18

Photovoltaic Cells and Systems

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18.1 Introduction

The ability of certain materials to convert sunlight to electricity was first discovered by Becquerel in 1839, when he discovered the photogalvanic effect. A number of other significant discoveries ultimately paved the way for the fabrication of the first solar cell in 1954 by Chapin, Fuller, and Pearson [1]. This cell had a conversion efficiency of 6%. Within 4 years, solar cells were used on the Vanguard I orbiting satellite. The high cost of boosting a payload into space readily justified the use of these cells, even though they were quite expensive.

Space applications eventually led to improved production efficiencies, higher conversion efficiencies, higher reliability, and lower cost for photovoltaic (PV) cells. By the 1980s, PV cells had been introduced to terrestrial applications where conventional electrical sources were expensive, and by the turn of the millennium, PV cells have become cost-effective in a wide range of utility interactive and stand-alone applications. Conversion efficiencies at the turn of the millennium for large-scale PV modules ranged from just under 10% for thin-film modules to over 30% for gallium arsenide (GaAs) concentrating cells.

This chapter presents a thumbnail sketch of the basic theory of solar cells and then focuses on several examples of PV applications in utility interactive systems and stand-alone systems. Each type of system generally requires a power electronics interface unit to enable the PV system to transfer solar electricity optimally to the desired load or storage system. The intent of this chapter is to present the *what* of PV systems. For the *why* and *how* of PV systems, the reader is referred to the references at the end of the chapter that provide detailed examples of specific PV system designs [1–3].

18.2 Solar Cell Fundamentals

Conversion of Sunlight to Electricity

To date, the most popular materials for direct conversion of sunlight to electricity have been crystalline silicon (Si), amorphous silicon (a-SiH), copper indium diselenide (CIS), cadmium telluride (CdTe), and gallium arsenide (GaAs). All of these semiconductor materials have band-gap energies between 1 and 2 eV. The band gap of a semiconductor is the energy required to excite an electron from the valence band to

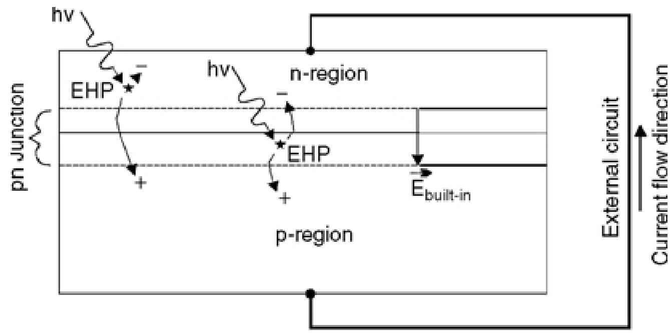

FIGURE 18.1 Effect of sunlight incident on the PV cell.

the conduction band of the semiconductor. Transferring the negative electron to the conduction band creates a positive hole in the valence band. Both charge carriers are then available for electrical conduction. Sunlight is a very convenient source of energy for creation of these electron–hole pairs (EHPs), since most of the energy in the solar spectrum is at levels higher than the band-gap energies of PV materials.

Once the EHP has been produced by an incident photon, the electron and hole must flow in opposite directions. Separation of electron and hole can be achieved by using a *pn*-junction. A *pn*-junction is composed of material that is rich in electrons on one side (the *n*-side) and rich in holes on the other side (the *p*-side). The *pn*-junction produces a built-in electric field, directed from the *n*-side to the *p*-side, that separates the photon-generated EHPs. The electrons are forced to the *n*-side and the holes are forced to the *p*-side by the junction electric field as long as the EHP is produced within or close to the *pn*-junction. If the EHP is generated too far from the junction, the electron and hole will recombine before they can be separated by the junction electric field.

Figure 18.1 shows photons ($h\nu$) entering a typical PV cell. Some of the photons will create EHPs close to the surface, some will create EHPs near or within the junction region, and some will penetrate beyond the junction. Generally, the highest-energy photons produce EHPs close to the surface, whereas the lowest-energy photons penetrate the deepest. This process of liberating an EHP results in the conversion of part of the energy of the incident photon to electricity. Any leftover energy is converted to heat.

If the EHP is produced near or within the *pn*-junction, the electron is swept into the *n*-region and the hole is swept into the *p*-region. The electrons (−) then diffuse toward the top of the cell and the holes (+) diffuse toward the bottom of the cell.

As the electrons reach the top surface, where there is a contact to an external circuit, they continue to flow into the external circuit. As the holes reach the bottom surface, where there is another contact to the external circuit, they recombine with electrons flowing in from the external circuit. For each electron that leaves the top, another enters the bottom. This completes the circuit, with electron flow in the external circuit and the flow of both electrons and holes within the PV cell. The challenge in the design of the PV cell is to absorb all incident photons close enough to the *pn*-junction so all electrons and holes generated will be collected. A further challenge in cell design is to minimize conversion of sunlight to heat and maximize conversion to electricity.

Because of the *pn*-junction, a voltage appears between the bottom and the top of the cell. This voltage is what forces the current through the external circuit. Depending upon the cell material, the voltage developed by the cell may range from very small up to about 1 V. Thus, to produce higher voltages, the cells must be connected in series. When cells are connected together, normally they are incorporated into PV *modules*, which often combine as many as 40 cells in series to produce voltages in the range of 20 V and currents of several amperes.

When voltages and currents beyond the capability of an individual module are desired, the modules can be connected into *arrays* that will produce higher voltages and higher currents. Although most cells produce only a few watts, and most modules produce 10 to 300 W, most arrays produce a few thousand watts. A few very large systems have been deployed that produce power in the megawatt range.

An important feature of all modern PV cells is that, over their lifetimes, they can produce up to ten times as much energy as was used in their fabrication and deployment.

Cell Performance

The ideal solar cell operates as a diode when in the dark, and operates almost as an ideal current source when operated under short-circuit conditions. The short-circuit current of the cell is close to directly proportional to the intensity of the sunlight incident on the cell. The current source nature of the cell means that if cells are connected in series to increase their overall voltage, the cells must be closely matched so each cell produces identical current under identical illumination conditions. If this is not the case, the voltage of the series combination will not be optimized. The *I–V* relationship for the ideal PV cell is given by

$$I = I_l - I_o(e^{qV/kT} - 1) \tag{18.1}$$

where I_l is the photon-generated current component, I_o is the cell reverse saturation current, and $kT/q = 25.7$ mV at a temperature of 25°C. More specifically, the photocurrent is related to sunlight intensity by the relationship:

$$I_l = I_l(G_o)\frac{G}{G_o} \tag{18.2}$$

where G is the sunlight intensity in W/m^2 and $G_o = 1000$ W/m^2. Note also from Eq. (18.1) that I_l is the short-circuit current of the PV cell, I_{SC}.

Figure 18.2a shows typical PV cell *I–V* characteristics as a function of incident sunlight, and Fig. 18.2b shows the temperature dependence of the output power of a cell. Note that as the temperature rises, the open circuit voltage of the cell, V_{OC}, decreases. For Si cells, the rate of decrease is 2.3 mV/°C/cell. Thus, a 36-cell module operating 25°C above ambient will lose $36 \times 2.3 \times 25 = 2070$ mV = 2.07 V. This is nearly a 10% loss in output voltage, which, when coupled with approximately temperature-independent current, results in a 10% power loss.

The departure of the *I–V* characteristic of a real cell from that of a perfect cell is measured by the *fill factor* (FF) of the cell. The assumption is that a perfect cell would have a rectangular characteristic, with

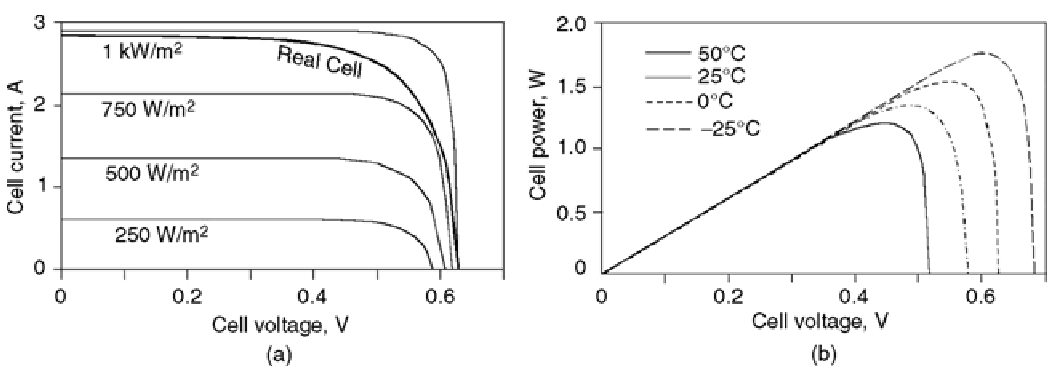

FIGURE 18.2 Dependence of PV cell characteristics on sunlight intensity and temperature. (a) Real and ideal PV cell *I–V* vs. sunlight intensity; (b) cell output power vs. cell temperature.

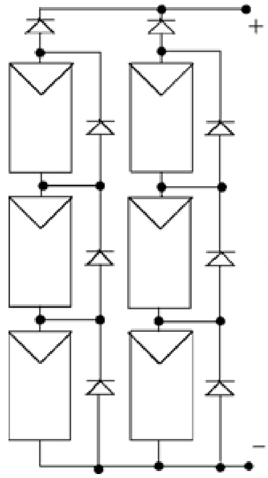

FIGURE 18.3 PV array showing modules with bypass and blocking diodes.

constant current up to the maximum cell voltage, and then constant voltage. The constant current would be the short-circuit current and the constant voltage would be the open-circuit voltage. The fill factor is thus defined as

$$FF = \frac{P_{max}}{I_{SC}V_{OC}} \tag{18.3}$$

Since the current produced by a cell depends upon the total power incident upon the cell, if a cell is shaded even partially, it will not produce the same current as unshaded cells. At a certain point of shading, the polarity of the cell voltage reverses to enable the cell to carry the current generated by the unshaded cells in the module. When this happens, the cell dissipates power, and can overheat to the point of cell degradation. To protect the module against cell degradation, bypass diodes are normally incorporated into the module design to shunt current away from shaded cells, as shown in Fig. 18.3.

If the voltage of a module drops below the voltage of other modules connected in parallel, it is possible for the current produced by the higher-voltage modules to flow in the reverse direction of the lower-voltage module. To prevent reverse flow of current through a module, a blocking diode is sometimes used in series with the module, as shown in Fig. 18.3.

18.3 Utility Interactive PV Applications

Perhaps the simplest PV application, except for connecting the PV array output directly to the load, is the utility interactive (UI) system. In a simple UI system, the PV array output is connected to the input of a DC-to-AC inverter, known as a power conditioning unit (PCU), the output of which is connected directly to the utility. When battery storage and alternative generation means are incorporated in the UI system, however, the system is no longer quite as simple. In either case, the PCU must be designed to meet a wide range of utility concerns. If the heart of the UI PV system is the PV array, then the PCU may be considered to be the brains of the system.

The PCU

Although the basic UI PV system is quite straightforward, the PCU is a very sophisticated piece of power electronics equipment. The PCU must meet the stringent design requirements of IEEE Standard 929 [4] and the stringent performance requirements of UL 1741 [5].

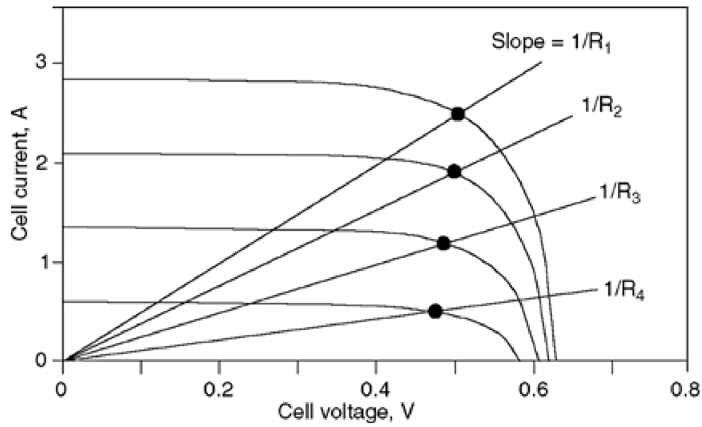

FIGURE 18.4 Cell *I–V* showing maximum power points and associated resistances.

Since PV arrays are still relatively costly, it is important for the PCU to extract maximum power from the array. This is done by incorporating maximum power-tracking circuitry into the PCU. Figure 18.4 shows the *I–V* characteristics of an array with the maximum power points indicated for each level of sunlight. The design challenge for the PCU is to vary the PCU input resistance, defined as the ratio of input voltage to input current, while sampling the PCU output power. When the PCU output power reaches a maximum level, the input resistance is fixed at the value that produces this level. Presumably when output power is a maximum, input power is also at a maximum, provided that PCU conversion losses remain at a constant percentage of the output power. The effective input resistance of the PCU can be varied by the use of a buck–boost DC-DC converter.

Nearly all modern PCUs use a pulse code modulation (PCM) scheme for generating an output waveform of appropriate amplitude and frequency. The PCU is generally designed to perform as a current source when it is connected to the utility, so the utility voltage can be used as a synchronization signal for PCU output frequency control. As long as the utility voltage is present at the proper amplitude and frequency, the PCU supplies power to the grid. However, if the utility voltage or frequency drifts outside prescribed limits for too long, the PCU is programmed to shut down its output to the utility. Although output is shut down, the PCU continues to monitor the utility voltage. The PCU reconnects to the utility after the PCU senses that the utility has remained within amplitude and frequency limits for a predetermined time.

IEEE 1741 prescribes limits for PCU output harmonics and general PCU power quality. It also requires the PCU to shut down under utility islanding conditions. Islanding occurs when the utility shuts down, leaving the PV source along with other PV sources connected to the disabled utility line. The trick here is for every UI PCU to be able to recognize that the presence of power on the utility line from other PCUs is not the same as power on the line from the utility. Several elegant software algorithms have been developed to prevent islanding [6].

The output power range of modern PCUs is from a few hundred watts to 100 kW. These units typically operate with efficiencies in excess of 90% for output powers between 10 and 100% of rated output power. They are capable of maximum power tracking over a wide range of incident sunlight. Many modern PCUs that can be used in a grid-independent mode have a sleep mode. In the sleep mode, the PCU sends out short pulses of AC voltage at regular intervals to sense for connected loads. If current is drawn when the voltage pulse is sent, the PCU recognizes that a load is connected and remains on until the load is no longer sensed. The sleep mode sensitivity is usually adjustable. If the PCU includes battery-charging capability from utility line input, then it normally also incorporates battery protection from overcharge or overdischarge. Additional features may include provision for code-required fusing and disconnects on the DC and AC sides of the PCU. A Web search for PV power conditioning units, or PV inverters, will yield information on a wide range of products. The important consideration in selection of a PCU for grid-connected applications is the UL 1741 listing.

It should also be noted that inverter output waveforms range from square to modified sine to pure sine. The cost of the inverter is generally increased as the quality of output waveform approaches pure sine. In the event that the PCU will operate in a stand-alone mode during utility failure, it is important to consider whether all loads to be supplied by the PCU will operate on the waveform generated by the PCU. For example, an electric igniter on a gas appliance may not operate when connected to a modified sine wave or to a square wave voltage waveform.

Simple UI PV System

Because the output of a UI PV system is connected directly to the electric grid, any excess output will be used by the grid and any deficiency in PV output will be made up by the grid. Hence, the sizing of the simple UI PV system is not necessarily related to the load at the UI PV installation site. The sizing is more likely to be governed either by available space for the array, available funding for the system, or a preference for PCU or modules.

The system shown schematically in Fig. 18.5 consists of matching the input voltage and current requirements of the PCU with the voltage and current output capabilities of the PV array and then connecting to the utility. The connection may be made either on the customer side or the utility side of the revenue meter. It should be noted that Fig. 18.5 is somewhat simplified, since actual installations may require DC and AC disconnect switches, fuses, ground-fault protection, and system grounding per the requirements of the National Electrical Code® (NEC) [7]. Wire size and insulation type are also specified by the NEC. Additional requirements may be placed upon the system by the local utility, local electrical inspector, or local fire inspector. All of these potential sources of system requirements should be consulted prior to any installation.

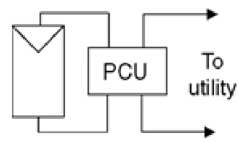

FIGURE 18.5 Simple UI PV system.

The PV output circuit is that part of the PV system that connects the PV array to the PCU. The NEC imposes a number of requirements on this DC circuit, including fusing, disconnects, and, in some cases, ground-fault protection, all of which add to the installation cost.

The desire to eliminate the PV output circuit has led to the development of the AC module. By mounting the PCU on the DC PV module, the PCU becomes a part of the module, so there is no PV output circuit—only the PCU output circuit. Since there is no particular economy of scale for PCUs, a popular match is between a 300 W module and a 300 W PCU, resulting in a 300 W AC module. When used in the United States, the AC module must meet all the requirements of IEEE 929 and UL 1741.

Although IEEE 929, UL 1741, and the NEC have solved the technical considerations for a UI PV installation, additional redundant requirements are still imposed in many jurisdictions. For example, at the time of this writing, one investor-owned utility requires the owner of a UI PV system to carry $1 million in liability insurance and to install an isolation transformer between the PV system and the grid connection.

UI PV System with Battery Backup

Figure 18.6 shows a simplified diagram of one way to configure a system with battery backup to provide for emergency power in the event of grid failure. Required fuses, disconnects, grounding, surge protection, and ground-fault protection are not shown. If a PV system is to provide emergency power in the event of grid failure, then the PV system must be designed to provide power to all designated emergency loads for a length of time required either by the owner or by a regulation. Sizing of the array and battery system will normally follow the procedure used for stand-alone systems. This requires identification of the energy requirements of each emergency load over the anticipated duration of a power outage. Since storage batteries are normally rated in ampere hours (Ah), the energy requirements of the load are normally converted to Ah at the voltage of the storage battery system.

For example, suppose it is determined that 10 kWh of battery storage will operate all the emergency loads over the anticipated duration of the power outage. Suppose also a PCU is chosen that has a nominal 48 VDC input. Dividing 10,000 Wh by 48 V results in a battery capacity of 208 Ah. However, if

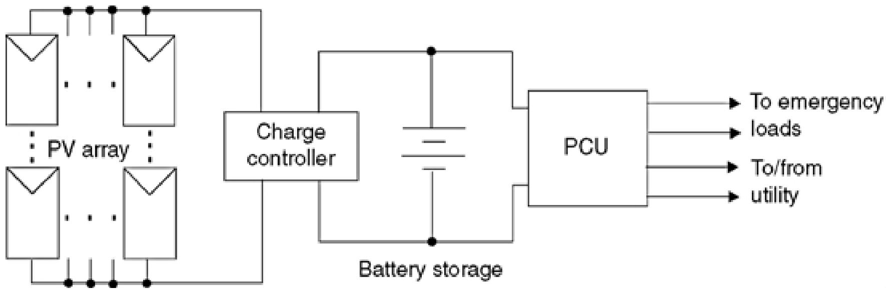

FIGURE 18.6 UI PV system with battery backup and emergency loads.

deep-discharge lead acid batteries are used, the batteries should not be allowed to discharge below 20% of their rated charge. Thus, the battery capacity needs to be 208 ÷ 0.8 = 260 Ah. If a 6-V, 130-Ah deep-discharge battery is available, then the system will require 16 of these batteries to store 260 Ah at 48 V. When batteries are connected in series–parallel combinations, it is important to use connecting cable lengths that will ensure equal charging and discharging rates for all batteries in the system. Furthermore, connecting cables must be fused close to the batteries in accordance with NEC requirements and a disconnect switch must be provided between batteries and PCU.

Sometimes the PCU in a UI system with battery backup will allow for charging of the batteries from the utility connection. In a system of this type, the utility is connected to the emergency loads when the utility is energized. In the event of utility failure, the PCU automatically switches to its battery input and powers the emergency loads from the battery storage, much the same as an uninterruptible power supply used in computer systems. If the utility remains down for a prolonged time, the PV system can be designed to provide the energy required by the emergency loads. This type of system is not UI in the purest sense, since it does not feed back power to the utility if the PV array is providing more power than is needed by the emergency load. Normally, however, the PV array is sized to meet the needs of the emergency loads over a prolonged utility outage. Array sizing will be discussed in Section 18.4.

If the PCU connection to the utility is bidirectional, then the system is interactive, with interesting control possibilities. Normally it would be desirable to size the PV system to meet the entire emergency load, since the emergency loads would then become essentially grid independent. When a significant PV array is incorporated into the system, it is desirable to optimize the utilization of the PV output. The control algorithm would be designed to incorporate utility charging of batteries only if the PV array has not brought the batteries to full charge by the end of daylight hours. In addition, as soon as the array has fully charged the batteries, any excess array output would be directed back to the utility. In many areas, this feeding of the array output to the utility will occur during utility peaking hours, thus increasing the value of the PV-generated electrical power. In fact, with adequate battery storage, the system can be controlled to feed power to the utility *only* during peaking times. During off-peak hours, assuming utility wholesale prices are low, the utility can then be used to charge the batteries with relatively low-cost electricity. Such a control strategy wins for everyone. A leveling effect is provided to the utility by the assist during peak hours and the battery charging during off-peak hours. The system owner experiences full utilization of the PV system output and the overall customer base benefits from incrementally cleaner air and a reduced need for siting of power plants and transmission lines.

18.4 Stand-Alone PV Systems

Systems with No Storage

Probably the simplest stand-alone PV system is the direct connection of array to either a fan or a pump. When enough sunlight is available to start the fan or pump, it starts and continues until insufficient sunlight is available to meet the fan or pump power requirements.

The next step is to incorporate some sort of power electronics into the system to provide a better match between PV system output and load requirements. For example, a small amount of energy storage can assist the PV system in overcoming the starting torque of the fan or pump. A maximum power tracker (MPT), as described earlier, can ensure that the PV output is matched to the load resistance. Providing an MPT allows a system with a fixed fan or pump size to provide maximum water or airflow for a given array size. Without the MPT, a larger array size will be needed to achieve the same performance from the fan or pump. Sizing of such a system involves the determination of minimum operating parameters for the pump or fan and then choosing the combination of array and MPT to meet these conditions.

Systems with Storage

If a system is to operate on cloudy days or after sundown, a means of energy storage will be required. Although exotic means such as fuel cells or hydrogen storage are possible, the most common storage means at the time of this writing is still the lead acid storage battery. For PV energy storage applications, the deep-discharge variety of lead acid battery is used, as opposed to the automotive type that provides high current for short time periods. Examples of systems that require storage include lighting systems, highway information and warning signs, cathodic protection systems, refrigeration systems, communication systems, and remote dwellings. If the grid connection is eliminated, the system shown in Fig. 18.6 is representative of a stand-alone system with battery storage. If the system has only DC loads, then the PCU is replaced with a discharge controller to disconnect the loads if the battery state of charge drops too low.

If the utility connection in Fig. 18.6 is replaced with an auxiliary fossil fuel or wind generator, the system then becomes a hybrid system, where an auxiliary power source is made available to augment the PV power. Hybrid systems are most cost-effective when the PV array must be sized to meet the demands of low sun periods with resulting significant excess PV energy during high sun periods. For example, in Fairbanks, AK, a one-axis tracking array that follows the sun from sunrise to sunset will be exposed to the equivalent of nearly 9 h of full sun in May, but will receive no sun at all in December. An alternative power source must then be provided for the winter months, unless no load is present.

Design of a system with storage involves determining the daily or weekly system load in Ah, determining the number of storage days required, determining system losses, determining the battery requirements, and determining the array requirements. The design also requires selecting appropriate charge controller, PCU or other power electronic equipment, switches, fuses, wires, and surge protectors.

The *connected* daily Ah load of the stand-alone system is the Ah that must be delivered to the load, including any losses in inversion of DC to AC to provide power to AC loads. Inverter losses are generally assumed to be 10% unless specific inverter (PCU) data indicate different loss values. The *corrected* Ah load of a PV system is the Ah that must be supplied to the batteries to overcome battery losses and wiring losses and still supply the connected load. Battery sizing and array sizing are based upon the corrected load of the system, which is typically about 12% higher than the connected Ah load.

The number of storage days, also known as days of autonomy, is determined by whether the load is considered to be critical or noncritical. Critical loads are defined as loads that are met 99% of the time by the PV system, whereas noncritical loads only require 95% system availability. Hence, critical loads require more days of autonomy, and the days of autonomy depend upon the specific geographic location. For example, in Albuquerque, NM, a critical load requires approximately 7 days of autonomy, whereas a critical load in Seattle, WA, requires approximately 16 days of autonomy. Noncritical loads in Albuquerque require only 2 days of autonomy, but in Seattle require 4 days of autonomy.

System losses can normally be considered to be 10% for battery charging and discharging losses, and 2 to 3% for wiring losses. Battery losses are due to conversion of electrical energy to heat energy while charging or discharging the batteries. In addition, the PV array is generally derated to account for elevated array temperatures and degradation of the array from dust and dirt.

Once the corrected load is known, battery sizing can be accomplished by using

$$\text{Ah} = \left(\frac{\text{Ah}}{\text{day}}\right)\left(\frac{\text{days}}{D_T D_{\text{ch}}(\text{disch})}\right) \tag{18.4}$$

where Ah is the required battery capacity, Ah/day is the system corrected load, days is the number of days of autonomy required, and D_T is a temperature correction factor that varies linearly from unity at 80°F to 0.72 at 32°F. D_{ch} is a discharge correction factor that is unity as long as the batteries discharge at less than the rated discharge rate. For faster discharge rates lasting more than 10 min, D_{ch} is the ratio of the rated discharge rate to the actual discharge rate. Finally, (disch) is the design depth of discharge, normally in the range of 0.5 to 0.8, with 0.8 representing the loss of 80% of rated charge.

Array sizing is also based on the corrected load of the system, since the array must supply the corrected load to the batteries at the selected battery voltage. Array sizing also depends upon any degradation of array output and upon available sunlight. In areas where the array is likely to become dusty or where it is likely to operate more than a few degrees above 25°C, the degradation factor may be as high as 15 to 20%. Sunlight is measured in terms of peak sun hours (PSH). The PSH for a location on a particular day is determined by measuring the daily kWh/m^2 incident upon the array. Monthly expected PSH are tabulated for many locations, based upon measurements over periods of 20 years or more. In addition to the PSH, standard deviations are also available for use when worst-case estimates need to be made. The Florida Solar Energy Center maintains a Web site with links to a wide range of PV information, including sunlight intensity data [8]. When the corrected load, system voltage, degradation factor, and PSH information are available, the array size can be determined from

$$I = \frac{\mathrm{Ah}}{\mathrm{PSH}_{\min} \times \eta} \tag{18.5}$$

where I is the rated array current, Ah is the system corrected load, $\mathrm{PSH}_{\min}$ is the minimum PSH for the PV system site, and η is the array degradation factor. Note that as PSH decreases for the winter months, η increases as the array temperature decreases. It is thus useful to estimate PSH and η for winter and summer and then use the smaller of the two products in Eq. (18.5). Modules are then connected in series to achieve the system design voltage and in parallel to obtain the system design current. System voltages typically are selected in multiples of 12, while system currents depend upon the specific loads.

The PSH for a PV array depends upon the month of the year as well as the tilt of the array. The PSH also depends upon whether the array is a fixed array or a single- or double-axis tracking array. The PSH tables typically list the available PSH for several different tilt angles. For best annual performance, the optimal tilt of a fixed PV array is approximately latitude −10°. If an array is to supply different loads for different seasons, then the array may be tilted to optimize seasonal performance.

After the batteries and array have been selected, the system power electronic components are selected. The charge controller is an important part of the system and can range from relatively simple design to relatively complex design. A simple controller monitors battery voltage and diverts the array current output when the battery voltage reaches the manufacturer's specified full-charge voltage. A better controller also monitors when the batteries are at the design discharge voltage and disconnects the batteries from the load at this point. An even better controller monitors the battery temperature and compensates the array disconnect voltage and the load disconnect voltage for temperature. A further controller improvement employs maximum power tracking to ensure maximum transfer of charge from array to batteries and provides for diversion of the PV output to an alternate load after the batteries are fully charged. Some controllers incorporate most of the features listed, but must be set either for charge control or discharge control. In a stand-alone system with AC loads, the PCU will normally incorporate the discharge protection feature. If no AC loads are present, a separate discharge controller may be needed.

The internal resistance of a battery system introduces a hysteresis effect into the charge and discharge process. When the batteries are charging, the terminal voltage becomes greater than the cell voltage as a result of the additional voltage drop across the internal battery resistance between the terminals and the cells. Hence, if the terminal voltage is sensed, it will drop when the charger is disconnected. This may cause the charger to be reconnected, if the terminal voltage drops below the full-charge value. Because of the hysteresis effect, charge controllers normally are designed to provide a three-stage charging process. Initially, the batteries are charged at constant current. When the batteries reach a predetermined terminal voltage, they are charged at constant voltage until the current drops to a prescribed level. At this point, the charge controller voltage decreases to complete the charging process at a lower current level.

During discharge, the battery terminal voltage is lower than the battery cell voltage, since the current through the battery internal resistance is now in the opposite direction. The discharge control must thus incorporate a means of avoiding oscillation on and off when the battery terminal voltage indicates that the battery is approaching minimum allowable charge.

The PCU in a stand-alone system does not need to comply with IEEE 929 or UL 1741. It thus can range from a relatively simple square wave inverter to a more-sophisticated, microprocessor-controlled PCM inverter that employs amplitude and/or frequency control of the output waveform as well as many other features described earlier in this chapter.

References

1. Markvart, T., Ed., *Solar Electricity,* John Wiley & Sons, Chichester, U.K., 1994.
2. Messenger, R. A. and Ventre, J., *Photovoltaic Systems Engineering,* CRC Press, Boca Raton, FL, 1999.
3. *Stand-Alone Photovoltaic Systems: A Handbook of Recommended Design Practices,* Sandia National Laboratories, Albuquerque, NM, 1995.
4. ANSI/IEEE P929, IEEE Recommended Practice for Utility Interface of Residential and Intermediate Photovoltaic (PV) Systems, IEEE Standards Coordinating Committee 21, Photovoltaics, Draft 10, February 1999.
5. UL 1741: 1999, Standard for Static Inverters and Charge Controllers for Use in Photovoltaic Power Systems, Underwriters Laboratories, Inc., Northbrook, IL, May 1999.
6. Kern, G. A., Bonn, R. H., Ginn, J., and Gonzalez, S., Results of Sandia National Laboratories grid-tied inverter testing, in *Proc. 2nd World Conference and Exhibition on PV Solar Energy Conversion,* Vienna, Austria, July, 1998.
7. *NFPA 70 National Electrical Code, 1999 Edition,* National Fire Protection Association, Quincy, MA, 1998.
8. http://alpha.fsec.ucf.edu/~pv (Florida Solar Energy Center PV home page).