Energia Fotovoltaica

Parte III - Sistemas Fotovoltaicos e Rastreamento do Ponto de Máxima Potência

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Bypass Diode Impact on Module

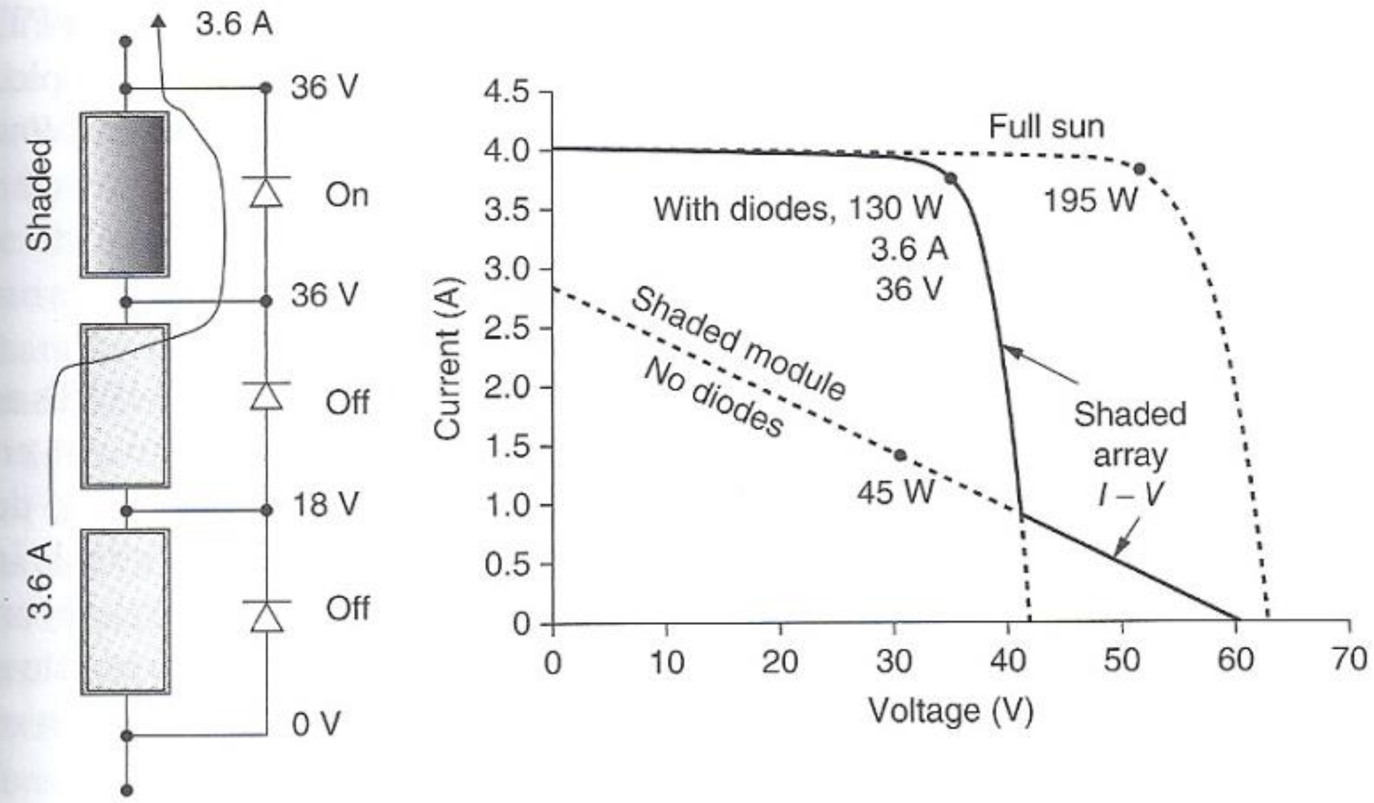
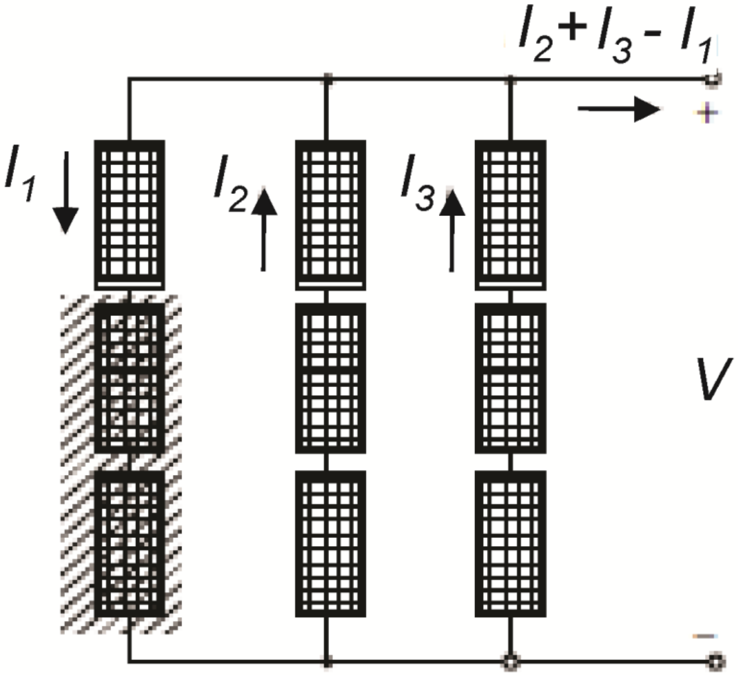


FIGURE 5.50 Showing the ability of bypass diodes to mitigate shading problems in a string of modules.

Bypass diodes also prevent overheating of shaded cells

Blocking Diodes

- Consider strings wired in parallel, where one string is in the shade (or defective);
- We want to prevent current from being ***drawn*** instead of supplied by that string:



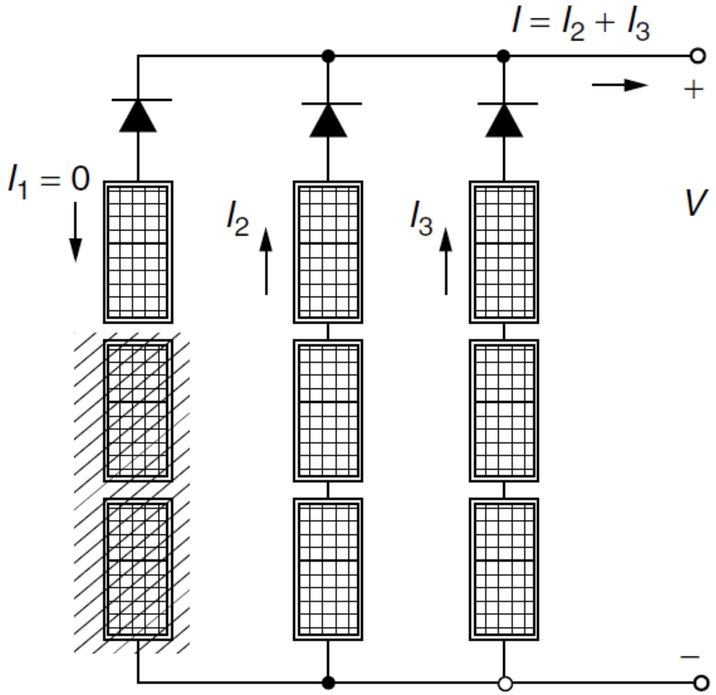
Without blocking diodes

Some current would flow in direction I_1!

Blocking Diodes

- Solution – blocking diode at the top of each string;
- Forward biased during normal operation, reverse biased when the string is shaded;

- Since they are conducting during normal operation, they cause an output voltage drop of ~0.6 V



With blocking diodes

PV and Dust

- Dust can degrade the performance of a PV system, sometimes *rather significantly* (> 15%);
- How much dust settles on a PV panel depends on a number of characteristics:
  - Amount of dust in the environment, humidity, wind, rain, *tilt of the panel*, panel surface finish, how often it is cleaned
  - Dust attracts dust!
- Dust can be reduced by: 1) manual cleaning (but this requires water and can be time consuming); 2) surface treatments; 3) electrostatic charge using surface material to repel dust; 4) robots.

PV and Dust: Robots Cleaning the Panels

The below image shows a robot cleaning solar panels using a water-free approach:


Ecoppia - Robotic Solar Cleaning Solution

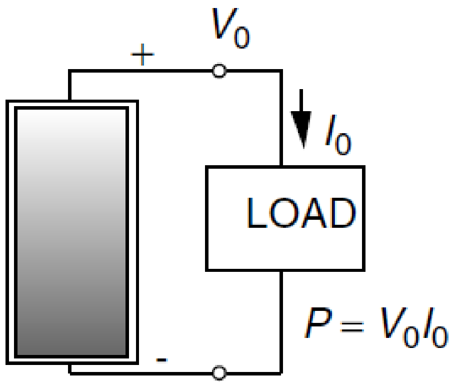
Image: http://www.ecoppia.com/solution/ketura-sun

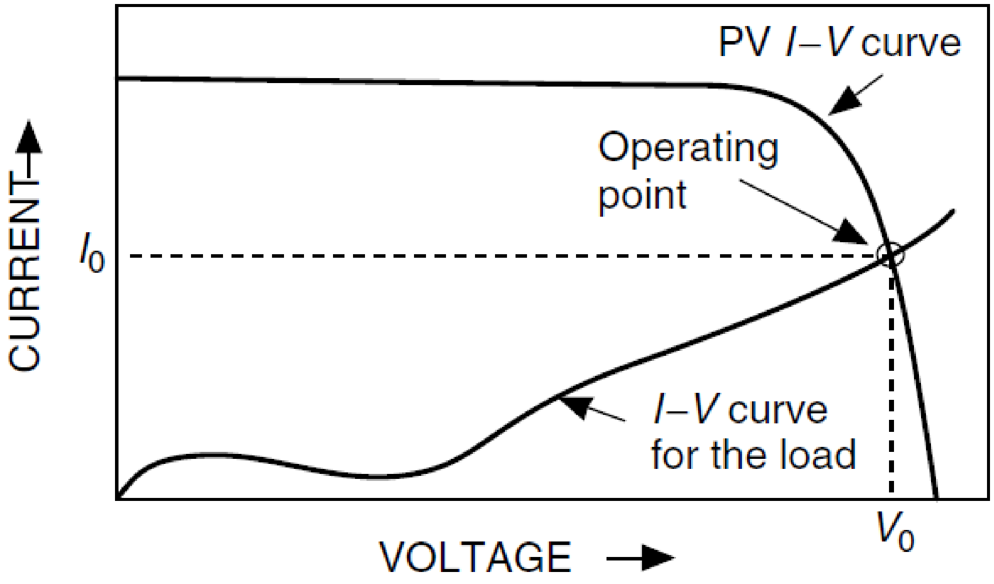
Current-Voltage Curves for Loads

- The *I*-*V* curve for PV defines the combinations of *I* and *V* permissible under existing ambient conditions;
- However, it does not tell anything about 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;
- Loads have their own *I*-*V* curves: when plotted onto the same graph of PVs, the intersection defines the operation point.

PV and Load I-V Curves

- The same voltage is across PVs and load, and the same current runs through them ⇒ The intersection point is where both PVs and load are satisfied.





Resistive Loads

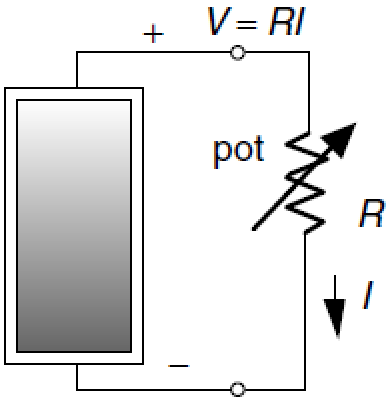
- The characteristic of a resistive load is

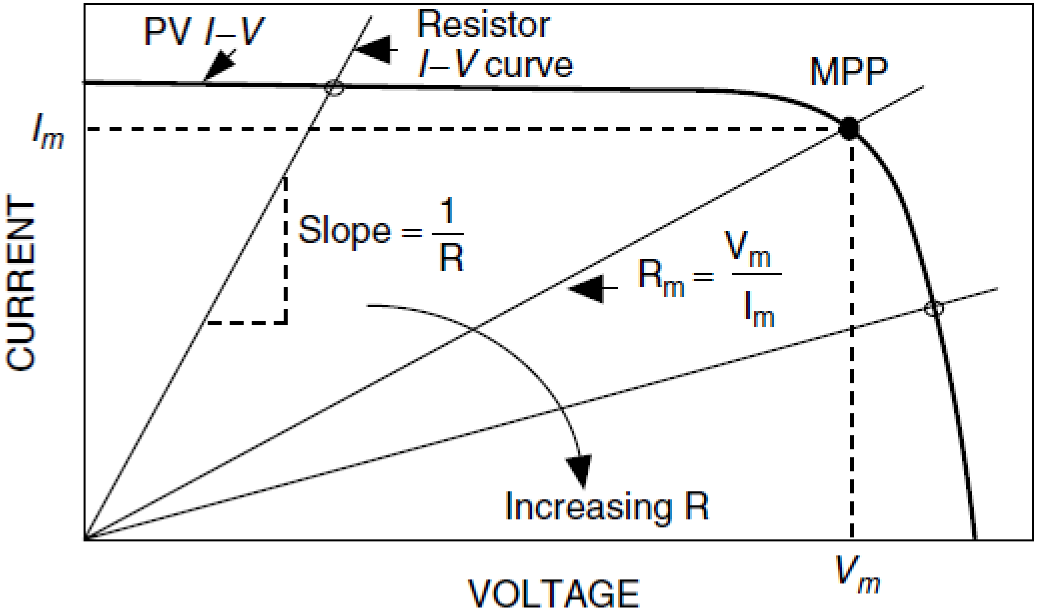
$$I = \left(\frac{1}{R}\right) V$$

- When plotted on $I \times V$ axes, this is a straight line with slope *1/R*;
- As *R* changes, the operating point where PV and load curves intersect moves along the PV *I-V*;
- This suggests a way to measure the PV *I-V* curve: by using a potentiometer as load and then varying its resistance.

Resistive Loads (cont'd)

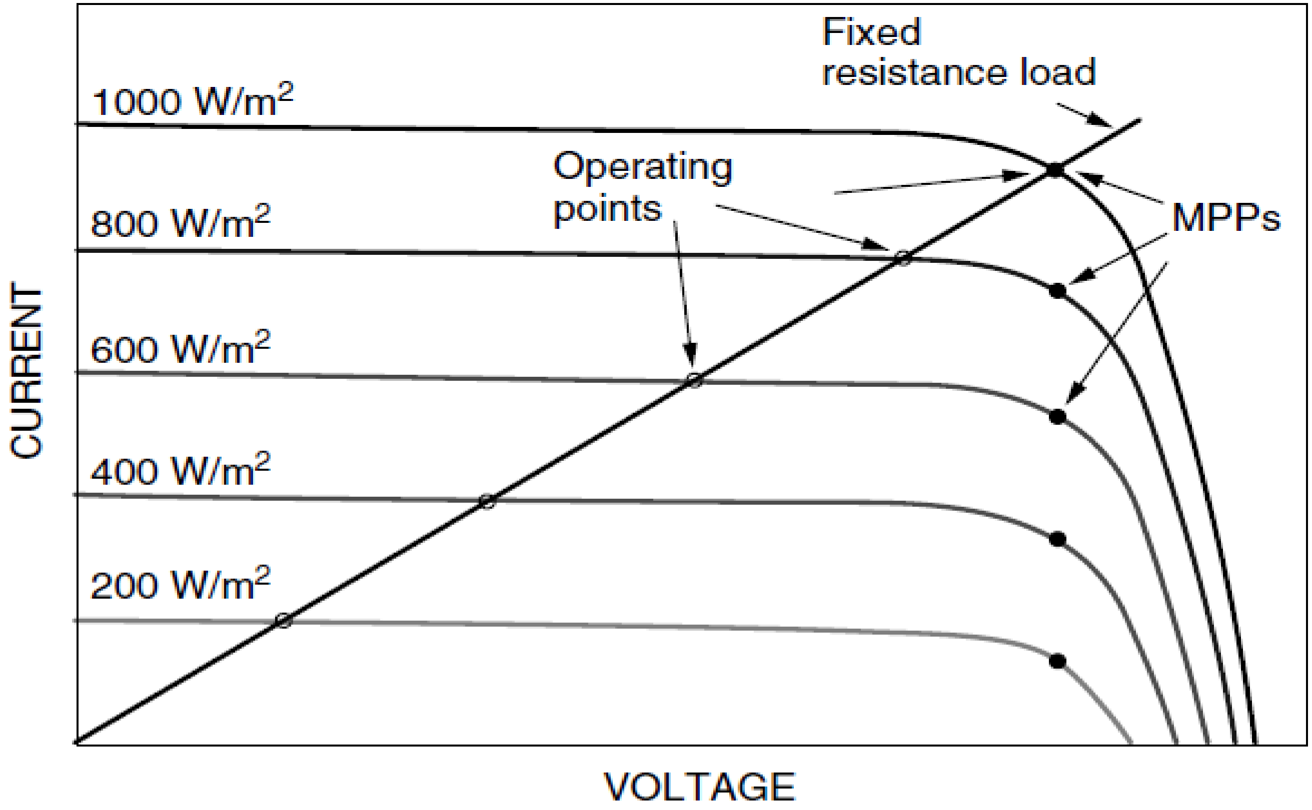
- As *R* increases, the operating point moves along the PV *I-V* curve from left to right;
- There is a particular *R* value, R_m , that results in max. power: the ***MPP***, whose coordinates are V_m and I_m ;
- Thus, the optimum *R* for max. power transfer is V_m/I_m under 1-sun, 25° C, AM 1.5.





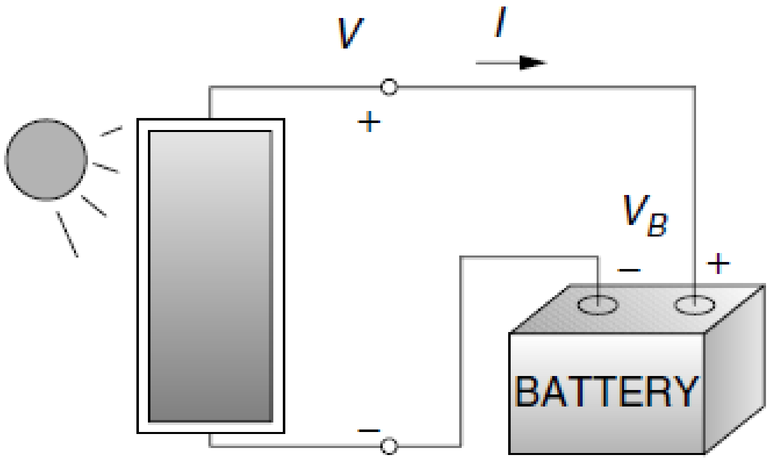
Resistive Loads (cont'd)

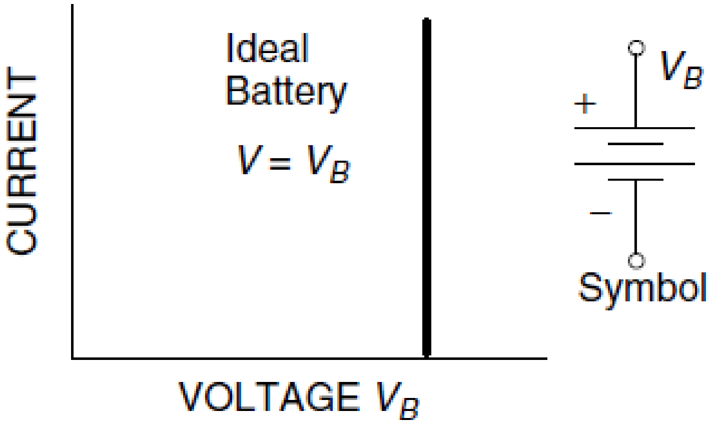
- However, with a fixed *R* the operating point slips off the MPP as conditions change ⇒ need of a MPP tracker (MPPT).



Battery *I-V* Curves

- PV systems are often employed for battery charging;
- Ideal battery: voltage remains constant no matter how much current is drawn:

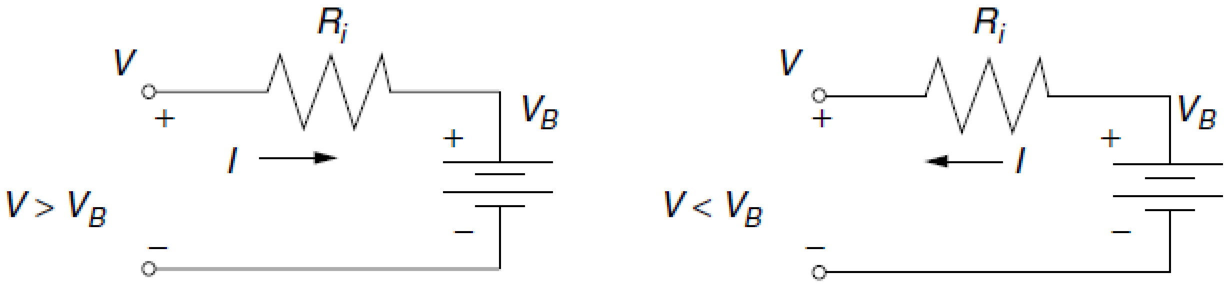




Battery *I-V* Curves (cont'd)

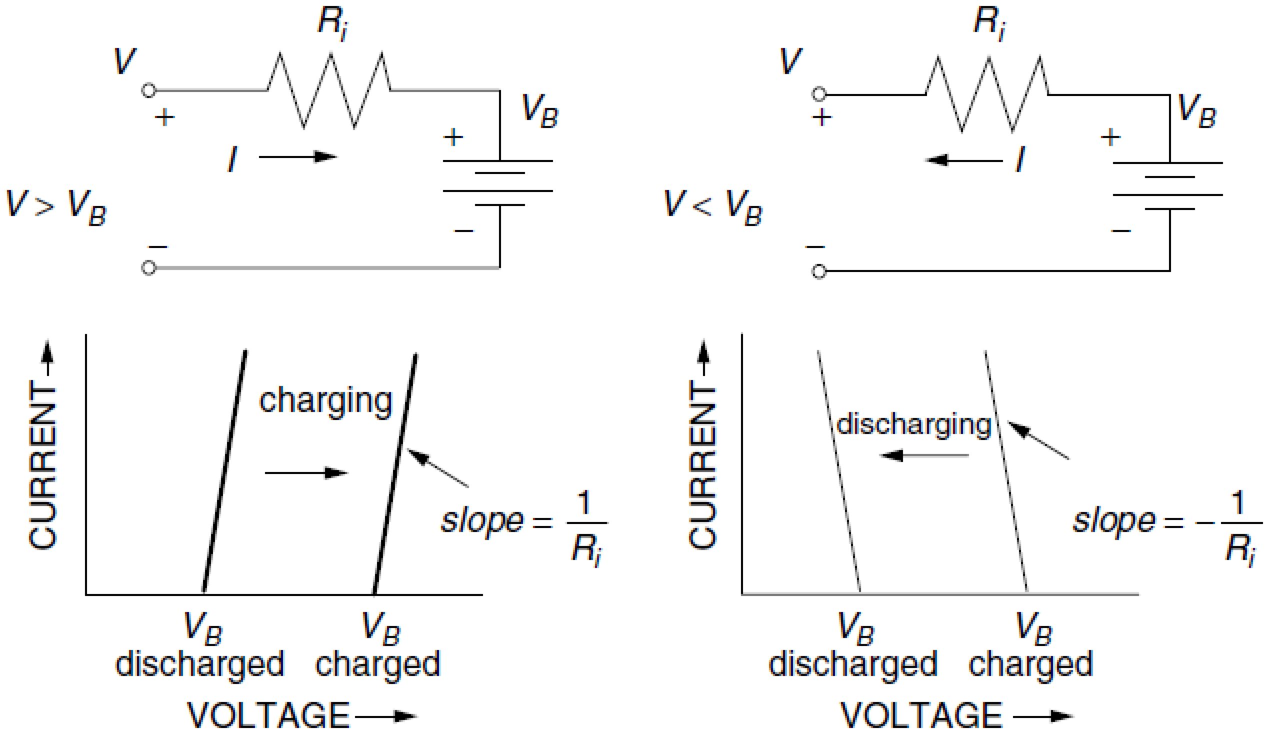
- A real battery has some internal resistance;
- Modeled as equiv. circuit consisting of an ideal batt. of voltage V_B in series with internal resistance R_i :

$$V = V_B + R_i I$$



Battery *I-V* Curves (cont'd)

- *I-V* battery curves: slightly-tilted straight lines with slope $1/R_i$
- Slope orientation for charge/discharge is distinct:

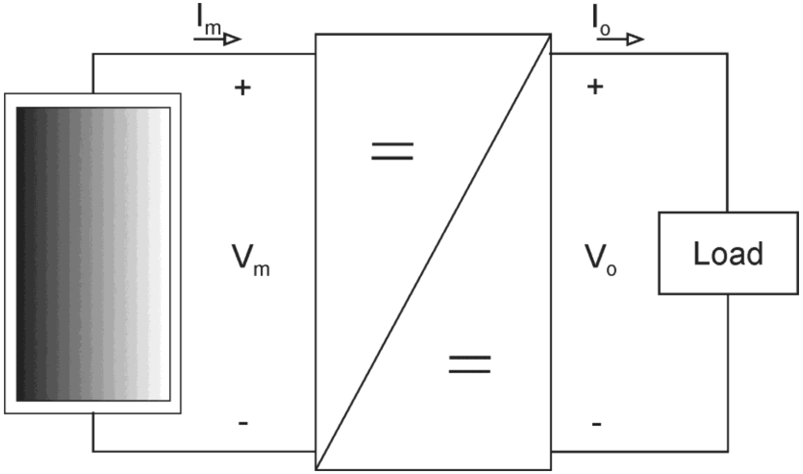


Maximum Power Point Trackers

- Maximum Power Point Trackers (MPPTs) are often a standard part of PV systems, especially grid-connected;
- Idea is to keep the operating point near the knee of the PV system's I-V curve;
- Buck-boost converter - a DC-to-DC converter - can either "buck" (lower) or "boost" (raise) the voltage;
- Varying the duty cycle of a buck-boost converter can be done such that the PV system will deliver the maximum power to the load.

DC-DC Converters

- PV operational goal is often to operate at the maximum power point. This requires that the apparent load resistance vary as the operating conditions vary;
- We want a design such that the output characteristics of the PV can be specified independently from the load, ideally with 100% efficiency;

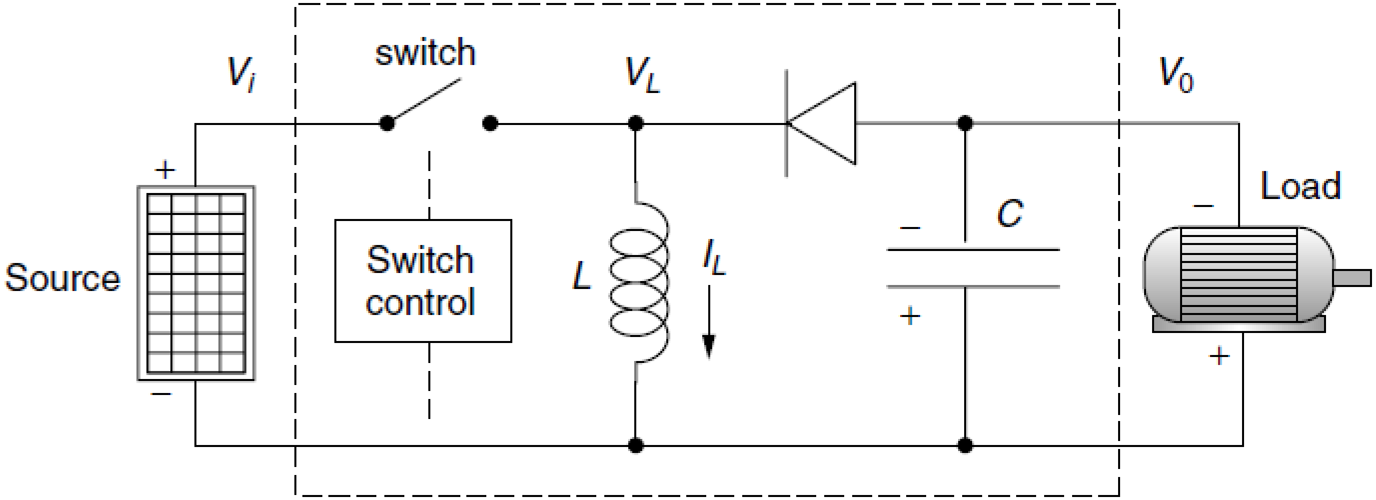


- This requires a dc-dc converter;
- Several dc-dc converter topologies: Buck, Boost, Buck-Boost.

DC-DC Converters

- DC-DC converters are able to convert DC voltages from one level to another;
- They became feasible after field-effect transistors (*FETs*) became available in the 1980s and insulated-gate bipolar transistors (*IGBTs*) in the 1990s;
- Converters make use of inductors and capacitors as energy storage devices;
- *Boost converter:* circuit used to *step up* DC voltages;
- *Buck converter:* always decreases the voltage.
- *Buck-boost converter:* may raise or lower DC voltage.

Buck-boost DC-DC Converter

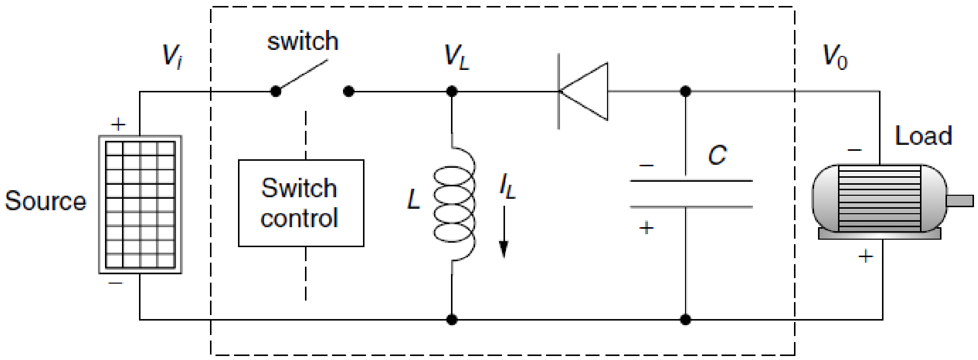


- L and C assumed as sufficiently large so we can treat L as a current source, and C as a voltage source;
- Transistor switch flips on and off at a rapid rate (on the order of 20 kHz), under control of a logic algorithm.

Buck-boost DC-DC Converter (cont'd)

- Two situations to consider: switch closed and switch open;

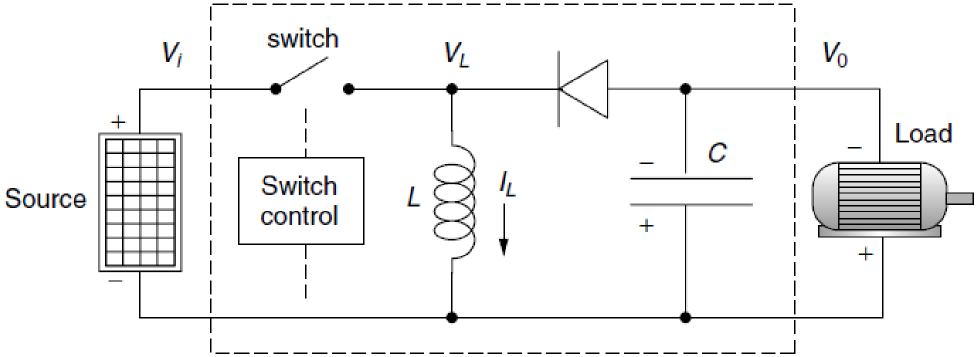
- Switch closed:
- V_i applied across L, driving current I_L through it;
- Diode blocks current to rest of circuit;



- Energy added to L magnetic field, I_L builds up $\Rightarrow$ L would eventually act as a short-circuit (if switch remained closed).

Buck-boost DC-DC Converter (cont'd)

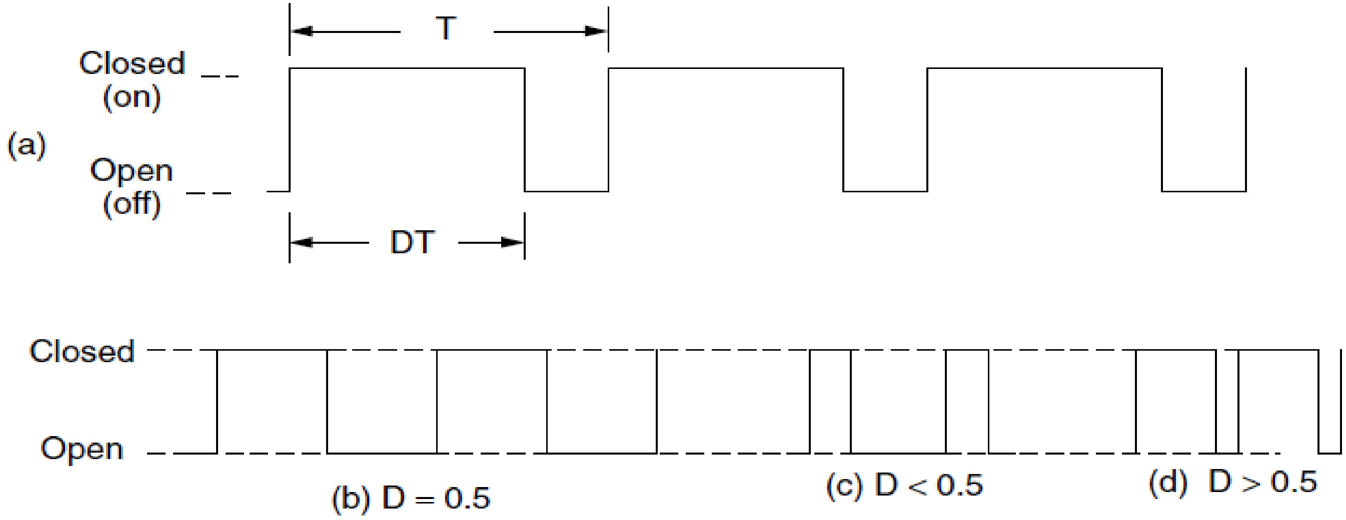
- When switch is opened:
- I_L continues to flow, but now through C, load and diode;



- A voltage appear across the load *(with a polarity reversal)* that keeps it powered after switch closes again;
- If switch cycles quickly enough, I_L does not drop much when it is open, until the next jolt of current from source $\Rightarrow I_L \simeq$ constant;
- Also, V_C does not drop much when switch is closed, before the next jolt of I_L charges it back again $\Rightarrow V_o \simeq$ constant (with opposite sign to V_i !)

Switch Duty Cycle

- Controls the relationship between V_i and V_o ;
- **Duty cycle *D*** $(0 < D < 1)$: fraction of time that the switch is closed:



- Pulse-width modulation (PWM): the above variation on the fraction of time the switch is in one state or the other.

Relationship between V_i and V_o

- It is assumed that all components are ideal: *L*, *C*, and diode do not consume any net energy over complete switching cycle:

Average power into converter = average delivered power

- Average power into the magnetic field of *L* from *t=0* to *DT*:

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

- Average power delivered from *t=DT* to *t=T* (w/ I_L and $V_o \cong$ constant:

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

Relationship between V_i and V_o (Cont'd)

- Over a complete cycle:

$$\bar{P}_{L,in} + \bar{P}_{L,out} = 0$$

or

$$V_i I_L D = V_o I_L (1 - D)$$

what leads to

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

- That is, we can bump DC voltages up and down just by varying the duty cycle;
- The sign change simply implies a change of polarity.

MPPTs – Example

- A PV module has its maximum power point at V_m = 17 V and I_m = 6A.
- What duty cycle should its MPPT have if the module is delivering power to a 10Ω resistance?

- Max power delivered by the PVs is 17V*6A = 102W

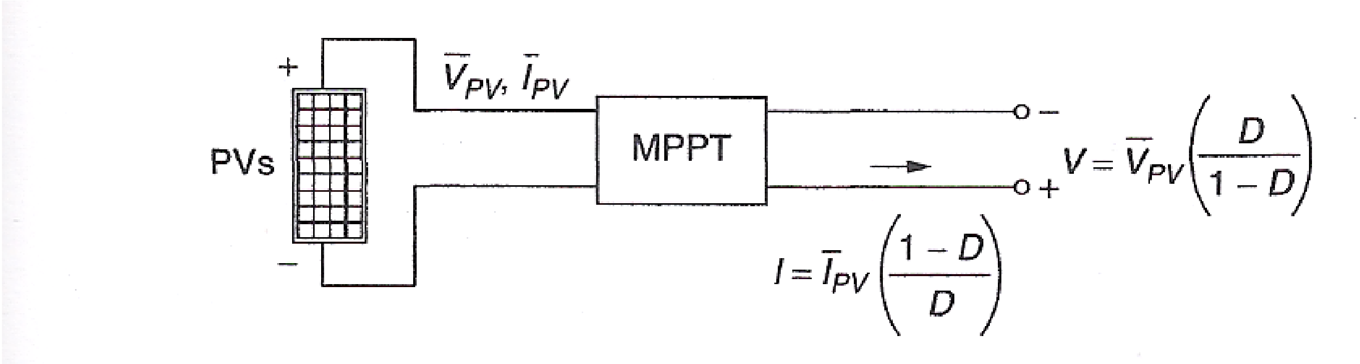
$$P = \frac{V_R^{\ 2}}{R} \qquad V_R = 31.9V$$

MPPTs – Example

- The converter must boost the 17 V PV voltage to the desired 31.9 V

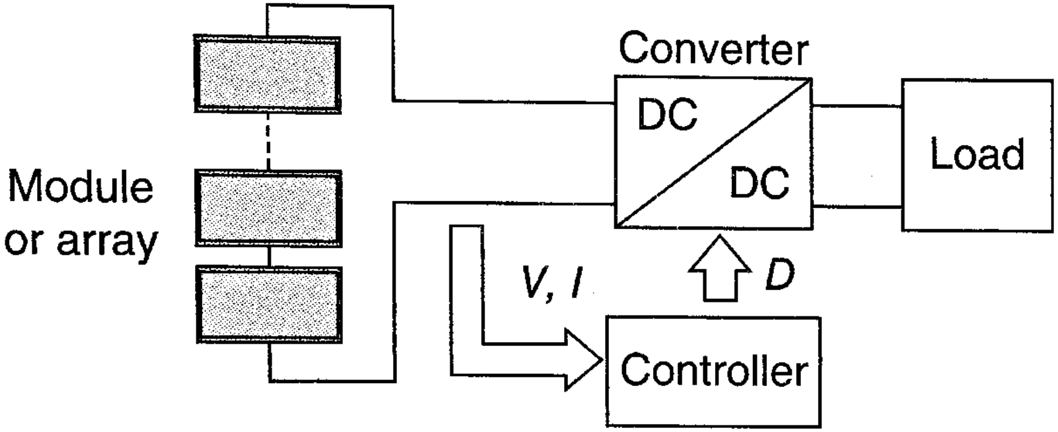
$$\frac{V_0}{V_i} = -\left(\frac{D}{1-D}\right) \qquad \frac{31.9}{17} = \left(\frac{D}{1-D}\right) = 1.88$$

- Solving gives $D = 0.65$



MPPT Controllers

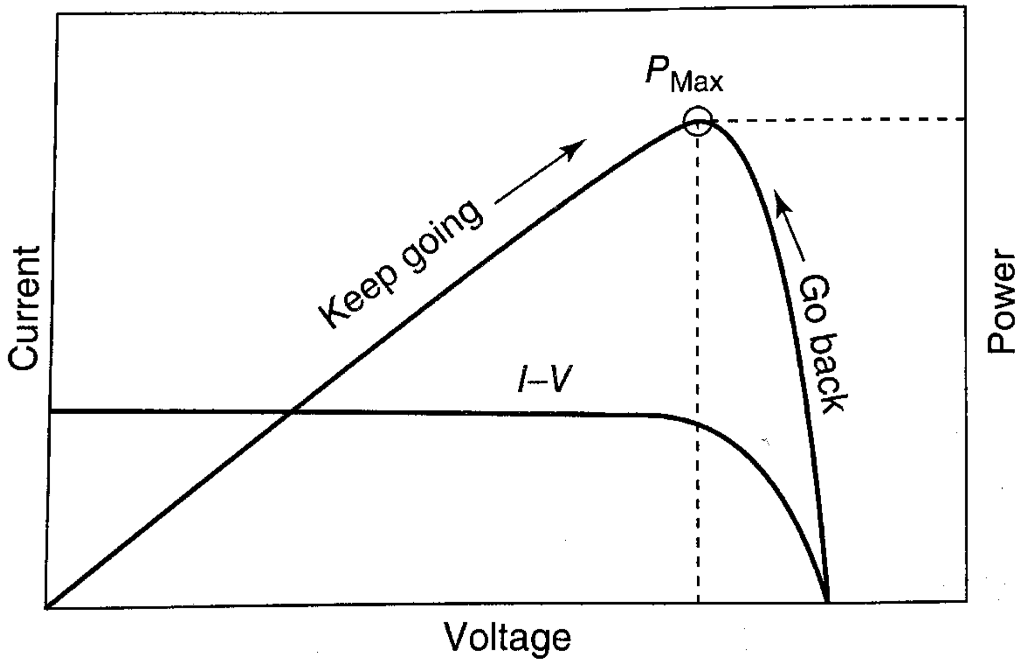
- An MPPT needs a *control unit* to adjust the duty cycle of its converter:



- The controller senses *I* and *V* delivered by the PVs and adjusts the converter to best match the desired output to the load.

The "Perturb-and-Observe" Method

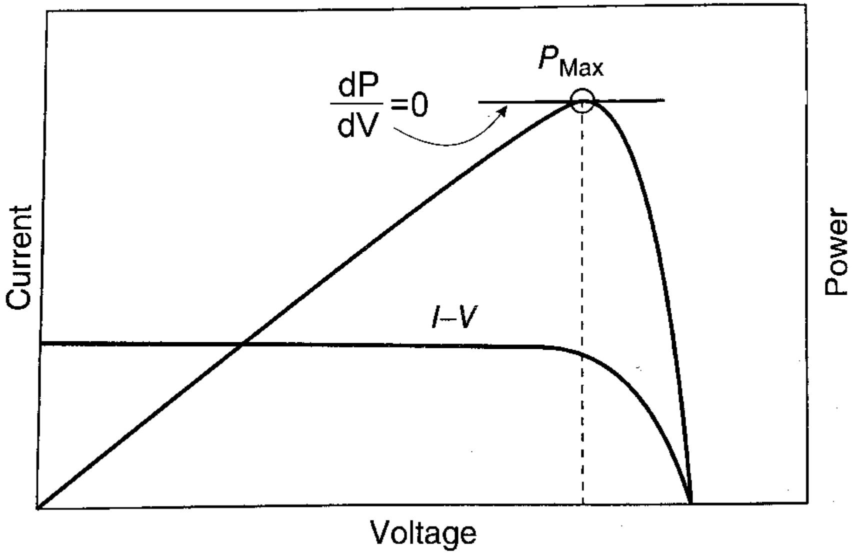
- If a perturbation that increases V also increases the power delivered P_o, then V continues to be increased until the P_o starts to decrease;
- if ΔV decreases P_o , next adjustment will be in the opposite direction:



The Incremental Conductance Method

- Based on the null slope of power curve at the MPP:

$$\frac{dP}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} \approx I + V\frac{\Delta I}{\Delta V}$$



- At the MPP:

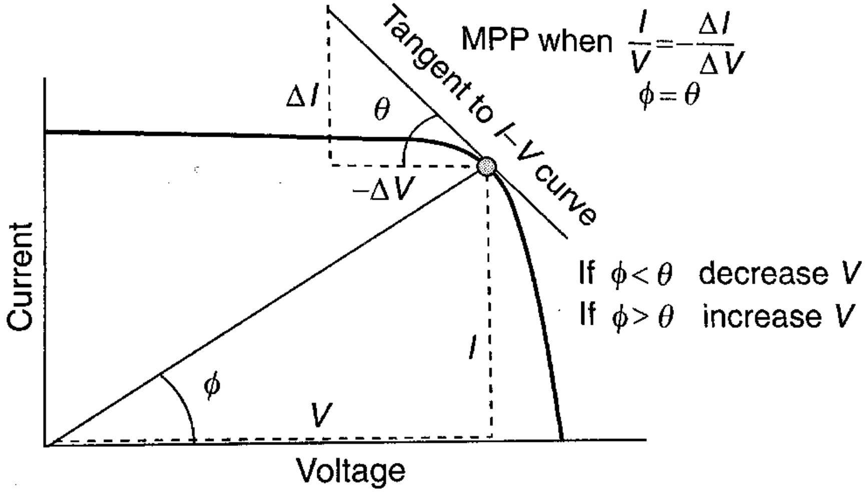
$$\frac{\Delta I}{\Delta V} = -\frac{I}{V}$$

I/V: Instantaneous conductance, based on measurements;

ΔI/ΔV: Incremental conductance.

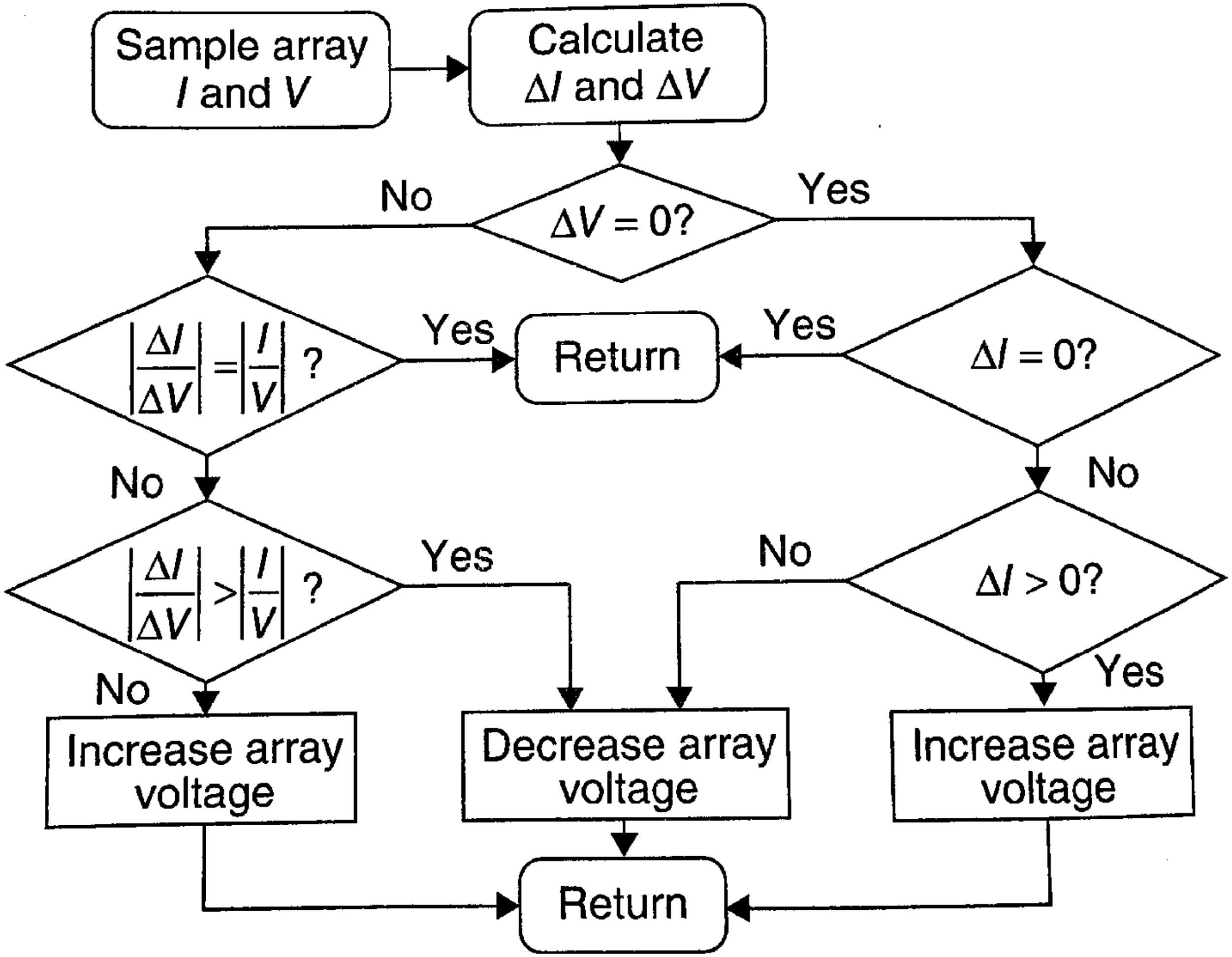
Increm. Conductance Method (cont'd)

- Inst. conductance: slope of line drawn from origin to operating point;
- Increm. conductance: negative slope ov I-V curve at same point;
- At MPP, $\theta = \varphi$;
- MPP is found by incrementing the duty cycle until $\theta = \varphi$;



- Having located the MPP, duty cycle remains fixed until new I and V measurements indicate a change is needed.

Incremental Conductance Algorithm



Grid-Connected Systems

- Can have a combiner box and a single inverter or small inverters for each panel
- Individual inverters make the system modular
- Inverter sends AC power to utility service panel
- Power conditioning unit (PCU) may include
  - MPPT
  - Ground-fault circuit interrupter (GFCI)
  - Circuitry to disconnect from grid if utility loses power
  - Battery bank to provide back-up power

Components of Grid-Connected PV

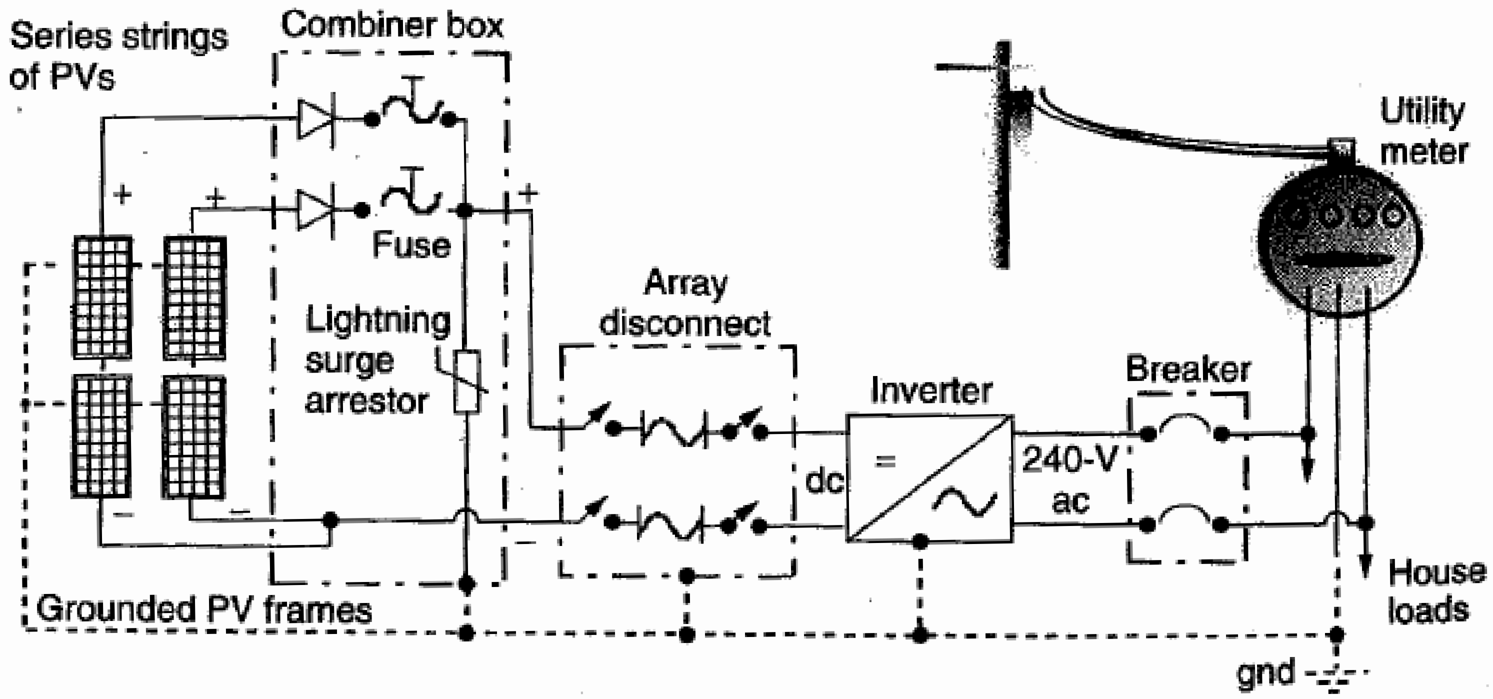


Figure 9.20 Principal components in a grid-connected PV system using a single inverter.

Individual Inverter Concept

- Easily allow expansion
- Connections to house distribution panel are simple
- Less need for expensive DC cabling

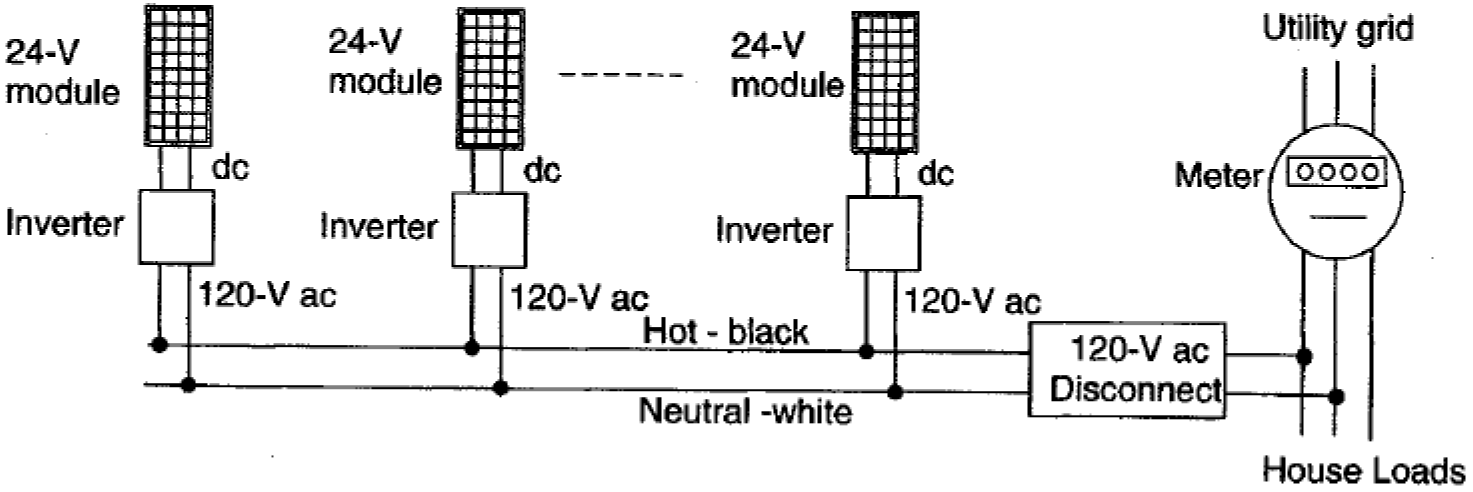


Figure 9.21 AC modules each have their own inverters mounted on the backside of the collector, allowing simple system expansion at any time.

Basic Voltage-Sourced Inverter Operation

- Ideally inverter takes a dc input and produces a constant ac frequency output
  - Output often doesn't look like a sine ware
  - Design goal is to minimize the harmonic content

212 INVERTERS

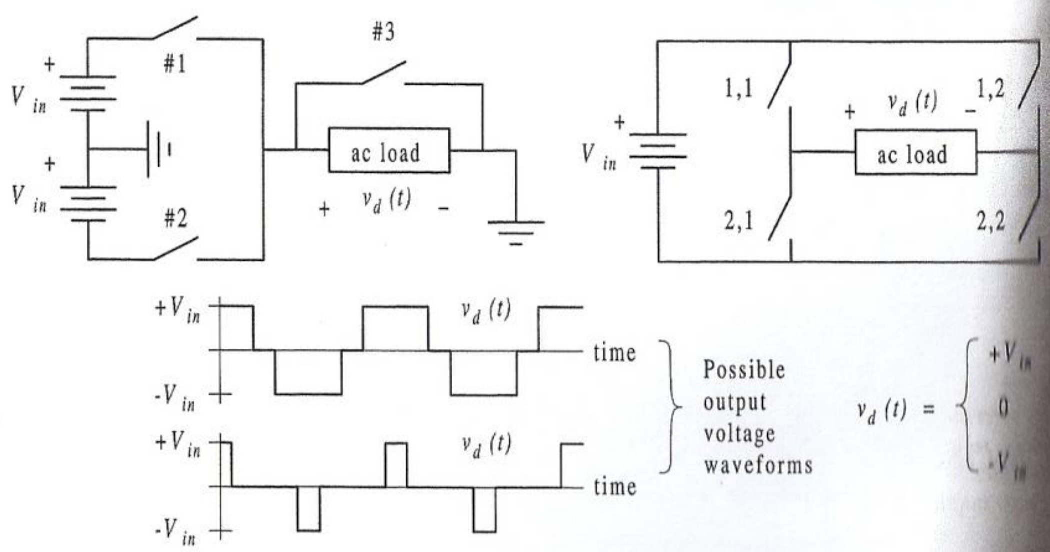


Figure 6.7 Three-level inverter approaches.

Filters can be used to eliminate harmonics

Figure 6.7 from *Elements of Power Electronics* by Phil Krein

Stand-Alone PV Systems

- When the grid isn't nearby, the extra cost and complexity of a stand-alone power system can be worth the benefits
- System may include batteries and a backup generator

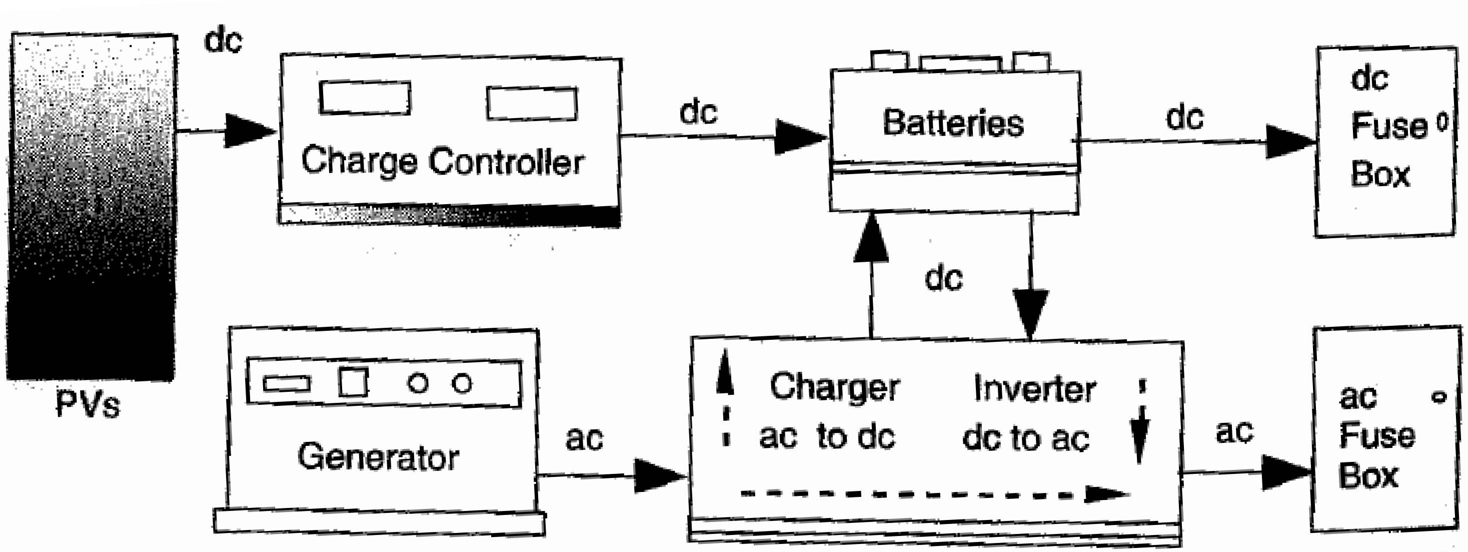


Figure 9.35 A stand-alone system with back-up generator and separate outputs for dc and ac loads.

Stand-Alone PV - Considerations

- PV System design begins with an estimate of the loads that need to be served by the PV system
- Tradeoffs between more expensive, efficient appliances and size of PVs and battery system needed
- Should you use more DC loads to avoid inverter inefficiencies or use more AC loads for convenience?
- What fraction of the full load should the backup generator supply?
- Power consumed while devices are off
- Inrush current used to start major appliances