Study of Maximum Power Point Tracking (MPPT) in Solar Panels

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Abstract: ***In the world of technological advancement, conventional resources of energy (fossil fuels, nuclear fuels, gas etc.) are at the edge of extinct. To overcome this problem, non-conventional energy sources (solar energy, wind energy, ocean thermal energy, biomass or biogas, geothermal, tidal energy etc.) play a vital role, in which solar energy is most important energy source, which produces electricity by the photovoltaic effect. Solar photovoltaic (PV) cells are used to convert solar energy into unregulated electrical energy. These solar PV cells exhibit nonlinear characteristics and give very low efficiency. Therefore, it becomes essential to extract maximum power from solar PV cells using maximum power point tracking (MPPT). The power output from a PV panel depends on a few parameters, such as the irradiation received by the panel, voltage, panel temperature, and so forth. The power output also varies continuously throughout the day as the conditions affecting it change. In recent years, a large number of techniques have been purposed for tracking the maximum power point (MPP). Maximum power point tracking is used in photovoltaic (PV) systems to maximize the photovoltaic array output power, irrespective of the temperature and radiation conditions and of the load electrical characteristics. The PV array is modeled using basic circuit equations. Its voltage-current characteristics are simulated with different conditions. The algorithms utilized for MPPT are generalized algorithms and are easy to model or use as a code. The algorithms are written in m-files of MATLAB.***

Keywords: Photovoltaic System, Maximum Power Point Tracking (MPPT), solar cells, PV Systems, Solar module etc

1. Introduction

Renewable energy is the energy which comes from natural resources such as sunlight, wind, rain, tides and geothermal heat. These resources are renewable and can be naturally replenished. Therefore, for all practical purposes, these resources can be considered to be inexhaustible, unlike dwindling conventional fossil fuels. The global energy crunch has provided a renewed impetus to the growth and development of Clean and Renewable Energy sources. Clean Development Mechanisms (CDMs) are being adopted by organizations all across the globe. Apart from the rapidly decreasing reserves of fossil fuels in the world, another major factor working against fossil fuels is the pollution associated with their combustion. Contrastingly, renewable energy sources are known to be much cleaner and produce energy without the harmful effects of pollution unlike their conventional counterparts.

1.1. Different sources of Renewable Energy

a) Wind power

Wind turbines can be used to harness the energy available in airflows. Current day turbines range from around 600 kW to 5 MW of rated power. Since the power output is a function of the cube of the wind speed, it increases rapidly with an increase in available wind velocity. Recent advancements have led to aerofoil wind turbines, which are more efficient due to a better aerodynamic structure.

b) Solar power

The tapping of solar energy owes its origins to the British astronomer John Herschel who famously used a solar thermal collector box to cook food during an expedition to Africa. Solar energy can be utilized in two major ways. Firstly, the captured heat can be used as solar thermal energy, with applications in space heating. Another alternative is the conversion of incident solar radiation to electrical energy, which is the most usable form of energy. This can be achieved with the help of solar photovoltaic cells or with concentrating solar power plants.

c) Small hydropower

Hydropower installations up to 10MW are considered as small hydropower and counted as renewable energy sources. These involve converting the potential energy of water stored in dams into usable electrical energy through the use of water turbines. Run-of-the-river Hydro-electricity aims to utilize the kinetic energy of water without the need of building reservoirs or dams.

d) Biomass

Plants capture the energy of the sun through the process of photosynthesis. On combustion, these plants release the trapped energy. This way, biomass works as a natural battery to store the sun's energy and yield it on requirement.

e) Geothermal

Geothermal energy is the thermal energy which is generated and stored within the layers of the Earth. The gradient thus developed gives rise to a continuous conduction of heat from the core to the surface of the earth. This gradient can be utilized to heat water to produce superheated steam and use it to run steam turbines to generate electricity. The main disadvantage of geothermal energy is that it is usually limited to regions near tectonic plate boundaries, though recent advancements have led to the propagation of this technology.

1.2. Renewable Energy trends across the globe

The current trend across developed economies tips the scale in favour of Renewable Energy. For the last three years, the continents of North America and Europe have embraced more renewable power capacity as compared to conventional power capacity. Renewable accounted for 60%

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of the newly installed power capacity in Europe in 2009 and nearly 20% of the annual power production.

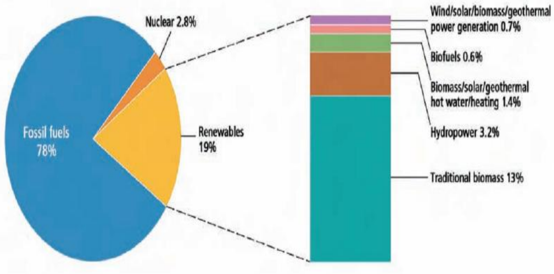

Figure 1: Global energy consumption in the year 2008.

As can be seen from the figure 1 wind and biomass occupy a major share of the current renewable energy consumption. Recent advancements in solar photovoltaic technology and constant incubation of projects in countries like Germany and Spain have brought around tremendous growth in the solar PV market as well, which is projected to surpass other renewable energy sources in the coming years. By 2009, more than 85 countries had some policy target to achieve a predetermined share of their power capacity through renewable. This was an increase from around 45 countries in 2005. Most of the targets are also very ambitious, landing in the range of 30-90% share of national production through renewable. Noteworthy policies are the European Union's target of achieving 20% of total energy through renewable by 2020 and India's Jawaharlal Nehru Solar Mission, through which India plans to produce 20GW solar energy by the year 2022.

2. Photovoltaic System

2.1 Photovoltaic cell

A photovoltaic cell or photoelectric cell is a semiconductor device that converts light to electrical energy by photovoltaic effect. If the energy of photon of light is greater than the band gap then the electron is emitted and the flow of electrons creates current. However a photovoltaic cell is different from a photodiode. In a photodiode light falls on n-channel of the semiconductor junction and gets converted into current or voltage signal but a photovoltaic cell is always forward biased. Figure 2 shows the Working of PV cell.

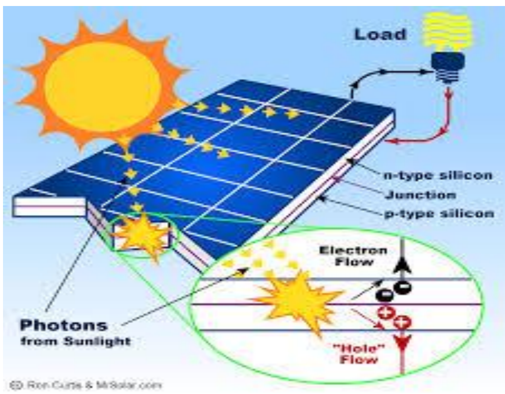

Figure 2: Working of PV cell.

2.2. PV module

Usually a number of PV modules are arranged in series and parallel to meet the energy requirements. PV modules of different sizes are commercially available (generally sized from 60W to 170W). For example, a typical small scale desalination plant requires a few thousand watts of power.

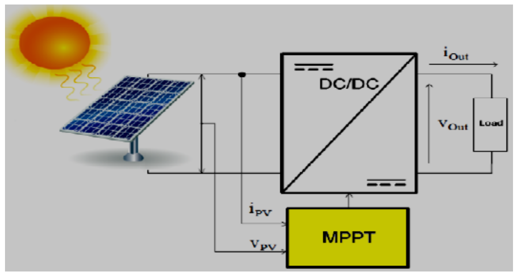

Figure 3: PV module and dc/ dc converter with MPPT.

2.3. PV modeling

A PV array consists of several photovoltaic cells in series and parallel connections. Series connections are responsible for increasing the voltage of the module whereas the parallel connection is responsible for increasing the current in the array. Typically a solar cell can be modeled by a current source and an inverted diode connected in parallel to it. It has its own series and parallel resistance. Series resistance is due to hindrance in the path of flow of electrons from n to p junction and parallel resistance is due to the leakage current.

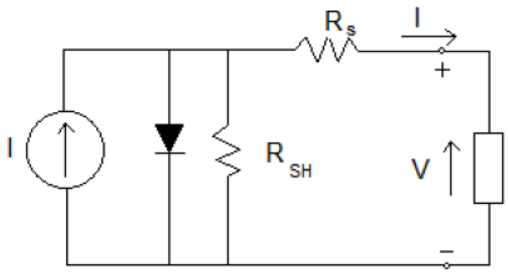

Figure 4: Single diode model of a PV cell

In this model we consider a current source (I) along with a diode and series resistance (R_s). The shunt resistance (R_{SH}) in parallel is very high, has a negligible effect and can be neglected. The output current from the photovoltaic array is

$$I = I_{sc} - I_d \quad (1)$$

$$I = I_o(e^{\frac{qV_d}{kT}} - 1) \quad (2)$$

Where Io is the reverse saturation current of the diode, q is the electron charge, V_d is the voltage across the diode, k is Boltzmann constant and T is the junction temperature in Kelvin (K).

From eq. (1) and (2)

$$I = I_o(e^{\frac{qV_d}{kT}} - 1) \quad (3)$$

Using suitable approximations

$$I = I_{SC} - I_o(e^{\frac{q(V+IR_S)}{nkT}} - 1) \quad (4)$$

Where, I is the photovoltaic cell current, V is the PV cell voltage; T is the temperature (in Kelvin) and n is the diode ideality factor.

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In order to model the solar panel accurately we can use two diode models but in our project our scope of study is limited to the single diode model. Also, the shunt resistance is very high and can be neglected during the course of our study.

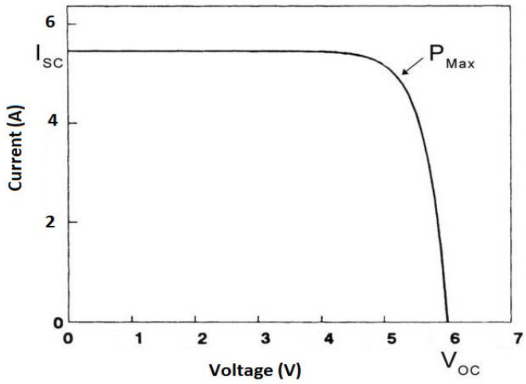

Figure 4: I-V characteristics of a solar panel.

The I-V characteristics of a typical solar cell are as shown in the Figure 4. When the voltage and the current characteristics are multiplied we get the P-V characteristics as shown in Figure 5. The point indicated as MPP is the point at which the panel power output is maximum.

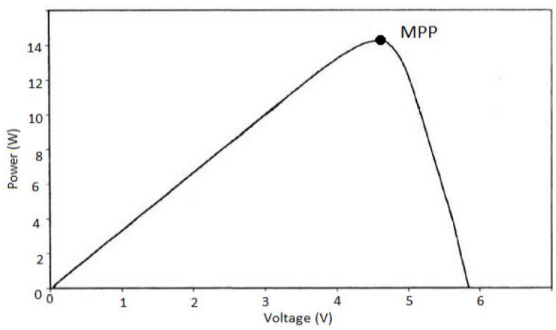

Figure 5: P-V characteristics curve of photovoltaic cell.

2.4. Boost Converter

As stated in the introduction, the maximum power point tracking is basically a load matching problem. In order to change the input resistance of the panel to match the load resistance (by varying the duty cycle), a DC to DC converter is required. It has been studied that the efficiency of the DC to DC converter is maximum for a buck converter, then for a buck-boost converter and minimum for a boost converter but as we intend to use our system either for tying to a grid or for a water pumping system which requires 230 V at the output end, so we use a boost converter.

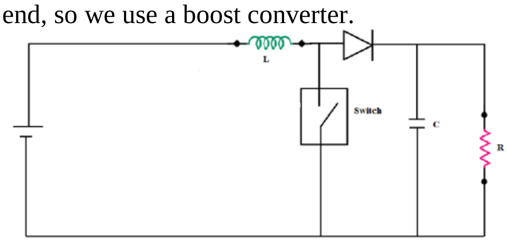

Figure 6: Circuit diagram of a Boost Converter.

2.4.1. Mode 1 operation of the Boost Converter

When the switch is closed the inductor gets charged through the battery and stores the energy. In this mode inductor current rises (exponentially) but for simplicity we assume that the charging and the discharging of the inductor are linear. The diode blocks the current flowing and so the load current remains constant which is being supplied due to the discharging of the capacitor.

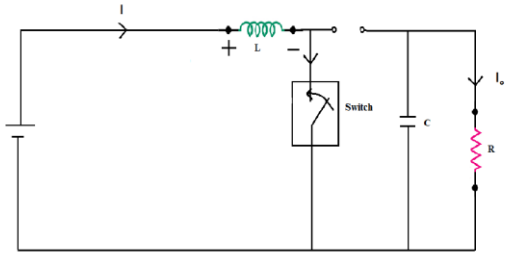

Figure 7: Mode 1 operation of Boost Converter.

2.4.2. Mode 2 operation of the Boost Converter

In mode 2 the switch is open and so the diode becomes short circuited. The energy stored in the inductor gets discharged through opposite polarities which charge the capacitor. The load current remains constant throughout the operation. The waveforms for a boost converter are shown in Figure 9.

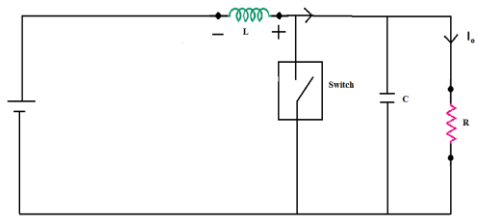

Figure 8: Mode 2 operation of Boost Converter.

3. Maximum Power Point Tracking Algorithms

A typical solar panel converts only 30 to 40 percent of the incident solar irradiation into electrical energy. Maximum power point tracking technique is used to improve the efficiency of the solar panel. According to Maximum Power Transfer theorem, the power output of a circuit is maximum when the Thevenin impedance of the circuit (source impedance) matches with the load impedance.

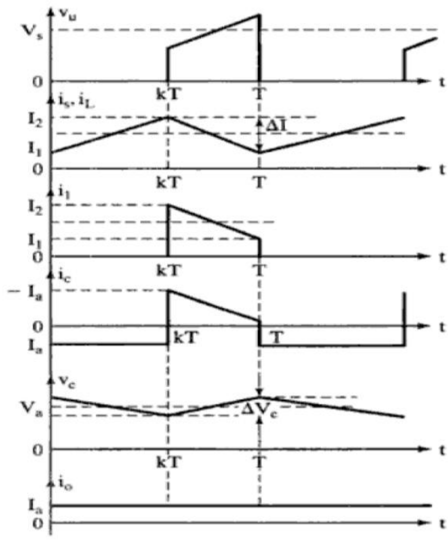

Figure 9: Waveforms for a Boost Converter

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Hence our problem of tracking the maximum power point reduces to an impedance matching problem. In the source side we are using a boost convertor connected to a solar panel in order to enhance the output voltage so that it can be used for different applications like motor load. By changing the duty cycle of the boost converter appropriately we can match the source impedance with that of the load impedance.

3.1. Different MPPT techniques

There are different techniques used to track the maximum power point. Few of the most popular techniques are:
1) Perturb and observe (hill climbing method)
2) Incremental Conductance method
3) Fractional short circuit current
4) Fractional open circuit voltage
5) Neural networks
6) Fuzzy logic

The choice of the algorithm depends on the time complexity the algorithm takes to track the MPP, implementation cost and the ease of implementation.

3.1.1 Perturb & Observe

Perturb & Observe (P&O) is the simplest method. In this we use only one sensor, that is the voltage sensor, to sense the PV array voltage and so the cost of implementation is less and hence easy to implement. The time complexity of this algorithm is very less but on reaching very close to the MPP it doesn't stop at the MPP and keeps on perturbing on both the directions. When this happens the algorithm has reached very close to the MPP and we can set an appropriate error limit or can use a wait function which ends up increasing the time complexity of the algorithm. However the method does not take account of the rapid change of irradiation level (due to which MPPT changes) and considers it as a change in MPP due to perturbation and ends up calculating the wrong MPP. To avoid this problem we can use incremental conductance method.

3.1.2 Incremental Conductance

Incremental conductance method uses two voltage and current sensors to sense the output voltage and current of the PV array.
At MPP the slope of the PV curve is 0.

$$\left(\frac{dP}{dV}\right)_{MPP} = \frac{d(VI)}{dV} \quad (5)$$

$$0 = I + V\left(\frac{dI}{dV}\right)_{MPP} \quad (6)$$

$$\left(\frac{dI}{dV}\right)_{MPP} = -\frac{I}{V} \quad (7)$$

The left hand side is the instantaneous conductance of the solar panel. When this instantaneous conductance equals the conductance of the solar then MPP is reached.

Here we are sensing both the voltage and current simultaneously. Hence the error due to change in irradiance is eliminated. However the complexity and the cost of implementation increase. As we go down the list of algorithms the complexity and the cost of implementation goes on increasing which may be suitable for a highly complicated system. This is the reason that Perturb and Observe and Incremental Conductance method are the most widely used algorithms. Owing to its simplicity of implementation we have chosen the Perturb & Observe algorithm for our study among the two.

3.1.3 Fractional open circuit voltage

The near linear relationship between V_{MPP} and V_{oc} of the PV array, under varying irradiance and temperature levels, has given rise to the fractional V_{oc} method.

$$V_{MPP} = k_1 V_{oc} \quad (8)$$

Where k_1 is a constant of proportionality; Since k_1 is dependent on the characteristics of the PV array being used, it usually has to be computed beforehand by empirically determining V_{MPP} and V_{oc} for the specific PV array at different irradiance and temperature levels. The factor k_1 has been reported to be between 0.71 and 0.78. Once k_1 is known, V_{MPP} can be computed with V_{oc} measured periodically by momentarily shutting down the power converter. However, this incurs some disadvantages, including temporary loss of power.

3.1.4 Fractional short circuit current

Fractional I_{SC} results from the fact that, under varying atmospheric conditions, I_{MPP} is approximately linearly related to the I_{SC} of the PV array.

$$I_{MPP} = k_2 I_{sc} \quad (9)$$

Where k_2 is a proportionality constant. Just like in the fractional V_{oc} technique, k_2 has to be determined according to the PV array in use. The constant k_2 is generally found to be between 0.78 and 0.92. Measuring I_{sc} during operation is problematic. An additional switch usually has to be added to the power converter to periodically short the PV array so that I_{sc} can be measured using a current sensor.

3.1.5 Fuzzy Logic Control

Microcontrollers have made using fuzzy logic control popular for MPPT over last decade. Fuzzy logic controllers have the advantages of working with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity.

3.1.6 Neural Network

Another technique of implementing MPPT which are also well adapted for microcontrollers is neural networks. Neural networks commonly have three layers: input, hidden, and output layers. The number nodes in each layer vary and are user-dependent. The input variables can be PV array parameters like V_{oc} and I_{sc}, atmospheric data like irradiance and temperature, or any combination of these. The output is usually one or several reference signals like a duty cycle signal used to drive the power converter to operate at or close to the MPP.

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Table 1: Characteristics of different MPPT techniques

MPPT Technique	Convergence speed	Implementation complexity	Periodic tuning	Sensed parameters
Perturb & observe	Varies	Low	No	Voltage
Incremental conductance	Varies	Medium	No	Voltage, current
Fractional V_{oc}	Medium	Low	Yes	Voltage
Fractional I_{sc}	Medium	Medium	Yes	Current
Fuzzy logic control	Fast	High	Yes	Varies
Neural network	Fast	High	Yes	Varies

3.2 Perturb & Observe Algorithm

The Perturb & Observe algorithm states that when the operating voltage of the PV panel is perturbed by a small increment, if the resulting change in power ΔP is positive, then we are going in the direction of MPP and we keep on perturbing in the same direction. If ΔP is negative, we are going away from the direction of MPP and the sign of perturbation supplied has to be changed.

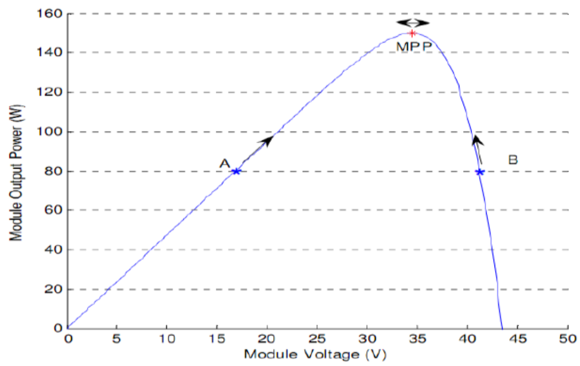

Figure 10: Solar panel characteristics showing MPP & operating points A and B.

Figure 10 shows the plot of module output power versus module voltage for a solar panel at a given irradiation. The point marked as MPP is the Maximum Power Point, the theoretical maximum output obtainable from the PV panel, consider A and B as two operating points. As shown in the figure above, the point A is on the left hand side of the MPP. Therefore, we can move towards the MPP by providing a positive perturbation to the voltage. On the other hand, point B is on the right hand side of the MPP. When we give a positive perturbation, the value of ΔP becomes negative, thus it is imperative to change the direction of perturbation to achieve MPP. The flowchart for the P&O algorithm is shown in Figure 11.

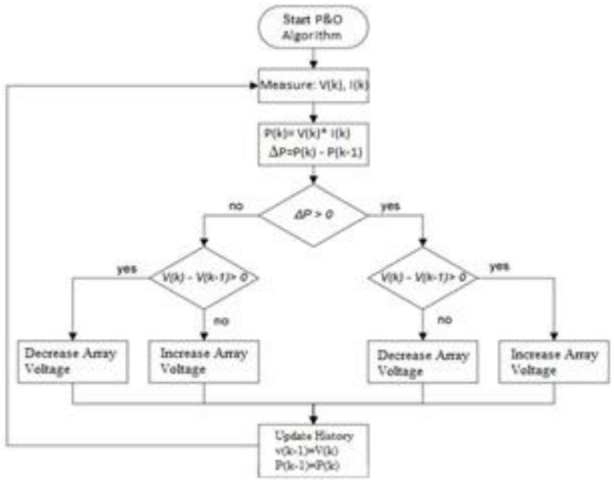

Figure 11: Flowchart of Perturb & Observe algorithm.

3.3 Limitations of Perturb & Observe algorithm

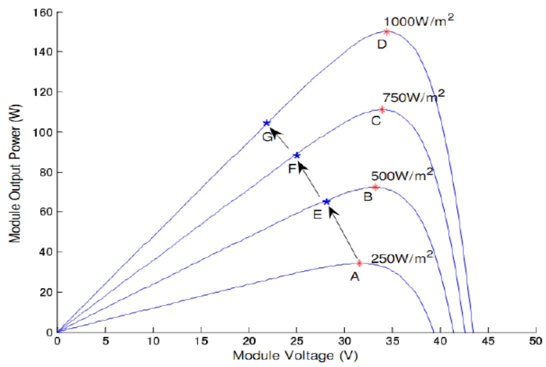

Figure 12: Curve showing wrong tracking of MPP by P&O algorithm under rapidly varying irradiance.

In a situation where the irradiance changes rapidly, the MPP also moves on the right hand side of the curve. The algorithm takes it as a change due to perturbation and in the next iteration it changes the direction of perturbation and hence goes away from the MPP as shown in the figure. However, in this algorithm we use only one sensor, that is the voltage sensor, to sense the PV array voltage and so the cost of implementation is less and hence easy to implement. The time complexity of this algorithm is very less but on reaching very close to the MPP it doesn't stop at the MPP and keeps on perturbing in both the directions. When this happens the algorithm has reached very close to the MPP and we can set an appropriate error limit or can use a wait function which ends up increasing the time complexity of the algorithm.

3.4 Implementation of MPPT using a boost converter

The system uses a boost converter to obtain more practical uses out of the solar panel. The initially low voltage output is stepped up to a higher level using the boost converter, though the use of the converter does tend to introduce switching losses. The block diagram shown in Figure 13 gives an overview of the required implementation.

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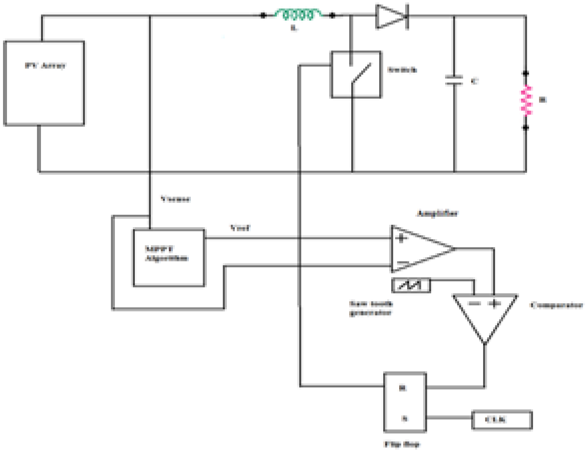

Figure 13: Requisite implementation for MPPT system.

4. Modeling of standalone PV system

4.1. Solar panel

The entire system has been modeled on MATLAB™ 2009a and Simulink™. The block diagram of the solar PV panel is shown in Figure 14 and Figure 15. The inputs to the solar PV panel are temperature, solar irradiation, number of solar cells in series and number of rows of solar cells in parallel.

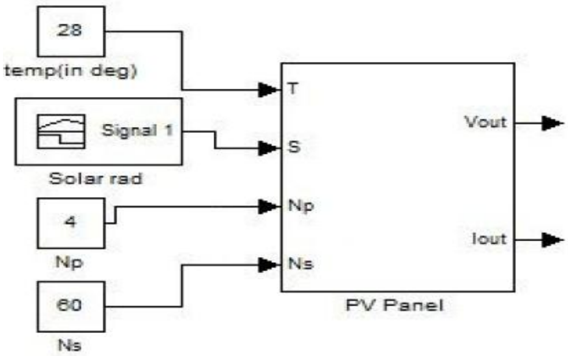

Figure 14: Masked block diagram of the modeled solar PV panel

The simulation is carried out for a cell surface temperature of 28° C, 60 solar cells in series and 4 rows of solar cells in parallel. The irradiation (shown in Figure 16) is taken to be varying, to reflect real life conditions and effectively show the use of an MPPT algorithm in field runs. It varies from 60 Watt per sq. cm. to 85 Watt per sq. cm, which is close to the day values of solar radiation received on the earth's surface. The simulation is run for a total of 0.12 seconds, with the irradiation taking up a new value every 0.03 seconds and staying constant for the consequent 0.03 seconds.

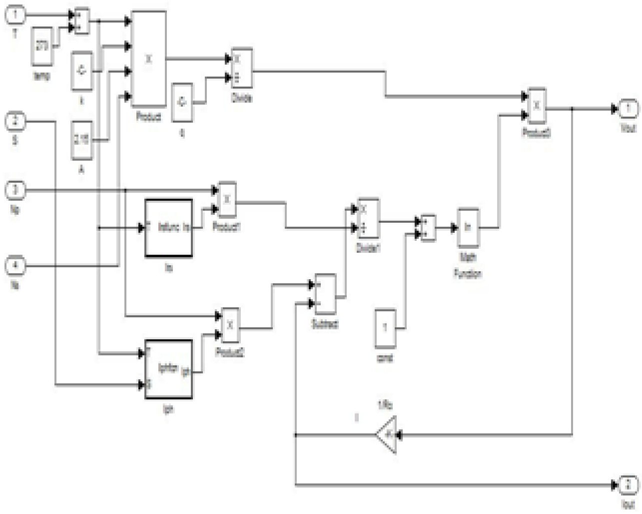

Figure15: Unmasked block diagram of the modeled solar PV panel.

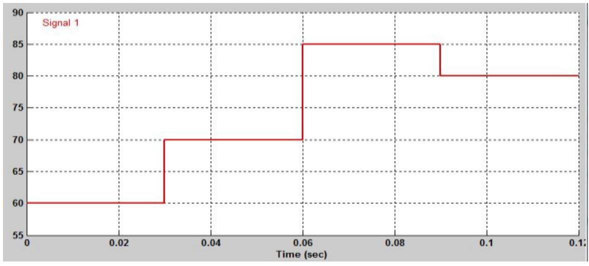

Figure 16: Irradiation signal (Watt per sq. cm. versus time).

4.2. MPPT Interfacing

The controlled voltage source and the current source inverter have been used to interface the modeled panel with the rest of the system and the boost converter which are built using the Sim-Power Systems module of MATLAB. The block diagram for the model shown in Fig. 17 is a simulation for the case where we obtain a varying voltage output. This model is used to highlight the difference between the power obtained on using an MPPT algorithm and the power obtained without using an MPPT algorithm. To compare the power output in both the cases stated above, the model is equipped with a manual switch as shown. When the switch is thrown to the left the circuit bypasses the MPPT algorithm and we obtain the desired power, voltage and current outputs through the respective scopes. Contrarily when the switch is thrown to the right, the embedded MPPT function block is included in the circuit and we obtain the desired outputs through the respective scopes.

4.3. Boost Converter

A boost converter has been used in our simulation. It finds applications in various real life scenarios like charging of battery bank, running of DC motors, solar water pumping etc. The simulation has been done for a resistive load of 300Ω. For efficient running of a motor, we should undergo load resistance matching techniques. In the boost converter circuit, the inductor has been chosen to be 0.763 mH and the capacitance is taken to be 0.611 μF for a ripple free current.

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PI Controller

The system also employs a PI controller. The task of the MPPT algorithm is just to calculate the reference voltage V_{ref} towards which the PV operating voltage should move next for obtaining maximum power output. This process is repeated periodically with a slower rate of around 1-10 samples per second. The external control loop is the PI controller, which controls the input voltage of the converter. The pulse width modulation is carried in the PWM block at a considerably faster switching frequency of 100 KHz. In our simulation, K_P is taken to be 0.006 and K_I is taken to be 7. A relatively high K_I value ensures that the system stabilizes at a faster rate. The PI controller works towards minimizing the error between V_{ref} and the measured voltage by varying the duty cycle through the switch. The switch is physically realized by using a MOSFET with the gate voltage controlled by the duty cycle. Table 2 shows the different parameters taken during the simulation of the model.

Table 2: Different parameters of the standalone PV system

Parameters	Value taken for simulation
Solar Module Temperature **(T)**	28°C
No of solar cells in series **(N_s)**	60
No of rows of solar cells in parallel **(N_p)**	4
Resistance of load **(R)**	300 Ω
Capacitance of boost converter **(C)**	0.611 μF
Inductance of boost converter **(L)**	0.763 mH
Switching frequency of PWM	100 KHz
Proportional gain of PI controller **(K_P)**	0.006
Integral gain of PI controller **(K_I)**	7

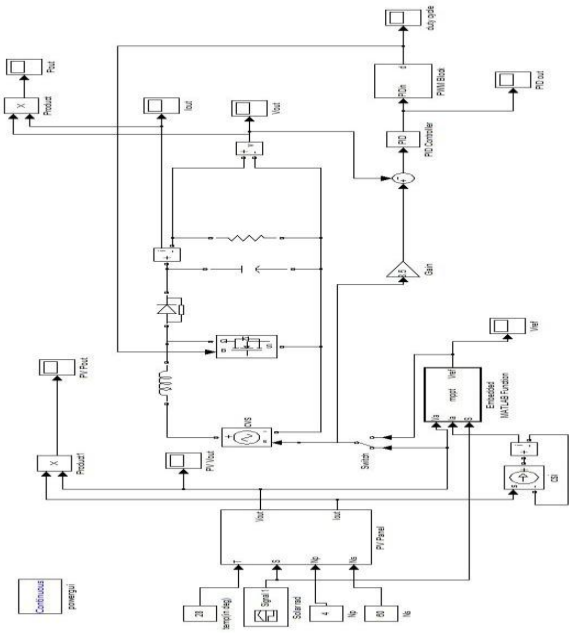

Figure 17: SIMULINK™ Model of MPPT system using P&O algorithm

5. Results

Case 1: Running the system without MPPT

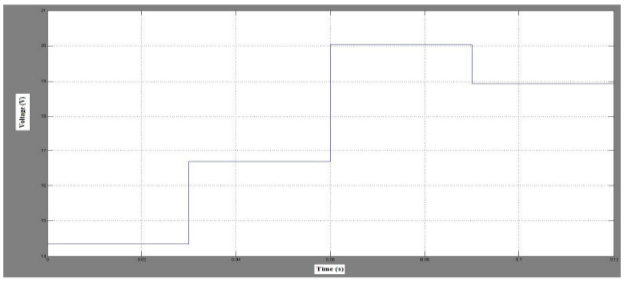

Figure 5.1: Plot of Output voltage of PV panel v/s time without MPPT.

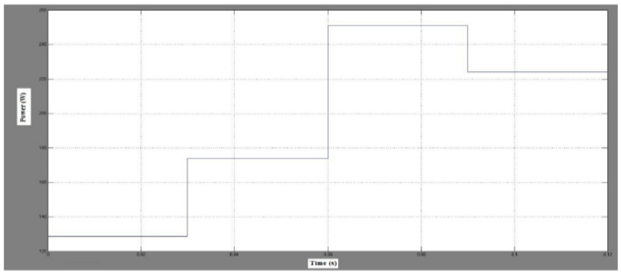

Figure 5.2: Plot of Power output of PV panel v/s time without MPPT.

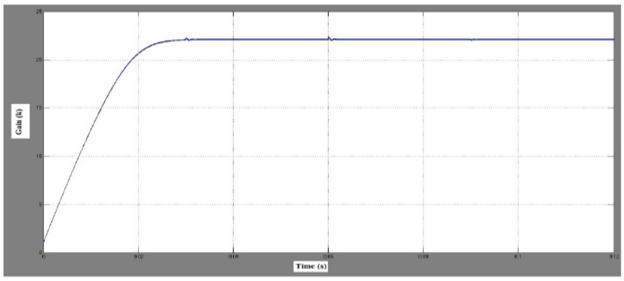

Figure 5.3: Plot of PI Control gain v/s time without MPPT.

Case 2: Running the system with MPPT

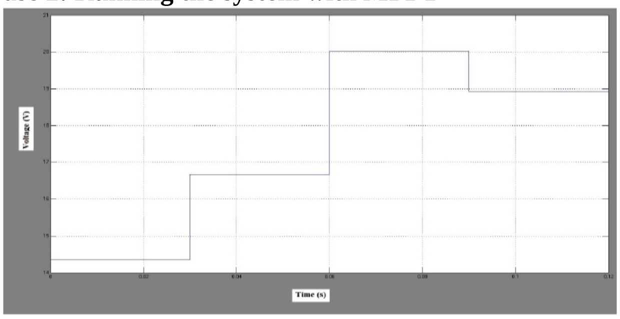

Figure 5.4: Plot of Output voltage of PV panel v/s time with MPPT

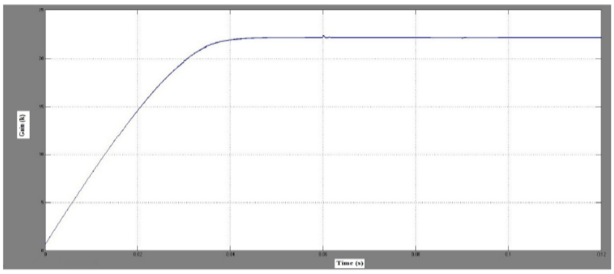

Figure 5.5: Plot of PI Control gain v/s time with MPPT.

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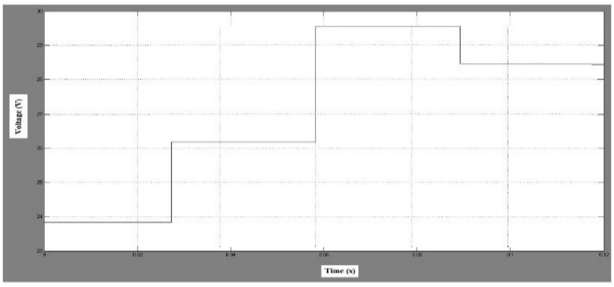

Figure 5.6: Plot of calculated MPPT V_{ref} voltage v/s time with MPPT.

6. Conclusion

In the Present Work, the maximum power point tracking is successfully carried out by using perturb and observe method. The PV module working on photovoltaic effect actually improves the system efficiency. Compared to other methods of maximum power point tracking, the perturbed & observe method seems to be easy for the optimization of the photovoltaic system using boost converter. The Performance has been studied by the MATLAB. In future, the maximum power point tracking could be carried out without the use of controllers in order to reduce the cost and complications of hardware can be removed.

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