficiency of the boost converter
D: Dc-dc converter duty cycle
Ipv: PV array output current
Vpv: PV array output voltage
ID: Dc bus current (inverter side)
VD: Dc bus voltage (inverter side)

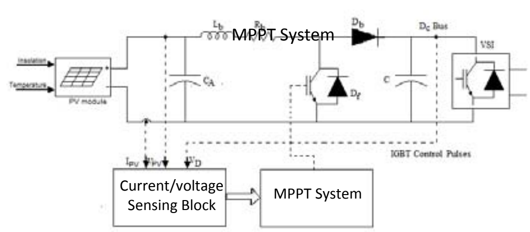

Fig. 4. Schematic of the boost dc-dc converter as a part of the grid-connected PV system

The main role of the Boost DC-DC converter is to insure:

• Set the PV operating point (V_{PV}, I_{PV}) to MPP
• Efficiently step up the photovoltaic array voltage V_{PV} to a higher DC voltage *VDC*

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2.3. MPPT ALGORITHM

In MPP operation, the PV-array produces maximum power under variable conditions of the solar irradiance and environmental temperature. The maximum power point tracking (MPPT) algorithm that is used, is based on the differentiation of PV power and on condition of zero slope of PV curve.

$$P = V \times I$$

(8)

Differencing the eq. 5 gives:

$$\frac{dP}{dV} = \frac{dVI}{d}$$

(9)

In condition of zero slope of PV curve where:

$\frac{dP}{dV} = 0$, we have:

$$\frac{dI}{dV} = -\frac{I}{V}$$

(10)

When $\frac{dI}{dV} < -\frac{I}{V}$ the voltage must be reduced in order to achieve MPP operation. When $\frac{dI}{dV} > -\frac{I}{V}$ the voltage must be raised in order to achieve the maximum power point of the PV generator as shown in Fig.5. , A dc/dc PWM converter is used for that raison.

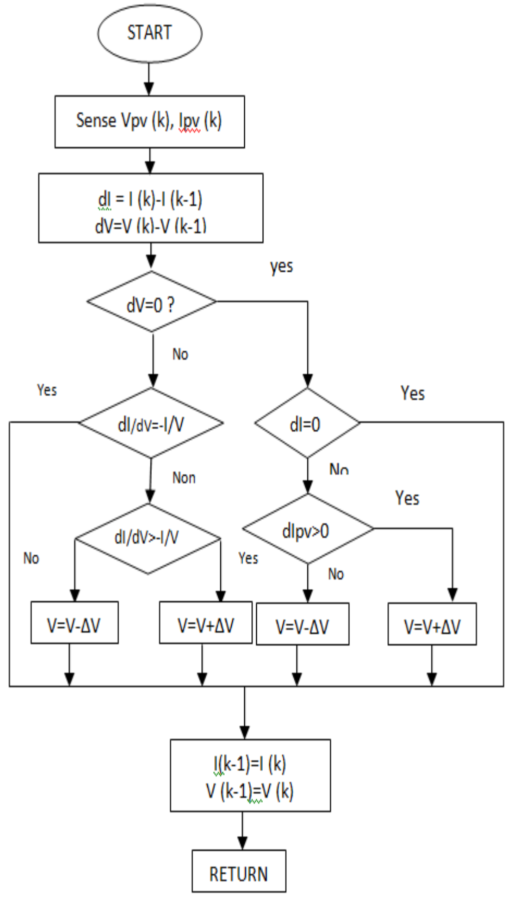

Fig. 5. Flow chart of used MPPT algorithm

2.4. INVERTER MODELLING

In the case of grid-connected PV system, different inverter topologies and controllers are usually used for interfacing the PVG and the utility grid [9]-[10]. Two inverter configurations and three inverter topologies can be identified in such applications, namely: central inverter, string inverter and integrated inverter for configuration; and topologies with or without transformer [6]. These interfaces use various PWM single-phase inverters configurations and topologies, governed with different suitable control strategies to transfer powers and to shape the utility line current, making it follow a reference sinusoidal waveform (Fig.6,7.). In Matlab/Simulink environment, the single-phase inverter can be modelled by four IGBTs switches.

The two main function of the dc-ac converter is:

- Efficiently generate AC output current in phase with the AC grid voltage
- Balance the average power delivery from the PV array to the grid, $P_{Inverter} = P_{pv} \times \square_{dc-dc} \times \square_{dc-ac}$

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2.4.1. CURRENT CONTROLLER SCHEME

The widely used control strategies categories are: power-current controller, power-controller, and current controller [8]. The well-known two-level current hysteresis band controller is the mainly suitable for this application and the most simple to implement in Matlab/Simulink environment. Fig. 3 shows two-level hysteresis band principle, and the obtained currents and voltage waveforms. If ripples are of great concern, a three level hysteresis controller is preferred. Compared with tow level hysteresis control, three-level hysteresis control has lower inductor current ripple under the same average switching frequency. Moreover much lower frequency and higher efficiency can be obtained with a double frequency strategy [11].

The control variable for the DC-AC inverter is the RMS current reference $I_{RMS\ ref}$

The inverter output current is controlled so that it is in phase with the grid voltage and so that it's RMS value equals the reference: $I_{RMS} = I_{RMS\ ref.}$

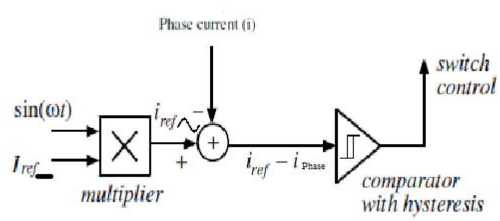

Fig.6. Principle of hysteresis controller

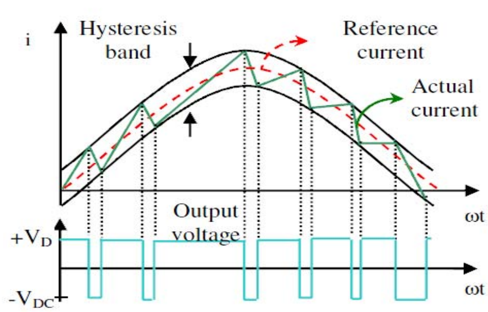

Fig.7. Current and voltages waveforms

3. CONTROL OF THE GRID-CONNECTED PV SYSTEM

The system model shown in Fig.1. demonstrates PV solar cell array connected to a 50 HZ, 220 V UG through a DC/DC boost converter and DC/AC inverter.. The 400 V obtained from DC/DC converter is applied to a signal dc to ac inverter. The task of the boost DC/DC converter drains the power from the PV solar cell array and supplies the DC link capacitor with a maximum power point tracker obtained from the MPPT controller. An LCL filter is inserted after the dc-ac inverter in order to eliminate the harmonics contained in both the voltage and current of the inverter output.

The main task of the grid connected photovoltaic system control system is to be sure that the signals of the inverter output and grid signals have the same frequency, phase and RMS values.

Any deviation in these parameters PV system must be disconnected from the grid, in real life systems; sensors are used to sense the lines for any deviations in frequency and voltage and will disconnect the PV system from the grid when necessary.

4. SIMULATION RESULTS AND DISCUSSION

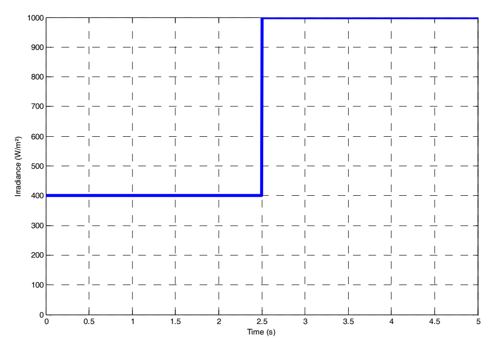

Fig.8. Solar irradiation

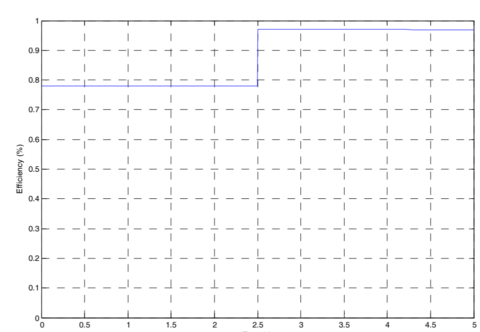

Fig.9. DC-DC Boost efficiency

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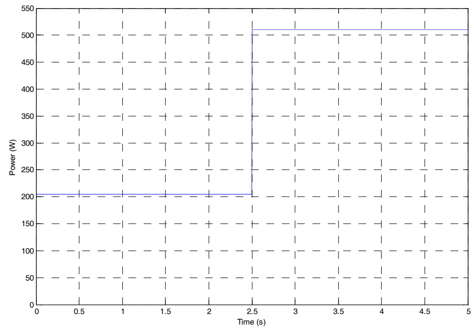


Fig.10.Power Vs time

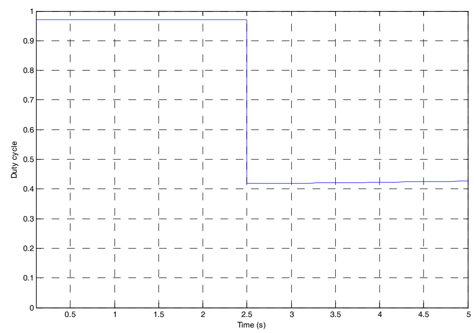


Fig.11. DC-DC Boost duty cycle

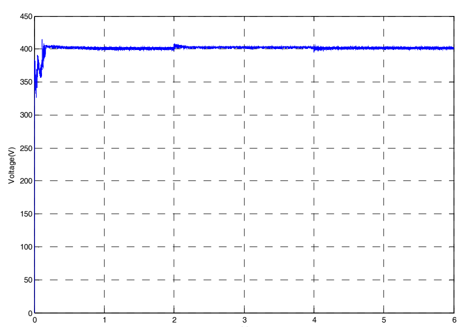
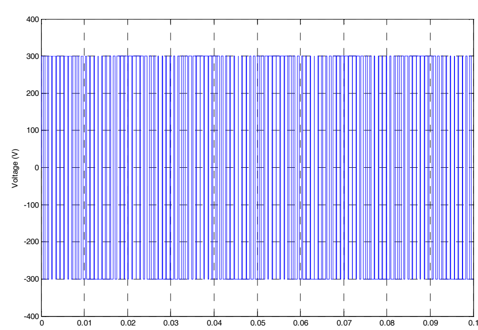
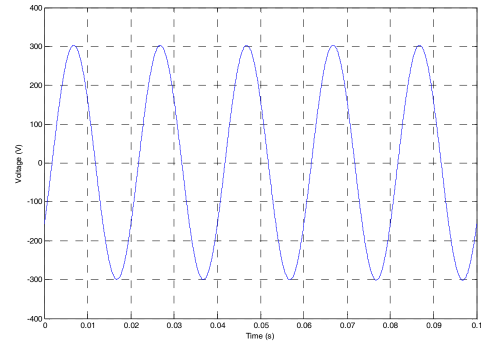


Fig.12. PV voltage output feeding the VSI



(a)



(b)

Fig.13. Simulation of the inverter output Voltage (V) before (a) and after filtering (b)

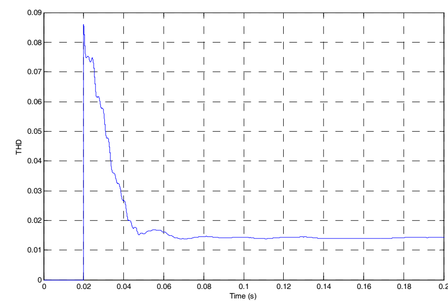


Fig.14. THD of the VSI output before filtering

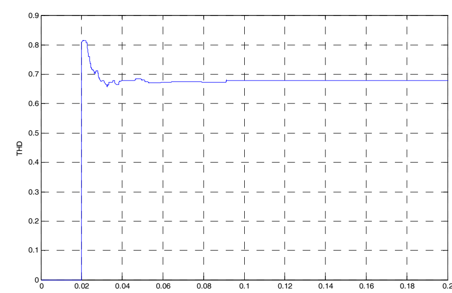
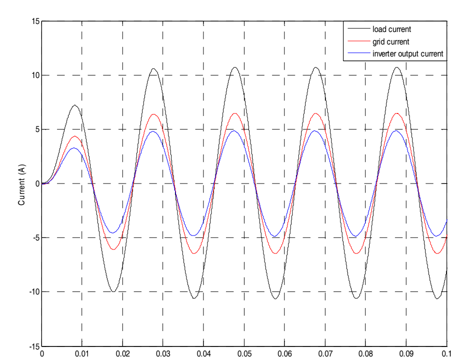


Fig.15. THD of the VSI output voltage after filtering



(a)

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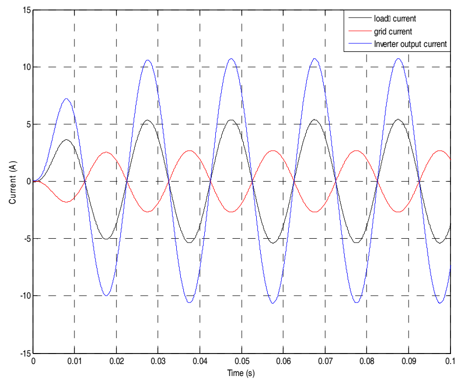
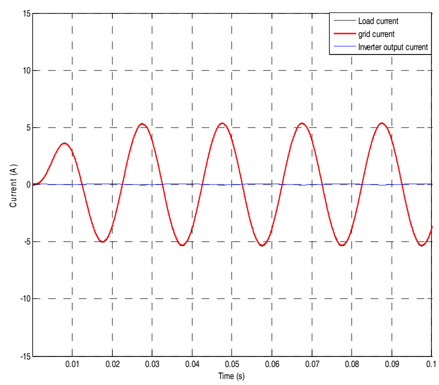


(b)



(c)

Fig.16. Operation modes: (a) Low insolation level,(b) High insolation level, (c) Absence of insolation

In order to investigate the effectiveness of the proposed model and control algorithms of the signal phase grid connected PV system, a group of simulations results has been presented using Sim Power Systems of MATLAB / Simulink environment:

In Fig.8. Two irradiance levels of 400W/m² and 1000 W/m² were applied on the PV array to test the performance of the PV system while maintaining the cell temperature constant at 25 ºC.

In Fig.9. The efficiency of the dc-dc boost converter modified its value from 79 % for 400 W/m² to 98 % for 1000 W/m² as response of the irradiance variation; it's obvious that the efficiency is higher at interesting level of irradiance.

In Fig.10. Shows that the PV generator provides high power generation under higher irradiance level (1000 W/m²) comparing to the low level.

In Fig.11.The behavior of the boost's duty cycle against the change in irradiance, we can see that the boost responds rapidly by going from 0.95 to 0.42 just after the change in order to modify the DC-DC boost output voltage under the effect of the MPPT Tracker.

In Fig.12.the voltage coming from the PV generator after the optimization of the dc-dc converter due to the MPPT tracker, this voltage is maintained at 300 V because the MPPT system kept the voltage constant despite the change in irradiance and that proofs the chosen MPPT method is suitable for this kind of systems.

In Fig.13. The Simulation results of the inverter output Voltage before and after filtering which give a total harmonic distortion (THD) of 68% before filtering (Fig.14.) , and only 1.8% after filtering by the second order LCL filter (Fig.15.).

Fig.16.a indicates that there is insufficient PV energy whereby the utility is concerned to cover this short coming of energy. This condition occurs at low insolation periods, in early morning or late evening.

Fig.16.b illustrates that the PV energy is large than load demand; the excess energy is will exported to the utility. The suitable times for that are usually from late morning to middle evening.

Fig.16.c shows that, the PV energy is zero and the load is completely supplied by the utility. This condition usually happens at nighttimes or at short specific weather conditions where the pV array may be covered quietly cloud.

5. CONCLUSIONS

In order to construct a PV grid connected system, a number of parameters have to be taking into account and to be optimized in order to achieve maximum power generation. The maximum power point tracking algorithm when applied an accurate PV model has the ability to increase the efficiency of the system. In addition to that a controller has to be used in order to achieve the synchronization to the grid and to perform the power management between the system and the electrical grid.

Moreover, this study shows that the proposed control scheme offers a simple way to study the performance for utility interface applications. It is simple to implement and capable of producing satisfactory sinusoidal current and voltage waveforms. To get better power quality, other control schemes for different inverter configurations and topologies are suggested.

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