PHOTO VOLTAIC TECHNOLOGY:

The Kyoto agreement on global reduction of greenhouse gas emissions has prompted renewed interest in renewable energy systems worldwide. Many renewable energy technologies today are well developed, reliable, and cost competitive with the conventional fuel generators. The cost of renewable energy technologies is on a falling trend and is expected to fall further as demand and production increases. There are many renewable energy sources such as biomass, solar, wind, mini-hydro, and tidal power. One of the advantages offered by renewable energy sources is their potential to provide sustainable electricity in areas not served by the conventional power grid.

The growing market for renewable energy technologies has resulted in a rapid growth in the need for power electronics. Most of the renewable energy technologies produce DC power, and hence power electronics and control equipment are required to convert the DC into AC power.

Inverters are used to convert DC to AC. There are two types of inverters: stand-alone and grid-connected. The two types have several similarities, but are different in terms of control functions.

A stand-alone inverter is used in off-grid applications with battery storage. With backup diesel generators (such as PV–diesel hybrid power systems), the inverters may have additional control functions such as operating in parallel with diesel generators and bidirectional operation (battery charging and inverting). Grid-interactive inverters must follow the voltage and frequency characteristics of the utility-generated power presented on the distribution line. For both types of inverters, the conversion efficiency is a very important consideration. Details of stand-alone and grid-connected inverters for PV and wind applications are discussed in this chapter.

The density of power radiated from the sun (referred to as the ‘‘solar energy constant’’) at the outer atmosphere is 1.373kW/m^2. Part of this energy is absorbed and scattered by the earth’s atmosphere. The final incident sunlight on earth’s surface has a peak density of 1kW/m^2 at noon in the tropics. The technology of photovoltaic

(PV) is essentially concerned with the conversion of this energy into usable electrical form. The basic element of a PV system is the solar cell.

Solar cells can convert the energy of sunlight directly into electricity. Consumer appliances used to provide services such as lighting, water pumping, refrigeration, telecommunications, and television can be run from photovoltaic electricity.

Solar cells rely on a quantum-mechanical process known as the ‘‘photovoltaic effect’’ to produce electricity. A typical solar cell consists of a p n junction formed in a semiconductor material similar to a diode. Figure 1 shows a schematic diagram of the cross section through a crystalline solar cell. It consists of a 0.2–0.3mm thick mono-crystalline or polycrystalline silicon wafer having two layers with different electrical properties formed by ‘‘doping’’ it with other impurities (e.g., boron and phosphorus). An electric field is established at the junction between the negatively doped (using phosphorus atoms) and the positively doped (using boron atoms) silicon layers. If light is incident on the solar cell, the energy from the light (photons) creates free charge carriers, which are separated by the electrical field. An electrical voltage is generated at the external contacts, so that current can flow when a load is connected. The photocurrent (I_{ph}), which is internally generated in the solar cell, is proportional to the radiation intensity.

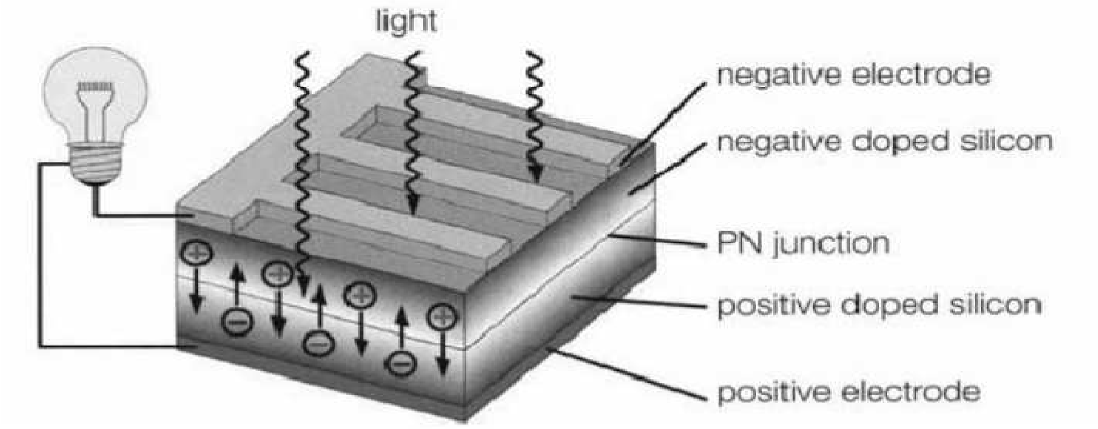


Figure 1: Solar Cell

A simplified equivalent circuit of a solar cell consists of a current source in parallel with a diode as shown in Fig. 2a. A variable resistor is connected to the solar cell generator as a load. When the terminals are short-circuited, the output voltage and also the voltage across the diode are both zero. The entire photocurrent (I_{ph}) generated by the solar radiation then flows to the output. The solar cell current has its maximum (I_{sc}). If the load resistance is increased, which results in an increasing voltage across the p n junction of the diode, a portion of the current flows through the diode and the output current decreases by the same amount. When the load resistor is open circuited, the output current is zero and the entire photocurrent flows through the diode. The relationship between current and voltage may be determined from the diode characteristic equation:

$$I = I_{ph} - I_0(e^{\frac{qv}{kt}} - 1) = I_{ph} - I_d$$

where q is the electron charge, k is the Boltzmann constant, I_{ph} is photocurrent, I_0 is the reverse saturation current, Id is diode current, and T is the solar cell operating temperature (K). The current versus voltage (I-V) of a solar cell is thus equivalent to an ‘‘inverted’’ diode

characteristic curve shown in Fig.2.

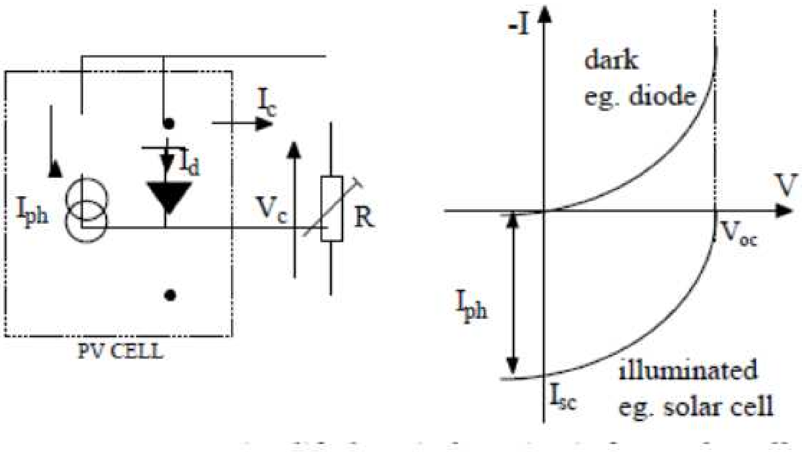


Figure 2: Equivalent circuit of a solar cell

A number of semiconductor materials are suitable for the manufacture of solar cells. The most common types using silicon semiconductor material (Si) are:

- Monocrystalline Si cells
- Polycrystalline Si cells
- Amorphous Si cells

A solar cell can be operated at any point along its characteristic current–voltage curve, as shown in Fig. 3. Two important points on this curve are the open circuit voltage (V_{oc}) and short-circuit current (I_{sc}). The open-circuit voltage is the maximum voltage at zero current, whereas the short circuit current is the maximum current at zero voltage. For a silicon solar cell under standard test conditions, V_{oc} is typically 0.6–0.7 V, and I_{sc} is typically 20–40mA for every square centimeter of the cell area. To a good approximation, I_{sc} is proportional to the illumination level, whereas V_{oc} is proportional to the logarithm of the illumination level.

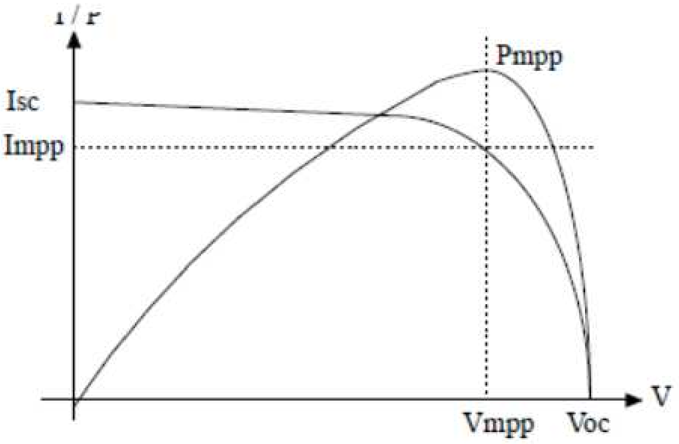


Figure 3: I vs. V characteristics of a solar cell

A plot of power (P) against voltage (V) for this device (Fig. 3) shows that there is a unique point on the I-V curve at which the solar cell will generate maximum power. This is known as the maximum power point (V_{mp}, I_{mp}). To maximize the power output, steps are usually taken during fabrication to maximize the three basic cell parameters: open-circuit voltage, short-circuit current, and fill factor (FF)—a term describing how ‘‘square’’ the I-V curve is, given by

$$Fill\ Factor = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}}$$

For a silicon solar cell, FF is typically 0.6–0.8.

Because silicon solar cells typically produce only about 0.5 V, a number of cells are connected in series in a PV module. A panel is a collection of modules physically and electrically grouped together on a support structure. An array is a collection of panels (see Fig. 4).

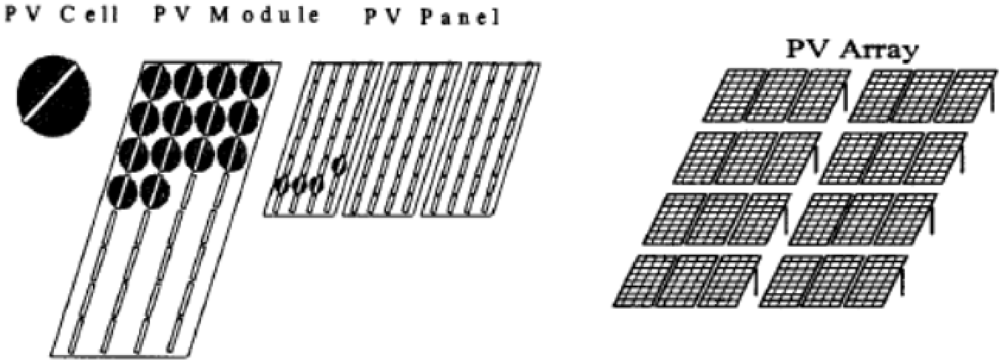


Figure 4: Elements of SPV system

The effect of temperature on the performance of a silicon solar module is illustrated in Fig. 6.5.

Note that I_{sc} slightly increases linearly with temperature, but V_{oc} and the maximum power P_m

decrease with temperature.

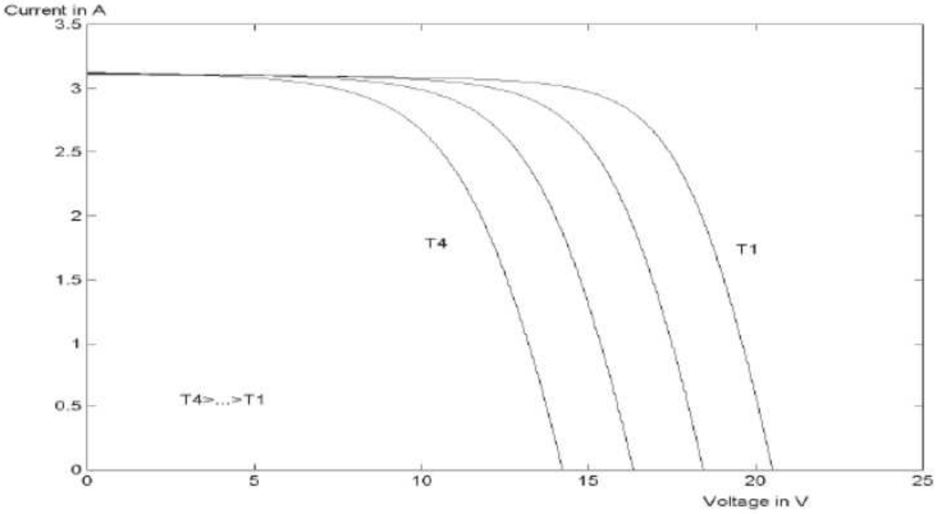


Figure 5: Effect of temperature on the performance of Silicon solar module

Figure 6 shows the variation of PV current and voltages at different insolation levels. From Figs. 5 and 6, it can be seen that the I V characteristics of solar cells at a given insolation and temperature consist of a constant-voltage segment and a constant-current segment. The current is limited, as the cell is short-circuited. The maximum power condition occurs at the knee of the characteristic where the two segments meet.

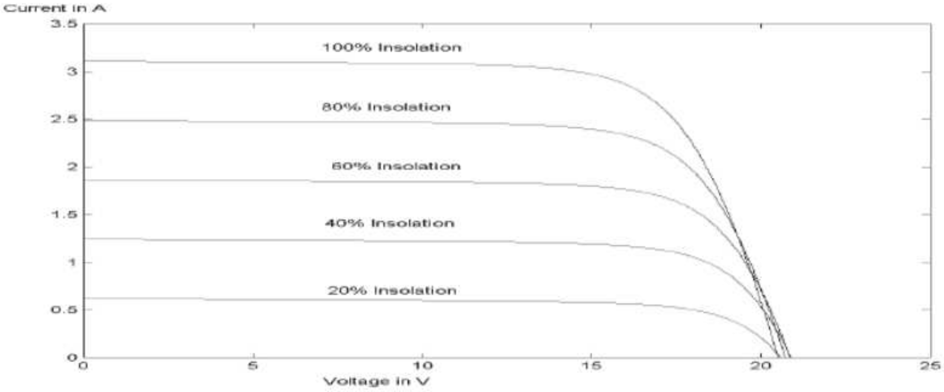


Figure 6: I-V characteristics for different insolation levels

ARRAY DESIGN

The major factors influencing the electrical design of the solar array are as follows:

- The sun intensity
- The sun angle
- The load matching for maximum power
- The operating temperature

These factors are discussed in the following subsections.

SUN INTENSITY:

The magnitude of the photocurrent is maximum under a full bright sun (1.0 sun). On a partially sunny day, the photocurrent diminishes in direct proportion to the sun intensity. At a lower sun intensity, the I-V characteristic shifts downward as shown above. On a cloudy day, therefore, the short-circuit current decreases significantly. The reduction in the open-circuit voltage, however, is small. The photo conversion efficiency of the cell is insensitive to the solar radiation in the practical working range. This means that the conversion efficiency is the same on a bright sunny day as on a cloudy day. We get a lower power output on a cloudy day only because of the lower solar energy impinging on the cell.

SUN ANGLE:

The cell output current is given by $I = I_o \cos\theta$, where I_o is the current with normal sun (reference), and θ is the angle of the sun line measured from the normal. This cosine law holds well for sun angles ranging from 0 to about 50°. Beyond 50°, the electrical output deviates significantly from the cosine law, and the cell generates no power beyond 85°, although the mathematical cosine law predicts 7.5% power generation.

SHADOW EFFECT:

The array may consist of many parallel strings of series-connected cells. Two such strings are shown in Figure 9.13. A large array may get partially shadowed due to a structure interfering with the sun line. If a cell in a long series string gets completely shadowed, it loses the photo-voltage but still must carry the string current by virtue of its being in series with all other cells operating in full sunlight. Without internally generated voltage, the shadowed cell cannot produce power. Instead, it acts as a load, producing local I^2R loss and heat. The remaining cells in the string must work at higher voltage to make up the loss of the shadowed cell voltage.

TEMPERATURE EFFECTS:

With increasing temperature, the short-circuit current of the cell increases, whereas the open-circuit voltage decreases. The effect of temperature on PV power is quantitatively evaluated by examining the effects on the current and the voltage separately.

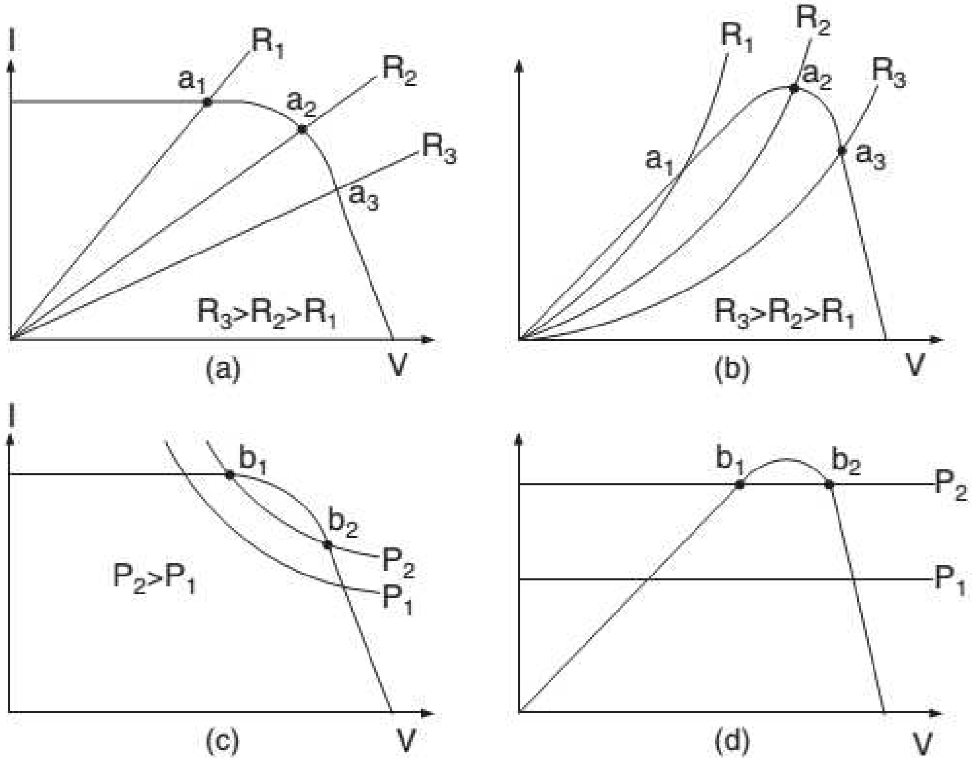
EFFECT OF CLIMATE:

On a partly cloudy day, the PV module can produce up to 80% of its full sun power. It can produce about 30% power even with heavy clouds on an extremely overcast day. Snow does not usually collect on the module, because it is angled to catch the sun. If snow does collect, it quickly melts. Mechanically, the module is designed to withstand golf-ball-size hail.

ELECTRICAL LOAD MATCHING:

The operating point of any power system is the intersection of the source line and the load line. If the PV source having the I-V and P-V characteristics shown in

Figure is supplying power to a resistive load R_1, it will operate at point A_1.If the load resistance increases to R_2 or R_3, the operating point moves to A_2 or A_3, respectively. The maximum power is extracted from the module when the load resistance is R_2. Such a load that matches with the source is always necessary for the maximum power extraction from a PV source.



Operating stability and electrical load matching with constant-resistive load and constant-power load.

SUN TRACKING:

More energy is collected by the end of the day if the PV module is installed on a tracker with an actuator that follows the sun. There are two types of sun trackers:

- One-axis tracker, which follows the sun from east to west during the day.
- Two-axis tracker, which follows the sun from east to west during the day, and from north to south during the seasons of the year.