3

SOLAR POWER SYSTEM DESIGN CONSIDERATIONS

Introduction

This section is intended to acquaint the reader with the basic design concepts of solar power applications. The typical solar power applications that will be reviewed include stand-alone systems with battery backup, commonly used in remote telemetry; vehicle charging stations; communication repeater stations; and numerous installations where the installation cost of regular electrical service becomes prohibitive. An extended design application of stand-alone systems also includes the integration of an emergency power generator system.

Grid-connected solar power systems, which form a large majority of residential and industrial applications, are reviewed in detail. To familiarize the reader with the prevailing state and federal assistance rebate programs, a special section is devoted to reviewing the salient aspects of existing rebates.

Solar power design essentially consists of electronics and power systems engineering, which requires a thorough understanding of the electrical engineering disciplines and the prevailing standards outlined in Article 690 of the National Electrical Code (NEC).

The solar power design presented, in addition to reviewing the various electrical design methodologies, provides detailed insight into photovoltaic modules, inverters, charge controllers, lightning protection, power storage, battery sizing, and critical wiring requirements. To assist the reader with the economic issues of solar power cogeneration, a detailed analysis of a typical project, including system planning, photovoltaic power system cogeneration estimates, economic cost projection, and payback analysis, is covered later in Chapter 8.

Solar Power System Components and Materials

As described later in this chapter (see the section entitled “Ground-Mount Photovoltaic Module Installation and Support Hardware”), solar power photovoltaic (PV) modules are constructed from a series of cross-welded solar cells, each typically producing a specific wattage with an output of 0.5 V.

Effectively, each solar cell could be considered as a 0.5-V battery that produces current under adequate solar ray conditions. To obtain a desired voltage output from a PV panel assembly, the cells, similar to batteries, are connected in series to obtain a required output.

For instance, to obtain a 12-V output, 24 cell modules in an assembly are connected in tandem. Likewise, for a 24-V output, 48 modules in an assembly are connected in series. To obtain a desired wattage, a group of several series-connected solar cells are connected in parallel.

The output power of a unit solar cell or its efficiency is dependent on a number of factors such as crystalline silicon, polycrystalline silicon, and amorphous silicon materials, which have specific physical and chemical properties, details of which were discussed in Chapter 2.

Commercially available solar panel assemblies mostly employ proprietary cell manufacturing technologies and lamination techniques, which include cell soldering. Soldered groups of solar cells are in general sandwiched between two tempered-glass panels, which are offered in framed or frameless assemblies.

Solar Power System Configuration and Classifications

There are four types of solar power systems:

1. Directly connected dc solar power system
2. Stand-alone dc solar power system with battery backup
3. Stand-alone hybrid solar power system with generator and battery backup
4. Grid-connected solar power cogeneration system

DIRECTLY CONNECTED DC SOLAR POWER SYSTEM

As shown in Figure 3.1, the solar system configuration consists of a required number of solar photovoltaic cells, commonly referred to as PV modules, connected in series or in parallel to attain the required voltage output. Figure 3.2 shows four PV modules that have been connected in parallel.

The positive output of each module is protected by an appropriate overcurrent device, such as a fuse. Paralleled output of the solar array is in turn connected to a dc motor via a two-pole single throw switch. In some instances, each individual PV module is also

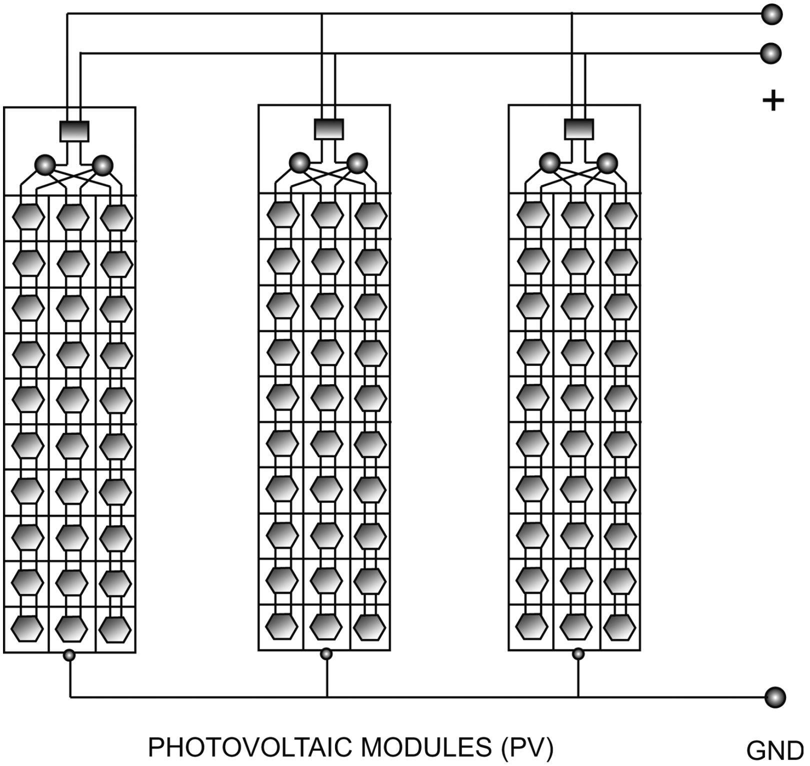


Figure 3.1 A three-panel solar array diagram.

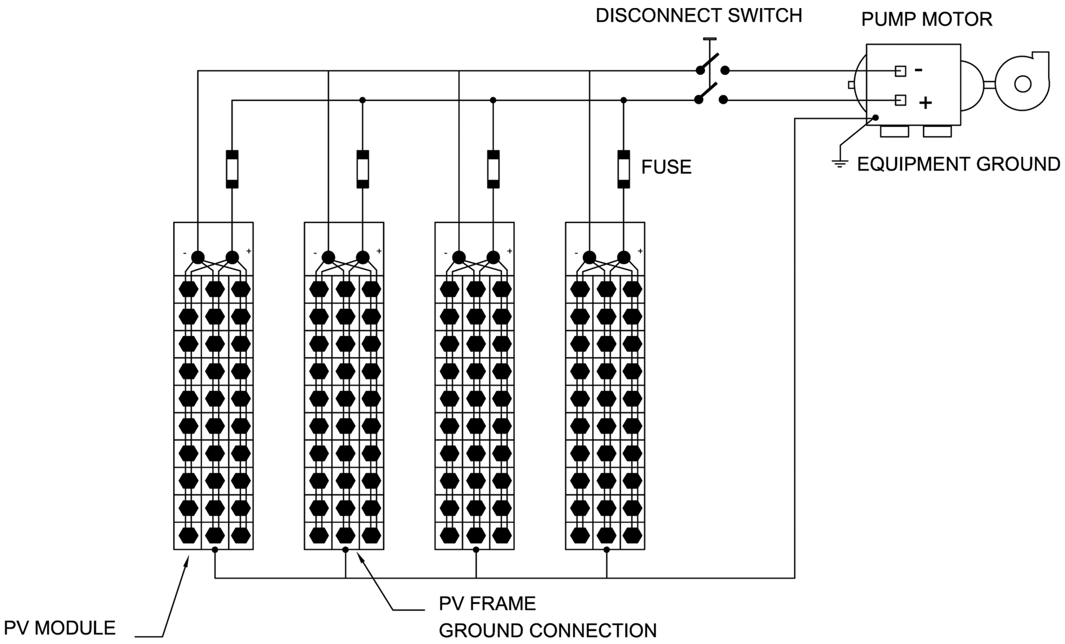


Figure 3.2 A directly connected solar power dc pump diagram.

protected with a forward-biased diode connected to the positive output of individual solar panels (not shown in Figure 3.2).

An appropriate surge protector connected between the positive and negative supply provides protection against lightning surges, which could damage the solar array system components. In order to provide equipment-grounding bias, the chassis or enclosures of all PV modules and the dc motor pump are tied together by means of grounding clamps. The system ground is in turn connected to an appropriate grounding rod. All PV interconnecting wires are sized and the proper type selected to prevent power losses caused by a number of factors, such as exposure to the sun, excessive wire resistance, and additional requirements that are mandated by the NEC.

The photovoltaic solar system described is typically used as an agricultural application, where either regular electrical service is unavailable or the cost is prohibitive. A floating or submersible dc pump connected to a dc PV array can provide a constant stream of well water that can be accumulated in a reservoir for farm or agricultural use. In subsequent sections we will discuss the specifications and use of all system components used in solar power cogeneration applications.

STAND-ALONE DC SOLAR POWER SYSTEM WITH BATTERY BACKUP

The solar power photovoltaic array configuration shown in Figure 3.3, a dc system with battery backup, is essentially the same as the one without the battery except that there are a few additional components that are required to provide battery charge stability.

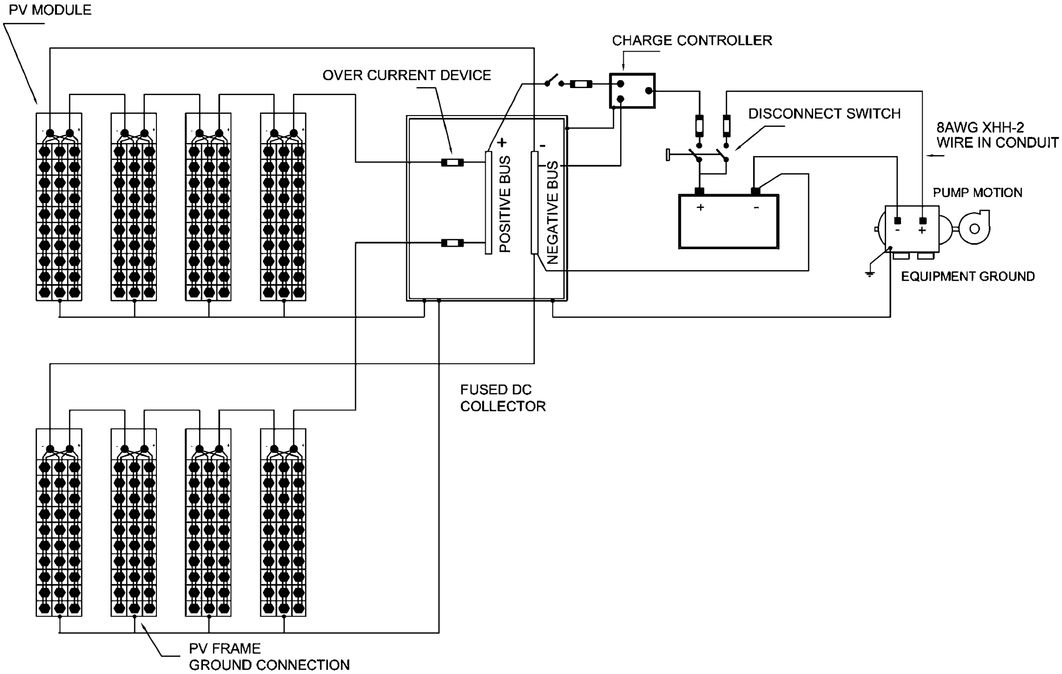


Figure 3.3 Battery-backed solar power–driven dc pump.

Stand-alone PV system arrays are connected in series to obtain the desired dc voltage, such as 12, 24, or 48 V; outputs of that are in turn connected to a dc collector panel equipped with specially rated overcurrent devices, such as ceramic-type fuses. The positive lead of each PV array conductor is connected to a dedicated fuse, and the negative lead is connected to a common neutral bus. All fuses as well are connected to a common positive bus. The output of the dc collector bus, which represents the collective amperes and voltages of the overall array group, is connected to a dc charge controller, which regulates the current output and prevents the voltage level from exceeding the maximum needed for charging the batteries.

The output of the charge controller is connected to the battery bank by means of a dual dc cutoff disconnect. As depicted in Figure 3.3, the cutoff switch, when turned off for safety measures, disconnects the load and the PV arrays simultaneously.

Under normal operation, during the daytime when there is adequate solar insolation, the load is supplied with dc power while simultaneously charging the battery. When sizing the solar power system, take into account that the dc power output from the PV arrays should be adequate to sustain the connected load and the battery trickle charge requirements.

Battery storage sizing depends on a number of factors, such as the duration of an uninterrupted power supply to the load when the solar power system is inoperative, which occurs at nighttime or during cloudy days. Note that battery banks inherently, when in operation, produce a 20 to 30 percent power loss due to heat, which also must be taken into consideration.

When designing a solar power system with a battery backup, the designer must determine the appropriate location for the battery racks and room ventilation, to allow for dissipation of the hydrogen gas generated during the charging process. Sealed-type batteries do not require special ventilation.

All dc wiring calculations discussed take into consideration losses resulting from solar exposure, battery cable current derating, and equipment current resistance requirements, as stipulated in NEC 690 articles.

STAND-ALONE HYBRID AC SOLAR POWER SYSTEM WITH GENERATOR AND BATTERY BACKUP

A stand-alone hybrid solar power configuration is essentially identical to the dc solar power system just discussed, except that it incorporates two additional components, as shown in Figure 3.4. The first component is an inverter. Inverters are electronic power equipment designed to convert direct current into alternating current. The second component is a standby emergency dc generator, which will be discussed later.

Alternating-current inverters The principal mechanism of dc-to-ac conversion consists of chopping or segmenting the dc current into specific portions, referred to as square waves, which are filtered and shaped into sinusoidal ac waveforms.

Any power waveform, when analyzed from a mathematical point of view, essentially consists of the superimposition of many sinusoidal waveforms, referred to as harmonics. The first harmonic represents a pure sinusoidal waveform, which has a unit base wavelength, amplitude, and frequency of repetition over a unit of time called

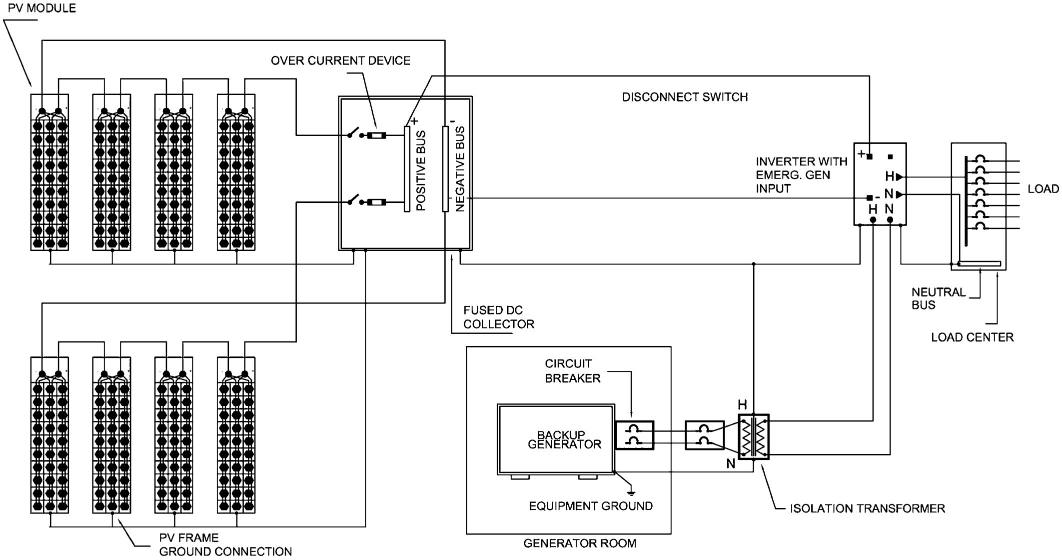


Figure 3.4 **Stand-alone hybrid solar power system with standby generator.**

a cycle. Additional waveforms with higher cycles, when superimposed on the base waveform, add or subtract from the amplitude of the base sinusoidal waveform.

The resulting combined base waveform and higher harmonics produce a distorted waveshape that resembles a distorted sinusoidal wave. The higher the harmonic content, the squarer the waveshape becomes.

Chopped dc output, derived from the solar power, is considered to be a numerous superimposition of odd and even numbers of harmonics. To obtain a relatively clean sinusoidal output, most inverters employ electronic circuitry to filter a large number of harmonics. Filter circuits consist of specially designed inductive and capacitor circuits that trap or block certain unwanted harmonics, the energy of which is dissipated as heat. Some types of inverters, mainly of earlier design technology, make use of inductor coils to produce sinusoidal waveshapes.

In general, dc-to-ac inverters are intricate electronic power conversion equipment designed to convert direct current to a single- or three-phase current that replicates the regular electrical services provided by utilities. Special electronics within inverters, in addition to converting direct current to alternating current, are designed to regulate the output voltage, frequency, and current under specified load conditions. As discussed in the following sections, inverters also incorporate special electronics that allow them to automatically synchronize with other inverters when connected in parallel. Most inverters, in addition to PV module input power, accept auxiliary input power to form a standby generator, used to provide power when battery voltage is dropped to a minimum level.

A special type of inverter, referred to as the *grid-connected* type, incorporates synchronization circuitry that allows the production of sinusoidal waveforms in unison with the electrical service grid. When the inverter is connected to the electrical service grid, it can effectively act as an ac power generation source. Grid-type inverters used in grid-connected solar power systems are strictly regulated by utility agencies that provide net metering.

Some inverters incorporate an internal ac transfer switch that is capable of accepting an output from an ac-type standby generator. In such designs, the inverters include special electronics that transfer power from the generator to the load.

Standby generators A standby generator consists of an engine-driven generator that is used to provide auxiliary power during solar blackouts or when the battery power discharge reaches a minimum level. The output of the generator is connected to the auxiliary input of the inverter.

Engines that drive the motors operate with gasoline, diesel, natural gas, propane, or any type of fuel. Fuel tank sizes vary with the operational requirements. Most emergency generators incorporate underchassis fuel tanks with sufficient fuel storage capacity to operate the generator up to 48 hours. Detached tanks could also be designed to hold much larger fuel reserves, which are usually located outside the engine room. In general, large fuel tanks include special fuel-level monitoring and filtration systems. As an option, the generators can be equipped with remote monitoring and annunciation panels that indicate power generation data and log and monitor the functional and dynamic parameters of the engine, such as coolant temperature, oil pressure, and malfunctions.

Engines also incorporate special electronic circuitry to regulate the generator output frequency, voltage, and power under specified load conditions.

Hybrid system operation As previously discussed, the dc output generated from the PV arrays and the output of the generator can be simultaneously connected to an inverter. The ac output of the inverter is in turn connected to an ac load distribution panel, which provides power to various loads by means of ac-type overcurrent protection devices.

In all instances, solar power design engineers must ensure that all chassis of equipment and PV arrays, including stanchions and pedestals, are connected together via appropriate grounding conductors that are connected to a single-point service ground bus bar, usually located within the vicinity of the main electrical service switchgear.

In grid-connected systems, switching of ac power from the standby generator and the inverter to the service bus or the connected load is accomplished by internal or external automatic transfer switches.

Standby power generators must always comply with the National Electrical Code requirements outlined in the following articles:

- Electrical Service Requirement, NEC 230
- General Grounding Requirements, NEC 250
- Generator Installation Requirements, NEC 445
- Emergency Power System Safety Installation and Maintenance Requirements, NEC 700

GRID-CONNECTED SOLAR POWER COGENERATION SYSTEM

With reference to Figure 3.5, a connected solar power system diagram, the power cogeneration system configuration is similar to the hybrid system just described. The essence of a grid-connected system is *net metering*. Standard service meters are odometer-type counting wheels that record power consumption at a service point by means of a rotating disc, which is connected to the counting mechanism. The rotating discs operate by an electrophysical principle called *eddy current*, which consists of voltage and current measurement sensing coils that generate a proportional power measurement.

New electric meters make use of digital electronic technology that registers power measurement by solid-state current- and voltage-sensing devices that convert analog measured values into binary values that are displayed on the meter bezels by liquid-crystal display (LCD) readouts.

In general, conventional meters only display power consumption; that is, the meter counting mechanism is unidirectional.

Net metering The essential difference between a grid-connected system and a stand-alone system is that inverters, which are connected to the main electrical service, must have an inherent line frequency synchronization capability to deliver the excess power to the grid.

Net meters, unlike conventional meters, have a capability to record consumed or generated power in an exclusive summation format; that is, the recorded power registration is the net amount of power consumed—the total power used minus the amount of power that is produced by the solar power cogeneration system. Net meters are supplied

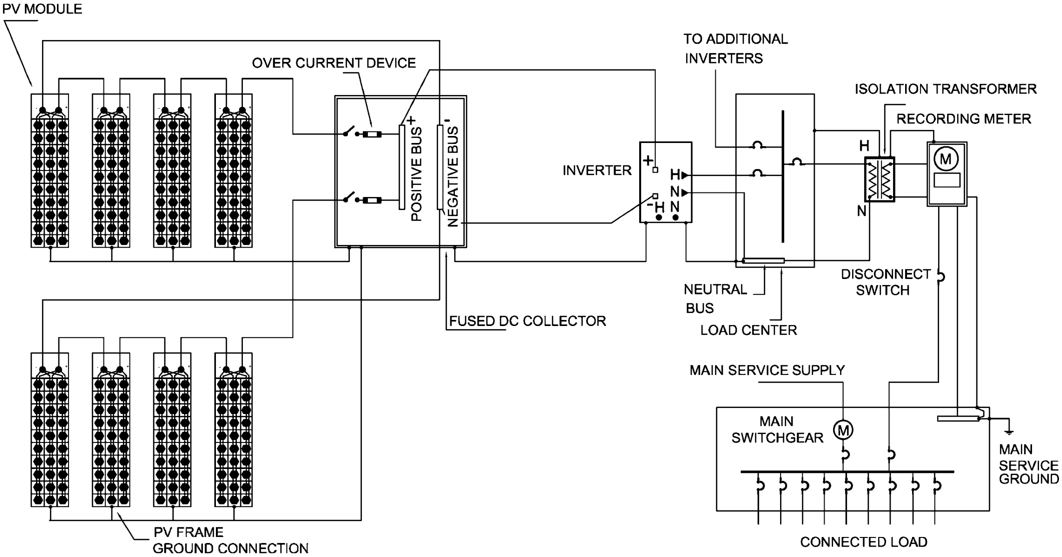


Figure 3.5 Grid-connected hybrid solar power system with standby generator.

and installed by utility companies that provide grid-connection service systems. Net-metered solar power cogenerators are subject to specific contractual agreements and are subsidized by state and municipal governmental agencies. The major agencies that undertake distribution of the state of California's renewable energy rebate funds for various projects are the California Energy Commission (CEC), Southern California Edison, Southern California Gas (Sempra Power), and San Diego Gas and Electric (SG&E), as well as principal municipalities, such as the Los Angeles Department of Water and Power. When designing net metering solar power cogeneration systems, the solar power designers and their clients must familiarize themselves with the CEC rebate fund requirements. Essential to any solar power implementation is the preliminary design and economic feasibility study needed for project cost justification and return-on-investment analysis. The first step of the study usually entails close coordination with the architect in charge and the electrical engineering consultant. A preliminary PV array layout and a computer-aided shading study are essential for providing the required foundation for the design. Based on the preceding study, the solar power engineer must undertake an econometrics study to verify the validity and justification of the investment. Upon completion of the study, the solar engineer must assist the client to complete the required CEC rebate application forms and submit it to the service agency responsible for the energy cogeneration program.

Grid-connection isolation transformer In order to prevent spurious noise transfer from the grid to the solar power system electronics, a delta-y isolation transformer is placed between the main service switchgear disconnects and the inverters. The delta winding of the isolation transformer, which is connected to the service bus, circulates noise harmonics in the winding and dissipates the energy as heat.

Isolation transformers are also used to convert or match the inverter output voltages to the grid. Most often, in commercial installations, inverter output voltages range from 208 to 230 V (three phase), which must be connected to an electric service grid that supplies 277/480 V power.

Some inverter manufacturers incorporate output isolation transformers as an integral part of the inverter system, which eliminates the use of external transformation and ensures noise isolation.

Storage Battery Technologies

One of the most significant components of solar power systems consist of battery backup systems that are frequently used to store electric energy harvested from solar photovoltaic systems for use during the absence of sunlight, such as at night and during cloudy conditions. Because of the significance of storage battery systems it is important for design engineers to have a full understanding of the technology since this system component represents a notable portion of the overall installation cost. More importantly, the designer must be mindful of the hazards associated with handling, installation, and maintenance. To provide an in-depth knowledge about the battery technology, this section covers the physical and chemical principles, manufacturing, design application, and maintenance procedures of the storage battery. In this section we will also attempt to analyze and discuss the advantages and disadvantages of different types of commercially available solar power batteries and their specific performance characteristics.

HISTORY

In 1936, while excavating the ruins of a 2000-year-old village near Baghdad, called Khujut Rabu, workers discovered a mysterious small jar identified as a Sumerian artifact dated to 250 BC. This jar, which was identified as the earliest battery, was a 6-in-high pot of bright yellow clay that included a copper-enveloped iron rod capped with an asphalt-like stopper. The edge of the copper cylinder was soldered with a lead-tin alloy comparable to today's solder. The bottom of the cylinder was capped with a crimped-in copper disk and sealed with bitumen or asphalt. Another insulating layer of asphalt sealed the top and also held in place the iron rod that was suspended into the center of the copper cylinder. The rod showed evidence of having been corroded with an agent. The jar when filled with vinegar produces about 1.1 V of electric potential.

A German archaeologist, Wilhelm Konig, who examined the object (see Figures 3.6 and 3.7), came to the surprising conclusion that the clay pot was nothing less than

Figure 3.6 The Baghdad battery.

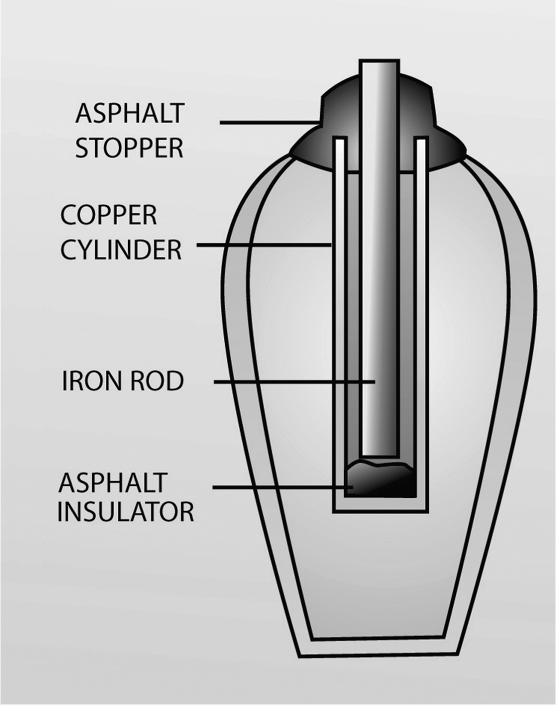


Figure 3.7 The Baghdad battery elements.

an ancient electric battery. It is stipulated that the Sumerians made use of the battery for electroplating inexpensive metals such as copper with silver or gold.

Subsequent to the discovery of this first battery, several other batteries were unearthed in Iraq, all of which dated from the Parthian occupation between 248 BCE and 226 CE.

In the 1970s, German Egyptologist Arne Eggebrecht built a replica of the Baghdad battery and filled it with grape juice, which he deduced ancient Sumerians might have used as an electrolyte. The replica generated 0.87 V of electric potential. Current generated from the battery was then used to electroplate a silver statuette with gold.

However, the invention of batteries is associated with the Italian scientist Luigi Galvani, an anatomist who, in 1791, published works on animal electricity. In his experiments, Galvani noticed that the leg of a dead frog began to twitch when it came in contact with two different metals. From this phenomenon he concluded that there is a connection between electricity and muscle activity. Alessandro Conte Volta, an Italian physicist, in 1800, reported the invention of his electric battery or “pile.” The battery was made by piling up layers of silver, paper or cloth soaked in salt, and zinc (see Figure 3.8). Many triple layers were assembled into a tall pile, without paper or cloth between the zinc and silver, until the desired voltage was reached. Even today the French word for battery is *pile,* pronounced “peel” in English. Volta also developed the concept of the electrochemical series, which ranks the potential produced when various metals come in contact with an electrolyte.

Figure 3.8 Alessandro Volta's pile.

The battery is an electric energy storage device that in physics terminology can be described as a device or mechanism that can hold kinetic or static energy for future use. For example, a rotating flywheel can store dynamic rotational energy in its wheel, which releases the energy when the primary mover such as a motor no longer engages the connecting rod. Similarly, a weight held at a high elevation stores static energy embodied in the object mass, which can release its static energy when dropped. Both of these are examples of energy storage devices or batteries.

Energy storage devices can take a wide variety of forms, such as chemical reactors and kinetic and thermal energy storage devices. Note that each energy storage device is referred to by a specific name; the word *battery,* however, is solely used for electrochemical devices that convert chemical energy into electricity by a process referred to as galvanic interaction. A galvanic cell is a device that consists of two electrodes, referred to as the anode and the cathode, and an electrolyte solution. Batteries consist of one or more galvanic cells.

Note that a battery is an electrical storage reservoir and not an electricity-generating device. Electric charge generation in a battery is a result of chemical interaction, a process that promotes electric charge flow between the anode and the cathode in the presence of an electrolyte. The electrogalvanic process that eventually results in depletion of the anode and cathode plates is resurrected by a recharging process that can be repeated numerous times. In general, batteries when delivering stored energy incur energy losses as heat when discharging or during chemical reactions when charging.

The Daniell cell The Voltaic pile was not good for delivering currents over long periods of time. This restriction was overcome in 1820 with the Daniell cell. British researcher John Frederich Daniell developed an arrangement where a copper plate was located at the bottom of a wide-mouthed jar. A cast-zinc piece commonly referred to as a crowfoot, because of its shape, was located at the top of the plate, hanging on the rim of the jar. Two electrolytes, or conducting liquids, were employed. A saturated copper-sulfate solution covered the copper plate and extended halfway up the remaining distance toward the zinc piece. Then, a zinc-sulfate solution, which is a less dense liquid, was carefully poured over a structure that floated above the copper sulfate and immersed zinc.

In a similar experiment, instead of zinc sulfate, magnesium sulfate or dilute sulfuric acid was used. The Daniell cell was also one of the first batteries that incorporated mercury, which was amalgamated with the zinc anode to reduce corrosion when the batteries were not in use. The Daniell battery, which produced about 1.1 V, was extensively used to power telegraphs, telephones, and even to ring doorbells in homes for over a century.

Plante's battery In 1859 Raymond Plante invented a battery that used a cell by rolling up two strips of lead sheet separated by pieces of flannel material. The entire assembly when immersed in diluted sulfuric acid produced an increased current that was subsequently improved upon by insertion of separators between the sheets.

The carbon-zinc battery In 1866, Georges Leclanché, in France developed the first cell battery. The battery, instead of using liquid electrolyte, was constructed from moist ammonium chloride paste and a carbon and zinc anode and cathode. It was sealed and sold as the first dry battery. The battery was rugged and easy to manufacture and had a good shelf life. Carbon-zinc batteries were in use over the next century until they were replaced by alkaline-manganese batteries. Figure 3.9 depicts graphics of a lead acid battery current flow process.

Lead-acid battery suitable for autos In 1881 Camille Faure produced the first modern lead-acid battery, which he constructed from cast-lead grids that were packed with lead oxide paste instead of lead sheets. The battery had a larger current-producing capacity. Its performance was further improved by the insertion of separators between the positive and negative plates to prevent particles falling from these plates, which could short out the positive and negative plates from the conductive sediment.

The Edison battery Between the years 1898 and 1908, Thomas Edison developed an alkaline cell with iron as the anode material (–) and nickel oxide as the cathode material (+). The electrolyte used was potassium hydroxide, the same as in modern nickel-cadmium and alkaline batteries. The cells were extensively used in industrial

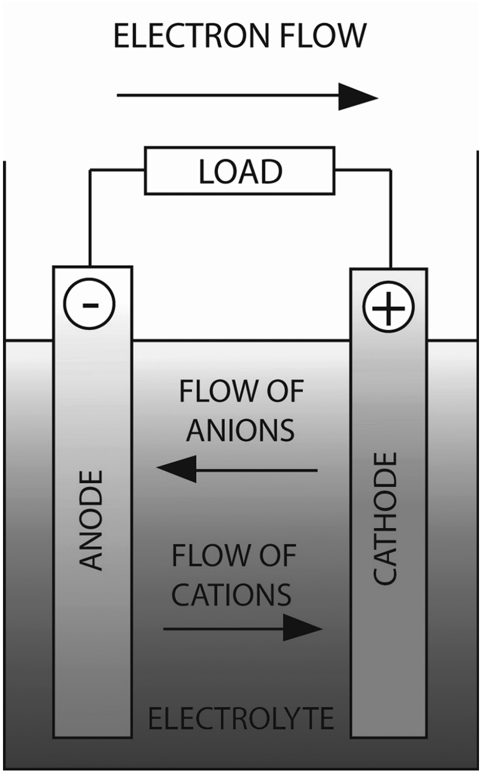


Figure 3.9 Lead-acid battery current.

and railroad applications. Nickel-cadmium batteries are still being used and have remained unchanged ever since.

In parallel with Edison's work, Jungner and Berg in Sweden were working on the development of the nickel-cadmium cell. In place of the iron used in the Edison cell, they used cadmium, with the result that the cell operated better at low temperatures and was capable of self-discharge to a lesser degree than the Edison cell, and in addition the cell could be trickle-charged at a reduced rate. In 1949 the alkaline-manganese battery, also referred to as the alkaline battery, was developed by Lew Urry at the Eveready Battery Company laboratory in Parma, Ohio. Alkaline batteries are capable of storing higher energy within the same package size than comparable conventional dry batteries.

Zinc-mercuric oxide alkaline batteries In 1950 Samuel Ruben invented the zinc-mercuric oxide alkaline battery (see Figure 3.10), which was licensed to the P.R. Mallory Co. The company later became Duracell, International. Mercury compounds have since been eliminated from batteries to protect the environment.

Deep-discharge batteries used in solar power backup applications in general have lower charging and discharging rate characteristics and are more efficient. A battery rated at 4 ampere-hours (Ah) over 6 hours might be rated at 220 Ah at the 20-hour rate

Figure 3.10 Alkaline batteries.

and 260 Ah at the 48-hour rate. The typical efficiency of a lead-acid battery is 85 to 95 percent, and that of alkaline and nickel-cadmium (NiCd) batteries is about 65 percent.

Practically all batteries used in PV systems and in all but the smallest backup systems are lead-acid type batteries. Even after over a century of use, they still offer the best price-to-power ratio. It is not recommended, however, to use NiCd batteries in systems that operate in extremely cold temperatures such as at –50°F or below.

NiCd batteries are expensive to buy and very expensive to dispose off due to the hazardous nature of cadmium. We have had almost no direct experience with these (alkaline) batteries, but from what we have learned from others we do not recommend them—one major disadvantage is that there is a large voltage difference between the fully charged and discharged states. Another problem is that they are very inefficient—there is a 30 to 40 percent heat loss just during charging and discharging.

It is important to note that all batteries commonly used in deep-cycle applications are lead-acid batteries. This includes the standard flooded (wet), gelled, and absorbed glass mat (AGM) batteries. They all use the same chemistry, although the actual construction of the plates and so forth can vary considerably.

Nickel-cadmium, nickel-iron, and other types of batteries are found in some systems but are not common due to their expense and/or poor efficiency.

MAJOR BATTERY TYPES

Solar power backup batteries are divided into two categories based on what they are used for and how they are constructed. The major applications where batteries are used as solar backup include automotive systems, marine systems, and deep-cycle discharge systems.

The major manufactured processes include flooded or wet construction, gelled, and AGM types. AGM batteries are also referred to as “starved electrolyte” or “dry” type, because instead of containing wet sulfuric acid solution, the batteries contain a fiberglass mat saturated with sulfuric acid, which has no excess liquid.

Common flooded-type batteries are usually equipped with removable caps for maintenance-free operation. Gelled-type batteries are sealed and equipped with a small vent valve that maintains a minimal positive pressure. AGM batteries are also equipped with a sealed regulation-type valve that controls the chamber pressure within 4 pounds per square inch (lb/in^2).

As described earlier, common automobile batteries are built with electrodes that are grids of metallic lead containing lead oxides that change in composition during charging and discharging. The electrolyte is dilute sulfuric acid. Lead-acid batteries, even though invented nearly a century ago, are still the battery of choice for solar and backup power systems. With improvements in manufacturing, batteries can last as long as 20 years.

Nickel-cadmium, or alkaline, storage batteries, in which the positive active material is nickel oxide and the negative material contains cadmium, are generally considered very hazardous due to the cadmium. The efficiency of alkaline batteries ranges from 65 to 80 percent compared to 85 to 90 percent for lead-acid batteries. Their nonstandard voltage and charging current also make them very difficult to use.

Deep-discharge batteries used in solar power backup applications in general have lower charging and discharging rate characteristics and are more efficient.

In general, all batteries used in PV systems are lead-acid type batteries. Alkaline-type batteries are used only in exceptionally low temperature conditions of below –50°F. Alkaline batteries are expensive to buy and due to the hazardous contents are very expensive to dispose off.

BATTERY LIFE SPAN

The life span of a battery will vary considerably with how it is used, how it is maintained and charged, the temperature, and other factors. In extreme cases, it can be damaged within 10 to 12 months of use when overcharged. On the other hand if the battery is maintained properly, the life span could be extended over 25 years. Another factor that can shorten the life expectancy by a significant amount is when the batteries are stored uncharged in a hot storage area. Even dry charged batteries when sitting on a shelf have a maximum life span of about 18 months; as a result most are shipped from the factory with damp plates. As a rule, deep-cycle batteries can be used to start and run marine engines. In general, when starting, engines require a very large inrush of current for a very short time. Regular automotive starting batteries have a large number of thin plates for maximum surface area. The plates, as described earlier, are constructed from impregnated lead paste grids similar in appearance to a very fine foam sponge. This gives a very large surface area, and when deep-cycled, the grid plates quickly become consumed and fall to the bottom of the cells in the form of sediment. If automotive batteries are deep-cycled, they will generally fail after 30 to 150 deep cycles, whereas they may last for thousands of cycles in normal starting use discharge conditions. Deep-cycle batteries are designed to be discharged down time after time and are designed with thicker plates.

The major difference between a true deep-cycle battery and regular batteries is that the plates in a deep-cycle battery are made from solid lead plates and are not impregnated with lead oxide paste. Figure 3.11 shows a typical solar battery bank system.

Figure 3.11 **Deep-cycle battery bank system.** *Courtesy of Solar Integrated Technologies.*

Stored energy in batteries in general is discharged rapidly. For example, short bursts of power are needed when starting an automobile on a cold morning, which results in high amounts of current being rushed from the battery to the starter. The standard unit for energy or work is the joule (J), which is defined as 1 watt-second of mechanical work performed by a force of 1 newton (N) or 0.227 pound (lb) pushing or moving a distance of 1 meter (m). Since 1 hour has 3600 seconds, 1 watt-hour (Wh) is equal to 3600 J. The stored energy in batteries is either measured in milliampere-hours if small or ampere-hours if large. Battery ratings are converted to energy if their average voltages are known during discharge. In other words, the average voltage of the battery is maintained relatively unchanged during the discharge cycle. The value in joules can also be converted into various other energy values as follows:

Joules divided by 3,600,000 yields kilowatt-hours.

Joules divided by 1.356 yields English units of energy foot-pounds.

Joules divided by 1055 yields British thermal units.

Joules divided by 4184 yields calories.

BATTERY POWER OUTPUT

In each instance when power is discharged from a battery, the battery's energy is drained. The total quantity of energy drained equals the amount of power multiplied by the time the power flows. Energy has units of power and time, such as kilowatt-hours or watt-seconds. The stored battery energy is consumed until the available voltage and current levels of the battery are exhausted. Upon depletion of stored energy, batteries are recharged over and over again until they deteriorate to a level where they must be replaced by new units. High-performance batteries in general have the following notable characteristics. First, they must be capable of meeting the power demand requirements of the connected loads by supplying the required current while maintaining a constant voltage, and they must have sufficient energy storage capacity to maintain the load power demand as long as required. In addition, they must be as inexpensive and economical as possible and be readily replaced and recharged.

BATTERY INSTALLATION AND MAINTENANCE

Unlike many electrical apparatuses, standby batteries have specific characteristics that require special installation and maintenance procedures, which if not followed can impact the quality of the battery performance.

Battery types As mentioned earlier, the majority of today's emergency power systems make use of two types of batteries, namely, lead-acid and nickel-cadmium (NiCd). Within the lead-acid family, there are two distinct categories, namely, flooded or vented (filled with liquid acid) and valve-regulated lead acid (VRLA, immobilized acid).

Lead-acid and NiCd batteries must be kept dry at all times and in cool locations, preferably below 70°F, and must not be stored for long in warm locations. Materials such as conduit, cable reels, and tools must be kept away from the battery cells.

Battery installation safety What separates battery installers from the layperson is the level of awareness and respect for dc power. Energy stored in the battery cell is quite high, and sulfuric acid (lead-acid batteries) or potassium hydroxide (a base used in NiCd batteries) electrolytes could be very harmful if not handled professionally. Care should always be exercised when handling these cells. Use of chemical-resistant gloves, goggles, and a face shield, as well as protective sleeves, is highly recommended. The battery room must be equipped with an adequate shower or water sink to provide for rinsing of the hands and eyes in case of accidental contact with the electrolytes. Stored energy in a single NiCd cell of 100-Ah capacity can produce about 3000 A if short circuited between the terminal posts. Also, a fault across a lead-acid battery can send shrapnel and terminal post material flying in any direction, which can damage the cell and endanger workers.

Rack cabinet installation Stationary batteries must be mounted on open racks or on steel or fiberglass racks or enclosures. The racks should be constructed and maintained in a level position and secured to the floor and must have a minimum of 3 feet of walking space for egress and maintenance.

Open racks are preferable to enclosures since they provide a better viewing of electrolyte levels and plate coloration, as well as easier access for maintenance. For multistep or bleacher-type racks, batteries should always be placed at the top or rear of the cabinet to avoid anyone having to reach over the cells. Always use the manufacturer-supplied connection diagram to ensure the open positive and negative terminals when charging the cells. In the event of installation schedule delays, if possible, delay delivery.

BATTERY SYSTEM CABLES

Appendix A provides code-rated dc cable tables for a variety of battery voltages and feed capacities. The tables provide American Wire Gauge (AWG) conductor gauges and voltage drops calculated for a maximum of a 2 percent drop. Whenever larger drops are permitted, the engineer must refer to NEC tables and perform specific voltage drop calculations.

CHARGE CONTROLLERS

A charge controller is essentially a current-regulating device that is placed between the solar panel array output and the batteries. These devices are designed to keep batteries charged at peak power without overcharging. Most charge controllers incorporate special electronics that automatically equalize the charging process.

DC FUSES

All fuses used as overcurrent devices, which provide a point of connection between PV arrays and collector boxes, must be dc rated. Fuse ratings for dc branch circuits, depending on wire ampacities, are generally rated from 15 to 100 A. The dc-rated fuses familiar to solar power contractors are manufactured by a number of companies such as Bussman, Littlefuse, and Gould and can be purchased from electrical suppliers.

Various manufacturers identify the fuse voltage by special capital letter designations. The following are a sample of time-delay type fuse designations used by various manufacturers.

Bussman

Voltage rating up to 125 V dc and current ampacity range of 1 to 600 A– Special fuse designation for this class of fuse is FRN-R.

Voltage rating up to 300 V dc and current ampacity range of 1 to 600 A– Special fuse designation for this class of fuse is FRS-R.

Littlefuse

Voltage rating up to 600 V dc and current ampacity range of 1 to 600 A– IDSR.

Photovoltaic output as a rule must be protected with extremely fast-acting fuses. The same fuses can also be utilized within solar power control equipment and collector boxes. Some of the fast-acting fuses used are manufactured by the same companies listed before:

Bussman

Midget fast-acting fuse, ampacity rating 0.1 to 30 A– Special fuse designation for this class of fuse is ATM.

JUNCTION BOXES AND EQUIPMENT ENCLOSURES

All junction boxes utilized for interconnecting raceways and conduits must be of waterproof construction and be designed for outdoor installation. All equipment boxes, such as dc collectors must either be classified as MENA 3R or NEMA 4X.

Solar Power System Wiring

This section covers solar power wiring design and is intended to familiarize engineers and system integrators with some of the most important aspects related to personnel safety and hazards associated with solar power projects.

Residential and commercial solar power systems, up until a decade ago, because of a lack of technology maturity and higher production costs, were excessively expensive and did not have sufficient power output efficiency to justify a meaningful return on investment. Significant advances in solar cell research and manufacturing technology have recently rendered solar power installation a viable means of electric power cogeneration in residential and commercial projects.

As a result of solar power rebate programs available throughout the United States, Europe, and most industrialized countries, solar power industries have flourished and expanded their production capacities in the past 10 years and are currently offering reasonably cost effective products with augmented efficiencies.

In view of constant and inevitable fossil fuel-based energy cost escalation and availability of worldwide sustainable energy rebate programs, solar power because of its inherent reliability and longevity, has become an important contender as one of the most viable power cogeneration investments afforded in commercial and industrial installations.

In view of the newness of the technology and constant emergence of new products, installation and application guidelines controlled by national building and safety organizations such as the National Fire Protection Association, which establishes the guidelines for the National Electrical Code (NEC), have not been able to follow up with a number of significant matters related to hazards and safety prevention issues.

In general, small-size solar power system wiring projects, such as residential installations commonly undertaken by licensed electricians and contractors who are trained in life safety installation procedures, do not represent a major concern. However, large installations where solar power produced by photovoltaic arrays generates several hundred volts of dc power require exceptional design and installation measures.

An improperly designed solar power system in addition to being a fire hazard can cause very serious burns and in some instances result in fatal injury. Additionally, an improperly designed solar power system can result in a significant degradation of power production efficiency and minimize the return on investment.

Some significant issues related to inadequate design and installation include improperly sized and selected conductors, unsafe wiring methods, inadequate overcurrent protection, unrated or underrated choice of circuit breakers, disconnect switches, system grounding, and numerous other issues that relate to safety and maintenance.

At present the NEC in general covers various aspects of photovoltaic power generation systems; however, it does not cover special application and safety issues. For example, in a solar power system a deep-cycle battery backup with a nominal 24 V and 500 Ah can discharge thousands of amperes of current if short circuited. The enormous energy generated in such a situation can readily cause serious burns and fatal injuries.

Unfortunately most installers, contractors, electricians, and even inspectors who are familiar with the NEC most often do not have sufficient experience and expertise with dc power system installation; as such requirements of the NEC are seldom met. Another significant point that creates safety issues is related to material and components used, which are seldom rated for dc applications.

Electrical engineers and solar power designers who undertake solar power system installations of 10 kWh or more (nonpackaged systems) are recommended to review 2005 NEC Section 690 and the suggested solar power design and installation practices report issued by Sandia National Laboratories.

To prevent the design and installation issues discussed, system engineers must ensure that all material and equipment used are approved by Underwriters Laboratories. All components such as overcurrent devices, fuses, and disconnect switches are dc rated. Upon completion of installation, the design engineer should verify, independently of the inspector, whether the appropriate safety tags are permanently installed and attached to all disconnect devices, collector boxes, and junction boxes and verify if system wiring and conduit installation comply with NEC requirements. The recognized materials and equipment testing organizations that are generally accredited in the United States and Canada are Underwriters Laboratories (UL), Canadian Standards Association (CSA), and Testing Laboratories (ETL), all of which are registered trademarks that commonly provide equipment certification throughout the North American continent.

Note that the NEC, with the exception of marine and railroad installation, covers all solar power installations, including stand-alone, grid-connected, and utility-interactive cogeneration systems. As a rule, the NEC covers all electrical system wiring and installations and in some instances has overlapping and conflicting directives that may not be suitable for solar power systems, in which case Article 690 of the code always takes precedence.

In general, solar power wiring is perhaps considered one of the most important aspects of the overall systems engineering effort; as such it should be understood and applied with due diligence. As mentioned earlier, undersized wiring or a poor choice of material application cannot only diminish system performance efficiency but can also create a serious safety hazard for maintenance personnel.

WIRING DESIGN

Essentially solar power installations include a hybrid of technologies consisting of basic ac and dc electric power and electronics—a mix of technologies, each requiring specific technical expertise. Systems engineering of a solar power system requires an intimate knowledge of all hardware and equipment performance and application requirements. In general, major system components such as inverters, batteries, and emergency power generators, which are available from a wide number of manufacturers, each have a unique performance specification specially designed for specific applications.

The location of a project, installation space considerations, environmental settings, choice of specific solar power module and application requirements, and numerous other parameters usually dictate specific system design criteria that eventually form the basis for the system design and material and equipment selection.

Issues specific to solar power relate to the fact that all installations are of the outdoor type, and as a result all system components, including the PV panel, support structures, wiring, raceways, junction boxes, collector boxes, and inverters must be selected and designed to withstand harsh atmospheric conditions and must operate under extreme temperatures, humidity, and wind turbulence and gust conditions. Specifically, the electrical wiring must withstand, in addition to the preceding environmental adversities, degradation under constant exposure to ultraviolet radiation and heat. Factors to be taken into consideration when designing solar power wiring include the PV module's short-circuit current (Isc) value, which represents the maximum module output when output leads are shorted. The short-circuit current is significantly higher than the normal or nominal operating current. Because of the reflection of solar rays from snow, a nearby body of water or sandy terrain can produce unpredicted currents much in excess of the specified nominal or Isc current. To compensate for this factor, interconnecting PV module wires are assigned a multiplier of 1.25 (25 percent) above the rated Isc.

PV module wires as per the NEC requirements are allowed to carry a maximum load or an ampacity of no more than 80 percent; therefore, the value of current-carrying capacity resulting from the previous calculation is multiplied by 1.25, which results in a combined multiplier of 1.56.

The resulting current-carrying capacity of the wires if placed in a raceway must be further derated for specific temperature conditions as specified in NEC wiring tables (Article 310, Tables 310.16 to 310.18).

All overcurrent devices must also be derated by 80 percent and have an appropriate temperature rating. Note that the feeder cable temperature rating must be the same as that for overcurrent devices. In other words, the current rating of the devices should be 25 percent larger than the total sum of the amount of current generated from a solar array. For overcurrent device sizing NEC Table 240-6 outlines the standard ampere ratings. If the calculated value of a PV array somewhat exceeds one of the standard ratings of this table, the next highest rating should be chosen.

All feeder cables rated for a specific temperature should be derated by 80 percent or the ampacity multiplied by 1.25. Cable ratings for 60, 75, and 90°C are listed in NEC Tables 310.16 and 310.17. For derating purposes it is recommended that cables rated for 75°C ampacity should use 90°C column values. Various device terminals, such as terminal block overcurrent devices must also have the same insulation rating as the cables. In other words, if the device is in a location that is exposed to a higher temperature than the rating of the feeder cable, the cable must be further derated to match the terminal connection device. The following example is used to illustrate these design parameter considerations.

A wiring design example Assuming that the short-circuit current Isc from a PV array is determined to be 40 A, the calculation should be as follows:

1. PV array current derating = 40 × 1.25 = 50 A.
2. Overcurrent device fuse rating at 75°C = 50 × 1.25 = 62.5 A.
3. Cable derating at 75°C = 50 × 1.25 = 62.5. Using NEC Table 310-16, under the 75°C columns we find a cable AWG #6 conductor that is rated for 65-A capacity. Because of ultraviolet (UV) exposure, XHHW-2 or USE-2 type cable, which has a 75-A capacity, should be chosen. Incidentally, the "–2" is used to designate UV exposure protection. If the conduit carrying the cable is populated or filled with four to six conductors, it is suggested, as previously, by referring to NEC Table 310-15(B)(2)(a), that the conductors be further derated by 80 percent. At an ambient temperature of 40 to 45°C a derating multiplier of 0.87 is also to be applied: 75 A × 0.87 = 52.2 A. Since the AWG #6 conductor chosen with an ampacity of 60 is capable of meeting the demand, it is found to be an appropriate choice.
4. By the same criteria the closest overcurrent device, as shown in NEC Table 240.6, is 60 A; however, since in step 2 the overcurrent device required is 62.5 A, the AWG #6 cable cannot meet the rating requirement. As such, an AWG #4 conductor must be used. The chosen AWG #4 conductor under the 75°C column of Table 310-16 shows an ampacity of 95.

If we choose an AWG #4 conductor and apply conduit fill and temperature derating, then the resulting ampacity is 95 × 0.8 × 0.87 = 66 A; therefore, the required fuse per NEC Table 240-6 will be 70 A.

Conductors that are suitable for solar exposure are listed as THW-2, USE-2, and THWN-2 or XHHW-2. All outdoor installed conduits and wireways are considered to be operating in wet, damp, and UV-exposed conditions. As such, conduits should be capable of withstanding these environmental conditions and are required to be of a thick wall type such as rigid galvanized steel (RGS), intermediate metal conduit (IMC), thin wall electrical metallic (EMT), or schedule 40 or 80 polyvinyl chloride (PVC) nonmetallic conduits.

For interior wiring, where the cables are not subjected to physical abuse, special NEC code approved wires must be used. Care must be taken to avoid installation of underrated cables within interior locations such as attics where the ambient temperature can exceed the cable rating.

Conductors carrying dc current are required to use color coding recommendations as stipulated in Article 690 of the NEC. Red wire or any color other than green and white is used for positive conductors, white for negative, green for equipment grounding, and bare copper wire for grounding. The NEC allows nonwhite grounded wires, such as USE-2 and UF-2, that are sized #6 or above to be identified with a white tape or marker.

As mentioned earlier, all PV array frames, collector panels, disconnect switches, inverters, and metallic enclosures should be connected together and grounded at a single service grounding point.

PHOTOVOLTAIC SYSTEM GROUND-FAULT PROTECTION

When a photovoltaic system is mounted on the roof of a residential dwelling, NEC requirements dictate the installation of ground-fault protection (detection and interrupting) devices (GFPD). However, ground-mounted systems are not required to have the same protection since most grid-connected system inverters incorporate the required GFPDs.

Ground-fault detection and interruption circuitry perform ground-fault current detection, fault current isolation, and solar power load isolation by shutting down the inverter. This technology is currently going through a developmental process, and it is expected to become a mandatory requirement in future installations.

PV SYSTEM GROUNDING

Photovoltaic power systems that have an output of 50 V dc under open-circuit conditions are required to have one of the current-carrying conductors grounded. In electrical engineering, the terminologies used for grounding are somewhat convoluted and confusing. In order to differentiate various grounding appellations it would be helpful to review the following terminologies as defined in NEC Articles 100 and 250.

Grounded. Means that a conductor connects to the metallic enclosure of an electrical device housing that serves as earth.

Grounded conductor. A conductor that is intentionally grounded. In PV systems it is usually the negative of the dc output for a two-wire system or the center-tapped conductor of an earlier bipolar solar power array technology.

Equipment grounding conductor. A conductor that normally does not carry current and is generally a bare copper wire that may also have a green insulator cover. The conductor is usually connected to an equipment chassis or a metallic enclosure that provides a dc conduction path to a ground electrode when metal parts are accidentally energized.

Grounding electrode conductor. A conductor that connects the grounded conductors to a system grounding electrode, which is usually located only in a single location within the project site, and does not carry current. In the event of the accidental shorting of equipment the current is directed to the ground, which facilitates actuation of ground-fault devices.

Grounding electrode. A grounding rod, a concrete-encased ultrafiltration rate (UFR) conductor, a grounding plate, or simply a structural steel member to which a grounding electrode conductor is connected. As per the NEC all PV systems—whether grid-connected or stand-alone, in order to reduce the effects of lightning and provide a measure of personnel safety—are required to be equipped with an adequate grounding system. Incidentally, grounding of PV systems substantially reduces radio-frequency noise generated by inverter equipment.

In general, grounding conductors that connect the PV module and enclosure frames to the ground electrode are required to carry full short-circuited current to the ground; as such, they should be sized adequately for this purpose. As a rule, grounding conductors larger than AWG #4 are permitted to be installed or attached without special protection measures against physical damage. However, smaller conductors are required to be installed within a protective conduit or raceway. As mentioned earlier, all ground electrode conductors are required to be connected to a single grounding electrode or a grounding bus.

EQUIPMENT GROUNDING

Metallic enclosures, junction boxes, disconnect switches, and equipment used in the entire solar power system, which could be accidentally energized are required to be grounded. NEC Articles 690, 250, and 720 describe specific grounding requirements. NEC Table 25.11 provides equipment grounding conductor sizes. Equipment grounding conductors similar to regular wires are required to provide 25 percent extra ground current-carrying capacity and are sized by multiplying the calculated ground current value by 125 percent. The conductors must also be oversized for voltage drops as defined in NEC Article 250.122(B).

In some installations bare copper grounding conductors are attached along the railings that support the PV modules. In installations where PV current-carrying conductors are routed through metallic conduits, separate grounding conductors could be eliminated since the metallic conduits are considered to provide proper grounding when adequately coupled. It is, however, important to test conduit conductivity to ensure that there are no conduction path abnormalities or unacceptable resistance values.

Entrance Service Considerations for Grid-Connected Solar Power Systems

When integrating a solar power cogeneration within an existing or new switchgear, it is of the utmost importance to review NEC 690 articles related to switchgear bus capacity.

As a rule, when calculating switchgear or any other power distribution system bus ampacity, the total current-bearing capacity of the bus bars is not allowed to be loaded more than 80 percent of the manufacturer’s equipment nameplate rating. In other words, a bus rated at 600 A cannot be allowed to carry a current burden of more than 480 A.

When integrating a solar power system with the main service distribution switchgear, the total bus current-bearing capacity must be augmented by the same amount as the current output capacity of the solar system. For example, if we were to add a 200-A solar power cogeneration to the switchgear, the bus rating of the switchgear must in fact be augmented by an extra 250 A. The additional 50 A represents an 80 percent safety margin for the solar power output current. Therefore, the service entrance switchgear bus must be changed from 600 to 1000 A or at a minimum to 800 A.

As suggested earlier, the design engineer must be fully familiar with the NEC 690 articles related to solar power design and ensure that solar power cogeneration system electrical design documents become an integral part of the electrical plan check submittal documents.

The integrated solar power cogeneration electrical documents must incorporate the solar power system components such as the PV array systems, solar collector distribution panels, overcurrent protection devices, inverters, isolation transformers, fused service disconnect switches, and net metering within the plans and must be considered as part of the basic electrical system design.

Electrical plans should incorporate the solar power system configuration in the electrical single-line diagrams, panel schedule, and demand load calculations. All exposed, concealed, and underground conduits must also be reflected on the plans with distinct design symbols and identification that segregate the regular and solar power system from the electrical systems.

Note that the solar power cogeneration and electrical grounding should be in a single location, preferably connected to a specially designed grounding bus, which must be located within the vicinity of the main service switchgear.

Lightning Protection

In geographic locations, such as Florida, where lightning is a common occurrence, the entire PV system and outdoor-mounted equipment must be protected with appropriate lightning arrestor devices and special grounding that could provide a practical mitigation and a measure of protection from equipment damage and burnout.

LIGHTNING'S EFFECT ON OUTDOOR EQUIPMENT

Lightning surges are comprised of two elements, namely voltage and the quantity of charge delivered by lightning. The high voltage delivered by lightning surges can cause serious damage to equipment since it can break down the insulation that isolates circuit elements and the equipment chassis. The nature and the amount of damage are directly proportional to the amount of current resulting from the charge.

In order to protect equipment damage from lightning, devices known as surge protectors or arrestors are deployed. The main function of a surge arrestor is to provide a direct conduction path for lightning charges to divert them from the exposed equipment chassis to the ground. A good surge protector must be able to conduct a sufficient current charge from the stricken location and lower the surge voltage to a safe level quickly enough to prevent insulation breakdown or damage.

In most instances all circuits have a capacity to withstand certain levels of high voltages for a short time; however, the thresholds are so narrow that if charges are not removed or isolated in time, the circuits will sustain an irreparable insulation breakdown.

The main purpose of a surge arrestor device is, therefore, to conduct the maximum amount of charge and reduce the voltage in the shortest possible time. Reduction of a voltage surge is referred to as clamping, shown in Figures 3.12 and 3.13. Voltage clamping in

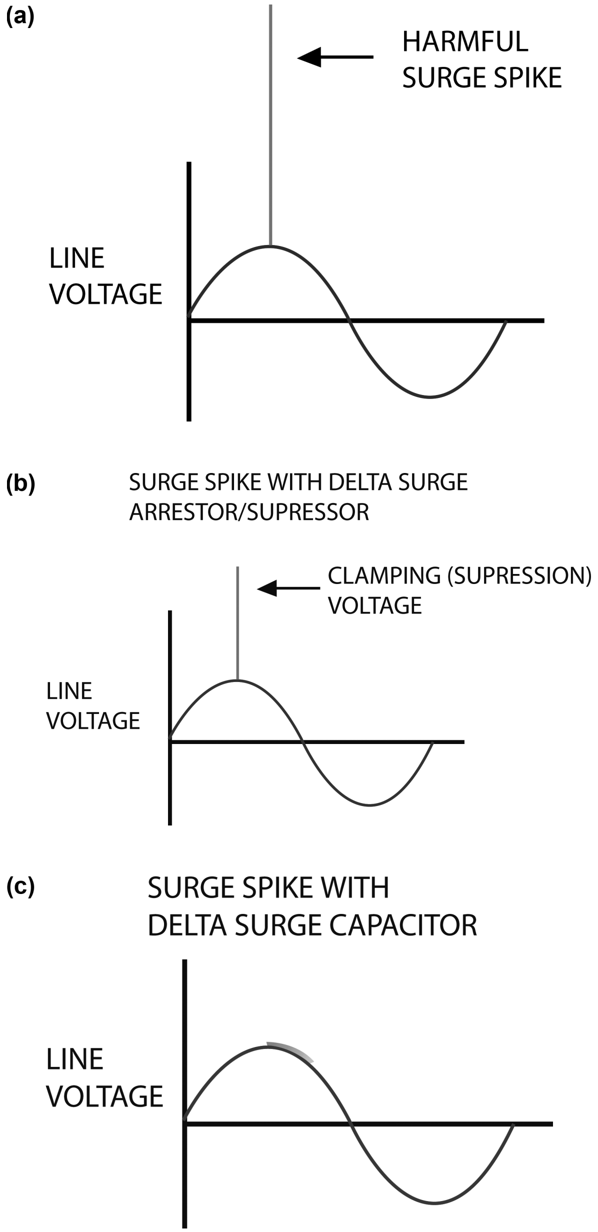


Figure 3.12 **Effect of (a) lightning surge spike (b) lightning surge spike clamping, and (c) lightning surge spike suppression.**

Courtesy of Delta Surge Arrestor.

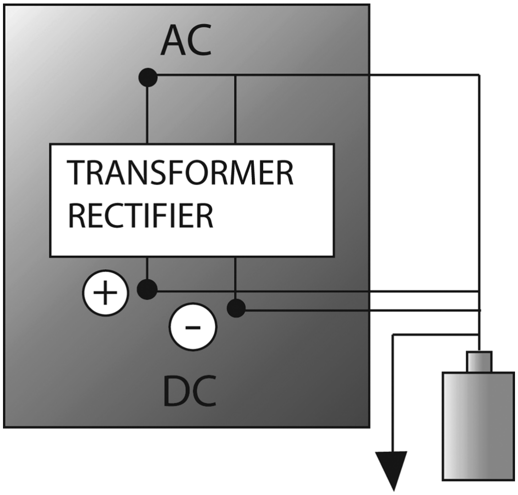


Figure 3.13 Deployment of a lightning surge arrestor in a rectifier circuit.

general depends on device characteristics such as internal resistance, the response speed of the arrestor, and the point in time at which the clamping voltage is measured.

When specifying a lightning arrestor, it is necessary to take into account the clamping voltage and the amount of current to be clamped, for example, 500 V and 1000 A. Let us consider a real-life situation where the surge rises from 0 to 50,000 V in 5 nanoseconds (ns). At any time during the surge, say at 100 ns, the voltage clamping would be different from say the lapsed time, at 20 ns, where the voltage could have been 25,000 V; nevertheless, the voltage will be arrested, since high current rating will cause adequate conductivity which will remove the surge current from the circuit rapidly and will therefore provide better protection.

The following is a specification for a Delta lightning arrestor rated for 2300 V and designed for secondary service power equipment such as motors, electrical panels, transformers, and solar power cogeneration systems.

Model 2301–2300 series specification

Type of design: silicone oxide varistor

Maximum current capacity: 100,000 A

Maximum energy dissipations: 3000 J per pole

Maximum time of 1-mA test: 5 ns

Maximum number of surges: unlimited

Response time to clamp 10,000 A: 10 ns

Response time to clamp 25,000 A: 25 ns

Leak current at double the rated voltage: none

Case material: PVC

Central Monitoring and Logging System Requirements

In large commercial solar power cogeneration systems, power production from the PV arrays is monitored by a central monitoring system that provides a log of operation performance parameters. The central monitoring station consists of a PC-type computer that retrieves operational parameters from a group of solar power inverters by means of an RS-232 interface, a power line carrier, or wireless communication system. Upon receipt of performance parameters, a supervisory software program processes the information and provides data in display or print format. Supervisory data obtained from the file can also be accessed from distant locations through Web networking.

Some examples of monitored data are:

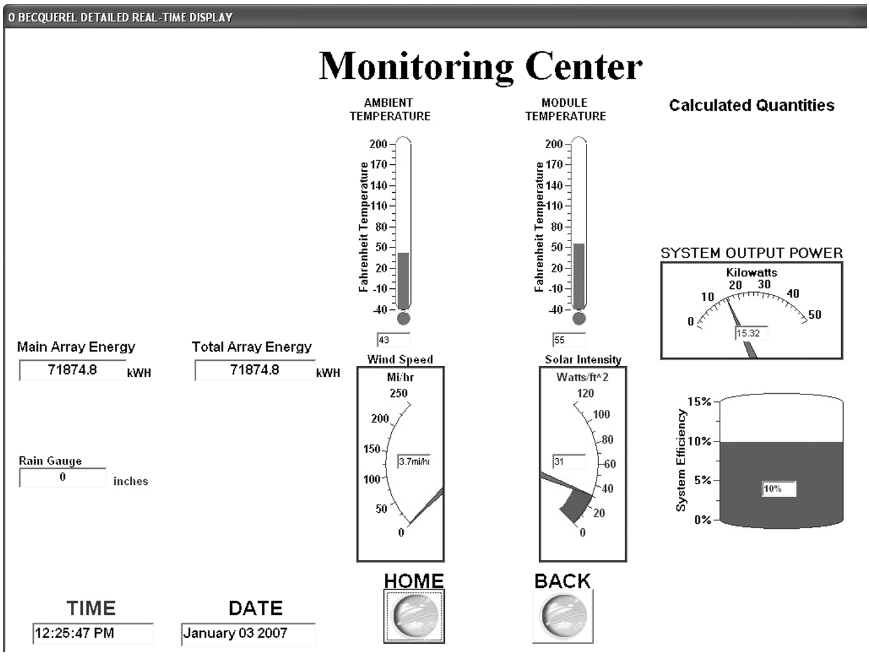
- Weather-monitoring data
- Temperature
- Wind velocity and direction
- Solar power output
- Inverter output
- Total system performance and malfunction
- Direct-current power production
- Alternating-current power production
- Accumulated, daily, monthly, and yearly power production

The following is an example of a data acquisition system by Heliotronics referred to as Sunlogger, which has been specifically developed to monitor and display solar power cogeneration parameters.

SUN VIEWER DATA ACQUISITION SYSTEM

The following solar power monitoring system by Heliotronics, called the Sun Viewer, is an example of an integrated data acquisition system that has been designed to acquire and display real-time performance parameters by filed installed electric power and atmospheric measurement sensors. The system, in addition to providing vital system performance data monitoring and measurement, provides the means to view instantaneous real-time and historical statistical energy measurement data essential for system performance evaluation, research, and education. Figure 3.14 depicts a typical presentation of field measurement on a display monitor.

The system hardware configuration of the Sun Viewer consists of a desk to computer based data logging software that processes and displays measured solar power photovoltaic array and atmospheric output parameters from the following sensors and equipment:



Main Array Energy
71874.8 kWH

Total Array Energy
71874.8 kWH

Rain Gauge
0 inches

TIME
12:25:47 PM

DATE
January 03 2007

Figure 3.14 **Depiction of a typical presentation of field measurement on a display monitor.** *Graphics courtesy of Heliotronics.*

Meteorological data measurements An anemometer is a meteorological instrument that provides the following meteorological measurements:

- Ambient air temperature sensor
- Wind speed
- Outdoor air temperature sensor
- Pyrometer for measuring solar insolation

Photovoltaic power output performance measurement sensors

- AC current and voltage transducer
- DC current and voltage transducer
- Kilowatt-hour meter transducer
- Optically isolated RS-422 or RS-232C modem

Sun Viewer display and Sun Server monitoring software The Sun Viewer display and Sun Server monitoring software provide acquisition and display of real-time data every second and display the following on a variety of display monitors:

- DC current
- DC voltage

- AC current
- AC voltage
- AC kilowatt-hours
- Solar plane of array irradiance
- Ambient temperature
- Wind speed

The calculated parameters displayed include:

- AC power output
- Sunlight conversion efficiency to ac power
- Sunlight conversion efficiency to dc power
- Inverter dc-to-ac power conversion efficiency
- Avoided pollutant emissions of CO_2, SO_x, NO_x gases

The preceding information and calculated parameter are displayed on monitors and updated once every second. The data are also averaged every 15 minutes and stored in a locally accessible database. The software includes a “Virtual Array Tour” that allows observers to analyze the solar photovoltaic component of the photovoltaic array and monitoring system. It also provides an optional portal Web capability whereby the displayed data could be monitored from a remote distance over the Internet.

The monitoring and display software can also be customized to incorporate descriptive text, photographs, schematic diagrams, and user-specific data. Some of the graphing capabilities of the system include the following:

- Average plots of irradiance, ambient temperature, and module temperature that are updated every 15 minutes and averaged over one day.
- Daily values or totals of daily energy production, peak daily power, peak daily module temperature, and peak daily irradiance plotted over a specified month.
- Monthly values of energy production; incident solar irradiance; and avoided emission of CO_2, NO_x, and SO_x plotted over a specified year.

GENERAL DESCRIPTION OF A MONITORING SYSTEM

The central monitoring system discussed here reflects the actual configuration of the Water and Life Museum project, located in Hemet, California, and was designed by the author. This state-of-the-art monitoring system provides a real-time interactive display for education and understanding of photovoltaics and the solar electric installation as well as monitoring of the solar electric system for maintenance and troubleshooting purposes.

The system is made up of wireless inverter data transmitters, a weather station, a data storage computer, and a data display computer with a 26-in LCD screen. In the Water and Life Museum project configuration, the inverters, which are connected in parallel, output data to wireless transmitters located in their close proximity. Wireless transmitters throughout the site transmit data to a single central receiver located in a central data gathering and monitoring center. The received data are stored and analyzed using the sophisticated software in computer-based supervisory systems that also serve as a data-maintenance interface for the solar power system. A weather station also transmits weather-related information to the central computer.

The stored data are analyzed and forwarded to a display computer that is used for data presentation and storing information, such as video, sound, pictures, and text file data.

DISPLAYED INFORMATION

A standard display will usually incorporate a looping background of pictures from the site, graphical overlays of the power generation in watts and watt-hours for each building, and the environmental impact from the solar system. The display also shows current meteorological conditions.

Displayed data in general should include the following combination of items:

Project location (on globe coordinates—zoom in and out)

Current and historic weather conditions

Current positions of the sun and moon, with the date and time

Power generation from the total system and/or the individual solar power arrays

Historic power generation

Solar system environmental impact

Looping background solar system photos and videos

Educational PowerPoint presentations

Installed solar electric power overview

Display of renewable energy system environmental impact statistics

The display should also be programmed to periodically show additional information related to the building's energy management or the schedule of maintenance relevant to the project:

Weather station transmitted data. Transmitted data from the weather monitoring station should include air temperature, solar cell temperature, wind speed, wind direction, and sun intensity measured using a pyrometer.

Inverter monitoring transmitted data. Each inverter must incorporate a watt-hour transducer that will measure dc and ac voltage, current, and power; ac frequency; watt-hour accumulation; and inverter error codes and operation.

Typical central monitoring computer. The central supervising system must be configured with a CPU with a minimum of 3 GHz of processing power, 512 kilobytes of random-access memory (RAM), and a 60-gigabyte (Gbyte) hard drive. The operating system should preferably be based on Windows XP or an equivalent system operating software platform.

Wireless transmission system specification. Data communication system hardware must be based upon a switch selectable RS-232/422/485 communication transmission protocol, have a software selectable data transmission speed of 1200 to 57,600 bits/s, and be designed to have several hop sequences share multiple frequencies. The system must also be capable of frequency hopping from 902 to 928 MHz on the FM bandwidth and be capable of providing transparent multipoint drops.

ANIMATED VIDEO AND INTERACTIVE PROGRAMMING REQUIREMENTS

A graphical program builder must be capable of animated video and interactive programming and have an interactive animation display feature for customizing the measurements listed earlier. The system must also be capable of displaying various customizable chart attributes, such as labels, trace color and thickness, axis scale, limits, and ticks. The interactive display monitor should preferably have a 30- to 42-in LCD or light-emitting diode (LED) flat monitor and a 17- to 24-in touch screen display system.

Ground-Mount Photovoltaic Module Installation and Support Hardware

Ground-mount outdoor photovoltaic array installations can be configured in a wide variety of ways. The most important factor when installing solar power modules is the PV module orientation and panel incline. A ground-mount solar power installation is shown in Figure 3.15.

In general, the maximum power from a PV module is obtained when the angle of solar rays impinge directly perpendicular (at a 90-degree angle) to the surface of the panels. Since solar ray angles vary seasonally throughout the year, the optimum average tilt angle for obtaining the maximum output power is approximately the local latitude minus 9 or 10 degrees (see Appendix B for typical PV support platforms and hardware and Appendix A for tilt angle installations for the following cities in California: Los Angeles, Daggett, Santa Monica, Fresno, and San Diego).

In the northern hemisphere, PV modules are mounted in a north-south tilt (high end north) and in the southern hemisphere, in a south-north tilt. Appendix A also includes U.S. and world geographic location longitudes and latitudes.

To attain the required angle, solar panels are generally secured on tilted prefabricated or field-constructed frames that use rustproof railings, such as galvanized Unistrut or commercially available aluminum or stainless-steel angle channels, and

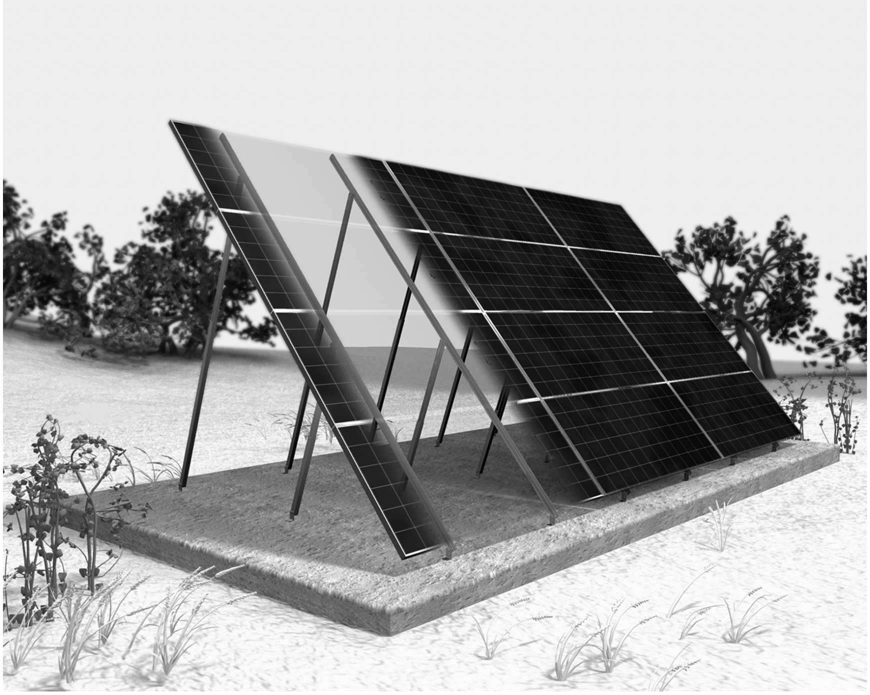


Figure 3.15 **A typical ground mount solar power installation used in solar farms.** *Courtesy of UniRac.*

fastening hardware, such as nuts, bolts, and washers. Prefabricated solar power support systems are also available from UniRac and several other manufacturers.

When installing solar support pedestals, also known as stanchions, attention must be paid to structural design requirements. Solar power stanchions and pedestals must be designed by a qualified, registered professional engineer. Solar support structures must take into consideration prevailing geographic and atmospheric conditions, such as maximum wind gusts, flood conditions, and soil erosion.

A typical ground-mount solar power installation includes agricultural grounds; parks and outdoor recreational facilities; carports; sanitariums; and large commercial solar power-generating facilities, also known as solar farms (see Figure 3.15). Most solar farms are owned and operated by electric energy-generating entities such as Edison. Prior to the installation of a solar power system, structural and electrical plans must be reviewed by local electrical service authorities, such as building and safety departments. Solar power installation must be undertaken by a qualified licensed electrical contractor with special expertise in solar power installations.

A solar mounting support system profile, shown in Figure 3.16, consists of a galvanized Unistrut railing frame that is field-assembled with standard commercially available manufactured components used in the construction industry. Basic frame components in general include a 2-in galvanized Unistrut channel, 90-degree and T-type connectors, spring-type channel nuts and bolts, and panel hold-down T-type or fender washers.

Figure 3.16 A single PV frame ground-mount solar power support.

Courtesy of UniRac.

The main frame that supports the PV modules is welded or bolted to a set of galvanized rigid metal round pipes or square channels. The foundation support is built from 12- to 18-in-diameter reinforced concrete cast in a sauna tube. Then, the metal support structure is secured to the concrete footing by means of expansion bolts. The depth of the footing and dimensions of channel hardware and method of PV module frame attachment are designed by a qualified structural engineer.

A typical solar power support structural design should withstand wind gusts from 80 to 120 miles per hour (mi/h). Prefabricated structures that are specifically designed for solar power applications are available from a number of manufacturers. Prefabricated solar power support structures, although somewhat more expensive, are usually designed to withstand 120-mi/h wind gusts and are manufactured from stainless steel, aluminum, or galvanized steel materials.

Roof-Mount Installations

Roof-mount solar power installations are made of either tilted or flat-type roof support structures or a combination of both. Installation hardware and methodologies also differ depending on whether the building already exists or is a new construction. Roof attachment hardware material also varies for wood-based and concrete constructions.

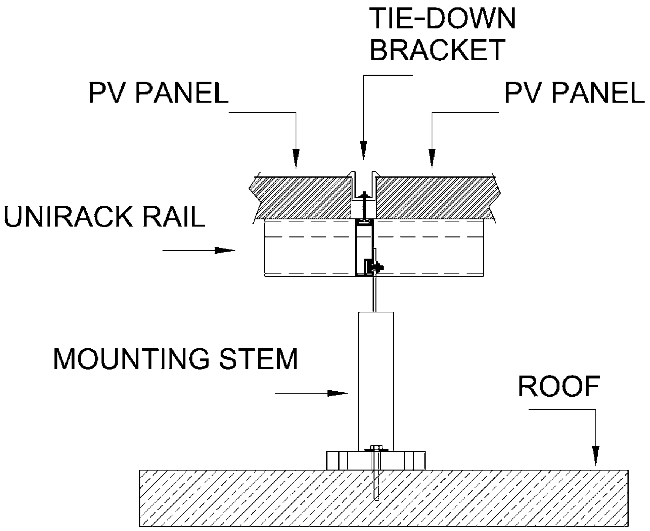


Figure 3.17 **Typical roof-mount solar power installation detail.** *Courtesy of Vector Delta Design Group.*

Figure 3.17 depicts a prefabricated PV module support railing system used for roof-mount installations.

WOOD-CONSTRUCTED ROOFING

In new constructions, the PV module support system installation is relatively simple since locations of solar array frame pods, which are usually secured on roof rafters, can be readily identified. Prefabricated roof-mount stands that support railings and associated hardware, such as fasteners, are commercially available from a number of manufacturers. Solar power support platforms are specifically designed to meet physical configuration requirements for various types of PV module manufacturers.

Some types of PV module installation, such as in Figure 3.18 and 3.19, have been designed for direct mounting on roof framing rafters without the use of specialty railing or support hardware. As mentioned earlier, when installing roof-mount solar panels, care must be taken to meet the proper directional tilt requirement. Another important factor to be considered is that solar power installations, whether ground or roof mounted, should be located in areas free of shade caused by adjacent buildings, trees, or air-conditioning equipment. In the event of unavoidable shading situations, the solar power PV module location, tilt angle, and stanchion separations should be analyzed to prevent cross shading. Figure 3.20 depicts a prefabricated PV module support railing for roof-mount by UniRac.

LIGHTWEIGHT CONCRETE-TYPE ROOFING

Solar power installation PV module support systems for concrete roofs are configured from prefabricated support stands and railing systems similar to the ones used in wooden

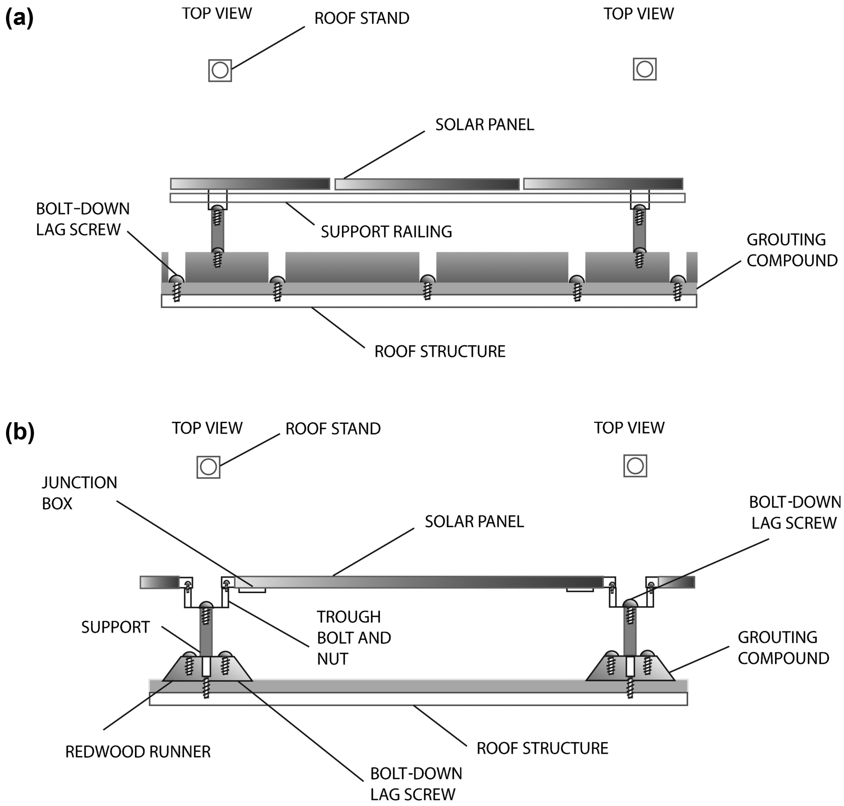


Figure 3.18 **Typical roof-mount solar power railing installation detail. (a) Side view. (b) Front view.** *Courtesy of Vector Delta Design Group.*

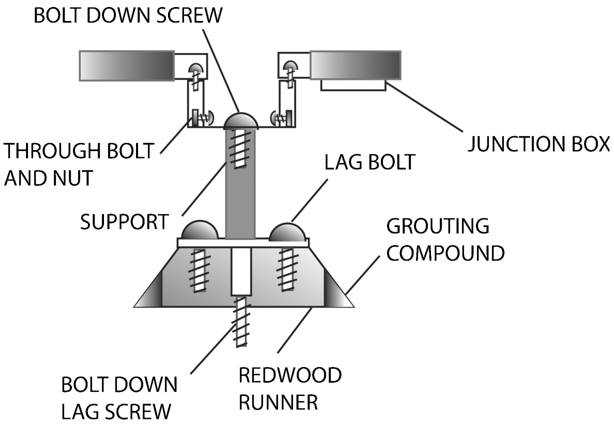


Figure 3.19 **Typical roof mount solar power railing installation penetration detail.** *Courtesy of Vector Delta design Group.*

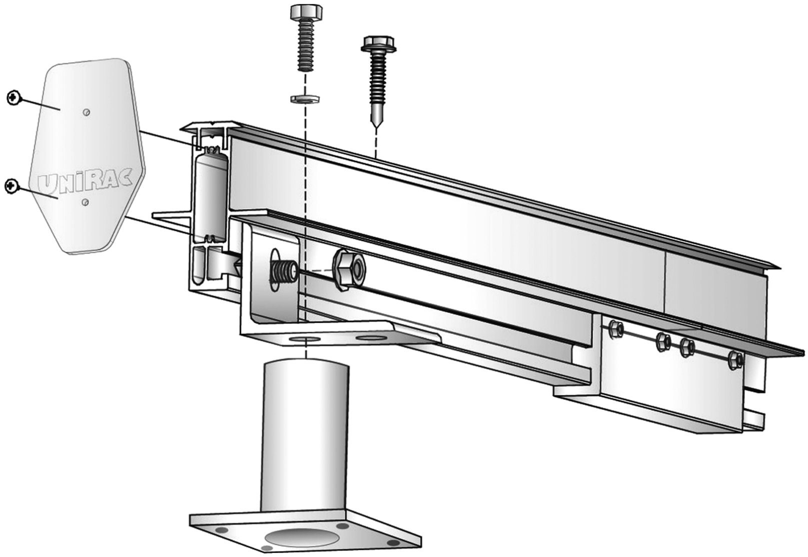


Figure 3.20 Prefabricated PV module support railing for roof-mount system. *Courtesy of UniRac.*

roof structures. Stanchions are anchored to the roof by means of rust-resistant expansion anchors and fasteners.

In order to prevent water leakage resulting from roof penetration, both wood and concrete standoff support pipe anchors are thoroughly sealed with waterproofing compounds. Each standoff support is fitted with thermoplastic boots that are in turn thermally welded to roof cover material, such as single-ply PVC. Figure 3.21 depicts a wood roof-mount standoff support railing system assembly detail.

PHOTOVOLTAIC STANCHION AND SUPPORT STRUCTURE TILT ANGLE

As discussed earlier, in order to obtain the maximum output from the solar power systems, PV modules or arrays must have an optimum tilt angle that will ensure a perpendicular exposure to sun rays. When installing rows of solar arrays, spacing between stanchions must be such that there should not be any cross shading. In the design of a solar power system, the available roof area is divided into a template format that compartmentalizes rows or columns of PV arrays.

BUILDING—INTEGRATED PHOTOVOLTAIC SYSTEMS

A custom-designed and manufactured photovoltaic module is called a building-integrated photovoltaic module (BIPV) shown in Figure 2.17. This type of solar panel is constructed by laminating individual solar cells in a desired configuration, specifically

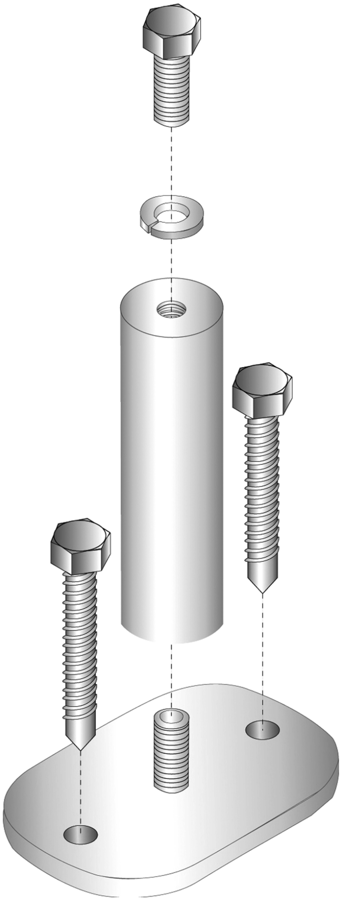


Figure 3.21 **Wood roof-mount standoff support railing system assembly detail.** *Courtesy of UniRac.*

designed to achieve a special visual effect, and are typically deployed in a solarium or trellis type of structure. Because of the separation gap between the adjacent cells, BIPV modules when compared to standard PV modules produce less energy per square foot of area.

Under operational conditions, when solar power systems actively generate power, a line carrying current at several hundred volts could pose serious burns or bodily injury and electric shock if exposed during the roof demolition process. To prevent injury under fire hazard conditions, all roof-mount equipment that can be accessed must be clearly identified with large red-on-white labels. Additionally, the input to the inverter from the PV collector boxes must be equipped with a crowbar disconnect switch that will short the output of all solar arrays simultaneously.

Solar Tracking Systems Tracking systems are support platforms that orient solar photovoltaic module assemblies by keeping track of the sun's movement from dusk to dawn, thus maximizing solar energy power generation efficiency. Trackers are classified as passive or active and may be constructed to track in single or dual axis.

Single-axis trackers usually have a single-axis tilt movement, whereas dual-axis trackers also move in regular intervals adjusting for an angular position as shown in Figure 3.23 through 3.27.

In general single-axis trackers compared to fixed stationary tilted PV support systems increase solar power capture by about 20 to 25 percent. Dual-axis trackers on the other hand can increase solar power production from 30 to 40 percent. Solar power concentrators which use Fresnel lenses to focus the sun's energy on a solar cell, require a high degree of tracking accuracy to ensure that the concentrated sunlight is focused precisely on the PV cell.

Fixed-axis systems orient the PV modules to optimize power production for a limited time performance and generally have a relatively low annual power production. On the other hand, single-axis trackers, although less accurate than dual-axis tracker applications, produce strong power in the afternoon hours and are deployed in applications such as grid-connected solar power farms that enhance power production in the morning and afternoon hours.

Compared to the overall cost of photovoltaic systems, trackers are relatively inexpensive devices that significantly increase the power output performance efficiency of the PV panels. Even though some tracker systems operate with some degree of reliability, they usually require seasonal position adjustments, inspection, and periodic lubrication.

Basic physics of solar intensity The amount of solar intensity of light that impinges upon the surface of solar photovoltaic panels is determined by an equation referred to as Lambert's cosine law, which states that the intensity of light (I) falling on a plane is directly proportional to the cosine of the angle (A) made by the direction of the light source to the normal of the plane:

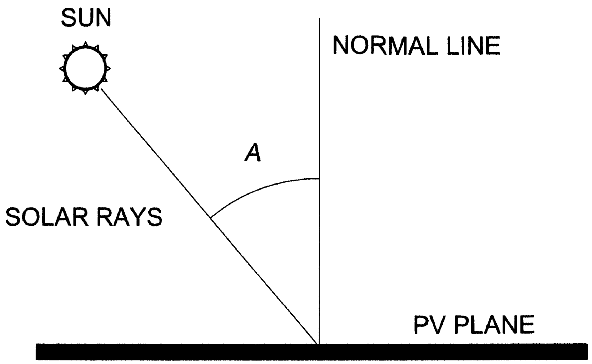
$$I = k \times \cos A$$

where k is Lambert's constant. This equation is depicted in Figure 3.22. In other words, during the summer when the angle of the sun is directly overhead, the magnitude of intensity is at its highest, since the cosine of the angle is zero; therefore, $\cos 0 = 1$, which implies $I = k$.

The main objective of all solar trackers is to minimize the value of the cosine angle and maximize the solar intensity on the PV planes.

Polar trackers Polar trackers are designed to have one axis rotate in the same pattern as Earth, hence the name. Essentially polar trackers are in general aligned perpendicular to an imaginary ecliptic disc that represents the apparent mathematical path of the sun. To maintain relative accuracy, these types of tracker are manually adjusted to compensate for the seasonal ecliptic shifts that occur with the seasons. Polar trackers are usually used in astronomical telescope mounts where high-accuracy solar tracking is an absolute requirement.

Horizontal—axle trackers Horizontal trackers are designed to orient a horizontal axle by either passive or active mechanisms. Essentially a long tubular axle is supported



$I = k \cos A$

I = SOLAR INTENSITY
k = LAMBERT'S CONSTANT
A = SOLAR ANGLE

Figure 3.22 Solar intensity equation diagram.

by several bearings that are secured to some type of wooden, metallic, or concrete pylon structure frame. The tubular axles are installed in a north-south orientation, whereas PV panels are mounted on the tubular axle that rotates on an east-west axis and tracks the apparent motion of the sun throughout daylight hours. Note that single-axis trackers do not tilt toward the equator. As a result their power tracking efficiency is significantly reduced in midwinter; however, their productivity increases substantially during the spring and summer seasons when the sun path is directly overhead in the sky. Because of the simplicity of their mechanism, horizontal-axle single-axis trackers are considered to be very reliable, easy to clean and maintain, and not subject to self-shading.

Passive trackers The rotational mechanism of a passive tracker is based on the use of low-boiling-point compressed gas fluids that are moved or displaced from the east to the west side by solar heat that converts the liquid to gas causing the tracker to tilt from one side to another. The imbalance created by the movement of the liquid-gas material creates the fundamental principle of bidirectional movement. Note that various climatic conditions such as temperature fluctuations, wind gusts, and solar clouding adversely affect the performance of passive solar trackers. As such they are considered to have unreliable tracking efficiency; however, they do provide better solar output performance capability than fixed-angle solar support platforms. Figure 3.23 depicts Zomeworks passive solar tracker component diagram.

One of the major passive solar tracker manufacturers is Zomeworks, which manufactures a series of tracking devices called Track Rack. Tracking devices begin tracking the sun by facing the racks westward. As the sun rises in the east, it heats an unshielded west side liquid-gas filled canister, forcing the liquid into the shaded east-side canister. As the liquid moves through a copper tube to the east-side canister, the tracker rotates so that it faces east.

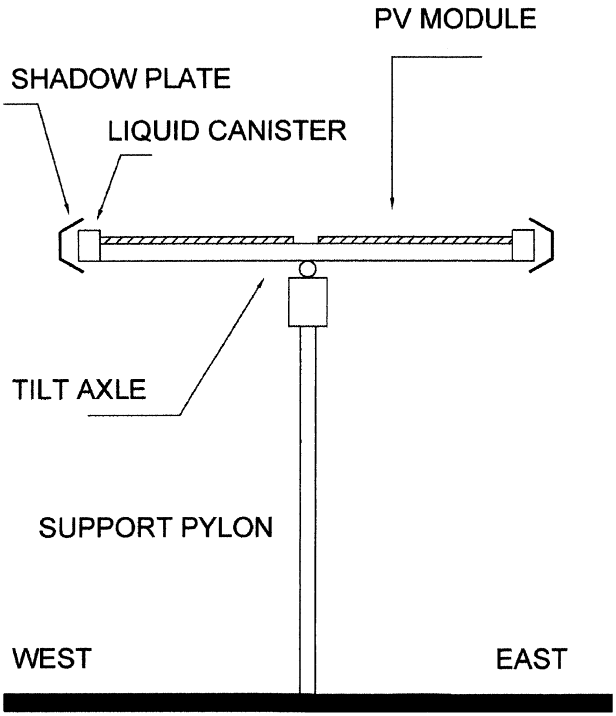


Figure 3.23 Zomeworks passive solar tracker.

The heating of the liquid is controlled by aluminum shadow plates. When one of the canisters is exposed to the sun more than the other, its vapor pressure is increased, hence forcing the liquid to the cooler, shaded side. The shifting weight of the liquid causes the rack to rotate until the canisters are equally shaded. Figure 3.24 depicts Solar tracker eastern sunrise position of Zomeworks passive solar tracker.

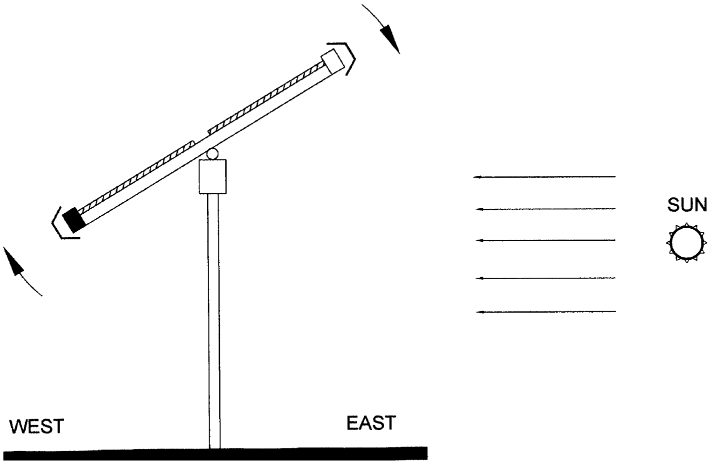


Figure 3.24 Solar tracker eastern sunrise position.

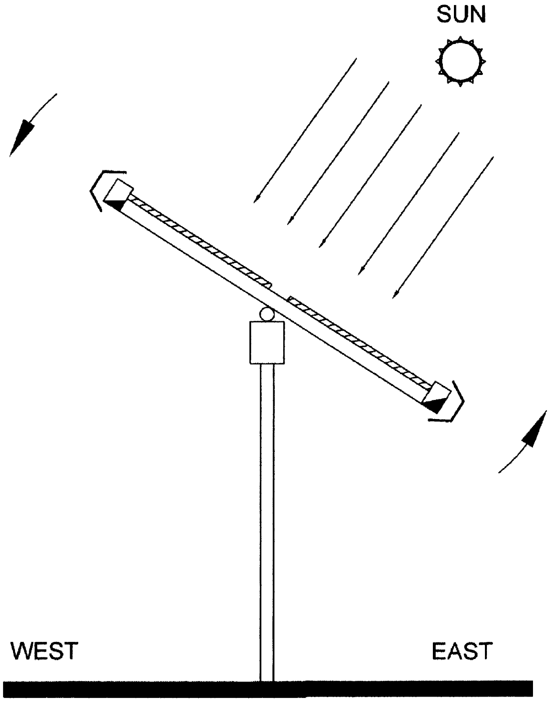


Figure 3.25 Sunrise shifting position of tracker.

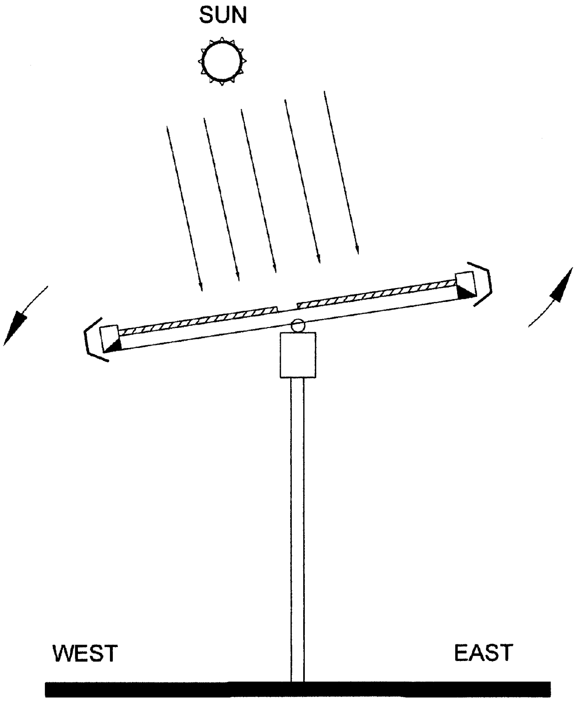


Figure 3.26 Liquid movement shifting position of tracker.

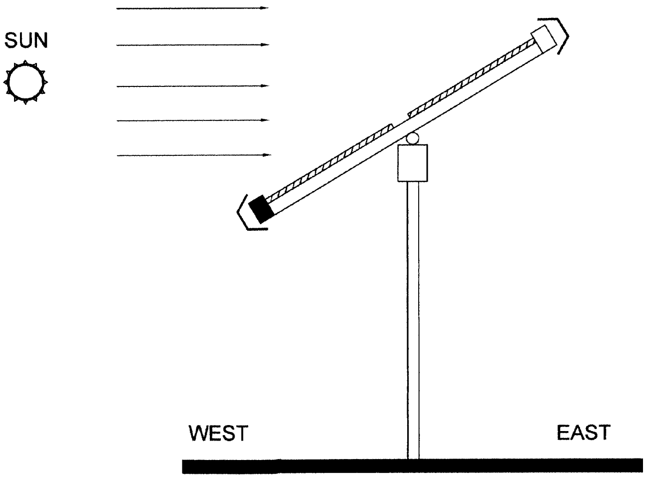


Figure 3.27 Position of tracker after completing daily cycle.

As the sun moves, the rack follows at approximately 15 degrees per hour continually seeking equilibrium as the liquid moves from one side of the track to the other.

The rack completes its daily cycle facing west. It remains in this position overnight until it is awakened by the rising sun the following morning.

Active trackers Active trackers use motors and gear trains to control axle movements by means of programmable controlled timers, programmable logic controllers, and microprocessor-based controllers or global-positioning-based control devices that provide precise power drive data to a variety of electromechanical movement mechanisms. Programs within the control computational systems use a combination of solar movement algorithms that adjust rotational axis movement in orientations that constantly maintain a minimal cosine angle throughout all seasons.

Vertical-axle trackers Vertical-axle trackers are constructed in such a manner as to allow pivotal movement of PV panels mounted about a vertical axis. These types of trackers have a limited use and are usually deployed in high latitudes, where the solar path travels in a long arc. PV panels mounted on a vertical-axle system are suitable for operation during long summer days in northern territories, which have extended solar days.

Electric Shock Hazard and Safety Considerations

Power arrays, when exposed to the sun, can produce several hundred volts of dc power. Any contact with an exposed or uninsulated component of the PV array can produce serious burns and fatal electric shock. The electrical wiring design and installation methodology are subject to rigorous guidelines, which are outlined in the National Electrical Code (NEC) Article 690.

System components, such as overcurrent devices, breakers, disconnect switches, and enclosures, are specifically rated for the application. All equipment that is subject to maintenance and repair is marked with special caution and safety warning tags to prevent inadvertent exposure to hazards (see Appendix B for typical sign details).

SHOCK HAZARD TO FIREFIGHTERS

An important safety provision, which has been overlooked in the past, is collaborating with local fire departments when designing roof-mount solar power systems on wood structures. In the event of a fire, the possibility of a serious shock hazard to firefighters will exist in instances when roof penetration becomes necessary.

SAFETY INSTRUCTIONS

- Do *not* attempt to service any portion of the PV system unless you understand the electrical operation and are fully qualified to do so.
- Use modules for their intended purpose only. Follow all the module manufacturer's instructions. Do *not* disassemble modules or remove any part installed by the manufacturer.
- Do *not* attempt to open the diode housing or junction box located on the back side of any factory-wired modules.
- Do *not* use modules in systems that can exceed 600 V open circuit.
- Do *not* connect or disconnect a module unless the array string is open or all the modules in the series string are covered with nontransparent material.
- Do *not* install during rainy or windy days.
- Do *not* drop or allow objects to fall on the PV module.
- Do *not* stand or step on modules.
- Do *not* work on PV modules when they are wet. Keep in mind that wet modules when cracked or broken can expose maintenance personnel to very high voltages.
- Do *not* attempt to remove snow or ice from modules.
- Do *not* direct artificially concentrated sunlight on modules.
- Do *not* wear jewelry when working on modules.
- Avoid working alone while performing field inspection or repair.
- Wear suitable eye protection goggles and insulating gloves rated at 1000 V.
- Do *not* touch terminals while modules are exposed to light without wearing electrically insulated gloves.
- Always have a fire extinguisher, a first-aid kit, and a hook or cane available when performing work around energized equipment.
- Do *not* install modules where flammable gases or vapors are present.

Maintenance

In general, solar power system maintenance is minimal, and PV modules often only require a rinse and mopping with mild detergent once or twice a year. They should be visually inspected for cracks, glass damage, and wire or cable damage. A periodic check of the array voltage by a voltmeter may reveal malfunctioning solar modules.

TROUBLESHOOTING

All photovoltaic modules become active and produce electricity when illuminated in the presence of natural solar or high ambient lighting. Solar power equipment should be treated with the same caution and care as regular electric power service. Unlicensed electricians or inexperienced maintenance personnel should not be allowed to work with solar power systems.

In order to determine the functional integrity of a PV module, the output of one module must be compared with that of another under the same field operating conditions. One of the best methods to check module output functionality is to compare the voltage of one module to that of another. A difference of greater than 20 percent or more will indicate a malfunctioning module. Note that the output of a PV module is a function of sunlight and prevailing temperature conditions, and as such, electrical output can fluctuate from one extreme to another.

When electric current and voltage output values of a solar power module are measured, short-circuit current (Isc) and open-circuit voltage (Voc) values must be compared with the manufacturer's product specifications.

To obtain the Isc value a multimeter ampere meter must be placed between the positive and negative output leads shorting the module circuit. To obtain the Voc reading a multimeter voltmeter should simply be placed across the positive and negative leads of the PV module.

For larger current-carrying cables and wires, current measurements must be carried out with a clamping meter. Since current clamping meters do not require circuit opening or line disconnection, different points of the solar arrays can be measured at the same time. An excessive differential reading will be an indication of a malfunctioning array.

Note that problems resulting from module malfunction or failure seldom occur when a PV system is put into operation; rather most malfunctions result from improper connections or loose or corroded terminals. In the event of a damaged connector or wiring, a trained or certified technician should be called upon to perform the repairs. PV modules, which are usually guaranteed for an extended period of time, that are malfunctioning should be sent back to the manufacturer or installer for replacement. *Caution:* Do not to disconnect dc feed cables from the inverters unless the entire solar module is deactivated or covered with a canvas or a nontransparent material.

The following safety warning signs must be permanently secured to solar power system components.

WARNING SIGNS

For a solar installation system:

> Electric shock hazard—Do not touch terminals—Terminals on both line and load sides may be energized in open position.

For a switchgear and metering system:

> Warning—Electric shock hazard—Do not touch terminals—Terminals on both the line and load side may be energized in the open position.

For pieces of solar power equipment:

> Warning—Electric shock hazard—Dangerous voltages and currents—No user-serviceable parts inside—Contact qualified service personnel for assistance.

For battery rooms and containers:

> Warning—Electric shock hazard—Dangerous voltages and currents—Explosive gas—No sparks or flames—No smoking—Acid burns—Wear protective clothing when servicing typical solar power system safety warning tags.

Photovoltaic Design Guidelines

When designing solar power generation systems, the designer must pay specific attention to the selection of PV modules, inverters, and installation material and labor expenses, and specifically be mindful of the financial costs of the overall project. The designer must also assume responsibility to assist the end user with rebate procurement documentation. The following are major highlights that must be taken into consideration.

Photovoltaic module design parameters

1. Panel rated power (185, 175, 750 W, etc.)
2. Unit voltage (6, 12, 24, 48 V, etc.)
3. Rated amps
4. Rated voltage
5. Short-circuit amperes
6. Short-circuit current
7. Open-circuit volts
8. Panel width, length, and thickness
9. Panel weight
10. Ease of cell interconnection and wiring

11. Unit protection for polarity reversal
12. Years of warranty by the manufacturer
13. Reliability of technology
14. Efficiency of the cell per unit surface
15. Degradation rate during the expected life span (warranty period) of operation
16. Longevity of the product
17. Number of installations
18. Project references and contacts
19. Product manufacturer's financial viability

Inverter and automatic transfer system

1. Unit conversion efficiency
2. Waveform harmonic distortion
3. Protective relaying features (as referenced earlier)
4. Input and output protection features
5. Service and maintenance availability and cost
6. Output waveform and percent harmonic content
7. Unit synchronization feature with utility power
8. Longevity of the product
9. Number of installations in similar types of application
10. Project references and contacts
11. Product manufacturer's financial viability

Note that solar power installation PV cells and inverters that are subject to the California Energy Commission's rebate must be listed in the commission's eligible list of equipment.

Installation contractor qualification

1. Experience and technical qualifications
2. Years of experience in solar panel installation and maintenance
3. Familiarity with system components
4. Amount of experience with the particular system product
5. Labor pool and number of full-time employees
6. Troubleshooting experience
7. Financial viability
8. Shop location
9. Union affiliation
10. Performance bond and liability insurance amount
11. Previous litigation history
12. Material, labor, overhead, and profit markups
13. Payment schedule
14. Installation warranty for labor and material