Lecture 7 – Solar Photovoltaics (II)

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ECE180J

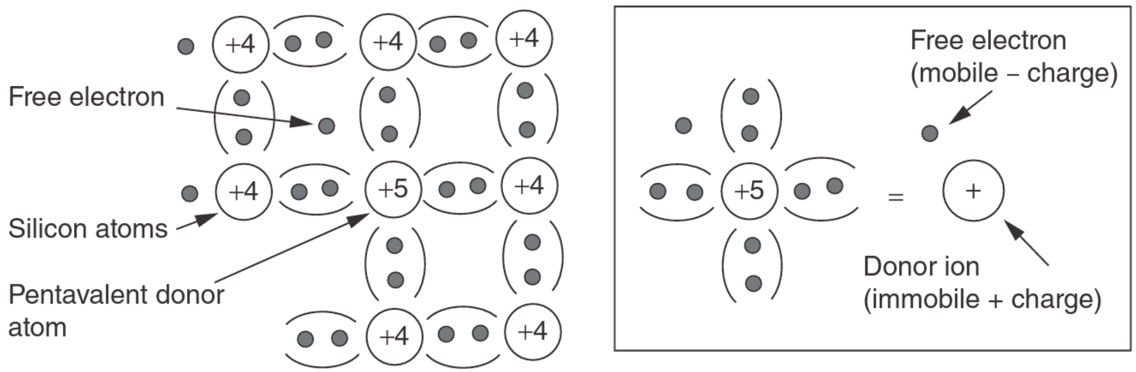
Outline

- P-N Junction Diodes
- Equivalent Circuits and I-V Curve
- Cell, Module, and Array
- Shading Impact and Mitigation
- Maximum Power Point Tracker

- B1: Chap 5

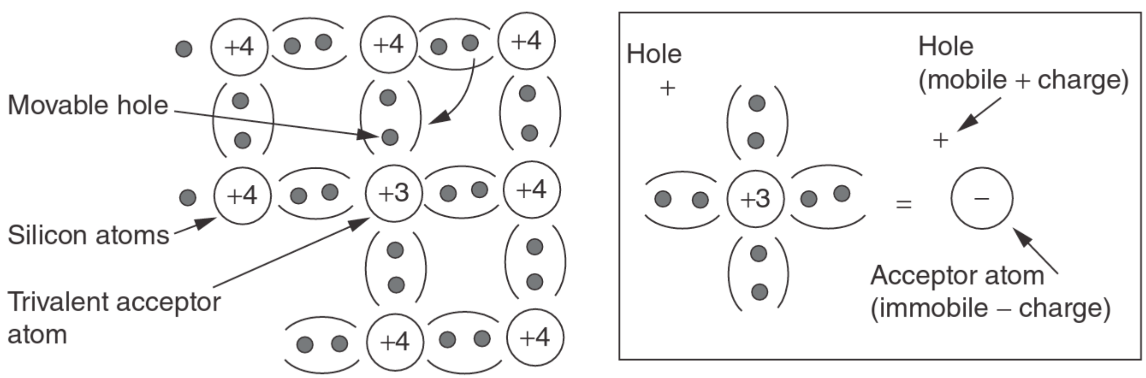
Donor and Acceptor Atoms

A built-in electric field is needed to continuously sweep electrons away from holes: Pushes them in two different directions.



(a) The donor atom in Si crystal (b) Representation of the donor atom

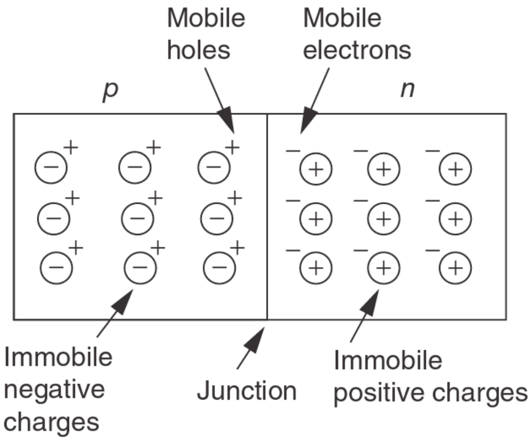
FIGURE 5.10 An n-type material. (a) The pentavalent donor. (b) The representation of the donor as a mobile, negative charge with a fixed, immobile positive charge.



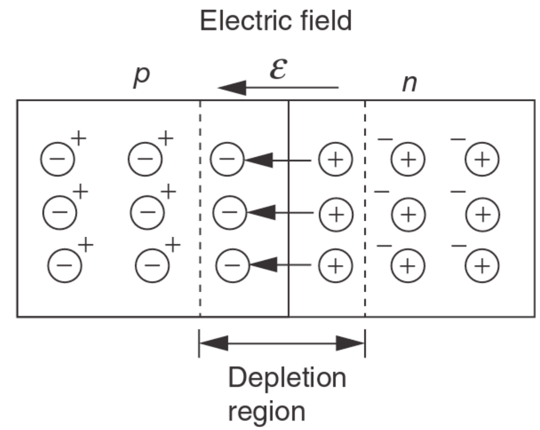
(a) An acceptor atom in Si crystal (b) Representation of the acceptor atom

FIGURE 5.11 In a p-type material, trivalent acceptors contribute mobile, positively charged holes while leaving immobile, negative charges in the crystal lattice.

P-N Junction



(a) When first brought together



(b) In steady state

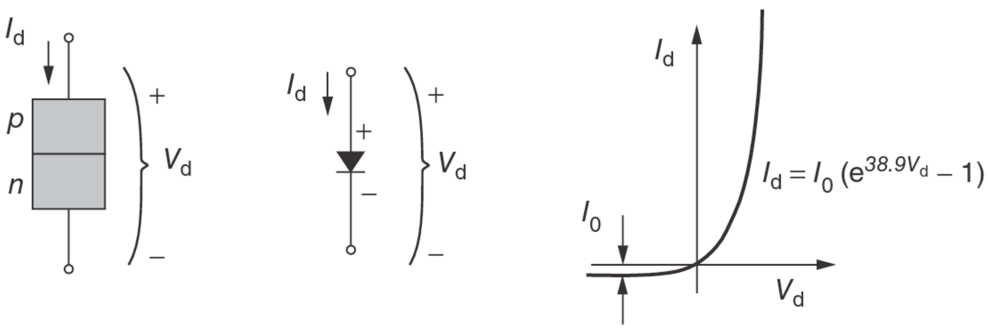
Fig (a): In the n-region, mobile electrons drift by diffusion across the junction.

In the p-region, mobile holes drift by diffusion across the junction.

Fig (b): When an electron crosses the junction, it fills a hole leaving an immobile, positive charge behind in the n-region, while it creates an immobile negative charge in the p-region.

- Immobile charged atoms in the p and n regions create an electric field that works against the continued movement of electrons and holes across the junction.
- As the diffusion process continues, the electric field countering that movement increases until eventually all further movement stops.

P-N Junction Diodes



(a) *p–n* junction diode

(b) Symbol for real diode

(c) Diode characteristic curve

The current-voltage (I-V) curve for the p-n junction diode is given by the Shockley diode equation:

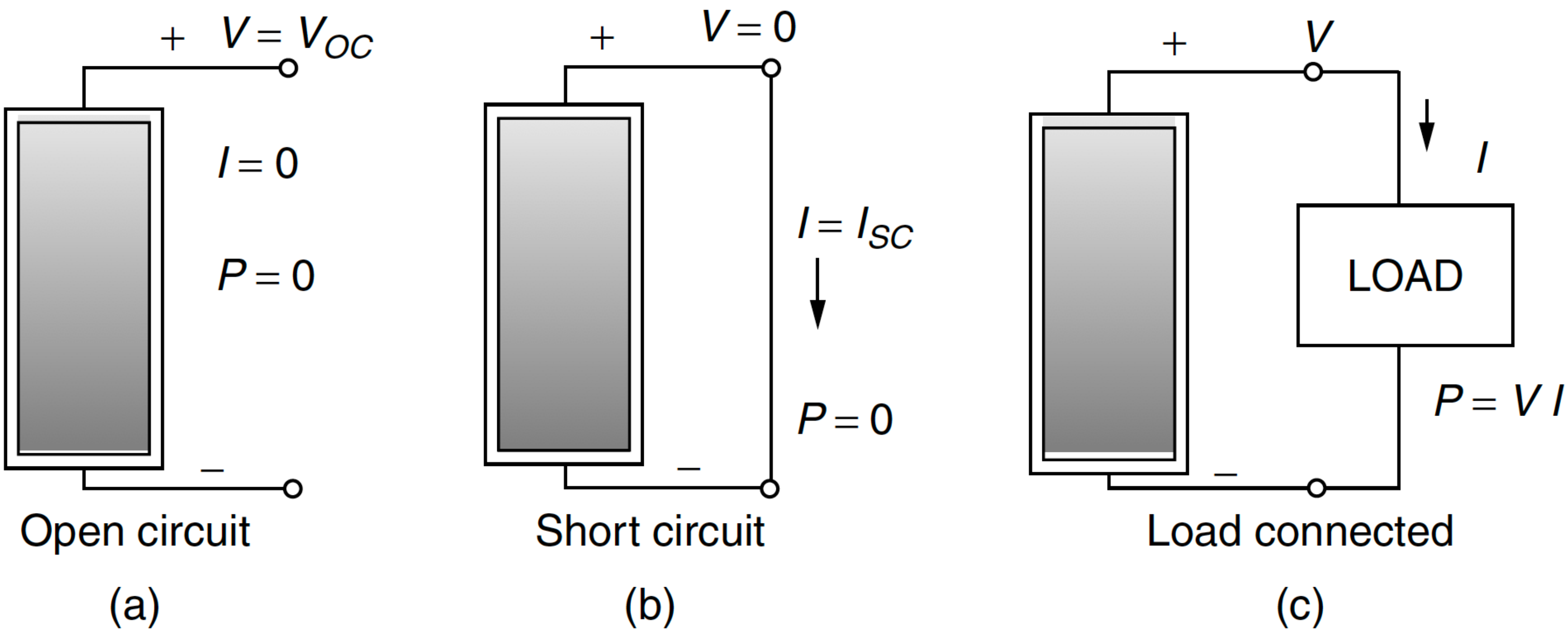
$$I_d = I_0\left(e^{qV_d/kT} - 1\right) \qquad \text{Equation 5.5}$$

where I_d is the diode current in the direction of the arrow (A), V_d is the voltage across the diode terminals from the p-side to the n-side (V), I_0 is the reverse saturation current (A), q is the electron charge (1.602×10^{-19} C), k is Boltzmann's constant (1.381×10^{-23} J/K), and T is the junction temperature (K).

$$\frac{qV_d}{kT} = \frac{1.602 \times 10^{-19}}{1.381 \times 10^{-23}} \cdot \frac{V_d}{T\,(\mathrm{K})} = 11{,}600\frac{V_d}{T\,(\mathrm{K})}$$

$$\Longrightarrow \qquad I_d = I_0\left(e^{38.9V_d} - 1\right) \quad (\text{at } 25^\circ\mathrm{C})$$

Open and Short Circuits



Electrical Characteristics of PV Cells

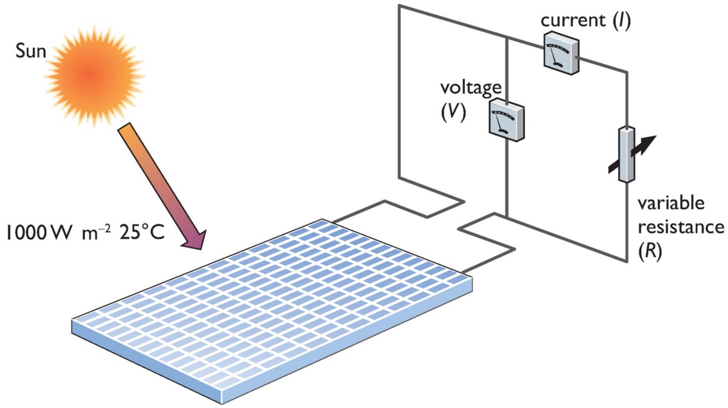
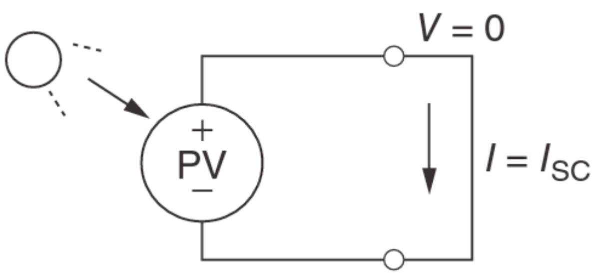
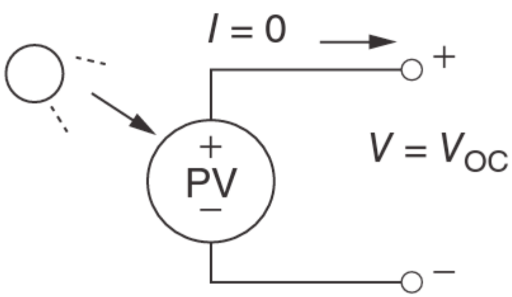


Figure: A PV cell connected to a variable resistance, with ammeter and voltmeter



(a) Short-circuit current



(b) Open-circuit voltage

$R = 0$

Short circuit current I_{sc}:

get maximum current in the circuit, which is proportional to solar intensity

$R \to \infty$

Open circuit voltage V_{oc}:

get maximum voltage across the cell

Example

Example 5.2 A p–n Junction Diode. Consider a p–n junction diode at 25°C with a reverse saturation current of 10^{-9} A. Find the voltage drop across the diode when it is carrying the following:

a. no current (open-circuit voltage)
b. 1 A
c. 10 A

Solution

a. In the open-circuit condition, $I_\mathrm{d} = 0$, so from Equation 5.5 $V_\mathrm{d} = 0$.
b. With $I_\mathrm{d} = 1$ A, we can find V_d by rearranging Equation 5.5:

$$V_\mathrm{d} = \frac{1}{38.9}\ln\left(\frac{I_\mathrm{d}}{I_0}+1\right) = \frac{1}{38.9}\ln\left(\frac{1}{10^{-9}}+1\right) = 0.532\ \mathrm{V}$$

c. With $I_\mathrm{d} = 10$ A,

$$V_\mathrm{d} = \frac{1}{38.9}\ln\left(\frac{10}{10^{-9}}+1\right) = 0.592\ \mathrm{V}$$

Equivalent Circuits for PV Cells

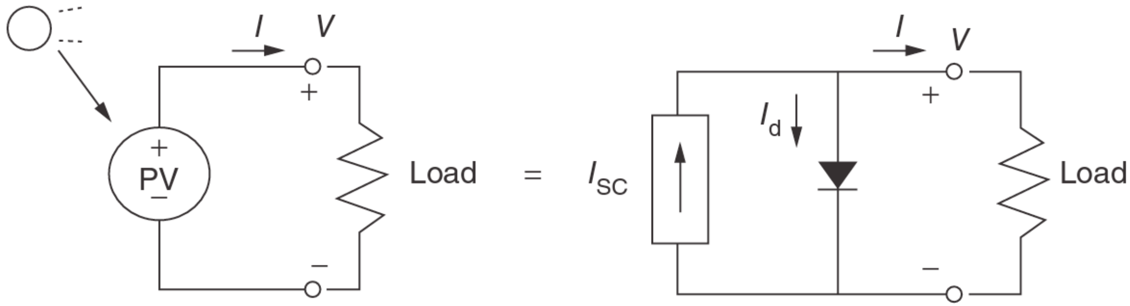


FIGURE 5.23 A simple equivalent circuit for a PV cell consists of a current source driven by sunlight in parallel with a real diode.

By KCL: $I = I_{SC} - I_d = I_{SC} - I_0\left(e^{qV/kT} - 1\right)$

$$\xrightarrow{\text{Set } I = 0} \quad \boxed{V_{OC} = \frac{kT}{q}\ln\left(\frac{I_{SC}}{I_0} + 1\right) \qquad \text{Equation 5.11}}$$

If $T = 25°\text{C} = 298.15°\text{K}$

$$I = I_{SC} - I_0\left(e^{38.9V} - 1\right)$$

$$V_{OC} = 0.0257\ \ln\left(\frac{I_{SC}}{I_0} + 1\right)$$

Example

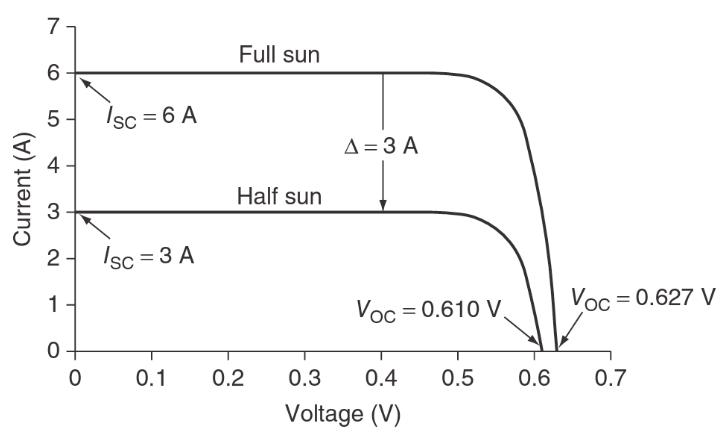
Example 5.3 The *I–V* Curve for a PV Cell. Consider a 150 cm^2 PV cell with reverse saturation current $I_0 = 10^{-12}$ A/cm^2. In full sun, it produces a short-circuit current of 40 mA/cm^2 at 25°C. What would be the short-circuit current and open-circuit voltage in full sun and again for 50% sun. Plot the resulting *I–V* curves.

Solution. The reverse saturation current $I_0 = 10^{-12}\ \text{A/cm}^2 \times 150\ \text{cm}^2 = 1.5 \times 10^{-10}$ A. At full sun short-circuit current, I_{SC}, is $0.040\ \text{A/cm}^2 \times 150\ \text{cm}^2 = 6.0$ A. From Equation 5.11, the open-circuit voltage for a single cell is

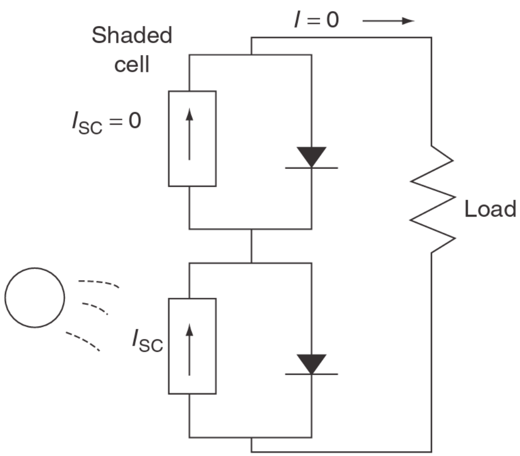
$$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{6.0}{1.5 \times 10^{-10}} + 1\right) = 0.627\ \text{V}$$

Since short-circuit current is proportional to solar intensity, at half sun $I_{SC} = 3$ A and the open-circuit voltage is

$$V_{OC} = 0.0257 \ln\left(\frac{3.0}{1.5 \times 10^{-10}} + 1\right) = 0.610\ \text{V}$$



More Accurate Equivalent Circuits for PV Cells



- No current through the load if one PV cell is shaded.
- The real situation is not that bad.
- More accurate model is needed!

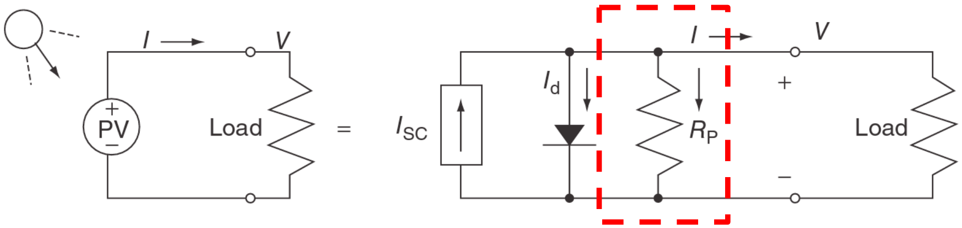
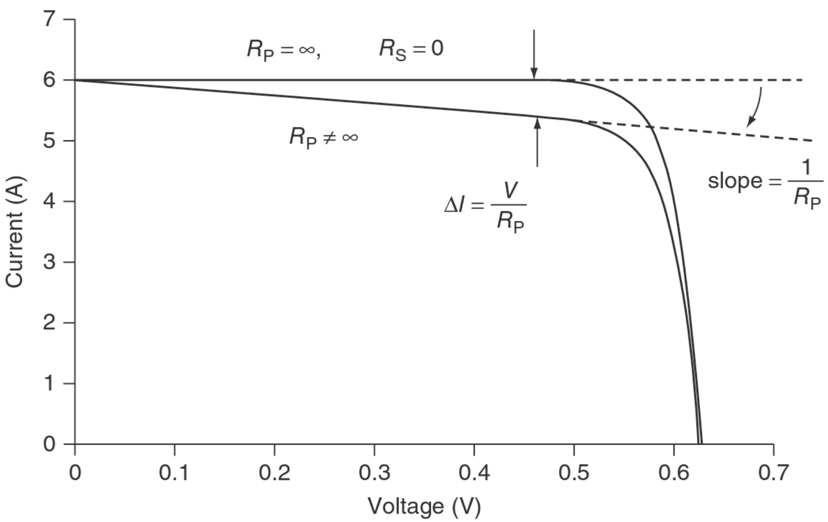


FIGURE 5.27 The simple PV equivalent circuit with an added parallel resistance.

$$I = (I_{SC} - I_d) - \frac{V}{R_P}$$

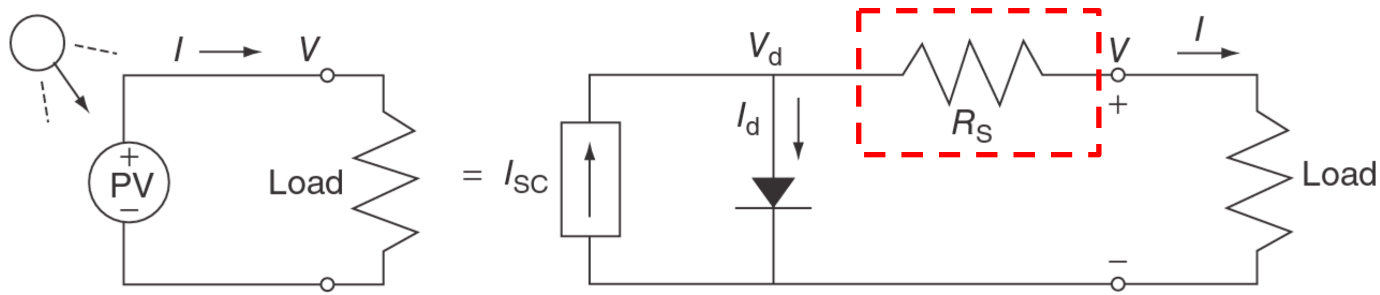
$$R_P > \frac{100 V_{OC}}{I_{SC}}$$



A PV Equivalent Circuit with Series Resistance

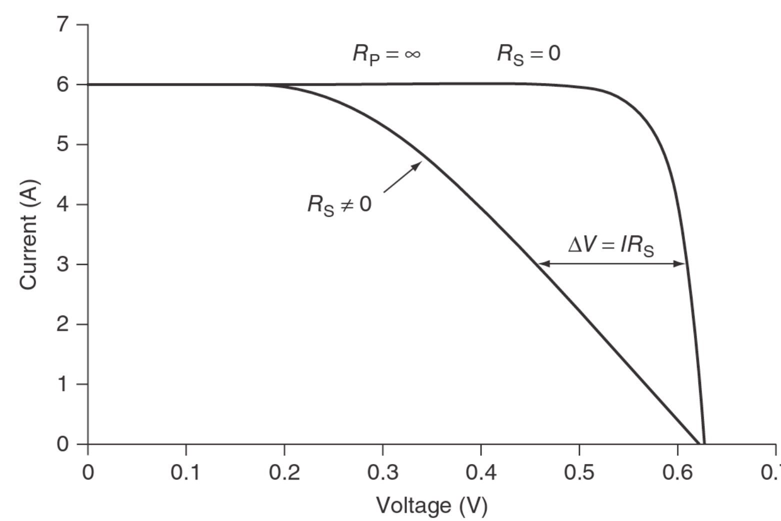
To model

- contact resistance associated with the bond between the cell and its wire leads.
- resistance of the semiconductor itself.

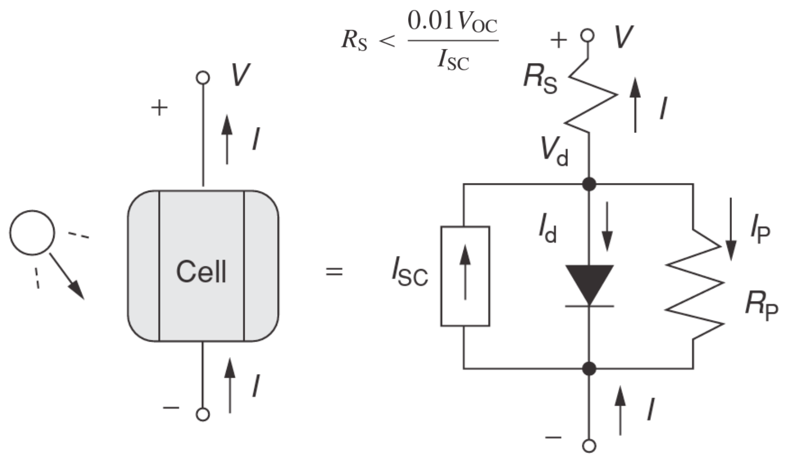


$$\begin{cases} I = I_{SC} - I_d = I_{SC} - I_0 \left(e^{qV_d/kT} - 1 \right) \\ V_d = V + IR_S \end{cases}$$

$$\Rightarrow I = I_{SC} - I_0 \left\{ \exp\left[\frac{q}{kT}(V + IR_S) \right] - 1 \right\}$$



Equivalent Circuit with Series/Parallel Resistances



By KCL & KVL:

$$\begin{cases} I_{SC} = I + I_d + I_P \\ V_d = V + IR_S \end{cases} \Rightarrow$$

$$I = I_{SC} - I_0 \left\{ \exp\left[\frac{q}{kT} (V + IR_S) \right] - 1 \right\} - \left(\frac{V + IR_S}{R_P} \right)$$

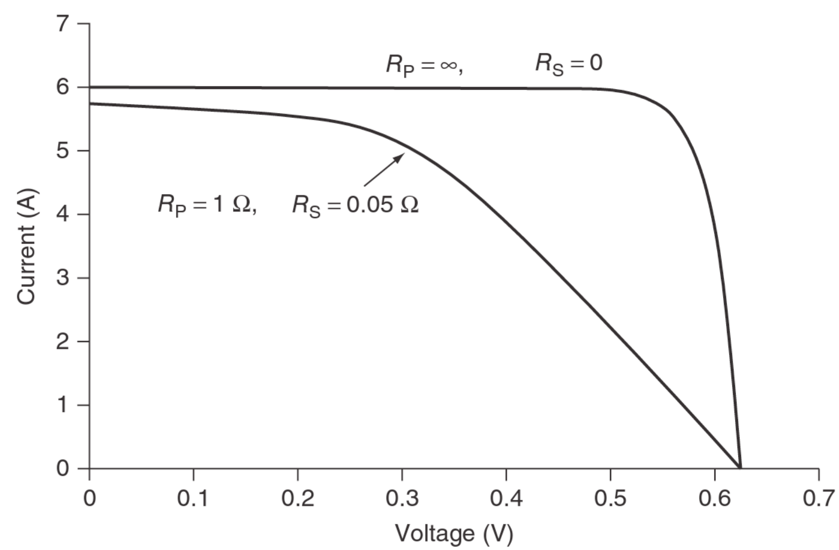
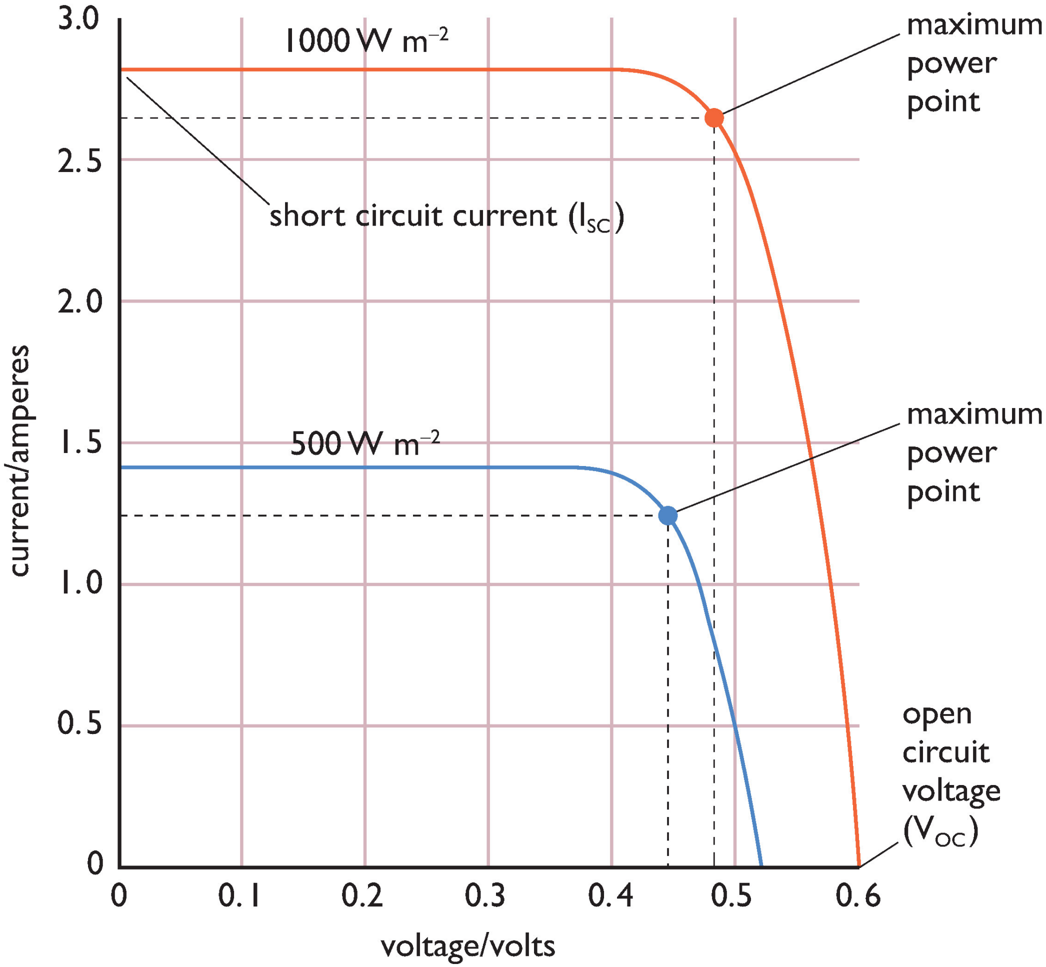


FIGURE 5.32 Series and parallel resistances in the PV equivalent circuit decrease both voltage and current delivered. To improve cell performance, high R_P and low R_S are needed.

Maximum Power Point



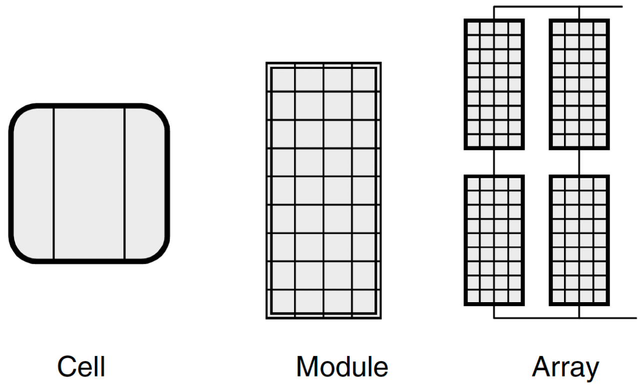
$I_{sc} \propto$ intensity of solar radiation

V_{oc} only changes slightly

We want the PV module to work at the maximum power point (MPP).

Many PV systems incorporate MPP tracking circuit.

From Cell to Module & Array



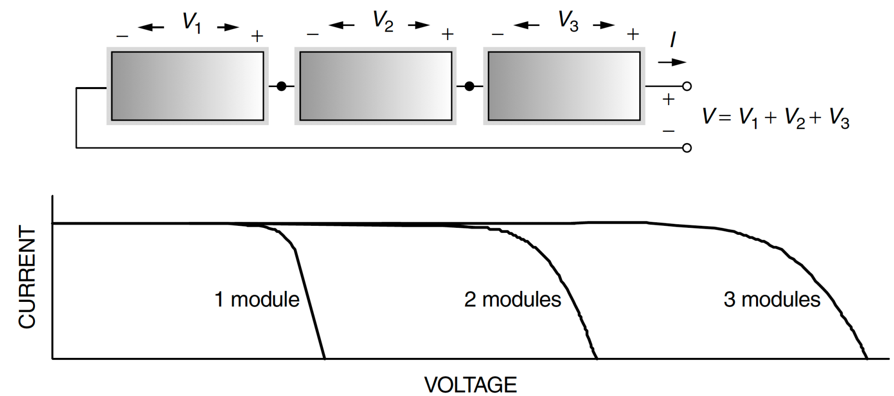


Fig-b: For modules in series, at any given current the voltages add.

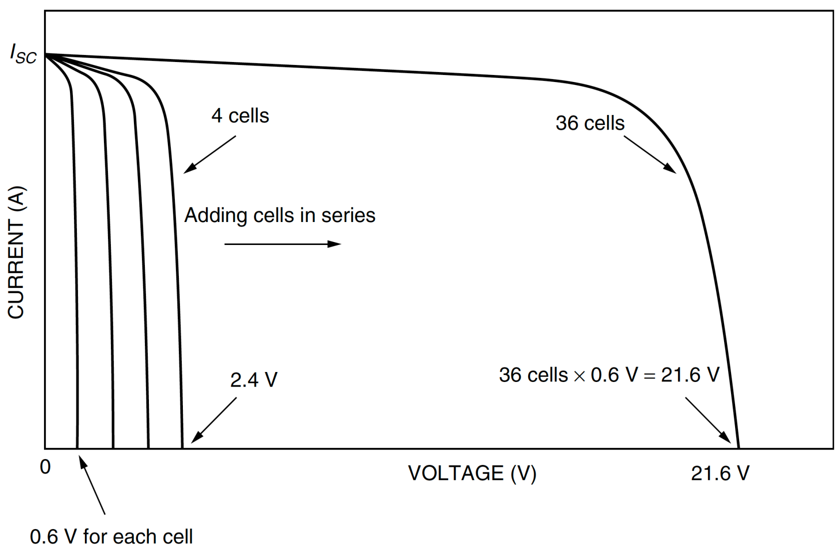


Fig-a: For cells wired in series, their voltages at any given current add: $V_{\text{module}} = n\,(V_{\text{d}} - IR_{\text{S}})$

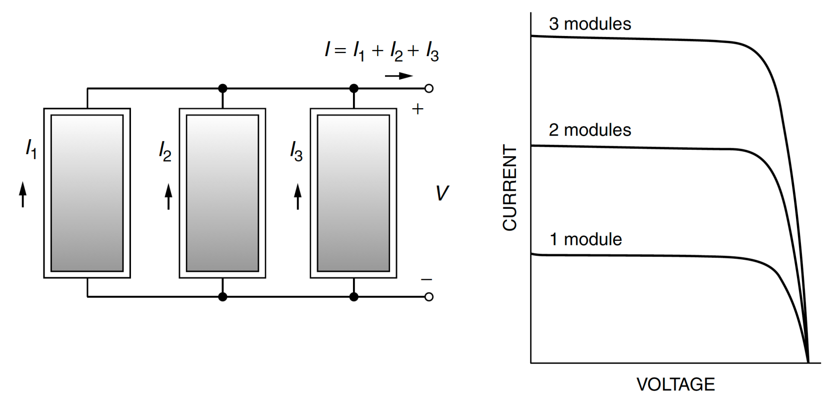
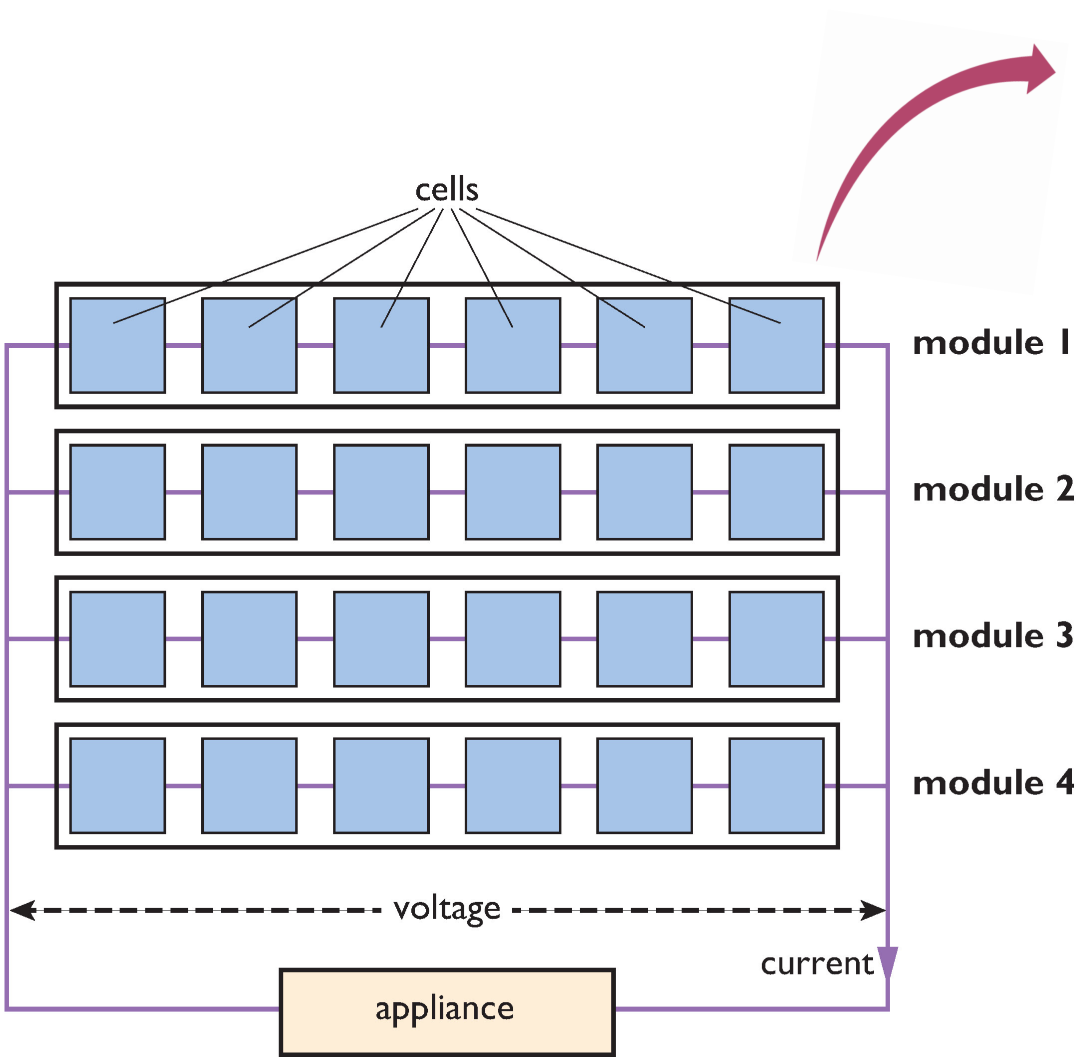


Fig-c: For modules in parallel, at any given voltage the currents add.

From Cell to Module and Array



- V_{tot} = # of cells x V_{cell}
- I_{tot} = # of modules x I_{module}

Example of PV Module

Example 5.4 Voltage and Current From a PV Module. A PV module is made up of 72 identical cells, all wired in series. With 1-sun insolation (1 kW/m^2), each cell has short-circuit current $I_{SC} = 6.0$ A and at 25°C, its reverse saturation current is $I_0 = 5 \times 10^{-11}$ A. Parallel resistance $R_P = 10.0\ \Omega$ and series resistance $R_S = 0.001\ \Omega$.

a. Find the voltage, current, and power delivered when the diode voltage in the equivalent circuit for each cell is 0.57 V.
b. Set up a spreadsheet for I and V of the entire module and present a few lines of output show how it works.

Solution

a. Using $V_d = 0.57$ V in Equation 5.19 along with the other data gives current

$$I = I_{SC} - I_0\left(e^{38.9V_d} - 1\right) - \frac{V_d}{R_P}$$

$$= 6.0 - 5 \times 10^{-11}\left(e^{38.9\times 0.57} - 1\right) - \frac{0.57}{10.0} = 5.73 \text{ A}$$

Under these conditions, Equation 5.21 gives the voltage produced by the 72-cell module:

$$V_{module} = n\,(V_d - IR_S) = 72\,(0.57 - 5.73 \times 0.001) = 40.63 \text{ V}$$

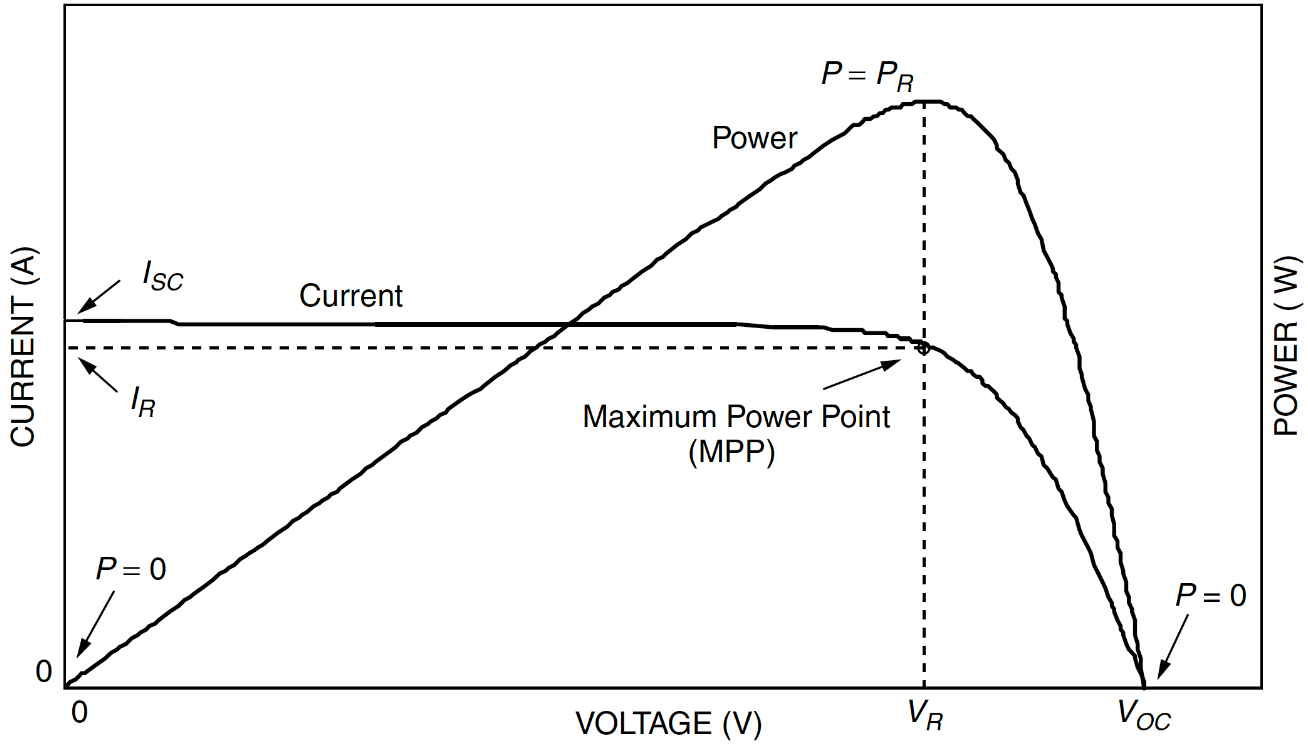
Power delivered is therefore

$$P(\text{Watts}) = V_{module}\, I = 40.63 \text{ V} \times 5.73 \text{ A} = 232.8 \text{ W}$$

Number of cells, n		72	
Parallel resistance/cell R_P (ohms)		10.0	
Series resistance/cell R_S (ohms)		0.001	
Reverse saturation current I_0 (A)		5E-11	
Short-circuit current at 1-sun (A)		6.0	
V_d	$I = I_{SC} - I_0\left(e^{38.9V_d} - 1\right) - V/R_p$	$V_{module} = n\,(V_d - IR_S)$	$P(W) = V \times I$
0.53	5.9020	37.735	222.7
0.54	5.8797	38.457	226.1
0.55	5.8471	39.179	229.1
0.56	5.7996	39.902	231.4
0.57	**5.7299**	**40.627**	**232.8**
0.58	5.6276	41.355	232.7
0.59	5.4771	42.086	230.5
0.60	5.2555	42.822	225.0

Note that we have found the maximum power point (MPP) for this module, which is at $I = 5.73$ A, $V = 40.627$ V, and $P = 232.8$ W. This could be described as a 233-W module. It would be easy to draw the entire I–V curve from this spreadsheet.

Fill Factor



$$\text{Fill factor (FF)} = \frac{\text{Power at the maximum power point}}{V_{OC}\ I_{SC}} = \frac{V_R I_R}{V_{OC} I_{SC}}$$

FF: around 70–75% for crystalline silicon solar modules
closer to 50–60% for multi-junction amorphous-Si modules

Maximum Power Point

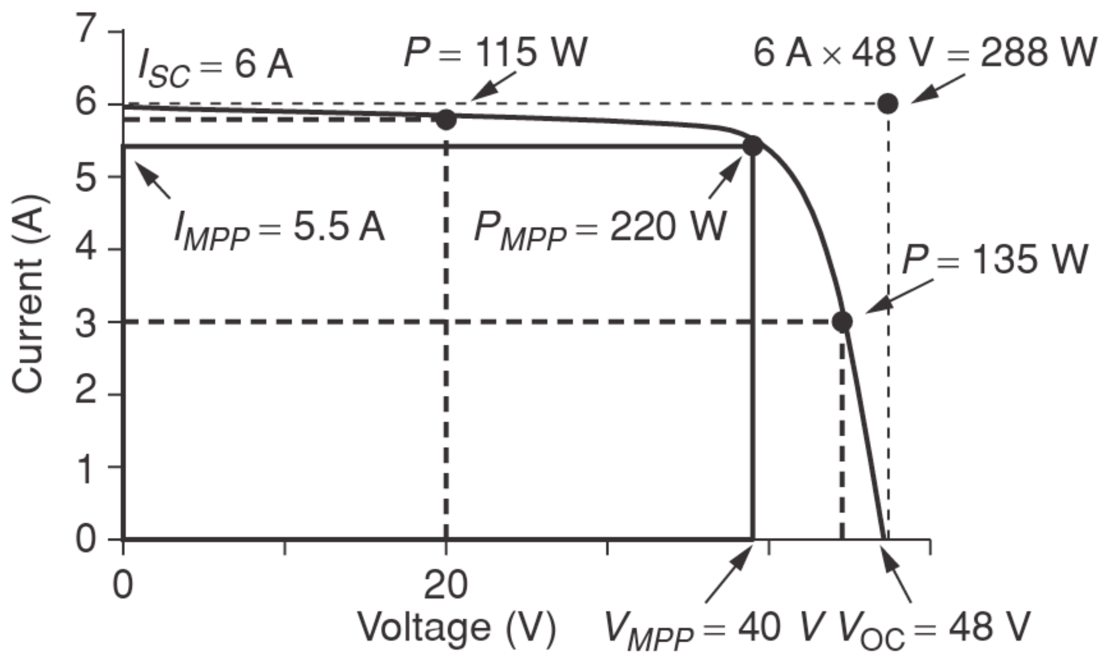


FIGURE 5.41 The maximum power point (MPP) corresponds to the biggest rectangle that can fit beneath the *I*–*V* curve. The fill factor (FF) is the ratio of the area (power) at MPP to the area formed by a rectangle with sides V_{OC} and I_{SC}.

$$\text{Fill factor} = \frac{40\text{V} \times 5.5\text{A}}{48\text{V} \times 6\text{A}} = \frac{220\text{W}}{288\text{W}} = 0.76$$

Impacts of Temperature & Insolation

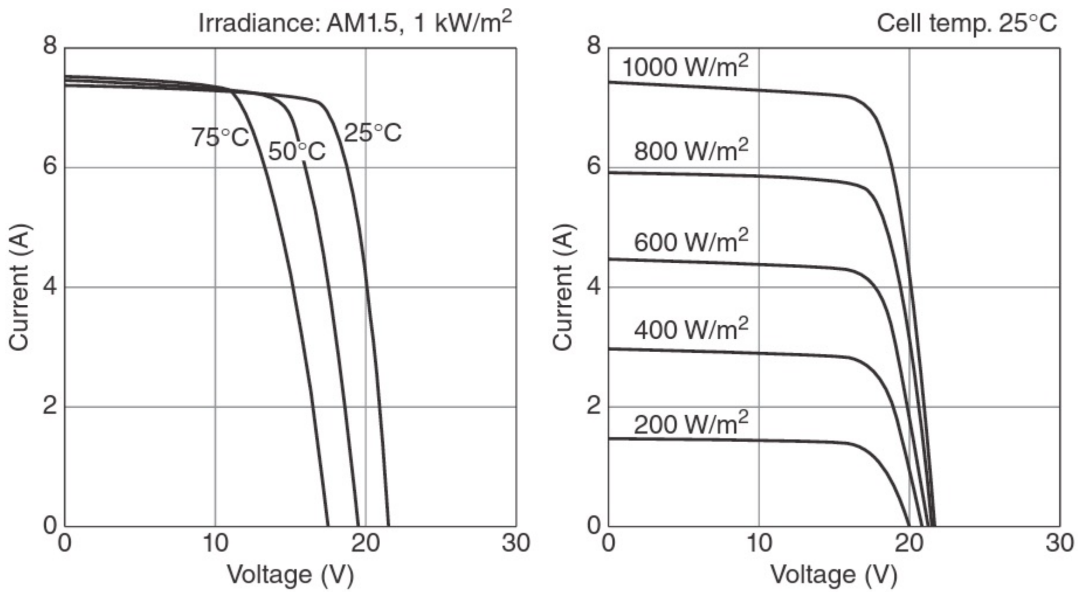


Fig: I-V curves under various cell temperatures and irradiance levels for the Kyocera KC120-1 PV module.

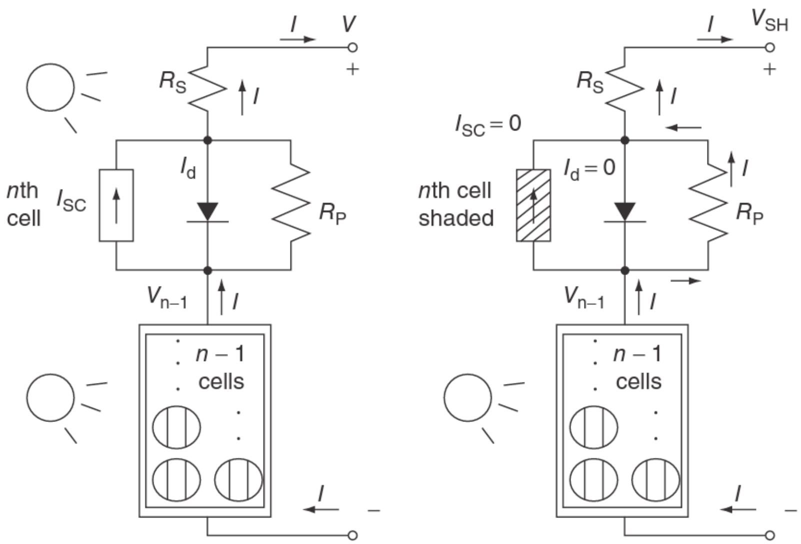
$$T_{\text{cell}} = T_{\text{amb}} + \left(\frac{\text{NOCT} - 20^\circ}{0.8}\right) \cdot S$$

NOCT: nominal operating cell temperature

where T_{cell} is cell temperature (°C), T_{amb} is ambient temperature, and S is solar insolation (kW/m^2).

Shading Impact: Voltage Drop

Even a small fraction of a single module is shaded, the performance of an entire string of modules can be compromised.



(a) All cells in the sun
(b) Top cell shaded

$$V_{SH} = V_{n-1} - I\,(R_P + R_S)$$

$$= \left(\frac{n-1}{n}\right) V - I\,(R_P + R_S)$$

$$\Delta V = V - V_{SH} = V - \left(1 - \frac{1}{n}\right) V + I\,(R_P + R_S)$$

$$= \frac{V}{n} + I\,(R_P + R_S) \qquad \text{Equation 5.29,}$$

$$\cong \frac{V}{n} + I \cdot R_P \qquad (R_P \gg R_S)$$

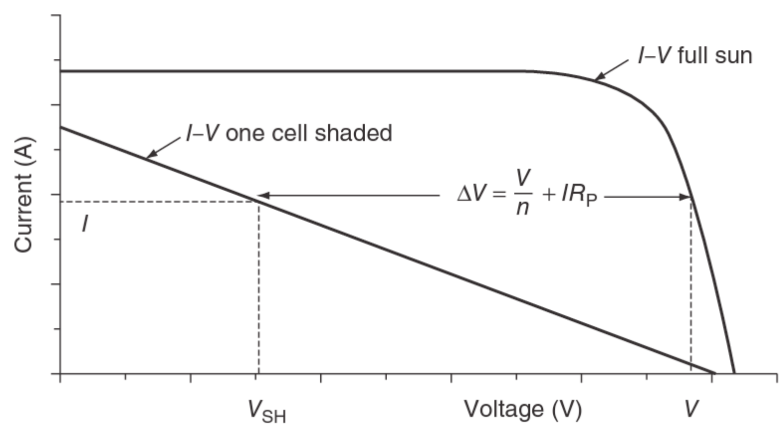


FIGURE 5.44 Effect of shading one cell in an n-cell module. At any given current, module voltage drops from V to $V - \Delta V$.

Example

Example 5.6 Impacts of Shading on a PV Module. The 72-cell PV module described in Example 5.4 had a parallel resistance per cell of $R_P = 10.0\ \Omega$ and a series resistance R_S of $0.001\ \Omega$. In full sun and at current $I = 5.73$ A, the output voltage of the module was found to be $V = 40.63$ V. If one cell is shaded, find the following if somehow the same 5.73 A is forced to flow through the module.

a. The module output voltage.
b. Power dissipated in the shaded cell.

Solution

a. From Equation 5.29, the drop in module voltage will be

$$\Delta V = \frac{V}{n} + I\,(R_P + R_S) = \frac{40.63}{72} + 5.73 \times (10.0 + 0.001) = 57.87\ \text{V}$$

(obviously, we could have ignored R_S).

The module output voltage will now be $40.63 - 57.87 = -17.24$ V

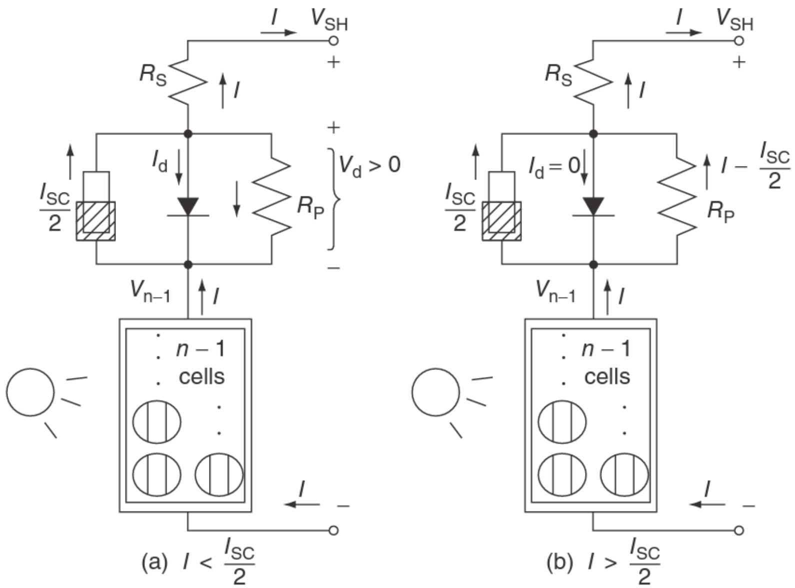
(Yes, this is possible. For example, if this module with one shaded cell is part of a string of modules and the good ones are trying to drive 5.73 A through the whole string, then it would be better to completely remove that shaded module from the string than to leave it in place!)

b. Since that 5.73 A flows through both R_S and R_P, the power dissipated in that shaded cell will be

$$P = I^2\,(R_P + R_S) = (5.73)^2\,(10.0 + 0.001) = 69.7\ \text{W}$$

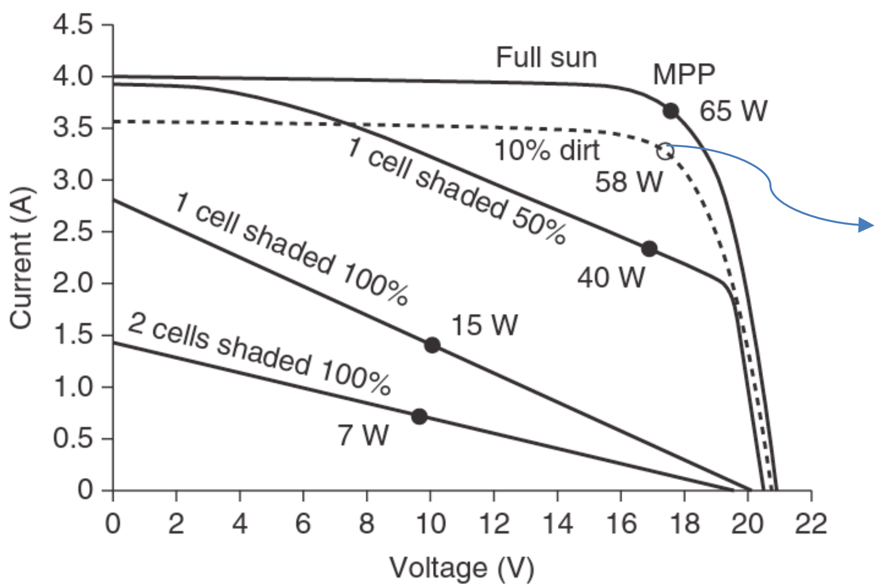
All of that power dissipated in the shaded cell is converted to heat, which can cause a local hot spot that may permanently damage the plastic laminates enclosing the cell.

Partial Shading Impacts on I-V Curves



(a) if $I < I_{SC}/2$, the diode still conducts with 1 cell half-shaded

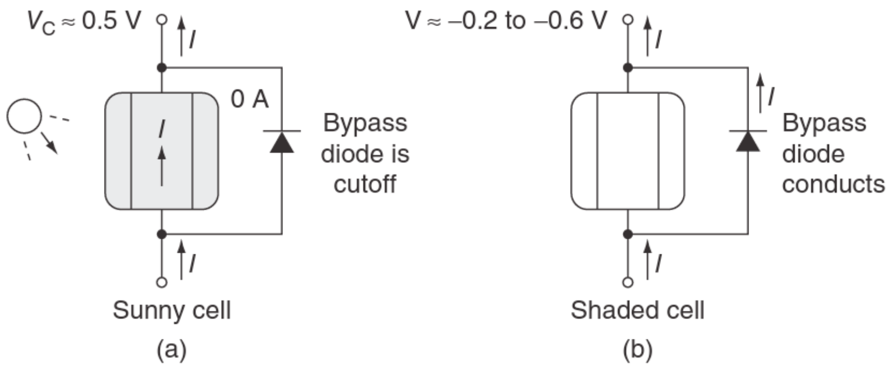
(b) if $I > I_{SC}/2$, the diode shuts off, and current passes through R_P in an opposite direction which can result in large voltage drop in V_{SH}.



Uniformly distributed dirt.

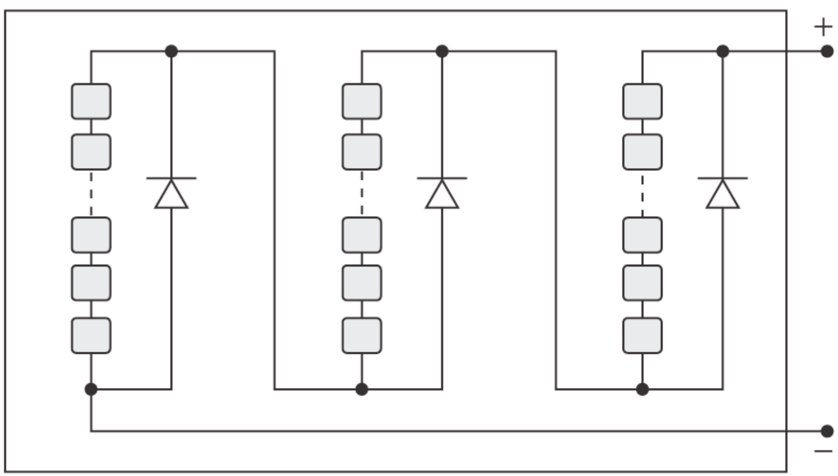
When modules get dirty, the I-V curve shifts downward just the way it would if the Sun were a bit less intense.

Shade Mitigation: Bypass Diodes

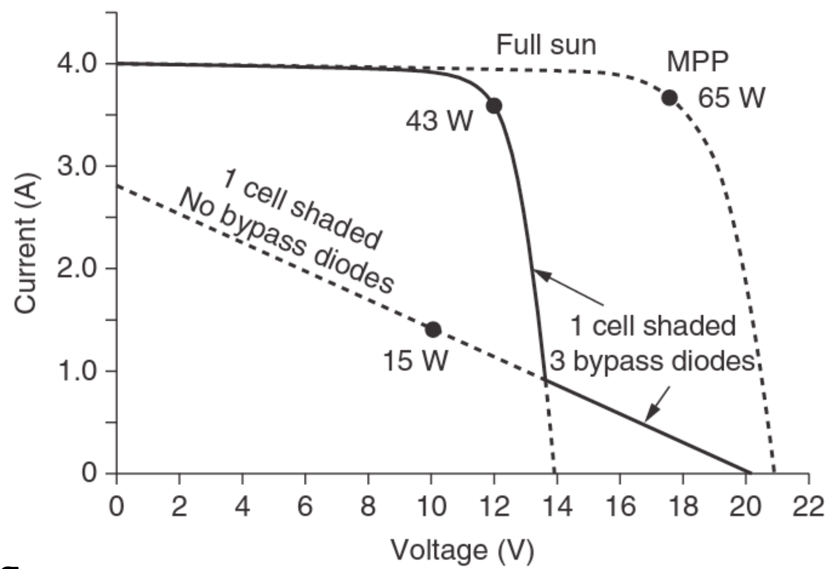


(a) Bypass diode is cut off due to the voltage rise across the cell in the Sun

(b) When the cell is shaded, the current is diverted to flow through the diode, which limits the voltage drop to 0.2~0.6V, rather than a large drop if there is no bypass diode.



3 bypass diodes, each covering 1/3 of the string



Bypass Diodes (cont’d)

Bypass diodes help current go around a shaded/malfunctioning module within a string. This

1. improves the string performance
2. prevents hot spots from developing in individual shaded cells

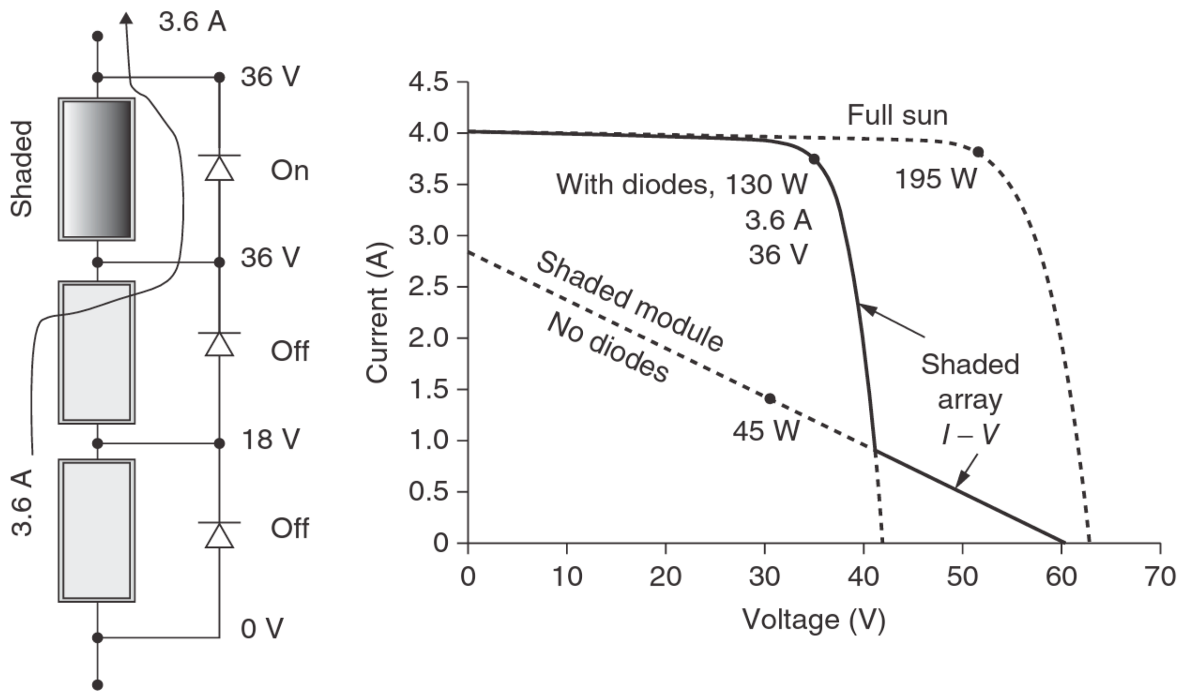
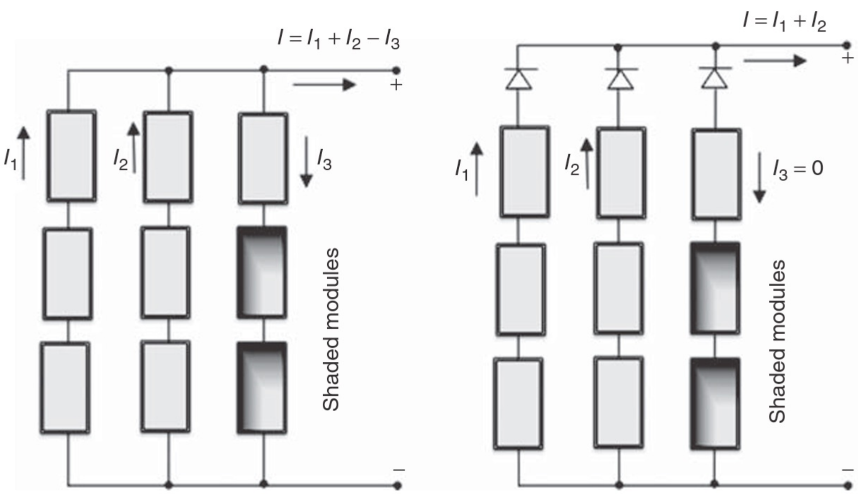
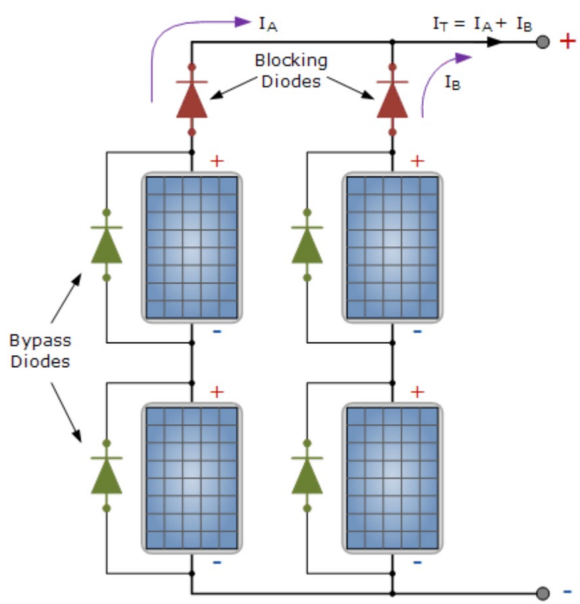


FIGURE 5.50 Showing the ability of bypass diodes to mitigate shading problems in a string of modules.

Shade Mitigation: Blocking Diodes



(a) Without blocking diodes (b) With blocking diodes



A malfunctioning or shaded string can withdraw current from the rest of the array.

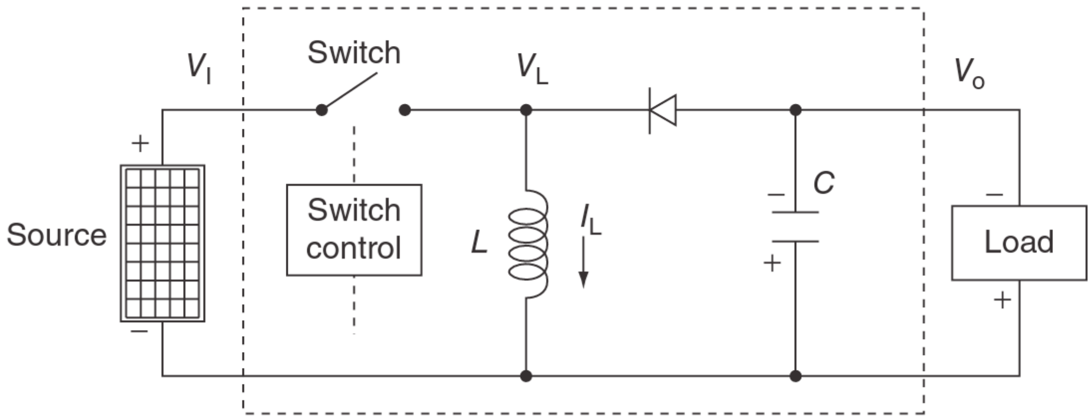
Adding blocking diodes at the top of each string can prevent

- the current generated by the other parallel connected PV panels in the same array flowing back through a weaker (shaded) network
- the fully charged batteries from discharging or draining back through the array at night.

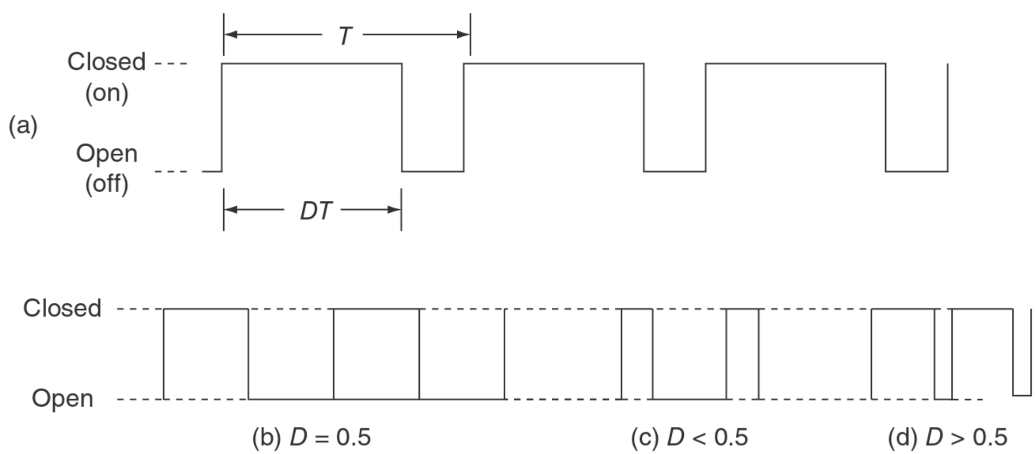
https://www.electronics-tutorials.ws/diode/bypass-diodes.html

Maximum Power Point Tracker (MPPT)

The key of MPPTs is to convert DC voltages from one level to another



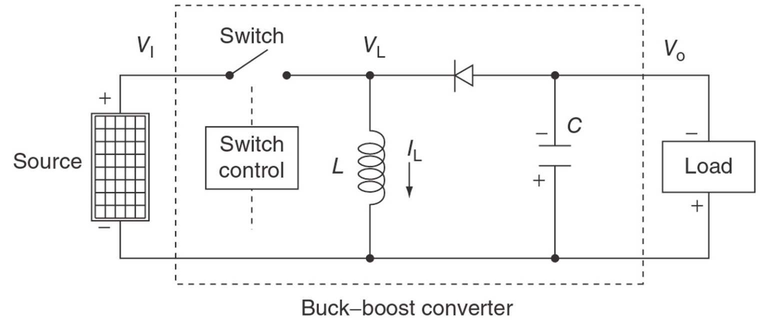
Buck–boost converter



- The transistor switch flips on and off at a rapid rate (on the order of 20 kHz) under some sensing/controlling signals and logic algorithms.
- Two insights with fast switching: I_L and V_O are essentially constant!
- Duty cycle: the fraction of the time when the switch is closed.

Change DC Voltage Levels

Analysis is based on the energy balance for the magnetic field of the inductor:



The average power put into the magnetic field of the inductor:

$$\bar{P}_{L,\,\mathrm{in}} = \frac{1}{T}\int_0^{DT} V_{\mathrm{i}} I_{\mathrm{L}} \mathrm{d}t \;= V_{\mathrm{i}} I_{\mathrm{L}} D$$

When the switch opens, the magnetic field begins to collapse, and starting supporting the load. The average power delivered:

$$\bar{P}_{L,\,\mathrm{out}} = \frac{1}{T}\int_{DT}^{T} V_{\mathrm{L}} I_{\mathrm{L}} \mathrm{d}t = \frac{1}{T}\int_{DT}^{T} V_{\mathrm{o}} I_{\mathrm{L}} \mathrm{d}t \;= V_{\mathrm{o}} I_{\mathrm{L}} (1-D)$$

$$\Longrightarrow \boxed{\frac{V_{\mathrm{o}}}{V_{\mathrm{i}}} = -\left(\frac{D}{1-D}\right)}$$

$$D = \frac{1}{2} \to V_o = V_i, \quad D = \frac{2}{3} \to V_o = 2V_i, \quad D = \frac{1}{3} \to V_o = \frac{1}{2}V_i.$$

Example

Example 5.7 Duty Cycle for a MPPT. Under certain ambient conditions, a particular PV module has its maximum power point at $V_{\mathrm{m}} = 30$ V and $I_{\mathrm{m}} = 6$ A. What duty cycle should be provided to a buck–boost converter if the module is to deliver 12 V to charge a battery? How many amperes would be delivered to the battery? If the ambient were to cool off some without a change in insolation, should the duty cycle be increased or decreased?

Solution. $$\frac{12}{30} = \left(\frac{D}{1 - D}\right) = 0.4 \quad \Longrightarrow \quad D = \frac{0.4}{1.4} = 0.286$$

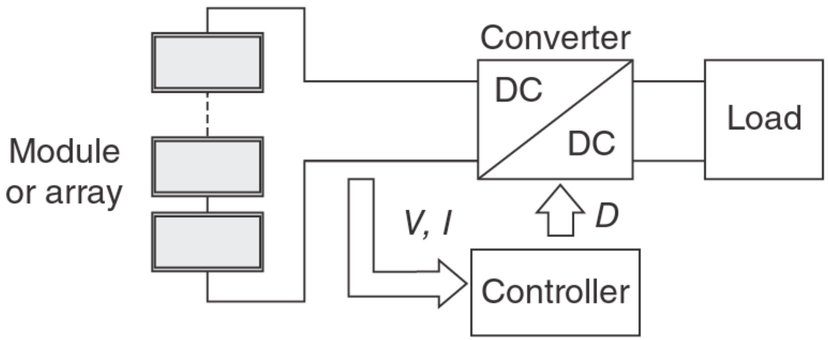
Since we will assume a 100% efficient converter, input power equals output power so that

$$V_{\mathrm{PV}} \cdot I_{\mathrm{PV}} = V_{\mathrm{Battery}} \cdot I_{\mathrm{Battery}}$$

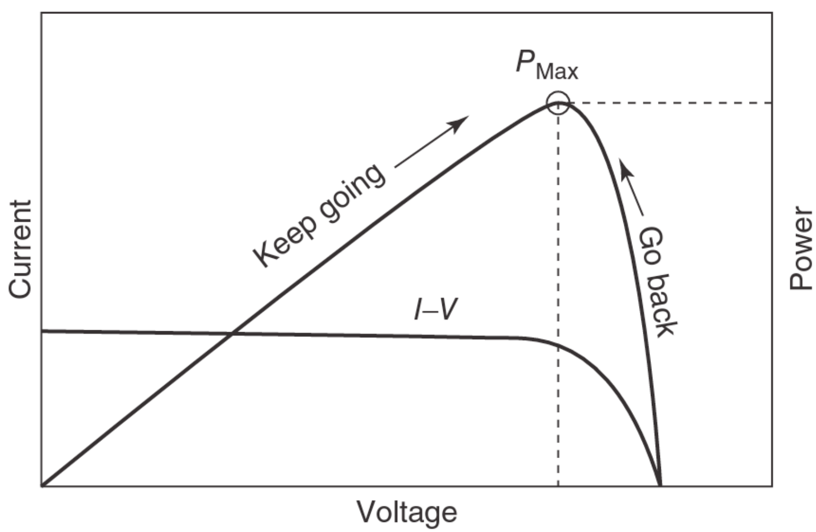
$$I_{\mathrm{Battery}} = \frac{30\mathrm{V} \cdot 6\mathrm{A}}{12\mathrm{V}} = 15\mathrm{A}$$

With cooler temperatures, the PV voltage at the MPP increases somewhat (e.g., see Fig. 5.35) so the duty cycle D should be decreased a bit.

MPPT Controllers



MPPT needs to know how to adjust D to keep the voltage on its MPP. This is achieved by a control unit.



$$\text{At the MPP: } \frac{\mathrm{d}P}{\mathrm{d}V} = 0$$

$$\frac{\mathrm{d}P}{\mathrm{d}V} = I\frac{\mathrm{d}V}{\mathrm{d}V} + V\frac{\mathrm{d}I}{\mathrm{d}V}$$

$$= I + V\frac{\mathrm{d}I}{\mathrm{d}V} \approx I + V\frac{\Delta I}{\Delta V}$$

$$\Rightarrow \text{At the MPP : } \boxed{\frac{\Delta I}{\Delta V} = -\frac{I}{V}}$$

Incremental Conductance MPP Method