POWER ELECTRONIC APPLICATIONS TO RENEWABLE ENERGY SYSTEMS

UNIT-I

Solar cell characteristics and their measurement

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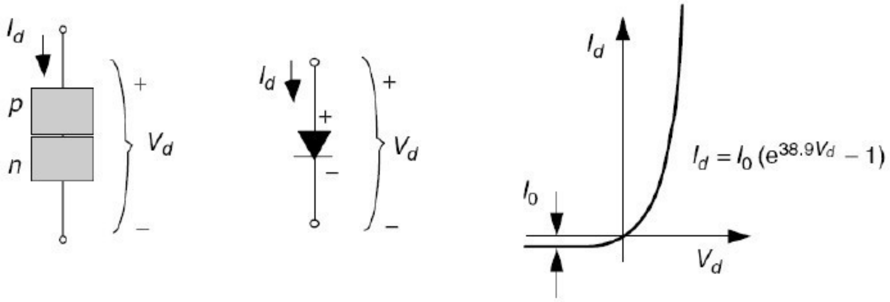
1. Solar Cell I-V Characteristics:

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.



(a) *p–n* junction diode

(b) Symbol for real diode

(c) Diode characteristic curve

Figure-1 : A *p–n* junction diode allows current to flow easily from the *p*-side to the *n*-side, but not in reverse. (a) *p–n* junction (b) its symbol (c) its characteristic curve.

If we apply a voltage $\mathbf{V_d}$ 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 ($\approx 10^{-12}$ A/cm^2) reverse saturation current $\mathbf{I_0}$ 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 $\mathbf{I_d}$ is the diode current in the direction of the arrow (A), $\mathbf{V_d}$ is the voltage across the diode terminals from the *p*-side to the *n*-side (V), $\mathbf{I_0}$ is the reverse saturation current (A), **q** is the electron charge (1.602 × 10^{-19} C), **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 $\mathbf{I_d}$ 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 25^0C is often used as a standard, which when substituted in the Shockley diode equation gives the following diode current I_d.

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

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, $\mathbf{I_d}$ = 0, so from equation for I_d we get $\mathbf{V_d}$ = 0.

b) With $\mathbf{I_d}$ = 1 A, we can find $\mathbf{V_d}$ by rearranging the above equation for '$\mathbf{I_d}$' :

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

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 $\mathbf{I_d}$ = 10 A,

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

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'*** to which it is exposed.

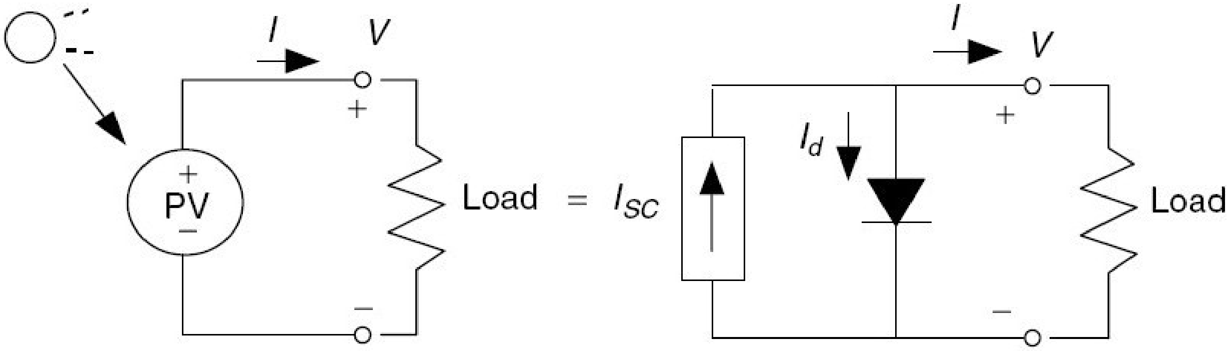


Figure-2: A simple equivalent circuit of a photovoltaic (Solar) cell consists of a current source driven by sunlight in parallel with a real diode.

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, $\mathbf{I_{SC}}$). When the leads of the equivalent circuit for the PV cell are shorted together, no current flows in the (real) diode since $\mathbf{V_d}$ = 0.That means I_d =

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**

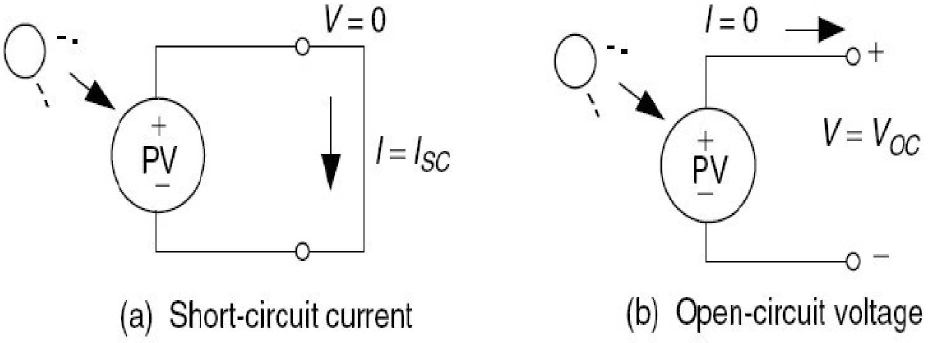


Figure-3: Two important parameters for a Solar cell are the short-circuit current I_{SC} and the open-circuit voltage V_{OC}.

Now we can write a voltage and current equation for the equivalent circuit of the PV cell shown in figure (b) starting with

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

and then substituting the value of I_d as per the Shockley equation into the above equation for **I** we get :

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

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 below shows the current–voltage relationship for a PV cell when it is dark (no illumination) and light (with illumination) based on the above equation.

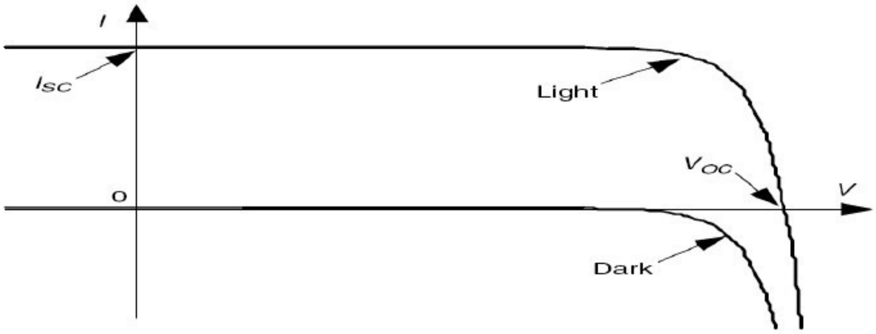


Figure-4: Photovoltaic current–voltage relationship for "dark" (no sunlight) and "light" (an illuminated cell). The dark curve is just the diode curve turned upside-down. The light curve is the dark curve plus I_{SC}.

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 $\mathbf{V_{OC}}$:

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

And at 25^0C, both the above equations (8.8) and (8.9) become

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

And

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

In both of the above equations (9&10) , short-circuit current, $\mathbf{I_{SC}}$, is directly proportional to solar ***'Insolation'***, which means that we can now quite easily plot sets of PV current–voltage curves for varying sunlight for any given Solar Cell. Also, quite often laboratory specifications for the performance of photovoltaics are given per cm^2 of junction area, in which case the currents in the above equations are written as current densities. Both these points are illustrated in the following example.

Example-2: I –V Curve of a Photovoltaic Cell. Consider a 100-cm^2 photovoltaic cell with reverse saturation current **I_0** = 10^{-12} A/cm^2. In full sun, it produces a short-circuit current of 40 mA/cm^2 at 25°C. Find the open-circuit voltage at full sun and again for 50% sunlight. Plot the results.

Solution: The reverse saturation current of the cell **I_0** = 10^{-12} A/cm^2× 100 cm^2 = 1 × 10^{-10} A. At full sun **I_{SC}** is 0.040 A/cm^2 × 100 cm^2 = 4.0 A. From (8.11) the open-circuit voltage @ full sun light is:

$$V_{OC} = 0.0257 \ \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{4.0}{10^{-10}} + 1\right) = 0.627 \text{ V}$$

Since short-circuit current is directly proportional to solar intensity, at half sun **I_{SC}** = 2A and the open-circuit voltage @ half sun light is:

$$V_{OC} = 0.0257 \ln\left(\frac{2}{10^{-10}} + 1\right) = 0.610 \text{ V}$$

Plot of the current using the equation $I = I_{SC} - I_0(e^{38.9 \text{ V}} - 1)$ @ full sun light @ half sun light along with the corresponding open circuit voltages is shown below.

It can be noticed that with reduced Sunlight intensity only **I_{SC}** gets reduced correspondingly but the reduction in **V_{OC}** is quite small (0.627 to 0.61 V)

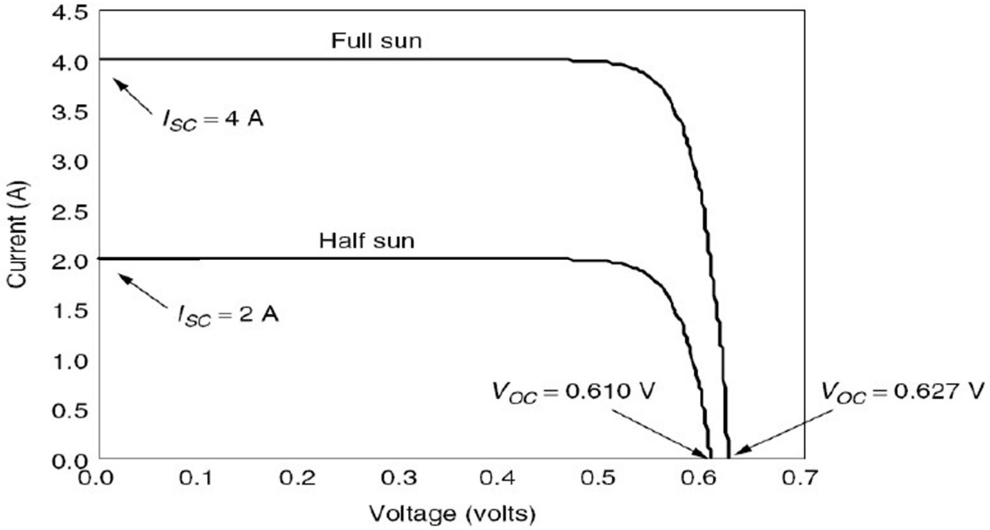


Figure-5: I-V Plot corresponding to the above Problem

2. Maximum Power Point

Let us consider, for the moment, a single PV module connected to a load as shown in the figure below. The load might be a dc motor driving a pump or it might be a battery, for example. Before the load is connected, the module sitting in the sun will produce an open-circuit voltage V_{OC}, but no current will flow. If the terminals of the module are shorted together (which doesn't damage the module at all, by the way), the short-circuit current I_{SC} will flow, but the output voltage will be zero. In both cases, since power is the product of current and voltage, no power is delivered by the module and no power is received by the load. When a load is connected, some combination of current and voltage will result and power will be delivered. To figure out how much power is delivered, we have to consider the **I-V** characteristic curve of the **module** as well as the **I-V** characteristic curve of the **load**.

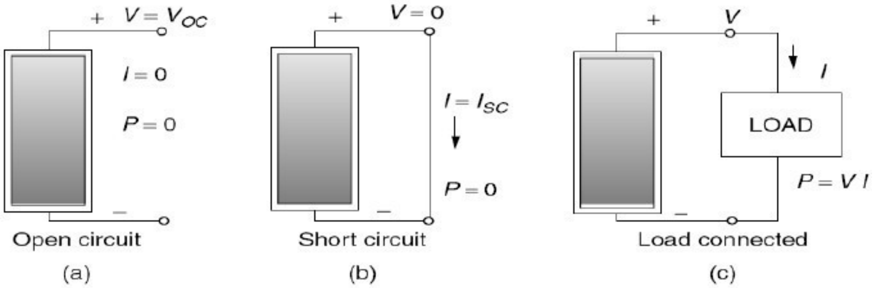


Figure-6: No power is delivered when the circuit is open (a) or shorted (b). When the load is connected (c), the same current flows through the load and module and the same voltage appears across them.

Figure-7 below shows a generic **I-V** curve for a PV module, identifying key parameters like open-circuit voltage V_{OC} and short-circuit current I_{SC} that we have explained**.** Also shown is the product of voltage and current, i.e., the power delivered by the module. At the two ends of the **I-V** curve, the output power is zero since either current or voltage is zero at those points. The ***'Maximum Power Point'*** (MPP) is that spot near the knee of the **I-V** curve at which the product of current and voltage reaches its maximum. The voltage and current at the MPP are designated as V_m and I_m *in* general and as V_R and I_R (*rated voltage* and *rated current*) under idealized test conditions.

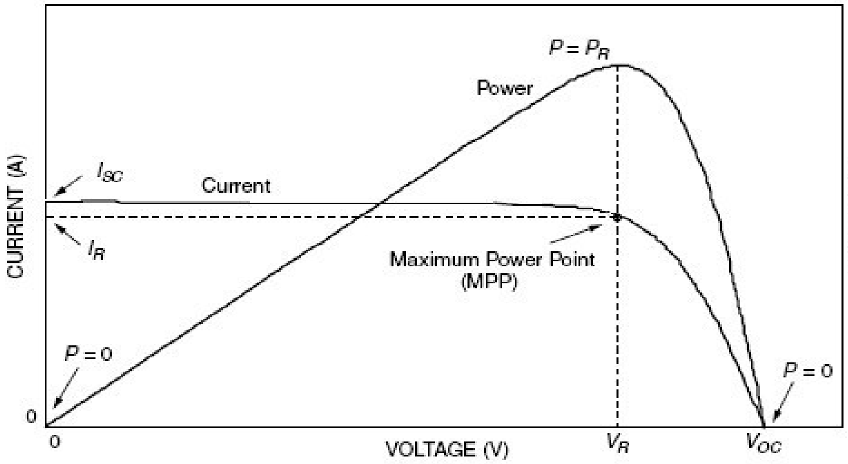


Figure-7: The I –*V* curve and power output for a PV module. At the maximum power point (MPP) the module delivers the Maximum Power that it can under the given conditions of sunlight and temperature .

Another way to visualize the location of the *Maximum Power Point* is by trying to find the biggest possible rectangle that will fit beneath the **I-V** curve. As shown in the figure-**8** below the sides of the rectangle correspond to current and voltage, and so its area is power.

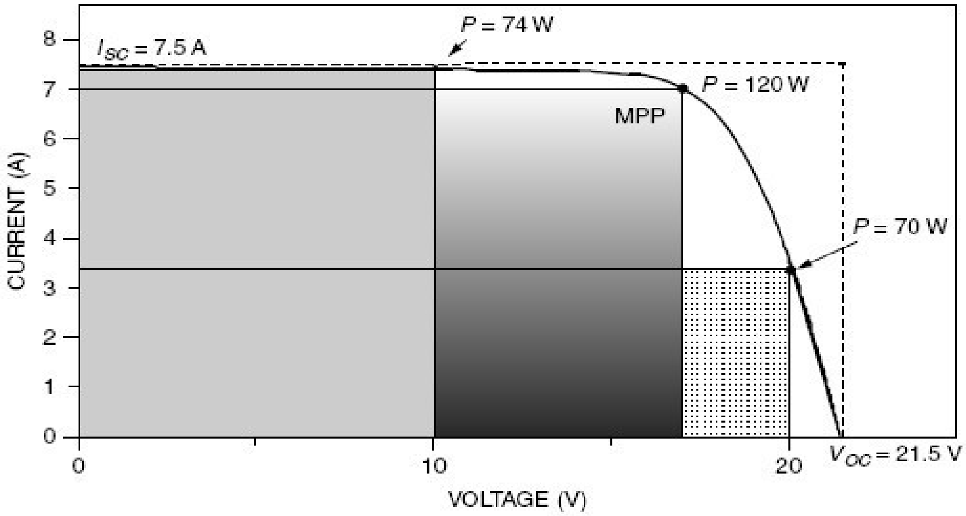


Figure-8: The Maximum Power Point (MPP) corresponds to the biggest rectangle that can fit beneath the *I* –*V* curve. The fill factor (FF) is the ratio of the area (power) at MPP to the area formed by a rectangle with sides V_{OC} and I_{SC}.

The italicized material given below between the marked lines is not in syllabus. Furnished just for information only.

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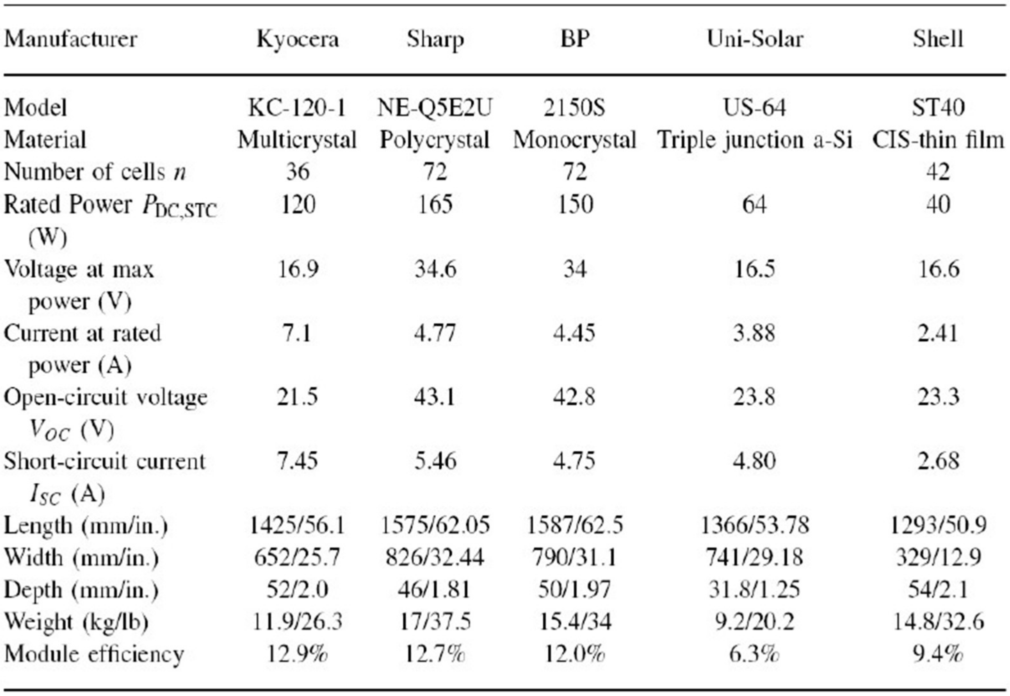
Since PV I –V curves shift all around as the amount of insolation changes and as the temperature of the cells varies, standard test conditions (STC) have been established to enable fair comparisons of one module to another. Those test conditions include a solar irradiance of 1 kW/m^2 (1 sun) with spectral distribution Shown in 'unit-1 Fig-22', corresponding to an air mass ratio of 1.5 (AM 1.5). The standard cell temperature for testing purposes is 25◦C (it is important to note that 25◦ is cell temperature, not ambient temperature). Manufacturers always provide performance data under these operating conditions, some examples of which are shown in table below. The key parameter for a module is its rated power; to help us remember that it is dc power measured under standard test conditions, it has been identified in the table below as PDC, STC. Later we'll learn how to adjust rated power to account for temperature effects as well as see how to adjust it to give us an estimate of the actual ac power that the module and inverter combination will deliver.

Table: Examples of PV Module Performance Data Under Standard Test Conditions (1 kW/m2, AM 1.5, 25◦C Cell Temperature)



Manufacturer	Kyocera	Sharp	BP	Uni-Solar	Shell
Model	KC-120-1	NE-Q5E2U	2150S	US-64	ST40
Material	Multicrystal	Polycrystal	Monocrystal	Triple junction a-Si	CIS-thin film
Number of cells n	36	72	72		42
Rated Power $P_{DC,STC}$ (W)	120	165	150	64	40
Voltage at max power (V)	16.9	34.6	34	16.5	16.6
Current at rated power (A)	7.1	4.77	4.45	3.88	2.41
Open-circuit voltage V_{OC} (V)	21.5	43.1	42.8	23.8	23.3
Short-circuit current I_{SC} (A)	7.45	5.46	4.75	4.80	2.68
Length (mm/in.)	1425/56.1	1575/62.05	1587/62.5	1366/53.78	1293/50.9
Width (mm/in.)	652/25.7	826/32.44	790/31.1	741/29.18	329/12.9
Depth (mm/in.)	52/2.0	46/1.81	50/1.97	31.8/1.25	54/2.1
Weight (kg/lb)	11.9/26.3	17/37.5	15.4/34	9.2/20.2	14.8/32.6
Module efficiency	12.9%	12.7%	12.0%	6.3%	9.4%

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3. Cell efficiency & Fill Factor

Cell Efficiency: It is defined as the ratio of maximum electrical power output to the radiation power input to the cell and it is expressed in percentage. It is considered that the radiation power on the earth is about 1000 watt/square meter hence if the exposed surface area of the cell is A then total radiation power on the cell will be 1000 A watts. Hence the efficiency of a solar cell may be expressed as**:**

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

Fill factor**:** This is another quantity that is often used to characterize module performance. The *fill factor* (FF) is the ratio of the power at the maximum power point to the product of $\mathbf{V_{OC}}$ and $\mathbf{I_{SC}}$

$$\text{Fill factor (FF)} = \frac{\text{Power at the maximum power point}}{V_{OC}\ I_{SC}} = \frac{V_R I_R}{V_{OC} I_{SC}}$$

So FF can be visualized as the ratio of two rectangular areas i.e. ratio of the rectangle area corresponding to MPP and the rectangle area corresponding to $\mathbf{V_{OC}}$ **&** $\mathbf{I_{SC}}$ (shown in dotted lines) as shown in the earlier figure .

Fill factors of around 70–75% for crystalline silicon solar modules are typical.

4. Effect of irradiation and temperature:

I-V curves shift with change in cell temperatures and Insolation. Manufacturers often provide *I* –*V* curves that show how the curves shift as insolation and cell temperature changes. Figure below shows examples for a typical ***(the Kyocera 120-W)*** multi crystal (poly crystal) - silicon module described in the table above.

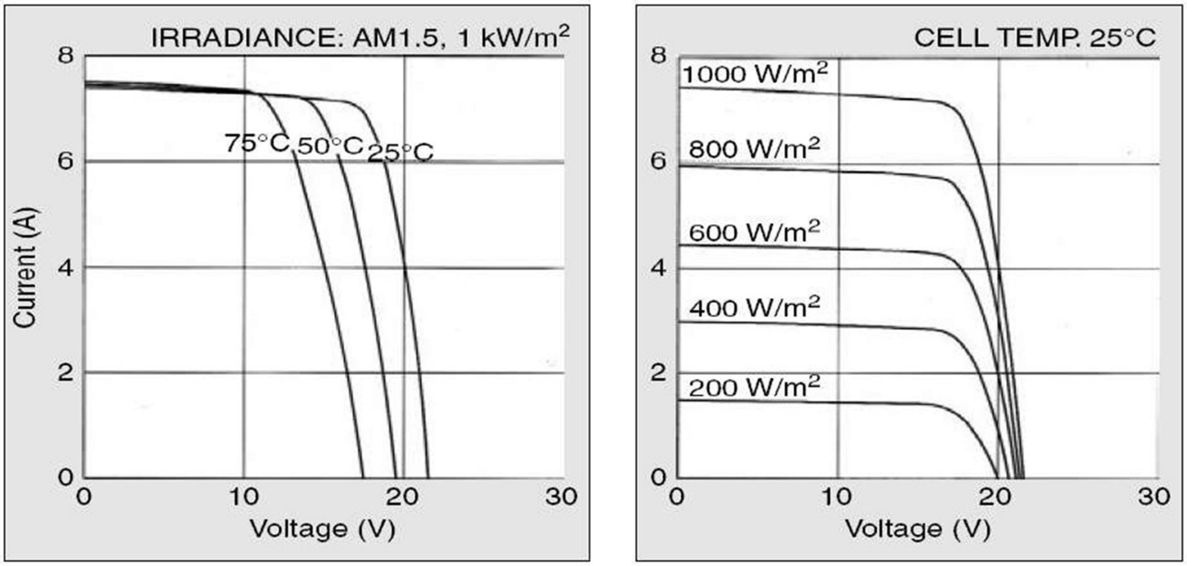

Figure-9: Current-voltage characteristic curves under various cell temperature and irradiance levels for a typical PV module.

As can be seen in the figure above, as cell temperature ***increases***, the open-circuit voltage **V_{OC}** ***decreases*** substantially while the short-circuit current **I_{SC}** ***increases*** only slightly thus effectively decreasing the maximum power and efficiency. Solar cells therefore perform better on cold, clear days than hot ones. Due to this significant shift in performance as cell temperature changes, the temperature needs to be included in any estimate of module performance.

Cell temperature varies not only because of ambient temperature change, but also because of change in insolation on the cell. Since only a small fraction of the insolation hitting a module is converted to electricity and carried away, most of that excess incident energy is absorbed and converted into heat.

5. Principles of Maximum Power Point Trackers:

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).

We also know that the operating point of any power system i.e. 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-9 (a) & (b) below and supplying power to three different loads R_1,R_2,and R_3. As the load resistance increases from R_1 to R_2 the operating point shifts from A_1 to A_2 and when load resistance increases from R_2 to R_3, the operating point moves from A_2 to A_3. As can be seen the maximum power is delivered by the module to the load when the load resistance is R_2. 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.

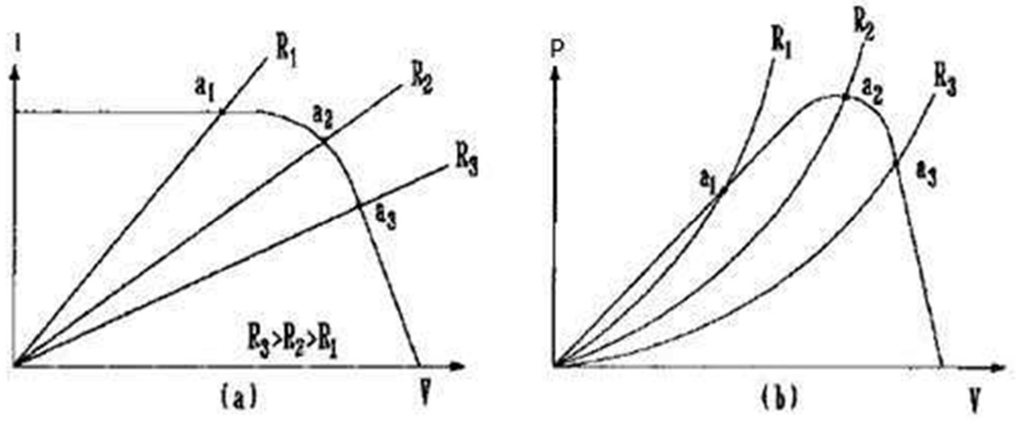

Figure-9: Demonstration of the point that Maximum Power Transfer From a given Solar cell @ given conditions takes place only with a specific load.

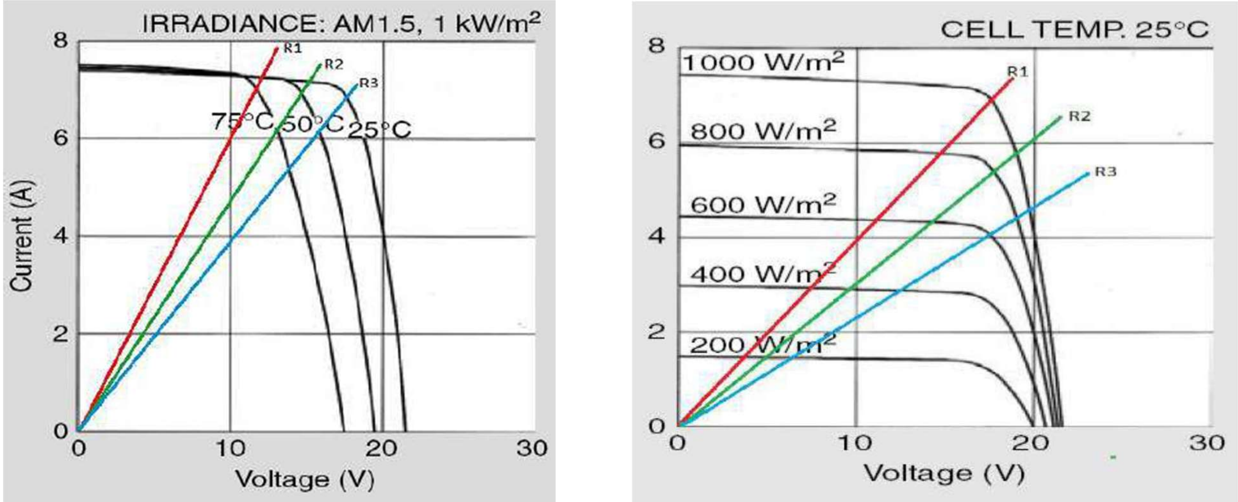

Figure-10: (a) Effect of Temperature and (b) Insolation along with load on the shift of the Maximum Power Point.

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.

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.

In order to carry out such complex functions Maximum power point trackers normally utilize microprocessor based controllers with sophisticated control algorithms.

Solar Power plants operate in both Off - Grid and ON - Grid modes. MPPTs make the best use of all the energy generated by the panels in both the cases as below:

- In the case of ON-Grid PV plants, MPPT is used to extract the maximum power from a PV array, convert this to alternating current (AC) and forward the excess energy to the power grid after catering to the local Load. If the power is less, then it draws the additional power from the Grid.

- In the case of OFF - Grid PV plants where battery storage is necessary, MPPTs are used as charge controllers to extract the full power from the Solar cell and distribute between the load and for charging the battery as necessary.

6. 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.

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.

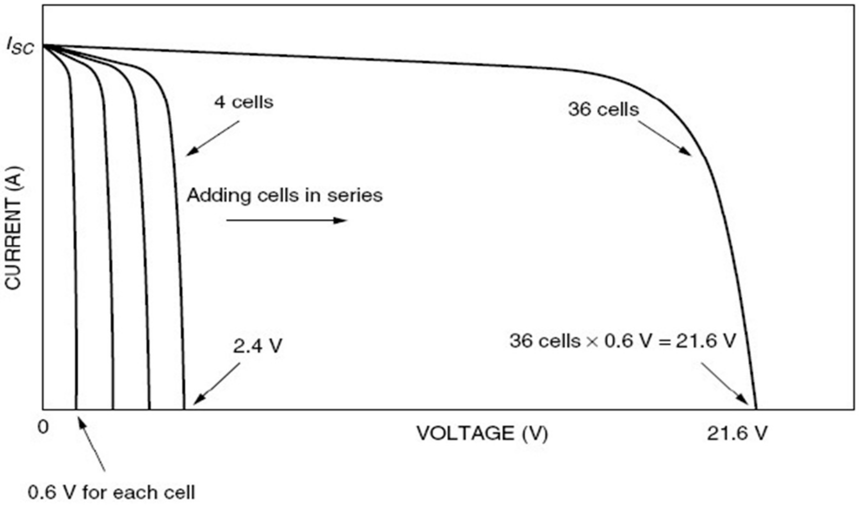

Figure-11: For cells wired in series, their voltages at any given current add. A typical module will have 36 cells.

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.

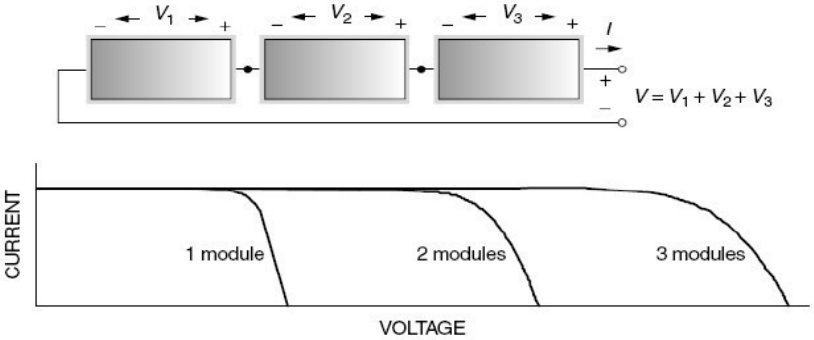

Figure-12: Modules in series, at any given current the voltages add

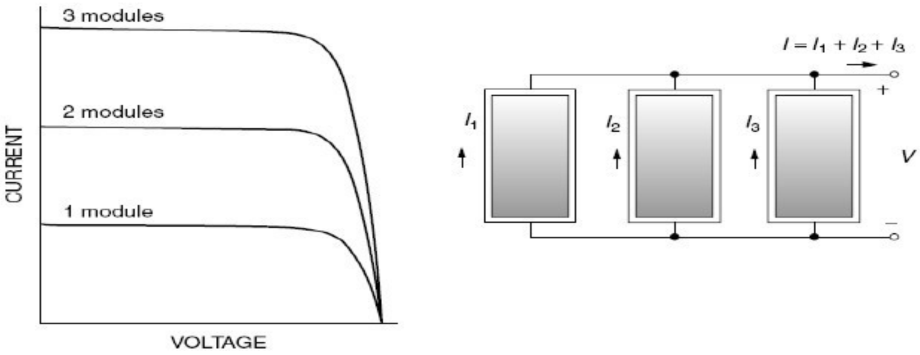

Figure-13: Modules in parallel, at any given voltage the currents add.

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*.** Figure below shows this distinction between cells, modules, and arrays.

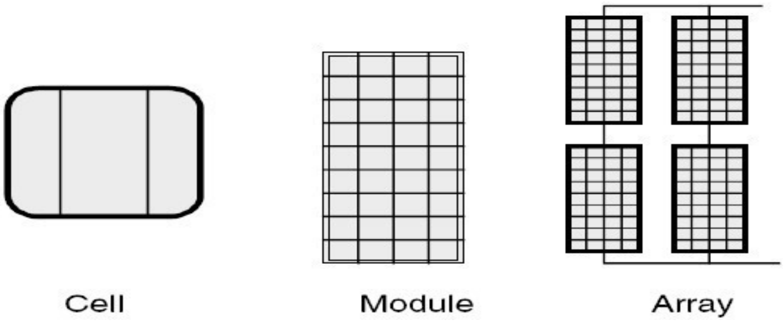

Figure-14: Photovoltaic cells, modules, and arrays

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Figure below shows the actual construction of a module in a frame that can be mounted on a structure.

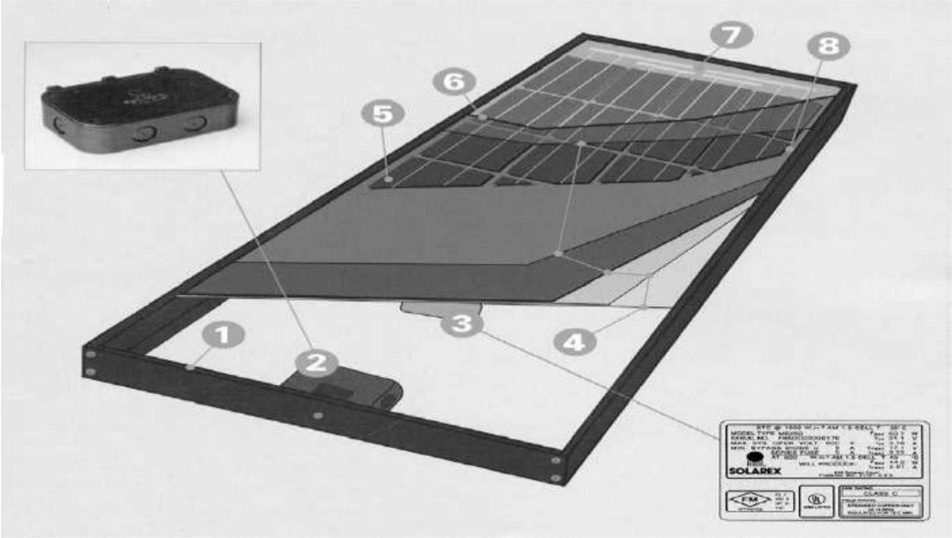

Figure-15: Construction of pv module in Frame : 1) frame, 2) weatherproof junction box, 3) rating plate, 4) weather protection 5) PV cell, 6) tempered high transmissivity cover glass, 7) outside electrical bus, 8) frame clearance.

Mounting of the Modules:

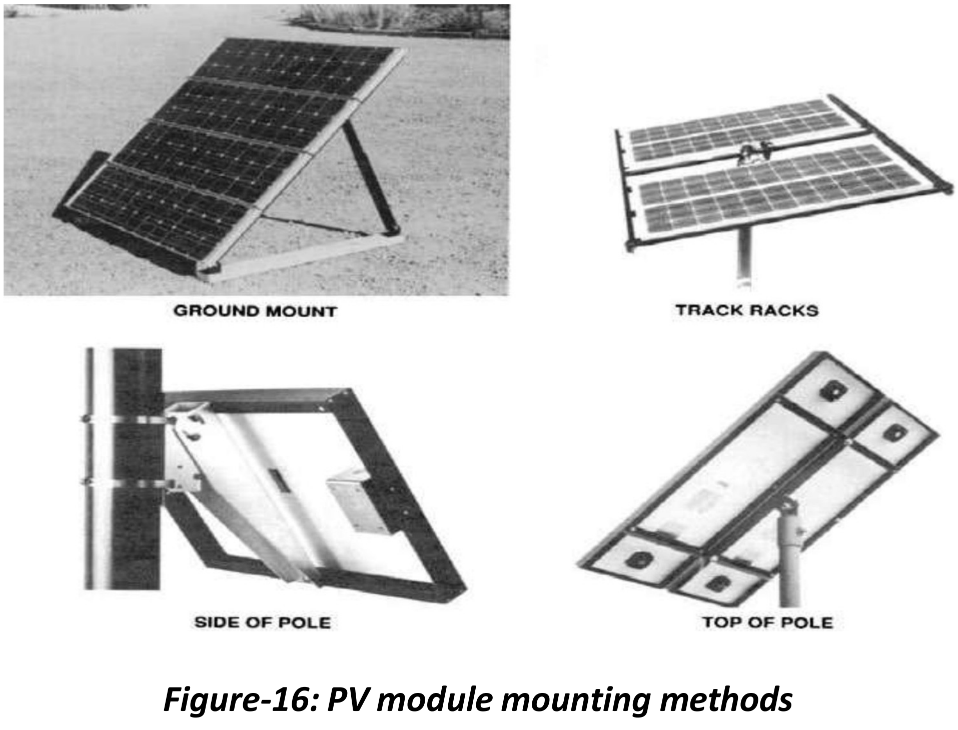
GROUND MOUNT
TRACK RACKS
SIDE OF POLE
TOP OF POLE

Figure-16: PV module mounting methods

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7. 0 Balance of systems:

The array of a set of PV modules by itself does not constitute the total PV power system. We need several other components and subsystems to have a complete solar power station. All other components and subsystems other than the main PV panels together are known as BOS (**B**alance **O**f **S**ystems).

The following are some of the major BOS components/subsystems: (1) Mounting Structure (2) Cables and Protection devices (3) Inverters (4) Energy Storage systems (Batteries) (5) Charge Controllers and will be explained briefly.

7.1 Mounting Structure

The PV module should be designed in such a way that it can withstand rain, hail, wind and other adverse conditions. The common aspects to be taken care of in the design and selection of the mounting structures are (i) Durability of the design (ii) Tilt angle (iii) Orientation and (iv) PV array shading. Correct and optimum Tilting angle maximizes the efficiency of the solar PV module. Hence a well designed mounting structure apart from giving strength and capability to withstand high winds also serves as a PV module tilting structure which tilts the PV arrays at an angle determined by the latitude of the site location, to maximize the solar insolation falling on the panels. At any given location tilt is required in NS and EW directions to maximize the solar insolation on the panel. But normally tilt is given NS alone and in EW the Panel mount has to track the Sun from morning to evening. Normally low cost systems use fixed tilt in both axes. For EW if tracking feature is required it requires an electrical drive for the Mount.
Similarly, shading has a significant effect on PV generation. Partial shading can reduce the system production up to 90 %. Thus, it is essential that the PV arrays are installed at a suitable location without any shading.

For PV array installation with multiple rows the shading de-rate factor should account for losses that may occur when a row shades an adjacent row.

7.2. Cables and Protection Devices

The main purpose of cabling is to allow a safe passage of current. Appropriate cable sizing allows the current to be transferred within an acceptable loss limit to ensure optimal system performance. In order to establish connection between solar PV modules, charge controller, battery, Inverter and finally the Load, cables are needed. The size of the cable is determined based on the transmission length, voltage, flowing current and the conductor material. The cable in installation sites should be sized correctly. An undersized cable can lead not only to lower efficiency but also to fire hazards. In addition to the appropriate sizing, selection of relevant type of wire is also important in the case of solar PV application. For outdoor applications UV stabilized cable must be used, while normal residential wires/cables can be used indoors. This ensures the long term and safe functioning of the cable and hence reduction in the system ongoing maintenance.

7.3. Inverters:

Islanding is the condition in which a distributed generator (DG) continues to power a location even though electrical grid power is no longer present. Islanding can be dangerous to utility workers, who may not realize that a circuit is still powered and proceed for service on live lines which is very dangerous. Additionally, without strict frequency control (without Grid frequency reference required for the local PV Plant is lost) the balance between load and generation in the islanded circuit is going to be violated, leading to abnormal frequencies and voltages. For those reasons, distributed generators must detect islanding and immediately disconnect from the circuit. This is called anti**-islanding**.

*Some designs, commonly known as a **micro grid**, allow for intentional islanding. In case of an outage, a micro grid controller disconnects the local circuit from the grid on a dedicated switch and enables the distributed generator(s) to power the entire local load.*

Types of Inverters and Their Classification:
Inverters can be classified based on three aspects. 1. Their basic design 2.Their topology, i.e. size, voltage and power level 3. Their utility based on the type of plant.

Basic Design:

Inverters can be classified by their output waveform into four categories: square wave, modified square wave, also called quasi-square wave, multilevel and sine wave (synthesized from a high frequency PWM). The square and quasi-square wave inverters are not recommended due to their poor quality waveform. Multilevel and sine wave inverters are considered to be the state of the art technology. The Multilevel inverter is based on low frequency and the sine wave inverter is based on high switching frequency. Multilevel inverters are the best available solution for high power applications. However, for medium and low power applications, there is not a clear tradeoff to make it more appealing than sine wave inverters, or vice versa. High frequency inverters favor compactness and reduced cost, while low frequency ones are claimed to have the best efficiency and robustness. The final choice of one inverter over the other depends on the application. In our application of stand-alone renewable energy systems (SARES), multilevel inverters have great potential with their reliability, surge power capacity and efficiency.

Based on size: Based on the size of the Solar Plant the solar PV inverters can be classified into (i) Centralized inverters (ii) String inverters (iii) Multi string inverters and (iv) Module integrated inverter.

Centralized Inverters:

In this category, a single large inverter is connected to many PV modules wired in series to form strings with up to 600 V/1,000 V of open-circuit voltage. All the solar PV modules are connected in strings, generating a sufficient high voltage to avoid further amplification and the strings are then connected in parallel to support high power to output as shown in the figure below.

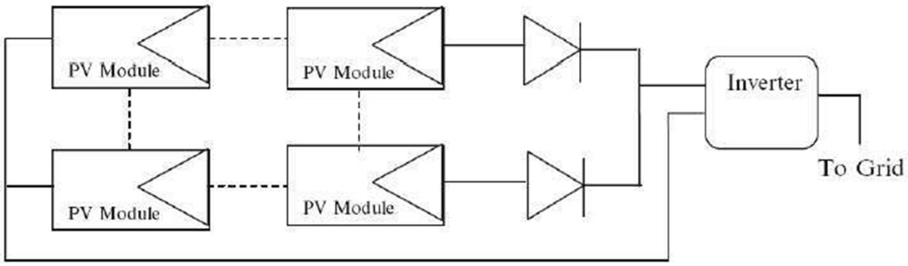

Figure-17: Centralized Inverter

The conversion efficiency of many central inverters is 95 % or higher, and they feature a relatively low unit cost per watt. However, central inverters have multiple drawbacks.

String Inverters:

This topology is introduced into the market relatively recently and is suitable for small loads. Figure below shows string of PV modules connected in series with an Inverter. With such a single string load current would be limited

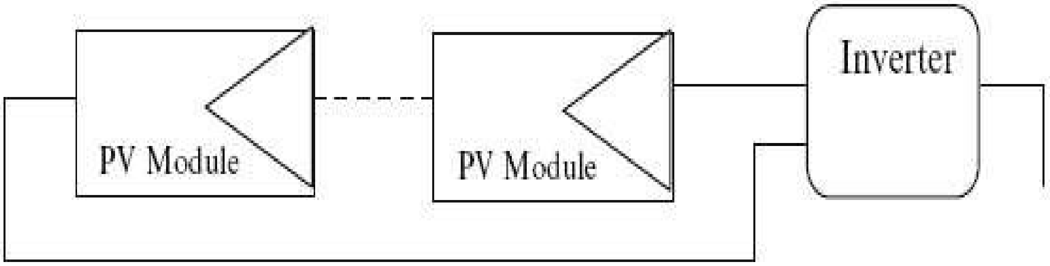

Figure-18: String inverters

Multi-string Inverters:

The above mentioned current limitation can be overcome n this configuration shown below. ***DC-DC converter*** is implemented for each string for MPP tracking and power combination of different string to a DC bus.

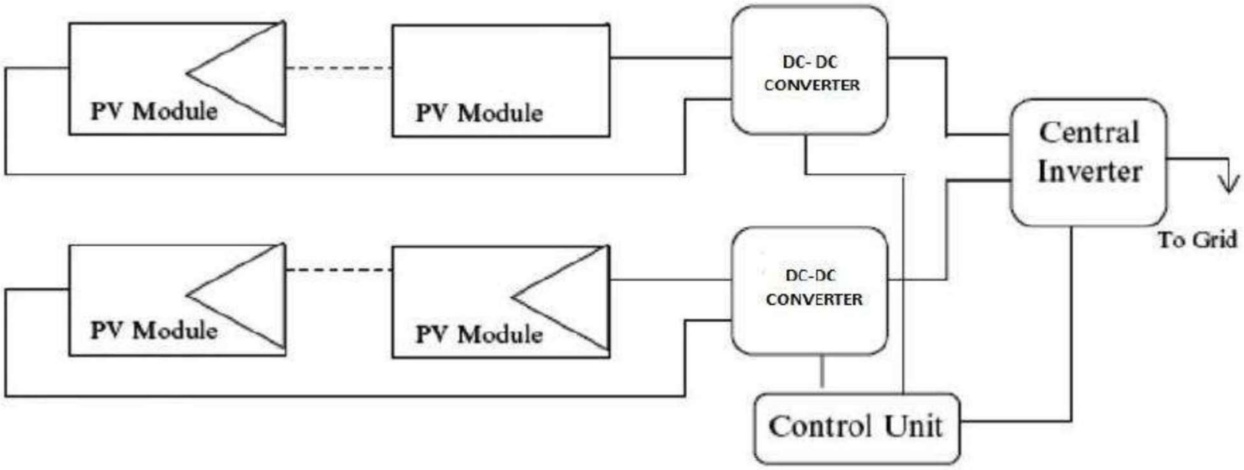

Figure-19: Multi-string inverters

Multi-string inverter features optimal MPP tracking for a single string of PVs. A big power stage works as a grid connected half bridge inverter without transformer. The multi-string inverter is useful when PV strings of different rated power, different orientation are combined.

Module Integrated Inverter/Micro-inverters:

Micro inverters are complete, environmentally protected integrated units consisting of solar cells, inverter, and other components, designed to generate AC power with a single unit.

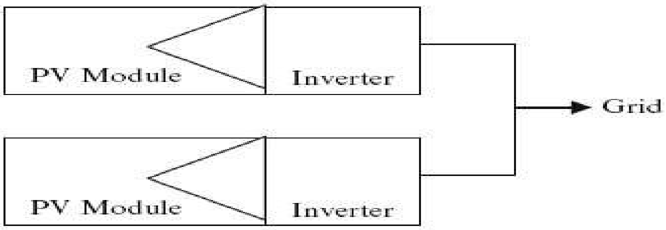

Figure-20: Micro-Inverters

The micro-inverter, also called AC module is the integration of PV and inverter into one electrical device. In an AC module, a micro-inverter is directly integrated with a PV panel, yielding a module that natively generates grid-compatible AC power.

7.4 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. Presently a lot of R&D work is going on in the field of batteries and other Energy storage systems for their effective and efficient use not only in Solar PV Systems but also in wind energy systems and Electric vehicles.

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 %). 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'. 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.

7.5 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.

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.

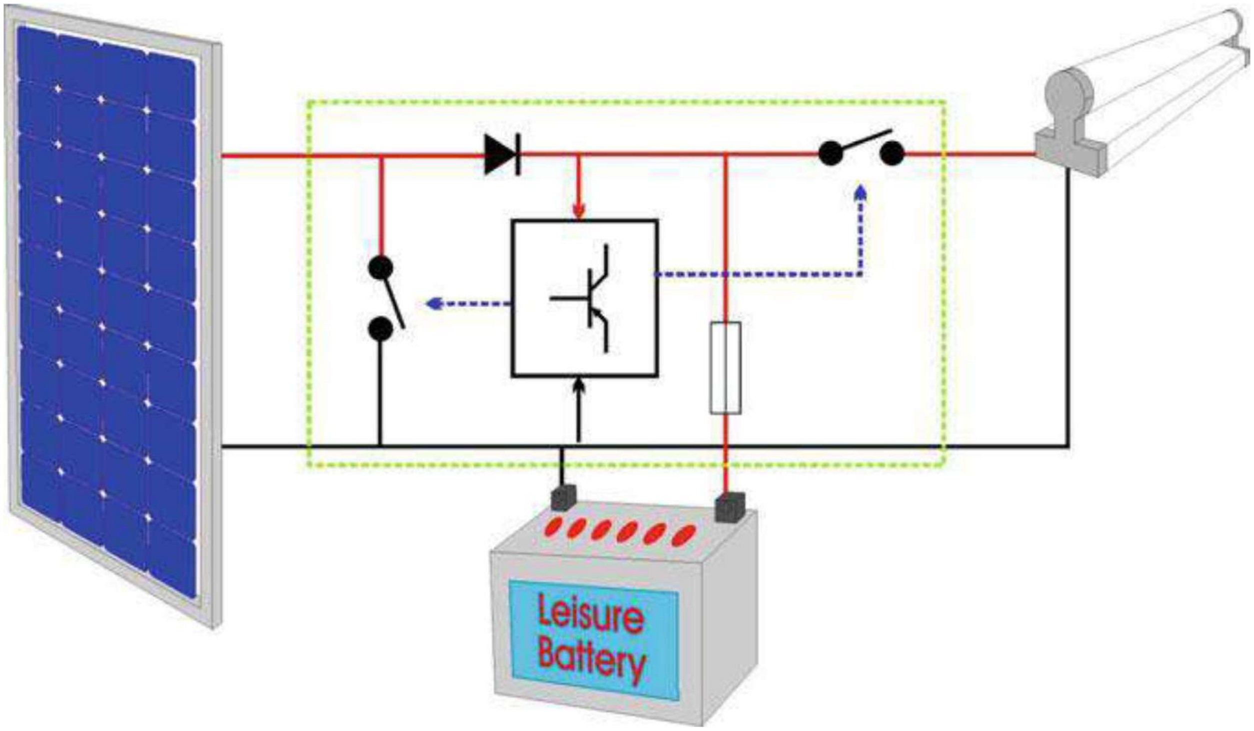

Figure-21: Circuit diagram of a solar-charge controller

8.0 Classification of PV systems:

Photovoltaic power systems can be classified according to several criteria based on their size, physical location, functional & operational requirements, their subsystem configurations, how the equipment is connected to other power sources , electrical loads etc. The two principal classifications are 'Grid-connected' or 'Utility-Interactive systems' and 'Stand-alone systems'. Photovoltaic systems can be designed to provide DC and/or AC power service, can operate interconnected with or independent of the utility grid, and can be combined with other energy sources and energy storage systems. When they are connected and operate with other Energy sources they are termed as 'Hybrid Systems'. It is difficult to draw a fine line between the various types of PV systems that are being designed and commissioned because of several attributes commonly shared by any system. However the most commonly adopted classifications are:

Based on size and Location:

1. *Central PV Power Station System*: One of the most important and essential requirement of such Plants is to cater to the large needs of the users of the normal Grid power to reduce the dependence on thermal power gradually and in a phased manner. Though DG power has its own advantages, such plants cannot be setup in urban areas by users of low income group who form a large part of the urban population and their need has to be met by CG only.

2. *Distributed PV System*: Distributed generation refers to solar power plants setup near the load centre i.e. where it will be used.. Distributed generation may serve a single user, such as a home or business, in which case it is also classified as '*Standalone* 'or it may be part of a micro grid (a smaller grid that is also tied into the larger electricity delivery system), such as at a major industrial facility, a military base, or a large college campus in which case it is also termed as *'Grid Interactive*' systems.

Based on other criterion like configuration, connection with Grid, storage etc.:

1. Stand-alone PV system
2. Grid Interactive PV System
3. Hybrid solar PV system

8.1. Stand-alone PV system:

Important features:

- Stand-alone Solar systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply certain DC and/or AC electrical loads.
- PV panels are connected in series/parallel to obtain the desired DC voltage and also to sustain the connected load while simultaneously charging the batteries to give the required backup power.
- The charge controller regulates the current output and prevents the voltage level from exceeding the maximum value for charging the batteries.
- During the sunshine hours, the load is supplied with DC power while simultaneously charging the battery.
- Battery bank sizing depends on a number of factors, such as the duration of an uninterrupted power supply required to the load when there is less or no radiation from the sun.
- The battery bank while giving back up facility results in around 20–30 % power loss due to heat when in operation.
- When designing a solar PV system with a battery backup, the designer must take this loss into account and also should plan a location with adequate space and ventilation for safe housing of the battery racks.
- Normally when Grid is close by, people will not go for a Standalone system with full battery backup since utility supply on Grid itself will serve as power backup when there is no adequate Sunshine. Only a small battery backup is normally provided as contingency to support essential loads.
- But in case of remote locations where nearby Grid access is not there Standalone PV systems must have battery backup except for direct online systems.

- Further, the solar and wind power outputs can fluctuate on an hourly or daily basis. The stand-alone system must, therefore, have some means of storing energy, which can be used to supply the load during the periods of low or no power output as and when required.
- The major application of stand-alone power systems are in remote areas where utility lines are uneconomical to install due to terrain, the '***right of way***' difficulties or the environmental concerns. Even without these constraints, building new transmission lines is expensive in far off areas.

Stand alone systems can be designed and configured in different ways with or without control functions like charge controller or MPPT, with or without battery backup etc based on user requirements and budget. This has become possible due to the enormous development in the field of Electronics and Computers which takes care of all complex monitoring and control functions. To understand and appreciate the versatility of such PV systems in terms of their capabilities, we will study one system with battery backup and several other control features.

Standalone PV system with battery backup and some additional features:

Figure-22 below shows a Standalone PV system with battery backup along with several features/ important subsystems like MPPT, Battery Charger etc.In such a stand-alone PV power system the peak power tracker senses the voltage and current outputs of the array and continuously adjusts the operating point using the switching Regulator to extract the maximum power under the given climatic conditions. The output of the array goes through this regulator to the inverter, which converts DC into AC. The array output in excess of the load requirement is used to charge the battery. The battery charger is usually a DC-DC buck converter. When the sun is not available, the battery discharges to the inverter to power the loads. The battery discharge diode D_b is to prevent the battery from being charged when the charger is opened after a full charge or for other reasons. The array diode D_a is to isolate the array from the battery, thus keeping the array from acting as load on the battery when it is not generating power.

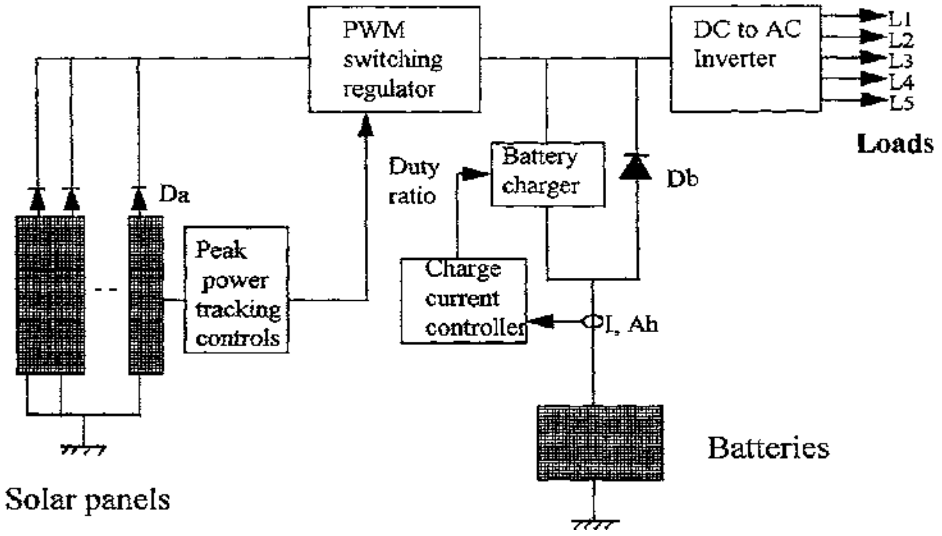

Figure-22: Photovoltaic stand-alone power system with battery backup and other subsystems like battery charger, Charge controller, MPPT etc.

8.2. Grid interactive PV systems:

Important features:

- A **Grid-connected Photo Voltaic (PV) system** is a Solar PV Power generating system that is connected to the utility Grid. A grid-connected PV system consists of a Grid Interface system apart from the normal solar panels, Inverters and a power conditioning unit. They range from small residential and commercial roof top systems to large utility-scale Solar Power Stations.. A grid-connected system will include an integrated battery system as well but of a very small capacity to serve as a backup for essential monitoring and control functions.
- Grid-connected or utility-interactive PV systems are designed to operate in parallel and interconnected with the electric utility grid. The most important subsystem in grid-connected PV systems is Power Conditioning Unit (PCU). It generally includes MPPT, charge controller and most importantly the grid interface unit apart from the Inverter. Apart from the inverter, the PCU mainly consists of a Grid interface between the PV system, AC output circuits and the

electric utility network, typically at an on-site distribution panel or service entrance.

  - This allows the AC power produced by the PV system to either supply on-site electrical loads or to back-feed the grid when the PV system output is greater than the on-site load demand. At night and during other periods when the electrical loads are greater than the PV system output, the balance of power required by the loads is received from the electric utility.
  - This interface also automatically stops supplying power to the grid when the utility grid is not energized. This safety feature is required in all grid-connected PV systems, and ensures that the PV system will not continue to operate and feed back into the utility grid when the grid is down for service or repair.
  - The grid interface also incorporates synchronization circuitry that allows the production of sinusoidal waveforms in synchronization with the electrical service grid.

- One of the important and useful feature of a grid-connected system is net metering. Net meters have a capability to record consumed or generated power in an exclusive summation format. The recorded power registration is the net amount of power consumed—the total power used minus the amount of power that is produced by the solar power system and fed into the grid.Net meters are supplied and installed by utility companies that provide Grid-connection service systems. Net metered solar PV power plants are subject to specific contractual agreements and are subsidized by state governmental agencies.

The wind and photovoltaic power systems have made a successful transition from small stand-alone systems to large grid-connected systems with several safety and consumer friendly features like 'Ant islanding' and 'net meetering'. In nutshell, the grid supplies power to the site loads when needed, or absorbs the excess power from the site when available.

Typical Grid Interactive PV system:

Typically a Grid Interactive PV system comes with battery backup as shown in the figure-23 below. When an outage occurs, the unit disconnects from the utility and powers specific loads. If the outage occurs in daylight, the PV array will be able to assist the load in supplying the power.

The major component is the Power Conditioning Unit (PCU) shown as a single big block in the figure. As already explained the PCU consists of several other important subsystems like MPPT, Charge controller, Interfacing & Controller section etc. apart from the inverter.

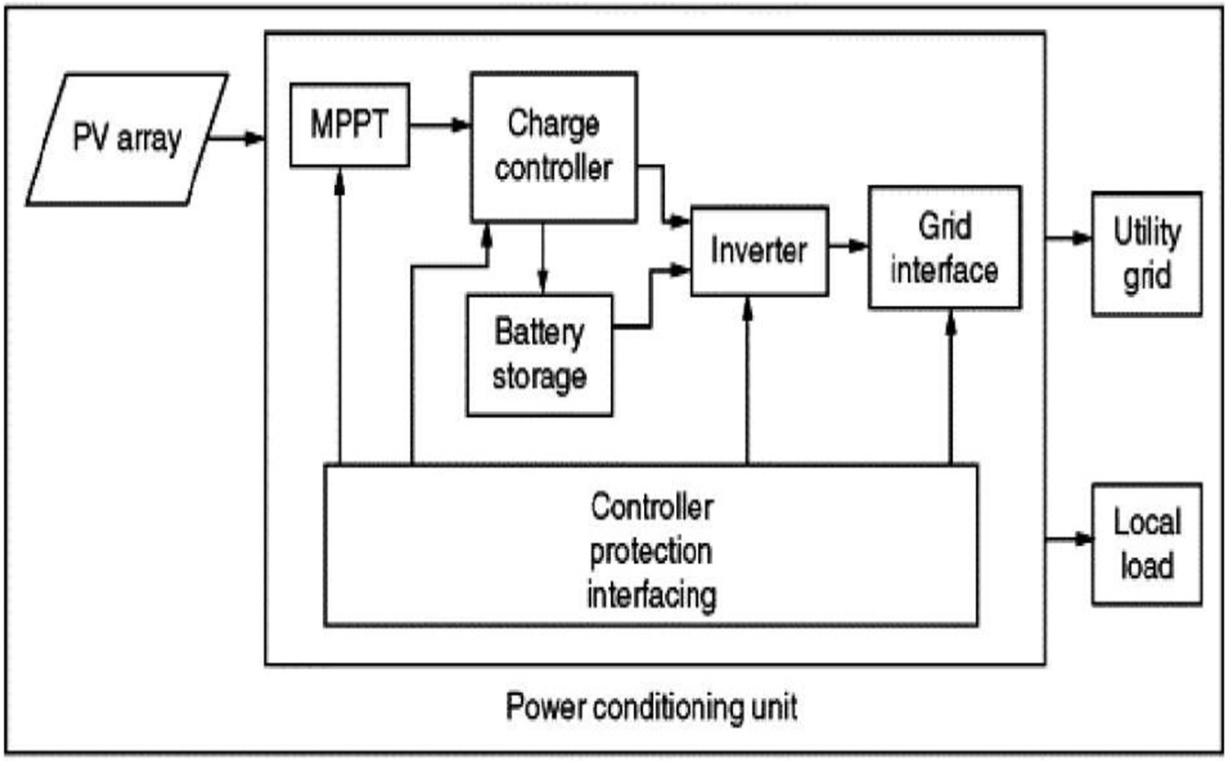

Figure-23: Grid Connected PV system with battery backup

The inverter is the key to the successful operation of the system, and it is also the most complex hardware. The inverter requirements include operation over a wide range of voltages and currents and regulate output voltage and frequency while providing AC power with good power quality which includes low total Harmonic distortion and high power factor, in addition to highest possible efficiency for all solar irradiance levels.

Inverters can be centralized inverters for the whole array of PV or separate string inverters for each PV module.

The special features like (i) Grid Interface Requirements (ii) Synchronizing with Grid etc. related to "Grid Interactive systems" will be covered at the end in Unit-5 after covering Wind electrical systems since these aspects are common to both Solar and Wind Electrical systems.

8.3 Hybrid solar PV system:

Hybrid Solar PV systems generally refer to the combination of more than one power source. The certainty of meeting load demands at all times is greatly enhanced by the hybrid system using more than one power source. Most hybrid systems use diesel generator as second source along with PV or Wind Turbine power systems which act as the primary power sources, since Diesel Generator (mostly abbreviated as DG Power) provides more predictable power on demand.

Though almost all solar PV systems generally use battery bank to store energy output from the panels to accommodate a pre-defined period of insufficient sunshine, there may be still exceptional periods of poor weather when another alternative source such as a Diesel Generator is required for guaranteed power availability. The batteries meet the daily short term load fluctuations & PV source power short falls, while the Diesel Generator takes care of the long-term load fluctuations & PV source power short falls. For example, the diesel generator is used in the worst case weather condition, such as extended overcasts in case of PV Hybrid systems and or during windless days or weeks in case of Wind power systems.

PV-Wind- DG Hybrid systems:

Though PV-hybrid systems are combined with other power sources - typically diesel generators as explained, occasionally another renewable supply such as a wind turbine is also used if suitable and favorable site conditions for both Solar and Wind power generation are available at the same place. This configuration is normally used in remote locations where large power plants are required to supply power to the Grid on a totally commercial scale/basis.

In the case of PV – Wind Energy systems one major advantage is optimum utilization of the vacant space between the Wind turbine towers by locating the PV modules in-between. But PV modules should have a adequate 'Shadow effect' mitigating diodes.

In this combination of Hybrid system the PV generator and the Wind Generator together would usually be sized to meet the base load demand, taking into consideration the duration of time in which each of these systems will be available independently and together. Like for example Day time and night time, summer and rainy season etc. This arrangement offers all the benefits of PV in respect of low operation and maintenance costs, but additionally ensures a secure supply.

Figure below shows the simple block diagram of a typical Solar PV hybrid system along with DG and Wind Power systems.

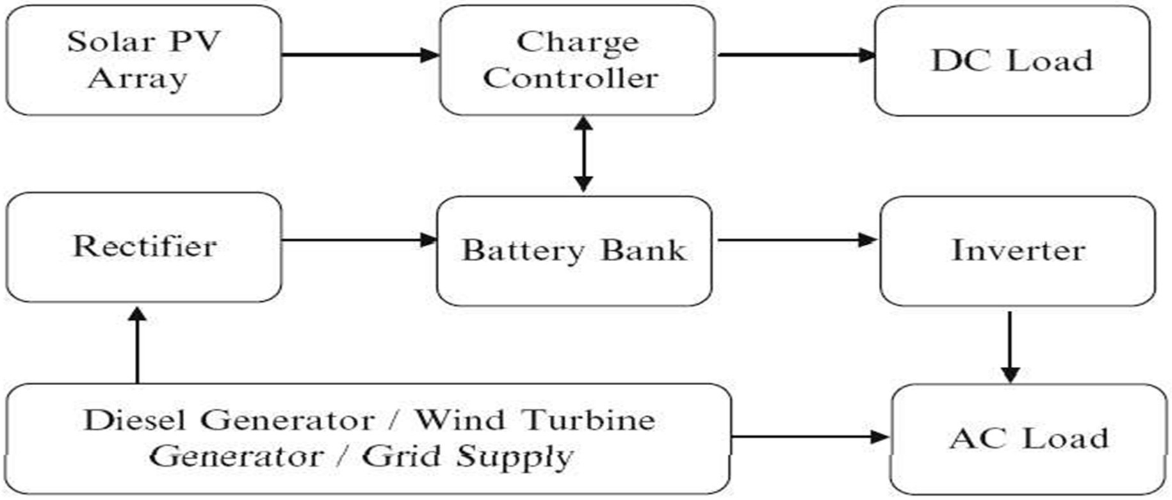

Figure-24: Block diagram of PV - DG - Wind Hybrid system

9. Important Formulae:

1. Shockley diode equation:

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

where **I_d** is the diode current (A), **V_d** is the voltage across the diode terminals from the *p*-side to the *n*-side (V), **I_0** is the reverse saturation current (A), **q** is the electron charge (1.602×10^{-19} C), **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 **I_d** and taking the junction temperature of 25^0 which is a standard we get

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

2. Solar cell I-V relation:

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

Where **'I_{SC}'** is the short circuit current of the Solar Cell obtained with load terminals shorted (i.e. V=0) and all other terms being same as defined for simple P-N Junction diode.

When the load terminals of the PV cell are left open, **I** = 0 and we can solve the above equation for the open-circuit voltage **V_{OC}** :

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

And at 25^0C, the above two equations become

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

And

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