



Charge Controllers

PV systems that have a battery bank use a charge controller to control battery charging and discharging. There are several different types of charge controllers available for use in a PV system. Having knowledge of the operating principles and features of various charge controllers helps a PV installer choose the correct type and size charge controller for the PV system being installed. This chapter takes a detailed look at common types of charge controllers and their operating principles. A discussion of charge controller features and how to select a charge controller is also included.

Glossary of Terms

algorithm A series of functions programmed into a charge controller so that the controller optimizes system performance during various levels of battery discharging and charging.

charge resumption set point (CRSP) The voltage level setting of a charge controller that results in a charging current being supplied to the batteries.

charge termination set point (CTSP) The voltage level setting of a charge controller that results in the battery charging current being stopped.

low voltage disconnect (LVD) The amount of voltage set on a charge controller that, when reached, causes system loads to be disconnected to prevent battery over-discharging.

maximum power point tracking (MPPT) A charge controller type that is micro-processor controlled to regulate battery charging and to continuously adjust the PV system array operation at its maximum power point even as operating conditions change.

pulse-width modulation A way to simulate a waveform by switching an electronic device ON and OFF at a high rate of speed for variable lengths of time.

PV output circuit The circuit conductors between the PV source circuits (the PV array) and the DC utilization equipment.

self-regulating PV system A PV system that has batteries but no charge controller.

Objectives

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

- Demonstrate an understanding of charge controller operating principles.
- Identify different types of charge controllers.
- Demonstrate an understanding of common charge controller features.
- Demonstrate an understanding of how to select a charge controller

CHAPTER 7

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Introduction to Charge Controllers

A photovoltaic (PV) system charge controller (Figure 7-1) has a primary function of preventing the batteries used in a PV system from being overcharged by the PV system array. It also protects batteries from being over-discharged by the electrical load. Figure 7-2 shows the location of a charge controller in a basic stand-alone PV system that supplies only DC loads. Charge controllers come in sizes that are rated from a few amps to sizes that are rated up to 80 amps. If a higher current rating is needed, two or more charge controllers can be used, and the PV system array is divided into subarrays (Figure 7-3). Although it is rarely used, one charge controller can be used with multiple battery banks in a PV system (Figure 7-4). This situation could happen if an existing PV system is expanded and the new battery bank voltage is different than the original battery bank.



Courtesy of Schneider Electric

FIGURE 7-1

A typical charge controller used in a PV system with batteries. This is a Schneider Electric Xantrex XW MPPT Solar Charge Controller.

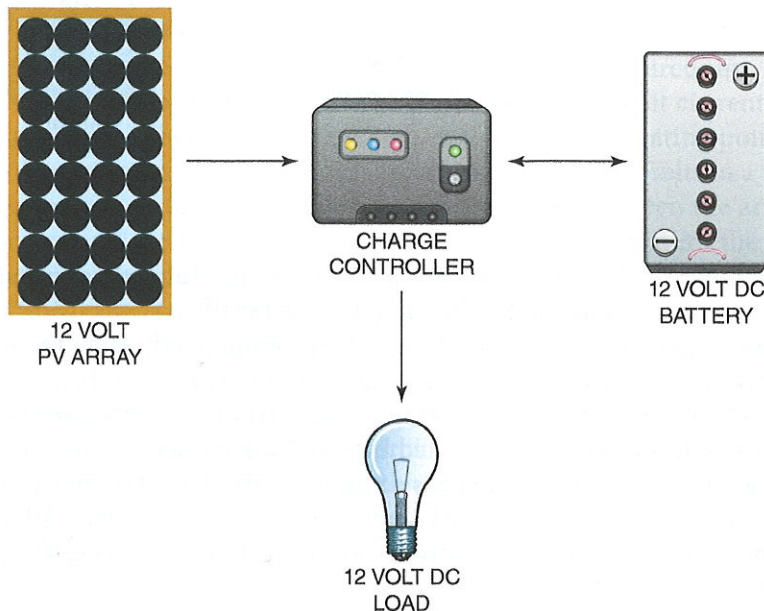
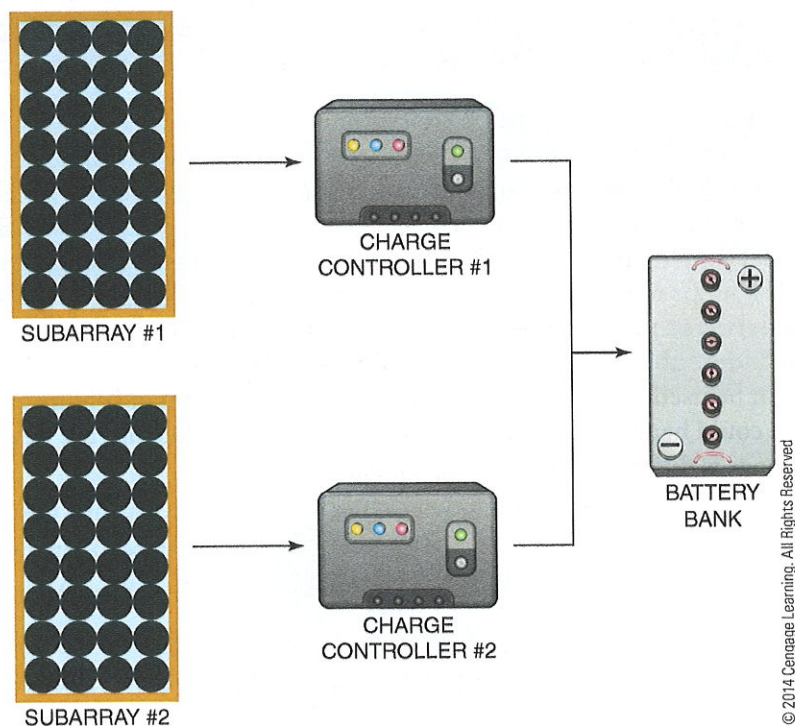


FIGURE 7-2

A simple PV system with storage batteries. The charge controller controls electricity flow among the PV array, battery bank, and electrical load.

FIGURE 7-3

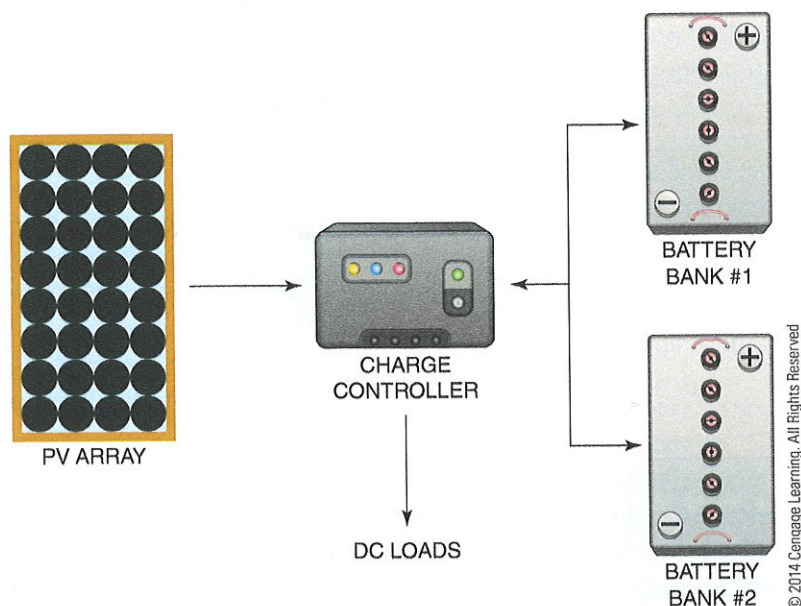
Some larger PV systems may require multiple charge controllers. In this illustration, each charge controller is connected to a different subarray. All of the charge controllers are connected to the same battery bank.



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FIGURE 7-4

A single charge controller can be used to charge more than one battery bank; however, this installation is rarely used.



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Section 690.72(A) of the *National Electrical Code*® requires equipment like charge controllers to control the charging process for PV systems using batteries. Charge controllers are not required, but are recommended, when the design of the PV array source circuit is matched exactly to the voltage and charge current requirements of a battery bank. In addition, the maximum charge current in amp-hours must be less than 3% of the rated battery bank capacity in amp-hours. For example, a 100 Ah battery bank needs a charge controller if the maximum array charging current equals or exceeds 3 amps ($100 \text{ Ah} \times 3\% = 3 \text{ Ah}$). A PV system that has batteries but no charge controller is often referred to as a **self-regulating PV system** (Figure 7-5).

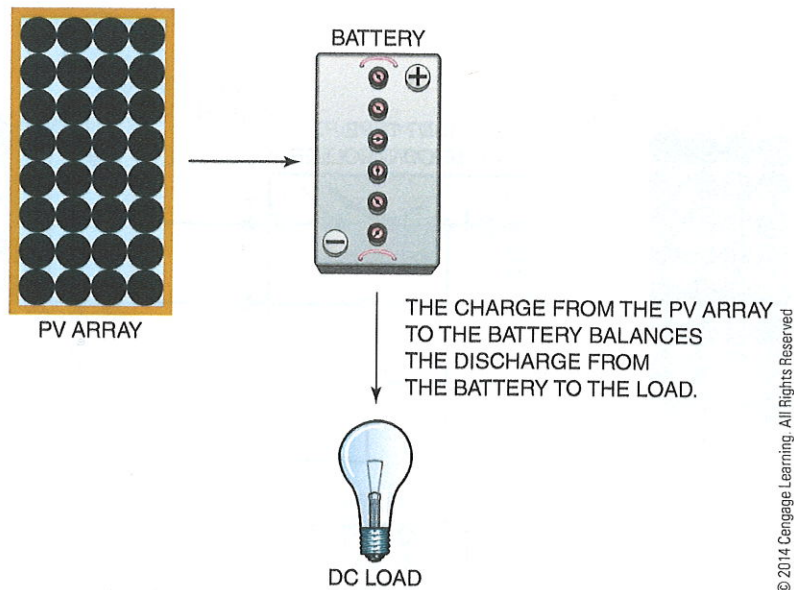


FIGURE 7-5

A small PV system may not need a charge controller. To make this system work, the batteries must be oversized, the load must be the same on a day-to-day basis, and the array current must be large enough to adequately charge the batteries but be limited to an amount that won't cause an overcharge situation.

Charge Controller Types

Charge controllers use algorithms to control current and voltage to or from a battery so that the battery maintains a certain state of charge. An **algorithm** is simply a series of functions that has been programmed into the charge controller so that the controller will optimize system performance during various levels of battery discharging and charging. Today's charge controllers use electronic switching control, typically transistors, to control battery charging and discharging. Charge controllers can be separated into two categories: standard charge controllers and maximum power point tracking (MPPT) charge controllers. There are several different charge controller types. The following paragraphs cover the most common charge controller types used in PV systems.

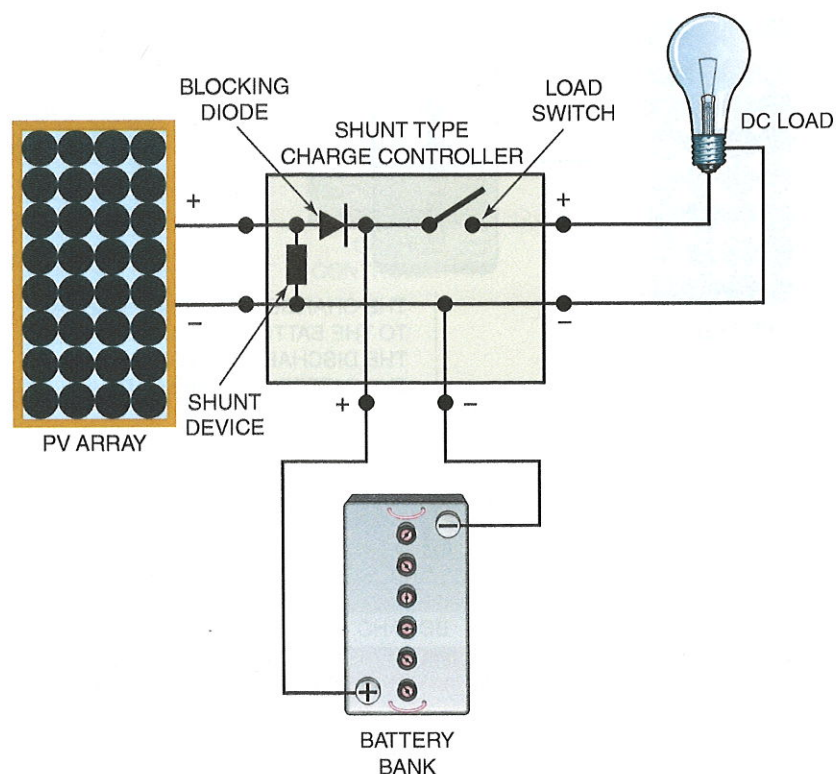
Shunt-Type Charge Controllers

Shunt controllers are designed for small PV systems and are considered to be a standard charge controller. They work to prevent overcharging by "shunting" or bypassing the batteries when they are fully charged by short circuiting the array (Figure 7-6). This is possible because the available short circuit current from an array is quite low. When the array is short circuited, the operating point on the array's I-V curve moves near the short circuit condition and results in a very limited power output. A blocking diode is located in series between the array short circuit device and the batteries in the charge controller to prevent the batteries from short circuiting. Unlike the PV array, the available short circuit current from the batteries is extremely large and can cause severe system damage.

This controller type has heat sinks with fins to help dissipate the heat generated by the controller. The heat buildup is the main reason why these controllers are limited in size and should only be connected to array source circuits of 20 amps or less. Because a shunt-type charge controller uses a simple design, it is relatively inexpensive to purchase. However, even though the cost to purchase is reasonable, the disadvantages of the controller's limited load-handling capability and the need for it to be located in the open for air ventilation makes the shunt-type charge controller less popular than some other types.

FIGURE 7-6

A shunt-type charge controller regulates battery charging by short-circuiting the PV system array.



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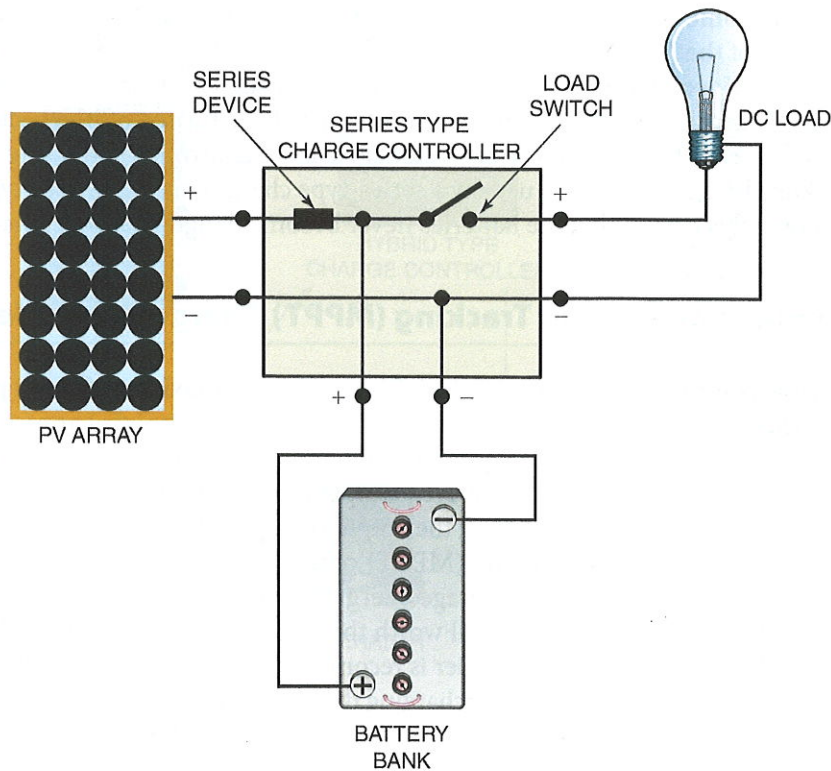
Series Type Charge Controllers

Another standard charge controller is a series-type charge controller. It prevents battery overcharging by switching the current path from the PV system array off (Figure 7-7) when battery voltage reaches the **charge termination set point (CTSP)**. The series charge controller automatically allows charging when the battery voltage reaches the **charge resumption set point (CRSP)**. As the battery reaches full charge, the series-type charge controller's switching device opens, causing the operating point on the PV array's I-V curve to move near the open-circuit condition. This results in a very limited power output.

Unlike the shunt-type charge controller, the series-type charge controller uses a sensor (instead of a blocking diode) to prevent reverse current flow at night. It has a small physical size and is inexpensive to purchase. Because this style of charge controller produces very little heat, there is no large heat sink required. It has a greater load capability than the shunt-type controller and does not require a lot of ventilation.

Pulse-Width Modulation (PWM)-Type Charge Controller

The **pulse-width modulation** controller is a very common standard controller type. Its electronic circuitry allows it to simulate a variable charging current. It charges a battery by rapidly switching the full charging current ON and OFF for varying lengths of time. The length of the charge pulse gradually decreases as battery voltage rises. The PWM type of charge controller is a variation of the series-type charge controller and does not use blocking diodes but rather just opens the circuit between the batteries and the array when it gets dark outside. It works very well with sealed batteries but has a limited number of PV array module configurations and voltages.



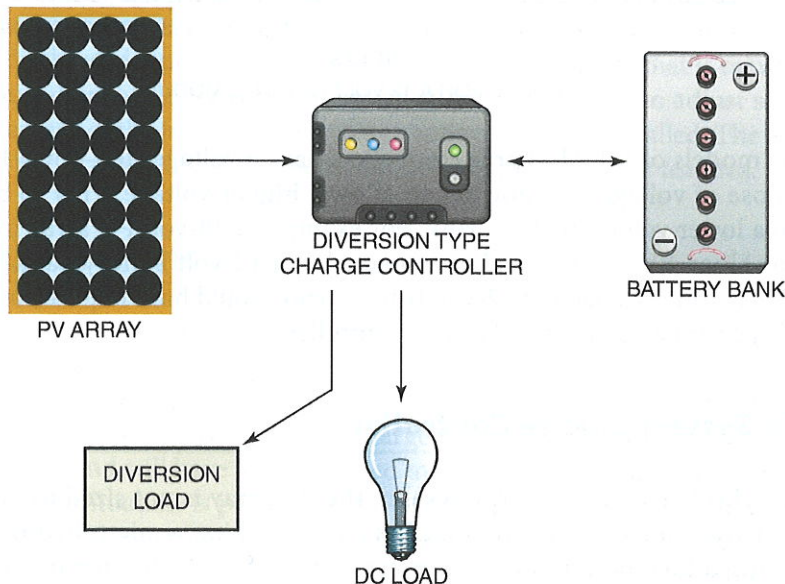
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FIGURE 7-7

A series-type charge controller regulates battery charging by opening the PV system source circuit from the array.

Diversion-Type Charge Controller

The diversion-type standard charge controller differs from the other charge controllers in how it regulates the charging current delivered to the batteries. It diverts excess charging current to some type of electrical load such as a fan or heater (Figure 7-8). Diversion charge controllers automatically establish different charging currents based on the battery's state of charge. Full current is applied when the battery state of charge is low, and a trickle charge is applied as the battery reaches full charge. This method tends to lengthen battery life. A diversion charge controller can produce a relatively large amount of heat, so it needs to be installed so that it is adequately ventilated. This type of controller does not usually have a way to prevent reverse leakage at night, so blocking diodes may have to be installed.



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FIGURE 7-8

A diversion-type charge controller regulates battery charging by diverting electrical power to another load when the batteries are fully charged.

Because some diversionary loads cannot be available at all times, *Section 690.72(B)(1)* of the *National Electrical Code*® requires a backup type of charge control to prevent overcharging of a battery bank. For example, if the diversionary load is an electric heater, the heater's thermostat may have turned off the heater so that it can't accept the current the diversionary charge controller is sending to it. The backup charge controller is usually a series-type charge controller. This type of installation helps ensure that the batteries never become dangerously overcharged.

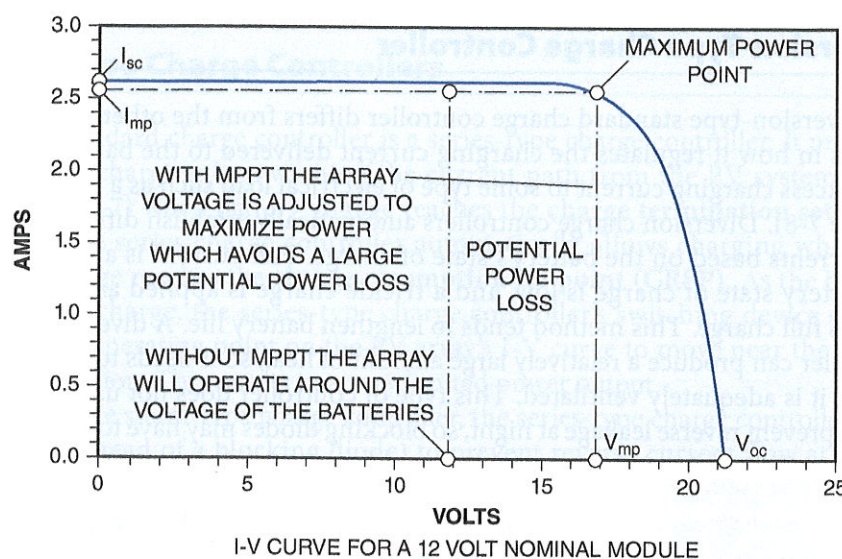
Maximum Power Point Tracking (MPPT) Charge Controllers

Most charge controllers installed in today's PV systems are **maximum power point tracking (MPPT)** charge controllers. This type of charge controller is microprocessor controlled to regulate battery charging and to continuously adjust the PV system array operation at its maximum power point even as operating conditions change. It is able to accomplish this task by manipulating the output voltage of the PV system array.

Maximum power point tracking (MPPT) optimizes the battery performance of a PV system (Figure 7-9). The average energy gain of a PV system when using MPPT is 10% or more. This gain is well worth the extra initial cost of MPPT charge controllers. This type of charge controller is recommended for use in colder climates because of its ability to prevent the overcharging that can occur at lower temperatures. It also provides a greater control over the depth of discharge (DOD).

FIGURE 7-9

Maximum power point tracking (MPPT) optimizes the battery performance of a PV system. The average energy gain of a PV system when using MPPT is 10% or more.

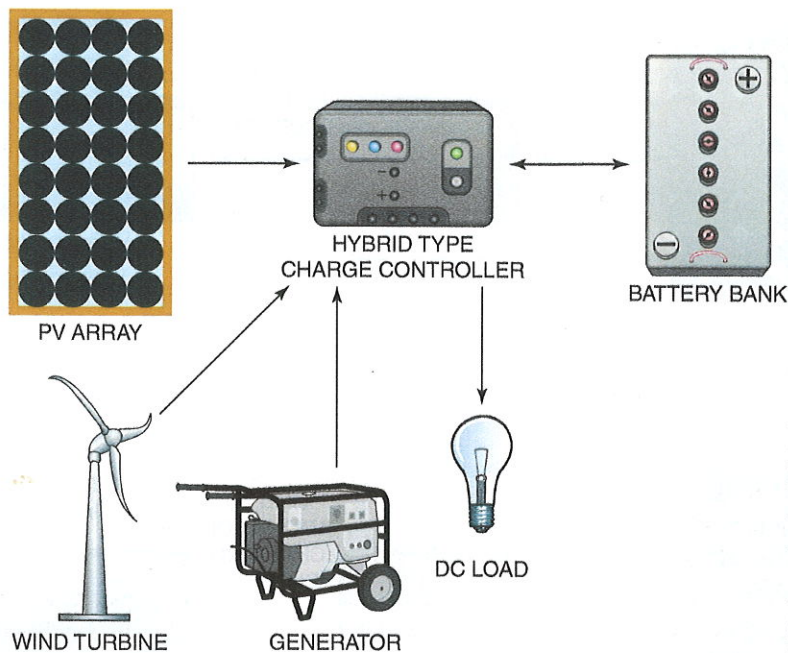


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Some models of MPPT charge controllers have a voltage step-down feature. The purpose of voltage step down is to allow a higher voltage array to be connected to a lower voltage battery bank. For example, a 48-volt PV array installed in a stand-alone PV system can be connected to a 12-volt battery bank. Before this feature became available, a 12-volt battery bank would have required a 12-volt array voltage with a 12-volt-rated charge controller.

Hybrid System Charge Controller

In a true hybrid renewable energy system, the PV array is not sized to meet the entire electrical load. Other sources such as a wind turbine, a micro-hydro system, or even a fossil fuel-powered generator are all used to help provide the required

**FIGURE 7-10**

A hybrid system charge controller is designed to manage multiple sources of electrical power like PV, wind, and micro-hydro.

amount of electrical power. A hybrid system charge controller is similar in many respects to the types of charge controllers previously described, but it is designed to manage multiple sources of electrical power (Figure 7-10). Hybrid system charge controllers have the ability to automatically start and stop an engine-powered generator.

Charge Controller Features

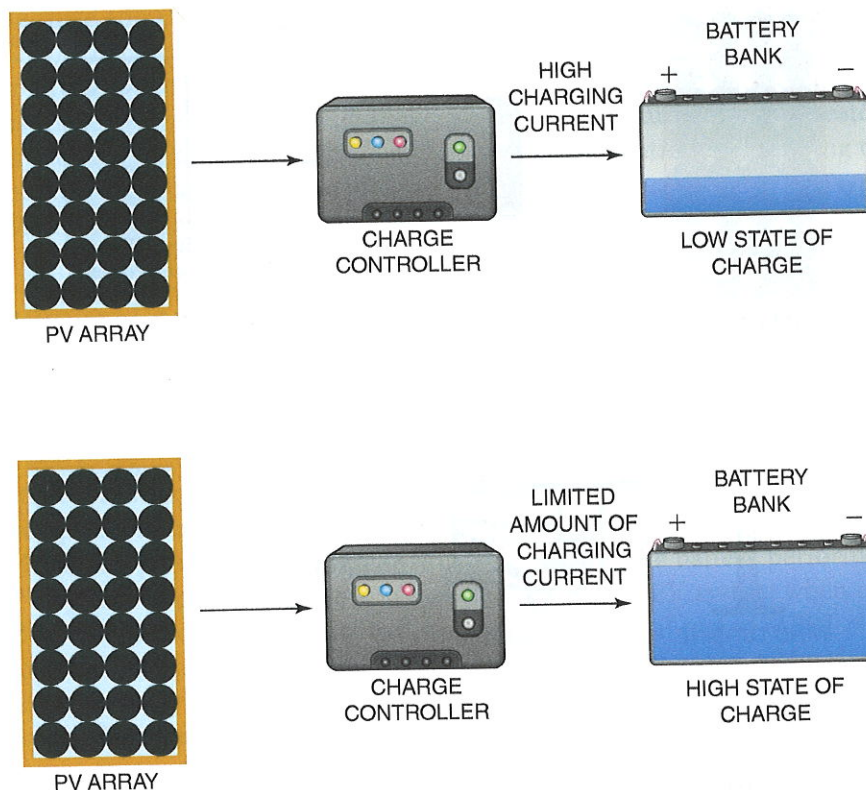
When an installer chooses a charge controller for use in a PV system, there are many features that must be considered. Charge controller features make a PV system more flexible. This flexibility means that a higher level of PV system charge control is possible. Charge controllers not only need to protect batteries from being overcharged or over-discharged, but they also need to have a user interface that is easy for a PV system installer to use. The user interface allows an installer to adjust settings to take advantage of the features of the charge controller being installed. The following paragraphs discuss many of the more desirable charge controller features.

Overcharge Protection

Overcharge protection is considered to be the most important feature that a charge controller must have (Figure 7-11). Overcharge occurs when a fully charged battery continues to receive a charging current. Lead-acid and Ni-Cad batteries can experience thermal failure when overcharged. At the very least, batteries will lose their capacity and will have to be replaced much earlier than necessary when overcharged. This situation is possible during times of high insolation that cause the PV array to produce amounts of electricity that are greater than the electrical load demand. In this instance, a charge controller will limit the amount of charging

FIGURE 7-11

Overcharge protection is considered to be the most important feature that a charge controller must have. Batteries are protected when a charge controller terminates or limits the amount of charging current.



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current that is applied to the batteries and keep them from being overcharged. When a battery has a low state of charge, the charge controller will deliver a large charging current in an effort to charge the battery in a timely manner. As the battery gets closer to full charge, the charge controller will adjust the applied current so that the battery gradually reaches full charge and is not damaged in the process.

Over-Discharge Protection

Over-discharge is when a battery's state of charge has gotten so low that it cannot supply electricity at a sufficient voltage level without damaging the battery. This condition can occur when a PV system array has not received enough solar insolation. It can also occur if the array has not been sized large enough to produce enough charging current as well as provide electrical power for normal loads. The depth of discharge (DOD) can be set on a charge controller to limit the amount of discharge a battery bank can sustain before the charge controller shuts off the electrical loads and does not allow them to be energized until the battery bank is charged (Figure 7-12). Many charge controllers activate lights or buzzers to indicate low battery voltage. They may also automatically start up a standby power supply like a gas or diesel generator to power the loads until the battery bank is fully charged. The generator can also be used to charge the battery bank.

Other Common Charge Controller Features

Other common features that can be found on charge controllers used in today's PV market include these:

- ◆ LED indicating lights that quickly tell the PV system owner and maintenance technicians the status of the system's operation. Examples are having an

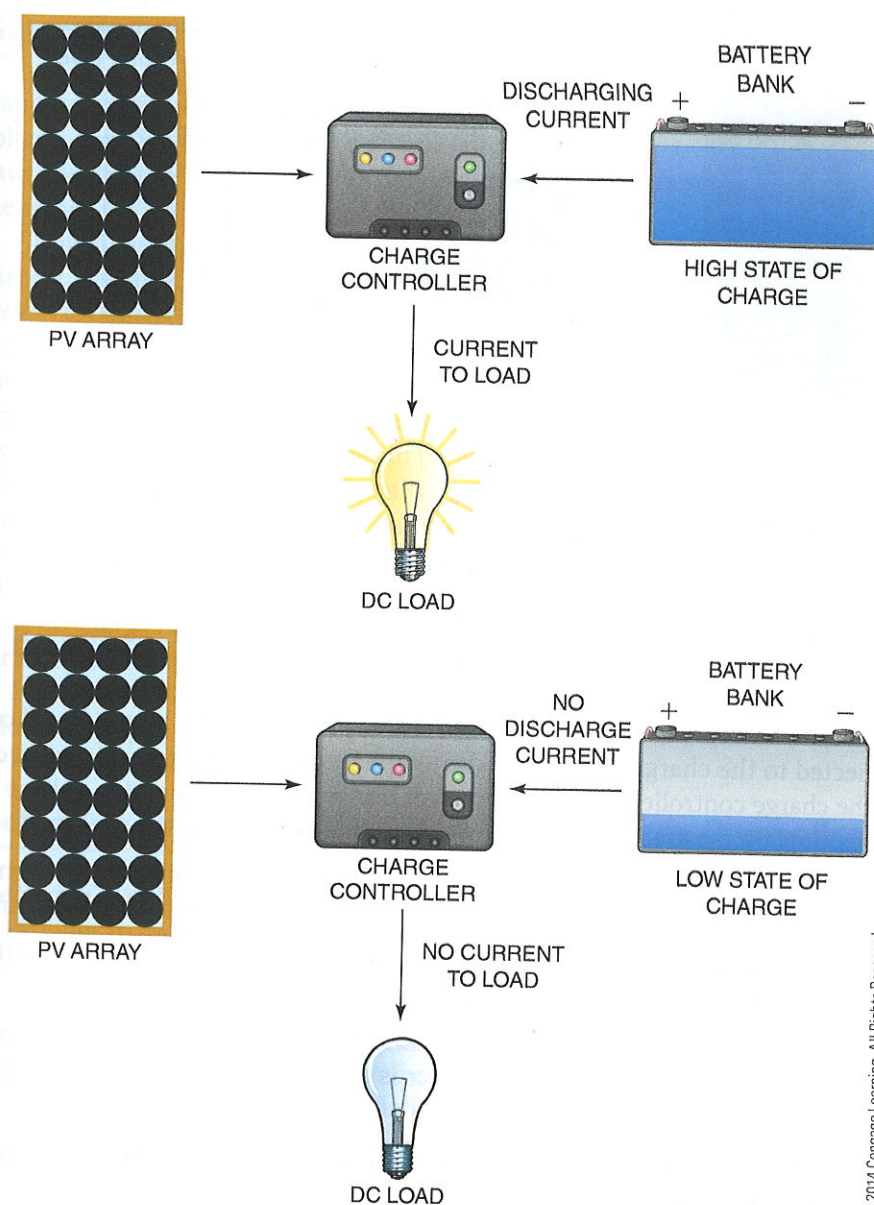


FIGURE 7-12

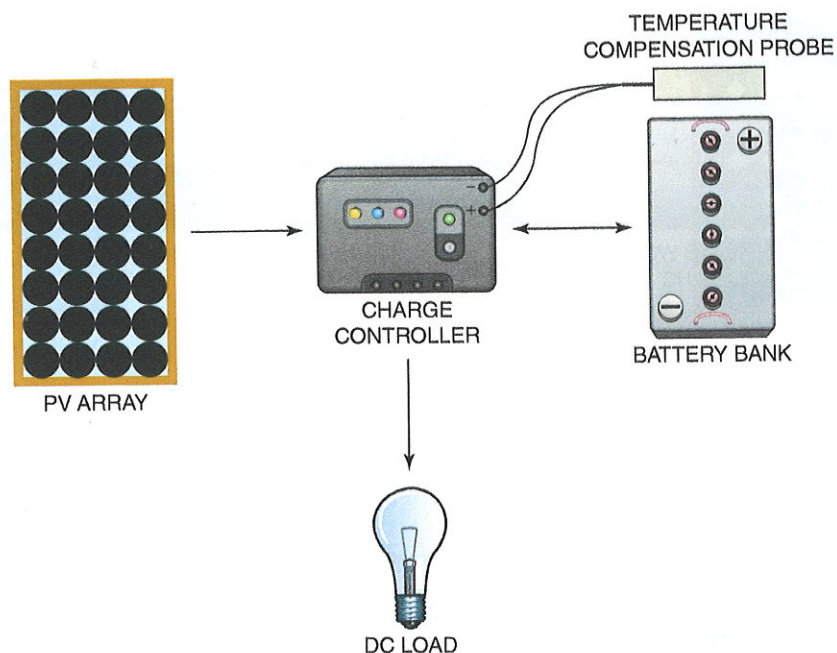
Over-discharge protection is also an important feature for a charge controller to have. Batteries are protected from over-discharge when a charge controller disconnects loads when the battery voltage reaches a predetermined set point.

indicating light tell when the batteries are fully charged or when the low voltage disconnect (LVD) has turned off the load.

- ♦ Meters are often included and allow real-time monitoring of the PV system. Meters are for the most part digital read-out meters, but there may be some older charge controllers that use analog meters. Some charge controllers have data ports that allow data recorders or remote monitoring equipment to easily be connected. Data displayed by these meters can include array voltage, battery voltage, load amps, array amps, array amp-hours, kilowatt-hour production, and charging history.
- ♦ Temperature compensation for charging batteries when the temperature is above or below 77°F (25°C) is a valuable charge controller feature. Remember that battery temperature affects the charging and discharging rate. In colder temperatures, the charge termination set point (CTSP) is reached before the battery has a chance to become fully charged. In warmer temperatures, this situation is reversed. To correct this, the temperature compensation feature adjusts the CTSP about 2.77 mV per degree Fahrenheit from 77°F (about 5 mV per degree Celsius from 25°C) per battery cell. To use the temperature compensation

FIGURE 7-13

To use the temperature compensation feature, a temperature probe is placed with the batteries and connected to the charge controller.



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feature, a temperature probe (Figure 7-13) is placed with the batteries and connected to the charge controller. The temperature at the batteries is relayed to the charge controller, and the charge controller adjusts its charging voltage depending on the ambient temperature surrounding the batteries.

- ◆ A **low voltage disconnect (LVD)** feature allows the charge controller to automatically shut down DC loads when the battery reaches a specified discharge limit.
- ◆ A low voltage warning beeper can be set to sound an alarm when the battery state of charge drops to a preset level.
- ◆ A generator start control feature can automatically start a fuel-powered generator when extra electrical power is needed for battery charging or for supplying heavy electrical loads.
- ◆ An array power diverter feature can divert excess PV system array charging power to other noncritical loads.
- ◆ Some charge controllers have timers that can be set for preset run times for loads like security lighting.
- ◆ Manufacturers often provide several enclosure options for charge controllers that allow them to be located outdoors or indoors, protected from the weather.
- ◆ An automatic equalization feature equalizes batteries automatically on a regular basis.
- ◆ Other charge controller features may be available, depending on the specific charge controller manufacturer.

Charge Controller Selection

Charge controllers are selected for use in a PV system based on certain selection criteria. The selection criteria are different when you are selecting a standard type of charge controller versus a maximum power point tracking (MPPT) and/or voltage step-down charge controller.

Selecting a Standard Charge Controller

Standard charge controllers must have a voltage rating that matches the DC system voltage. For example, a standard charge controller used in a 48 VDC system must have a voltage rating of 48 volts. The voltage input and the voltage output will be the same.

It must also be capable of handling the maximum PV array short circuit (Isc) current. Use the PV array short circuit current rating plus a 25% safety margin. *Section 690.8(A)(1)* of the NEC® requires the PV array current to be calculated as the sum of the short circuit current ratings of all the parallel-connected modules multiplied by 125%. For example, a PV system array consists of four series strings with each string connected in parallel with each other. Each string has an Isc of 5 amps. The array Isc would be 20 amps (4 strings in parallel $\times$ 5 amps per string = 20 amps). The PV array short circuit current would be 25 amps (20 amps $\times$ 1.25 = 25 amps). The NEC® calls this circuit the **PV output circuit** and in *Section 690.2* it is defined as the circuit conductors between the PV source circuits (the PV array) and the DC utilization equipment.

The charge controller must also be capable of handling the maximum DC load current that will pass through it. For example, if the DC load were determined to be 2400 watts at 48 volts, the DC load current would be 50 amps (2400 watts/48 volts = 50 amps).

Selecting an MPPT and/or Step-Down Charge Controller

Specifying a MPPT charge controller and/or a step-down type controller requires an installer to look at some other selection criteria. This type of charge controller has an input voltage and current that differs from the output voltage and current. The output voltage must be equal to the battery voltage. The input voltage from the PV system array has to fall into the input range of the charge controller. Under no circumstances can the maximum voltage of the charge controller be exceeded.

The total input voltage is calculated by adding up all of the open-circuit voltages (Voc) of the series-connected array modules and then multiplying by the voltage correction factor found in *Table 690.7* of the NEC® (Figure 7-14). *Section 690.7(A)* requires the correction factor to be based on the lowest expected ambient temperature that the array will be subjected to. The temperature correction factor only has to be applied if the ambient temperature is below 77°F (25°C). Some manufacturers supply Voc temperature correction factors and you are required to use those numbers rather than the *Table 690.7* numbers. One source for valid lowest expected ambient temperature data is the Extreme Annual Mean Minimum Design Dry Bulk Temperature found in the ASHRAE Handbook—Fundamentals. (ASHRAE stands for the American Society of Heating, Refrigeration, and Air-Conditioning Engineers.) For example, an array has five modules wired in series and each module has a Voc of 45 volts. The lowest expected ambient temperature at the array is 32°F (0°C). According to *Table 690.7*, the correction factor is 1.10. Therefore, the PV system array input voltage to the charge controller is 224 volts [(5 $\times$ 45 volts) $\times$ 1.10 = 224 volts]. The selected MPPT charge controller must have an input voltage range high enough to handle at least 224 volts.

If the battery voltage is 12 volts, then you must be able to set the MPPT charge controller output voltage for 12 volts. The maximum output current in amps must also be determined. This will be the maximum amount of amperage applied to the batteries.