PEAK POWER OPERATION:

The sun tracker drives the module mechanically to face the sun to collect the maximum solar radiation. However, that in itself does not guarantee the maximum power output from the module. As was seen in Figure, the module must operate electrically at a certain voltage that corresponds to the peak power point under a given operating condition. First we examine the electrical principle of peak-power operation.

If the array is operating at any point at voltage V and current I on the I-V curve, the power generation is $P = VI$ watts. If the operation moves away from the preceding point such that the current is now $I + \Delta I$, and the voltage is $V + \Delta V$, then the new power is as follows:

$$P + \Delta P = (V + \Delta V)(I + \Delta I) \qquad \text{(i)}$$

which, after ignoring a small term, simplifies to the following:

$$\Delta P = \Delta V \cdot I + \Delta I \cdot V \qquad \text{(ii)}$$

ΔP would be zero if the array were operating at the peak power point, which necessarily lies on a locally flat neighborhood. Therefore, at the peak power point, the preceding expression in the limit becomes:

$$\frac{dV}{dI} = -\frac{V}{I} \qquad \text{(iii)}$$

We note here that dV/dI is the dynamic impedance of the source, and V/I the static impedance. Thus, at the peak power point, the following relation holds:

$$\text{Dynamic impedance } Z_d = -\text{static impedance } Z_s \qquad \text{(iv)}$$

There are three electrical methods of extracting the peak power from a PV source, as described in the following text:

1. In the first method, a small signal current is periodically injected into the array bus, and the dynamic bus impedance (Z_d = dV/dI) and the static bus impedance (Z_s = V/I) are measured. The operating voltage is then increased or decreased until Z_d equals $-Z_s$. At this point, the maximum power is extracted from the source.
2. In another method, the operating voltage is increased as long as dP/dV is positive. That is, the voltage is increased as long as we get more power. If

dP/dV is sensed negative, the operating voltage is decreased. The voltage stays the same if dP/dV is near zero within a preset deadband.

3. The third method makes use of the fact that for most PV cells, the ratio of the voltage at the maximum power point to the open-circuit voltage (i.e., V_{mp}/V_{oc}) is approximately constant, say K. For example, for high quality crystalline silicon cells, K = 0.72. An unloaded cell is installed on the array and kept in the same environment as the power-producing cells, and its open-circuit voltage is continuously measured. The operating voltage of the power-producing array is then set at $K \cdot V_{oc}$, which will produce the maximum power.

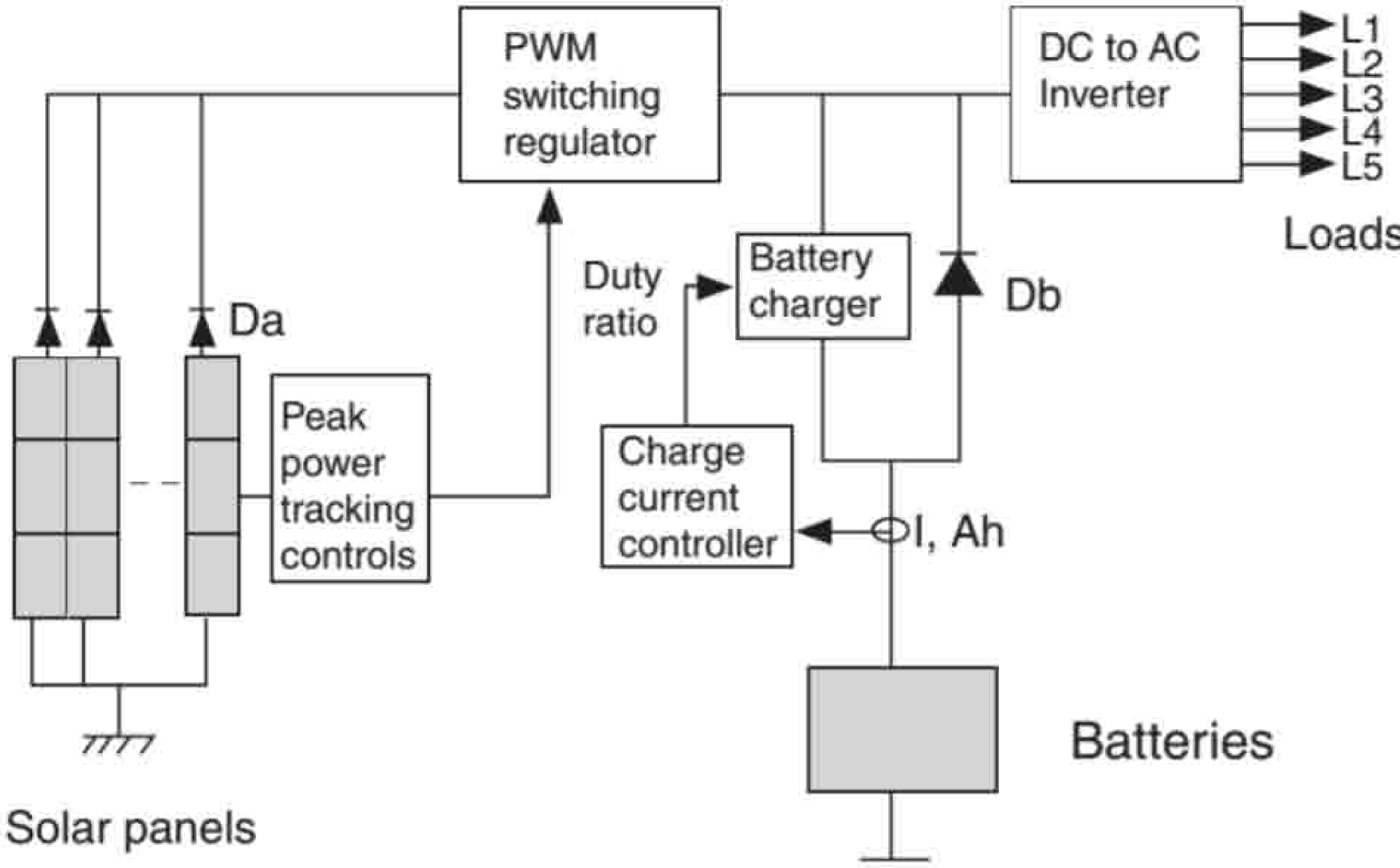
SYSTEM COMPONENTS:

The array by itself does not constitute the PV power system. We may also need a structure to mount it, a sun tracker to point the array to the sun, various sensors to monitor system performance, and power electronic components that accept the DC power produced by the array, charge the battery, and condition the remaining power in a form that is usable by the load. If the load is AC, the system needs an inverter to convert the DC power into AC at 50 or 60 Hz.

Figure shows the necessary components of a stand-alone PV power system. The peak-power tracker senses the voltage and current outputs of the array and continuously adjusts the operating point to extract the maximum power under varying climatic conditions. The output of the array goes to the inverter, which converts the DC into AC. The array output in excess of the load requirement is used to charge the battery. The battery charger is usually a DC–DC buck converter. If excess power is still available after fully charging the battery, it is shunted in dump heaters, which may be a room or water heater in a stand-alone system. When the sun is not available, the battery discharges to the inverter to power the load. The battery discharge diode Db is to prevent the battery from being charged when the charger is opened after a full charge or for other reasons. The array diode Da is to isolate the array from the battery, thus keeping the array from acting as the load on the battery at night. The mode controller collects system signals, such as the array and the battery currents and voltages, and keeps track of the battery state of charge by bookkeeping the charge/discharge ampere-hours. It uses this information to turn on or off the battery charger, discharge converter, and dump loads as needed. Thus, the mode controller is the central controller of the entire system.

In the grid-connected system, dump heaters are not required, as all excess power is always fed to the grid lines. The battery is also eliminated, except for a few small critical loads, such as the start-up controller and the computer. DC power is first converted into AC by the inverter, ripples are filtered, and only then is the filtered power fed into the grid lines.

In the PV system, the inverter is a critical component, which converts the array DC power into AC for supplying the loads or interfacing with the grid. A new product line recently introduced into the market is the AC PV module, which integrates an inverter directly into module design. It is presently available in a few hundred watts capacity. It provides utility-grade 60-Hz power directly from the module junction box. This greatly simplifies PV system design.



Peak-power-tracking PV power system showing major components

Types of PV Power Systems

Photovoltaic power systems can be classified as follows:

- Stand-alone
- Hybrid
- Grid connected

Stand-alone PV systems, shown in Fig. 7a, are used in remote areas with no access to a utility grid. Conventional power systems used in remote areas often based on manually controlled diesel generators operating continuously or for a few hours. Extended operation of diesel generators at low load levels significantly increases maintenance costs and reduces their useful life. Renewable energy sources such as PV can be added to remote area power systems using diesel and other fossil fuel powered generators to provide 24-hour power economically and efficiently. Such systems are called ‘‘hybrid energy systems.’’ Figure 7a shows a schematic of a PV–diesel hybrid system. In grid-connected PV systems, as shown in Fig.7c, PV panels are connected to a grid through inverters without battery storage. These systems can be classified as small systems, such as residential rooftop systems or large grid-connected systems. The grid interactive inverters must be synchronized with the grid in terms of voltage and frequency.

Stand-Alone PV Systems

The two main stand-alone PV applications are:

- Battery charging
- Solar water pumping

(a) Battery charging

Battery manufacturers specify the nominal number of complete charge and discharge cycles as a function of the depth-of-discharge (DOD), as shown in Fig. 23.8. Although this information can be used reliably to predict the lifetime of lead-acid batteries in conventional applications, such as uninterruptable power supplies or electric vehicles, it usually results in an overestimation of the useful life of the battery bank in renewable energy systems.

Two of the main factors that have been identified as limiting criteria for the cycle life of batteries in photovoltaic power systems are incomplete charging and prolonged operation at a low state of charge (SOC). The objective of improved battery control strategies is to extend the lifetime of lead-acid batteries to achieve the typical number of cycles shown in Fig. 8. If this is achieved, an optimum solution for the required storage capacity and the maximum depth-of-discharge of the battery can be found by referring to the manufacturer's information.

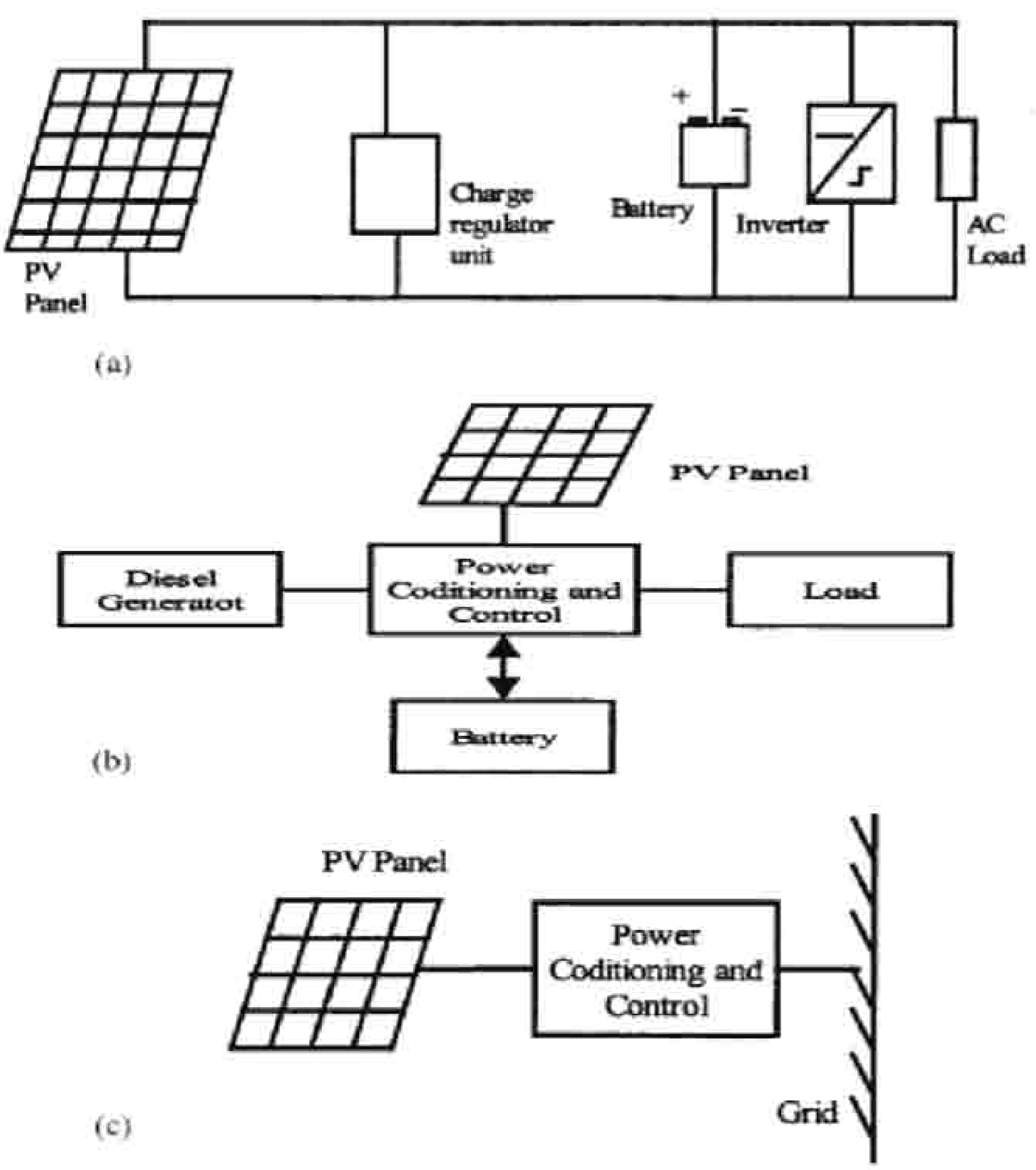


Figure 7: (a) Stand Alone PV system (b) PV-diesel hybrid system (c) Grid-connected PV system

Increasing the capacity will reduce the typical depth-of discharge and therefore prolong the battery lifetime. Conversely, it may be more economic to replace a smaller battery bank more frequently.

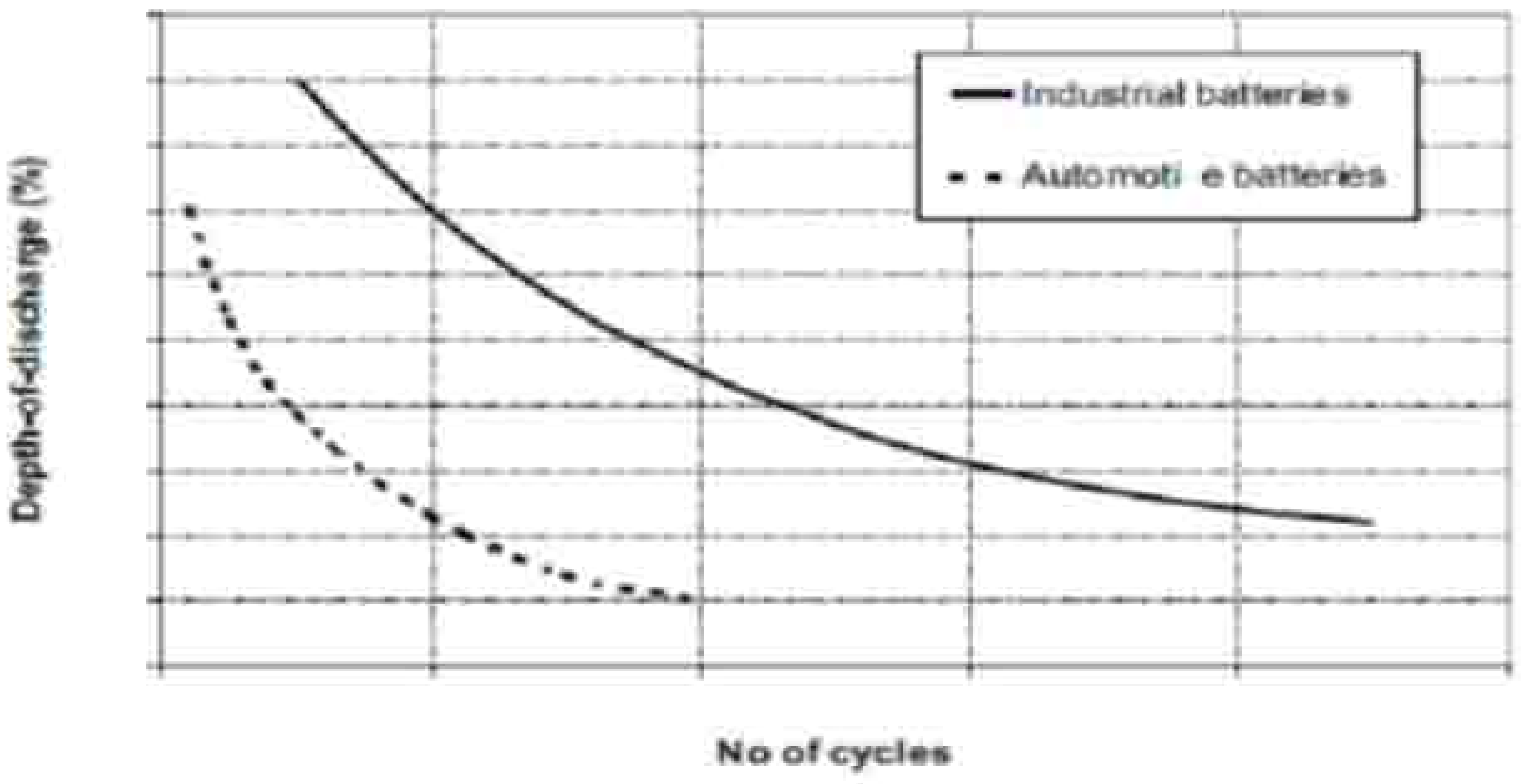


Figure 8: No. of battery cycles and Depth of discharge

(b) Solar Water Pumping:

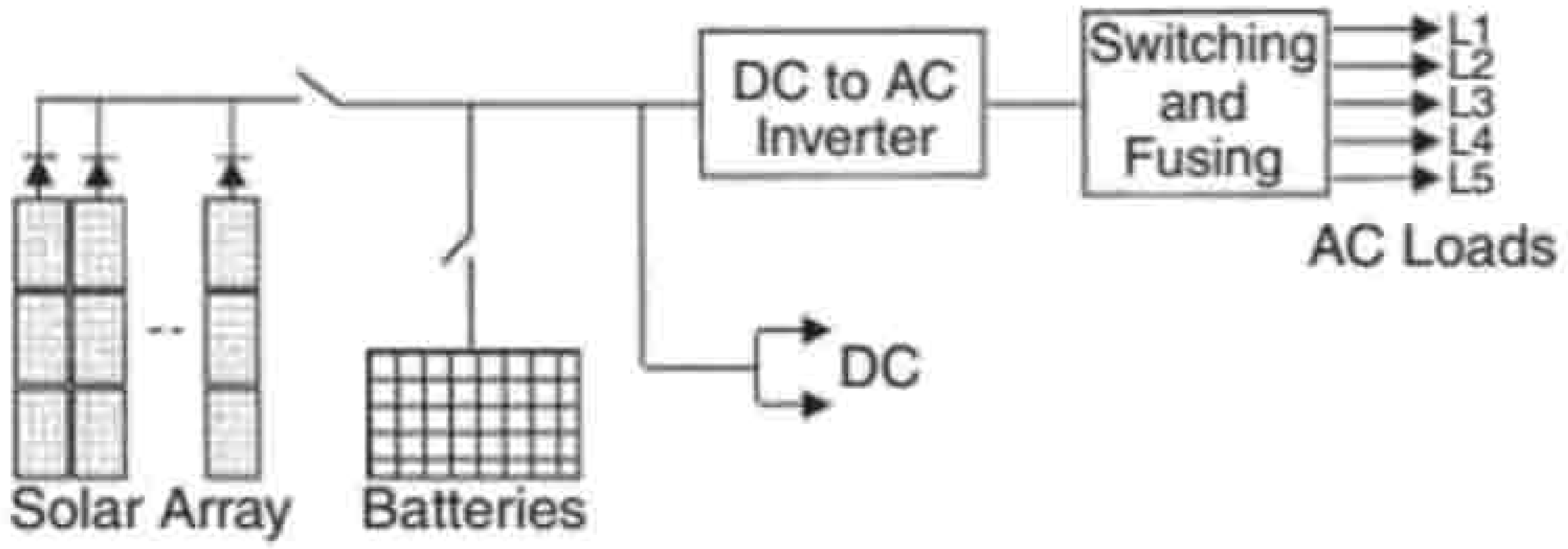
In many remote and rural areas, hand pumps or diesel driven pumps are used for water supply. Diesel pumps consume fossil fuel, affect the environment, need more maintenance, and are less reliable. Photovoltaic (PV)-powered water pumps have received considerable attention because of major developments in the field of solar-cell materials and power electronic systems technology.

Two types of pumps are commonly used for water-pumping applications: Positive displacement and centrifugal. Both centrifugal and positive displacement pumps can be further classified into those with motors that are surface mounted, and those that are submerged into the water (‘‘submersible’’).

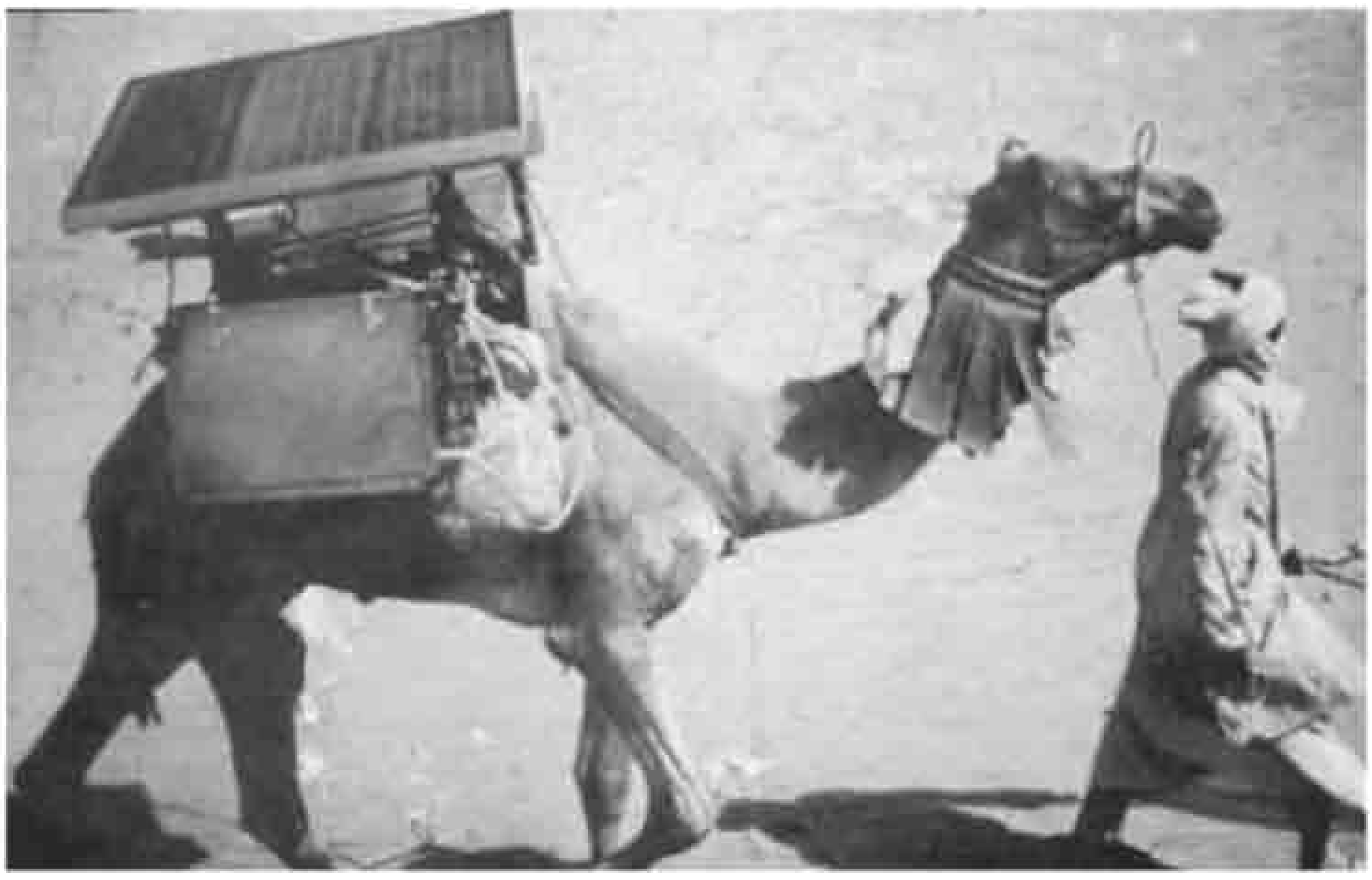
Displacement pumps have water output directly proportional to the speed of the pump, but almost independent of head. These pumps are used for solar water pumping from deep wells or bores. They may be piston-type pumps or use a diaphragm driven by a cam or rotary screw, or use a progressive cavity system. The pumping rate of these pumps is directly related to the speed, and hence constant torque is desired.

The typical PV stand-alone system consists of a solar array and a battery connected as shown in Figure. The PV array supplies power to the load and charges the battery when there is sunlight. The battery powers the load otherwise. An inverter converts the DC power of the array and the battery into 60 or 50 Hz power. Inverters are available in a wide range of power ratings with efficiencies ranging from 85 to 95%. The array is segmented with isolation diodes for improving reliability. In such a design, if one string of the solar array fails, it does not load or short the remaining strings. Multiple inverters are preferred for reliability. For example, three inverters, each with a 35% rating, are preferred to one with a 105% rating. If one such inverter fails, the remaining two can continue supplying most loads until the failed one is repaired or replaced. The same design approach also extends to using multiple batteries.

Most stand-alone PV systems are installed in developing countries to provide basic necessities such as lighting and pumping water.



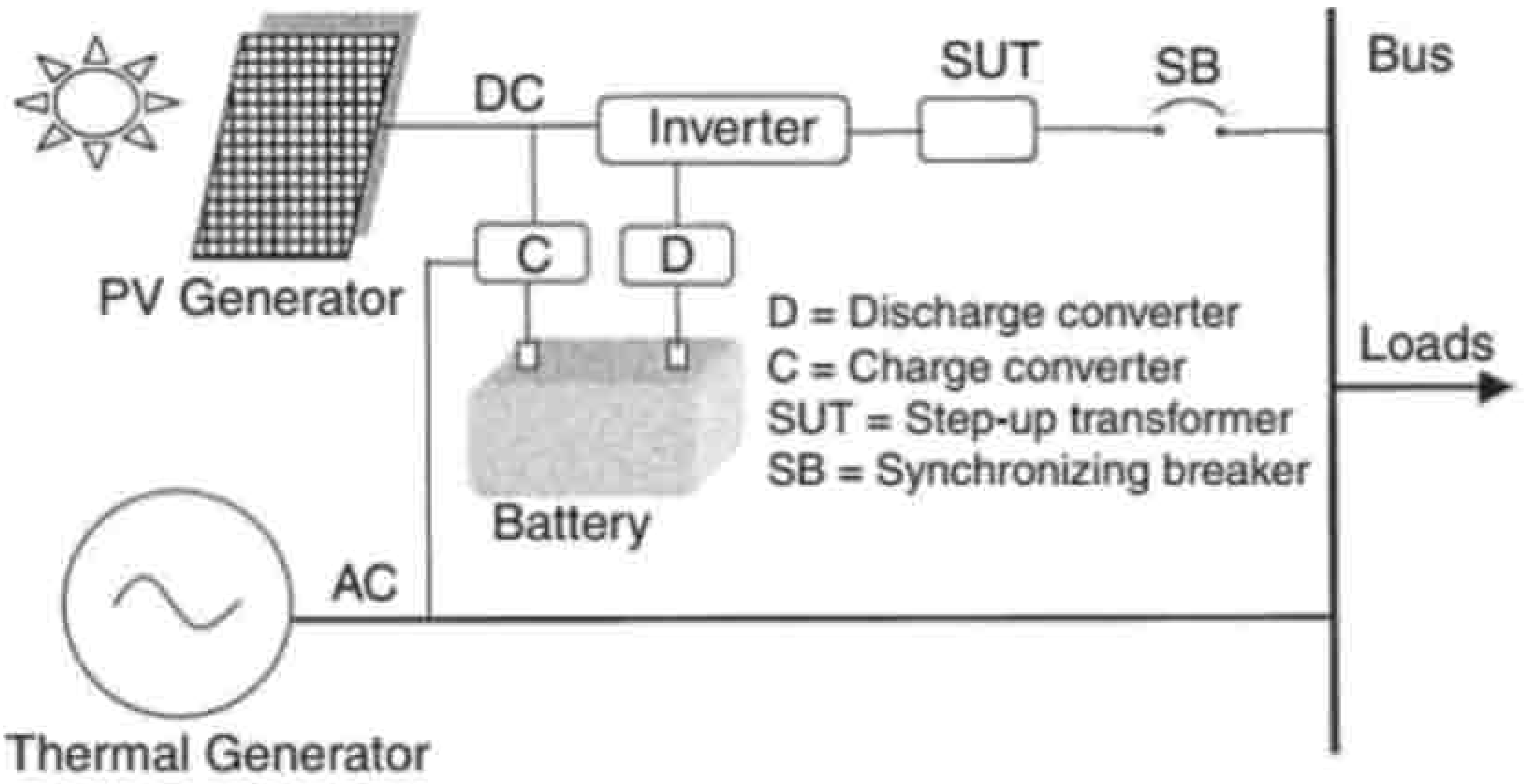
PV stand-alone power system with battery.



A traveling clinic uses photovoltaic electricity to keep vaccines refrigerated in the African desert area.

Photovoltaic (PV) power systems have made a successful transition from small stand-alone sites to large grid-connected systems. The utility interconnection brings a new dimension to the renewable power economy by pooling the temporal excess or the shortfall in the renewable power with the connecting grid that generates base-load power using conventional fuels. This improves the overall economy and load availability of the renewable plant site — the two important factors of any power system. The grid supplies power to the site loads when needed or absorbs the excess power from the site when available. A kilowatthour meter is used to measure the power delivered to the grid, and another is used to measure the power drawn from the grid. The two meters are generally priced differently on a daily basis or on a yearly basis that allows energy swapping and billing the net annual difference.

In the below figure is a typical circuit diagram of the grid-connected PV power system. It interfaces with the local utility lines at the output side of the inverter as shown. A battery is often added to meet short-term load peaks. In the U.S., the Environmental Protection Agency sponsors grid-connected PV programs in urban areas where wind towers would be impractical. In recent years, large building-integrated PV installations have made significant advances by adding grid connections to the system design. For example, Figure shows the building-integrated PV system on the roof of the Northeastern University Student Center in Boston. The project was part of the EPA PV DSP program. The system produces 18 kW power and is connected to the grid. In addition, it collects sufficient research data using numerous instruments and computer data loggers. The vital data are sampled every 10 sec, and are averaged and stored every 10 min. The incoming data includes information about air temperature and wind speed. The performance parameters include direct current (DC) voltage and current generated by the PV roof and the alternating current (AC) power at the inverter output side.



Electrical schematic of the grid-connected PV system