# Photovoltaic Systems I

EE 446/646

PV System Types & Goal

- **Types of PV Systems:**
  - Grid-tied systems that feed power directly into the utility grid,
    - Residential Systems (1-10kW)
    - Commercial/industrial systems (10-250 kW)
    - Utility systems (10's – 100's MW)
  - stand-alone systems that serve the load and charge batteries, perhaps with generator back-up,
    - Applications in which the load is directly connected to the PV: case of water-pumping systems.
- **Goal:** to learn how to properly size photovoltaic systems to provide for the various types of systems above.
  - Power delivered by a photovoltaic system will be a function of not only ambient conditions (i.e., solar intensity, spectral variations associated with overcast conditions, ambient temperature, and wind speed) but also of loads the photovoltaics are supplying.

Grid-Connected PV Systems (residential)

- If the PV supplies less than the immediate demand of the building, the building draws supplementary power from the utility grid.
- If the PV supplies more power than is needed, the excess is sent back onto the grid - spinning the electric meter backwards.
- The system is relatively simple since failure-prone batteries are not needed for back-up power, although sometimes they may be included if utility outages are problematic.

Residential Grid Connected PV System
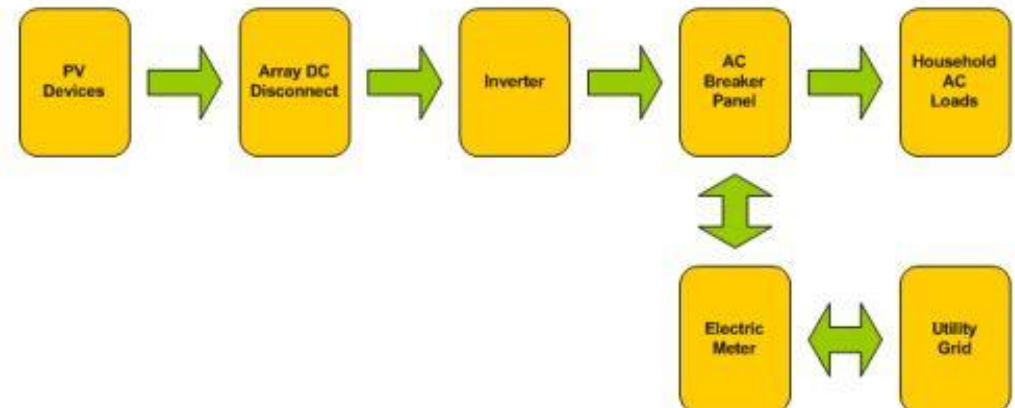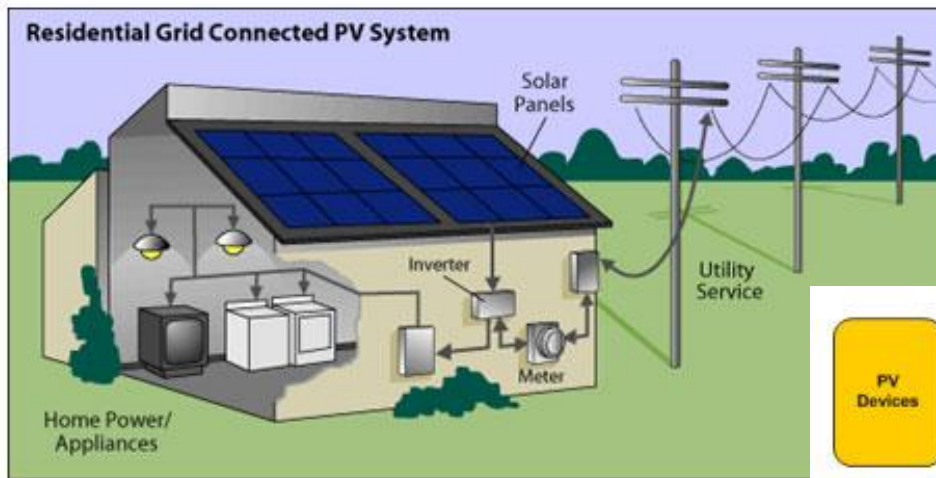
Grid-Connected PV Systems (residential)

- Grid-connected PV systems have a number of desirable attributes.
  - Their relative simplicity results in high reliability;
  - their maximum-power-tracking unit assures high PV efficiency;
  - their potential to be integrated into the structure of the building (i.e. no additional cost to land), in some cases, materials displaced by PVs in such systems may offset some of their costs;
  - their ability to deliver power during the middle of the day, when utility rates are highest, increases the economic value of their kilowatt-hours.
- On the other hand, they have to compete with the retail price of utility power.

Grid-Connected PV Systems (Commercial, and Utility Scale)

- Commercial/industrial electricity rates are different from residential rates.

- Utility scale PV systems have to compete with the electricity wholesale prices.

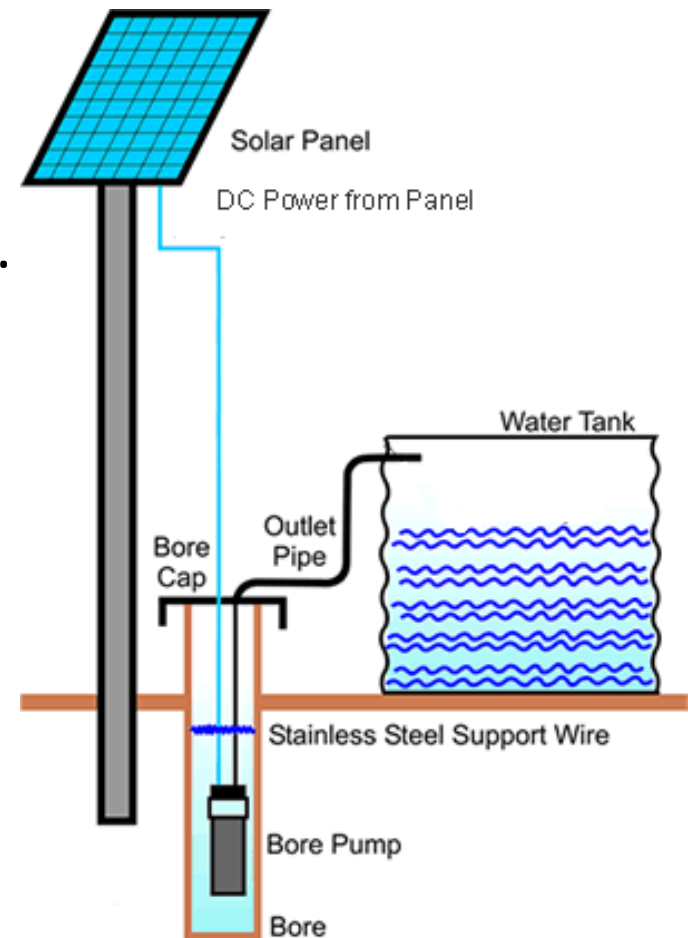# Stand-alone (off-grid) PV system

- Stand-alone PV systems are cost effective in remote locations.
- These systems suffer from several inefficiencies, including:
  - battery losses, and the system requires more attention and care,
  - the PV usually operates well off its most efficient operating point.
  - if generator usage is to be minimized (or eliminated), those using the energy may need to modify their lifestyles.
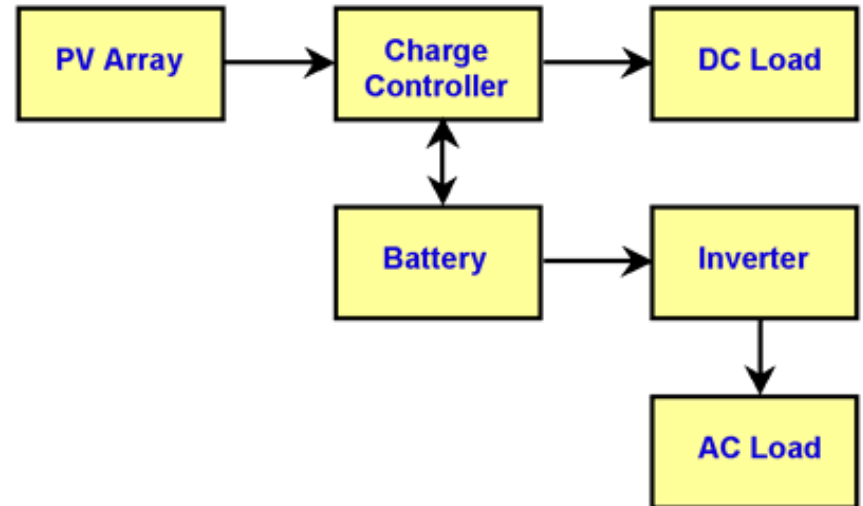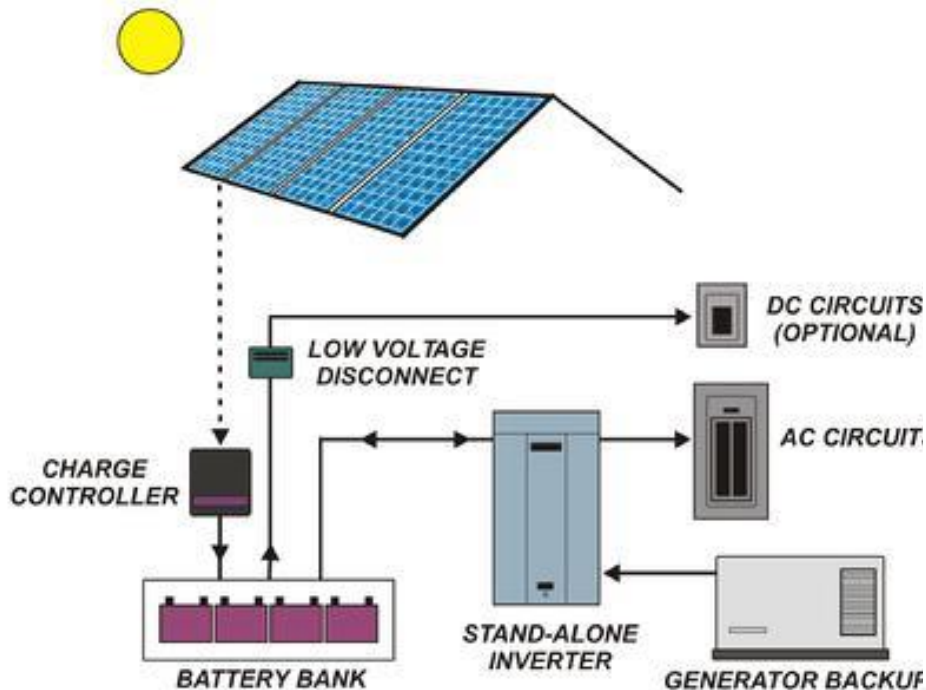
Water pumping PV system

- In here, the PV is directly coupled to the load, without any batteries or major power conditioning equipment.

- When the sun shines, water is pumped. There is no electric energy storage, but potential energy may be stored in a tank of water up the hill for use when needed.

Solar Panel

DC Power from Panel

Water Tank

Bore Cap

Outlet Pipe

Stainless Steel Support Wire

Bore Pump

Bore

- The I –V curve of a photovoltaic cell, module, or array does not by itself tell us anything about just where on that curve the system will actually be operating. This determination is a function of the load into which the PV delivers its power.

- Loads do have their own I-V curves: The same voltage is across both the PV and load, and the same current runs through the PV and load.

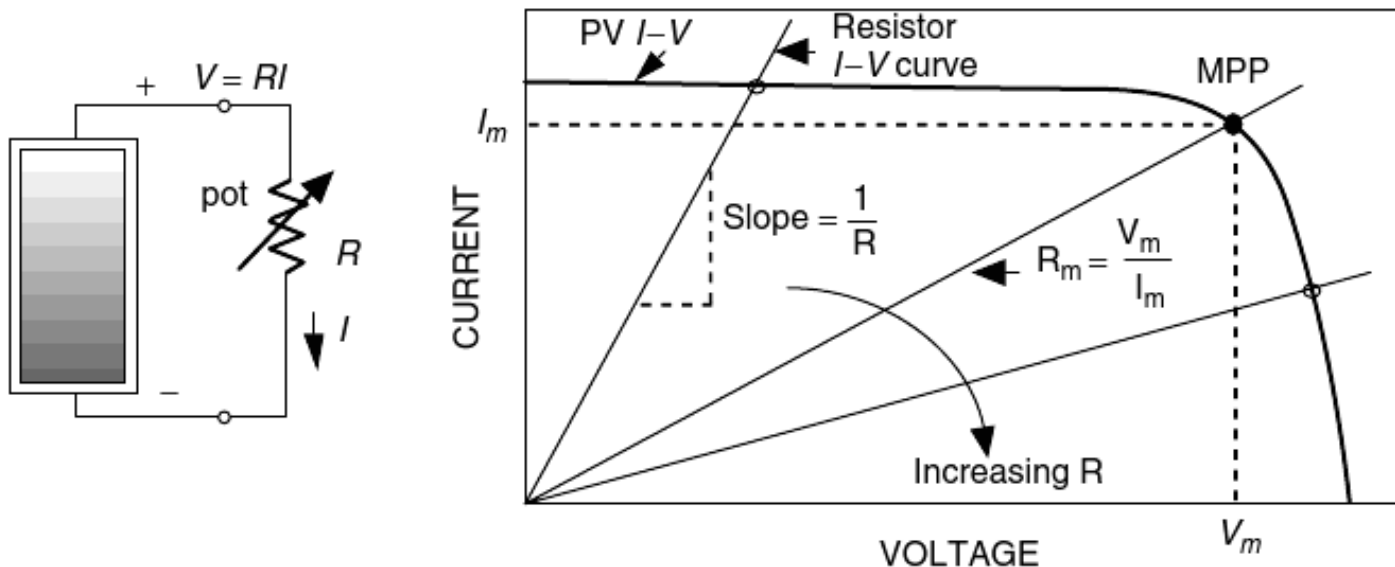- the intersection point of the two curves is *the operating point*.
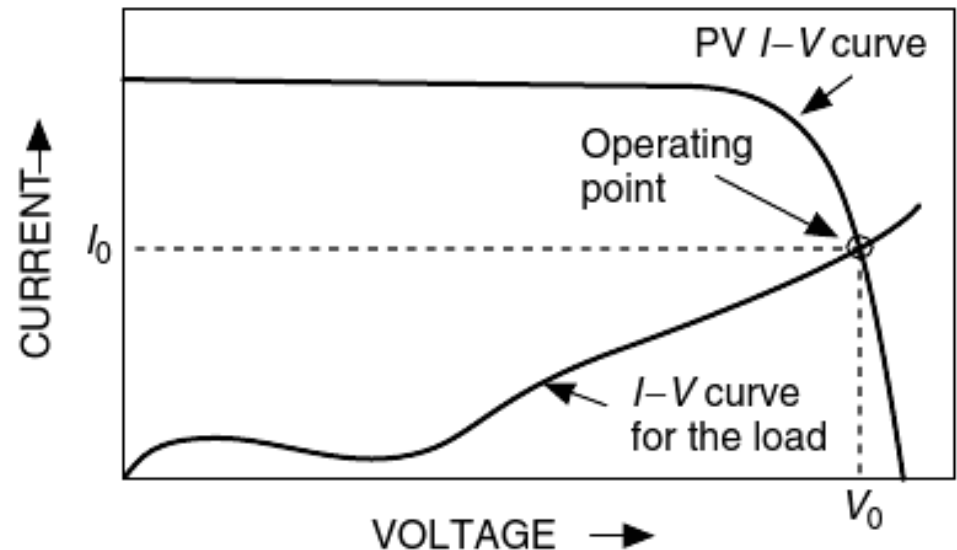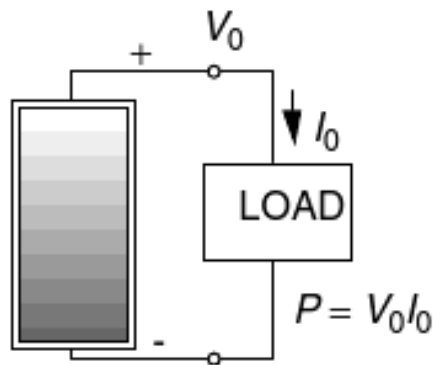
Resistive Load I-V Curve

- Ohm's law: $\qquad$ **V = IR** or **I = V/R**

- As R increases, the intersection point moves along the PV I –V curve from left to right.

- The value of resistance that will result in maximum power:

$$R_m = V_m/I_m$$

- were V_m and I_m are the voltage and current at the maximum power point (MPP).

Resistive Load I-V Curve

- With a fixed resistance the operating point slips off the MPP as the solar irradiance changes.

- Later, a device called a maximum power point tracker (MPPT) will be introduced, the purpose of which is to keep the PVs operating at their highest efficiency point at all times.
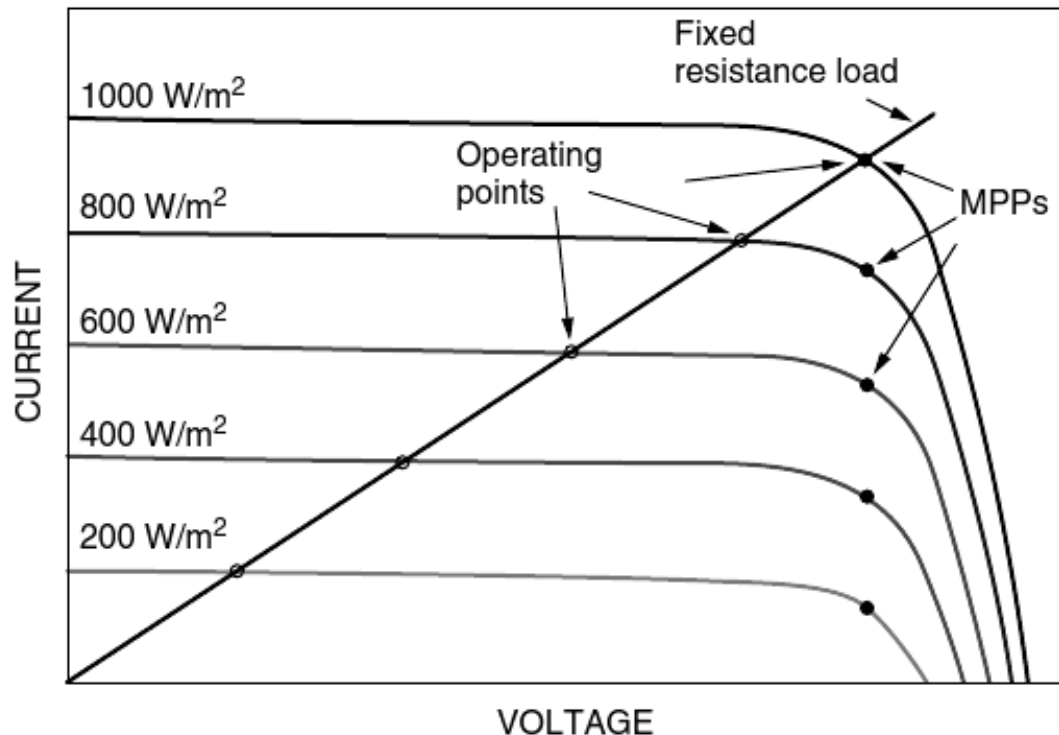
Example

- **Problem 6.8:** You have four PV modules with identical I–V curves ($I_{sc} = 1$ A, $V_{oc} = 20$ V) as shown. There are three ways you could wire them up to deliver power to a DC motor (which acts like a 10-Ω load):
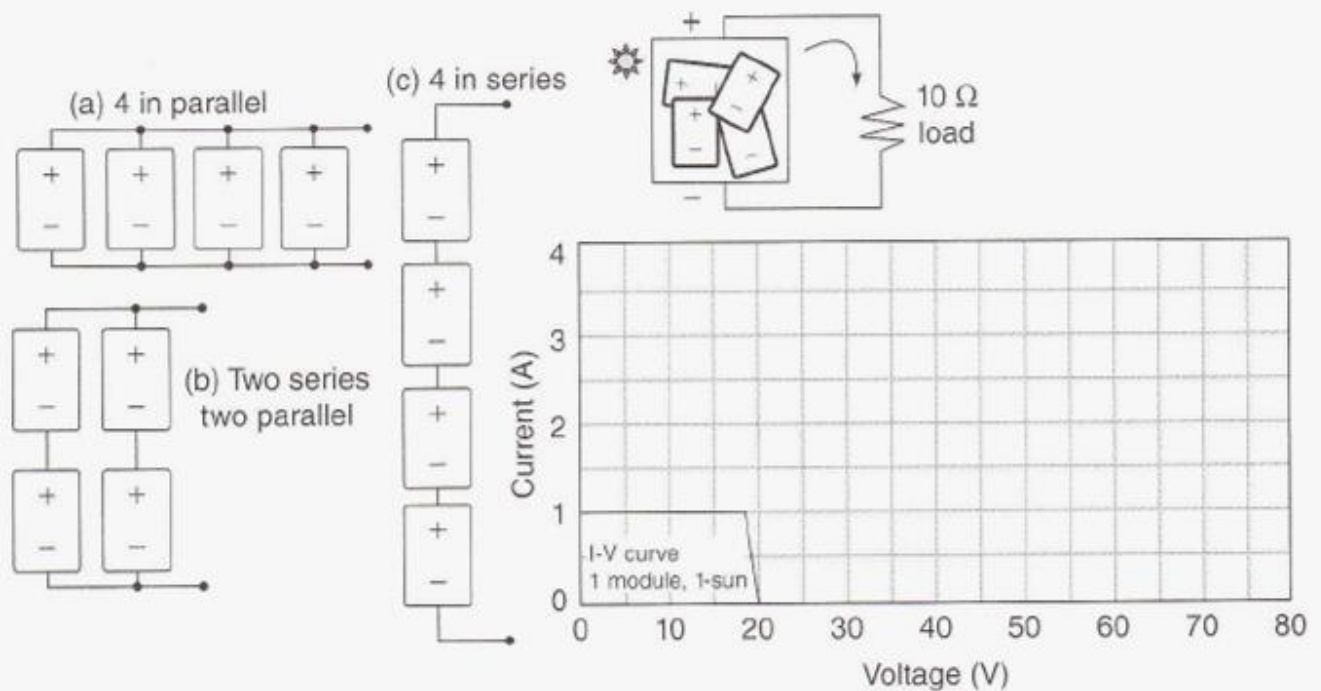

FIGURE P6.8

Draw the I–V curves for all three combinations on the same graph. Which wiring system would be best? Briefly explain your answer.

DC motor I-V curve

- DC motors (such as those used in PV-water-pumping systems) exhibit a current– voltage relationship that is similar to that of a resistor.

- As the motor spins, it develops a voltage (back emf) that is proportional to the motor speed (ω).

- The voltage – current relationship for a dc motor is given by

$$V = IR + e \quad \text{with} \quad e = k\omega$$

- where R is the motor armature resistance and k is a constant.
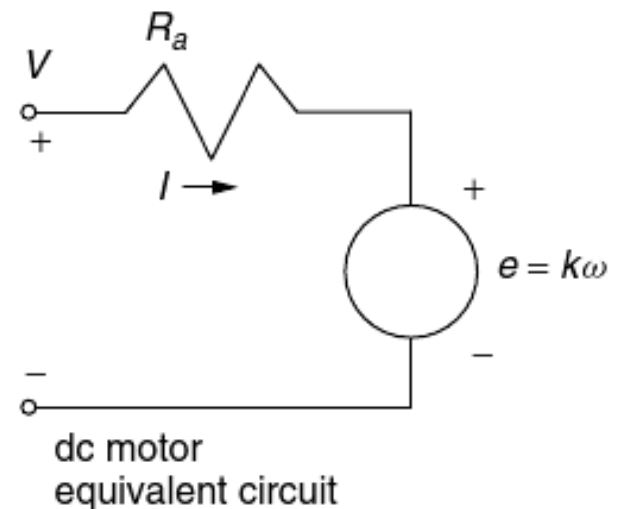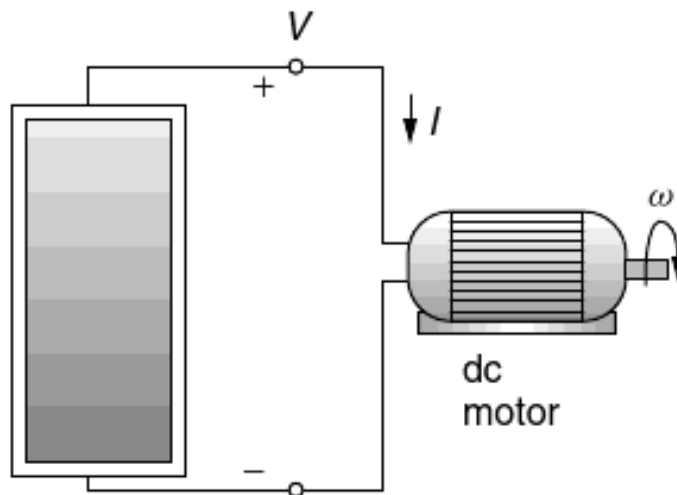
DC motor I-V curve

- At start-up, while ω = 0, the current rises rapidly with increasing voltage until it is sufficient to create enough torque to break the motor loose from static friction.

- Once the motor starts to spin, the back emf drops the current, and thereafter I rises more slowly with increasing voltage.

- A dc motor runs at *nearly constant speed* for any given applied voltage even though the torque requirement of its load may change. Furthermore, the motor *torque is proportional to armature current.*
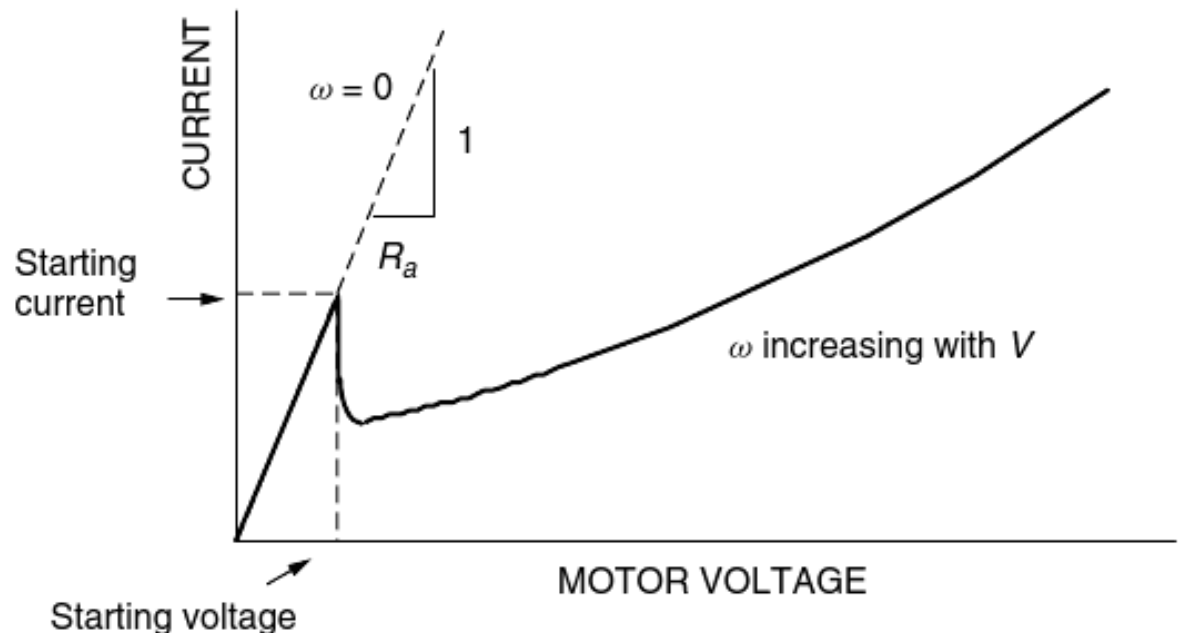
DC motor I-V curve

- The mismatch of operating points with the ideal MPP is apparent in the figure below.
- Notice that the motor doesn't have enough current to overcome static friction until insolation reaches at least 400 W/m^2. Once it starts spinning, however, it only needs about 200 W/m^2 to keep running.
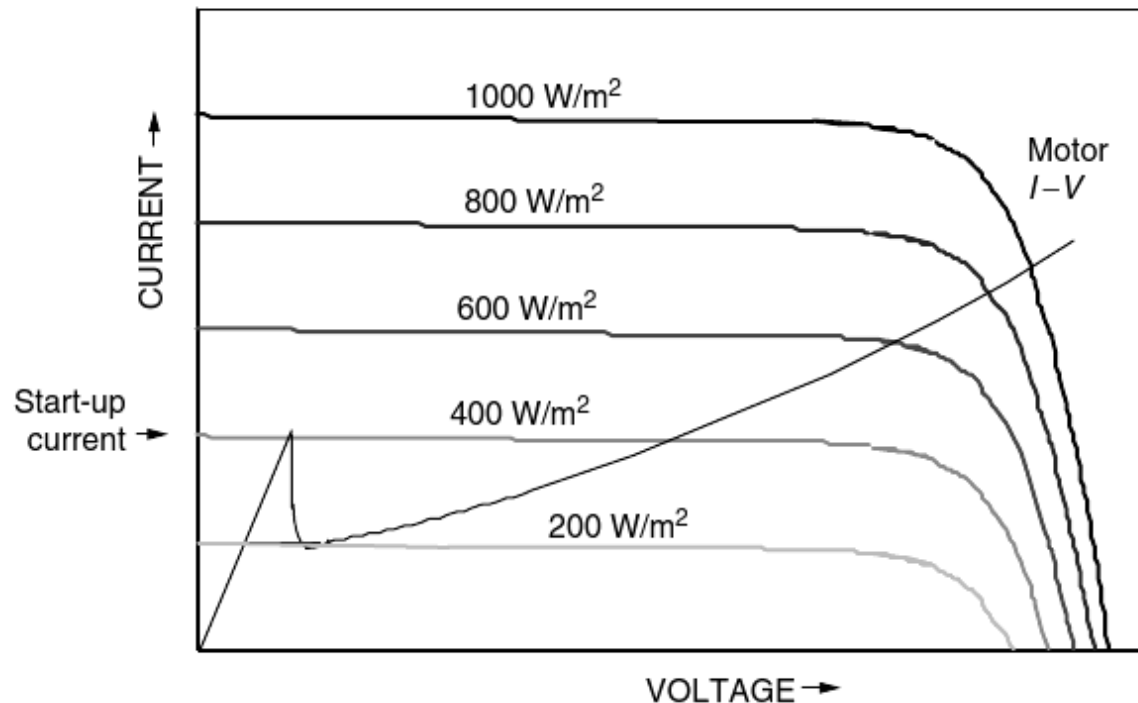
Battery I-V Curve

- For most off-grid applications, energy is stored in batteries for use whenever it is needed.

- An ideal battery has an I –V curve that is a vertical line (i.e., the voltage is constant for any current).

- A real battery has some internal resistance and is often modeled with an equivalent circuit consisting of an ideal battery of voltage V_B in series with some internal resistance R_i.
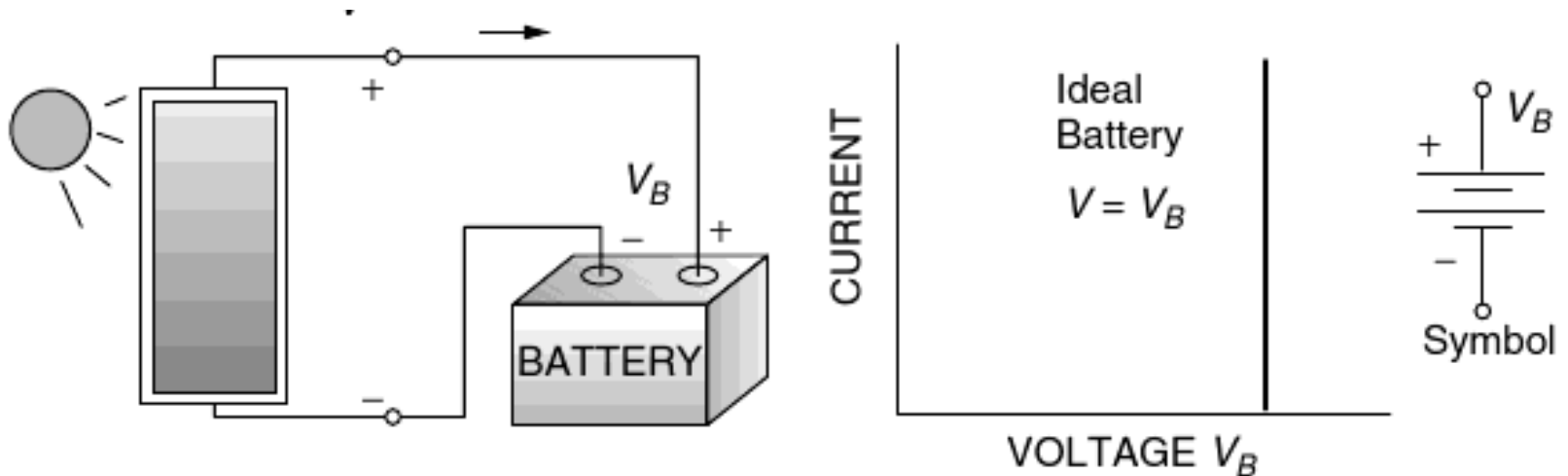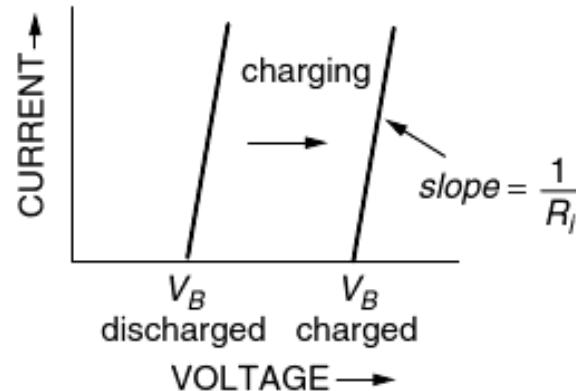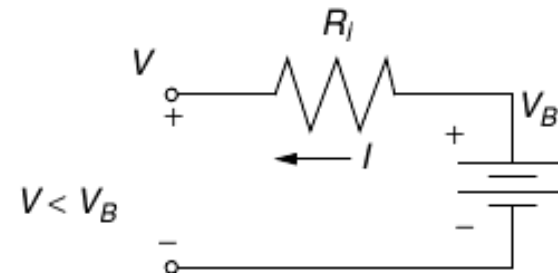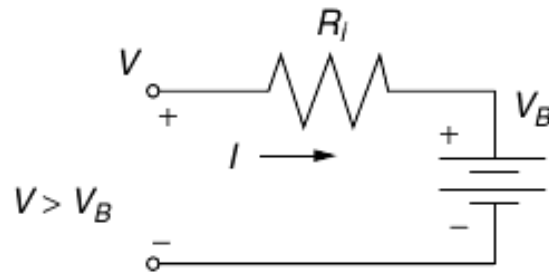
Battery I-V Curve

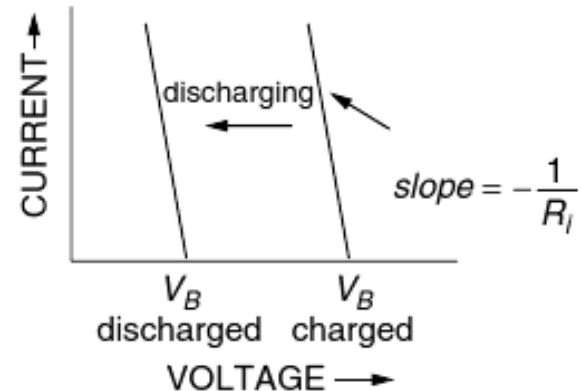- During the charge cycle, $V = V_B + R_i I$

with $V > V_B$; as the process continues, V_B increases so the I –V line slides to the right.

- During the discharge cycle, $V = V_B - R_i I$

with $V < V_B$, the slope of the I –V line flips, and the I –V curve moves back to the left.
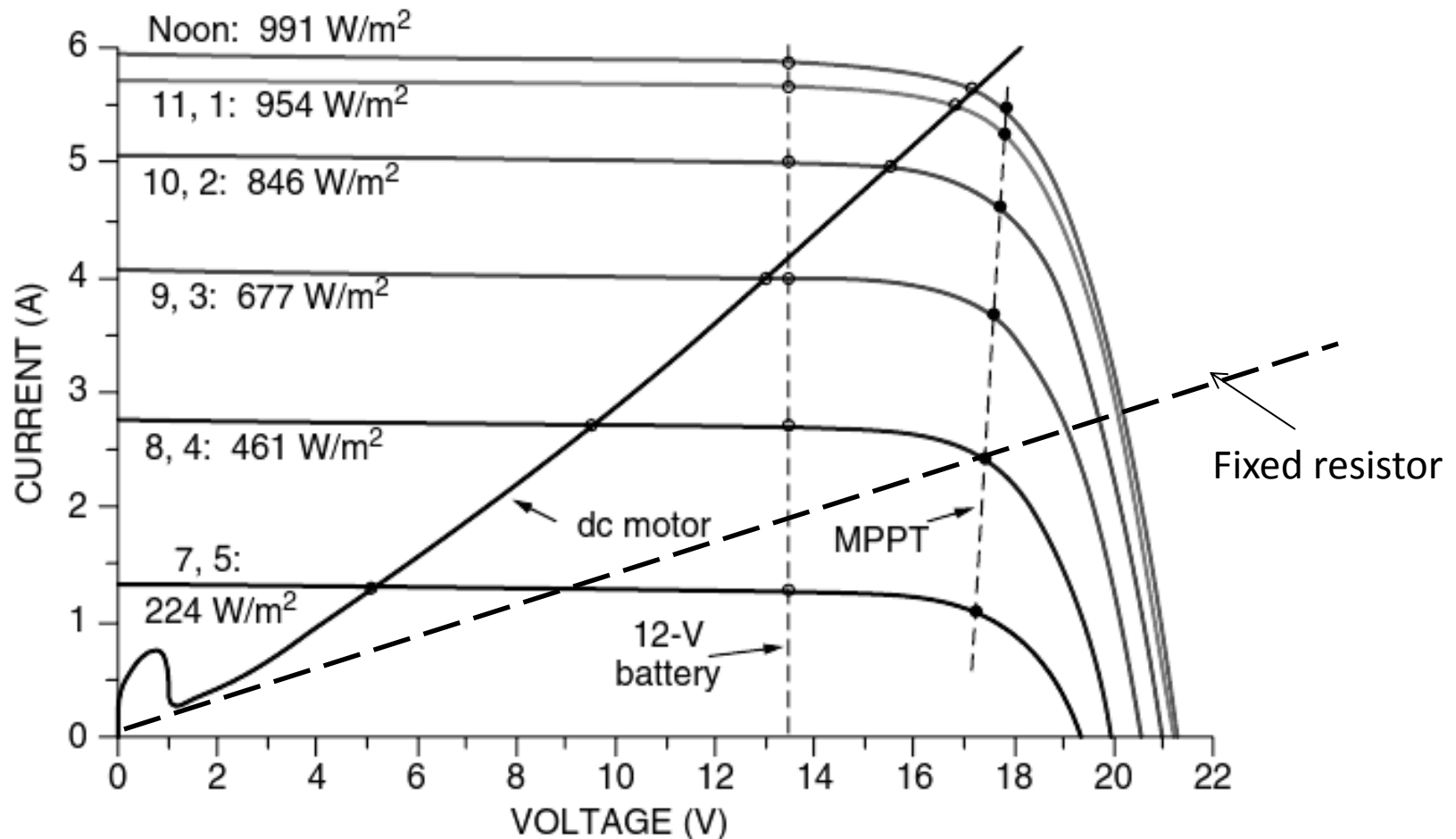

(a) Charging

(b) Discharging

Example: Hour-by-hour I –V curves with three different load types: dc motor, fixed resistor, 12-V battery
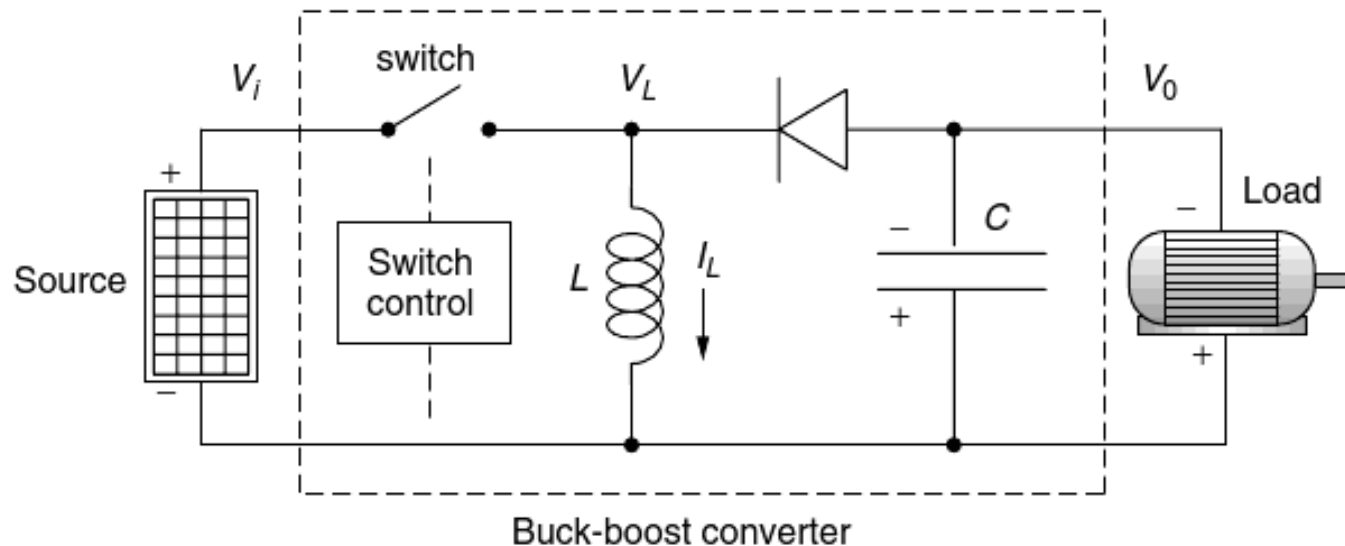
Maximum Power Point Tracker (MPPT)

- Significant efficiency gains could be realized if the operating points for resistive, dc motor, and battery loads could somehow be kept near the knee of the PV I –V curves throughout the ever-changing daily conditions.

- Devices to do just that, called maximum power trackers (MPPTs), are available and are a standard part of many PV systems— especially those that are grid-connected.

- The key is to be able to convert dc voltages from one level to another.

- A buck-boost converter is capable of raising or lowering a dc voltage from its source to whatever dc voltage is needed by the load (see next slide)

  - The transistor switch flips on and off at a rapid rate (on the order of 20 kHz) under the control of some sensing and logic circuitry.
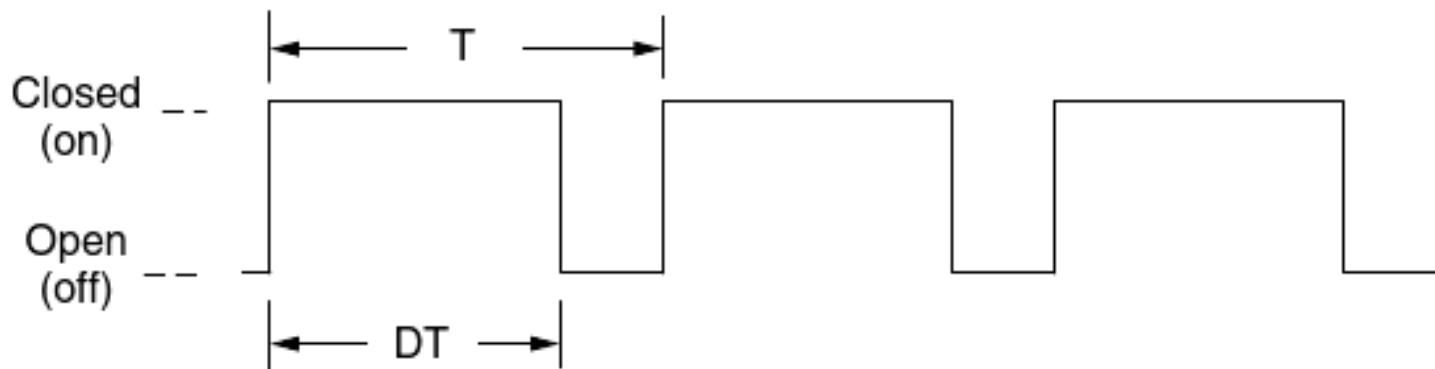
Maximum Power Point Tracker (MPPT)

- When the switch is closed, the input voltage is applied across the inductor, driving current through the inductor. The load is served by the capacitor.

- When the switch is open, the inductor current now flows through the capacitor, the load, and the diode.

- With a fast enough switch and a large enough inductor and capacitor, the circuit can be designed to have nearly constant inductor current and capacitor voltage.

Buck-boost converter

Maximum Power Point Tracker (MPPT)

- The duty cycle D (0 < D < 1) of the switch is the fraction of the time that the switch is closed (see figure below).
- The variation in the fraction of time the switch is in one state or the other is referred to as pulse-width modulation (PWM).
- Over a complete cycle, the energy flow into and out of the inductor must be equal – this results in the following relation between the input and output voltages:

$$\frac{V_0}{V_i} = -\left(\frac{D}{1-D}\right)$$

Maximum Power Point Tracker (MPPT)

- For D = 0.5, the output voltage is the same as the input voltage.
- For D = 0.67, the output voltage is double the input voltage,
- For D = 0.33, the output voltage is half the input voltage

- An actual MPP tracker needs some way for the dc-to-dc converter to know the proper duty cycle to provide at any given instant.

  - This can be done with a microprocessor that periodically varies the duty cycle up and down a bit while monitoring the output power to see whether any improvement can be achieved.

- One way to visualize the impact of the MPPT is to redraw the I –V curves using D as a parameter. For the MPPT's output voltage and current, one goes up and the other goes down compared with the original PV I –V curve (see next slide).

Maximum Power Point Tracker (MPPT)
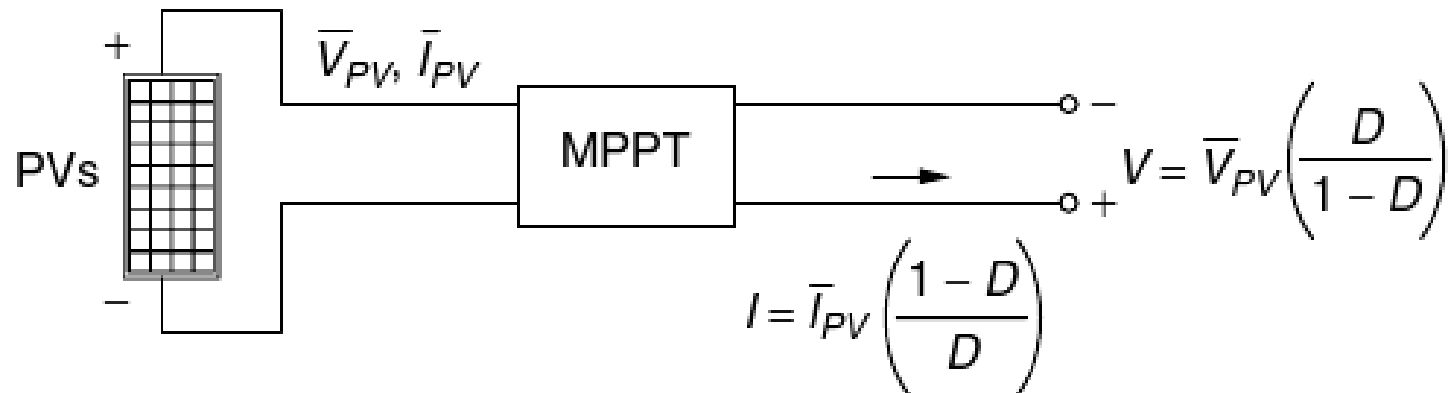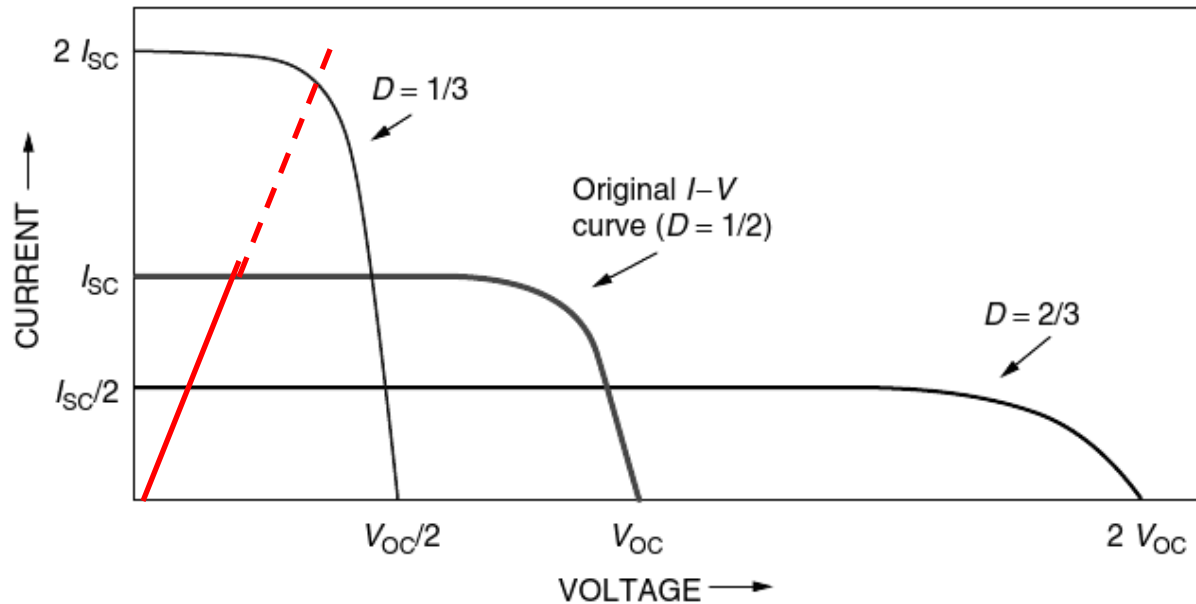
MPPT Techniques

- ## Most common among many methods:
  - Perturb-and-observe (hill climbing)
  - Incremental conductance method
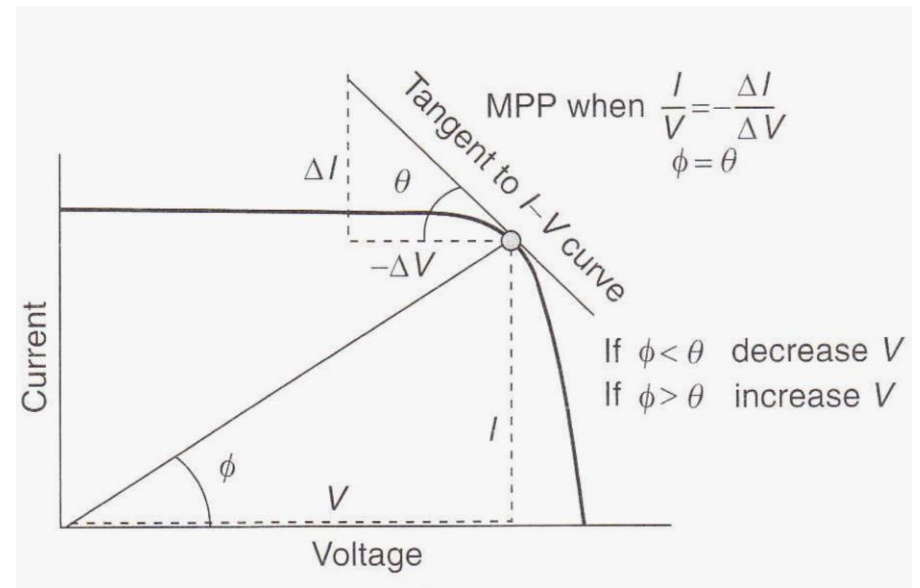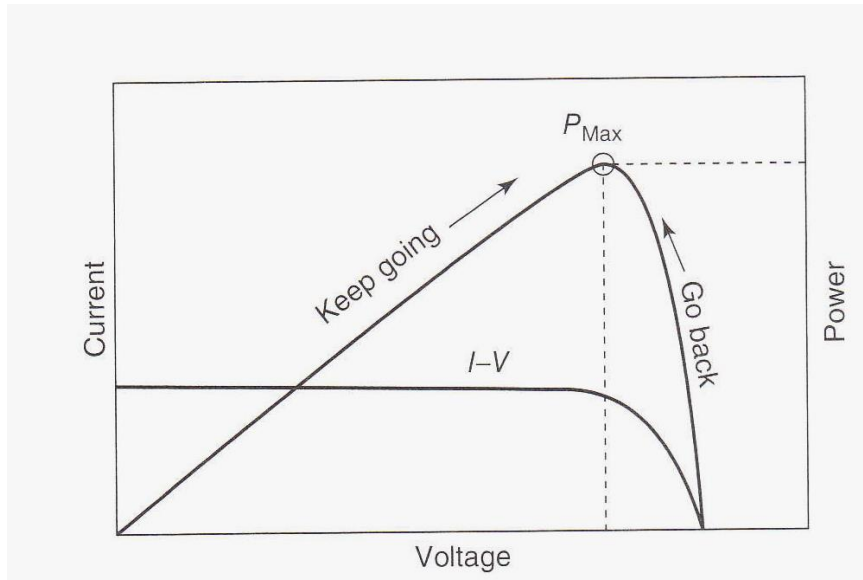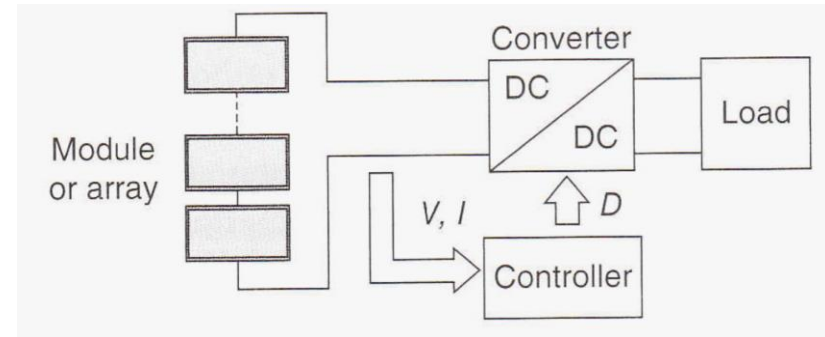
Example (Refer to Problem 5.13)

5.13 Consider a single 87.5 W, First Solar CdTe module (Table 5.3) used to charge a 12-V battery.

a. What duty cycle should be provided to an MPP, buck–boost converter to deliver 14 V to the battery when the module is working at standard test conditions? How many amperes will it deliver to the battery under those conditions?

b. Suppose ambient temperature is 25°C with 1-sun of insolation. Recalculate the amperes delivered to the battery.

- Module voltage and current at maximum power: V = 49.2 V, I = 1.78 A, NOCT = 45 deg., Power temp. coeff. = -.25%.

- 14/49.2 = 0.284 = D/(1-D). Hence D = 0.284/1.284 = 0.222 or 22.2%. Current delivered to battery: I = 87.5/14 = 6.25 A

- Cell temp. = 25 +(45-20)x1/0.8 = 56.25 deg. Module maximum power = 87.5*(1-0.0025(56.25-25))= 80.7 W. Battery current: I = 80.7/14 = 5.76 A

5.13 Consider a single 87.5 W, First Solar CdTe module (Table 5.3) used to charge a 12-V battery.

a. What duty cycle should be provided to a maximum-power-point, buck-boost converter to deliver 14-V to the battery when the module is working at standard test conditions (STC)? How many amps will it deliver to the battery under those conditions?

SOLN:

a. The First Solar module has an STC MPP of 1.78 A, 49.2 V. So the converter needs to drop the 49.2 V down to 14 V. From (5.36)

$$\frac{D}{1-D} = \frac{14V}{49.2V}$$

$$14 - 14D = 49.2D \quad .... \quad D = \frac{14}{14+49.2} = 0.2215$$

Since we assume power in equals power out,

$$49.2 \times 1.78 = 14 \times I_B$$

$$I_B = \frac{49.2 \times 1.78}{14} = 6.255A$$

b. Suppose ambient temperature is 25°C with 1-sun of insolation. Recalculate the amps delivered to the battery.

SOLN:

b. First find cell temperature. From the table, NOCT = 45°C so from (5.23):

$$T_{cell} = T_{amb} + \left(\frac{NOCT-20}{0.8}\right)S = 25 + \left(\frac{45-20}{0.8}\right)1 = 56.25°$$

These cells have a - 0.25%/°C power degradation, so at 25°C:

Power loss = 0.25%/°C x (56.25-25)°C = 7.8125%

Power @ 25°C = 87.5 (1 - 0.078125) = 80.39 W

Again, with power in equal power out:

80.39 = 14V x I A   Charging current = 80.39/14 = 5.74 A

That's a loss of 8.2% due to temperature.