IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676, p-ISSN: 2320-3331, Volume 16, Issue 4 Ser. II (Jul. – Aug. 2021), PP 29-37
www.iosrjournals.org

Maximum Power Point Tracking for Photovoltaic Application

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Abstract: *This paper presents the simulation of the Bp350 Photovoltaic (PV) module using MATLAB/Simulink. The I–V and P–V characteristics are obtained for varying solar insolation keeping cell temperature constant at room temperature. The effect of a change in temperature is also observed to provide better understanding on the behaviour of the system model. Maximum Power Point Tracking (MPPT) control technique which is based on the Perturb and Observe (P&O) and Incremental Conductance (InCond) is also described.*

Index Terms: *Photovoltaic (PV); Maximum Power Point Tracking (MPPT); Maximum Power Point (MPP); Perturb and Observe (P&O); Incremental Conductance (InCond), Standard Test Condition (STC)-Solar insolation, 1000W/m*^{2} *, Cell temperature, 25*^{0}*C , Air mass, 1.5*

Date of Submission: 06-08-2021 Date of Acceptance: 20-08-2021

I. Introduction

The contribution of renewable energy resource to the global energy mix is significant in meeting the projected energy demand by 2035 [2, 19]. Subsequently, reducing the amount of Green House Gas (GHG) emission and putting the world onto a more sustainable path. For example, the world energy consumption is estimated at about 10Tera-Watt (TW) per year and by 2050, it is projected to need about 30TW [35]. [35] is of the opinion that the world will need about 20TW of non-CO2 energy to stabilize CO2 in the atmosphere by mid-century [35]. In this context, Photovoltaic (PV) is a “key technology option to realize the shift to a decarbonized energy supply” [20].

As opposed to the working principle of conventional and other renewable sources, PV technology operates by directly converting sunlight into electricity by means of PV effect [6]. These amongst other peculiar advantages such as low maintenance cost, absence of noise and absence of fuel makes the technology stand out. The main application of PV technology are either in stand-alone systems such as street lighting, electric vehicle, terrestrial application and much more or in grid-tie systems like power plants or hybrid system [11, 28].

Despite claims that PV technology is still considered the most expensive renewable energy technology [7, 13], recent publication have revealed that the technology is cost effective in many areas especially in remote locations where grid system cost is high[4, 19, 20, 30]. According to the PV status report (2012), PV electricity generation have gained considerable attention globally and in some markets, the price of PV generated electricity is already cheaper than residential electricity retail prices [20]. However, [19] suggest that the fall in the price of the technology, the rising price in fossil fuel, carbon pricing and most especially, continued subsidies are factors that have favoured the growth of the PV industry [19].

The application of PV technology has two limitations: (a) low energy conversion especially under low insolation and (b) the power output from PV system depends on atmospheric conditions [1, 10, 11]. Since the low energy conversion of PV technology is dependent on the material and structure of the semiconductor available [16]. The key function in most PV application is therefore to extract maximum power from the PV system at any given time [38]. However, this key function is complicated by uncertain non-linear Current-Voltage (V-I) and Power-Voltage (P-V) characteristics that vary with change in atmospheric condition [1, 6, 11].

Maximum Power Point (MPP) is a unique point on the I–V and P–V curve such that the PV module operates and produces maximum power. The location of the MPP is unknown but can be estimated via mathematical model and (or) control algorithms [11]. As such, Maximum Power Point Trackers (MPPT) plays an important role in PV system by maintaining the PV module operating point at its MPP in order to optimize the ratio between power output and installation cost [1, 11].

In this study, Bp350 PV module is presented in the form of masked block using MATLAB/Simulink in Section II. The non-linear nature of the I-V and P-V characteristics are also presented based on the mathematical equations of a single PV cell which provides the possible prediction of the PV module behaviour under different varying parameters such as solar insolation and cell temperature. Section III provides a brief description of two MPPT techniques under the hill climbing principle-P&O and InCond. Section IV provides conclusion and explanation for further study.

II. Photovoltaic (PV) Model

PV cells have always been aligned closely with other electronic devices [33]. The theory of solid state that defines electron states, electronic properties of solid and much more is used to explains P – N Junction which forms the basic block of most electronic components such as diode, transistors and subsequently, PV cells [13]. The structure of PV cells are basically P – N junction fabricated in two or more thin wafer or layers of doped semiconductor materials [22, 37]. Doping implies impregnation of a semiconductor material such as silicon, group 4 element by a positive or negative element [13].

When sunlight strikes the surface of the PV cell, it can be absorbed, reflected or transmitted through the material [22]. The striking light with higher energy than the band-gap of the PV material will increase the energy of the electron thus causing the electrons to break free from the atom binding them to create electron – hole (e-h) pairs. Otherwise, the electrons will not have sufficient energy to break free from the atom

If these e-h pair are amply near the P – N junction, its electric field will cause the charge to separate creating a barrier – electrons will move towards the end of the N side of the junction while holes will move towards the end of the P side of the junction. Therefore, if the junction is connected to an external circuit, (Load) electric current will flow [13, 22].

2.1 PV Cell

The equivalent circuit of a non-ideal single solar cell is generally accepted in literature as a current source connected in parallel with a rectifying diode, series resistance and shunt resistance as shown in Fig 1.
The net current by applying Kirchhoff Current Law (KCL) is therefore the difference between the photocurrent, I_{ph} the rectifying diode current, I_D and the current flowing through the shunt resistance I_{sh} expressed in equation (1) [7, 27, 36, 37]

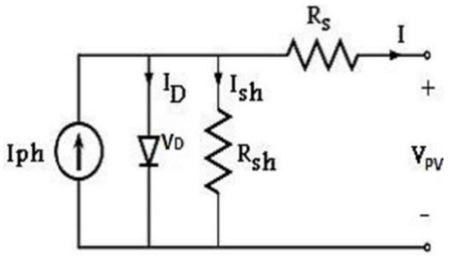

Figure 1: PV cell equivalent circuit

$$I = I_{ph} - I_D - I_{sh} \quad (1)$$

The photocurrent, I_{ph} expressed mathematical in equation (2)

$$I_{ph} = I_{phref}\frac{S}{S_{ref}}[1+\propto(T_c + T_{cref})] \quad (2)$$

Where: I_{phref} is the photocurrent at Standard Test Conditions (STC); S_{ref} is the solar radiation at STC (1000W/m^2); T_{cref} is the reference temperature (25^{0}C); S is the instantaneous solar radiation (W/m^2); T_c is the instantaneous temperature (^{0}C); $\propto$ is the current temperature coefficient for I_{ph} (% /^{0}C).
Shockley equation provides the diode current, I_D seen in equation (3)

$$I_D = I_o\left[exp\left(\frac{V_D}{mkT_c}\right) - 1\right] \quad (3)$$

The reverse saturation current I_o which depends strongly on temperature (A) is expressed in equation (4)

$$I_o = DT_c\left(exp\left(\frac{q\varepsilon G}{mk}\right)\right) \quad (4)$$

Where: D is the photocurrent losses due to charge carrier diffusion; m is the diode ideality factor (1≤2); q is electron charge (1.6 X 10^{-19} C); k is Boltzmann constant (1.38 X 10^{-23}J/K); εG is the material band gap energy (for example 1.12eV is for silicon material).
The current flowing through the shunt resistance I_{sh} is given by equation (5)

$$I_{sh} = \frac{V_D}{R_{sh}} \quad (5)$$

Where: V is the external voltage (V); R_{sh} is the shunt resistance (Ω) and is usually very large; R_s is the series resistance (Ω) and is very small
Another parameter that depends on the cell temperature, the Boltzmann's constant and the charge of the electron is the thermal voltage, V_t

$V_t = \frac{kT_c}{q}$ (6)

In literature, equation (1) is usually expressed and simplified to;

$I = I_{ph} - I_o \left[exp\left(\frac{V_D}{V_t}\right) - 1 \right] - \frac{V_D}{R_{sh}}$ (7)

Also applying Kirchhoff Voltage Law (KVL), the PV output voltage is the difference between the voltage across the rectifying diode, V_D and the product of the series resistance R_s and net current, I expressed in equation (8)

$V_{pv} = V_D - IR_s$ (8)

Two parameters usually given in manufacturers PV data sheet are the open circuit voltage, V_{oc} and short circuit current, I_{sc}. To determine I_{sc}, V_{pv} is set to zero. If we ignore equation (5),

$I_{sc} = I_{ph}$ (9)

This implies that the short circuit current value changes directly proportional to the incident irradiance. However to determine V_{oc}, the net current I is set to zero, thus presented in equation (10)

$V_{oc} = V_t \ln \frac{I_{ph}}{I_o}$ (10)

In order to achieve the desired voltage and current level in the design of PV module, PV cells are connected in series and parallel combination. It is should be noted that when cells are connected in series, the voltage level increase with the number of cells connected in series while current remain same. If the cells are connected in parallel, the current level increases with the number of cells connected in parallel while voltage remains same.

Since single PV cells generates a voltage output less than 1 volt. 72 cells was selected for the BP350 PV module connected in 2 parallel strings of 36 cells as provided in the manufacturers data-sheet shown in Table 1.

2.2 Simulation of PV module in MATLAB/Simulink

Based on equation (3), (4), (5), (6), (7) and (8), the MATLAB/Simulink model shown in Fig. 2 was developed based on [26]. The PV module model is implemented as a masked subsystem in Simulink

Table 1: Parameters of BP350 PV Module under STC

Electrical Characteristics	BP 350
Maximum power (P max)	50W
Voltage at Pmax (V mp)	17.3V
Current at Pmax (Imp)	2.89A
Short circuit current (I sc)	3.17A
Open circuit voltage(V oc)	21.8V
Temperature coefficient of I sc	(0.065 ± 0.015)%/ 0 C
Temperature coefficient of V oc	− (80 ± 10)mV/0 C
Temperature coefficient of power	− (0.5 ± 0.05)% / 0 C
Nominal Operating Cell Temperature (NOCT)	47±20 C

Under STC, the I-V and P-V curves are generated as shown in Figure.3. The following result is shown in Table 2

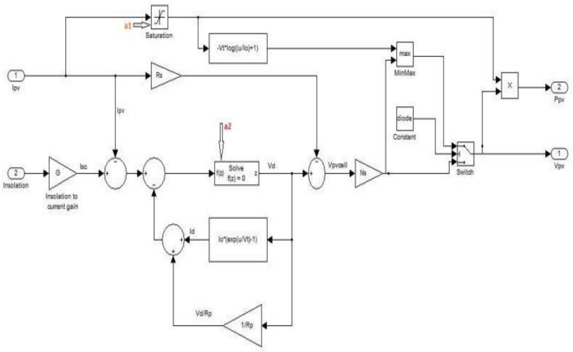

Figure 2: Under masked subsystem of BP350 module in Simulink

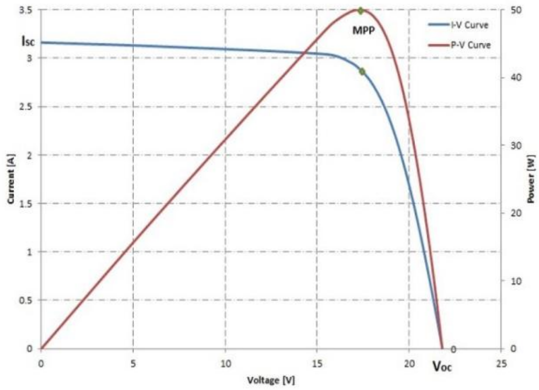

Figure 3: I-V curve and P-V curve for Bp350 PV module under STC

Table 2: Bp 350 Simulated result under STC

Electrical Characteristics	Simulated result
Maximum power (P max)	49.9923W
Voltage at Pmax (V mp)	17.36V
Current at Pmax (Imp)	2.88A

These values are closely similar to that provided in the manufacturers' data-sheet under STC in Table 1

2.2.1 Effect of change in solar insolation

Based on the above subsystem in Figure 2, the model simulation results obtained are shown in Figure 4 and Figure 5. Cell temperature was kept constant at 25^0C while solar insolation was varied at intervals of 200W/m^2

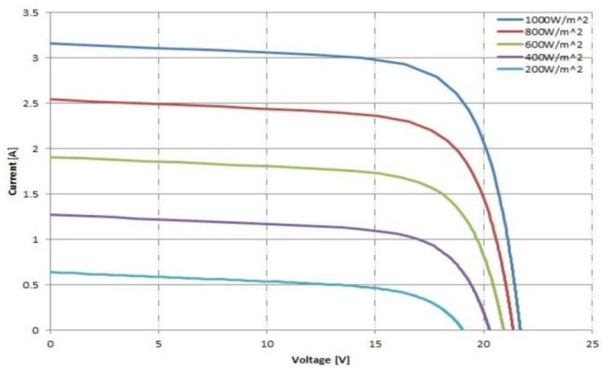

Figure 4: I-V curve for Bp350 PV at various solar insolation levels

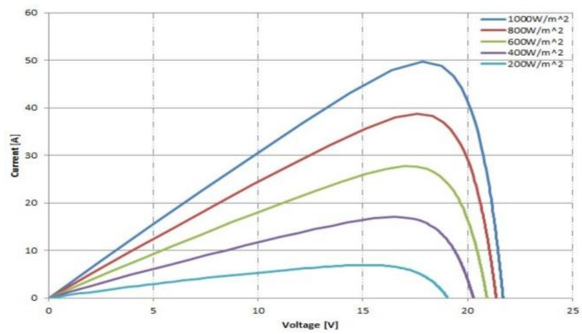

Figure 5: P-V curve for Bp350 PV at various solar insolation levels

As seen from Figure 4 and Figure 5, the PV module current is strongly dependent on the solar insolation as expressed in (9). It can be observed that from 200W/m^2 to 1000W/m^2, only a small change in PV module voltage occurs.

2.2.2 Effect of change in temperature

Based on (2), (4) and (6) the effect of change in temperature can be observed using an M file [15]. For a given solar insolation of 1000W/m^2, when the cell temperature increases, voltage drops while current increases slightly.

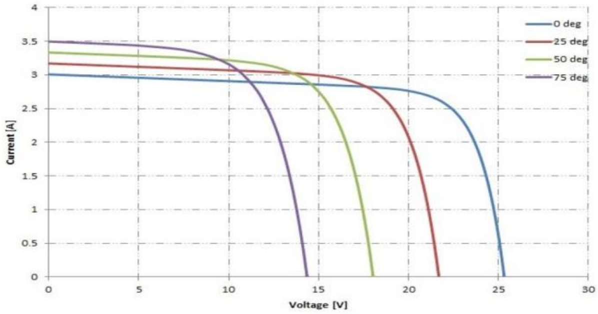

Figure 6: I-V curve for Bp350 PV at different temperature level

This behaviour is seen in Figure 6 and Figure 7 by observing a single cell and the entire PV module I-V characteristics based on the information provided in the manufacturers data sheet
It can be observed from Figure 7 that at 0^0C the voltage is higher than that stated under STC

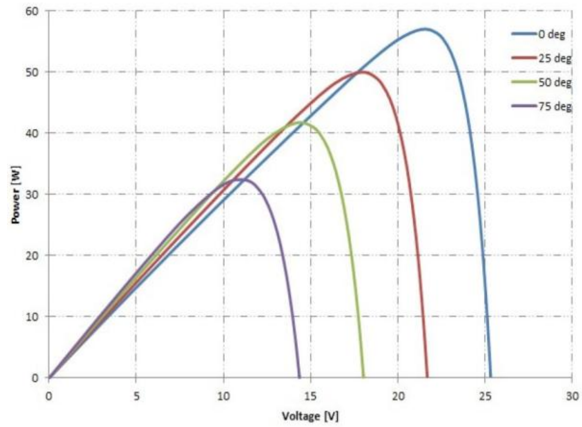

Figure 7: I-V curve for Bp350 PV at different temperature level

III. Maximum Power Point Tracker

Many MPPT control techniques have been proposed and published in literature. These techniques vary in many aspects such as complexity, convergence speed, multiple local maxima, hardware implementation, sensor, cost and much more. In [1, 10, 11, 12] an overview of these methods has been presented. Among several MPPT control techniques, Perturb and Observe (P&O) and Incremental Conductance (InCond) techniques continue to be the most widely used techniques due to simplicity in implementation and cost [10, 12]. Other techniques such as the fuzzy logic, array reconfiguration and neural network have the advantage of working with imprecise input [14], being fast, robust and having quiet good performance under varying atmospheric condition [6]. However, the implementation is limited to the end-user's knowledge of digital circuit and cost [10]

The problem considered by MPPT control techniques is to automatically find the current or voltage at P_{max} under a given solar insolation and temperature [10]. For instance, in cases of multiple local maxima under partial shading conditions, the control technique may also have to seek the true MPP from other local maxima. However, in various instances, the PV systems should operate close or on the point to extract maximum power at any given input condition [12]. In this paper, emphasis on two hill climbing techniques are highlighted.

3.1 Hill climbing method

The hill climbing MPPT techniques are so named because of the hill shaped upward convexity of the P – V curve [34]. The principle of operation is based on moving the operating point of the PV module/array in the direction in which power increases [17]. In other words, the techniques repeatedly searches for an optimum power output by incrementally changing the operating point until no further improvements can be found. Since this technique is based on actual power output detection, the optimum operating point under varying irradiance and temperature can be achieved [31].

The average increase in energy extraction is found to be 16 to 43 % using conventional hill climbing techniques [34] and can rise as high as 99% efficiency [1, 11]. However, the time taken to seek the MPP is longer because of the iterative operation. P&O is the most commonly implemented "hill climbing technique" and is highlighted in the Subsection 3.1.1. The concept of operation of InCond will also be discussed in Section 3.1.2

3.1.1 Perturb and Observe (P&O)

P&O MPPT control technique is an iterative method of obtaining MPP. The conventional method operates by periodically perturbing the PV terminal voltage and (or) current. The resulting change in PV power output is detected and compared with the previous cycle [17, 29]. The direction of change is such that the MPPT technique maintains the same direction if PV power output increases and reverse if otherwise.

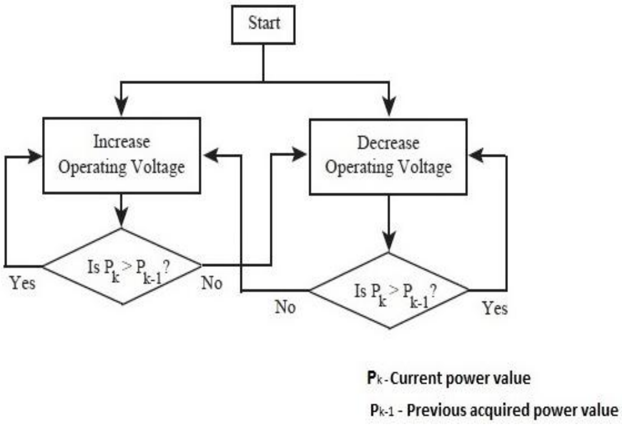

Figure 8: P&O MPPT flowchart [29]

[11] suggest there are many different adaptation of P&O control techniques available in literature. [10] on the other hand is of the opinion that most P&O control techniques tend to "repeat what seems to be conventional wisdom" [10]. For example, a technique may have presented in the context of a buck converter and later, with a boost-buck converter with minimal change. However, the common P&O techniques found in literature are the classic, the optimized and the three points weight comparison P&O algorithms [5, 11]. With emphasis on highlighting the P&O technique, the simplest form of P&O is considered as shown in the flowchart in Figure 8.

Other than the common advantage of simplicity in implementation and cost effectiveness, this technique does not require a previous knowledge of PV characteristics as shown in Fig 8. However, since the process continues to oscillate around the MPP till it stabilizes, oscillation around the MPP is a common setback associated with this technique. [1, 14] suggest the oscillation is true under rapidly changing atmospheric condition as a result of moving clouds. [11, 18] also suggest that the oscillation hold true under constant or slowly varying atmospheric conditions but [18] noted that the MPPT algorithms deviates from the MPP under rapidly changing atmospheric conditions. [12] is of the opinion that the oscillation is a function of the reference characteristics, that's to say, "tracking PV power by changing PV voltage is less sensitive to changes in irradiance". However, as irradiance decreases, it becomes an issue thus searching for the maximum current better locates the MPP at lower irradiance [12]. Under constant, slowing varying or rapid varying atmospheric condition, it is general agreed that the oscillation result in power loss.

3.1.2 Perturb and Observe (P&O)

[18] noted the inability for conventional P&O algorithms to relate to change in power under rapidly varying atmospheric condition. As such an alternative procedure called Incremental Conductance was proposed for tracking under the aforementioned condition. The basic idea is based on the fact that the slope of the PV power curve is zero at MPP that is to say, when the PV power is differentiated with respect to voltage and the result is equated to zero expressed mathematically in equation (11). The following relationships are also presented to find the relative location of the operating point to the MPP. Equation (12) suggest "on the left of MPP" while equation (13) "on the right of MPP"[18]

$$\frac{dP}{dV} = 0 \qquad (11)$$

$\frac{dP}{dV} > 0$ (12)

$\frac{dP}{dV} < 0$ (13)

The relation in equation (11) – equation (13), can be written further in terms of current and voltage using

$\frac{dP}{dV} = \frac{d(IV)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV}$ (14)

That is, if the operating point is at MPP, equation (14) becomes;

$I + V\frac{dI}{dV} = 0$ (15)

$\frac{dI}{dV} = -\frac{I}{V}$ (16)

If the operating point is on the left of MPP, equation (14) becomes;

$I + V\frac{dI}{dV} > 0$ (17)

$\frac{dI}{dV} > -\frac{I}{V}$ (18)

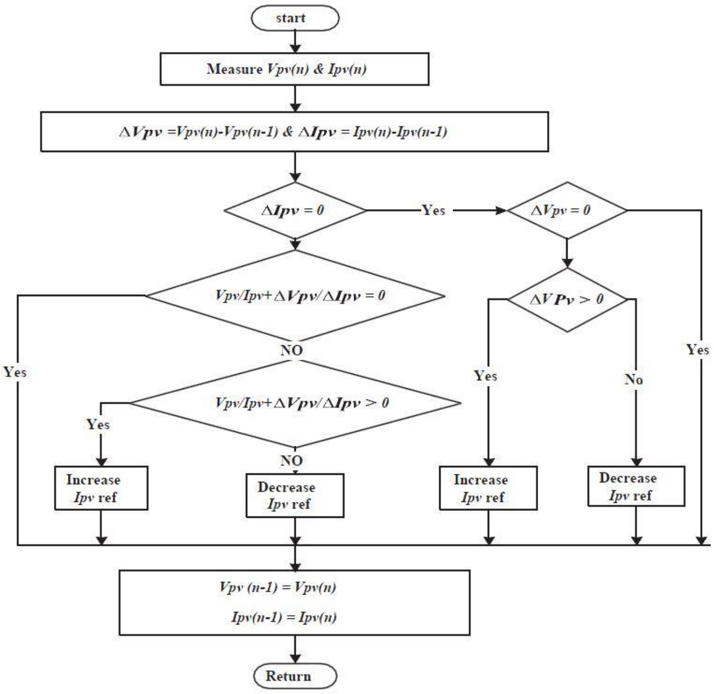

Figure 9: InCond MPPT flowchart [10]

If the operating point is on the right of MPP, equation (14) becomes;

$I + V\frac{dI}{dV} < 0$ (19)

$\frac{dI}{dV} < -\frac{I}{V}$ (20)

The detailed operation of the InCond algorithms can be represented with the flow chart in Figure 9.

At the start of the cycle, the algorithm will obtain the present values of I and V. It then calculates the incremental changes by finding the difference between the present and previous values of current and voltage. The main check is carried out by comparing the instantaneous conductance $\left(\frac{I}{V}\right)$ to the incremental conductance $\left(\frac{dI}{dV}\right)$ as shown in the relationship in equation (16), (18) and (20) with respect to the change in atmospheric conditions. The voltage adjustment is a function of the condition for MPP and as such, voltage adjustment is made till the condition for MPP is reached. Then, the algorithms will bypass the voltage adjustment to end the cycle. it should be noted that at the end of the cycle, the current and voltage data will be stored as previous values for the next cycle.

IV. Conclusion

The Bp350 PV module model based on the mathematical model of a PV cell is developed using MATLAB/Simulink. The fundamental parameters usually found in the manufacturers' data-sheet such as $V_{mp}, I_{mp}, V_{oc}, I_{sc}, \propto$ were used for the 50W module selected for this study. The I – V and P – V characteristics were generated using the developed model. The variables S and T_c which affects the performance of the PV panel was studied under a static environment at fixed interval to observe the behaviour of a PV system. In addition, the result generated provides an understanding on how the MPPT algorithm works with respect to the change in atmospheric condition and how the voltage and(or) current is varied to extract maximum power.

4.1 Recommendation

Prior to the establishment of the EN 50530 standard "Overall efficiency of grid connected photovoltaic inverters". Comparison of the performance of MPPT has been done in various ways as specified in [9], thus leading to inconsistent results [3, 38]. EN 61683 [9] is considered and evaluated under fixed environmental condition including irradiance and temperature of static MPPT performance as in a similar case considered in the result shown in Section 2. EN 50530 [8] test standard on the other hand, characterizes the performance measurement by verifying the static and dynamic MPPT performance and overall DC-AC conversion efficiency [8]. Thus, operation of the PV system under actual weather can be considered as function of the dynamic change of irradiance.

The impetus for further research is to design and test the performance of InCond MPPT technique based on the irradiation profile of the above mentioned standard. For simplicity and effectiveness purpose, the algorithm considered is based on the hill climbing principle in Section 3.1.2. which consists of moving the operation point of the PV array in the direction power increases is referenced [34]. The output considered is in DC power, so DC-AC conversion is not needed. However, an ideal DC-DC converter would be used to provide the actual power generated by the PV module. Partially shaded condition will not be considered as irradiation is assumed to be uniformly spread over the PV module. The performance will be restricted to the energy output from the MPPT device as cost and other parameters are not considered. The system will not be built in this research, as it may be considered for more future work and development under a practical environment. It will also not include discussion about actual implementation of the MPPT techniques.

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Abu, A.S.P. "Maximum Power Point Tracking for Photovoltaic Application." *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, 16(4), (2021): pp. 29-37.