CHAPTER 5

MICROGRID SOLAR ENERGY SYSTEMS

5.1 INTRODUCTION

From the beginning of recorded history, humans have worshipped the sun. The first king of Egypt was Ra, the sun god. The sun god of justice for Mesopotamia was Shamash. In Hinduism, the sun god, Surya, is believed to be the progenitor of mankind. Apollo and Helios were the two sun divinities of Ancient Greece. The sun also figured prominently in the religious traditions of Zoroastrianism (Iran) and Buddhism (Asia), as well as in the Aztec (Mexico) and Inca (Peru) cultures.[1]

The sun's energy is the primary source of energy for life on our planet. When the sun disappears from our universe, we will cease to exist.[2] Solar energy is a readily available renewable energy; it reaches earth in the form of electromagnetic waves (radiation). Many factors affect the amount of radiation received at a given location on earth. These factors include location, season, humidity, temperature, air mass, and the hour of day. *Insolation* refers to exposure to the rays of the sun, i.e., the word insolation has been used to denote the solar radiation energy received at a given location at a given time. The phrase *incident solar radiation* is also used; it expresses the average irradiance in watts per square meter (W/m^2) or kilowatt per square meter (kW/m^2).

The surface of the earth is coordinated with imaginary lines of latitude and longitude as shown in Fig. 5.1(a). Latitudes on the surface of the earth are

Design of Smart Power Grid Renewable Energy Systems, First Edition. Ali Keyhani.

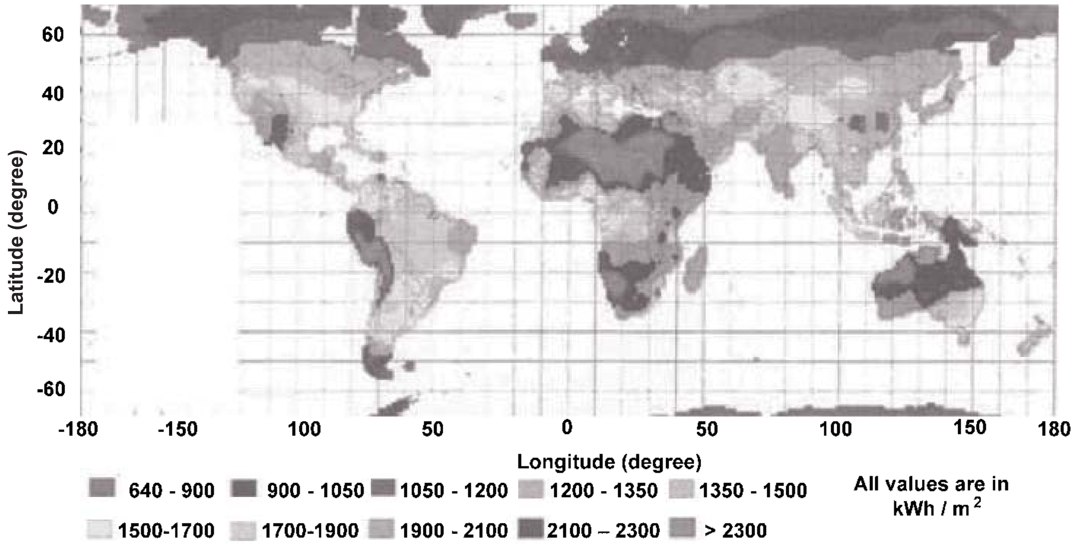
imaginary parallel lines measured in degrees. The lines subtend to the plane of the equator. The latitudes vary from 90° south (S) and 90° north (N). The longitudes are imaginary lines that vary from 180° east (E) to 180° west (W). The longitudes converge at the poles (90° north and 90° south). The radiation of the sun on the earth varies with the location based on the latitudes. Approximately, the region between 30° S and 30° N has the highest irradiance as depicted in Fig. 5.1. The latitude on which the sun shines directly overhead between these two latitudes depends on the time of the year. If the sun lies directly above the northern hemisphere, it is summer in the north and winter in the southern hemisphere. If it is above the southern hemisphere, it is summer in the southern hemisphere and winter in the north.

Figure 5.1(b) is a plot showing the irradiance at different locations on the earth marked by its latitude and longitude. The latitude varies from –90° to 90°, which is 90° N and 90° S, respectively. Similarly, the longitudes vary from –180° to 180°, which is 180° W and 180° E, respectively. The z-axis of the plot gives the irradiance in kWh/m^2. The points on the z-axis convey the amount of irradiance. The colors on the plot represent the intensity of the irradiance as given in Fig. 5.1(b).

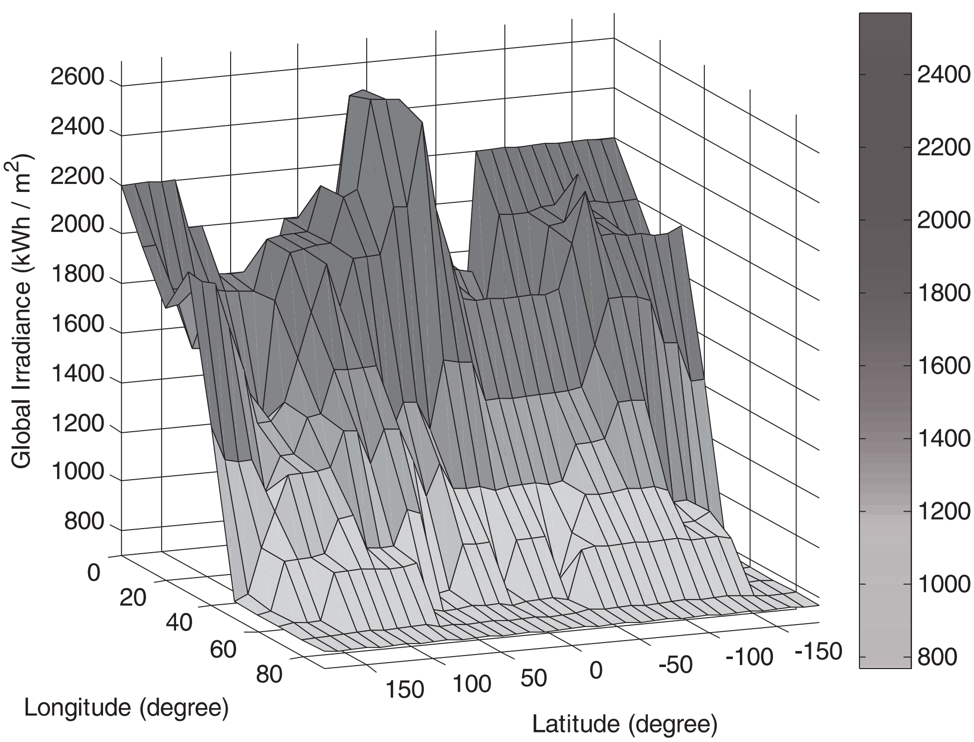
The sun's position as seen from earth between latitudes 15°N and 35°N is the region with the most solar energy. This semiarid region, as shown in Fig. 5.1(b) and Fig. 5.1(c), is mostly located in Africa, the Western United States, the Middle East, and India. These locations have over 3,000 hours of intense sunlight radiation per year. The region with the second largest amount of solar energy radiation lies between 15°N latitude and the equator and has approximately 2,500 hours of solar energy per year. The belt between latitude 35°N and 45°N has limited solar energy. However, typical sunlight radiation is roughly about the same as the other two regions, although there are clear seasonal differences in both solar intensity and daily hours. As winter approaches, the solar radiation decreases; by midwinter, it is at its lowest level. The 45°N latitude and the region beyond experience approximately half of the solar radiation as diffused radiation. The energy of sunlight received by the earth can be approximated to equal 10,000 times the world's energy requirements.[3]

The sun's radiation is in the form of ultraviolet, visible, and infrared energy as depicted in Fig. 5.2. The majority of the energy is in the form of a short wave that is used in the planet's heat cycle, weather cycle, wind, and waves. A small fraction of the energy is utilized for photosynthesis in plants and the rest of the solar energy is emitted back into space.

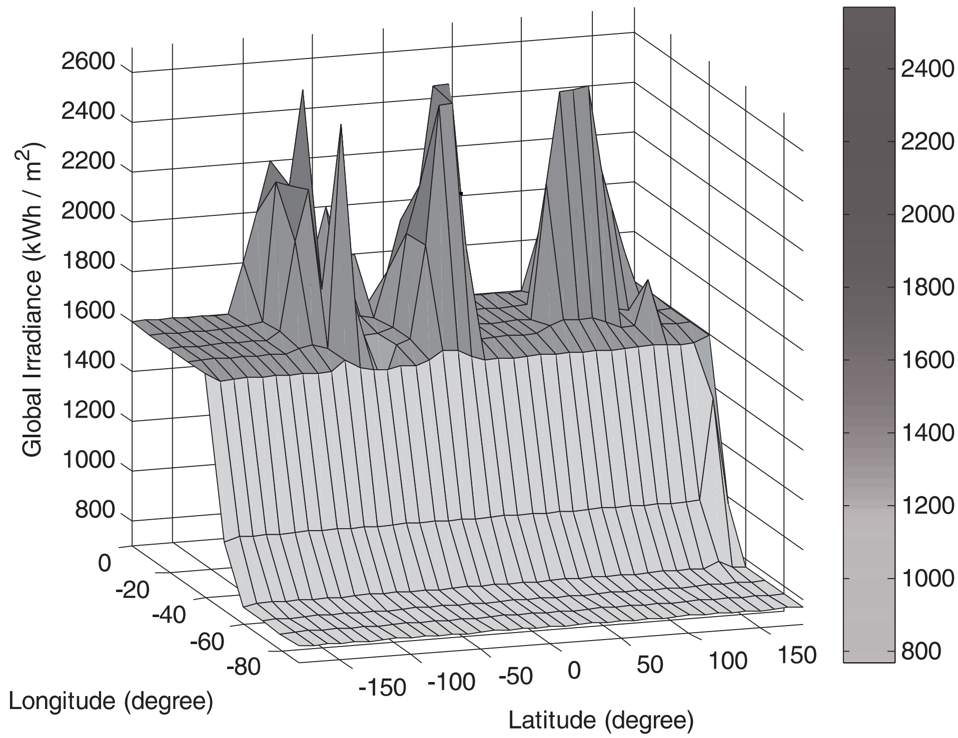
The solar energy reaching the atmosphere is constant; hence the term *solar constant*. The solar constant is computed to be in the range of 1.4 kW/m^2, or 2.0 $cal/cm^2/min$. Sunlight's shorter wavelengths scatter over a wider area than the longer wavelengths of light. The scattering may be due to gas molecules, pollution, and haze. The blue and violet light have the maximum atmospheric scattering at sunrise and sunset without affecting the red rays of sunlight.


60
40
20
0
-20
-40
-60
Latitude (degree)
-180
-150
100
50
0
50
100
150
180
Longitude (degree)
640 - 900
900 - 1050
1050 - 1200
1200 - 1350
1350 - 1500
1500-1700
1700-1900
1900 - 2100
2100 – 2300
> 2300
All values are in kWh / m²

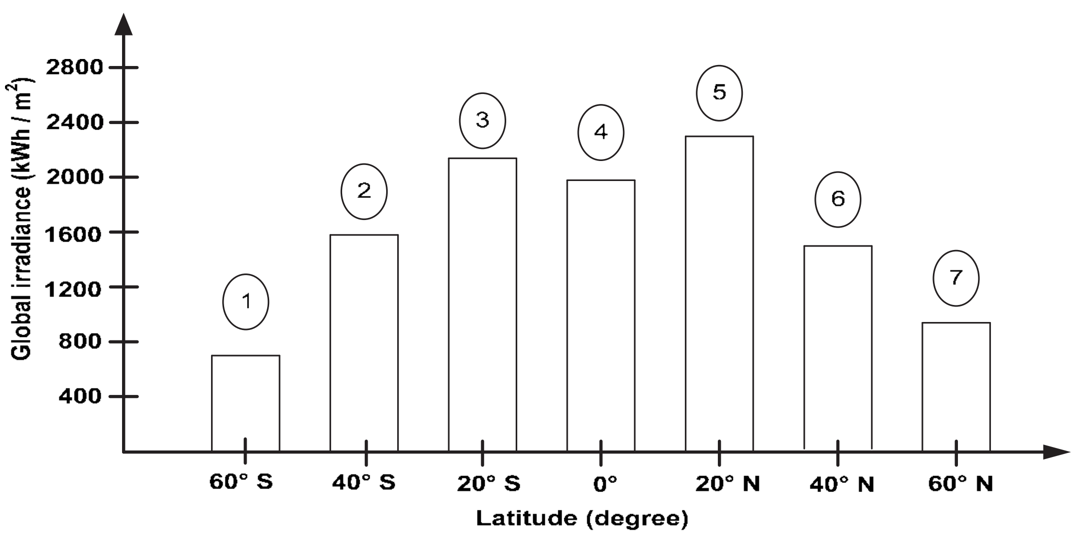
(a)


Global Irradiance (kWh / m²)
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
0
20
40
60
80
Longitude (degree)
150
100
50
0
-50
-100
-150
Latitude (degree)
2400
2200
2000
1800
1600
1400
1200
1000
800

(b)



(c)



(d)

Figure 5.1 **(a)** The Global Irradiation Values for the World (kWh/m^2).[2,3] **(b)** The Average Northern Hemisphere Global Irradiation Source by Longitude and Latitude.[4,9] **(c)** The Average Southern Hemisphere Global Irradiation Source by Longitude and Latitude. **(d)** The Average World Global Irradiation Source by Regions.[4,9] Region 1: Argentina, Chile; Region 2: Argentina, Chile; Region 3: Brazil, South Africa, Peru, Australia, Mozambique; Region 4: Indonesia, Brazil, Nigeria, Columbia, Kenya, Malaysia; Region 5: India, Pakistan, Bangladesh, Mexico, Egypt, Turkey, Iran, Algeria, Iraq, Saudi Arabia; Region 6: China, United States, Japan, Germany, France, United Kingdom, South Korea; Region 7: Russia, Canada, Sweden, Norway.

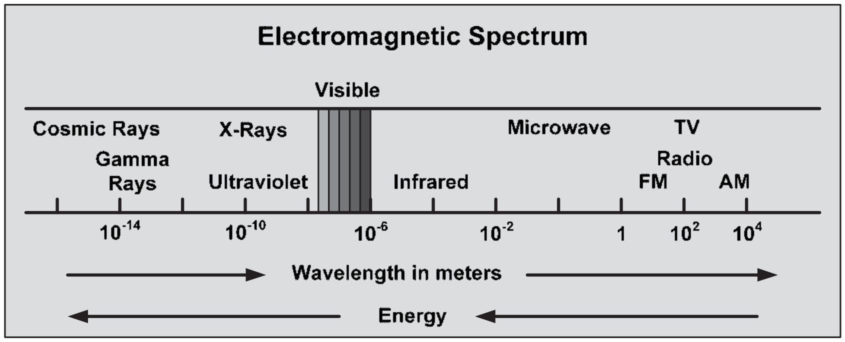


Figure 5.2 The Electromagnetic Spectrum.[1,2]

5.2 THE SOLAR ENERGY CONVERSION PROCESS: THERMAL POWER PLANTS

Auguste Mouchout constructed a parabolic mirror to channel the sun's energy to power a steam engine in 1866.[5] Todays' thermal solar electric power plant also uses the sun's heat energy to generate steam power for running the turbines.

Concentrating solar power (CSP) systems have locating lenses designed for concentrating the sunlight into the receiver, which acts as a boiler to generate steam. The system uses a tracking control system for maximum efficiency. A number of concentrating technologies exists; a parabolic mirror that uses materials that are silver-based or of polished aluminum is often used. Figure 5.3 depicts the CSP system located in the Mojave Desert in California, which uses a parabolic mirror.

Solar power towers (see Fig. 5.4) generate steam power by creating intense concentrated solar energy that is directed via a tower heat processing system.[2] The system uses a large number of sun-tracking mirrors, or parabolic reflectors. The number of mirrors depends on the system capacity. Another type of mirror used is called a heliostat (from *Helios*, the Greek word for sun). Earlier power towers used water/steam as the heat-transfer fluid. More recent advanced designs have used molten nitrate salt.

A French physicist, Augustin-Jean Fresnel (1788–1827),[7] developed the Fresnel lens, which has a large aperture and short focal length. Its construction requires less material than a conventional lens, and it allows for more light to pass through.

The compact linear Fresnel reflector (CLFR) is used in solar power plants. The CLFR system uses Fresnel lens and reflectors that are located on a single axis to concentrate the solar energy to generate steam. The CLFR uses a number of thin mirror strips to focus high-intensity sunlight into a heat-processing system. Flat mirrors are much cheaper to produce than parabolic ones and they facilitate a greater number of reflectors for use in steam generation. Figure 5.5 depicts a CLFR power generating station.

Figure 5.3 The Concentrated Parabolic Trough Solar Power System.[6] (Photo courtesy of the California Energy Commission)

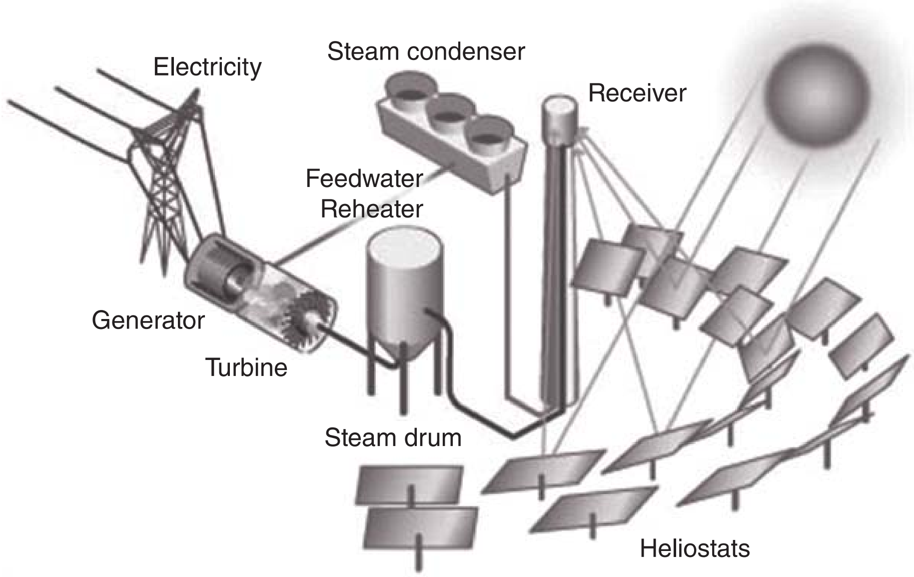


Figure 5.4 A Steam Solar Power Generating Station.[1]

Another type of solar heat engine is the Stirling engine.[1] It operates by cyclic compression with expansion of the working fluid such as air or other gas. It uses two different temperature levels in its thermodynamic process converting heat energy into mechanical work. The Stirling solar dish engine system is an active area of research.[4]

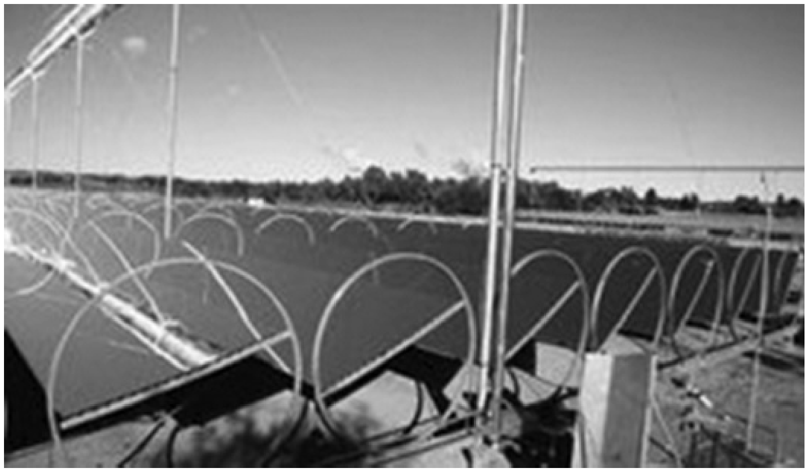


Figure 5.5 A Linear Fresnel Reflector (CLFR) Concentrating Solar Power (CSP) Technology.[2]

5.3 PHOTOVOLTAIC POWER CONVERSION

Solar cells convert the radiation energy directly to electric energy. Solar cells, also called photovoltaic (PV) cells, were developed by Carlson and Wronski in 1976.[8] A PV module consists of a number of PV cells. When sunlight strikes the PV cell, electrons are freed from their atoms. The freed electrons are directed toward the front surface of the solar cell. This process creates a current flow that occurs between the negative and positive sides. The PV photon cell charge offers a voltage of 1.1 up to 1.75 electron volt^2 (eV^2) with a high optical absorption. Figure 5.6 depicts a solar cell structure.[2]

Figure 5.6 depicts a photovoltaic (PV) cell structure. A photovoltaic (PV) module connects a number cell of PV cells in series. You may think of a PV cell as a number of capacitors that are charged by photon energy of light. Figure 5.7 depicts how the irradiance energy of the sun is converted to electric energy using PV cells.

5.4 PHOTOVOLTAIC MATERIALS

The manufacture of PV cells is based on two different types of material: (1) a semiconductor material that absorbs light and converts it into electron–hole pairs, and (2) a semiconductor material with junctions that separate photo-generated carriers into electrons and electron holes. The contacts on the front and back of the cells allow the current to the external circuit. Crystalline silicon cells (c-Si) are used for absorbing light energy in most semiconductors used in solar cells. Crystalline silicon cells are poor absorbers of light energy[6]; they have an efficiency in the range of 11 to 18% of that of solar cells. The most-efficient monocrystalline c-Si cell uses laser-grooved, buried grid contacts, which allow for maximum light absorption and current collection.[6] Each

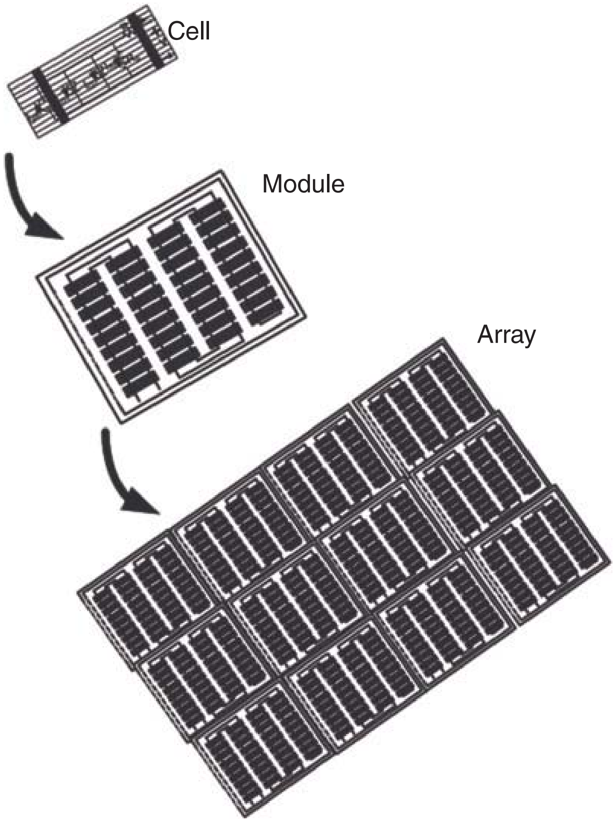


Figure 5.6 A Solar Cell or Photovoltaic Cell Structure.[9]

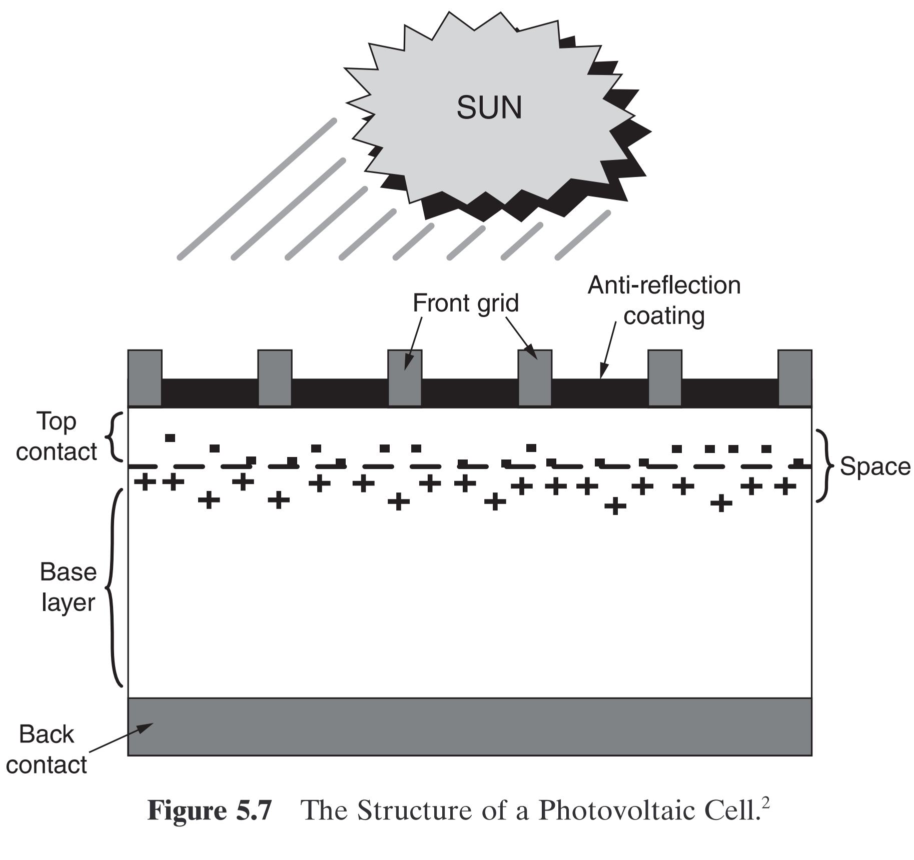


Figure 5.7 The Structure of a Photovoltaic Cell.[2]

of the c-Si cells produces approximately 0.5 V. When 36 cells are connected in series, it creates an 18 volt module. In the thin-film solar cell, the crystalline silicon wafer has a very high cost. Other common materials are amorphous silicon (a-Si), and cadmium telluride and gallium, which are another class of polycrystalline materials.[6] The thin-film solar cell technology uses a-Si and a p-i-n single-sequence layer, where "p" is for positive and "n" for negative, and "i" for the interface of a corresponding p- and n-type semiconductor.[10] Thin-film solar cells are constructed using lamination techniques, which promote their use under harsh weather conditions: they are environmentally robust modules. Due to the basic properties of c-Si devices, they may stay as the dominant PV technology for years to come. However, thin-film technologies are making rapid progress and a new material or process may replace the use of c-Si cells.[8]

Here we briefly introduce PV technology as it exists today. But as an evolving technology, students and engineers should recognize that these advances will come from basic research in material engineering and read the *IEEE Spectrum* to keep up with the developments in PV technology. Below we continue our discussion on how to develop models to study the integration of PV sources into the smart power grid system.

5.5 PHOTOVOLTAIC CHARACTERISTICS

As sun irradiance energy is captured by a PV module, the open-circuit voltage of the module increases.[1,4] This point is shown in Fig. 5.8 by V_{oc} with

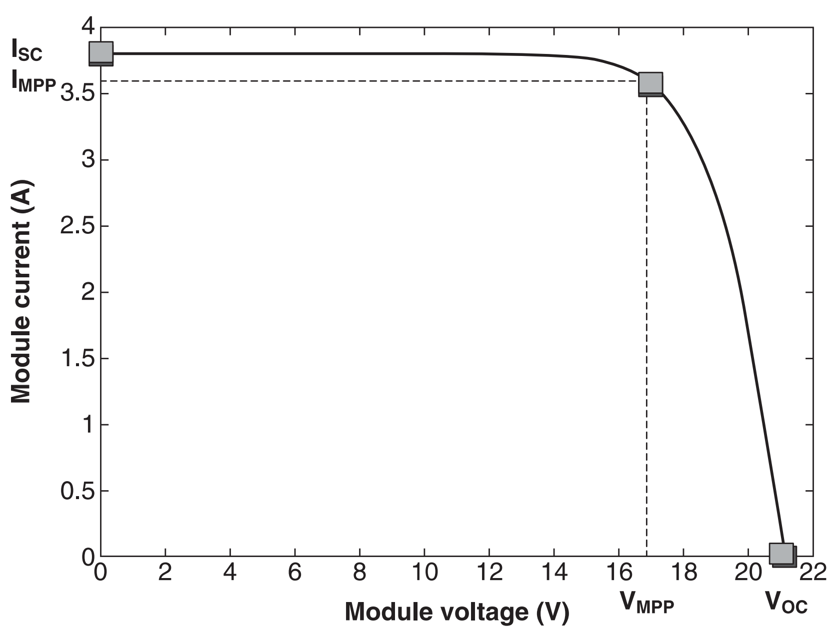


Figure 5.8 The Operating Characteristics of a Photovoltaic Module.[9]

TABLE 5.1 Voltage and Current Characteristics of Typical Photovoltaic Modules.

Module	Type 1	Type 2	Type 3	Type 4
Power (Max), W	190	200	170	87
Voltage at maximum power point (MPP), V	54.8	26.3	28.7	17.4
Current at MPP, A	3.47	7.6	5.93	5.02
V_{OC} (open-circuit voltage), V	67.5	32.9	35.8	21.7
I_{SC} (short-circuit current), A	3.75	8.1	6.62	5.34
Efficiency	16.40%	13.10%	16.80%	>16%
Cost	$870.00	$695.00	$550.00	$397.00
Width	34.6″	38.6″	38.3″	25.7″
Length	51.9″	58.5″	63.8″	39.6″
Thickness	1.8″	1.4″	1.56″	2.3″
Weight	33.07 lbs	39 lbs	40.7 lbs	18.3 lbs

TABLE 5.2 Cell Temperature Characteristics of a Typical Photovoltaic Module.

Typical Cell Temperature Coefficient		
Power	$T_k(P_p)$	–0.47%/°C
Open-circuit voltage	$T_k(V_{oc})$	–0.38%/°C
Short-circuit current	$T_k(I_{sc})$	0.1%/°C

TABLE 5.3 Maximum Operating Characteristics of a Typical Photovoltaic Module.

Limits	
Maximum system voltage	600 V DC
Operating module temperature	–40°C to 90°C
Equivalent wind resistance	Wind speed: 120 mph

zero-input current. If the module is short-circuited, the maximum short-circuit current can be measured. This point is shown in Fig. 5.8 by I_{SC} with zero-output voltage. The point on the I versus V characteristic where maximum power (P_{MPP}) can be extracted lies at a current I_{MPP} and the corresponding voltage point, V_{MPP}. Typical data for a number of PV modules are given in Table 5.1. This information is used to design PV strings and PV-generating power sources.

PV module selection criteria are based on a number of factors[11]: (1) the performance warranty, (2) module replacement ease, and (3) compliance with natural electrical and building codes. A typical silicon module has a power of 300 W with 2.43 m^2 surface area; a typical thin film has a power of 69.3 W with

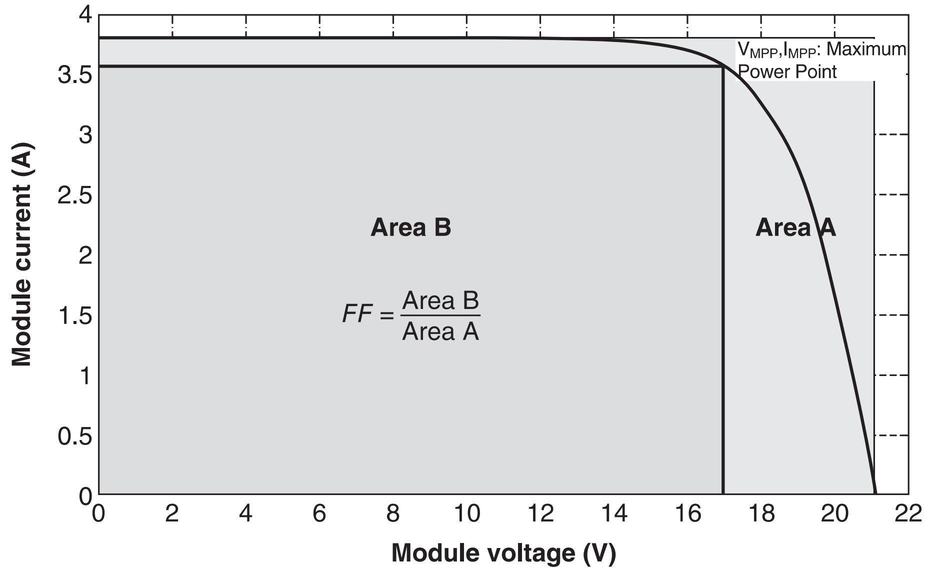


Figure 5.9 Photovoltaic Module Fill Factor.

an area of 0.72 m^2. Hence, the land required by a silicon module is almost 35% less. Typical electrical data apply to standard test considerations (STC). For example, under STC, the irradiance is defined for a module with a typical value such as 1000 W/m^2, spectrum air mass (AM) 1.5, and a cell temperature of 25°C.

The PV fill factor (*FF*), as shown in Fig. 5.9, is defined as a measure of how much solar energy is captured. This term is defined by PV module open circuit voltage (V_{oc}), and PV module short-circuit current (I_{sc}).

$$FF = \frac{V_{MPP} I_{MPP}}{V_{OC} I_{SC}} \tag{5.1}$$

And

$$P_{\max} = FF \cdot V_{OC} I_{SC} = V_{MPP} I_{MPP} \tag{5.2}$$

As seen in Fig. 5.9, the maximum value for FF is unity. However, this value can never be attained. Some PV modules have a high fill factor. In the design of PV system a PV module with a high FF would be used. For high-quality PV modules, FFs can be over 0.85. For typical commercial PV modules, the value lies around 0.60. Figure 5.10 depicts a three-dimensional display of a typical PV module and the fixed irradiance energy received by the module. As shown, a typical PV module characteristic is not only a function of irradiance energy, but it is also a function of temperature.

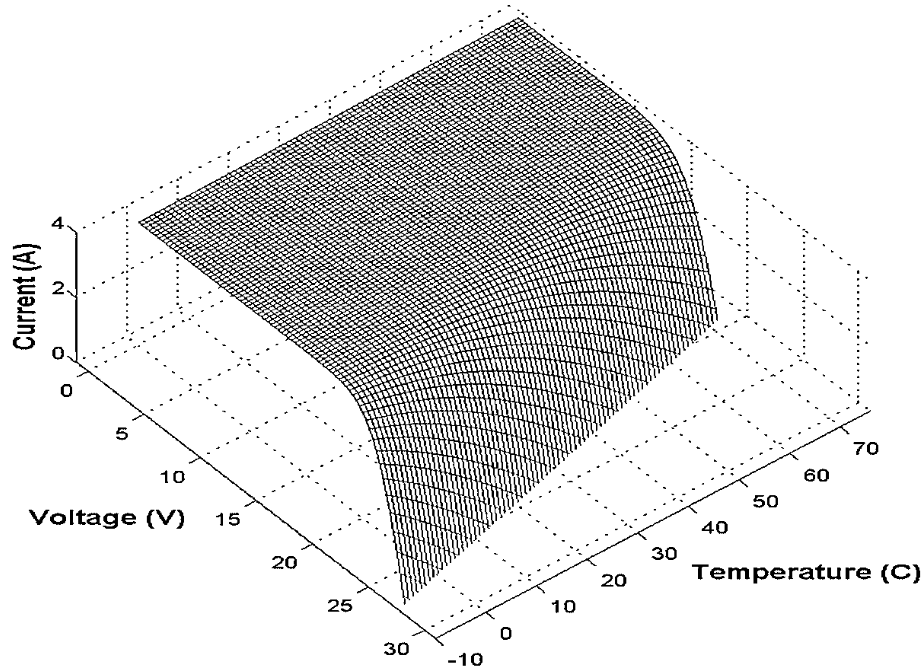


Figure 5.10 Three-Dimensional I–V Curve and Temperature for a Typical Photovoltaic Module.

5.6 PHOTOVOLTAIC EFFICIENCY

The PV module efficiency, η is defined as:

$$\eta = \frac{V_{MPP} I_{MPP}}{P_S} \tag{5.3}$$

where $V_{MPP} I_{MPP}$ is the maximum power output, P_{mpp} and P_S is the surface area of the module. The PV efficiency can be also defined as:

$$\eta = FF \cdot \frac{V_{OC} I_{SC}}{\int_0^{\infty} P(\lambda) \cdot d\lambda} \tag{5.4}$$

where $P(\lambda)$ is the solar power density at wavelength λ.

Figure 5.11 depicts a PV module consisting of 36 PV cells. If each cell is rated at 1.5 V, the module rated voltage is 54 V.

A string is designed by connecting a number of PV modules in series. A number of strings connected in parallel make an array. Two general designs of PV systems can be envisioned. Figure 5.13 depicts a PV design based on a central inverter. Figure 5.14 depicts the utilization of multiple inverters.

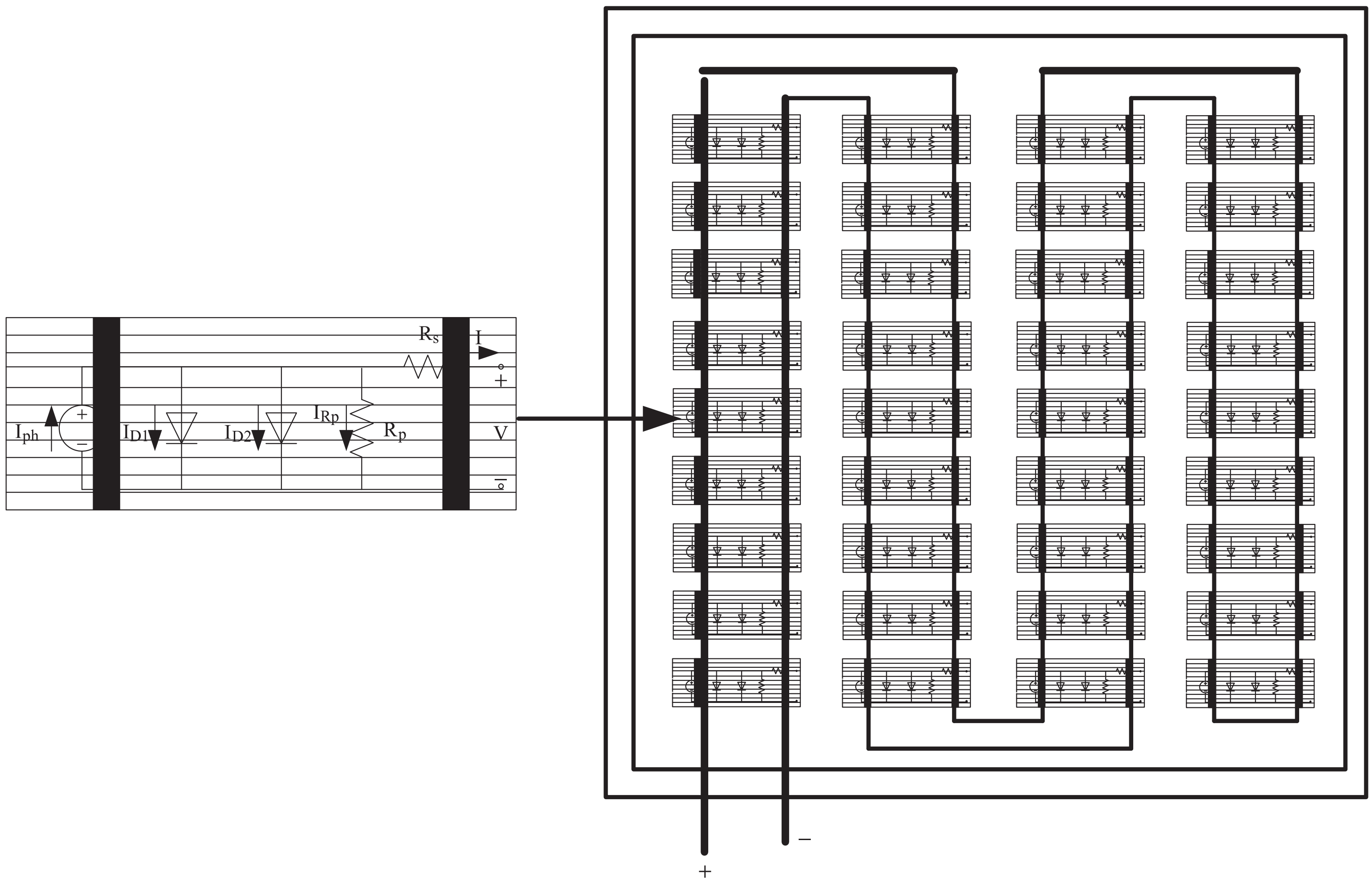


Figure 5.11 A Photovoltaic Module Consisting of 36 Photovoltaic Cells.

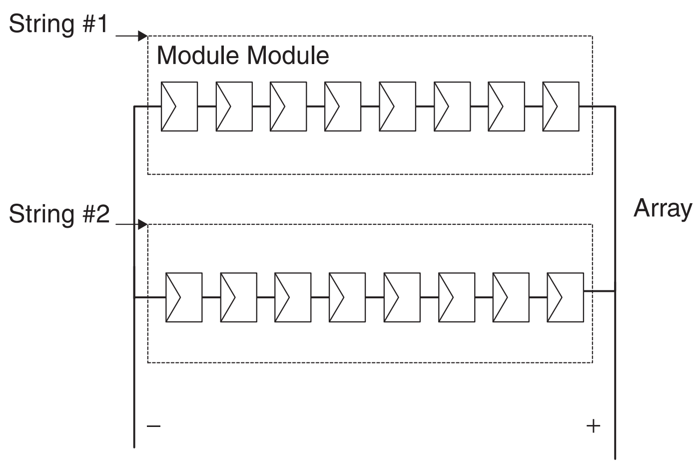


Figure 5.12 Basic Configuration Showing Modules, Strings, and an Array.

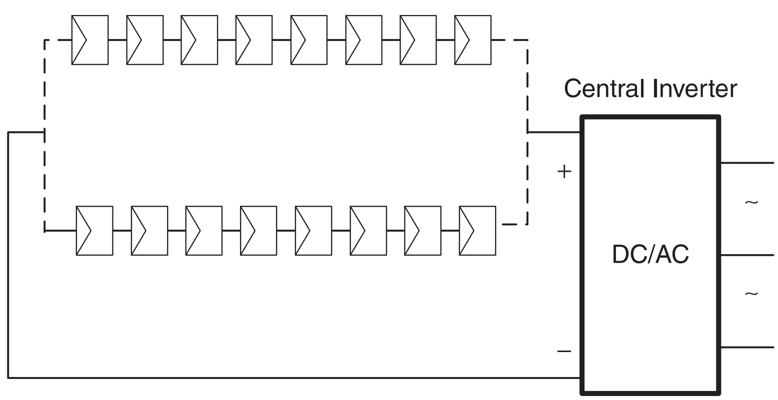


Figure 5.13 Central Inverter for a Large-Scale Photovoltaic Power Configuration.

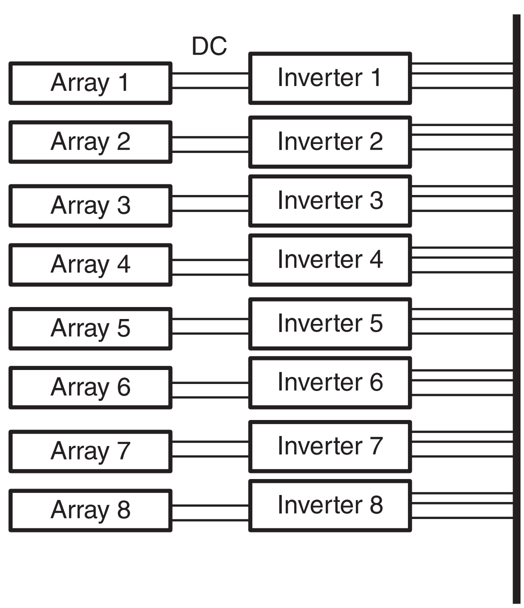


Figure 5.14 General Structure of Photovoltaic Arrays with Inverters.

Basically, to provide a higher DC operating voltage, modules are connected in series. To provide a higher operating current, the modules are connected in parallel.

$$\text{V (series connected)} = \sum_{j=1}^{n} V_j;\ n\text{: number of series connected panels} \tag{5.5}$$

For parallel connected panels,

$$\text{I (parallel connected)} = \sum_{j=1}^{m} I_j;\ m\text{: number of parallel connected panels} \tag{5.6}$$

In a PV system consisting of a number of arrays, all arrays must have equal exposure to sunlight: the design should place the modules of a PV system such that some of them will not be shaded. Otherwise, unequal voltages will result in some strings with unequal circulating current and internal heating producing power loss and lower efficiency. Bypass diodes are usually used between modules to avoid damage. Most new modules have bypass diodes in them as shown in Fig. 5.15 to ensure longer life. However, it is very difficult to replace built-in diodes if a diode fails in a panel.

The photovoltaic (PV) industry, the International Society for Testing and Materials (ASTM)[8], and the U.S. Department of Energy have established a standard for terrestrial solar spectral irradiance distribution. The irradiance of a location is measured by an instrument called a pyranometer.[9] Figure 5.16 depicts irradiance in W/m^2 per nanometer (nm) as a function of wavelength in nanometers (nm).

The solar spectrum is the plot of the irradiance from the sun received at a particular location at a given temperature and air mass flow. The intensity (W/m^2/nm) of the radiation is plotted as a function of wavelength (nm). The

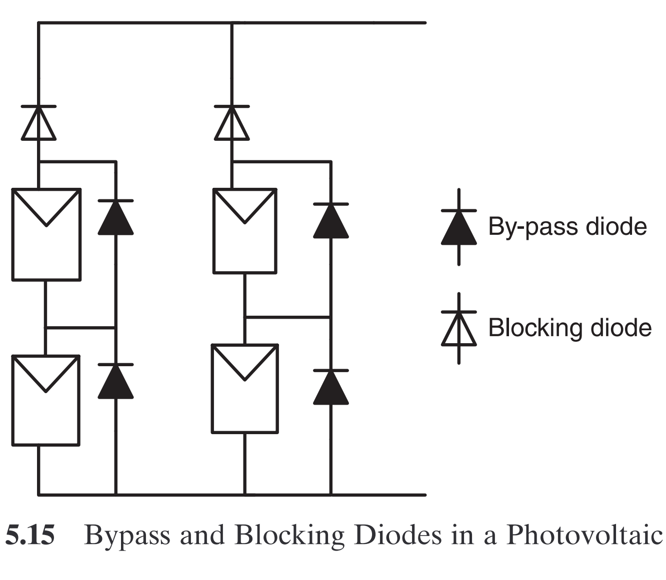


Figure 5.15 Bypass and Blocking Diodes in a Photovoltaic Array.

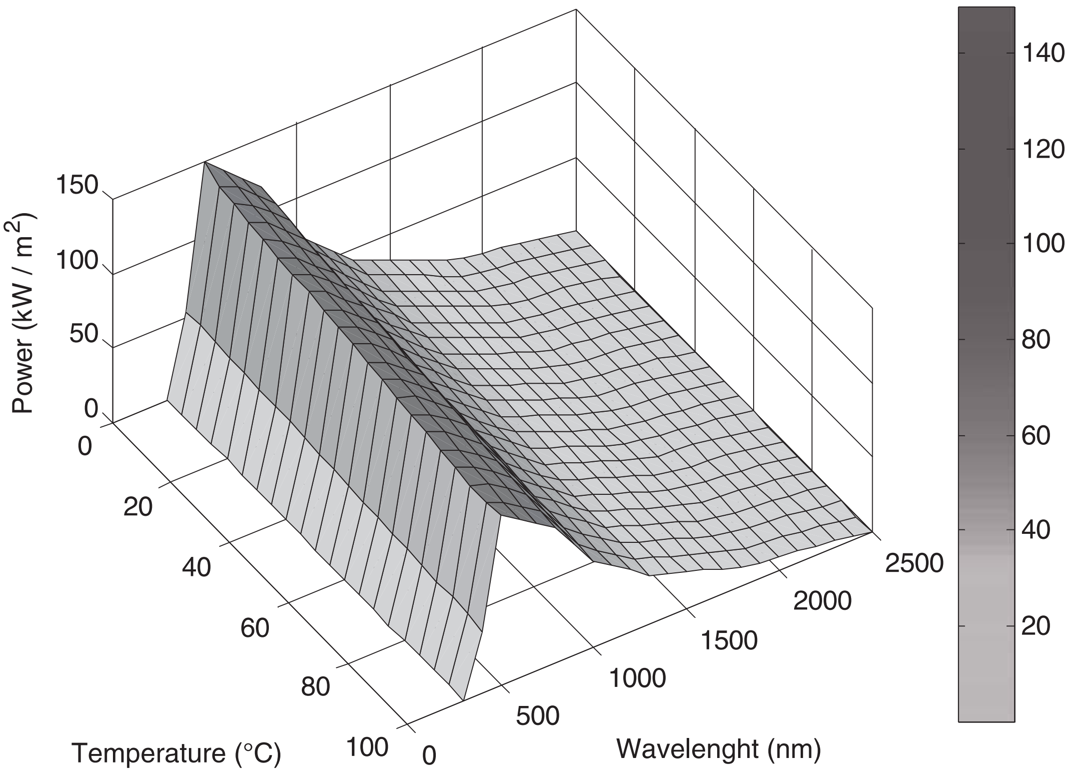


Figure 5.16 Spectra for Photovoltaic Performance Evaluation.[12,15]

photovoltaic modules convert the radiation energy to electrical energy. The amount of energy produced by the PV module is directly proportional to the area of the module. The kW/m^2 /nm of the PV module is plotted as a function of wavelength and estimated temperature from the solar spectrum. The above curve is plotted with an air mass of 1.5.

The PV modules are tested under a nominal temperature (NT). The NT is used to estimate the cell temperature based on the ambient temperature as shown below.

$$T_c = T_a + \left(\frac{NT - 20}{Kc}\right) \cdot S \tag{5.7}$$

The cell temperature, T_c and the ambient temperature, T_a are in degrees centigrade. The operating nominal temperature, NT designates the cell temperature as tested by manufacturers; S is the solar insolation (kW/m^2). Kc is a constant empirically computed from test data; it is in the range of 0.7 to 0.8.

5.7 THE DESIGN OF PHOTOVOLTAIC SYSTEMS

The design of engineering systems is based on trial and error. Nevertheless, the design must demonstrate a clear understanding of the scientific and engineering principles behind the proposed design. In this sense, "trial and error" is for fine-tuning the final design. However, all engineering systems must be based on the underlying physical process.

In concrete terms, if we are designing a PV-generating system, we are using manufactured PV modules that have certain characteristics. However, in defining the overall objective of the PV systems we are putting into place, then some PV modules may satisfy those objectives and some may not. Therefore, we need to test available PV modules against our design specifications.

For a PV-generating system, the first specification is the power requirement in kW or MW that we intend to produce. If the PV system is to operate as an independent power generating station, the rated load voltage is specified. For example, for a residential PV system, we may install from a few kilowatts of power to serve the residential loads at a nominal voltage of 120 V and 207.8 V. If the residential PV is connected to the local utility, then the interconnection voltage must be specified for the design of such a system. Other design restrictions may also apply to a particular design. Again, consider the case of designing a residential PV system. We already know that a PV module generates a DC voltage source and DC power. How high a DC voltage is safe in a residential system is determined by the electric codes of a particular locality. In principle, we may want to design the residential PV system at a lower DC voltage and higher PV DC voltage for more-involved power systems at commercial and industrial sites. Another design consideration for residential users may be the weight and surface area needed for a PV system. Finally, it is understood that the PV designer always seeks to design a PV system to satisfy site constraints at the lowest installed and operating costs.

Table 5.4 defines a few terms that we have discussed in this chapter. We will use these terms to introduce the design of PV systems.

We know that all PV-generating stations are designed based on connecting PV modules to generate the required power (the terms PV module and PV panel are used interchangeably). One PV module has a limited power rating; therefore, to design a higher power rating, we construct a string by connecting a number of PV modules in series.

$$SV = NM \times V_{OC} \tag{5.8}$$

where SV defines, the string voltage and V_{oc} is the open circuit voltage of a module.

As an example, if the number of modules is five and the open-circuit voltage of the module is 50 V, we have:

$$SV = 5 \times 50 = 250\ V \text{ DC}$$

This may be a high voltage in a residential PV system. We can think of a PV cell, a module, or an array as a charged capacitor. The amount of charge of a

TABLE 5.4 Photovoltaic Design Terms.

Terms	Abbreviations	Descriptions
String voltage	SV	String voltage for series-connected modules
Power of a module	PM	Power produced by a module
String power	SP	Power that can be generated in one string
Number of strings	NS	Number of strings per array
Number of arrays	NA	Number of arrays in a design
Surface area of a module	SM	Surface area of a module
Total surface area	TS	Total surface area
Array power	AP	Array power is generated by connecting a number of strings in parallel
Number of modules	NM	Number of modules per string
Total number of modules	TNM	Total number of modules in all arrays put together
Array voltage for maximum power point tracking	V_{AMPP}	The operating voltage for maximum power point tracking of an array
Array current for maximum power point tracking	I_{AMPP}	The operating current for maximum power point tracking of an array
Array maximum power point	P_{AMPP}	The maximum operating power of an array
Number of converters	NC	Total number of DC/DC converters
Number of rectifiers	NR	Total number of AC/DC rectifiers
Number of inverters	NI	Total number of inverters

PV system is a function of sun irradiance. At full sun, the highest amount of charge is stored that will generate the highest open-circuit voltage for a PV system. In general, the open-circuit voltage of a PV panel for a residential system might be set at a voltage lower than 250 V DC. The rated open-circuit voltage is governed by local electric codes. In general, the open-circuit string voltage is less than 600 V DC for a commercial and industrial system at this time. However, higher DC voltage designs of PV systems are considered for higher power PV sites.

The string power, *SP*, is the power that can be produced by one string.

$$SP = NM \times PM \tag{5.9}$$

where *NM* is the number of modules and *PM* is the power produced by a module.

For example, if a design uses four PV modules, each rated 50 W, then the total power produced by the string is given as

$$SP = 4 \times 50 = 200 \text{ W}$$

As we discussed, for producing higher rated power from a PV-generating station, we can increase the string voltage. In addition, we can connect a number of strings in parallel and create an array. Therefore, the array power, AP is equal the number of string times the string power.

$$AP = NS \times SP \tag{5.10}$$

If the number of strings is 10 and each string is producing 200 W, we have:

$$AP = 10 \times 200 = 2000 \text{ W}$$

The DC power produced by an array is the function of the sun's position and irradiance energy received by the array. An array can be located on roofs or free-standing structures. The array power is processed by a converter to extract maximum power from the sun's irradiance energy. Because the transfer of DC power over a cable at low voltages results in high power losses, the array power is either converted to AC power by using a DC/AC inverter or in some applications, the array power is converted to a higher DC voltage power to produce higher AC voltage and to process higher rated power.

To obtain the maximum power out of an array, the maximum power point (MPP) tracking method is used. The MPP tracking method locates the point on the trajectory of power produced by an array where the array voltage and array current are at its maximum point and the maximum power output for the array.

The array MPP is defined as

$$P_{MPP} = V_{AMPP} \times I_{AMPP} \tag{5.11}$$

where V_{AMPP} is the array voltage at MPP tracking and I_{AMPP} is the array current at its maximum power point tracking (MPPT).

An array is connected to either an inverter or a boost converter and the control system operates the array at its MPP tracking.

The final design of a PV system is based on the MPP operation of a PV array generating station. Keeping in mind, however, the converter control system is designed to locate the maximum operating point based on generated array voltage and array current, thus accommodating the changing irradiance energy received by an array as the sun's position changes during the day.

The inverter output voltage is controlled by controlling the inverter amplitude modulation index. To process the maximum power by an inverter, the amplitude modulation index, M_a should be set at maximum value without producing the unwanted harmonic distortion. The value of M_a is set less than one and in the range of 0.95 to produce the highest AC output voltage.

Example 5.1 Design a PV system to process 10 kW of power at 230 V, 60 Hz single-phase AC. Determine the following:

i) Number of modules in a string and number of strings in an array
ii) Inverter specification and one-line diagram

The PV module data is given below.

Solution
The load voltage is specified as 230 V single-phase AC. To acquire maximum power from the PV array, we select a modulation index of $M_a = 0.9$. The inverter input voltage is given by

$$V_{idc} = \frac{\sqrt{2}V_{ac}}{M_a}$$

$$V_{idc} = \frac{\sqrt{2} \times 230}{0.9} = 361.4\ V \tag{5.12}$$

The inverter is designed to operate at the MPPT of PV array. Therefore, the number of modules to be connected in series in a string is given by

$$NM = \frac{V_{idc}}{V_{MPP}} \tag{5.13}$$

where V_{MPP} is the voltage at the MPP of PV of the module.

$$NM = \frac{361.4}{50.6} \approx 7$$

The string voltage is given as

$$SV = NM \times V_{MPP} \tag{5.14}$$

Using this module, string voltage (see Table 5.5) for this design is

$$SV = 7 \times 50.6 = 354.2\ V$$

i) The power generated by one string is given by:

$$SP = NM \times P_{MPP}$$

where P_{MPP} is the nominal power generated at the MPP tracking.

TABLE 5.5 The Voltage and Current Characteristics of a Typical Photovoltaic Module.

Power (max)	300 W
Maximum voltage, P_{MPP}	
Voltage at maximum power point (MPP), V_{MPP}	50.6 V
Current at MPP, I_{MPP}	5.9 A
V_{oc} (open-circuit voltage)	63.2 V
I_{sc} (short-circuit current)	6.5 A

TABLE 5.6 Photovoltaic Specifications for 10 kW Generation.

Modules per String	Strings per Array	Number of Arrays	String Voltage (V)
7	5	1	354.2

The power generated by a string for this design is given as

$$\text{kW per string} = 7 \times 300 = 2100\ W$$

To calculate the number of strings for a 10 kW PV system, we divide the PV power rating by power per string

$$NS = \frac{AP}{SP} \tag{5.15}$$

where NS is the number of strings and AP is the array power and SP is the string power. For this design we have:

$$NS = \frac{10 \times 10^3}{2100} = 5$$

Therefore, we have five strings and one array to generate 10 kW of power.

ii) In the final design, the inverter should be rated such that it is able to process generation of 10 kW and supply the load at 230 V AC from its array at its MPPT. Based on the PV module of Table 5.5, the string voltage is specified as

$$V_{idc} = 354.2\ V$$

TABLE 5.7 Inverter Specifications.

Input Voltage V_{idc} (V)	Power Rating (kW)	Output Voltage, V_{AC} (V)	Amplitude Modulation Index, M_a	Frequency Modulation Index, M_f
354.2	10	230	0.92	100

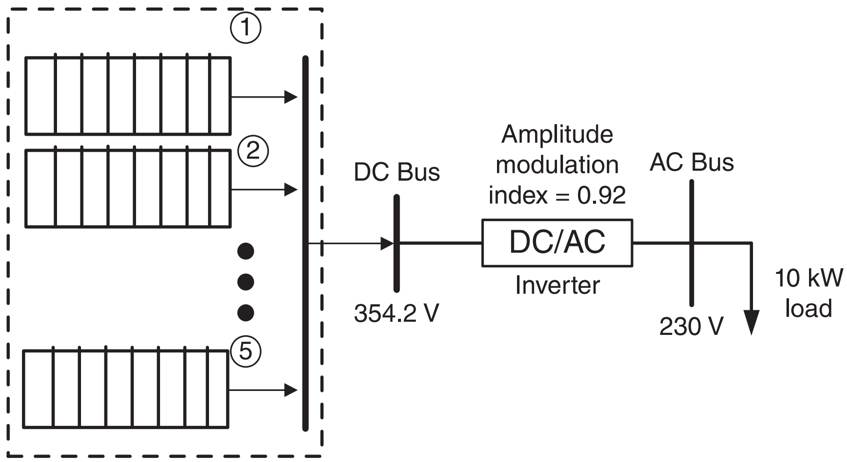


Figure 5.17 The One-Line Diagram of Example 5.1.

and the modulation index is given as follows:

$$M_a = \frac{\sqrt{2}V_{ac}}{V_{idc}}$$

$$\mathrm{M_a} = \frac{\sqrt{2} \times 230}{354.2} = 0.92$$

Let us select a switching frequency of 6 kHz. Therefore, the frequency modulation index is given by

$$M_f = \frac{f_S}{f_e} = \frac{6000}{60} = 100$$

The one-line diagram is given in Fig. 5.17.

Example 5.2 Design a PV system to process 500 kW of power at 460 V, 60 Hz, three-phase AC, and using PV data of Example 5.1. Determine the following:

i) Number of modules in a string and number of strings in an array
ii) Inverter and boost specification
iii) The output voltage as a function and total harmonic distortion
iv) The one-line diagram of this system

Solution
The load is 500 kW rated at 460 V AC. Based on the voltage of the load and an amplitude modulation index of 0.9, we have the following input DC voltage for a three-phase inverter:

$$V_{idc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}M_a} = \frac{2\sqrt{2}\times 460}{\sqrt{3}\times 0.9} = 835\,V \tag{5.16}$$

We will limit the maximum string voltage to 600 V DC. Therefore, we can use a boost converter to boost the string voltage to 835 V.

If we select an approximate string voltage of 550 V, we have:

i) The number of modules in a string is given by

$$\frac{V_{string}}{V_{MPP}} = \frac{550}{50.6} \approx 11$$

where V_{MPP} is the voltage of a module at MPPT.

The string power, SP can be computed as

$$SP = NM \times P_{MPP}$$

Using a module rated at 300 W, we have:

$$SP = 11 \times 300 = 3300\,W$$

The string voltage is given as:

$$SV = NM \times V_{MPP}$$

Therefore, the string voltage, SV, for this design is

$$SV = 11 \times 50.6 = 556.6\,V$$

TABLE 5.8 Photovoltaic Specifications.

Modules per String	Strings per Array	Number of Arrays	String Voltage (V)
11	6	25	556.6

If we design each array to generate a power of 20 kW, then the number of strings, NS, in an array is given by:

$$NS = \frac{power\ of\ one\ array}{power\ of\ one\ string}$$

$$NS = \frac{20}{3.3} = 6$$

The number of array, NA, for total power generation is

$$NA = \frac{PV\ generation}{power\ of\ one\ array} \tag{5.17}$$

Therefore, $NA = \frac{500 \cdot kW}{20 \cdot kW} = 25$

ii) The inverters should be rated to withstand the output voltage of a boost converter and should be able to supply the required power. The inverter is rated at 100 kW with input voltage of 835 V DC and the amplitude modulation index of 0.9. The output voltage of inverter is 460 V AC.

The number of inverters, NI, needed to process a generation of 500 kW is given by

$$NI = \frac{PV\ generation}{power\ of\ one\ inverter} \tag{5.18}$$

Therefore, $NI = \frac{500}{100} = 5$

Hence, we need to connect five inverters in parallel to supply the load of 500 kW, if a switching frequency is set at 5.04 kHz.

Therefore, the frequency modulation index, M_f, is given by

$$M_f = \frac{f_S}{f_e} = \frac{5040}{60} = 84$$

TABLE 5.9 Inverter Specifications.

Number of Inverters	Input Voltage V_{idc} (V)	Power Rating (kW)	Output Voltage, V_{AC} (V)	Amplitude Modulation Index, M_a	Frequency Modulation Index, M_f
5	835	100	460	0.90	84

TABLE 5.10 Boost Converter Specifications for a Generation of 500 kW.

Number of Boost Converters	Input Voltage, V_i (V)	Power Rating (kW)	Output Voltage, V_o (V)	Duty Ratio, D
25	556.6	20	835	0.33

TABLE 5.11 Harmonic Content of Line-to-Neutral Voltage Relative to the Fundamental.

3rd Harmonic	5th Harmonic	7th Harmonic	9th Harmonic
0.01%	0.02%	0	0.03%

The number of boost converters needed is the same as the number of arrays, which is 25, and the power rating of each boost converter is 20 kW.

The boost converter input voltage is equal to the string voltage:

$$V_i = 556.6\ V$$

The output voltage of the boost converter is equal to the inverter input voltage:

$$V_{idc} = V_o = 835\ V$$

The duty ratio of the boost converter is given by

$$D = 1 - \frac{V_i}{V_o}$$

$$D = 1 - \frac{556.6}{835} = 0.33$$

iii) With a frequency modulation of 84, the harmonic content of the output voltage was computed from a simulation testbed using a fast Fourier method; it is tabulated below.

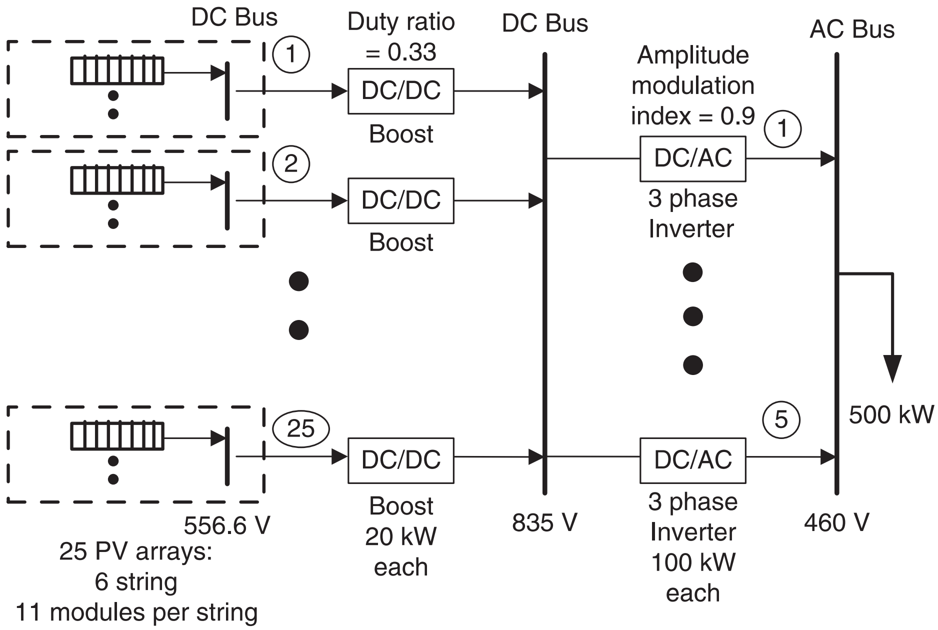


Figure 5.18 The One-Line Diagram of Example 5.2.

The output line-to-neutral voltage as a function of time is

$$
\begin{aligned}
V_{ac} &= \frac{460\sqrt{2}}{\sqrt{3}} \cdot \sin(2\pi 60 \cdot t) + \frac{0.01}{100} \times \frac{460\sqrt{2}}{\sqrt{3}} \cdot \sin(2\pi \times 3 \times 60 \cdot t) \\
&\quad + \frac{0.02}{100} \times \frac{460\sqrt{2}}{\sqrt{3}} \cdot \sin(2\pi \times 5 \times 60 \cdot t) + \frac{0}{100} \times \frac{460\sqrt{2}}{\sqrt{3}} \cdot \sin(2\pi \times 7 \times 60 \cdot t) \\
&\quad + \frac{0.03}{100} \times \frac{460\sqrt{2}}{\sqrt{3}} \cdot \sin(2\pi \times 9 \times 60 \cdot t) \\
&= 376 \sin(2\pi 60 \cdot t) + 0.037 \sin(6\pi 60 \cdot t) + 0.075 \sin(10\pi 60 \cdot t) \\
&\quad + 0.113 \sin(18\pi 60 \cdot t)
\end{aligned}
$$

The total harmonic distortion is given by

$$THD = \sqrt{\sum (\%harmonic)^2} = \sqrt{0.01^2 + 0.02^2 + 0^2 + 0.03^2} = 0.04\%$$

iv) The one-line diagram is given in Fig. 5.18

Example 5.3 Design a PV system to process 1000 kW of power at 460 V, 60 Hz three-phase AC using the PV data given in Table 5.12. Determine the following:

i) Number of modules in a string, number of strings in an array, number of arrays, surface area for PV, weight of PV, and cost