

CHAPTER 8

Inverters



Solar cells in photovoltaic modules produce direct current (DC) electricity. Batteries used in stand-alone PV systems or as backup power in a grid-tie system also produce DC electricity. With very few exceptions, electrical loads in residential and commercial buildings use alternating current (AC) electricity. Inverters are used to convert the DC electricity produced by modules and batteries to usable AC electricity. In this chapter, we take a detailed look at the purpose and operating principles of inverters. The different inverter types and features are covered. A comparison of grid-tie inverters and stand-alone system inverters is presented, and coverage of microinverters is included.

Glossary of Terms

bimodal inverter An inverter type that can operate as either a grid-tie or stand-alone inverter.

grid-tie inverter An inverter type that is connected to, and works in parallel with, the electric utility grid.

microinverter A small inverter that is installed at each PV system module to change the module-produced DC electricity into AC electricity.

power conditioning unit (PCU) Equipment that can perform electrical power processing and control functions, as well as perform as an inverter.

stand-alone inverter An inverter type that is connected to the PV system batteries and operates independently of the PV array and the utility grid.

Objectives

Upon completion of this chapter, the student should be able to

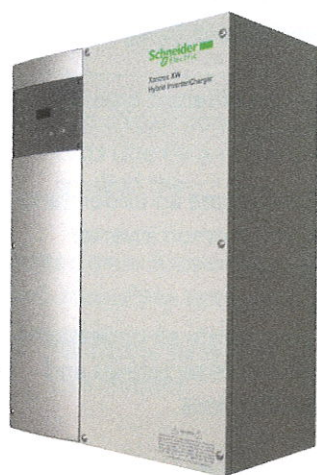
- Demonstrate an understanding of inverter operating principles.
- Identify different types of inverters.
- Demonstrate an understanding of common inverter features.
- Demonstrate an understanding of inverter ratings and specifications.
- Demonstrate an understanding of how to select an inverter.



Courtesy of Schneider Electric

FIGURE 8-1

An example of a grid-tie inverter.



Courtesy of Schneider Electric

FIGURE 8-2

An example of a stand-alone inverter.

Introduction to Inverters

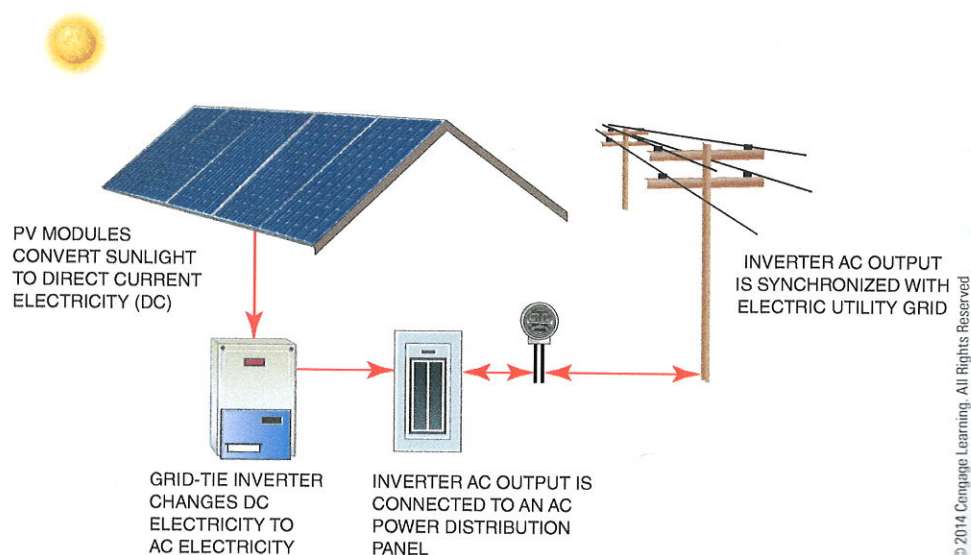
The type of photovoltaic (PV) module most commonly used and discussed in this textbook produces direct current (DC) electricity. Batteries can be used to store the DC electricity produced by PV modules for use when the modules are not exposed to sunlight, such as at night or on dark and stormy days. In a PV system, the primary purpose of an inverter is to change the DC produced by the PV array or supplied from the system batteries to alternating current (AC). PV systems typically have an inverter because almost all electrical loads in buildings operate on AC. Inverters are also used in a PV system to feed AC electricity into the utility electrical grid.

Inverter Categories

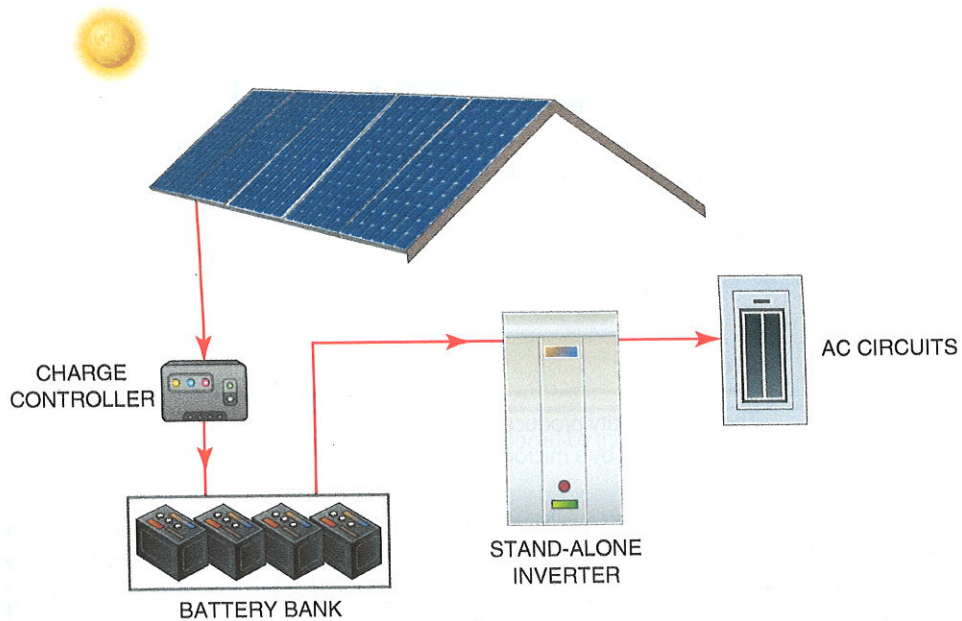
There are two main categories of inverters: the **grid-tie inverter** (Figure 8-1) and the **stand-alone inverter** (Figure 8-2). Some inverters may have both capabilities built in for future utility grid connection and are referred to as a **bimodal inverter**.

A grid-tie inverter, often called a utility-interactive inverter, is designed to be connected to the electric utility grid (Figure 8-3). It converts the DC electricity produced by the PV array into AC electricity with the proper voltage and frequency so that it can be synchronized with, and connected to, the utility power grid, without any problems. This type of inverter reacts to the incoming DC voltage from the PV system array. Because the utility grid also supplies needed electrical power to the AC loads in a building, the AC loads themselves do not affect the performance of a grid-tie inverter.

Stand-alone inverters are connected to the batteries in a stand-alone PV system (Figure 8-4). The battery DC power is converted to AC power by the stand-alone inverter. The PV system array DC power is used to charge the batteries and supply power to any DC loads in a building. Unlike a grid-tie inverter, the performance of a stand-alone inverter is not affected by the PV system array, but it is affected by the AC loads in a building.

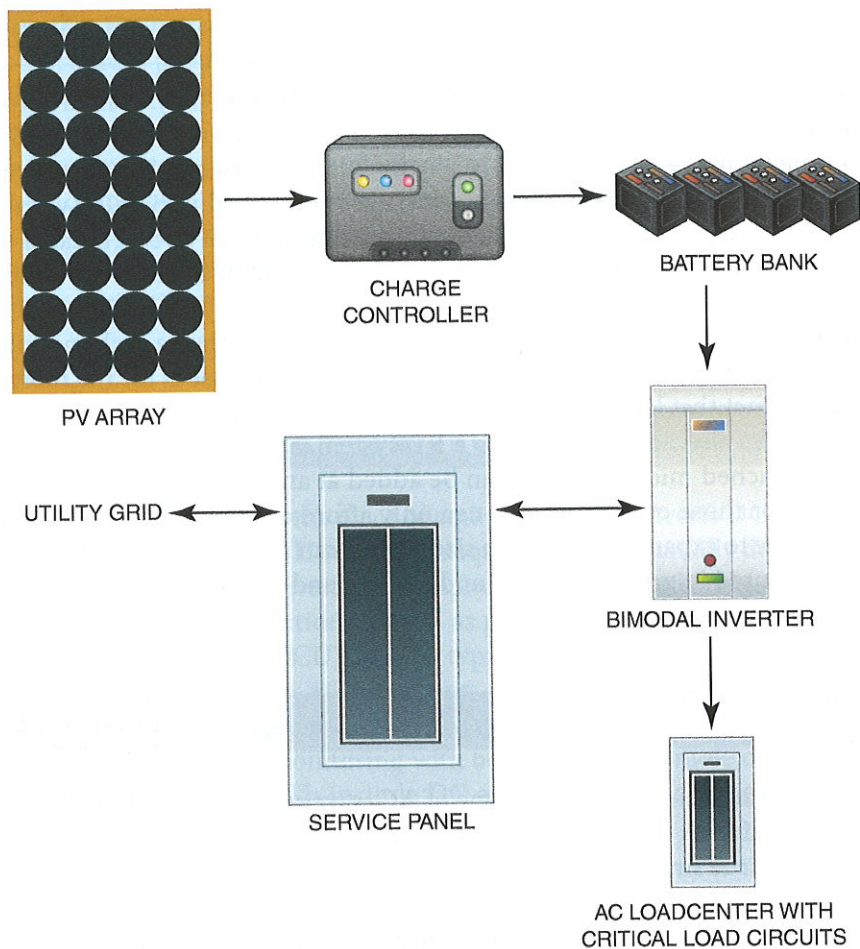
**FIGURE 8-3**

A grid-tie inverter is connected to the electric utility grid in an interactive PV system.

**FIGURE 8-4**

A stand-alone inverter is connected to the batteries in a stand-alone PV system.

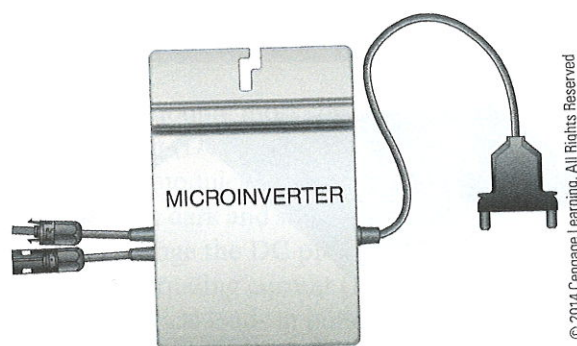
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**FIGURE 8-5**

A bimodal inverter can work as either a grid-tie or stand-alone inverter.

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A bimodal inverter can work as either a grid-tie or stand-alone inverter. However, they cannot work in both modes at the same time. A bimodal inverter is sometimes called a battery-based interactive inverter or a multimode inverter. This inverter type is often used in small PV systems where battery backup is used in a grid-tie system to

**FIGURE 8-6**

The DC electricity produced by a PV module is changed from DC to AC by a microinverter right at the module.

provide backup electrical power to critical loads should the electric utility grid go down (Figure 8-5). In this type of PV system, a subpanel with critical load circuits is fed by the bimodal inverter when the backup battery power is required. In normal operation, the critical load circuits of the subpanel are supplied power by the utility grid.

Microinverters

A relatively new style of inverter is a **microinverter** (Figure 8-6). A microinverter is connected at each PV module in an array. The DC electricity produced by a PV module is changed from DC to AC by the microinverter right at the module. A string of PV modules with microinverters are connected in parallel with each other to form AC circuits. Each AC circuit is connected to a circuit breaker in an electrical panel, allowing the PV array electrical power to be used by the building's electrical system or applied to the electric utility grid.

Microinverters add to the overall cost of a PV array because each module requires its own microinverter. However, the additional expense is for the most part offset by the fact that larger inverters and DC system components are not needed. Microinverters also add flexibility to a PV system, and new strings of PV modules with attached microinverters can be added at any time. This system feature works well for those customers who can only afford a smaller PV system to start but would like to expand their system size as they can afford to. Remember, microinverters are used in grid-tie systems and not in stand-alone systems.

Inverter Waveforms

Inverters also are classified for the type of AC waveform they produce. The three common waveforms that inverters produce are the square wave, modified square wave, and the true sine wave (Figure 8-7).

A square wave inverter is suitable for small resistive heating loads, some small appliances, and incandescent lighting. This type of inverter is relatively inexpensive but has the disadvantage of possibly burning up electric motors in certain equipment.

A modified square wave inverter is suitable for operating a wide variety of loads, including motors, lights, TVs, and other electronic equipment. However, some electronic equipment may pick up inverter noise. One disadvantage is that

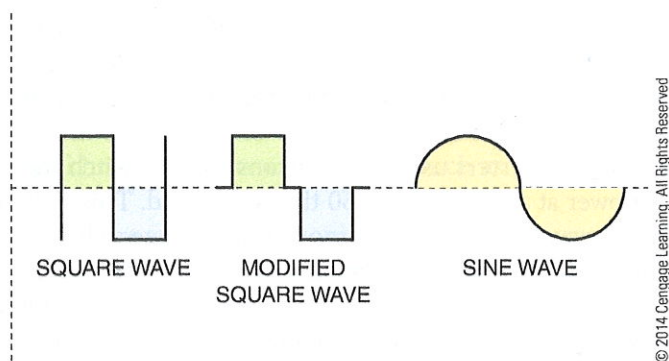


FIGURE 8-7

The three common waveforms produced by inverters.

clocks, appliances, and other equipment that use digital timekeepers will run either fast or slow. Another disadvantage is that you should never charge cordless power tool battery packs on a modified square wave inverter unless you know for sure that the battery charger is designed to work correctly. Many electricians and other trades people have burned up their battery chargers on a construction site when they plugged them into an on-site generator that produces a modified square wave.

A true sine wave inverter is suitable for sensitive electronic equipment. It produces an output with very little distortion. It has high surge capabilities and can feed electricity back into the utility grid with no problems. It is the first choice for inverters if it fits the system budget; it is the only choice if the system you are installing is a grid-tie system.

Power Conditioning Units (PCU)

PV installers usually refer to the piece of equipment that converts DC electricity to AC electricity as an inverter. However, the equipment may actually do more things than make the DC to AC conversion. Equipment that can perform electrical power processing and control functions as well as performing as an inverter is called a **power conditioning unit (PCU)**. A PCU typically offers functions such as rectifying AC to DC, transforming AC voltage up or down, converting one DC voltage level to another DC voltage level (DC-DC converter), and maximum power point tracking (MPPT). System monitoring with both local and remote displays is possible with a PCU. Many PCUs include DC and AC disconnects and overcurrent protection devices.

Inverter Operation

The first inverters were electromechanical devices that were basically motor-generator sets that used a DC electric motor to turn an AC generator (alternator), producing the desired AC output voltage. This type of inverter was

not practical for a PV system because of its low efficiency and large physical size. As a result, solid-state (also called “static”) inverters were developed, and today all inverters used in PV systems are static inverters that use electronic components and circuits to convert DC to AC.

Early solid-state inverters used a basic transistor to switch the polarity of the incoming DC power at approximately 60 times a second. This switching sequence creates a square wave instead of a smooth sine wave. The square-wave AC electricity is then passed through a transformer to step the voltage up to a usable level such as 120 volts or 240 volts. Newer inverters use more sophisticated solid-state circuits. Most of today’s inverters use metal-oxide semiconductor field effect transistors (MOSFETs) or insulated gate bipolar transistors (IGBTs) to produce a true sine wave. There are some lower cost basic inverters that use thyristors called silicon-controlled rectifiers (SCRs).

Common Inverter Features and Specifications

The inverters available today have multiple features and are much more sophisticated than the inverters used in early PV systems. The following paragraphs discuss several of the most common inverter features and specifications that apply to both stand-alone and grid-tie inverters.

Inverter Efficiency

Inverter efficiency has improved over the years, and now many grid-tie inverters are rated up to 95% efficient. High quality stand-alone inverters have peak efficiency of about 90%. The efficiency of an inverter is an indication of how well it converts the incoming DC power to the outgoing AC power. Low-quality inverters that produce a modified sine wave may only have efficiencies of 75% to 85%. When selecting an inverter, always try to have the inverter efficiency be 90% or higher. Inverters should also have low standby losses and a high efficiency when no loads are on.

Frequency Regulation

Inverters should have good frequency regulation so that they maintain a 60 Hz output frequency over a variety of operating conditions. Inverters designed for installation in North America have a 60 Hz output frequency. Those inverters designed for installation in Europe, Asia, and many other parts of the world must be designed to have an output frequency of 50 Hz.

Harmonic Distortion

Harmonics are parts of a waveform that is a multiple of the fundamental waveform frequency. For example, the third harmonic of a fundamental 60 Hz waveform is 180 Hz. Harmonic waveforms tend to distort the fundamental current waveform and are not desirable in the output of an inverter. Total harmonic distortion (THD) is the ratio of the sum of all harmonic parts of a waveform to the fundamental

part of the waveform. THD is expressed as a percentage. For example, a current waveform with a THD of 5% indicates that 5% of the total current is at frequencies higher than the fundamental frequency. Inverters should have low harmonic distortion to smooth out unwanted output peaks on the current sine wave. This minimizes harmful heating effects on AC loads such as motors that are supplied by an inverter.

Grid-tie inverters are specifically required to have low harmonic distortion so that there will be no adverse effects when the inverter is interconnected to the electric utility grid. The Institute of Electrical and Electronic Engineers (IEEE) Standard 519 limits the total harmonic distortion to 5% and any single harmonic to no more than 3%. If these limits are exceeded, the grid-tie inverter must disconnect itself from the grid.

Power Factor Correction

Typical electric utility interconnection agreements require grid-tie inverters to maintain an output power factor between 95% (0.95 PF) leading and 95% (0.95 PF) lagging. Most of today's grid-tie inverters produce an output power factor of 100% (1.0 PF) on a constant basis. The power factor for the output power of stand-alone inverters depends on the connected load. This means that they will only operate at a power factor of 1.0 when the electrical loads are purely resistive. Any time the electrical loads are more inductive or capacitive, the power factor will be less than 100% (1.0 PF).

Size and Weight

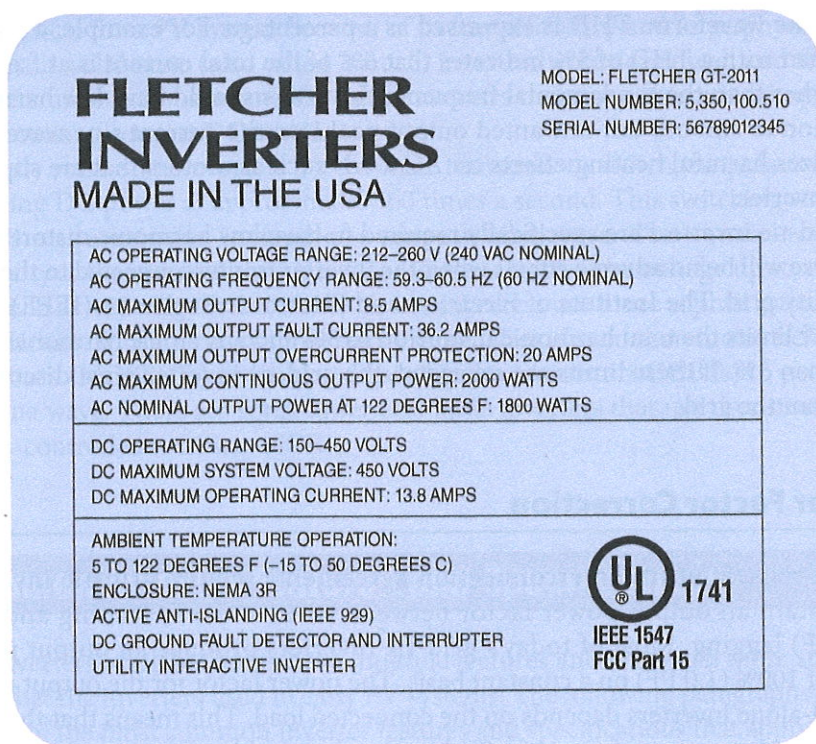
Inverters vary in physical size and weight. Some inverters weigh 200 lbs. or more, especially if they have transformers to step up the voltage. When possible, installers should choose lightweight inverters because they are easier to handle and mount. Always follow the manufacturer's instructions when handling and mounting an inverter.

Remote Control and Data Monitoring

Remote control and data monitoring allow for programming and monitoring from a remote location. User interfaces include displays and controls on the inverter itself. Some inverters also include software that enables a user to download data to a computer for more in-depth analysis of system operation.

Series and Parallel Inverter Connections

There are times when parallel operation of inverters is desirable. Parallel operation of inverters allows more loads to be served because the current ratings of the inverters add up. Inverters connected in series are used to operate higher voltage loads because the voltage outputs of the inverters add up. If the PV system installation requires multiple inverters to be used, they must be designed specifically for series or parallel connection. Always follow the manufacturer's instructions when connecting multiple inverters together.

**FIGURE 8-8**

A typical nameplate from a grid-tie inverter.

Grid-tie Inverter Features and Specifications

Because of the need for the grid-tie inverter's output power sine wave to be as pure as possible, the inverter must meet Institute of Electrical and Electronic Engineers (IEEE) Standard 1547. To make sure that electromagnetic interference (EMI) is kept to an acceptable level, Federal Communications Commission (FCC) Part 15 must be met. They must also meet the safety requirements of Underwriters Laboratories (UL) 1741. *Section 690.4(D)* of the *NEC*® requires inverters, along with other PV system equipment, to be listed by a nationally recognized testing laboratory (NRTL) like UL. An NRTL label must be located where it can easily be seen on each inverter. The nameplate on a grid-tie inverter typically has this information (Figure 8-8).

Additional features that are desirable in a grid-tie inverter include the following:

- ◆ Maximum power point tracking (MPPT) that allows the PV system to operate at the highest level of efficiency possible. MPPT was covered in detail in Chapter 7.
- ◆ Ground fault protection (GFP) as required by the *National Electrical Code*® for certain PV systems. Because of this requirement, most grid-tie inverters manufactured today include a GFP feature. GFP requirements are covered in detail in Chapter 9.
- ◆ AC and DC disconnects are available on some inverters. Many installers choose to install external disconnects in addition to the built-in disconnects of the inverter so that the inverter can safely be removed for repair or replacement.

NEMA Enclosure Selection Chart

For Indoor Use	Type of Enclosure									
Provides a Degree of Protection Against the Following Conditions	1*	2*	4	4X	5	6	6P	12	12K	13
Access to hazardous parts	X	X	X	X	X	X	X	X	X	X
Ingress of solid foreign objects (falling dirt)	X	X	X	X	X	X	X	X	X	X
Ingress of water (Dripping and light splashing)	—	X	X	X	X	X	X	X	X	X
Ingress of solid foreign objects (Circulating dust, lint, fibers, and flying)	—	—	X	X	—	X	X	X	X	X
Ingress of solid foreign objects (Settling airborne dust, lint, fibers, and flying)	—	—	X	X	X	X	X	X	X	X
Ingress of water (Hosedown and splashing water)	—	—	X	X	—	X	X	—	—	—
Oil and coolant seepage	—	—	—	—	—	—	—	X	X	X
Oil and coolant spraying and splashing	—	—	—	—	—	—	—	—	—	X
Corrosive agents	—	—	—	X	—	—	X	—	—	—
Ingress of water (Occasional temporary submersion)	—	—	—	—	—	X	X	—	—	—
Ingress of water (Occasional prolonged submersion)	—	—	—	—	—	—	X	—	—	—

For Outdoor Use	Type of Enclosure									
Provides a Degree of Protection Against the Following Conditions	3	3X	3R*	3RX*	3S	3SX	4	4X	6	6P
Access to hazardous parts	X	X	X	X	X	X	X	X	X	X
Ingress of water (Rain, snow, and sleet)	X	X	X	X	X	X	X	X	X	X
Sleet	—	—	—	—	X	X	—	—	—	—
Ingress of solid foreign objects (Windblown dust, lint, fibers, and flyings)	X	X	—	—	X	X	X	X	X	X
Ingress of water (Hosedown)	—	—	—	—	—	—	X	X	X	X
Corrosive agents	—	X	—	X	—	X	—	X	—	X
Ingress of water (Occasional temporary submersion)	—	—	—	—	—	—	—	—	X	X
Ingress of water (Occasional prolonged submersion)	—	—	—	—	—	—	—	—	—	X

* These enclosures may be ventilated.

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FIGURE 8-9

NEMA enclosure type numbers for PV system enclosures used indoor or outdoor.

- ♦ Inverters can be installed indoors or outdoors depending on the type of National Electrical Manufacturers Association (NEMA) enclosure they have. The chart shown in Figure 8-9 can be used as a selection guide for the type of enclosure needed for a specific inverter installation location. Manufacturers typically offer their inverters with weatherproof enclosures that allow an installer to locate them either inside or outside.

Specifying a Grid-Tie inverter

There are a few things to consider when specifying a grid-tie inverter. The main inverter specification to consider is the inverter's power rating. Grid-tie inverters are available in power ratings that range from around 500 watts for a small PV system up to 500 kW or more for large-scale PV systems. The output power rating

of a grid-tie inverter determines how much input power from the PV array it can handle. In a grid-tie system, the PV array is sized to match the AC loads of a building, the PV system owner's budget, or the available area where the array will be located. Once the PV system array size is determined, the amount of power that must be handled by the system inverter can be calculated. This value is found by taking the standard test condition (STC) DC wattage value of the array and multiplying by the efficiency of the inverter. For example, if a PV array has a DC power rating of 4000 watts and an inverter has an efficiency rating of 90%, the AC output power would be 3600 watts. Therefore, the minimum AC output power rating of the inverter would need to be at least 3600 watts.

Another consideration is the input voltage. The PV array voltage must fall in the input voltage range of the grid-tie inverter. Most require a DC input of 75–600 volts. The actual range could be something like 150–450 volts DC. In this range an array configuration that provided a 300-volt input voltage would work well. PV modules are connected in series so that the voltage values of each module add up to equal a voltage that falls in the input voltage range. Care must be taken when determining the configuration of the PV array so that during very hot or very cold weather the voltage of the array will not fall out of the input voltage range. If it does, the inverter will shut down.

The inverter output voltage is another important item to consider. The output voltage on smaller PV systems must match the required voltage of a building's electrical loads. Typically, inverters rated 6 kW or less supply an AC output voltage of 120 volts, 240 volts, or 120/240 volts single phase. Larger inverters produce three-phase AC voltages of 208 volts, 277 volts, or 480 volts. Grid-tie inverters have to maintain the AC output voltage at minus 10% to plus 5% of the nominal system voltage. This means that a low of 108 volts to a high of 126 volts for a 120-volt nominal system could be seen.

Current ratings of the inverter must also be considered. The current rating on the DC input side of the inverter limits the amount of current that a PV array can deliver. Therefore, the array must be sized and configured so the rated DC input current is not exceeded. The AC output side current rating is not as critical for a grid-tie inverter because a grid-tie PV system is not typically designed to supply all of the AC loads in a building. The maximum continuous AC output current and the maximum continuous DC input currents at specific temperatures are given for each inverter. These currents are used to help size conductors, disconnects, and overcurrent protection for the input and output circuits. This is covered in more detail in Chapter 9.

Stand-Alone Inverter Features and Specifications

Stand-alone inverters have many features and specifications that must be considered when choosing the right inverter for a stand-alone PV system installation.

High surge capacity is needed in a stand-alone inverter to be able to power electric motors that have starting currents of six to eight times the normal running current. The PV system may also need to operate loads at the same time, and when they all are energized at the same time, a surge capacity is required.

Sealed or vented enclosures are available for stand-alone inverters. Sealed enclosures are used for outdoor installations and protect the inverter from things like bugs, dust, and rain or snow.

Some stand-alone inverters have a battery-charging capability. This feature eliminates the need for a separate charge controller. A separate fuel-powered generator is often connected to the inverter to supply battery-charging power when there is extended periods of time without an adequate amount of solar insolation. If the inverter has a built-in battery charger, it should have an automatic warning or shut-off when battery level is low. This helps prevent over-discharging of the system batteries.

Many stand-alone inverters with a battery charger feature have a generator auto start and stop feature. With this feature, the inverter can be programmed to automatically start and then stop a generator when the batteries get discharged to a specific level.

Specifying a Stand-Alone Inverter

The things to consider when specifying a stand-alone inverter are very similar to those for specifying a grid-tie inverter and include the AC output wattage, the DC voltage from the batteries, the AC output voltage, and the frequency. In addition, you need to consider the surge capacity and the waveform type of a stand-alone system inverter.

The AC power output rating of a stand-alone inverter must be large enough so that the inverter can handle the AC electrical load. For example, if the total AC load that must be operated is 3600 watts, you will need an inverter with an output wattage rating of at least 3600 watts. A standard-size stand-alone inverter made by many manufacturers is 4000 watts. Manufacturers make stand-alone inverters as small as 50 watts. The most common sizes are 3 kW, 4 kW, 5 kW, and 6 kW. Larger power ratings are available but are rarely used in a stand-alone system.

The DC input voltage from the batteries is used to determine the DC input voltage rating of a stand-alone inverter. Smaller stand-alone inverters of 1 kW or less are made to operate on 12-volt DC batteries or some battery configuration resulting in multiples of 12 volts, such as 24 or 48 volts. Larger stand-alone inverters are made to operate on 24, 48, or 60 volts.

The output voltage of a stand-alone inverter has to match the required voltage of a building's electrical loads. Typically, inverters rated 6 kW or less supply an AC output voltage of 120 volts, 240 volts, or 120/240 volts single phase. Two stand-alone inverters with an output voltage rating of 120 volts can be connected together to supply electrical loads requiring the larger 240 volt single-phase voltage. Larger stand-alone inverters produce three-phase AC voltages of 208 volts, 277 volts, or 480 volts.

The surge capacity is listed as the maximum AC output current available for a specific length of time. For example, a stand-alone inverter may have a continuous output current rating of 30 amps but could have a surge current rating of 70 amps for 100 milliseconds. Many installers use the "two and a half" rule of thumb when selecting an inverter with the proper surge capacity. Because it is very difficult to determine the exact amount of surge current needed, many installers multiply the required load wattage by 2.5. This results in an inverter power rating that should be able to handle the loads that require a surge of current to get started. For example, if the regular amount of power required for the loads in a building that will operate at the same time is 1500 watts, the minimum wattage rating of the inverter should be 3750 watts ($1500 \times 2.5 = 3750$ watts). Some installers use a larger number in their rule of thumb for surge loads. Using a larger number will allow the system to be sized in anticipation of more surge loads being added in the future but it will increase the initial cost of a stand-alone PV system.

As discussed earlier in this chapter, there are three different waveforms that an inverter may produce. When choosing a stand-alone inverter, it is important to take into account the type of waveform the AC output voltage will have because it needs to match the waveform required for the loads it will be powering. Even though the initial cost may be higher, it is a good installation practice to install a stand-alone inverter that will produce a true sine wave even though the loads can operate adequately on a modified square wave.

Bimodal Inverter Features and Specifications

If the PV system is utility interconnected but also has battery backup to power loads when the grid is down a bimodal inverter needs to be specified. Bimodal inverters will need to have features that are a combination of a grid-tie and a stand-alone inverter. These features include:

- ◆ Battery charging capability
- ◆ Automatic warning or shutoff when battery level is low
- ◆ High surge capacity for motor loads
- ◆ Generator auto start and stop
- ◆ Availability as a power conditioning unit (PCU) with disconnects and over-current protection devices
- ◆ Sealed or vented enclosures

Specifying a bimodal inverter requires considering the same basic items that are considered when specifying a grid-tie or stand-alone inverter. These specifications include the following:

- ◆ AC output wattage
- ◆ DC input voltage from batteries
- ◆ AC Output voltage
- ◆ AC output frequency
- ◆ Surge capacity