Three Phase Grid Connected Solar Photovoltaic System with Power Quality Analysis

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Abstract— The evaluation of power electronics has emerged since last few decades ago. In modern contest the world is moving from conventional energy sources to the renewable one. It is due to it greater abundance and environment friendly characteristics. Solar energy is one of the most promising renewable resources that can be used to produce electric energy through photovoltaic process. A significant advantage of photovoltaic (PV) systems is the use of the abundant and free energy from the sun. Power electronic devices used as interface between renewable power and its user. It makes the power generated by renewable sources suitable for utilization. Solar power contribution in power generation has been increasing very fast and cost of power generated by solar photovoltaic is falling rapidly. Solar photovoltaic cell converts solar energy directly into dc power. Power is mostly transmitted and utilized in ac form because of advantages associated with it. To convert the dc power into ac, a highly efficient converter is required for optimum utilization of energy. The MPPT algorithm uses the IPV and VPV of the PV array and gives the MPP and a VDCREF. This voltage is then passed on to the inverter and then further to the three-phase grid. In this thesis the behavior of the active and reactive power of the grid which is supplied by the PV array is investigated. The various currents such as inverter current, grid current and load currents are also investigated.

***Keywords*—Photo Voltaic model, Grid Connected Solar PV Systems, Three Phase Circuit, MPPT, Power Quality**

I. Introduction

There are different sources of energy existing in this world. These sources are categorizes mainly into two groups. (a) Renewable (that don't get exhausted and replenished on its own), (b) Non-renewable (a source that requires a large amount of time). Renewable & non-renewable energy sources produce secondary energy sources such as electricity and hydrogen etc. However,
in the present scenario most of the energy requirement is fulfilled by conventional or non-renewable energy sources. These are formed over a prolonged
period of time under high pressure & temperature inside the earth's crust, hence are called fossil fuels. The increased concerns over the climate changes and other environmental impact due to the extreme dependence on fossil fuel have led

to the proliferation of renewable energy sources like wind and solar photovoltaic power across the globe, Solar PV energy source, which currently ranks third among the most deployed renewable energy sources in the world, after hydro and wind power.

The demand for electric energy is expected to increase globally due to the rapid population growth and industrialization. This rapid increase in the energy demand requires electric utilities to increase their generation. In the last six decades, India's energy use has increased 16 times and the installed energy capacity by 84 times, still India is facing the problem of acute power deficit. The present scenario indicates that India's future energy requirements are going to be extremely high. In order to meet the ever increasing power requirements, huge amount of power needs to be generated in the existing power sector.

Penetration of solar energy is increasing rapidly over the last decade due to its availability and climate-friendly attributes. Solar energy is free from greenhouse gas (GHG) emission and plays a key role in developing a sustainable power system for the future. However, the intermittent nature of solar energy creates a number of potential challenges in integrating large-scale photovoltaic (PV) with the grid. Voltage fluctuation, voltage management, harmonic distortion, demand management, and load rejection are the major potential issues concerning the application of photovoltaic in Single Wire networks. Of particular interest was the adverse effect on voltage instability of the network with varying PV penetration. Studies shows that voltage raises across the network would exceed regulatory standards with the high penetration of PV in networks.

II. Scope of Work

The increased concerns over the climate changes and other environmental impact due to the extreme dependence on fossil fuel have led to the proliferation of renewable energy sources like solar photovoltaic power across the globe. Solar PV is a sustainable energy source, which currently ranks third among the most deployed renewable energy sources in the world, after hydro and wind power. AC modules are considered as the new face of PV power and it employs a commercial PV module together with an inverter. The composite system is more flexible, easier to handle and feeds power directly into the utility grid. The power output of an AC module must meet the utility requirements in power quality. Grid synchronization is another major concern for grid-connected systems requiring the grid variables to be monitored continuously. .The objective of this article is

- To design and develop MATLAB/Simulink model of Solar PV system.
- To develop the MATLAB simulation model of three phase solar PV system with low voltage grid integration with various control schemes.
- Analyze the performance of parameters of grid such as voltage, current and power as the percentage penetration of solar PV increases.

III. SYSTEM DESCRIPTION

The downward tendency in the price of the photovoltaic modules, together with their increasing efficiency, put solid-state inverters under the spot lights as enabling technology for integrating PV systems into grid. Grid synchronization unit plays important role for grid connected SPV systems. The given system consists of a SPV array, DC/DC boost converter and a three phase voltage source converter with grid synchronization control schemes.

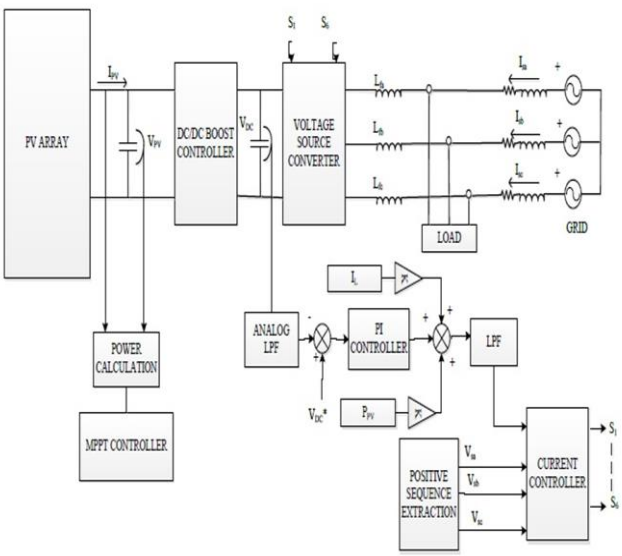

Figure 1 System Design

A. *Component modeling*

The proposed system consists of various components like PV array, DC-DC converter and a three phase voltage source converter along it's with control algorithm. The present section describes the detailed modeling of each component of the given system.

a) *PV Array Modeling*

A single diode model has been considered to model the solar cell for this work. Equation based modeling of PV cell as well as PV module is presented in this section.

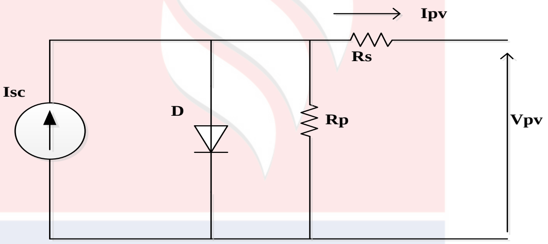

Figure 2 Equivalent Circuit Model of Solar Module

From the above circuit diagram, the I-V characteristics can be obtained by

$$I_{sc} - I_D - \frac{V_D}{R_p} - I_{PV} = 0 \quad (3.1)$$

Thus,

$$I_{PV} = I_{sc} - I_D - \frac{V_D}{R_p} \quad (3.2)$$

The reverse saturation current I_{rs} is given as

$$I_{rs} = I_{scref} + \left[\exp\left(\frac{qVoc}{NskAT}\right) - 1\right] \quad (3.3)$$

The module saturation current varies with the cell temperature is given by

$$I_o = I_{rs}\left[\frac{\left(\frac{T}{T_{ref}}\right)^3 e^{qCg}}{Ak} * \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (3.4)$$

The basic equation that describes the current output of the PV module of the single-diode model is given in equation (3.5).

$$I_{PV} = I_{sc}N_p - N_s I_o\left[\exp\left\{\frac{q(V_{PV}+I_{PV}Rs)}{N_s AkT}\right\} - 1\right] V_{PV} + \frac{I_{PV}Rs}{Rp} (3.5)$$

Where k is the Boltzmann constant (1.38 x 10^{-23} J K^{-1}), q is the electronic charge (1.602 x 10^{-19} C), T is the cell temperature (K); A is the diode ideality factor, R_s the series resistance (Ω) and R_p is the shunt resistance (Ω). N_S is the number of cells connected in series = 36. N_p is the number of cells connected in parallel = 1. The MATLAB Simulation of Solar PV panel is shown in the Figure 3.

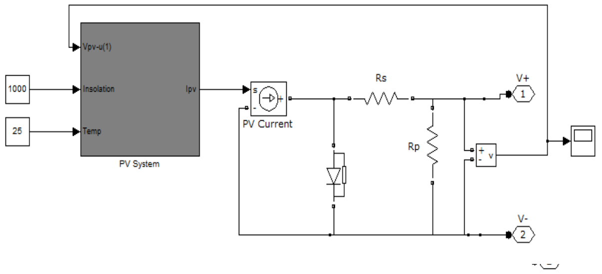

Figure 3 MATLAB Simulation of Solar PV Panel

b) *DC/DC Boost Converter Modeling*

Output of PV array is highly affected by the meteorological parameters like irradiance, temperature and keeps on changing. A control technique named as MPPT (maximum power point tracking) is required to continuously track the maximum power point of PV array. A power converter is required to implement the MPPT control and to step up the voltage level at a value so that the DC link voltage can be maintained at a constant value.

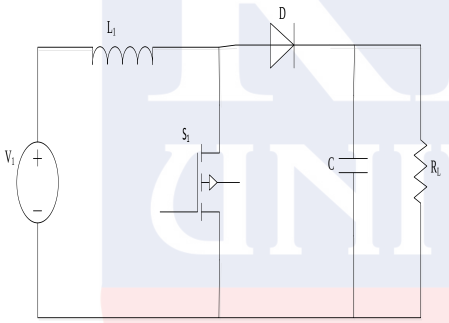

Figure 4 Equivalent Circuit Model of DC/DC Boost Converter

Table 1 Parameter Calculations for DC/DC Boost Converter

Parameter	**Formula**	**Value**
PV Output voltage (V_{PV})	-	650 V
Switching Frequency (f_{sw})	-	10.6kHz
Duty Cycle (D)	$D = 1 - \frac{V_{PV}}{V_{DC}}$	0.375
Input Inductance (L_1)	$L_1 = \frac{V_{PV}\,D}{2\Delta i_1 f_{sw}}$	1.5 mH
DC link Capacitors (C)	$C = \frac{I_{in}D}{\Delta v f_{sw}}$	2800μF

Where,
I_{in}= Input current to DC/DC boost converter
Δi_1 = Input Current ripple (about 10%)
Δv = Input voltage ripple (3 %)

c) *Voltage Source Converter Modeling*

The three phase voltage source converter consists of a six switching devices which converts DC voltage into AC voltage. The VSC consists of capacitors to filter the DC link voltage. In the VSC, IGBT semiconductor switches are used and designed for 415 V, 25 kW at 0.8 p.f. lagging load. Figure 5 shows a circuit representation of three phase voltage source converter.

Table 2 Parameter Calculations for Voltage Source Converter

Parameter	**Formula**	**Value**
RMS Load current (I_{RMS})	$\frac{VA}{3V_o}$	25 A
Switching Frequency (f_{sw})	-	10kHz

Where,
VA= Load Power/Power factor
V_o = Output voltage (Line to line)

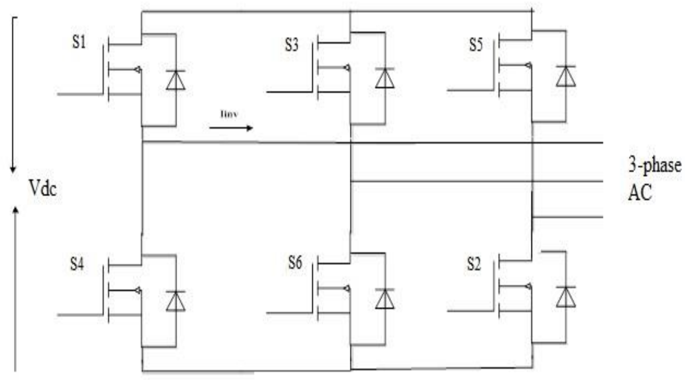

Figure 5 Circuit Diagram of Voltage Source Inverter (VSI)

d) *MPPT Controller*

The application of perturbation the output power is compared with the previous perturbation cycle power output. If the power increases then the increment in voltage or current remains continuous in same direction. If power decreases then the variation in voltage or current in reverse direction. A flowchart illustrating the operation of this method is shown in Figure 6.

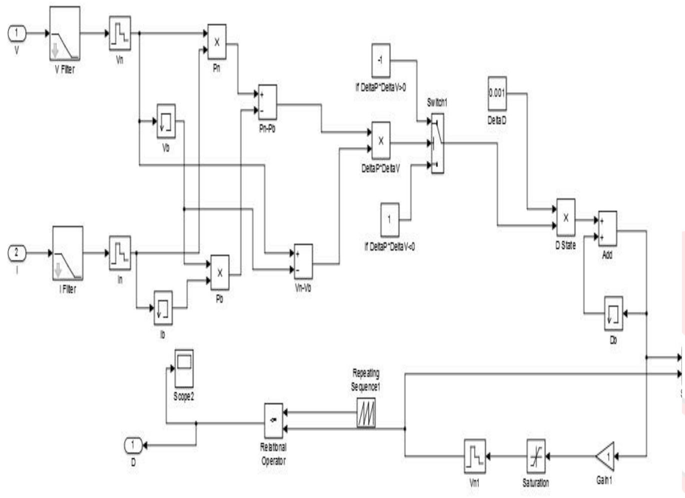

Figure 6 MATLAB Simulation of P&O MPPT Controller

e) Inverter Controller

DC-AC stage must only inject active component of grid current. So for this the steady state current error between the actual and desired grid current should remain zero at any grid frequency. Phase locked loop (PLL) tracks the phase of input voltage signal and generate unit voltage templates (sine and cosine components). The d-q components of currents passed by

a filter which filter out high frequency harmonic components. Then again d-q frame is transformed back to 3-phase components. This current is then compared with source current and error between them is fed to Hysteresis-based PWM signal generator to produce final switching signals which are the pulses for inverter.

System terminal voltages are given as,

v_α=$V_m$cos(ωt+Φ) (3.6)

And current are given as:

i_α=$I_m$cos(ωt+ θ_n) (3.7)

Following equation gives

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3.8)$$

i_d= In phase component of Grid current

i_q= Reactive component of Grid current

$$\begin{bmatrix} i_d = I\cos(\Phi - \theta_n) \\ i_q = -I\sin(\Phi - \theta_n) \end{bmatrix} (3.9)$$

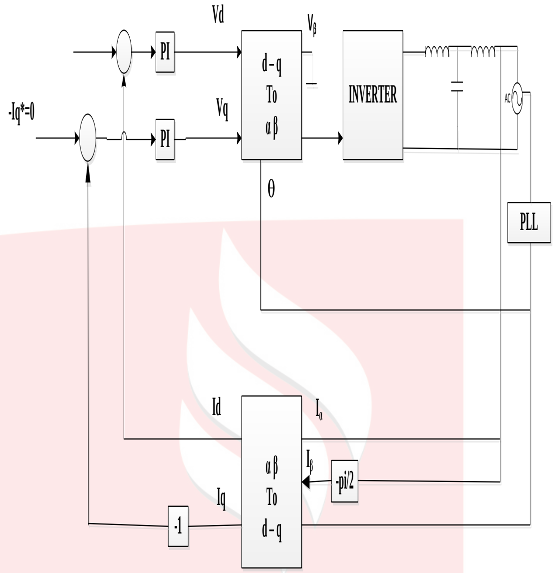

Figure 7 Reference Current Extraction using SRF Theory

These reference currents are compared with actual current and error between both will be the required amount of reactive current supplied by inverter. Error of current is used to generate pulses for inverter. The MATLAB Simulation of SRF control based Scheme for Grid Synchronization.

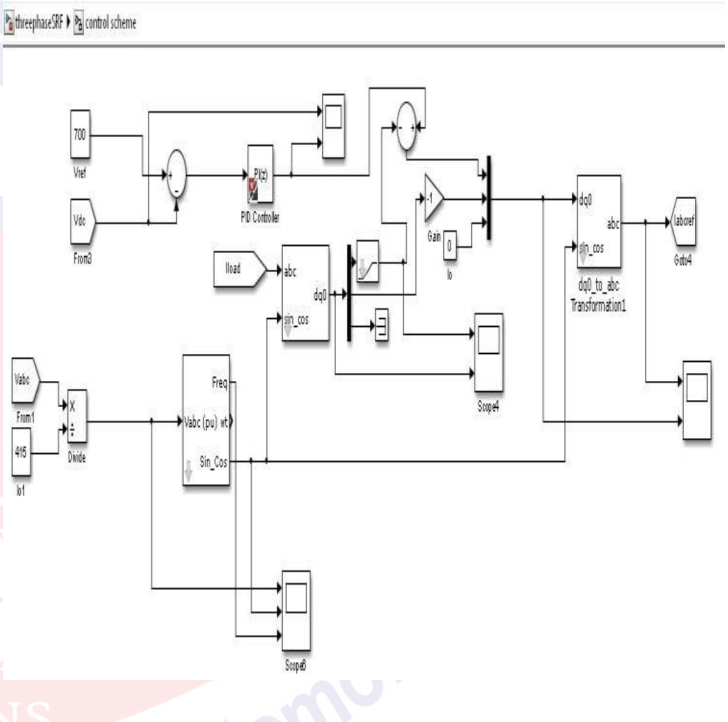

Figure 8 MATLAB Simulation of SRF Control Scheme for Grid Synchronization

f) Connected Load

There are different types of load connected to a grid. They can be classified in various categories according to various factors such as nature of load, load function, load operation time, load phases etc.

In this dissertation load connected to the 3 phase grid connected solar PV system is of following type

1. Continuous connected load- A three phase balanced lagging load of 50 KVA is always connected to the system
2. Non-linear load- A single phase diode bridge connected lagging load is also connected.
3. Discontinuous load- A three phase balanced load is connected through circuit breaker which is at times applied to the system.

Now, the MATLAB simulated model of a 3-phase grid connected system is shown in the Figure 5.10 which incorporate a PV array connected to a DC-DC boost converter, a DC to AC three phase voltage source inverter, a three phase 415 V grid with the above mentioned load connected at PCC point.

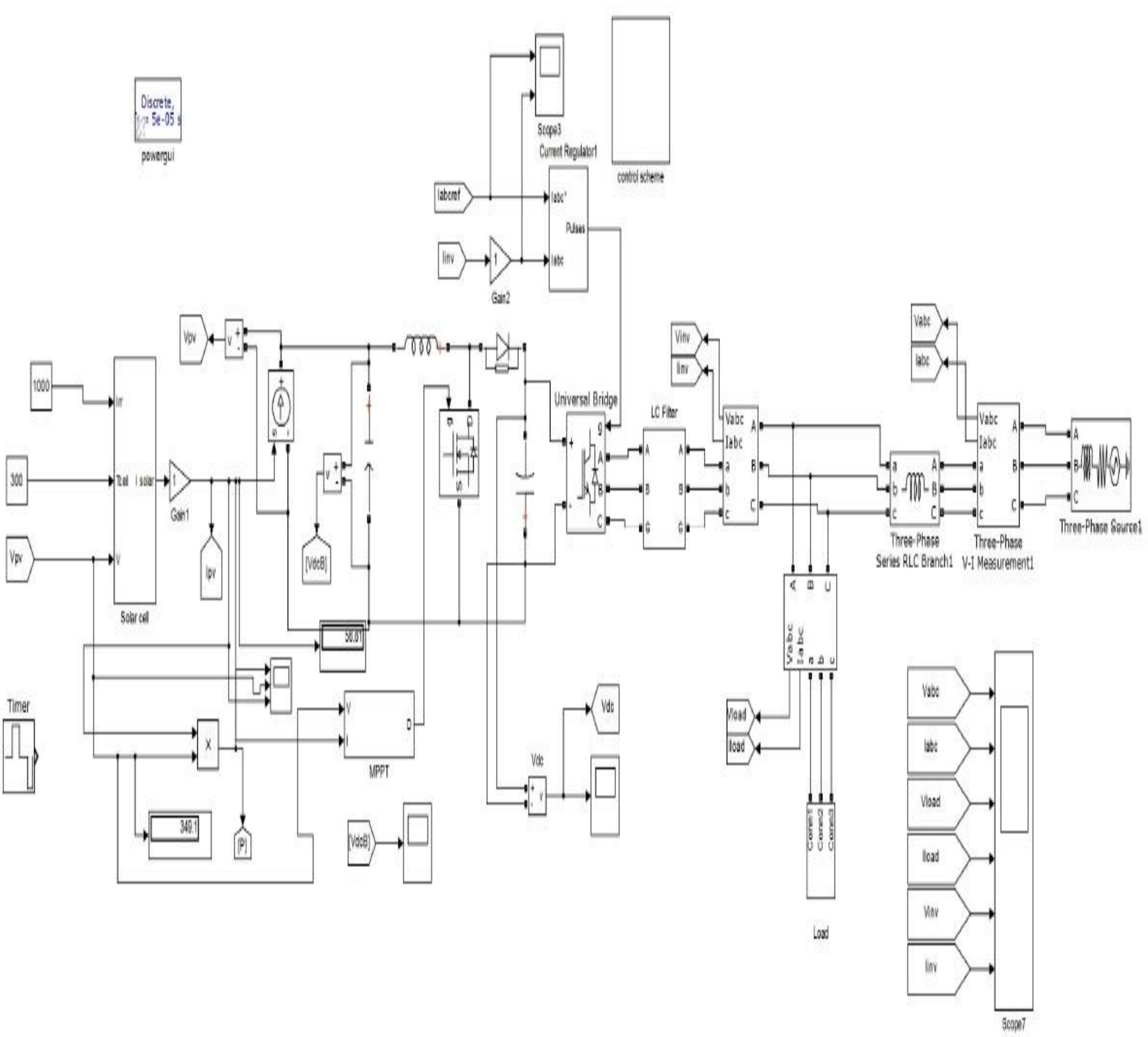

Figure 9 MATLAB Simulation of Grid Connected Solar PV

IV. Results and Discussions

The performance of three phase grid connected solar PV System is analyzed for different kind of loads. Also the impacts of changing meteorological parameters especially irradiance is studied. Impacts of increasing percentage penetration of solar PV on the existing grid is also analysed through THD and voltage at the PCC point.

A. Performance of Three Phase Grid Connected System

A 5 KW grid connected solar PV system MATLAB model is simulated as shown in the previous chapter. Its performance is analyzed by observing the various parameters like dc power supplied by solar PV system, dc link voltage, 3phase voltage and active & reactive power supplied by the system etc. at constant irradiance and at changing irradiance

a) DC Power Supplied by the Solar PV System

Power supplied by solar PV system is dependent on the voltage and the current of solar panel which in turn dependent on the irradiance and temperature. At constant ambient temperature DC power supplied by solar PV panel follows the irradiance pattern. This can be shown by the Figures10 and Figure 11.

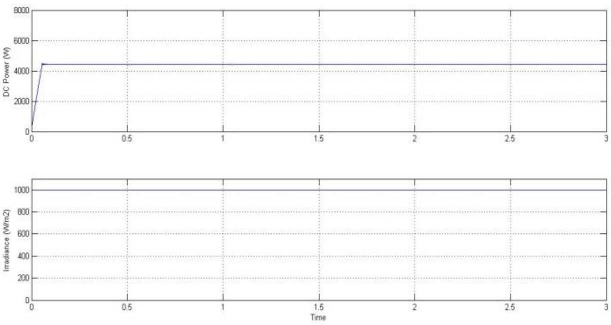

Figure 10 DC Power of Solar PV System at Constant Irradiance

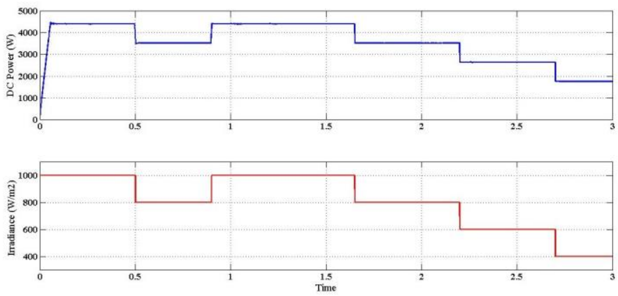

Figure 11 DC Power of Solar PV System at varying irradiance

b) PV Voltage and Current

Solar PV voltage and current is very important parameter for the performance of solar PV system. These are the parameters which are used as input to MPPT control which in turn generate pulses for DC-DC boost converter. As mentioned in the previous chapters that PV voltage does not vary much due to change of irradiance but current is purely dependent on the irradiance pattern.

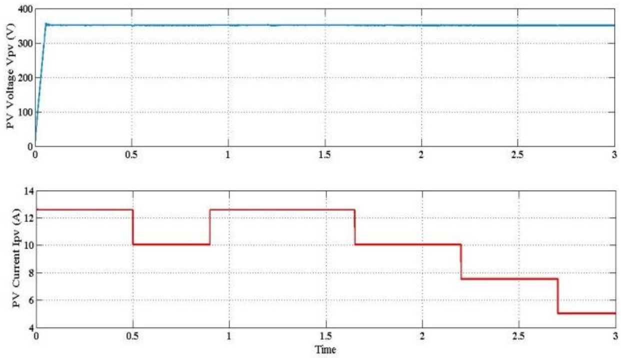

Figure 12 PV Voltage and Current

c) DC Link Voltage

DC link voltage is the voltage that is applied to the inverter input. A DC-DC converter is used to maintain dc link voltage of desired value. A high value capacitor is used to maintain the DC link voltage constant. An almost constant 700 V DC link is obtained from boost converter. This can be shown in the Figure 13

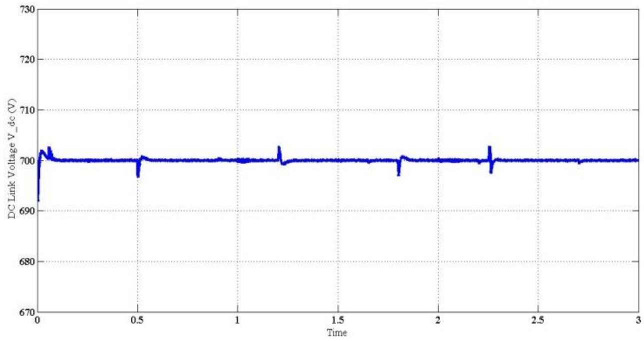

Figure 13 DC link voltages

6.2.4 Inverter Voltage and Current

Inverter (VSI) produces a three phase ac voltage output to supply the three phase load at PCC point. A three phase universal bridge utilizing IGBT switch is used in MATLAB simulation work to convert DC link voltage to three phase ac. Pulses for IGBT switches is produced by inverter control block. The three phase balanced voltage and current supplied by inverter is shown in the Figure 14. As VSI uses solid state switches which produces current harmonics that can be clearly shown in the Figure 14.

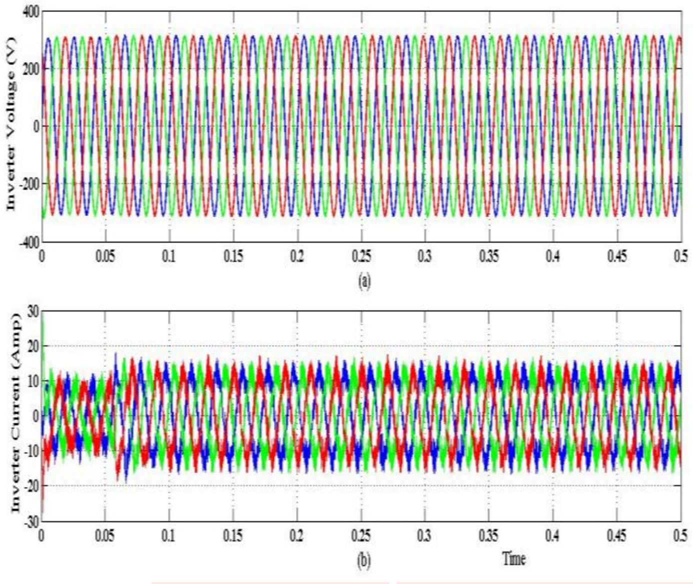

Figure 14 Inverter (a) voltages (b) Current

d) Power Supplied to Grid

Active power and reactive power both are supplied by the system. As shown in the Figure 15 and Figure 16 the active power is dependent on the irradiance parameter and the almost constant reactive power is supplied irrespective of the meteorological parameter variation. Only the partial requirement of reactive power is supplied by solar PV system.

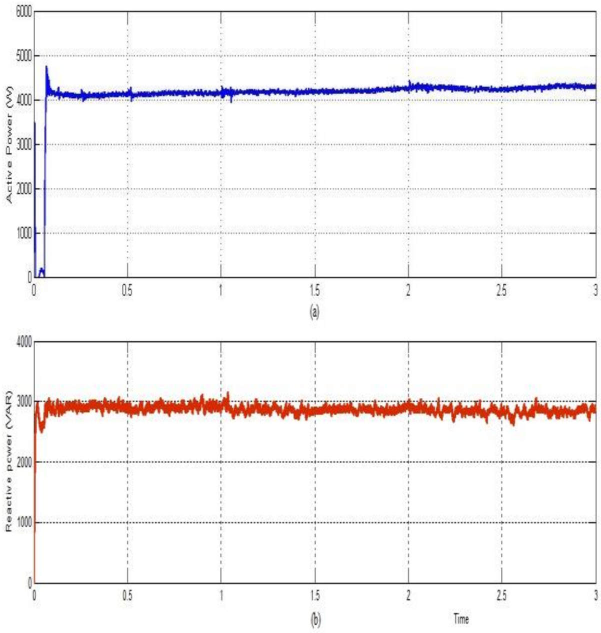

Figure 15 Power supplied to grid at constant irradiance a) Active power b) Reactive power

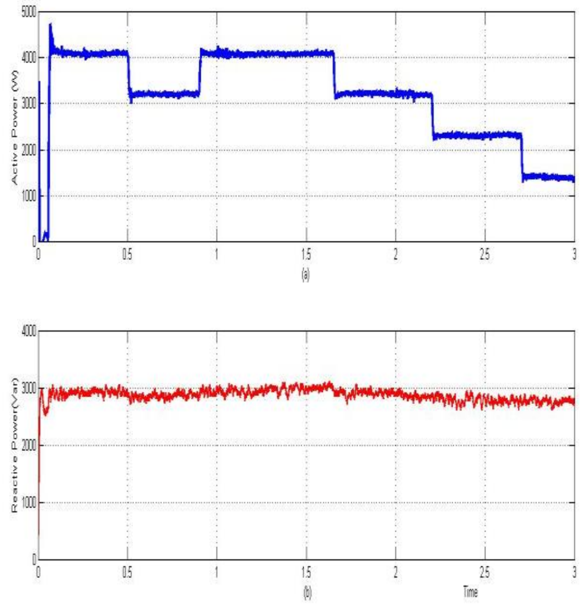

Figure 16 Power Supplied to Grid at Varying Irradiance a) Active power b) Reactive power

B. Power quality analysis of system

Power quality of a grid connected solar PV system can be analyzed by the PCC point voltage analysis for different kinds of loads and for changing meteorological conditions, harmonic distortion in voltage at PCC point and harmonic distortion in current in the grid for different levels of percentage penetration.

a) Harmonic Analysis of Grid

As grid integration of solar PV system requires DC-DC Converter and three phases VSI which utilize many power electronics switches which in turn produced harmonics in the system. Hence, harmonic analysis is important for grid integrated system. However, a VSI is used as inverter and a synchronous reference frame theory is used to extract reference current for inverter control hence voltage generated is almost balanced while the current harmonics is very high in the system.

Now as the percentage penetration level of solar PV system increases in the grid the more and more current harmonics are introduced in the grid. Initially grid current is same as load current with harmonics 0.51% as penetration level increases up-to 30% the current harmonics of grid also increases to 5.18% which is beyond standard permissible limit of 5%.

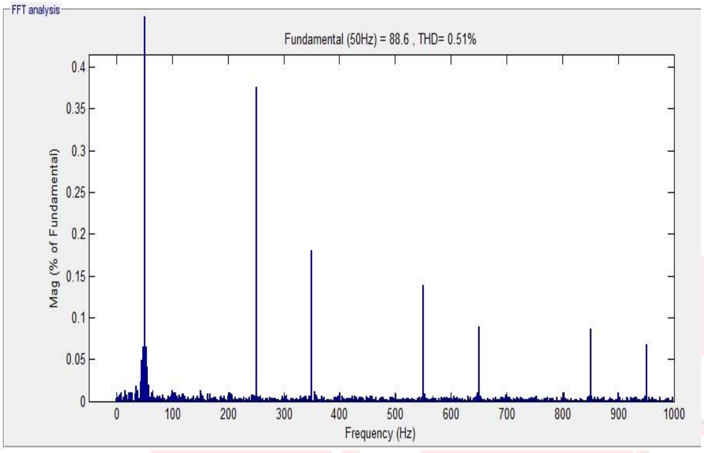

Figure 17 THD of Load Current

The MATLAB simulated three phase grid connected solar PV system is discussed. Power, voltage and current produced by solar PV at constant and varying irradiance conditions, dc link voltage after applying P&O MPPT technique and active and reactive power supplied by inverter due to inverter control is presented and are satisfactory.

Also, power quality analysis of three phase grid connected system is presented when the percentage penetration of solar PV increased from 10% to 30% on the basis of harmonic distortion in the current of grid and voltage at the PCC point. The same comparison is given in the table 3.

Table 3 Comparison of power quality at different percentage penetration

% Penetration of SPV	% Current THD of Grid	% Voltage THD of PCC Point
0	0.5	0.2
10	3.52	1.5
15	4.33	1.4
20	4.54	1.31
25	4.78	1.27
30	5.18	1.22

V. Future Work

Power efficiency is a key driving force due to the continual increase of energy consumption and costs. The present work can also be extended in future.

- The hardware can be developed for grid connected 3 phase Solar PV systems.
- After developing the hardware, power quality analysis of grid connected PV systems can be carried out.
- Further, the Solar PV system can also be integrated with a DSTATCOM for complete reactive power compensation.
- Also, the grid integrated Solar PV systems are integrated with filters (passive or hybrid filters) to contain the harmonic level of existing grid to prescribed value as per power quality standards.

VI. Conclusion

The objective of this paper is to develop a three phase grid connected solar PV system with different types of loads such as linear, non-linear and discontinuous. Also analyse the performance of this system to constant and changing irradiance levels and power quality analysis of the PCC point and then study the effect on grid current harmonic distortion when the percentage penetration of solar PV system in the grid system increases from 10% to 30%.

Performance analysis of three phase grid connected system with P&O MPPT technique and inverter control scheme bases on synchronous reference frame theory is carried out. Further power quality three phase grid connected system is analyzed on the basis of variation of PCC point voltage at the discontinuous load and total harmonic distortion (THD) analysis of the grid current for increasing percentage penetration of Solar PV in the existing grid. As distribution grid is weak grid i.e. high R/X ratio PCC point voltage is affected by sudden load change or change in irradiance which directly affects the active power supplied by the Solar PV.

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