CHAPTER 2

PHOTOVOLTAIC SYSTEM

2.1 Introduction

A **photovoltaic system** is a system which uses solar cells to convert light into electricity. A photovoltaic system consists of multiple components, including cells, mechanical and electrical connections and mountings and means of regulating and/or modifying the electrical output.

Due to the low voltage of an individual solar cell (typically 0.5V), several cells are combined into photovoltaic modules, which are in turn connected together into an array. The electricity generated can be either stored, used directly (island/standalone plant)or fed into a large electricity grid powered by central generation plants (grid-connected/grid-tied plant) or combined with one or many domestic electricity generators to feed into a small grid (hybrid plant). Depending on the type of application, the rest of the system ("balance of system" or "BOS") consists of different components. The BOS depends on the load profile and the system type. Systems are generally designed in order to ensure the highest energy yield for a given investment.

2.2 PHOTOVOLTAIC SYSTEMS

The simplest photovoltaic system is one in which the cells can be connected directly to the load, supplying power whenever there is illumination (fig-2.1). Water pumping using a DC motor to drive the pump is an example of such system.

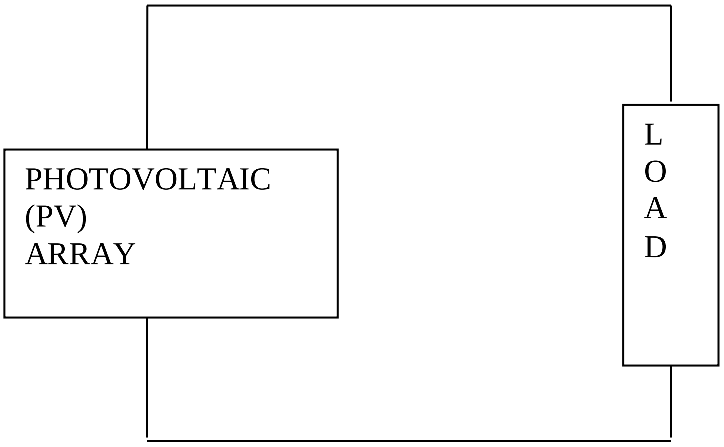


Fig-2.1 A simple photovoltaic system

For the smaller, cost-effective power applications the direct connection (through a blocking diode) or the array to the storage system and then to the load may prove to be the most cost effective and require least maintenance. Direct electrical connection of the array to the battery system without regulation is advisable only when the peak output current of the array is less than 5% of the charge capacity of the batteries (Ampere hour rating) in the system (fig-2.2).

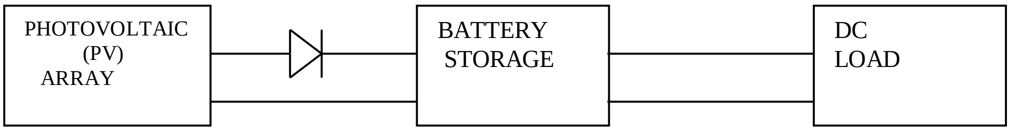


Fig-2.2 Self-regulated PV system

Most PV systems utilize a voltage regulator, either in parallel or series with the PV array, the storage system, and load. PV power system are normally designed to recover quickly from worst case load and weather conditions, this results in the arrays having excess power capability under normal load conditions, especially at the beginning of their lives. To regulate the voltage within required limits to prevent battery overcharge, and out gassing, a voltage regulator must dissipate the excess available power (fig-2.3).

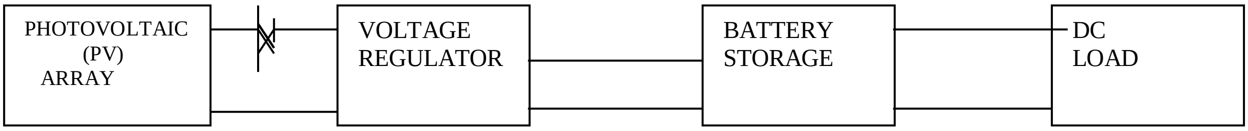


Fig-2.3 PV system utilizing voltage regulator

A photovoltaic plant is known in the block diagram of fig-2.4. Steering arrangement is needed to track the direct component of solar radiation. For connection to the grid there are facilities also. Maximum power point tracker (MPPT) is used to utilize maximum available power.

Some PV systems have power inverter as elements of power conditioner. An inverter is an electrical device that switches the array output direct current (DC) at a desired frequency (usually 50 Hz) for AC applications. This conditioned power can then be used in place of utility power for conventional AC electricity.

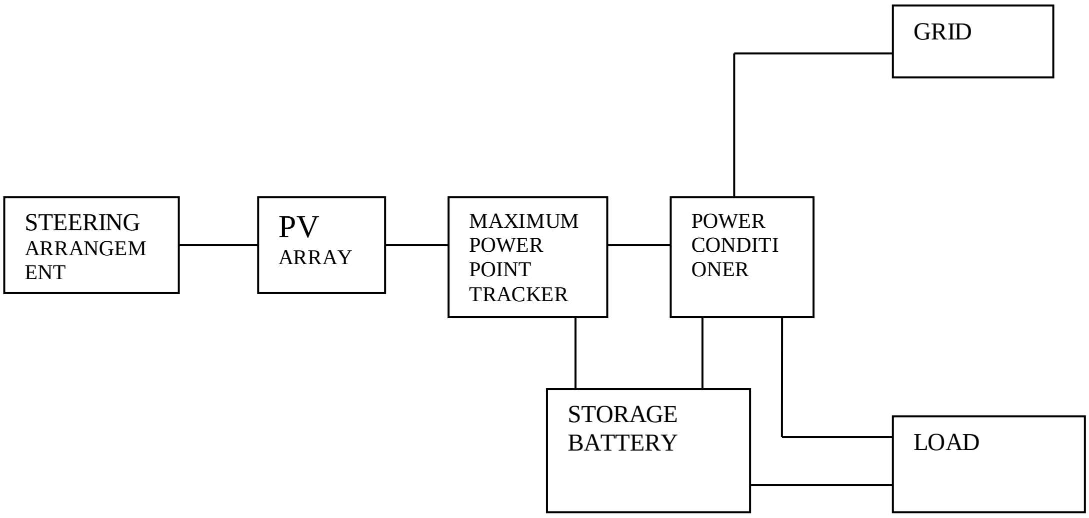
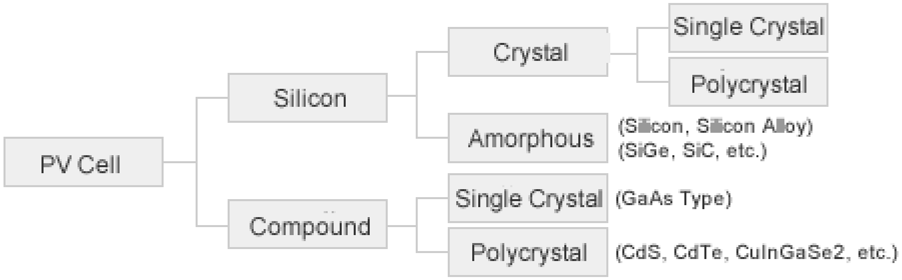


Fig-2.4 A photovoltaic plant in block diagram

2.3 COMPONENT OPERATION



2.3.1 Photovoltaic Cells

At the present time, most commercial photovoltaic cells are manufactured from silicon, the same material from which sand is made. In this case, however, the silicon is extremely pure.

The four general types of silicon photovoltaic cells are:

1. Single-crystal silicon.
2. Polycrystalline silicon (also known as multicrystal silicon).
3. Ribbon silicon.
4. Amorphous silicon (abbreviated as “aSi,” also known as thin film silicon).

1. Single-crystal silicon

Most photovoltaic cells are single-crystal types. To make them, silicon is purified, melted, and crystallized into ingots. The ingots are sliced into thin wafers to make individual cells. The cells have a uniform color, usually blue or black (Figure 2-5).

Fig-2.5: Single-Crystal Cells

2. Polycrystalline silicon

Polycrystalline cells are manufactured and operate in a similar manner. The difference is that lower cost silicon is used. This usually results in slightly lower efficiency, but polycrystalline cell manufacturers assert that the cost benefits outweigh the efficiency losses.

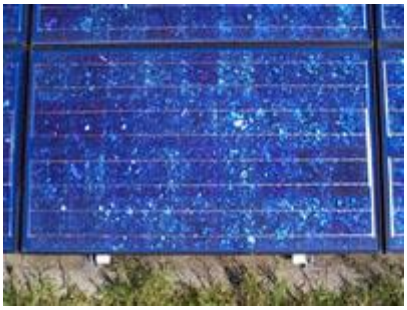


Fig-2.6 Polycrystalline Silicon Cells

The surface of polycrystalline cells has a random pattern of crystal borders instead of the solid color of single crystal cells (Fig- 2.6).

3. Ribbon silicon

Ribbon-type photovoltaic cells are made by growing a ribbon from the molten silicon instead of an ingot. These cells operate the same as single and polycrystalline cells.

The anti-reflective coating used on most ribbon silicon cells gives them a prismatic rainbow appearance.

4. Amorphous or thin film silicon

The previous three types of silicon used for photovoltaic cells have a distinct crystal structure. Amorphous silicon has no such structure. Amorphous silicon is sometimes abbreviated “aSi” and is also called thin film silicon.

Amorphous silicon units are made by depositing very thin layers of vaporized silicon in a vacuum onto a support of glass, plastic, or metal.

Amorphous silicon cells are produced in a variety of colors (Figure 2-7).

Fig-2.7 An Amorphous Silicon Module

2.3.2 Photovoltaic Modules

For almost all applications, the one-half volt produced by a single cell is inadequate. Therefore, cells are connected together in series to increase the voltage. Several of these series strings of cells may be connected together in parallel to increase the current as well.

These interconnected cells and their electrical connections are then sandwiched between a top layer of glass or clear plastic and a lower level of plastic or plastic and metal. An outer frame is attached to increase mechanical strength, and to provide a way to mount the unit. This package is called a “module” or “panel” (Figure 2-8). Typically, a module is the basic building block of photovoltaic systems. Table 2-1 is a summary of currently available modules.

Fig-2.8 A Photovoltaic Module

2.3.3 Describing Photovoltaic Module Performance

To insure compatibility with storage batteries or loads, it is necessary to know the electrical characteristics of photovoltaic modules.

As a reminder, “I” is the abbreviation for current, expressed in amps. “V” is used for voltage in volts, and “R” is used for resistance in ohms.

A photovoltaic module will produce its maximum current when there is essentially no resistance in the circuit. This would be a short circuit between its positive and negative terminals.

This maximum current is called the short circuit current, abbreviated I(sc). When the module is shorted, the voltage in the circuit is zero.

Conversely, the maximum voltage is produced when there is a break in the circuit. This is called the open circuit voltage, abbreviated V(oc). Under this condition the resistance is infinitely high and there is no current, since the circuit is incomplete.

These two extremes in load resistance, and the whole range of conditions in between them, are depicted on a graph called a I-V (current-voltage) curve. Current, expressed in amps, is on the vertical Y-axis. Voltage, in volts, is on the horizontal X-axis (Figure 2-9).

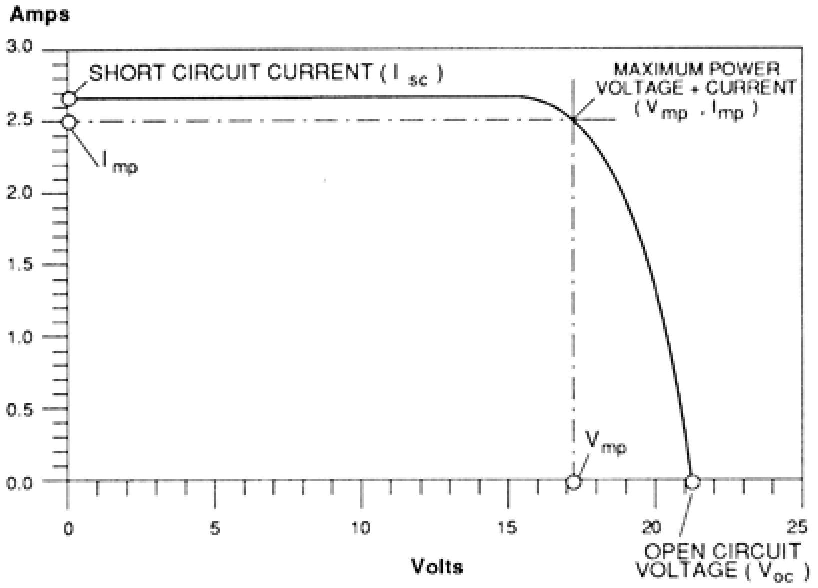


Fig-2.9: A Typical Current-Voltage Curve

As you can see in Figure 2-9, the short circuit current occurs on a point on the curve where the voltage is zero. The open circuit voltage occurs where the current is zero.

The power available from a photovoltaic module at any point along the curve is expressed in watts. Watts are calculated by multiplying the voltage times the current (watts = volts x amps, or W = VA).

At the short circuit current point, the power output is zero, since the voltage is zero.

At the open circuit voltage point, the power output is also zero, but this time it is because the current is zero.

There is a point on the "knee" of the curve where the maximum power output is located. This point on our example curve is where the voltage is 17 volts, and the current is 2.5 amps. Therefore the maximum power in watts is 17 volts times 2.5 amps, equaling 42.5 watts.

The power, expressed in watts, at the maximum power point is described as peak, maximum, or ideal, among other terms. Maximum power is generally abbreviated as "I (mp)." Various manufacturers call it maximum output power, output, peak power, rated power, or other terms.

The current-voltage (I-V) curve is based on the module being under standard conditions of sunlight and module temperature. It assumes there is no shading on the module.

Standard sunlight conditions on a clear day are assumed to be 1000 watts of solar energy per square meter (1000 W/m2or lkW/m2). This is sometimes called "one sun," or a "peak sun." Less than one sun will reduce the current output of the module by a proportional amount. For example, if only one-half sun (500 W/m2) is available, the amount of output current is roughly cut in half (Figure 2-10).

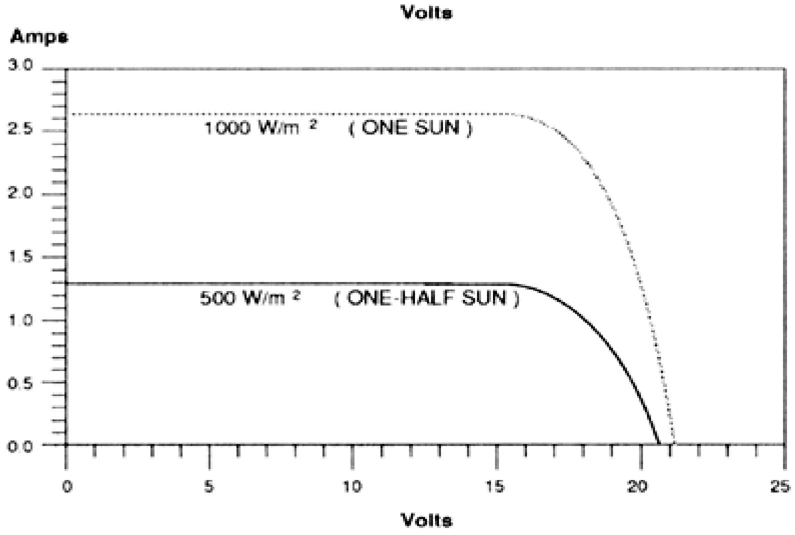


Fig-2.10

A Typical Current-Voltage Curve at One Sun and One-half Sun

For maximum output, the face of the photovoltaic modules should be pointed as straight toward the sun as possible. Section 2.3.5 contains information on determining the correct direction and module tilt angle for various locations and applications.

Because photovoltaic cells are electrical semiconductors, partial shading of the module will cause the shaded cells to heat up. They are now acting as inefficient conductors instead of electrical generators. Partial shading may ruin shaded cells.

Partial module shading has a serious effect on module power output. For a typical module, completely shading only one cell can reduce the module output by as much as 80% (Figure 2-11). One or more damaged cells in a module can have the same effect as shading.

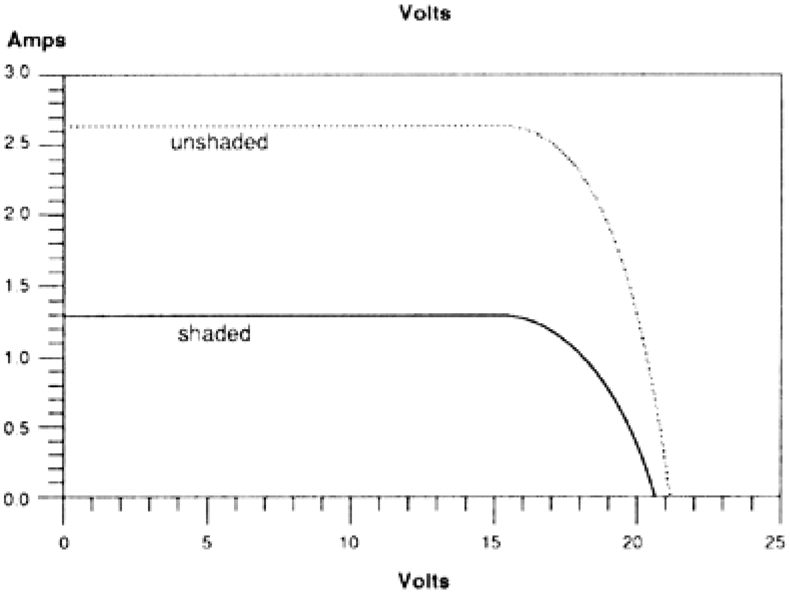


Fig-2.11

A Typical Current-Voltage Curve for an Unshaded Module and for a Module with One Shaded Cell

This is why modules should be completely unshaded during operation. A shadow across a module can almost stop electricity production. Thin film modules are not as affected by this problem, but they should still be unshaded.

Module temperature affects the output voltage inversely. Higher module temperatures will reduce the voltage by 0.04 to 0.1 volts for every one Celsius degree rise in temperature (0.04V/0C to 0.1V/0C). In Fahrenheit degrees, the voltage loss is from 0.022 to 0.056 volts per degree of temperature rise (Figure 2-12).

This is why modules should not be installed flush against a surface. Air should be allowed to circulate behind the back of each module so it's temperature does not rise and reducing its output. An air space of 4-6 inches is usually required to provide proper ventilation.

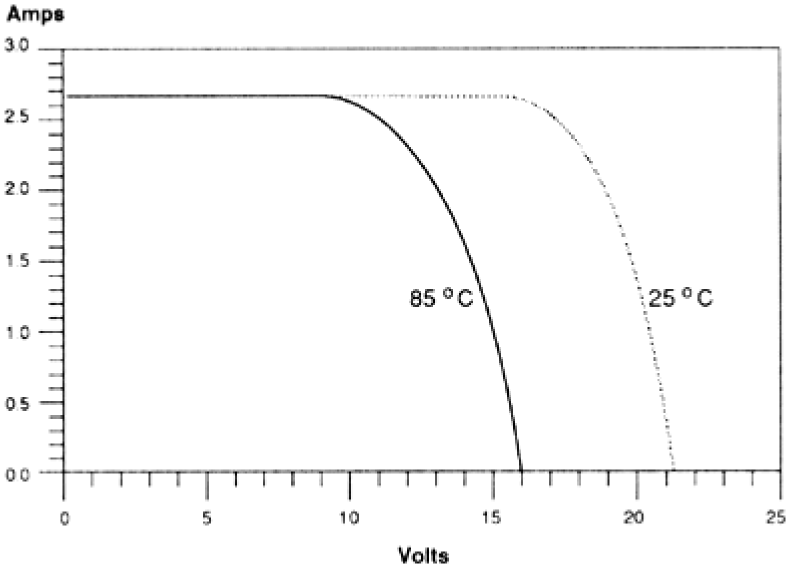


Fig-2.12

A Typical Current-Voltage Curve for a Module at 25°C (77°F) and 85°C (185°F)

The last significant factor which determines the power output of a module is the resistance of the system to which it is connected. If the module is charging a battery, it must supply a higher voltage than that of the battery.

If the battery is deeply discharged, the battery voltage is fairly low. The photovoltaic module can charge the battery with a low voltage, shown as point #1 in Figure 2-13. As the battery reaches a full charge, the module is forced to deliver a higher voltage, shown as point #2. The battery voltage drives module voltage.

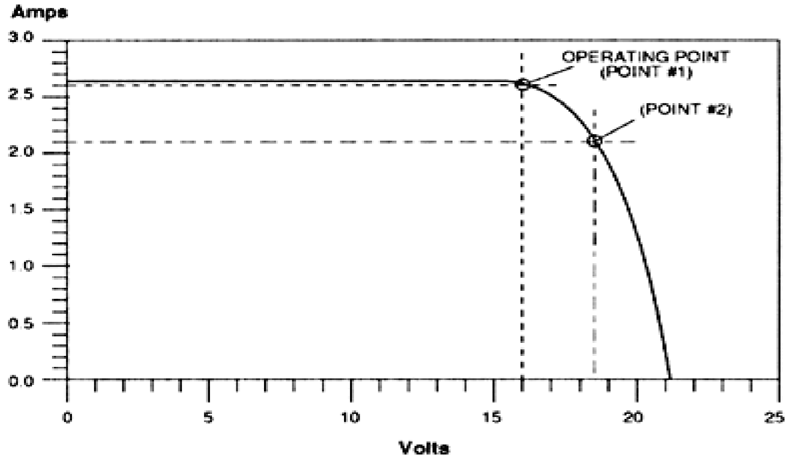


Fig- 2.13

Operating Voltages During a Battery Charging Cycle

Eventually, the required voltage is higher than the voltage at the module’s maximum power point. At this operating point, the current production is lower than the current at the maximum power point. The module’s power output is also lower.

To a lesser degree, when the operating voltage is lower than that of the maximum power point (point #1), the output power is lower than the maximum. Since the ability of the module to produce electricity is not being completely used whenever it is operating at a point fairly far from the maximum power point, photovoltaic modules should be carefully matched to the system load and storage.

Using a module with a maximum voltage which is too high should be avoided nearly as much as using one with a maximum voltage which is too low.

The output voltage of a module depends on the number of cells connected in series. Typical modules use either 30, 32, 33, 36, or 44 cells wired in series.

The modules with 30-32 cells are considered self regulating modules. 36 cell modules are the most common in the photovoltaic industry. Their slightly higher voltage rating, 16.7 volts, allows the modules to overcome the reduction in output voltage when the modules are operating at high temperatures.

Modules with 33 - 36 cells also have enough surplus voltage to effectively charge high antimony content deep cycle batteries. However, since these modules can overcharge batteries, they usually require a charge controller.

Finally, 44 cell modules are available with a rated output voltage of 20.3 volts. These modules are typically used only when a substantially higher voltage is required.

As an example, if the module is sometimes forced to operate at high temperatures, it can still supply enough voltage to charge 1 2 volt batteries.

Another application for 44 cell modules is a system with an extremely long wire run between the modules and the batteries or load. If the wire is not large enough, it will cause a significant voltage drop. Higher module voltage can overcome this problem.

It should be noted that this approach is similar to putting a larger engine in a car with locked brakes to make it move faster. It is almost always more cost effective to use an adequate wire size, rather than to overcome voltage drop problems with more costly 44 cell modules.

2.3.4 Photovoltaic Arrays

In many applications the power available from one module is inadequate for the load. Individual modules can be connected in series, parallel, or both to increase either output voltage or current. This also increases the output power.

When modules are connected in parallel, the current increases. For example, three modules which produce 15 volts and 3 amps each, connected in parallel, will produce 15 volts and 9 amps (Figure 2-14).

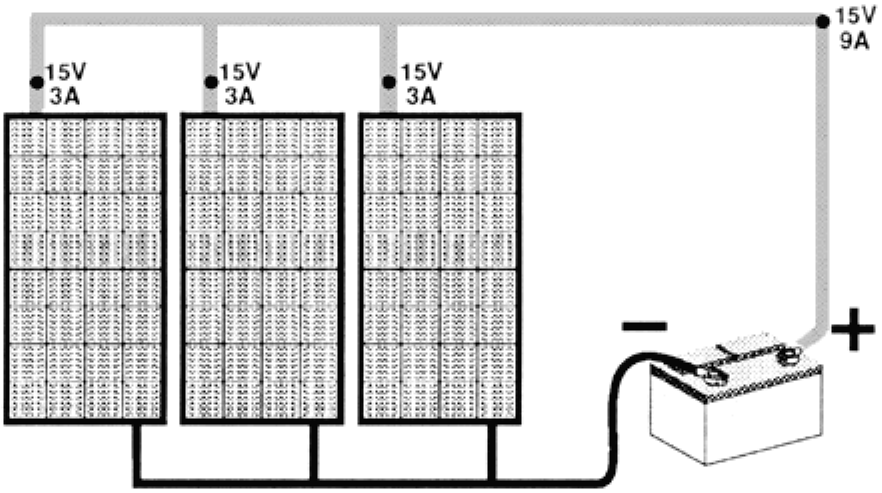


Fig-2.14

Three Modules Connected in Parallel

If the system includes a battery storage system, a reverse flow of current from the batteries through the photovoltaic array can occur at night. This flow will drain power from the batteries.

A diode is used to stop this reverse current flow. Diodes are electrical devices which only allow current to flow in one direction (Figure 2-15). A blocking diode is shown in the array in Figure 2-16.

Diodes with the least amount of voltage drop are called schottky diodes, typically dropping .3 volts instead of .7 volts as in silicon diodes.

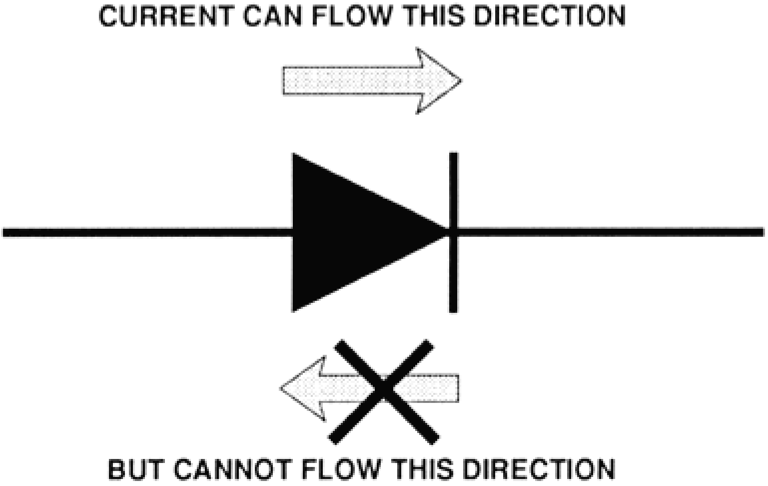


Fig-2.15: Basic Operation of a Diode

Because diodes create a voltage drop, some systems use a controller which opens the circuit instead of using a blocking diode.

If the same three modules are connected in series, the output voltage will be 45 volts, and the current will be 3 amps.

If one module in a series string fails, it provides so much resistance that other modules in the string may not be able to operate either. A bypass path around the disabled module will eliminate this problem (Figure 2-16). The bypass diode allows the current from the other modules to flow through in the “right” direction.

Many modules are supplied with a bypass diode right at their electrical terminals. Larger modules may consist of three groups of cells, each with its own bypass diode.

Built in bypass diodes are usually adequate unless the series string produces 48 volts or higher, or serious shading occurs regularly.

Combinations of series and parallel connections are also used in arrays (Figure 2-17). If parallel groups of modules are connected in a series string, large bypass diodes are usually required.

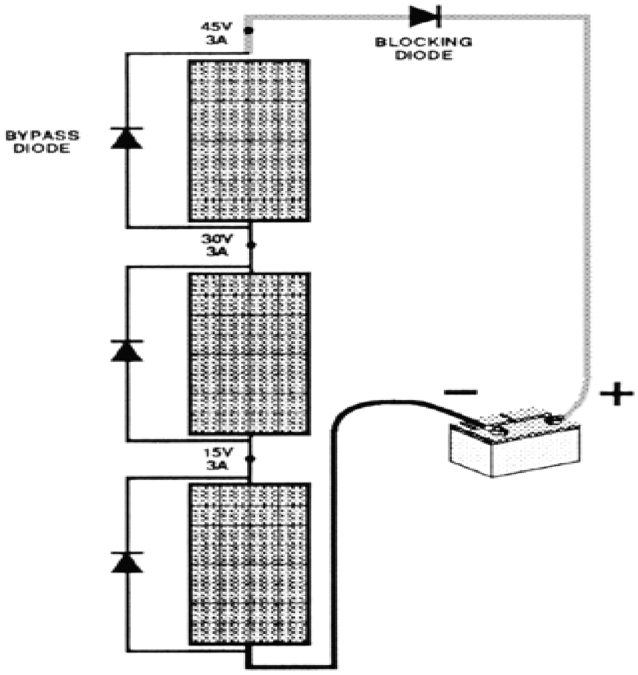


Fig-2.16

Three Modules Connected in Series with a Blocking Diode and Bypass Diodes

Isolation diodes are used to prevent the power from the rest of an array from flowing through a damaged series string of modules. They operate like a blocking diode. They are normally required when the array produces 48 volts or more. If isolation diodes are used on every series string, a blocking diode is normally not required.

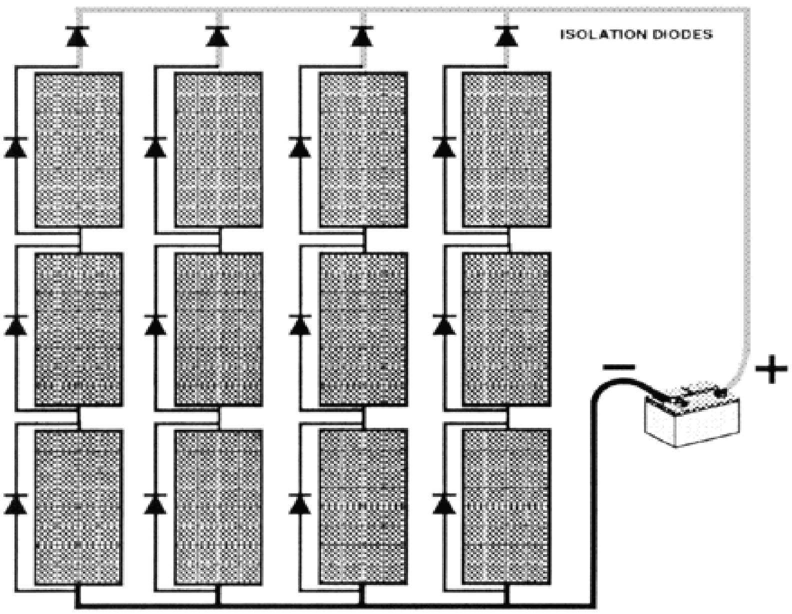


Fig-2.17

Twelve Modules in a Parallel-Series Array with Bypass Diodes and Isolation Diodes

1.Flat-plate stationary arrays

Stationary arrays are the most common. Some allow adjustments in their tilt angle from the horizontal. These changes can be made any number of times throughout the year, although they are normally changed only twice a year. The modules in the array do not move throughout the day (Figure 2-18).

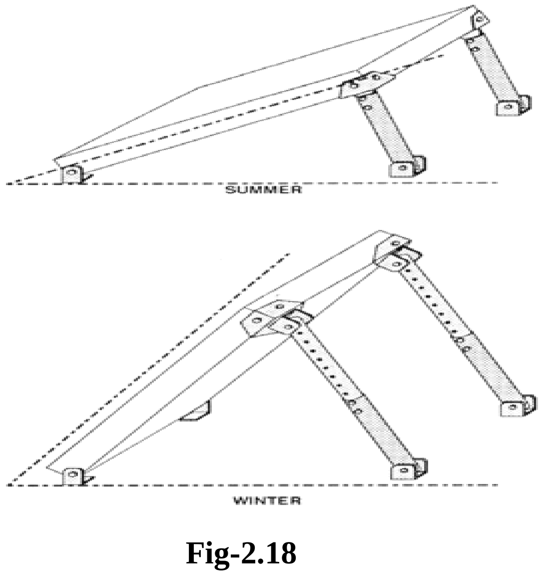


Fig-2.18

Adjustable Array Tilted for summer and Winter Solar Angles

Although a stationary array does not capture as much energy as a tracking array that follows the sun across the sky, and more modules may be required, there are no moving parts to fail. This reliability is why a stationary array is often used for remote or dangerous locations. Section 2.3.5 contains information on determining the correct tilt angle and orientation for different photovoltaic applications.

2. Portable arrays

A portable array may be as small as a one square foot module easily carried by one person to recharge batteries for communications or flashlights. They can be mounted on vehicles to maintain the engine battery during long periods of inactivity. Larger ones can be installed on trailers or truck beds to provide a portable power supply for field operations (Figures 2-19 and 2-20)

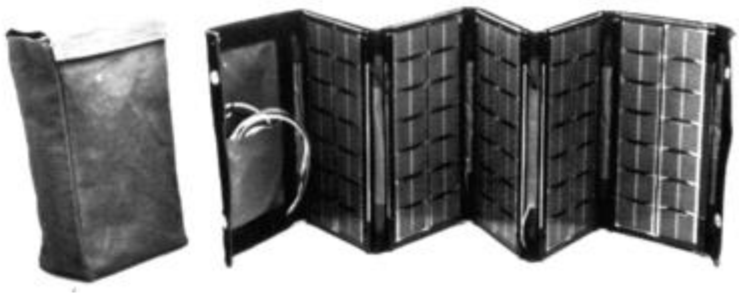


Figure2-19:
Personal Photovoltaic Array
Photo Courtesy of Arco Solar, Inc.

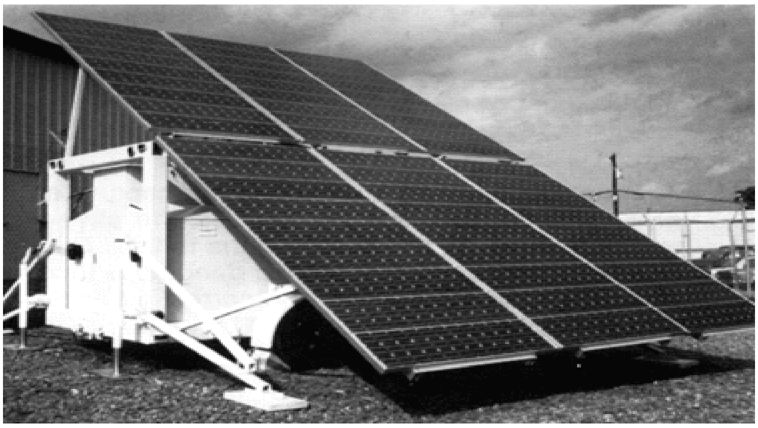


Fig-2.20
Personal Photovoltaic Array

3.Tracking arrays

Arrays that track, or follow the sun across the sky, can follow the sun in one axis or in two (Figure 2-21). Tracking arrays perform best in areas with very clear climates. This is because following the sun yields significantly greater amounts of energy when the sun's energy is predominantly direct. Direct radiation comes straight from the sun, rather than the entire sky.

Normally, one axis trackers follow the sun from the east to the west throughout the day. The angle between the modules and the ground does not change. The modules face in the "compass" direction of the sun, but may not point exactly up at the sun at all times.

Two axis trackers change both their east-west direction and the angle from the ground during the day. The modules face straight at the sun all through the day. Two axis trackers are considerably more complicated than one axis types.

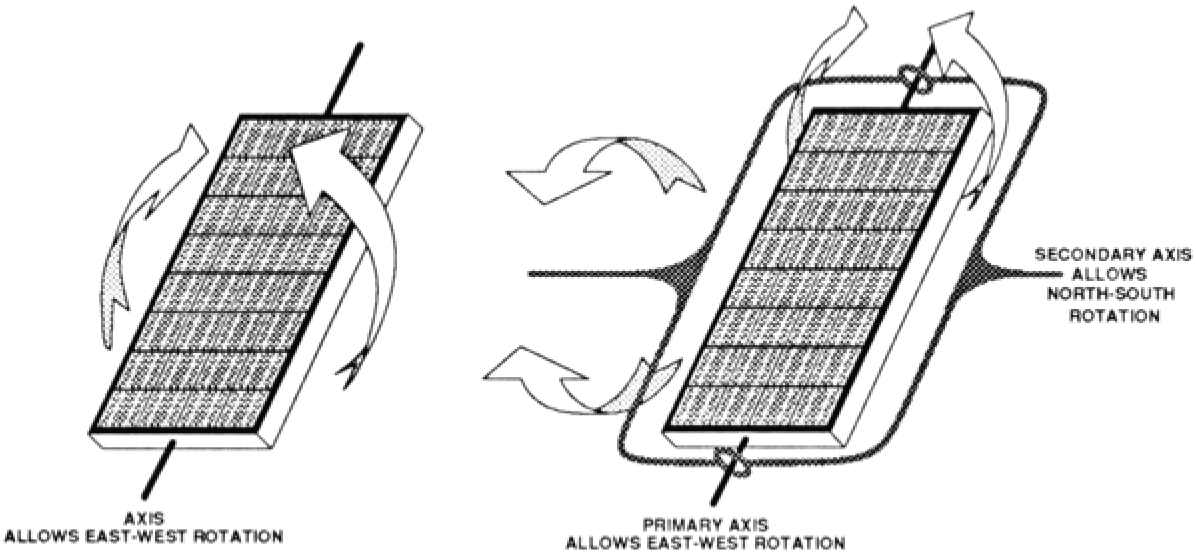


Fig-2.21

One Axis and Two Axis Tracking Arrays

Three basic tracking methods are used. The first uses simple motor, gear, and chain systems to move the array. The system is designed to mechanically point the modules in the direction the sun should be. No sensors or devices actually confirm that the modules are facing the right way.

The second method uses photovoltaic cells as sensors to orient the larger modules in the array. This can be done by placing a cell on each side of a small divider, and mounting the package so it is facing the same way as the modules (Figure 2-22).

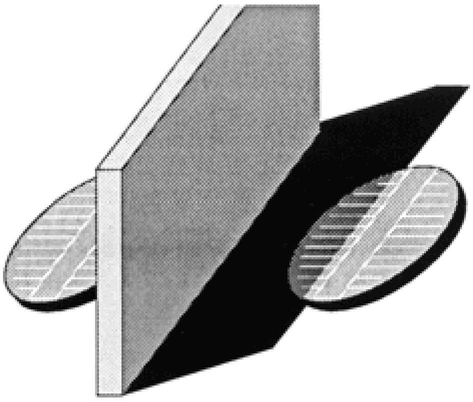


Fig- 2.22

Photovoltaic Cells

Used as Solar Orientation Sensor

An electronic device constantly compares the small current flow from both cells. If one is shaded, the device triggers a motor to move the array until both cells are exposed to equal amounts of sunlight.

At night or during cloudy weather, the output of both sensor cells is equally low, so no adjustments are made. When the sun comes back up in the morning, the array will move back to the east to follow the sun again.

Although both methods of tracking with motors are quite accurate, there is a “parasitic” power consumption. The motors take up some of the energy the photovoltaic system produces.

A method which has no parasitic consumption uses two small photovoltaic modules to power a reversible gear motor directly. If both modules are in equal sunlight, as shown in Figure 2-23, current flows through the modules and none flows through the motor.

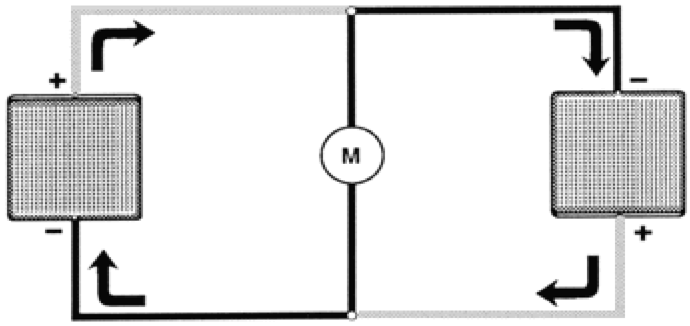


Fig-2.23

Current Flow with Both Modules in Equal Sunlight

If the right module is shaded, it acts as a resistor (Figure 2-24). Now the current will flow through the motor, turning it in one direction.

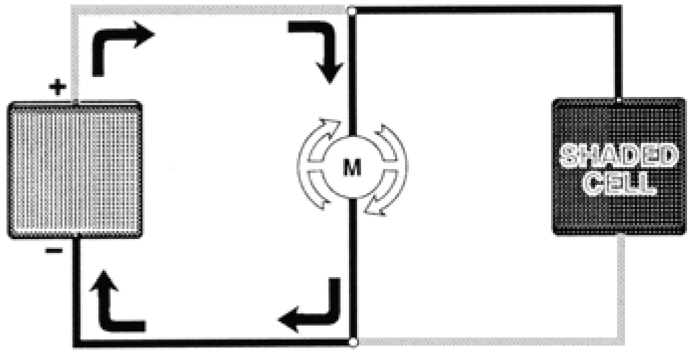


Fig-2.24

Current Flow with One Module Shaded

If the other module, shown in Figure 2-25 on the left, is shaded, the current from the right module flows in the opposite direction. The motor will turn in the opposite direction as well.

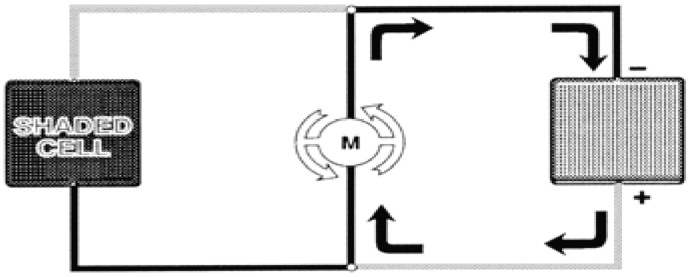


Fig-2.25

Current Flow with the Other Module Shaded

The motor must be able to turn in both directions.

A third tracking method uses the expansion and contraction of fluids to move the array. Generally, a container is filled with a fluid that vaporizes and expands considerably whenever it is in the sun. It condenses and contracts similarly when in the shade. These "passive" tracking methods have proven to be reliable and durable, even in high wind situations.

One system, the 9'SUN SEEKER" TM from Robbins Engineering, uses the pressure of the expansion and contraction to operate a hydraulic cylinder. Flexible piping from two containers filled with freon goes to opposite sides of a piston in the cylinder (Figure 2-26).

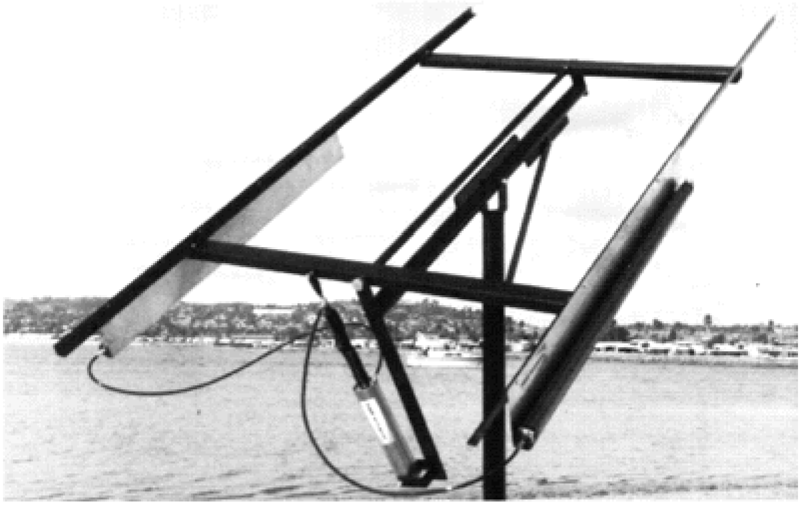


Fig- 2.26

Sun Seeker System without Modules

If the array is facing the sun, the pressure in both containers stays the same, and the piston will not move in the cylinder. However, when the sun moves the shading on the containers changes, placing them under different pressures.

The pressure difference, brought to the cylinder by the piping, will move the piston. The shaft from the piston will move the array. When the array is pointed back at the sun, the pressure stops increasing in the cylinder, and the piston and rod stop moving.

Another way to move the array with an expansive fluid is to use the change in fluid weight when it vaporizes. The Solar Track Rack TM by Zomeworks uses this method

The fluid-filled containers are integrated into the sides of the array mounting structure. They are connected together flexible piping, which is protected in the mounting structure. As long as the array is facing directly at the sun, the shades cover each container equally.

When the array is no longer facing directly at the sun, one container is exposed to more heat from the sun. This causes the fluid in that container to boil out of that container into the other one. Now the shaded container has more fluid in it and is heavier. The array will drop down like a “teeter-totter” in the direction of the shaded container until the shading equalizes on the two containers again.

Since this method is more sensitive, wind can move the array. A shock absorber is included in the system to absorb such rapidly applied forces.

Reflectors

Reflectors are sometimes used to increase the amount of solar energy striking the modules (Figure 2-27). Since reflectors cost less than photovoltaic modules, this method may be used for some applications. There are several problems with reflectors, however.

Not all photovoltaic modules are designed for the higher temperatures reflectors cause. The performance and physical structure of many modules will suffer if reflectors are used with them. Remember that higher module temperatures mean lower output voltages.

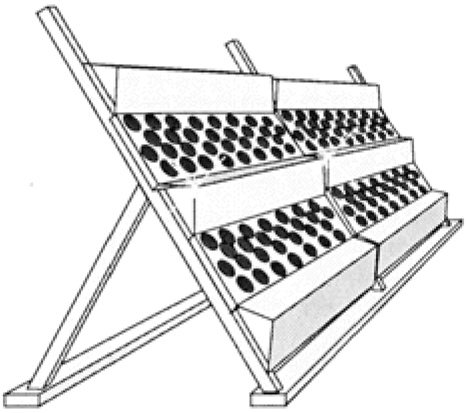


Fig-2.27
Reflectors on a Fixed Photovoltaic Array

Another problem is that reflectors work mostly with sunlight coming directly from the sun. Since a great deal of the sun’s energy in cloudy climates comes to the earth’s surface from all parts of the sky, reflectors are most effective in clear climates.

In all but the clearest of climates, the amount of direct solar energy is rarely high enough to justify the use of reflectors all year.

By increasing the overall surface area of the array, reflectors also increase the array’s wind loading characteristics.

Finally, some type of tracking system may be required. This increases the system cost, may add a parasitic power loss, and can reduce the system reliability. Poorly designed or improperly installed reflectors have been known to shade modules.

Concentrators

Concentrators use lenses or parabolic reflectors to focus light from a larger area onto a photovoltaic cell of smaller area. The cells are spread out more than a typical module, and must be a high temperature type. They may have a heat removal system to keep module temperatures down and output voltages up. These systems have the same disadvantages of reflectors, and are higher in cost. As a consequence, large systems feeding a utility grid are usually the only ones using reflectors or concentrators.

Bracket mounting

Small arrays of one or two modules can use simple brackets to secure the modules individually to a secure surface . The surface may be a roof, wall, post, pole, or vehicle. Brackets can include some method to adjust the tilt angle of the module.

The brackets are usually aluminum. If steel is used, it should be painted or treated to prevent corrosion. Galvanized steel is normally avoided, because the continuous grounding used on arrays aggravates the galvanic corrosion that occurs between galvanized steel and almost all other metals.

Fastener hardware should be stainless steel or cadmium plated to prevent corrosion. Identical metals should be used for components and fasteners whenever possible.

Pole mounting

Typically, up to four modules can be connected together and mounted on a pole (Figure 2-28). Typically, 2 ½” nominal steel pipe (O.D. of 3”) is used.

Black iron or steel pipe can be used, if painted. Galvanized pipe, rarely available in this size, can be used if compatible fasteners are used. Larger arrays can be pole mounted, if hardware sizes are appropriately increased.

The same types of materials used for bracket mounting should be used for pole mounting.

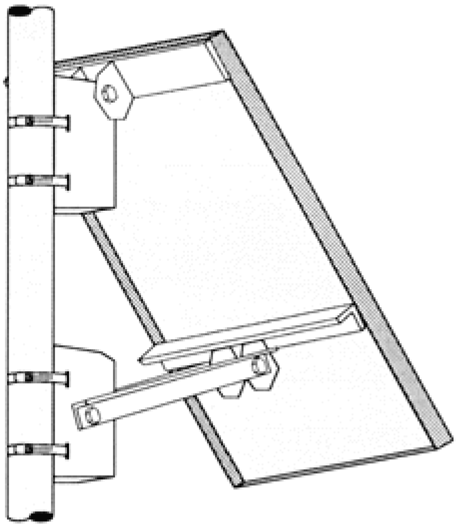


Fig- 2.28

Pole Mount of Photovoltaic Array

Ground mounting

For arrays of eight or more modules, ground mounting is usually the most appropriate technique. The greatest concern is often the uplifting force of wind on the array. This is why most ground mounted arrays are on some kind of sturdy base, usually concrete.

Concrete bases are either piers, a slab with thicker edges, or footings at the front and rear of the array (Figure 2-30). All three usually include a steel reinforcement bar.

In some remote sites it may be more desirable to use concrete block instead of poured concrete. The best way to do this is to use two-web bond-beam block, reinforce it with steel, and fill the space between the webs with concrete or mortar.

Pressure-treated wood of adequate size is sometimes used for ground mounting. This can work well in fairly dry climates, but only if the beams are securely anchored to the ground, and regular inspection and maintenance is provided.

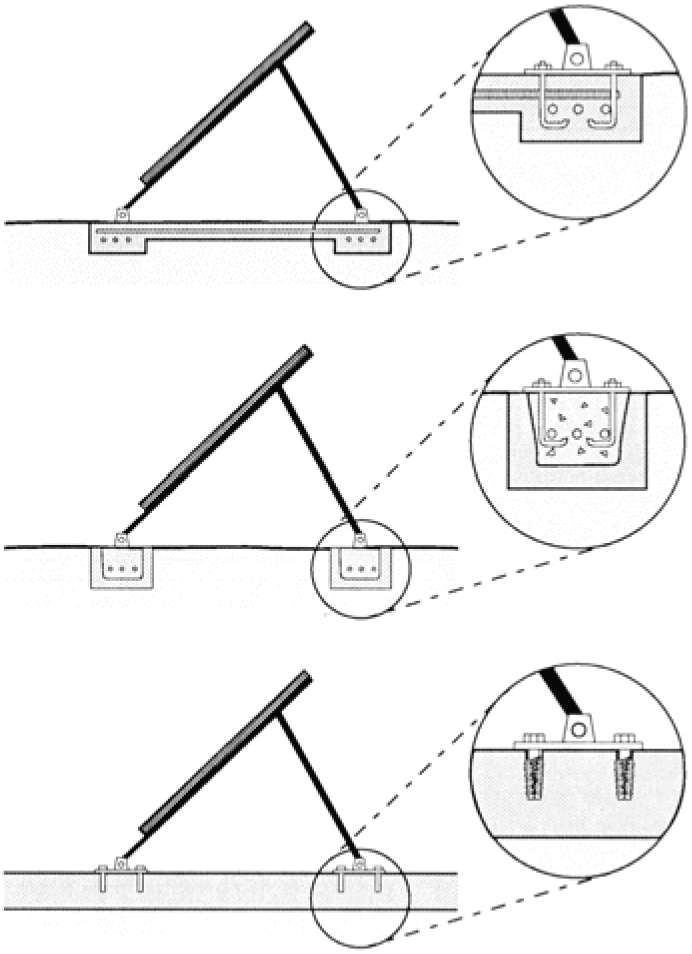


Fig-2.30

Concrete Bases

The array’s mounting hardware can be bolted to an existing slab. With extensive shimming, some mountaintop arrays are bolted to exposed rock. In either case, adequately sized expansion-type anchor bolts are used. The heads of the bolts should be covered with some type of weatherproof sealant. Silicone sealant is the best choice.

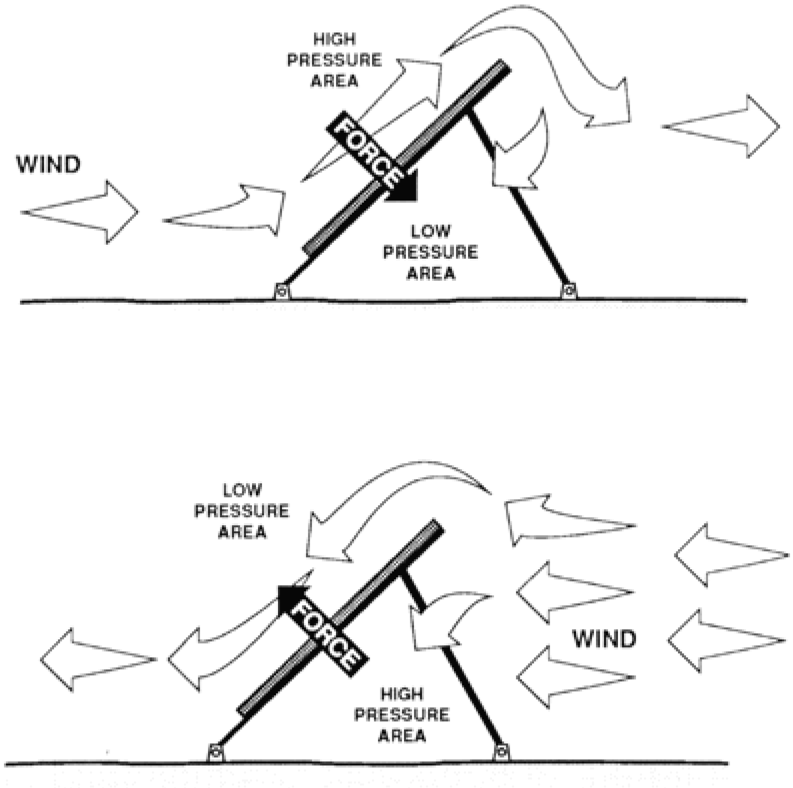


Fig-2.31 Forces on a Photovoltaic Array

Structure mounting

Photovoltaic modules mounted on buildings or other structures are subjected to downward force when the wind hits their front surfaces. When the wind strikes the back of the modules, upward force is generated (Figure 2-31).

For this reason, the attachment to the building of modules with exposed backs is designed to resist both directions of force.

Another consideration when modules are mounted to a structure is the trapped heat between the module and the structure. Remember that module voltage drops with increased temperature.

Generally, photovoltaic arrays are mounted on structures in such a way that air can maturely circulate under the modules. This keeps the modules operating at the lowest possible temperature and highest possible output voltage. Access to the back of the modules also simplifies service operations.

2.3.5 Module Tilt and Orientation

Permanently mounted modules should be tilted up from the horizontal (Figure 2-32 and Table 2-2). The correct tilt angle varies with the times of year the system is used, and the latitude of the site. The tilt angle is measured from the horizontal, not from a pitched roof or hillside.

The tilt should be within 10 degrees of the listed angle. For example, a system used throughout the year at a latitude of 350 can have a tilt angle of 250 to 450 without a noticeable decrease in annual performance.

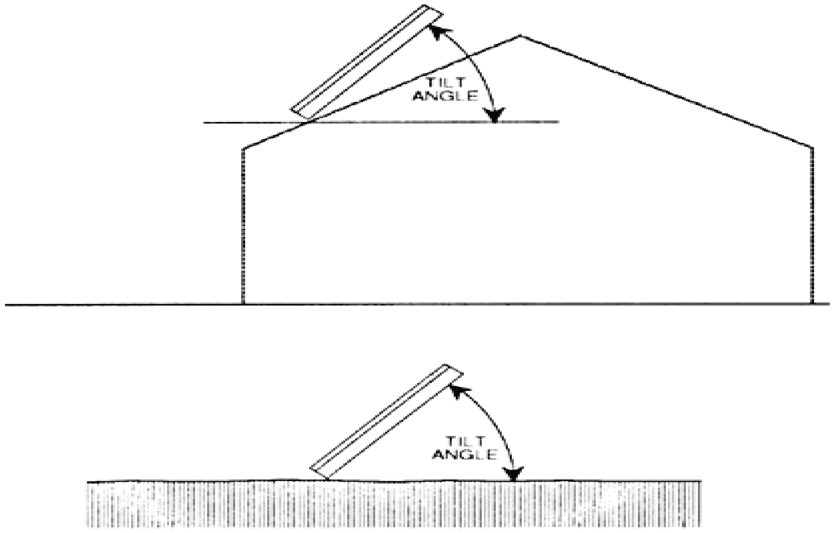


Fig-2.32 Module Tilt Measured form the Horizontal on Level and Tilted Surfaces

Table 2-1 Photovoltaic Module Tilt Angles

Time of Year System is Used the Most	Recommended Tilt Angle
All Year	Latitude
Mostly Winter	Latitude + 15°
Mostly Summer	Latitude - 15°
Mostly Fall or Spring	Latitude

2.4 Basic System Operation

2.4.1 Direct (Direct Coupled) DC System

The simplest photovoltaic system is made up of an array connected directly to a load. If the array includes more than one module, bypass diodes are used (Figure 2-33).
Applications requiring the most power during the sunniest part of the day are ideal for this type of system. Pumping water for irrigation or to a storage tank, running a fan for ventilation, or operating a pump to collect solar heat are examples of appropriate applications. Lighting and other loads which are rarely used during the daylight hours would probably never be supplied with power by a system of this type.

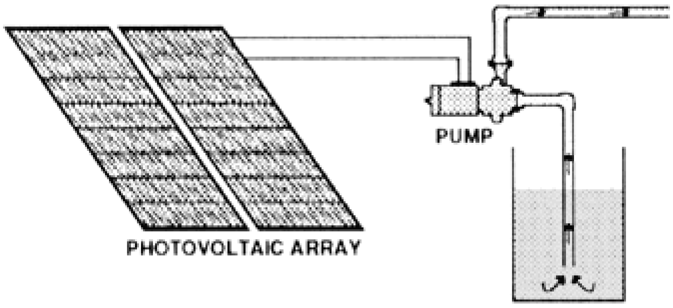


Fig- 2.33

Direct DC System

The load must run on DC (Direct Current) electricity. This normally means a DC motor is used to run a pump, fan, or other device. As the sunlight gets more intense, the motor runs faster. Thus, the more sunlight, the more water or air that is moved.

2.4.2 Power Point Tracking DC System

The performance of a direct DC system can be increased by adding a power point tracker (Figure 2-34).

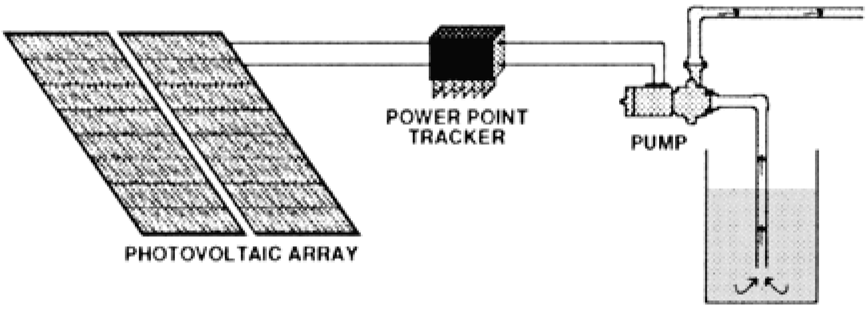


Fig- 2.34
Power Point Tracking
DC System

The power point tracker constantly monitors the system performance and makes electrical adjustments to keep the system operating as close as possible to its maximum output.

2.4.3 Self-Regulated DC System

If battery storage is added to the system, some means must be used to prevent overcharging the batteries. The simplest way to do this is to use self-regulating modules. These modules are designed to deliver a voltage that is too low to overcharge the battery. (Figure 2-35). Careful matching of component sizes and loads is critical.

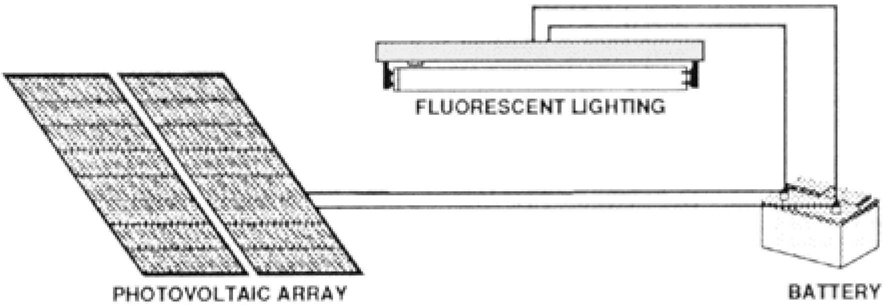


Fig- 2.35

Self-Regulated DC System

Again, the loads are DC only. If adequate battery storage is provided, and the loads are used consistently, this can be a reliable system. Because electricity is stored, lighting and other devices can be used after dark or during cloudy weather.

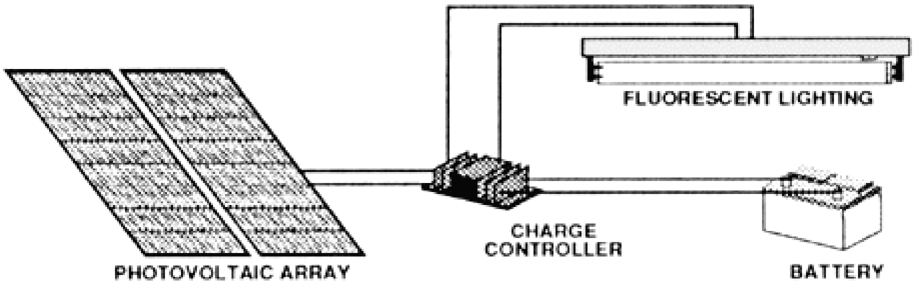
2.4.4 Regulated DC System

Most systems do not have self-regulated modules. Furthermore, many systems require some way to prevent damaging the batteries from charge levels which are too high or too low.

A charge controller, sometimes called a charge regulator, is used to keep the batteries from being overcharged. An optional feature of many controllers is a load cutoff. This turns off some or all of the loads whenever the batteries' state of charge gets too low (Figure 2-36).

Fig-2.36

Regulated DC System



Although the additional component adds to the complexity of the system, draws additional power, and can reduce overall reliability, the charge controller extends the battery life.

This is probably the most common photovoltaic system.

2.45 Direct AC System

In some cases, such as deep well water pumping, AC loads must be provided with power, but only during the day. If the DC output of a photovoltaic array is converted to AC with an inverter, it can supply the AC load directly (Figure 2-37)

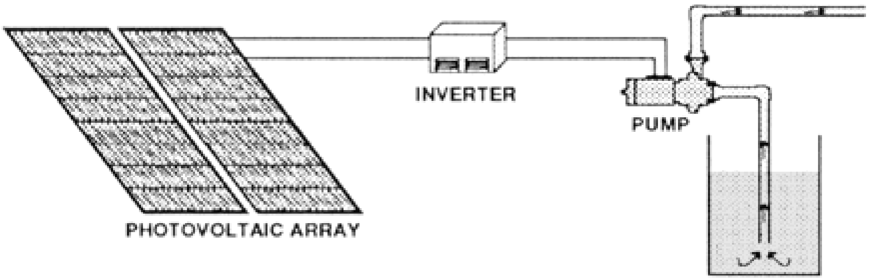


Fig- 2.37

Direct AC System

This system is appropriate for many of the same situations as the direct DC system. The inverter must be protected from temperature extremes and inclement weather. The cost of an inverter is significant, and it reduces the overall system efficiency. However, if the application requires a device which cannot operate on or be converted to DC, this is the simplest way to do the job.

2.4.6 AC System with Storage

If the AC load must run during periods when the photovoltaic array cannot supply power, battery storage and a charge controller must be included (Figure 2-38).

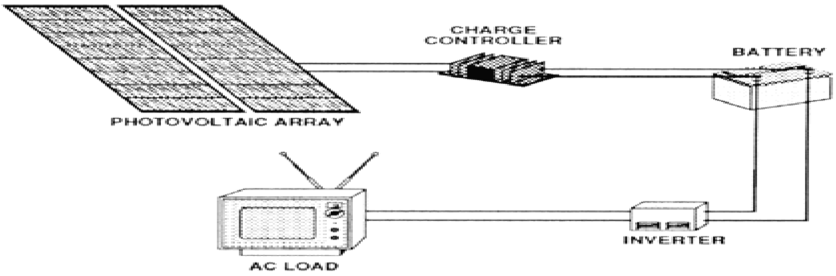


Fig- 2.38

AC System with Storage

The combined inefficiencies of the batteries and the inverter reduce overall system performance. Nevertheless, AC applications exist which will require the complexity and expense of this type of photovoltaic system.

2.4.7 Mixed AC/DC System

A good compromise is to supply every possible need with a DC device, and use AC only for those loads for which there is no alternative (Figure 2-39).

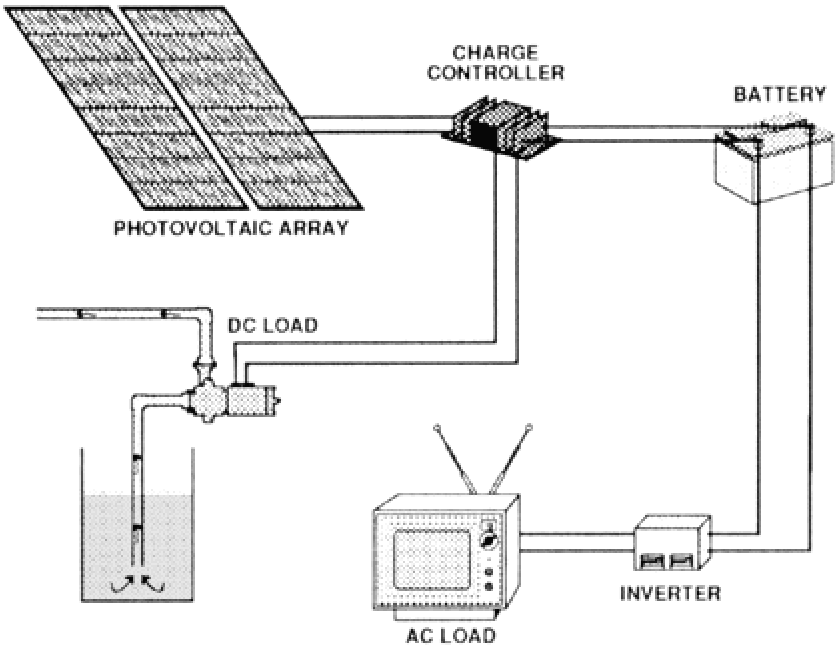


Fig-2.39 Mixed AC/DC System

This compromise allows the most effective use of the energy available from the photovoltaic array, while satisfying the load requirements.

2.5. SYSTEM COMPONENT OPERATION

2.5.1 Battery and Other Storage

Batteries store the electrical energy generated by the modules during sunny periods, and deliver it whenever the modules cannot supply power

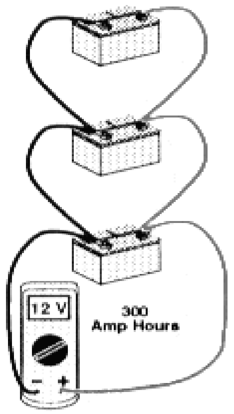
Normally, batteries are discharged during the night or cloudy weather. But if the load exceeds the array output during the day, the batteries can supplement the energy supplied by the modules.

The interval which includes one period of charging and one of discharging is described as a “cycle.” Ideally, the batteries are recharged to 100% capacity during the charging phase of each cycle. The batteries must not be completely discharged during each cycle.

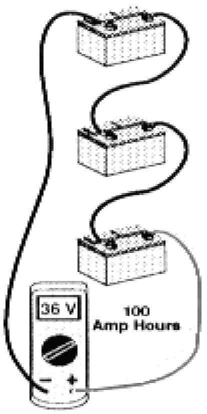
No single component in a photovoltaic system is more affected by the size and usage of the load than storage batteries. If a charge controller is not included in the system, oversized loads or excessive Use can drain the batteries’ charge to the point where they are damaged and must be replaced. If a controller does not stop overcharging, the batteries can be damaged during times of low or no load usage or long periods of full sun.

For these reasons, battery systems must be sized to match the load. In addition, different types and brands of batteries have different “voltage set point windows.” This refers to the range of voltage the battery has available between a fully discharged and fully charged state.

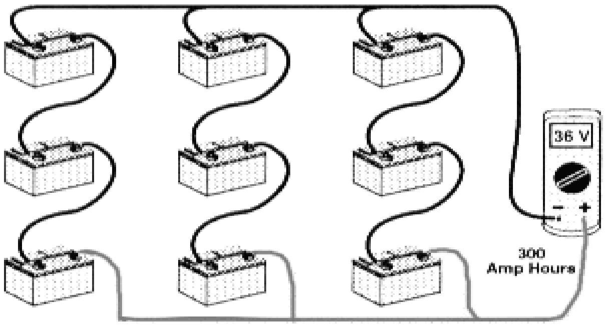
As an example, a battery may have a voltage of 14 volts when fully charged, and 11 when fully discharged. Assume the load will not operate properly below 12 volts. Therefore, there will be times when this battery cannot supply enough voltage for the load. The battery’s voltage window does not match that of the load.



PARALLEL



SERIES



SERIES-PARALLEL

2.5.2 Charge Controllers

The primary function of a charge controller in a stand-alone PV system is to protect the battery from overcharge and over discharge. Any system that has unpredictable loads, user intervention, optimized or undersized battery storage (to minimize initial cost), or any characteristics that would allow excessive battery overcharging or over discharging requires a charge controller and/or low-voltage load disconnect. Lack of a controller may result in shortened battery lifetime and decreased load availability (Reference 1).

Systems with small, predictable, and continuous loads may be designed to operate without a battery charge controller. If system designs incorporate oversized battery storage and battery charging currents are limited to safe finishing charge rates (C/SO flooded or C/1OO sealed) at an appropriate voltage for the battery technology, a charge controller may not be required in the PV system .Proper operation of a charge controller should prevent overcharge or over discharge of a battery regardless of the system sizing/design and seasonal changes in the load profile and operating temperatures. The algorithm or control strategy of a battery charge controller determines the effectiveness of battery charging and PV array utilization, and ultimately the ability of the system to meet the load demands. Additional features such as temperature compensation, alarms, and special algorithms can enhance the ability of a charge controller to maintain the health, maximize capacity, and extend the lifetime of a battery.

Shunt controller

A shunt controller regulates the charging of a battery by interrupting the PV current by short-circuiting the array. A blocking diode is required in series between the battery and the switching element to keep the battery from being shortened when the array is shunted. This controller typically requires a large heat sink to dissipate power. Shunt type controllers are usually designed for applications with PV currents less than 20 amps due to high current switching limitations (Figures 2-40).

Shunt-linear

This algorithm maintains the battery at a fixed voltage by using a control element in parallel with the battery. This control element turns on when the VR set point is reached, shunting power away from the battery in a linear method (not on/off), maintaining a constant voltage at the battery. This relatively simple controller design utilizes a Zener power diode which is the limiting factor in cost and power ratings.

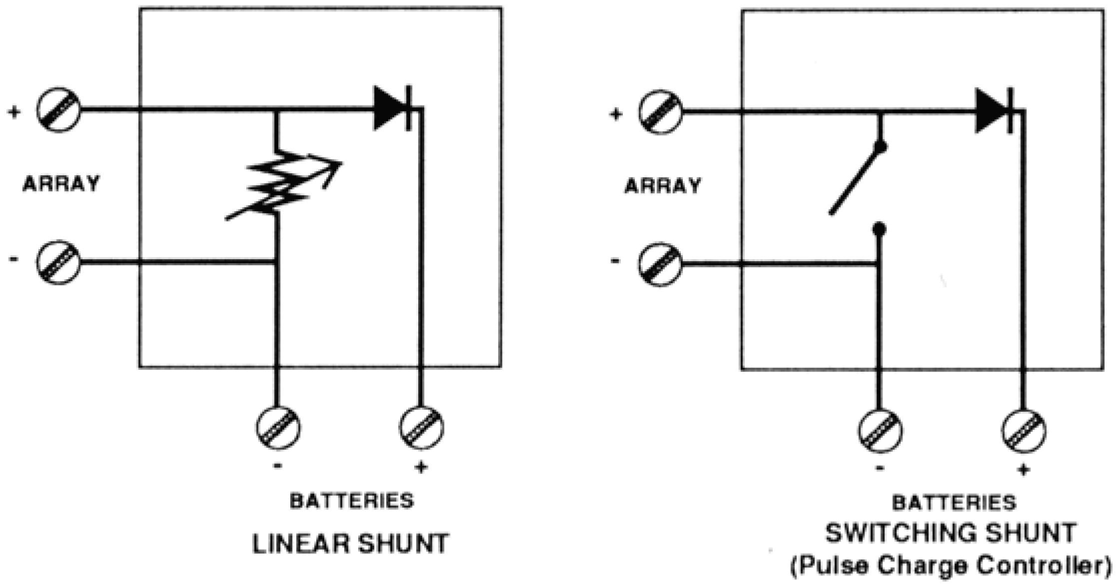


Fig- 2.40

Block Diagram of Linear and Switching Shunt Charge Controllers

Shunt-interrupting

This algorithm terminates battery charging when the VR set point is reached by short-circuiting the PV array. This algorithm has been referred to as “pulse charging” due to the pulsing effect when reaching the finishing charge state. This should not be confused with Pulse-Width Modulation (PWM).

Series Controller

Several variations of this type of controller exist, all of which use some type of control element in series between the array and the battery .

Series-interrupting: This algorithm terminates battery charging at the VR set point by open-circuiting the PV array.

2.6 Operation of a photovoltaic cell

Typically, most of the cell has a slight positive electrical charge. A thin layer at the top has a slight negative charge.

The cell is attached to a base called a “backplane.” This is usually a layer of metal used to physically reinforce the cell and to provide an electrical contact at the bottom.

Since the top of the cell must be open to sunlight, a thin grid of metal is applied to the top instead of a continuous layer. The grid must be thin enough to admit adequate amounts of sunlight, but wide enough to carry adequate amounts of electrical energy (Figure 2-41)

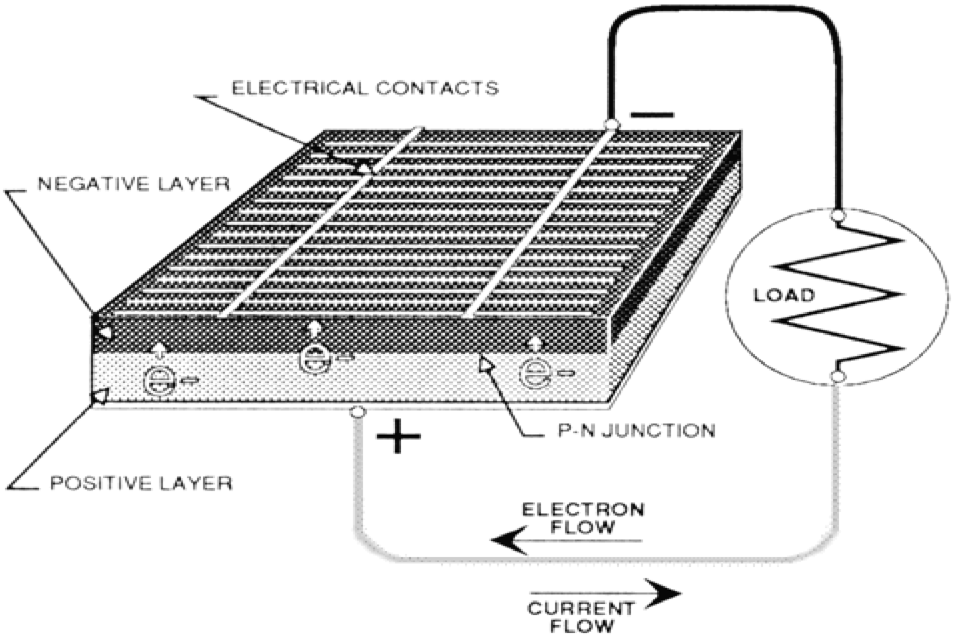


Fig-2.41 Operation of a Photovoltaic Cell

Light, including sunlight, is sometimes described as particles called “photons.” As sunlight strikes a photovoltaic cell, photons move into the cell.

When a photon strikes an electron, it dislodges it, leaving an empty “hole”. The loose electron moves toward the top layer of the cell. As photons continue to enter the cell, electrons continue to be dislodged and move upwards (Figure 2-41)

If an electrical path exists outside the cell between the top grid and the backplane of the cell, a flow of electrons begins. Loose electrons move out the top of the cell and into the external electrical circuit. Electrons from further back in the circuit move up to fill the empty electron holes.

Most cells produce a voltage of about one-half volt, regardless of the surface area of the cell. However, the larger the cell, the more current it will produce.

Current and voltage are affected by the resistance of the circuit the cell is in. The amount of available light affects current production. The temperature of the cell affects its voltage. Knowing the electrical performance characteristics of a photovoltaic power supply is important, and is covered in the next section.

2.7 POWER CONDITIONING AND CONTROL UNIT

A photovoltaic system in general may consists of the cells, a storage medium ,some form of backup either in the form of an auxiliary generator or the electricity supply grid, electrical loads and power conditioning and control unit. Power conditioning and control units are required to provide an interface between these different systems elements.

2.8 Types of PV system

Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. The two principal classifications are,

1. Grid-Connected or Utility-Interactive Systems.
2. Stand-Alone Systems.

Grid-Connected PV System

Photovoltaic systems can be designed to provide DC and/or AC power service, can operate interconnected with or independent of the utility grid, and can be connected with other energy sources and energy storage systems.

Grid-connected or utility-interactive PV systems are designed to operate in parallel with and interconnected with the electric utility grid. The primary component in grid-connected PV systems is the inverter, or power conditioning unit (PCU). The PCU converts the DC power produced by the PV array into AC power consistent with the voltage and power quality requirements of the utility grid, and automatically stops supplying power to the grid when the utility grid is not energized. A bi-directional interface is made between the PV system AC output circuits and the electric utility network, typically at an on-site distribution panel or service entrance. This allows the AC power produced by the PV system to either supply on-site electrical loads, or to back-feed the grid when the PV system output is greater than the on-site load demand. At night and during other periods when the electrical loads are greater than the PV system output, the balance of power required by the loads is received from the electric utility This safety feature is required in all grid-connected PV systems, and ensures that the PV system will not continue to operate and feed back into the utility grid when the grid is down for service or repair.

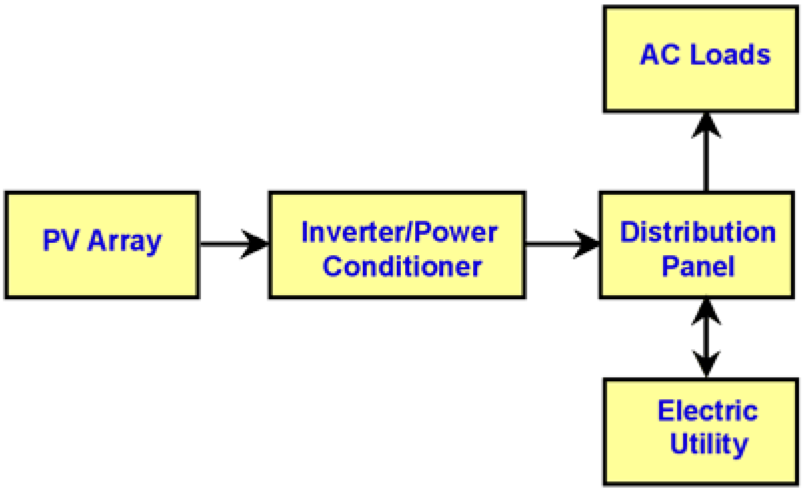


Fig 2.42. Diagram of grid-connected photovoltaic system

Stand-alone PV System

Stand-alone PV systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply certain DC and/or AC electrical loads. These types of systems may be powered by a PV array only, or may use wind, an engine-generator or utility power as an auxiliary power source in what is called a PV-hybrid system. The simplest type of stand-alone PV system is a direct-coupled system, where the DC output of a PV module or array is directly connected to a DC load (Figure 2.43). Since there is no electrical energy storage (batteries) in direct-coupled systems, the load only operates during sunlight hours, making these designs suitable for common applications such as ventilation fans, water pumps, and small circulation pumps for solar thermal water heating systems. Matching the impedance of the electrical load to the maximum power output of the PV array is a critical part of designing well-performing direct-coupled system. For certain loads such as positive-displacement water pumps, a type of electronic DC-DC converter, called a maximum power point tracker (MPPT), is used between the array and load to help better utilize the available array maximum power output.

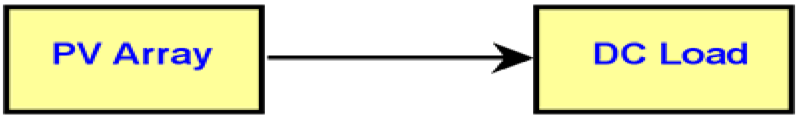


Fig 2.43 Direct-coupled PV system.

In many stand-alone PV systems, batteries are used for energy storage. Figure 2.44 shows a diagram of a typical stand-alone PV system powering DC and AC loads. Figure 2.45 shows how a typical PV hybrid system might be configured.

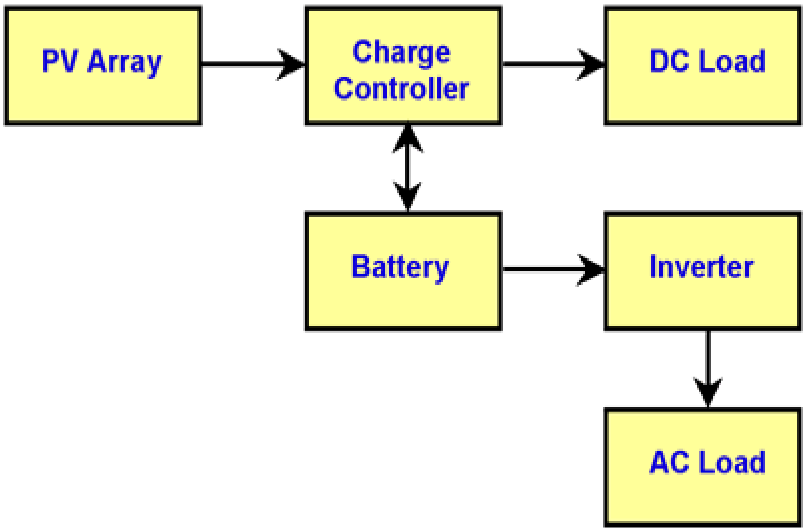


Fig2.44. Diagram of stand-alone PV system with battery storage powering DC and AC loads.

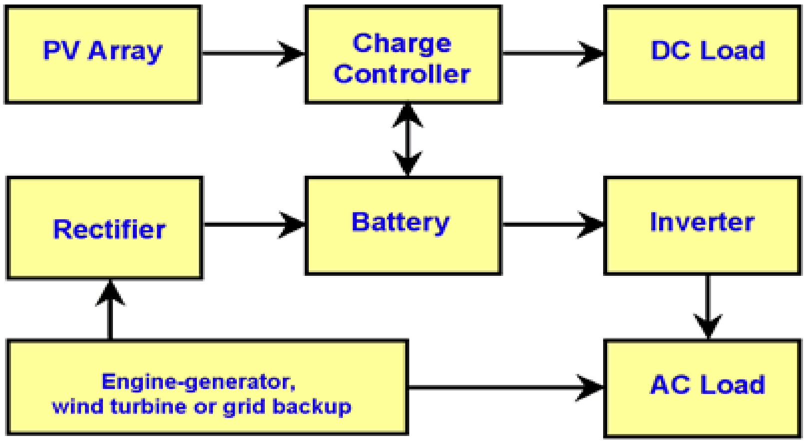


Fig 2.45. Diagram of photovoltaic hybrid system.