CLEAN ENERGY GENERATION, INTEGRATION AND STORAGE (EEE-801)

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Lecture-10
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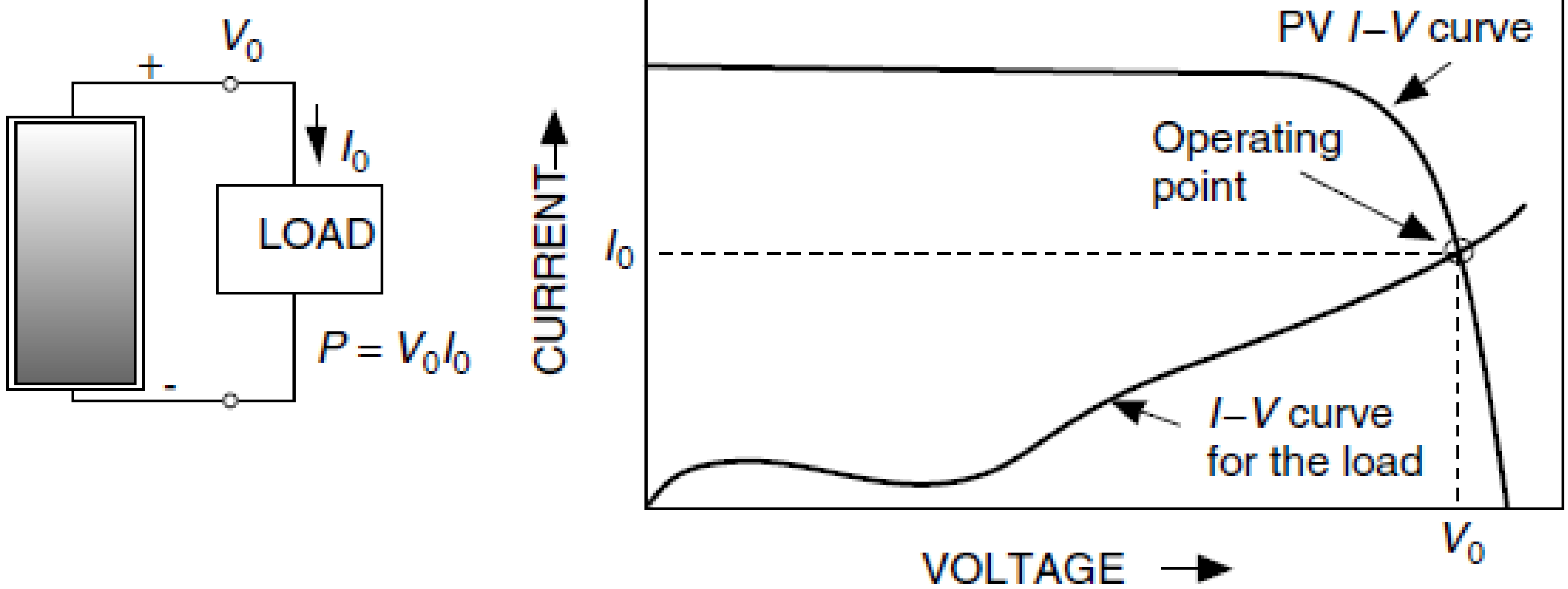
PV Systems: Current-Voltage Curves for Loads

- **While the I –V curve for a photovoltaic cell, module, or array defines the combinations of voltage and current that are permissible under the existing ambient conditions, it 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 PVs deliver their power. Just as PVs have an I –V curve, so do loads.**
- **As shown in Figure on next slide, the same voltage is across both the PVs and load, and the same current runs through the PVs and load. Therefore, when the I –V curve for the load is plotted onto the same graph that has the I –V curve for the PVs, the intersection point is the one spot at which both the PVs and load are satisfied. This is called the operating point.**

PV Systems: Current-Voltage Curves (Cont)

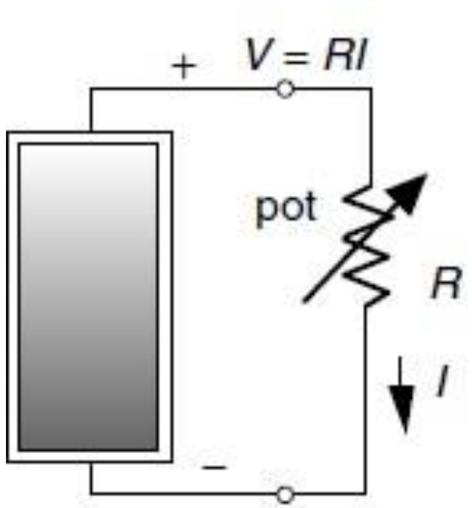
Here PV means Photovoltaic

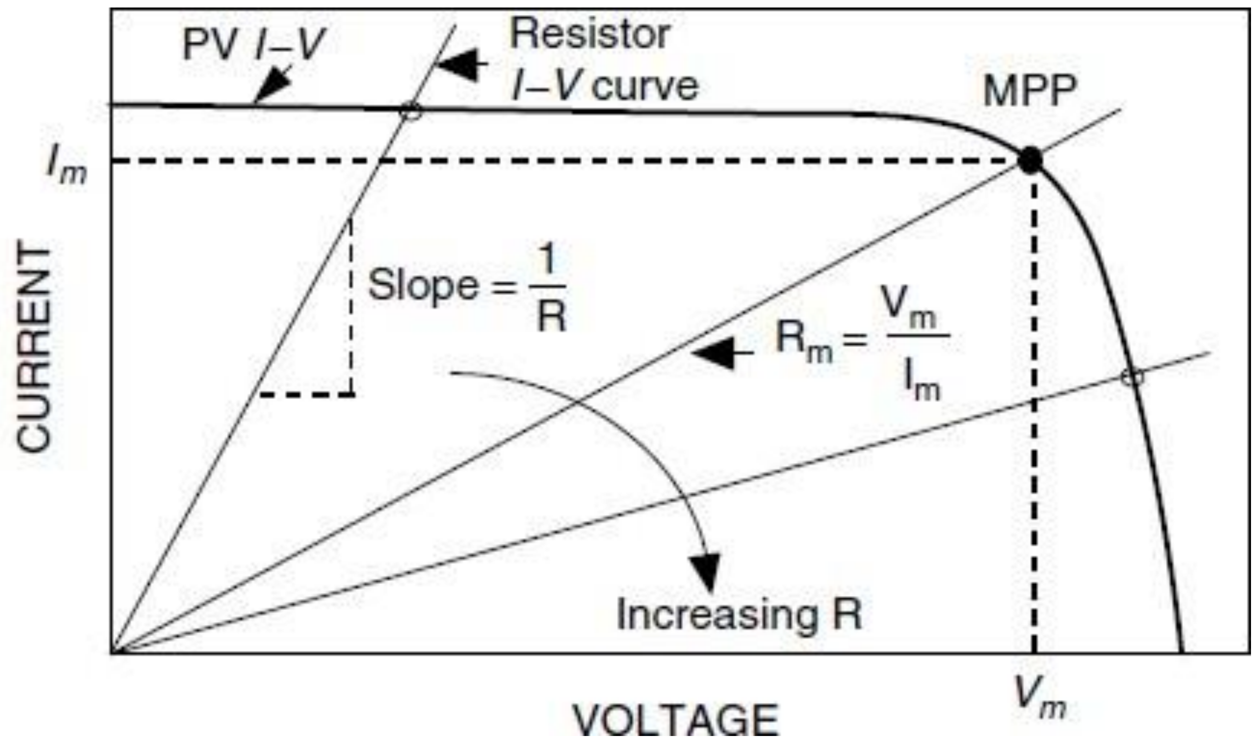


PV Systems: Simple Resistive-Load I-V Curve

- **To illustrate the importance and need for load curves, consider a simple resistive load as shown in Figure on next slide. For the load,**
- $V = IR \qquad OR \qquad I = \left(\frac{1}{R}\right)V$
- **which, when plotted on current versus voltage axes, is a straight line with slope 1/R. As R increases, the operating point where the PV and resistance I –V curves intersect moves along the PV I –V curve from left to right. In fact, that suggests a simple way to actually measure the I –V curve for PV module. By using a variable resistance, called a potentiometer, or pot, as the load, and then varying its resistance, pairs of current and voltage can be obtained, which can be plotted to give the module I –V curve.**

PV Systems: Simple Resistive-Load I-V (Cont)

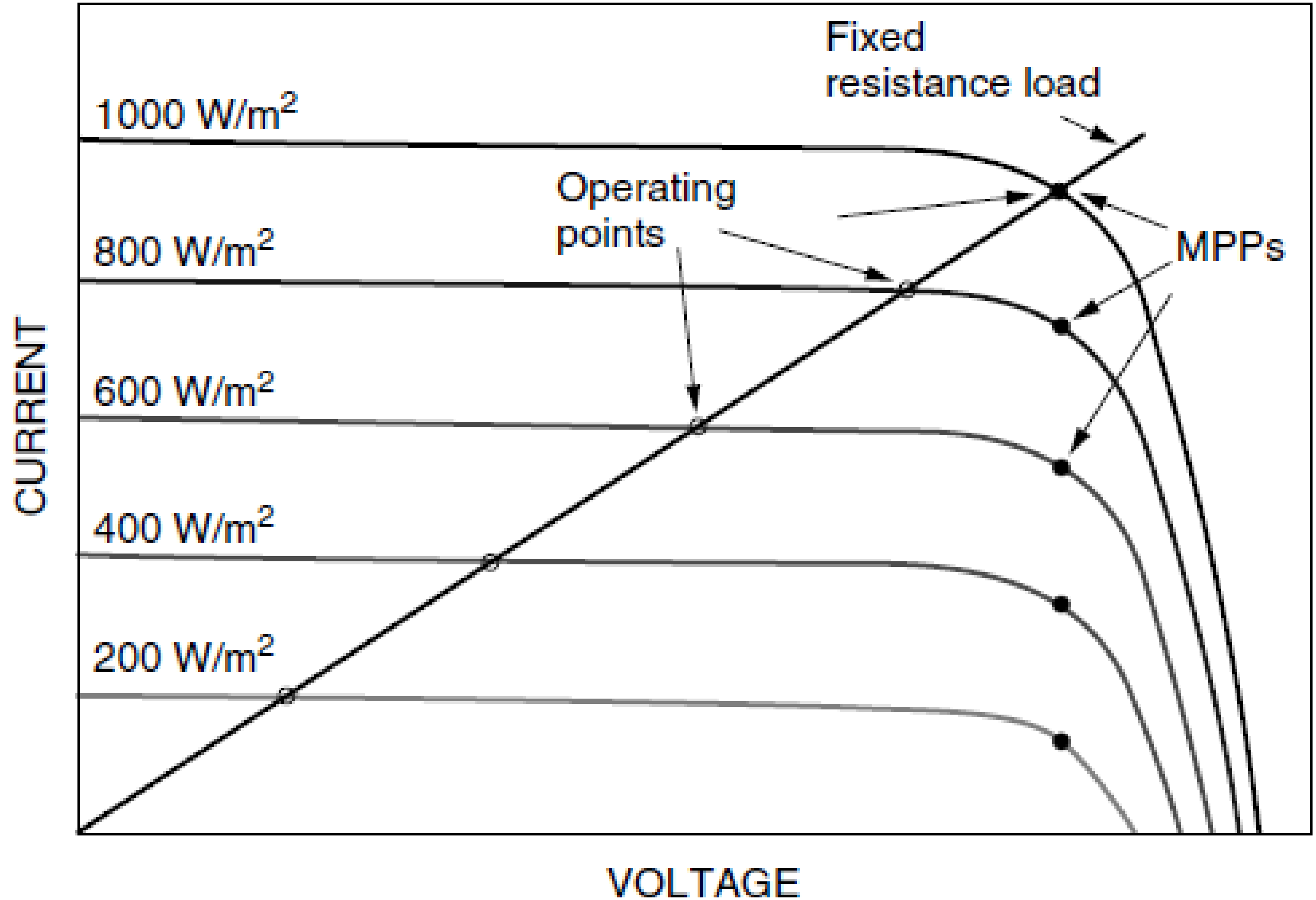




PV Systems: Simple Resistive-Load I-V (Cont)

- **Since power delivered to any load is the product of current and voltage, there will be one particular value of resistance that will result in maximum power:**
- $R_m = \; V_m \;\; I_m$
- **where V_m and I_m are the voltage and current at the maximum power point (MPP).**
- **Under the special conditions at which modules are tested, the MPP corresponds to the rated voltage V_R and current I_R of the module. That means the best value of resistance, for maximum power transfer, should be $V_R \; I_R$ under 1-sun, 25◦C, AM 1.5 conditions.**
- **As Figure on next slide shows, however, with a fixed resistance the operating point slips off the MPP as conditions change and the module becomes less and less efficient. 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.**

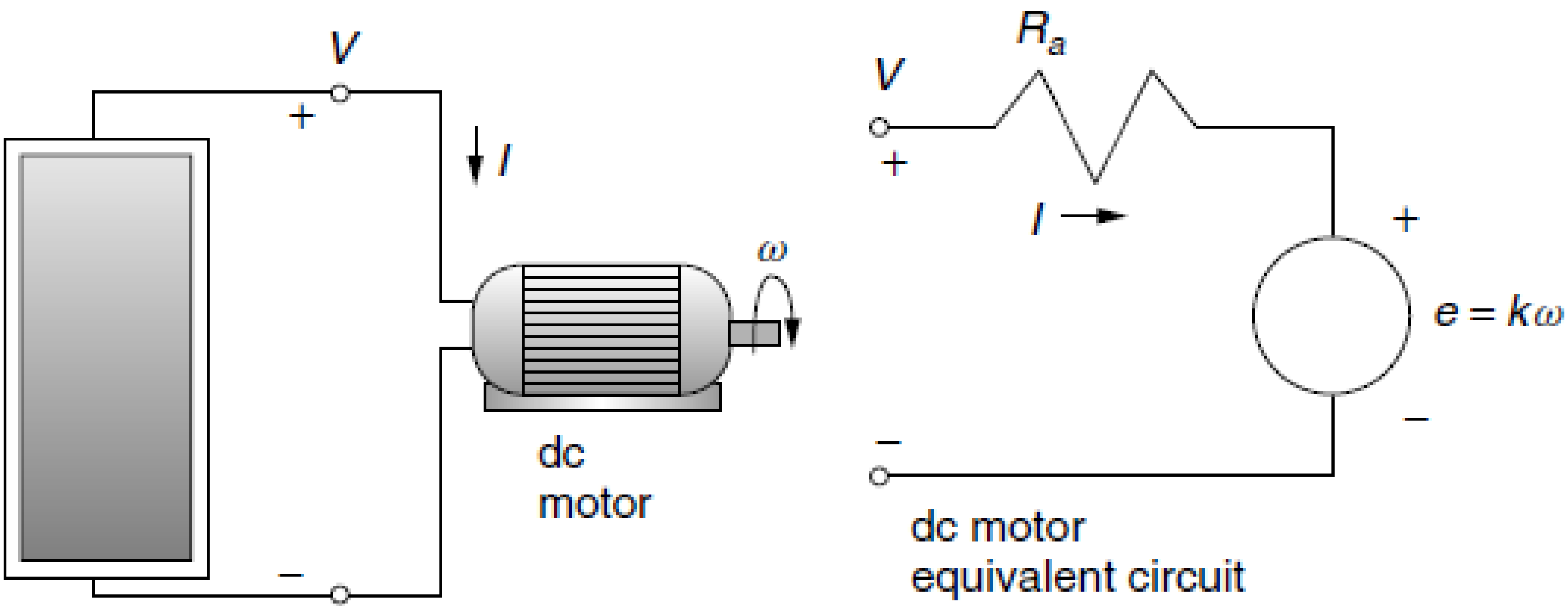
PV Systems: Simple Resistive-Load I-V (Cont)



PV Systems: DC Motor I-V Curve

- **While it is not often that a load would be an actual resistor, dc motors, such as those often used in PV-water-pumping systems, do exhibit a current–voltage relationship that is quite similar to that of a resistor.**
- **Most are permanent-magnet dc motors, which can be modeled as shown in Figure on next slide. Notice that as the motor spins, it develops a back electromotive force e, which is a voltage proportional to the speed of the motor (ω) that opposes the voltage supplied by the photovoltaics.**
- **From the equivalent circuit, the voltage–current relationship for the dc motor is simply**
- $V = IR_a + k\omega$ k?
- **where back emf e = kω and R_a is the armature resistance.**

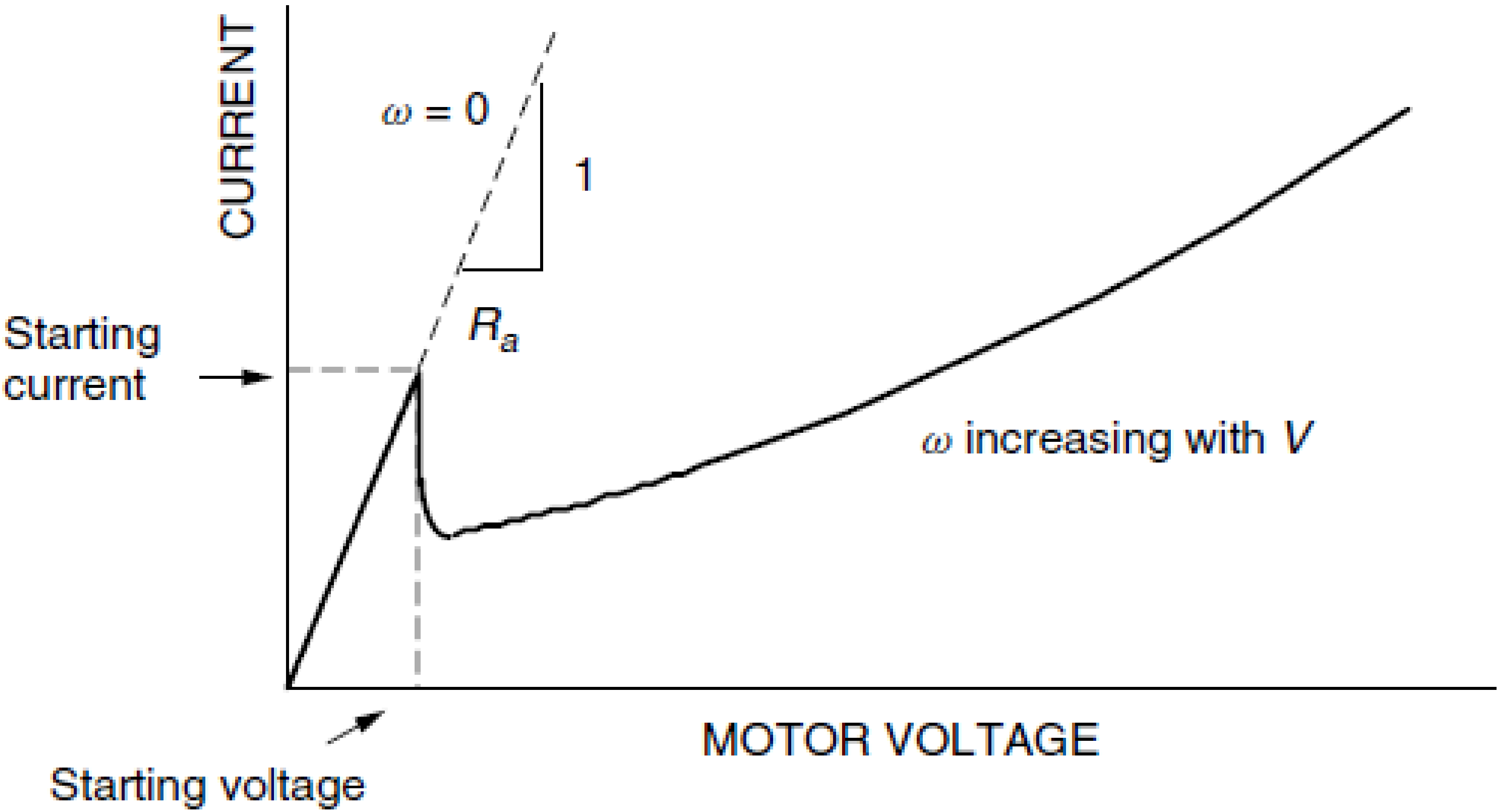
PV Systems: DC Motor I-V Curve (Continued)



PV Systems: DC Motor I-V Curve (Cont)

- **A dc motor runs at nearly constant speed for any given applied voltage even though the torque requirement of its load may change. For example, as the torque requirement increases, the motor slows slightly, which drops the back emf and allows more armature current to flow.**
- **Since motor torque is proportional to armature current, the slowing motor draws more current, delivers more torque to the load, and regains almost all of its lost speed.**
- **Based on $V = IR_a + k\omega$, the electrical characteristic curve of a dc motor will appear to be something like the one shown in Figure.**

PV Systems: DC Motor I-V Curve (Continued)



PV Systems: DC Motor I-V Curve (Cont)

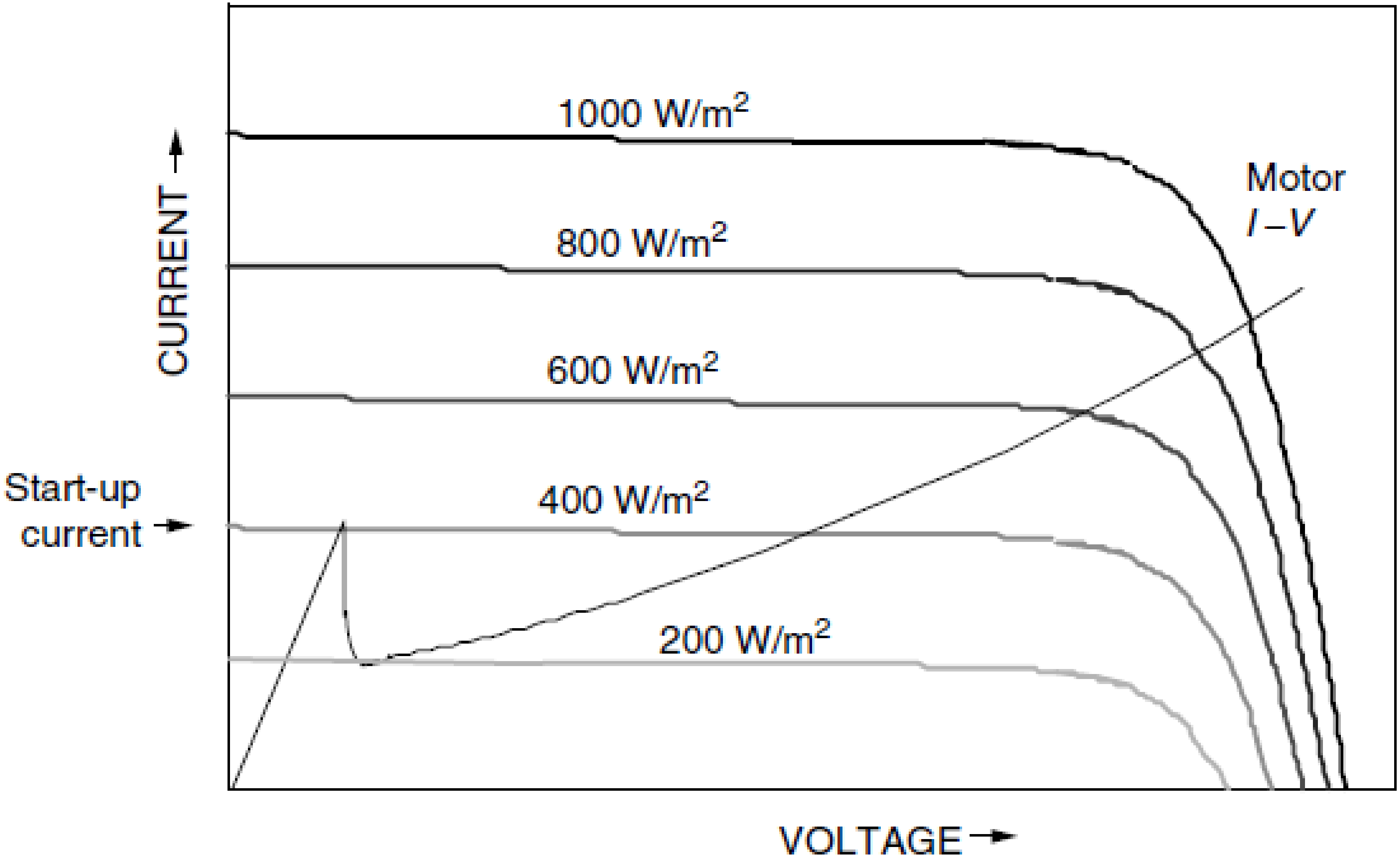
- **Notice that at start-up, while ω = 0, the current rises rapidly with increasing voltage until current is sufficient to create enough starting torque to break the motor loose from static friction.**

- **Once the motor starts to spin, back emf drops the current and thereafter *I* rises more slowly with increasing voltage. Notice that if you stall a dc motor while the voltage is way above the starting voltage, the current may be so high that the armature windings will burn out. That is why you should never leave the power on a dc motor if the armature is mechanically stuck for some reason.**

PV Systems: DC Motor I-V Curve (Cont)

- A dc motor I –V curve is superimposed on a set of photovoltaic I –V curves in Figure on next slide. The mismatch of operating points with the ideal MPP is apparent.
- Notice in this somewhat exaggerated example 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.
- This could mean that a fair amount of insolation is unusable in the morning while the motor struggles to break loose, which adds to the inefficiency of this simple PV–motor setup.

PV Systems: DC Motor I-V Curve (Cont)



PV Systems: DC Motor I-V Curve (Cont)

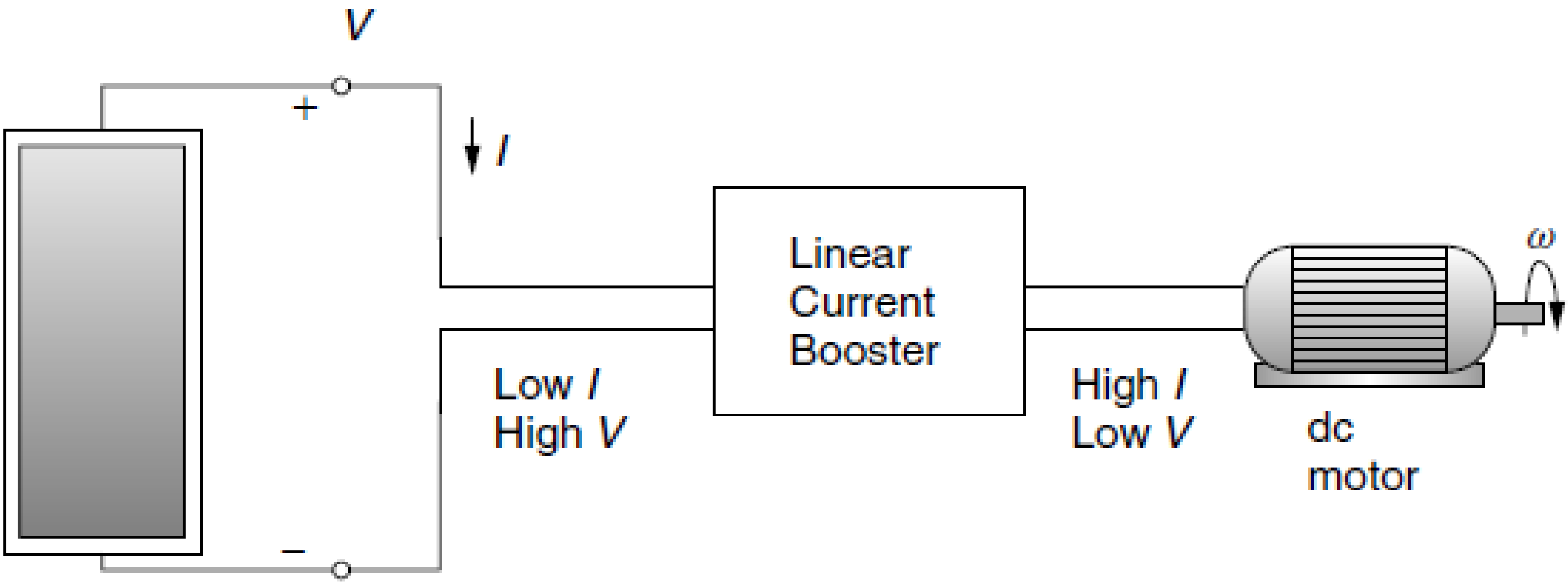
- There is a device, called a linear current booster (LCB), that is designed to help overcome this loss of potentially usable insolation when current delivered to the motor is insufficient to overcome friction as shown in Figure on next slide.

- Notice from the I –V curves of Figure on previous slide shows that the operating point in the morning is nowhere near the knee of the insolation curve where maximum power is available. Out by the knee of the curve, the PVs may be able to supply enough power to overcome friction, but without some clever electronics, this power would be delivered with relatively low current and relatively high voltage and still wouldn't start the motor.

An increase in voltage will see a reduction in current to supply the same load, and vice-versa. If you are using a DC motor, then speed is directly proportional to applied voltage, and most mechanical loads (fans, pumps, etc) will need more torque to turn faster, so you can increase torque by increasing voltage.

- What an LCB does is to shift this relationship around. By converting low-current, high-voltage power into high-current, low-voltage power, they can get the motor started earlier in the morning. The lower voltage, however, means that the motor will spin at a slower rate, but at least it is working. In addition, the motor with an LCB will not stall as early in the afternoon, though it will slow down. So there are additional gains.

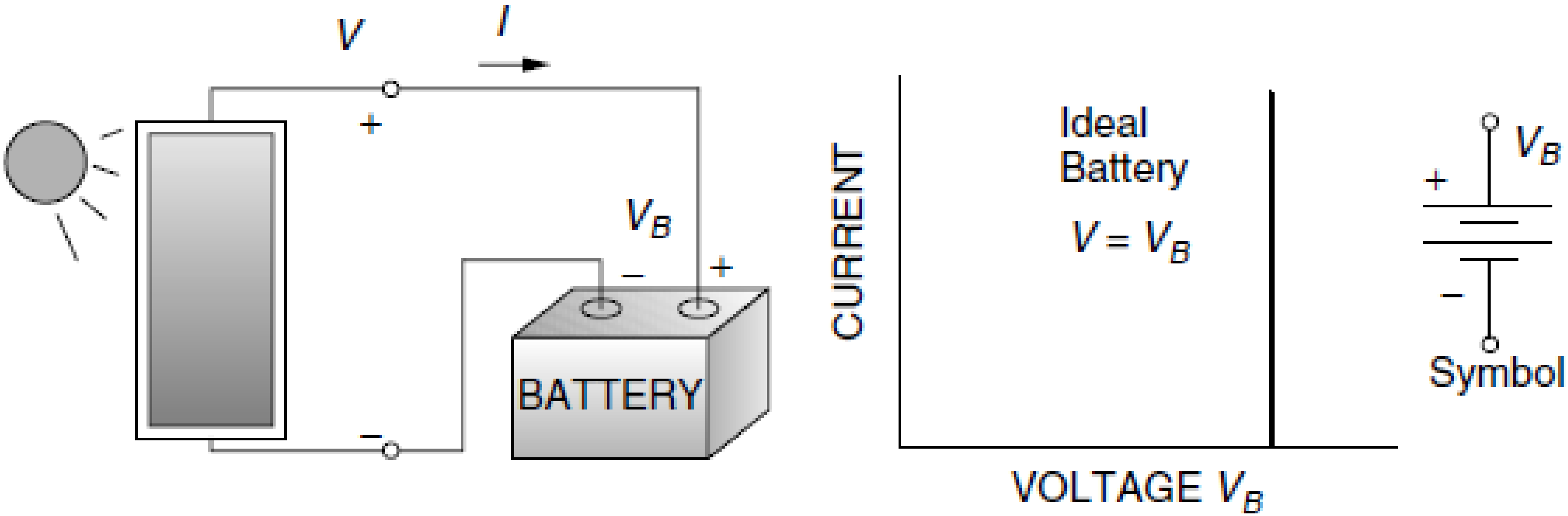
PV Systems: DC Motor I-V Curve (Cont)



PV Systems: Battery I-V Curves

- **Since PVs only provide power during the daylight hours and many applications require energy when the sun isn't shining, some method of energy storage often is needed. For a water pumping system, this might be the potential energy of water stored in a tank.**
- **For grid-connected systems, the utility lines themselves can be thought of as the storage mechanism: PV energy is put onto the grid during the day and taken back at night. For most off-grid applications, however, energy is stored in batteries for use whenever it is needed.**
- **An ideal battery is one in which the voltage remains constant no matter how much current is drawn. This means that it will have an I–V curve that is simply a straight up-and-down line as shown in Figure on next slide.**

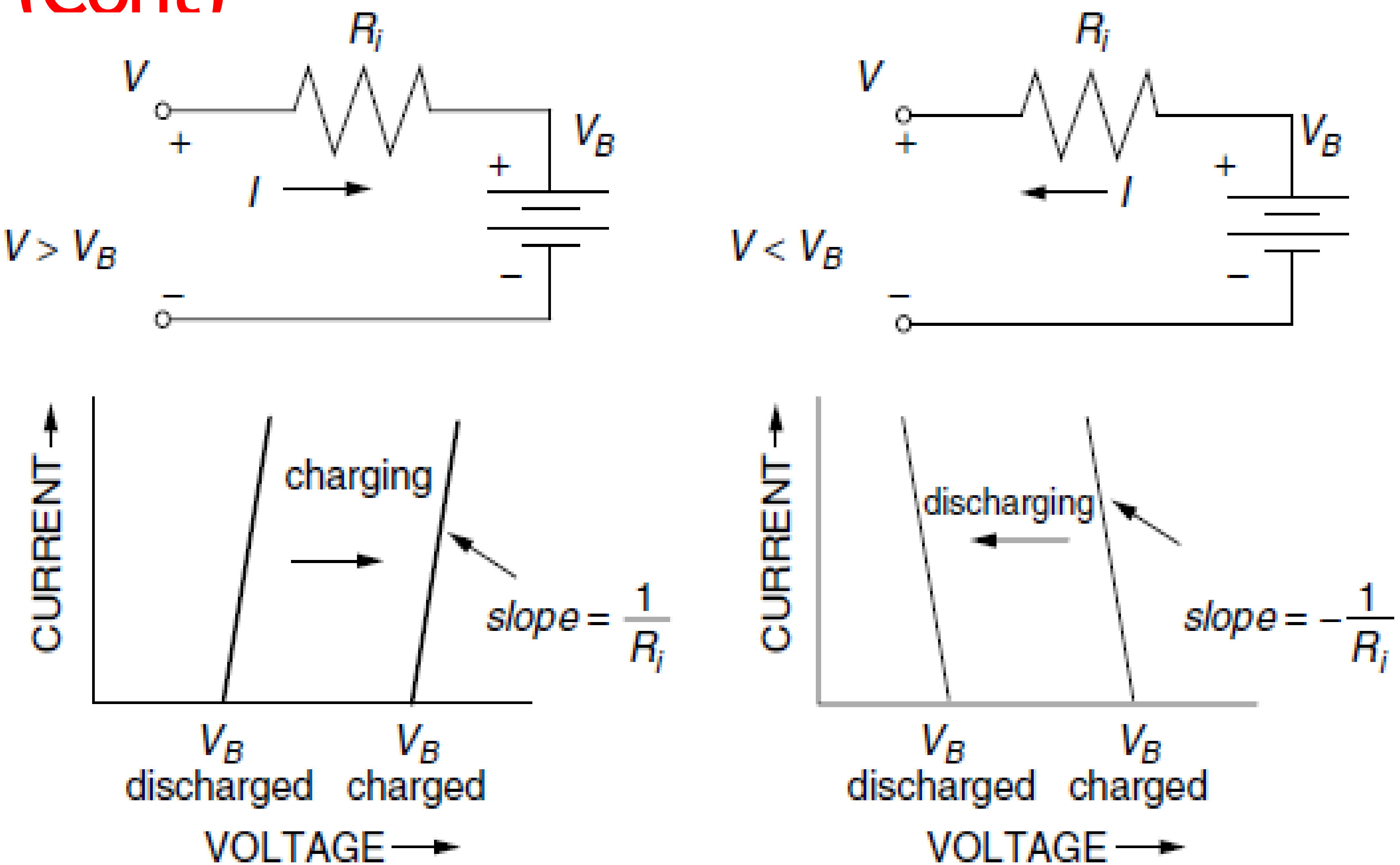
PV Systems: Battery I-V Curves (Cont)



PV Systems: Battery I-V Curves (Cont)

- **A real battery, on the other hand, 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 as shown in Figure on next slide. During the charge cycle, with positive current flow into the battery, we can write**
- $V = V_B + R_i I$
- **which plots as a slightly-tilted, straight line with slope equal to $1 R_i$. During charging, the applied voltage needs to be greater than V_B; as the process continues, V_B itself increases so the I–V line slides to the right as shown in Figure (a).**
- **During discharge, the output voltage of the battery is less than V_B, the slope of the I–V line flips, and the I–V curve moves back to the left as shown in Figure (b).**

PV Systems: Battery I-V Curves (Cont)



(a) Charging

(b) Discharging

PV Systems: Battery I-V Curves (Cont)

- The simple equivalent circuit representation of Figure on previous slide is complicated by a number of factors, including the fact that the open-circuit voltage (V_B) depends not only on the state of charge but also on battery temperature and how long it has been resting without any current flowing.
- For a conventional 12-V lead-acid battery at 78◦F, which has been allowed to rest for a few hours, V_B ranges from 12.7 V for a fully charged battery to about 11.7 V for one that has only a few percent of its charge remaining.
- Internal resistance is also a function of temperature and state of charge as well the age and condition of the battery.

PV Systems: Problem No.1

- **Suppose that a nearly depleted 12-V lead-acid battery has an open-circuit voltage of 11.7 V and an internal resistance of 0.03 Ω.**

a. What voltage would a PV module operate at if it is delivering 6 A to the battery?

b. If 20 A is drawn from a fully charged battery with open-circuit voltage 12.7 V, what voltage would the PV module operate at?

PV Systems: Solution of Problem No.1

- **a). The PV voltage would be**

$$V = V_B + R_i I = 11.7 + 0.03 \times 6 = 11.88 \text{ V}$$

- **b).**

While drawing 20 A after V_B has reached 12.7 V, the output voltage of the battery would be

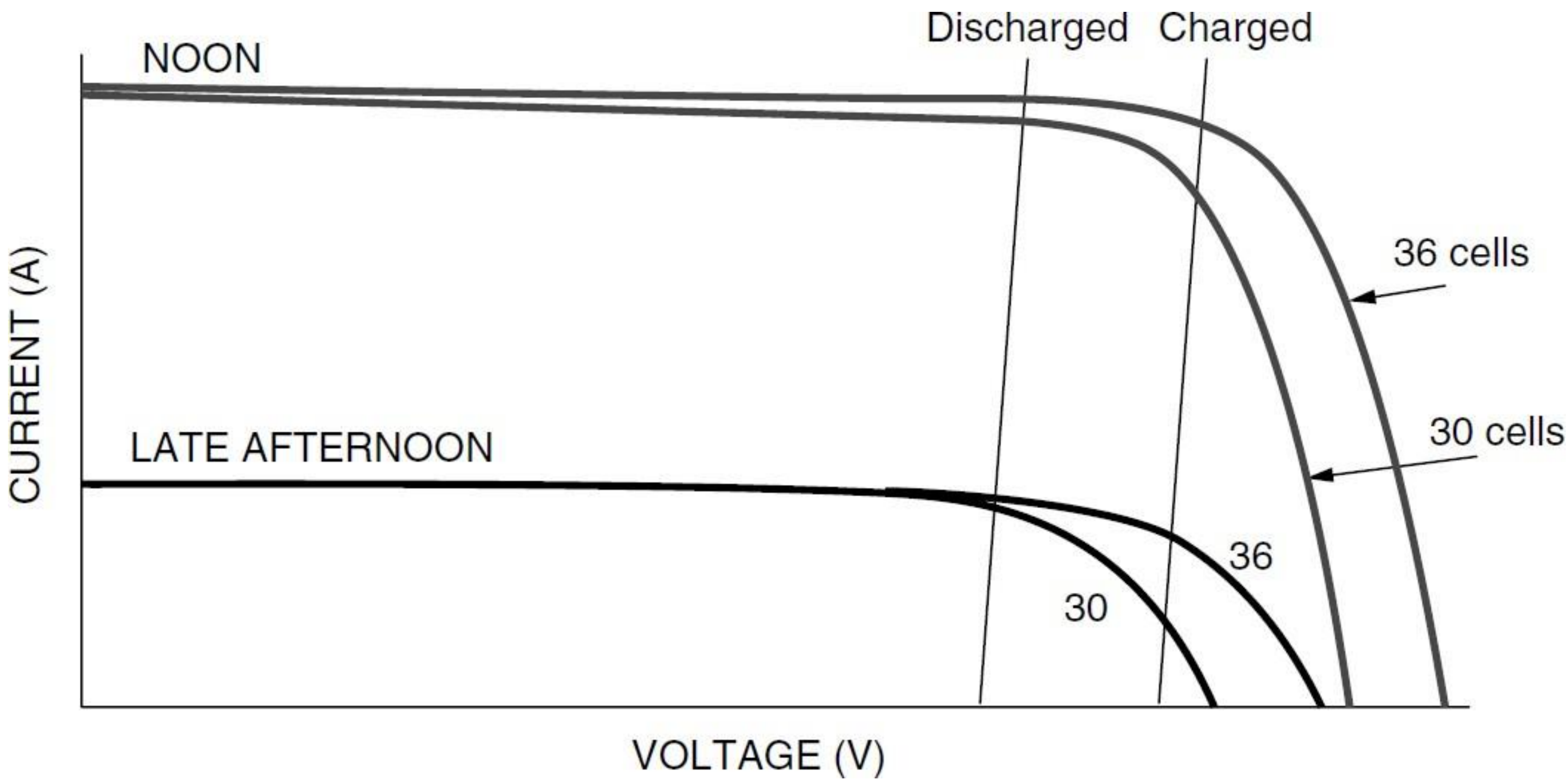
$$V_{\text{load}} = V_B - I R_i = 12.7 - 20 \times 0.03 = 12.1 \text{ V}$$

and since the voltage that the PVs operate at is determined by the battery voltage, they would also be at 12.1 V.

PV Systems: Battery I-V Curves (Cont)

- Since the I–V curve for a battery moves toward the right as the battery gains charge during the day, there is a chance that the PV operating point will begin to slide off the edge of the knee—especially late in the day when the knee itself is moving toward the left. This may not be a bad thing, however, since current has to be slowed or stopped anyway when a battery reaches full charge.
- If the PV–battery system has a charge controller, it will automatically prevent overcharging of the batteries. For very small battery charging systems, however, the charge controller can sometimes be omitted if modules with fewer cells in series are used. Such self-regulating modules sometimes have 33, or even 30, cells instead of the usual 36 to purposely cause the current to drop off as the battery approaches full charge as shown in Figure on next slide.

PV Systems: Battery I-V Curves (Cont)



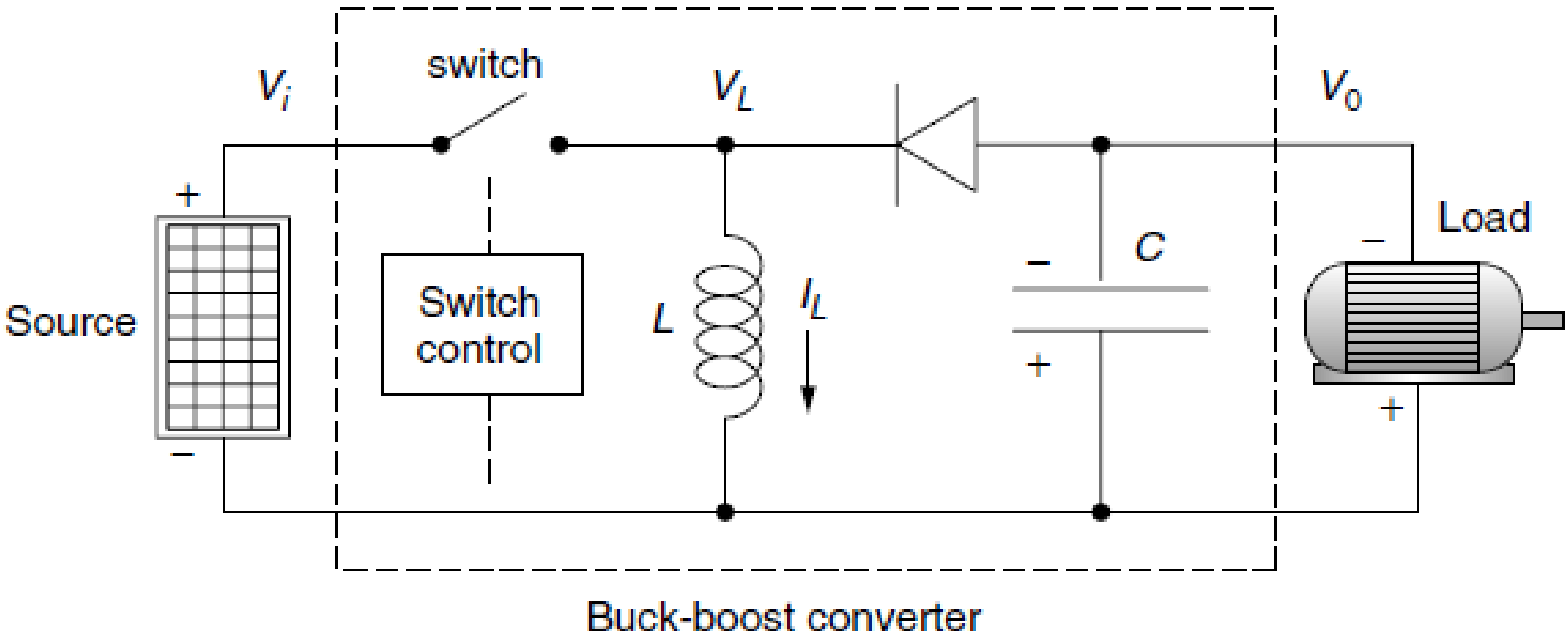
PV Systems: Maximum Power Point Trackers

- **Clearly, 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.**
- **There are some very clever, quite simple circuits that are at the heart of not only MPPTs but also linear current boosters (LCBs) as well as a number of other important power devices. The key is to be able to convert dc voltages from one level to another—something that was very difficult to do efficiently before high-power, field-effect transistors (FETs) became available in the 1980s and insulated-gate bipolar transistors (IGBTs) became available in the 1990s.**
- **At the heart of modern switched-mode dc-to-dc converters is one of these transistors used as a simple on–off switch that either allows current to pass or blocks it.**

PV Systems: Maximum Power Point (Cont)

- **A boost converter is a commonly used circuit to step up the voltage from a dc source, while a buck converter is often used to step down voltage. The circuit of Figure shown on next slide is a combination of these two circuits and is called a buck-boost converter.**
- **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. The source in this case is shown as being a PV module and the load is shown as a dc motor, but the basic concept is used for a wide variety of electric power applications.**
- **The transistor switch flips on and off at a rapid rate (on the order of 20 kHz) under control of some sensing and logic circuitry that isn't shown. Also not shown is a capacitor across the PVs that helps smooth the voltage supplied by the PVs.**

PV Systems: Maximum Power Point (Cont)



PV Systems: Maximum Power Point (Cont)

- **To analyze the buck-boost converter, we have to go back to first principles. Conventional dc or ac circuit analysis doesn't help much and instead the analysis is based on an energy balance for the magnetic field of the inductor. Basically there are two situations to consider: the circuit with the switch closed and the circuit with the switch open.**
- **When the switch is closed, the input voltage V_i is applied across the inductor, driving current I_L through the inductor. All of the source current goes through the inductor since the diode blocks any flow to the rest of the circuit.**
- **During this portion of the cycle, energy is being added to the magnetic field in the inductor as current builds up. If the switch stayed closed, the inductor would eventually act like a short-circuit and the PVs would deliver short-circuit current at zero volts.**

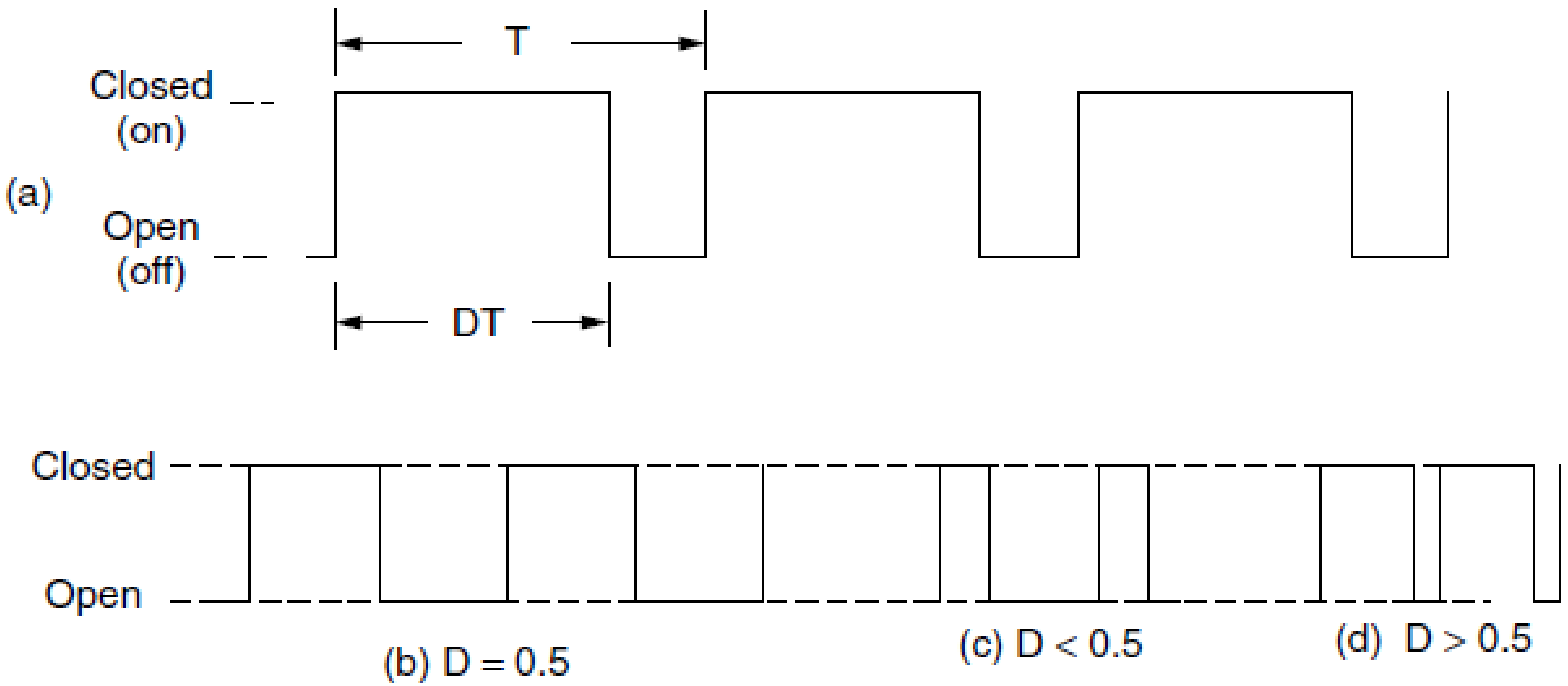
PV Systems: Maximum Power Point (Cont)

- When the switch is opened, current in the inductor continues to flow as the magnetic field begins to collapse (remember that current through an inductor cannot be changed instantaneously—to do so would require infinite power).
- Inductor current now flows through the capacitor, the load, and the diode. Inductor current charging the capacitor provides a voltage (with a polarity reversal) across the load that will help keep the load powered after the switch closes again.
- If the switch is cycled quickly enough, the current through the inductor doesn't have a chance to drop much while the switch is open before the next jolt of current from the source. With a fast enough switch and a large enough inductor, the circuit can be designed to have nearly constant inductor current. That's our first important insight into how this circuit works: Inductor current is essentially constant.

- If the switch is cycled quickly enough, the voltage across the capacitor doesn't have a chance to drop much while the switch is closed before the next jolt of current from the inductor charges it back up again. Capacitors, recall, can't have their voltage change instantaneously so if the switch is cycling fast enough and the capacitor is sized large enough, the output voltage across the capacitor and load is nearly constant. We now have our second insight into this circuit: Output voltage V_o is essentially constant (and opposite in sign to V_i).

- Finally, we need to introduce the duty cycle of the switch itself. This is what controls the relationship between the input and output voltages of the converter. The duty cycle D (0 < D < 1) is the fraction of the time that the switch is closed, as illustrated in Figure on next slide. This variation in the fraction of time the switch is in one state or the other is referred to as pulse-width modulation (PWM).

PV Systems: Maximum Power Point (Cont)



PV Systems: Maximum Power Point (Cont)

- For this simple description, all of the components in the converter will be considered to be ideal. As such, the inductor, diode and capacitor do not consume any net energy over a complete cycle of the switch. Therefore the average power into the converter is equal to the average power delivered by the converter; that is, it has 100% efficiency. Real MPPTs have efficiencies in the mid-90% range, so this isn't a bad assumption.
- Now focus on the inductor. While the switch is closed, from time t = 0 to t = DT, the voltage across the inductor is a constant V_i. The average power put into the magnetic field of the inductor during one complete cycle is given by

$$\overline{P}_{L,\text{in}} = \frac{1}{T}\int_0^{DT} V_i I_L \, dt = \frac{1}{T} V_i \int_0^{DT} I_L \, dt$$

PV Systems: Maximum Power Point (Cont)

- Under the assumption that inductor current is constant, the average power into the inductor is

$$\overline{P}_{L,\text{in}} = \frac{1}{T} V_i I_L \int_0^{DT} dt = V_i I_L D$$

- When the switch opens, the inductor's magnetic field begins to collapse, returning the energy it just acquired. The diode conducts, which means that the voltage across the inductor V_L is the same as the voltage across the load V_o. The average power delivered by the inductor is therefore

$$\overline{P}_{L,\text{out}} = \frac{1}{T} \int_{DT}^{T} V_L I_L \, dt = \frac{1}{T} \int_{DT}^{T} V_0 I_L \, dt$$

PV Systems: Maximum Power Point (Cont)

- With good design, both V_o and I_L are essentially constant, so average power from the inductor is

$$\overline{P}_{L,\text{out}} = \frac{1}{T} V_0 I_L (T - DT) = V_0 I_L (1 - D)$$

- Over a complete cycle, average power into the inductor equals average power out of the inductor. So, we get

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

- The above equation is pretty interesting. It tells us we can bump dc voltages up or down (there is a sign change) just by varying the duty cycle of the buck-boost converter. Longer duty cycles allow more time for the capacitor to charge up and less time for it to discharge, so the output voltage increases as D increases.

- For a duty cycle of 1/2, the output voltage is the same as the input voltage. A duty cycle of 2/3 results in a doubling of voltage, while D = 1/3 cuts voltage in half.

PV Systems: Maximum Power Point (Cont)

- **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.**

PV Systems: Problem. No.2

- Under certain ambient conditions, a PV module has its maximum power point at V_m = 17 volts and I_m=6 A. What duty cycle should an MPPT have if the module is delivering power to a 10 ohm resistance?

Solution. The maximum power delivered by the PVs is $P = 17\text{ V} \times 6\text{ A} = 102\text{ W}$. To deliver all of that 102 W to the 10 Ω resistor means that the resistor needs a voltage of

$$P = \frac{{V_R}^2}{R} = 102 = \frac{{V_R}^2}{10}$$

$$V_R = \sqrt{102 \cdot 10} = 31.9\text{ V}$$

The MPPT must bump the 17-V PV voltage to the desired 31.9-V resistor voltage.

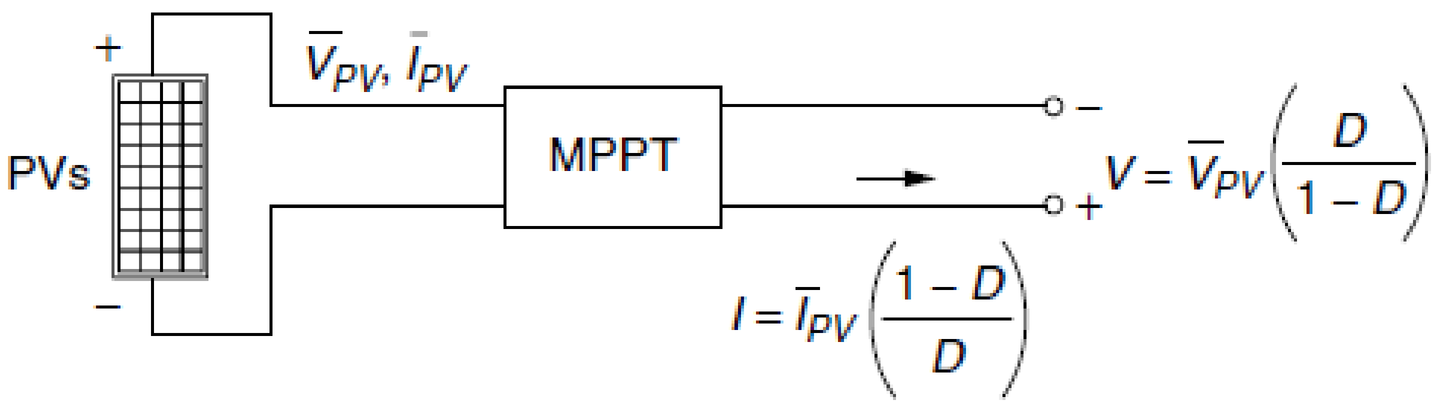
$$\frac{31.9}{17} = \left(\frac{D}{1-D}\right) = 1.88$$

$$D = 1.88 - 1.88D$$

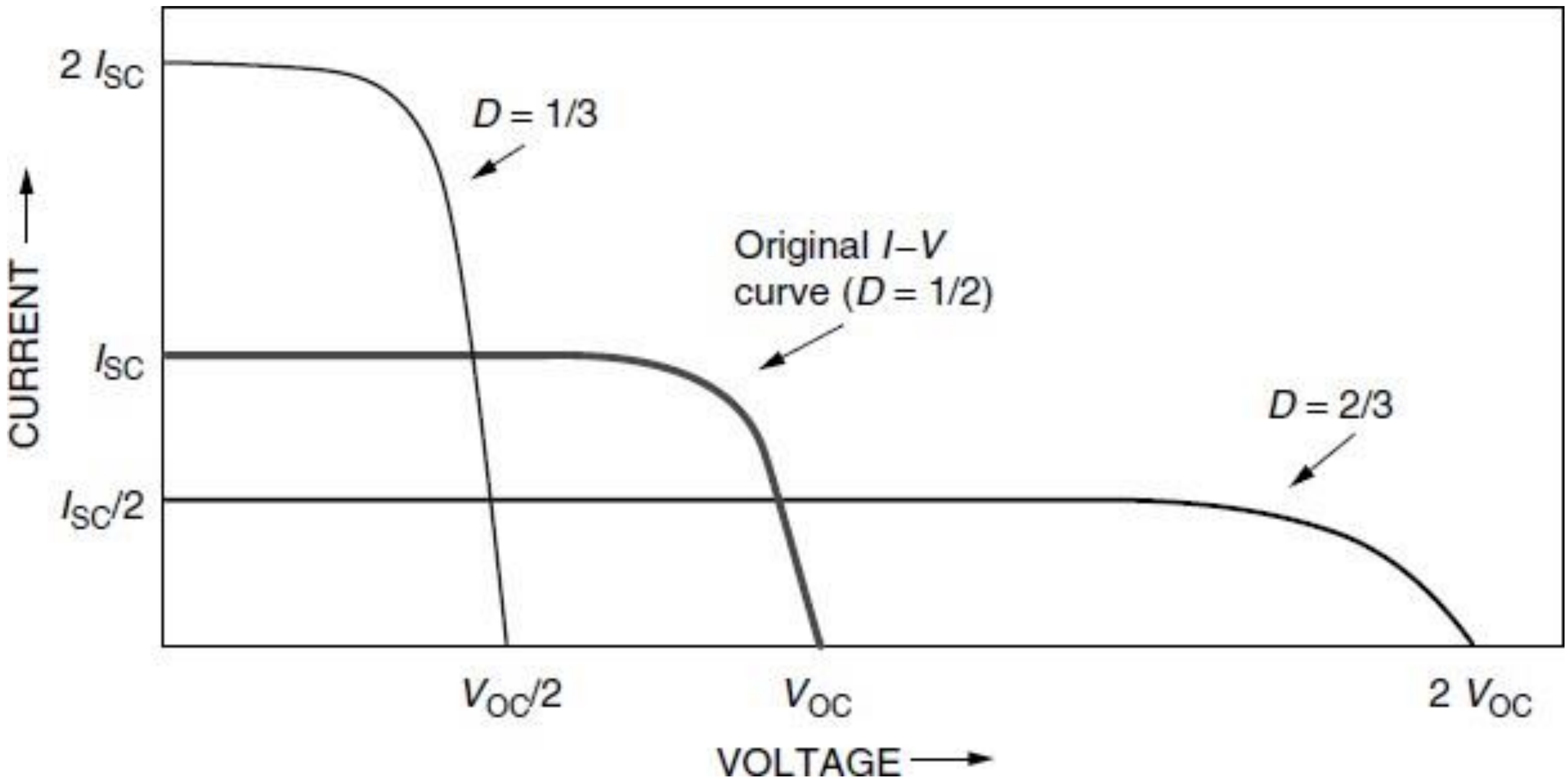
$$D = \frac{1.88}{2.88} = 0.65$$

PV Systems: Comments for Problem. No.2

- For a 100% efficient MPPT, the product of current and voltage (power) from the PVs is the same as the current-voltage product delivered by the MPPT to the load as shown in below figure.
- One way to visualize the impact of the MPPT is to redraw the PV 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 as shown in Figure on next slide.



PV Systems: Comments for Problem. No.2 (Cont)



PV Systems: Hourly I-V Curves

- **As a typical solar day progresses, ambient temperature and available insolation are constantly changing. That means, of course, that the I–V curve for a PV array is constantly shifting and the operating point for any given load is constantly moving around as well. Manufacturers provide I –V curves for various temperatures and solar intensity, but there are times when hour-by-hour curves are helpful.**

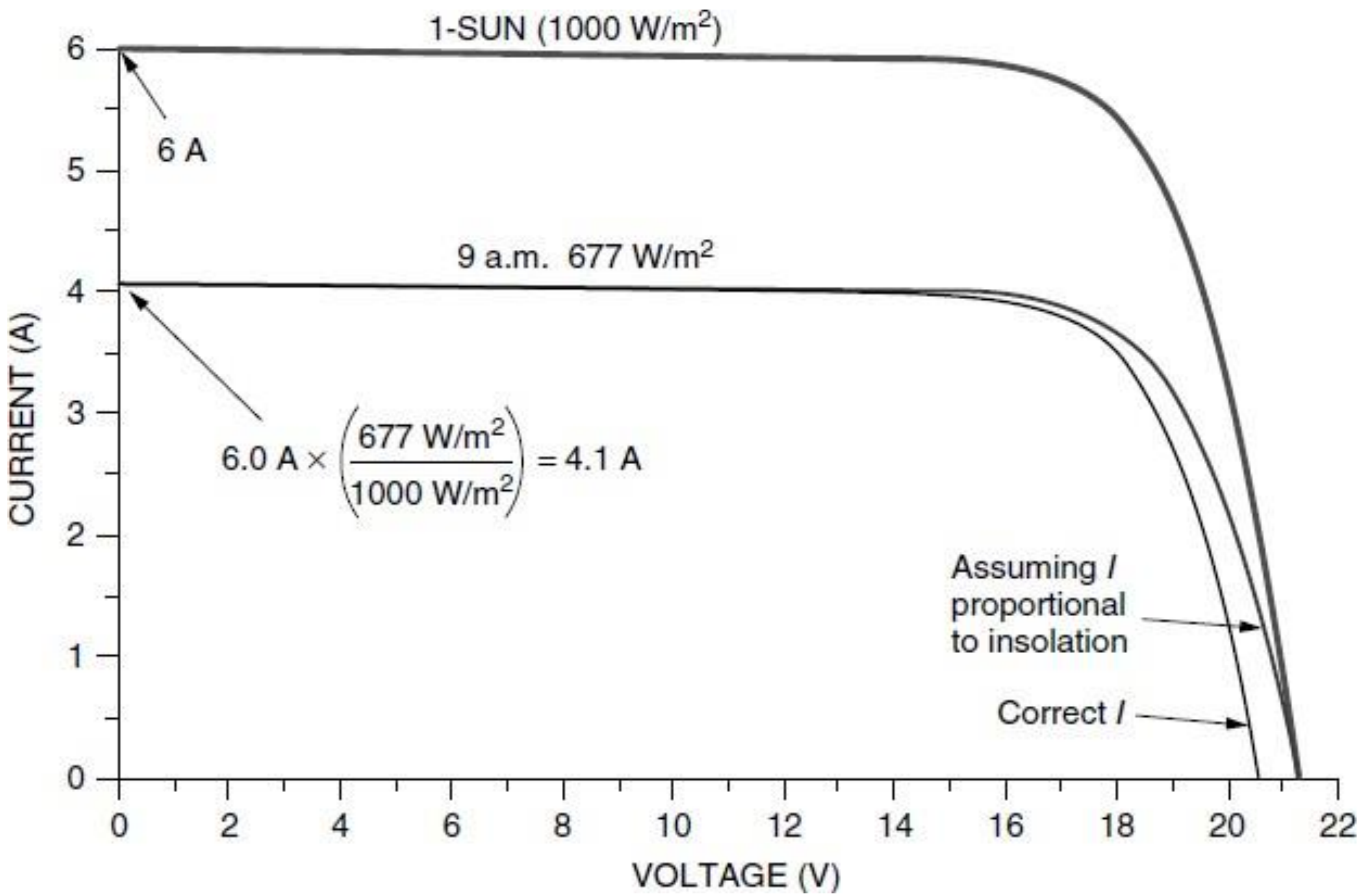
- **Over most of a PV I–V curve, current at any voltage is directly proportional to insolation. That suggests we can simply scale the 1-sun (1000 W/m^2) I–V curve by moving it up or down in proportion to the anticipated insolation. This generalization is completely true for short-circuit current I_{SC}(i.e., V = 0).**

- **Recall, however, that open-circuit voltage V_{OC}decreases somewhat as insolation decreases, so the simple assumption of current being proportional to insolation breaks down near V_{OC} . Under most circumstances, however, the operating voltage of a system is around the knee, or even lower, where current is very close to being proportional to insolation.**

PV Systems: Hourly I-V Curves (Cont)

- **Figure on the next slide illustrates this point. In it, a 1-sun I –V curve having I_{sc} = 6 A has been drawn along with two I –V curves that would be expected if insolation happened to be 677 W/m^2.**
- **One of the curves uses the assumption that current is proportional to insolation, the other properly accounts for the drop in V_{oc} as insolation decreases. As can be seen, there is very little difference between the 677-W/m^2 curves as long as the module doesn't operate below the knee.**
- **The simple assumption that current is proportional to insolation makes it easy to draw hour-by-hour I –V curves for clear days.**
- **Since the 1-sun I –V curve itself depends on cell temperature, and cell temperature depends on insolation and ambient temperature, we could imagine adjusting the 1-sun reference curve on an hour-by-hour basis as well.**
- **But since our purpose is to illustrate certain principles, that degree of refinement will be ignored here.**

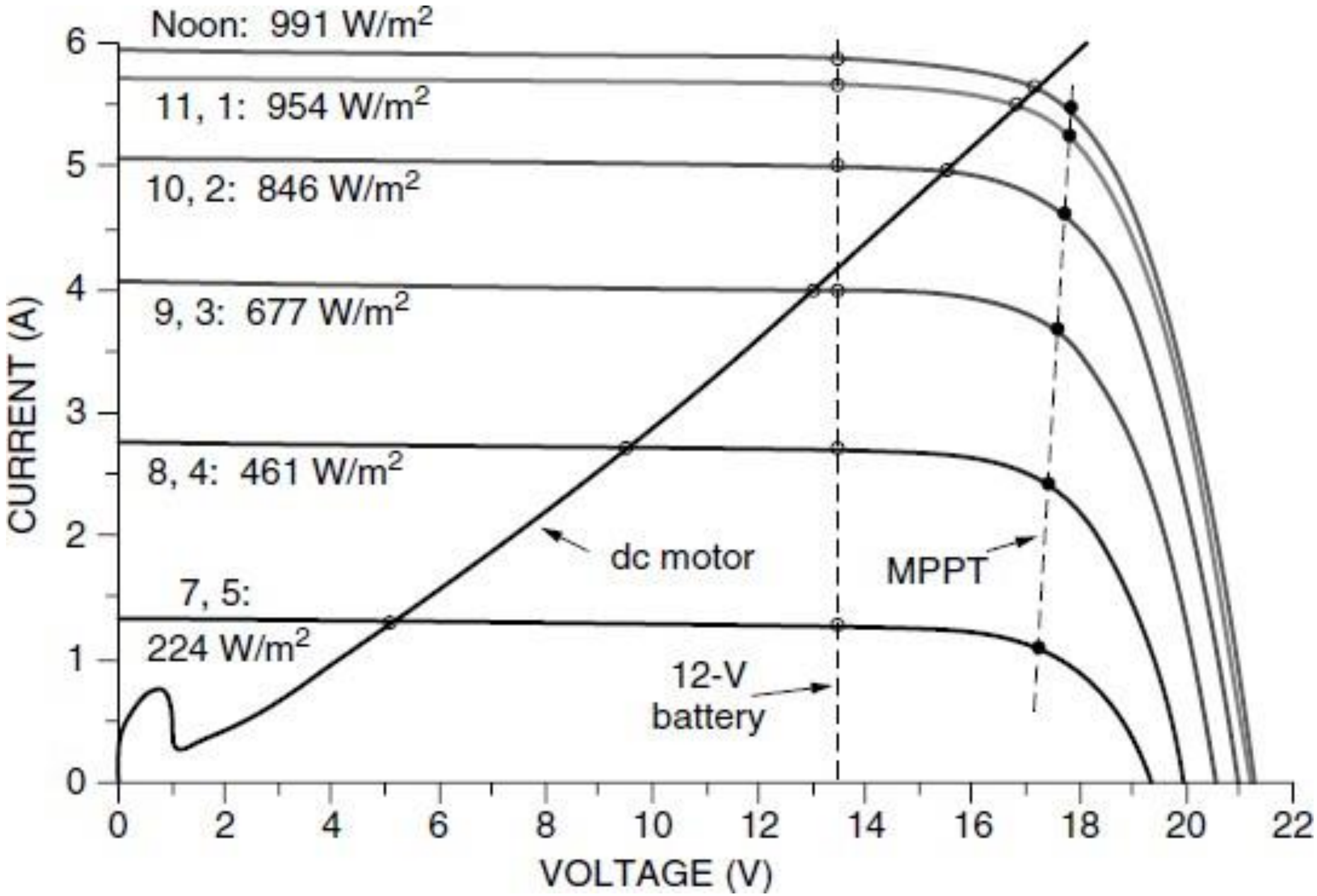
PV Systems: Hourly I-V Curves (Cont)



PV Systems: Hourly I-V Curves (Cont)

- In Figure on next slide, hourly PV I –V curves have been drawn using insolations corresponding to a south-facing collector in April at 40◦ latitude with tilt angle of 40◦ using clear-sky values.
- The module is the same one used in the example in Figure shown on previous slide. Superimposed onto these I –V curves are example I –V curves for three different kinds of loads: a dc motor, a 12-V battery with a constant charging voltage of 13.5 V, and a maximum power point tracker (MPPT).
- As can be seen, the dc motor has been well matched to the 1-sun I –V curve, but does poorly in the early morning and late afternoon. The 12-V battery is consistently somewhat below the maximum power point. Table is shown on next slides provides a compilation of the hourly performance of each of these loads. The dc motor loses about 15% of the available daily energy because it doesn't operate at the maximum power point while the 12-V battery loses 17%.

PV Systems: Hourly I-V Curves (Cont)



PV Systems: Daily Energy Delivered to Three Loads

Time	Insolation (W/m^2)	dc Motor			12-V Battery			MPPT		
		Amps	Volts	Watts	Amps	Volts	Watts	Amps	Volts	Watts
7	224	1.3	5.0	6.5	1.3	13.5	17.6	1.1	17.3	19.0
8	461	2.7	9.6	25.9	2.7	13.5	36.5	2.5	17.4	43.5
9	677	4.0	13.0	52.0	4.0	13.5	54.0	3.7	17.5	64.8
10	846	5.0	15.6	78.0	5.0	13.5	67.5	4.7	17.6	82.7
11	954	5.3	16.9	89.6	5.6	13.5	75.6	5.2	17.7	92.0
12	991	5.5	17.1	94.1	5.9	13.5	79.7	5.4	17.8	96.1
1	954	5.3	16.9	89.6	5.6	13.5	75.6	5.2	17.7	92.0
2	846	5.0	15.6	78.0	5.0	13.5	67.5	4.7	17.6	82.7
3	677	4.0	13.0	52.0	4.0	13.5	54.0	3.7	17.5	64.8
4	461	2.7	9.6	25.9	2.7	13.5	36.5	2.5	17.4	43.5
5	224	1.3	5.0	6.5	1.3	13.5	17.6	1.1	17.3	19.0
W-h:	7315			598			582			700
Eff. vs. MPPT:				85%			83%			100%

[a] Without an MPPT, the dc motor is unable to collect 15% of the available energy and the 12-V battery loses 17%