UNIT 1 PHOTOVOLTAIC EFFECT

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1.1 INTRODUCTION

Photovoltaics are the technology for conversion of solar radiation (sunlight) directly into electricity. A photovoltaic cell, also called a PV or a solar cell, is the device used for this purpose.

Solar cells are generally made of high purity silicon wafers. Several materials such as silicon thin films (polycrystalline and amorphous), gallium arsenide (GaAs), cadmium telluride (CdTe), copper indium diselenide (CIS), etc. are also used to make solar cells.

The PV technology has emerged as a promising technology to generate electricity for small applications like lighting and meeting other electrical needs of households in un-electrified areas. Solar PV technology offers an excellent opportunity to provide electricity in a decentralized manner at locations where it is difficult to take grid power due to scattered populations. This is because it is not economical to take grid connected power to such locations. Moreover solar radiation, the source of solar energy is free, clean and in abundance.

Objectives

After studying this unit, you will be able to understand

- photovoltaic effect,
- the solar cell and its efficiency,
- PV systems for power generation, and
- PV systems for domestic applications.

1.2 PHOTOVOLTAIC EFFECT

The photovoltaic (PV) effect is defined as the process of generation of an electromotive force as a result of the absorption of solar radiation. The devices used to convert sunlight to electricity by the use of photovoltaic effect are called solar cells or PV cells.

The photoelectric effect was first observed in 1839 by a French physicist, Edmund Bequerel, who found that certain materials are capable of producing small amounts of electric current when exposed to light. In 1873 British scientist Willoughby Smith observed that ability of selenium to conduct electricity increased in direct proportion to the amount of light falling on it. In 1880 Charles Fritts made the first selenium based solar cell. In 1905 Albert Einstein described the nature of light and the photoelectric effect on which photovoltaic technology is based. Albert Einstein won a Nobel Prize in physics for this.

The first silicon based photovoltaic module was built by Bell Laboratories in 1954 which had an efficiency of about 6%. It was too expensive to gain widespread use. In the 1960s, the space industry began to make the first serious use of the PV technology to provide power aboard spacecraft. Through the space programmes, the technology advanced, its reliability was established and the cost began to decline. During the energy crisis in the 1970s, PV technology gained recognition as a reliable and potential source of power for domestic and industrial applications.

A typical solar cell has two layers of semiconductor material generally silicon crystals. Since crystallized silicon is not a good conductor of electricity, some impurities are added intentionally (a process referred as doping). The bottom layer of the PV cell is doped with boron creating a positive charge (p). The top layer is doped with phosphorous creating a negative charge (n). The surface between p-type and n-type semiconductors is called a p-n junction (some times also called a junction diode). The movement of electrons from p-type layer to n-type layer results when sunlight gets absorbed at the p-n junction.

You may understand photovoltaic effect by observing the following :

(1) Solar radiations (sunlight) are made of bundles of light energy called photons, or light quanta. Photons behave like particles having zero mass and travel with the speed of light. Each photon is associated with a particular wavelength of solar spectrum and has energy defined by that wavelength.

(2) Photons associated with different wavelengths have different energies.

(3) Solar cell is made of semiconductor material. When a photon strikes a solar cell, it may be either reflected, absorbed or pass through. Photons which get absorbed transfer their energy to the electrons in the semiconductor enabling them to generate electricity.

(4) When enough photons are absorbed by a solar cell, electrons get detached from the material's atoms and move to the surface. The energy of a photon is transferred to an electron in an atom of the semiconductor device. With its newfound energy, the electron is able to escape from its normal position associated with a single atom in the semiconductor and is free to move and create to a current in an electrical circuit.

(5) When electrons (-ve charge) are able to leave their position, holes (+ve charge) are created.

(6) When large number of electrons travel towards the front surface of the cell, an imbalance of charge between the cell's front and back surfaces creates a voltage potential similar to the negative and positive terminals of a battery.

(7) The electricity flows when two surfaces are connected through an electrical load.

This is shown in Figure 2.1.

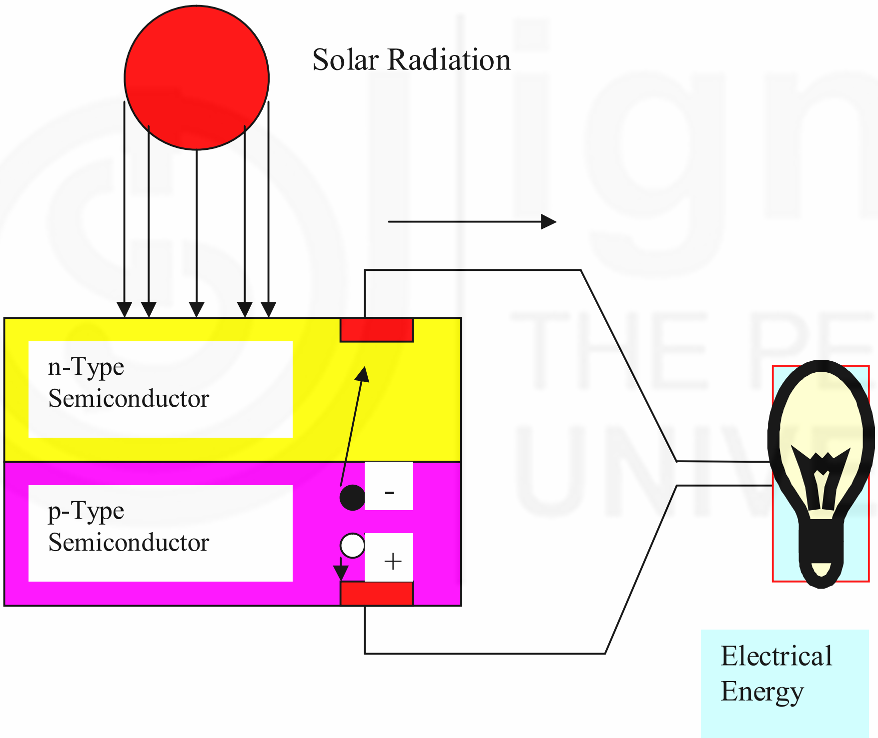

Figure 2.1 : Photovoltaic Effect

To be Remembered

- Photovoltaic cells are made of at least two layers of semiconductor material. One layer has a positive charge while the other negative charge.
- When light falls on the cell, some of the photons are absorbed by the semiconductor atoms, freeing electrons from to flow through an external circuit and back into the positive layer.
- This flow of electrons produces electric current.
- Each absorbed photon can free only one electron creating a electron-hole pair.

1.2.1 Conditions for Occurrence of Photovoltaic Effect

The basic conditions for the photovoltaic effect to occur are :

(1) absorption of photons creating electron-hole pairs in a semiconductor

(2) separation of the electrons and holes so that their recombination is inhibited.

(3) collection of the electrons and holes, separately, by each of two current-collecting electrodes so that current can be induced to flow in a circuit external to the semiconductor itself.

There are many ways to achieve these conditions. One common approach for separating the electrons from the holes is to use a single-crystal semiconductor p-n junction as discussed above.

1.3 SOLAR CELL AND EFFICIENCY

There are three basic types of solar cells made from silicon. These are :

(a) Single-crystal solar cell

(b) Polycrystalline solar cell

(c) Amorphous solar cell

We will briefly describe these cells in the following sections :

1.3.1 Single-Crystal Silicon Solar Cell

Single-crystal cells are sliced into round or hexagonal wafers form in long cylinders. The process is highly energy intensive and also results in material waste but gives the highest efficiency cells of the order of 25% which could be further enhanced to about 30% when used in combination with concentrators.

1.3.2 Polycrystalline Silicon Solar Cell

The polycrystalline cells are made of molten silicon cast into ingots or drawn into sheets and thereafter sliced into squares. The efficiency of these cells is about 15% but cost is relatively less as compared to single-crystal cells.

1.3.3 Amorphous Silicon Solar Cells (a-Si cells)

The silicon is sprayed onto a glass or metal surface in thin films. This results in making the module in one step. The production approach is least expensive but the efficiency of these cells is about 5%.

1.4 CONVERSION EFFICIENCY AND POWER OUTPUT

In order to understand the concept of the efficiency of a solar PV cell, you need to know a little bit of physics of semiconductors.

When P-type and N-type semiconductors are brought in close contact a p-n junction is formed. P-type and N-type semiconductors are relatively good conductors but the junction where they are joined becomes non-conducting. This non conducting layer is formed because electrons in N-type and holes in P-type recombine and eliminate each other. A common solar cell is basically a large p-n junction.

When sunlight falls on a semiconductor p-n junction (e.g. crystalline silicon), electrons within the crystal lattice may be freed creating there by an electron-hole pair. These free carrier pairs are separated by the p-n junction and contribute to electric current. Only photons with a certain level of energy are able to free electrons in the semiconductor material from their atomic bonds to produce an electric current.

This level of energy, known as the "band gap energy," is the amount of energy required to dislodge an electron from an atom and allow it to become part of an electrical circuit.

However, photons with more energy than the band gap energy will expend that extra amount as heat when freeing electrons. A key to obtaining an efficient PV cell is to convert as much sunlight as possible into electricity.

Crystalline silicon has band gap energy of 1.1 eV (electron volt). The band gap energies of other effective photovoltaic semiconductors range from 1.0 to 1.6 eV. Photons in this energy range, can free electrons without creating too much extra heat. The photon energy varies according to the different wavelengths of the light. The entire spectrum of sunlight, from infrared to ultraviolet, has photons of energy range from about 0.5 eV to about 2.9 eV.

Solar radiations are electromagnetic radiations which travel at the speed of light. The speed is related to the wavelength and frequency of the radiation by the following equation :

$$c = \lambda \nu \qquad \ldots (2.1)$$

where c = speed of light,

λ = wavelength, and

ν = frequency.

According to the quantum theory, an electromagnetic wave (solar radiation) is made up of discrete bundles of energy called photons having energy $h\nu$.

Thus,

$$E = h\nu \qquad \ldots (2.2)$$

where E = energy of a photon, and

h = Planck constant = 6.6×10^{-34} J.s.

It is interesting to see that while all the photons travel at the speed of light but there exists a distribution of energy among them.

Example 1.1

Determine the range of wavelengths of solar radiation capable of generating electron-hole pairs in silicon. The energy gap of silicon is 1.12 eV.

Solution

Using Eqs. (2.1) and (2.2), we have

$$\lambda = \frac{hc}{E}$$

$h = 6.6 \times 10^{-34}$ J.s

$c = 3 \times 10^{8}$ m/s

$E = 1.12$ eV $= 1.12 \times 1.602 \times 10^{-19}$ J (1 eV $= 1.602 \times 10^{-19}$ J)

Thus, $$\lambda = \frac{6.6x10^{-34} x3x10^{8}}{1.12x1.602x10^{-19}} = 1.11 \text{ x } 10^{-6} \text{ m} = 1.11 \text{ µm}$$

We can thus conclude :

- The solar radiations with wavelength less than 1.11 µm are capable for generating electron-hole pairs in silicon solar cell and hence contribute to the electricity generation.
- Another interesting fact is that each photon can produce only one free electron-hole pair.
- Photons of wavelength 1.1µm i.e having energy more than 1.12 eV will only help to thermally heat the solar cell.

Most PV cells cannot use about 55 % of the energy of sunlight, because this energy is below the band gap of the semiconductor material.

To be Remembered

When solar radiation with photon energy *h* ν (h is the Plank's Constant and ν is the frequency) greater than the energy gap strikes a p-n junction, electrons in the valance band may gain enough energy to jump to the conduction band. This in turn results in the production of electron-hole pair. The junction acts to separate the pairs; the electrons move from p-side to n-side.

Now we have to make use of solar generated electron-hole pairs. The electrons from the n-side have to be taken through an external circuit to do useful work and then return to p-side for allowing them to meet and recombine with the holes coming from the opposite direction. Such an arrangement is shown in Figure 2.2.

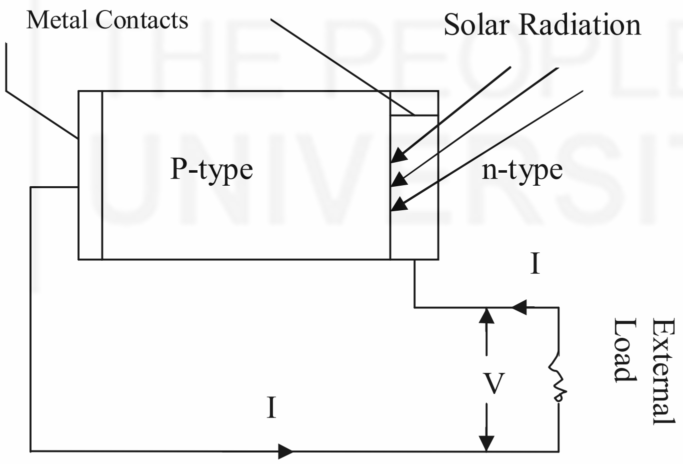

Figure 4.2 : Operation of a Photovoltaic Junction

The junction current, I_j is defined as the net current flow from p-side to n-side due to all charge carriers. The electrons in the p-side and holes in the n-side are called minority carriers. These minority carriers can cross the junction easily. The majority carriers (holes in the p-side and electrons in the n-side) can not cross the junction unless they have energies in excess of the barrier.

The net output current, I, of a solar cell is given by the following relation :

$$I = I_s - I_j = I_s \qquad \ldots (4.3)$$

where I_s is the light generated current.

The light generated current acts as a constant current source supplying the current to either the junction or to the connected load.

The output power, P, is then given by

$$P = I\,V \qquad \text{. . . (4.4)}$$

The maximum power that can be obtained from the PV cell is given by

$$P_{max} = I_{max} \times V_{max} \qquad \text{. . . (4.5)}$$

Figure 4.3 shows the voltage-current characteristics of a solar cell. The short circuit current and open circuit voltage are shown in the figure. The maximum power occurs when the *I V* product has the maximum value.

The conversion efficiency for a maximum power output is given by

$$\eta_{\max\ power} = \frac{P_{\max}}{P_{in}} \qquad \text{. . . (4.6)}$$

where P_{in} is the input to the solar cell.

The energy produced, S_p (I), per unit of active area of photovoltaic system, A_p, is given by the following relation :

$$S_p(I) = \eta\ R_B(I)\,A_p \ \text{for cell temperature}\ T_c \leq 25\ °C \qquad \text{. . . (4.7)}$$

$$= [\eta - 0.005(T_c - 25)]\ R_B(I)\ A_p \ \text{for}\ T_c \geq 25\ °C$$

where R_B (I) is the monthly average global radiation for I^{th} period, W/m^2.

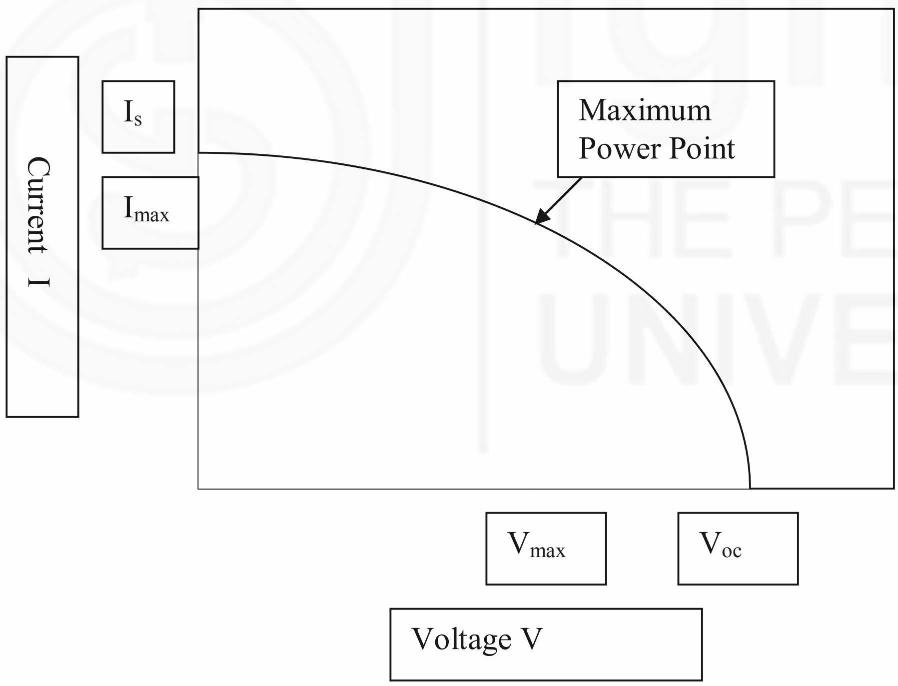

Figure 4.4 : Voltage-current Characteristics of a Solar Cell

Example 1.2

A solar cell is having an area of 25×10^{-4} m^2 and produces power of 0.2 W. If the intensity of solar radiation is 700 W/m^2, find the efficiency of the solar cell.

Solution

The efficiency of solar cell is given by

$$\eta = \frac{Output\ \ Power}{Input\ \ Power}$$

Input power = Intensity of solar radiation × Area of solar cell

$= 700 \times 25 \times 10^{-4}$

$= 1.75$ W

Power output = 0.2 W

Thus, $\eta = 0.2/1.75 = 0.114 = 11.4\%$.

SAQ 3

What factors affect the efficiency of a PV module?

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Example 1.3

A solar PV cell is irradiated by solar insolation of 900 W/m^2. The maximum power output per unit area of the cell is 100 W/m^2.

Determine the following :

(1) The maximum conversion efficiency.

(2) The cell area for an output of 950 W at the condition of maximum power.

Solution

The following data are given :

$P_{in}/A = 900$

$P_{max}/A = 100$ W/ m^2

The maximum conversion efficiency is given by Eq. (4.6)

$$\eta_{\max\ power} = \frac{P_{\max} / A}{P_{in} / A} = 100/900 = 11.11\ \%$$

The cell area for an output of 950 W at the condition of maximum power is calculated by using the following relation :

$$A = P_{output\ required}/(P_{max}/A) = 950/100 = 9.5\ m^2$$

1.5 SIZING OF PHOTOVOLTAIC SYSTEMS

The applications of solar PV technology are increasing very rapidly. At present, the following three areas are gaining importance :

(1) Domestic applications (home light, street light, community light, etc.).

(2) In agriculture sector for lift irrigation.

(3) Power generation.

For making solar PV system, you need to know the following things :

(1) The energy to be used by the appliances under consideration.

(2) The energy storage capacity of the battery.

(3) The energy to be used by the appliances under consideration.

(4) The size of solar PV system.

Let us briefly consider these parameters.

1.5.1 Energy to be Used by the Appliances under Consideration

- The ratings of all electricity using appliances are given in watts, W (e.g. 18 W CFL).
- You can compute the energy consumed by simply multiplying the power rating by the hours of use.
- For example, a 18 CFL, if used for 5 hours is going to consume $18 \times 5 = 90$ Wh from the battery.
- In similar way, you can work out the total energy requirement.

1.5.2 Storage Capacity of the Battery

- The storage capacity of the battery is measured in Amp. Hours, e.g. 20 Ah.
- If this value of Ah is multiplied by the battery voltage (for example 12V), you will get Wh. Thus, for the current case, we get 20 Ah $\times$ 12 V = 240 (AV) h = 240 Wh.
- This simply means that the battery is able to supply 240 W for 1 hour, or 120 W for 2 hours, or 80 W for 3 hours. In other words, if more energy is taken from the battery, it will discharge faster.

1.5.3 The Size of Solar PV System

For calculating the energy which can be supplied by the solar cell panel, you need to adopt the following procedure :

- Multiply the wattage of the solar panel by the hours of the sunshine available.
- The result so obtained may be multiplied by a factor 0.85 to account for additional losses.
- Thus for a 15 W panel, 6 hours of sunshine, the energy supplied will be $15 \times 6 \times 0.85 = 76.5$Wh.

Example 1.4

During night hours, you wish to use a light bulb (CFL) and a fan for 3 hours. The total wattage of CFL and fan is 60 W. Determine the size of the battery.

Solution

Total watt hours required = 60 W $\times$ 3 hrs = 180 Wh

If you decide to buy a 12 V battery, its Ah rating will be 180 Wh/12 V = 15 Ah.

For a 6 V battery, Ah rating will be 180 Wh/6V = 30 Ah.

1.6 PHOTOVOLTAIC CELLS, MODULES, PANELS AND ARRAYS

You have learnt that solar PV devices use semiconducting materials to convert sunlight directly into electricity. The current produced by a single solar cell is not enough to run electrical equipments. In order to increase their utility, solar PV cells are arranged in particular sequences as shown in Figure 4.5. Solar cells (the smallest unit of a system) are connected and packaged together in solar modules. Multiple modules are connected in series and parallel combination into an array.

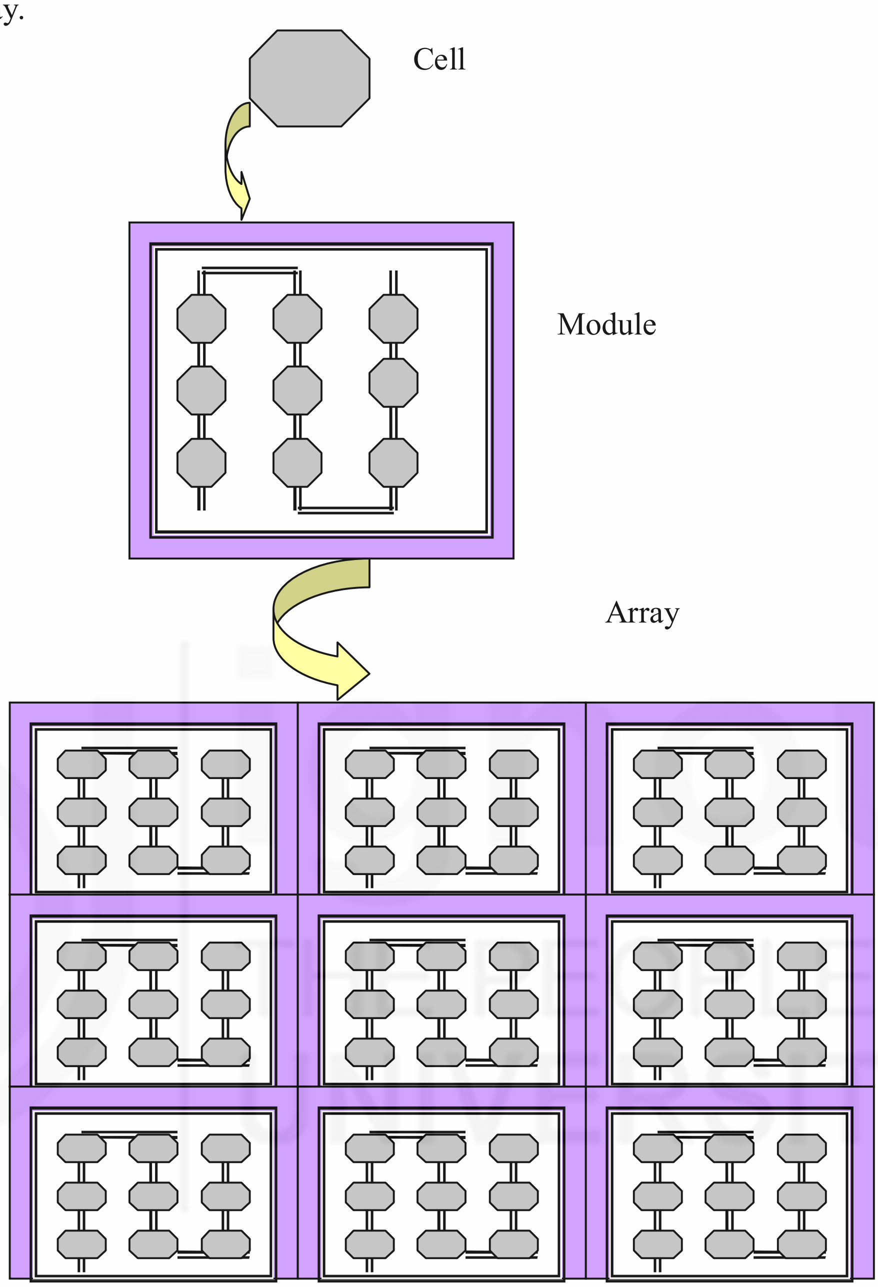

Figure 4.5 : PV Cells, Modules and Arrays

> **SAQ 2**
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> Define the concept of generating electricity from the sun.
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1.6.1 PV Module

When many individual PV cells are interconnected together in a sealed package, it is called a module. The current and voltage are governed by the following norms :

- When two modules are connected together in series, their voltage is doubled while the current remains constant.
- When two modules are connected in parallel, their current is doubled while the voltage remains constant.

1.6.2 PV Array

In order to achieve the desired voltage and current, modules are interconnected in series and parallel combination which is called a PV array. This type of flexibility of PV system allows us to create solar power systems that can meet a wide variety of electrical needs, no matter how large or small.

1.6.3 Power and Energy Output

Power available from a solar panel is specified either as peak power or average power produced during one day. The energy is expressed as watt-hour or Wh. This indicates the amount of energy produced during a certain period of time.

SAQ 3

What is a Solar Photovoltaic system? Describe its operating principle.

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1.7 CLASSIFICATION OF PV SYSTEMS

Photovoltaic power systems are generally classified according to the functional and operational requirements, the component configurations, and how these are to be connected to other power sources and electrical loads. The two principle classifications are :

(1) grid-connected or utility-interactive PV systems.

(2) stand-alone PV systems.

Photovoltaic systems can be designed to provide DC and/or AC power applications, can operate interconnected with or independent of the utility grid, and can be connected with other energy sources and energy storage systems.

1.7.1 Grid-Connected PV Systems

A grid-connected PV system is shown in Figure 4.6. The primary component of such a system is an inverter. It is also called power conditioning unit (PCU). The PCU converts the DC power produced by the PV array into AC electricity of the same quality that comes from the power grid. Any energy that is not used is fed back into the power grid for others to use.

The PCU automatically stops supplying power to the grid when the utility grid is not energized. During off sunshine hours and during other periods when the electrical loads are greater than the PV system output, the balance of power required by the loads is received from the electric utility. This safety feature is required in all grid-connected PV systems, and ensures that the PV system will not continue to operate and feed back onto the utility grid when the grid is down for service or repair.

1.7.2 Stand-Alone PV Systems

Stand-alone PV systems, as the name indicates, are designed to operate independent of the electric utility grid. Such systems are sized to supply certain DC and/or AC electrical loads. These types of systems may be powered by a PV array only, or may use biomass/biogas based power generation system. Such types of systems are called a PV-hybrid system. The simplest type of stand-alone PV system is shown in Figure 4.7. Such a system operates during sunlight hours.

In many stand-alone PV systems, batteries are used for energy storage. Figure 4.8 shows a diagram of a typical stand-alone PV system powering DC and AC loads. Figure 4.9 shows a typical PV hybrid system.

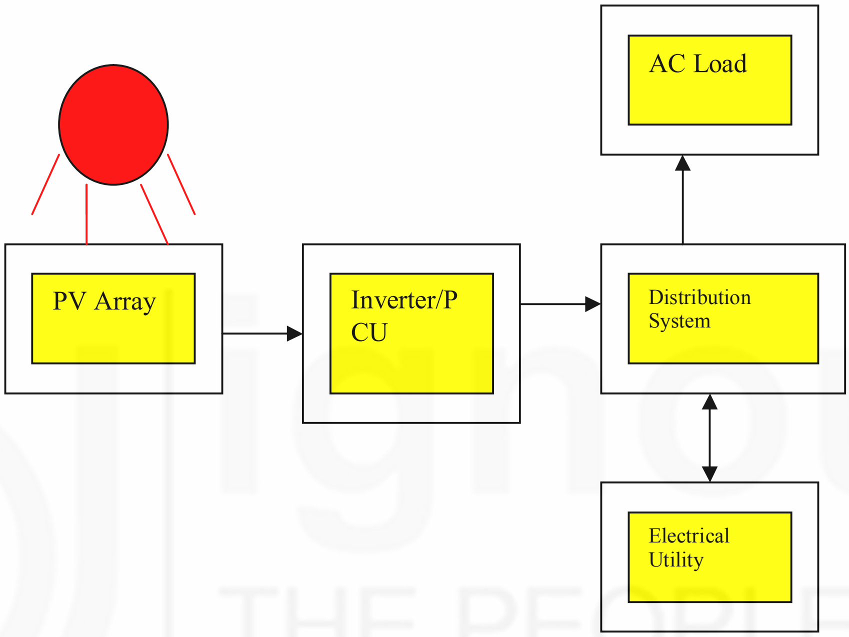

Figure 4.6 : A Schematic Diagram of Grid-connected PV System

Figure 4.7 : Simplest Type of Stand-alone PV System

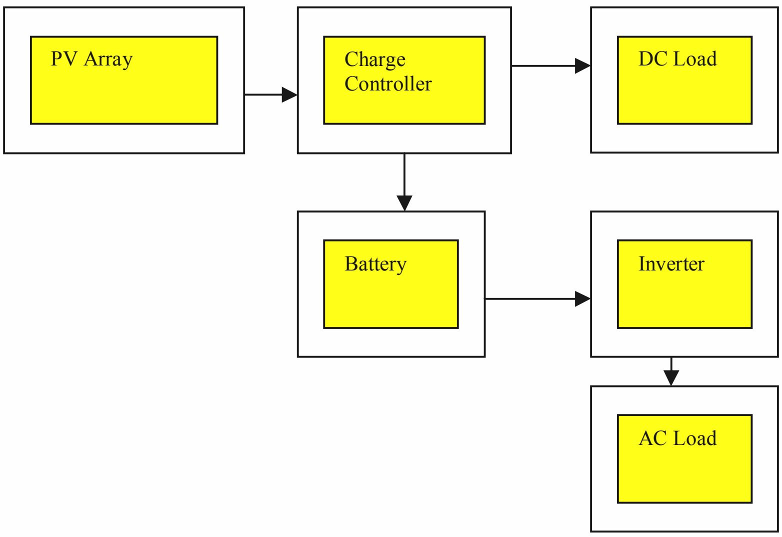

Figure 4.8 : Diagram of Stand-alone PV System with Battery Storage Powering DC and AC Loads

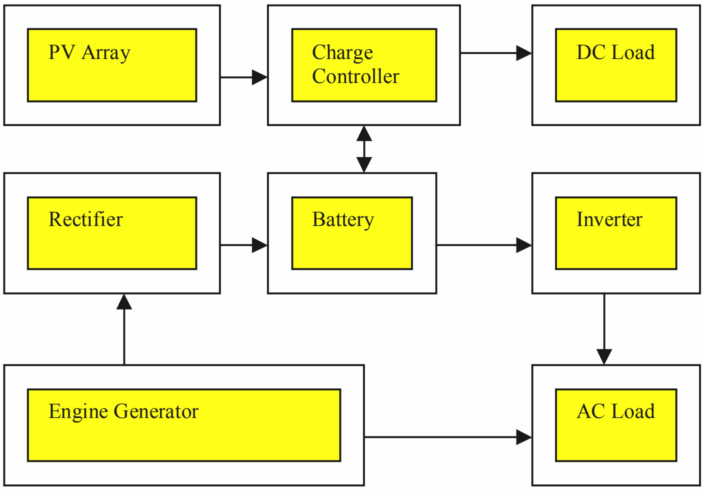

Figure 4.9 : Diagram of Photovoltaic Hybrid System

SAQ 4

Write down the applications of solar PV energy.

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1.8 LET US SUM UP

The photovoltaic effect is the generation of electricity as a result of the absorption of solar radiation. The energy conversion devices used to convert sunlight to electricity by the use of photovoltaic effect are called solar cells.

A solar cell is a semi-conducting device made of silicon or other materials, which, when exposed to sunlight, generates electricity. The magnitude of the electric current generated depends on the intensity of the solar radiation, exposed area of the solar cell, the type of material used in fabricating the solar cell, and ambient temperature. Solar cells are connected in series and parallel combinations to form modules that provide the required power.

Solar radiations (sunlight) are made of photons, or light quanta of solar energy. The photons are associated with of various wavelengths of solar radiation and hence contain various amounts of energy depending upon the wavelength.

Solar cell is made of semiconductor material. When photons strike a solar cell, they may be either reflected, absorbed or pass through. Those photons which get absorbed provide energy to generate electricity. When enough photons are absorbed by the solar cell, electrons get displaced from the material's atoms and migrate to the surface. When electrons are able to leave their position, holes are created. When large number of electrons travel towards the front surface of the cell, an imbalance of charge between the cell's front and back surfaces creates a voltage potential similar to the negative and positive terminals of a battery. The electricity flows when two surfaces are connected through an electrical load.

There are three basic types of solar cells made from silicon. These are : (1) single-crystal, (2) polycrystalline and (3) amorphous. Single-crystal cells have efficiency of the order of 25% which could be further enhanced to about 30% when used in combination with concentrators. The efficiency of polycrystalline cells is about 15% and that of amorphous silicon is about 5%.

The most applications of solar PV technology are in domestic applications (home light, street light, community light, etc.), in agriculture sector for lift irrigation and in power generation.

1.9 KEY WORDS

Battery

A device that stores energy and produces electric current by chemical action.

Electricity

A form of energy generated by magnetic, radiant and chemical effects. Electric current is created by a flow of charged particles (electrons).

Inverter

A device that converts direct current to alternating current.

Kilowatt (KW)

A unit of electric power (energy consumed per unit time) equivalent to 1,000 watts.

Kilowatt-hour (KWh)

A unit of energy; the energy consumed by 1 KW of power in 1 hour.

PV Module

When many individual PV cells are interconnected together in a sealed package, it is called a module. .

PV Array

In order to achieve the desired voltage and current, modules are interconnected in series and parallel combination which is called a PV array.

Stand Alone PV System

Stand-alone PV systems are designed to operate independent of the electric utility grid. Such systems are sized to supply certain DC and/or AC electrical loads.

Solar Cell/Solar Photovoltaic Cell

A semiconductor device capable of converting solar radiations directly into electricity.

1.10 ANSWERS TO SAQS

SAQ 1

The efficiency of a solar cell depends upon the intensity of solar radiation and the cell temperature. The current generated by the module increases with the radiation, and the voltage remains more or less constant.

Temperature increase of the cells gives an increase of generated current, but at the same time a reduction (greater than the current increase) of the voltage. The net effect is that the module power decreases when temperature increases.

SAQ 2

The electricity generation is based on a physical phenomenon known as "photovoltaic effect". The concept is basically the conversion of solar radiations into electrical energy using semiconductor devices called photovoltaic cells (PV cells) or simply solar cells. Solar cells are able to produce a current of between 2 and 4 Amps at a voltage of 0.46 to 0.48 Volts.

SAQ 3

A photovoltaic system converts solar radiations into electrical energy. The system has the following elements :

(a) A photovoltaic device which consists of photovoltaic modules. These modules convert solar radiations into direct (DC) electrical current.

(b) A battery for storing the energy produced by the PV modules and allows the supply of electrical current in the absence of daylight or on cloudy days.

(c) A power conditioning unit which ensures that the system always operates at the point of maximum efficiency.

(d) An inverter that transforms the DC current stored in the battery to 230 V AC current.

SAQ 4

There are numerous applications of solar PV. In fact every application that requires electricity to operate can by powered using a correctly sized photovoltaic system. In rural and remote places, far away from the electrical grid, solar PV is the most preferred option available today. The popular applications are home electrification, water pumping systems and irrigation, outdoor lighting, radio and TVs, etc.