UNIT–III: Solar Photovoltaic Systems

Semiconductor Materials Overview

1. Semiconductor materials come from different groups in the periodic table, yet share certain similarities.
2. The properties of the semiconductor material are related to their atomic characteristics and change from group to group.
3. Researchers and designers take advantage of these differences to improve the design and choose the optimal material for a PV application.

The atoms in a semiconductor are materials from either group IV of the periodic table, or from a combination of group III and group V (called III-V semiconductors), or of combinations from group II and group VI (called II-VI semiconductors). Because different semiconductors are made up of elements from different groups in the periodic table, properties vary between semiconductors. Silicon, which is a group IV, is the most commonly used semiconductor material as it forms the basis for integrated circuit (IC) chips and is the most mature technology and most solar cells are also silicon based. A full periodic table is given in the page Periodic Table. Several of the material properties of silicon are given in the page Silicon Material Parameters

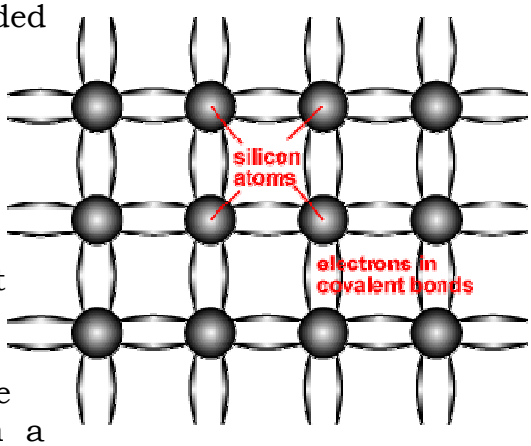
A section from the periodic table. More common semiconductor materials are shown in blue. A semiconductor can be either of a single element, such as Si or Ge, a compound, such as GaAs, InP or CdTe, or an alloy, such as $Si_xGe_{(1-x)}$ or $Al_xGa_{(1-x)}As$, where x is the fraction of the particular element and ranges from 0 to 1.

		IIIA	IVA	VA	VIA	VIIA	VIIIA
							2 He 4.003
		5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
IB	IIB	13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)

Semiconductor Structure

Overview

1. Semiconductors are made up of atoms bonded together to form a uniform structure
2. Each silicon atom has four valence electrons which are shared, forming covalent bonds with the four surrounding Si atoms.
3. Understanding how these atoms are arranged is vital in understanding the material properties of different semiconductors, and how best to engineer them.



Semiconductors, such as Silicon (Si) are made up of individual atoms bonded together in a

regular, periodic structure to form an arrangement whereby each atom is surrounded by 8 electrons. An individual atom consists of a nucleus made up of a core of protons (positively charged particles) and neutrons (particles having no charge) surrounded by electrons. The number of electrons and protons is equal, such that the atom is overall electrically neutral. The electrons surrounding each atom in a semiconductor are part of a covalent bond. A covalent bond consists of two atoms "sharing" a pair of electrons. Each atom forms 4 covalent bonds with the 4 surrounding atoms. Therefore, between each atom and its 4 surrounding atoms, 8 electrons are being shared. The structure of a semiconductor is shown in the figure below.

Schematic representation of covalent bonds in a silicon crystal lattice. Each line connecting the atoms represents an electron being shared between the two. Two electrons being shared are what form the covalent bond.

Conduction in Semiconductors Overview

1. Semiconductors act as insulators at low temperatures and conductors at higher temperatures.
2. Conduction occurs at higher temperature because the electrons surrounding the semiconductor atoms can break away from their covalent bond and move freely about the lattice
3. The conductive property of semiconductors forms the basis for understanding how we can use these materials in electrical devices.
   The bond structure of a semiconductor determines the material properties of a semiconductor. One key effect are the energy levels which the electrons can occupy and how they move about the crystal lattice. The electrons in the covalent bond formed between each of the atoms in the lattice structure are held in place by this bond and hence they are localizedto the region surrounding the atom. These bonded electrons cannot move or change energy, and thus are not considered "free" and cannot participate in current flow, absorption, or other physical processes of interest in solar cells. **However, only at absolute zero are all electrons in this "stuck," bonded arrangement.** At elevated temperatures, especially at the temperatures where solar cells operate, electrons can gain enough energy to escape from their bonds. When this happens, the electrons are free to move about the crystal lattice and participate in conduction. At room temperature, a semiconductor has enough free electrons to allow it to conduct current. At or close to absolute zero a semiconductor behaves like an insulator.

   When an electron gains enough energy to participate in conduction (is "free"), it is at a high energy state. When the electron is bound, and thus cannot participate in conduction, the electron is at a low energy state. Therefore, the presence of the bond between the two atoms introduces two distinct energy states for the electrons. The electron cannot attain energy values intermediate to these two levels; it is either at a low energy position in the bond, or it has gained enough energy to break free and therefore has a certain minimum energy. This minimum energy is called the "band gap" of a semiconductor. The number and energy of these free electrons, those electrons participating in conduction, is basic to the operation of electronic devices.

The space left behind by the electrons allows a covalent bond to move from one electron to another, thus appearing to be a positive charge moving through the crystal lattice. This empty space is commonly called a "hole", and is similar to an electron, but with a positive charge.

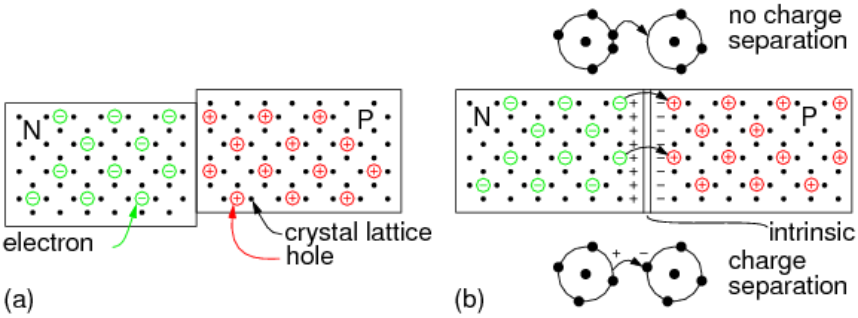
The most important parameters of a semiconductor material for solar cell operation are:

- the band gap;
- the number of free carriers (electrons or holes) available for conduction; and
- the "generation" and recombination of free carriers (electrons or holes) in response to light shining on the material.

The P-N Junction

If a block of P-type semiconductor is placed in contact with a block of N-type semiconductor in Figurebelow(a), the result is of no value. We have two conductive blocks in contact with each other, showing no unique properties. The problem is two separate and distinct crystal bodies. The number of electrons is balanced by the number of protons in both blocks. Thus, neither block has any net charge.

However, a single semiconductor crystal manufactured with P-type material at one end and N-type material at the other in Figure below (b) has some unique properties. The P-type material has positive majority charge carriers, holes, which are free to move about the crystal lattice. The N-type material has mobile negative majority carriers, electrons. Near the junction, the N-type material electrons diffuse across the junction, combining with holes in P-type material. The region of the P-type material near the junction takes on a net negative charge because of the electrons attracted. Since electrons departed the N-type region, it takes on a localized positive charge. The thin layer of the crystal lattice between these charges has been depleted of majority carriers, thus, is known as the *depletion region*. It becomes nonconductive intrinsic semiconductor material. In effect, we have nearly an insulator separating the conductive P and N doped regions.

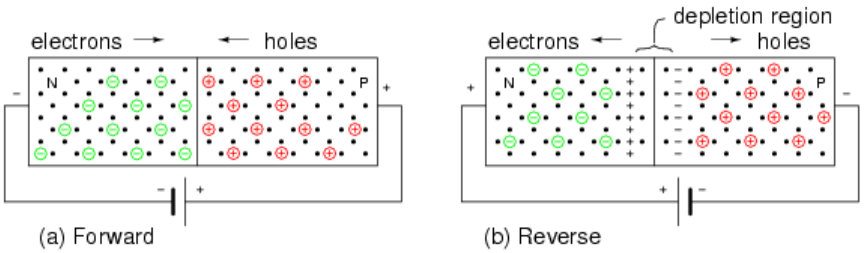


(a) Blocks of P and N semiconductor in contact have no exploitable properties. (b) Single crystal doped with P and N type impurities develops a potential barrier.

This separation of charges at the PN junction constitutes a potential barrier. This potential barrier must be overcome by an external voltage source to make the junction conduct. The formation of the junction and

potential barrier happens during the manufacturing process. The magnitude of the potential barrier is a function of the materials used in manufacturing. Silicon PN junctions have a higher potential barrier than germanium junctions.

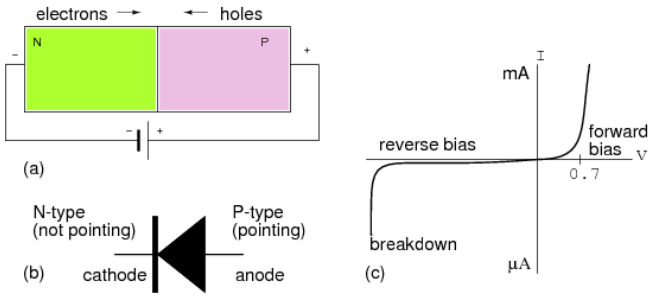
In Figure below(a) the battery is arranged so that the negative terminal supplies electrons to the N-type material. These electrons diffuse toward the junction. The positive terminal removes electrons from the P-type semiconductor, creating holes that diffuse toward the junction. If the battery voltage is great enough to overcome the junction potential (0.6V in Si), the N-type electrons and P-holes combine annihilating each other. This frees up space within the lattice for more carriers to flow toward the junction. Thus, currents of N-type and P-type majority carriers flow toward the junction. The recombination at the junction allows a battery current to flow through the PN junction diode. Such a junction is said to be *forward biased*.



(a) Forward battery bias repels carriers toward junction, where recombination results in battery current. (b) Reverse battery bias attracts carriers toward battery terminals, away from junction. Depletion region thickness increases. No sustained battery current flows.

If the battery polarity is reversed as in Figure above(b) majority carriers are attracted away from the junction toward the battery terminals. The positive battery terminal attracts N-type majority carriers, electrons, away from the junction. The negative terminal attracts P-type majority carriers, holes, away from the junction. This increases the thickness of the no conducting depletion region. There is no recombination of majority carriers; thus, no conduction. This arrangement of battery polarity is called *reverse bias*.

The diode schematic symbol is illustrated in Figure below (b) corresponding to the doped semiconductor bar at (a). The diode is a *unidirectional* device. Electron current only flows in one direction, against the arrow, corresponding to forward bias. The cathode, bar, of the diode symbol corresponds to N-type semiconductor. The anode, arrow, corresponds to the P-type semiconductor. To remember this relationship, **N**ot-pointing (bar) on the symbol corresponds to **N**-type semiconductor. **P**ointing (arrow) corresponds to **P**-type.



(a) Forward biased PN junction, (b) Corresponding diode schematic symbol (c) Silicon Diode I vs V characteristic curve.

If a diode is forward biased as in Figure above(a), current will increase slightly as voltage is increased from 0 V. In the case of a silicon diode a measurable current flows when the voltage approaches 0.6 V in Figureabove(c). As the voltage increases past 0.6 V, current increases considerably after the knee. Increasing the voltage well beyond 0.7 V may result in high enough current to destroy the diode. The forward voltage, V_F, is a characteristic of the semiconductor: 0.6 to 0.7 V for silicon, 0.2 V for germanium, a few volts for Light Emitting Diodes (LED). The forward current ranges from a few mA for point contact diodes to 100 mA for small signal diodes to tens or thousands of amperes for power diodes.

If the diode is reverse biased, only the leakage current of the intrinsic semiconductor flows. This is plotted to the left of the origin in Figure above(c). This current will only be as high as 1 μA for the most extreme conditions for silicon small signal diodes. This current does not increase appreciably with increasing reverse bias until the diode breaks down. At breakdown, the current increases so greatly that the diode will be destroyed unless a high series resistance limits current. We normally select a diode with a higher reverse voltage rating than any applied voltage to prevent this. Silicon diodes are typically available with reverse break down ratings of 50, 100, 200, 400, 800 V and higher. It is possible to fabricate diodes with a lower rating of a few volts for use as voltage standards.

- **REVIEW:**
- PN junctions are fabricated from a monocrystalline piece of semiconductor with both a P-type and N-type region in proximity at a junction.
- The transfer of electrons from the N side of the junction to holes annihilated on the P side of the junction produces a barrier voltage. This is 0.6 to 0.7 V in silicon, and varies with other semiconductors.
- A forward biased PN junction conducts a current once the barrier voltage is overcome. The external applied potential forces majority carriers toward the junction where recombination takes place, allowing current flow.
- A reverse biased PN junction conducts almost no current. The applied reverse bias attracts majority carriers away from the junction. This increases the thickness of the nonconducting depletion region.

- Reverse biased PN junctions show a temperature dependent reverse leakage current. This is less than a μA in small silicon diodes.

Difference between Intrinsic Semiconductors and Extrinsic Semiconductors

Semiconductors are the foundation of modern electronics. Lets see the differences between their two types :- Intrinsic Semiconductors and Extrinsic Semiconductors .

Intrinsic Semiconductors	Extrinsic Semiconductors
Intrinsic semiconductors, also called an undoped semiconductors or i-type semiconductor, are pure semiconductor without any significant dopant species present. The number of charge carriers is therefore determined by the properties of the material itself instead of the amount of impurities.	These are impure semiconductors. When a small quantity of impurity is mixed in a pure or intrinsic conductor, conductivity of semiconductor increases. Such an impure semiconductor is called extrinsic semiconductor.
Conductivity of intrinsic semiconductors is poor.	Conductivity of extrinsic semiconductors is large.
Number of electrons in conduction band and holes in valence band are approximately equal.	If it is an n-type electrons are in majority and if it is a p-type holes are in majority.
Fermi energy level lies at the centre of forbidden energy gap.	In n-type Fermi-level lies near the bottom of conduction band and in p-type near the top of valence base .

Solar Cell Structure

A solar cell is an electronic device which directly converts sunlight into electricity. Light shining on the solar cell produces both a current and a voltage to generate electric power. This process requires firstly, a material in which the absorption of light raises an electron to a higher energy state, and secondly, the movement of this higher energy electron from the solar cell into an external circuit. The electron then dissipates its energy in the external circuit and returns to the solar cell. A variety of materials and processes can potentially satisfy the requirements for photovoltaic energy conversion, but in practice nearly all photovoltaic energy conversion uses semiconductor materials in the form of a *p-n* junction.

Types of photovoltaic cells

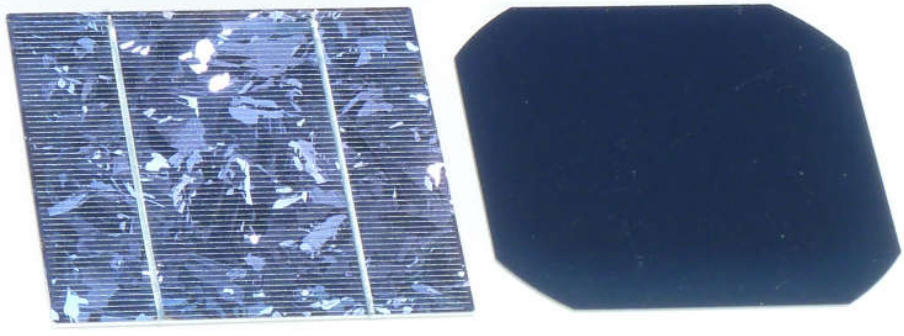
Photovoltaic cells or **PV cells** can be manufactured in many different ways and from a variety of different materials. Despite this difference, they all perform the same task of harvesting solar energy and converting it to

useful electricity. The most common material for solar panel construction is silicon which has semiconducting properties.[2]Several of these solar cells are required to construct a solar panel and many panels make up a photovoltaic array.

There are three types of PV cell technologies that dominate the world market: mono crystalline silicon, polycrystalline silicon, and thin film. Higher efficiency PV technologies, including gallium arsenide and multi-junction cells, are less common due to their high cost, but are ideal for use in concentrated photovoltaic systems and space applications.[3]There is also an assortment of emerging PV cell technologies which include Perovskite cells, organic solar cells, dye-sensitized solar cells and quantum dots.

Mono crystalline Silicon Cell

The first commercially available solar cells were made from mono crystalline silicon, which is an extremely pure form of silicon. To produce these, a seed crystal is pulled out of a mass of molten silicon creating a cylindrical ingot with a single, continuous, crystal lattice structure. This crystal is then mechanically sawn into thin wafers, polished and dopedto create the required p-n junction. After an anti-reflective coating and the front and rear metal contacts are added, the cell is finally wired and packaged alongside many other cells into a full solar panel.[3] Monocrystalline silicon cells are highly efficient, but their manufacturing process is slow and labour intensive, making them more expensive than their polycrystalline or thin film counterparts.



An image comparing a polycrystalline silicon cell (left) and a mono crystalline silicon cell (right).

Polycrystalline Silicon Cell

Instead of a single uniform crystal structure, polycrystalline (or multicrystalline) cells contain many small grains of crystals (see figure 2). They can be made by simply casting a cube-shaped ingot from molten silicon, then sawn and packaged similar to monocrystalline cells. Another method known as edge-defined film-fed growth (EFG) involves drawing a thin ribbon of polycrystalline silicon from a mass of molten silicon. A cheaper but less efficient alternative, polycrystalline silicon PV cells

dominate the world market, representing about 70% of global PV production in 2015.

Thin Film Cells



Figure. A thin film solar panel composed of non-crystalline silicon deposited on a flexible material.

Although crystalline PV cells dominate the market, cells can also be made from thin films—making them much more flexible and durable. One type of thin film PV cell is **amorphous silicon** (a-Si) which is produced by depositing thin layers of silicon on to a glass substrate. The result is a very thin and flexible cell which uses less than 1% of the silicon needed for a crystalline cell.[3] Due to this reduction in raw material and a less energy intensive manufacturing process, amorphous silicon cells are much cheaper to produce. Their efficiency, however, is greatly reduced because the silicon atoms are much less ordered than in their crystalline forms leaving 'dangling bonds' that combine with other elements making them electrically inactive. These cells also suffer from a 20% drop in efficiency within the first few months of operation before stabilizing, and are therefore sold with power ratings based on their degraded output.[3]

Other types of thin film cells include **copper indium gallium diselenide** (CIGS) and **cadmium telluride** (CdTe). These cell technologies offer higher efficiencies than amorphous silicon, but contain rare and toxic elements including cadmium which requires extra precautions during manufacture and eventual recycling.[3]

High Efficiency Cells

Other cell technologies have been developed which operate at much higher efficiencies than those mentioned above, but their higher material and manufacturing costs currently prohibit wide spread commercial use.

Gallium Arsenide

Silicon is not the only material suitable for crystalline PV cells. Gallium arsenide (GaAs) is an alternative semiconductor which is highly suitable for PV applications. Gallium arsenide has a similar crystal structure to that of mono crystalline silicon, but with alternating gallium and arsenic atoms.



NASA's Juno Spacecraft with gallium arsenide multi-junction solar cells.

Due to its higher light absorption coefficient and wider band gap, GaAs cells are much more efficient than those made of silicon. Additionally, GaAs cells can operate at much higher temperatures without considerable performance degradation, making them suitable for concentrated photovoltaics. GaAs cells are produced by depositing layers of gallium and arsenic onto a base of single crystal GaAs, which defines the orientation of the new crystal growth. This process makes GaAs cells much more expensive than silicon cells, making them useful only when high efficiency is needed, such as space applications.

Multi-Junction

The majority of PV cells, including those discussed above, contain only one p-n junction of semiconductor material which converts energy from one discreet portion of the solar spectrum into useful electricity. Multi-junction cells have 2 or more junctions layered on top of each other, allowing energy to be collected from multiple portions of the spectrum. Light that is not absorbed by the first layer will travel through and interact with subsequent layers. Multi-junction cells are produced in the same way as gallium arsenide cells—slowly depositing layers of material onto a single crystal base, making them very expensive to produce, and only commercially viable in concentrated PV systems and space applications.[3]

To increase their utility, a number of individual PV cells are interconnected together in a sealed, weatherproof package called a Panel (Module). For example, a 12 V Panel (Module) will have 36 cells connected in series and a 24 V Panel (Module) will have 72 PV Cells connected in series

To achieve the desired voltage and current, Modules are wired in series and parallel into what is called a PV Array. The flexibility of the modular PV system allows designers to create solar power systems that can meet a wide variety of electrical needs. Fig. 5 shows PV cell, Panel (Module) and Array.

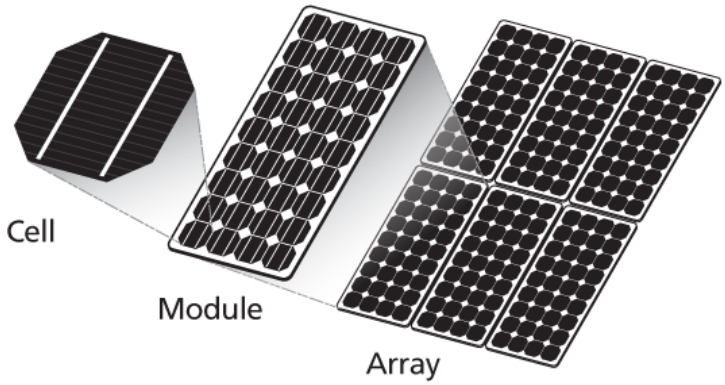


Fig.5. PV cell, Module and Array

The cells are very thin and fragile so they are sandwiched between a transparent front sheet, usually glass, and a backing sheet, usually glass or a type of tough plastic. This protects them from breakage and from the weather. An aluminum frame is fitted around the module to enable easy fixing to a support structure. The picture in Fig. 6 below shows a small part of a Module with cells in it. It has a glass front, a backing plate and a frame around it.

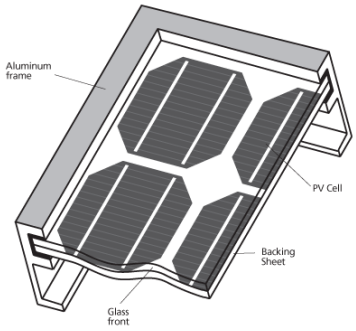


Fig. Construction of a typical Mono-crystalline PV / Solar Panel

As mentioned, PV / Solar cells are wired in series and in parallel to form a PV / Solar Panel (Module). The number of series cells indicates the voltage of the Panel (Module), whereas the number of parallel cells indicates the current. If many cells are connected in series, shading of individual cells can lead to the destruction of the shaded cell or of the lamination material, so the Panel (Module) may blister and burst. To avoid such an operational condition, Bypass Diodes are connected anti-parallel to the solar cells as in Fig.7 As a consequence, larger voltage differences cannot arise in the reverse-current direction of the solar cells. In practice, it is sufficient to connect one bypass diode for every 15-20 cells. Bypass diodes also allow current to flow through the PV module when it is partially shaded, even if at a reduced voltage and power. Bypass diodes do not cause any losses, because under normal operation, current does not flow through them.

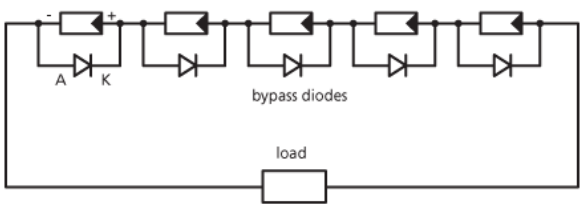
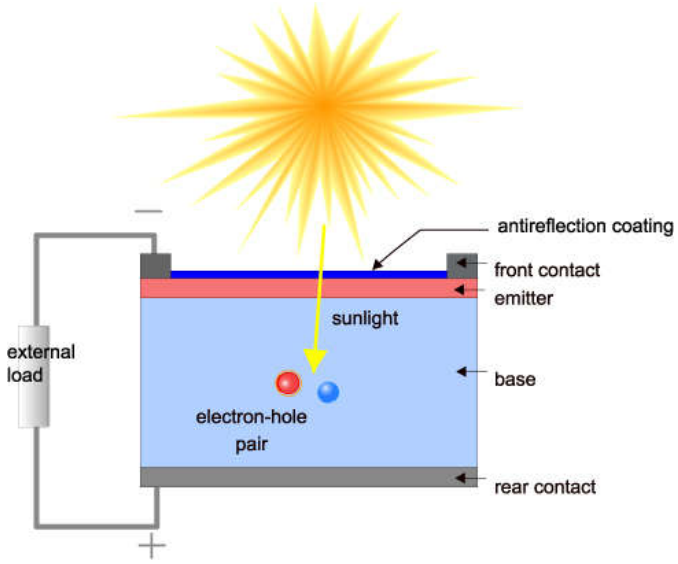


Fig.7. Parallel PV cell with bypass diodes



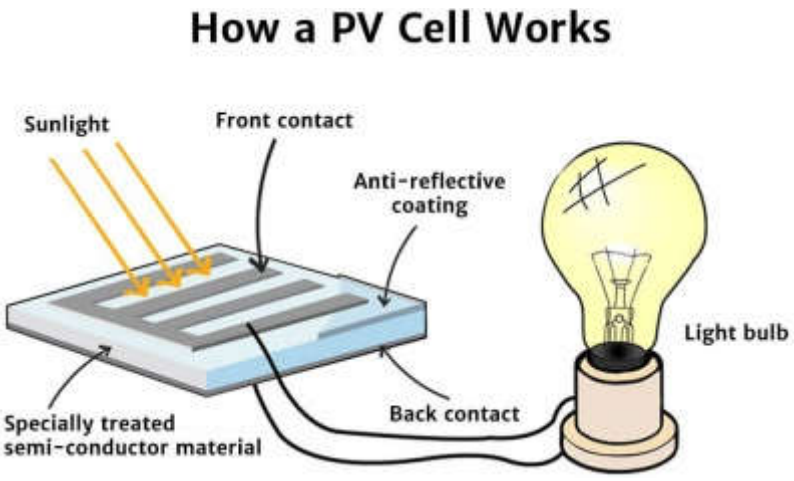
Cross section of a solar cell.

The basic steps in the operation of a solar cell are:

- the generation of light-generated carriers;
- the collection of the light-generated carries to generate a current;
- the generation of a large voltage across the solar cell; and
- the dissipation of power in the load and in parasitic resistances.

How a PV Cell Works

Solar panels convert the sunlight's photon energy into electricity.
Sunlight is composed of photons, or particles of radiant solar energy. These photons contain various amounts of energy depending on the wavelength of the solar spectrum. When



the photons strike a solar cell, some are absorbed while others are reflected. When the material absorbs sufficient photon energy, electrons within the solar cell material dislodge from their atoms. The electrons migrate to the front surface of the solar cell, which is manufactured to be more receptive to the free electrons. When many electrons, each carrying a negative charge, travel toward the front surface of the cell, the resulting imbalance of charge between the cell's front and back surfaces creates a voltage potential like the negative and positive terminals of a battery. When the two surfaces are connected through an external load, electricity flows.

How do solar panels work?

Individual solar cells vary in size from about 1 cm to about 10 cm across. A cell of this size can only produce 1 or 2 watts, which isn't enough power for most applications. To increase power output, cells are electrically connected into a module. Modules are connected to form an array. The term "array" refers to the entire generating plant, whether it is made up of one or several thousand modules.



Large banks of solar cells maximise the amount of solar energy they can generate.

The performance of a photovoltaic array is dependent upon sunlight. Climate (e.g. clouds, fog) has a significant effect on the amount of solar energy received by a PV array and, in turn, its performance.

Solar Cell I-V Characteristic and the Solar Cell I-V Curve

Solar Cell I-V Characteristic Curves show the current and voltage (I-V) characteristics of a particular photovoltaic (PV) cell, module or array giving a detailed description of its solar energy conversion ability and efficiency. Knowing the electrical I-V characteristics (more importantly P_{max}) of a solar cell, or panel is critical in determining the device's output performance and solar efficiency.

Photovoltaic solar cells convert the suns radiant light directly into electricity. With increasing demand for a clean energy source and the sun's potential as a free energy source, has made solar energy conversion as part of a mixture of renewable energy sources increasingly important. As a result, the demand for efficient solar cells, which convert sunlight directly into electricity, is growing faster than ever before.

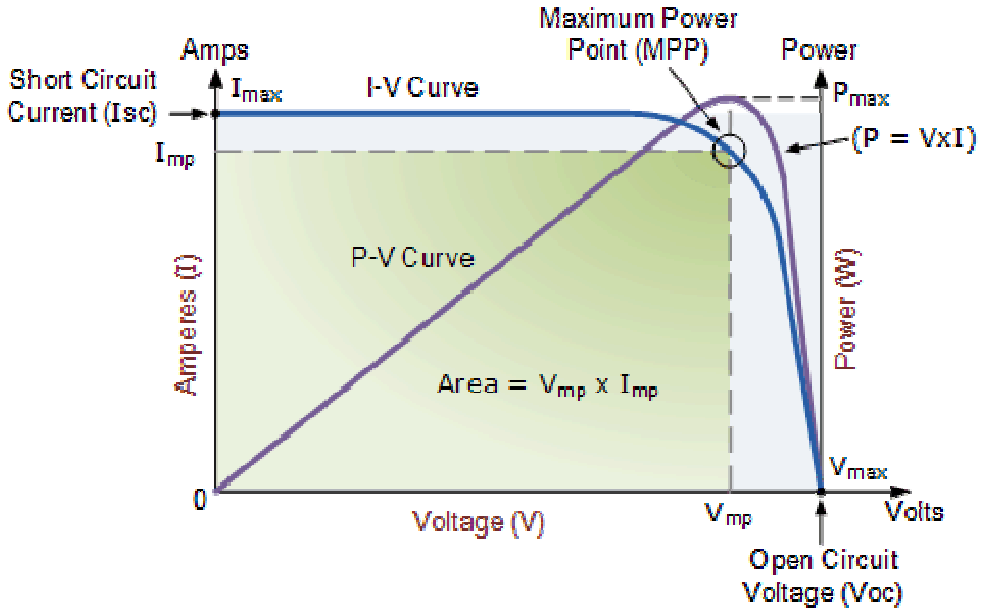
Photovoltaic (PV) cells are made made almost entirely from silicon that has been processed into an extremely pure crystalline form that absorbs the photons from sunlight and then releases them as electrons, causing an electric current to flow when the photoconductive cell is connected to an external load. There are a variety of different measurements we can make to determine the solar cell's performance, such as its power output and its conversion efficiency.

The main electrical characteristics of a PV cell or module are summarized in the relationship between the current and voltage produced on a typical solar cell I-V characteristics curve. The intensity of the solar radiation (insolation) that hits the cell controls the current (I), while the increases in the temperature of the solar cell reduces its voltage (V).

Solar cells produce direct current (DC) electricity and current times voltage equals power, so we can create solar cell I-V curves representing the current versus the voltage for a photovoltaic device.

Solar Cell I-V Characteristics Curves are basically a graphical representation of the operation of a solar cell or module summarising the relationship between the current and voltage at the existing conditions of irradiance and temperature. I-V curves provide the information required to configure a solar system so that it can operate as close to its optimal peak power point (MPP) as possible.

Solar Cell I-V Characteristic Curve



The above graph shows the current-voltage (I-V) characteristics of a typical silicon PV cell operating under normal conditions. The power delivered by a solar cell is the product of current and voltage (I x V). If the multiplication is done, point for point, for all voltages from short-circuit to open-circuit conditions, the power curve above is obtained for a given radiation level.

With the solar cell open-circuited, that is not connected to any load, the current will be at its minimum (zero) and the voltage across the cell is at its maximum, known as the solar cells **open circuit voltage**, or Voc. At the other extreme, when the solar cell is short circuited, that is the positive and negative leads connected together, the voltage across the cell is at its minimum (zero) but the current flowing out of the cell reaches its maximum, known as the solar cells **short circuit current**, or Isc.

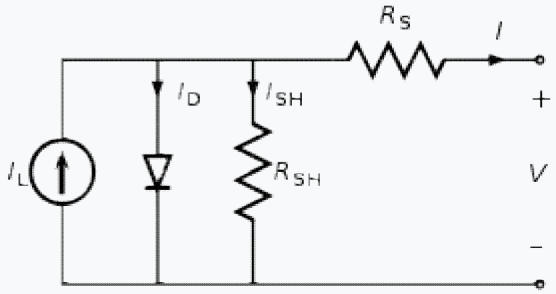
Then the span of the solar cell I-V characteristics curve ranges from the short circuit current (Isc) at zero output volts, to zero current at the full open circuit voltage (Voc). In other words, the maximum voltage available from a cell is at open circuit, and the maximum current at closed circuit. Of course, neither of these two conditions generates any electrical power, but there must be a point somewhere in between were the solar cell generates maximum power.

However, there is one particular combination of current and voltage for which the power reaches its maximum value, at Impand Vmp. In other words, the point at which the cell generates maximum electrical power and this is shown at the top right area of the green rectangle. This is the "maximum power point" or **MPP**. Therefore the ideal operation of a photovoltaic cell (or panel) is defined to be at the maximum power point.

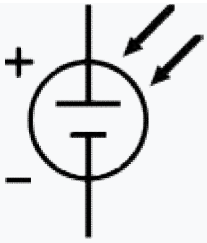
The maximum power point (MPP) of a solar cell is positioned near the bend in the I-V characteristics curve. The corresponding values of Vmp and Imp can be estimated from the open circuit voltage and the short circuit current: Vmp ≅ (0.8–0.90)Voc and Imp ≅ (0.85–0.95)Isc. Since solar cell output voltage and current both depend on temperature, the actual output power will vary with changes in ambient temperature.

Thus far we have looked at **Solar Cell I-V Characteristic Curve** for a single solar cell or panel. But many photovoltaic arrays are made up of smaller PV panels connected together. Then the I-V curve of a PV array is just a scaled up version of the single solar cell I-V characteristic curve as shown.

Equivalent circuit of a solar cell



The equivalent circuit of a solar cell

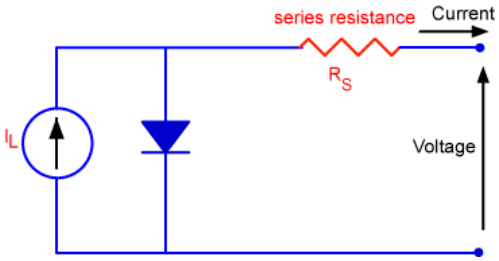


The schematic symbol of a solar cell

To understand the electronic behaviour of a solar cell, it is useful to create a model which is electrically equivalent, and is based on discrete ideal electrical components whose behaviour is well defined. An ideal solar cell may be modelled by a current source in parallel with a diode; in practice no solar cell is ideal, so a shunt resistance and a series resistance component are added to the model. The resulting equivalent circuit of a solar cell is shown on the left. Also shown, on the right, is the schematic representation of a solar cell for use in circuit diagrams.

Series Resistance

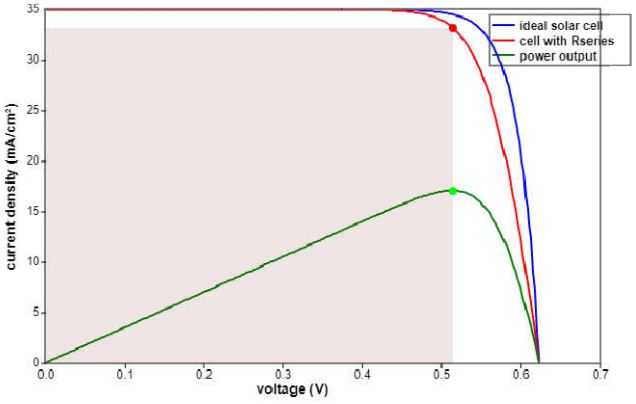
Series resistance in a solar cell has three causes: firstly, the movement of current through the emitter and base of the solar cell; secondly, the contact resistance between the metal contact and the silicon; and finally the resistance of the top and rear metal contacts. The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current.



Schematic of a solar cell with series resistance.

$$I = I_L - I_0 \exp[q(V + IR_S) / nkT]$$

where: I is the cell output current, I_L is the light generated current, V is the voltage across the cell terminals, T is the temperature, q and k are constants, n is the ideality factor, and R_S is the cell series resistance. The formula is an example of an implicit function due to the appearance of the current, I, on both sides of the equation and requires numerical methods to solve.



The effect of the series resistance on the IV curve is shown below. To generate the plot the voltage across the diode is varied thereby avoiding the need to solve an implicit equation.

Cell series resistance, R_S = 1 Ω cm^2

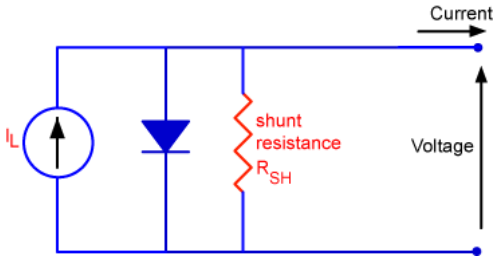
The effect of series resistance depens on fill factor. The area of the solar cell is 1 cm^2 so that the units of resistance can be either ohm or ohm cm^2. The short circuit current (I_{SC}) is unaffected by the series resistance until it is very large.

Series resistance does not affect the solar cell at open-circuit voltage since the overall current flow through the solar cell, and therefore through the series resistance is zero. However, near the open-circuit voltage, the IV curve is strongly affected by the series resistance. A straight-forward method of estimating the series resistance from a solar cell is to find the slope of the IV curve at the open-circuit voltage point.

An equation for the FF as a function of series resistance can be determined by noting that for moderate values of series resistance, the maximum power may be approximated as the power in the absence of series resistance minus the power lost in the series resistance.

Shunt Resistance

Significant power losses caused by the presence of a shunt resistance, R_{SH}, are typically due to manufacturing defects, rather than poor solar cell design. Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current. Such a diversion reduces the amount of current flowing through the solar cell junction and reduces the voltage from the solar cell. The effect of a shunt resistance is particularly severe at low light levels, since there will be less light-generated current. The loss of this current to the shunt therefore has a larger impact. In addition, at lower voltages where the effective resistance of the solar cell is high, the impact of a resistance in parallel is large.



Circuit diagram of a solar cell including the shunt resistance.

The equation for a solar cell in presence of a shunt resistance is:

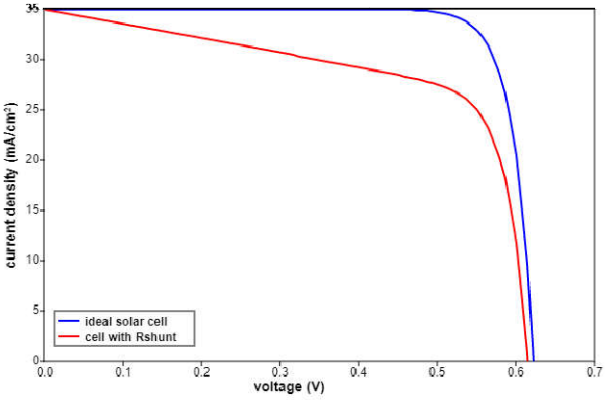
$$\mathbf{I=I_L-I_0exp[qV/nkT]-V/R_{SH}}$$

where: I is the cell output current, I_L is the light generated current, V is the voltage across the cell terminals, T is the temperature, q and k are constants, n is the ideality factor, and R_{SH} is the cell shunt resistance.

The effect of a low shunt resistance is shown in below.

Cell shunt resistance is: 1.00e+3 ohm cm^2

The effect of shunt resistance on fill factor in a solar cell: The area of the solar cell is 1 cm^2, the cell series resistance is zero, temperature is 300 K, and I_0 is 1 x 10^{-12} A/cm^2.



An estimate for the value of the shunt resistance of a solar cell can be determined from the slope of the IV curve near the short-circuit current point.

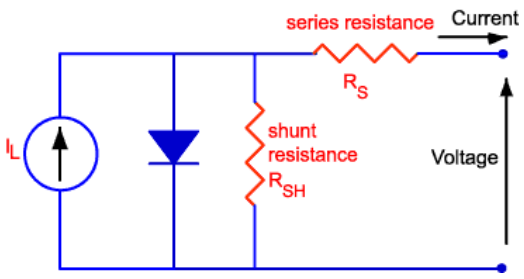
The impact of the shunt resistance on the fill factor can be calculated in a manner similar to that used to find the impact of series resistance on fill factor. The maximum power may be approximated as the power in the absence of shunt resistance, minus the power lost in the shunt resistance.

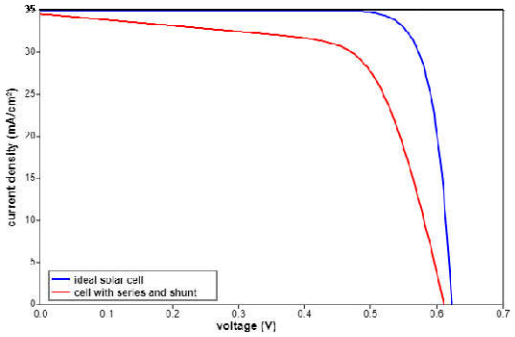
Impact of Both Series and Shunt Resistance

In the presence of both series and shunt resistances, the IV curve of the solar cell is given by;

$$I = I_L - I_0 \exp\left[\frac{q(V + IR_S)}{nkT}\right] - \frac{V + IR_S}{R_{SH}}$$

and the circuit diagram of the solar cell is given as;





Parasitic series and shunt resistances in a solar cell circuit.

Solar Photovoltaic Systems

Solar Photovoltaic System uses solar cells to convert light into electricity. A PV system consists of PV modules and balance of systems (BOS). Balance of systems includes module support structure, storage, wiring, power electronics, etc.

DC (direct current) electricity is generated when solar radiation strikes the PV module. Power can be used in any DC load directly during this generation. But the generation exists during daytime. So, some storage device is needed to run the system at night or in low sunshine hour. Again this power cannot be used to run any AC (alternate current) load. Inverter has to be used to convert DC into AC.

Solar PV systems are categories into

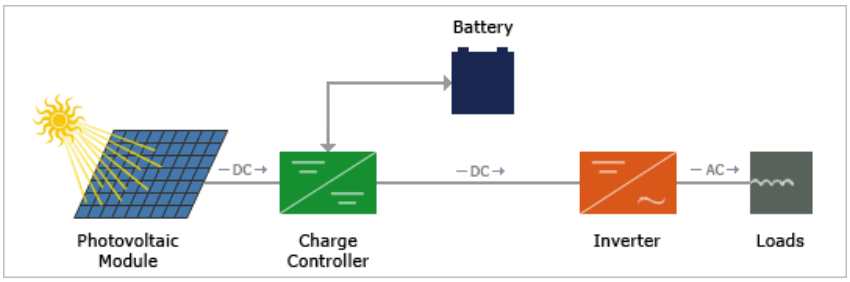
- Stand-alone PV systems (also called off-grid systems)
- Grid connected PV systems (also called on-grid systems)
- Hybrid systems

a) Stand-alone PV systems:

Stand-alone systems are not connected with utility power lines and these are self sufficient systems. These systems could either be used to charge the batteries that serve as an energy storage device or could work directly using the solar energy available in the daytimes. These systems consist of the following:

- Solar panels mounted on the roof or in open spaces. Photovoltaic modules produce direct current (DC) electrical power.
- Batteries to store DC energy generated by the solar panels.
- Charge controller to prevent overcharging the battery.
- Inverter to convert electricity produced by the system from DC to AC power.

The following diagram shows PV system powering AC loads with battery bank. DC loads can also be connected directly to the battery bank. It is also possible to power the AC load without battery, but in that case it would be confined only to daytime when solar radiation is sufficient to generate required electricity.



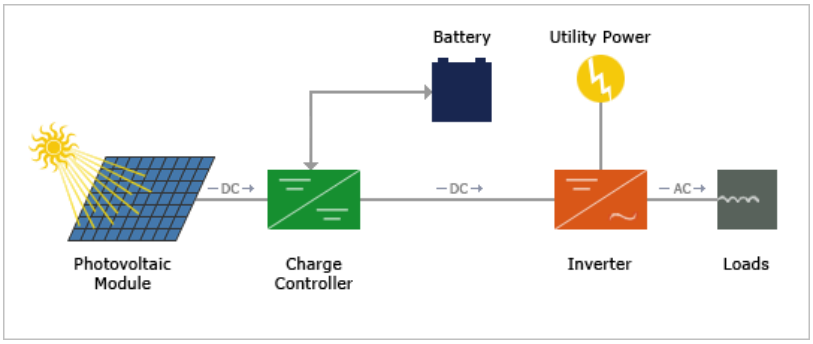
b)Grid connected PV systems :

A grid connected photovoltaic system will be interacted with utility grid. The main advantage of this system is that power can be drawn from the utility

grid and when power is not available from grid, PV system can supplement that power. These grid connected systems are designed with battery or without battery storage. These systems consist of the following:

- Solar panels mounted on the roof or in open spaces. Photovoltaic modules produce direct current (DC) electrical power.
- Batteries to store DC energy generated by the solar panels.
- Charge controller to prevent overcharging the battery.
- Specially designed inverter to transform the PV generated DC electricity to the grid electricity (which is of AC) at the grid voltage.

The following diagram shows PV system powering AC loads. This system is connected to utility power supply and having battery storage for backup.

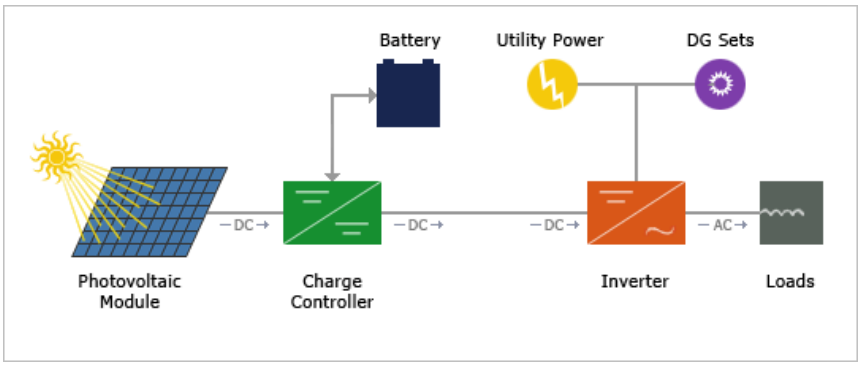


c)Hybrid systems :

System with more than one source of power is called Hybrid system. It is often desirable to design a system with additional source of power. The most common type of hybrid system contains a gas or diesel powered engine generator. Another hybrid approach is a PV/Wind system. Adding a wind turbine to a PV system provides complementary power generation. These systems consist of the following:

- Solar panels mounted on the roof or in open spaces. Photovoltaic modules produce direct current (DC) electrical power.
- Batteries to store DC energy generated by the solar panels.
- Charge controller to prevent overcharging the battery.
- Specially designed inverter to transform the PV generated DC electricity to the grid electricity (which is of AC) at the grid voltage.

The following diagram shows PV system powering AC loads. This system is connected to utility power supply & diesel generator and having battery storage for backup.



System design: storage sizing – PV system sizing:

Sizing Objectives

- Sizing is the basis for PV system electrical designs, and establishes the sizes and ratings of major components needed to meet a certain performance objective
- The sizing of PV systems may be based on any number of factors, depending on the type of system and its functional requirements.

Sizing Principles

The sizing principles for interactive and stand-alone PV systems are based on different design and functional requirements.

- Utility-Interactive Systems (without energy storage):
  1. Provide supplemental power to facility loads.
  2. Failure of PV system does not result in loss of loads.

- Stand-Alone Systems (with energy storage):
  1. Designed to meet a specific electrical load requirement.
  2. Failure of PV system results in loss of load.

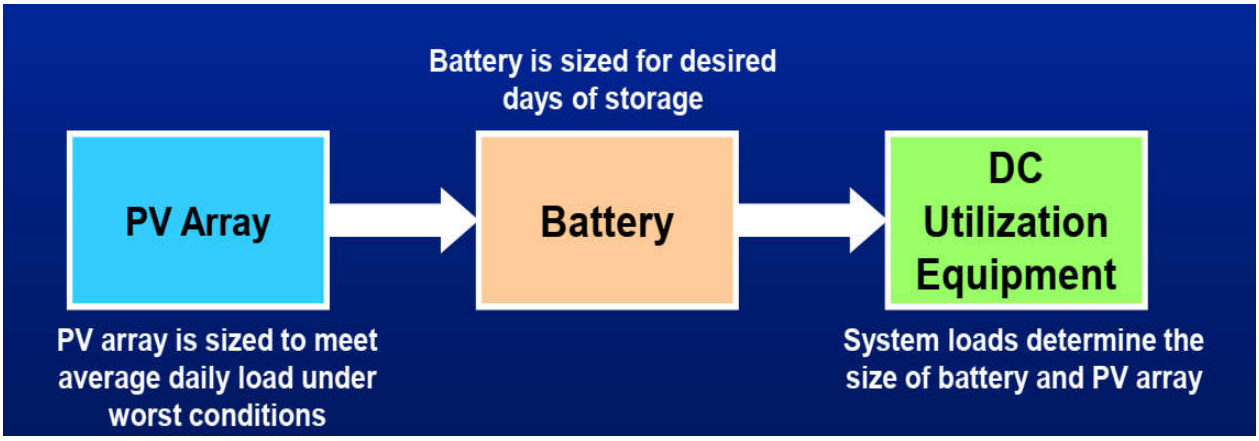
Sizing Stand-Alone Systems

The sizing objective for any type of stand-alone PV system is a critical balance between energy supply and demand.

- The PV array must provide enough energy to meet the load plus system losses under the worst case conditions.
- Consequently, the efficiency of the electrical loads is a critical concern.

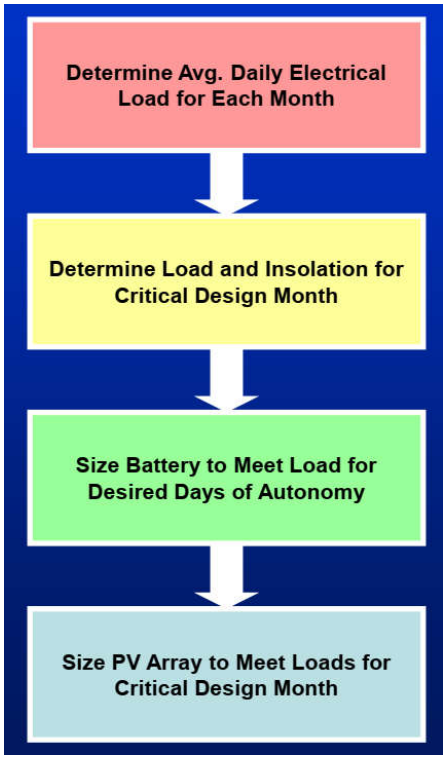
- Stand-alone PV systems can be considered a type of banking system.

  The battery is the bank account. The PV array produces energy (income) and charges the battery (deposits), and the electrical loads consume energy (withdrawals).



1.Stand-alone PV systems are sized to meet specific load requirements, and involve the following key steps:

- Determine the average daily load requirements for each month.
- Conduct a critical design analysis to determine the month with the highest load to solar insolation ratio.
- Size battery bank for system voltage and required energy storage capacity.
- Size PV array to meet average daily load requirements during period with lowest sunlight and highest load (usually winter).
- Sizing stand-alone PV systems begins with determining the electrical load, and then sizing the battery and PV array to meet the average daily load during the critical design month.



2.Load Analysis:

- The energy consumption for electrical loads is estimated on an average daily basis for each month of the year.
- Use worksheets to list each load, its average power, daily time of use and compute energy consumption.
- List AC and DC loads separately, and apply inverter efficiency to determine the DC energy required for AC loads.
- The daily DC energy required is used to size the battery and PV array.
- The peak AC power demand dictates the size of inverter required.
- Explore opportunities for improvements in load efficiency and end-use practices to reduce size and costs of PV system required.

3.Critical Design Analysis:

- A critical design analysis evaluates the ratio of the average daily load energy requirements and available solar insolation for each month.
- Use a worksheet to list the average daily loads for each month, and divide the loads by the available solar insolation for different array tilt angles.
- The critical design month is the month with the highest ratio of load to solar insolation, and defines the optimal tilt angle that results in the smallest array possible.
- For constant loads, the critical design month is the month with the greatest average daily load.

4.Selecting the System DC Voltage:

- The DC voltage for stand-alone PV systems is selected based on the operating voltages for DC utilization equipment, including loads and inverters.
- Higher DC voltages are used for systems with higher power loads to reduce the system currents and the size of the conductors and switchgear required.
- Smaller stand-alone systems used for residential and small off grid application typically use 12 V, 24 V or 48 V systems, while larger systems may use even higher DC voltages.

5.Selecting an Inverter:

Selecting an inverter for stand-alone systems is based on the following:

- Nominal system DC voltage (battery)
- AC output voltage
- Peak AC power required for cumulative load
- Surge current requirements, if any
- Additional features (battery charger, etc.)

6.System Availability:

- System availability is a statistical parameter, and represents the percentage of time over an average year that a stand-alone PV system meets the system loads.
- The sizing of stand-alone PV systems is based on long-term averages for solar insolation, and invariably, 100% load availability can never be achieved.
- Higher system availability can be achieved by increasing the size of the PV array and/or battery.

7.Sizing the Battery:

Batteries for stand-alone systems are sized to store energy produced by the array for use by the system loads as required.

The total amount of rated battery capacity required depends on the following:

- Desired days of storage to meet system loads with no recharge from PV
- Maximum allowable depth-of-discharge
- Temperature and discharge rates
- System losses and efficiencies
- The system voltage defines the number of series-connected battery cells required.
- The total capacity needed defines the number of parallel battery strings required.

8.Autonomy:

- Autonomy is the number of days that a fully charged battery can meet the system loads without any recharge from the PV array.

- The specified autonomy and maximum allowable depth-of discharge define the total amount of battery capacity required for a given system load.
- Greater autonomy periods are used for more critical applications and increase system availability, but at higher cost due to the larger battery required.

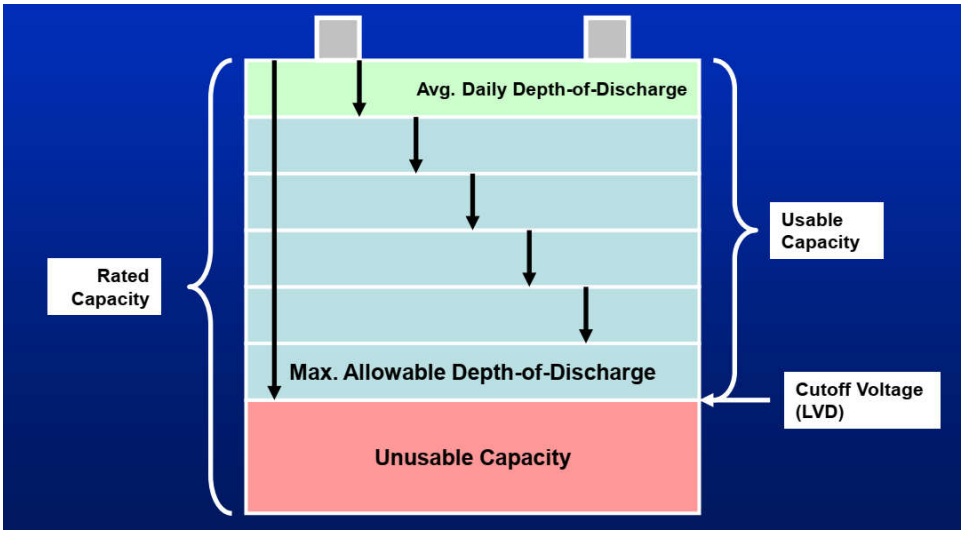
9.Factors Affecting Battery Sizing:

Greater autonomy periods increase the size of the battery and increase availability, and decrease average daily depth-of discharge.

- Maximum depth-discharge defines the usable battery capacity and is defined by the load cut-off voltage.
- Greater allowable DOD provides greater system availability, but at the expense of battery health.
- Depth-of-discharge must be limited in cold climates to protect lead-acid batteries from freezing.
- Rated battery capacity is affected by temperature, discharge rate and age of the battery.

10.Sizing the Battery:

Battery sizing is based on rated capacity and specified limits of operation.

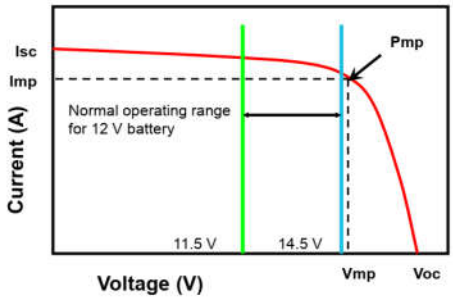


11. Sizing the PV Array

- The PV array for stand-alone systems is sized to meet the average daily load during the critical design month.
- System losses, soiling and higher operating temperatures are factored in estimating array output.
- The system voltage determines the number of series-connected modules required per source circuit.
- The system power and energy requirements determine the total number of parallel source circuits required.

12.PV Array Battery Charging:

Standard silicon PV modules with series-connected cells are optimally suited for charging a nominal 12 V lead-acid battery



WHAT IS MPPT?

PV modules still have relatively low conversion efficiency; therefore, controlling maximum power point tracking (MPPT) for the solar array is essential in a PV system. The amount of power generated by a PV depends on the operating voltage of the array. A PV's maximum power point (MPP) varies with solar insulation and temperature.

MPPT or **Maximum Power Point Tracking** is algorithm that included in charge controllers used for extracting maximum available power from PV module under certain conditions. The voltage at which PV module can produce maximum power is called 'maximum power point' (or peak power voltage).

How MPPT works?

The major principle of MPPT is to extract the maximum available power from PV module by making them operate at the most efficient voltage (maximum power point).

➢ MPPT checks output of PV module, compares it to battery voltage then fixes what is the best power that PV module can produce to charge the battery and converts it to the best voltage to get maximum current into battery. MPPT is most effective under these conditions:

•Cold weather, cloudy or hazy days: Normally, PV module works better at cold temperatures and MPPT is utilized to extract maximum power available from them. When battery is deeply discharged: MPPT can extract more current and charge the battery if the state of charge in the battery is lowers.

MPPT solar charge controller:

A MPPT **solar charge controller** is the charge controller embedded with MPPT algorithm to maximize the amount of current going into the battery from PV module.

➢ MPPT is DC to DC converter which operates by taking DC input from PV module, changing it to AC and converting it back to a different DC voltage and current to exactly match the PV module to the battery.

➢ Examples of DC to DC converter are

• **Boost converter**

• **Buck converter**

➢ MPPT algorithm can be applied to both of them depending on system design.

DC-DC CONVERTER

DC/DC converters are used in applications where an average output voltage is required, which can be higher or lower than the input voltage.The choice of the appropriate DC/DC converter for the implementation of both the MPPT system and its integration in the facility array has not been explicitly studied, despite its affecting significantly the optimum operation of the photovoltaic system. The aim of this work is to make a comparative of the photovoltaic system performance using the three basic topologies of three different DC-DC converters (Buck and Boost converter) and MPPT tracker, for that we require the study of characteristics and properties of DC/DC converters, especially as regards the input impedance that they present under certain operating conditions. So that it may be possible to make a decision on the best configuration to be used

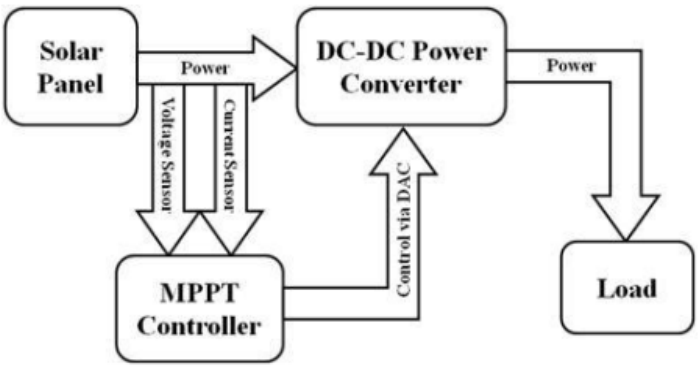


Fig 5: DC – DC converter for operation at the MPP

Fig.6 shows the diagram of a solar panel connected to a DC/DC converter, where the resistance shown at the converter‟s input is represented by Ri (RL is the converter‟s load resistance). In relation to the photovoltaic module, the converter is its Ri value load resistance. Assuming converters without losses, the ratio of input resistance to load resistance is shown in

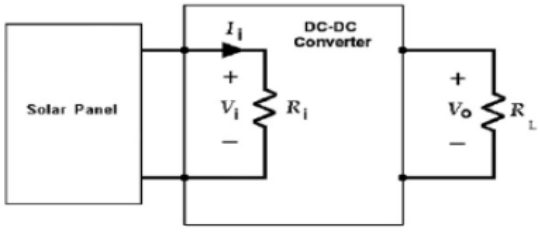


Fig 6: Panel–converter connection.

Table 1: Rin value for converters

Converter	Kcrit	Rin(CCM)	Rin(DCM)
Buck	1-D	$\frac{R_L}{D}$	$\frac{R_L}{4}(1+\sqrt{1+4K/D^2})^2$
Boost	$D(1-D)^2$	$R_L.(1-D)^2$	$\frac{4.R_L}{(1+\sqrt{1+D^2/K})^2}$
Buck-boost With $K=\frac{2Leqv}{R_L.Tc}$	$(1-D)^2$	$\frac{R_L.(1-D)^2}{D^2}$	$\frac{K.R_L}{D^2}$ DCM happens for K≤ Kcrit

Table 1, both for CCM and DCM.

The ratio of the time interval in which the switch is on (T_{ON}) to the commutation period (T_C) is called duty cycle (D) of the converter. If K value is lower than or equal to another one called Kcrit, the converter will operate in DCM. Conversely, if K exceeds the value of Kcrit, the converter will operate in CCM. As observed in Table 1, the value of Kcrit is different for each type of converter.

A. Buck Converter

This is a converter whose output voltage is smaller than the input voltage and output current is larger than the input current. The circuit diagram is shown in the following figure .

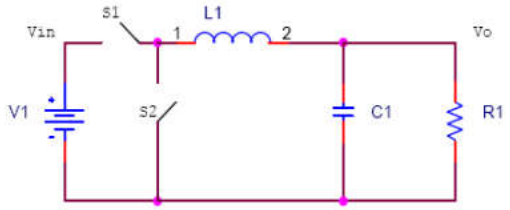


Fig 8: Buck Converter

The conversion ratio is given by the following expression

$\frac{Vo}{Vin} = \frac{Iin}{Io} = D$ ..... (1)

Where D is the duty cycle. This expression gives us the following relationships:

$Vin = \frac{Vo}{D}$ ..... (2)

$Iin = Io\ D$ ..... (3)

Knowing Vin and Iin, we can find the input resistance of the converter. This is given by

$Rin = \frac{Vin}{Iin} = \frac{Vo/D}{IoD} = \frac{Vo/Io}{D^2} = \frac{Ro}{D^2}$ ..... (4)

Where Ro is the output resistance or load resistance of the converter. We know that D varies from 0 to ∞ (0 to 1 not inf). Hence Rin would vary from ∞ to Ro as D varies from 0 to 1 correspondingly.

The range of Rin values for buck converters as shown in the following figures:

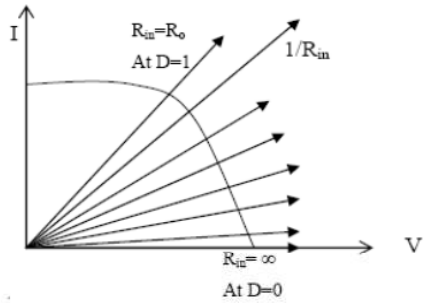


Fig 9: The range of Rin values for buck converters

Being the expressions of Rin continuous in D, for a scanning of the converter's duty cycle D 2 [0,1], Rin takes values that belong to the interval [RL,1), being R_L the load resistance or Ro. If R_{MPP} does not belong to the set of values allowed for Rin, the capture of MPP will not be possible, thus defining a ''non-capture zone'' for $R_L > R_{MPP}$ values. Fig. shows the effect graphically. The impedance at the input of a buck converter is always a version scaled by a factor greater than or equal to 1 (see Table 1) of the impedance connected to its output Ro (Ro= R_L). Therefore, the MPP capture will only be possible for $R_L \leq R_{MPP}$ values.

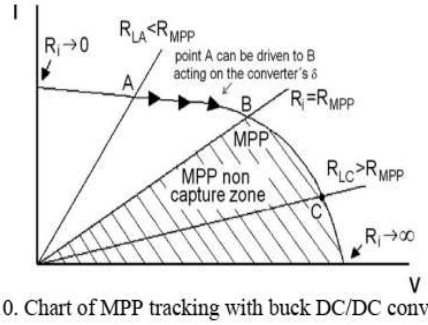


Fig 10. Chart of MPP tracking with buck DC/DC converter.

B. Boost Converter

This is a converter whose output voltage is larger than the input voltage and output current is smaller than the input current. The circuit diagram is shown in the following figure

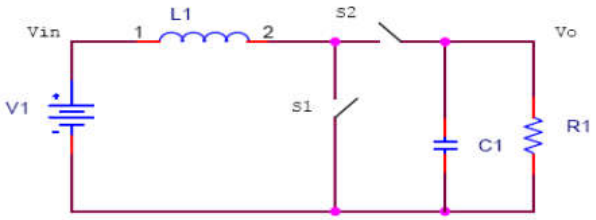


Fig 11: Boost Converter

The conversion ratio is given by the following expression:

$\frac{Vo}{Vin} = \frac{Iin}{Io} = \frac{1}{1-D}$ ..... (5)

Where D is the duty cycle. This expression gives us the following relationships:

Vin = Vo (1-D) ..... (6)

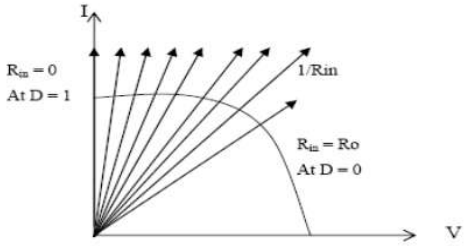
Iin= $\frac{Io}{1-D}$ ..... (7)

Rin=$\frac{Vin}{Iin} = \frac{Vo\,(1-D)}{(\frac{Io}{1-D})} = \frac{Vo}{Io}(1-D)^2$ so we get

Rin = $Ro(1-D)^2$..... (8)

Here(Consider Rin = Ri, Ro = R_L)

, Rin varies from Ro to 0 as D varies from 0 to 1 correspondingly. The range of Rin values for boost converters as shown in the following figures:



Figures 12: The range of Rin values for boost converters

The maximum power point tracking system will modify the value of Rin, trying to get Rin = R_{MPP}. However, this will not be possible if RMPP does not belong to the set of values allowed for Rin, that is, the system will not reach the MPP if R_L<R_{MPP}. The behavior is clearly opposite to that mentioned in the previous section, and therefore there is an inversion of zones with respect to the buck converter. Fig. shows this effect. The impedance at the input of a boost converter is always a lessened version in a factor lower than or equal to 1 (see Table 1) of the impedance connected to its output (R_L in our case). Therefore, the MPP capture will only be possible for $R_L \geq R_{MPP}$ values.

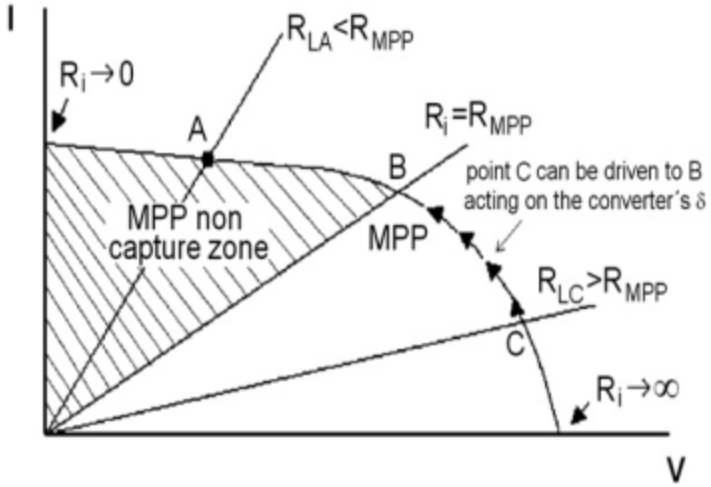
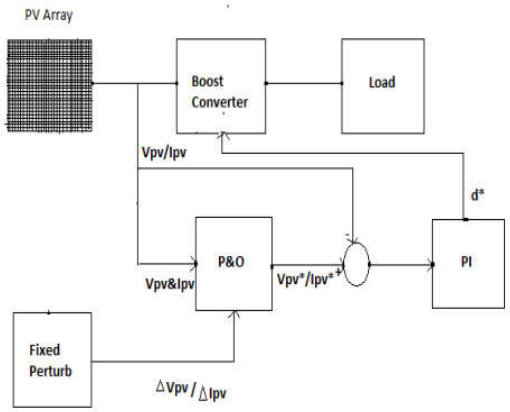


Fig 13: Chart of MPP tracking with boost DC/DC converter

PERTURB & OBSERVE METHOD (P&O):



Perturb and Observe (P&O) method A P&O method is the most simple, which moves the operating point toward the maximum power point periodically increasing or decreasing the PV array voltage by comparing power quantities between in the present and past. The block diagram of P&O method is illustrated in Fig.

If the power increased, the perturbation is continuous in the same direction in the next perturbation cycle, otherwise the perturbation direction is reversed. This way, the operating point of the system gradually moves towards the MPP and oscillates around it in steady-state conditions. Large perturbation step sizes yield fast tracking of the MPP under varying atmospheric conditions but result in reduced average power conversion in steady state due to large oscillations around the MPP. Hence the famous trade off problem between faster response and steady-state oscillations is inherent. Moreover, the perturbation is not generic. In order to overcome all this, high performance P&O technique is proposed.

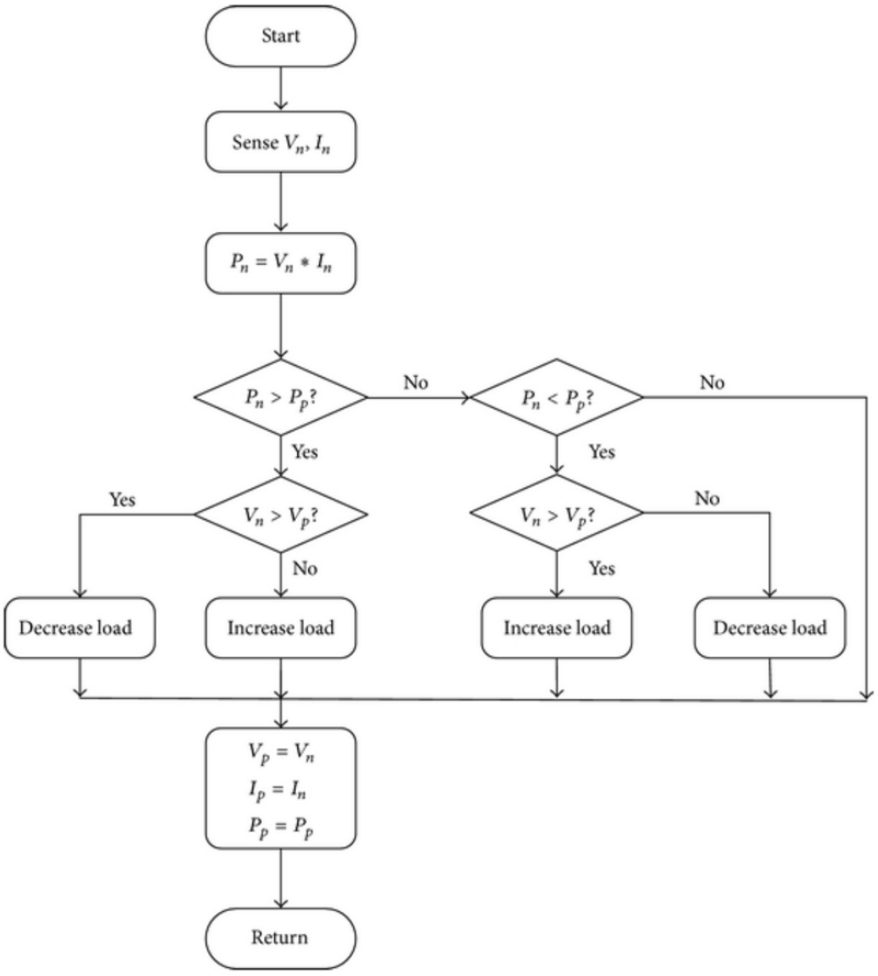


Fig 3.1:Flow chart of the MPPT algorithm with P&O method.

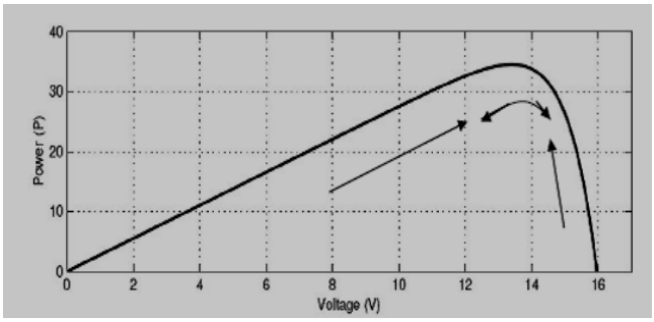


Figure 5(a). Graph Power versus Voltage for Perturb and Observe Algorithm

HILL CLIMBING ALGORITHM:

The hill climbing algorithm locates the maximum power point by relating changes in the power to changes in the control variable used to control the array. This system includes the perturb and absorb algorithm Hill-climbing algorithm involves a perturbation in the duty ratio of the power inverter. In the case of a PV array connected to a system, perturbing the duty ratio of power inverter perturbs the PV array current and consequently perturbs the PV array voltage. Figure 7.1 shows the characteristic of PV array curve. In this method, by incrementing the voltage, the power increases when operating on the left of the MPP and decreases the power when on the right of the MPP. Therefore, if there is an increase in power, the subsequent perturbation is kept at same point to reach the MPP and if there is a decrease in power, the perturbation is reversed. This algorithm is summarized in Table 7.1. The process is repeated periodically until the MPP is reached. The system then oscillates about the MPP. The oscillation is minimized by reducing the perturbation step size.

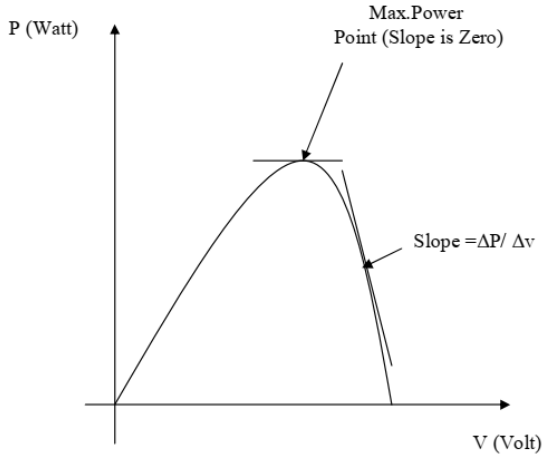


Figure 7.1 Characteristic PV Array Power Curve

Table 7.1 Summary of Hill Climbing Algorithm

Perturbation	Change in Power	Next Perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

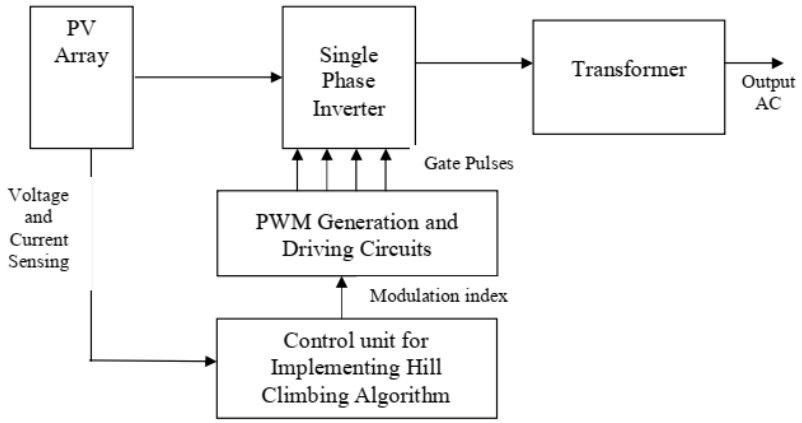


Figure 7.2 Block Diagram of Entire System

Figure 7.2 shows the entire block diagram of the proposed system. In this, the PV array output vary with temperature, insolation, angle of incidence and the PV characteristics of the PV cell or array which is used. So in order to track the maximum power point for a particular condition, the voltage and current is sensed and is scaled to 5V through an operational amplifier and is given as an input to the analog channel of the PIC microcontroller for making necessary control action. The PIC microcontroller tracks the variation of dp/dv which is either positive, negative or zero. If it is zero, it doesn't make any change in control signal. Whereas if it is positive, it increments the modulation index and if it is negative, it decrements the modulation index. The PIC microcontroller sends necessary signal to PWM generator which generates gate pulses for triggering the inverter.

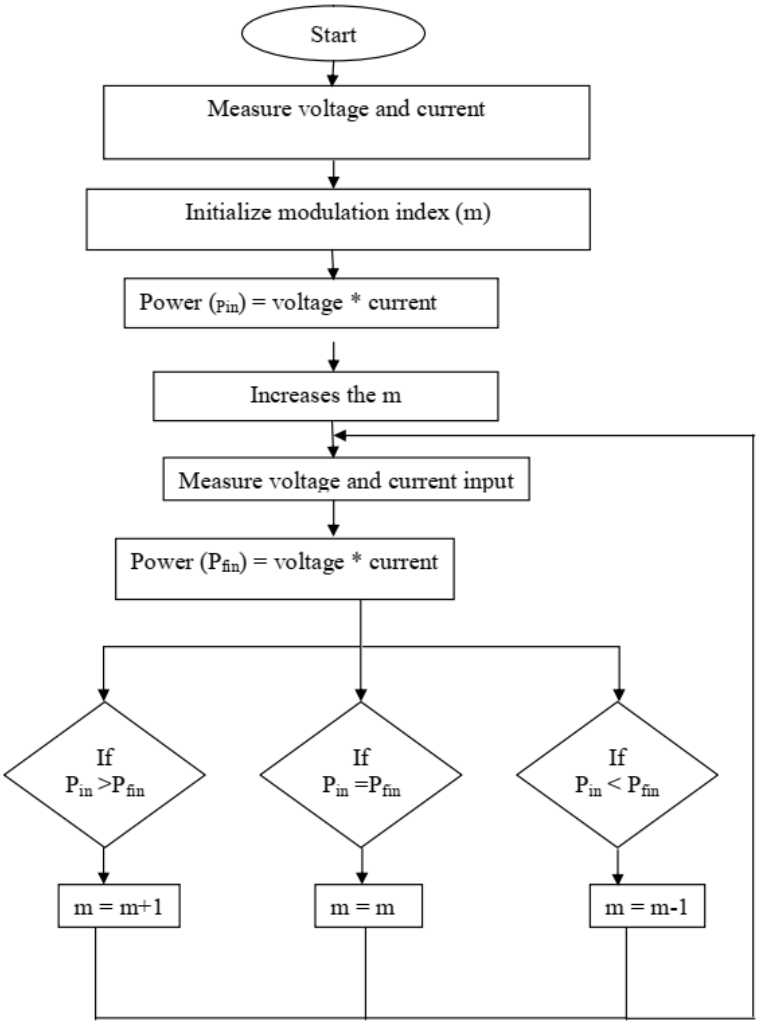


Figure 7.3 Flow Chart for Calculating Modulation Index Value

The algorithm used for MPPT is discussed below:

Step 1: Sensing and measuring the voltage and current of PV array

Step 2: Initialize the modulation index to a particular value

Step 3: The initial power Pin is calculated

Step 4: Increase the value of m

Step 5: Sense the PV array voltage and current

Step 6: Calculate the modified power Pfin

Step 7: If the change in power is positive, increase m value; if it is negative, decrease m value' and if there is no change in power, m value is retained.

Step 8: Repeat step 5.