VICTORIA UNIVERSITY OF WELLINGTON TE HERENGA WAKA NEW ZEALAND

XMUT204 Electronic Design

Note 2g: Special Purpose Diodes (Solar Cells II)

1. Design of Solar Cells

Solar power is usable energy generated from the sun in the form of electric or thermal energy. Solar energy is captured in a variety of ways. The most common of which is with photovoltaic solar panels that convert the sun's rays into usable electricity.

Aside from using photovoltaics to generate electricity, solar energy is commonly used in thermal applications to heat indoor spaces or fluids. Residential and commercial property owners can install solar hot water systems and design their buildings with passive solar heating in mind to fully take advantage of the sun's energy with solar technology.

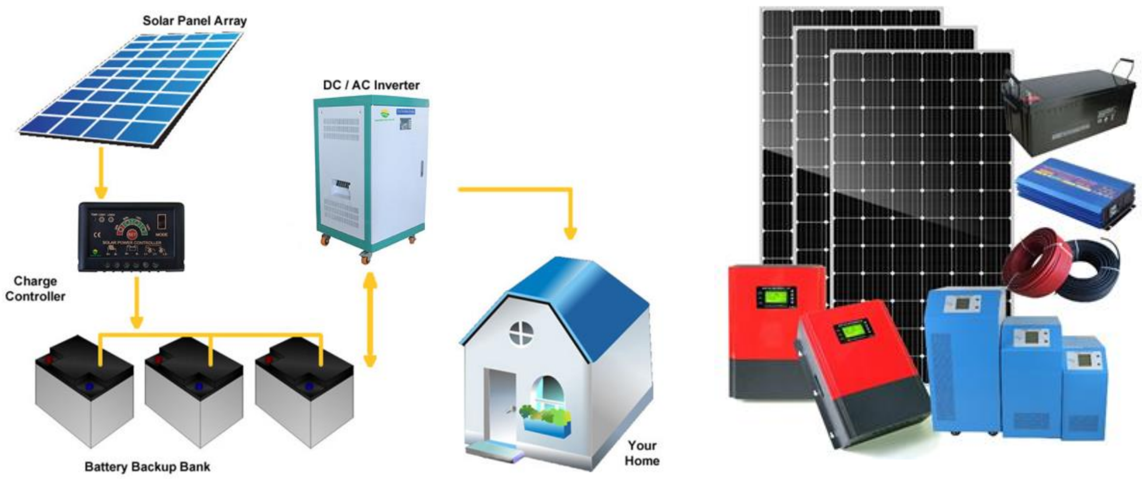


Figure 1: Solar power systems

Solar panels are installed at three main scales: residential, commercial, and utility. Residential-scale solar is typically installed on rooftops of homes or in open land (ground-mounted) and is generally between 5 and 20 kilowatts (kW), depending on the size of a property. Commercial solar energy projects are generally installed at a greater scale than residential solar. Though individual installations can vary greatly in size, commercial-scale solar serves a consistent purpose: to provide on-site solar power to businesses and non-profits. Finally, utility-scale solar projects are typically large, several megawatt (MW) installations that provide solar energy to a large number of utility customers.

1.1. The Solar Power System

A basic solar power system that can supply power to ac loads generally consists of four components, as shown in the block diagram in the figure below. These components are the solar panel, the charge controller, the batteries, and the inverter. For supplying only dc loads, such as solar-powered instruments and dc lamps, the inverter is not needed. Some solar power systems do not include battery backup or the charge controller and are used to provide supplemental power only when the sun is shining.

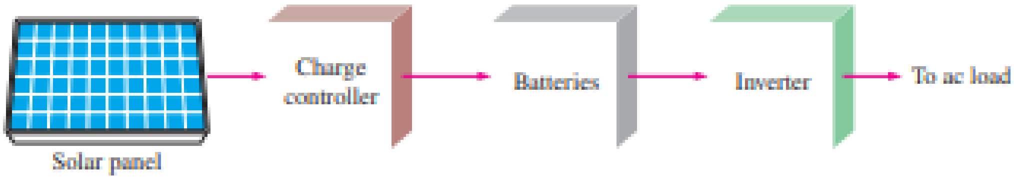


Figure 2: Basic solar power system with battery backup.

Efficiency is an important characteristic of a solar power system. Energy loss due to voltage drops, the photovoltaic process, and other factors are inevitable, so minimizing losses is a critical consideration in solar power systems.

1.2. Solar Panel

The solar panel collects energy from the sun and converts it to electrical energy through the photovoltaic process. Of course, the solar panel will not produce the specified power output all of the time. For example, if there is 4 hours of peak sun during a given day, a 60 W panel will produce 4 x 60 W = 240 Wh of energy. For the hours that the sun is not peak, the output will depend on the percentage of peak sun and is less than the specified output. A system is typically designed taking into account the annual of average peak sun per day for a given geographical area.

1.3. Charge Controller

A charge controller, also called a charge regulator, takes the output of the solar panel and ensures that the battery is charged efficiently and is not overcharged. Generally, the charge controller is rated based on the amount of current it can regulate. The operation of many solar charge controllers is based on the principle of pulse-width modulation. Also, some controllers include a charging method that maximizes charging, called maximum power point tracking. The charge controller and batteries in a solar power system will be examined in more detail in the subsequent sections.

1.4. Battery

Deep-cycle batteries, such as lead-acid, are used in solar power systems because they can be charged and discharged hundreds or thousands of times. Recall that batteries are rated in ampere-hours (Ah), which specifies the current that can be supplied for certain number of hours. For example, a 400 Ah battery can supply 400 A for one hour, 4 A for 100 hours, or 10 A for 40 hours. Batteries can be connected in series to increase voltage or in parallel to increase amp-hrs.

1.5. Inverter

The inverter changes DC voltage stored in the battery to the standard 120-240 Vac used in most common applications such as lighting, appliances, and motors. Basically, in an inverter, the dc from the battery is electronically switched on and off and filtered to produce a sinusoidal ac output. The ac output is then applied to a step-up transformer to get 120 Vac. The inverter in a solar system will be covered in more detail in the subsequent sections.

2. Design of Controller Unit

2.1. The Charge Controller

A solar charge controller is needed in solar power systems that use batteries to store the energy, with the exception of very low-power systems. The solar charge controller regulates the power from the solar panels primarily to prevent overcharging the batteries. Overcharging batteries reduce battery life and may damage the batteries.

Generally, there is no need for a charge controller with trickle-charge solar panels, such as those that produce five watts or less. A good rule-of-thumb is that if the solar panel produces about two watts or less for each 50 battery amp-hrs (Ah), then you don't need one. A charge controller is required if the solar panel produces more than two watts for each 50 Ah of battery rating. For example, a 12 V battery rated at 120 Ah will not require a charge controller, as the following calculation shows, because the solar power is less than 5 W.

In this case, the charging circuit is shown in the figure below. The diode prevents the battery from discharging back through the solar panel when the panel voltage drops below the battery voltage. For example, when the solar panel is producing 16 V, the diode is forward-biased and the battery is charging. When the battery voltage is 12 V and the panel output drops to less than 12.7 V, the diode is reverse-biased and the battery cannot discharge back through the solar cells.

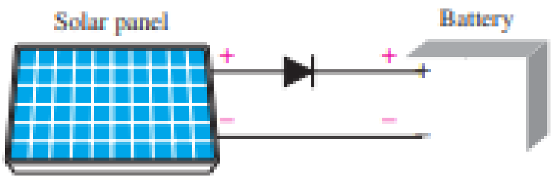


Figure 3: Simple trickle charging in a small solar system (less than 5 W).

For solar systems of more than about 5 W, a charge controller is necessary. Basically, charge controllers regulate the 16–20 V output of the typical 12 V solar panel down to what the battery needs depending on the amount of battery charge, the type of battery, and the temperature. Solar panels produce more voltage at cooler temperatures.

2.2. Types of Charge Controllers

Three basic types of charge controllers are on/off, PWM, and MPPT. The most basic controller is the on/off type, which simply monitors the battery voltage and stops the charging when the battery voltage reaches a specified level in order to prevent overcharging. It then restarts the charging once the battery voltage drops below a predetermined value. Figure below shows the basic concept.

The switch shown represents a transistor that is turned on and off. The voltage of the battery is fed back to the control circuit. When the voltage is below a set low value, the control circuit turns the switch on to charge the battery. When the battery charges to a set high value, the control circuit turns the switch off. The diode prevents discharge back through the control circuit when the output of the panel is lower than the battery.

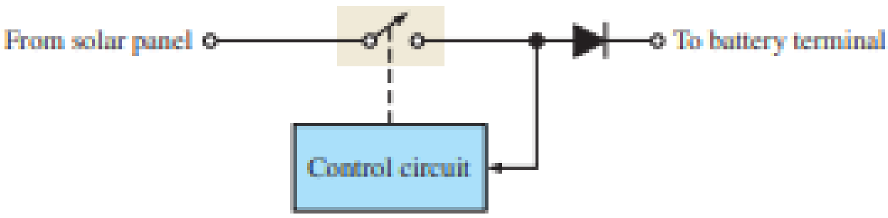


Figure 4: Basic concept of the on/off charge controller.

PWM (pulse width modulation) charge controllers gradually reduce the amount of power applied to the batteries as the batteries get closer to full charge. This type of controller allows the batteries to be more fully charged with less stress on the batteries. This extends the life of the batteries and constantly maintains the batteries in a fully charged state (called "float") during sunlight hours. The PWM controller produces a series of pulses to charge the batteries instead of a constant charge.

The battery voltage is constantly monitored to determine how to adjust the frequency of the pulses and the pulse widths. When the batteries are fully charged and there is no load to drain them, the controller produces very short pulses at a low rate or no pulses at all. When the batteries are discharged, long pulses at a high rate are sent or the controller may go into a constant-charging mode, depending on the amount of discharge.

Figure below shows the basic concept of a PWM charge controller. In part (a), the PWM and control circuit produces pulses based on the input from the sampling circuit. The sampling circuit determines the actual battery voltage by sampling the voltage between pulses. The diode acts as a rectifier and also blocks discharge of the battery back through the charger at night. Part (b) demonstrates how the battery charges during each pulse and how the width and the time between pulses change as the battery charges.

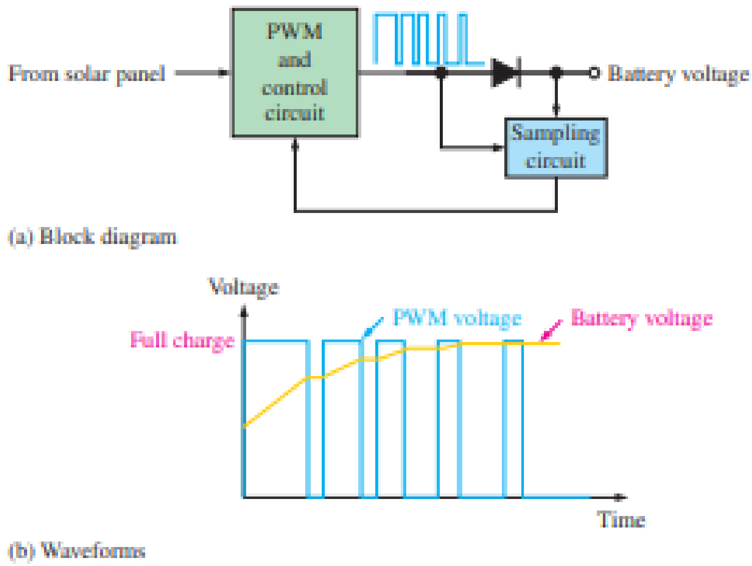


Figure 5: Basic concept of a PWM charge controller.

As you have learned, the output voltage of a solar panel varies greatly with the amount of sunlight and with the air temperature. For this reason, solar panels with voltage ratings higher than the battery voltage must be used in order to provide sufficient charging voltage to the battery under less than optimum conditions. As mentioned earlier, a 12 V solar panel may produce 20 V under optimum conditions but can produce only a certain amount of current.

For example, if a solar panel can produce 8 A at 20 V, it is rated at 160 W. Batteries like to be charged at a voltage a little higher than their rated voltage. If a 12 V battery is being charged at 14 V, and it is drawing the maximum 8 A from the solar panel, the power delivered to the battery is 8 A x 14 V = 112 W instead of the 160 W produced by the solar panel at 20 V. The batteries only stored 70% of the available energy because the 12 V battery cannot operate at 20 V.

MPPT (maximum power point tracker) charge controllers eliminate much of the energy loss found in the other types of controllers and produce much higher efficiencies. The MPPT continuously tracks the input voltage and current from the solar panel to determine when the peak input power occurs and then adjusts the voltage to the battery to optimize the charging. This results in a maximum power transfer from the solar panel to the battery.

In the figure below, the blue curve is the voltage-current characteristic for a certain solar panel under a specified condition of incident light. The green curve is the power showing where the peak occurs, which is in the knee of the V-I curve. If the incident light decreases, the curves will shift down.

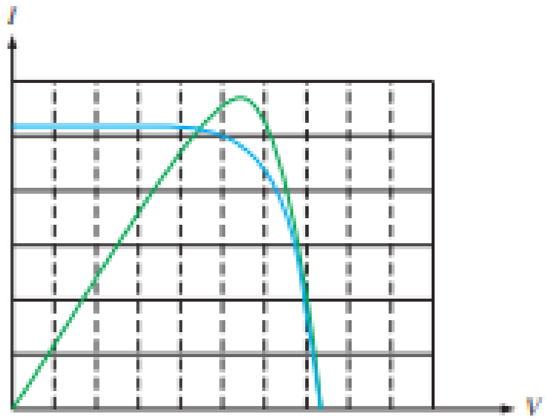


Figure 6: Example of a solar panel V-I and power curves.

The MPPT is basically a DC-to-DC converter. A simplified block diagram showing the basic functional concept is shown in the figure below. Although there are several ways in which the MPPT can be implemented, the figure illustrates the basic functions. The DC/AC converter, the transformer, and the AC/DC converter isolate the dc input from the dc output, so the output can be adjusted for maximum power.

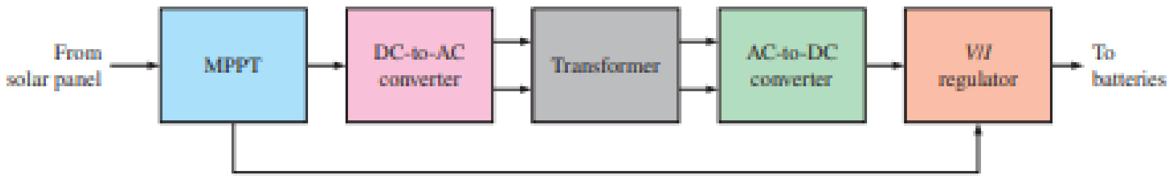


Figure 7: Basic concept of an MPPT charge controller.

For example, if a 160 W solar panel produces 20 V at 8 A, it needs to be reduced to approximately 13.6 V to charge a 12 V battery. A normal charger will not be able to provide more than 8 A at 13.6 V (or 109 W), which means the panel is not being used efficiently and only 76% of the available power from the solar panel is used.

An MPPT charge controller can supply about 11 A at 13.6 V (150 W), thus decreasing the charging time and producing a better match between the panel and the battery. In this case, the panel is being used more efficiently because it is able to deliver about 94% of the available power to the battery.

3. Design of Storage Units

3.1. The Batteries

Deep-cycle (deep discharge) sealed lead-acid batteries are the most common batteries in solar power systems because their initial cost is lower and they are readily available. Unlike automobile batteries, which are shallow-cycle, deep-cycle batteries can be repeatedly discharged by as much as 80 percent of their capacity, although they will have a longer life if the cycles are shallower.

Deep-cycle batteries are required in solar power systems simply because the sunlight is not at its maximum all of the time—it is an intermittent energy source. When the light intensity from the sun decreases because of clouds or goes away entirely at night, the output from a solar panel drops drastically or goes to zero. During the periods of low light or no light, the batteries will discharge significantly when a load is connected. Typically, the voltage output of a solar panel must be at least 13.6 V to charge a 12 V battery.

Solar panels are usually rated at voltages higher than the nominal output. For example, most 12 V solar panels produce 16 V to 20 V at optimal light conditions. The higher voltage outputs are necessary so that the solar panel will still produce a sufficient charging voltage during some non-optimal conditions.

3.2. Battery Connections

Batteries can be connected in series to increase the output voltage and in parallel to increase the ampere-hour capacity, as illustrated in the figure below for any number of batteries. Several series connections of batteries can be connected in parallel to achieve both an increase in amp-hrs and output voltage.

For example, assume a system uses 12 V, 200 Ah batteries. If the system requires 12 V and 600 Ah, three parallel-connected batteries are used. If the system requires 24 V and 200 Ah, two series-connected batteries are used. If 24 V and 600 Ah are needed, three pairs of series batteries are connected in parallel

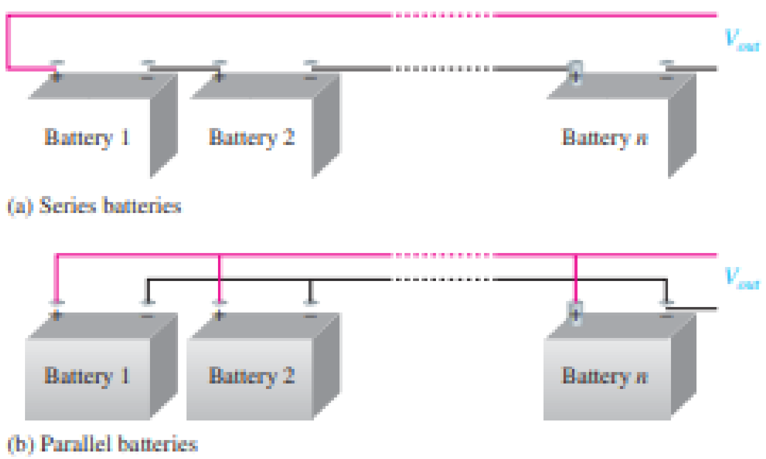


Figure 8: Battery connections

4. Design of Inverter System

4.1. The Inverter

The inverter is a dc-to-ac converter that takes the output of the batteries in a solar power system and converts it to a standard 120 V, 60 Hz output voltage. This is the same as the voltage provided by the electric utilities companies. Some inverters can produce 240 V.

Basically, an inverter switches the dc output of the storage battery on and off and processes the result to create a pure sine wave, a stepped wave called a modified or quasi sine wave (sometimes called a modified square wave), or a square wave. Most inverters produce a pure sine wave, which is the type that the power company generates. Other outputs are found in cheaper inverters and are limited to providing power at lower efficiencies to only certain types of loads. The square wave inverter is seldom used, although it can be used as the basis for generating a pure sine wave. These three types of inverter outputs are shown in the figure below.

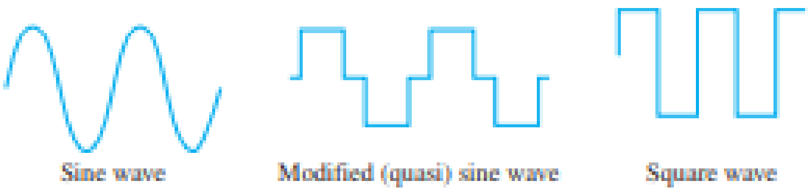


Figure 9: Types of inverter outputs.

Recall from your systems and signals course that the harmonic content of a square wave includes a fundamental sine wave at the frequency of the square wave and a series of odd harmonics. One method of implementing a relatively pure sine wave inverter uses a dc to square wave inverter. The square wave is processed through a filter system to eliminate all of the odd harmonics, leaving only the fundamental sine wave, as illustrated in the figure below. A step-up transformer is used to produce the required 120 V, 60 Hz sine wave.

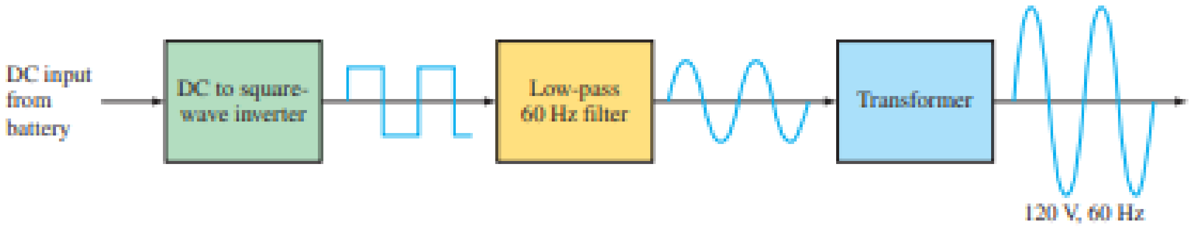


Figure 10: Basic concept of a pure sine wave inverter.

A switching circuit can be used in the conversion of dc voltage to an ac square wave voltage. One method is illustrated in the figure below where switch symbols are used to represent switching transistors such as CMOS. In part (a), switches S2 and S3 are on for a specified time and S1 and S4 are off. The direct current is through the load as shown creating a positive output voltage, as indicated. In part (b), opposite switches are on and off. The current is in the opposite direction through the load and the output voltage is negative. The complete on/off cycle of the switches produces an alternating square wave. The transistors are switched by a timing control circuit which is not shown for simplicity. The load is the filter in the pure sine wave inverter.

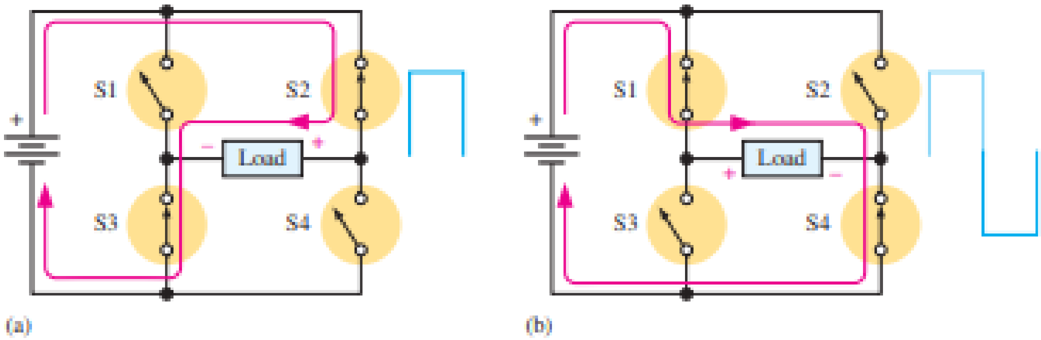


Figure 11: A method of producing a square wave from a dc voltage.

Inverters can have two types of interface: stand-alone and grid-tie. The stand-alone inverter is used in applications where all of the output power is used for a specified load, such as lighting, appliances, and motors, and is independent of the electrical power grid. Figure below represents a stand-alone system.

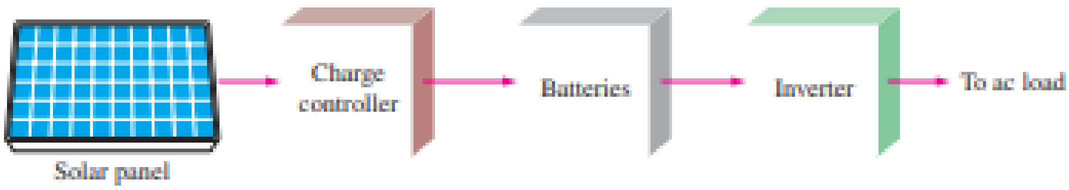


Figure 12: Stand-alone solar power system

The grid-tie inverter is used in applications where all or part of the output power is provided to the electrical gird. For example, a home solar power system may share excess power not used in the home with the power company for credit if net metering is available. Some power companies have a net metering policy in which a special meter is installed and all power going to the electrical grid is deducted from power used by the on-site consumer. A large solar power system may be entirely devoted to producing power for the electrical gird.

4.2. The Grid-Tie System

A grid-tie inverter (GTI) must synchronize its ac output frequency (60 Hz) and phase with that of the grid, limit its amplitude for compatibility with the grid, and adjust its power factor to unity (voltage and current in phase). For safety reasons, grid-tie inverters have to disconnect from the grid if the grid goes down in a blackout. An option with grid-tie systems is that the solar panel can connect directly to the inverter with no battery backup. However, batteries allow the consumer to have energy available when they lose power from the grid. Figure below shows the basic concept of a grid-tie solar power system with backup batteries.

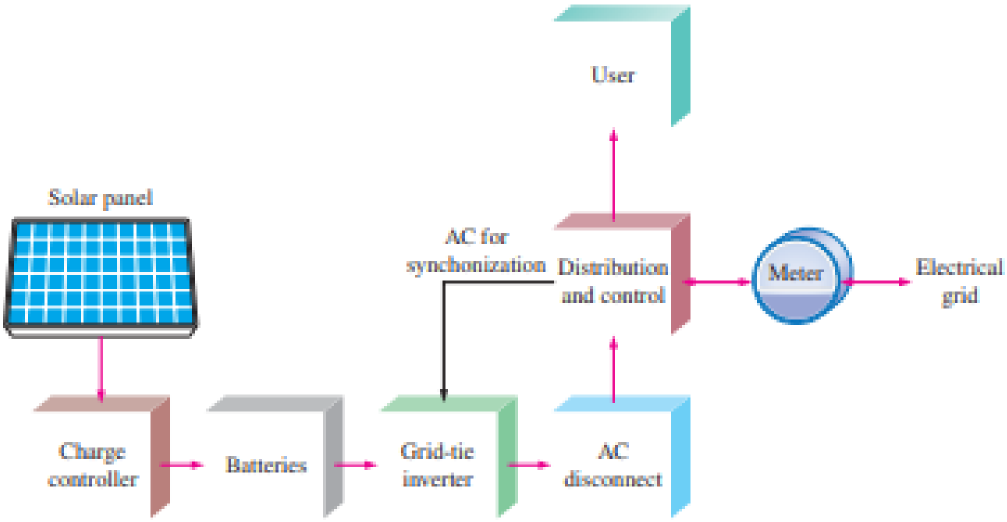


Figure 13: Basic concept of grid-tie solar power system with battery backup.

During normal operation, the grid is supplying electrical power to the user and the power from the grid-tie inverter is fed back into the grid through the distribution and control circuits for credit from the power company. If the grid goes down, the ac disconnect prevents the power from the grid-tie inverter from feeding into the solar power is then switched directly to the user.

5. Design of Tracking System

Solar tracking is the process of moving the solar panel to track the daily movement of the sun and the seasonal changes in elevation of the sun in the southern sky. The purpose of a solar tracker is to increase the amount of solar energy that can be collected by the system. For flat-panel collectors, an increase of 30% to 50% in collected energy can be realized with sun tracking compared to fixed solar panels.

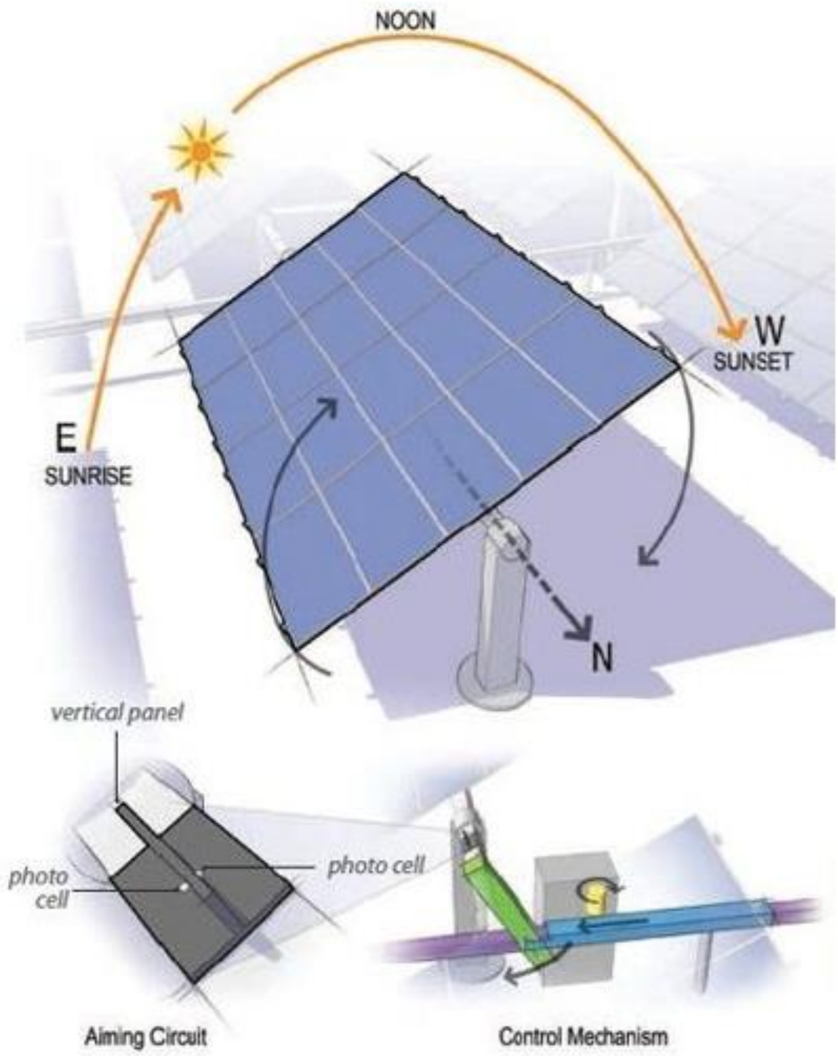


Figure 14: Tacking systems of solar cells

Before looking at methods for tracking, let's review how the sun moves across the sky. The daily motion of the sun follows the arc of a circle from east to west that has its axis pointed north near the location of the North Star. As the seasons change from the winter solstice to the summer solstice, the sun rises a little further to the north each day. Between the summer solstice and the winter solstice, the sun moves further south each day. The amount of the north-south motion depends on your location.

5.1. Single-Axis Solar Tracking

For flat-panel solar collectors, the most economical and generally most practical solution to tracking is to follow the daily east-west motion, and not the annual north-south motion. The daily east-to-west motion can be followed with a single-axis tracking system. There are two basic single-axis systems: polar and azimuth.

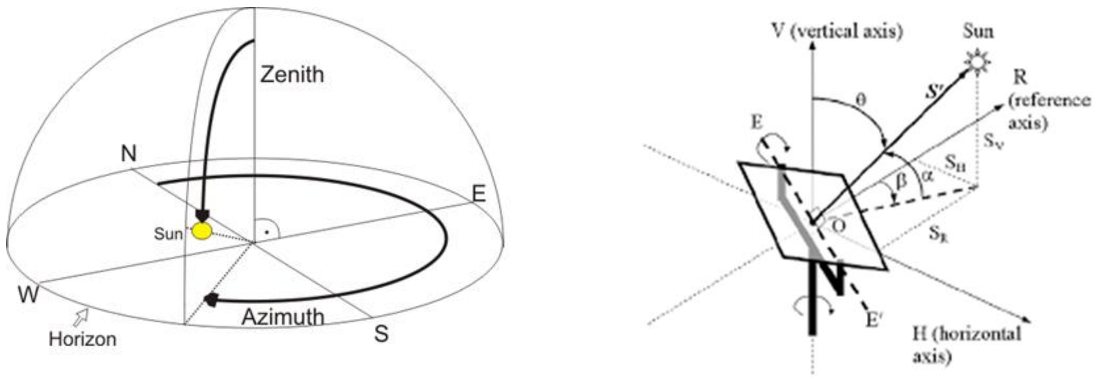


Figure 15: Mechanisms of the tracking systems of solar systems

In a polar system, the main axis is pointed to the polar north (North Star), as shown in part (a) of the figure below. (In telescope terminology, this is called an equatorial mounting.) The advantage is that the solar panel is kept at an angle facing the sun at all times because it tracks the sun from east to west and is angled toward the southern sky.

In an azimuth tracking system, the motor drives the solar panel and frequently multiple panels. The panels can be oriented horizontally but still track the east-to-west motion of the sun. Although this does not intercept as much of the sunlight during the seasons, it has less wind loading and is more feasible for long rows of solar panels. Part (b) of the figure below shows a solar array that is oriented horizontally with the axis pointing to true north and uses azimuth tracking (east to west). As you can see, sunlight will strike the polar-aligned panel more directly during the seasonal movement of the sun than it will with the horizontal orientation of the azimuth tracker.

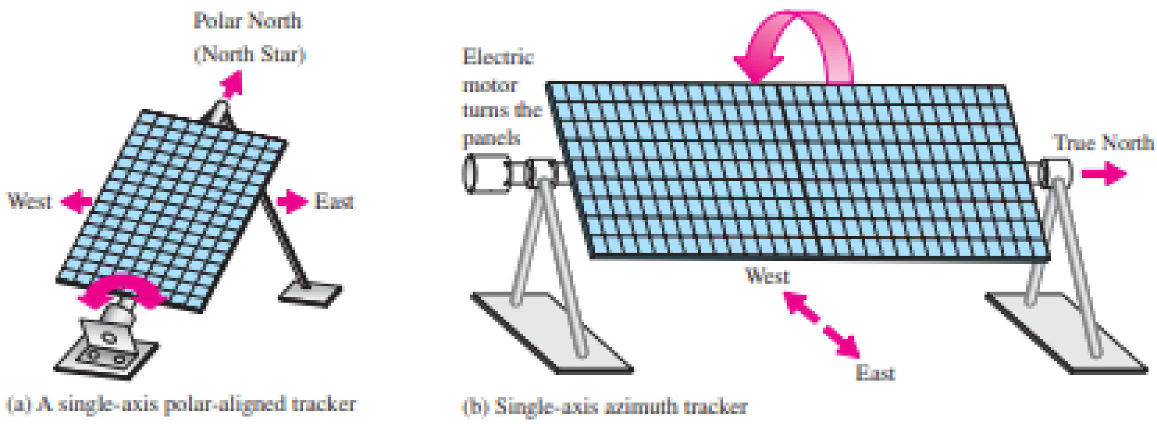


Figure 16: Types of single-axis solar tracking.

Some solar tracking systems combine both the azimuth and the elevation tracking, which is known as dual-axis tracking. Ideally, the solar panel should always face directly toward the sun so that the sun light rays are perpendicular to the panel. With dual-axis tracking, the annual north-south motion of the sun can be followed in addition to the daily east-to-west movement. This is particularly important with concentrating collectors that need to be oriented correctly to focus the sun on the active region. Figure below is an example showing the improvement in energy collection of a typical tracking panel versus a non-tracking panel for a flat solar collector. As you can see, tracking extends the time that a given output can be maintained.

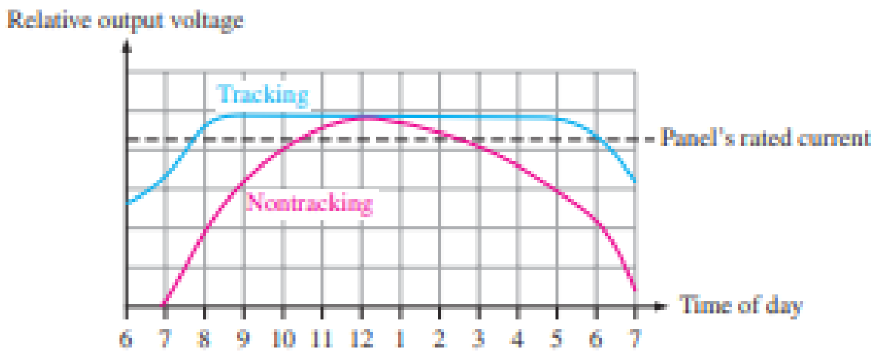


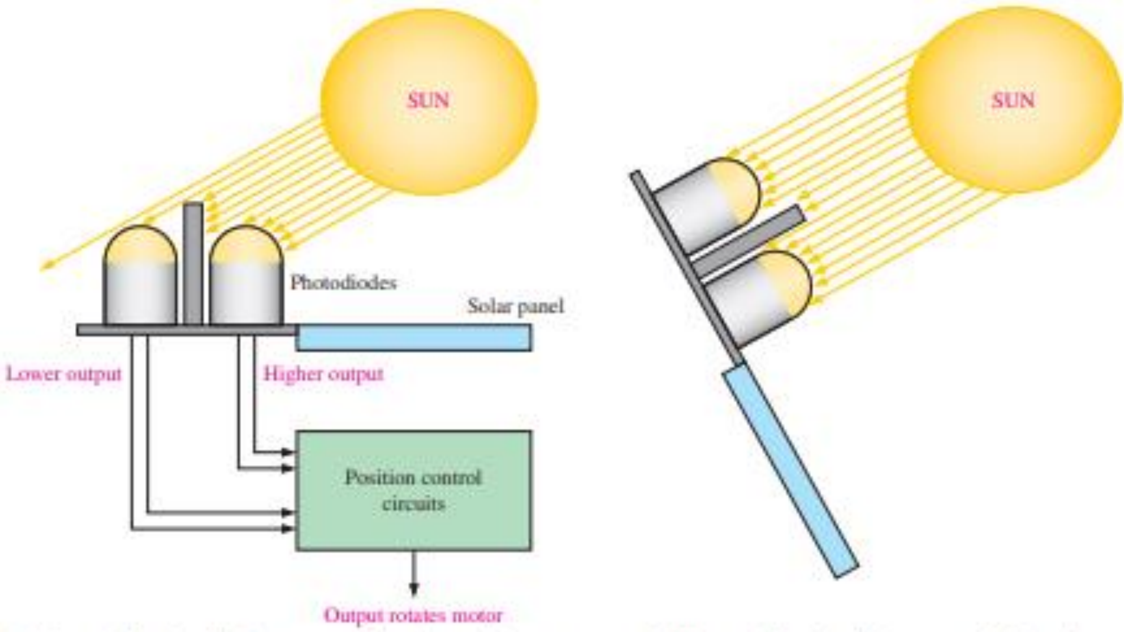
Figure 17: Graphs of voltages in tracking and non-tracking (fixed) solar panels.

There are several methods of implementing solar tracking. Two main ones are sensor controlled and timer controlled.

5.2. Sensor-Controlled Solar Tracking

This type of tracking control uses photosensitive devices such as photodiodes or photoresistors. Typically, there are two light sensors for the azimuth control and two for the elevation control. Each pair senses the direction of light from the sun and activates the motor control to move the solar panel to align perpendicular to the sun's rays.

Figure below shows the basic idea of a sensor-controlled tracker. Two photodiodes with a light-blocking partition between them are mounted on the same plane as the solar panel.



(a) Outputs of the photodiodes are unequal if solar panel is not directly facing the sun.

(b) Outputs of the photodiodes are equal when solar panel orientation is optimum.

Figure 18: Simplified illustration of a light-sensing control for a solar-tracking system. Relative sizes are exaggerated to demonstrate the concept.

If the solar panel is not facing directly toward the sun, the light strikes the panel and the photodiode assembly at an angle so that one of the diodes is shaded or partially shaded by the partition and receives less light than the other, as illustrated in part (a) in the figure above . As a result, the photodiode with the most light produces a higher current than the partially shaded device. The difference in currents from the two diodes is sensed by an operational amplifier and sends an output voltage to the motor. The motor rotates the solar panel until both photodiodes produce the same current and then is stopped by the control circuit, as illustrated in part (b). The light-blocking partition between the diodes is oriented vertically for azimuth tracking and horizontally for elevation tracking. The photodiode assemblies must face in the same direction as the solar panel, so they are mounted on the solar panel frame.

5.3. Dual-Axis Solar Tracking

As mentioned, a dual-axis system tracks the sun in both azimuth and elevation. It requires two photo-sensing elements and two motors, as shown in the figure below. The outputs from the two pairs of sensors go to the position-control circuits. A circuit detects the differential between the two azimuth sensor outputs and, if the differential is sufficient, the azimuth motor is advanced westward until a balance occurs between the two sensors.

Similarly, another circuit detects the differential between the two elevation sensor outputs and, correspondingly, advances the elevation motor to rotate the solar panel either up or down until a balance occurs between the two sensors. When night falls and the solar panel is at its western-most position, the position-control circuits detect no output from the azimuth sensors and send a reset command to the azimuth motor to cause it to turn the solar panel back to its east most position to await sunrise the next day. The system must be sensitive enough to detect very small differences in photodiode output because the more closely the sun is tracked, the better the energy collection efficiency.

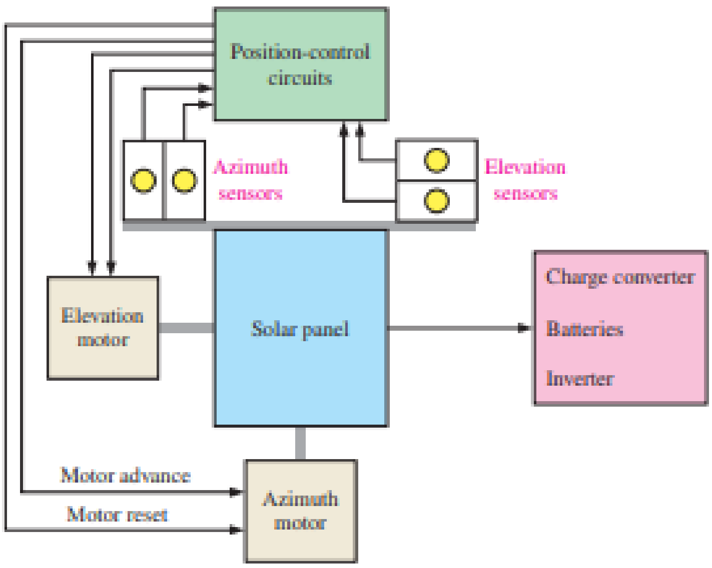


Figure 19: Block diagram of a dual-axis sensor controlled tracking solar power system.

A drawback of the sensor-controlled system is its sensitivity requirement for cloudy days or a passing cloud, when the differences in detected light are much smaller. The system must be able to distinguish between two low-light levels. Also, a certain amount of energy must be diverted to power the electronics and motors, although this is a requirement of most types of tracking systems.

5.4. Timer-Controlled Solar Tracking

Solar tracking can also be accomplished by using an electronic timer that causes the motors to move incrementally in azimuth and elevation. During the day the sun moves from east-to-west and this takes approximately 12 hours at summer solstice.

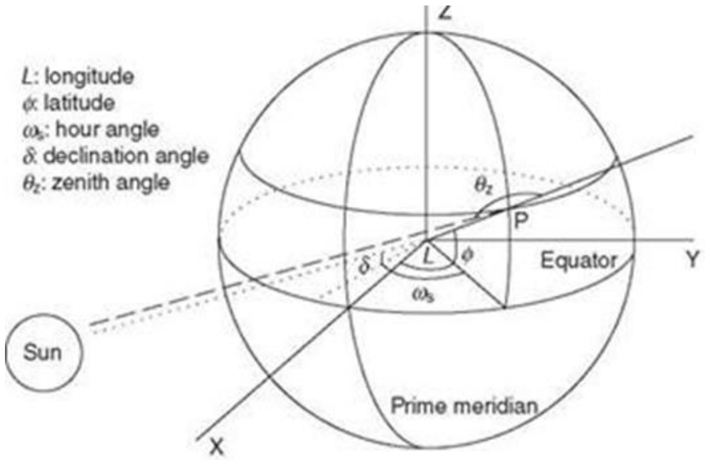


Figure 20: Angle and timing of the rotation of the sun

The sun moves at a rate of approximately 15° per hour. A timer-controlled tracking system can be designed to follow the sun at desired increments. For example, the panel azimuth position could advance every minute (60 times an hour), every 5 minutes (12 times an hour), or every 15 minutes (4 times an hour), depending on the tracking accuracy desired.

The sun moves slowly in elevation as it progresses from winter solstice to summer solstice and back again, traversing an angle of 47° in six months. This is a rate of 8° per month. The tracking system could make one adjustment in the elevation or tilt of the solar panel each week or each month, depending on the accuracy desired.

Generally, a timer-controlled tracker uses an accurate time source, such as a crystal oscillator, a microprocessor with associated timing and control circuits, and motor interface circuits. The advantage of this type of tracking is that it is independent of the amount of sunlight that is striking the solar panel. Like the sensor-controlled system, the electronics and motors use extra energy. A simple block diagram is shown in the figure below.

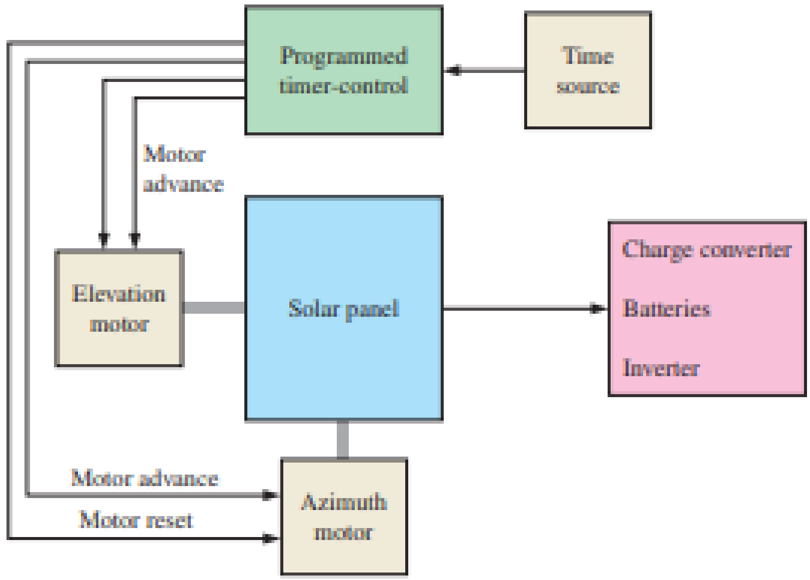


Figure 21: Block diagram of a dual-axis timer-controlled tracking solar power system.

Example for Tutorial – Solar System Estimations

1. You are tasked to work on an engineering project installing a solar panel system for smart off-grid bus shelters in a city.

   Given in the table below is the estimated energy used in the shelter that has its energy provided by a solar panel on its roof.

Appliance	Appliance Categories	Quantity	Watts (V*A) Multi* 1.5 for AC	Estimated Operation Hours/day
LED Lights	Night use	2	2.85	14
High Flux LED	Night use	6	12	14
Cell phone charger	Average use	2	5	15
WI-FI router	24 hours use	1	20	24
Solar charger controller	24 hours use	1	1	24
Sensor	24 hours use	1	1	24

   For the given solar panel system, assumes on average 3 hours sun hour per day, 20% energy losses, and 30 days per month.

   a. Calculate the total energy usage. [20 marks]
   b. Calculate overall power consumption (in kWh/month). [10 marks]

c. Calculate wattage of the solar panels. [10 marks]
d. Determine the size of the battery. [5 marks]
e. Determine the rating of the inverter. [2.5 marks]
f. Suggest type of charge controller and its rating. [2.5 marks]

Answer

a. Calculate energy usage of the bus shelter as outlined in the table below.

Appliance	**Appliance Categories**	**Quantity**	**Watts (V*A) Multi* 1.5 for AC**	**Estimated Operation Hours/day**	**Watts Hours/day**
LED Lights	Night use	2	2.85	14	80
High Flux LED	Night use	6	12	14	1008
Cell phone charger	Average use	2	5	15	150
WI-FI router	24 hours use	1	20	24	480
Solar charger controller	24 hours use	1	1	24	24
Sensor	24 hours use	1	1	24	24
Total Watt Hours per day					1770.00

b. Calculate overall power consumption (in KWh/month):

1770 Wh/day ÷ 3 sun hours/day = 590 W

590 W ÷ 0.8 (system losses) =737.5 W

Wh = 737.5 W x 30 days Wh = 22,125 Watt-hours (22.125 kWh/month)

The project will be dealing with lower voltage devices, hence a 12 V system is chosen.

c. Calculate wattage of the solar panels:

1770 Wh/day ÷ 3 sun hours/day = 590 W

590 W ÷ 0.8 (system losses) =737.5 W

737.5/250 = 2.95 (e.g. 3 Solar panels 250 Watts)

For the project, we would be using 3 panels of 250 Watts each.

d. Battery sizing is determined from the following formulae:

Battery Capacity (Ah) = Total Watt-hours per day used by appliances x Days of autonomy (0.85 x 0.6 x nominal battery voltage)

For this project, the daily average energy consumption per day is 1770 (W-h/day) for the month of December.

Battery Capacity (Ah) = 1770 x 2 (0.85 x 0.6 x 12) = 578.4 Ah

As a result, a 578.4 Ah battery capacity is required for the system.

e. Inverter sizing:

As per part (b), the inverter size should be based on the wattage and voltage level of the system. This project employs a 12 V, 2 kW system, hence the inverter that should be used should be of similar rating.

f. Charge controller sizing:

For this project, a PWM charge controller is to be used. Following steps will enable us to size the required charge controller.

- Voltage level of the system: 12V
- Maximum amperage: 10 A

There a PWM controller should be used with 12 V and 10 A with rated voltage and current specifications.