12-Inverters, Interconnection and Other Considerations

ECEGR 4530

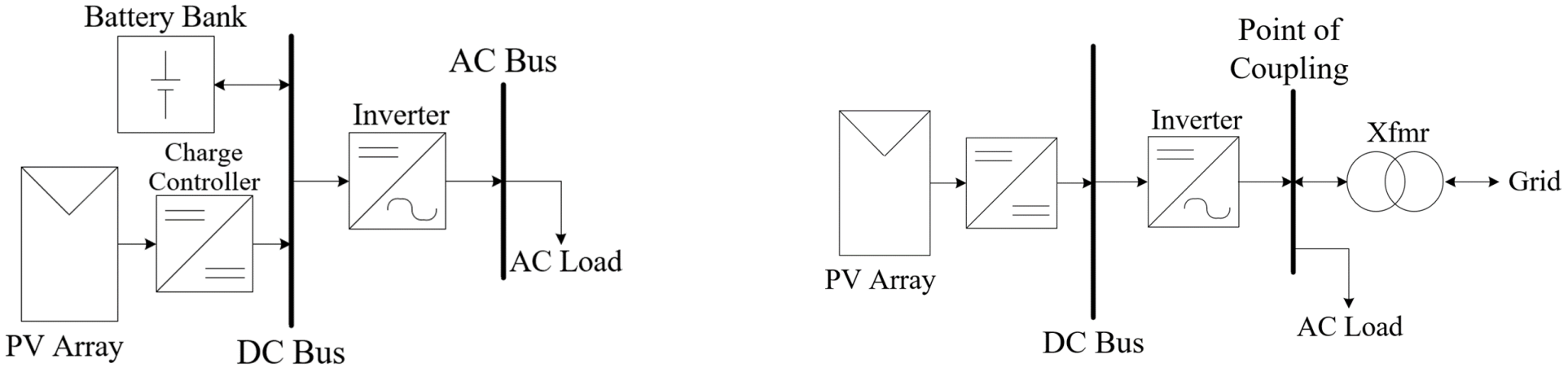
Renewable Energy Systems

Overview

- Inverters
- Grid-Tied Considerations
- PV Panel Discharge Protection
- PV Shading

Inverters

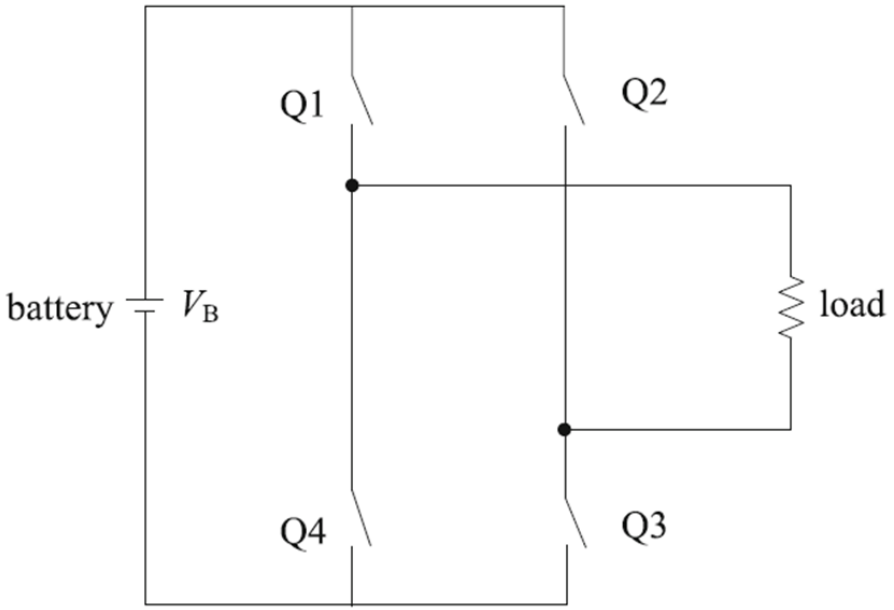
- Inverters are required in stand-alone systems if AC load is to be served OR
- If the systems is grid connected



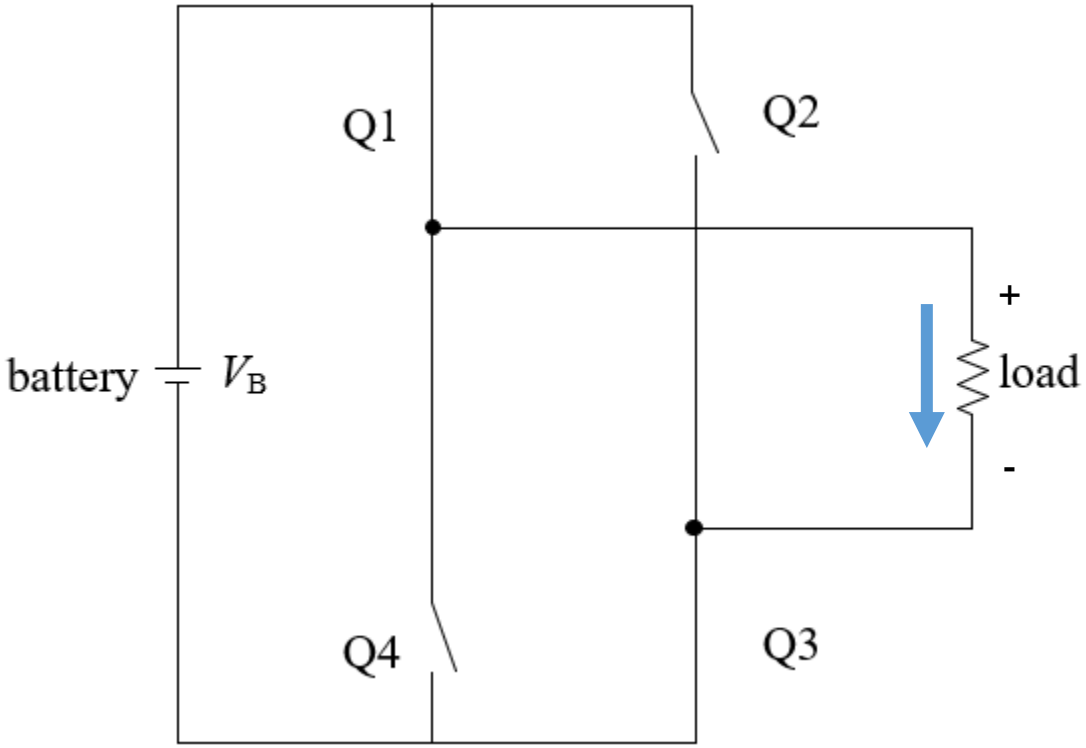
Consider Stand-alone inverters first

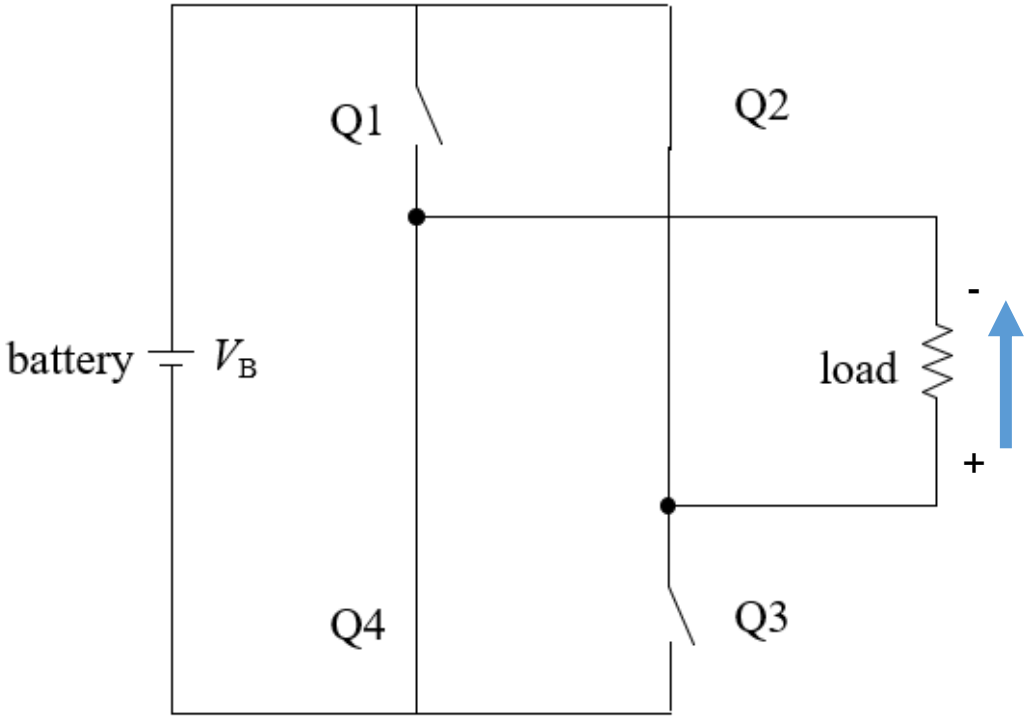
Inverter

- Use solid-state switching to alternate polarity of voltage applied to a load
- Switch in pairs
  - Q1, Q3 open and close at same time
  - Q2, Q4 open and close at the same time
- Voltage output can be increased via DC—DC converter at the input or transformer at the output (or both)



Inverters: Basic Circuit





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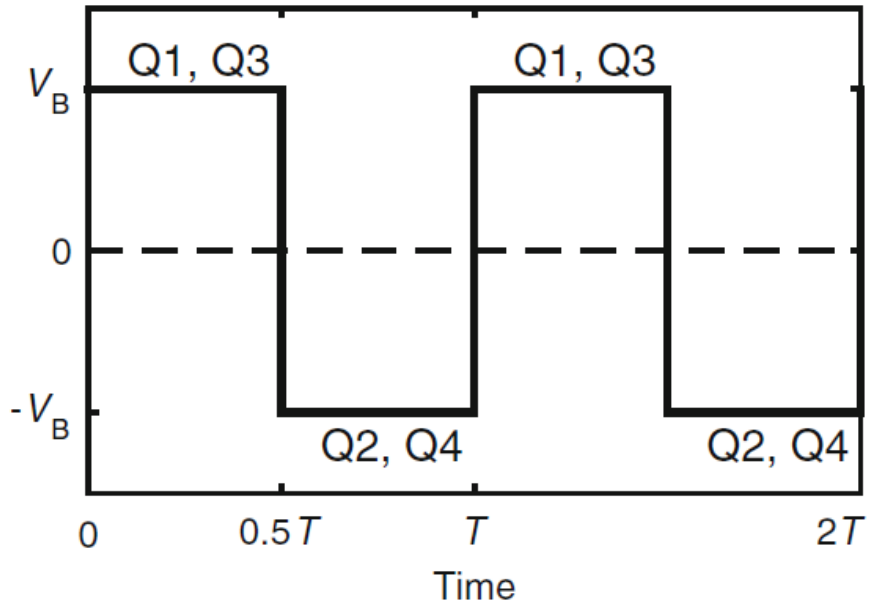
Output Signal

- Waveform is square
- Centered at zero



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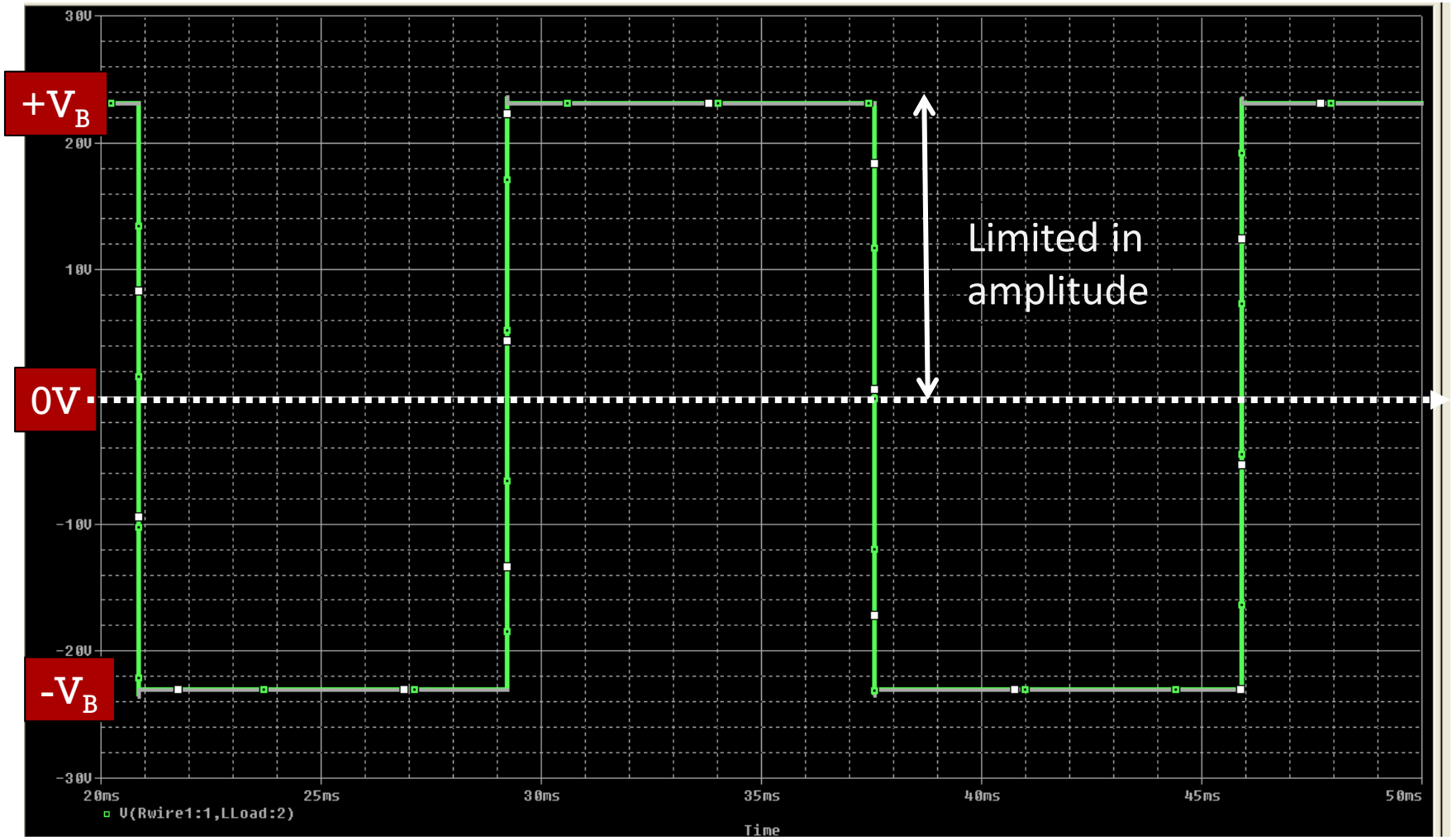
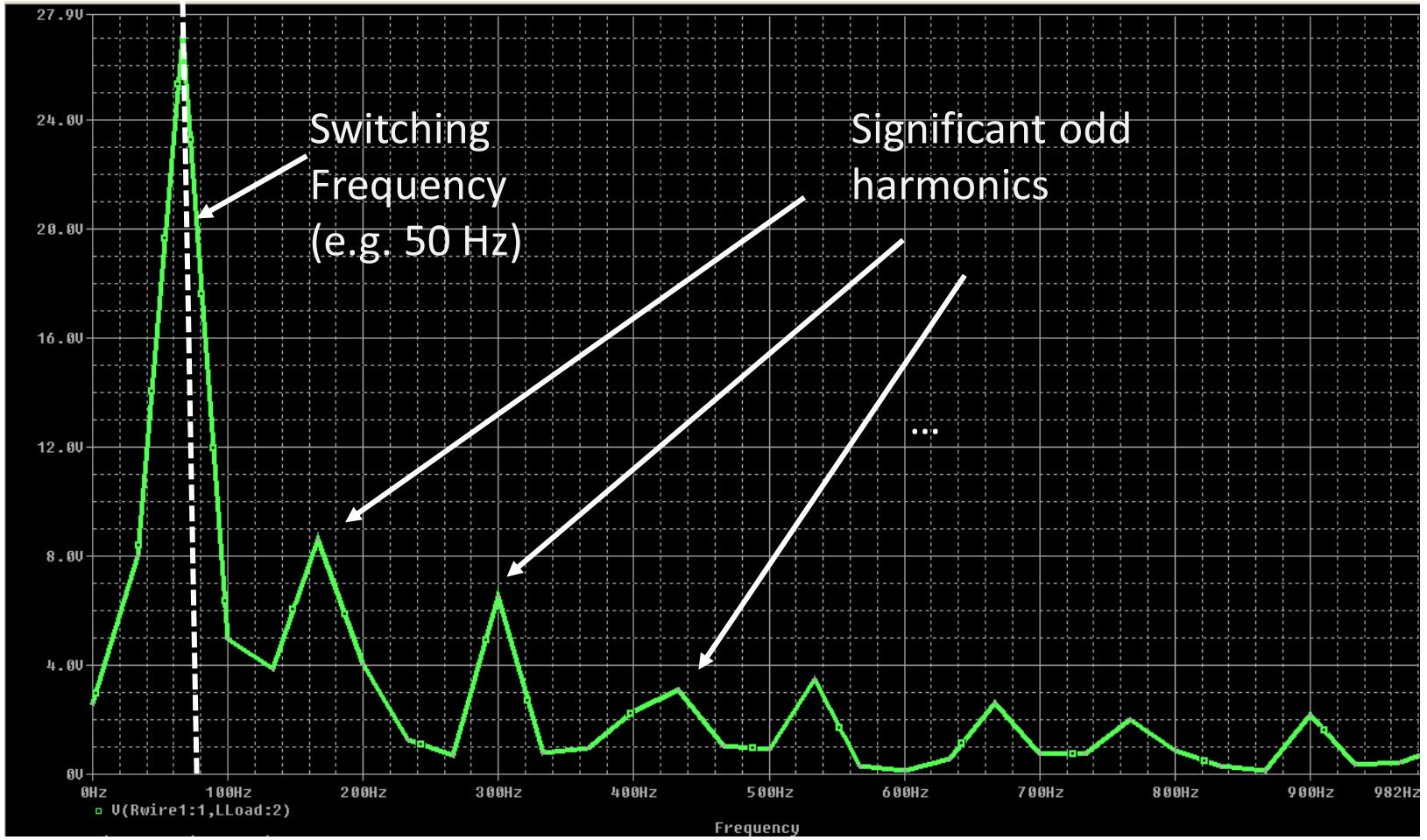
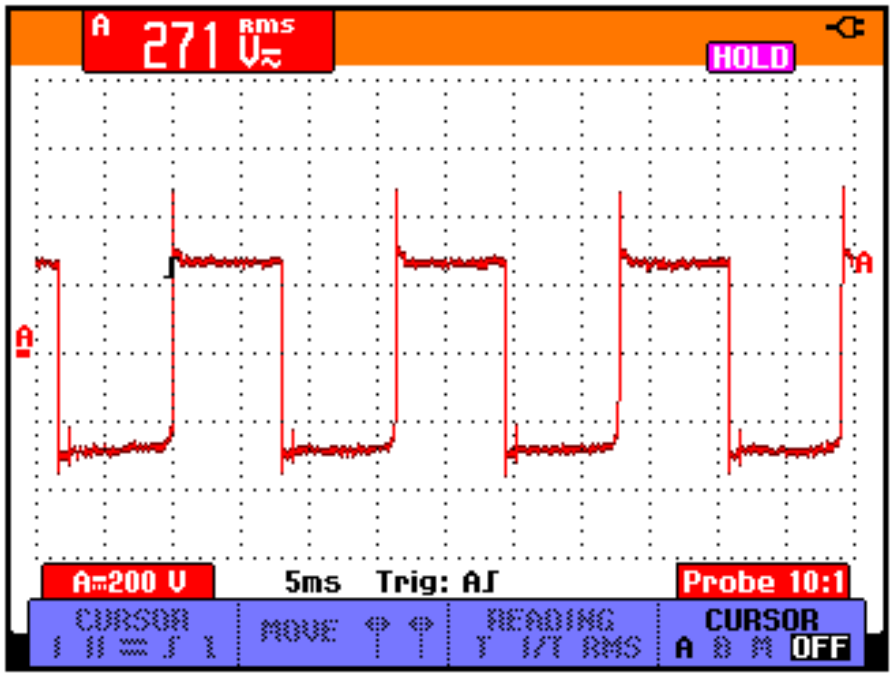

30V
20V
10V
0V
-10V
-20V
-30V
+V_B
-V_B
Limited in amplitude
20ms
25ms
30ms
35ms
40ms
45ms
50ms
V(Rwire1:1,LLoad:2)
Time

Inverter

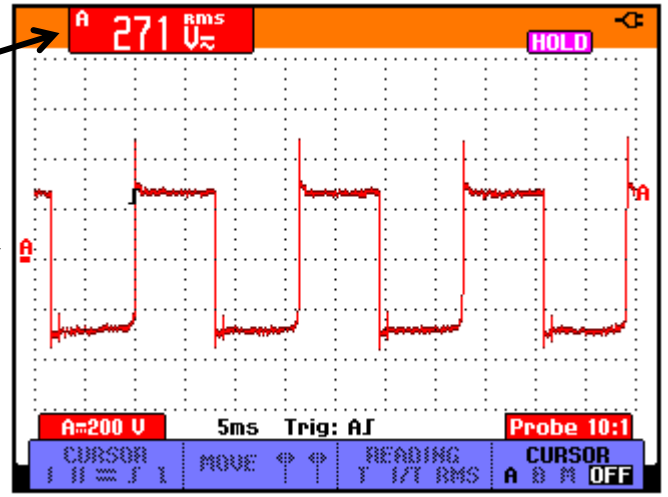

27.9V
24.0V
20.0V
16.0V
12.0V
8.0V
4.0V
0V
0Hz
100Hz
200Hz
300Hz
400Hz
500Hz
600Hz
700Hz
800Hz
900Hz
982Hz
V(Rwire1:1,LLoad:2)
Frequency
Switching Frequency (e.g. 50 Hz)
Significant odd harmonics
…

Squarewave Inverter

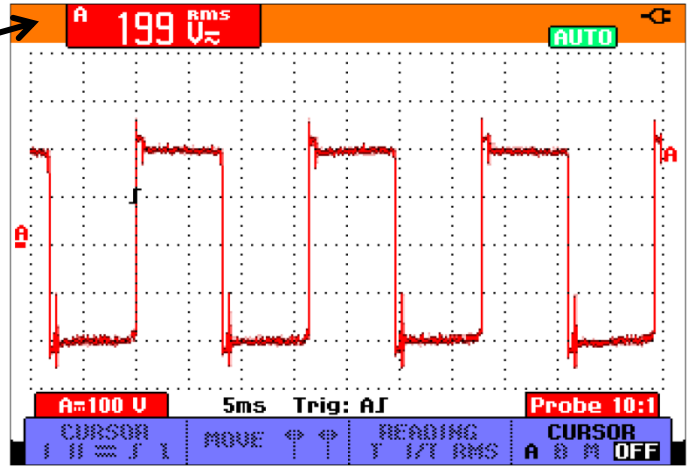


Poor Voltage Regulation

V_{batt} = 12.4



V_{batt} = 9



Inverter

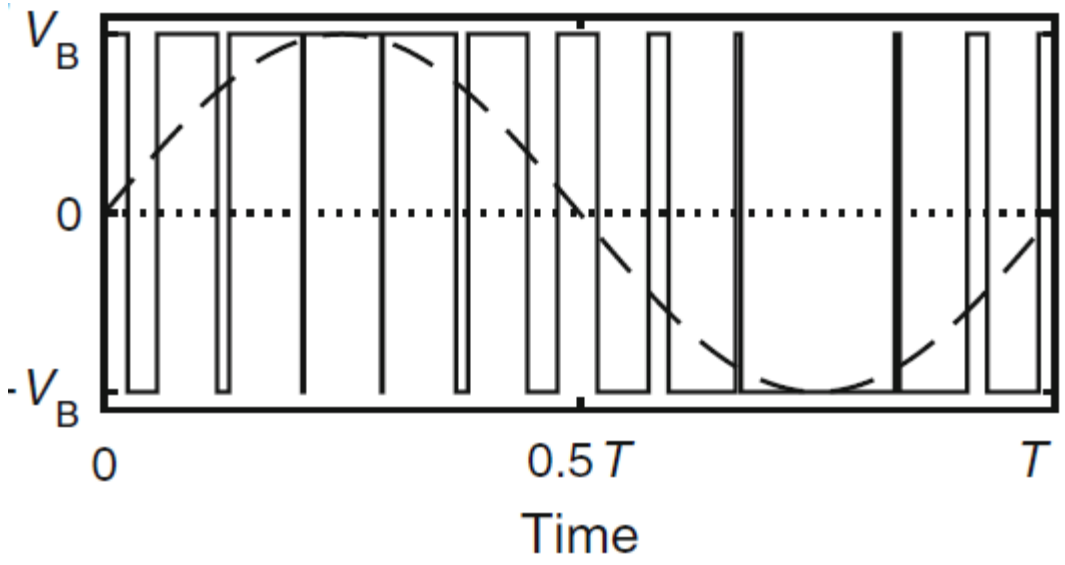
- MPPT can be used between PV and inverter
- Voltage can be stepped up to 120 Vac using a transformer
- Some ac loads can handle "dirty" power, many cannot

Inverter

- Full bridge inverter output may be filtered to better approximate a sine wave
  - Significant harmonics are close to fundamental
  - Large capacitor is required
- A better approach is to use pulse width modulation (PWM) to control the switches

PWM Inverters

- Distortion in output can be reduced using PWM
- Vary duty cycle over the course of the output



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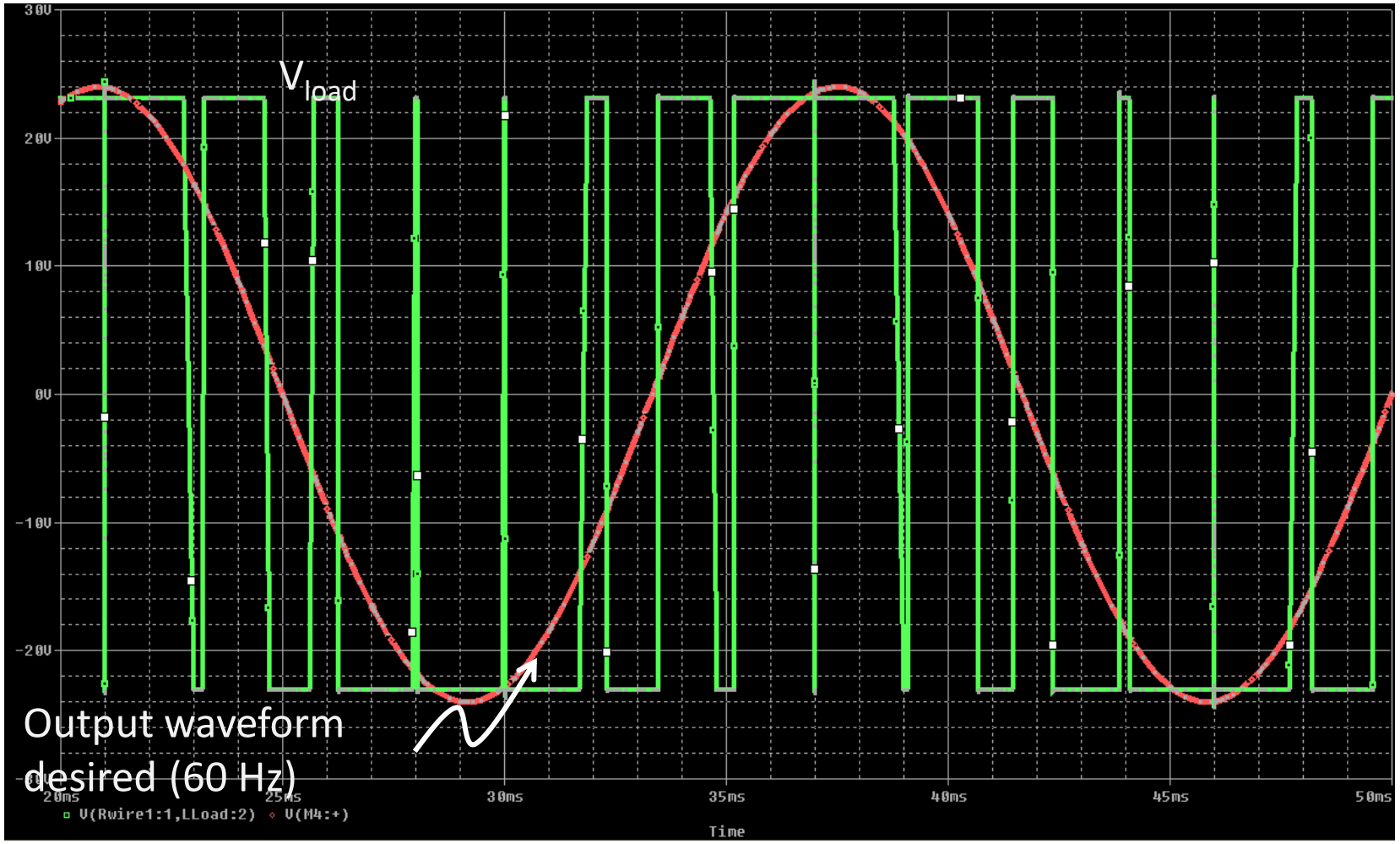
PWM Inverter

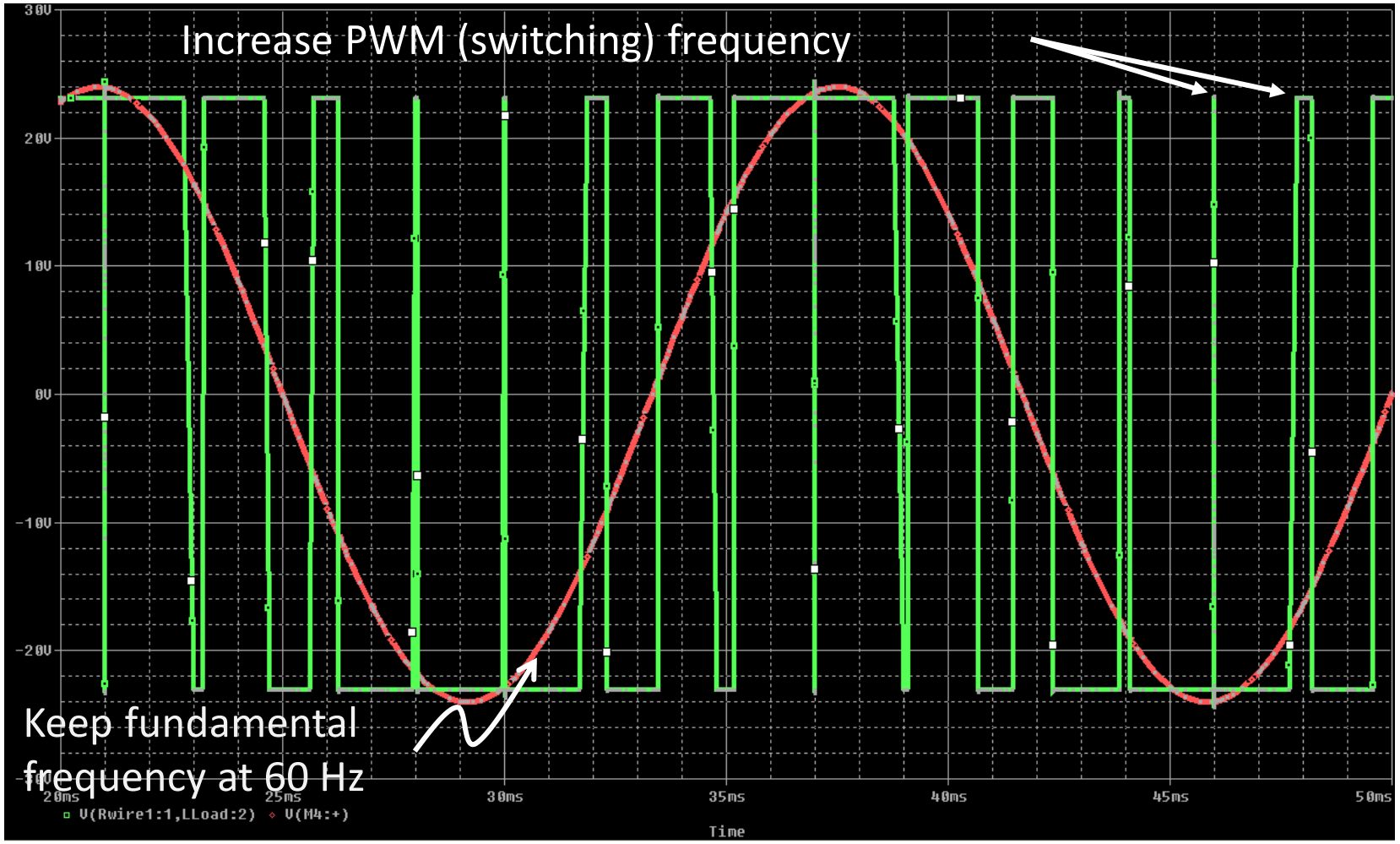
- Switching frequency should be much greater (4kHz - 10kHz) than fundamental frequency (60 Hz or 50 Hz)

- Basic idea: vary the duty ratios within each switching period to replicate a sine wave

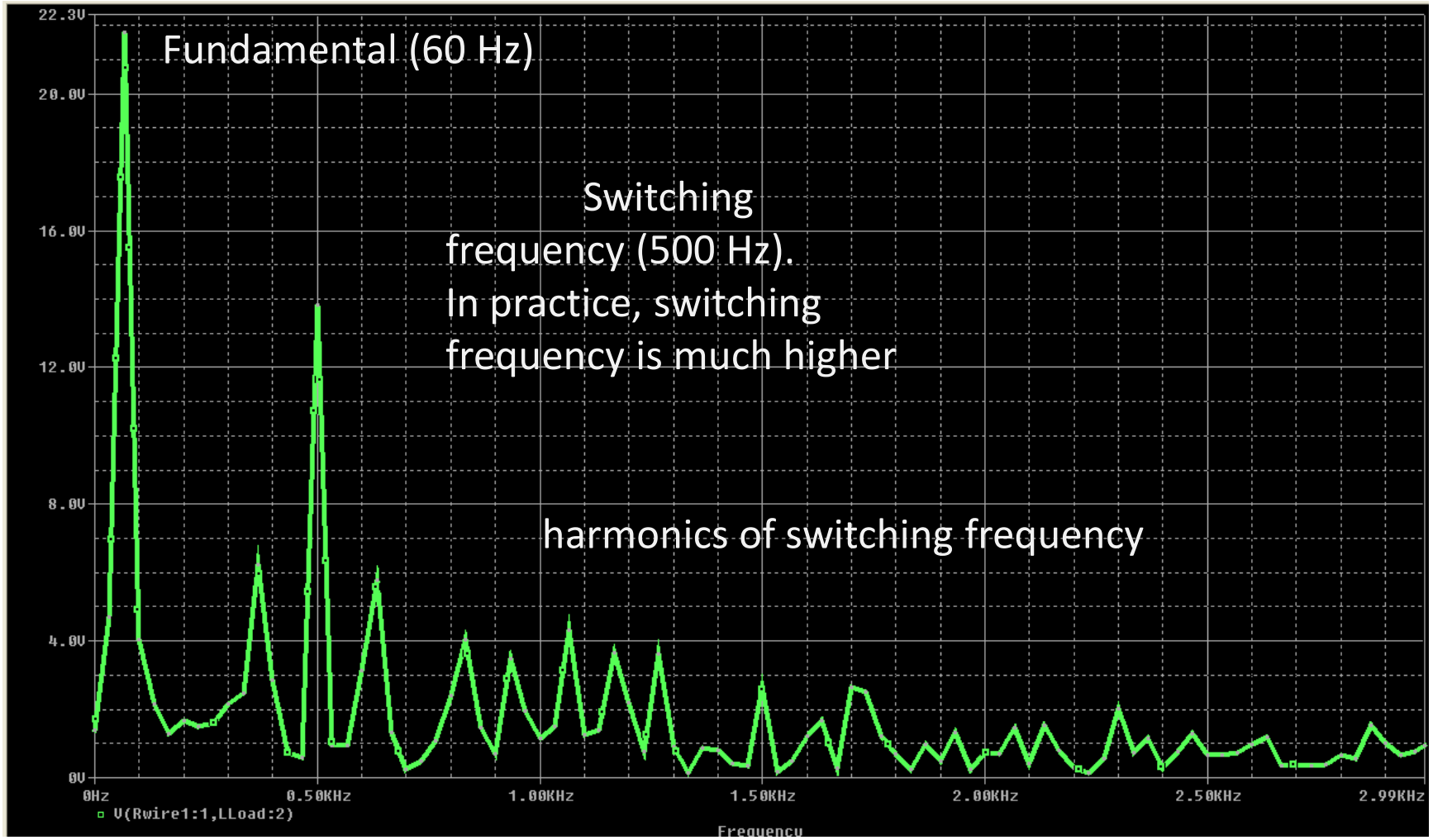
PWM Inverter



PWM Inverter



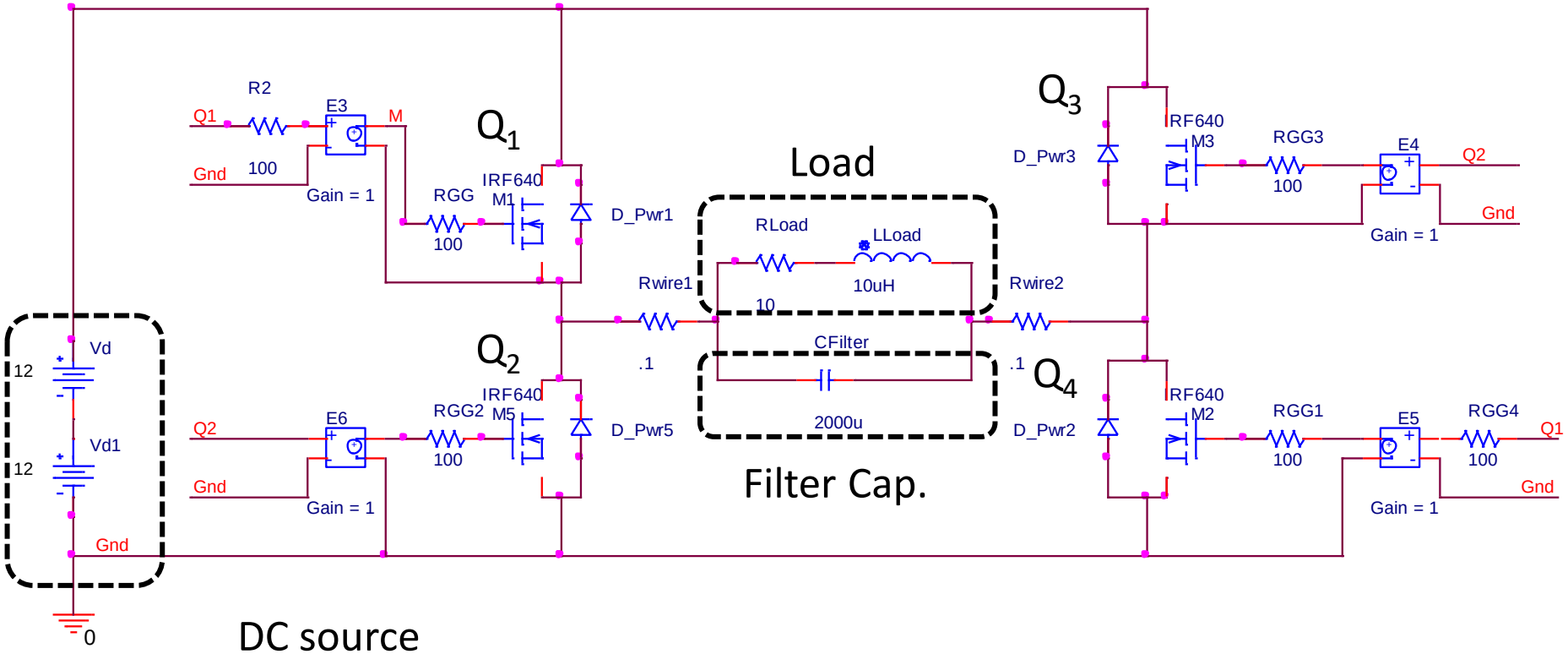
PWM Inverter



PWM Inverter

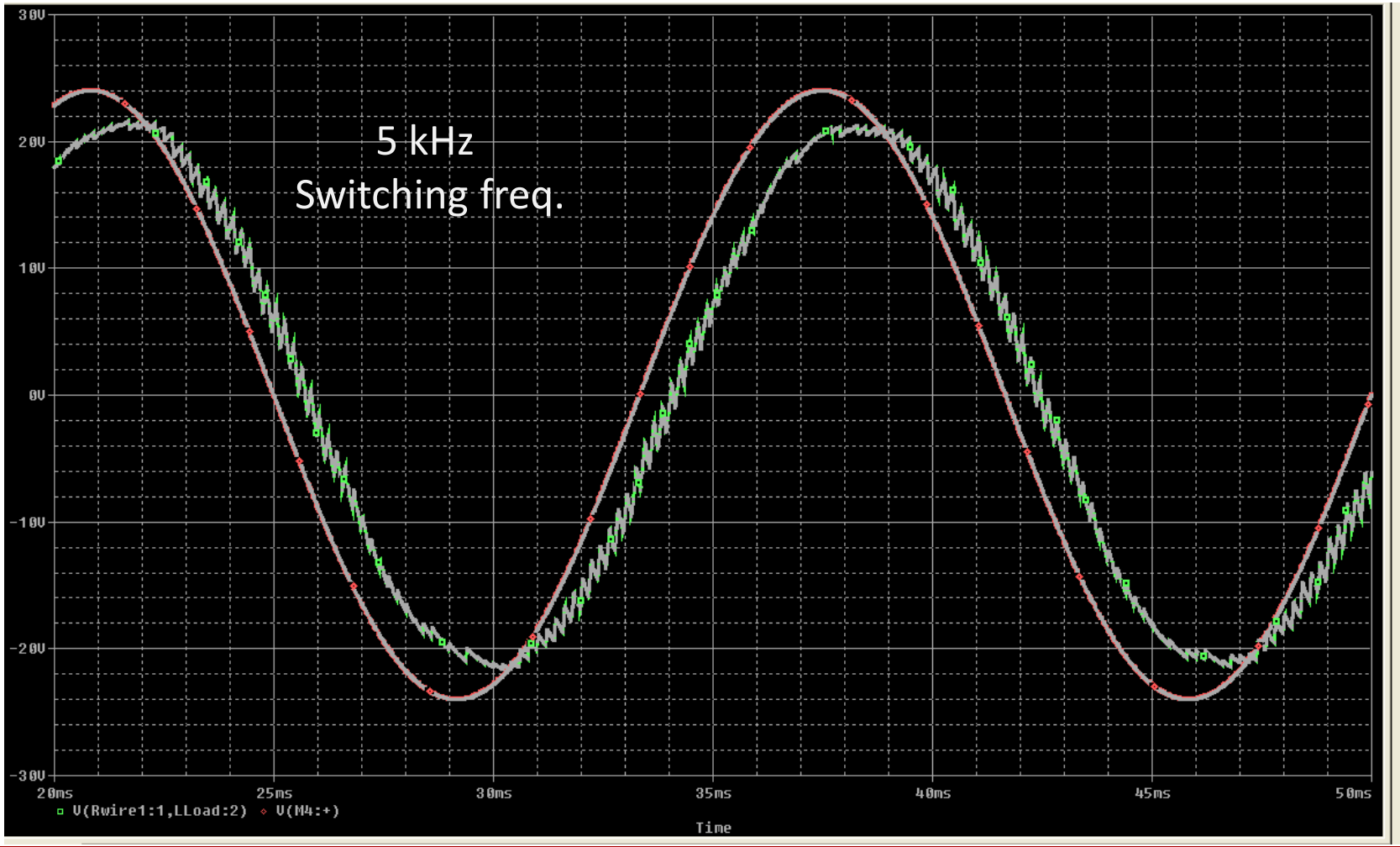
- Use a low-pass filter to remove frequency components greater than the switching frequency
- Result should closely approximate a sine wave

PWM Inverter

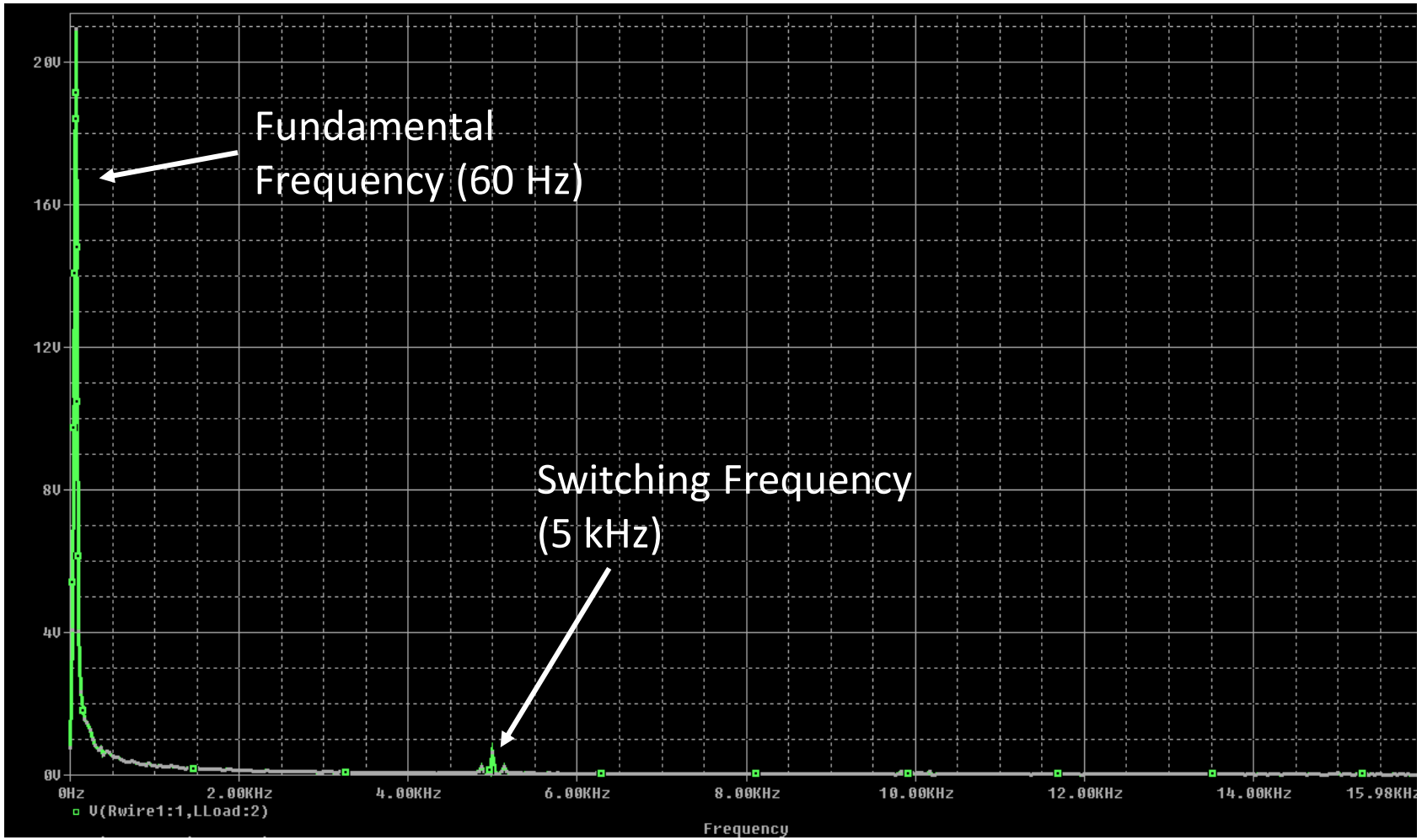


DC source
(Battery or PV with MPPT
or capacitor DC link)

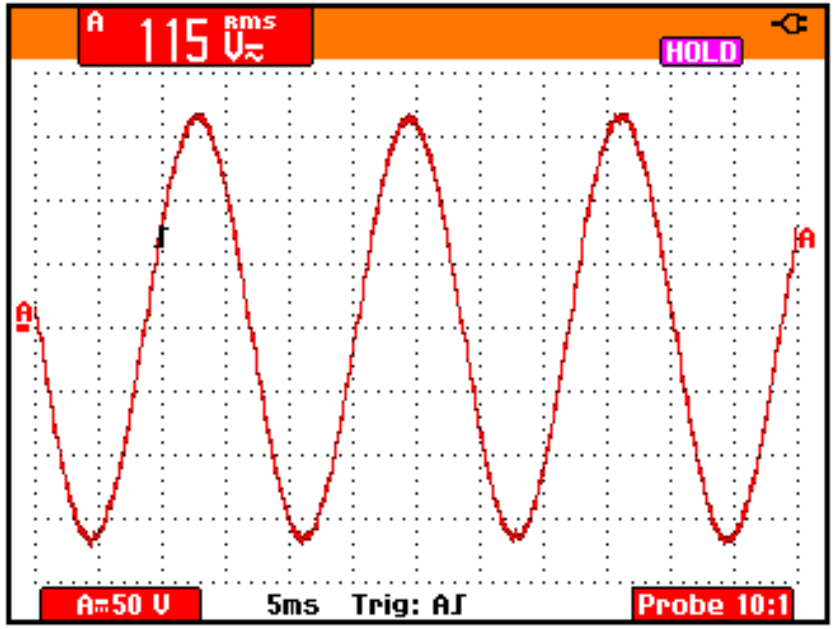
PWM Inverter



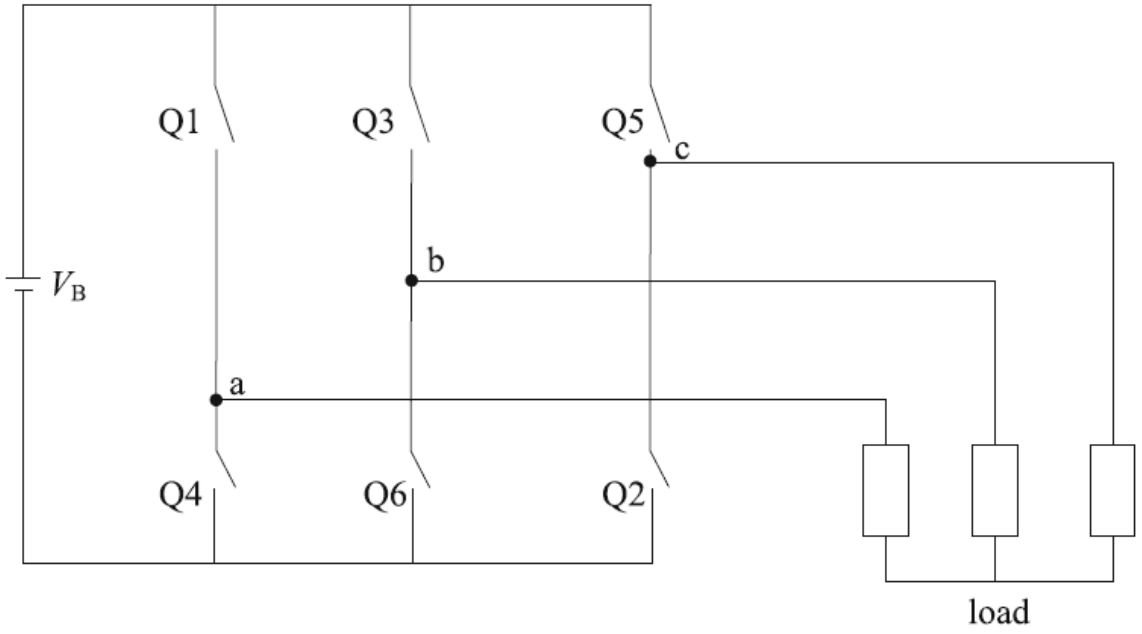
PWM Inverter

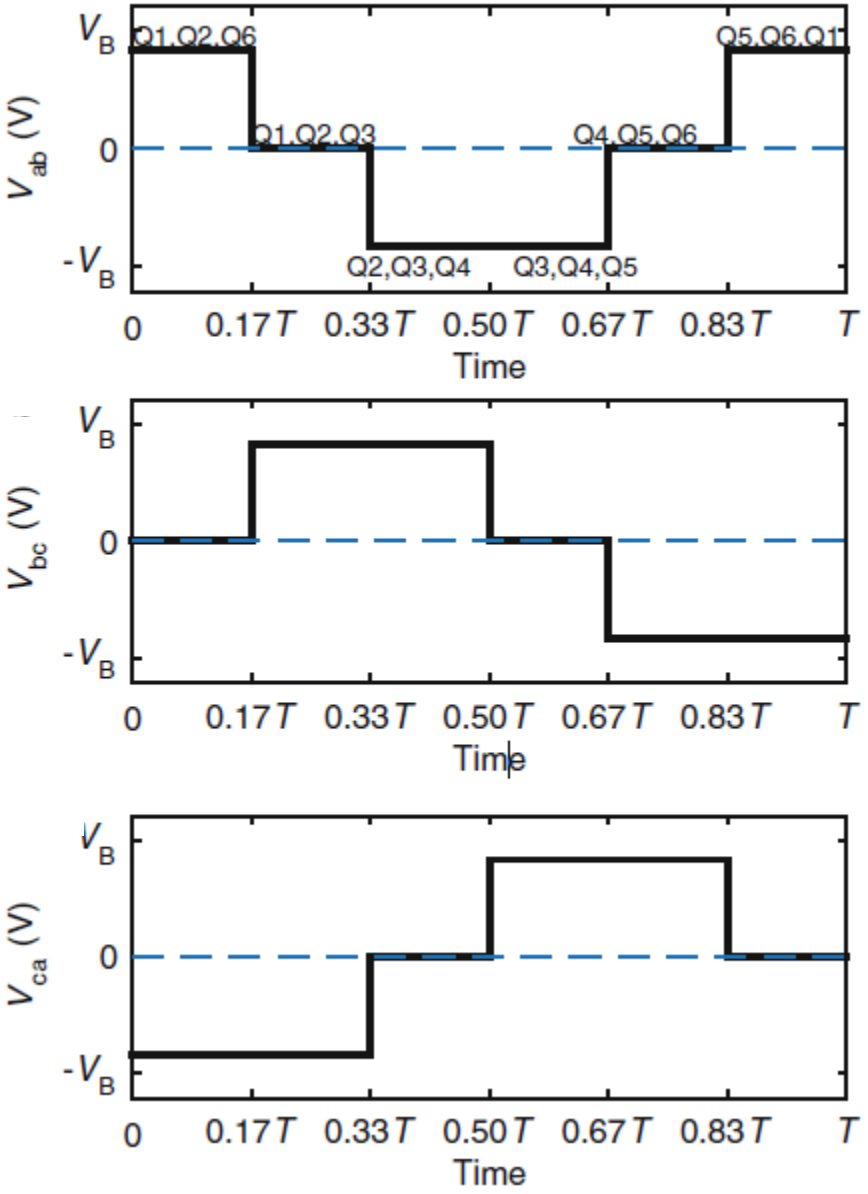


PWM Inverter



Three-Phase Inverters





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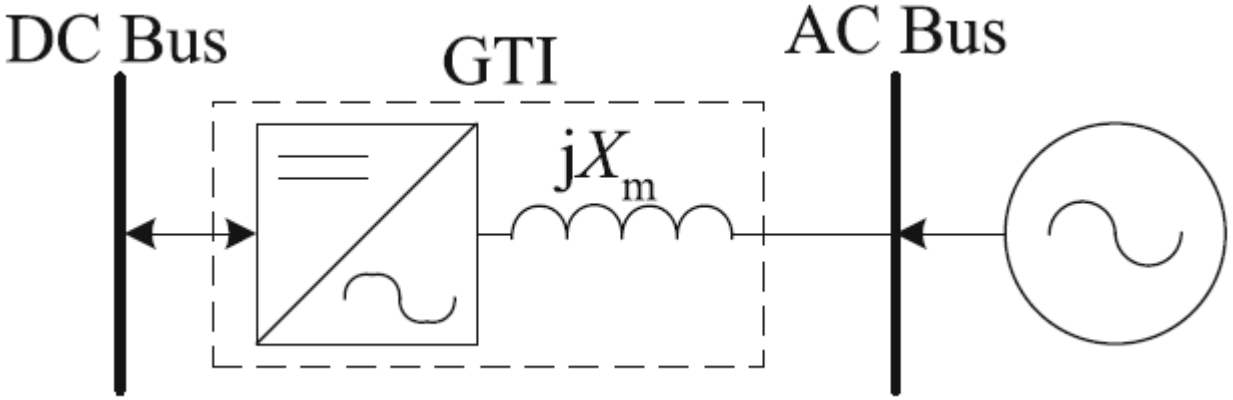
Inverters

- Inverters tied to the grid require special performance characteristics
  - Must be able to synchronize with the grid
    - Closely follow voltage amplitude AND frequency
  - Must disconnect if the grid losses power
  - Must have acceptable power quality

Grid Tied Inverters (GTI)

- Certain inverters can be coupled to the grid



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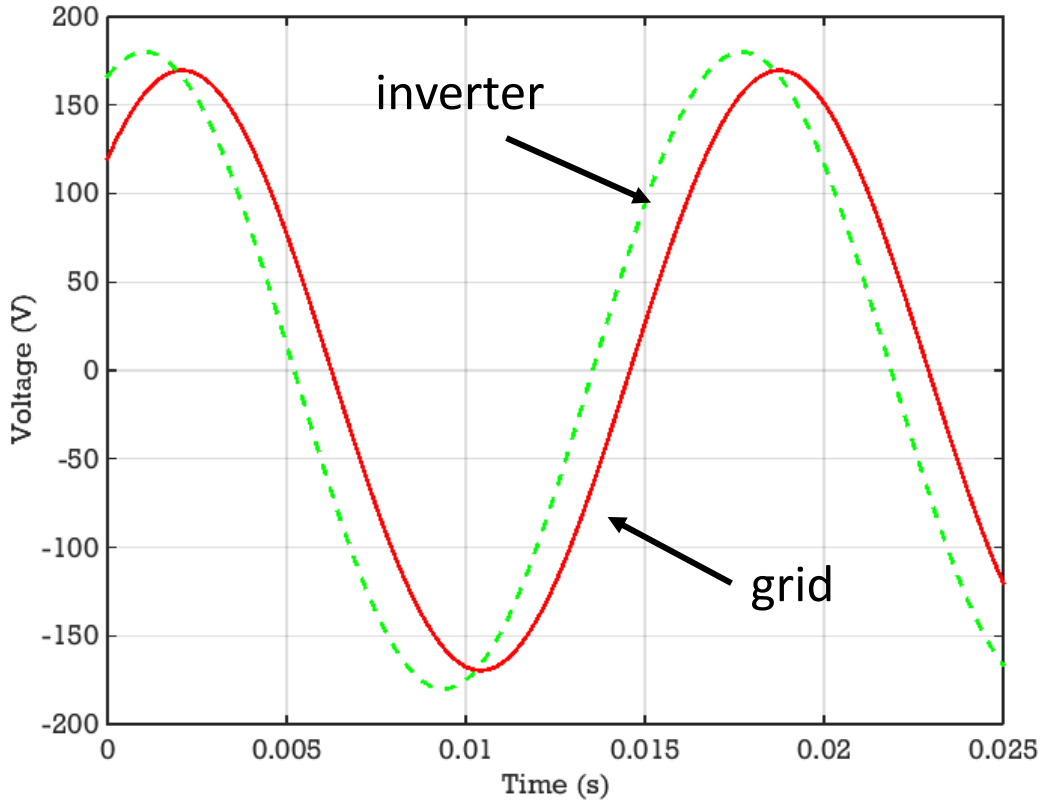
Grid Connection

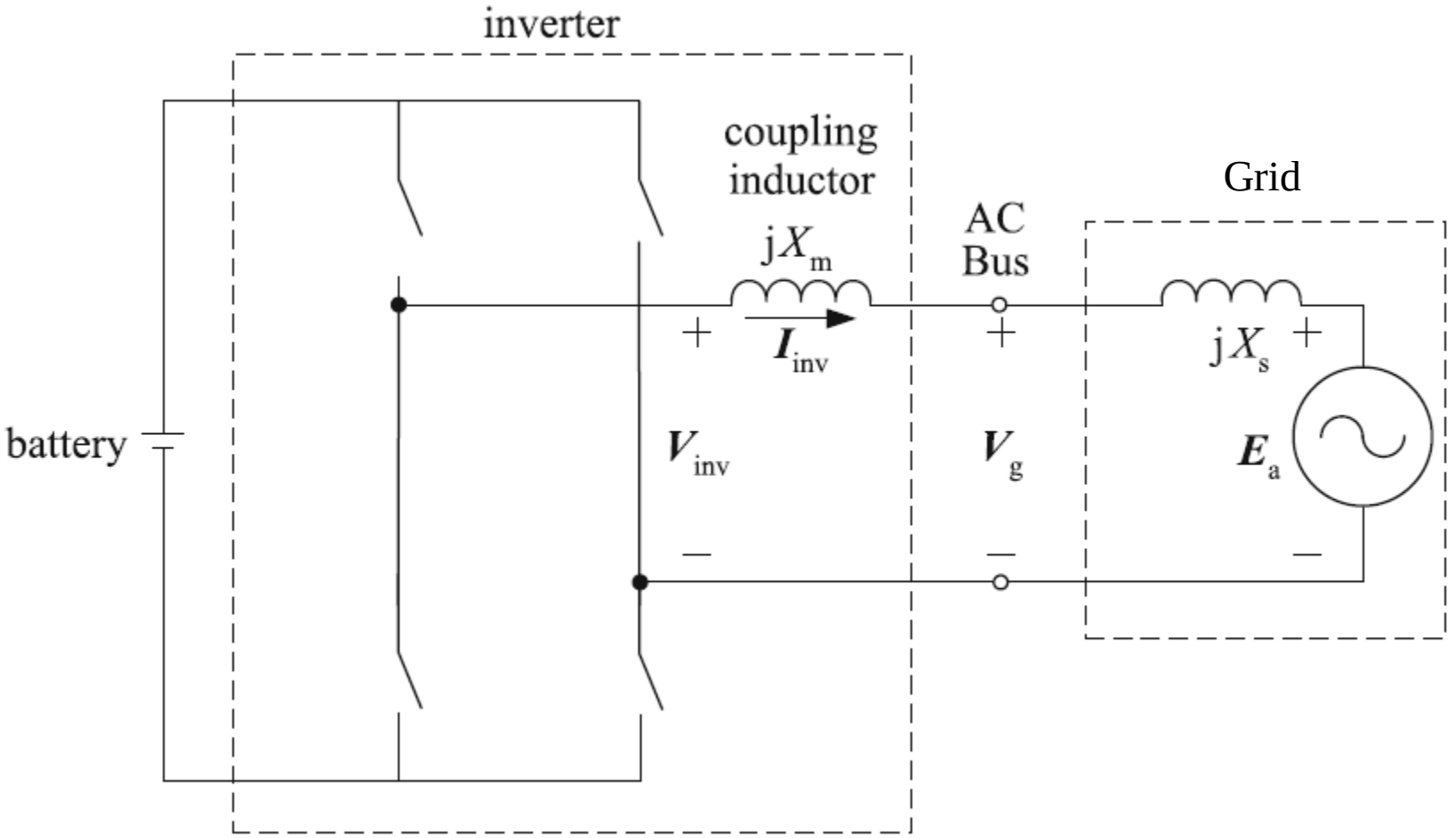


By adjusting the timing (phase) of the inverter switching, it is possible to make inverter voltage
lead or lag grid
voltage, as well
as make the magnitude larger or smaller.

GTI

- Inverters have large coupling inductors
- Inverter current:

$$I_{inv} = \frac{V_{inv} - V_g}{jX_m}$$



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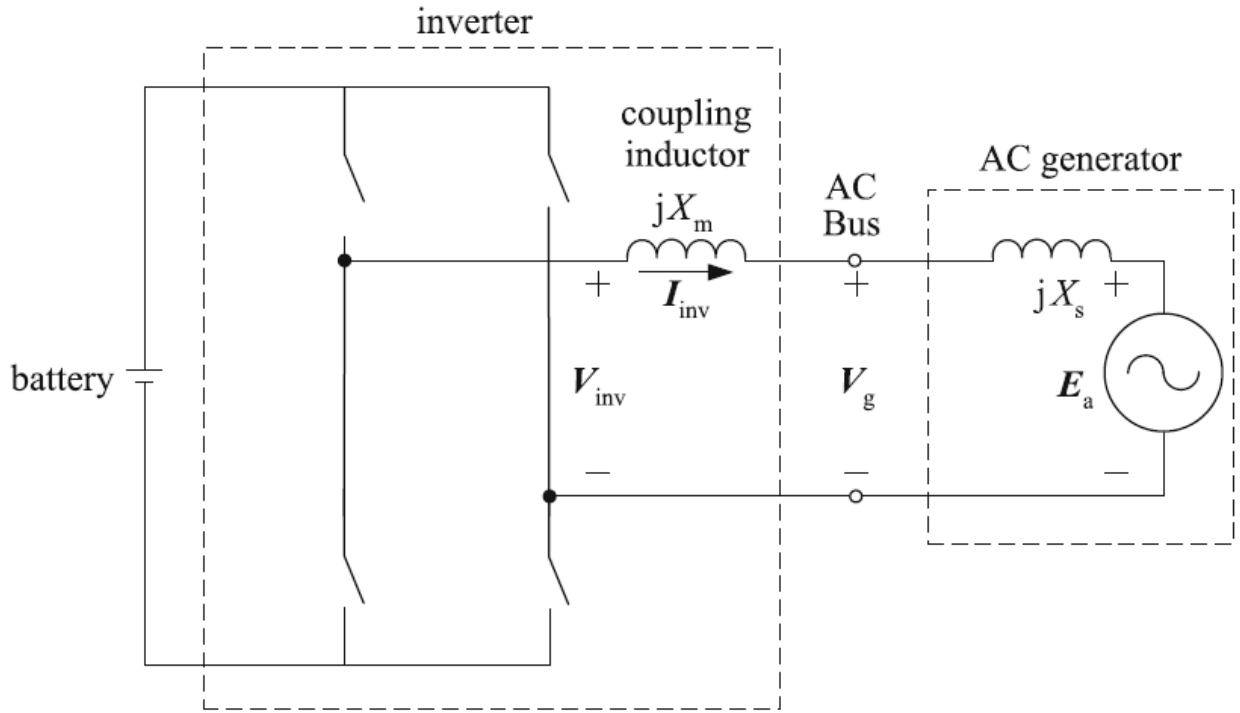
Inverter Power

$$P_{inv} = \mathrm{Re}\left\{ \boldsymbol{V}_{inv} \boldsymbol{I}_m^* \right\} = \mathrm{Re}\left\{ \boldsymbol{V}_{inv} \left(\frac{\boldsymbol{V}_{inv} - \boldsymbol{V}_g}{\mathrm{j}X_m} \right)^* \right\}$$

$$P_{inv} = \mathrm{Re}\left\{ \frac{|\boldsymbol{V}_{inv}|^2}{-jX_m} - \frac{\boldsymbol{V}_m \boldsymbol{V}_g}{-\mathrm{j}X_m} \right\}$$

$$P_{inv} = \mathrm{Re}\left\{ \frac{|\boldsymbol{V}_{inv}|^2}{-\mathrm{j}X_m} - \frac{|\boldsymbol{V}_{inv}||\boldsymbol{V}_g|\cos(\delta) + \mathrm{j}|\boldsymbol{V}_m||\boldsymbol{V}_g|\sin(\delta)}{-\mathrm{j}X_m} \right\}$$

$$P_{inv} = \frac{|\boldsymbol{V}_{inv}||\boldsymbol{V}_g|\sin(\delta)}{X_m}$$



Power supplied by the inverter can be controlled by adjusting the inverter's voltage magnitude and phase.

This equation may look familiar from ECEGR 3500 (synchronous generators)

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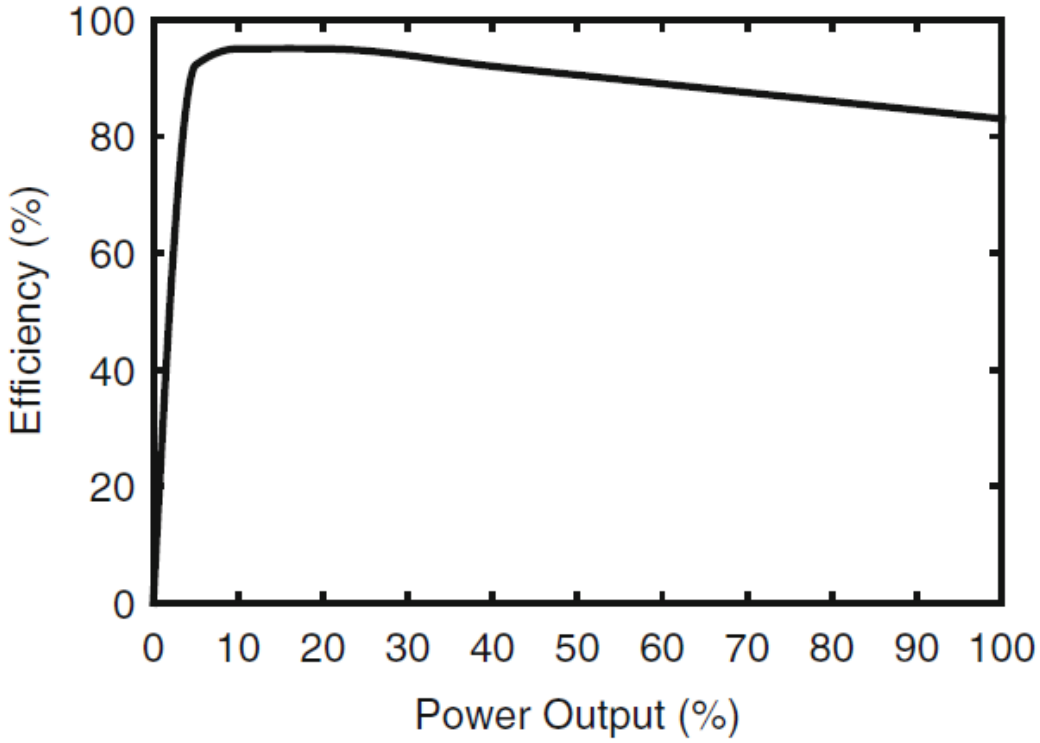
Inverter Efficiency

- Inverter efficiency is not constant, and is non-linear
- Low efficiency at low-loading
- Inverter efficiency is sometimes reported as the "European" efficiency, which considers different operating points

$$\eta_{inv} = 0.03\eta_{inv}(0.05) + 0.06\eta_{inv}(0.10) + 0.13\eta_{inv}(0.20) + 0.10\eta_{inv}(0.30) + 0.48\eta_{inv}(0.50) + 0.20\eta_{inv}(1.00)$$



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Effects of PV on the Grid

- Let

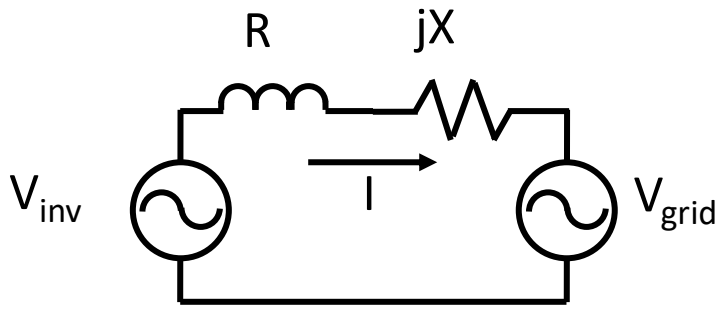
$$\mathbf{Z} = 0.1 + j1\Omega$$

$$\mathbf{V}_{grid} = 120\angle 0°\,\mathbf{V}$$

$$\mathbf{P} = 6000\mathbf{W}$$

$$\mathbf{Q} = 0\mathbf{VAR}$$

} Production from PV

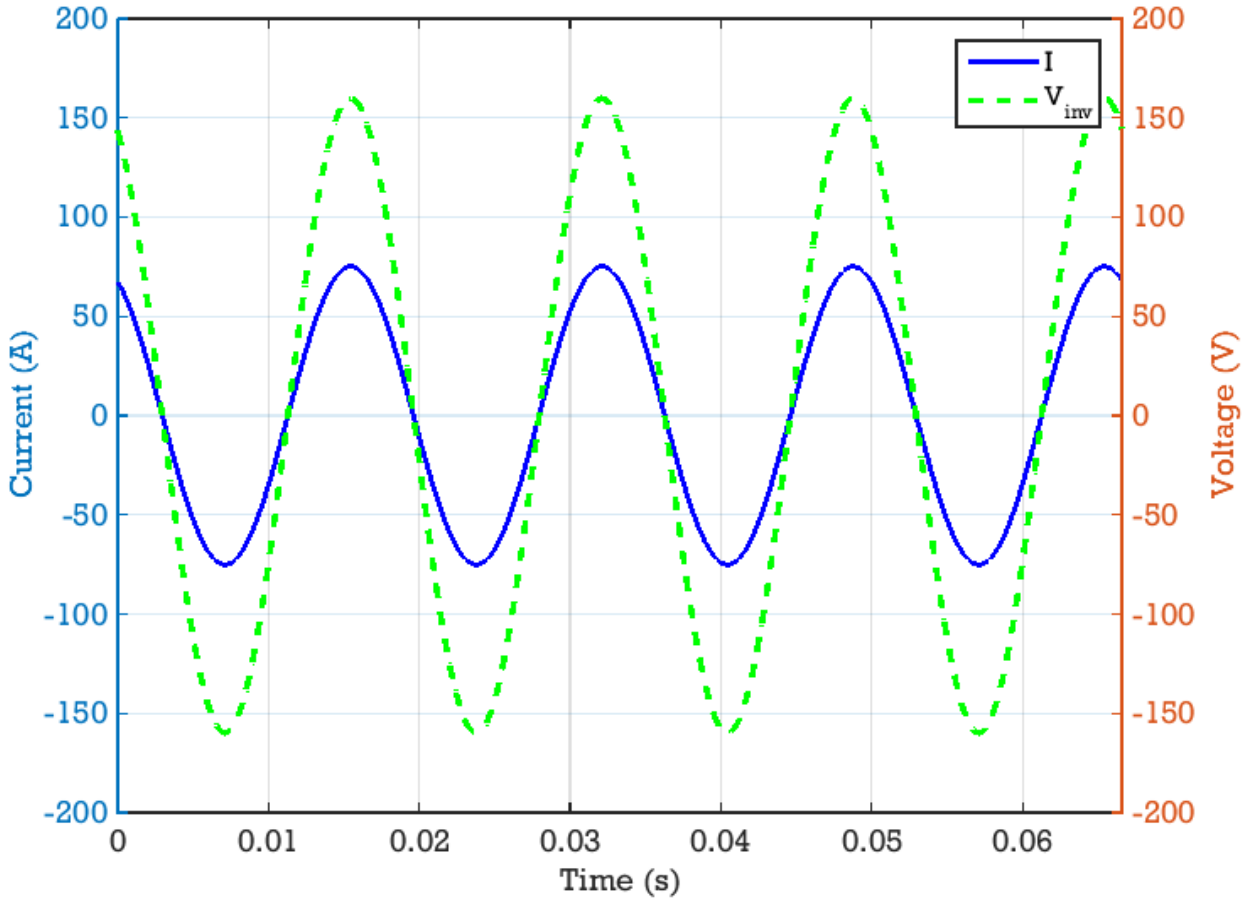


- We can show that:

$$\mathbf{V}_{inv} = 113\angle 26.2°\,\mathbf{V}$$

$$\mathbf{I} = 53.1\angle 26.2°\,\mathbf{A}$$

Inverter Waveforms



Inverter producing
at unity power factor

Grid Connection

- Note: voltage at the inverter end of the distribution line is low (113V)
  - Other customers on the line will be affected
- Some inverters are able to adjust phase so that the power factor can be controlled (e.g. supply power at unity power factor, or leading/lagging)
- See IEEE 1547 (Standard for Interconnecting Distributed Resources with Electric Power Systems)

Grid Connection

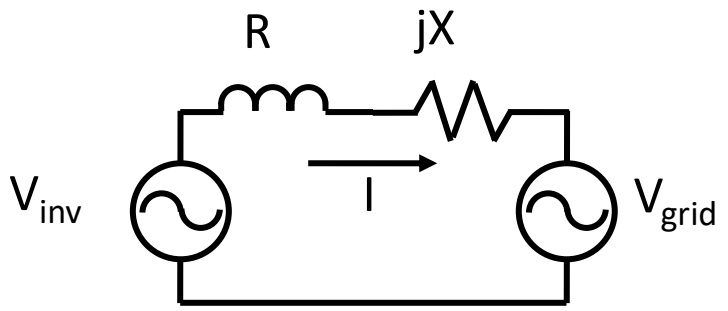
- Now let

$$\mathbf{Z} = 0.1 + j1\Omega$$
$$\mathbf{V}_{grid} = 120\angle 0°\,\mathbf{V}$$

Same as before

$$\mathbf{P} = 6000\mathbf{W}$$
$$\mathbf{Q} = 1500\mathbf{VAR}$$

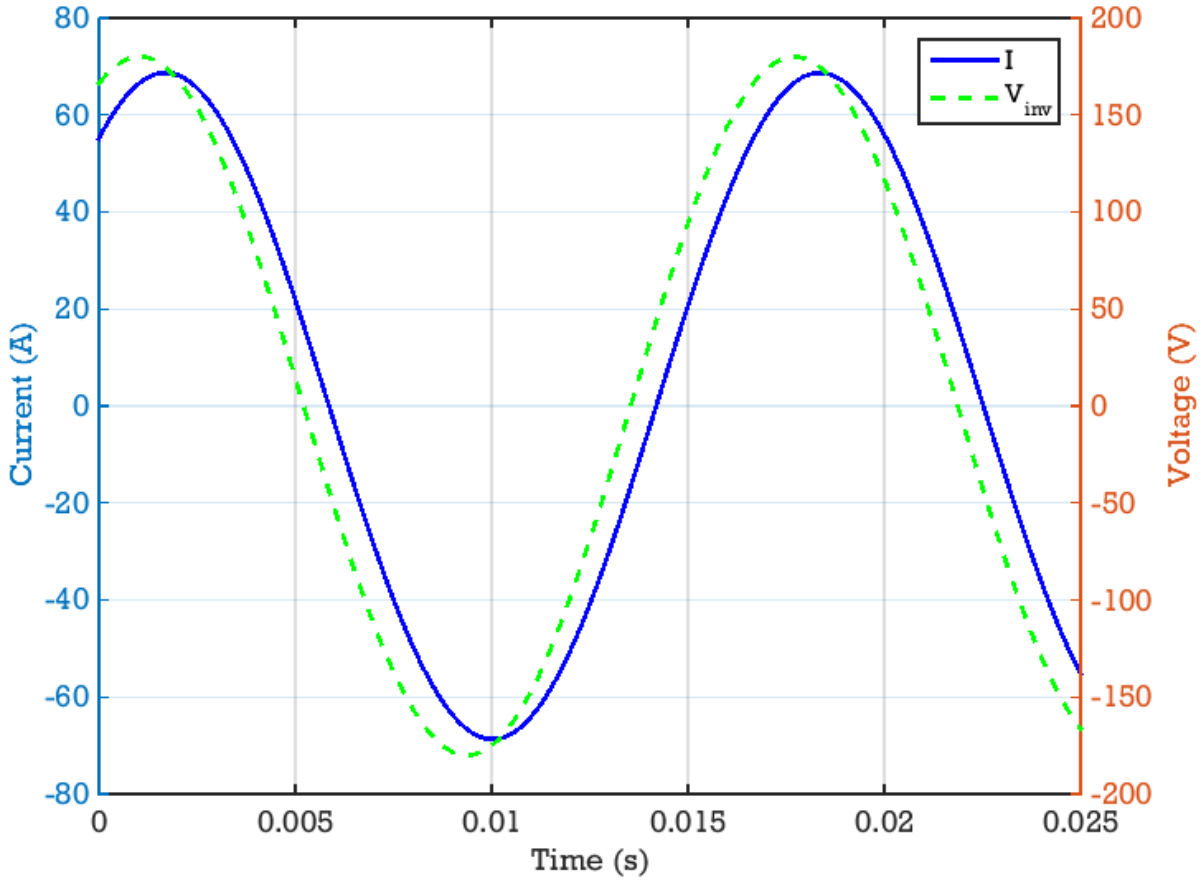
PV supplying reactive power



- We can show that:

$$\mathbf{V}_{inv} = 127.3\angle -22.5°\,\mathbf{V}$$
$$\mathbf{I} = 48.6\angle -36.5°\,\mathbf{A}$$

Inverter Waveforms



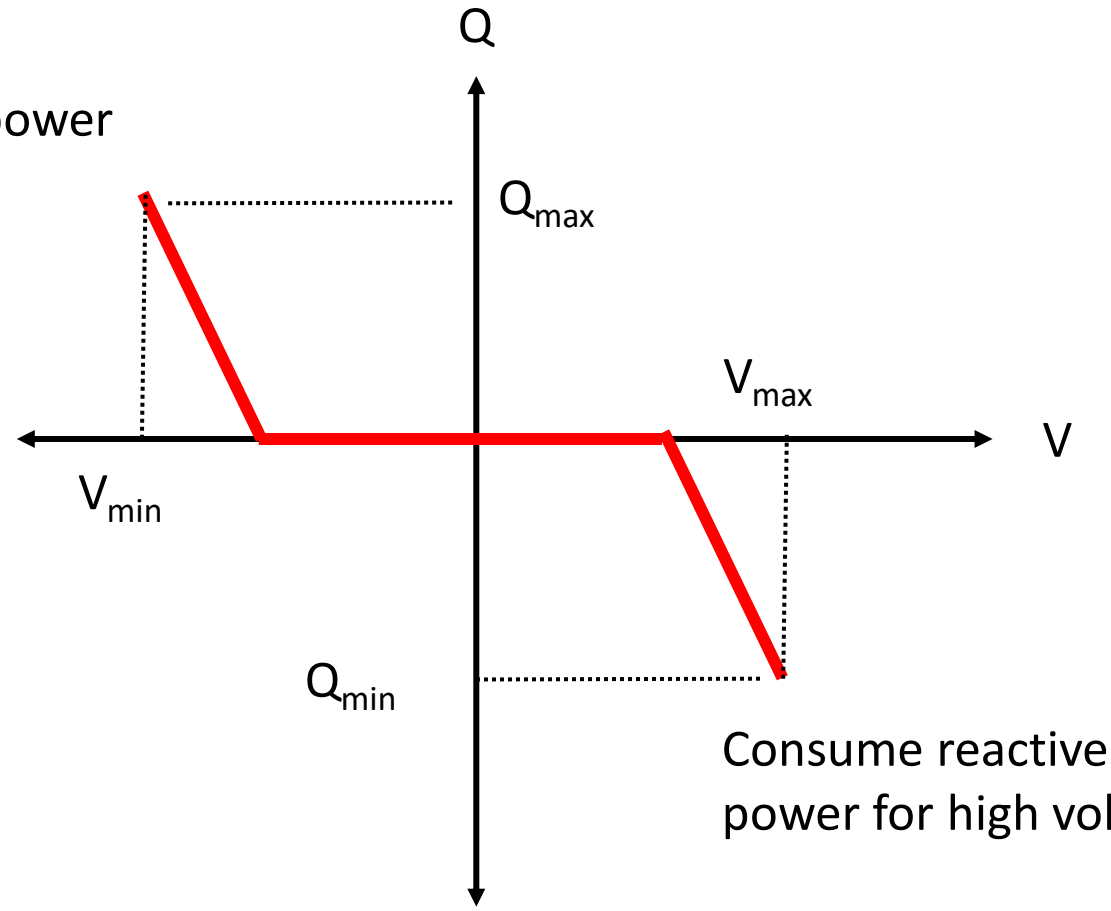
Inverter
current and voltage
are out of phase.

Reactive Power Control

- The voltage at the end of the line is improved
- Inverter is supplying reactive power (PF = 0.97)
- In general, the voltage magnitude at a node is more sensitive to the reactive power than the active power
- Adjust inverter power factor to enhance voltage regulation of the line

Example Control Scheme

Inject reactive power for low voltage



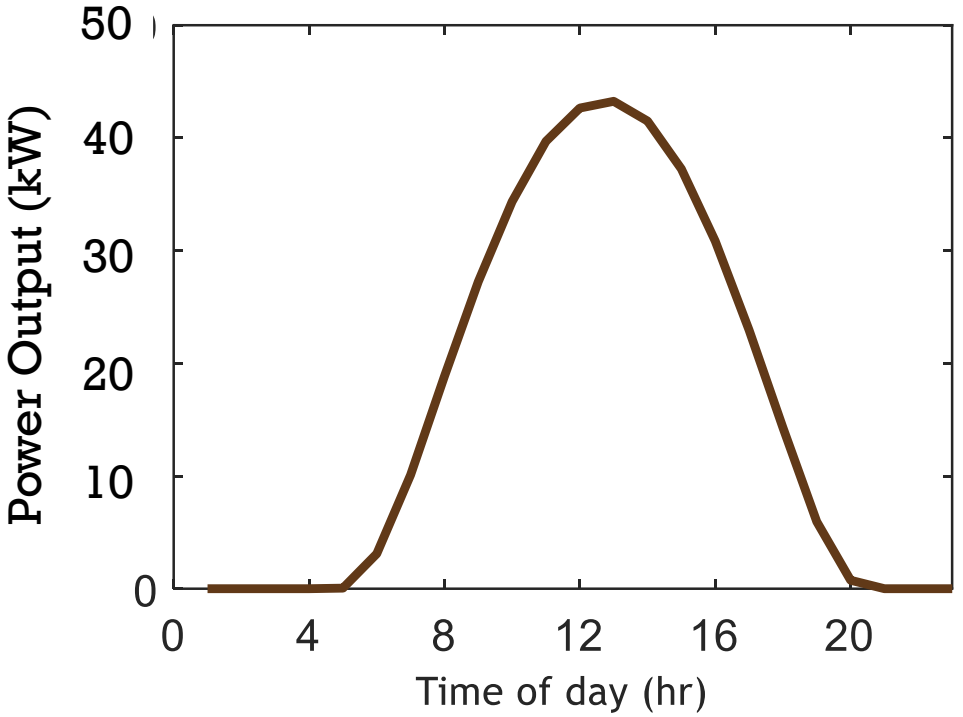
Consume reactive power for high voltages

Inverter Sizing

- Assume you have a PV power plant whose PV array is rated at 45 kW
- What should the power rating of the inverter be?
- What factors should you consider?

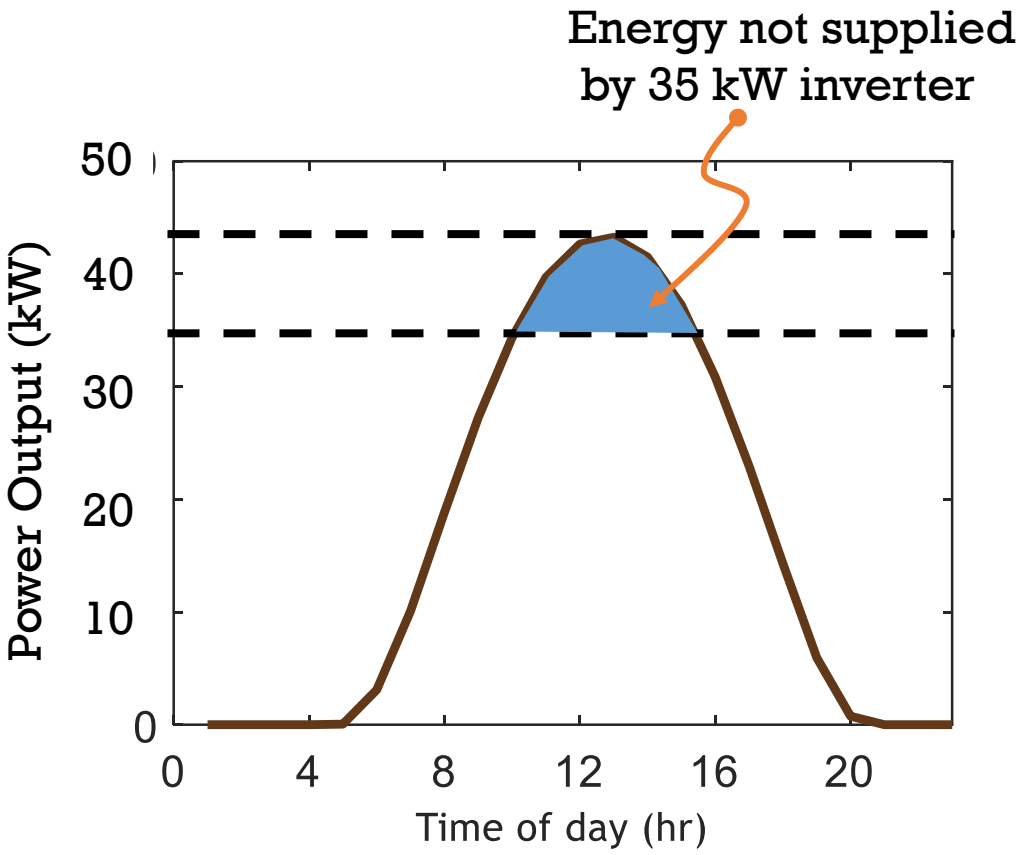
Inverter Sizing

- Recall that a 45 kW array will usually (or maybe never) produce 45 kW
- Power production will vary throughout the year
- Larger inverters cost additional money



Inverter Sizing

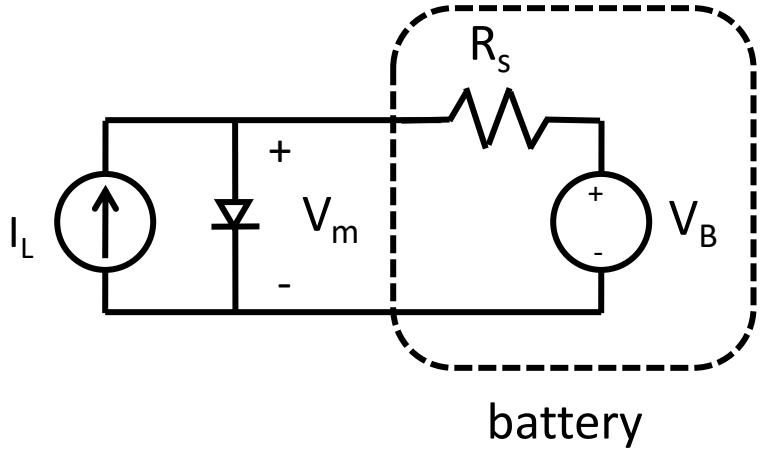
- Consider two inverter sizes, one at 45kW, and one at 35kW
- The 35kW inverter will cost approximately 35/45 = 78% the cost of the 45 kW inverter, but it will not be able to sell all of the energy produced by the array
- If the cost savings exceeds the loss in revenue, then use the small inverter

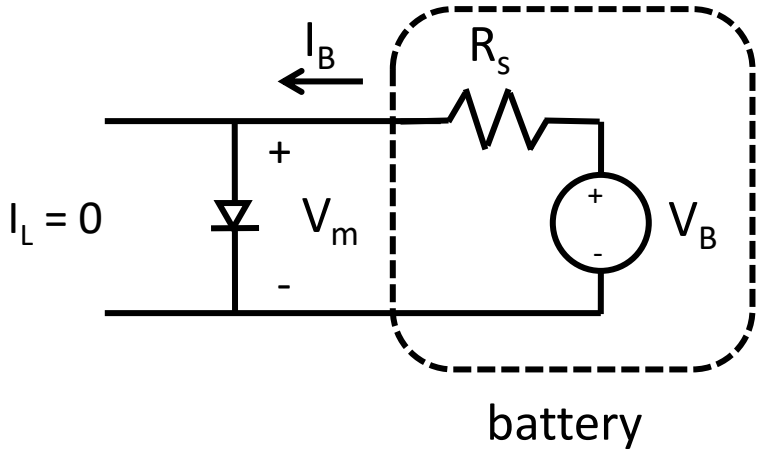


Shading

Discharge Protection

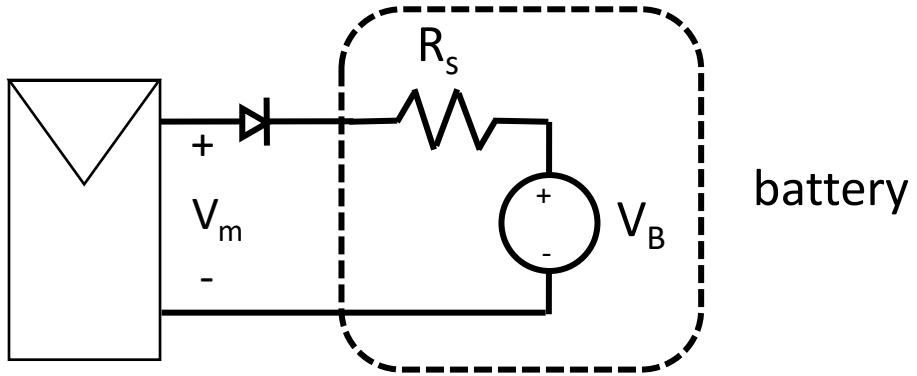
- Consider a PV panel connected to a battery
- What happens at night?
  - $I_L = 0$
  - Diode can be forward biased
    - depends on number of cells in series in the module
  - Battery discharges through PV
  - How can we prevent this?





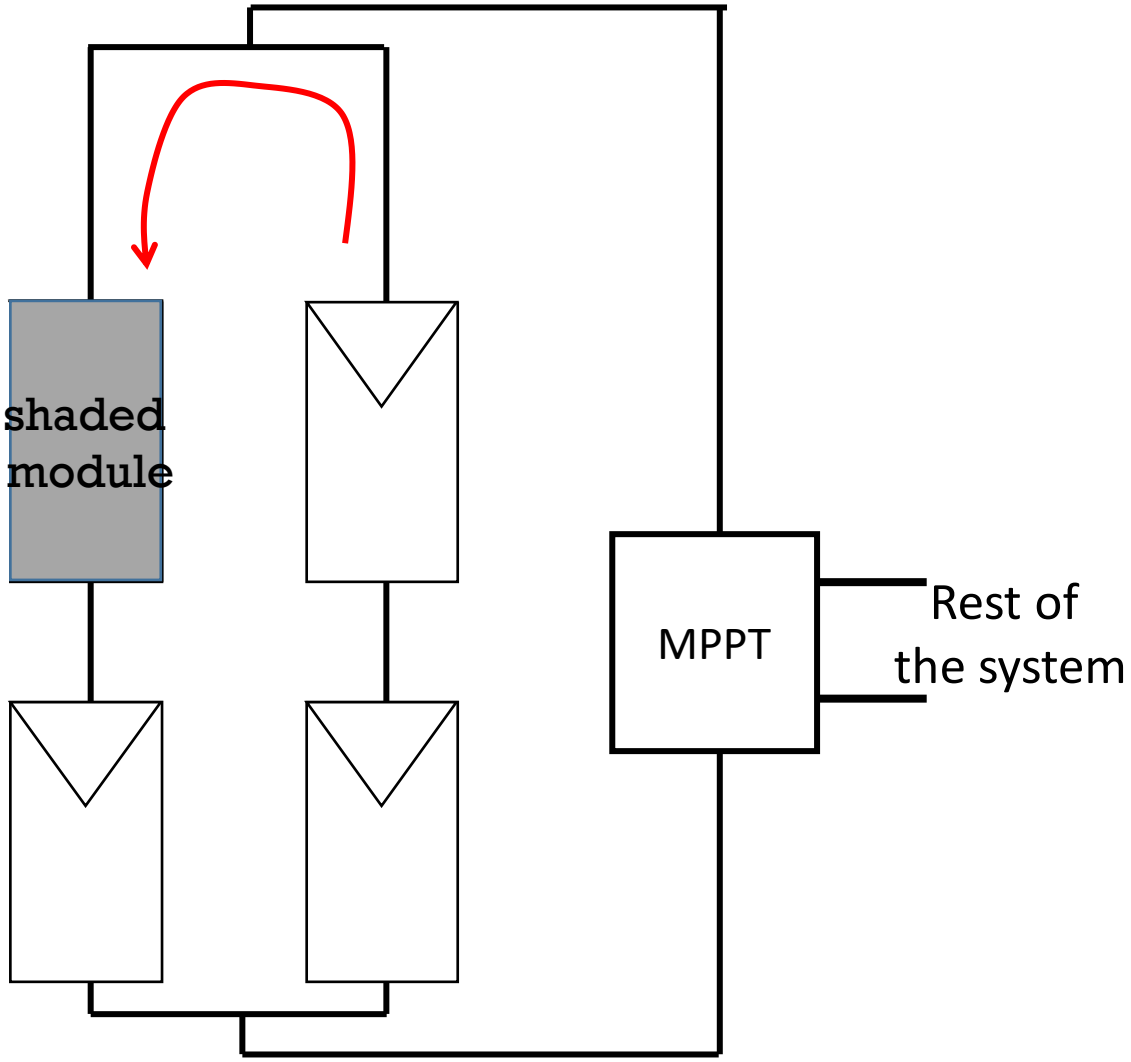
Battery Charging

- Add a blocking diode
- Less efficient operation during charging
  - Power loss due to diode voltage drop
- Prevents discharging when $V_m < V_B$



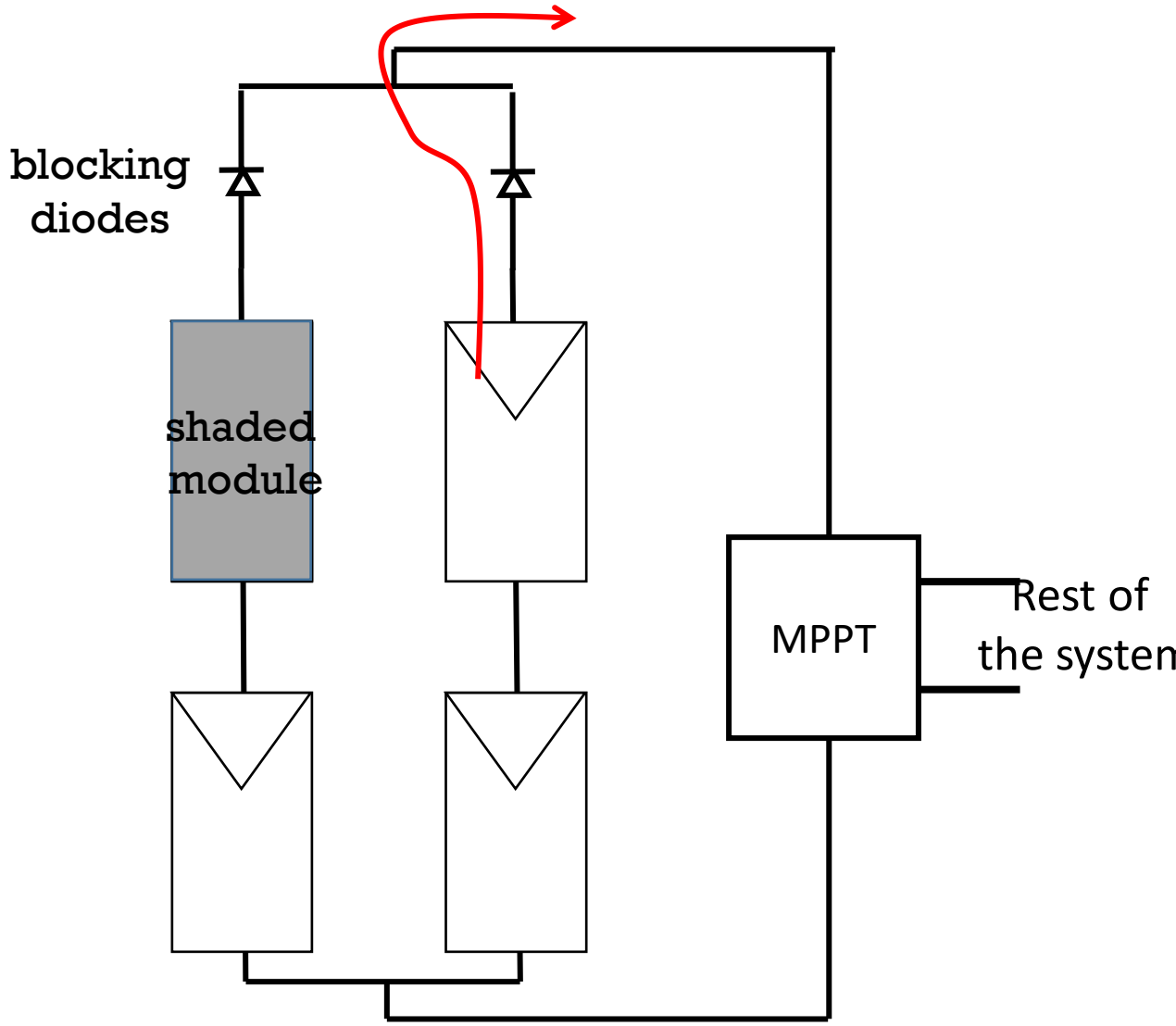
Blocking Diodes

- The same problem can occur when a portion of a PV module (or a PV module in string) is shaded
- Voltage in shaded string is reduced
- Any strings in parallel may have current flow through the shaded string

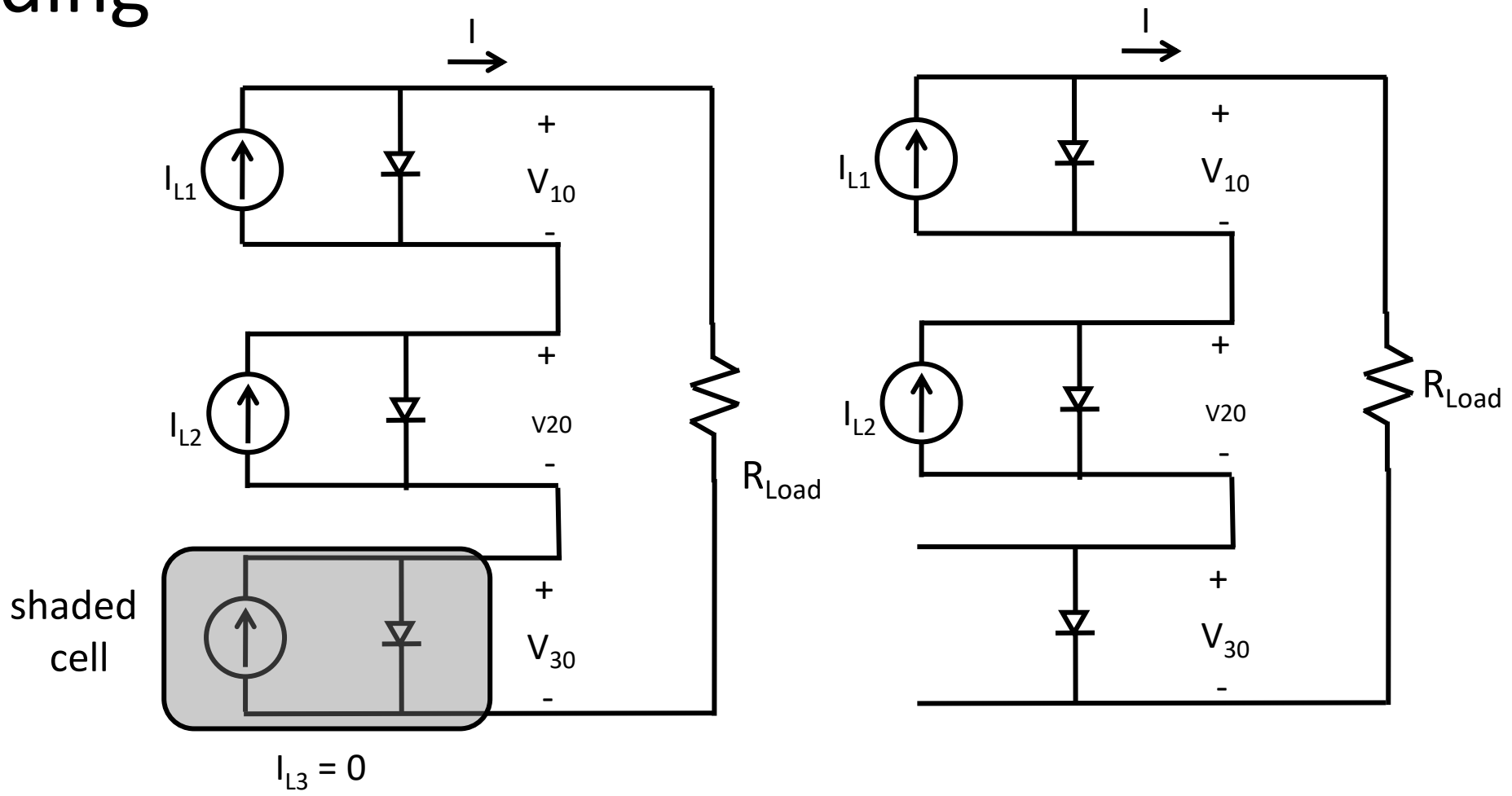


Blocking Diodes

- Blocking diodes installed when strings are in parallel to prevent on string from sending current through the other
- Under unshaded operation, there is loss associated with the blocking diodes

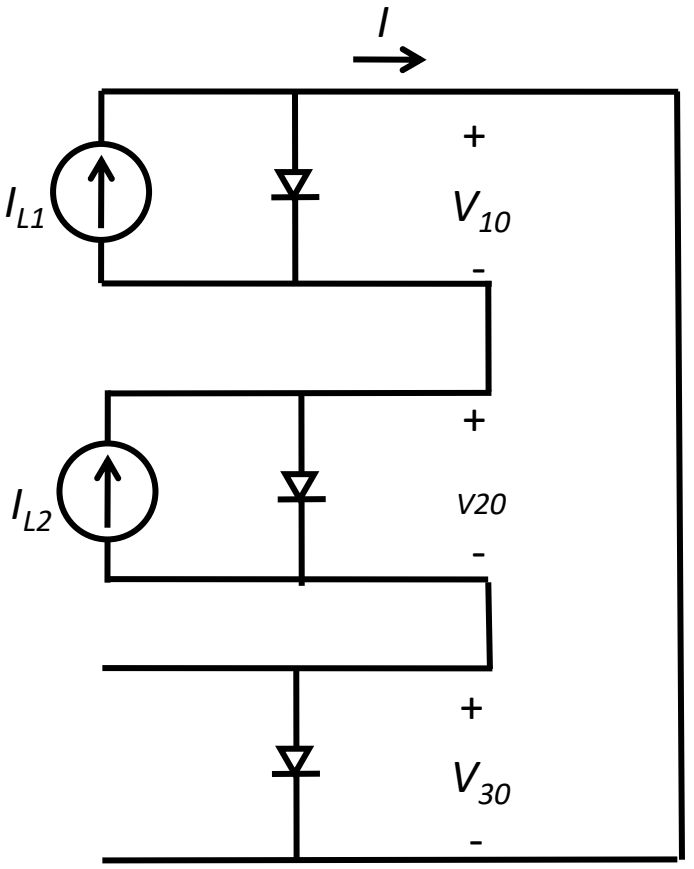


Shading


I
I_{L1}
+
V_{10}
-
+
I_{L2}
V20
-
+
V_{30}
-
R_{Load}
shaded
cell
$I_{L3} = 0$
I
I_{L1}
+
V_{10}
-
+
I_{L2}
V20
-
+
V_{30}
-
R_{Load}

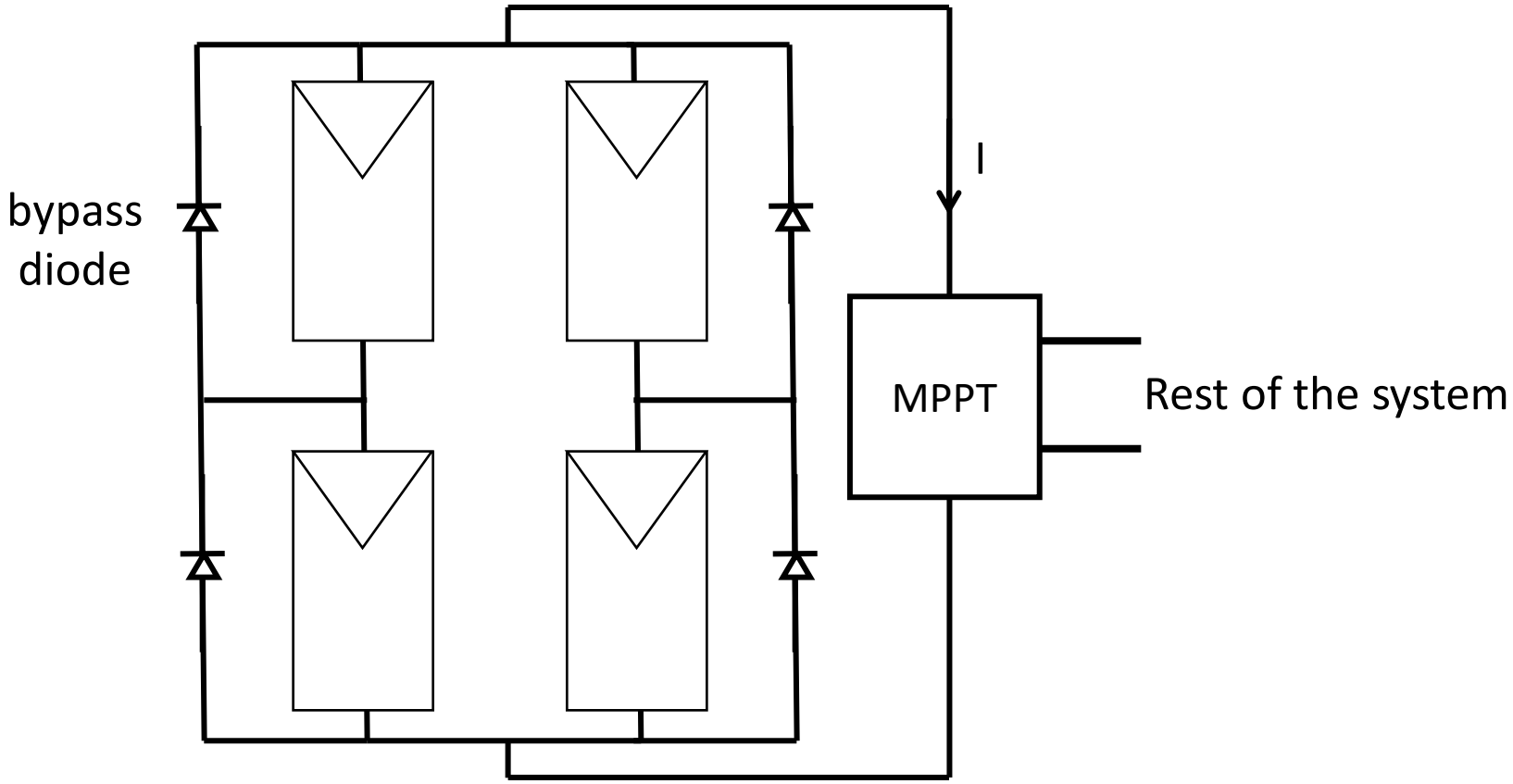
Shading

- Voltage across shaded cell
  - $V_{30} = -V_{10} - V_{20}$
- Shaded cell is a reversed biased diode
- Power is <u>dissipated</u>
  - Overheating and damage can occur
- Output current is severely reduced



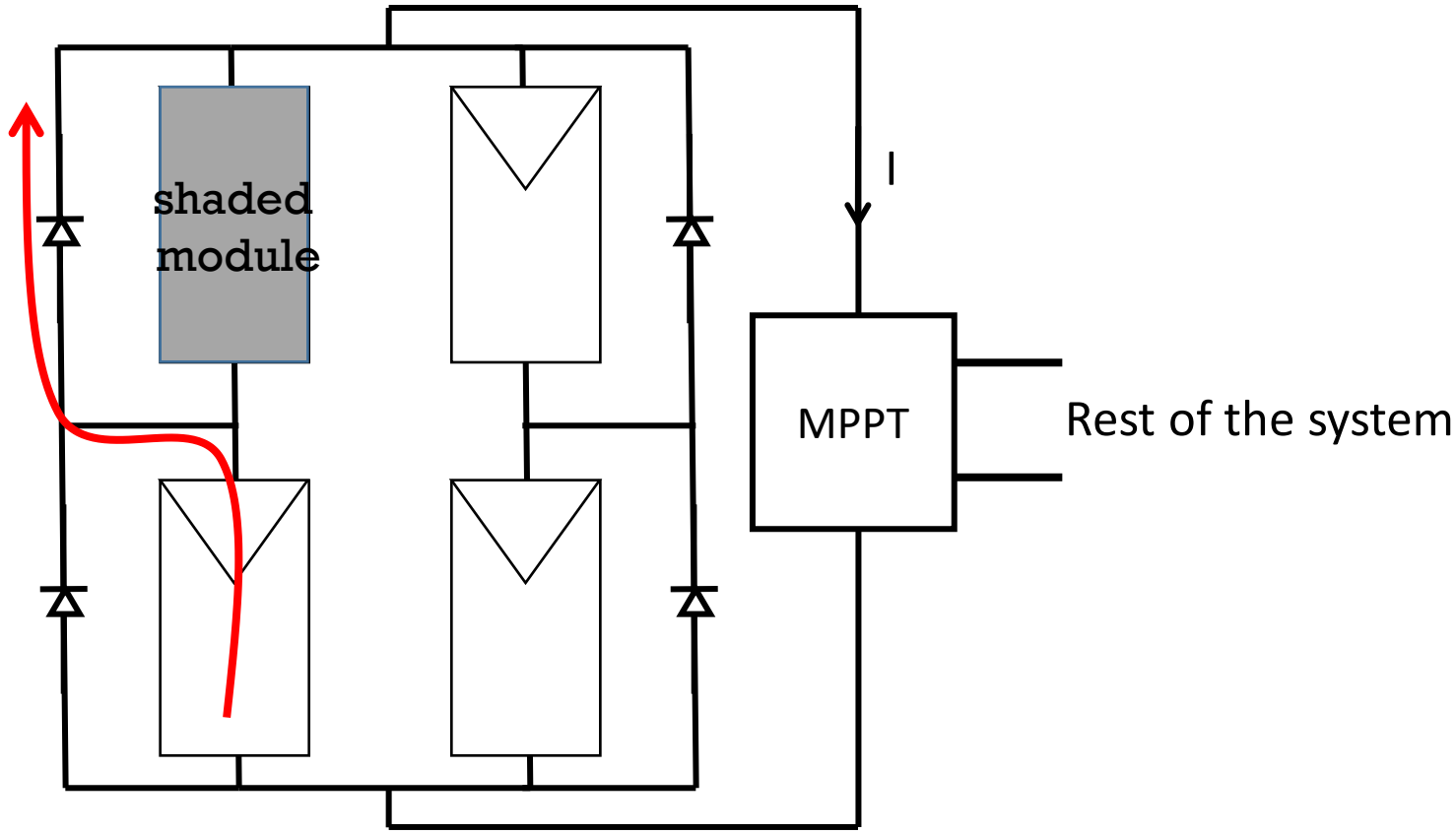
Shading

- Solution to shading is to use bypass diodes (blocking diodes not shown)



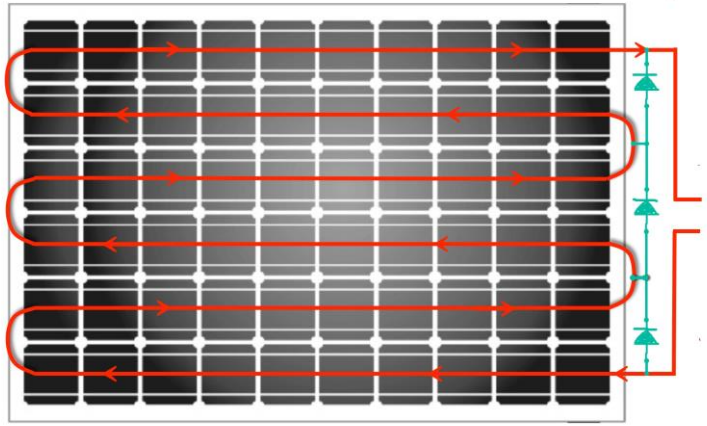
Bypass-Diodes

Current bypasses the shaded module



Bypass diodes

- Most larger PV modules contain bypass diodes



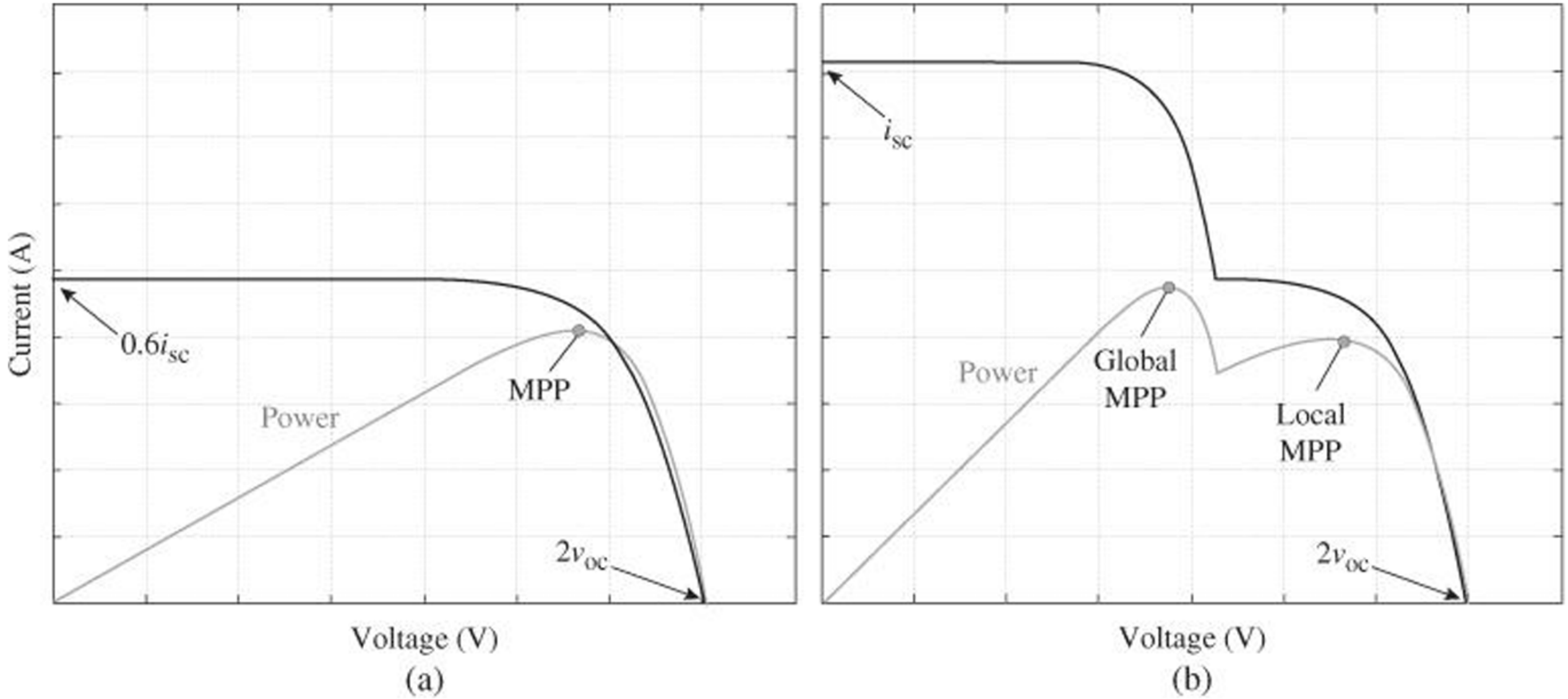
Itek SE 72-Cell Module

Design & Engineering Data

GENERAL DATA	
Cell Type	• 72 high-efficiency monocrystalline p-type cells • 6 x 12 cell matrix
Solar Glass	• Ultra-clear anti-reflective treatment • Tempered, with low iron content • Anti-glare prismatic subsurface texture
Backsheet	• Multi-layered • Engineered adhesion for maximum weather protection
Frame	• High-strength corrosion-resistant anodized aluminum • Compatible with standard racking, accommodating both top-down clamps and bottom-flange mounting
Cable	• 90°C 12AWG PV wire
Junction Box	• 3 bypass diodes • 1000 VDC MC4 connectors • Tigo TS4
Grounding	• Certified for Wiley Electronics WEEB™ grounding clips • Eight standard grounding locations per module for reduced ground wire length

Without bypass diode

With bypass diode



Abu-Rub, Haitham, Malinowski, Mariusz, and Al-Haddad, Kamal. *Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications*. 1st ed. New York: Wiley, 2014. Wiley