

Modelling of PV Module with MPPT algorithm implemented with BOOST Converter

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Abstract: The use of renewable energy sources is increasing and will play an important role in the future power systems. In this Research paper a five parameter model of PV modules has been implemented in Simulink/Matlab. The parameters of the model are determined by an approximation method using data sheet values. Inputs to the model include light intensity and ambient temperature. The outputs are any measurements of interests as well as power, cell temperature and voltage. Effects of varying the model parameters are demonstrated. Inputs to the PV module are Irradiance and Temperature, as these two parameters do not remain constant at all the time, to operate the PV Cell/Module at maximum power point, a maximum power point tracker algorithm (MPPT) is implemented. In the present work, Perturb and Observe (P&O) algorithm is implemented with Boost converter.

Keywords: Photovoltaic Module, Thermal Voltage, Ideality Factor, Maximum power point tracker (MPPT), Boost Converter.

I. INTRODUCTION

Emissions of CO₂ and other greenhouse gasses are leading to climate change [1]. The greenhouse effect of CO₂ is well understood and it is clear that the emissions must be reduced to avoid undesirable scenarios. To reverse the trend, there is a great need for accelerating the development and implementation of renewable energy technologies. Use of renewable energy sources is rising at an increasing rate. The global PV capacity is escalating rapidly with an average annual growth for the last decade of 40% [2]. In figure 1 the development of total capacity up to year 2014 is shown. Predictions by IEA state that this trend will continue and that photovoltaic will provide 11% of the global electricity generation by 2050 [2].

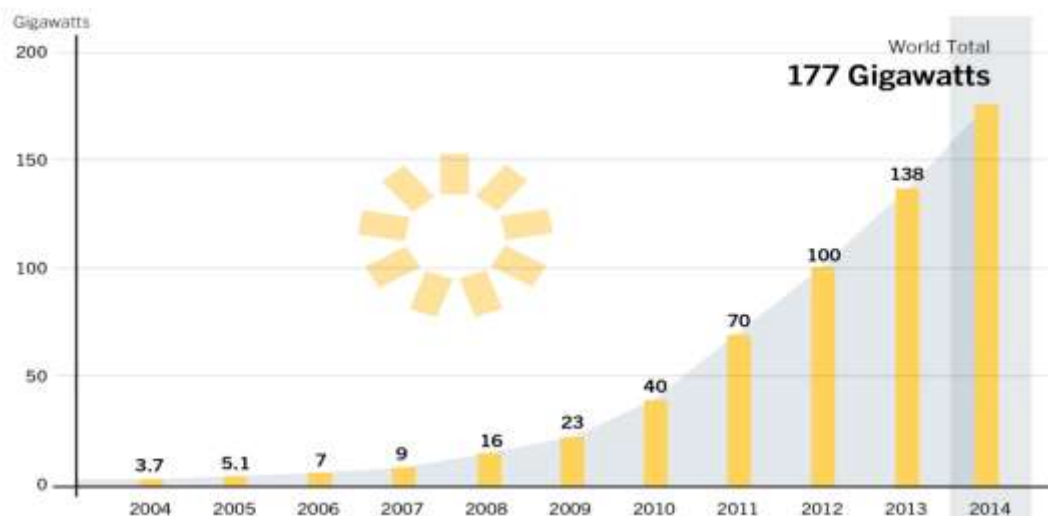


Fig. 1 Global Solar PV Capacity

The need for a cleaner environment and the continuous increase in energy needs makes decentralized renewable energy production more and more important. This continuously-increasing energy consumption overloads the distribution grids as well as the power stations, therefore having a negative impact on power availability, security and quality [3]. One of the solutions for overcoming this is the Distributed Generation (DG) system. DG systems using renewable

energy sources like solar, wind or hydro have the advantage that the power is produced in close proximity to where it is consumed. This way the losses due to transmission lines are not present. In the last decade solar energy technologies have become less expensive and more efficient, which have made it to an attractive solution, being cleaner and more environmentally friendly energy resource than traditional ones like fossil fuels, coal or nuclear. Nevertheless, a PV system is still much more expensive than traditional ones, due to the high manufacturing costs of PV panels, but the energy that drives them –the light from the sun- is free, available almost everywhere and will still be present for millions of years, long after all non-renewable energy sources have been depleted.

One of the major advantages of PV technology is that it has no moving parts. Therefore, the hardware is very robust; it has a long lifetime and low maintenance requirements. And, most importantly, it is one solution that offers environmentally friendly power generation [4]. Nowadays, PV panels are not only used in space applications, but they are present in everyday life: powering wrist watches, small calculators, supplying loads in remote sites and, last but not least, they are connected to the public grid, generating the green power of the future. [5]

II. PHOTOVOLTAIC SYSTEM

A) Introduction

Photovoltaic cell directly converts sunlight into electricity. Cells can be connected together to form a module or an array. The direct output from a module or array may serve some small loads like DC-motors or lighting systems, but to provide power to fit more sophisticated demands, power electronic converters are needed. This also enables to tailor the load seen from the PV module to that which will make the module operate at the maximum power point (MPP). Photovoltaic cells connected together form a module or panel. A connection of one or more modules is called an array. A photovoltaic cell is essentially a semiconductor diode where the p-n junction is exposed to light. The exposure leads to the breaking of electron bonds in the semiconductor. These charge carriers create an electric current when the cell is short circuited. The PV phenomenon may be described as absorption of solar radiation, the generation and transport of free carriers at the p-n junction, and the collection of these electric charges at the terminals of the PV device [6].

1.) *Ideal PV Cell*: The simplest model to represent a PV module is the ideal diode model with the equivalent circuit model shown in figure 1.

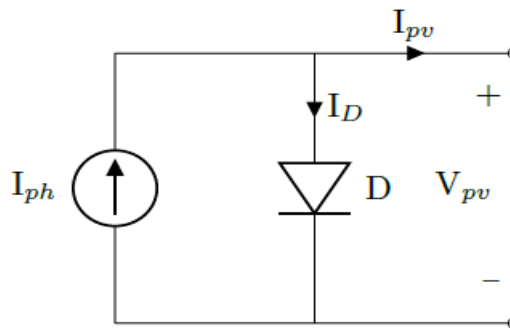


Fig. 2 : Ideal PV Cell

This model consists of only a current source and a diode in parallel and it describes the behaviour of an ideal PV module.

$$I_{pv} = I_{ph} - I_0 \left(\exp\left(\frac{V_{pv}}{a n_c v_{th}}\right) - 1 \right) \dots\dots\dots (1)$$

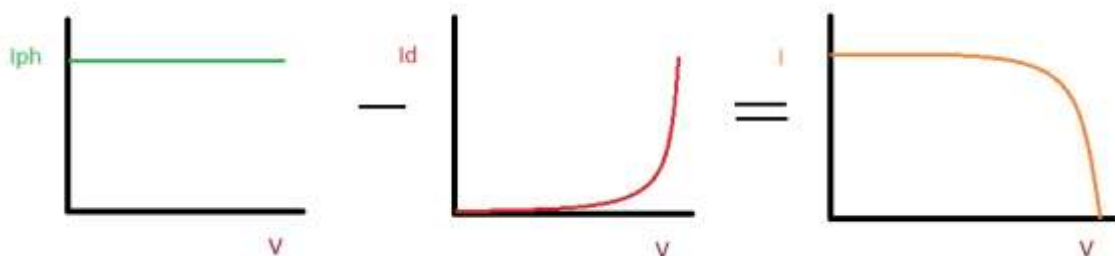


Fig. 3: Characteristic of Ideal PV Cell

2.) *PV Cell Parameters:* The following are some parameters characterizing a photovoltaic module.

Short circuit current, I_{sc} - The short circuit current is the maximum current from a solar cell which occurs when the voltage is zero. It is for many solar cells very close to the photo current I_{ph} and it is therefore often characterized as the maximum current that can be drawn from the cell [6].

Open circuit voltage, V_{oc} - The open circuit voltage is the maximum voltage from a solar cell that occurs when the current is zero. This voltage is dependent on cell temperature; it becomes smaller with higher temperature.

Fill Factor, FF - The Fill Factor is a measure of how good the voltage and current at maximum power point compares to the open circuit voltage and short circuit current. The calculation of Fill factor is shown in equation (2)

$$FF = \frac{V_{mpp} \times I_{mpp}}{V_{oc} \times I_{sc}} \dots\dots\dots (2)$$

The fill factor refers to the degree at which the actual operating conditions lives up to the potential power of $I_{sc}V_{oc}$. It is impossible to have a fill factor of 1.

Efficiency- Efficiency is defined as energy output divided by energy input. In the case of solar cells the efficiency equation can be presented in several ways as follows:

$$Eff = \frac{V_{mpp} \times I_{mpp}}{P_{in}} = \frac{V_{oc} \times I_{sc} \times FF}{P_{in}} \dots\dots\dots (3)$$

Here P_{in} is the irradiance from the sun on the area of the PV cell and Eff is the efficiency. Testing of efficiency is done at standard test conditions (STC), which is 1000 W/m² of sunlight intensity, 25 C temperature and 1.5 air mass.

Nominal operating cell temperature, NOCT - The nominal operating cell temperature reflects that the operating conditions often are not STC. The NOCT refers to the cell temperature in a case of 800 W/m² of irradiance, 20C ambient temperature and an average wind of 1 m/s. This temperature is given by manufacturers in solar cell specifications and it gives information on the temperature inside the cell. The NOCT is used in modelling the cell temperature.

Ideality factor - The ideality factor is a measure of how well the diode follows the ideal diode equation (1).

3.) *Five Parameter Model:*

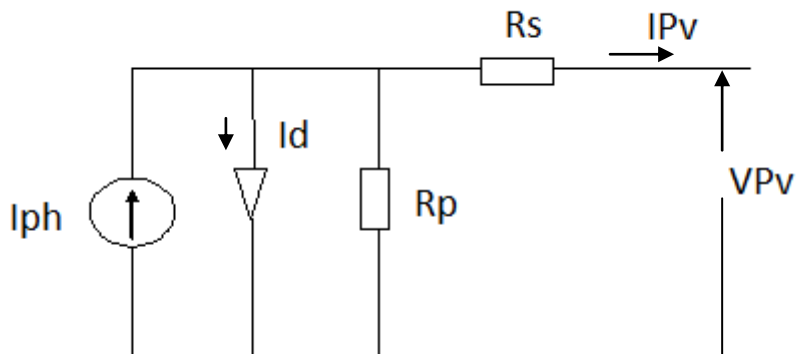


Fig. 4 Single Diode Five Parameter Photovoltaic Equivalent Circuit

PV Output current is:

$$I_{PV} = I_{ph} - I_0 \left[\exp \left(\frac{V_{pv} + I_{pv} \times R_s}{a n_c V_{th}} \right) - 1 \right] - \left(\frac{V_{pv} + I_{pv} \times R_s}{R_p} \right) \dots\dots\dots (4)$$

Where,

I_{PV} = PV Current output

V_{pv} = PV Voltage output

I_{ph} = Light generated current

I_o = Reverse saturation current

k = Boltzmann's constant (1.38×10^{-23} J/K)

a = Ideality Factor

T = Temperature (K)

R_s = Series Resistance

R_p = Parallel Resistance

3.1) *Thermal Voltage:* The thermal voltage of a module with N_c cells is given by equation:

$$V_{thmodule} = \frac{kT}{q} = N_c \times V_{thcell} \dots\dots\dots (5)$$

Where, N_c is the number of cells in a module, k is the Boltzmann's constant (1.38×10^{-23} J/K) and q is the electron charge (1.6×10^{-19} C). In some papers [7 and 20], this relation is not calculated separately, but used directly in the single diode model equations. The thermal voltage is used in the equations in this paper because it simplifies the modelling by separating out this relation into a subsystem.

3.2) *Diode Reverse Saturation Current:* The diode reverse saturation current can be calculated by substituting the open circuit conditions (V = V_{oc} and I = 0) into equation (4) as shown in equation (6).

$$I_o = \frac{I_{sc}}{\exp\left(\frac{V_{oc}}{aN_cV_{th}}\right)} - 1 \dots\dots\dots (6)$$

Equation (6) does not depend on temperature (except from V_{th}) and it is therefore only accurate at the temperature at which the input values are given. There are several ways to model the temperature dependence of I_o and one of those is shown in equation(7) [7]:

$$I_o(T) = \left(\frac{I_{sc} + K_i(T - T_{ref})}{\exp(V_{oc} + K_v(T - T_{ref}) \times aN_cV_{th})} \right) - 1 \dots\dots\dots (7)$$

Here I_o is given by equation (6), E_g is the band gap energy of the semiconductor (1.12 eV for polycrystalline silicone at 25 degree C [6]), V_{th} is given in equation (5) and T_{ref} is the reference temperature at which I_o is calculated. The nominal or reference saturation current is usually calculated with values from data sheets.

3.3) *Photoelectric Current:* The photoelectric current (I_{ph}) depends on the temperature and solar radiation as shown in equation (8).

$$I_{ph} = \frac{(I_{phref} + K_t(T - T_{ref}))G}{G_{ref}} \dots\dots\dots (8)$$

Here I_{phref} is the photoelectric current at reference irradiance and temperature (usually 1000 W/m² and 25 degree C), G is the incident irradiance (in W/m²) and G_{ref} is the reference or nominal irradiance (usually 1000 W/m²). I_{phref} can be assumed to be approximately equal to I_{sc}. This is a very common assumption in PV modelling [6]. The assumption gives a good approximation because the series resistance is usually very small and the parallel resistance is large.

3.4) *Ideality Factor:* The ideality factor (a) can be arbitrarily chosen and still give decent accuracy in modelling [6]. It describes the degree of ideality of the diode. The choice or otherwise determination of the value of the ideality factor used in modelling depends on the other parameters used in the model. As with the other parameters, a initial "guess" can be made and the best value approximated by iteration. There are several ways to determine approximate the ideality factor [8]. The approximation method discussed in next section does not include approximation of ideality factor. All the other parameters are determined by iteration based on the data sheet values and an assumed value of the ideality factor. Choosing different ideality factor values results in different approximated values for the other parameters. The approximation method determines the parameters so that the model fits the data sheet values even if the ideality factor

chosen is not very accurate. Testing of model accuracy compared to measured power data with different Ideality factors chosen revealed that the accuracy does not change much as long as the ideality factor is within certain limits.

3.5) *Cell Operating Temperature:* The cell temperature will differ from the ambient temperature and can be assumed to be a linear function of the irradiance [15] as shown in equation (9)

$$T_{CELL} = T_{AMBIENT} + Kt \times G \dots\dots\dots (9)$$

Here T_{CELL} is the cell operating temperature; $T_{AMBIENT}$ is the ambient temperature, Kt is the proportionality factor calculated in equation (10) and G is the incident Irradiance.

$$Kt = \frac{NOCT (degree\ C - 20\ C)}{800 \frac{W}{m^2}} \dots\dots\dots (10)$$

The NOCT (Nominal Operating Cell Temperature) is usually given in commercial module specifications.

B) Approximation Model Parameters from Datasheet

In this heading a method for approximating the five variables in the five parameter model is outlined. To approximate the variable for the five parameter model by this method, the specifications shown in table 1 are needed. In addition, an assumption of the diode ideality factor must be made if there is no real data available.

Specifications from data sheet

Maximum power	Pmpp (W)
Maximum power voltage	Vmpp (V)
Maximum power current	Impp (A)
Open circuit voltage	Voc (V)
Short circuit current	Isc (A)
Short circuit current temperature coefficient	Ki (A/degreeC)
Open circuit voltage temperature coefficient	Kv (V/degreeC)
Number of cells in module	Nc

Table 1- Required input from data sheet

1) *Reverse Saturation Current:* The first calculation that should be done, is to use equation (7) to calculate the nominal reverse saturation current of the diode (I_0). All the variables needed for this calculation are present in table 1.

2) *Series Resistance:* The series resistance can be calculated by the maximum power rating at STC. The derivative of maximum output power with respect to output voltage at the maximum power point is zero [16] as expressed in equation (11).

$$\frac{dP}{dV(mpp)} = \frac{d(IV)}{dV(mpp)} = I_{mpp} + V_{mpp} \left(\frac{dI}{dV(mpp)} \right) = 0 \dots\dots\dots (11)$$

Using equation (4) the differential of the module current with respect to module voltage can be calculated and substituted into equation (11) [17]. The series resistance can then be calculated as shown in equation (12):

$$R_s = \frac{Vmpp}{Impp} - \frac{aNcVth \times Rp}{(I_0 \times Rp \exp(Vmpp + Impp \times R_s \times a \times Nc \times Vth) + aNcVth)} \dots\dots\dots (12)$$

3) *Parallel Resistance:* At the maximum power point, equation (6) results in equation (13).

$$\frac{Pmpp}{Vmpp} = Impp = I_{ph} - I_0 \left[\exp \left(\frac{Vmpp + Impp \times R_s}{aNcVth} \right) - 1 \right] - \frac{Vmpp + Impp \times R_s}{Rp} \dots (13)$$

This can be rearranged into equation (14):

$$R_p = \frac{V_{mpp} + I_{mpp} \times R_s}{I_{ph} - I_{mpp} - I_o \left[\exp \left(\frac{V_{mpp} + I_{mpp} \times R_s}{a n C V_{th}} \right) - 1 \right]} \dots \dots \dots (14)$$

4) *Photoelectric current:* - It is often assumed that the photoelectric current (I_{ph}) is equal to the short circuit current (I_{sc}). A better approximation can be made by using the series and parallel resistors to calculate the current as shown in equation (15):

$$I_{ph} = \frac{(R_p + R_s)}{R_p} \times I_{sc} \dots \dots \dots (15)$$

c) *Iteration Method:*

Because all of these parameters are mutually dependent, iteration is a decent way to find values that fits well and gives a small error. A way to determine how "good" the values are needed. In [17] it is suggested to iterate the parameters and minimize the error values given in equation (19).

$$Err1 = \frac{V_{mpp}}{I_{mpp}} - \frac{a n C V_{th} \times R_p}{(I_o \times R_p \exp(V_{mpp} + I_{mpp} \times R_s \times a n C V_{th}) + a n C V_{th})} - R_s \dots (16)$$

$$Err2 = \frac{V_{mpp} + I_{mpp} \times R_s}{I_{ph} - I_{mpp} - I_o \left[\exp \left(\frac{V_{mpp} + I_{mpp} \times R_s}{a n C V_{th}} \right) - 1 \right]} - R_p \dots \dots \dots (17)$$

$$Err3 = \frac{(R_p + R_s)}{R_p} \times I_{sc} - I_{ph} \dots \dots \dots (18)$$

$$Err = (Err1)^2 + (Err2)^2 + (Err3)^2 \dots \dots \dots (19)$$

The parameters can be iterated with small steps to give good accuracy. After the iteration, the values that gave the smallest error are the ones that fits the data sheet values the best according to this method. A flowchart of the approximation algorithm is shown in figure 4.

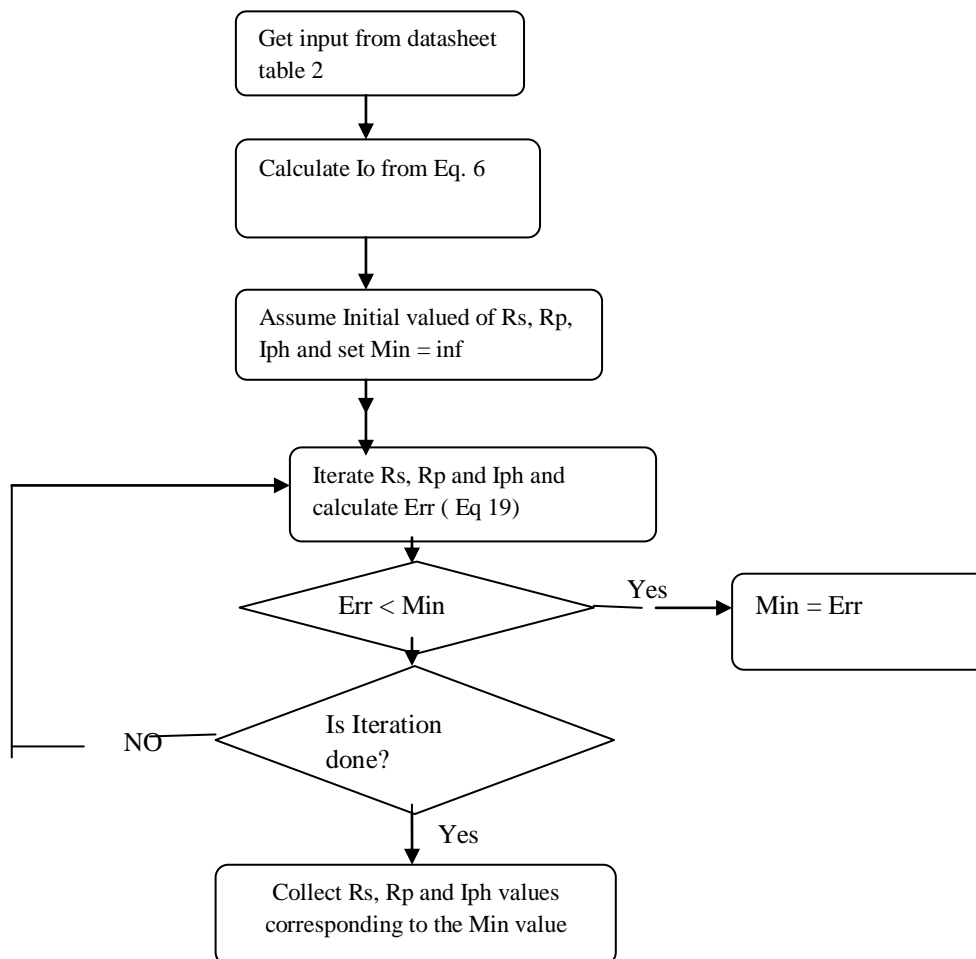


Fig. 5

III. MPPT ALGORITHMS

It is important to try to extract the maximum amount of power possible from photovoltaic arrays. The current-voltage and the power-voltage relationship is shown in the figures 5. At any time, there is a voltage level that will give maximum power. To always operate at this voltage level, DC-DC converter controlled by maximum power point tracking (MPPT) algorithms is inserted after the PV modules to ensure optimal operating conditions. Methods of maximum power point tracking can generally be divided into two categories: Direct and indirect methods [18].

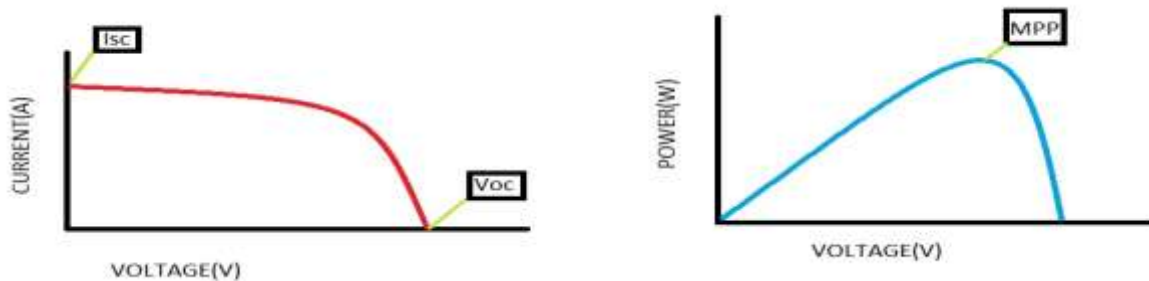


Fig. 6 I- V curve and P- V curve

A. Indirect Methods of Maximum Power Point Tracking

Indirect methods entail estimating the MPP by measurements of the photovoltaic voltage (V_{pv}) and current (I_{pv}) and using some model of the system to give an approximation of the MPP. This model can be mathematical equations and numerical approximations applied by look-up tables. These equations or numerical approximations are dependent on the actual system of which it is to give an approximation of MPP. In other words, an indirect method of MPPT is only valid for the exact PV generator it is designed for. Aging and other changes in system characteristics will reduce the accuracy of the method. The fact that the methods needs to be modified for each system and that changes are not handled well are the major drawbacks of using indirect methods. Varying irradiance and temperature must be accounted for by measurement and either input to mathematical equations or input to look-up tables. The look-up tables and mathematical equations can never perfectly model the real conditions. The look-up table method can never account precisely for all conditions as the data has to be measured and regression used between actual data. There are several indirect methods available: Curve-fitting, look-up table, open- voltage PV generator, short circuit PV generator and the open circuit cell. These methods will not be reviewed further in this paper but are explained in detail in [21].

B. Direct Methods of Maximum Power Point Tracking

Direct methods of acquiring the MPP do not require any prior knowledge of the system characteristics. The algorithms use measurements of voltage and/or current and take into account the variation of these state variables. These methods can also be called "true seeking" methods, since the correct operating point is obtained by "seeking" and not by any approximations of system characteristics and behaviour. The ability to find the MPP is unaffected by variables like isolation, temperature or degradation levels [21 and 22]. The major drawback of these methods are that they can be more complicated and that undesirable errors can affect the tracker accuracy.

The following methods/algorithms are included under the "direct method" category: Perturb and observe (P&O), incremental conductance, differentiation, feedback voltage (current), auto oscillation, fuzzy logic and others [21]. The Perturb and observe and the incremental conductance method are reviewed further in this paper.

1.) *Incremental Conductance Method:* The theory of the incremental conductance method [9-13] is to determine the variation direction of the terminal voltage for the PV modules by measuring and comparing the incremental conductance and instantaneous conductance of PV modules. If the value of incremental conductance is equal to the instantaneous conductance, it represents that the maximum power point is found.

When the operating behaviour of PV Modules is within the constant current area, the output power is proportional to the terminal voltage. That means output power increases linearly with the increasing terminal voltage of PV modules i.e. $\frac{dP}{dV} > 0$. When the operating point passes through the maximum point, its operating behaviour is similar to constant

voltage. Therefore output power decreases with the terminal voltage, i.e. $\frac{dP}{dV} < 0$. When the operating point reaches to the Maximum Point, slope becomes zero, i.e. $\frac{dP}{dV} = 0$. Further as

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I \frac{dV}{dV} + V \frac{dI}{dV} = I + V \frac{dI}{dV} \quad \text{--- (20)}$$

By the relationship of $\frac{dP}{dV} = 0$, we have $\frac{dI}{dV} = -\frac{I}{V}$

dI and dV represent the current error and voltage error respectively. The static conductance (G_s) and dynamic conductance (G_d) of PV modules is defined as

$$G_s = -\frac{I}{V} \text{ and } G_d = \frac{dI}{dV}$$

The maximum power point can be found when $G_s = G_d$.

2.) *Perturb and Observe Method*: The Perturb and Observe (P&O) algorithm is also called “hill – climbing”, but both names refer to the same algorithm depending on how it is implemented. Hill-climbing involves perturbation to the Duty Cycle of the Power Converter and P&O a perturbation in the operating voltage of the Dc link between the PV array and the Power Converter [14]. In case of the Hill-Climbing, perturbing the duty cycle of the converter implies modifying the voltage of Dc link between the PV array and the Power converter, so both names refer to the same technique. In this method, the sign of the last perturbation and the sign of the last increment in the power are used to decide what the next perturbation should be. If there is increment in the power, the perturbation should be kept in the same direction and if the power decreases, then the next perturbation should be in the opposite direction.

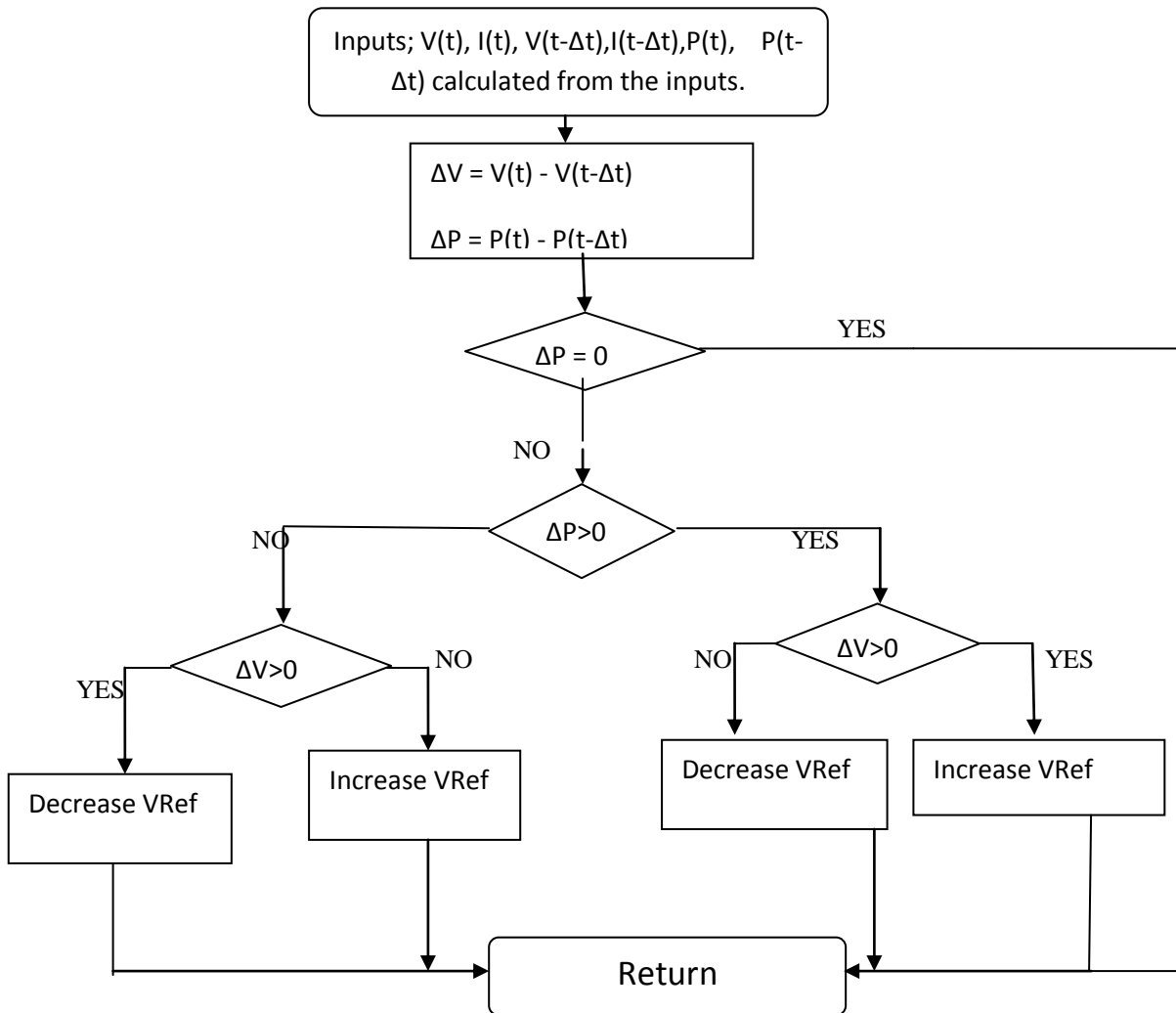


Fig.7 The flow chart of Perturb & Observe Algorithm

IV. DC- DC CONVERTER

A. INTRODUCTION

DC-DC converters can be used as switching mode regulators to convert an unregulated dc voltage to a regulated dc output voltage. The regulation is normally achieved by PWM at a fixed frequency and the switching device is generally BJT, MOSFET or IGBT. The minimum oscillator frequency should be about 100 times longer than the transistor switching time to maximize efficiency. This limitation is due to the switching loss in the transistor. The transistor switching loss increases with the switching frequency and thereby, the efficiency decreases. The core loss of the inductors limits the high frequency operation. Control voltage V_c is obtained by comparing the output voltage with its desired value. Then the output voltage can be compared with its desired value to obtain the control voltage V_{cr} . The PWM control signal for the dc converter is generated by comparing DC-DC converters can be used as switching mode regulators to convert an unregulated dc voltage to a regulated dc output voltage.

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B. BOOST CONVERTER AND ITS OPERATION

The figure 7 below shows a step up or PWM boost converter. It consists of a dc input voltage source V_g , boost inductor L , controlled switch S , diode D , filter capacitor C , and the load resistance R . When the switch S is in the on state, the current in the boost inductor increases linearly and the diode D is off at that time. When the switch S is turned off, the energy stored in the inductor is released through the diode to the output RC circuit.

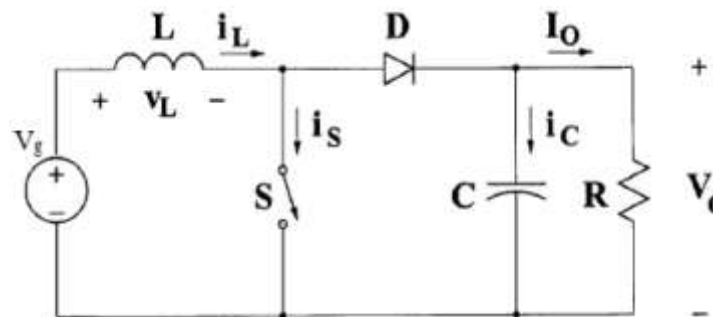


Fig. 8 Circuit Diagram of Boost Converter

STEADY STATE ANALYSIS OF THE BOOST CONVERTER:

- 1.) *Off State:* In the OFF state, the circuit becomes as shown in the Figure 8 below. When the switch is off, the sum total of inductor voltage and input voltage appear as the load voltage

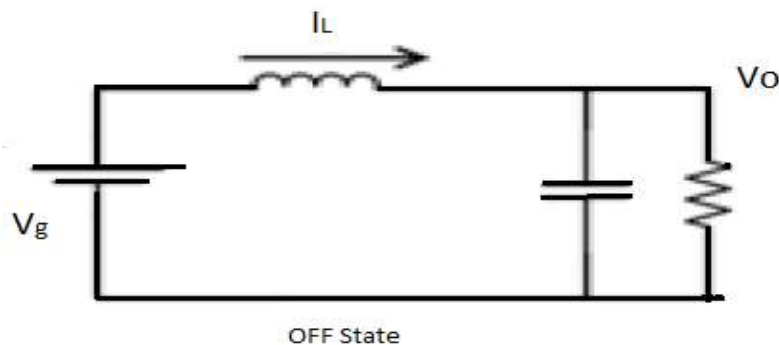


Fig. 9 The OFF state diagram of the boost converter

2.) *On State*: In ON state, the circuit diagram will look as shown in fig 9.

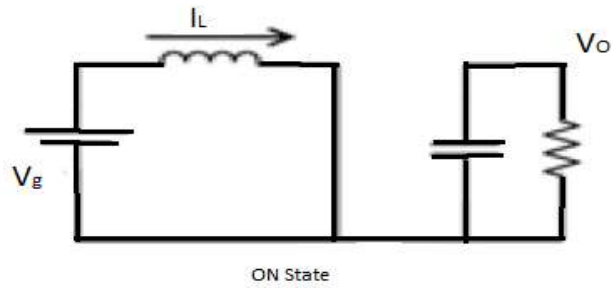


Fig. 10 The ON state diagram of the Boost Converter

When the Switch is at ON position, the inductor is charged from the input voltage source V_g and the capacitor discharge across the load. The Duty Cycle, $D = \frac{T_{on}}{T}$ where $T = \frac{1}{f}$.

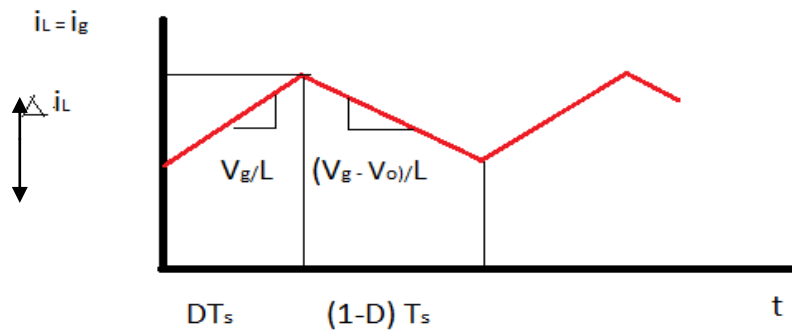


Fig. 11 Inductor Current Waveform

From the inductor voltage balance equation, we have:-
 $V_g(DT_s) + (V_s - V_o)(1-D)T_s = 0$ (21)

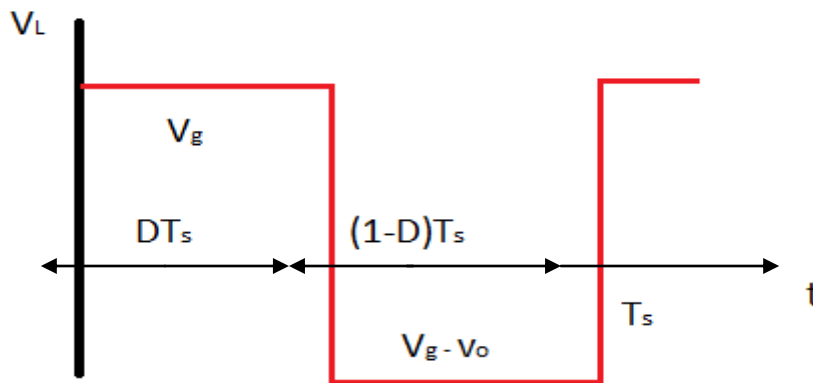


Fig. 12: Inductor Voltage Waveform

From the inductor voltage balance equation, we have:-

$$V_g(DT_s) + (V_s - V_o)(1-D)T_s = 0 \quad \text{..... (22)}$$

$$V_g(DT_s) - V_g(DT_s) - V_gT_s + V_oDT_s - V_oT_s = 0 \quad \text{.....(23)}$$

$$V_o = V_g / (1-D) \quad \text{..... (24)}$$

$$\text{Conversion ratio, } M = V_o / V_g = 1 / (1-D) \quad \text{..... (25)}$$

V. SIMULINK IMPLEMENTATION & RESULTS

The Matlab Simulink model of the complete system is shown in the fig. 12. Figure 12 is the top PV module/array model that contains all the other subsystems. Here are the inputs of irradiance and ambient temperature and outputs of module voltage and current. The MPPT algorithm and converter are under the "MPPT And Voltage Controller" subsystem (Fig 14) and all the equations modelling the behavior of a PV module are under the "PV Module string" subsystem (Fig 13).

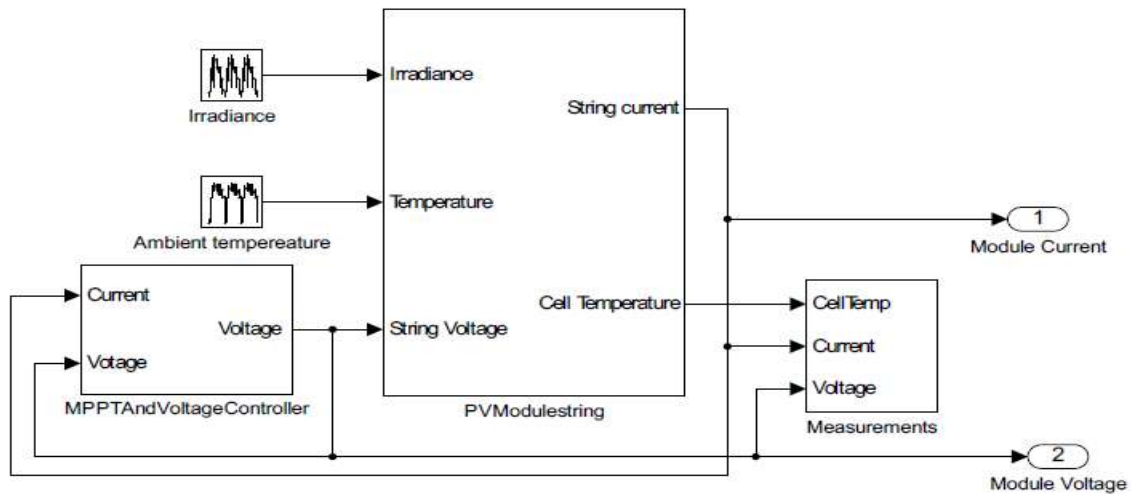


Fig. 13 Top PV Module

The variables and inputs are set to the values that are given in the table 2.

Table.2: Parameter values and Test conditions:

Rated Power	Pmpp	85W
Voltage at mpp	Vmpp	18V
Current at mpp	Impp	4.72A
Open circuit voltage	Voc	22.03V
Short circuit current	Isc	5A
Current coefficient	Ki	0.00325A/degreeC
Voltage coefficient	Kv	-0.08V/degreeC
Temperature coefficient	Kt	0.0338degreeC/Wm ²
Number of cells	Ncells	36
Nominal operating cell temp	Tn	47degreeC
Reference cell temp	Tref	320.15 K
Reference irradiance	Iro	1000W/m ²

Table.3: Data Sheet Values

Parallel resistance	Rp	414 ohm
Series resistance	Rs	0.22 ohm
Reverse saturation current	Io	4.2263e ⁽⁻⁹⁾ A
Photo current	Iph	5.0559A
Ideality factor	a	1.14

Table. 4: Test Conditions

Irradiance	Irradiance	1000W/m ²
Ambient Temperature	T _{amb}	273.15+25 K

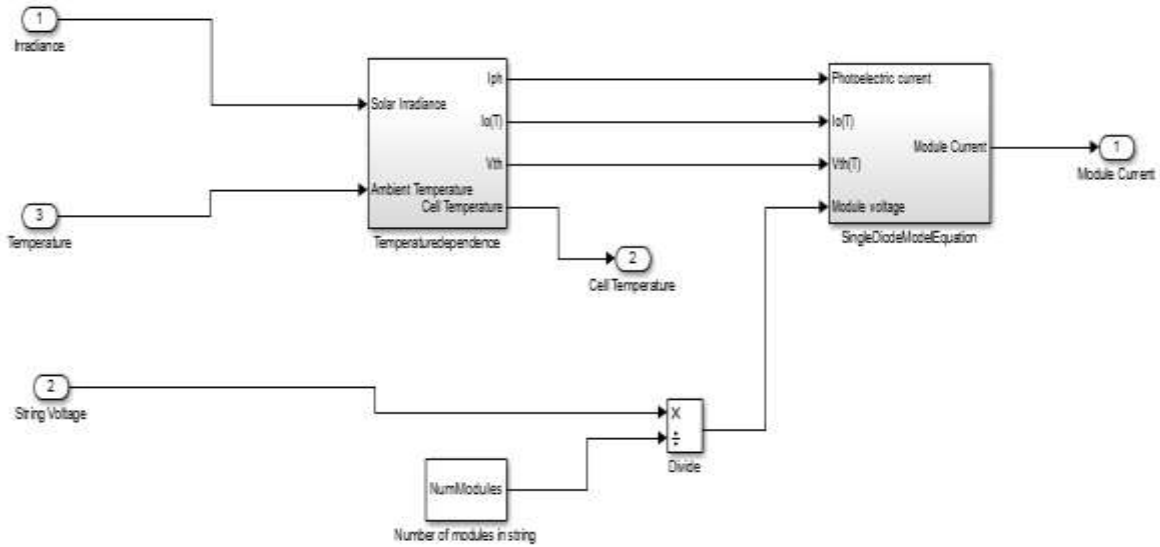


Fig. 14: this is the subsystem named "PVModulestring" from figure 12.

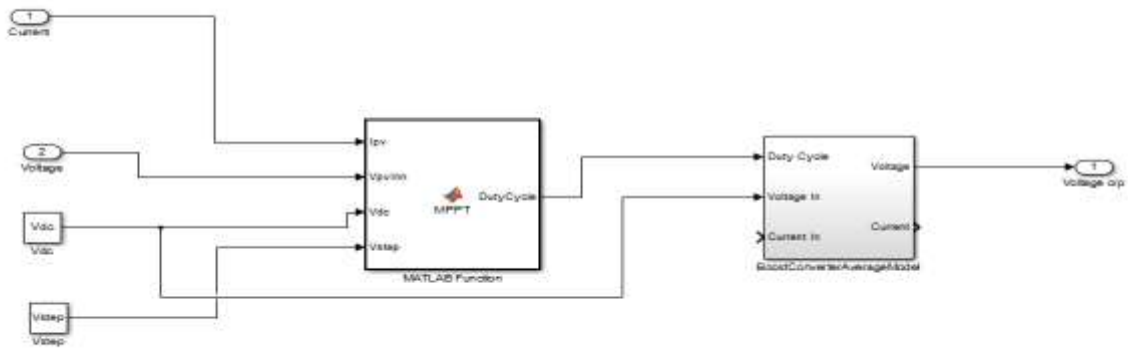


Fig. 15 : This is the subsystem labeled "MPPT And Voltage Controller".

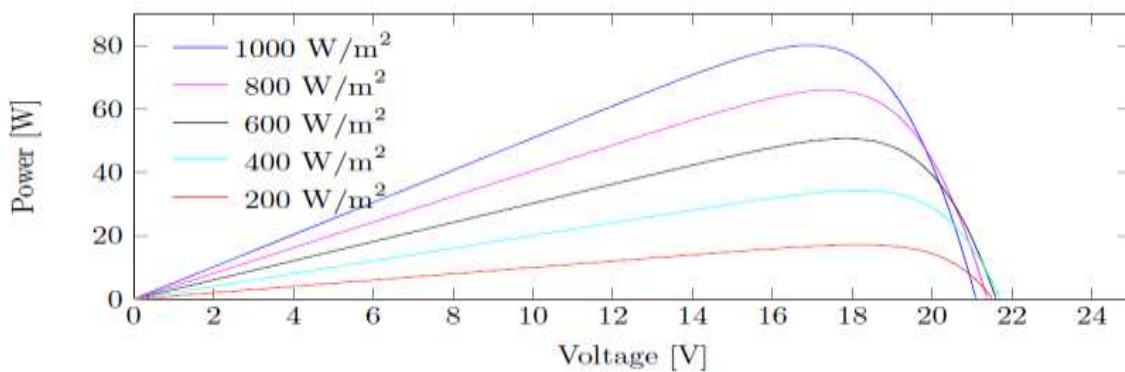


Fig.16: P-V curves with different solar irradiance values

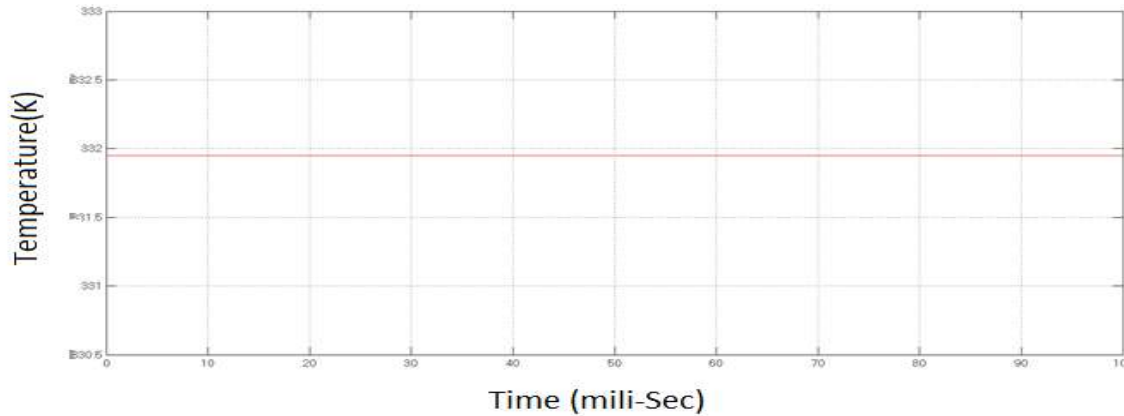


Fig 17: Temperature curve for the operation.

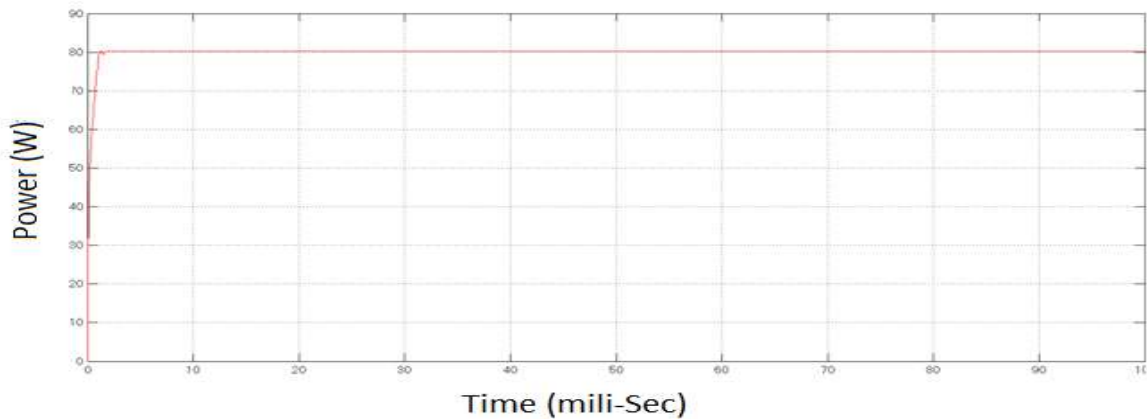


Fig 18: Maximum Power output curve

Fig 16 shows Power curves for different Irradiance values. Fig 17 & Fig 18 shows temperature value and the maximum power attained for the simulink time.

CONCLUSIONS

A Simulink implementation based on the five parameter diode PV model has been constructed. All the parameters in the PV model can be estimated by the parameter approximation method. This method is implemented in such a way that it enables easy simulation of different solar modules just supplying data sheet parameter values to the script. Maximum power point tracking using the Perturb and Observe algorithm has been implemented. The maximum power point tracking implementations successfully keeps the voltage close to the MPP most of the time. Implementation of Boost converter with P&O algorithm tracks the maximum power point well near by the actual value as results shows.

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