Modeling and Design of MPPT Controller Using Stepped P&O Algorithm in Solar Photovoltaic System

R. Prakash, B. Meenakshipriya, R. Kumaravelan

Abstract—This paper presents modeling and simulation of Grid Connected Photovoltaic (PV) system by using improved mathematical model. The model is used to study different parameter variations and effects on the PV array including operating temperature and solar irradiation level. In this paper stepped P&O algorithm is proposed for MPPT control. This algorithm will identify the suitable duty ratio in which the DC-DC converter should be operated to maximize the power output. Photo voltaic array with proposed stepped P&O-MPPT controller can operate in the maximum power point for the whole range of solar data (irradiance and temperature).

Keywords—Photovoltaic (PV), Maximum Power Point Tracking (MPPT), Boost converter, Stepped Perturb & Observe method (Stepped P&O).

I. INTRODUCTION

A photovoltaic panel has an output characteristic dependent on conditions such as illumination intensity and temperature. Each output characteristics has a unique Maximum Power Point (MPP) where the current-voltage product is greatest. Grid connected PV system should have a MPPT controller to control the power flow to the grid. The purpose of a maximum power point tracker (MPPT) is to ensure a photovoltaic panel runs at its highest level of efficiency by keeping it operating at the MPP, regardless of changes in external conditions. An MPPT typically consists of a step-up or step-down DC-DC converter. These converters are used to regulate the voltage and current at the load. It can be achieved by some form of duty-cycle control circuit. The conventional MPPT methods are generally categorized into the following groups:

1) Perturbation and observation (P&O) methods.
2) Incremental conductance methods.
3) Constant current or constant voltage and
4) Advanced techniques (e.g., fuzzy control and Voltage based Scheme)

Among them Perturb-and-observe (P&O) method is widely used in practical PV systems for the MPPT control due to its simple implementation, high reliability, and tracking

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efficiency. The main advantage of proposed stepped P&O algorithm is to vary the duty ratio of the boost converter in order to operate the PV system at Maximum power point.

II. PRACTICAL CIRCUIT MODEL OF PV CELL

Ideal diode equation describes the operation of the solar PV cell. Sun light exposure of a solar PV cell results in the creation of an electric current [4].

$$I_d = I_{o,cell} \left[exp\left(\frac{qV}{akT}\right) - 1 \right] \qquad (1)$$

The circuit consists of an ideal current source (representing the current generated due to photon interaction) and an ideal diode [5], [11].
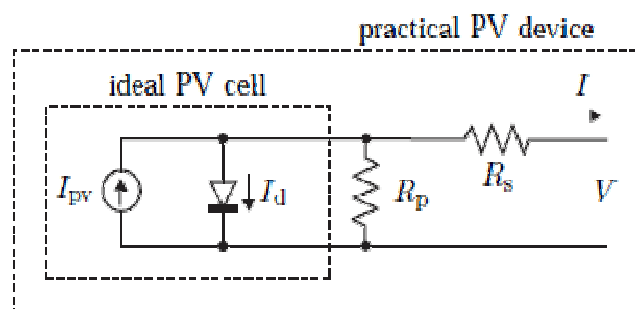

Fig. 1 Practical model of a PV cell

The basic equation from the theory of Photovoltaic system that mathematically describes I-V characteristic of the ideal photovoltaic cell is [2], [4], [11], [12]

$$I = I_{pv,cell} - I_d \qquad (2)$$

$$I = I_{pv,cell} - I_{o,cell} \left[exp\left(\frac{qV}{akT}\right) - 1 \right] \qquad (3)$$

where,

$I_{pv,cell}$ is current generated by incident light [A]
$I_{o,cell}$ is reverse saturation current of diode [A]
q is the electron charge [1.60217646 x10^{-19} C]
k is the Boltzmann constant [1.3806503 x 10^{-23} J/ K]
T is the temperature of the p-n junction [K] and
a is the diode ideality constant ($1 \le a \le 1.5$).

In practical devices, PV cell have parameters like parasitic series resistance (R_s) and parasitic shunt resistance (R_p). R_s represent the resistance of the semiconductor material and R_p accounts for the loss caused by a slight leakage current which penetrates through the parallel resistive path to the device.

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III. MODELING OF PHOTO VOLTAIC ARRAYS

Practical arrays are composed of several photovoltaic cells that are connected in series and parallel. Cells connected in parallel increase the output current and cells connected in series provide greater output voltages. The observation of the characteristics at the terminals of the photovoltaic array requires additional parameters to the basic equation (3). So it can be expressed [2], [3], [9], [11] as

$$I = I_{pv} - I_o \left[exp\left(\frac{V+R_sI}{V_t a}\right) - 1 \right] - \frac{V+R_sI}{R_p} \qquad (4)$$

The I-V characteristic of the photovoltaic device depends on the internal characteristics of the device (R_s, R_p) and on external influences such as irradiation level and temperature [11]. It can be expressed in (5):

$$I_{pv} = \left(I_{pv,n} + K_I \, \Delta T\right) \frac{G}{G_n} \qquad (5)$$

where,
I_{pv} is the light-generated current at the nominal condition (Usually 25° C and 1000 W/m^2)

$$\Delta T = T - T_n$$

(T and T_n the actual and nominal temperatures [K])
G is the irradiation on the device surface [W/m^2], and
G_n is the nominal irradiation [W/m^2].

It is difficult to determine the light-generated current (I_{pv}) of the elementary cells, without the influence of the series and parallel resistances. The diode saturation current I_0 to improve photovoltaic model [11] is described by:

$$I_o = \frac{I_{sc,n} + K_I \, \Delta T}{exp\left(\frac{V_{oc,n} + K_V \, \Delta T}{a \, V_{t,n}}\right) - 1} \qquad (6)$$

The saturation current I_o is strongly dependent on the temperature. Current and voltage coefficients K_I and K_V in (6) are introduced to achieve the best possible I-V curve fitting for different nominal temperatures. This equation simplifies the model and minimizes the model error. Effectiveness of (6) is tested in MATLAB/Simulink and compared with the experimental results.

A. Adjusting the Model Parameters (R_s and R_p)

This paper proposes a method for adjusting R_s and R_p based on the fact that there is only one pair (R_s, R_p) that ensures $P_{max,m} = P_{max,e} = V_{mp}$. I_{mp} at the (V_{mp}. I_{mp}) point of the I-V curve, i.e. the maximum power calculated by the I-V model of (4), $P_{max,m}$, is equal to the maximum experimental power from the datasheet, $P_{max,e}$, at maximum power point (MPP). The R_s and R_p may be found by making $P_{max,m} = P_{max,e}$ to get the I-V and P-V curve model fits with the experimental data.

$$P_{max,m} = V_{mp} \left\{ I_{pv} - I_o \left[exp\left(\frac{q}{kT} \frac{V_{mp} + R_sI_{mp}}{a \, N_s}\right) - 1 \right] - \frac{V_{mp} + R_sI_{mp}}{a \, N_s} \right\} = P_{max,e} \quad (7)$$

$$R_p = V_{mp} \frac{V_{mp} + I_{mp} R_s}{\left\{ V_{mp}I_{pv} - V_{mp} \, I_o exp\left(\frac{q}{kT} \frac{V_{mp} + R_sI_{mp}}{a \, N_s}\right) + V_{mp}I_o - P_{max,e} \right\}} \quad (8)$$

It shows that for any value of R_s there will be a value of R_p that makes the mathematical I-V curve cross the experimental (V_{mp}, I_{mp}) point. This equation must be solved by a numerical method. In the iterative process R_s must be incremented from $R_s = 0$. Adjusting the P-V curve to match the experimental data requires finding the curve for several values of R_s and R_p.

These iterations are done until $P_{max,m} = P_{max,e}$ in [6], [11]. By increasing R_s the peak power ($P_{max, m}$) moves towards the Maximum Power Point of the P-V curve [11]. For every P-V curve, there is a corresponding I-V curve that crosses the experimental MPP point at (V_{mp}, I_{mp}). Figs. 2 and 3 show the P-V and I-V curve of a TITANS6_60 solar array for various values of R_s and R_p. These results are compared and matches with the experimental data.
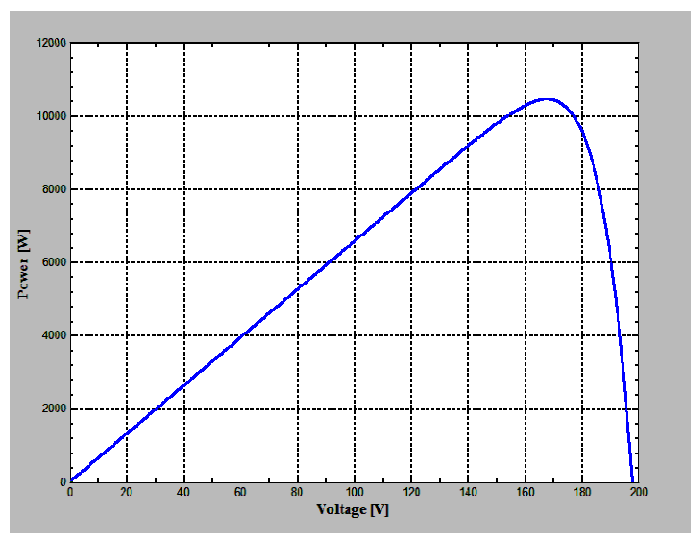

Fig. 2 I-V curve for TITANS6_60

TABLE I
PARAMETERS OF THE TITANS6_60 SOLAR ARRAY AT 25^{0}C,
1.5 ARITHMETIC MERIDIAN, 1000 W/ m^2

I_{scn}	8.21 A
V_{ocn}	37.0 V
I_{mp}	7.44 A
V_{mp}	28.9 V
$P_{max,e}$	215.016 W
K_v	-0.123 V/K
K_i	3.18x10^{-3} A/K
N_s	60

Table I shows the different parameters of PV panel which are taken from TITANS6_60 manufacture datasheet.

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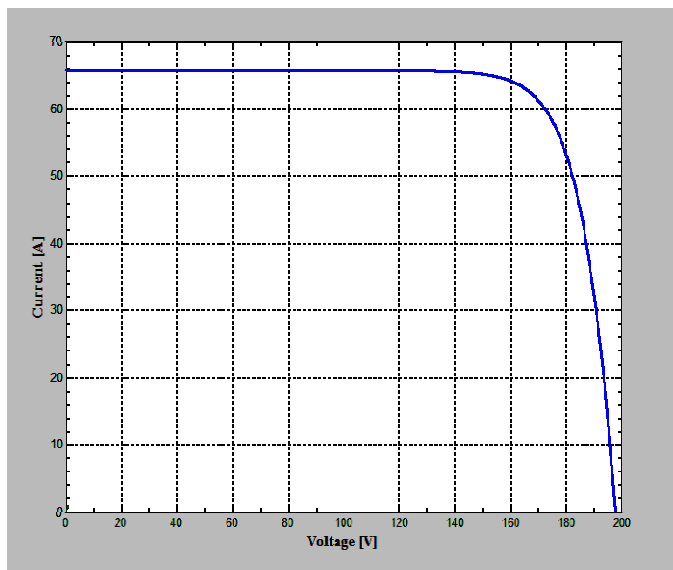
Fig. 3 P-V curve for TITANS6_60

TABLE II
PARAMETERS OF THE ADJUSTED MODEL OF THE TITANS6_60 SOLAR ARRAY
AT NOMINAL OPERATING CONDITION

$I_{sc,n}$	8.21 A
$V_{oc,n}$	37.0 V
I_{mp}	7.44 A
V_{mp}	28.9 V
$P_{max,e}$	215.016 W
$I_{o,n}$	2.90204×10^{-10} A
I_{pv}	8.264950 A
a	1
R_s	0.438800 Ω
R_p	65.570456 Ω

The calculated R_s and R_p values using (10) and (11) are given in Table II. These results are used in the simulation model as shown in Fig. 4 to get the required power rating.

Further improvement of a model can be done by introducing the equation

$$I_{pv,n} = \frac{R_s + R_p}{R_p} \cdot I_{sc,n} \qquad (9)$$

Each iteration updates the R_s and R_p towards the best solution. In order to get the best solutions R_s and R_p values are initialized [11]. Initial value of R_s may be zero.

$$R_{s,max} = \frac{V_{oc,n} - V_{mp}}{I_{mp}} \qquad (10)$$

Similarly the initial value of R_p may be given by

$$R_{p,min} = \frac{V_{mp}}{I_{sc,n} - I_{mp}} - \frac{V_{oc,n} - V_{mp}}{I_{mp}} \qquad (11)$$

It determines the minimum value of R_p, which is the slope of the line segment between the short-circuit and the maximum-power.

B. Simulation Model of PV Array

The photovoltaic array can be simulated with an equivalent circuit model of a photovoltaic system using MATLAB/simulink environment.
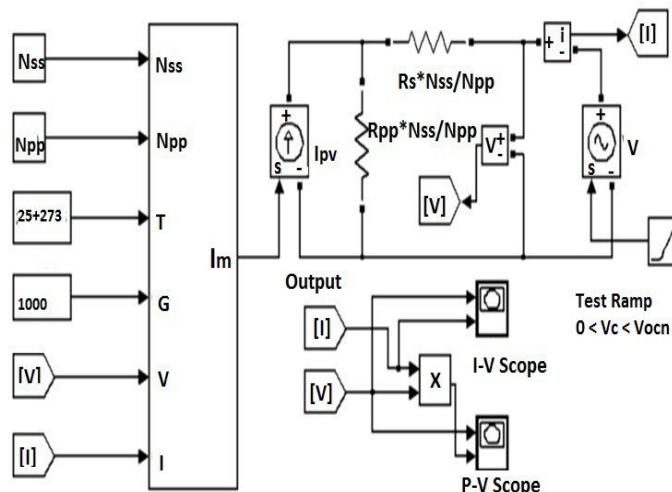

Fig. 4 Generalized simulation model of a PV system

In the system considered, there are 48 numbers of TITANS6_60 solar array for 10 kW power generation. The panels are arranged in two parallel combination of Nss = 6 (series) and Npp = 4 (parallel) manner to get a required current and voltage ratings. The parameters of solar panel as shown in Table II are given as input to the simulink model to plot and analyse the output characteristics of proposed system.
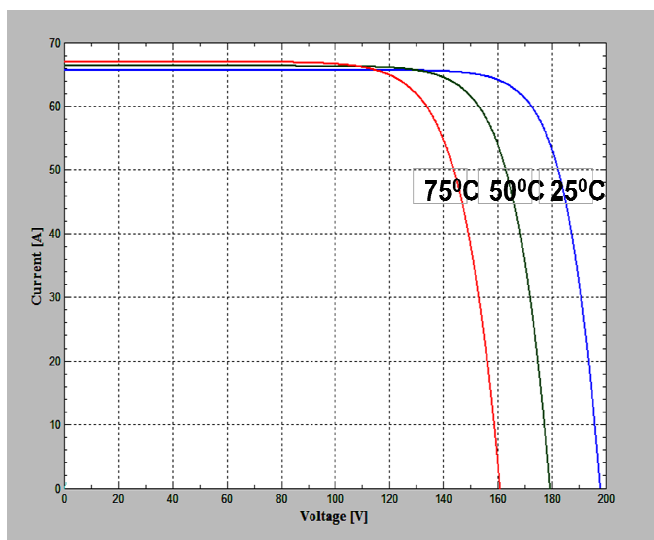

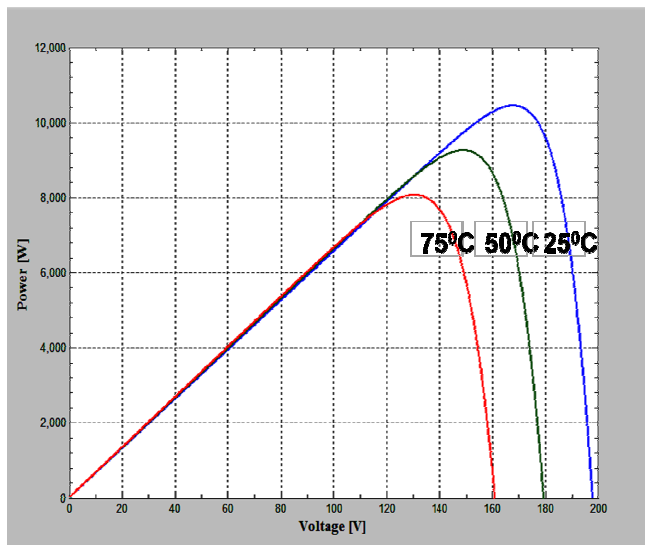Fig. 5 I-V Curve for different temperature levels at 1000 W/m²

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Fig. 6 P-V Curve for different temperature levels at 1000 W/m^2

Simulation results shown in Figs. 5 and 6 represented the I-V and P-V curve for different temperature levels at 1000 W/m^2.
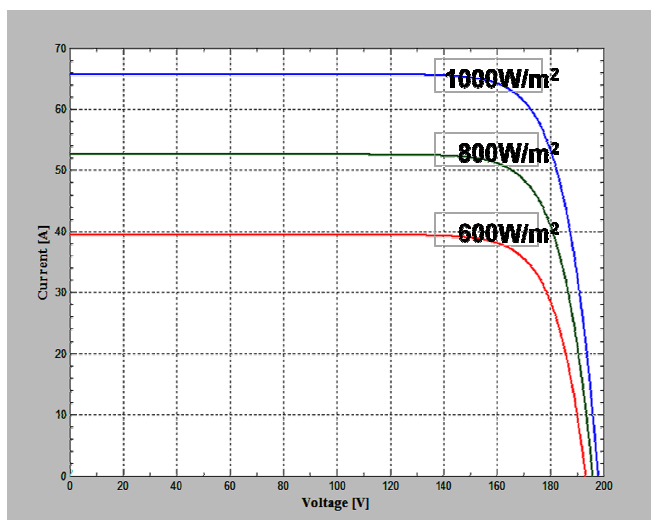

Fig. 7 I-V Curve for different irradiation levels at 25°C

I-V and P-V Curve shown in Figs. 7 and 8 are plotted for different irradiation levels at 25°C. These figures clearly show how the dependency of output current I and output voltage V on temperature and insolation translate into a dependency of the output power on the same two parameters. These simulation results provide the knowledge of designing the MPPT controller with the proposed algorithm.
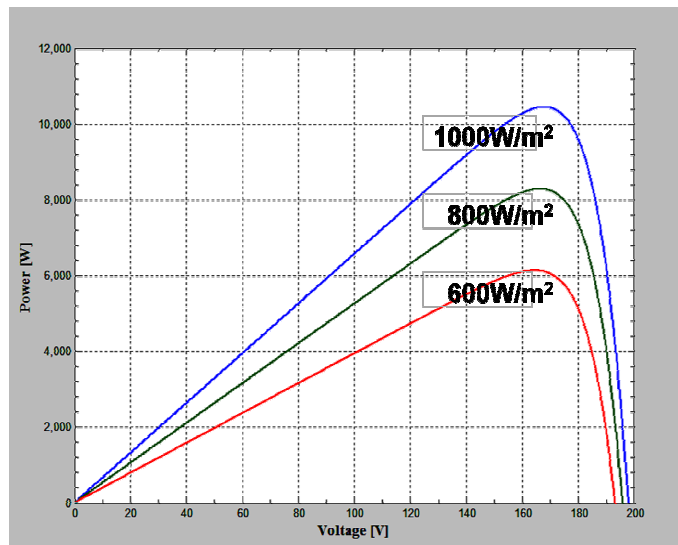

Fig. 8 P-V Curve for different irradiation levels at 25° C

IV. BOOST CONVERTER DESIGN

The typical DC-DC boost converter is shown in Fig. 9 where the input voltage variation V_{in} (min) = 130V is obtained when the system connected with load as indicated in Table III and V_{in} (max) = 200V of open circuit value from experimental data of a proposed system configuration. Nominal output voltage (V_{out}) and maximum output current (I_{out}) of a Boost converter is to be fixed as 440V and 72A respectively. Minimum and maximum duty ratio for the boost converter switch (SW) D(min) = 53.48% and D(max) = 68.18% are determined from (12) and (13).
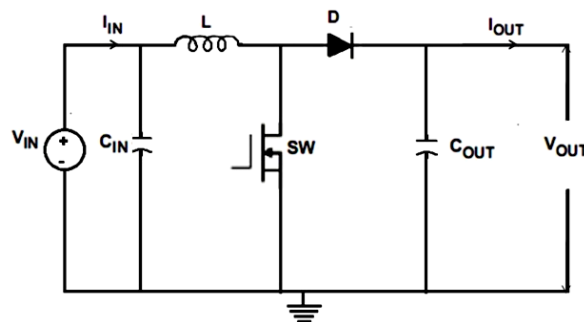

Fig. 9 DC-DC Boost Converter

TABLE III
EXPERIMENTAL DATA OF 10 KW PV SYSTEM USING TITANS6_60

Temp (^{0}C)	Irradiation (W/m^2)	Solar		
		Power (kW)	Voltage (V)	Current(A)
26.3	250	3.3	177	18.6
27.2	520	5.2	152	34.4
28.6	630	6.2	140	45.6
28.9	640	6.4	130	49.0
29.0	650	6.0	133	45.0
29.8	570	5.6	136	41.2
30.2	480	4.5	137	32.8
31.6	310	2.9	136	21.3

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The readings taken from 10 kW solar power plant is given in Table III. These results are used for the selection of inductor, diode and capacitor to get the required power rating.

The nominal switching frequency of the converter switch is considered as f_{sw} = 10 kHz.

$$D(min) = 1 - \left(\frac{V_{i\,max}}{V_{0\,min}}\right) \quad (12)$$

$$D(max) = 1 - \left(\frac{V_{i\,min}}{V_{0\,max}}\right) \quad (13)$$

A. Inductor Selection

Boost inductor can be selected in order to minimize the output current ripple in input current. It maintains the output continuously and boost the voltage and current when the converter switch is operated at higher switching frequency. From (14) minimum inductance value is obtained as L = 34.55µH.

$$L > \frac{D * V_{in} * (1-D)}{(2 * f_{sw} * I_{out})} \quad (14)$$

Peak value of inductor current can be determined in order to select the proper inductor value form (15).

$$I_{peak} = \frac{V_{in\,max} * D}{f_{sw} * L} \quad (15)$$

B. Diode Selection

To reduce losses, Schottky diodes should be used. The forward current rating needed is equal to the maximum output current $I_F = I_{out}$ (max). Schottky diodes have a much higher peak current rating than average rating. Therefore the higher peak current in the system is not a problem. The other parameter has to be checked in the power dissipation of the diode. It has to handle $P_D = I_F$ x V_F power rating. Where, I_F is average forward current of the boost converter diode and V_F is forward voltage of the boost converter diode.

C. Capacitor Selection

The certain minimum value for the input capacitor is necessary to stabilize the input voltage due to the peak current requirement of a switching power supply. The best practice is to use low Equivalent Series Resistance (ESR) ceramic capacitors. Otherwise, the capacitor can lose much of its capacitance due to DC bias or temperature. The value can be increased if the input voltage is noisy.

With external compensation, (16) can be used to adjust the output capacitor values for a desired output voltage ripple:

$$C_{out} > \frac{I_{out}}{V_{ripple} * f_{sw}} \quad (16)$$

Minimum capacitance value required is C_{out} = 240uF. Actual value of capacitance selected is higher than critical capacitance of the boost rectifier as calculated from (16).

V. STEPPED P&O ALGORITHM

Perturbation and Observation (P&O) method is one of the most efficient methods among all the MPPT strategies. In general, P&O algorithm uses a fixed step size, which is determined by the accuracy and tracking speed requirements. However, if the step size is increased for tracking speed-up, the accuracy is decreased. Because P&O fails to track the power under fast varying atmospheric conditions [8], [10], [13], [14] resulting in a comparatively low efficiency and vice versa. These drawbacks of traditional P&O algorithm can be eliminated by varying the step size under varying atmospheric conditions. It will effectively reduces the power losses in the system and operate the PV system close to MPP.

In this paper, stepped P&O algorithm is proposed for the MPPT method and is dedicated to find a simple, effective way to improve tracking accuracy and to overcome the drawbacks in traditional MPPT algorithms.

The flowchart of the stepped P&O MPPT algorithm is shown in Fig. 10, where the step size is automatically tuned according to the PV array operating point. When a step change in the solar irradiance occurs, the step size is automatically tuned according to the operating point [7]. If the operating point is far from the MPP, it increases the step size which enables a fast tracking ability.

The proposed MPPT controller will change the duty ratio of the Boost converter [1], [7] as follows:

$$D^*(k) = D(k) - N.\frac{\Delta P}{\Delta I} \quad (17)$$

where N is the scaling factor, which determines the performance of the MPPT system and is tuned at the design process. The MPPT control system has an inherent characteristic as follows:

- $\frac{\Delta P}{\Delta I} > 0$ PV operating point at the left of the MPP
- $\frac{\Delta P}{\Delta I} = 0$ PV operating point at MPP
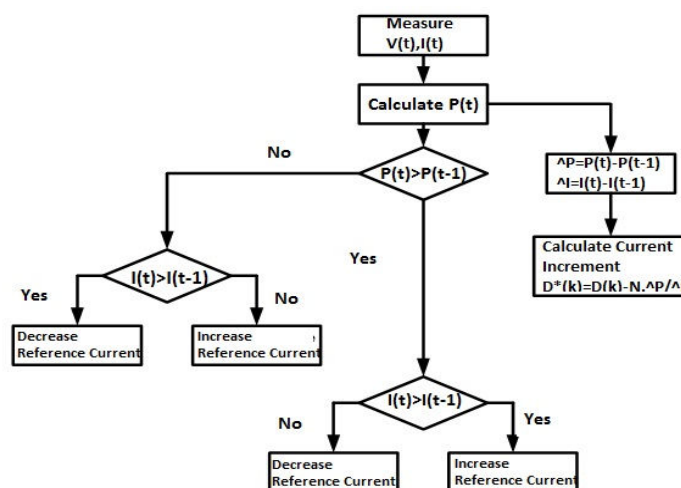- $\frac{\Delta P}{\Delta I} < 0$ PV operating point at the right of the MPP

Fig. 10 Stepped Perturb and Observe (P&O) method

Proposed 10 kW PV system is connected with the 8 kW load. The PV system with Stepped P&O algorithm is tested

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using MATLAB/ Simulink as shown in Fig. 11. The input voltage and current of the PV array is given as input to the stepped P&O controller. The proposed controller will calculate the actual power input to the converter. The algorithm is effectively the changes the duty ratio of the converter from 53.48% to 68.18% according to the load variation and also to the changes in physical parameters such as temperature and irradiation levels. It operates the converter around the maximum power point. It improves the efficiency of the boost converter as well as overall performance of the PV system.
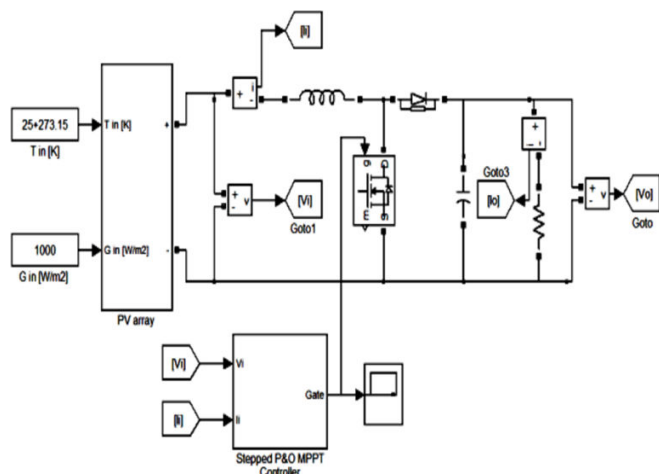

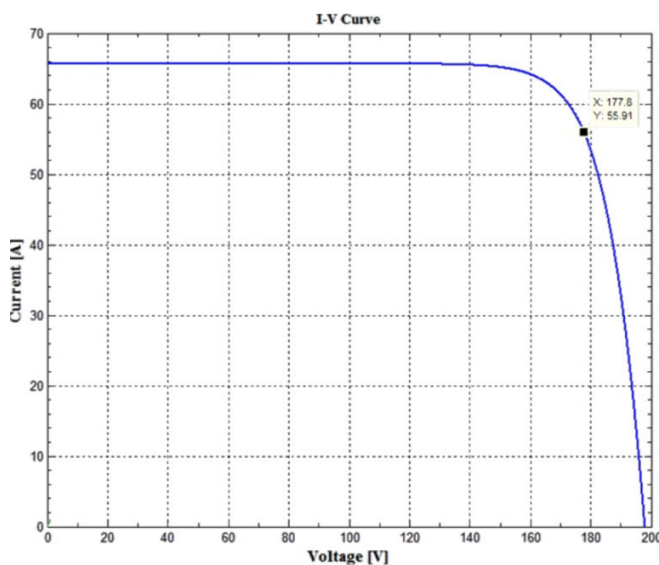Fig. 11 Simulation model of PV array with stepped P&O MPPT controller
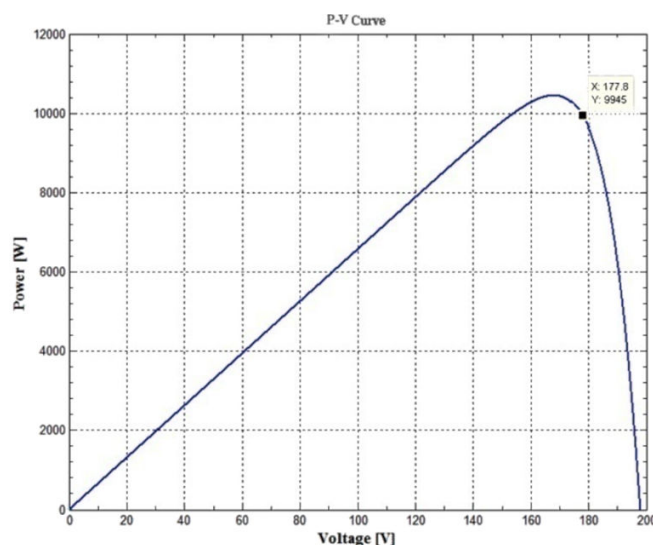

Fig. 12 I-V Curve at 25°C and 1000 W/m^2

Fig. 13 P-V Curve at 25°C and 1000 W/m^2

The proposed stepped P&O MPPT controller is operating the system around Maximum power point. The simulation results shown in Fig. 12 and 13 indicate the remarkable operating points of a proposed PV system at 25°C and 1000 W/m^2.

VI. CONCLUSION

This paper proposes generalized simulation model for photo voltaic array to be used in MATLAB-Simulink GUI environment. The proposed model has a generalized structure. So the model has been used to develop a 10 kW power generation along with boost converter and Stepped P&O MPPT controller. The output power characteristic of PV module is thoroughly investigated. The method is very simple and the experimental results show that proposed Stepped P&O MPPT method is able to considerably increase the efficiency of the PV system during rapidly changing irradiance. It shows the effectiveness of the algorithm around MPP. This will improve the overall performance of the photovoltaic system under different temperature and irradiation levels. This model will be used to study the influence of PV array as a part of proposed hybrid power system which consist of PV and Wind with batteries as a storage device.

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