5. Solar Photovoltaic

Technologies-Amorphous, monocrystalline, polycrystalline; V-I characteristics of a PV cell, PV module, array, Power Electronic Converters for Solar Systems, Maximum Power Point Tracking (MPPT) algorithms. Converter Control.

Introduction

What is photovoltaic (PV) technology and how does it work? PV materials and devices convert sunlight into electrical energy. A single PV device is known as a cell. An individual PV cell is usually small, typically producing about 1 or 2 watts of power. These cells are made of different semiconductor materials and are often less than the thickness of four human hairs. In order to withstand the outdoors for many years, cells are sandwiched between protective materials in a combination of glass and/or plastics.

To boost the power output of PV cells, they are connected together in chains to form larger units known as modules or panels. Modules can be used individually, or several can be connected to form arrays. One or more arrays is then connected to the electrical grid as part of a complete PV system. Because of this modular structure, PV systems can be built to meet almost any electric power need, small or large.

PV modules and arrays are just one part of a PV system. Systems also include mounting structures that point panels toward the sun, along with the components that take the direct-current (DC) electricity produced by modules and convert it to the alternating-current (AC) electricity used to power all of the appliances in your home.

The largest PV systems in the country are located in California and produce power for utilities to distribute to their customers. The Solar Star PV power station produces 579 megawatts of electricity, while the Topaz Solar Farm and Desert Sunlight Solar Farm each produce 550 megawatts.

Monocrystalline pv panels:

Like their given name, the monocrystalline solar panels are composed of monocrystalline cells. They are that type of cell that, a simple view, can be identified by its “black” color and with the corners cut with a chamfer (result of the cut of the cell).

The most common mode of manufacture of monocrystalline silicon cells (sc-Si) consists of starting from a single crystal silicon ingot, obtained by the methods of Czochralski (Cz) or the floating zone (FZ), and cut into wafers which constitute the substrate on which all the remaining process takes place (union “pn”, metallization, etc.).

Fig.1. monocrystalline

The above image is an example of this type of cell that we discussed. In addition to this, note that monocrystalline solar panels are the most efficient of all available in the sector.

Polycrystalline Solar Modules:

As we discussed with monocrystalline models, polycrystalline solar panels are composed, in this case, of polycrystalline cells. We can differentiate it by its "bluish" color and do not have the chamfer in the corners like the monocrystalline ones.

Polycrystalline silicon (mc-Si) cells also use silicon wafers as a substrate, but unlike monocrystallins, they come from cutting a silicon block that has been slowly allowed to solidify in a crucible and is made up of many small crystals of silicon.

This type of processing is less costly than the previous one, but considerably reduces the efficiency of the cells.

Fig.2.polycrystalline

We see in the image the visual difference between a polycrystalline cell and the previous monocrystalline cell from the previous point.

More recent advances, such as diamond wafer cutters, used by manufacturers such as SolarWorld, have led to an improvement in the silicon utilization efficiency (less material is wasted) and to wafer wafer thickness of less than 200 microns, although this thickness is close to its physical limit because we must take into account that the cell must be strong enough not to break in its subsequent manipulation for the manufacture of the panel.

In addition to this, it has been possible to improve the losses by reflection and a better capture of the light inside the cell by means of texturizing techniques and antireflective treaties.

As can be seen in the image, a series of micro-perforations with the aspect of an inverted pyramid have been practiced on the cell, which they do is to help improve the uptake of sunlight from the cell and, consequently, from the solar panel.

As we have already mentioned in previous articles, the conducting grid that forms the front contact of the cell usually consists on a series of "fingers" that are in direct contact with the semiconductor and that are connected between them by means of metallic strips (what is usually called Bus Bar).

The design of these "fingers" and the Bus Bar that cover the cell affects the solar panels efficiency in two ways:

On the one hand, it involves a shading that prevents some of the available radiation from reaching the interior of the cell and, on the other hand, introduces a resistance, due to the metal-semiconductor junction and the resistance of the material used. In this sense, it has evolved from the conventional technique of screen printing to laser buried contact, achieving a 25% improvement in the efficiency of the cell without raising the cost of manufacturing.

Both the mono and polycrystalline cells described have approximately 0.5 volt open circuit (Voc) and about 3 amps short current (the current is directly proportional to the cell area).

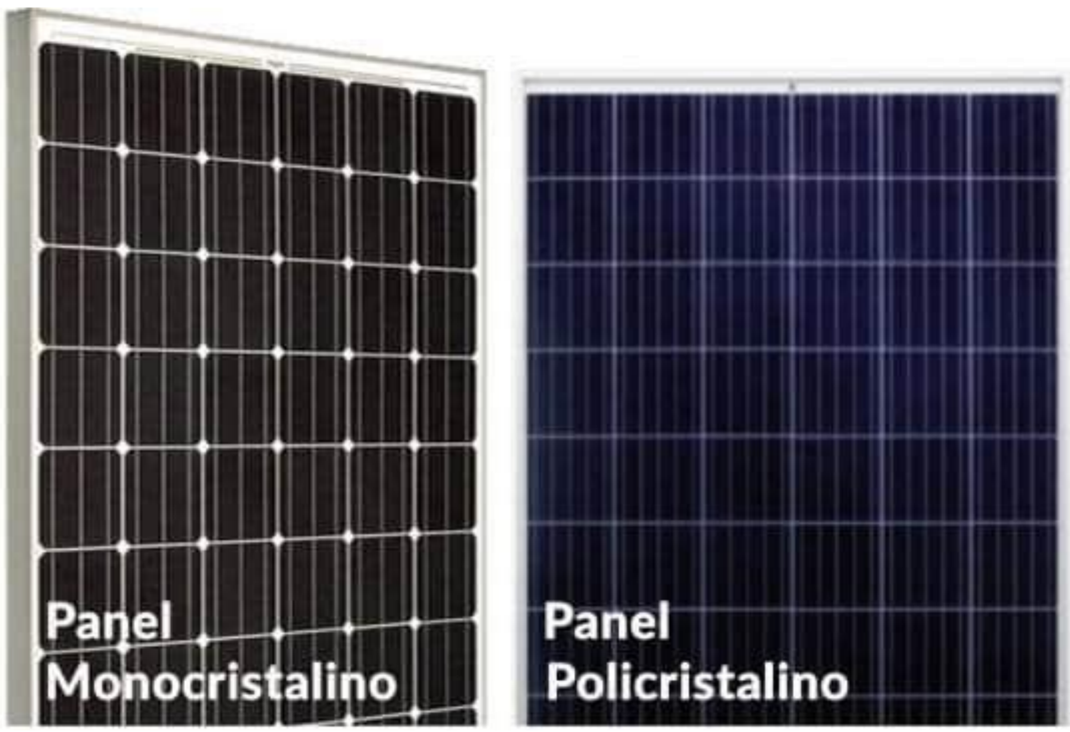

Fig.3.PV Panel

Of course, once the cells are obtained, they are assembled and passed a production process to give rise to what we end up seeing in our photovoltaic installation, which are the monocrystalline or polycrystalline solar panels depending on the type of cell.

3 Amorphous silicon panels (thin film):

Although the most common types of panels are the ones described, mono and polycrystalline, we must not forget also amorphous silicon solar panels, or also called "thin film".

The operation of a thin film solar cell of amorphous silicon is the same as the crystalline but its elaboration is very different. The characteristic aspects of this technology are:

Simple manufacturing process and easy automation.

Need for little active material and reduction of energy and cost.

Easy to realize flexible modules and with optimal quantum efficiency in a wide range of the spectrum.

Amorphous silicon cells have been the first thin-film cells to be marketed. However, due to the drop in prices experienced by crystalline solar panels, they have been losing positions in the market and are currently very small.

A-Si amorphous silicon technology has a considerably lower efficiency than those based on crystalline silicon, mainly due to the poor quality of the silicon used, whose internal structure makes it difficult to collect the photogenerated carriers. However, they are especially suitable for use in cloudy places, in dusty atmospheres, etc.

Fig.4. amorphous

As can be seen in the picture, amorphous silicon solar panels do not consist on the attachment of individual cells as in the crystalline solar panels, but in a tailor-made sheet in which thin strips are seen separating the cells, created and connected to each other during the elaboration of the module itself, whose framing facilitates the handling and assembly thereof. The range of voltages is also wider than in crystalline silicon, ranging from a few volts to tens of volts and makes them interesting also for solar pumping systems.

Commercially, solar panels are classified by their peak power (Wp), which is the power they can generate under standard conditions of measurement (STC), in other words, the power indicated in the product data sheet. Another of the data that usually look at the nominal voltage, which will indicate if the panel will be suitable for isolated systems of 12V, 24V or for network connection and self-consumption.

V-I characteristics of a PV cell:

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 p-n junction device. It is formed by joining p-type (high concentration of hole or deficiency of electron) and n-type (high concentration of electron) semiconductor material. at the junction excess electrons from n-type try to diffuse to p-side and vice-versa. Movement of electrons to the p-side exposes positive ion cores in n-side, while movement of holes to the n-side exposes negative ion cores in the p-side. This results in an electric field at the junction and forming the depletion region. When sunlight falls on the solar cell, photons with energy greater than band gap of the semiconductor are absorbed by the cell and generate electron-hole (e-h) pair. These e-h pairs migrate respectively to n- and p- side of the pn junction due to electrostatic force of the field across the junction. In this way a potential difference is established between two sides of the cell. Typically 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 like a battery. If these two sides are connected by an external circuit, current will start flowing from positive to negative terminal of the solar cell. This is basic working principle of a solar cell. For silicon, the band gap at room temperature is Eg = 1.1 eV and the diffusion potential is UD = 0.5 to 0.7 V. Construction of a Si solar cell is depicted in Fig.5.

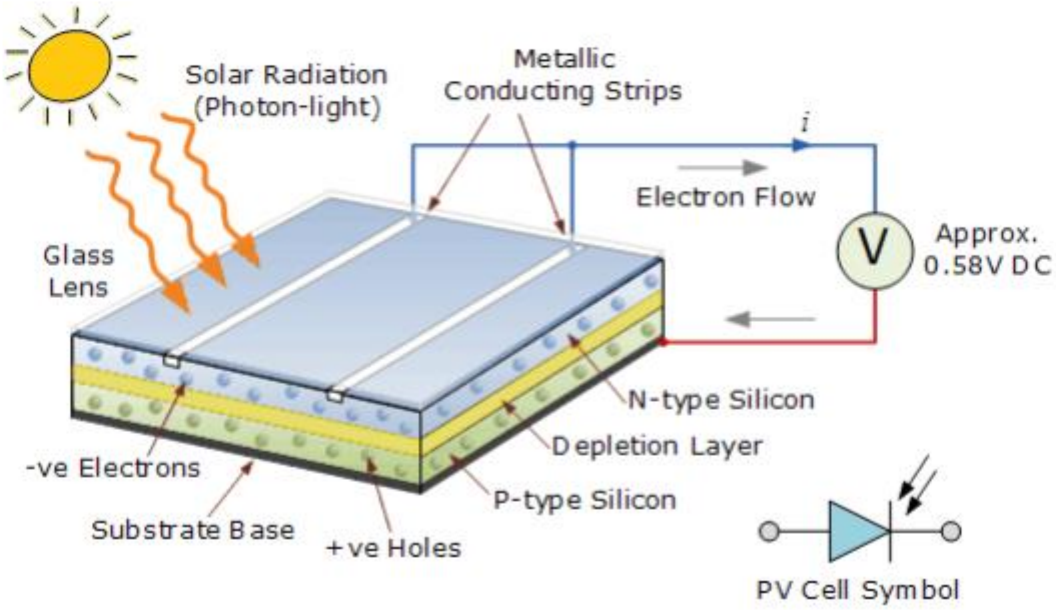

Fig. 5: Construction of a solar cell

Solar Cell I-V Characteristics Curve is the superposition of the I-V curve of the solar cell diode in absence (dark) and in presence of light. Illuminating a cell adds to the normal "dark" currents in the diode so that the diode law becomes

$$I = I_0 \left[\exp\left(\frac{qV}{nkT}\right) - 1\right] - I_L$$

where I0 = "dark saturation current" or diode leakage current in absence of light

q = electronic charge

V = applied voltage across the terminals of the diode

n = ideality factor

k = Boltzmann's constant

T = temperature

IL = light generated current.

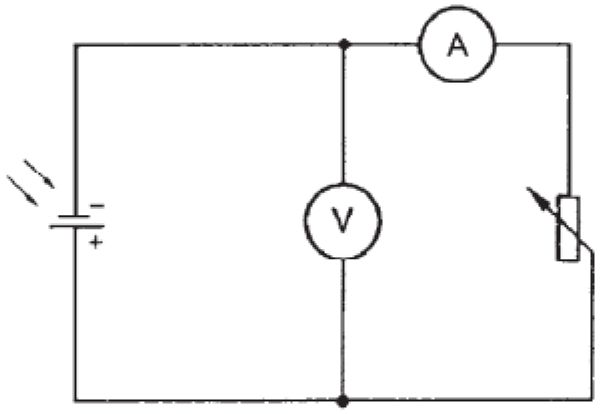

Fig.6. Circuit for I-V characteristics of solar cell

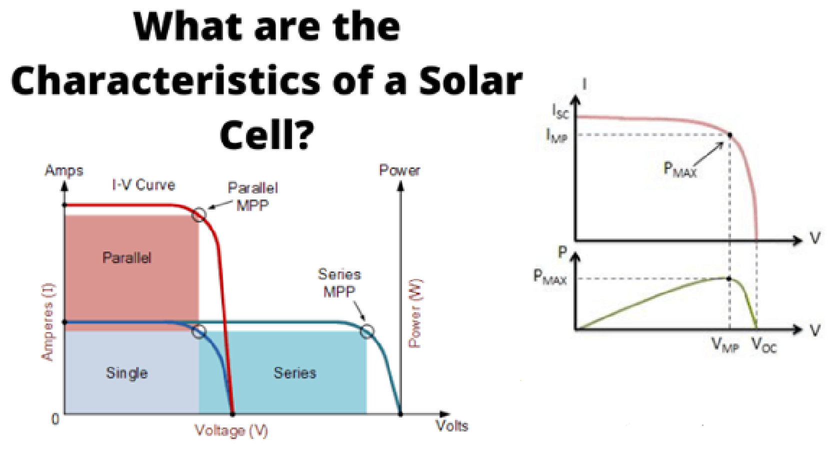

Fig.7.

Short Circuit Current of Solar Cell

The maximum current that a solar cell can deliver without harming its own constriction. It is measured by short circuiting the terminals of the cell at most optimized condition of the cell for producing maximum output. The term optimized condition I used because for fixed exposed cell surface the rate of production of current in a solar cell also depends upon the intensity of light and the angle at which the light falls on the cell. As the current production also depends upon the surface area of the cell exposed to light, it is better to express maximum current density instead maximum current. Maximum current density or short circuit current density rating is nothing but ration of maximum or short circuit current to exposed surface area of the cell.

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

Where, Isc is short circuit current, Jsc maximum current density and A is the area of solar cell.

Open Circuit Voltage of Solar Cell

It is measured by measuring voltage across the terminals of the cell when no load is connected to the cell. This voltage depends upon the techniques of manufacturing and temperature but not fairly on the intensity of light and area of exposed surface. Normally open circuit voltage of solar cell nearly equal to 0.5 to 0.6 volt. It is normally denoted by Voc.

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.

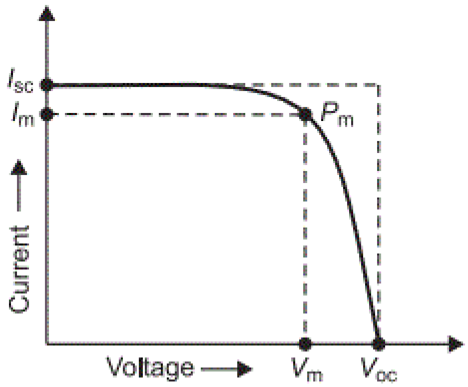

Fig.8.

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 Im.

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 Vm.

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

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 metre 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

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

PV modules generate DC current and voltage. However, to feed the electricity to the grid, AC current and voltage are needed. Inverters are the equipment used to convert DC to AC. In addition, they can be in charge of keeping the operating point of the PV array at the MPP. This is usually done with computational MPP tracking algorithms.

There are different inverter configurations depending on how the PV modules are connected to the inverter . The main types are described in this chapter. The decision on what configuration should be used has to be made for each case depending on the environmental and financial requirements. If the modules are not identical or do not work under the same conditions, the MPP is different in each panel and the resulting voltage-power characteristic has multiple maxima, which constitutes a problem, because most MPPT algorithms converge to a local maximum depending on the starting point. If the operating point is not the MPP, not all the possible power is being fed to the grid. For these reasons each case has to be carefully studied to optimize the plant and obtain the maximum performance.

The different configurations are described shortly in this chapter because they are not the focus of this thesis. More information about all the following topologies can be found in and .

Central inverter

It is the simpler configuration: PV strings, consisting of series connected PV panels, are connected in parallel to obtain the desired output power. The resulting PV array is connected to a single inverter, as is shown in Figure 9. In this configuration all PV strings operate at the same voltage, which may not be the MPP voltage for all of them.

The problem of this configuration is the possible mismatches among the different PV modules. If they are receiving different irradiation (shading or other problems), the true MPP is difficult to find and consequently there are power losses and the PV modules are underutilized.

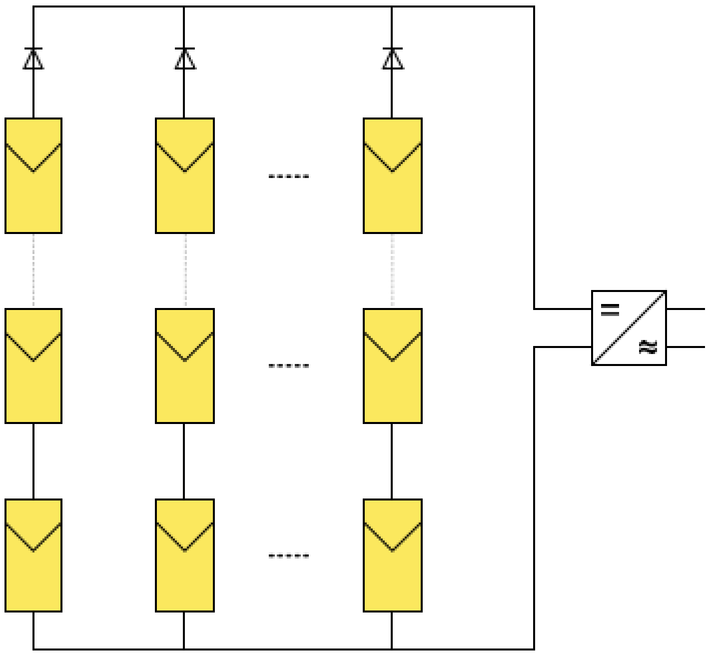

Fig.9. Central configuration

String inverter

In this configuration, every string of PV panels connected in series is connected to a different inverter, as can be seen in Figure 10. This can improve the MPP tracking in case of mismatches or shading, because each string can operate at a different MPP, if necessary, whereas in the central inverter there is only one operating point which may not be the MPP for each string, thus leading to power losses. On the other hand, the number of components of the system increases as well as the installation cost, as an inverter is used for each string.

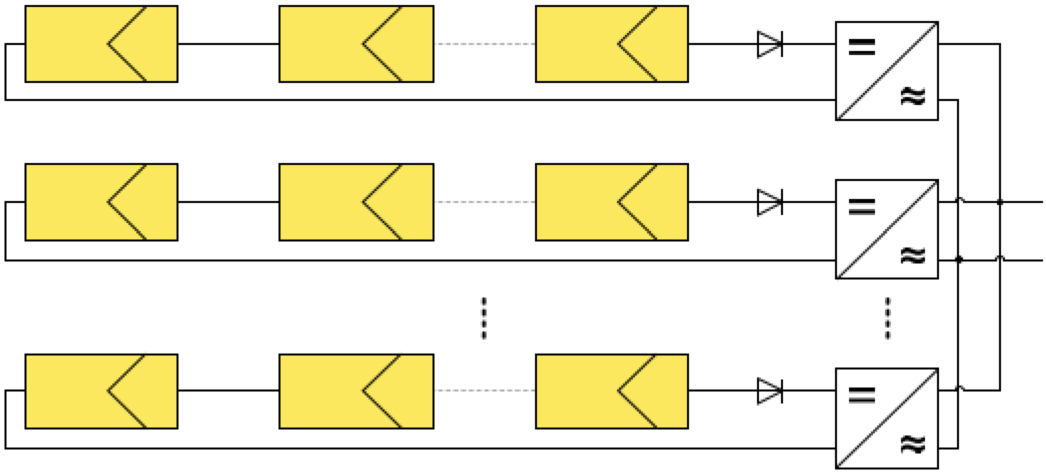

Figure 10 - String configuration.

Multi-string inverter

In this case each string is connected to a different DC-DC converter, which is in charge of the MPP tracking of the string, and the converters are connected to a single inverter, as depicted in Figure 11. The advantages related to MPP tracking are the same as in the string configuration; each string can have a different MPP. The disadvantages, an increase in the price compared to the central inverter, as a converter is used for each string.

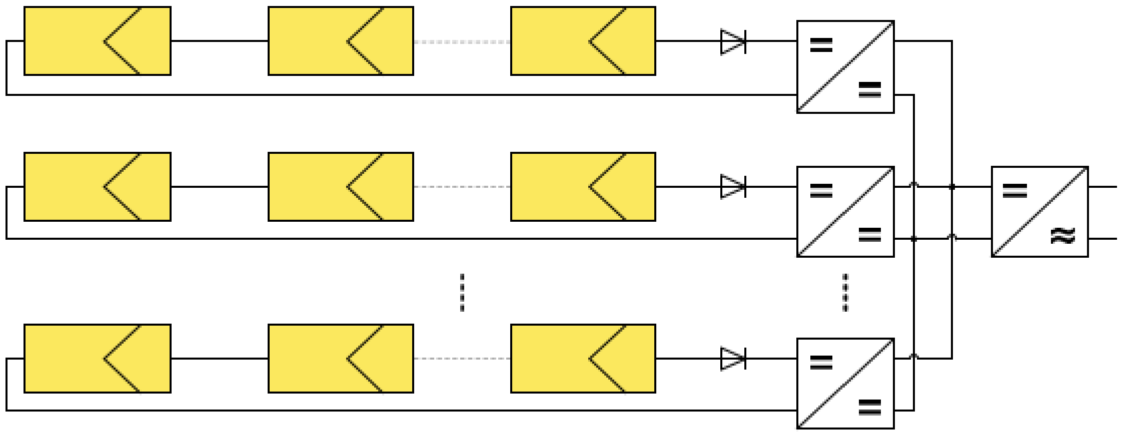

Fig.11.- Multi-string configuration.

Module integrated inverter

In this configuration, as shown in Figure 12, each PV module is connected to a different inverter and consequently the maximum power is obtained from each panel as the individual MPP is tracked by each inverter. This configuration can be used when the differences in the operating point of the different modules are large. However, it is more expensive because each panel has its own inverter.

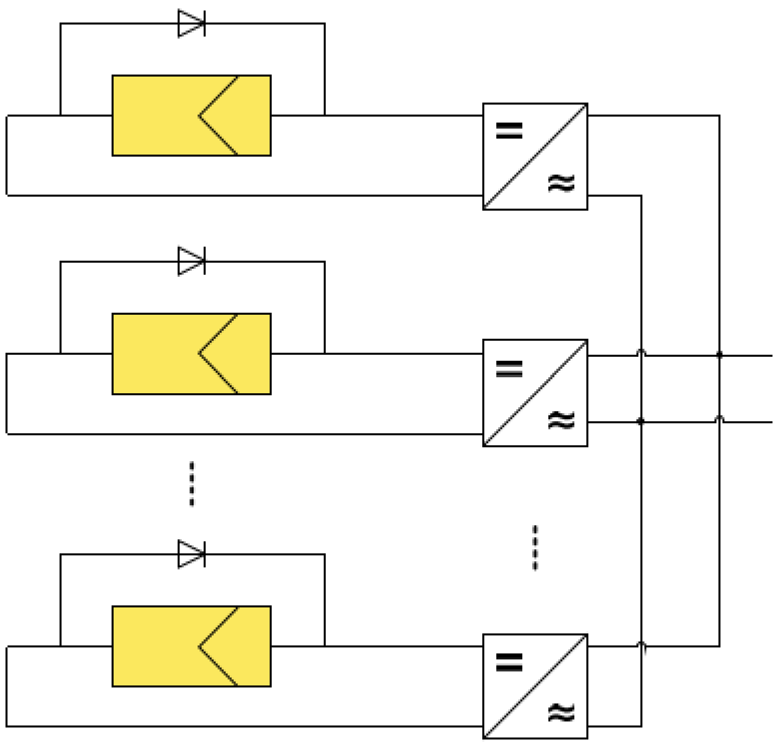

Fig.12. Individual inverter.

Maximum Power Point Tracking Algorithms

As was previously explained, MPPT algorithms are necessary in PV applications because the MPP of a solar panel varies with the irradiation and temperature, so the use of MPPT algorithms is required in order to obtain the maximum power from a solar array.

Over the past decades many methods to find the MPP have been developed and published. These techniques differ in many aspects such as required sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/or temperature change, hardware needed for the implementation or popularity, among others.

The P&O and the InCond algorithms are the most common. These techniques have the advantage of an easy implementation but they also have drawbacks, as will be shown later. Other techniques based on different principles are fuzzy logic control, neural network, fractional open circuit voltage or short circuit current, current sweep, etc. Most of these methods yield a local maximum and some, like the fractional open circuit voltage or short circuit current, give an approximated MPP, not the exact one. In normal conditions the V-P curve has only one maximum, so it is not a problem. However, if the PV array is partially shaded, there are multiple maxima in these curves. In order to relieve this problem, some algorithms have been implemented as in. In the next section the most popular MPPT techniques are discussed.

Hill-climbing techniques

Both P&O and InCond algorithms are based on the “hill-climbing” principle, which consists of moving the operation point of the PV array in the direction in which power increases . Hill-climbing techniques are the most popular MPPT methods due to their ease of implementation and good performance when the irradiation is constant . The advantages of both methods are the simplicity and low computational power they need. The shortcomings are also well-known: oscillations around the MPP and they can get lost and track the MPP in the wrong direction during rapidly changing atmospheric conditions. These drawbacks will be explained later.Perturb and observe The P&O algorithm is also called “hill-climbing”, but both names refer to the same algorithm depending on how it is implemented. Hill-climbing involves a perturbation on the duty cycle of the power converter and P&O a perturbation in the operating voltage of the DC link between the PV array and the power converter. In the case of the Hill-climbing, perturbing the duty cycle of the power converter implies modifying the voltage of the DC link between the PV array and the power converter, so both names refer to the same technique.

In this method, the sign of the last perturbation and the sign of the last increment in the power are used to decide what the next perturbation should be. As can be seen in Figure 13, on the left of the MPP incrementing the voltage increases the power whereas on the right decrementing the voltage increases the power.

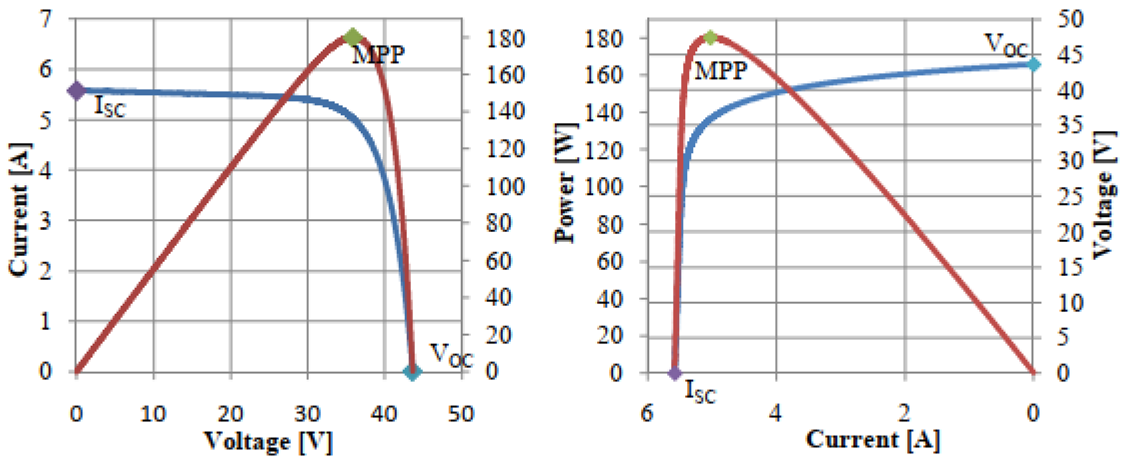

Fig.13. PV panel characteristic curves.

If there is an increment in the power, the perturbation should be kept in the same direction and if the power decreases, then the next perturbation should be in the opposite direction. Based on these facts, the algorithm is implemented. The process is repeated until the MPP is reached. Then the operating point oscillates around the MPP. This problem is common also to the InCond method, as was mention earlier. A scheme of the algorithm is shown in Figure 14.

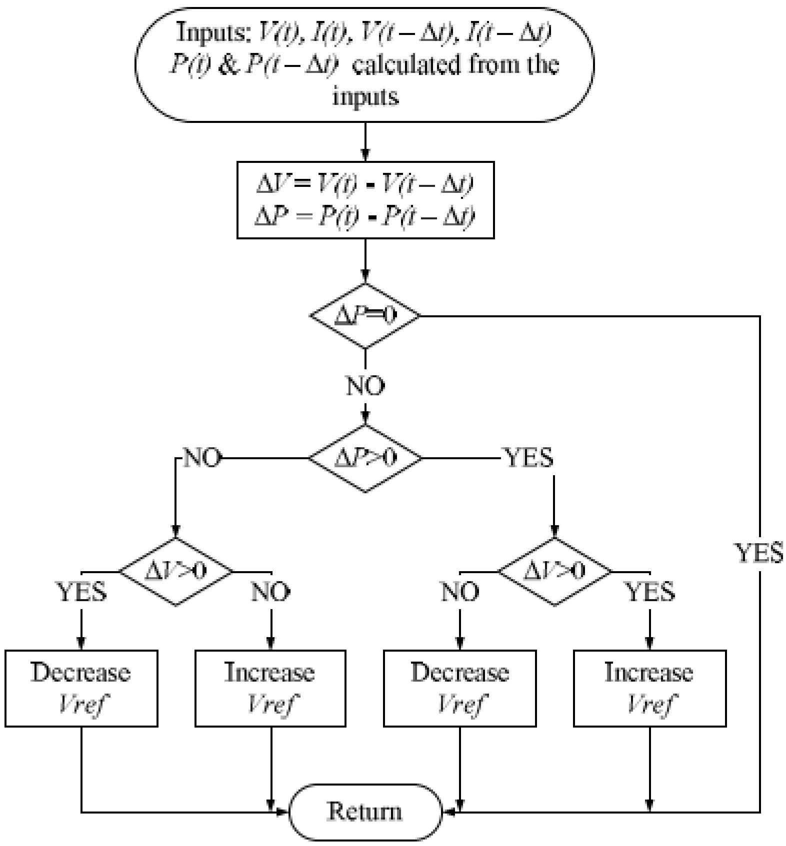

Fig.14 - The flowchart of the P&O Algorithm.

Incremental conductance

The incremental conductance algorithm is based on the fact that the slope of the curve power vs. voltage (current) of the PV module is zero at the MPP, positive (negative) on the left of it and negative (positive) on the right, as can be seen in Figure 13:

By comparing the increment of the power vs. the increment of the voltage (current) between two consecutives samples, the change in the MPP voltage can be determined.

$\Delta V/\Delta P = 0$ $(\Delta I/\Delta P = 0)$ at the MPP

$\Delta V/\Delta P > 0$ $(\Delta I/\Delta P < 0)$ on the left

$\Delta V/\Delta P < 0$ $(\Delta I/\Delta P > 0)$ on the right

By comparing the increment of the power vs. the increment of the voltage (current) between two consecutives samples, the change in the MPP voltage can be determined. A scheme of the algorithm is shown in Figure 15.

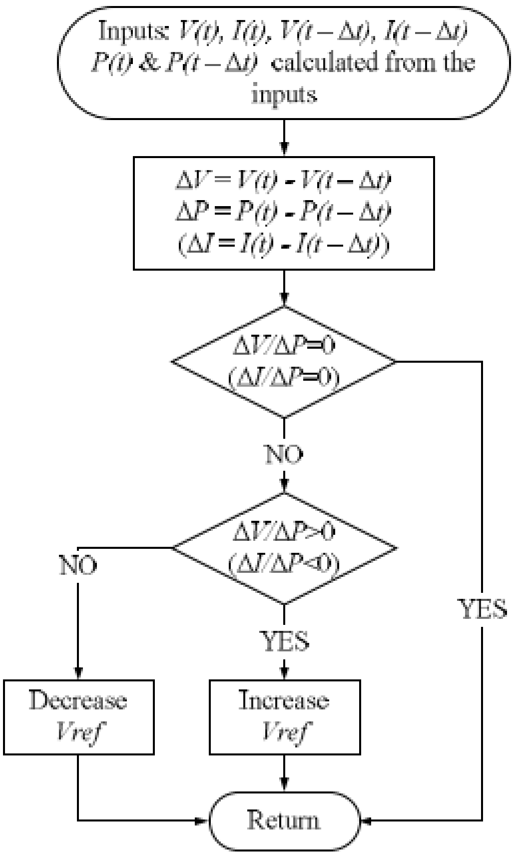

Fig. 15 Incremental Conductance algorithm.

In both P&O and InCond schemes, how fast the MPP is reached depends on the size of the increment of the reference voltage.

The drawbacks of these techniques are mainly two. The first and main one is that they can easily lose track of the MPP if the irradiation changes rapidly. In case of step changes they track the MPP very well, because the change is instantaneous and the curve does not keep on changing. However, when the irradiation changes following a slope, the curve in which the algorithms are based changes continuously with the irradiation, as can be seen in Figure 15, so the changes in the voltage and current are not only due to the perturbation of the voltage. As a consequence it is not possible for the algorithms to determine whether the change in the power is due to its own voltage increment or due to the change in the irradiation.

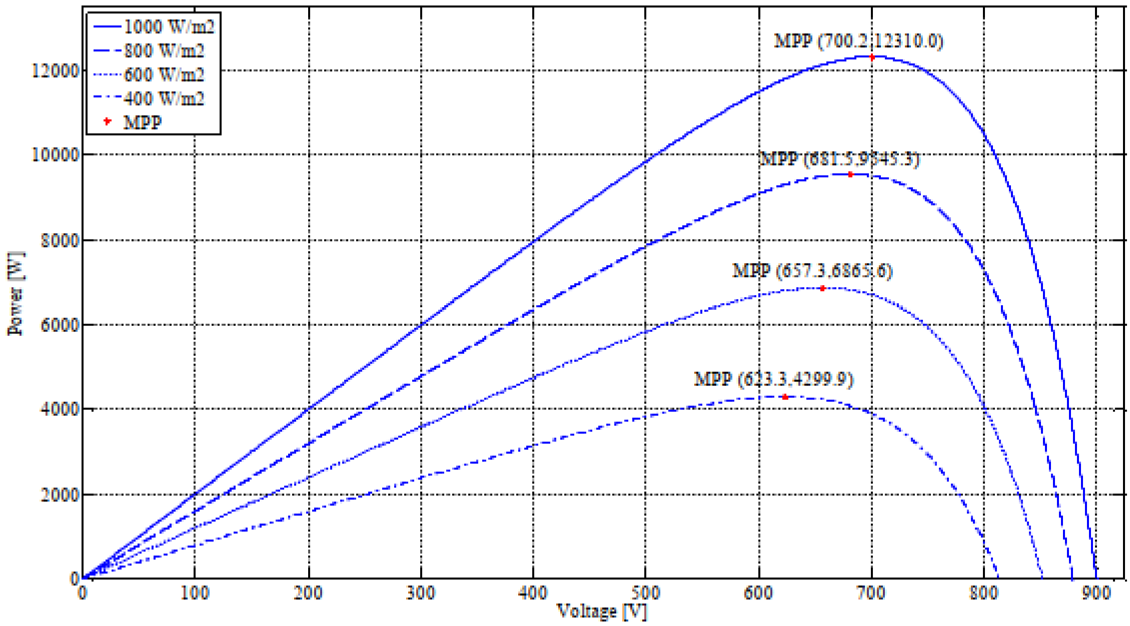

Fig.15. P-V curve depending on the irradiation.

The other handicap of both methods is the oscillations of the voltage and current around the MPP in the steady state . This is due to the fact that the control is discrete and the voltage and current are not constantly at the MPP but oscillating around it. The size of the oscillations depends on the size of the rate of change of the reference voltage. The greater it is, the higher is the amplitude of the oscillations. However, how fast the MPP is reached also depends on this rate of change and this dependence is inversely proportional to the size of the voltage increments. The traditional solution is a trade off: if the increment is small so that the oscillations decrease, then the MPP is reached slowly and vice versa, so a compromise solution has to be found.

Control Schemes For DC/AC Converter

For grid connected inverter, control strategies need to be employed on two parts i.e. control for dc side (PV module) and control for AC side (grid). In order to extract maximum amount of power from the power module MPPT technique is widely used on the DC side. For AC side control different types of current controllers are used for synchronisation with grid. MPPT and different controllers are discussed below in briefly.

DC Side Control Using MPPT

There is a difference between the mechanical tracking (sun tracking) and MPPT of solar PV modules. In the case of mechanical tracking, we mechanically rotate PV modules in order to intercept maximum radiation by the module (hence maximizes power generation) under a given condition, But in MPPT, There is no need of mechanical rotation of the PV module; this part is carried out by the electronic circuit. The MPPT mechanism uses an electronic circuitry and an algorithm. The MPPT mechanism is depends upon on the principle of impedance matching between the load and PV module, which is essential to transfer the maximum power. Different Methods are there for MPPT namely Perturb and observe, Incremental conductance, Fractional open circuit etc. Comparisons between few MPPT methods are given below .

Table : Comparision In MPPT Techniques

MPPT Method	Methodology	Convergence Speed	Complexity	Efficiency
Perturb and observe	Checks difference between current and next instant of points on P-V curve	Medium	Low	99.3% of the actual maximum power
Incremental conductance	Observes slope of P-V curve and finds maximum power region	Faster than P&O	Medium	99.2% of actual P_{max}
Fractional open circuit	Uses relation $V_{mpp}=K*V_{(oc)}$ to find MPP	Less	Low	93.1% of actual P_{max}

AC Side Current Control Techniques

Current control is necessary for the stability of grid current. A controller is design such that it compares grid reference current with actual grid current. The current controllers are divided into two types: linear and non-linear current controllers. In linear current control techniques are sub divided into PI current control, PR resonant current control and dq frame current controls. The non linear current control techniques are sub divided into dead beat control, hysteresis current control and sliding mode control. These all controllers we will be briefly discuss below:

PI Current Control

The PI controller is part of the classical controller's family. This family consist of proportional integral derivative (PID), Proportional controller and Proportional derivative (PD) controllers. The proportional part of the PI controller is related to reduce the ripple or transients while integral part is related with the minimization of the error. The proportional controller's steady state error is minimized by adding an integral component to a transfer function. The error signal is generated by comparing output current of the inverter with the reference current obtained from grid voltage. Then error signal is controlled by PI controller. The control signal from PI controller is then compared with triangular signals with constant switching frequency is used for obtaining PWM pulses. The advantages of PI controllers are: less effect of DC side ripple on AC output waveforms of inverter and reduction in steady state error. The typical block diagram of PI current control is shown below:

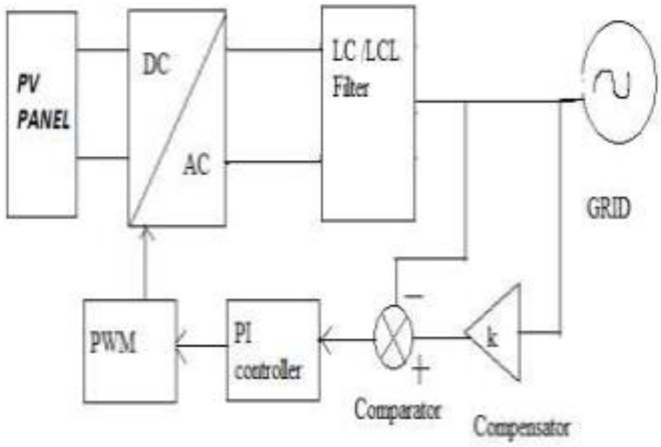

Fig .16. PI Controller

DQ Current Control

The current control gets easy when we convert AC component of current into DC. Using Clark's transformation three phase AC current component can equivalently converted into DC component. Tracking controllers used for AC component of current are more complex than Set Point controllers used for DC components. So in DQ current control three phase AC components of currents are transformed into two DC components namely d and q, which 90° apart from each other. Application of PI controller is there in dq control. Here as shown in figure (6)

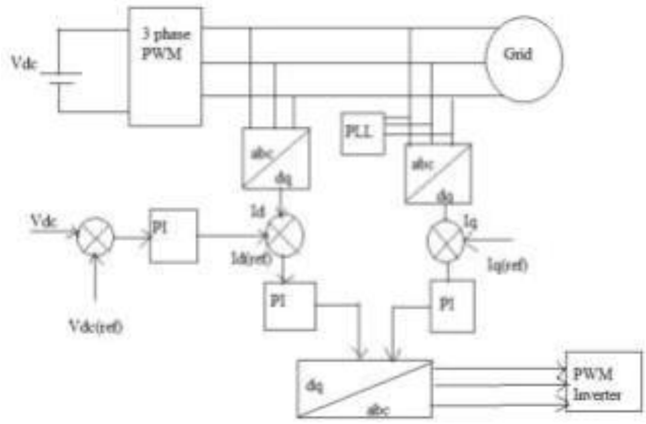

Fig .16. dq Control Strategy

PR Resonant Control

The implementation of the control technique is much simpler in PR compared to dq0. PI and PR controllers works in similar manner but they operate in two different operating frame. PI controller is efficient in tracking DC component while PR controllers are good in tracking AC signals. The integration take place in PI and PR are different. In PR controller integrator integrates frequencies which are closer to resonant. Harmonic compensation in PR controller is poor .

Hysteresis Controllers

Hysteresis control is one of the non linear current control techniques. It is simple and robust control technique. An adaptive band of controller must create to attain stable switching frequency, which is necessary step for the implementation of the hysteresis controller. Following is the block diagram for the hysteresis controller implemented to grid connected PV system.

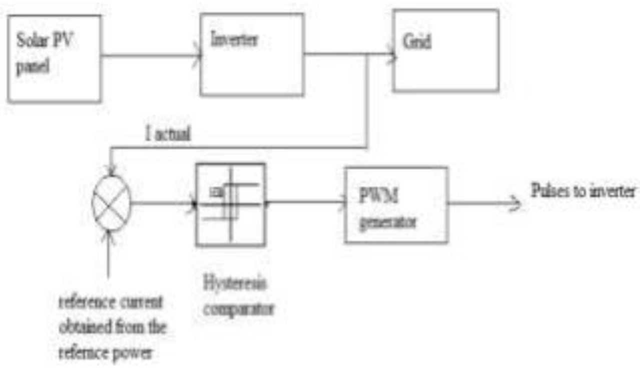

Fig .17. Hysteresis Control Technique

Sliding Mode Control

It is another non linear current control technique. Due to its robustness and improved performance it have been used extensively for the regulation of PWM inverter's output voltage. The performance of sliding mode control depends upon sliding surface and sampling time.

Advantage of sliding mode control technique is it's insensitivity towards parameter changes and load disturbance. Thus it is suitable for time varying system. It regulates system to follow trajectories defined by sliding surface which is similar to hysteresis band in hysteresis controller. To work system in desired manner, system has to be in equilibrium state. For design of sliding mode control three elements are necessary: sliding surface, equivalent control and selecting non linear control input to meet Lyapunov stability criterion .

Modified Ramp Control

In this control phase shift error is absent because phase shifter is used in it. A comparison is done between triangular waves and error signal. Triangular waves are of constant amplitude and frequency while error signals are derived from current controller. It is a non linear current control technique.

Predictive Controllers

With use of system model, predictive controllers predict the future response of the controlled parameters. Although it is easy in implementation it has more number of calculations than PI or PID controllers. Deatbeat controller is type of predictive controller. In which error is nullified at end of each cycle by selecting proper voltage vector. Model predictive controller (MPC) is also one of the types of predictive controllers.

Current Regulated Delta Controller

In this controller the switching frequency can be controlled desirably by using latching device. This controller is same as hysteresis controller except latching device. The latching device can enable by using clock signal.

Direct Power Control

In conventional direct power control method, three phase quantities are converted into dq axis frame and by using current control loop active and reactive power was derived. But in direct power control method using sliding surface three phase abc vectors transformed into αβ stationary reference frame. Then actual power is calculated using following equations

$$P(actual) = -1.5(Vg\alpha I\ g\alpha + Vg\beta I\ g\beta) \quad (1)$$

$$Q(actual) = -1.5(Vg\beta I\ g\beta - Vg\alpha I\ g\alpha) \quad (2)$$

The actual value of power is compared with reference value. Then state variable of sliding surface F is calculated with respect to power P and Q [3][23]. After that Vg is calculated using following equation

$$Vg = (1/D)[(Fp + Kp1sgn(Sp) + Fq + Kq1sgn(Sq))] \quad (3)$$

Finally using pulse width modulation, gate pulses are given to inverter. The advantage of this method is fast dynamic response.