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Integration of solar power to the electric grid: A case study

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Abstract

As the demand of electricity is increasing with each passing day and the conventional sources of energy are depleting, it becomes mandatory to include various renewable or non- conventional sources of energy for the generation of power. Solar energy is one of the promising sources of renewable energy in the modern day. In this paper integration of the solar power to the electric grid has been discussed. MPPT controller and a boost converter are used to obtain maximum power at the output and further synchronization of Voltage Source Inverter's output with the electric grid is presented.

Keywords: Solar Photovoltaic (SPV) System, Maximum Power Point tracker (MPPT), Perturb and observe algorithm, Phase Lock Loop (PLL), Voltage Source Inverter (VSI).

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1. Introduction

With the ever increasing demand of power, various conventional sources of energy like coal, uranium etc is exploited to such an extent that has resulted in the depletion of their sources. Being non - renewable is their one disadvantage and discharging harmful green house gases like carbon dioxide, carbon monoxide etc into the atmosphere is another cause of concern. Therefore, there is a need to switch towards various non-conventional, renewable sources of energy that pave no toxic effect to the atmosphere and are available free of cost. One of the examples of such a source of energy is solar photovoltaic energy which can be exploited extensively to generate power without damaging the atmosphere and can also be installed in such rural areas which are deserted from the main population with the help of stand-alone solar photovoltaic system [1].

As the conventional sources of energy are depleting, in order to slow down their rate of depletion, solar photovoltaic technology can be harnessed to pool its power to the main utility grid. This reduces the burden on the conventional power plants [1]. But one of the drawbacks of SPV system is that that of its low reliability as it is an intermittent source of energy which is available intermittently and uncertainly [1]. But if it pools it power with the main grid, this drawback can be overseen as because at night or days with low insolation, power can be supplied through the main grid that maintaining the reliability and efficiency at a high value and to do the same at stand-alone SPV system batteries can be incorporated [2].

The paper is organized as follows:
In section 2, classification of solar PV system has been discussed.
In section 3, various components of grid interactive solar PV system are described in detail.
In section 4, simulation based model of SPV array connected to the grid and its various results are presented.
In section 5, the paper is concluded.

2. Classification of Solar PV System

Solar PV systems are broadly classified as follows:

2.1 Stand Alone Solar PV system

The main components of a stand-alone SPV system consists of SPV Array, MPPT controller, DC-DC boost converter, batteries, dump load and DC/AC loads. The output voltage and current obtained from solar photovoltaic array is fed to the MPPT controller. The MPPT controller controls the switching of the DC-DC boost converter in such a way that maximum power is obtained at its output. This power is fed to the DC loads and by using suitable inverter, it can also supply power to various AC loads [3].The block diagram of stand-alone solar PV system is shown in Fig.1. If power generated is excess than its demand, it can be stored in batteries and can further supply the loads when demand is more than the generation, thus increasing the systems reliability. When the batteries are fully charged, the excess power is then dumped in the shunt connected dump loads/heaters. The battery discharge diode D_B keeps a check on the battery from being overcharged. The Array diode D_A provides isolation between the array and battery in order to prevent the discharging of the battery through array during low insolation periods or at night [3].

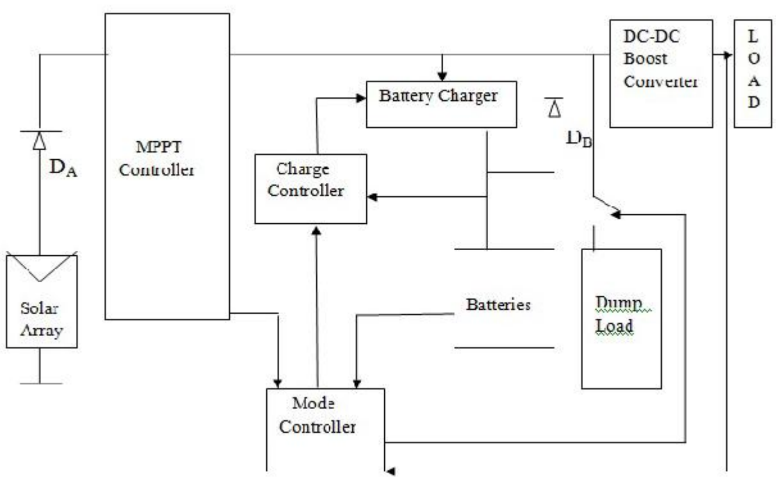


Fig.1: Block diagram of stand-alone SPV system.

2.2 Grid Interactive Solar PV System

The main components of grid interactive solar PV system consists of SPV array, MPPT controller, DC-DC boost converter, three phase voltage source inverter, filter and the grid. The voltage and current at the output of the array is fed to the MPPT controller which then controls the switching of the DC-DC boost converter in such a way that maximum power is obtained at its output. This DC-DC boost converter is therefore called as a MPPT tracker. This DC output power is then converted to AC by using three phase voltage source inverter which is then fed to the grid. As the output of the inverter is not synchronized with the grid and it also have harmonics [3]. Therefore with the help of phase lock loop, it is brought in synchronization with the grid and filter is used to remove the undesirable harmonics. Batteries are not required in this system as when the demand exceeds the generation, the excess demand is supplied by the grid. Also the excess power generated can be fed to the grid, so no dump heaters are required. The block diagram of grid interactive solar photo voltaic system is shown in Fig.2 [3].

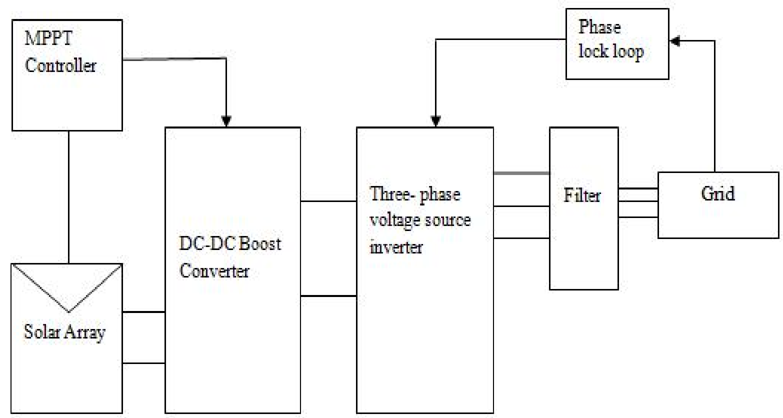


Fig.2: Block diagram of grid-interactive SPV system.

3. Components of Grid Interactive Solar PV system

The brief description about the components of grid-interactive SPV system is as follows:

3.1 SPV Cell, Module, Panel and Array

(i) *Solar Cell:* A solar cell is made up of thin layer of phosphorus-doped (N-Type) silicon on the top of thick layer of boron-doped (P-Type) silicon. A PN junction is developed where these two layers comes in contact with each other resulting in the formation of an electric field. When photons fall on the surface of the solar cell, it discharges the light generated electrons from the valence band to the conduction band. And if an electric load is connected across its terminals, current will start owing through it. The open circuit voltage of a typical solar cell is 0.7V DC under no load conditions. The current and power output of a solar PV cell depends upon its efficiency, surface area and intensity of sunlight falling on it [3].

(ii) *Solar PV Module*: Solar photovoltaic module is the basic building block of a solar photovoltaic system. It is made up of series combination of several SPV cells. This series combination is done as an individual solar cell cannot tolerate the outdoor harsh energy generation process all by itself and also the voltage and power generated by it is very small. Therefore in order to generate a reasonable voltage and power output, several SPV cells are connected in series. This series combination is then _xed on a several square feet sheet's durable back cover and a transparent cover is placed on top of it. In order to make it suitable for outdoor power generation purpose, it is sealed hermetically. In order to charge a 12 volt battery, generally a series combination of 32 or 36 solar cells is made in use which is usually the most common commercially used SPV module [3].

(iii) *Solar PV Panel:* A solar photo voltaic panel is made up of series and parallel combination of several SPV modules. In order to increase the current rating of the panel, series combination of modules is increased. Similarly the voltage rating of the panel is increased by connecting several modules in parallel combination [1]. This procedure of series- parallel combination of SPV modules is called as sizing which usually depends upon the voltage and the power ratings of the panel. Therefore while installing a panel for solar power generation; an installer must have knowledge about its various ratings [3].

(iv) *Solar PV Array:* Solar PV array is made up of interconnection or series- parallel combination of several SPV panels. These panels forming an array are installed in an open field area in such a way that no shadow falls on them. Further their installation is designed in such a way that even neighboring panels don't cast shadow on each other's surface throughout the year. The layout of the array along with its mechanical design like tilt angle, height, clearance between panels etc is done taking into account the local climatic conditions and several other factors. It is also provided with proper solar tracking mechanism [3].

3.2 Maximum Power Point Tracker

The maximum power point tracker tries to obtain maximum power at the out-put and load further adjusts itself to obtain maximum power point. Maximum power usually depends upon the voltage and the current output of the array. This voltage and current further depends upon the insolation and the temperature available. For varying insolation and temperature conditions, the operating point of a SPV system shifts from the maximum power point. Therefore in order to obtain maximum power at the output, an electronic maximum power point tracker is imposed between the solar array and the grid which is usually controlled by an MPPT controller. Generally in order to provide maximum power to load either at lower current higher voltage is provided or at higher current lower voltage is provided [4].With the help of simulation of a single solar cell , open circuit voltage, short circuit current and power are obtained which are further plotted to obtain PV and IV characteristics. Three cases are then discussed to see the behavior of PV and IV characteristics for different values of insolation and temperature [5].The simulation circuit of a solar cell is shown in Fig.3.

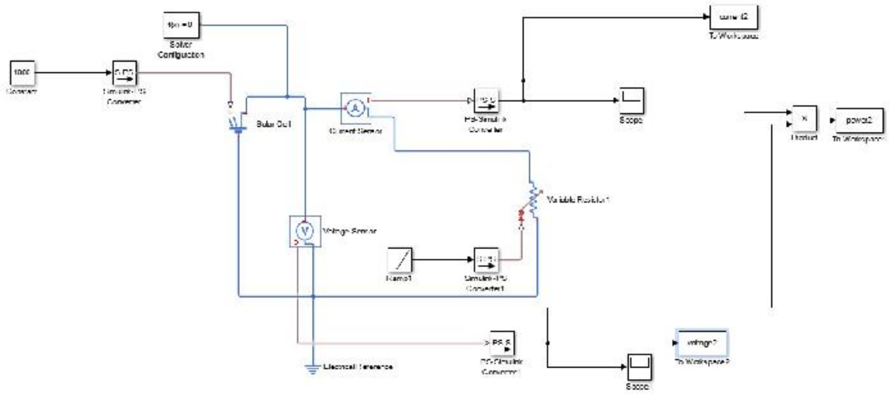


Fig.3: Simulation circuit of a solar cell.

Case 1: Insolation increased from 600 to 1000. When insolation is increased than the maximum power point, the maximum power and the short circuit current also increases as shown in Fig.4 and Fig.5.

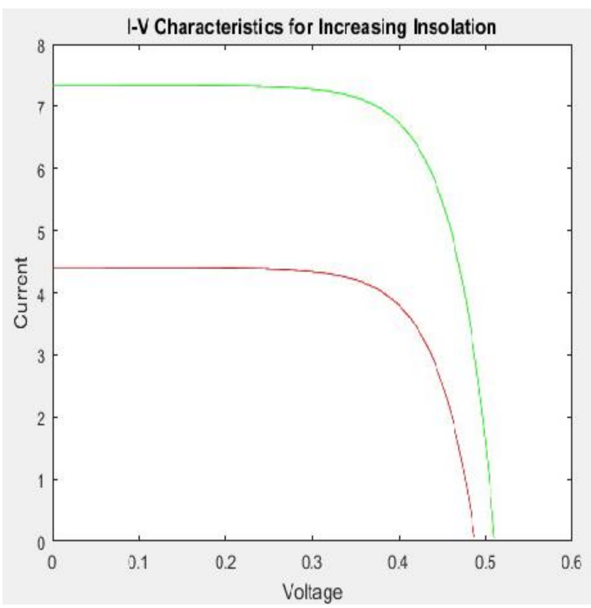


Fig.4: IV characteristics for increasing insolation.

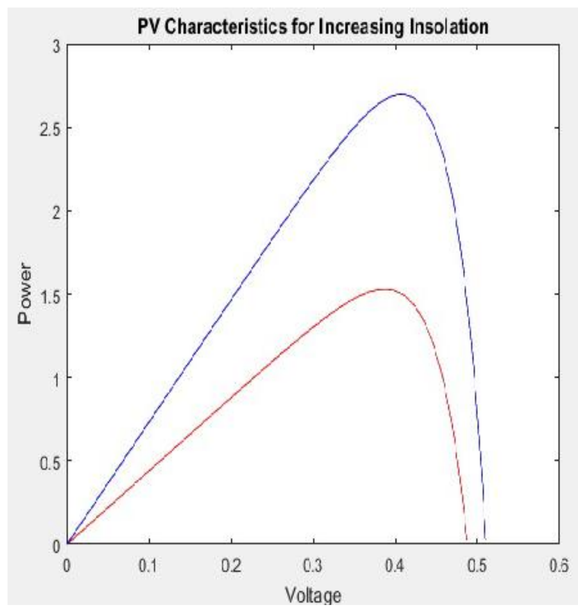
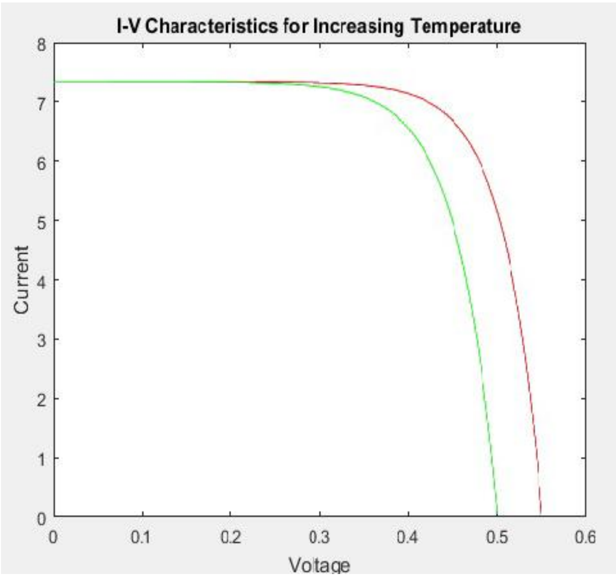


Fig.5: PV characteristics for increasing insolation.

Case 2: Temperature increased from 50°C to 75°C. With increase in temperature both the open circuit voltage and the maximum power point of a solar cell falls resulting in the reduction in maximum power as shown in Fig.6 and Fig.7.



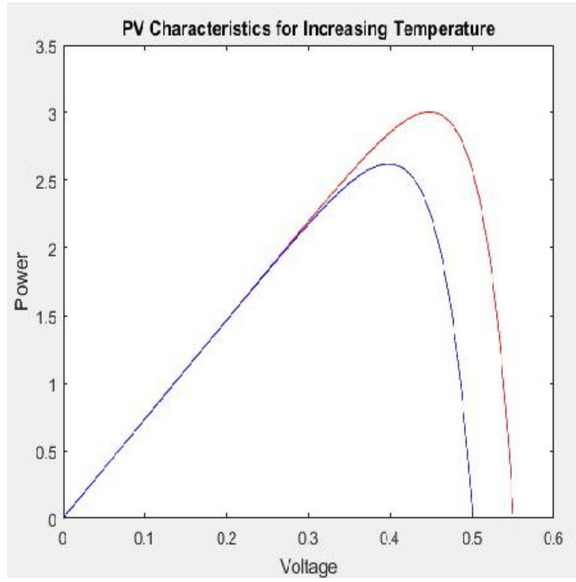
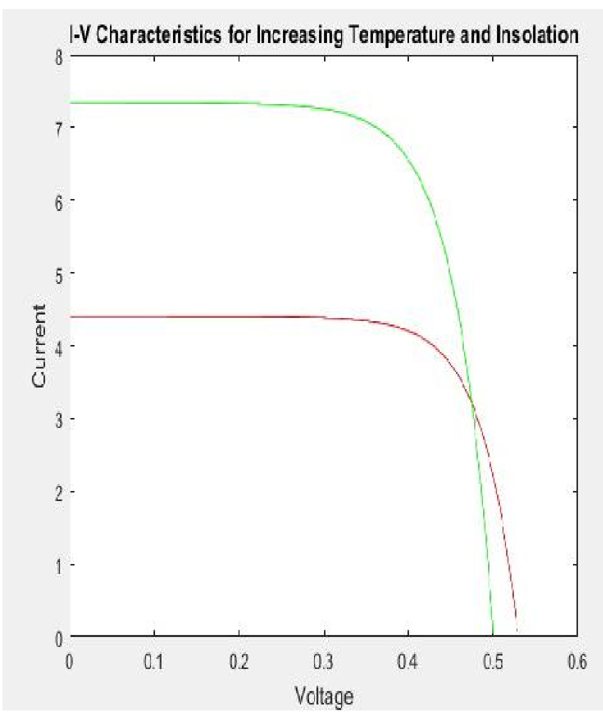


Fig.6: I-V Characteristics for increasing temperature

Fig.7: PV characteristics of increasing temperature.

Case 3: Both insolation and temperature increased from 600 and 50°C to 1000 and 75°C respectively. With increase in insolation as well as temperature, both the short circuit current and the maximum power increases as shown in Fig.8 and Fig.9.



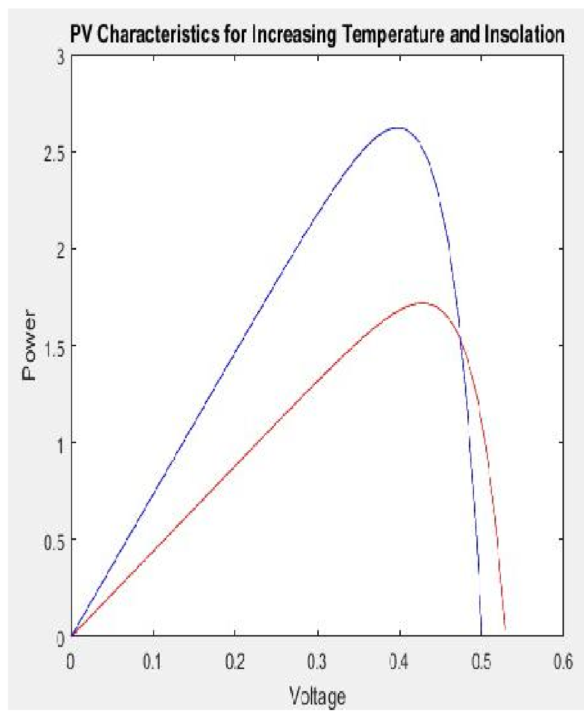


Fig.8: IV characteristics of increasing temperature and insolation.

Fig.9: PV Characteristics of increasing temperature and insolation.

3.*3 DC-DC Boost converter*

In SPV system, DC-DC boost converter is called as a maximum power point tracker as maximum power is obtained at its output terminals. The main elements of this converter are inductor, diode and an IGBT/Diode switch. Its switching is generally controlled by an MPPT controller by using PWM technique [6]. This converter is generally known as a step up converter as it raises the output voltage. The output voltage of boost converter is given by the following relation;

$$= \frac{1}{1-D} Vin \qquad (1)$$

Where V_o, V_{in} and D are the output voltage, input voltage and duty cycle of the DC-DC boost converter respectively. Simulation diagram of DC-DC boost converter with MPPT controller is shown in Fig.10.

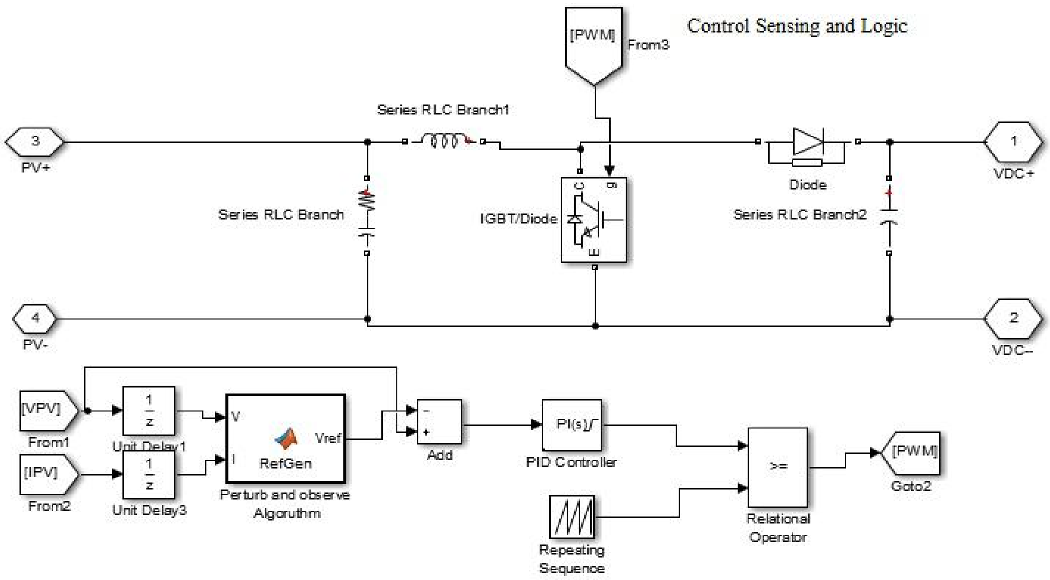


Fig.10: DC-DC boost converter as MPPT with MPPT controller.

3.4 MPPT Controller

The maximum output power depends upon insolation and temperature which varies throughout the year, so MPPT controller is used to find maximum power point from a solar array so that a maximum power is developed at the output under varying insolation and temperature [7]. Under normal conditions (No partial shading) the algorithms used by an MPPT Controller for finding maximum power point are Perturb and observe algorithm, Incremental Conductance algorithm and Ripple Co-relation algorithm [8].

Perturb and Observe is an iterative algorithm used by an MPPT controller to obtain maximum power point. This algorithm is applicable only when the insolation is uniform. It senses the arrays output voltage V and the output current I. The power P is then calculated using the relation;

$$P = V*I \quad (2)$$

The graph in the Fig.11 represents PV characteristic with one local or global maxima called as maximum power point as partial shading condition is not considered. This PV curve is divided into three region named as MPP region where $dP/dV = 0$, left hand region where $dP/dV > 0$ and right hand region where $dP/dV < 0$. Therefore in the left hand region if the voltage is increased, power increases and if voltage is decreased, power also decreases thus maintaining $dP/dV > 0$. In the right hand region if the voltage is increased, power decreases and if voltage is decreased, power increases thus maintaining $dP/dV < 0$. At the MPP region, $dP/dV = 0$ and maximum power point is obtained [9].

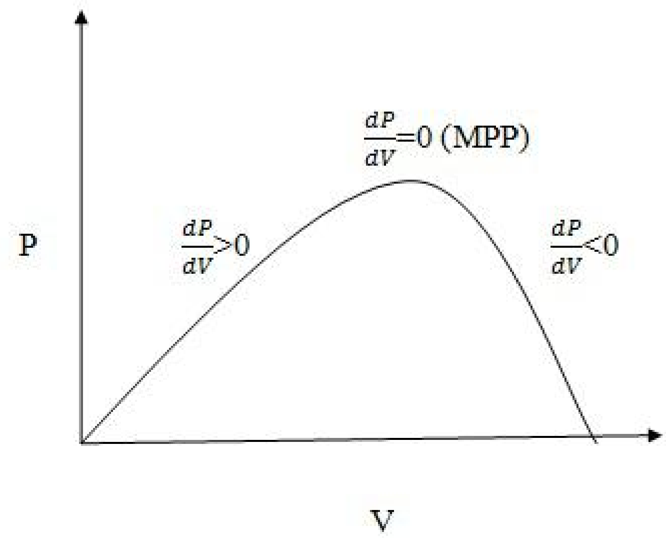


Fig.11: PV characteristics under normal condition.

Perturb and observe method uses this logic and perturbs the arrays output voltage and observes the change in power to determine whether it lies in the left, right or MPP region and if it lies in left or right region then it proceeds towards maximum power point accordingly. The first step is to sample the instantaneous voltage V(k) and current I(k) of the array and then instantaneous power P(k) is calculated using (2). The P(k) is then compared to P(k-1) sample and its difference is represented by ΔP. Similarly ΔV is calculated by subtracting V(k-1) sample from V(k). ΔP and ΔV are the numerator and the denominator of the slope dP/dV respectively. The flow chart of perturb and observe method is shown in Fig.12. Now the aim is to check whether the operating point is moving towards or away from the MPP and whether the perturbation or reference voltage Vref should be increased or decreased to reach the maximum power point where the slope is zero. It is briefly explained in below mentioned four cases [9]

Case 1: If both ΔP and ΔV are positive, slope is positive indicating that the operating point lies in the left hand region and is trying to approach the MPP, therefore the array's reference voltage Vref is increased so that the operating point reaches the maximum power point.

Case 2: If ΔP is positive and ΔV is negative, slope is negative indicating that the operating point lies in the right hand region and is trying to approach the MPP, therefore the array's reference voltage Vref is decreases so that the operating point reaches the maximum power point.

Case 3: If both ΔP and ΔV are negative, slope is positive indicating that the operating point lies in the left hand region and is trying to move away from the MPP, therefore the array's reference voltage Vref is increased so that the operating point reaches the maximum power point.

Case 4: If ΔP is negative and ΔV is positive, slope is negative indicating that the operating point lies in the right hand region and is moving away from the MPP, therefore the array's reference voltage Vref is decreased so that the operating point reaches the maximum power point.

This perturbation in the voltage is applied until maximum power point region is reached i.e. dP/dV = 0.

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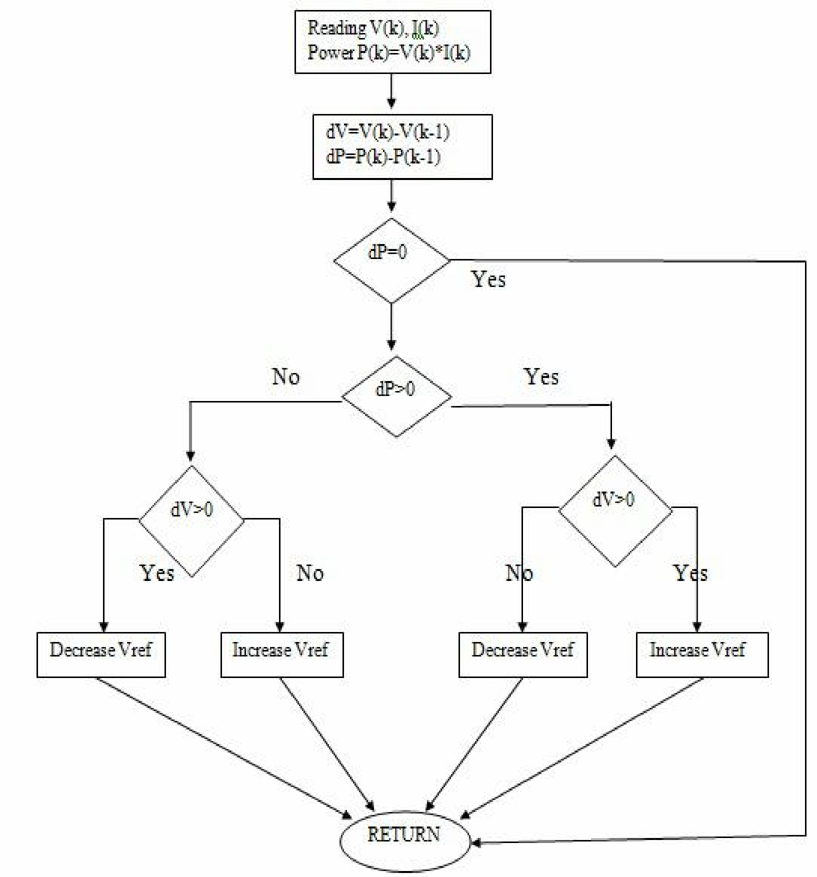

Fig.12: Flow chart of Perturb and Observe algorithm.

The perturb and observe method is widely used in PV system because it has reasonable dynamics and steady state MPPT tracking, analog and digital implication are possible and also it have low hardware and software complexity. However there are certain limitations of this method [8]. One of them is its power oscillations around the maximum power point. The magnitude of these oscillations can be reduced by the perturbation step size but it results in slowing down of tracking speed of MPP. In addition a small step size causes a slower response to the irradiance changes. Another drawback of this algorithm is that it does not operate under partial shading condition [9].

3.5 Three Phase Voltage Source Inverter

As the voltage generated at the output of the Boost converter is DC, so in order to convert it to AC, a three phase voltage source inverter is used. A current source inverter is not used as its switches generally does not self commutate, so pulse width modulation technique cannot be applied to it and also its switching frequency is low of the order of 1Khz, thus making it bulky in size. A voltage source inverter is small in size comparatively. It consists of six power electronic switches like an IGBT/Diode in a three leg format as shown in Fig.13. The switching frequency of IGBT switches is very high of the order of 20 KHz and also it can self commutate, so PWM technique (Sinusoidal PWM) can be used to control its switching [10].

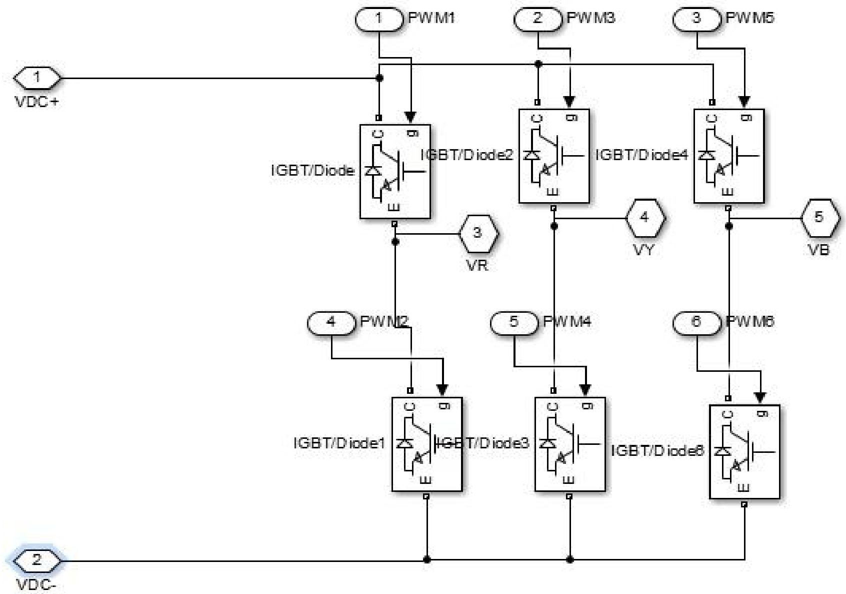

Fig.13: Three phase voltage source inverter with IGBT/Diode switches controlled by PWM technique.

Phase Locked Loop (PLL)
It is a module used for the detection of phase and it makes use of Parks transformation d-q reference frame for the measurement of grid's voltage, frequency and phase. This is done to lock the phase of output voltage of inverter with that of grid in such a way that there is zero phase difference between them [11]. The phase locked loop (PLL) generates the reference sinusoidal signals for the PWM with the feedback from the grid voltage. This reference voltage signal (Vref) so generated is then compared to a high frequency triangular wave which generates the pulses for controlling the switching of IGBT/Diode switches of the inverter [12]. Fig.14 represents the pulses generated by PWM technique to control the switching of IGBT/Diode switches of the three phase voltage source inverter.

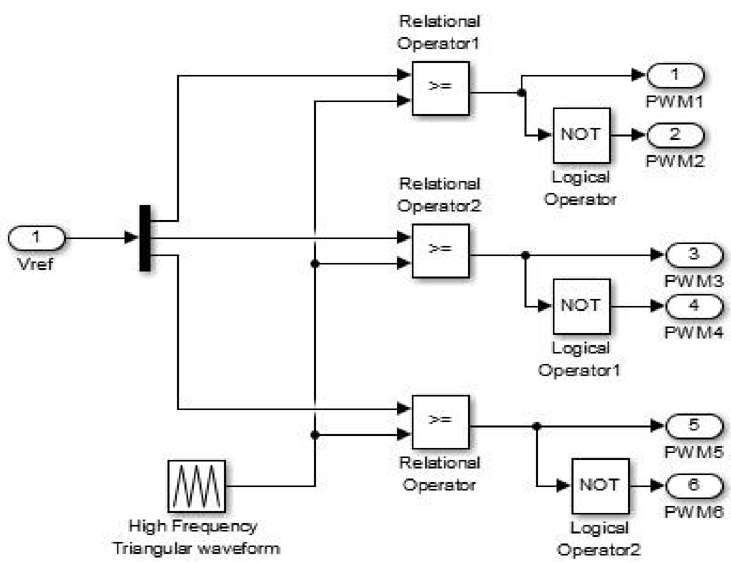

Fig.14: Simulink diagram of pulses generated by PWM technique for the IGBT/Diode switches of the voltage source inverter.

Thus the switching of the voltage source inverter is done in such a way that its output voltage, phase, frequency and phase sequence is synchronized with the voltage, phase, frequency and phase sequence of the grid respectively.

4. Results and Discussion

In this work, a simulation based model of SPV array connected to electric grid has been simulated as shown in Fig.15.

Specification of System Parameters The open circuit voltage of the SPV panel is 363V and MPPT voltage operating range is 270-300V. The switching frequency of boost converter is set to 5 KHz. The inductance and capacitance values of boost converter are equal to 1.45mH and 3227uF respectively. The output voltage of DC-DC boost converter is 600V. The switching frequency of inverter is 10 KHz. The resonant frequency is 1000Hz. The value of both inverter connected inductance and grid connected inductance of the filter is same and is equal to 500uH.The filter capacitance is connected in star between both these inductance's and its value is equal to 100uF. Grid line to line voltage and frequency is 400V (Rms) and 50 Hz respectively. The total rated power of the system is 100 KW.

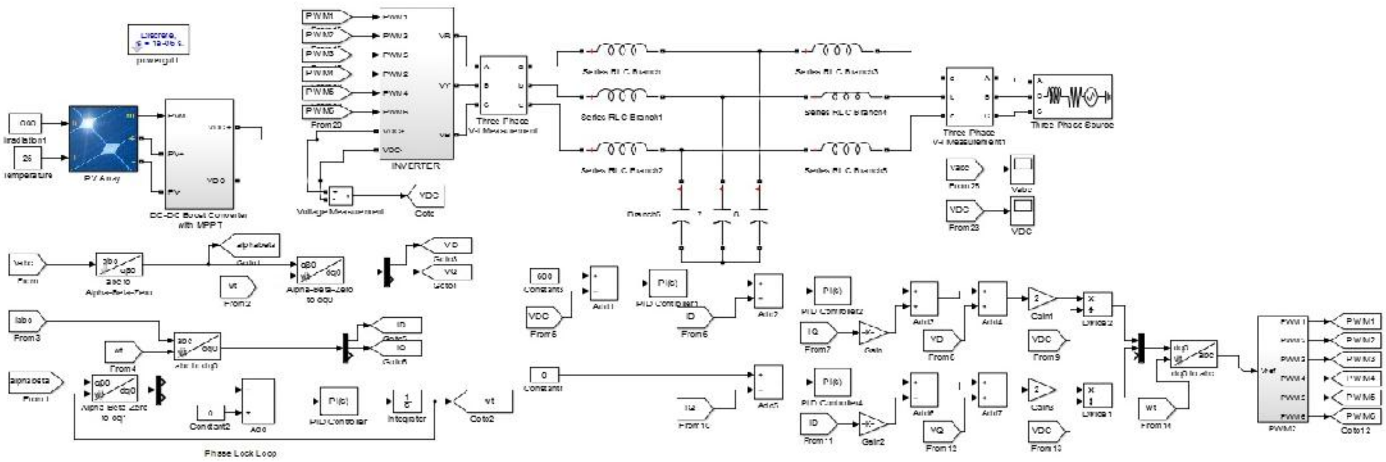

Fig.15: Grid interactive Solar Photovoltaic simulation model.

The simulation has been conducted in Simulink using Maths environment.

The voltage produced at the output terminals of DC-DC boost converter is step up DC voltage of 600V as shown in Fig.16. This DC voltage is fed to the three phase voltage source inverter which converts it to three phase sinusoidal AC voltage. This sinusoidal AC voltage is then synchronized with that of grid voltage. The current generated by the inverter have lot of harmonics. If this current is injected into the grid, it will deteriorate the grid voltage and can also cause a lot of power quality problems. So an LCL filter is generally connected at the inverter output. This filter produces sinusoidal current at the output without any harmonics. Hence the voltage produced at the output is not deteriorated as shown in Fig.17.

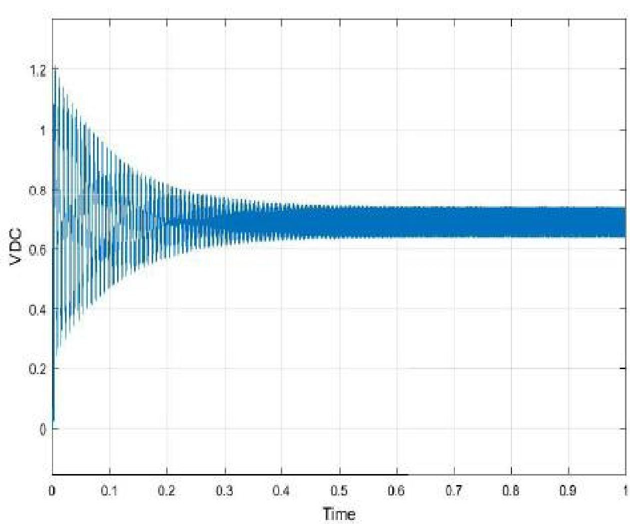

Fig.16: DC Voltage at the output of Boost Converter.

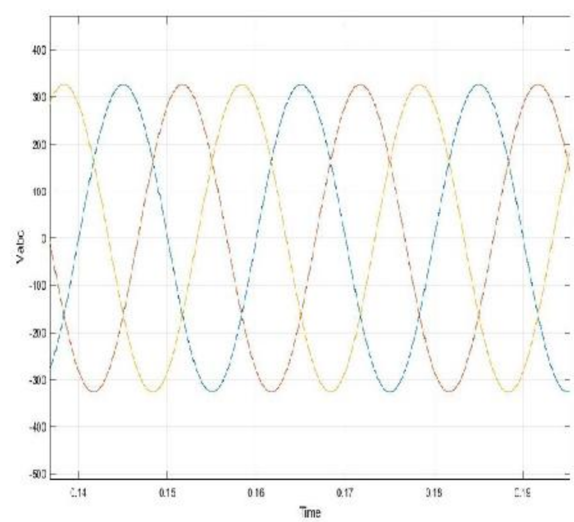

Fig.17: Three phase AC voltage fed to the grid

5. Conclusion

In this research work, modeling of a PV array connected to an electric grid is done under uniform temperature and insolation condition. All the components present in this system are also modeled and discussed individually. An MPPT controller based on Perturb and observes algorithm and a DC-DC boost converter are used to obtain maximum power at the output. A three phase voltage source inverter along with an LCL filter is used to obtain improved three phase sinusoidal voltage at the output. Phase locked loop generates the reference voltage for the Pulse Width Modulation technique which then control the switching of the voltage source inverter in such a way so that its output is synchronized with the grid.

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