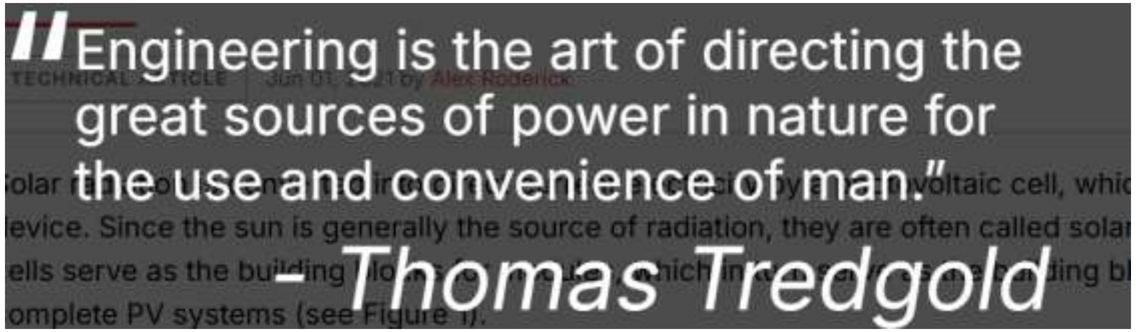
POWER ELECTRONIC APPLICATIONS TO RENEWABLE ENERGY SYSTEMS

PRESENTED BY

M NATARAJ
Assistant Professor in
Electrical and Electronics Engineering Department
NRCM Engineering College
Dhulapally, Secunderabad

SOLAR CELLS AND THEIR MEASUREMENT

UNIT 1



- Solar cell characteristics and their measurement,
- PV Module,
- PV array,
- Partial shading of a solar cell and a module, the diode,
- Power conditioning unit,
- maximum power point tracker,
  - Implementation of Perturb and Observe Method,
  - Incremental Conductance Method,
- Battery charger/discharge controller.

Solar cell characteristics and their measurement,

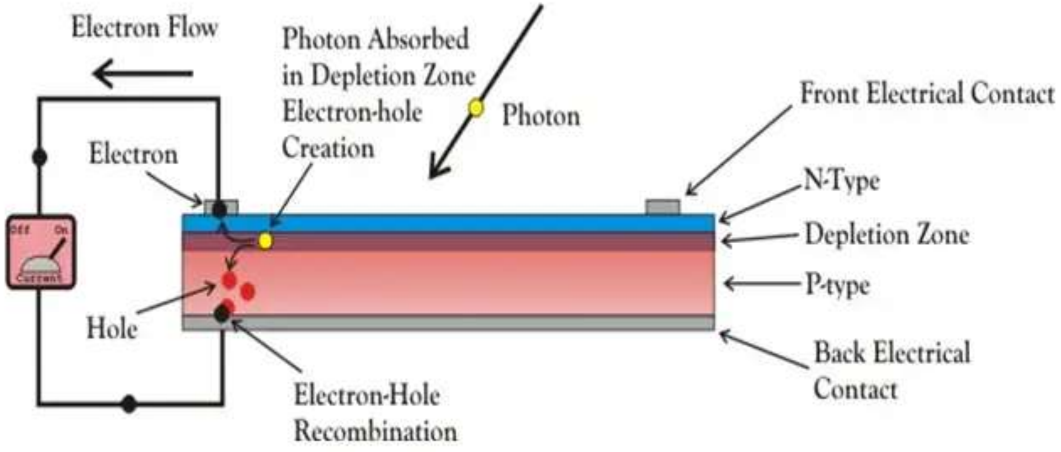
- Solar cells, also known as photovoltaic cells, convert sunlight into electricity.
- Key characteristics include
  - open-circuit voltage (Voc),
  - short-circuit current (Isc),
  - fill factor, and efficiency.
- These are measured using various techniques,
  - including I-V curve measurements.

What is a Solar Cell?

- A **solar cell** (also known as a photovoltaic cell or PV cell) is defined as an electrical device that converts light energy into electrical energy through the photovoltaic effect.
- A solar cell is basically a p-n junction diode.
- Solar cells are a form of photoelectric cell, defined as a device whose electrical characteristics – such as current, voltage, or resistance – vary when exposed to light.
- Individual solar cells can be combined to form modules commonly known as solar panels.
- The common single junction silicon solar cell can produce a **maximum open-circuit voltage** of approximately **0.5 to 0.6 volts**.
- By itself this isn't much – but remember these solar cells are tiny.
- When combined into a large solar panel, considerable amounts of renewable energy can be generated.

Construction of Solar Cell

- A solar cell functions similarly to a junction diode, but its construction differs slightly from typical p-n junction diodes.
- A very thin layer of p-type semiconductor is grown on a relatively thicker n-type semiconductor.
- We then apply a few finer electrodes on the top of the p-type semiconductor layer.
- These electrodes do not obstruct light to reach the thin p-type layer. Just below the p-type layer there is a p-n junction.
- We also provide a current collecting electrode at the bottom of the n-type layer.
- We encapsulate the entire assembly by thin glass to protect the **solar cell** from any mechanical shock



- **<u>Characteristics of Solar Cells:</u>**
- **Open-Circuit Voltage (Voc):**
  - The voltage across the cell when no current is flowing, indicating the maximum potential voltage the cell can produce.
- **Short-Circuit Current (Isc):**
  - The current flowing through the cell when the terminals are short-circuited, indicating the maximum current the cell can produce.
- **Fill Factor:**
  - A measure of the cell's efficiency, representing the ratio of the maximum power point (Pmax) to the product of Voc and Isc.
- **Efficiency:**
  - The percentage of solar energy converted into electrical energy.
- **Maximum Power Point (Pmax):**
  - The point on the I-V curve where the solar cell produces the most power, determined by the current (Imp) and voltage (Vmp) at that point.
- **<u>Measuring Solar Cell Characteristics:</u>**
- **I-V Curve Measurement:**
  - A series of voltages are applied to the solar cell while under illumination, and the corresponding current is measured at each voltage step, creating an I-V curve. This curve reveals key parameters like Voc, Isc, Pmax, Imp, and Vmp.
- **Solar Simulator:**
  - Devices that mimic sunlight conditions to accurately measure solar cell performance under standardized conditions (e.g., 1000 W/m² irradiance).
- **Measurement Validation:**
  - Ensuring the accuracy and reliability of measurements through established standards and calibration procedures.
- **Spectral Characteristics:**
  - Studying the cell's response to different wavelengths of light.
- **Temperature Dependence**
  - : Investigating how temperature affects the cell's performance.

- **Solar Cell Definition**: A solar cell (also known as a photovoltaic cell) is defined as a device that converts light energy into electrical energy using the photovoltaic effect.
- **Working Principle**: Solar cells generate electricity when light creates electron-hole pairs, leading to a flow of current.
- **Short Circuit Current**: This is the highest current a solar cell can provide under optimal conditions without being damaged.
- **Open Circuit Voltage**: The voltage across the solar cell’s terminals when there is no load connected, typically around 0.5 to 0.6 volts.
- **Efficiency**: The efficiency of a solar cell is the ratio of its maximum electrical power output to the input solar radiation power, indicating how well it converts light to electricity.

- Solar cell is the basic unit of solar energy generation system where electrical energy is extracted directly from light energy without any intermediate process.
- The working of a solar cell solely depends upon its photovoltaic effect hence a solar cell also known as photovoltaic cell.
- A solar cell is basically a semiconductor device.
- The solar cell produce electricity while light strikes on it and the voltage or potential difference established across the terminals of the cell is fixed to 0.5 volt and it is nearly independent of intensity of incident light
- whereas the current capacity of cell is nearly proportional to the intensity of incident light as well as the area that exposed to the light.
- Each of the solar cells has one positive and one negative terminal like all other type of battery cells.
- a solar or photovoltaic cell has negative front contact and positive back contact.
- A semiconductor p-n junction is in the middle of these two contacts.

- While sunlight falling on the cell some photons of the light are absorbed by solar cell.
- Some of the absorbed photons will have energy greater than the energy gap between valence band and conduction band in the semiconductor crystal.
- Hence, one valence electron gets energy from one photon and becomes excited and jumps out from the bond and creates one electron-hole pair.
- These electrons and holes of e-h pairs are called light-generated electrons and holes.
- The light-generated electrons near the p-n junction are migrated to n-type side of the junction due to electrostatic force of the field across the junction.
- Similarly the light-generated holes created near the junction are migrated to p-type side of the junction due to same electrostatic force.
- In this way a potential difference is established between two sides of the cell and if these two sides are connected by an external circuit current will start flowing from positive to negative terminal of the solar cell. This was basic working principle of a solar cell (https://www.humix.com/video/lBrAJeal472)
- different parameters of a solar or photovoltaic cell upon which the rating of a solar panel depends?
- During choosing a particular solar cell for specific project it is essential to know the ratings of a solar panel.
- These parameters tell us how efficiently a solar cell can convert the light to electricity.

Short Circuit Current of Solar Cell

- This is the maximum current a solar cell can deliver without damaging itself.
- It is measured by short-circuiting the cell's terminals under optimal conditions.
- These conditions include the intensity of light and the angle of light incidence.
- Since current production also depends on the exposed surface area, it is better to express this as maximum current density, which is the ratio of short circuit current to the cell's exposed surface area.

$$J_{sc} = \frac{I_{sc}}{A}$$

- Where,

  I_{sc} is short circuit current,

  J_{sc} maximum current density and

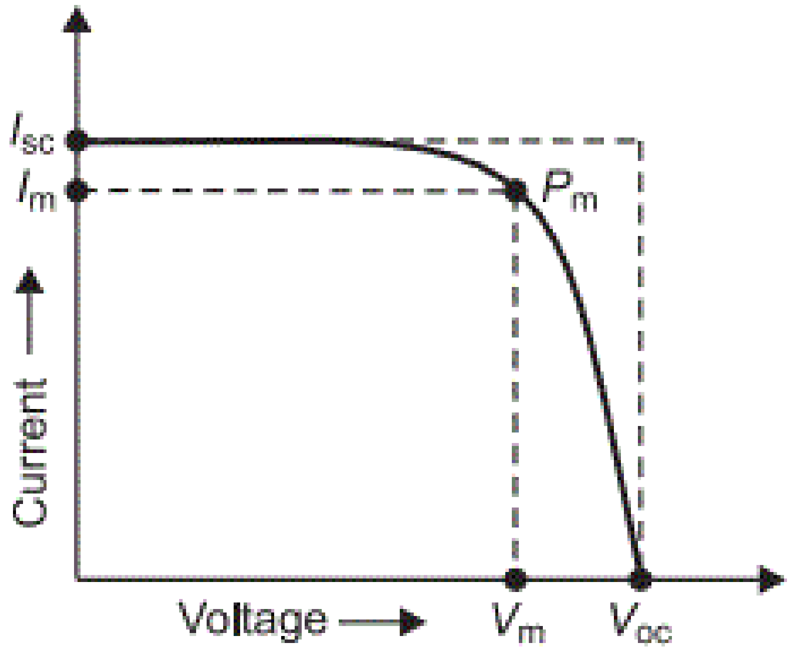
  A is the area of solar cell.

Open Circuit Voltage of Solar Cell

- This is the voltage measured across the cell's terminals when no load is connected.
- It depends on manufacturing techniques and temperature, but not significantly on light intensity or exposed surface area.
- The open circuit voltage of a solar cell is typically around 0.5 to 0.6 volts, denoted as V_{oc}.

Maximum Power Point of Solar Cell

- The maximum electrical power one solar cell can deliver at its standard test condition.
- If we draw the v-i characteristics of a solar cell maximum power will occur at the bend point of the characteristic curve. It is shown in the v-i characteristics of solar cell by Pm.
- characteristics curve of solar cell



- **Current at Maximum Power Point**

The current at which maximum power occurs. Current at Maximum Power Point is shown in the v-i characteristics of solar cell by $I_{m.}$

- **Voltage at Maximum Power Point**

The voltage at which maximum power occurs. Voltage at Maximum Power Point is shown in the v-i characteristics of solar cell by $V_{m.}$

- **Fill Factor of Solar Cell**

The ratio between product of current and voltage at maximum power point to the product of short circuit current and open circuit voltage of the solar cell.

$$Fill\ Factor = \frac{P_m}{I_{sc} \times V_{oc}}$$

- **Efficiency of Solar Cell**

This is defined as the ratio of the maximum electrical power output to the input radiation power, expressed as a percentage. On Earth, the radiation power is about 1000 watts per square meter. If the cell's exposed surface area is A, the total radiation power on the cell will be 1000 A watts. Hence the efficiency of a solar cell may be expressed as

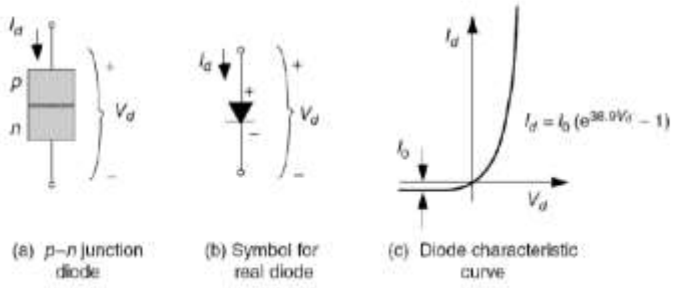
$$Efficiency(\eta) = \frac{P_m}{P_{in}} \approx \frac{P_m}{1000A}$$

- **Materials Used in Solar Cell**
  - Materials used in solar cells must possess a band gap close to 1.5 ev to optimize light absorption and electrical efficiency. Commonly used materials are-
  - Silicon.
  - GaAs.
  - CdTe.
  - $CuInSe_2$
- **Criteria for Materials to be Used in Solar Cell**
  - Must have band gap from 1ev to 1.8ev.
  - It must have high optical absorption.
  - It must have high electrical conductivity.
  - The raw material must be available in abundance and the cost of the material must be low.

- **Advantages of Solar Cell**
  - No pollution associated with it.
  - It must last for a long time.
  - No maintenance cost.
- **Disadvantages of Solar Cell**
  - It has high cost of installation.
  - It has low efficiency.
  - During cloudy day, the energy cannot be produced and also at night we will not get solar energy.
- **Uses of Solar Generation Systems**
  - It may be used to charge batteries.
  - Used in light meters.
  - It is used to power calculators and wrist watches.
  - It can be used in spacecraft to provide electrical energy.
- https://www.alternative-energy-tutorials.com/photovoltaics/solar-cell-i-v-characteristic.html

Solar Cell I-V Characteristics:

- **The p–n Junction Diode:** Understanding the I-V characteristics of a Solar cell is very important and for that it is desirable to quickly recapitulate the I-V characteristics of a simple P-N junction diode given in the figure below.
- If we apply a voltage V_d across the diode terminals with polarity as shown, a forward current would flow through the diode from the p-side to the n-side.
- But if we try to send current in the reverse direction, only a very small (≈10−12 A/cm2) reverse saturation current I_0 will flow.
- This reverse saturation current is the result of thermally generated carriers with the holes being swept into the p-side and the electrons into the n-side.
- In the forward direction, the voltage drop across the diode is only a few tenths of a volt.



The voltage - current characteristic curve for the p–n junction diode is given by the following Shockley diode equation:

$$I_d = I_0(e^{qV_d/kT} - 1)$$

where I_d is the diode current in the direction of the arrow (A),
V_d is the voltage across the diode terminals from the p-side to the n-side (V),
I_0 is the reverssaturation current (A),
q is the electron charge (1.602 × 10−19C),
k is Boltzmann's constant (1.381 × 10−23 J/K), and
T is the junction temperature (K).

- Substituting the above constants into the exponent of equation above for Id gives

$$\frac{qV_d}{kT} = \frac{1.602 \times 10^{-19}}{1.381 \times 10^{-23}} \cdot \frac{V_d}{T(\mathrm{K})} = 11,600\frac{V_d}{T(\mathrm{K})}$$

- A junction temperature of 25^0 C is often used as a standard, which when substituted in the Shockley diode equation gives the following diode current $I_{d.}$

$$I_d = I_0(e^{38.9V_d} - 1) \qquad (\text{at } 25^\circ\mathrm{C})$$

Example-1: A *p* –*n* Junction Diode. Consider a *p*–*n* junction diode at 25◦C with a reverse saturation current of 10^{-9} A. Find the voltage drop across the diode when it is carrying the following currents:

a) No current (open-circuit voltage) b) 1 A c) 10 A

- Solution: a) In the open-circuit condition, Id = 0, so from equation for Id we get Vd = 0.

b) With I_d = 1 A, we can find V_d by rearranging the equation for 'I_d' :

$$I_d = I_0(e^{38.9V_d} - 1) \qquad \text{(at } 25^{\circ}\text{C)}$$

$$\Rightarrow \qquad e^{38.9V_d} = \left(\frac{I_d}{I_0} + 1\right)$$

Taking natural logarithms (to the base 'e') on both side and then dividing both sides by 38.9 we get

$$V_d = \frac{1}{38.9}\ln\left(\frac{I_d}{I_0} + 1\right) = \frac{1}{38.9}\ln\left(\frac{1}{10^{-9}} + 1\right) = 0.532 \text{ V}$$

c) with Id = 10 A

$$V_d = \frac{1}{38.9}\ln\left(\frac{10}{10^{-9}} + 1\right) = 0.592 \text{ V}$$

- As can be seen, the voltage drop changes very little as the diode conducts more and more current, changing by only about 0.06 V as the current increased by a factor of 10. Often in normal electronic circuit analysis, the diode voltage drop when it is conducting rated current is about 0.6 V, which is quite in line with the above results

A Simple Equivalent Circuit of a Photovoltaic Cell:

- To derive the I-V characteristics of a Solar cell a simple equivalent circuit depicting all its characteristics is developed.
- It consists of a real PN Junction diode in parallel with an ideal current source as shown in the figure below.
- The ideal current source delivers current proportional to the solar 'Insolation'(solar radtion that reaches earth) to which it is exposed.

There are two important conditions for the actual Solar cell in its equivalent circuit as shown in the figure below (Figure -3).

They are:

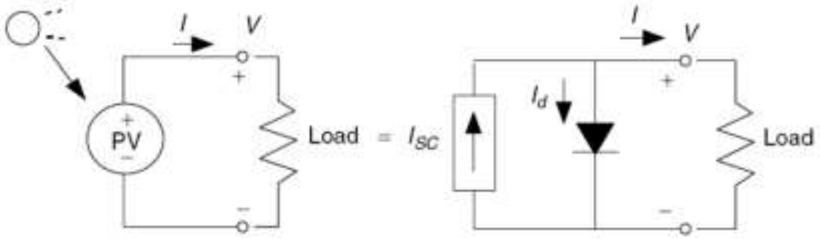
(a)The current that flows when the terminals are **shorted together** (the short circuit current, ISC). When the leads of the equivalent circuit for the PV cell are shorted together, no current flows in the (real) diode since Vd = 0.

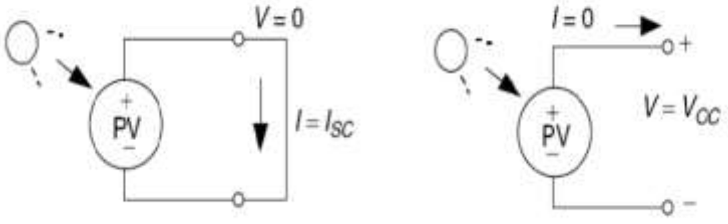
That means Id =0 and all the current from the ideal source I_{SC} flows through the shorted leads.

Since that short-circuit current is I_{SC}, the magnitude (maximum value) of the ideal current source itself is equal to I_{SC}.

(b) The voltage across the terminals when the leads are **left open (the open-circuit voltage, V_{OC}).**

Since output terminals are open no current flows in the load i.e. I =0



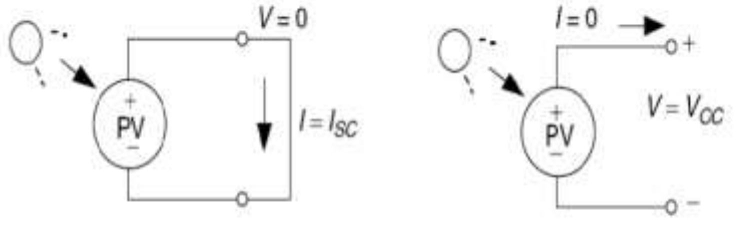


(a) Short-circuit current (b) Open-circuit voltage

- Now we can write a voltage and current equation for the equivalent circuit of the PV cell shown in figure (b) starting with and then substituting the value of Id as per the Shockley equation into the above equation for I we get :
- it is interesting to note that the second term in the above equation is just the diode equation with a negative sign.
- That means that a plot of the above equation is just I_{SC} added to the diode characteristic (in the first quadrant) turned upside down.
- Figure shows the current–voltage relationship for a PV cell when it is dark (no illumination) and light (with illumination) based on the above equation.
- When the leads from the PV cell are left open, I = 0 and we can solve the above equation (8.8) for the open-circuit voltage VOC :
- And at 25^0 C,

$$I = I_{SC} - I_0(e^{38.9\ V} - 1)$$

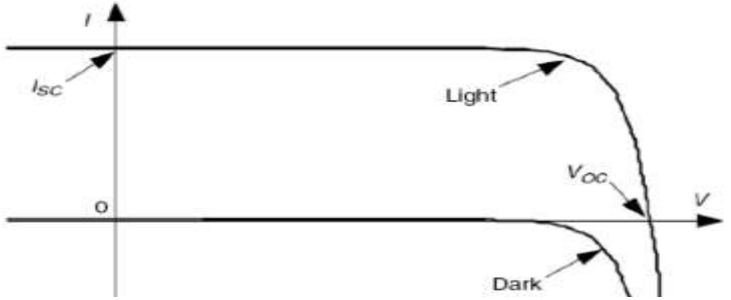
$$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right)$$



(a) Short-circuit current (b) Open-circuit voltage

$$I = I_{SC} - I_d$$

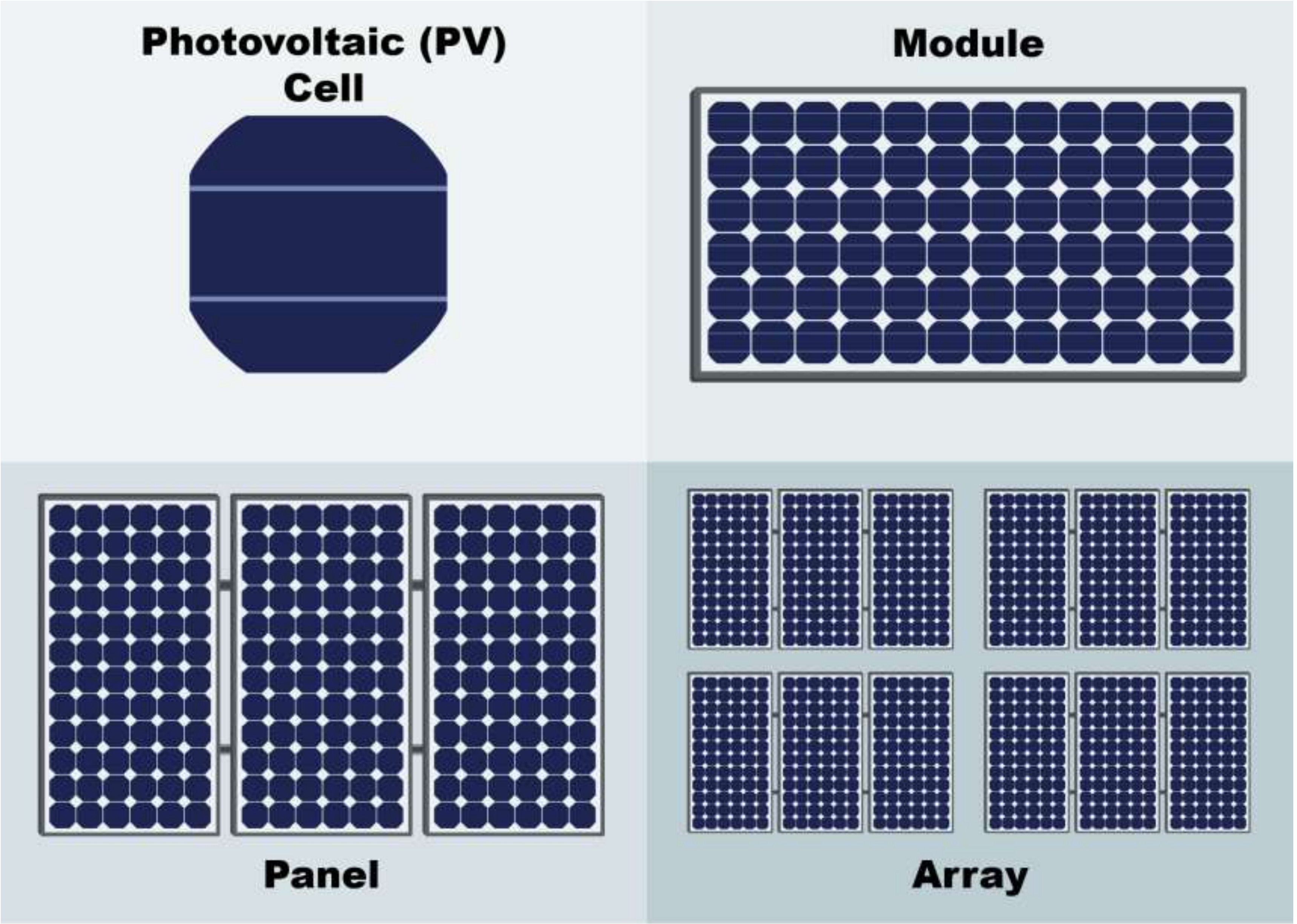
$$I = I_{SC} - I_0\left(e^{qV/kT} - 1\right)$$



$$V_{OC} = \frac{kT}{q} \ln\left(\frac{I_{SC}}{I_0} + 1\right)$$

PV Modules and Arrays:

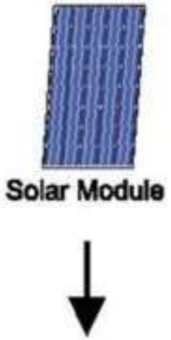
- **PV Modules:**
- An individual cell produces about one watt of power at about 0.5 V and they are of no practical use.
- Typically, it is a few square inches in size.
- Hence the basic building block for PV applications is a module consisting of a number of pre-wired cells in series, all encased in tough, weather-resistant packages in an area of several square feet. Such an encased panel is called a **Solar Module.**
- Most solar PV panels have 30 to 36 cells connected in series.
- Each cell produces about 0.5 V in sunlight, so a panel produces 15V to 18 V. These panels are designed to charge 12-V batteries.
- A 30-cell panel (15 V) can be used to charge the battery without a controller, but it may fail to charge the battery completely.


Photovoltaic (PV) Cell
Module
Panel
Array

THE PV SYSTEM

Photovoltaic Cell (Solar Cell)

- Sunlight hits solar cell and excites electrons
- Excited cells jump back and forth creating electricity
- Typical PV cell produces 1 or 2 watts of power (0.5 volts)

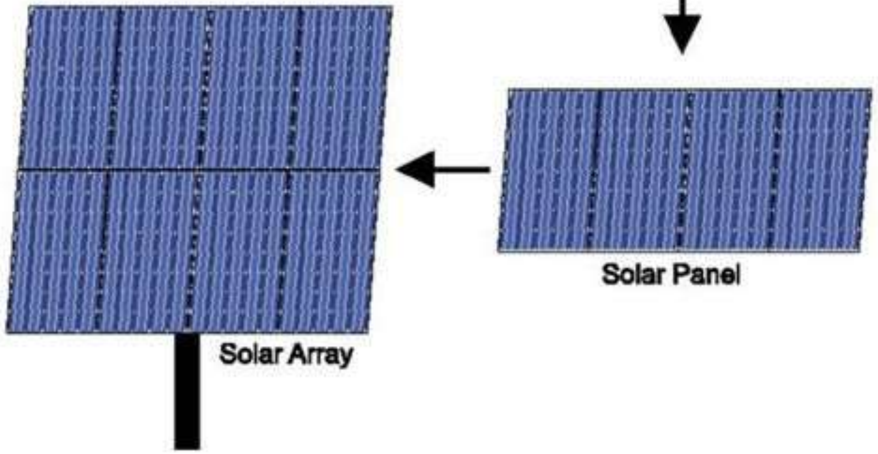


Solar Module

- To boost the power output of the single PV cells, individual PV cells are wired together to form modules
- Individual cells are placed into a protective frame and covered with glass
- EX. Solar/PV Modules:
  48 cells is approximately 175 watts
  60 cells is approximately 225 watts

Solar Array

- Multiple solar panels wired in parallel to increase voltage

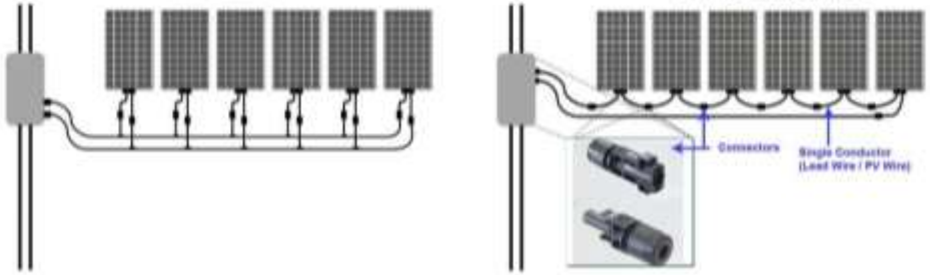


Solar Panel

- Modules connected to form larger units called panels

WIRING METHOD

There are two wiring methods used when designing a PV system. The methods are determined by the application, original equipment manufacture (OEM) and end users



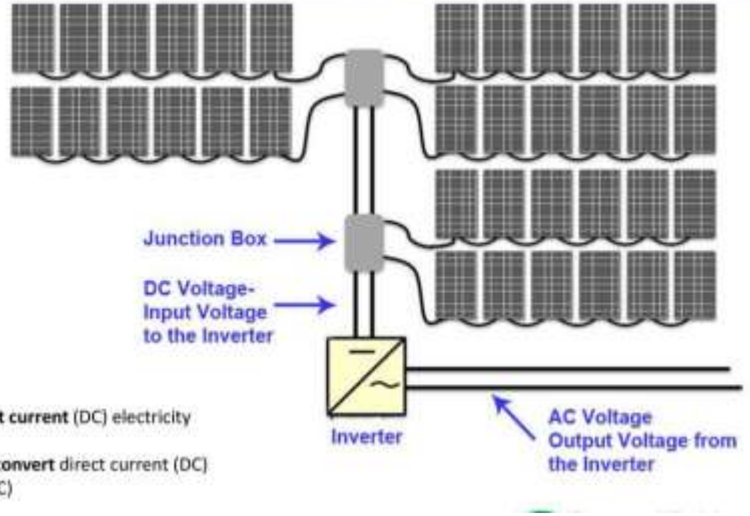
Combining PV Modules

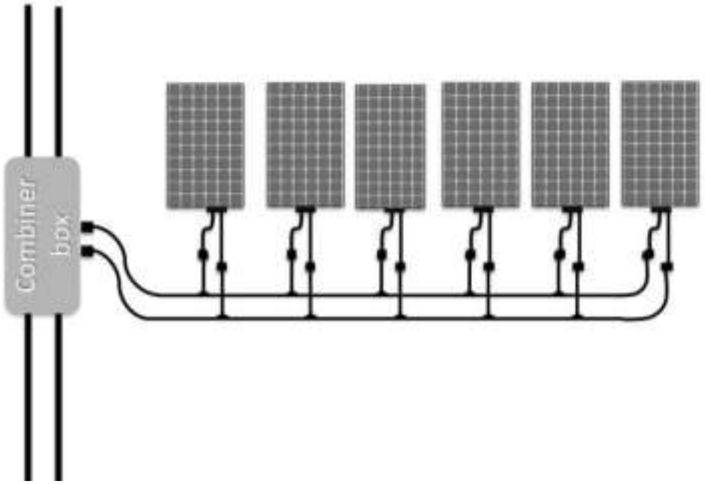
PV Modules can be wired in combination of series and parallel circuits to increase the voltage and current capacity required

Advantage of using a higher output voltage at the PV modules = smaller wires can be used to transfer electrical power

PV modules produce **direct current** (DC) electricity

Inverters main function = **convert** direct current (DC) into alternating current (AC)



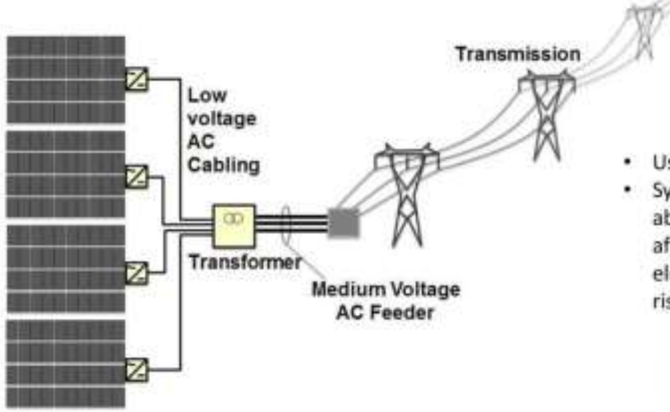


Combiner Box

Instead of having one inverter for the entire array, a combiner box could be installed on every few panels

The use of combiner boxes close to the PV modules allows for improved efficiency

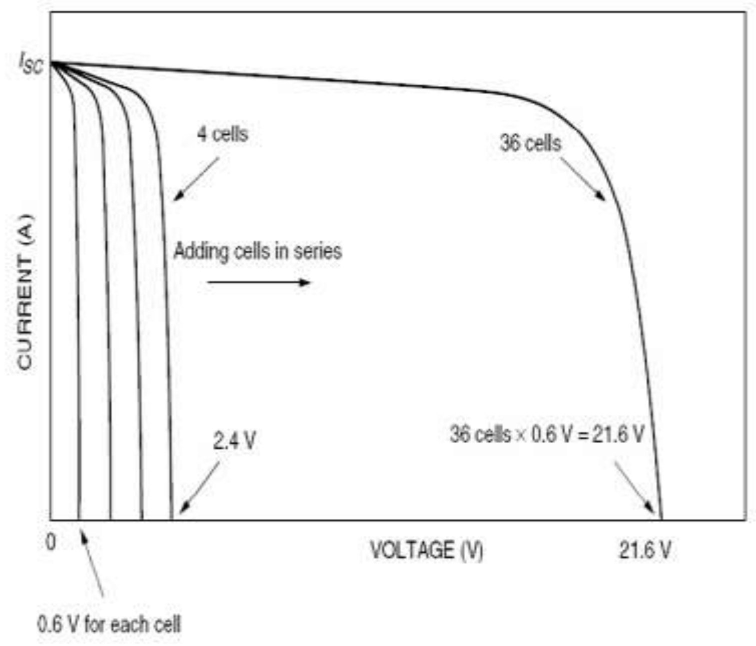
SOLAR POWER GENERATION



- Used by Utilities
- Systems offer businesses ability to generate affordable, clean electricity to stave off rising cost

General Cable

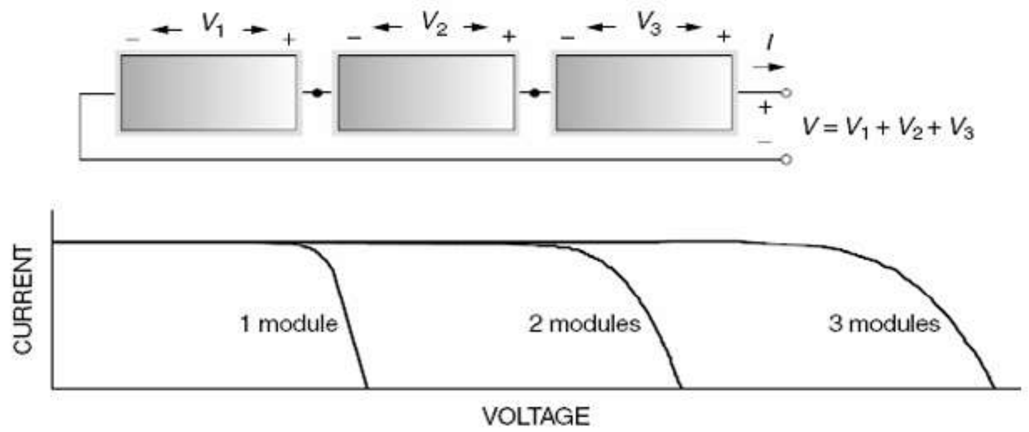
- A 36-cell panel (18 V) will do better, but needs a controller to prevent overcharging.
- The current depends on the size of each cell, and the solar radiation intensity.
- Most cells produce a current of 2 A to 3 A in bright sunlight.
- The current is the same in every cell because the cells are connected in series.
- For cells wired in series, their voltages at any given current add. A typical module will have 36 cells.



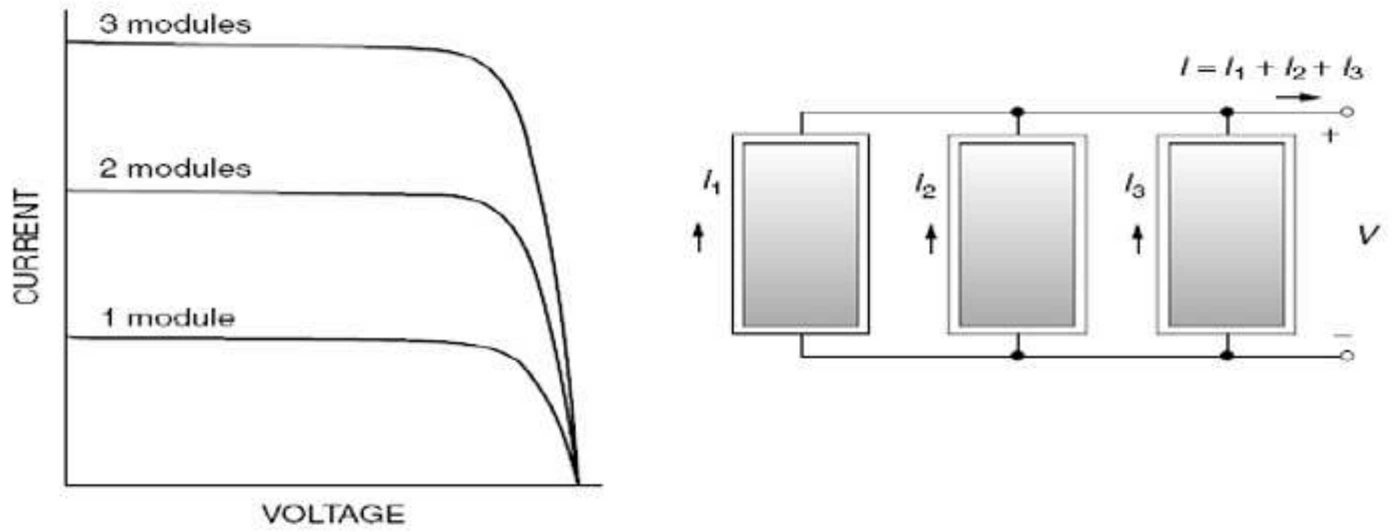
-11: For cells wired in series, their voltages at any given current add. A typical module will have 36 cells.

Arrays:

- Multiple modules, in turn, can be wired in series to increase voltage and in parallel to increase current, the product of which is power.



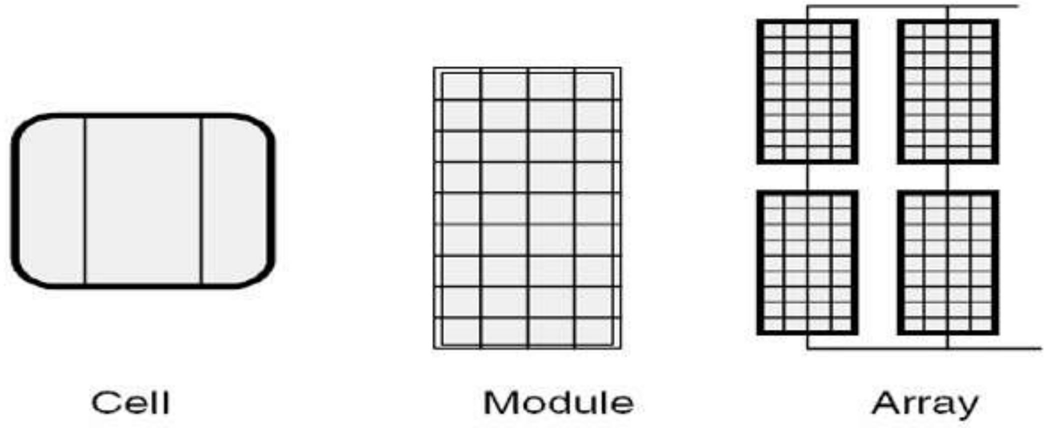
Modules in series, at any given current the voltages add



An important aspect in PV system design is deciding how many modules should be connected in series and how many in parallel to deliver the required energy.
Such combinations of modules are referred to as an **array.**

Modules in parallel, at any given voltage the currents add.

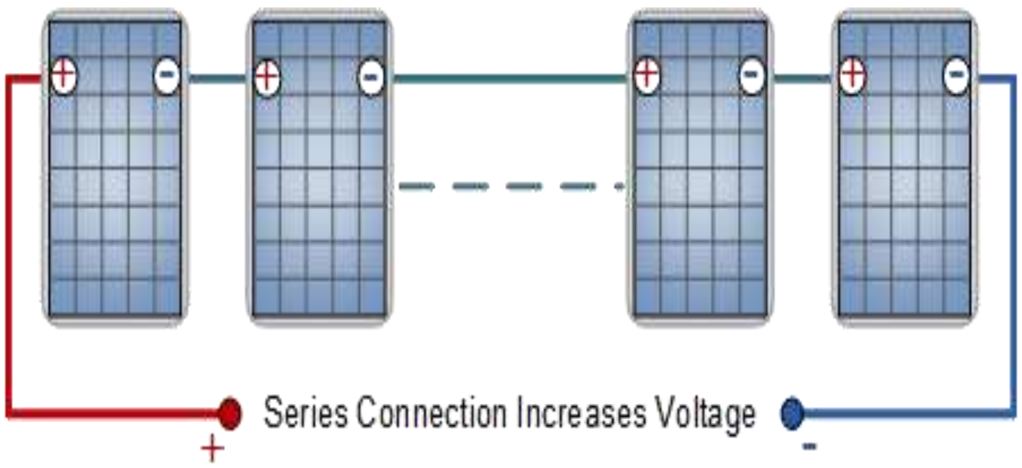
- A single **solar cell** does not produce enough power (voltage and current) to operate the load and, therefore, many cells are connected together to make a **PV module.**
- The PV modules are available in wattage rating of 3 Wp to 300 Wp.
- A PV module is characterized by several parameters including *I*sc, *V*oc, *I*m, *V*m, *W*p, (*P*max or *P*m), FF and η.
- The main parameter useful for the practical applications are *I*m, *V*m and *P*m.
- While showing a large number of modules, a representative symbol of module is used.
- Many times, in practice, we need power in large quantity, like in several hundred watts, kW and in MW. In order to have a large power generations (larger than a single PV module can produce), these solar PV modules are connected in **series and/or parallel combinations**
- **When many PV modules are connected in series, a single row of series connected PV modules is referred as PV module string.**



- In order to increase the current in PV system, the PV individual PV modules or PV module strings are connected in parallel.
- Such series and parallel combination of PV modules is referred as '**solar PV array**'**.**
- in both series and parallel combination of PV modules, the power of the PV modules always gets added.

- Photovoltaic solar panels are semiconductor devices that covert sunlight (irradiance) into electrical DC energy but it is the PV panels individual *solar cells* which are responsible for converting the sunlight into electricity.
- However, **the power output** from any type of **PV panel** is very much dependent upon the **intensity of the sunlight falling on its surface as well as its orientation, operating temperature and the connected load.**
- Solar cells are made of specially treated silicon material and designed to absorb as much sunlight as possible.
- Solar PV cells are interconnected electrically in series and parallel connections within a panel (module) to produce the desired output voltage and/or current values for that panel.
- Typically, solar PV panels consist of 36, or 60, or 72 interconnected solar cells.
- Most silicon solar cells produce about 0.5 to 0.6 volts DC, which is the main characteristic of a pn-junction, when there is no external load connected. If there is no-load connected, or a very low current demand, a photovoltaic cell generates its maximum output voltage, commonly called its open-circuit voltage, V_{OC}.
- As the load current demand from the cell increases, brighter sunlight (given in watts per metre squared, W/m^2) is required to produce the full output voltage. However, there is a maximum limit to the amount of current a solar cell can generate no matter how bright and intense the irradiance of the light.
- While individual solar cells can be interconnected together within a single PV panel, solar photovoltaic panels can themselves be connected together in series and/or parallel combinations to form an array increasing the total available power output for a particular solar application compared to a single panel.

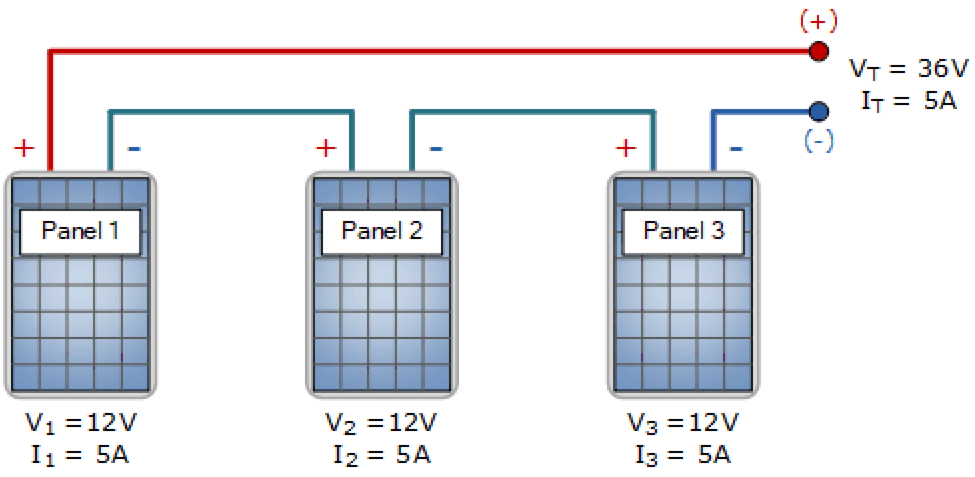
Series Connected Solar Panels



- All photovoltaic solar panels produce an output voltage when exposed to sunlight and we can increase the voltage output of the panels by connecting them in series.
- That is connecting solar panels in series increases the voltage of the system, so two panels connected in series will produce double the voltage as compared to just one panel but while the voltages add up, the amperage of each panel stays the same, that is currents in series do not add up.
- When solar photovoltaic panels are wired electrically in series, the negative (-) terminal of the first panel is connected to the positive (+) terminal of the next (second) panel, and the negative (-) of the second panel is connected to the positive (+) of the third panel, and so on until all the panels are connected together.

- Series connected solar panels are called a **string**, thus the use of the word "string" means that the panels are connected in series. Note that series strings of PV panels can be connected in parallel to increase the total current and therefore more power output

Series Connected Solar Panels of the Same Type



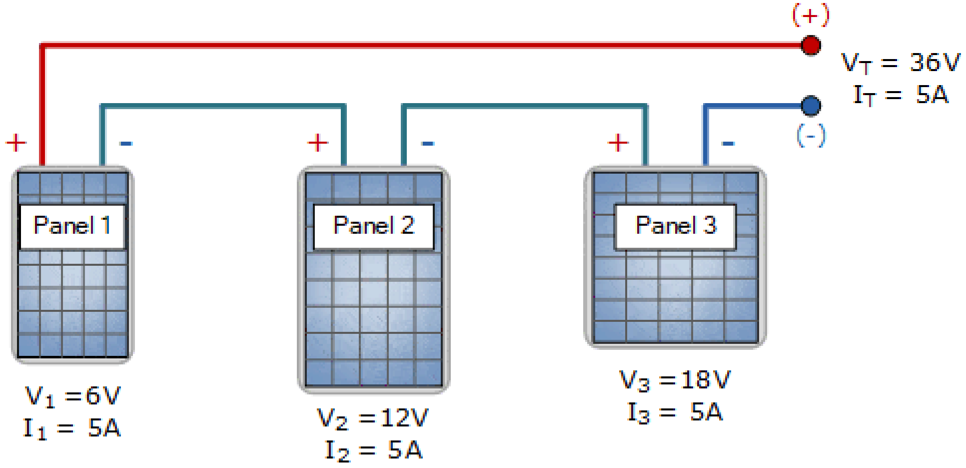
$$V_T = V_{(series)} = V_1 + V_2 + V_3 = 12 + 12 + 12 = 36\,\text{Volts}$$

$$I_T = I_{(series)} = I_1 = I_2 = I_3 = 5\,\text{Amperes}$$

Here ALL the solar PV panels are of the same type and power rating.
The total voltage output becomes the sum of the voltage output of each panel but the series string current is equal to the panel currents as shown.
Using the same three 12 volt, 5.0 ampere pv panels as shown above, we can see that when they are clearly connected together in a series string, the combined string produces a total of 36 volts (12 + 12 + 12) at 5.0 amps, giving total string wattage of 180 watts (volts x amps), compared to the 60 watts of one single panel.

Thus, if the series string consisted of "n" number of solar pv panels with exactly the same characteristics, then the series string voltage would be **V1 times "n" (V*n)** volts with the output current being **equal to I1**.
Thus the total power output of the string will be equal to V*I*n watts. .

Series Connected Solar Panels of Different Voltages

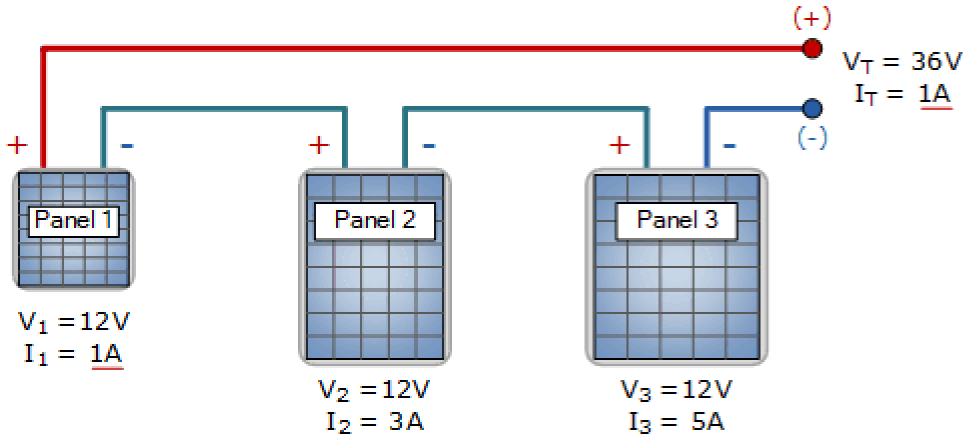


$$V_T = V_{(series)} = V_1 + V_2 + V_3 = 6 + 12 + 18 = 36\,\text{Volts}$$

$$I_T = I_{(series)} = I_1 = I_2 = I_3 = 5\,\text{Amperes}$$

in this method all the solar panels are of different types and therefore power rating but have a common current rating.
When the panels are connected together in series, the voltages still add the same as before so the string produces 36 volts DC at 5.0 amps, producing 180 watts.
Again the output voltage will depend on the number of connected panels but the string amperage remains the same at 5.0 amperes.

series Connected Solar Panels of Different Currents



So the total expected wattage from the three PV panels comes to 108 watts, but the power available to the connected load is only 36 (36 volts times 1 ampere) watts clearly reducing the strings actual wattage to about 33% of maximum, thereby wasting money on the purchase of the higher wattage solar panels.

Connecting solar panels in series with different current ratings should only be used provisionally, because as we have seen, the solar pv panel with the lowest rated current is the one which determines the current output of the whole array.

In this method all the solar panels are of different current rating but have the same nominal voltage.

The individual panel voltages will still add together as before, but this time the amperage will be limited to the value of the lowest panel in the series string, in this case 1 ampere.

Then the series string will produce 36 volts at 1.0 amp only.

Then no matter the actual maximum power rating of the connected panels, it will be the pv panel with the lowest current rating that decides the total power output of the series string.

For example, our three panels above have individual power ratings of:

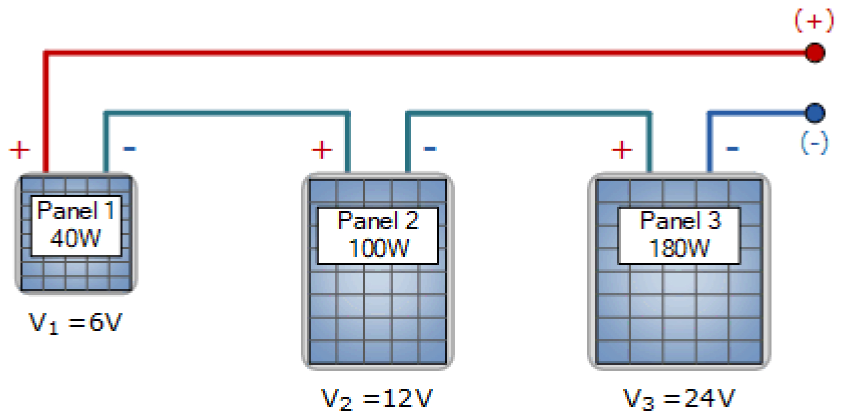
$$P_1 = V_1 \times I_1 = 12 \times 1 = 12 \text{ Watts}$$

$$P_2 = V_2 \times I_2 = 12 \times 3 = 36 \text{ Watts}$$

$$P_3 = V_3 \times I_3 = 12 \times 5 = 60 \text{ Watts}$$

$$P_T = P_1 + P_2 + P_3 = 12 + 36 + 60 = 108 \text{ Watts}$$

Solar Panels in Series of Different Wattage's



$$P = V \times I, \quad \therefore I = \frac{P}{V}$$

$$I_1 = \frac{P_1}{V_1} = \frac{40}{6} = 6.67 \text{ Amperes}$$

$$I_2 = \frac{P_2}{V_2} = \frac{100}{12} = 8.33 \text{ Amperes}$$

$$I_3 = \frac{P_3}{V_3} = \frac{180}{24} = 7.50 \text{ Amperes}$$

Here let us assume we have three solar pv panels of 40 watts, 100 watts, and 180 watts each connected together in a series string.

You may assume that the total wattage, P_T will be 320 watts (40 + 100 + 180), but this would not be the case.

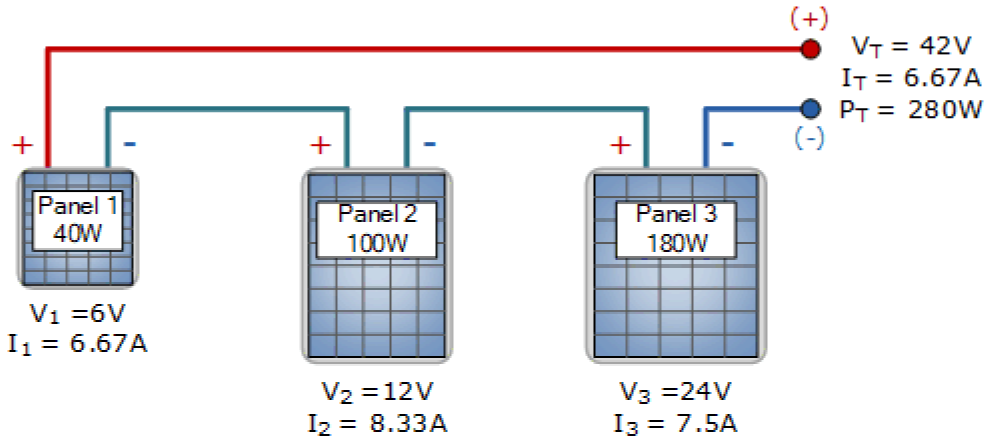
As we know the nominal voltage rating of each panel, we can use Ohms Law to determine the current strength of each panel and find the true output power rating of the series string.

As we have seen previously that the voltages add together so the total output voltage, V_T will be 42 volts (6 + 12 + 24).

However, the output current is limited by the panel with the lowest current output, which is panel No1 at 6.67 amperes.

Then the series string will produce a maximum output power of only 280 watts (42 x 6.67), which is 12.5% lower than the expected 320 watts, thus the pv array is only operating at 87.5% efficiency at full sun

Final Series String Connection



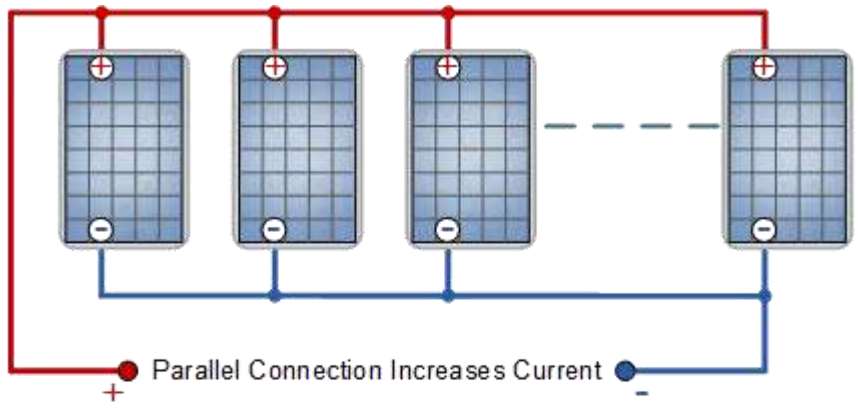
Parallel Connected Solar Panels:

The DC current output of a solar panel, (or cell) depends greatly on its surface area, efficiency, and the amount of irradiance (sunlight) falling onto its surface.
, photovoltaic solar panels are semiconductor devices that covert sunlight into electrical DC energy.
Connecting PV panels together in parallel increases current and therefore power output, as electrical power in watts equals “volts times amperes” (P = V x I).
Note that photovoltaic panels DO NOT produce or generate alternating current, (AC) that you find in your homes. That is, *alternating current solar panels* dos not exist.

- Photovoltaic cells produce their power output at about 0.5 to 0.6 volts DC, with current being directly proportional to the cell's area and irradiance.
- But it is the resistance of the connected load which ultimately determines the amount of amperage supplied by a panel, or pv cell.
- We measure electric current in amperes, commonly called "amps". Amps is the measurement of current that is effectively the rate of electrical charge flowing past a fixed point within a circuit.
- Thus, the more charge flowing past a point the greater the value of the current.
- Irradiance is the amount of solar radiation received at a given area on earth ,so as the current demand from a cell increases, brighter sunlight (given in watts per metre squared, W/m^2) is required to produce the full output power, but there is a maximum limit to the amount of current a solar cell can generate no matter how bright and intense the irradiance of the sunlight.
- ,

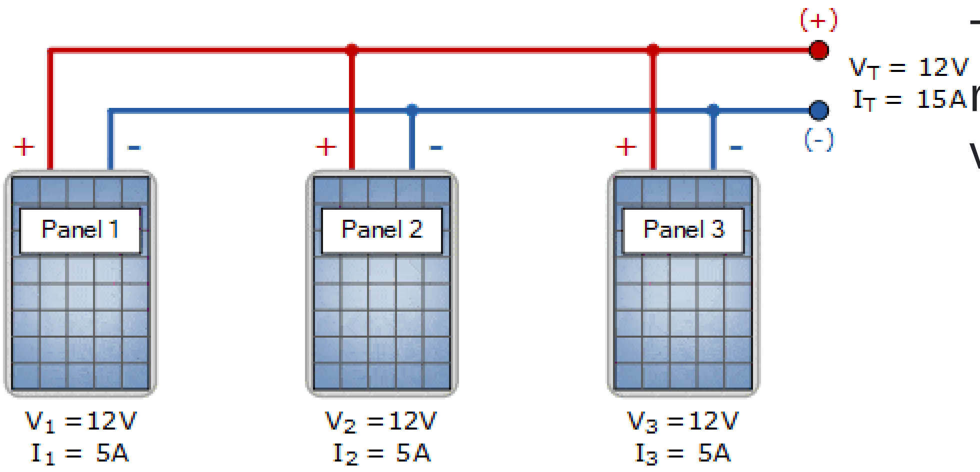
- While individual solar cells can be interconnected together within a single PV panel, solar photovoltaic panels can themselves be connected together in parallel strings to form an array of interconnected panels increasing the total available power output for a particular solar application compared to a single panel.
- If there is no-load connected to a solar panel's terminals, then the panel will generate no current as there is no electrical circuit for it to flow around.
- But if the terminals are shorted together, the current demand is very high so the photovoltaic panel generates its maximum output current, commonly **called its short-circuit current, I_{SC} from the available light.**
- When connecting solar panels together **in parallel, the total voltage output remains the same** as it would for a single panel, but **the output current becomes the sum of the amperage of each panel**.
- Thus **the effect of parallel wiring is that the voltage stays the same while the amperage adds up.**

Parallel Connected Solar Panels



- Photovoltaic solar panels generate a current when exposed to sunlight (irradiance) and we can increase the current output of an array by connecting the PV panels in parallel.
- That is connecting solar panels in parallel increases the available current of the system, so two identical panels connected in parallel will produce double the current as compared to just one single panel.
- But while the currents add up, the panel voltage stays the same.
- **When PV panels are wired electrically in parallel, the positive (+) terminals of all the panels are connected together (positive to positive), and all the negative (-) terminals are connected together (negative to negative).**
- When all the PV panels are wired together in parallel, you should be left with **one single positive terminal, or wire, and one single negative terminal**, or wire to attach to your regulator and batteries.
- Note that series strings of PV panels can also be connected in parallel (multi-strings) to increase current and therefore power output.

Parallel Connected Solar Panels of the Same Type



all the solar PV panels are of the same type and power rating. The total current output becomes the sum of the current rating of each individual panel but the parallel connected voltage is equal to the panel voltage as shown.

$$I_T = I_{(parallel)} = I_1 + I_2 + I_3 = 5 + 5 + 5 = 15\ \text{Amperes}$$

$$V_T = V_{(parallel)} = V_1 = V_2 = V_3 = 12\ \text{Volts}$$

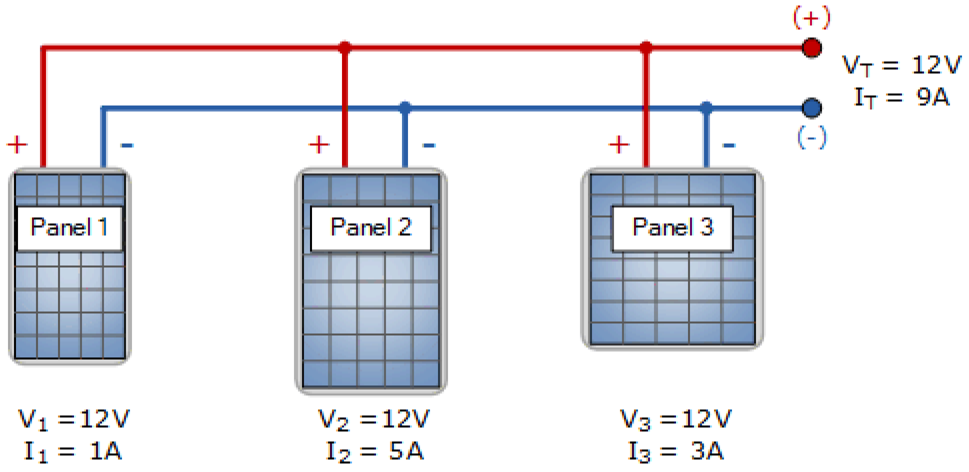
Using the same three 12 volt, 5.0 ampere pv panels from above, we can see that they are connected together in a parallel.

The combined connection produces a total of 15 amperes (5 + 5 + 5) at 12 volts DC, giving combined wattage of 180 watts (volts x amps), compared to the 60 watts of just one single panel.

So if the array consisted of “n” number of solar pv panels with exactly the same electrical characteristics, then the total current output would be **I_1 times “n” (I*n) amperes** with the output voltage being equal to V_1. Thus the total power output of the combination will be **equal to V*I*n watts.**

Parallel Connected Solar Panels of Different Currents

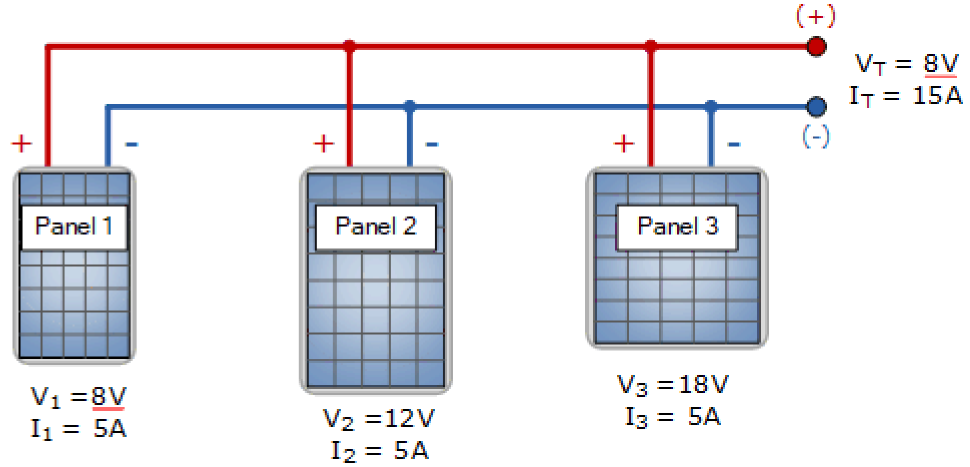
- in this method all the solar panels are of different types and therefore power rating but have a common voltage rating. That is the same nominal voltage is available from all the panels.
- We have seen previously that for parallel connected panels their currents add together, so no real problem there, just as long as the panel voltages are the same and the output voltage remains constant.
- This parallel combination produces 12 volts DC at 9.0 amperes, generating a maximum of 108 watts.
- Again the total output current, I_T will be the sum of the individual panels which will depend on the number of connected panels.
- As before the output voltage remains the same at 12 volts.



$$I_T = I_{(parallel)} = I_1 + I_2 + I_3 = 1 + 5 + 3 = 9\,\text{Amperes}$$

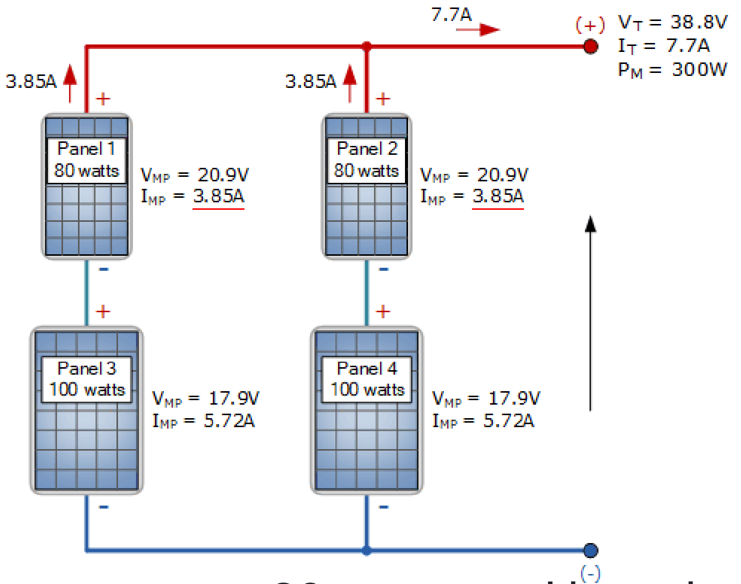
$$V_T = V_{(parallel)} = V_1 = V_2 = V_3 = 12\,\text{Volts}$$

Solar Panels in Parallel of Different Voltages



- Here all the solar panels are of different voltage ratings but have the same nominal current.
- The individual panel currents will still add together as before whether their strengths are the same or different, but this time the output voltage will be limited to the value of the lowest panel in the parallel combination, in this case 8 volts due to this voltage mismatch.
- Then in this simple example the parallel circuit will produce about 8 volts at 15 amperes.
- However, in reality the overall output voltage of the parallel combination will be somewhere between the lowest panel voltage and a mean (average) value determined by the rest of the panels in the array.
- At low output voltage levels this mismatch may not be a problem, but as the solar irradiance increases towards or beyond full sun (1000 W/m^2) the mismatch in the current-voltage (I-V) characteristics of each photovoltaic panel can cause significant power loss in a large array, so is best to be avoided.
- After all you would not connect a 6 volt battery in parallel with a 12 volt battery and expect the combination to produce a perfect 12 volt output, or the 6 volt battery not to overheat, which it will. But for this simple tutorial we will assume it to be equal to the lowest panel voltage value.

Parallel Connected Solar Panels of Different Wattages



if we connect an 80 watt panel in series with a 100 watt panel to form one series string, do the same for the second series string, and then connect these two series strings together in parallel, this will give us the following combination as above. hen as the parallel current is restricted by the lowest value panel, (panels 1 and 2), the total power output is calculated at 300 watts (P = V x I) and not the expected 360 watts, a reduction of nearly 17%. Then clearly when connecting solar panels in parallel it is more efficient to use pv panels of the same characteristics.

let us assume we have four solar PV panels, two are rated at 80 watts, 12 volts, and two are rated at 100 watts, 12 volts giving a theoretical total of 360 (80+80+100+100) watts at 12 volts.

We could connect all four together in a parallel combination (1 x 4), or connect the two 80 watt panels in series and the two 100 watt panels in series with the two series strings in parallel, (2 x 2). There are different wiring possibilities.

However, looking at the datasheet of the photovoltaic panels we can see that the maximum power point voltage (V_{MP}) and current (I_{MP}) values are different between the 80 watt panels and the 100 watt panels. Thus the panels are not the same as:

The characteristics given for the 80 watt panels are:

P_{MP} = 80 watts, V_{MP} = 20.9 volts, I_{MP} = 3.85 amperes

and the characteristics given for the 100 watt panels are:

P_{MP} = 100 watts, V_{MP} = 17.9 volts, I_{MP} = 5.72 amperes

https://www.alternative-energy-tutorials.com/solar-power/parallel-connected-solar-panels.html

POWER CONDITIONING UNIT(PCU)

- **A power conditioning unit is a device used to improve and maintain the quality of power delivered to any device or electrical load equipment.**
- It protects devices and **sensitive loads** by smoothing out potential voltage fluctuations, electrical noise, and spikes while simultaneously providing them with power.
- It protects devices from **power surges (sudden change in voltage)**and helps correct voltage, smoothing out electrical noise and distortion in the waveform.
- A PCU converts DC power from fuel cells into usable AC power.
- It consists of a DC-to-DC converter and an inverter that converts AC to DC. The former is used to increase a lower magnitude DC voltage to a higher one of at least 400 volts to produce at least 120 or 240 volts of AC power.
- a solar PCU utilizes solar power to charge battery banks. It comprises an integrated solar charge controller, grid charger and inverter system.
- The PCU is designed to monitor solar power, battery voltage and output load continuously.
- If the battery level falls below a certain point, the PCU transfers the load to the grid power that takes over charging the batteries.
- In essence, solar power conditioning units are similar to solar inverters that use solar energy to generate electricity. However, some key differences separate the two.
- An inverter takes direct current stored in batteries and converts it into alternating current, which is the form that is usable to power electronics and devices. But a solar PCU is far more versatile.
- A solar PCU prioritizes solar power charging during the day, and there are options to select the energy mode among the solar charger, grid or inverter.
- In all, the PCU is set to optimize power charging and reduce costs.

Solar PCUs are designed to utilize sunlight, meaning they have various intricate and interconnected segments that work in tandem to convert solar energy into usable power. The following are the major components of a solar PCU:

- **1. Solar Charger**

A solar charger is generally identified as a device that converts solar energy into power and electricity to devices and batteries. A PCU contains a solar charger as one of its optimal means of power charging.

Solar PCU prioritizes charging through solar energy with the help of solar chargers during the day. It converts sunlight into DC or direct current, which is used to charge the battery. A solar regulator feeds this current to the battery, ensuring that the battery is not damaged due to overcharging.

- **2. Inverter**

An inverter takes the (DC) or direct current stored in batteries and converts it to alternating current (AC) of at least 240 Volts. They regulate the flow of electrical power within the PCU. They convert the DC generated by solar power to usable AC by rapidly switching the direction of the flow of direct current.

In a PCU, the AC power made by the inverter is maintained in a clean, repeating sine wave that the grid system can use. The sine wave is the shape that electrical pressure or voltage forms. It is fed to the grid charger and does not damage electronic equipment as a compatible shape.

- **3. Grid charger**

After the inverter converts DC to AC power, a grid charger charges the battery or the hybrid system. The purpose of a grid charger is to maintain balance within a hybrid battery. A battery should have the same voltage in each cell that it is made of. Since a battery cannot hold power indefinitely, it starts leaking the energy in self-discharge over time. Ideally, each battery cell should discharge the same amount of voltage.

However, over time, each cell or module of the battery may have a different voltage. When the battery has uneven charge, any device or vehicle it powers can malfunction or show an error code. A grid charger solves this problem by charging all the cells in the battery to maximum capacity and allowing laggard cells to catch up. As a result, it balances the voltage all across the battery's cells.

A solar PCU uses a grid charger to charge devices when solar power is unavailable.

- .

- **4. Selector mechanism**

A selector mechanism shifts the power source from solar mode to inverter to grid charger. In a solar CPU, the selector mechanism is set to solar mode. However, when solar mode or enough solar power is unavailable, the inverter or the grid can also power the appliances and devices.

- **5. Battery bank**

The battery bank is where the solar charge is stored in the form of direct current to be utilized by the inverter. Solar energy is not always constant and is affected by varying factors like cloud formation, wind, weather, etc. Hence, it is important to have backup in case solar power is not viable. The battery bank can switch from solar charger to inverter to grid charger, which acts as an effective backup.

- **6. Control algorithm**

The control algorithm distinguishes the PCU from a solar charger or regular inverter. The control algorithm is responsible for setting priority and optimally selecting the power source for charging through the solar charger, grid charger or both. It also sets the source of alternating current output to either be from the grid or the inverter.

Once the solar charger stops charging, the PC consumes the stored energy as DC power from the battery bank. The inverter then converts the DC charge to the AC charge. Once a certain energy level has been utilized, the inverter stops, and the appliance is connected to power through the grid charger through the selector mechanism

Power Conditioning System

- **Definition of Power Conditioning System**
- **Power conditioning system** is broad umbrella term and is used to define an electrical equipment, or power electronics. It's used to **convert power** from a renewable energy system like a solar Photovoltaic system into a form suitable for subsequent or later use.**Why is it used?**
- **PCS** processes the electricity produced by a photovoltaic system. Thus, it can meet the specific and fluctuating demands of the load.
  it consists of:
- **Power conditioning system** provides an integrated system consisting of:
  - **A solar charge controller**
  - **An inverter and**
  - **A Grid charger**
- These three systems continuously monitor the
  - **state of battery voltage**, **solar output** and the **load.**

  WORKING:
- In **PCS** there is an option to **charge** the battery bank through either a **Solar** or **Grid/DG** set.
- The working is designed in such a way that if the battery voltage **drops down**, the **PCS** will automatically **transfer** the load to the **Grid/DG power** and also **charge simultaneously**.
- The design of the **power conditioning system** is such that it gives preference to the solar power and withdraws from Grid and/or DG power only when the solar power / battery charger is **unable to meet the load requirement.**

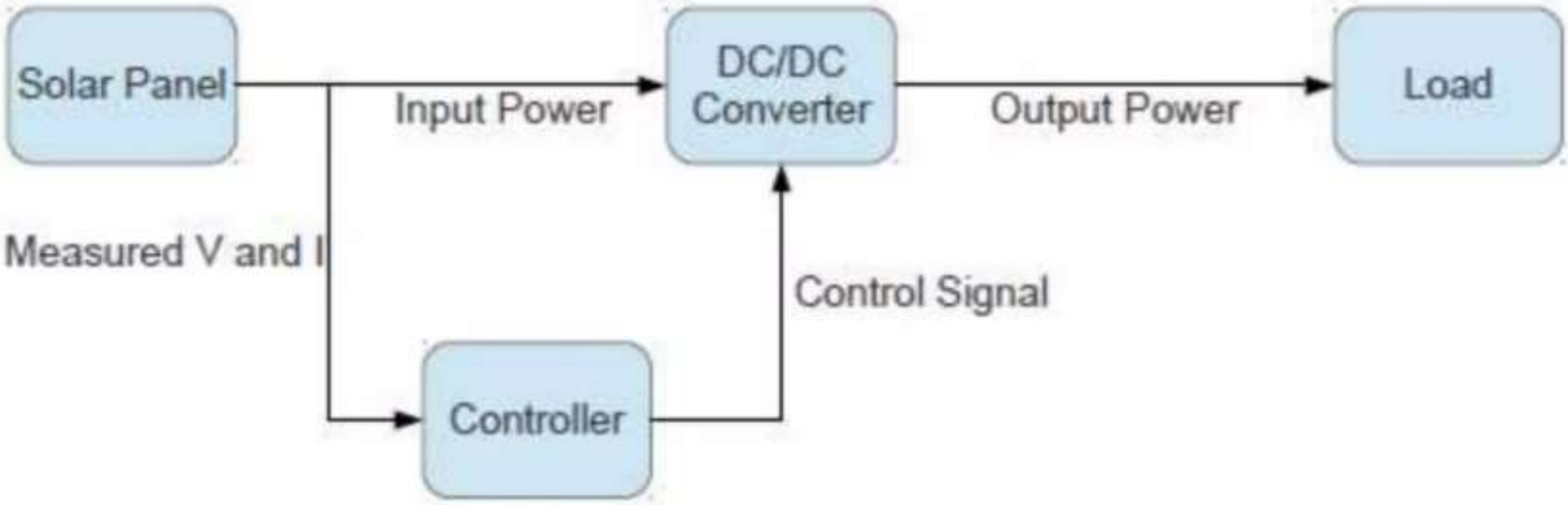
Functions

- Most power conditioners have these functions:
- **Limit current and voltage to maximize power output**
- **Convert DC power to AC**
- **Match the converted AC electricity to a utility's electrical network**
- **Have safeguards that protect utility personnel and the network from harm during repairs**
- **Other Important Things** Power conditioning equipment is an important component of the balance-of-system.
- Specific requirements of power conditioners depend on the type of PV system they are used with and the applications of that system.
- For DC applications, power conditioning is often done with **regulators**, which **control output** at some constant level of voltage and current to **maximize output**
- . For AC loads, power conditioning must include an inverter that converts the **direct current** generated by the PV array into **alternating current**.
- This understanding is important because many simple devices, ones that run on batteries, use **DC electricity**. On the other hand **AC electricity**, which is generated by utilities, is needed to run most modern appliances and electronic devices.

- **Power Conditioning System And Inverter: How are they related?**
- The term **Power conditioning system** (**PCS**) is interchangeably used with the term **inverter** in power sector.
- An inverter does the basic **DC to AC** conversion and there are other additional functions that are done by the so-called Power Conditioning Unit.
- The **PCS/ inverters**, beyond AC to DC conversion, as a unit can implement an **MPPT** mechanism before inverting the voltage.
- Thus ensuring that the PV modules or arrays are operating at their maximum power.
- Furthermore, the **inverter/PCS** can include a **battery charger**, a **DC-to-DC converter** for voltage step-up and step-down. Also, a **transformer** for grid isolation and voltage step-up.

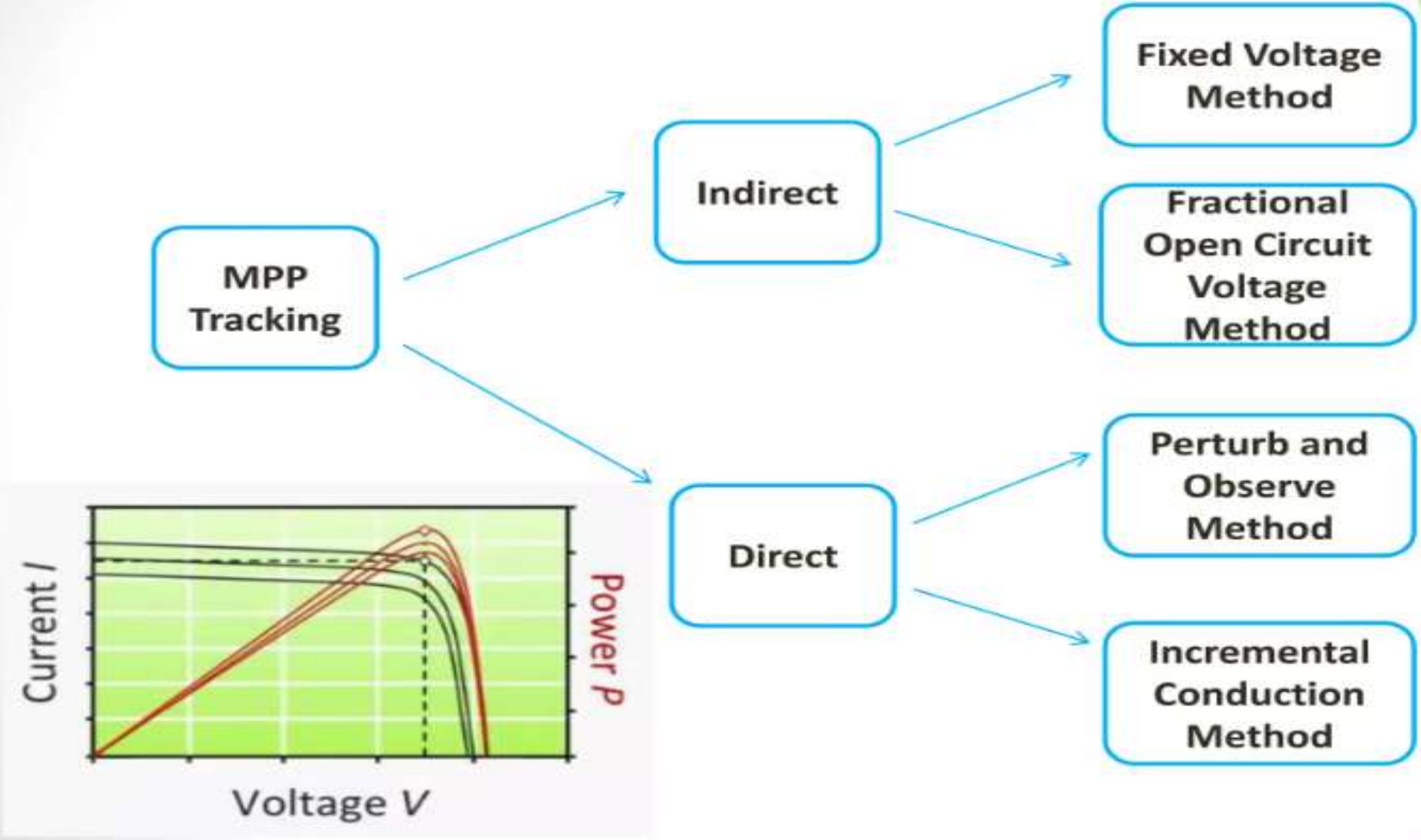
MAXIMUM POWER POINT TRACKER

- What is MPPT ?
- It is an electronic system that operates the photovoltaic modulesin a manner to extract the maximum power from the system.
- What is maximum power point ?
- It is a operating point at which maximum power can be extracted from the system. Usually represented as MPP.
- The output of solar module is a function of solar irradiance, temperature. Generally, MPPT is installed in between PV system and load.
- Coupling to the load for maximum power transfer may required either providing a higher voltage at lower current or lower voltage at higher current.



MPPT block scheme

MPPT Techniques



Maximum Power Point Tracking (MPPT) of Solar PV System :

- There are two popular techniques of MPPT of solar PV system-
  - **Perturb and Observe technique (P&O)**
  - **Incremental Conductance (INC)**

- **Perturb and Observe technique (Hill Climbing):**
  - The concept behind the P&O method is to modify the operating voltage or current of the PV panel until you obtain maximum power from it.
  - The controller operated by continuously monitoring the solar array voltage.
  - Hill climbing method can fail under rapid environment change conditions.

Introduction:

- To operate the photovoltaic modules in a manner to **extract the maximum power** from the system.
- This can increase the tracking efficiency.
- The MPPT can be achieved by modifying the output voltage and/or current.
- MPPT is most effective under Cold weather, cloudy or hazy days.

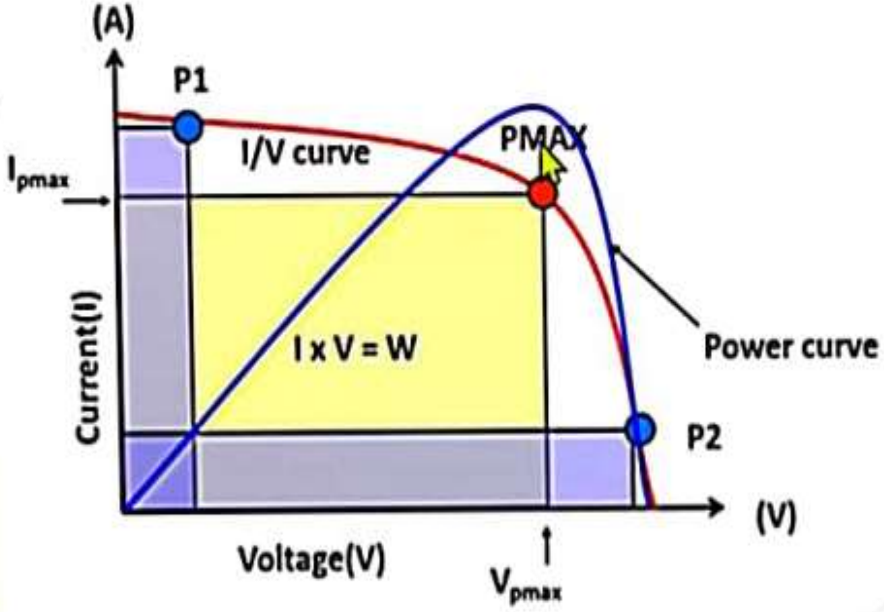


Fig. I-V and P-V characteristics of solar PV system

Introduction:

- A solar PV power system delivering power to load has following main components·
  - Solar module
  - Batteries and Converter circuitry
  - MPPT controller
- Generally MPPT is installed in between PV system and load.

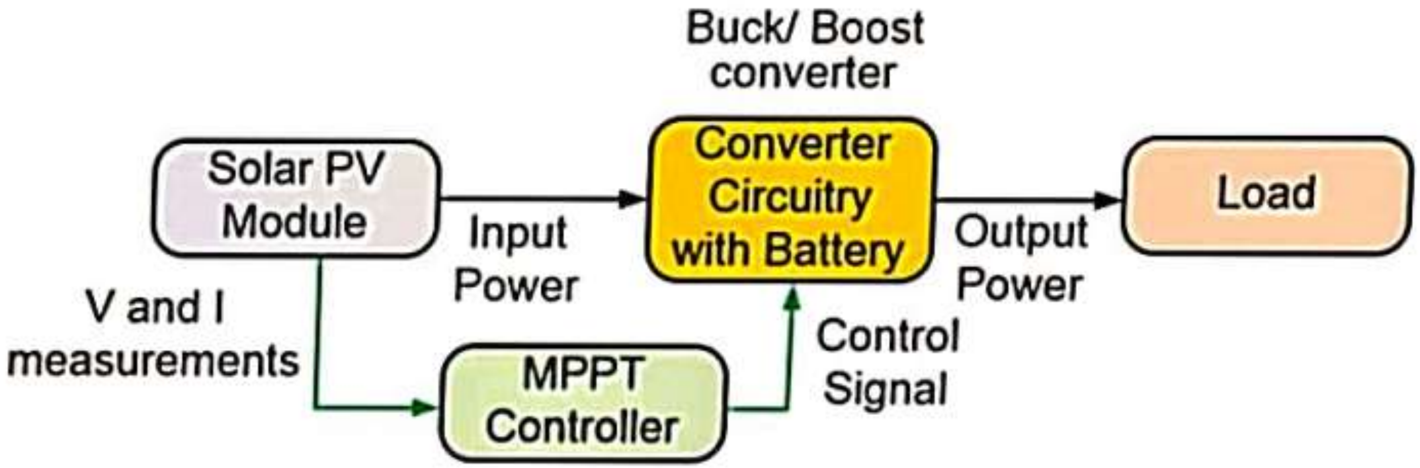


Fig. Conventional solar PV system delivering power to load

Maximum Power Point Tracking (MPPT) of Solar PV System :

- There is different power output at the level of solar insolation (kW/m^2) and temperature.
- The maximum point varies with the solar insolation and/or temperature.

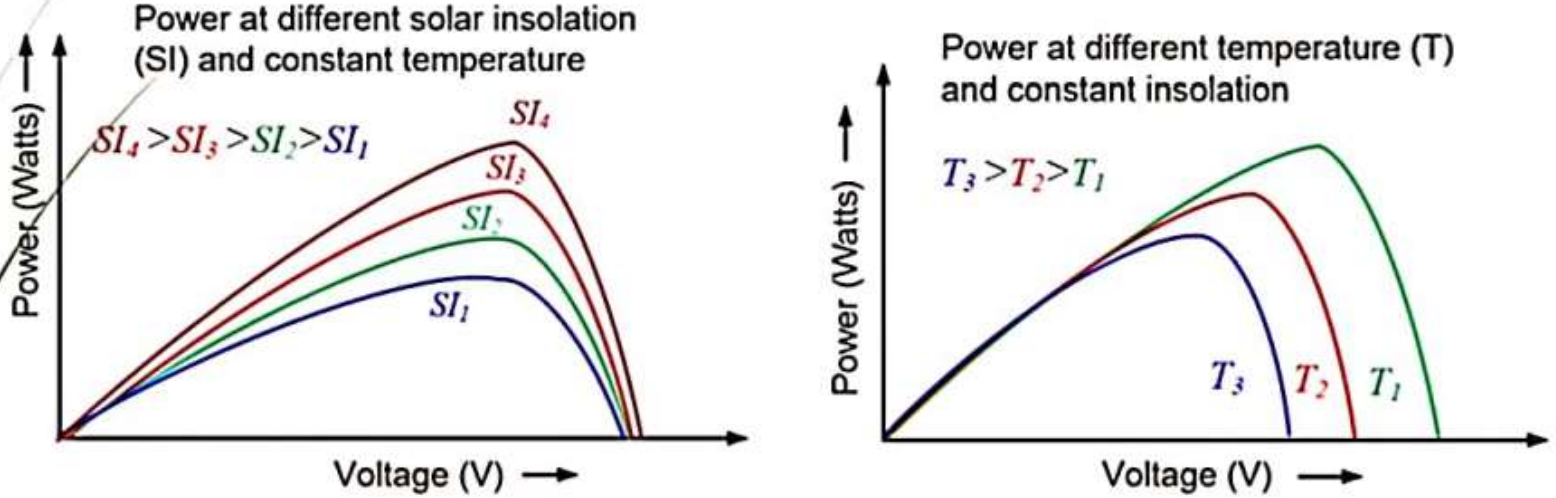
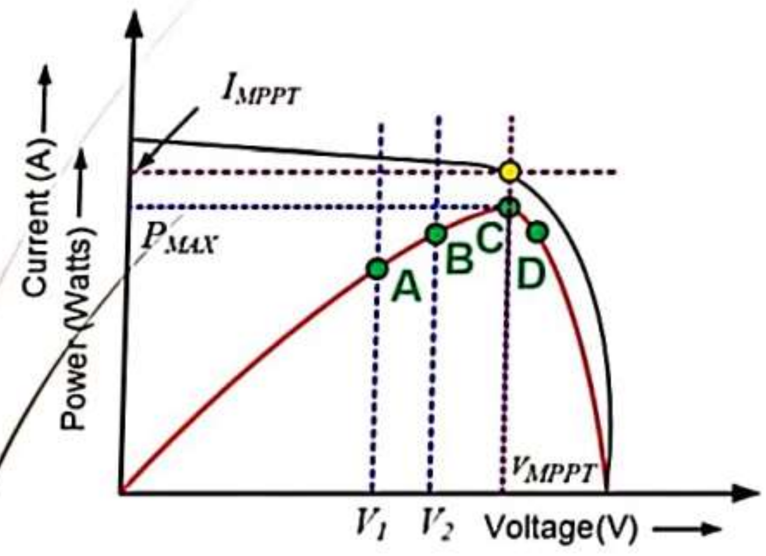
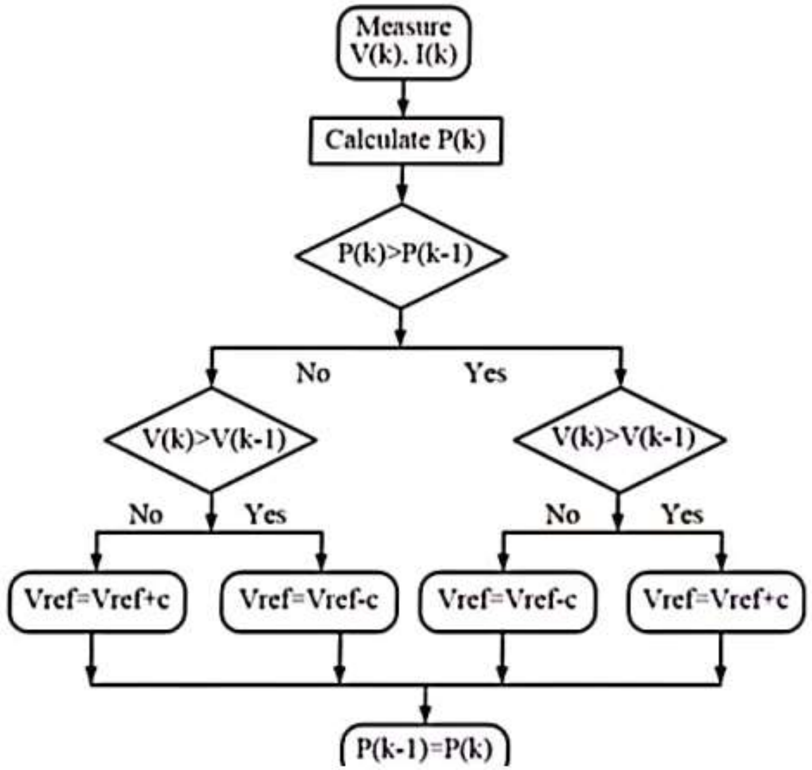


Fig. Power characteristics (P-V) of PV system

Maximum Power Point Tracking (MPPT) of Solar PV System :

- Perturb and Observe technique (Hill Climbing) -





Maximum Power Point Tracking (MPPT) of Solar PV System :

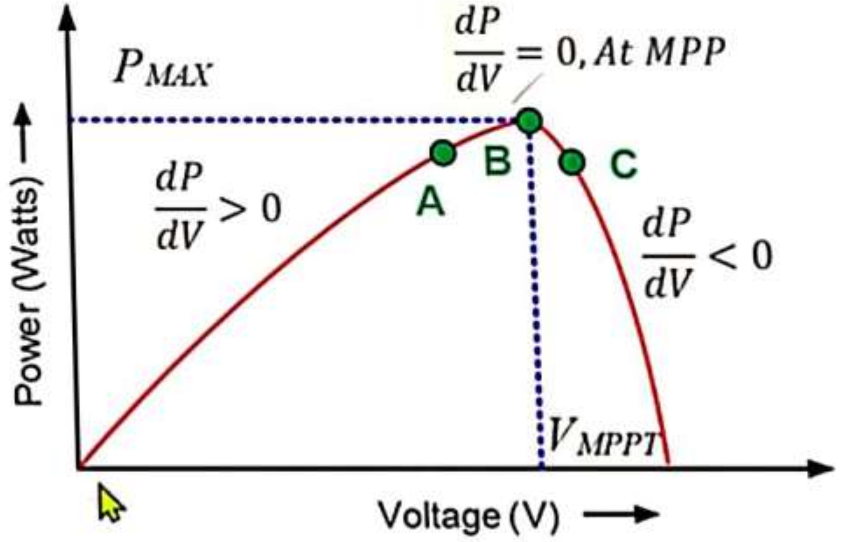
❑ Incremental Conductance (INC) :

- Incremental conductance uses two sensors, voltage and current sensors, to sense the output voltage and current of the PV array simultaneously.
- Incremental conductance considers the fact that the slope of the power-voltage curve.
- Based on fact that slope of P-V

$$\frac{dP}{dV} = 0, At\ MPP$$

$$\frac{dP}{dV} > 0, At\ Left\ MPP$$

$$\frac{dP}{dV} < 0, At\ Right\ MPP$$



Maximum Power Point Tracking (MPPT) of Solar PV System :

Incremental Conductance (INC) :

- The MPP can also be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance.

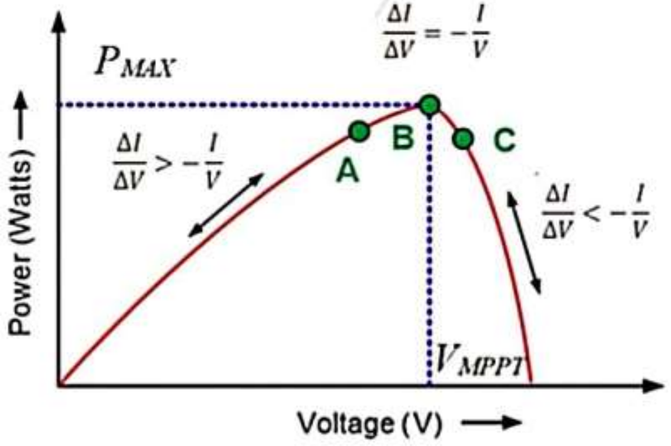
$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV}$$

$$For\ \frac{dP}{dV} = 0 \Rightarrow I + V\frac{dI}{dV} = 0\ which\ implies\ \frac{dI}{dV} = -\frac{I}{V}$$

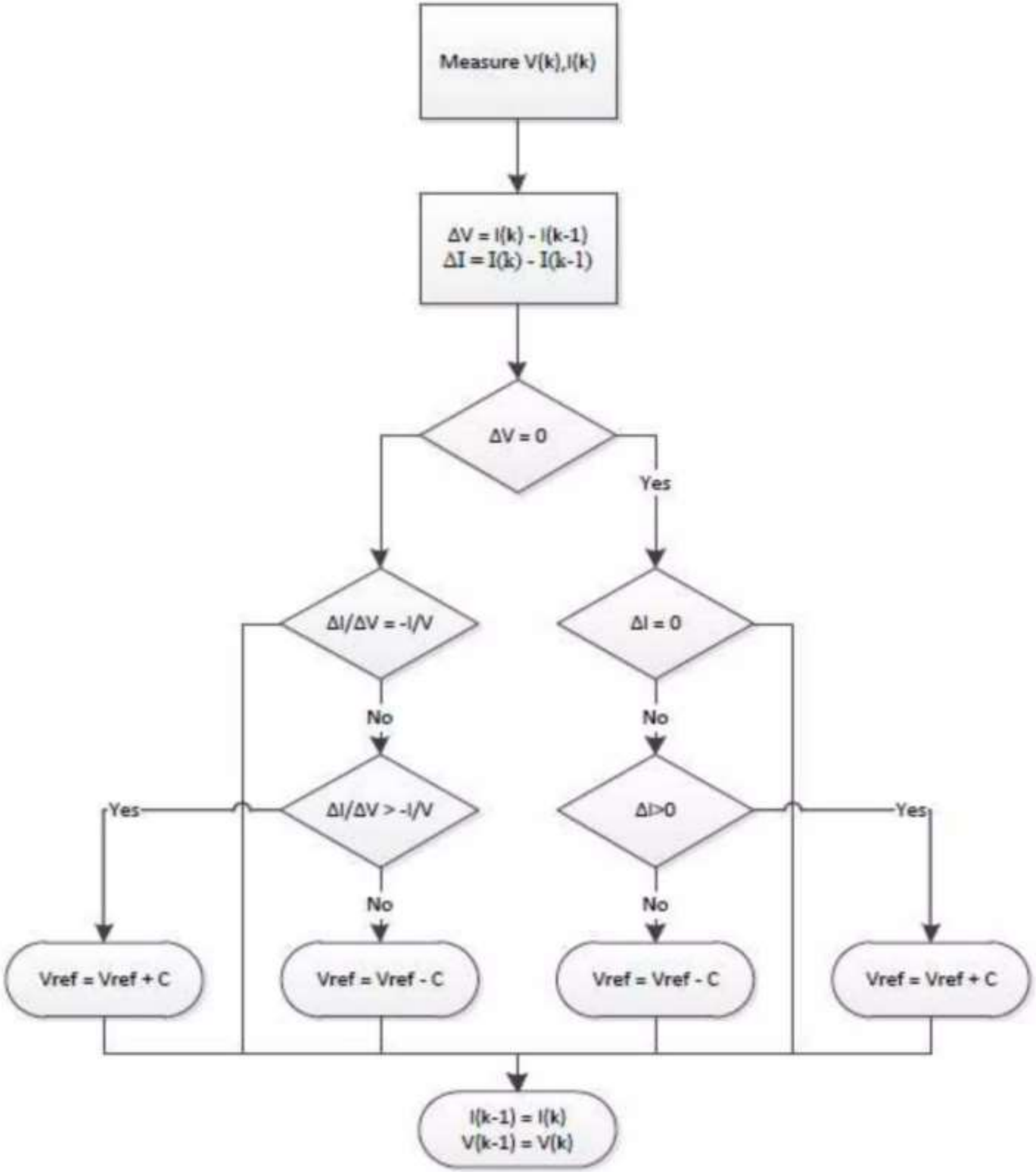
$$\frac{\Delta I}{\Delta V} = -\frac{I}{V} \quad At\ MPP$$

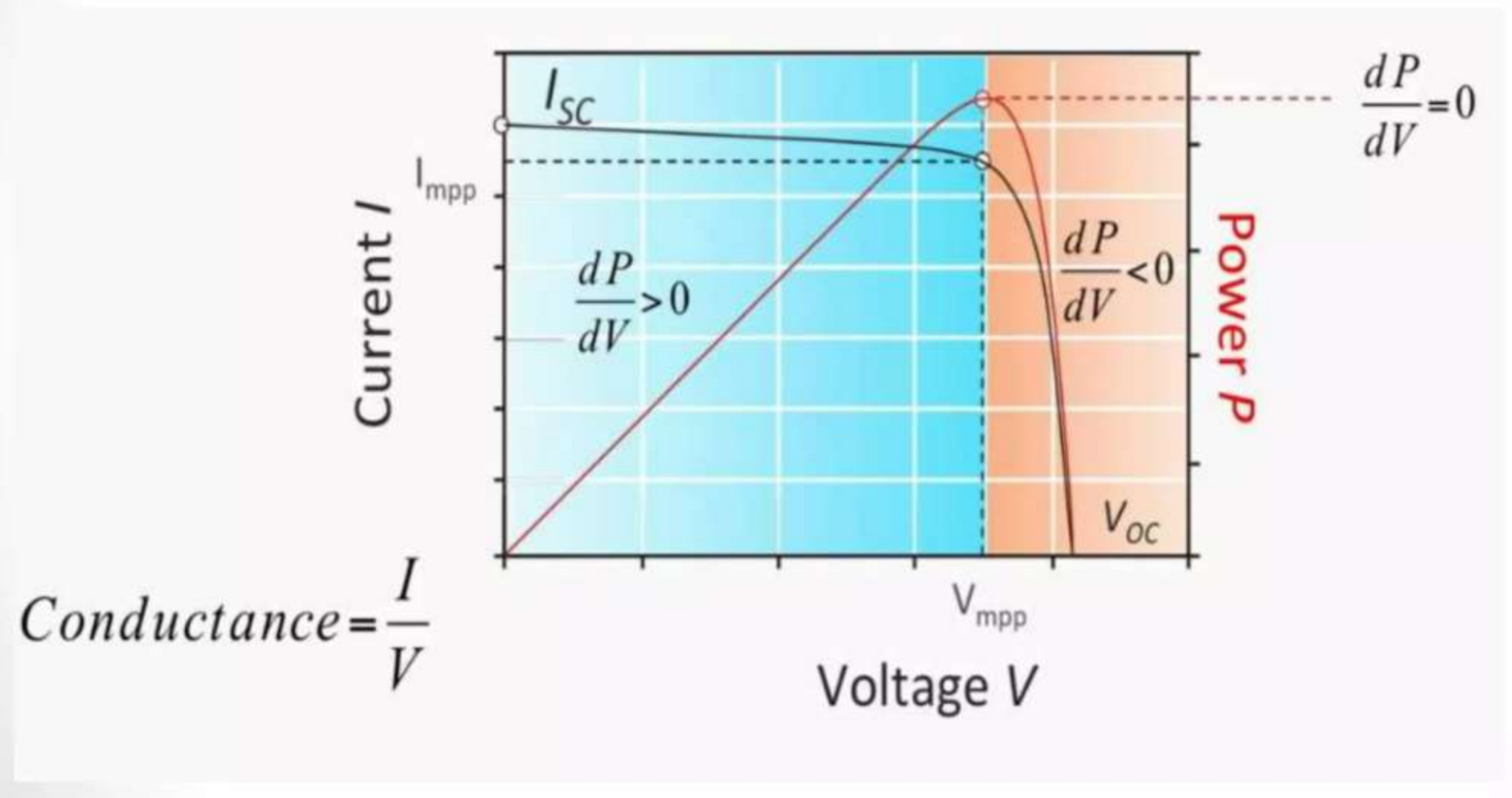
$$\frac{\Delta I}{\Delta V} > -\frac{I}{V} \quad At\ Left\ MPP$$

$$\frac{\Delta I}{\Delta V} < -\frac{I}{V} \quad At\ Right\ MPP$$

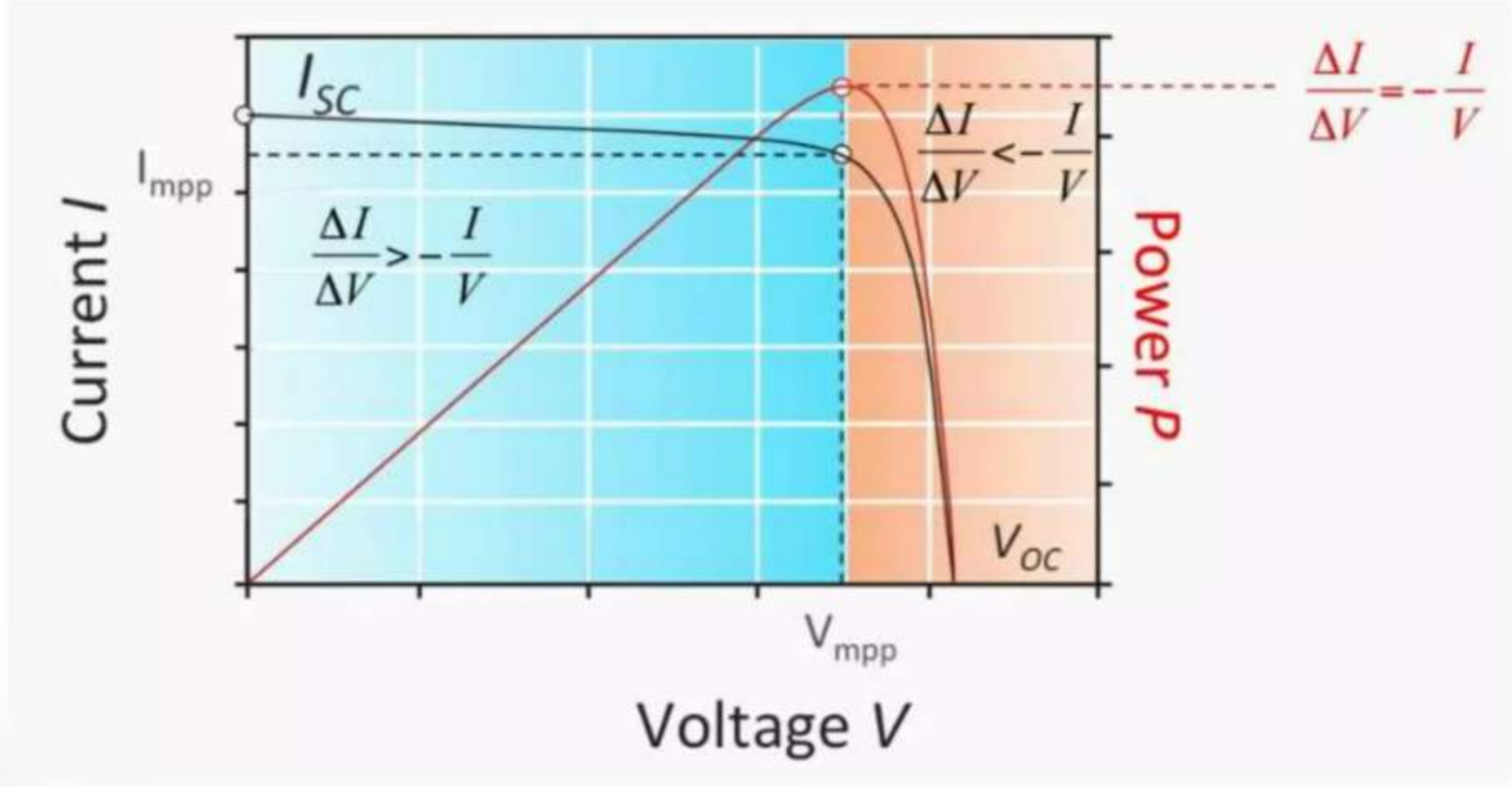


- The complexity and cost of implementation is higher.


Measure V(k),I(k)
ΔV = I(k) - I(k-1)
ΔI = I(k) - I(k-1)
ΔV = 0
Yes
ΔI/ΔV = -I/V
ΔI = 0
No
No
Yes
ΔI/ΔV > -I/V
ΔI>0
Yes
No
No
Vref = Vref + C
Vref = Vref - C
Vref = Vref - C
Vref = Vref + C
I(k-1) = I(k)
V(k-1) = V(k)



I_{SC}
I_{mpp}
Current I
$\frac{dP}{dV} > 0$
$\frac{dP}{dV} = 0$
$\frac{dP}{dV} < 0$
Power P
V_{OC}
V_{mpp}
Voltage V
$Conductance = \frac{I}{V}$

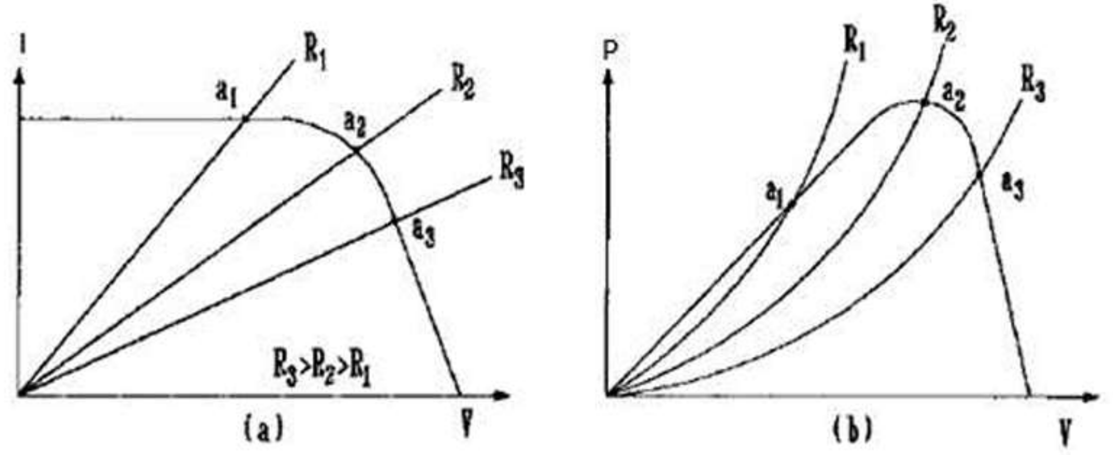


I_{SC}
I_{mpp}
$\frac{\Delta I}{\Delta V} > -\frac{I}{V}$
$\frac{\Delta I}{\Delta V} < -\frac{I}{V}$
$\frac{\Delta I}{\Delta V} = -\frac{I}{V}$
V_{OC}
V_{mpp}
Current I
Power P
Voltage V

Principles of Maximum Power Point Trackers:

- maximum power point tracker,
  - Implementation of Perturb and Observe Method,
  - Incremental Conductance Method,
- Maximum Power Point Tracking, frequently referred to as MPPT, operates Solar PV modules in a manner that allows the modules to produce all the power they are capable of generating.
- MPPT is not a mechanical tracking system but it works on a particular tracking algorithm and it is based on electronic control.
- However MPPT can be used in conjunction with a mechanical tracking system, but the two systems are completely different.
- The voltage at which PV module produces maximum power is called ‘Maximum Power Point’ and this lies somewhere close to the knee point.
- We have already seen that this Maximum Power Point in the I-V characteristics of a Solar cell shifts with solar radiation and solar cell temperature (operating conditions).

- the point at which maximum power is delivered by a source to a given load is the intersection point of the source line (in this case the I-V characteristic of the Solar Module) and the load line(V-I characteristic of the Load).
- Let us consider a PV source having the I-V and P-V characteristics as shown in figure-(a) & (b) below and supplying power to three different loads R1,R2,and R3.
- As the load resistance increases from R1 to R2 the operating point shifts from A1 to A2 and when load resistance increases from R2 to R3, the operating point moves from A2 to A3.
- As can be seen the maximum power is delivered by the module to the load when the load resistance is R2. In figure (a) it is @ the knee point of the I-V curve and in figure (b) it is @ the peak power point of the P-V curve.



- Further, when the temperature and solar radiation change along with load how the maximum power point shifts is shown in the figure-10 (a) and (b) above separately.
- These figures have been obtained by super imposing the different load lines on the earlier curves showing how the MPP varies with insolation and cell temperature.
- These figures clearly demonstrate how tricky it is to match the source with load with so many variables i.e. Cell temperature, Insolation and Load.
- From the above characteristics it can be observed that since a PV cell has an exponential relationship between current and voltage at higher voltages, maximum power generation and maximum power transfer to the load occur at the knee of the curve, when simultaneously the load resistance (V/I) is equal to the negative of the differential resistance at that point of the solar cell I-V characteristic. Such critical matching of Source with the Load in so many variable conditions is precisely what is done by the MPPT acting as an interface between the Source and the Load.

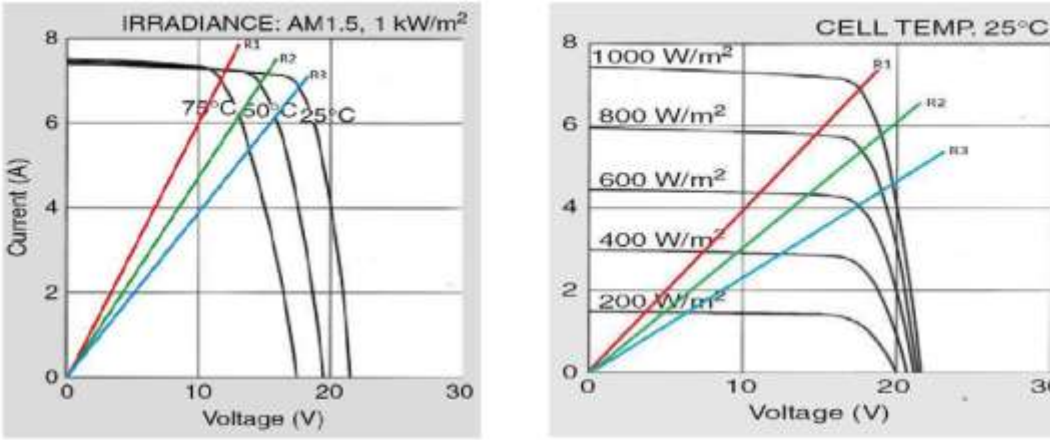


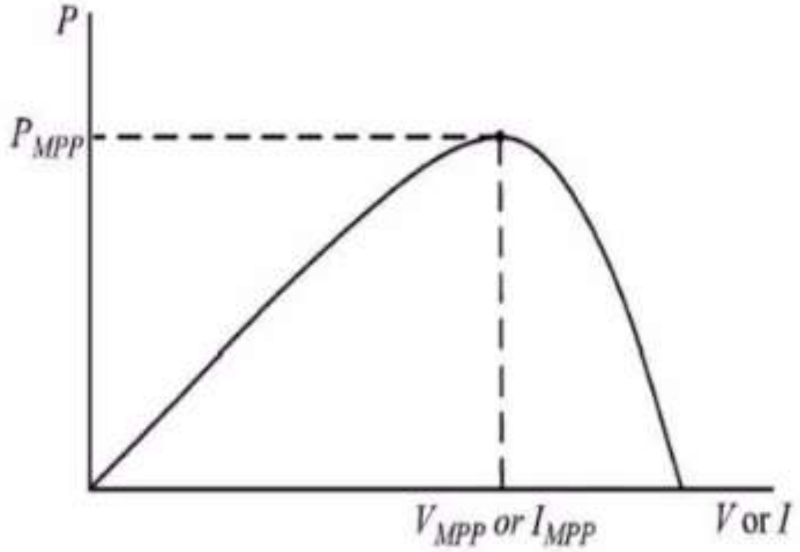
Figure-10: (a) Effect of Temperature and (b) Insolation along with load on the shift of the Maximum Power Point.

Thus, in summary a MPPT can be considered as a high-efficiency DC-to-DC converter that functions as an optimal electrical interface which:

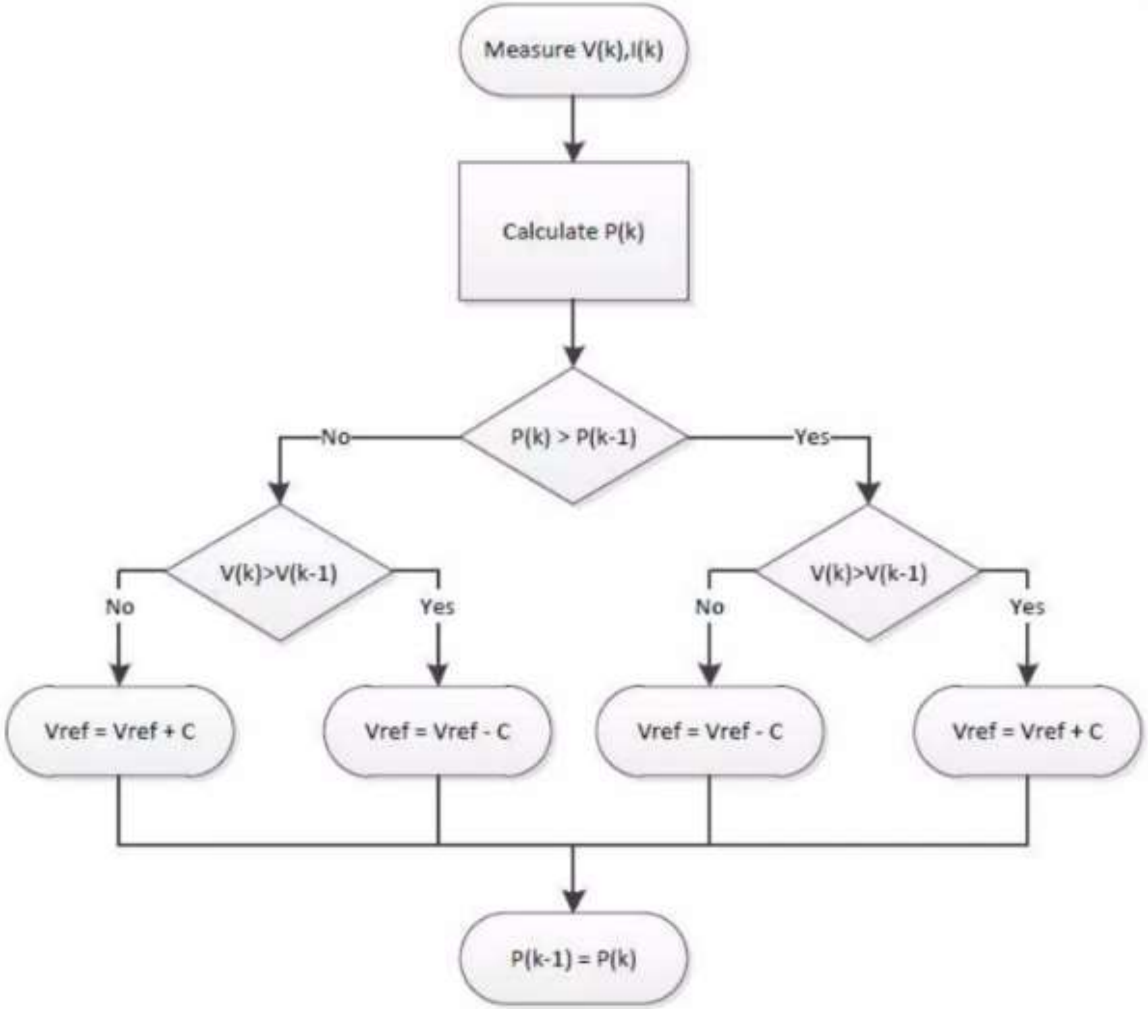
1. Has to first search and then establish the Input DC Voltage from a Solar module corresponding to the Maximum power point based on the prevailing operating conditions. And then
2. It has to convert this voltage into a DC Voltage again suitable to the varying Load conditions so as to extract the full power available from the Solar cell and deliver it to the load.

Perturb and observe(hill climbing)

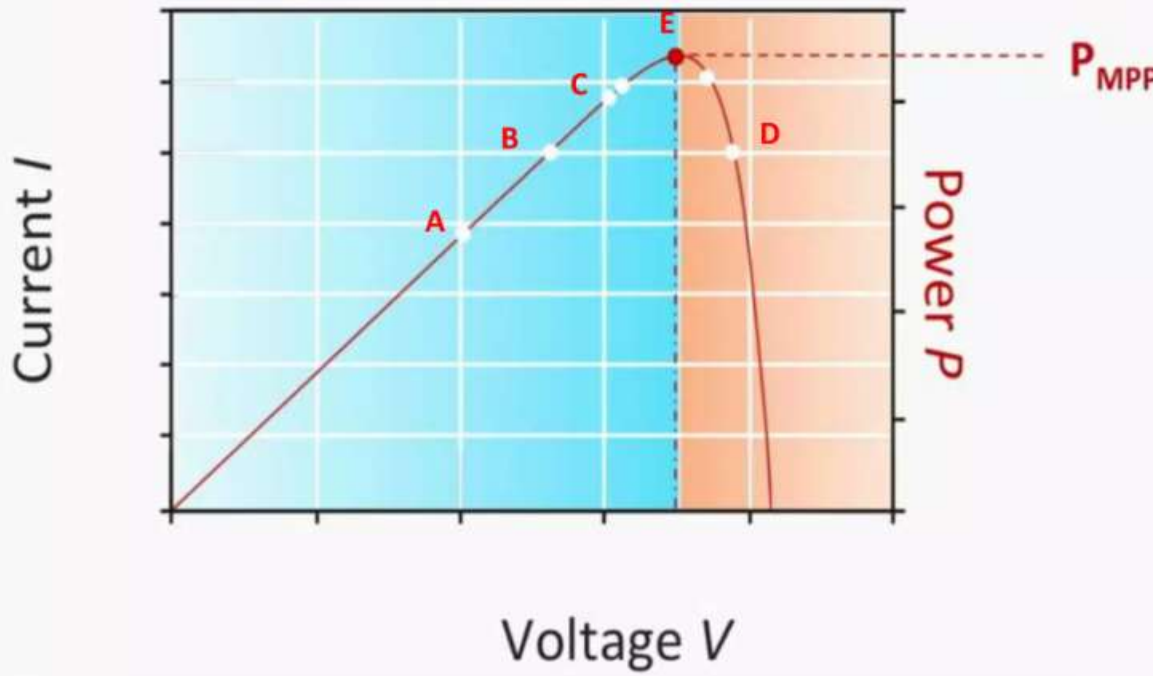
- The concept behind the P&O method is to modify the operating voltage or current of the PV panel until you obtain maximum power from it.
- The tracker operated by periodically incrementing or decrementing the solar array voltage.
- In this we use only voltage sensor, to sense the PV array voltage.
- Hill climbing method fail under rapid environment change conditions.



Perturb and observe(hill climbing)

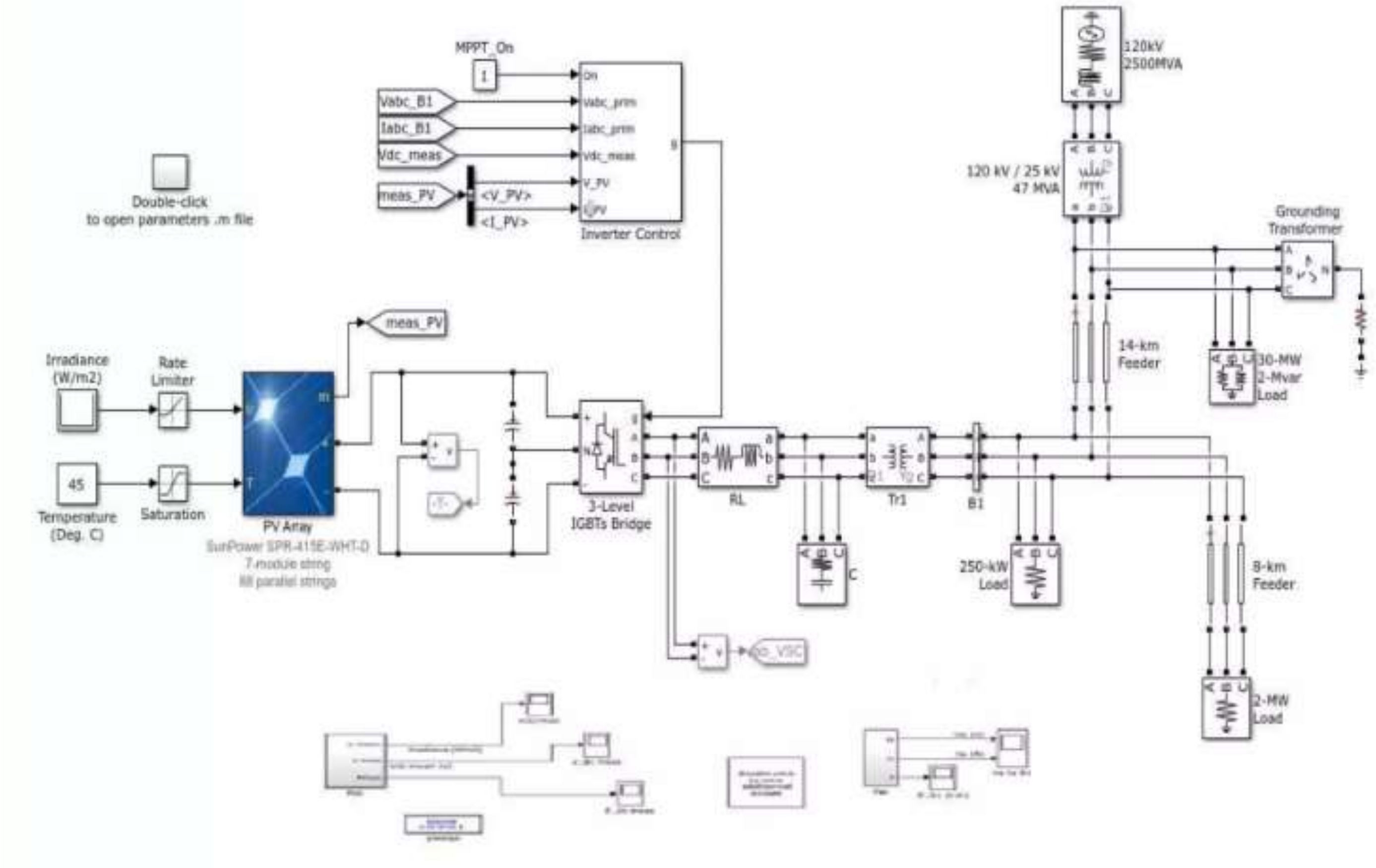


Perturb and observe(hill climbing)



- Incremental conductance uses two voltage and current sensors to sense the output voltage and current of the Pvarray
  Here we are sensing both current and voltage simultaneously.
- Hence the error due to change in irradiance is eliminated.
- However the complexity and cost of implementationincreases.

- Advantages
  MPPT method can extract maximum available power from the PV module.
  This can increase the tracking efficiency.
  If your energy use is greatest in the winter (typical in most homes) and you have cold winter weather, then you can gain a substantial boost in energy when you need it the most!



MPPT_On
1
Vabc_B1
Iabc_B1
Vdc_meas
meas_PV
<V_PV>
<I_PV>
Inverter Control
Double-click
to open parameters .m file
meas_PV
Irradiance
(W/m2)
Rate
Limiter
45
Temperature
(Deg. C)
Saturation
PV Array
SunPower SPR-415E-WHT-D
7-module string
88 parallel strings
3-Level
IGBTs Bridge
RL
C
Tr1
B1
250-kW
Load
120kV
2500MVA
120 kV / 25 kV
47 MVA
Grounding
Transformer
14-km
Feeder
30-MW
2-Mvar
Load
8-km
Feeder
2-MW
Load

- https://eepower.com/technical-articles/understanding-the-composition-of-a-solar-cell/#
- https://www.slideshare.net/slideshow/solar-pv-cells-module-and-array/65552362#20
- https://www.slideshare.net/slideshow/mppt-62585377/62585377
- https://youtu.be/0mujs7dVduY

Battery charger/discharge controller.

charge Control Methods

The charge control method is one of the most critical aspects of a solar energy storage battery. It is the process that determines how the battery is charged and how the energy is stored. The three most common charge control methods are:

1. Constant Voltage Charging:

This charge control method is one of the simplest and oldest charging methods. The technique maintains a constant voltage across the battery terminals as the battery charges. This method ensures that the battery is fully charged without the risk of overcharging it. The downside to this method is that it charges slowly and cannot be used to charge large batteries.

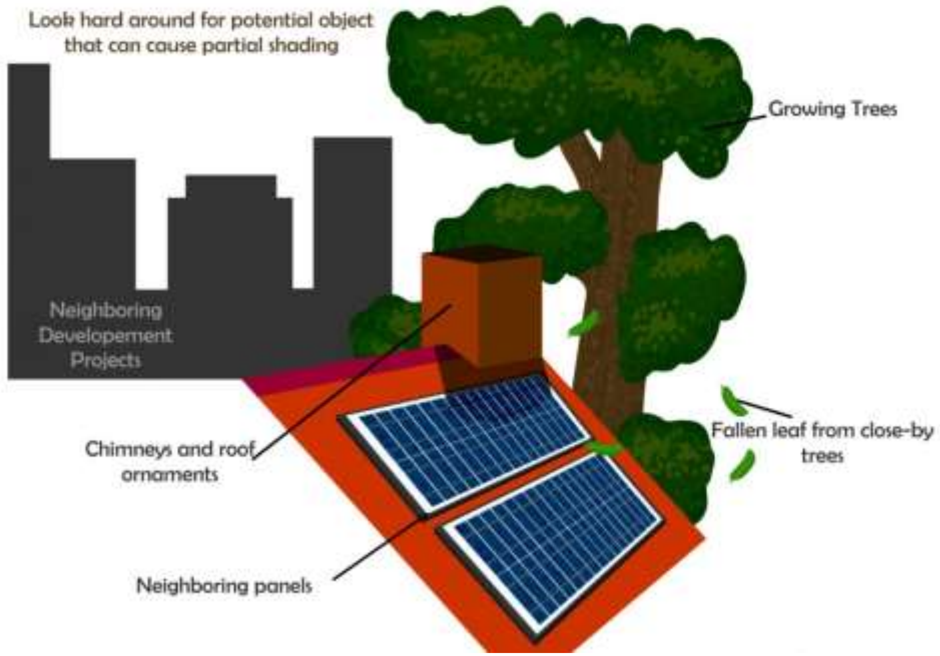
2. Constant Current Charging:

This charging method has become one of the most popular charging methods for modern solar energy storage batteries. The technique involves applying a constant current to the battery until it reaches its maximum capacity. Unlike the constant voltage charging method, this method charges the battery quickly and can be used to charge larger batteries. However, it requires more complex control circuitry and has a higher risk of overcharging the battery.

3. Trickle Charging:

This charge control method is used to maintain the battery's charge once it has reached its maximum capacity. The trickle charging method applies a low current charge to keep the battery fully charged and prevent it from discharging. This control method is commonly used in applications where the battery is expected to sit unused for long periods. However, it is not suitable for charging large batteries.

Partial shading of a solar cell and a module, the diode

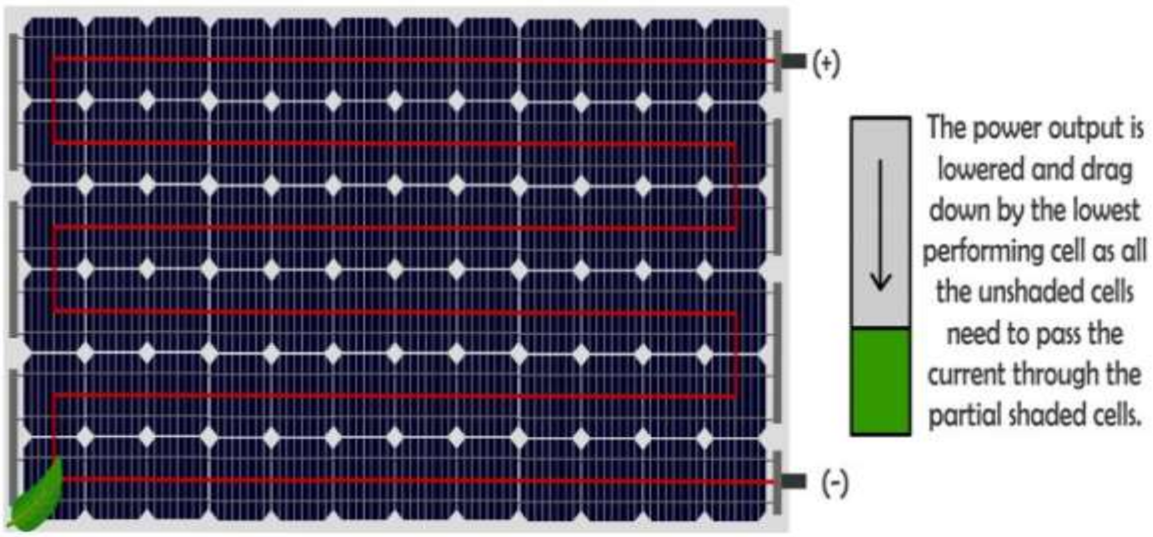


sources of partial shading will be shadow from a protruding pipe on the roof, roof ornaments, chimneys, flag pole or even shadow from the neighboring panels.

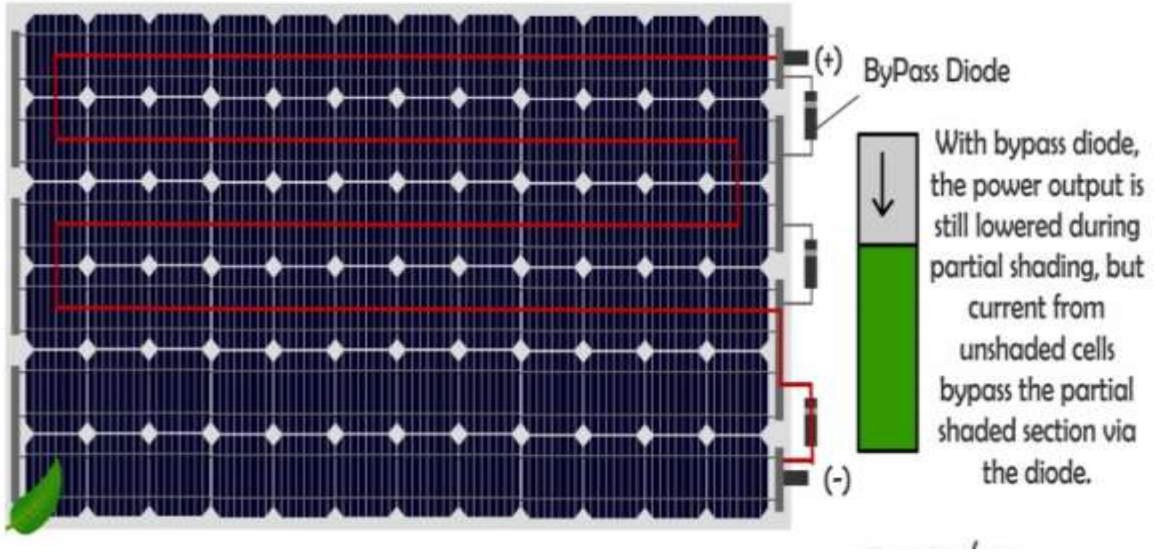
partial shading of a solar PV panel as it will severely impede the performance of a panel, even a small area of a solar PV cell. If the panel is part of a bigger string array in series, it can even cause a total shutdown of the string.

A partially shaded solar PV cells will cause an increase of internal resistance, which in turn reduce the amount of current that is able to pass through the semiconducting cell. This have great impact on solar PV panel power output as cells on a module is mostly arranged to be in series. A drop in current flow of a single cell will affect the whole string.

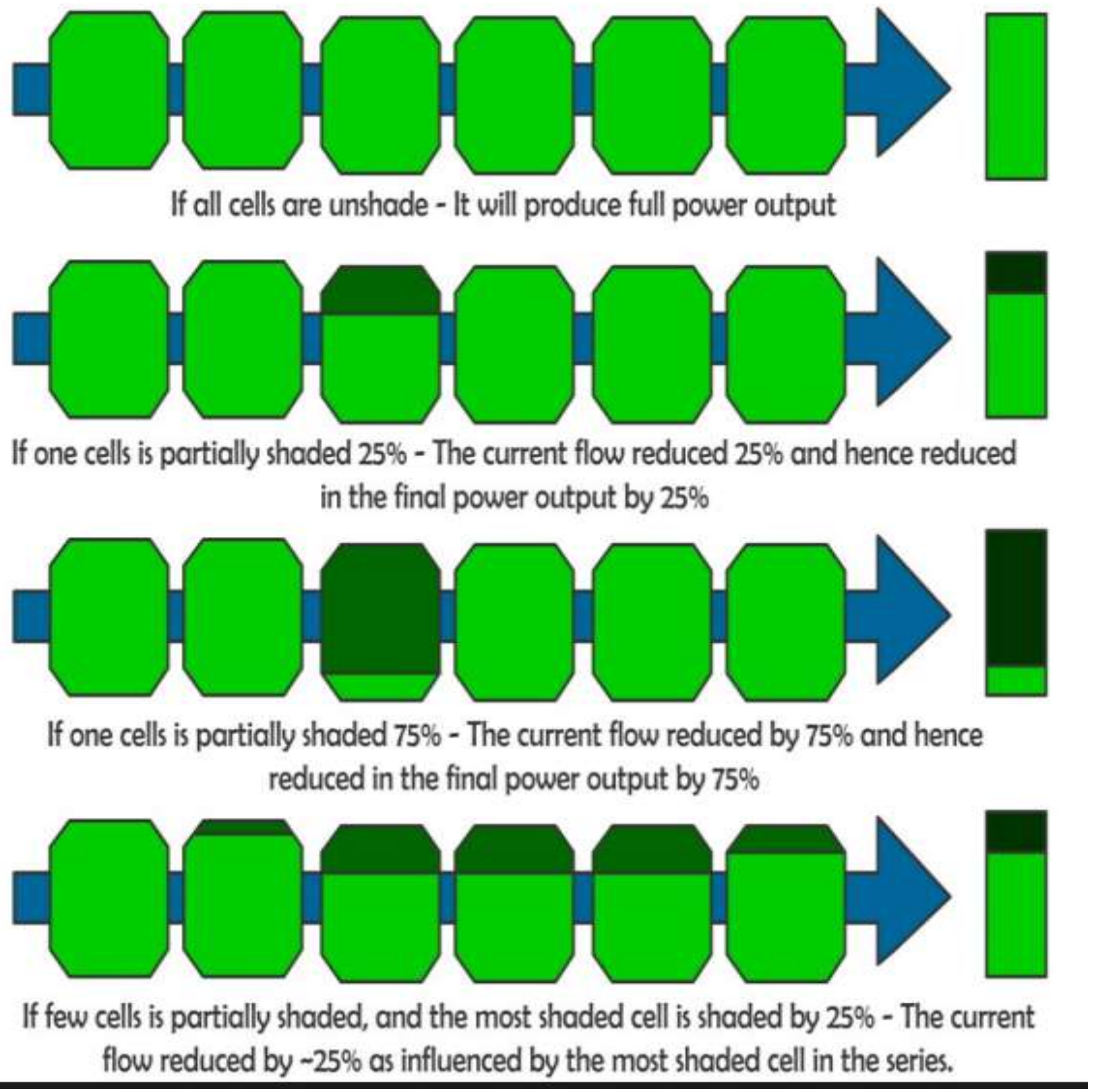
A partially shaded solar PV panel without Bypass Diode



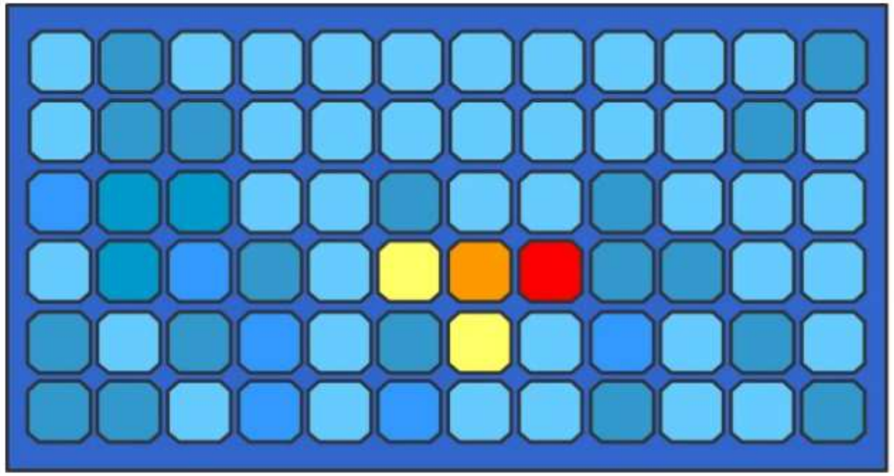
A partially shaded solar PV panel with Bypass Diode



Effects of Partial Shading of Solar PV Panel



- As **unshaded cells try to pass more current than the shaded cell is capable of handling** (partial shading cause drops in short-circuit current of that cell – which means less current can pass through that cell), and **excess power will be dissipated as heat.**
- The enormous **power dissipation** occurring in a small area results **in local overheating, or "hot-spots**", which in turn leads to destructive effects, such as **cell or glass cracking**, **melting of solder or degradation of the solar cell.**
- It can be seen via a infrared thermal imaging where **hot spots can be heated up to 100 degree Celsius**.
- There is other causes of hot spots such as **defective or broken cells** and **defective solder joints.**



An Infrared Thermal Imaging will tell you hot-spots on a working solar PV panel which indicate cells that are overheating and may indicate possible partial shading, defective or broken cells or defective solder joints.

The hot-spots on a solar PV panel should not be ignored.

Partial shading of a solar cell and a module, the diode

3 Solar Cells in Series (Without Shading)

Assume:

Each solar cell can generate:

Current (I) = 5 A

Voltage (V) = 0.6 V

So for 3 cells:

Total Voltage = 3 × 0.6 V = 1.8 V

Total Power = V × I = 1.8 V × 5 A = 9 W

If shading is severe, Cell 2 might not generate any current.
Instead, it's **forced to pass current** generated by other cells.
•This reverse bias can cause:

- **Power dissipation in the shaded cell**
- **Overheating ("hot spot")**
- **Permanent damage**

Now, One Cell is Partially Shaded

Let's say **Cell 2 is partially shaded**, and can now generate only **1 A** of current.

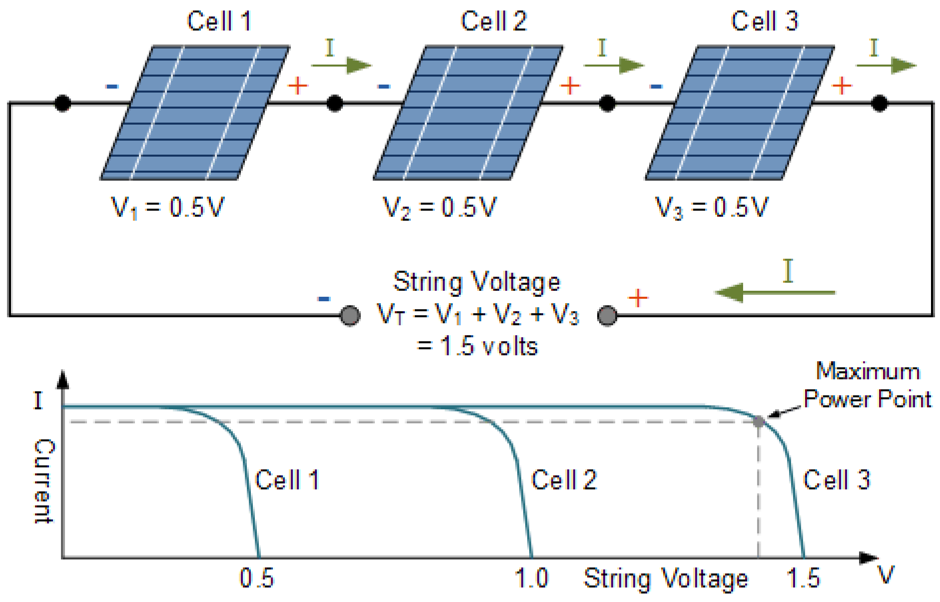
Because the cells are in series:

- The current through the entire string is limited to **1 A** (lowest cell current).

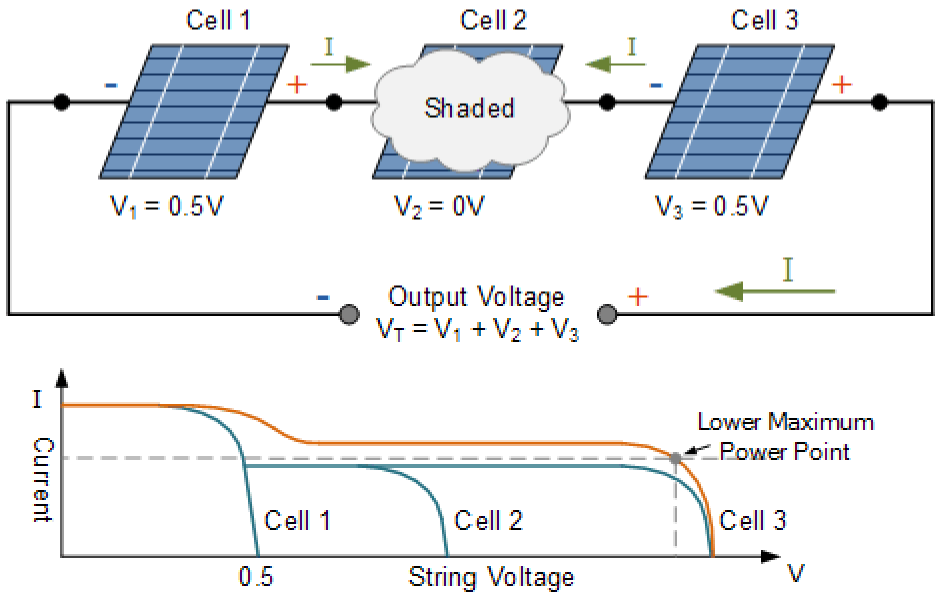
Total Voltage may still be close to 1.8 V (ignoring losses), but:

  - **New Power = 1.8 V × 1 A = 1.8 W**

That's **80% power loss!**



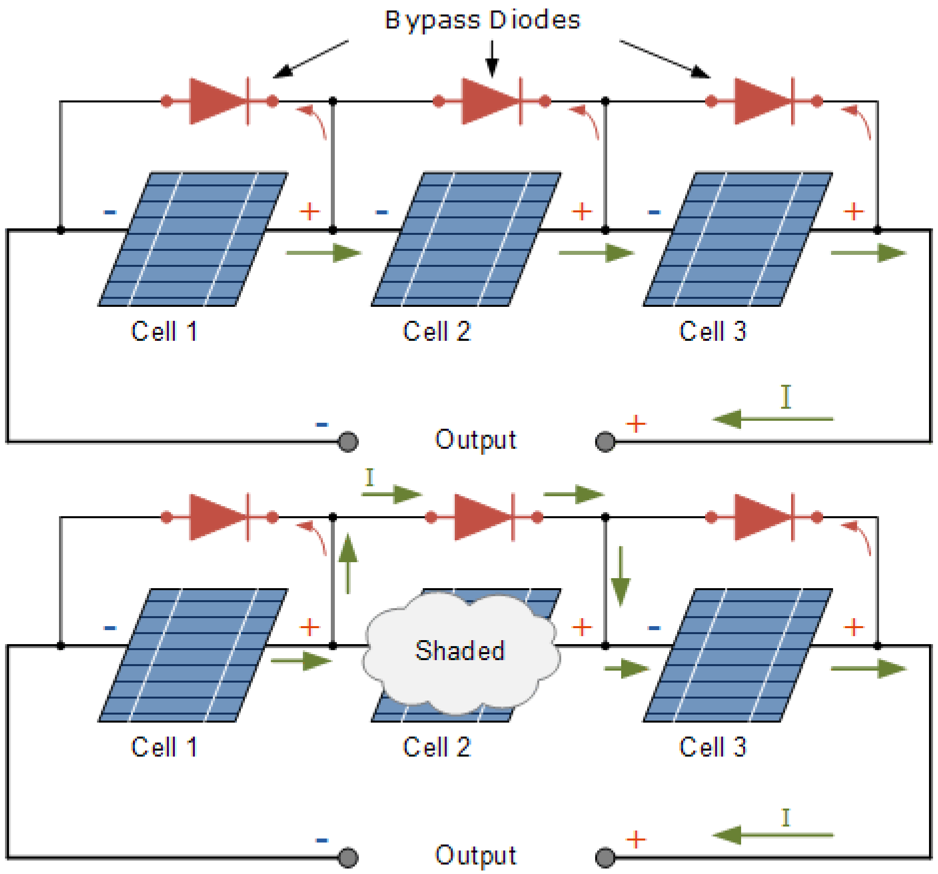
Cell 1
Cell 2
Cell 3
I
V1 = 0.5V
V2 = 0.5V
V3 = 0.5V
String Voltage
VT = V1 + V2 + V3
= 1.5 volts
I
Current
Maximum Power Point
Cell 1
Cell 2
Cell 3
0.5
1.0
String Voltage
1.5
V



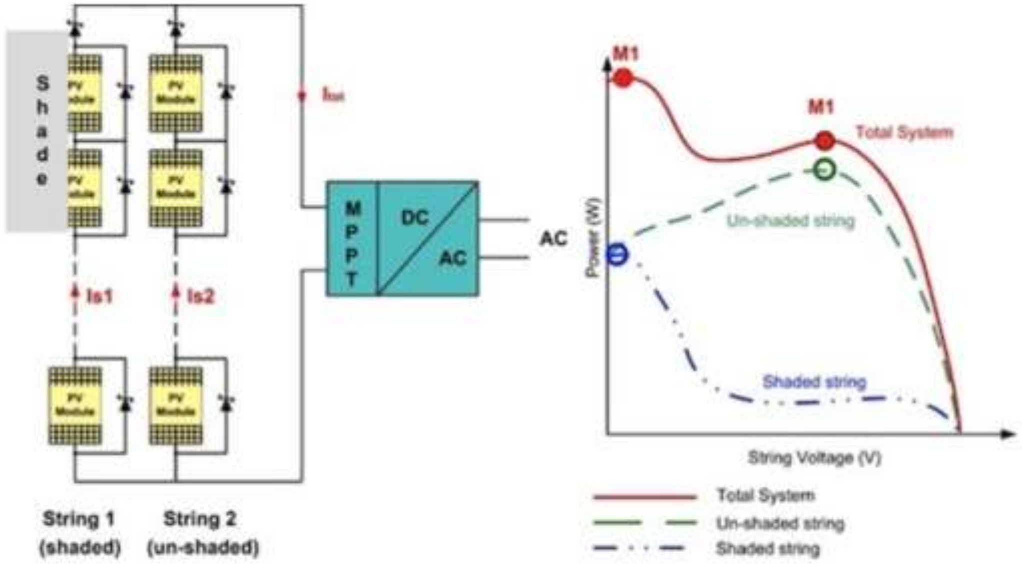
Cell 1
Cell 2
Cell 3
Shaded
I
V1 = 0.5V
V2 = 0V
V3 = 0.5V
Output Voltage
VT = V1 + V2 + V3
I
Current
Lower Maximum Power Point
Cell 1
Cell 2
Cell 3
0.5
String Voltage
V

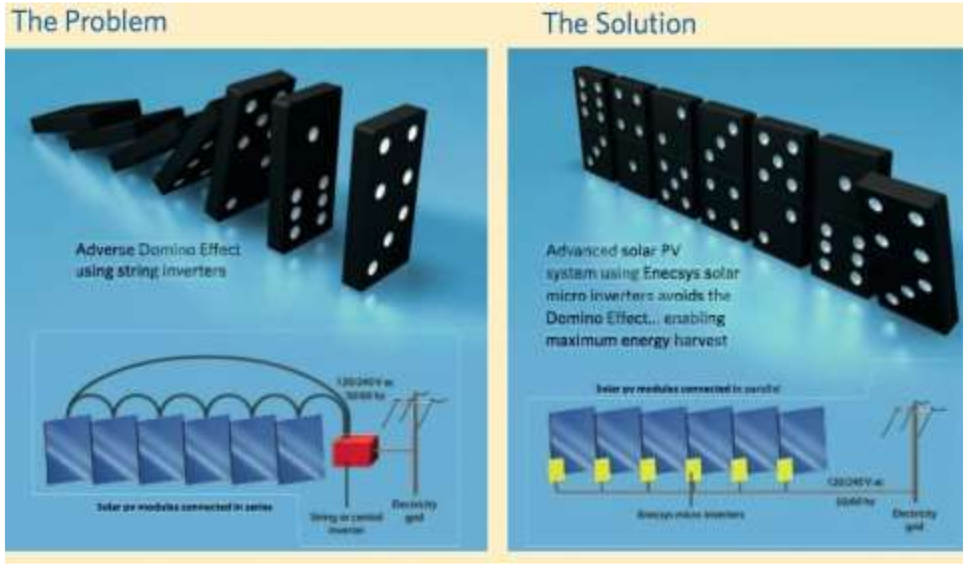
By pass diode

- If a **bypass diode** is connected across Cell 2:
- When Cell 2 is shaded, the diode turns **on**, letting current bypass the shaded cell.
- Now:
    - **Total Voltage = 0.6 + 0.6 = 1.2 V** (Cell 2 skipped)
    - **Current = 5 A**
        - **Power = 1.2 V × 5 A = 6 W**
- Better than 1.8 W, and no damage to Cell 2.



microinverters or power optimisers





If it is unavoidable to not place your solar panels in shade, then microinverters or power optimisers might be the right option for you. These devices get around the problem of partial shading by eliminating the need for or importance of strings in the first place. Both microinverters and power optimisers essentially allow every solar panel in a system to operate independently, so that overall system energy production is not disproportionately affected by just one or two shaded panels. (Space to watch: A newer technology by Maxim being used in a line of JinkoSolar panels promises to deliver even more granular shade protection than conventional microinverters or power optimisers.)

The main downside to these technologies is that they tend to be a bit more expensive than a system with a standard system containing a central string inverter, so there's no need to splash out on them in instances where shading is not an issue.

Batteries:

- In off-grid (Stand alone systems) and critical applications (such as back up in Grid connected systems), for storing the energy output from Solar PV systems energy storage systems are required.
- The most common medium of storage in PV systems are batteries or a battery bank depending upon the backup duration /capacity requirements of the specific system.
- There are many types of batteries suitable for use in a PV system for energy storage like lead acid batteries, alkaline batteries, nickel–cadmium batteries, and sealed batteries the most common type being lead acid batteries.
- One of the most expensive subsystems in the Standalone PV system is the batteries.

- The primary functions of batteries in a PV system:
- (a) **Energy Storage Capability and Autonomy:** to store electrical energy when it is produced by the PV array and to supply energy to electrical loads as needed or on demand.
- (b) **Voltage and Current Stabilization:** to supply power to electrical loads at stable voltages and currents, by suppressing or ‘smoothing out’ transients that may occur in PV systems.
- (c) **Supply Surge Currents:** to supply surge or high peak operating currents to electrical loads or appliances.

Important aspects of batteries in PV system:

- **Sizing:** Batteries play a vital role in terms of total plant efficiency, performance and maintenance cost of standalone (OFF Grid) systems and at the same time take a substantial portion of the total cost of a Standalone Solar power plant.
- Lower sizing results in reduction of battery life due to higher Depth of Discharge (DOD %). (a measure of how much of the battery's energy has been used up)
- Hence their sizing must be carried out carefully optimizing both cost and performance.

Selection:

- Selecting the suitable battery for a PV application and further their effective use depends on many factors and requires a comprehensive knowledge on the various types of batteries, their **merits & demerits** from the point of view of **quality, reliability, charge discharge characteristics, expected nominal life and finally cost.**
- Considerations in battery subsystem design also include the number of batteries in **series and parallel**, over-current and disconnect requirements.
- In the case of lead acid batteries, when used for high energy storage as a big bank, storage with **proper ventilation** is also to be addressed from safety point of view.

Charge discharge rates:

- A **higher current discharge** than the rating will dramatically **reduce the battery life.**
- This can be avoided by carefully sizing the battery according to the ‘C-rating’.
- The C-rating of a battery **indicates how fast it can be safely discharged relative to its capacity.**
- A higher C-rating means the battery can **deliver more power in a shorter amount of time**, while a lower C-rating indicates a slower discharge rate and longer run time.
- It signifies the **maximum amount of current** that can be safely drawn from the battery to provide adequate back up and without causing any damage.
- A discharge rate more than the C-ratings, may cause irreversible capacity loss due to the fact that the rate of chemical reactions taking place in the batteries cannot keep pace with the current being drawn from them.
- For such effective use and better performance, the batteries are charged and discharged using charge controllers.

- Solar Charge Controllers are controllers which regulate the power output or the DC output voltage of the solar PV panels to the batteries.
- Charge controllers take the DC output voltage as the input voltage and convert into same DC voltage but at a level required for battery charging.
- These are mostly used in off grid scenario and use Maximum Power Point Tracking scheme to maximize the output efficiency of the Solar PV Panel.
- **Working Principle:**
- A solar-charge controller monitors voltage across the battery and disconnects the battery from the PV array or diverts the power away from the battery when it is fully charged.
- This can be achieved by short circuiting the PV array (shunt regulator) or by disconnecting the positive and negative terminals.
- (Open-circuited series regulator) In addition to a shunt/series regulator, an auto cut off switch is also provided, which disconnects the electrical load for very low battery voltage.
- This is referred to as a "low-voltage disconnect function."
- The solar-charge controller (SCC) is provided between the solar PV panel and the batteries as shown in the figure below.

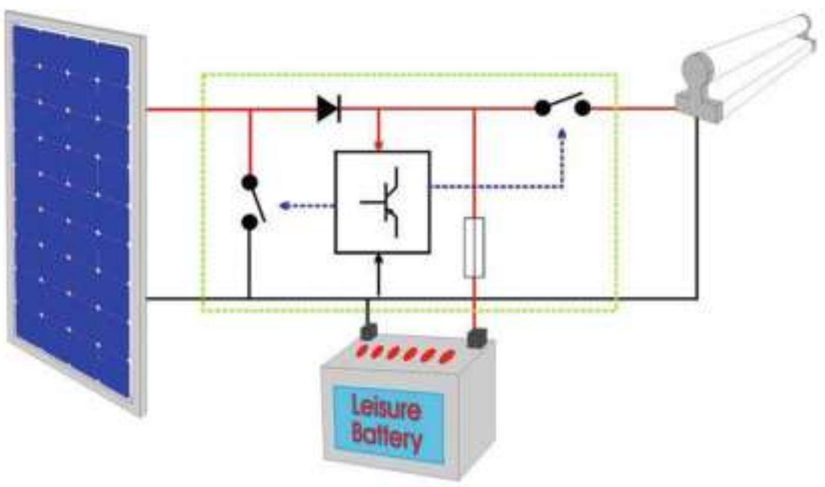


Figure-21: Circuit diagram of a solar-charge controller

Charge controllers:

- A charge controller, charge regulator or battery regulator limits the rate at which electric current is added to or drawn from electric batteries.
- It prevents overcharging and overvoltage, which can reduce battery performance or lifespan, and may also pose a safety risk. To protect battery life, charge controller prevents battery from deep discharging or it will perform controlled discharges, depending on the battery technology. The terms “charge controller” or “charge regulator” may refer either to a stand-alone device, or to a control circuitry integrated within a battery pack, battery-powered device, or battery charger.

Battery charger/discharge controller

- Battery charge/discharge controller is a device or circuit that manages the flow of electricity into and out of a battery, ensuring it is charged and discharged safely and efficiently.
- It protects the battery from damage due to **overcharging, over-discharging, and other electrical stresses**, ultimately prolonging its lifespan and maintaining optimal performance.
- A battery charge/discharge controller in a photovoltaic (PV) system manages the flow of electricity **between solar panels and batteries**, preventing overcharging and over-discharging.
- It protects the batteries from **damage and ensures their optimal performance** and longevity within the system
  Overcharge Protection:
- The controller regulates the voltage and current going into the battery from the solar panels, preventing it from exceeding safe limits and causing damage.
- **Over-discharge Protection:**
- The controller also disconnects the battery from the load (devices using the power) when the battery voltage drops too low, preventing it from being deeply discharged, which can shorten its lifespan.
- **Maintaining Optimal Voltage:**
- By managing the charging and discharging process, the controller helps keep the battery within its ideal voltage range, maximizing its performance and lifespan.