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Dynamic Modelling and Voltage Regulation of a Three Phase Grid Connected Photovoltaic System

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ABSTRACT: The demand for electrical energy is ever increasing, to supply this additional electrical energy, usage of renewable energy sources (RES) is solution to protect the environment and save limits of the fossil fuels. Solar energy as RES has widespread application due to its numerous advantages like abundant in nature, available free of cost, do not contaminate air & water, do not produce any greenhouse gases, hence saves environment, etc. Solar photovoltaic (PV) system converts the solar energy to electrical energy and are used for power generation, have advantages and challenges too. With variation in weather conditions, the solar insolation & temperature changes, leading to the deviation in the generated the system output voltage, hence proper controller has to be incorporated to maintain steady output voltage irrespective of the changes in the input. With increase in penetration of PV systems to the grid, more number of challenges like voltage quality, power quality, islanding, etc, has to be addressed. This paper presents mathematical modelling, voltage regulation and simulation of a three phase grid connected PV system. The presented model is designed using Simulink block libraries and developed in Matlab/Simulink environment. Simulations are carried out and the results are presented and deliberated..

KEYWORDS: Solar Cell, Maximum Power Point Tracker, Boost converter, Inverter, Phase Locked Loop, PI Controller, Grid, MATLAB/SIMULINK.

I.INTRODUCTION

Withincreasing in population & due to industrialization the demand for electrical energy is growing exponentially worldwide. To meet up the demand, more fossil fuels have to be burnt which leads to fossil fuels depletion, ecosystem destruction due to global warming, pollution, greenhouse effect, etc., to overcome these negative effects alternative energy source called renewable energy sources (RES) or non-conventional energy sources which are restored by natural biological process are more extensively used since past two decades. The RES's are wind energy, solar energy, tidal energy, ocean energy, bio-fuels, bio-energy, hydal energy, geo-thermal energy etc., among them solar energy is most widely used because of its numerous advantages.

Photovoltaic effect is the science of converting light energy to electrical energy. A photovoltaic (PV) system converts sun radiating energy into electrical energy. PV system has number of advantages, such as minimum maintenance due to no rotating parts, no noise, do not pollute atmosphere,greenhouse gases and more importantly the required input energy is completely free of cost. At the same time there are few challenges like, the input solar energy is not available always for 24 hours a day of 365 days in a year, voltage regulation islanding etc.,

The PV system can be operated in two modes, i.e., standalone and grid connected mode. The standalone mode of operation is the substitute for the main electric grid. In this mode of operation, the PV system supplies the generated power only to the remote, isolated loads which are not connected to the main electric grid. This mode of operation employs battery energy storage system for storing the power during the day time and supplying the power to the loads during night time. The applications of this mode of operation include street lighting, traffic signals, emergency, etc.

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The block diagram of standalone connected mode of operation is shown in Fig.1 below

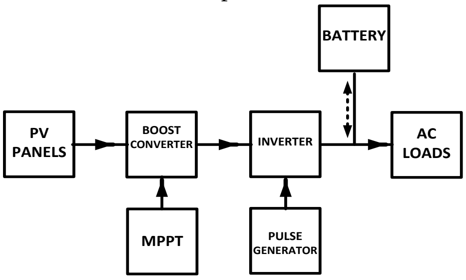

Fig.1. PV System Connected in Standalone Mode

In the grid connected mode of operation, the PV system supplies the generated power directly to the grid. This mode of operation doesn't have any battery energy storage system. The block diagram of grid connected mode of operation is shown in Fig.2 below.

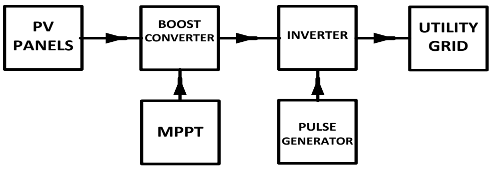

Fig.2. PV System Connected in Grid Connected Mode

With increase in concentration of PV systems connected to the grid, the efficiency of the grid increases also challenges at the same time do the challenges like voltage quality, power quality, islanding etc., The circuit of a grid connected PV system is shown in Fig.3 below.

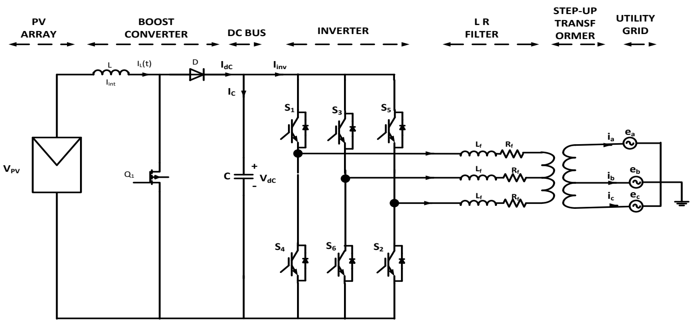

Fig.3. Grid Connected PV System

This present paper presents modelling, control and simulation of a three phase grid connected photovoltaic system. The control system has to perform two functions, one is on PV side, it has to track maximum power generated from the PV panels by using maximum power point tracker (MPPT) controller of perturb and observe (P&O) method and the other is on the grid side to synchronize the PV and grid with same frequency and phase so to regulate the DC link voltage to a constant value, and finally to provide a unity power factor.

The paper is organised as follows, different elements of the three phase grid connected PV system like PV cell, DC-DC boost converter, inverter, phase locked loop are modelled in section II, the simulation results of the grid connected PV system using PI controller are presented and discussed in section III, the paper is finally concluded in section IV.

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II.GRID CONNECTED PV SYSTEM

The three phase grid connected PV system constitutes of a PV panel, power conditioning devices i.e., a DC-DC converter & an inverter, filter and a transformer. The generated output PV power is fed to the utility grid directly without any tapings to the load.

A. Photovoltaic Cell Modelling

The basic element of a PV panel is a PV cell, it converts the input solar radiation to electrical energy. The ideal PV cell is represented by a current source in anti-parallel with diode, the practical PV cell is represented by a current source in anti-parallel with diode, a series resistance and a shunt resistance. An ideal PV cell and a practical PV cell is depicted in fig.4 below.

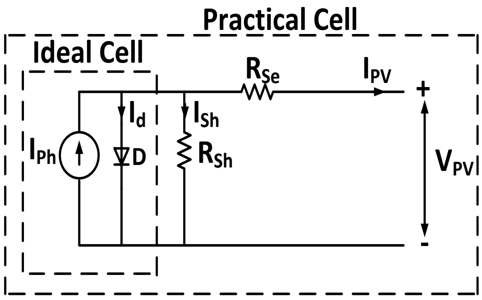

Fig.4. Ideal and Practical PV Cell

The load current 'I_{PV}' is given as

$$I_{PV} = I_{Ph} - I_d - I_{Sh} \tag{1}$$

$$I_{PV} = I_{Ph} - I_O\left[exp\left(\frac{V_{PV}+I_{PV}R_{Se}}{aV_T}\right) - 1\right] - \left(\frac{V_{PV}+I_{PV}R_{Se}}{R_{Sh}}\right) \tag{2}$$

Where 'I_{Ph}' is photon generated current, 'I_d' is diode current, 'I_{Sh}' is current flowing in shunt resistor 'R_{Sh}', 'I_O' is saturation current, 'R_{Se}' is the series resistance caused due to flow of current in the p-n material, the contact material between silicon and metal contact & its value should be as low as possible, i.e.,$R_{Se} \cong 0$, 'R_{Sh}' is the shunt resistance caused due to leakage of current at the edges & its value should be as high as possible, i.e.,$R_{Sh} = \infty$. The output of each PV cell is around 0.5 – 0.6 V and the generated current is around 26mA/cm^2.

To get higher voltages and currents at the output terminals of a PV panel, additional number of cells must be connected in series and parallel respectively. The number of PV cells connected in series & or parallel form a PV module, number of modules connected in series & or parallel form an PV array, and number of PV modules connected in series & or parallel form a PV panel. The figure.5 below shows a solar PV panel having 'N_{Se}' number of cell connected in series and 'N_{Sh}' number of cell connected in parallel.

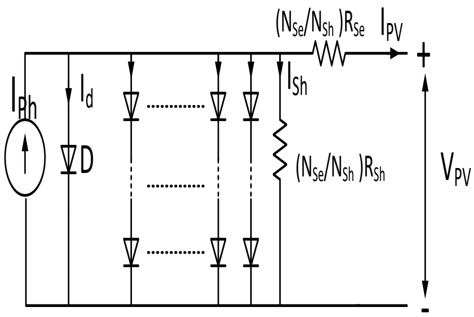

Fig.5. PV Panel

The PV panel generated output current 'I_{PV}' for the above shown PV panel is

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$$I_{PV} = I_{Ph}N_{Sh} - I_o N_{Sh}\left[exp\left(\frac{V_{PV}/N_{Se} + I_{PV}R_{Se}/N_{Se}}{aV_t}\right) - 1\right] + \left(\frac{V_{PV}/N_{Se} + I_{PV}R_{Se}/N_{Se}}{R_{Sh}}\right) \quad (3)$$

The I-V, P-V characteristics of a PV cell is non-linear in nature. The cell has to operate at a unique point so that maximum power is delivered to the load. That unique point is obtained using maximum power tracking point (MPPT). There are number of MPPT methods in the literature, to name a few, perturb & observe (P & O) method, Incremental conductance (INC Cond) method, fractional open circuit method, fractional short circuit method, etc.,

B. Power Conditioning Devices

These are power electronic devices that change the properties of the PV panel generated DC voltage, a boost converter steps up the input DC voltage and the inverter converts the input DC voltage to AC voltage and supplies to the load or grid

i. Boost Converter Modelling

The components of a DC-DC converter are an inductor, switch diode and a capacitor; it acts as an interface between PV panel and the load. It converts unregulated DC voltage into regulated DC voltage at a required voltage level. The magnitude of the output voltage depends upon 'ON' and 'OFF' switching duration. The pulse width modulation (PWM) switching is defined as keeping switching frequency constant and varying the switching 'ON' and 'OFF' duration time. The duty cycle 'k' is defined as the ratio of 'ON' time to the switching time. The converter operates in two modes continuous conduction mode and dis-continuous mode depending upon the absorption and release of energy. The circuit of a boost converter is shown in the circuit figure. 6 below.

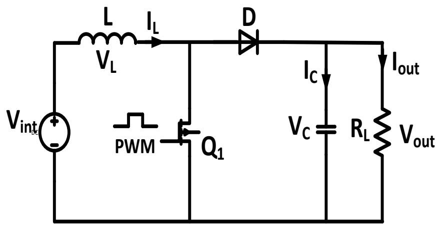

Fig.6. Boost converter

The output voltage 'V_{out}', is given as

$$V_{out} = \frac{1}{1-k}V_{int} \quad (4)$$

'V_{int}', is the input voltage and 'k', is the duty ratio which is give as

$$k = \frac{T_{ON}}{T} \quad (5)$$

'T_{ON}', is the time duration of switching 'ON', and 'T' is the total time duration of switching 'ON' and 'OFF'.The operation of the switch causes the circuit to work in two states, in one state the switch is 'open' and in the second state the switch is 'closed'. The figure.7 below depicts the same.

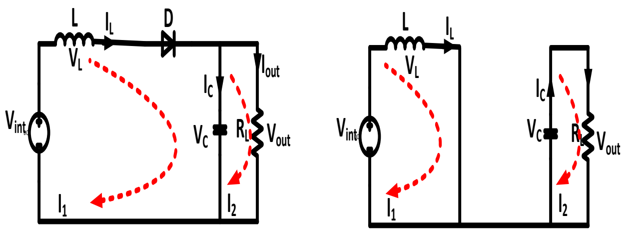

Fig.7. (a) Boost Converter Switch(a) Boost Converter Switch Opened Closed

When the switch is 'OFF',

$$V_L = V_{int} - V_{out} \quad (6)$$

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$$\frac{dI_L}{dt} = \frac{\Delta I_L}{\Delta t} = \frac{V_{int}-V_{out}}{L} \tag{7}$$

When the switch is 'ON', the supply voltage is equal to the inductor voltage,

$$V_L = V_{int} \tag{8}$$

$$\frac{dI_L}{dt} = \frac{\Delta I_L}{\Delta t} = \frac{V_{int}}{L} \tag{9}$$

ii. Inverter Modeling

The inverter converts the regulated DC voltage output obtained from boost converter into regulated AC voltage, the voltage source inverter (VSI) or current source inverter (CSI) can be used, generally VSI are used as they. The power circuit in the inverter consists of three arms and each arm having 2 switches. The inverter is shown in figure .8 below.

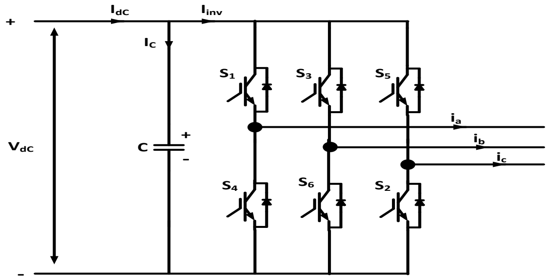

Fig.8. Inverter

The equivalent circuit of the inverter connected to the grid and the voltage vector diagram is shown in figure.9 below

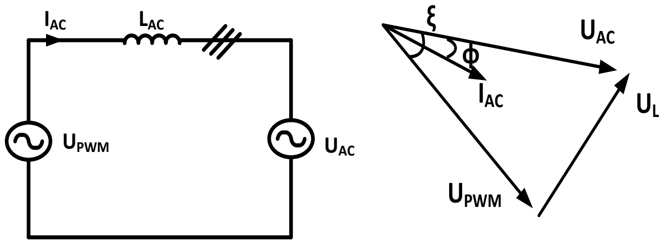

Fig.9.(a) Single Phase Representation (b) Phasor diagram of Inverter

For the grid connected PV system shown in figure.3, the voltage control loop transfer function and the current control loop transfer function is given below in the following equations.

$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \\ \frac{dv_{dc}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{R_f}{L_f} & \omega & \frac{k_d}{L_f} \\ -\omega & -\frac{R_f}{L_f} & \frac{k_q}{L_f} \\ \frac{k_d}{C_{dc}} & \frac{-k_q}{C_{dc}} & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} + \begin{bmatrix} \frac{-1}{L_f} & 0 & 0 \\ 0 & \frac{-1}{L_f} & 0 \\ 0 & 0 & \frac{1}{C_{dc}} \end{bmatrix} \tag{10}$$

$$\frac{v_{dc}}{v_{dc}^*} = \frac{k_p}{C_{dc}} \cdot \frac{\left(s+\frac{k_i}{k_p}\right)}{\left(s^2+\frac{k_p}{C_{dc}}\right).s+\frac{k_i}{C_{dc}}} \tag{11}$$

$$\frac{i_d}{i_d^*} = \frac{k_p}{L_f} \cdot \frac{s+\left(\frac{k_i}{k_p}\right)}{\left(s^2+\frac{(k_p+R_f)}{R_f}\right).s+\left(\frac{k_i}{L_f}\right)} \tag{12}$$

The resistance is neglected as it is small. The inverter current is controlled by regulating the amplitude of PWM and the lag angle between the inverter and the grid. The inverter output voltage is regulated by inverter reactive power and the phase angle is controlled by the inverter reactive power, according to relationship amongst the active power and system

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DC bus voltage, the reference for PI controller is taken as DC bus voltage, it regulates voltage angle and the voltage amplitude is regulated by taking reference as reactive power for PI controller. The active (P) and reactive power (Q) are used for controlling the inverter, to make the inverter operate at unity power factor the quadrature axis of current is made to zero. The inverter & grid voltages, currents are transformed from a-b-c to d-q frame using synchronous reference frame theory. By controlling active current (i_d) that is injected to the inverter, the constant DC link voltage can be obtained. The active reference current i_d^* is given as

$$i_d^* = k_p(V_{dc}^* - V_{dc}) + K_i \int (V_{dc}^* - V_{dc})dt \quad (13)$$

The PI controller gains are $k_p$and k_i.

The active and reactive power in-terms of d-q voltage and current is given as

$$\begin{cases} V_d^* = RI_d + V_d - \omega L I_q + L\frac{d}{dt}i_d \\ V_q^* = RI_q + V_q - \omega L I_d + L\frac{d}{dt}i_q \end{cases} \quad (14)$$

$$\begin{cases} P = V_d I_d + V_q I_q \\ Q = -V_d I_q + V_q I_d \end{cases} \quad (15)$$

To make inverter operate at unity power factor, quadrature axis component of current is made zero, $I_q = 0$. The active power and reactive power is modified as

$$\begin{cases} P = V_d I_d \\ Q = -V_d I_q \end{cases} \quad (16)$$

The measured values and the corresponding reference values are compared and the current controller reduces the error to zero by controlling, the controller diagram is shown in figure.10

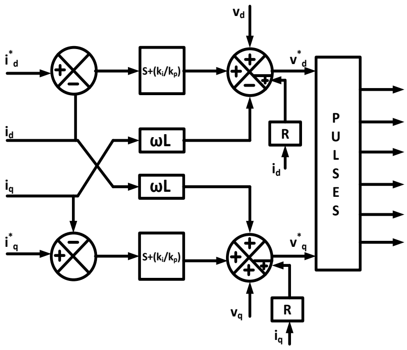

Fig.10. Controller for Generation of Pulses

The control is done using two loops current control loop and voltage control loop, the current control loop controls the current sent to the grid and the voltage control loop controls the DC link voltage.

iii. Phase Locked Loop

Grid synchronizations are very important for grid connected systems. A phase locked loop (PLL) technique is used for synchronisation of inverter with grid. The inverter output current is synchronized with d-q reference grid voltage frequency and phase. The operation of PLL is based on recognition of zero crossing voltage. The block diagram of the PLL is shown in figure.11 below.

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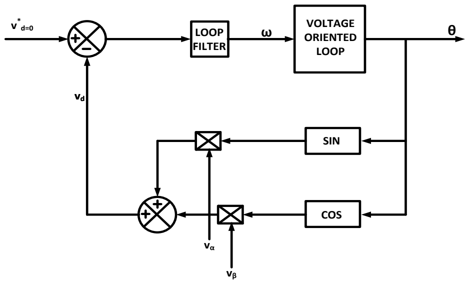

Fig.11.Block Diagram of the PLL

V. RESULT AND DISCUSSION

In The Simulink diagram of the grid connected photovoltaic system simulated using Matlab is shown in figure.12 below

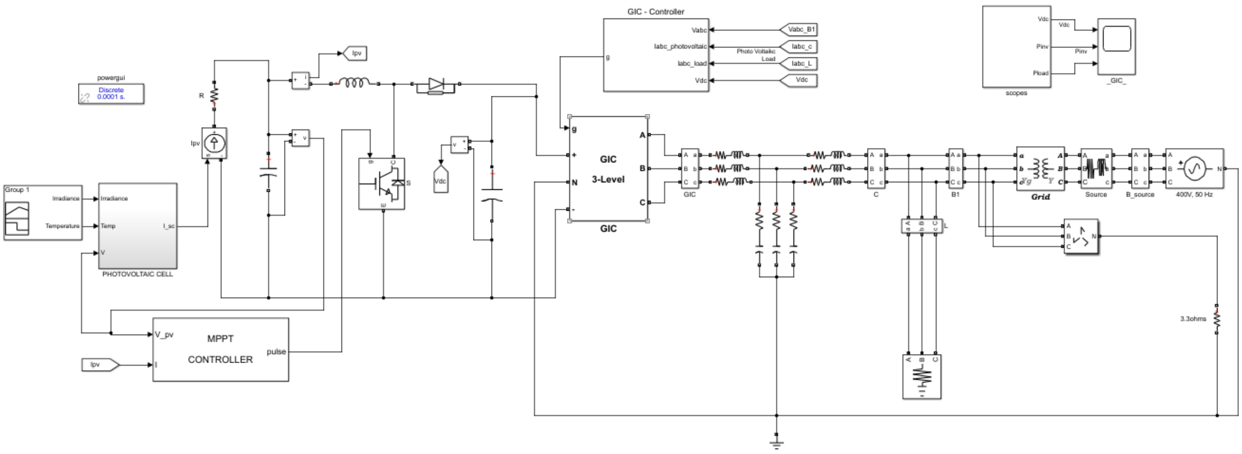

Fig.12.Simulink Diagram of the Grid Connected Photovoltaic System

The three phase grid connected PV system is simulated for an irradiation of 1000 W/m2 and at a temperature of 300C. The PV generated current Vs. time characteristics of the PV cell is shown in figure.13 below.

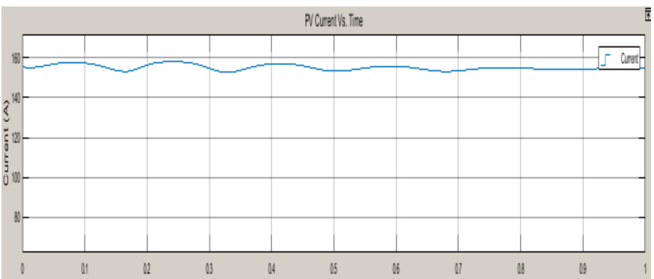

Fig.13.PV Generated Current Vs. Time

The PV generated voltage Vs. time characteristics of the PV cell is shown in figure.14 below.

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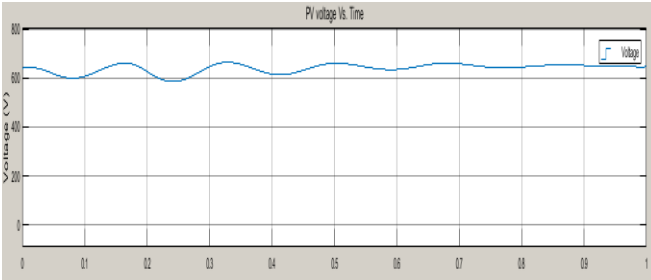

Fig.14.PV Generated Current Vs. Time

The PV generated power Vs. time characteristics of the PV cell is shown in figure.15 below.

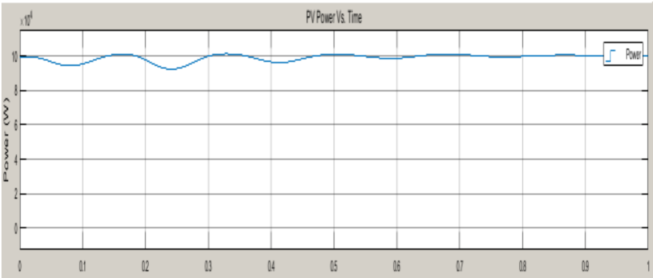

Fig.15. PV Generated Power Vs. Time

The current–voltage (I-V) characteristics of the PV cell are shown in figure.16 below.

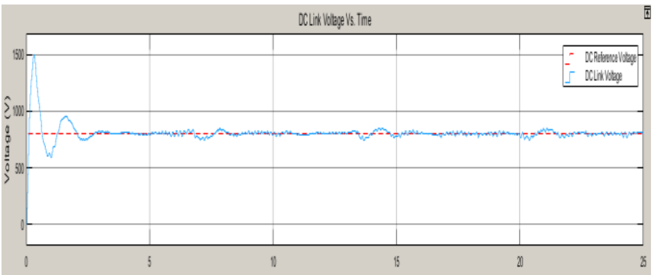

Fig.16.DC link Voltage Vs. Time

The inverter power output Vs. time characteristics of the PV cell are shown in figure.17 below.

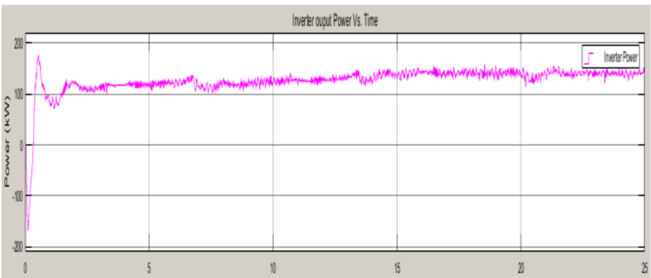

Fig.17.Inverter Output Power Vs. Time

The load power Vs. time characteristics is shown in figure.18 below.

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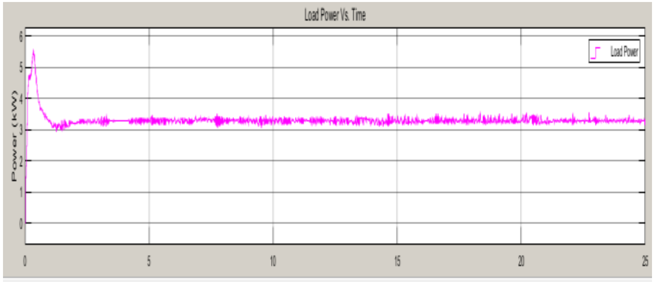

Fig.18.Load Power Vs. Time

VI.CONCLUSION

In this paper, a three phase grid connected PV system is modelled and simulated. The input parameters being, solar insolation of 1000 W/m2 and operating temperature of 300C. The current-voltage at this radiation intensity and ambient temperature are showed. P&O method of maximum power point tracking strategies is used in this work and is simulated. The DC/DC boost converter, inverter constitutes part of the PV system. The PI controller is used for voltage regulation of a three phase grid connected PV system. The DC link voltage, generated PV power output and the load power are showed are shown in the results.

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