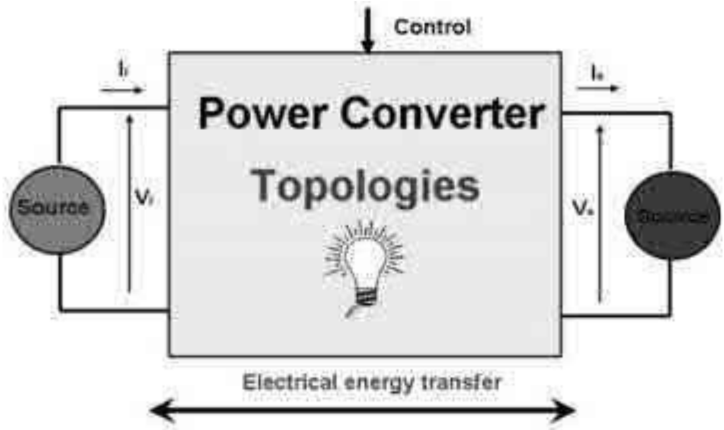
EE6009 POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS
UNIT III-POWER CONVERTERS AND ANALYSIS OF SOLAR PV SYSTEMS

3.1-POWER CONVERTERS: LINE COMMUTATED CONVERTERS (INVERSION-MODE) - BOOST AND BUCK-BOOST CONVERTERS- SELECTION OF INVERTER, BATTERY SIZING, ARRAY SIZING.

INTRODUCTION TO POWER CONVERTERS

The task of a power converter is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for the user loads. Energy was initially converted in electromechanical converters (mostly rotating machines). Today, with the development and the mass production of power semiconductors, static power converters find applications in numerous domains and especially in particle accelerators. They are smaller and lighter and their static and dynamic performances are better. A static converter is a meshed network of electrical components that acts as a linking, adapting or transforming stage between two sources, generally between a generator and a load.



Power converter definition

An ideal static converter controls the flow of power between the two sources with 100% efficiency. Power converter design aims at improving the efficiency. But in a first approach and to define basic topologies, it is interesting to assume that no loss occurs in the converter process of a power converter.

SOLAR PHOTO-VOLTAIC SYSTEM

Introduction

A photovoltaic system, also PV system or solar power system is a power system designed to supply usable solar power by means of photo-voltaic. It consists of an arrangement of several components, including solar panels to absorb and convert sunlight into electricity, a solar inverter to change the electric current from DC to AC, as well as mounting, cabling and other electrical accessories to set up a working system. It may also usea solar tracking system to improve the system's overall performance and include an integrated battery solution, as prices for storage devices are expected to decline. Strictly speaking, a solar array only encompasses the ensemble of solar panels, the visible part of the PV system, and does not include all the other hardware, often summarized as balance of system . Moreover, PV systems convert light directly into electricity and shouldn't be confused with other technologies, such as concentrated solar power or solar thermal, used for heating and cooling.

PV systems range from small, rooftop-mounted or building-integrated systems with capacities from a few to several tens of kilowatts, to large utility-scale power stations of hundreds of megawatts. Nowadays, most PV systems are grid-connected, while off-grid or stand-alone systems only account for a small portion of the market. Operating silently and without any moving parts or environmental emissions, PV systems have developed from being niche market applications into a mature technology used for mainstream electricity generation.

Working and components of a PV system

The solar energy conversion into electricity takes place in a semiconductor device that is called a solar cell. A solar cell is a unit that delivers only a certain amount of electrical power. In order to use solar electricity for practical devices, which require a particular voltage or current for their operation, a number of solar cells have to be connected together to form a solar panel, also called a PV module. For large-scale generation of solar electricity the solar panels are connected together into a solar array. The solar panels are only a part of a complete PV solar system. Solar modules are the heart of the system and are usually called the power generators. One must have also mounting structures to which PV modules are fixed and directed towards the sun.

For PV systems that have to operate at night or during the period of bad weather the storage of energy are required, the batteries for electricity storage are needed. The output of a PV module depends on sunlight intensity and cell temperature; therefore components that condition the DC (direct current) output and deliver it to batteries, grid, and/or load are required for a smooth operation of the PV system. These components are referred to as charge regulators. For applications requiring AC (alternating current) the DC/AC inverters are implemented in PV systems. These additional components form that part of a PV system that is called balance of system. The elements of a PV system are schematically presented in Figure 1.

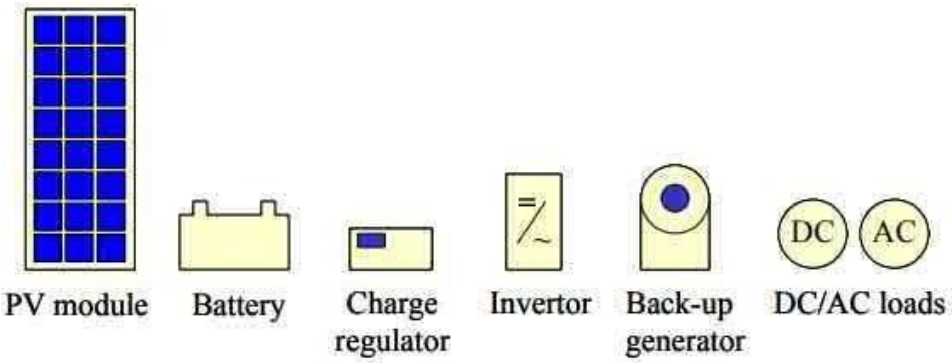


Figure 1: Components of a PV system

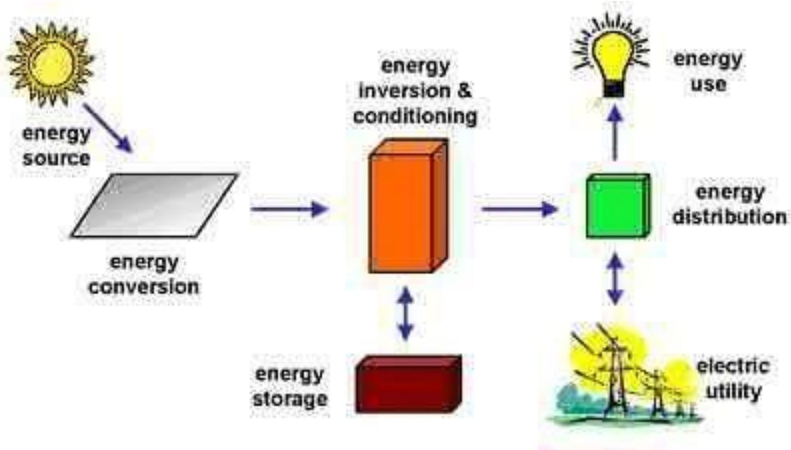
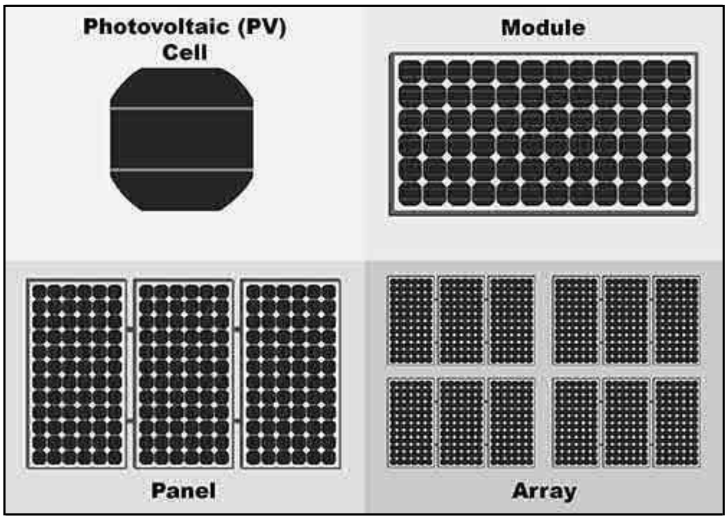


Figure 2: Major photovoltaic system components

Depending on the functional and operational requirements of the system, the specific components required may include major components such as a DC-AC power inverter, battery bank, system and battery controller, auxiliary energy sources and sometimes the specified electrical load (appliances). In addition, an assortment of balance of system hardware, including wiring, over current, surge protection and disconnect devices, and other power processing equipment. Figure 2 show a basic diagram of a photovoltaic system and the relationship of individual components. Batteries are often used in PV systems for the purpose of storing energy produced by the PV array during the day, and to supply it to electrical loads as needed (during the night and periods of cloudy weather). Other reasons batteries are used in PV systems are to operate the PV array near its maximum power point, to power electrical loads at stable voltages, and to supply surge currents to electrical loads and inverters. In most cases, a battery charge controller is used in these systems to protect the battery from overcharge and over discharge.

PV module and Array

Photovoltaic cells are connected electrically in series and/or parallel circuits to produce higher voltages, currents and power levels. Photovoltaic modules consist of PV cell circuits sealed in an environmentally protective laminate, and are the fundamental building blocks of PV systems. Photovoltaic panels include one or more PV modules assembled as a pre-wired, field- installable unit. A photovoltaic array is the complete power-generating unit, consisting of any number of PV modules and panels.



Photovoltaic cells, modules, panels and arrays

Mounting structures

The principal aim of the mounting structures is to hold the PV modules securely in place, which usually means that they have to resist local wind forces. When placed in a public area the structures should prevent stealing the modules. The further common requirements are not to cause shading of the modules and to be arranged so that there is an easy access to the modulesfor the maintenance or repair. The cost of the structures should be low. For integration in buildings, special mounting structures are being developed that together with the modules serve as building elements.

Energy storage

The simplest means of electricity storage is to use the electric rechargeable batteries, especially when PV modules produce the DC current required for charging the batteries. Most of batteries used in PV systems are lead-acid batteries. In some applications, for example when used in locations with extreme climate conditions or where high reliability is essential, nickel-cadmium batteries are used. The major difficulty with this form of storage is the relative high cost of the batteries and a large amount required for large-scale application.

Charge regulators

Charge regulators are the link between the PV modules, battery and load. They protect the battery from overcharge or excessive discharge. Charge and discharge voltage limits shouldbe carefully selected to suit the battery type and the operating temperature. These settings can significantly affect maximum operational life of a battery. High temperatures tend to reduce battery life because they accelerate corrosion and self-discharge. High temperatures may also increase out gassing during charging and therefore should be controlled. PV modules that are used to charge batteries usually operate at an approximately constant voltage, which is selectedto suit the local temperature. However some PV systems regulators employ a maximum power point tracker (MPPT), which automatically permits the PV modules to operate at the voltage that produces maximum power output. Such regulators employ an electronic DC-DC converter to maintain their output at the required system voltage. The benefit of using an MPPT depends on the application and should be weighed against its additional cost and reliability risks. For many applications, it may be equally or more cost effective to operate the system at a fixed voltage.

Inverters

The inverter's main functions are: transformation of DC electricity into AC, wave shaping of the output AC electricity, and regulation of the effective value of the output voltage. The most important features of an inverter for PV applications are its reliability and its efficiency characteristics. They are designed to operate a PV system continuously near its maximum power point. The technology for high-switching-frequency inverters (typically 20 kHz or higher) is made possible by switch-mode semiconductor power devices. The efficiencyof an inverter is normally quoted at its design operating power, but inverters in PV systems typically operate for much of their life at partial loads. For grid-connected operation, inverters must meet the requirements of the utilities concerning acceptable levels of harmonic distortion (quality of voltage and current output waveforms), and should not emit electrical noise, which could interfere with the reception of television or radio. They must also switch off when there isa grid failure for the safety of the engineers who have to repair the grid.

TYPES OF PV SYSTEMS

PV systems can be very simple, just a PV module and load, as in the direct powering of a water pump motor, or more complex, as in a system to power a house. Depending on the system configuration, we can distinguish three main types of PV systems: stand-alone, grid-connected, and hybrid.

Stand-alone systems

Stand-alone systems depend on PV power only. These systems can comprise only PV modules and a load or can include batteries for energy storage. When using batteries charge regulators are included, which switch off the PV modules when batteries are fully charged, and switch off the load in case batteries become discharged below a limit. The batteries must have enough capacity to store the energy produced during the day to be used at night and during periods of poor weather. Figure 1 shows schematically examples of stand-alone systems.

Grid-connected systems

Grid-connected PV systems have become increasingly popular as building integrated application. They are connected to the grid through inverters, and do not require batteries because the grid can accept all of the electricity that a PV generator can supply. Alternatively they are used as power stations. A grid-connected PV system is schematically presented in Figure 2.

Figure 1: Stand-alone systems

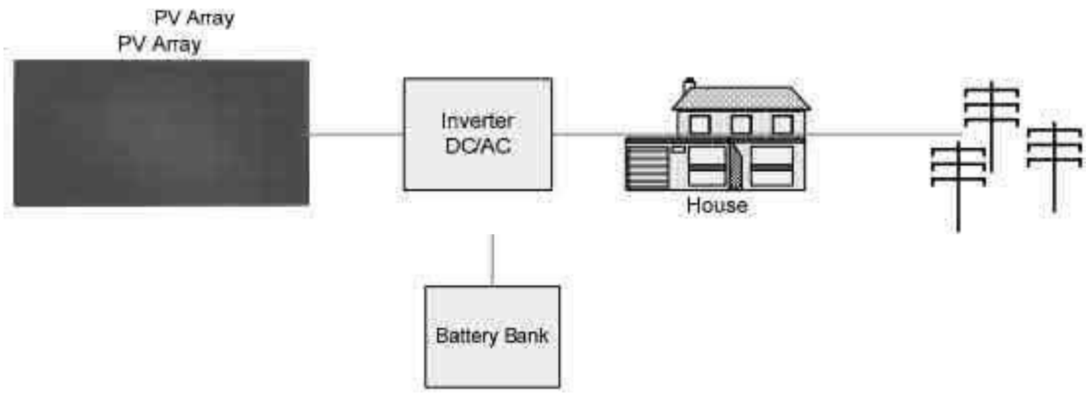


Figure 2: Grid-connected systems

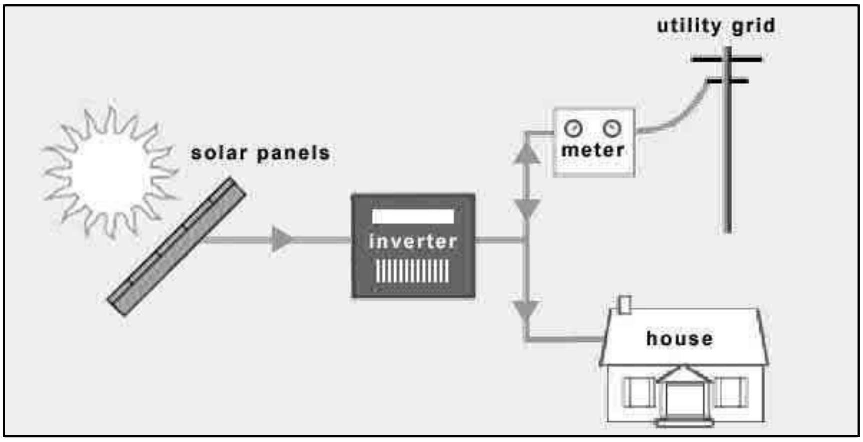


Figure 3: Hybrid PV-Diesel systems

Hybrid systems

Hybrid systems consist of combination of PV modules and a complementary means of electricity generation such as a diesel, gas or wind generator. In order to optimize the operations of the two generators, hybrid systems typically require more sophisticated controls than stand-alone PV systems. For example, in the case of PV/diesel systems, the diesel engine must be started when battery reaches a given discharge level and stopped again when battery reaches an adequate state of charge. The back-up generator can be used to recharge batteries only or to supply the load as well. A common problem with hybrid PV/diesel generators is inadequate control of the diesel generator. If the batteries are maintained at too high a state-of-charge by the diesel generator, then energy, which could be produced by the PV generator, is wasted. Conversely, if the batteries are inadequately charged, then their operational life will be reduced. Such problems must be expected if a PV generator is added to an existing diesel engine without installing an automatic system for starting the engine and controlling its output.

Equivalent circuit diagram of solar PV cell

Now a days, different semiconductor materials i.e. mono crystal polycrystalline and formless silicon are used. The single diode circuit configuration for PV cells is shown in Figure 1 and equation (1) shows the current expression. The double diode circuit configuration for PV cell is shown in Fig.2 and equation (2) shows the current expression.

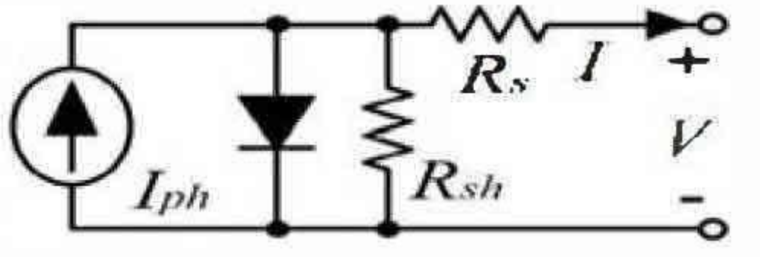


Figure 1: Single diode configuration for PV cell

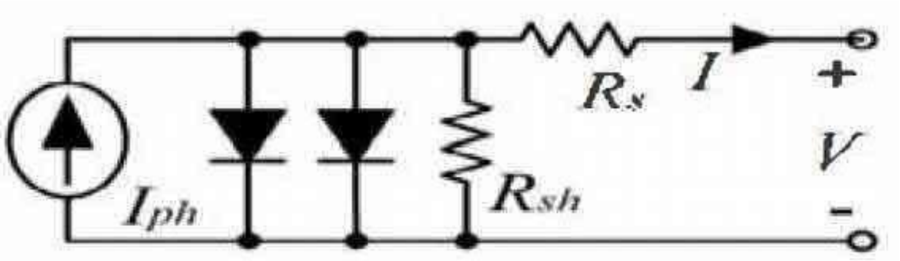


Figure 2: Double diode configuration for PV cell

For temperature dependence I_{ph} will be as shown in equation (3) for maximum power in case of single diode model.

$$I = I_{ph} - I_s\left[e^{\frac{q(V+IR_s)}{N_sKT_0A}} - 1\right] - \frac{V+IR_s}{R_{sh}} \qquad (1)$$

$$I = I_{ph} - I_{s1}\left[e^{\frac{q(V+IR_s)}{A_1KT}} - 1\right] - I_{s2}\left[e^{\frac{q(V+IR_s)}{A_2KT}} - 1\right]\frac{V+IR_s}{R_{sh}} \qquad (2)$$

$$I_{ph} = I_{ph(T=298K)}\left[1 + \left(T - 298K(5\times10^{-4})\right)\right] \qquad (3)$$

$$I_{S1} = K_1T^3e^{\frac{-E_S}{KT}} \qquad (4a)$$

$$I_{S2} = K_2T^{\frac{5}{2}}e^{\frac{E_S}{KT}} \qquad (4b)$$

Where

q	=	electron charge = 1.6 x 10^{-19} V
I_s	=	diode saturation current
I_{ph}	=	Photon Current
K_1	=	12000 A/m^2K^3
K_2	=	2.9 x 10^9 $A/m^2K^{5/2}$
R_s	=	Series Resistance
R_{sh}	=	Shunt Resistance
A	=	Diode ideality Factor
T_o	=	Operating temperature
N_s	=	No. of cells in series
K	=	Boltzmann constant = 1.38 x 10^{-23}J/K

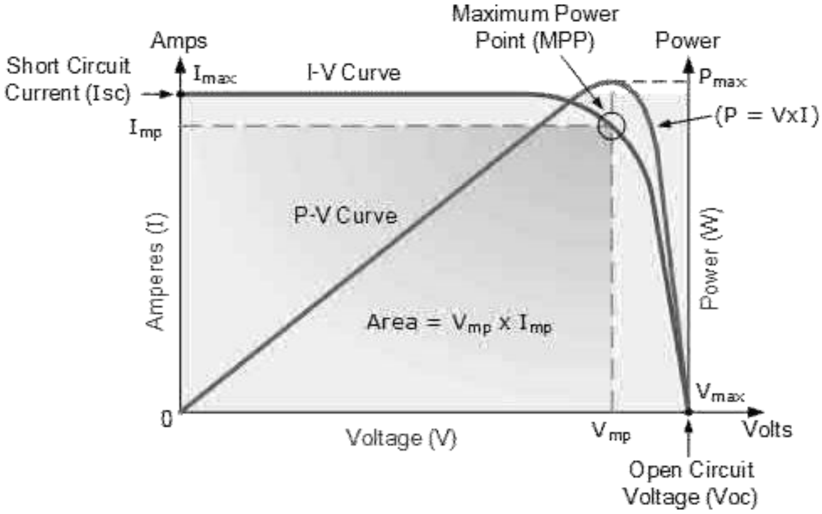
Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current. Such a diversion reduces the amount of current flowing through the solar cell junction and reduces the voltage from the solar cell. The effect of a shunt resistance is particularly more at low irradiance, since there will be less magnitude of 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. For the rise of series resistance the voltage and current density will be reduced and vice versa. For ideal solar plate R_s will be zero and the R_{sh} will be infinite. Therefore, for the maximum power from the solar PV cell Rs will be negligible value and the R_{sh} must have a higher value.

For maximum power in case of single diode model

$$\frac{dP_m}{dP_m} = \left[I_{ph} - I_{rs}\left[e^{\frac{q(V+qIR_s)}{N_s KT_0 A}} - 1\right] - \left[\frac{V + IR_s}{R_{sh}}\right] + V_m\left[-\frac{q}{N_s KT_0 A} I_{rs}\left[e^{\frac{q(V+IR_s)}{N_s KT_0 A}}\right] - \frac{1}{R_{sh}}\right]\right] = 0 \quad (5)$$

Characteristics of PV array and MPP

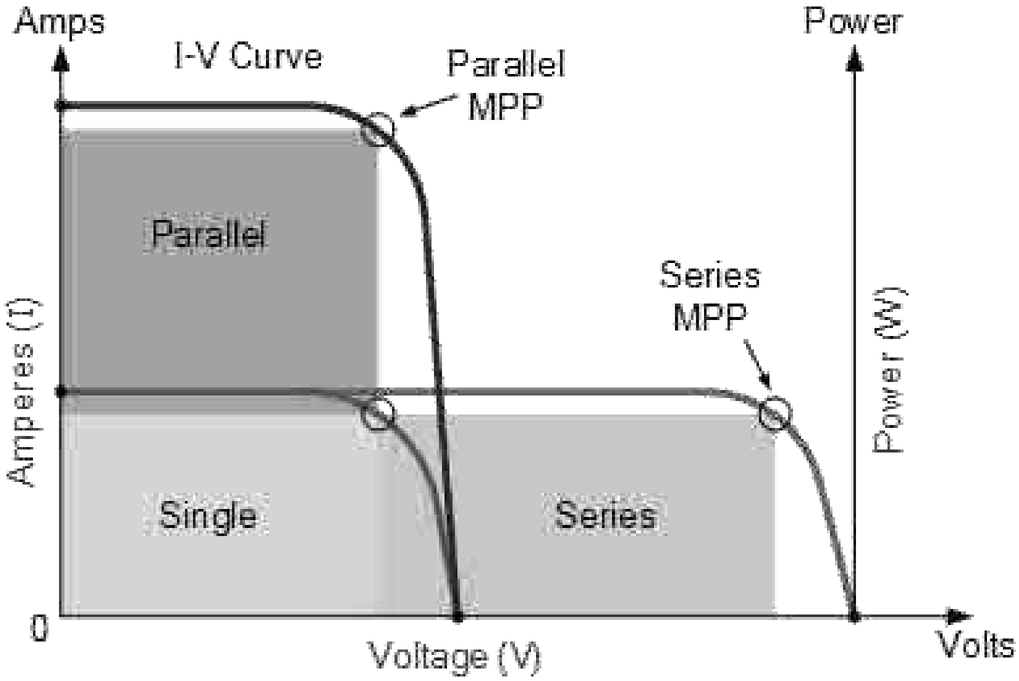
Solar Cell V-I Characteristics Curves are basically a graphical representation of the operation of a solar cell or module summarizing the relationship between the current and voltage at the existing conditions of irradiance and temperature. *V-I* curves provide the information required to configure a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



The above graph shows the *V-I* 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. 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 **V_{oc}**.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 **I_{sc}**.

Solar Panel I-V Characteristic Curves

Photovoltaic panels can be wired or connected together in either series or parallel combinations, or both to increase the voltage or current capacity of the solar array. If the array panels are connected together in a series combination, then the voltage increases and if connected together in parallels then the current increases.



The electrical power in Watts, generated by these different photovoltaic combinations will still be the product of the voltage times the current, (P = V x I). However the solar panelsare connected together, the upper right hand corner will always be the maximum power point (MPP) of the array.

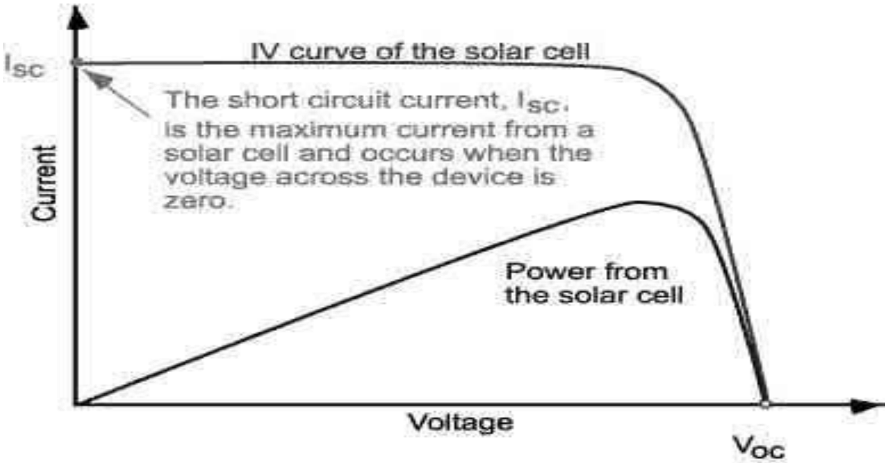
Open circuit voltage and short circuit current of PV system

Open-Circuit Voltage

The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current.

Short-Circuit Current

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as I_{SC}, the short-circuit current is shown on the V-I curve below.



Short-Circuit Current

The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell.

MPPT

Maximum power point tracking is often called as MPPT. This is an electronic system which commands a solar panel or a set of solar panels to generate the maximum amount of power. The MPPT is not a physical system strapped with solar trackers that position the panels so that they remain under the sun at all times. Although they can be used along with solar trackers, you must know that both are different systems. This fully electronic system varies the electrical operating point of the panels which enables them to deliver the maximum power. The Extra power generated by the panels is made available to the modules in the form of increased battery charging current.

PV POWER CONDITIONING SYSTEM

This is a power converter which interfaces the PV to utility grid and converts the DC supply from the PV plant to AC supply as requirement by the utility grid. Based on the galvanic connection between PV plant and grid, the power conditioning system (PCS) can be broadly classified into two types such as **isolated power conditioning system** and **non isolated power conditioning system**.

Isolated PV Power Conditioning System

In isolated type PV system the isolation between PV plant and grid is achieved by using a line frequency transformer at the output of the inverter (AC side) or by using high frequency transformer DC-DC converter at the input side of the inverter. In low frequency (power frequency) transformer system involves huge size, increasing magnetic loss and low efficiency than high frequency transformer based DC-DC converter system. This high frequency transformer involves complex control resonant problems and which increase the cost of the PV system.

Non Isolated PV Power Conditioning System

The non isolated grid connected PV system is again classified in to single-stage and multistage power conditioning systems. In single-stage, only one power processing stage is available to convert the PV power to AC supply. Nowadays, single stage power converters are most widely used in PV applications. The single- stage inverter can perform the buck, boost, and both buck- boost input voltage, inversion and maximum power point. The single-stage inverter has the advantages of improved efficiency, low cost, more reliability, modularity, and compact size than multistage power conversion systems.

Figure 1 shows a block diagram of conventional photovoltaic power conditioning systems. They consist of an inverter, LP-filter and line transformer. The filter eliminates/attenuates the harmonics on produced by the inverter, the filter output is stepped up at the grid level by a low frequency transformer.

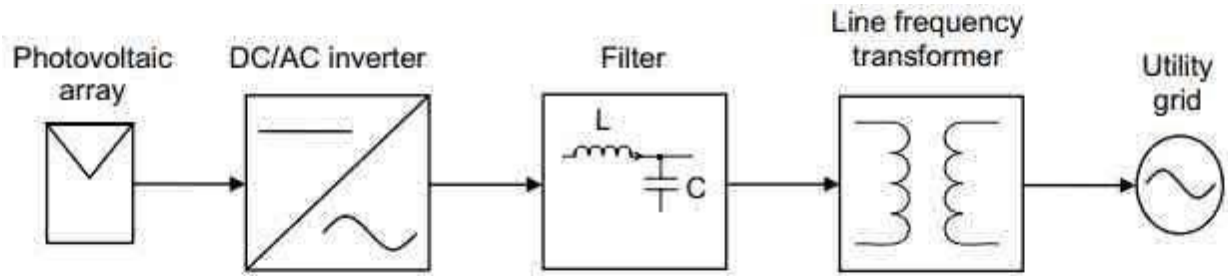


Figure 1: PV PCS with line frequency transformer

Figure 2 shows a block diagram of a conventional isolated type photovoltaic power conditioning system. In this system, a DC/DC converter using a high frequency transformer converts a DC voltage delivered by the PV into a controlled DC voltage suitable for the inverter.

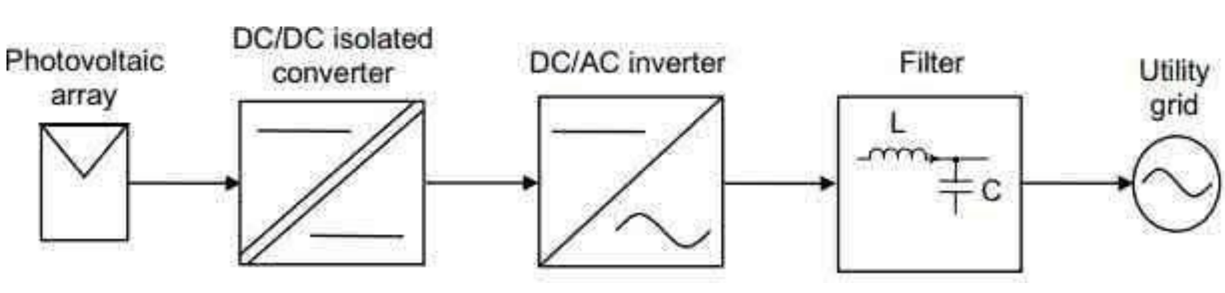


Figure 2: PV PCS with high frequency transformer

Figure 3 shows a block diagram of a conventional non-isolated type photovoltaic power conditioning system. In this system, a DC/DC non-isolated converter receives the fluctuating DC voltage delivered by the PV and converts it into DC voltage suitable for the inverter.

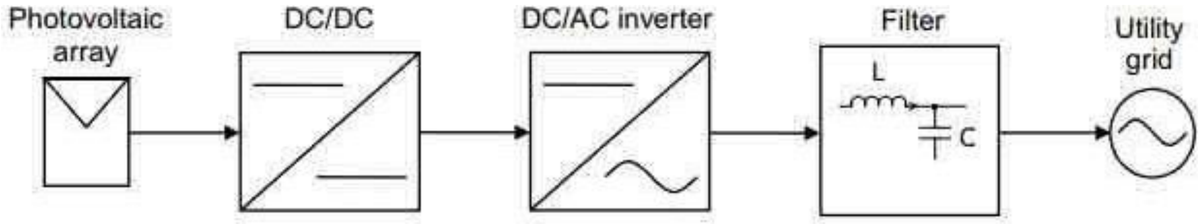


Figure 3: Conventional non-isolated type PV PCS