



Power Performance Analysis of PV Module with DC to DC Buck Converter

Niaj Murshed, Md. Salman Khan Tushar, Suman Chowdhury



Department of Electrical and Electronic Engineering, International University of Business Agriculture and Technology, Dhaka-1230, Bangladesh

* Corresponding Author email:
suman@iubat.edu

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Student(s)

- Niaj Murshed
- Md. Salman Khan Tushar

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- Suman Chowdhury

ABSTRACT

The power performance of PV module with dc-dc buck converter for photovoltaic energy application has been analyzed in this paper. Since the solar module produces DC voltage at various levels depending on irradiance variation, it is needed to connect a DC-DC converter to adjust the level of DC voltage at a certain level. The power output has been investigated by MATLAB simulation. To improve the output power Proportional Integral Derivative (PID) control is used. From the simulation it has been observed that around 13.85 Watts more output power can be extracted if PID control is used.

Keywords: PV Cell, Working Principle of PV Cell, PV Module, Simulation of PV Module, DC-DC Buck Converter, PID Controller, & Output Difference.

1 Introduction

More economic and environment friendly source is renewable energy source which refers to clean and sustainable energy source suppressing the bad effects generated by conventional sources of fossil fuel [1]. As a pollution and poisonous free, the solar energy considered as one of the big renewable energy sources plays a vital role in power demand [2]. For proper energy conversion of photovoltaic arrangement, fuel cell and wind power dc-dc converters are largely used [3-5]. To fulfill the specific demand of load a series or parallel connection of PV modules called PV array is needed to analyze. Normally, a series combination of PV modules has been operated to increase the output voltage level because PV module provides a voltage range of 12 V to 75 V in the output side [4]. To get a proper fixed voltage from a photovoltaic system, it is a fundamental requirement to use a dc-dc converter as a power converter [5]. The photovoltaic low voltage output can be utilized efficiently by developing an indirect connection without going for the utility on grid or off grid. To charge the rechargeable batteries, PV module can be a good source of energy provider for fulfilling the power requirement of the off-grid photovoltaic systems, street-lights, base transceiver stations, satellites, solar vehicles, as well as building integrated PV systems to save the power for winter or rainy season, during night time and so on. However, direct connection of PV module with battery for charging purpose can damage the batteries or can cause a reduction of life span of the battery to a great extent for



the fluctuation of voltage and current. To regulate the charging voltage of PV module or array, DC-DC converter is needed.

In 1953 - Gerald Pearson starts to research into lithium-silicon photovoltaic cells. On April 25, 1954, Bell Labs make declaration the invention of the first practical silicon solar cell. Shortly afterwards, they are shown at the National Academy of Science Meeting. These cells have about 6% efficiency. They have presented an experimental investigation to study a semiconductor material used in a PV cell and its importance in determining the efficiency of the solar cell at various parameters such as behavior with respect to temperature, weight and all those contributions to the deciding factor of efficiency of the PV cell. The inventor has conducted many experimental researches to devise improvised methods and apparatus for forming thin film layers of semiconductor materials [16].

The field of photovoltaic generally connected with multi-layer materials converts sun light directly into DC Electrical Power. This type of basic mechanism for this conversion is known as "The Photovoltaic Effect". Solar cells are typically configured as a co-operating sandwich of P-Type and N-Type semiconductors, in which the N-Type semi conductor material (on one side of the sandwich) exhibits an excess of electrons and the P-Type semiconductor material (on the other side of the sandwich) exhibits an excess of holes each of which signifies the absence of the an electron[17].

Researchers have worked on improving the efficiency of Solar Cells. They have found that the efficiency of the solar cell varies from 15 % to 22 % and innovations are being carried out by changing the combination of semiconductor material in the PV cell and found improved efficiency. The inventor has examined that the properties of semiconductor material came out with a combination of cells- cascaded cell, permits achieving more than overall efficiency of 23 %. Up to the present time it has been proposed to use either Germanium or Gallium Arsenide as the substrate for solar cell in which the principal active junction is formed of N-Type and P- Type Gallium Arsenide. Solar spectrums attempted for continuing to develop solar cells are efficiently used. The semiconductor used in the solar cell must be designed for a small band gap, since the semiconductor material is otherwise transparent to radiation with proton energy less than the band gap [18].

They have worked on application of circuit model for energy conversion system. The solar energy is directly converted to electrical energy without any electrical parts by the use of photovoltaic system. PV system is widely utilized to cater power demands of the society in many countries. The efficacy of the PV system depends on the operation of the system components and its performance. The efficiency of the solar system transformation technology reaches about 15 % to 25 % mainly because of the conversation of DC power to AC power through battery banks. The best way to utilize the PV system energy is to deliver it to the AC mains directly without battery banks. Studies on the PV system in operation reveal that inverters contribute to 63% failure rate, modules 15% and other components 23% with a failure occurring on an average of every 4 to 5 years. To reduce the failure rate of the PV systems, it is necessary to reduce failure rates of inverters and components of effective performance [19].

2 Working Principle Of PV Cell

A photovoltaic cell is constituted by a junction of two semi-conductors, one is doped P-type, and the other is doped N-type. When a junction is created between two semi-conductors, a diffusion process takes place between the electrons of N-type and the holes of P-type, which results to a depletion zone and an electric field generates across this zone as shown in figure 1. When the photovoltaic cell absorbs solar irradiations from the sun, these irradiations provide the electrons of P-type semi-conductor and the holes of N-type semi-conductor with more energy via the photons that hit them frequently. The particles, when charged with energy exceeding the band gap, can overcome the electric field of the depletion zone and can move each to the other side [6].

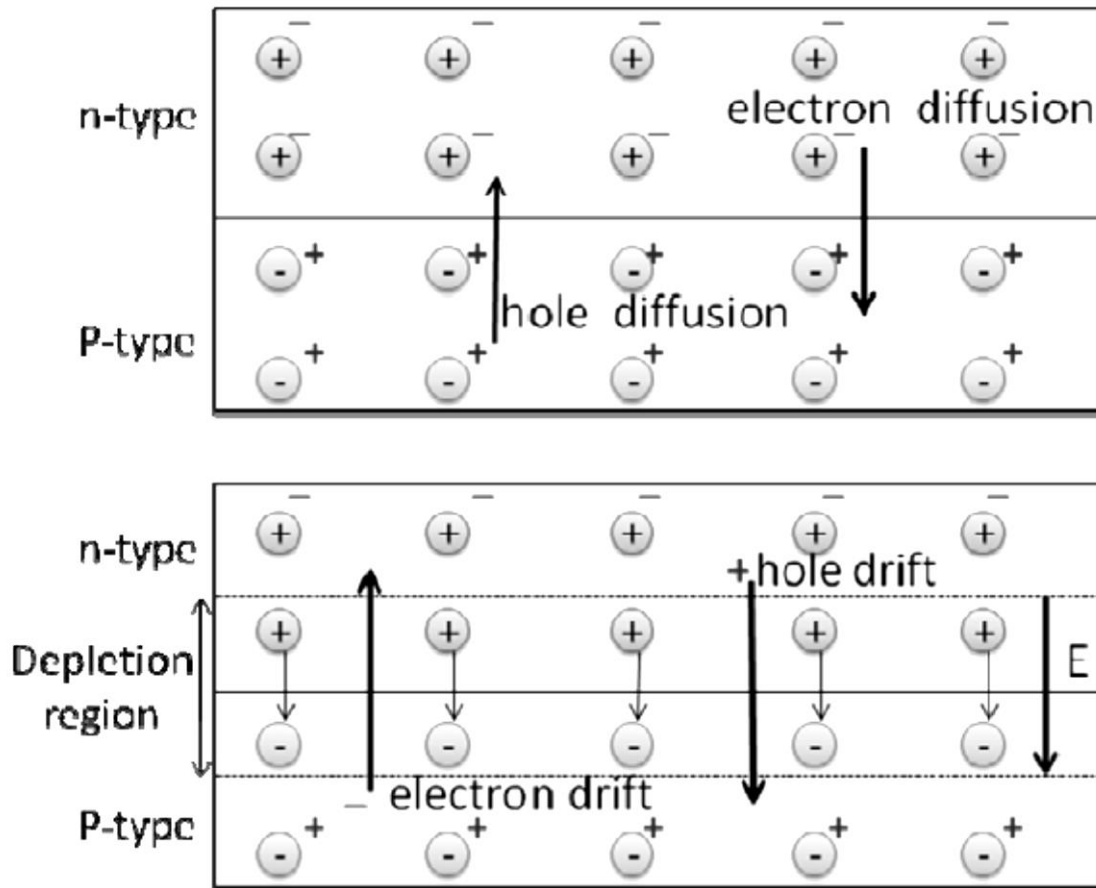


Figure 1: Process resulting from conjunction P and N type semi-conductors [6].

Finally, the positive and negative charges accrued in the P type N-type semi-conductors, respectively, as a result of potential difference created at the ends of the PV cell as shown in figure 2. It is true that some of the radiations spread by the sun are reflected by the surface of the PV cell. These reflected radiations are not converted to electric energy and we are concerned only about the radiations absorbed by the photovoltaic cells.

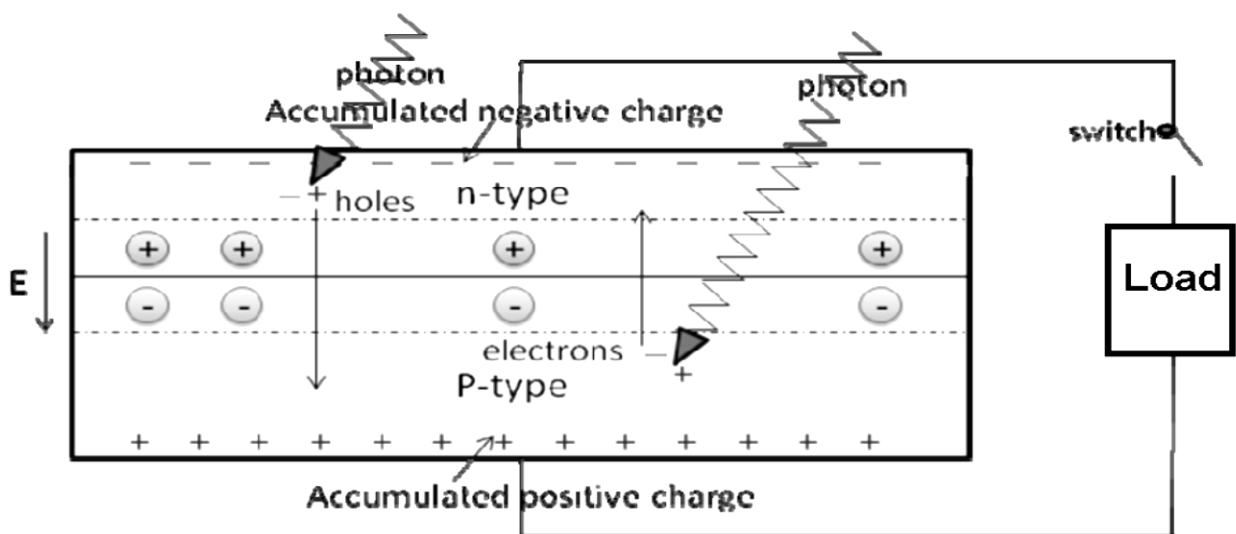


Figure 2: A photovoltaic cell operating principle [6].

3 Modelling of PV Cell

The equivalent circuit for the PV cell is shown in figure 3. The basic equation that can explain numerically the I-V properties of the PV cell can be represented by the root equation shown in equation (1) [7].

$$I = I_{ph} - I_s \left(\exp\left(\frac{q(V + IR_s)}{kT_c A}\right) - 1 \right) - (V + IR_s) / R_{sh} \quad (1)$$

where, I_{ph} stands for light generated current, I_s represents saturation of dark current, $q=1.6 \times 10^{-19}C$, k stands for Boltzmann's constant ($1.38 \times 10^{-23}J/K$), T_c is the cell temperature, A represents an ideality factor, R_{sh} is for shunt resistance and R_s stands for a series resistance. The light generated current primarily depends upon the solar irradiance and cell's temperature which is shown by equation (2) [7].

$$I_{ph} = (I_{sc} + K_1(T_c - T_{ref})) \cdot (G/G_n) \quad (2)$$

Where I_{sc} represents short circuit current of cell at $25^\circ C$, K_1 is the short circuit current temperature coefficient, T_{ref} is the reference temperature and G stands for the solar irradiance (kW/m^2) and G_n is standing for nominal solar radiation at STC (Standard test condition). On top of this, saturation current of cell varies with cell temperature expressed in equation (3) [7].

$$I_s = I_{rs} \left(\frac{T_c}{T_{ref}} \right)^3 \exp\left(\frac{qE_G}{k} \left(\frac{1}{T_{ref}} - \frac{1}{T_c} \right)\right) \quad (3)$$

Where I_{rs} is standing for the reverse saturation current at T_{ref} , E_G is for the band-gap energy of semiconductor material used in PV cell. The reverse saturation current related to open circuit voltage (V_{oc}) and short circuit current (I_{sc}) is provided by equation (4) [8].

$$I_{rs} = I_{sc} / \left(\exp\left(\frac{qV_{oc}}{kT_c A}\right) - 1 \right) \quad (4)$$

The electrical equivalent circuit for photovoltaic cell is shown in figure 3.

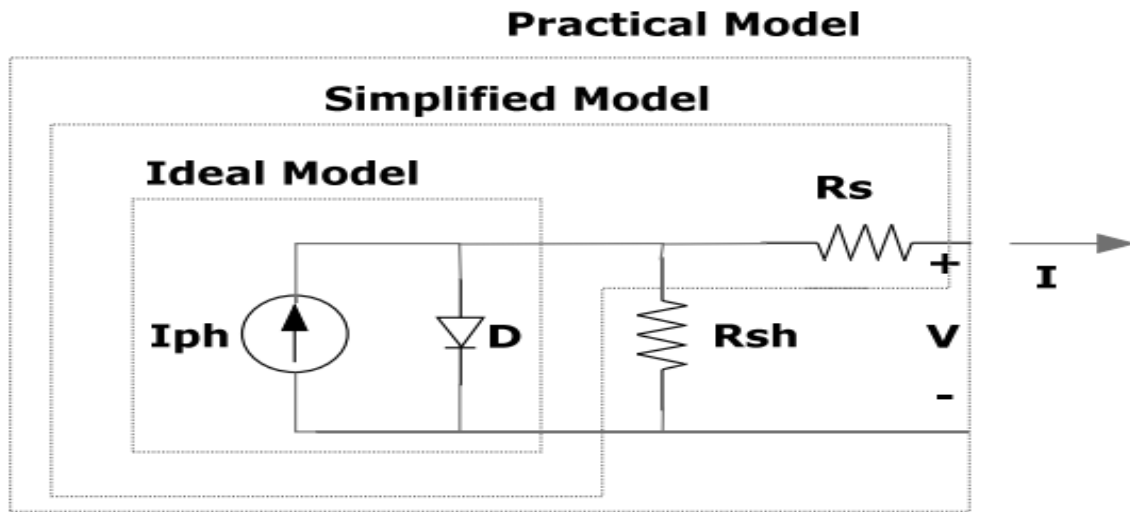


Figure 3: Equivalent one diode circuit diagram of PV cell [9]

A series or parallel of the modules develops a PV array. The equation for the PV array having N_s (series) and N_p (parallel) is given by (5) [10].

$$I = N_p I_{ph} - N_p I_s \left[\exp\left(\frac{q\left(\frac{V}{N_s} + \left(\frac{IR_s}{N_p}\right)\right)}{kT_c A}\right) - 1 \right] - \left(\frac{N_p V}{N_s} + IR_s \right) / R_{sh} \quad (5)$$

4 PV Module Simulation

For simulation of the PV Cell as well as PV Module, the data was obtained from a PV module with specification of CSS-MSP-100M-36. I_{sc} and V_{oc} of the solar cell are 5.08 A and 22.28 V, respectively. The specification sheet is shown in figure 4.

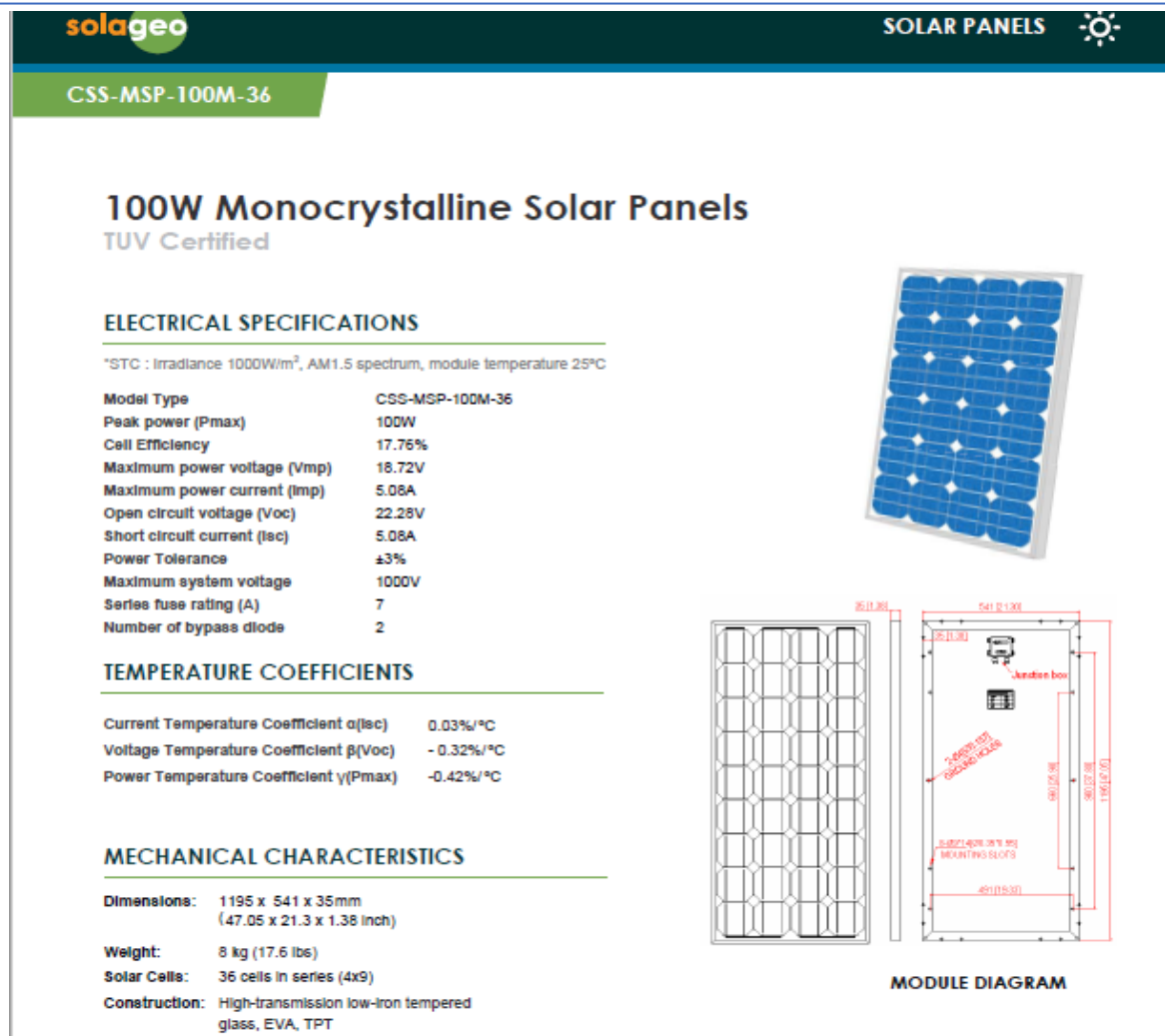


Figure 4: Data specification sheet.

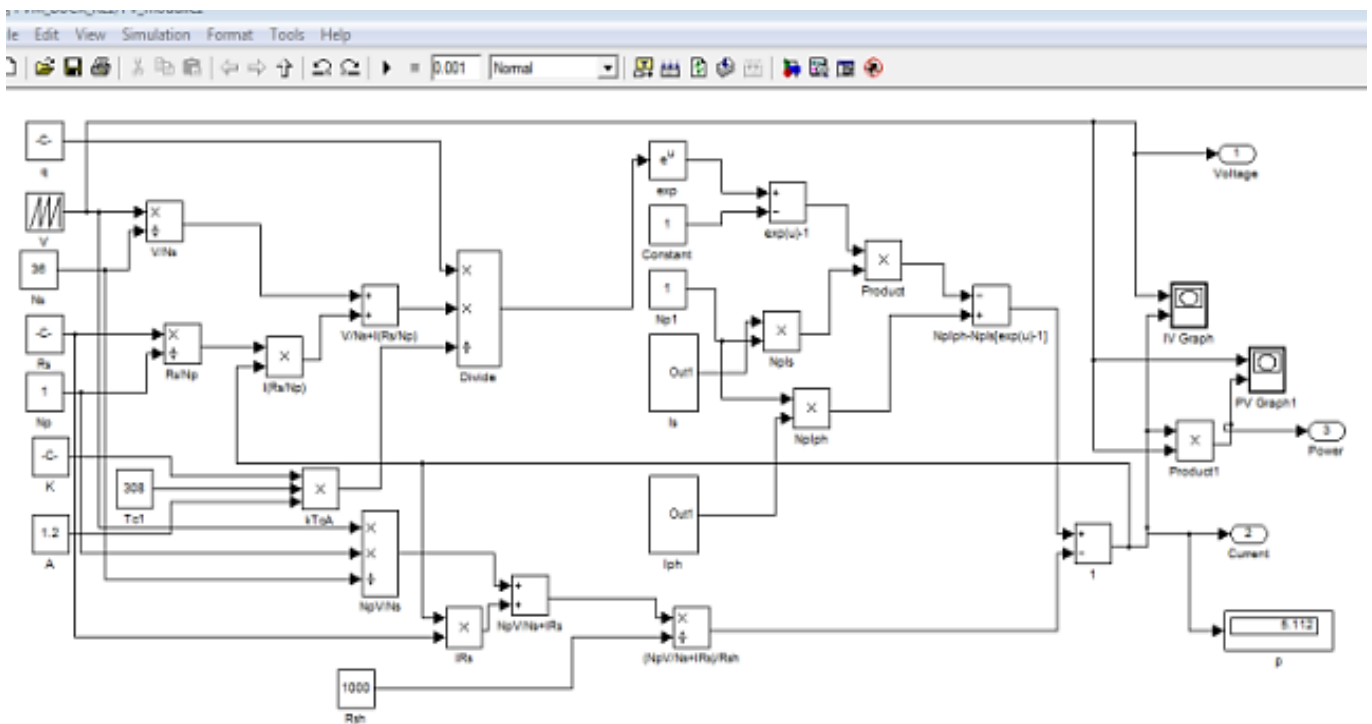


Figure 5: The simulink model of PV Module.

The total model of the PV module simulated by MATLAB/Simulink is given in figure 5. To observe the power performance of the PV module under various atmospheric conditions, it is required to estimate IV and PV characteristics. The IV & PV characteristics curve of photovoltaic module are as seen in figure 6 and 7. The current and power are generally taken along y-axis and voltage along x-axis. The following points may be noted from figure 6.

1. The short circuit current, $I_{sc} = 5.08 \text{ A}$
2. The open circuit voltage, $V_{oc} = 22.28 \text{ V}$
3. Maximum power voltage, V_{mp} is nearly 17.5 V
4. Maximum power current, I_{mp} is nearly 4.83 A

From figure 7, it has been seen that the peak power is around 84.53 Watts.

There would be no current flow if load is not connected across the PV module. Hence, the voltage across the PV reaches its maximum which is called the open circuit voltage (V_{oc}). And when a PV module is connected with load a peak is obtained named as short circuit current (I_{sc}).

The irradiation is affecting the short circuit current directly. The model is simulated under constant cell temperature of T_c is 25°C and 1000 W/m^2 irradiation level and the output of the PV module model is fed into the converter to step down the voltage level. Due to the various atmospheric conditions such as temperature and solar radiation, the efficiency of PV system goes down. Hence, to promote the performance of the PV module a buck converter is employed.

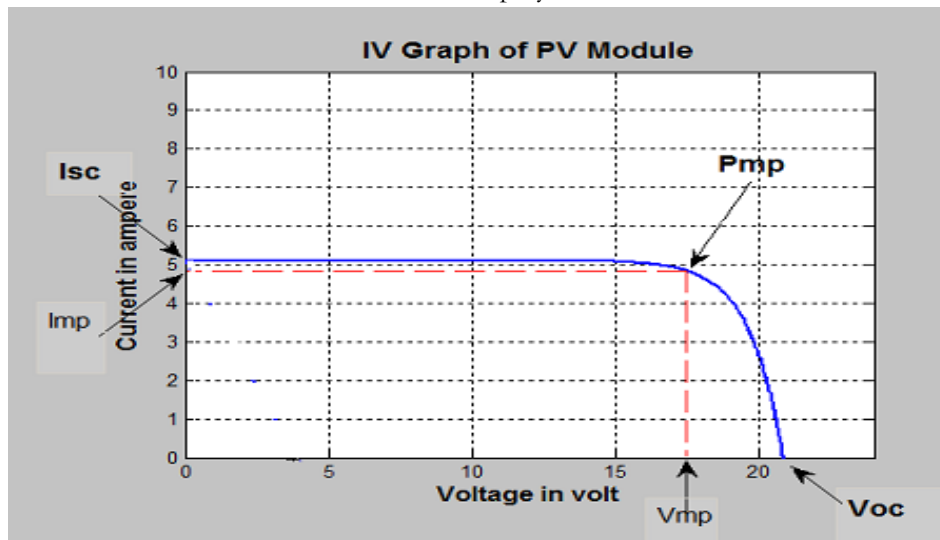


Figure 6: I-V characteristic curves of a PV module.

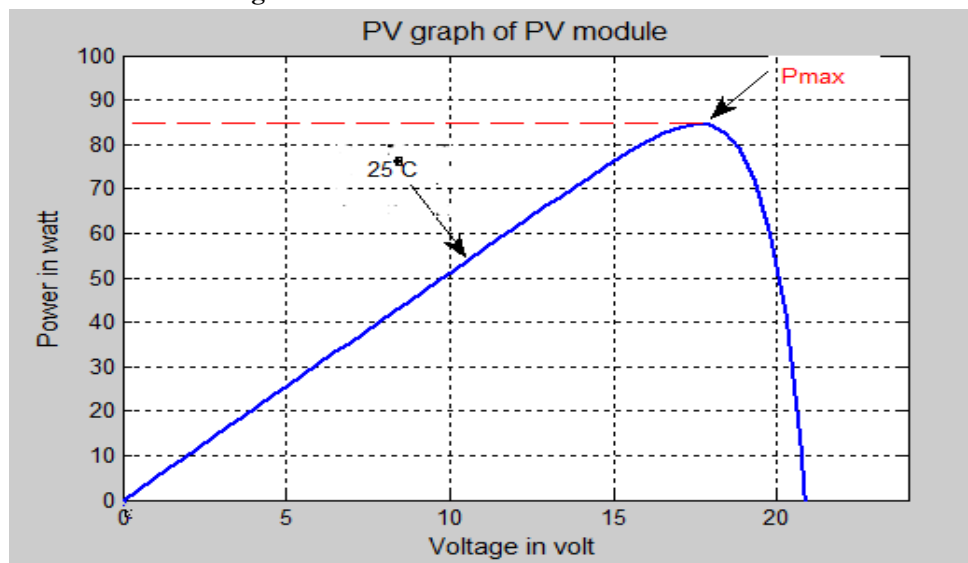


Figure 7: P-V characteristic curves of a PV module.

5 Principle of Operation of a Buck Converter

Normally MOSFET or BJT are used as power switches for a dc to dc buck converter to control the pulses. The circuit for buck converter is shown in Figure 8.

MOSFET is used as power switch in the above circuit which will step down the high to low direct current voltage. The circuit output voltage is always less than the input voltage [11].

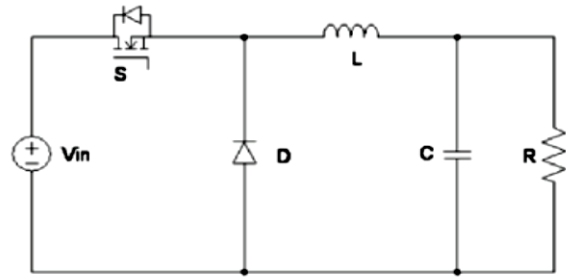


Figure 8: One diode buck converter [14].

The purpose of using inductor and capacitor is to generate the output that is filtered DC. So, LC low pass filter is connected with the basic circuit to produce filtered DC voltage. For switching on condition, the diode will be reverse biased and supply energy to load and inductor. Diode operates in forward bias and inductor current flows through the diode if the switch becomes off. Some of its stored energy needs to be transferred to load. This circuit diagram can be linked to obtain low level load from high input voltage [12] and also can be utilized in good range of stepdown converter [13]. The Buck Converter simulink model is shown in figure 9. The model uses three constant blocks that has been set by the user, such as V_{in} , V_{ref} and Load Resistance (R_L or R).

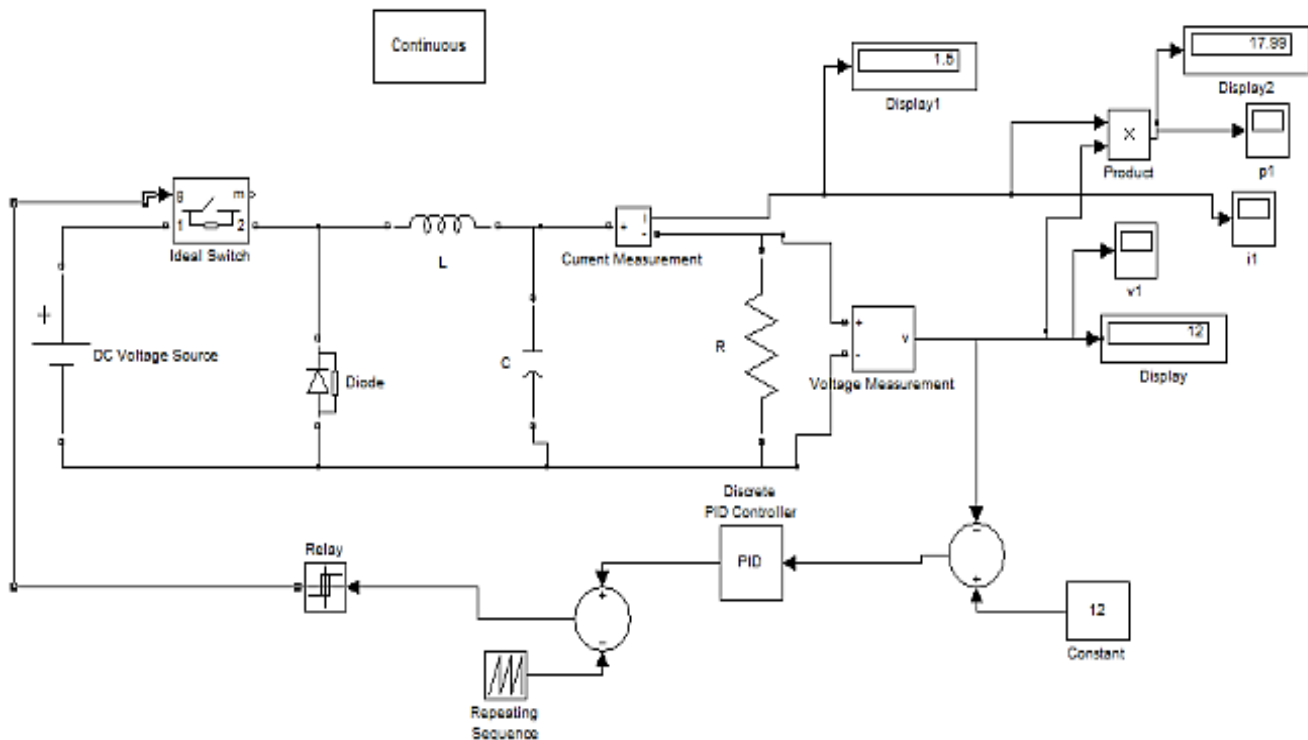


Figure 9: Simulink model of buck converter with PID control.

6 Numerical Computation of Buck Converter

In this section, for generating low output voltage from buck converter the linkage between input voltage (V_s) and duty cycle has been observed. Duty cycle is responsible for change of output voltage. The equation providing relation between output voltage (V_{out}), the input voltage (V_{in}) and duty cycle (D) is given below [15]:

$$V_{out} = V_{in} \times D \quad (6)$$

From Equation (1) the duty cycle, D can be calculated. Duty cycle can be varied in the range of 0 to 1 with the change of switching on time. Thus, to keep the output voltage at a lower level step down or buck

converter is done by fixing out the duty cycle operated in range of 0 to 1. By selection of inductor and capacitor, the ripple of output voltage can be reduced which is given by [15]

$$L = (D[V_{in} - V_{out}]) / (I_{ripple} \times F_s) \quad (7)$$

$$C = I_{ripple} / (8 \times F_s \times \Delta V) \quad (8)$$

Where,

V_{in} = Input Voltage,

V_{out} = Output voltage,

D = Duty Cycle,

F_s = Switching Frequency

I_{ripple} represents inductor ripple current; it is usually 30% of maximum output current. ΔV is the ripple of output voltage.

Input Voltage, $V_{in} = 22.28$ volt

Maximum output power, $P_{max} = 100$ watt

Let, Output voltage, $V_{out} = 12$ volt [battery voltage]

Output voltage ripple, $\Delta V = 120$ mV

$$= 0.12 \text{ volt}$$

Inductor ripple current, $I_{ripple} = 30\%$ of maximum inductor current ($I_{L,max}$)

Now,

Maximum inductor current, $I_{L,max} = (P_{max}) / (V_{out}) = 8.33$ amp

Duty cycle, $D = V_{out} / V_{in} = 12 / 22.28 = 0.5386 = 53.86\%$

So, $I_{ripple} = 0.3 \times 8.33 = 2.499$ amp

Now,

$L = (D[V_{in} - V_{out}]) / (I_{ripple} \times F_s) = (0.5386[22.28 - 12]) / (2.499 \times 500,000) = 4.43 \mu\text{H}$ [where, switching frequency, $F_s = 500$ KHz]

And $C = I_{ripple} / (8 \times F_s \times \Delta V) = 2.499 / (8 \times 500,000 \times 0.2) = 5.206 \mu\text{F}$ [where, maximum load resistance ($R_{L,max}$) = 8 Ω]

7 Simulation of PV Module with Buck Converter Using PID Controller

The sub-system of simulation of PV Module with dc to dc buck converter is as following in figure 10.

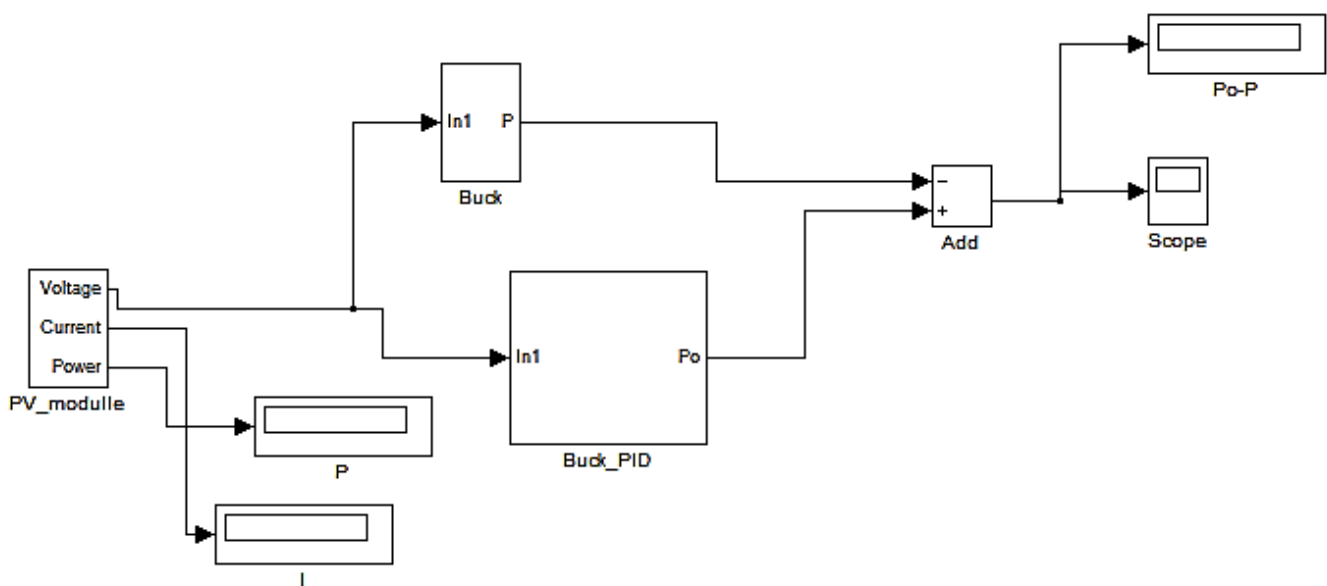


Figure 10: Simulink model of PV Module with Buck Converter.

The characteristics of the output waveform (voltage, current & power) of module with Buck Converter are shown in figures 11, 12 and 13, respectively. It shows that the maximum output response of PV Module with buck converter as well as PV Module with buck converter using PID control is at a range of 0.4×10^{-4} s to 0.6×10^{-4} s. From figure 11, we can see that the output voltage of PV module with dc to dc buck converter is 5.937 Volts at range of 0.4×10^{-4} s to 0.6×10^{-4} s, where the maximum value of voltage is 11.81 Volts. From figure 12, it can be said that the output current of PV module with dc to dc buck converter is 0.75 Ampere at the same range where the maximum value of current is 1.476 Ampere. And from figure 13, it is observed that the value of output power is 4.4 Watts at same time range, where the maximum value of power is 17.43 Watts.

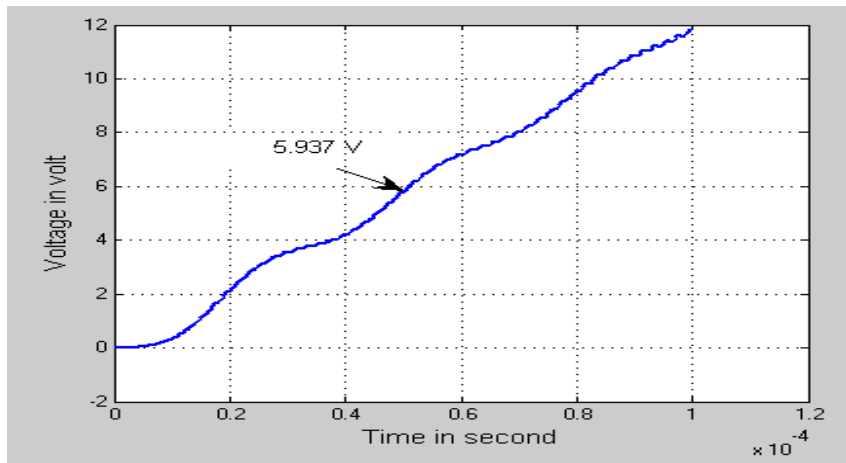


Figure 11: PV module output voltage with buck converter

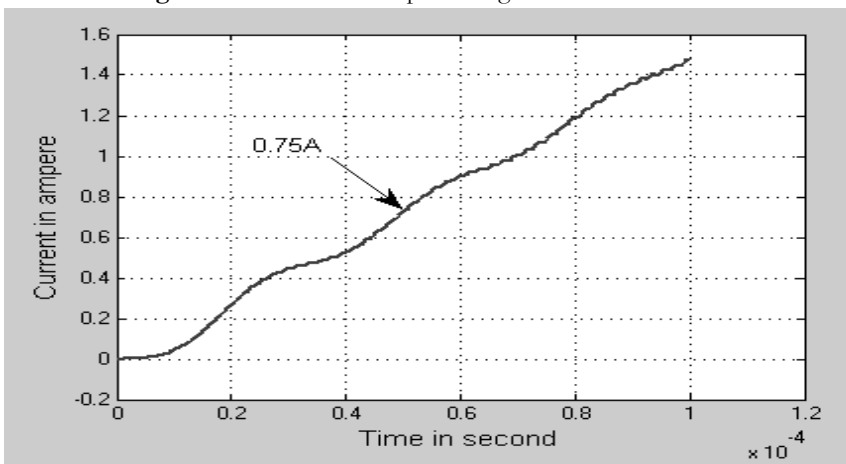


Figure 12: PV module output current with buck converter

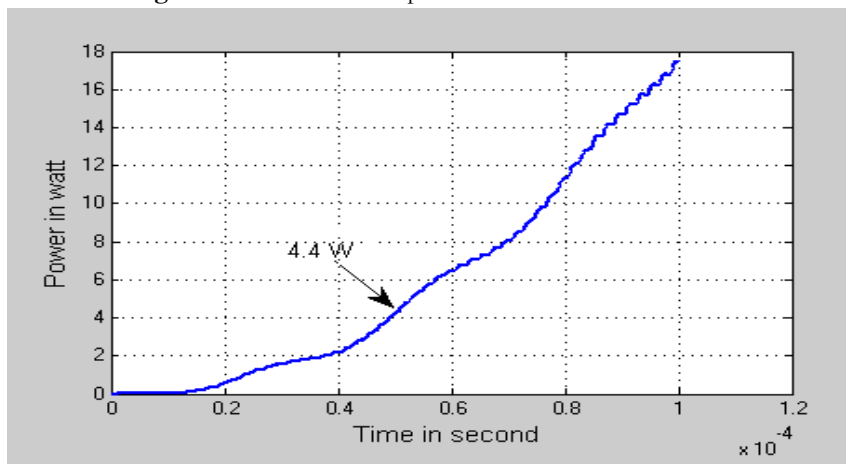


Figure 13: Output power of module with buck converter

Figures 11, 12 and 13 show the output response of PV Module with Buck converter that converts high input to lower output voltage. In this paper, we have seen that the output of buck converter is not a stable response. The PID controller gives faster response, less overshoot, less oscillation and makes the system stable. The error can be minimized if a manipulated variable is used for adjusting the process.

The output waveform of PV Module with DC – DC Buck Converter using PID Controller is shown by following three figures 14, 15 and 16 respectively. Figure 14 shows that the value of the maximum output voltage is 12.057 Volts at time range of 0.4×10^{-4} s to 0.6×10^{-4} s whereas figure 15 represents that the value of the maximum output current is 1.507 Ampere and figure 16 states that the value of the maximum output power is 18.25 Watts.

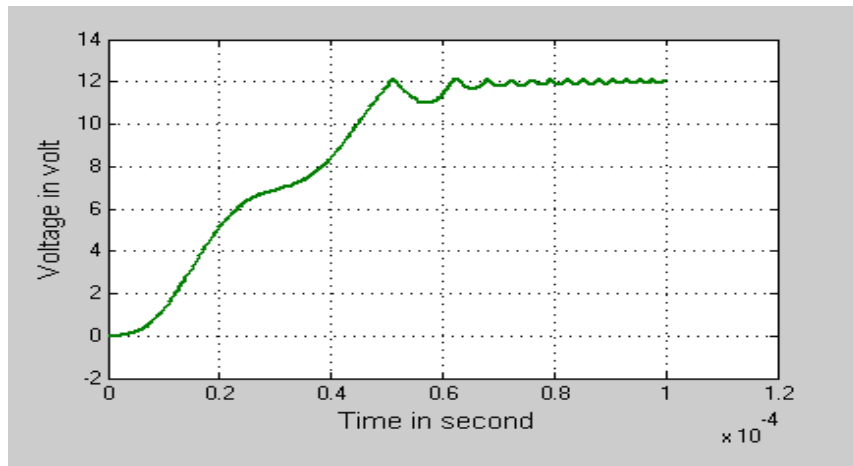


Figure 14: Output voltage of PV module with buck converter using PID control.

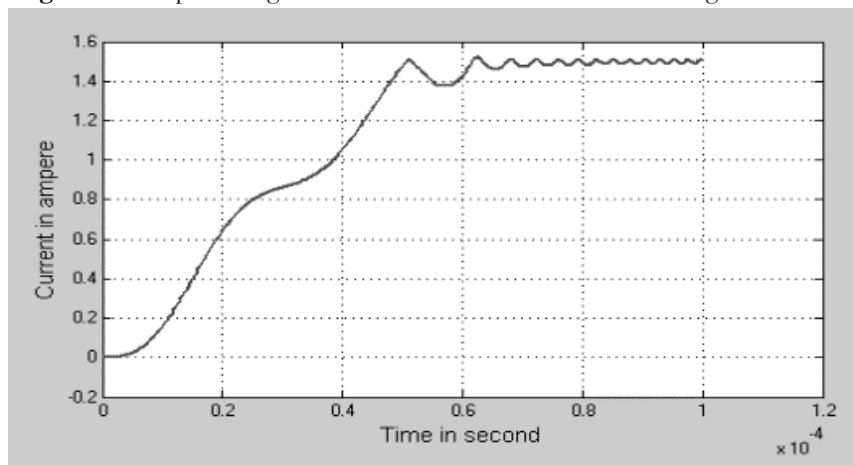


Figure 15: Output current of PV module with buck converter using PID control.

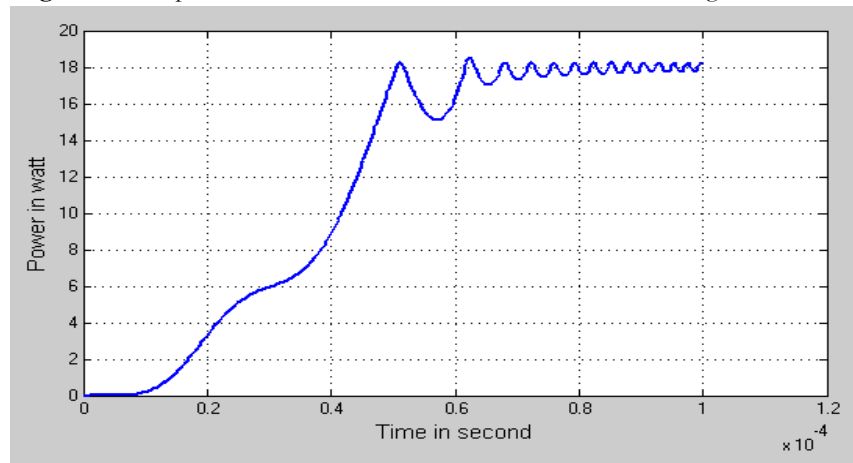


Figure 16: Output power of PV module with buck converter using PID control.

The simulink diagram has been proposed to investigate the output performance of PV module. The difference between PV module with buck converter and PV module with buck converter using PID control is helped to analyze the power performance. The simulation result is shown in below table 1.

Table 1: Performance parameter of PV module

Parameters	PV module with buck converter	PV module with buck converter using PID control	Differences
V(max) in volt	5.93	12.057	6.12
I (max) in ampere	0.75	1.51	0.76
Power (max) in watt	4.4	18.25	13.85

The graphical representation of these simulations is as follows:

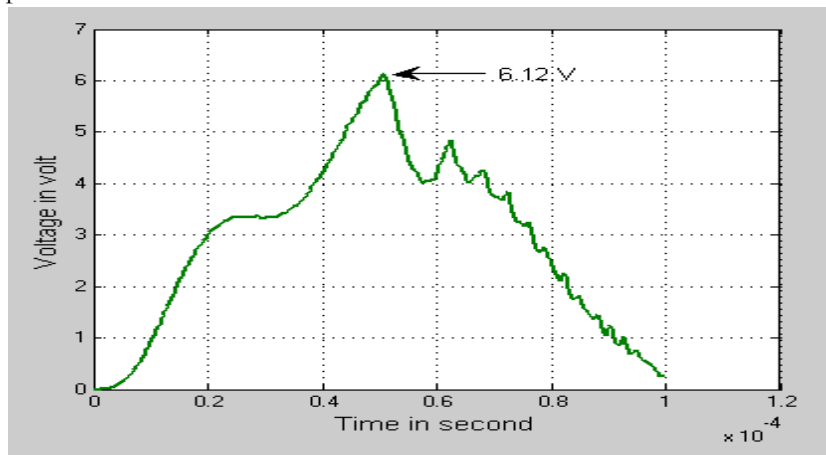


Figure 17: Output voltage difference between PV module with buck and PV module with buck using PID control.

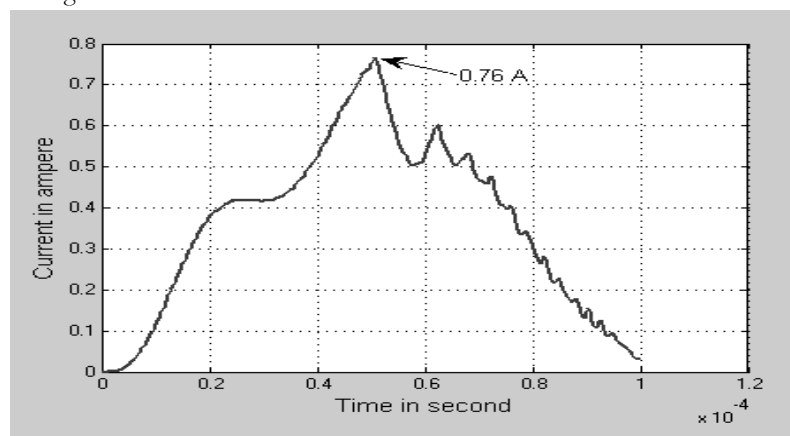


Figure 18: Output current difference between PV module with buck and PV module with buck using PID control.

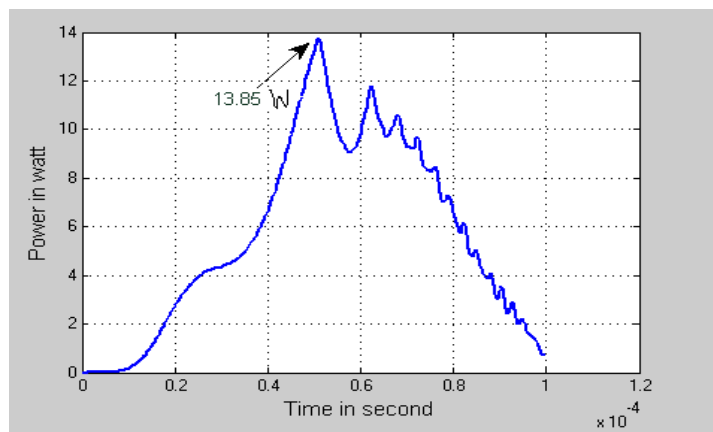


Figure 19: Output power difference between PV module with buck and PV module with buck using PID control.

In the above three figures 17, 18 and 19 represent the voltage, current and power differences between PV module with buck converter and PV module with buck converter using PID control, respectively. It has been realized that, maximum output and stable response can be obtained by the use of PID controller. Figure 17 shows the output voltage difference between PV module with buck converter and PV module with buck converter using PID control. From this curve it has been seen that the maximum voltage difference is 6.12 volt at time range of 0.4×10^{-4} s to 0.6×10^{-4} s whereas figure 18 shows that the maximum current difference is 0.76 Ampere and figure 19 represents that the maximum power difference is 13.85 Watts.

8 Conclusion

The simulation of photovoltaic module has been observed using buck converter to stabilize the output at a particular voltage level. To promote the output power performance as well as stabilization of voltage a PID control has been used. The maximum current obtained is 1.4 A for the PV module with buck converter whereas it is 1.5 A for the utilization of PID control. From the analysis, it has been found that around 6.2 V has been improved in the case of buck converter with PID control. Also, it has been found that around 0.76 A of current and 13.85 W of power have been improved when PID control is used. For the simulation purpose, taken values of inductor ripple current and output ripple voltage are 30 % and 1 % respectively. This ripple can be varied to check the performance variation of the buck converter in further investigation. Still more researches are needed to investigate the performance such as partial shading effect, solar irradiance effect, temperature effect etc.

9 Declarations

9.1 Acknowledgements

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9.2 Competing Interests

The authors declared that no conflict of interest exists in this work.

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