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Basics of Photovoltaic Power Systems

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---***ABSTRACT***---

Photovoltaic (PV) systems can be grouped into stand-alone systems and grid-connected systems. In stand-alone systems the solar energy yield is matched to the energy demand. Since the solar energy yield often does not coincide in time with the energy demand from the connected loads, additional storage systems (batteries) are generally used. If the PV system is supported by an additional power source – for example, a wind or diesel generator - this is known as a photovoltaic hybrid system. In grid-connected systems the public electricity grid functions as an energy store.

Keywords: *Photovoltaic – Electric hybrid system - electrical grid - solar cells*

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I. Introduction

While more and more grid-connected PV systems will be installed in Europe and North America in the coming years, in the long term it is expected that ever-increasing numbers of stand-alone systems will be installed, especially in developing countries. Small individual power supplies for homes - known as solar home systems – can provide power for lights, radio, television, or a refrigerator or a pump. And, increasingly, villages are gaming their own power supplies with an alternating current circuit and outputs in the two-digit kilowatt range [4]. Figure 1.1 illustrates the different types of PV systems

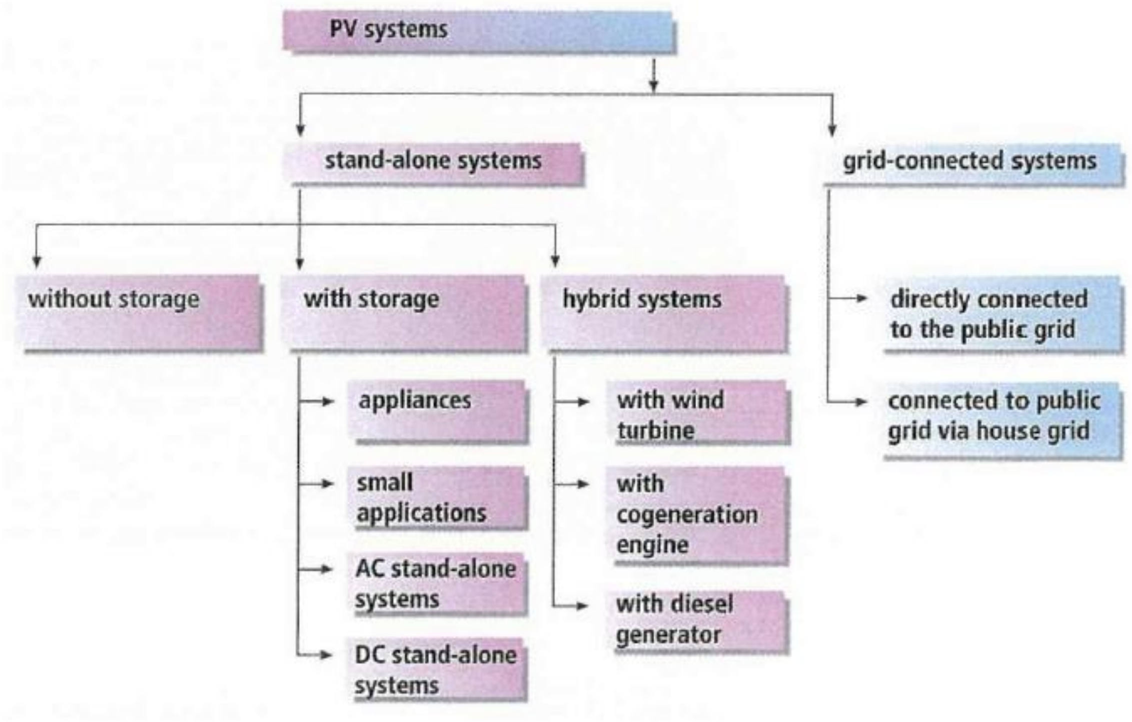

Figure 1.1 Types of PV systems

Stand-alone systems

The first cost-effective applications for photovoltaics were stand-alone systems. Wherever it was not possible to install an electricity supply from the mains utility grid, or where this was not cost-effective or desirable, stand-alone photovoltaic systems could be installed. There is great potential for using stand-alone systems in developing countries where vast areas are still frequently not supplied by an electrical grid.

Solar power is also on the advance when it comes to mini applications:

pocket calculators, clocks, battery chargers, flashlights, solar radios, etc., are well known examples of the successful use of solar cells in stand-alone applications. Other typical applications for stand-alone systems:

- mobile systems on cars, camper vans, boats, etc.
- remote mountain cabins, weekend and holiday homes and village electrification in developing countries.
- SOS telephones, parking ticket machines, traffic signals and observation systems, and communication stations,
- solar pump systems for drinking water and irrigation, solar water disinfection and desalination.

Stand-alone PV systems generally require an energy storage system because the energy generated is not usually (or infrequently) required at the same time as it is generated (i.e., solar energy is available during the day, but the lights in a stand-alone solar lighting system are used at night). Rechargeable batteries are used to store the electricity. However, with batteries, in order to protect them and achieve higher availability and a longer service life it is essential that a suitable charge controller is also used as a power management unit. Hence, a typical stand-alone system comprises the following main components:

1. PV modules, usually connected in parallel or series.
2. charge controller.
3. battery or battery bank.
4. load(s).
5. inverter - in systems providing alternating current (AC) power.

Figure 1.2 shows the principle of a stand-alone PV system supplying DC load only whereas, Figure 2.3 shows a stand-alone PV-wind hybrid system.

Components and sizing of stand-alone PV systems will be discussed later.

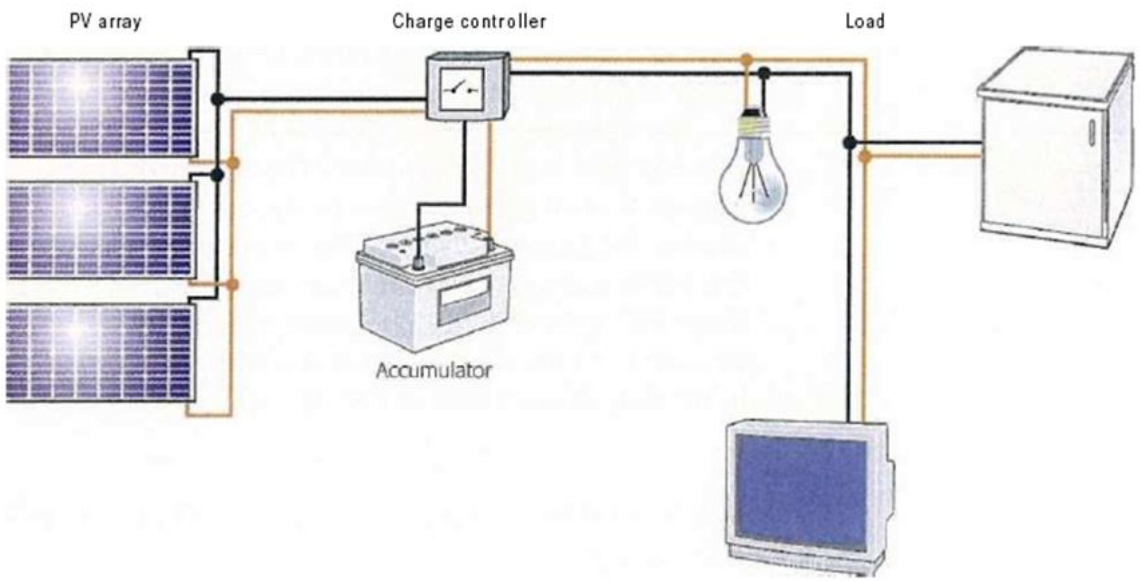

Figure 1.2 A stand-alone PV system: DC only

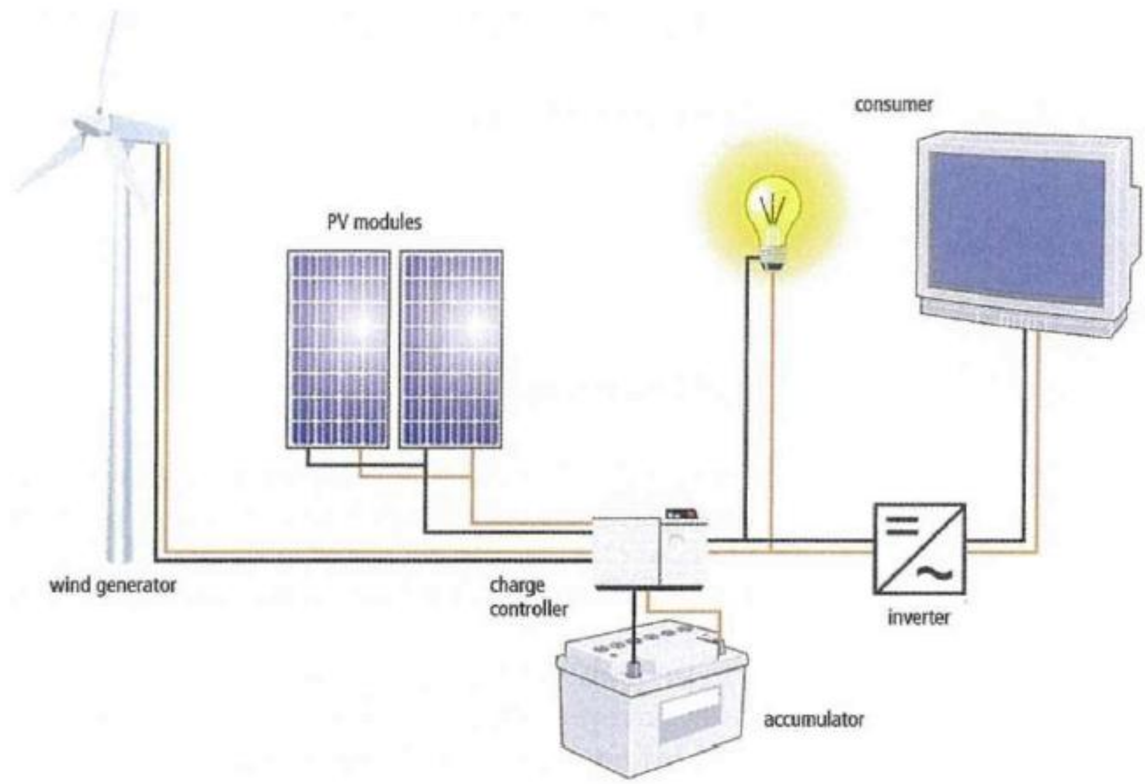

Figure 1.3 A stand-alone PV-wind hybrid system

Grid-connected systems
A grid-connected PV system essentially comprises the following components:

1. PV modules/array (multiple PV modules connected in series or parallel with mounting frame).
2. PV array combiner/junction box (with protective equipment).
3. direct current (DC) cabling.
4. DC mains disconnect/isolator switch.
5. Inverter.
6. AC cabling.
7. meter cupboard with power distribution system, supply and feed meter, and electricity connection.

Figure 1.4 shows the typical layout of a grid-connected PV system.
Whereas the first PV system installations were mounted on the roofs of private family houses, PV systems are increasingly being installed on all kinds of buildings as well as this, energy utilities, operating companies and investment companies, in particular, are building large-scale grid-connected PV systems as ground-mounting systems.

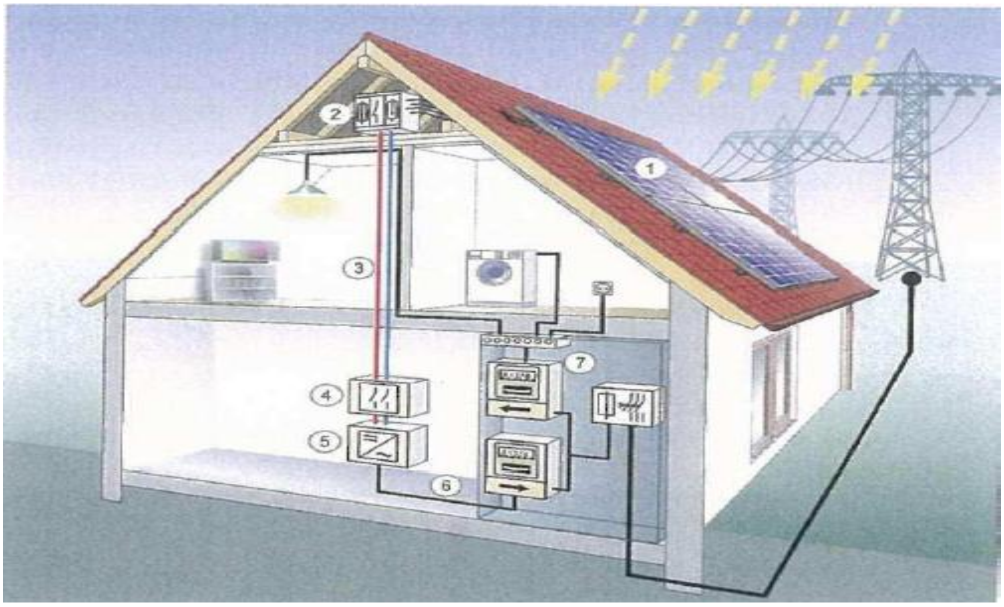

Figure 1.4 Principle of a grid-connected PV system

PV Cells

The term photovoltaics means the direct conversion of light into electrical energy using solar cells. Semiconductor materials such as silicon, gallium arsenide, cadmium telluride or copper indium Di selenide are used in these solar cells. The crystalline solar cell is the most used variety. During 2006, these had a worldwide market share of 95 per cent [4].

The PV cell is a specially designed pn junction or Schottky barrier device. The PV cells have much in common with other solid-state electronic devices, such as diodes, transistors and integrated circuits. Currently there are four main types of silicon PV cells in use:

- Single-crystal silicon,
- Polycrystalline silicon,
- Ribbon silicon, and
- Amorphous (ASI) or thin film silicon.

Most PV cells are produced with single-crystal silicon, the highest quality silicon available. Crystalline silicon cells hold the largest part of the market. The typical power output per cell ranges between 1 and 2 W at approximately 0.5-Volt DC. For practical operation, solar cells are usually assembled into modules. The modules have a long lifetime (20 years or more) and their best production efficiency is approaching 18% [1], [7], and [5]. Table 1.1 gives the maximum cell efficiencies in photovoltaics [4].

Table 1.1 Maximum efficiencies in photovoltaics

Solar cell material	Cell efficiency -n., (laboratory) (%)	Cell efficiency t i, (production) (%)	Module efficiency -n.,u (series production) (%)
Monocrystalline silicon	24.7	21.5	16.9
Polycrystalline silicon	20.3	16.5	14.2
Ribbon silicon	19.7	14	13.1
Crystalline thin-film silicon	19.2	9.5	7.9
Amorphous silicon[3]	13.0	10.5	7.5
Micromorphous silicon[3]	12.0	10.7	9.1
CIS	19.5	14.0	11.0
Cadmium telluride	16.5	10.0	9.0
III-V semiconductor	39.0[b]	27.4	27.0
Dye-sensitized call	12.0	7.0	5.0°
Hybrid HIT solar cell	21	18.5	16.8

Modules

Photovoltaic cells produce direct current, DC, electricity between 1 and 2W, not enough power for most applications. Solar cells are joined together in enclosed, protective casings called modules. These modules are mounted in one PV panel as shown in Fig. 1-5. These flat-plate PV panels can be mounted facing south, or they can be mounted on a tracking device that follows the sun, allowing them to capture the most sunlight over the course of a day. PV panels can provide enough power. Hundreds of arrays can be interconnected to form a single, large PV system.

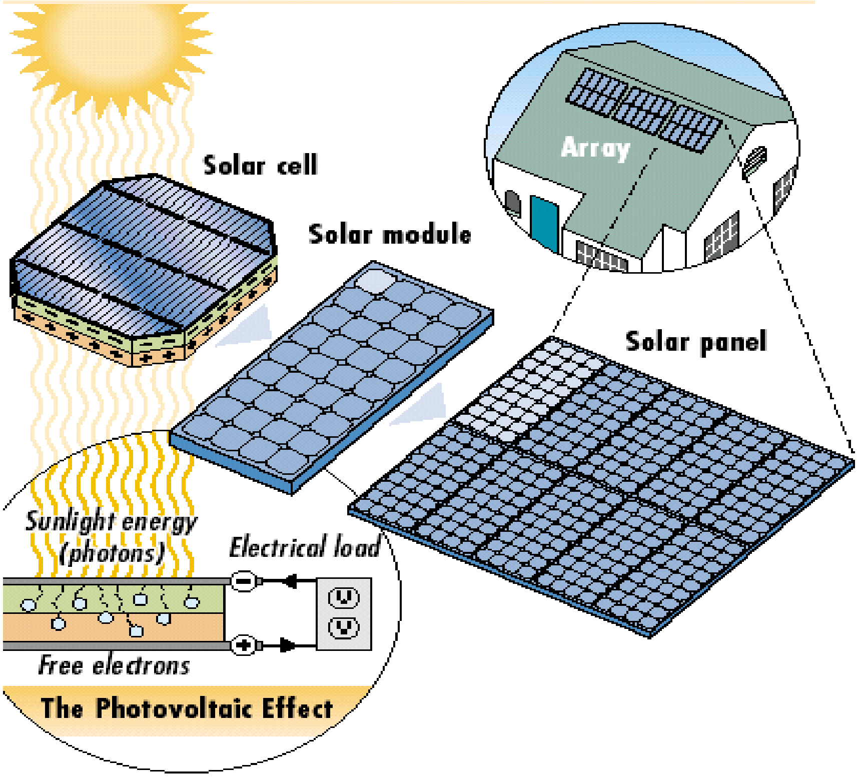

Fig. 1-5 Solar cell, solar module, and solar panel

Electrical connection of the cells

The electrical output of a single cell is dependent on the design of the device and the semiconductor materials chosen but is usually insufficient for most applications. In order to provide the appropriate quantity of electrical power, several cells must be electrically connected. There are two basis connection methods: series connection and parallel connection [3].

I- Series connection

The series connection of three individual cells as an example shown in Fig. (1-6) and the resultant group of connected cells is commonly referred to as a series string. The current output of the string is equivalent to the current of a single cell, but the voltage output is increased, being an addition of the voltage from all the cells in the string.

It is important to have well matched cells in the series string, particularly with respect to current. If one cell produces a significantly lower current than the other cells (under the same illumination conditions), then the string will operate at that lower current level and the remaining cells will not be operating at operating at their maximum power points [3].

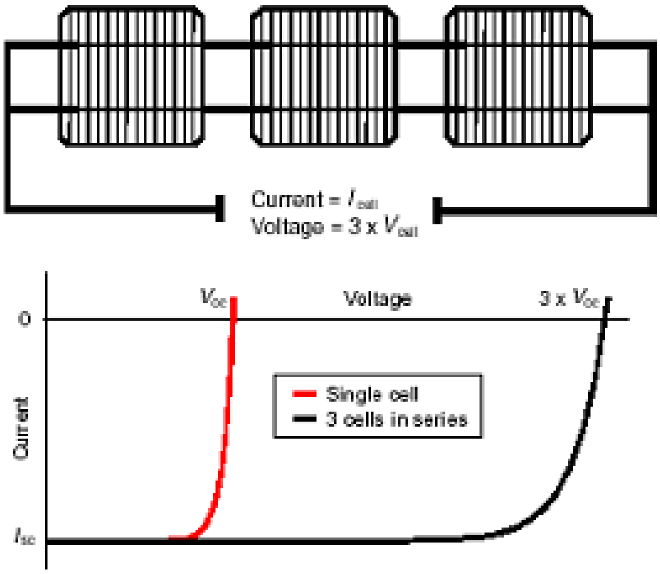

Fig. 1-6 Series connection of cells, with resulting current- voltage characteristic.

II- Parallel connection

The parallel connection of three individual cells as an example is showed in Fig. (1-7). In this case, the current from cell group is equivalent to the addition of the current from each cell, but the voltage remains equivalent to that of a single cell. As before, it is important to have the cells well matched in order to gain maximum output, but this time the voltage is the important parameter since all cells must be at the same operating voltage. If the voltage at the maximum power point is substantially different for one of the cells, then this will force all the cells to operate off their maximum power point, with the poorer cell being pushed towards its open-circuit voltage value and the better cells to voltages below the maximum power point voltage. In all cases, the power level will be reduced below the optimum [3].

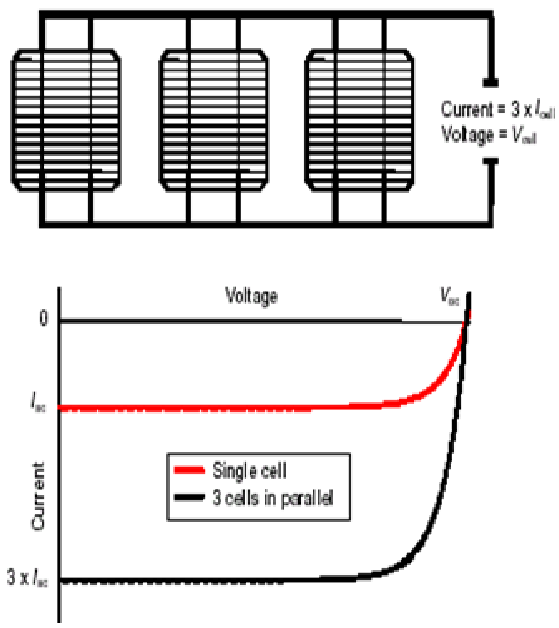

Fig. 1-7 Parallel connection of cells, with resulting current-voltage characteristic.

I-V Characteristics

A current vs. voltage (I-V) curve describes a module's output. This curve shows the performance of a module over a range of currents and voltages, usually at the standard test conditions (STC) of 1,000 w/m2 (One Sun) and 25° C. There are three particular points of particular interest on an I-V curve, the short circuit current Isc, the open-circuit voltage ,Voc, and the maximum power output ,Pmax,. Fig. (1-8) shows an I-V characteristic together with the power curve, to illustrate the position of the maximum power point. The maximum current output of a module occurs at the short circuit current.

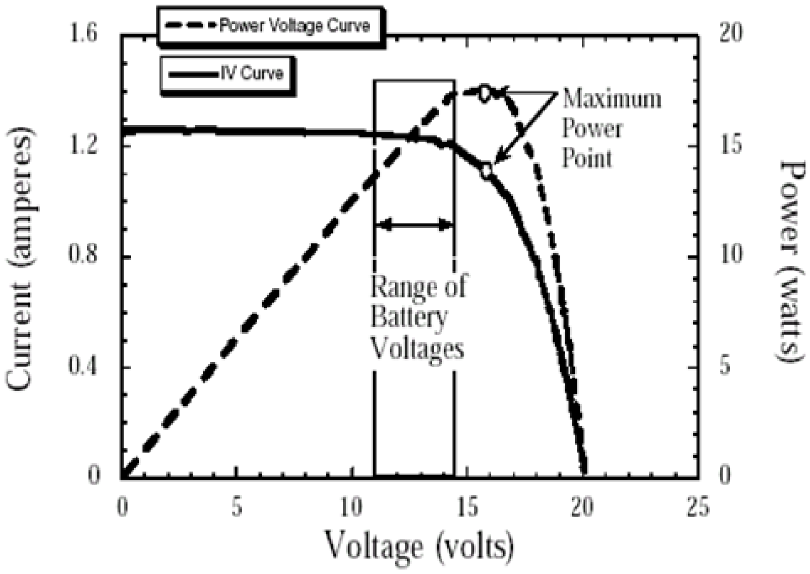

Fig1-8 Typical I-V characteristic of a crystalline silicon module with the variation of power with voltage.

At this point, the module is short-circuited, and the voltage is zero. On the contrary, the maximum voltage is produced at the open circuit voltage point; there is zero current at this point. The maximum power output of a module occurs at the knee of the curve. This is at the point where the product of the current and voltage of a point on the curve is at its highest. The power of a module is generally expressed in watts, which is equal to voltage x current. If Im represents the cell current at maximum power, and Vm represents the cell voltage at maximum power as shown in Fig. (1-9), then the cell maximum power can be expressed as follows [5]:

$$P_{\max} = I_m * V_m = FF * I_{sc} * V_{oc} \qquad (2\text{-}1)$$

Where FF is defined as the cell fill factor. The fill factor is a measured of the quality the cell. Cells with large internal resistance will have smaller fill factors, while the ideal cell will have a fill factor of unity. Note that a unity fill factor suggests a rectangular cell I-V characteristic. Such a characteristic implies that the cell has one region, A, where it operates as an ideal voltage source and another region, B, where it operates as an ideal current source. Although a real cell does not have a rectangular characteristic, it has a region where its operation approximates that of an ideal voltage source and another region where its operation approximates that of an ideal current source. Typical fill factors for real PV cells, depending on the technology, may vary from 0.5 to 0.82 [5]. No power is produced at either the short circuit current or the open circuit voltage points on the curve. Power production can only take place in between these points.

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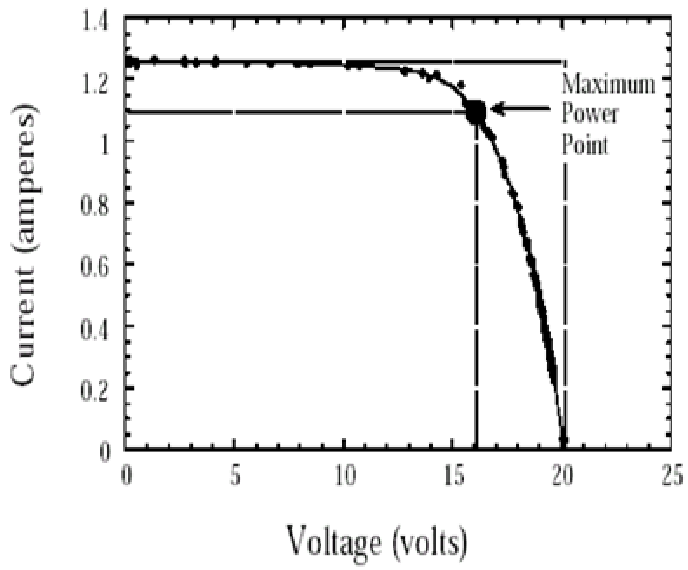

Fig. (1-9): Fill Factor for a PV module

As stated earlier, a module's I-V curve usually depicts output during STC. This means that the I-V curve shows the module's performance under optimal conditions. As the solar irradiance, GT, drops under 1,000 w/m2 though, so does the current and power output of the module Fig. (1-10) shows an I-V curve for 1,000 w/m2, 800 w/m2, 600w/m2, 400 w/m2, and 200 w/m2. Note the performance drop due to the loss of irradiance.

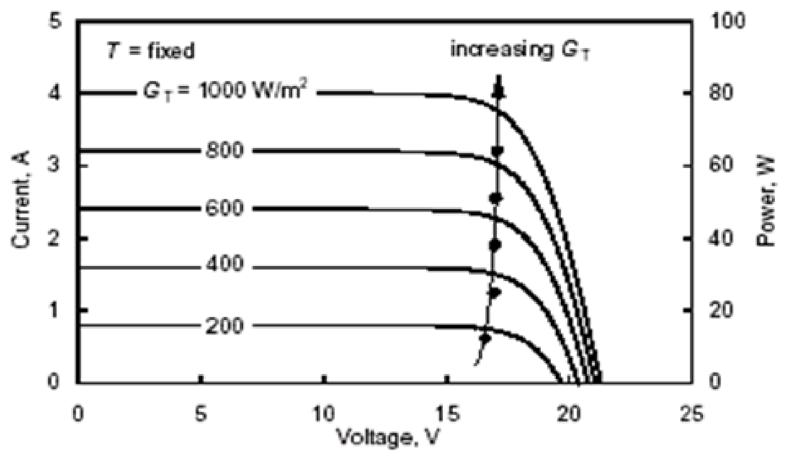

Fig. (1-10): I–V curves for a PV generator at different solar radiation levels.

The voltage and power outputs of modules are inversely related to temperature,

T. As temperature increases above 25° C, both the voltage and power output of the module decrease below STC values on the I-V curve. Because the voltage output of PV cells decreases about 0.5% for each degree Celsius above STC [5], it is vital that modules be mounted so that air can circulate around them unrestricted to keep the modules as cool as possible. Figure (1-11) shows a module's performance at STC of 25° C, 0° C and at 50° C. Note the performance loss associated with the increase in temperature

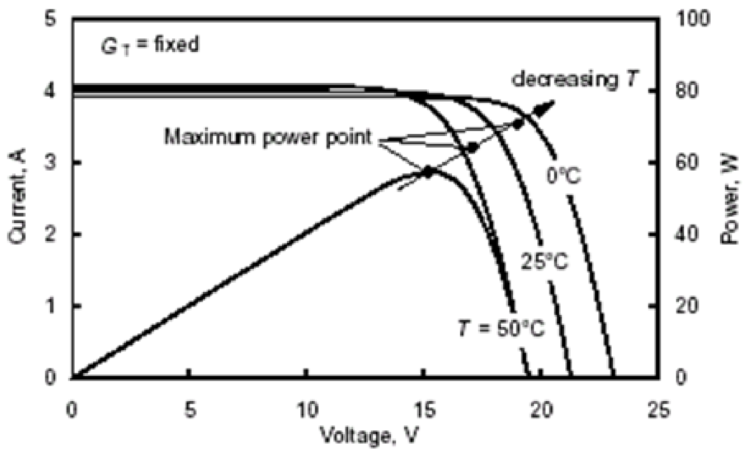

Fig. (1-11): I-V curves for a PV generator at temperature of 0° C, 25° C, and 50° C, with corresponding maximum power points.

Other factor that will result in a loss of power output from modules is shading. PV modules must be mounted so that there is a clear path between them and the sun. Shading of a small portion of a module can result in a loss of power from the entire array. Shaded cells cannot produce current and will become reversed biased. Reversed biased cells dissipate power as heat and will eventually cause failure. The performance of a shaded and unshaded module is displayed in Fig. (1-12) [5], and [2].

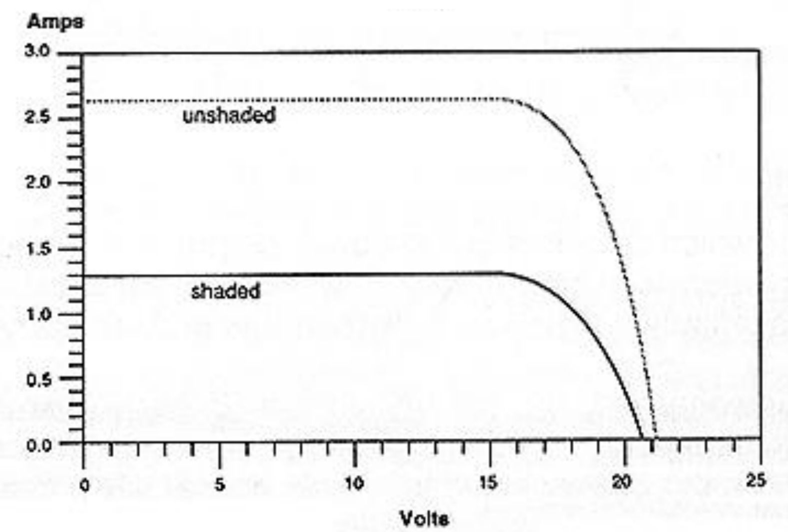

Fig. (1-12): I-V curve for an unshaded module and a module with a shaded cell.

Tilt Angle and Orientation

The orientation of the module with respect to the direction of the sun determines the intensity of the sunlight falling on the module surface. Two main parameters are defined to describe this as explained by Fig. 1.13 [4]

- The first: is the tilt angle, which is the angle between the plane of the module and the horizontal.
- The second: is the azimuth angle, which is the angle between the plane of the module and due south or sometimes due north depending on the definition used.

The optimum array orientation will depend on the latitude of the site, prevailing weather conditions and the loads to be met. The maximum annual output is obtained when the tilt angle is roughly equal to the latitude angle and the array faces due south (in the Northern Hemisphere) or due north (for the Southern Hemisphere) [3].

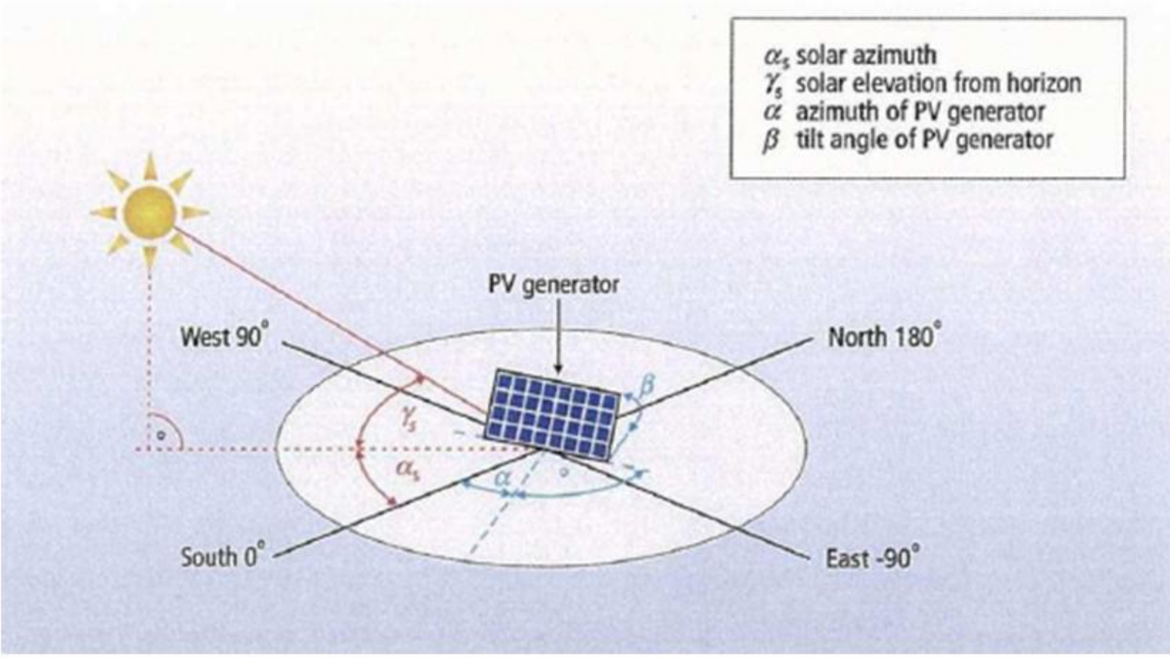

Fig. 1.13 Defining angles in solar technology

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