11-Inverters, Interconnection and Other Considerations

ECEGR 4530

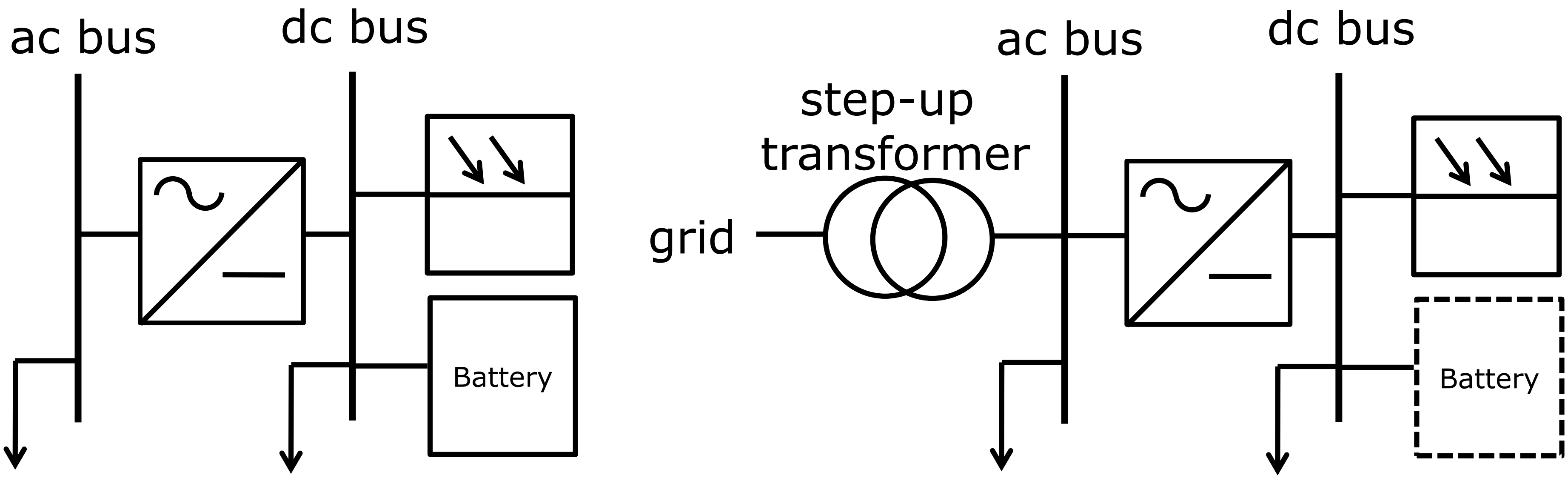
Renewable Energy Systems

Overview

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

Inverters

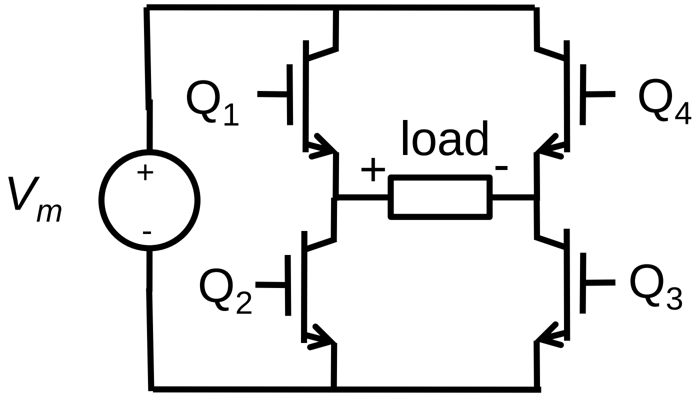
- Inverters are required in stand-alone systems if AC load is to be served OR
- If the systems is grid connected



Consider Stand-alone inverters first

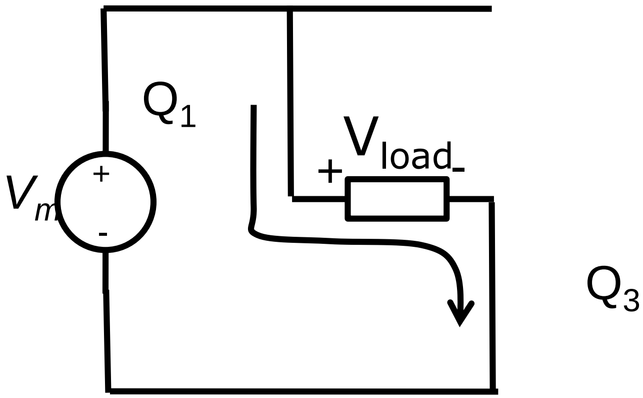
Inverter

- Power MOSFETs or SCRs (Silicon-Controlled Rectifier) used as switches
- Full-bridge inverter
- Square wave inverter switching pairs
  - Q_1, Q_3
  - Q_2, Q_4
- To avoid a dc offset, duty ratio of each switch = 0.50



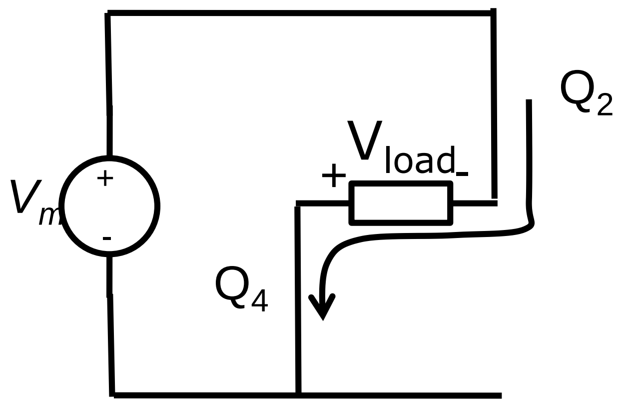
Inverter

- When $Q_1 = Q_3 = 1$
  - $Q_2 = Q_4 = 0$
- Positive voltage applied to load
- Positive current flows

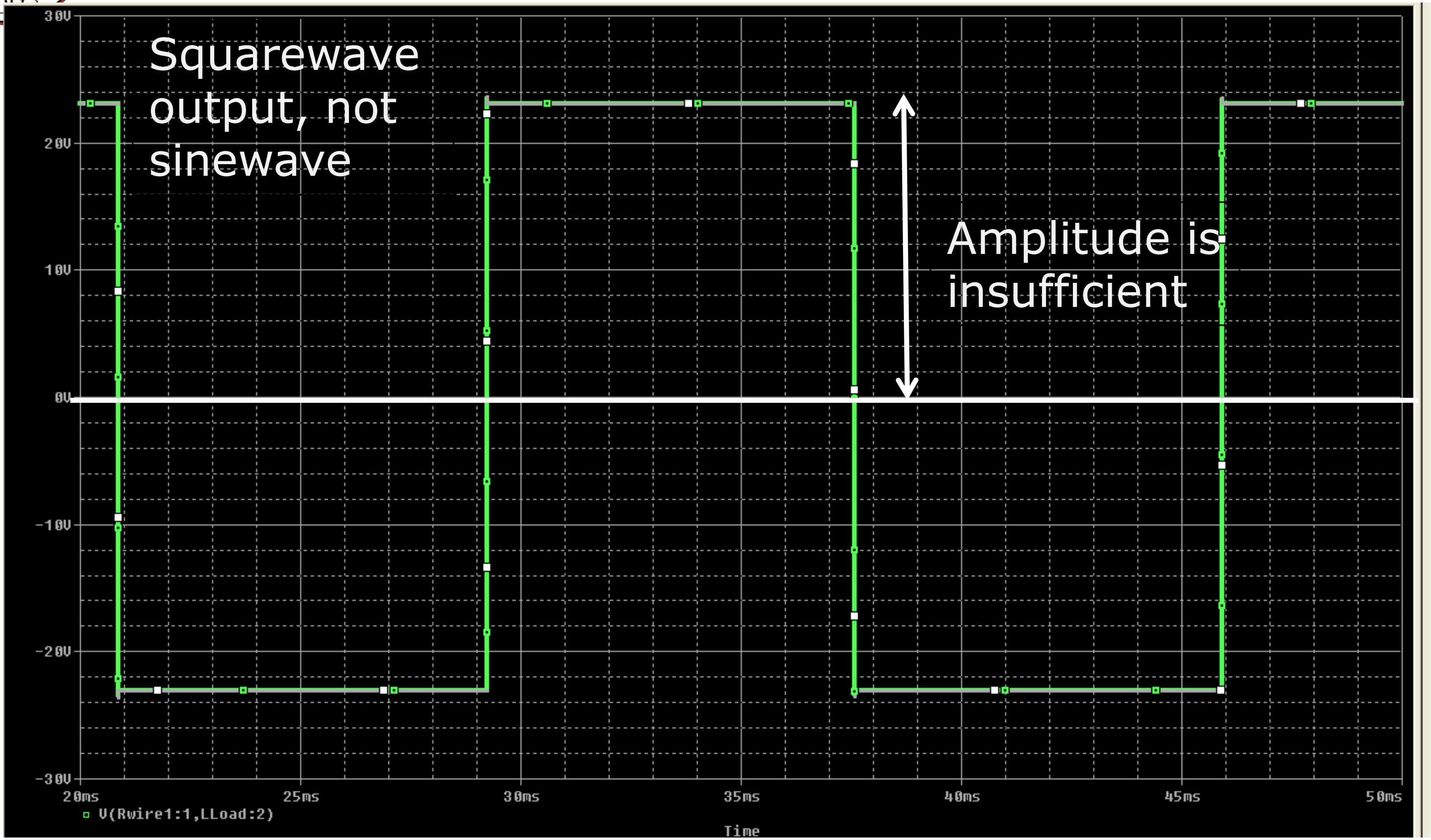


Inverter

- When $Q_2 = Q_4 = 1$
  - $Q_1 = Q_3 = 0$
- Negative voltage applied to load
- Negative current flows

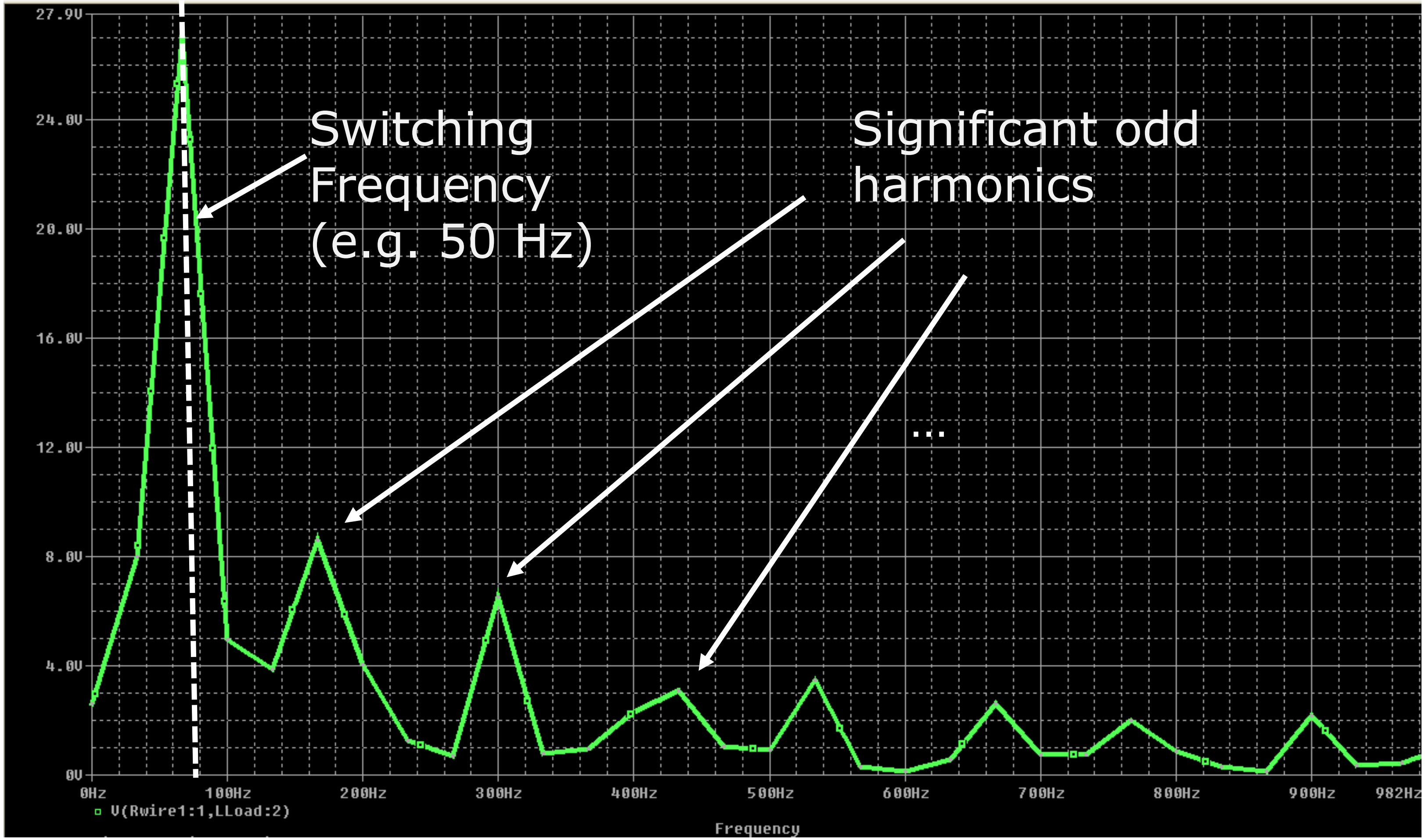


Inverter



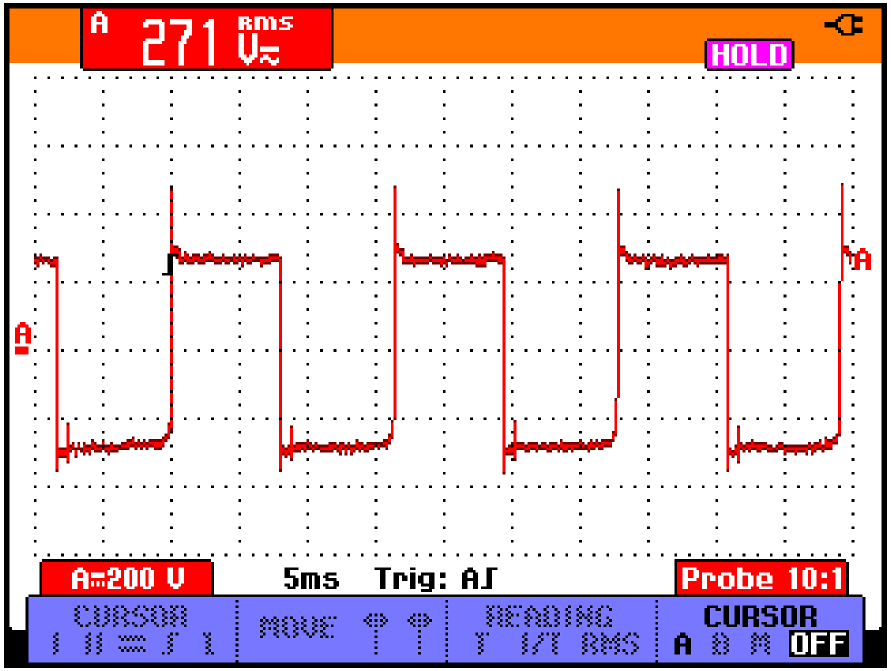
30V
20V
10V
0V
-10V
-20V
-30V
20ms
25ms
30ms
35ms
40ms
45ms
50ms
V(Rwire1:1,LLoad:2)
Time
Squarewave output, not sinewave
Amplitude is insufficient

Inverter



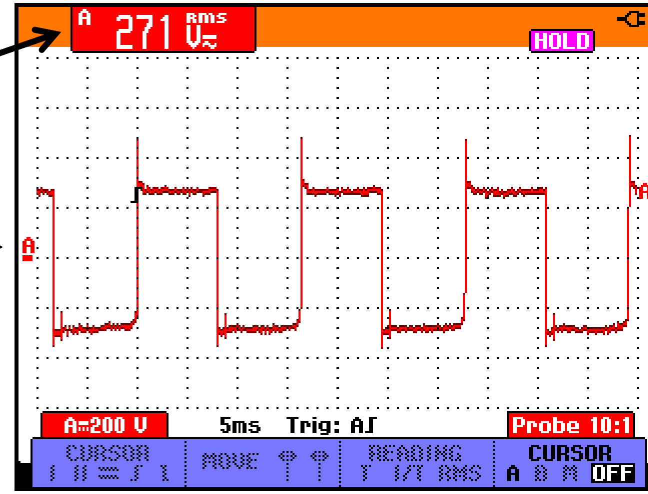
27.9V
24.0V
20.0V
16.0V
12.0V
8.0V
4.0V
0V
0Hz
100Hz
200Hz
300Hz
400Hz
500Hz
600Hz
700Hz
800Hz
900Hz
982Hz
V(Rwire1:1,LLoad:2)
Frequency
Switching Frequency (e.g. 50 Hz)
Significant odd harmonics
...

Squarewave Inverter

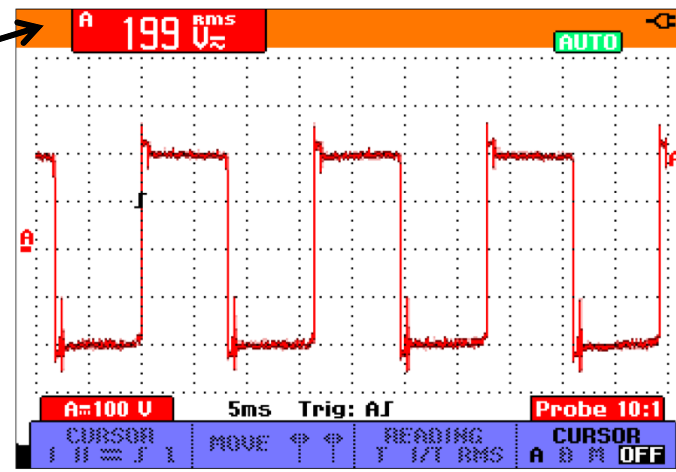


Poor Voltage Regulation

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

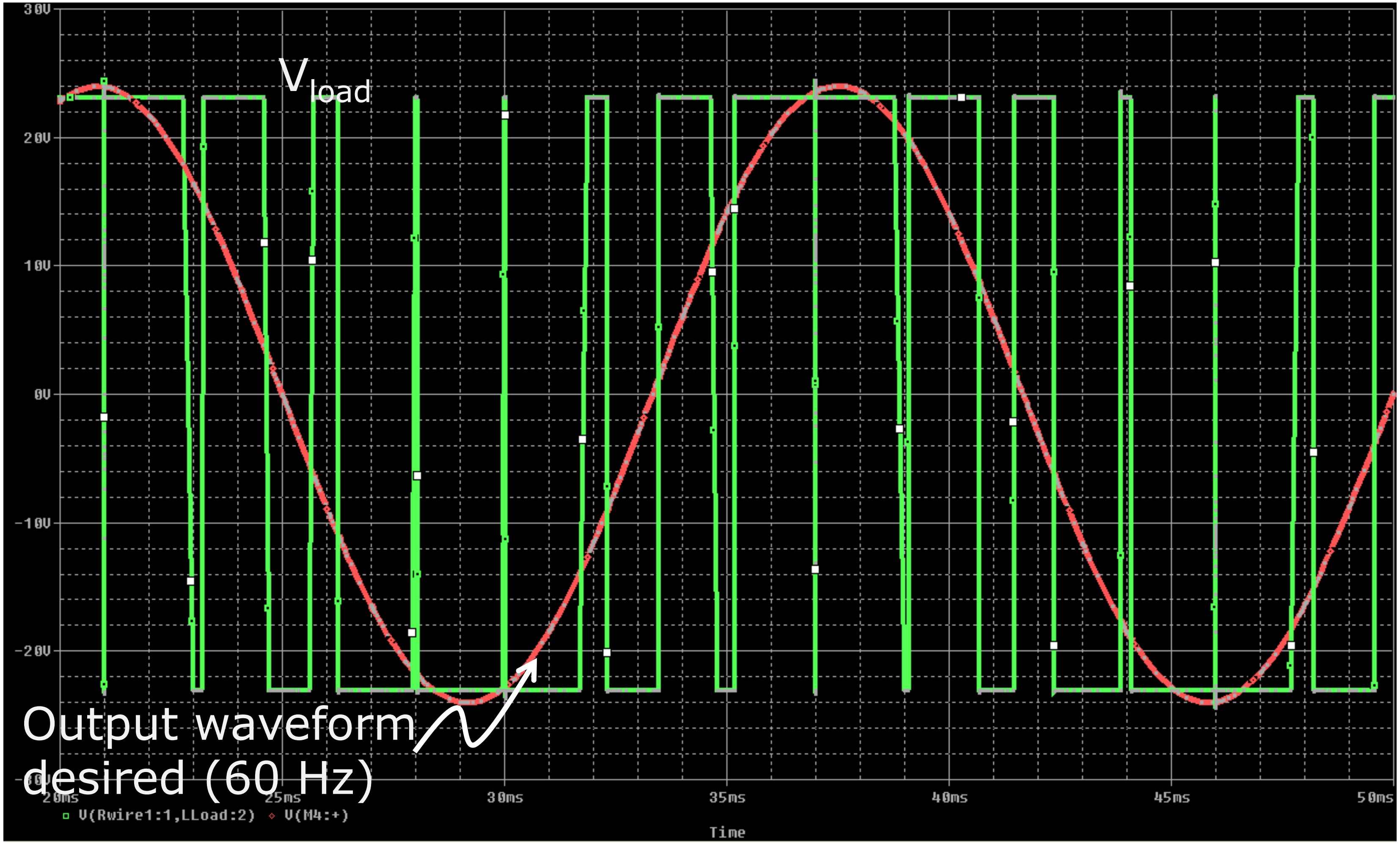
- Full bridge inverter output may be filtered to better approximate a sine wave
  - Significant harmonics are close to fundamental
  - Large capacitor is required
- A better approach is to use pulse width modulation (PWM) to control the switches

PWM Inverter

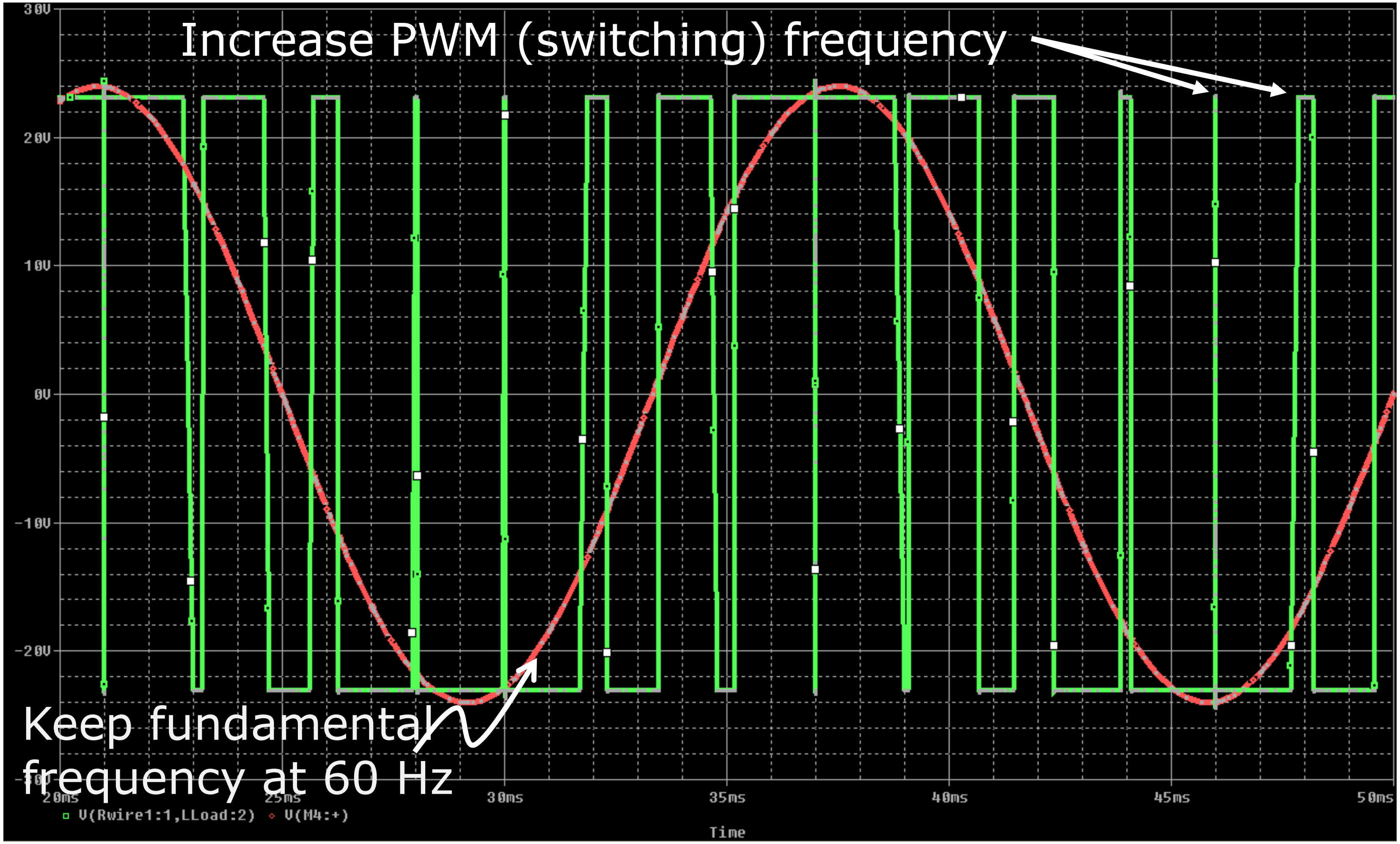
- Switching frequency should be much greater (4kHz - 10kHz) than fundamental frequency (60 Hz or 50 Hz)

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

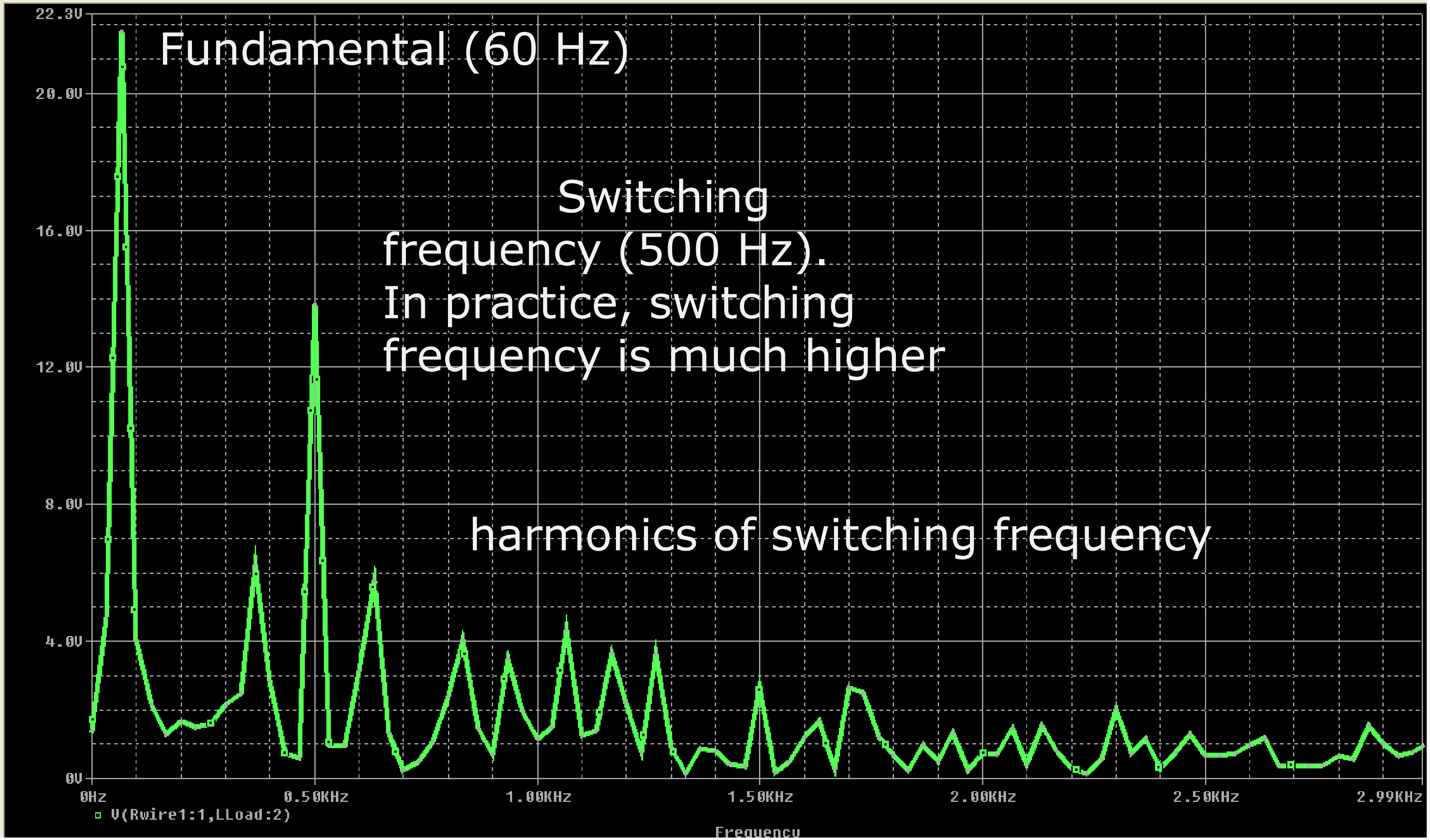
PWM Inverter



PWM Inverter



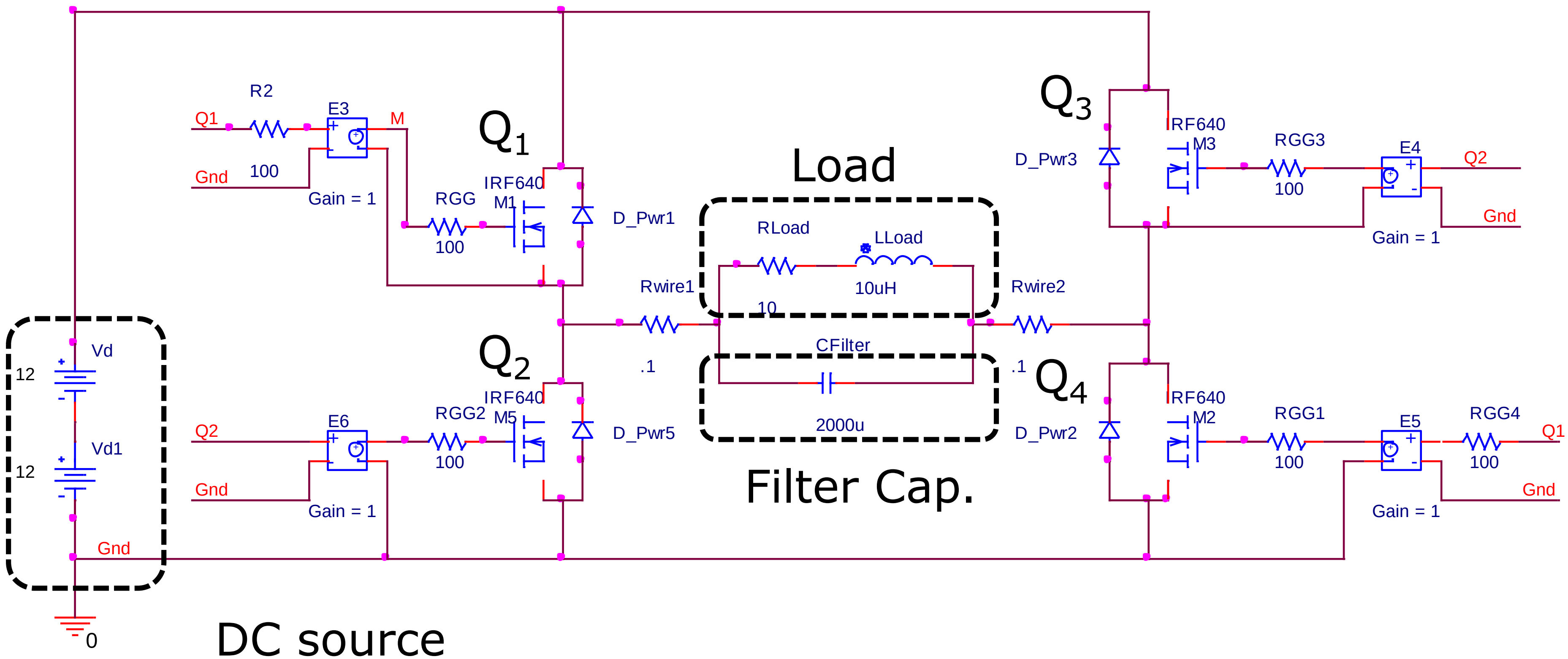
PWM Inverter



PWM Inverter

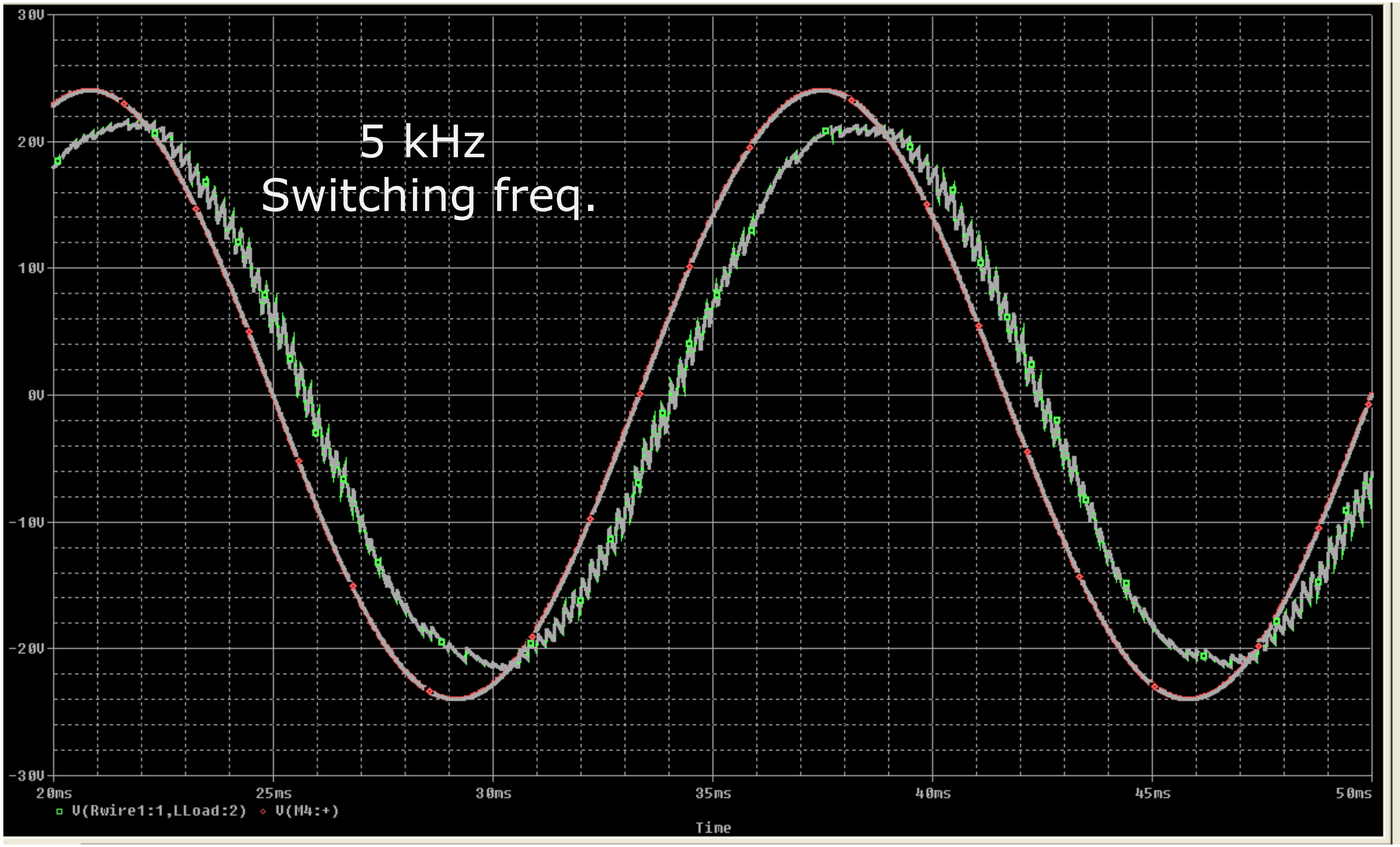
- Use a low-pass filter to remove frequency components greater than the switching frequency
- Result should closely approximate a sine wave

PWM Inverter

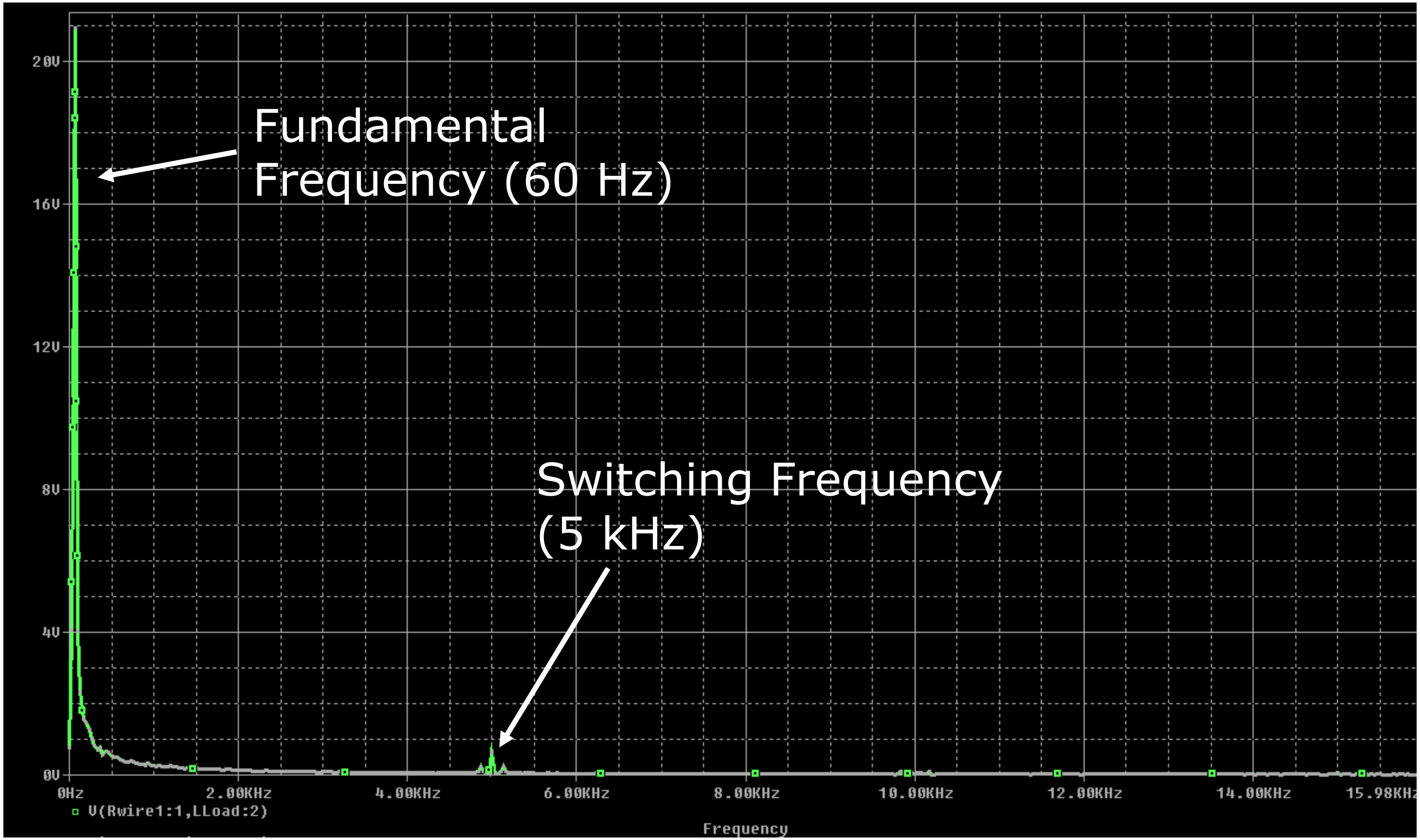


DC source
(Battery or PV with MPPT
or capacitor DC link)

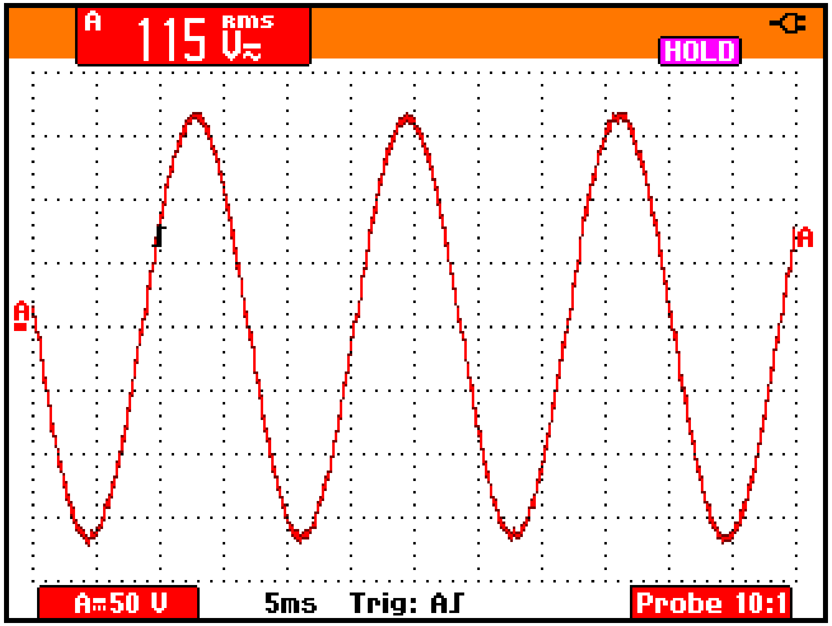
PWM Inverter



PWM Inverter

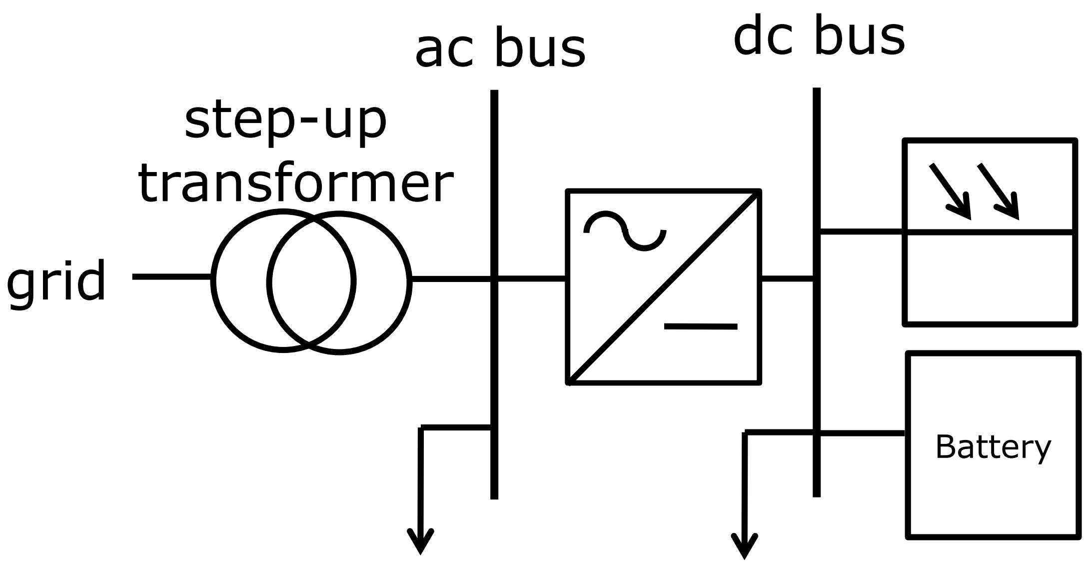


PWM Inverter



Grid Connected System

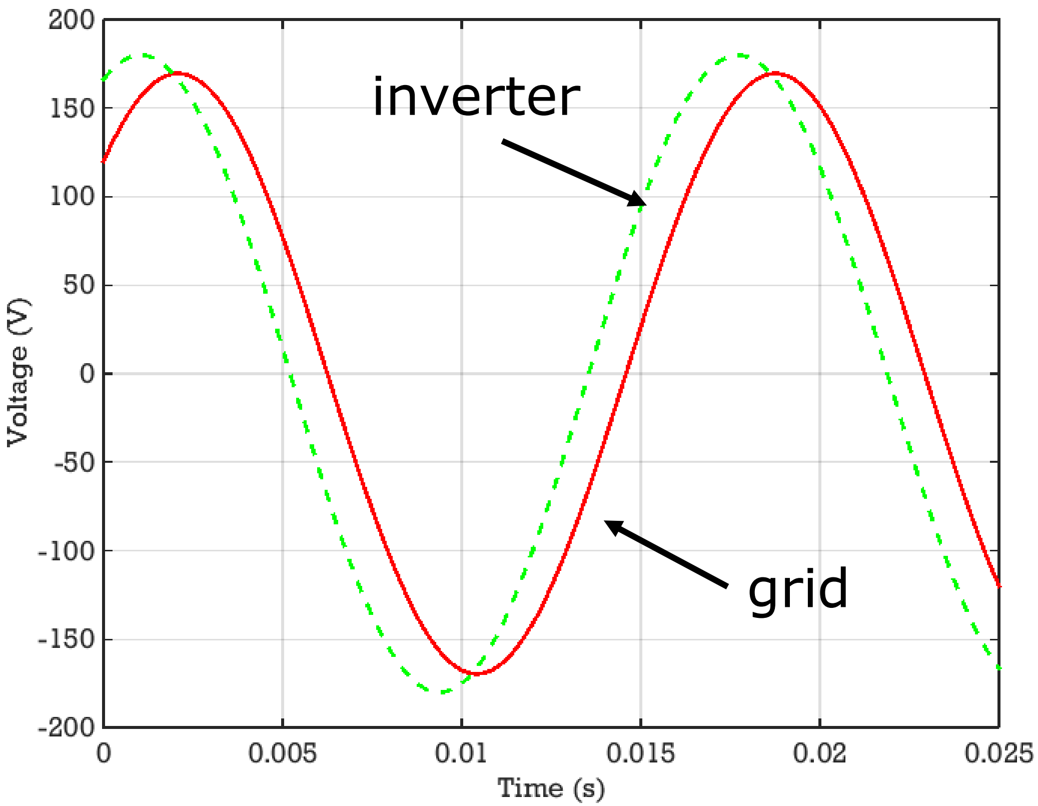
- Now connect to the grid



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

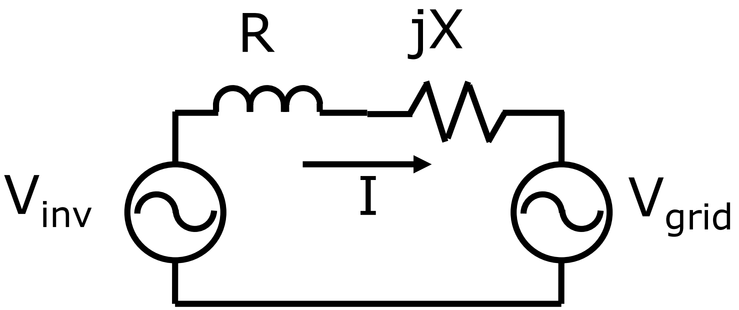
Grid Connection



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.

Grid Connection

- Consider the output of a PV inverter with voltage $\mathbf{V}_{inv}$
- Assume that $\mathbf{V}_{inv}$ is controllable within the limits of the inverter:
  - $|\mathbf{V}_{inv}|$, θ_{inv}, ω_{inv} are controllable
- The grid voltage is fixed $\mathbf{V}_{grid}$
- The distribution line connecting the inverter to the grid is $Z = R + jX$, with $X >> R$



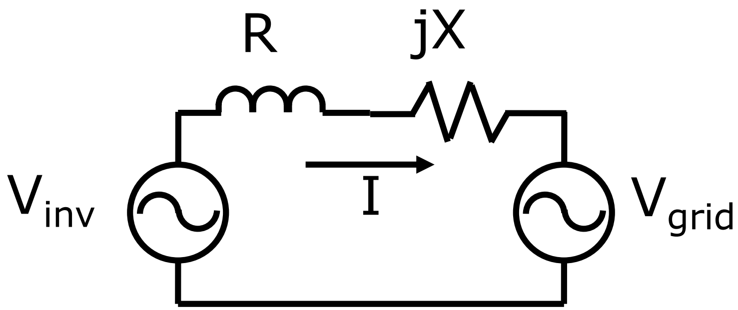
Grid Connection

- Using phasor analysis:

$$\mathbf{V}_{inv} = \mathbf{IZ} + \mathbf{V}_{grid}$$

$$P_{inv} = \mathrm{Re}\left\{\mathbf{V}_{inv}\mathbf{I}^{*}\right\}$$

$$Q_{inv} = \mathrm{Im}\left\{\mathbf{V}_{inv}\mathbf{I}^{*}\right\}$$



Grid Connection

- Let

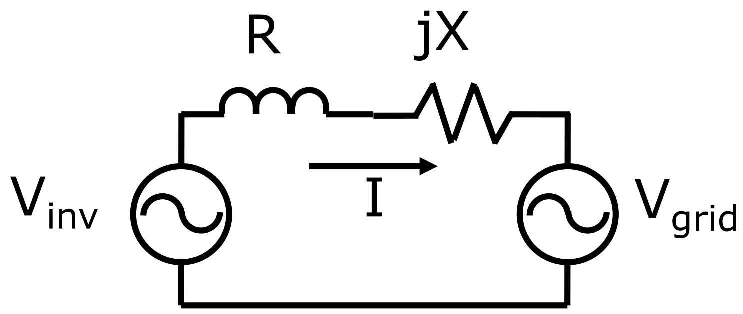
$$\mathbf{Z} = 0.1 + j1\Omega$$

$$\mathbf{V}_{grid} = 120\angle 0^\circ \mathbf{V}$$

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

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

} Production from PV

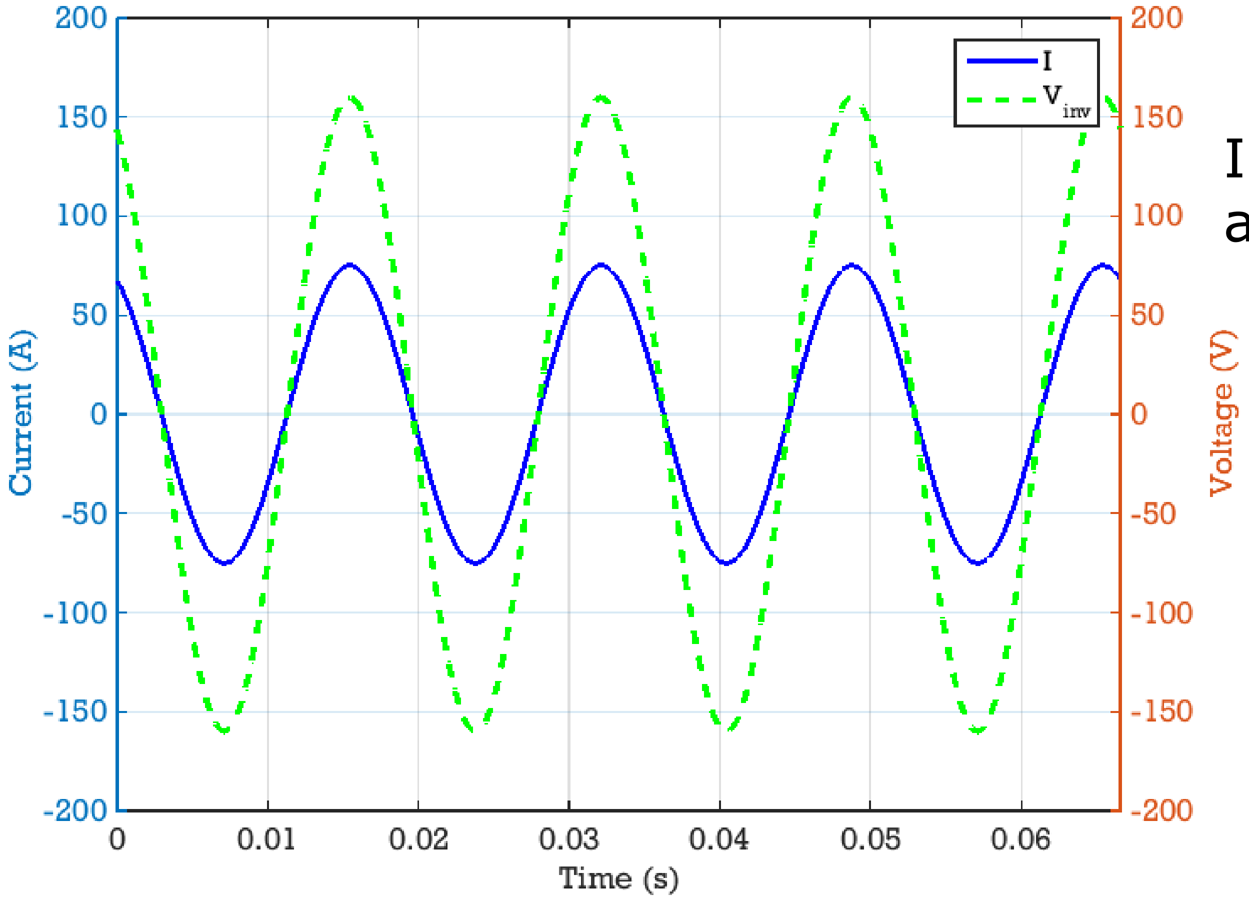


- We can show that:

$$\mathbf{V}_{inv} = 113\angle 26.2^\circ \mathbf{V}$$

$$\mathbf{I} = 53.1\angle 26.2^\circ \mathbf{A}$$

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

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

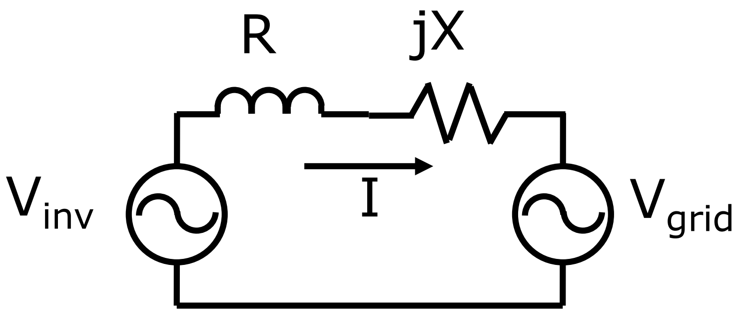
$$\mathbf{V}_{grid} = 120\angle 0°\,\mathbf{V}$$

Same as before

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

$$\mathbf{Q} = 1500\mathbf{VAR}$$

PV supplying reactive power

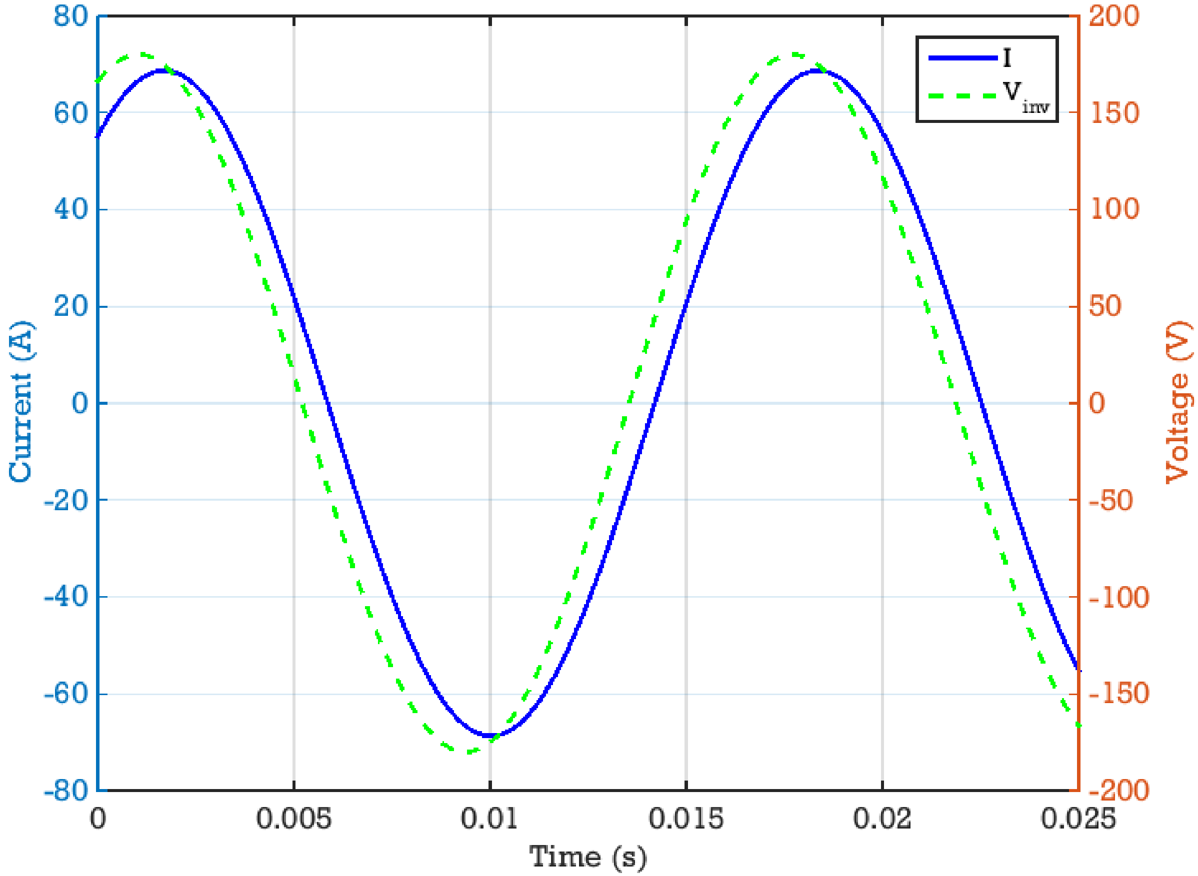


- We can show that:

$$\mathbf{V}_{inv} = 127.3\angle -22.5°\,\mathbf{V}$$

$$\mathbf{I} = 48.6\angle -36.5°\,\mathbf{A}$$

Inverter Waveforms

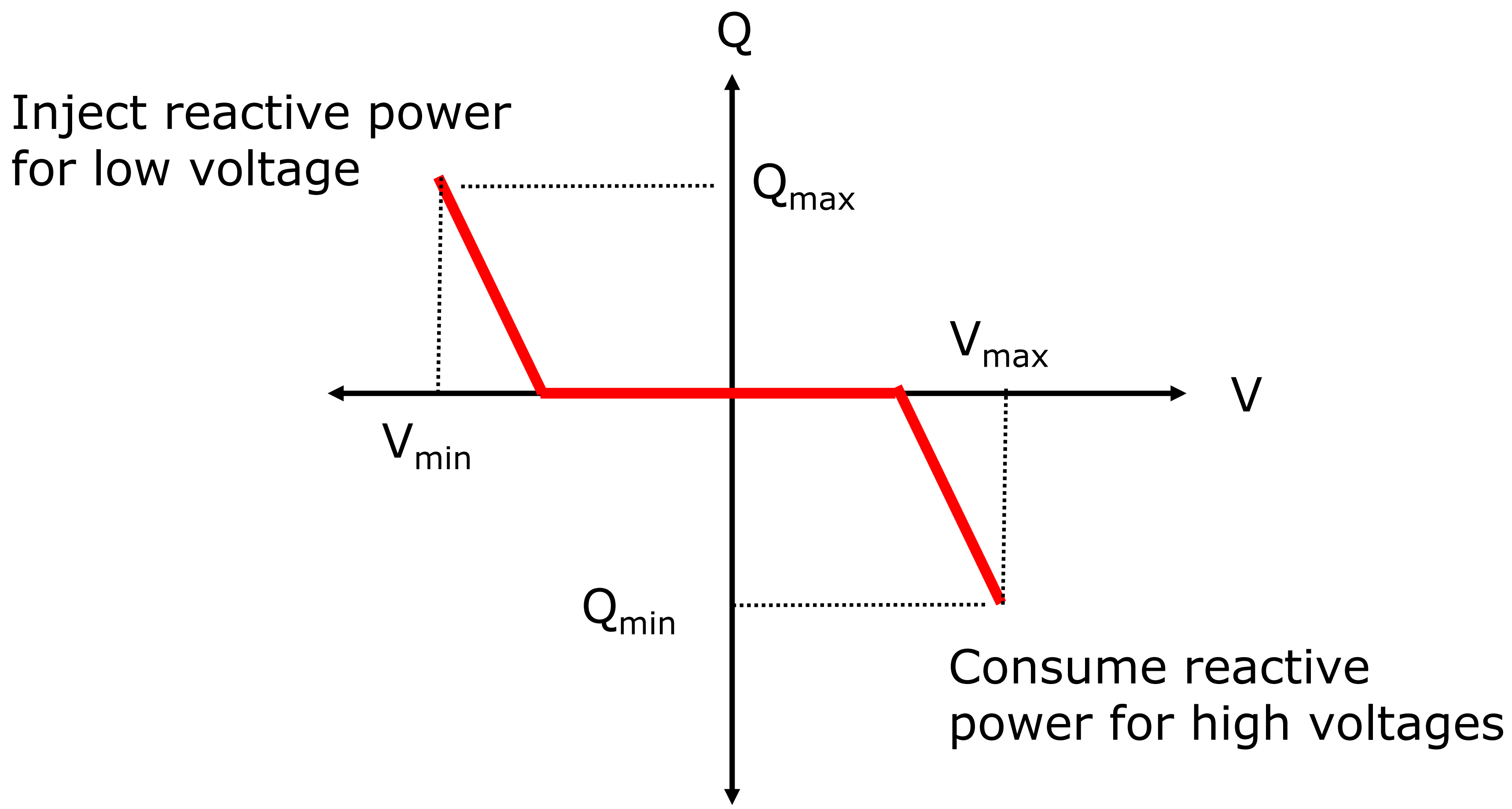


Inverter current and voltage are out of phase.

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

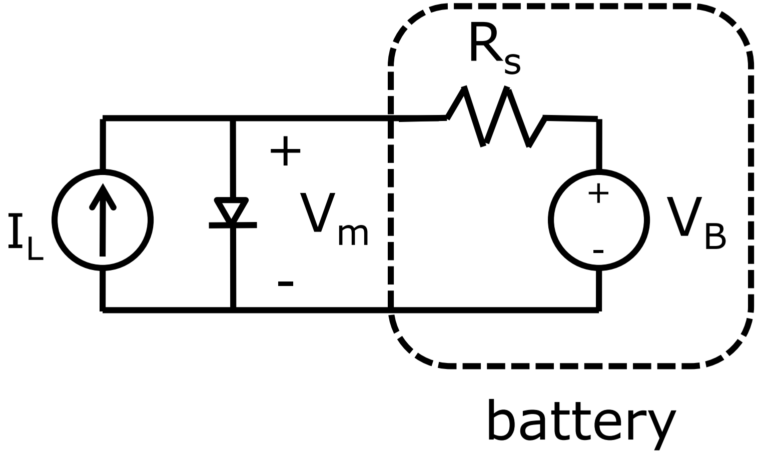


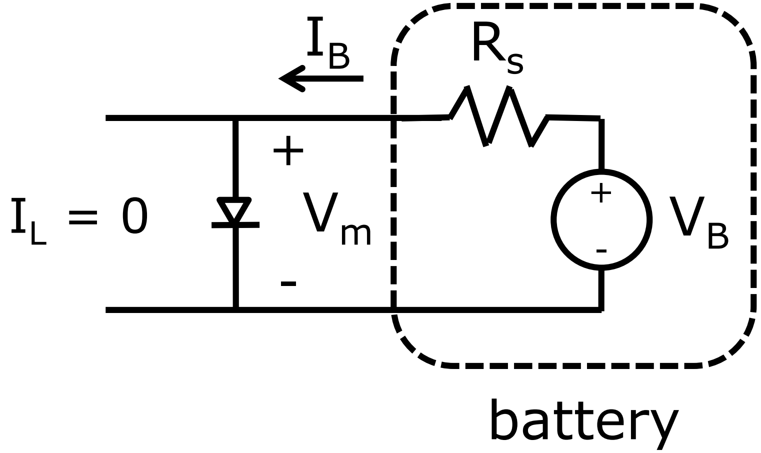
Reading

- http://spectrum.ieee.org/green-tech/solar/how-rooftop-solar-can-stabilize-the-grid

Discharge Protection

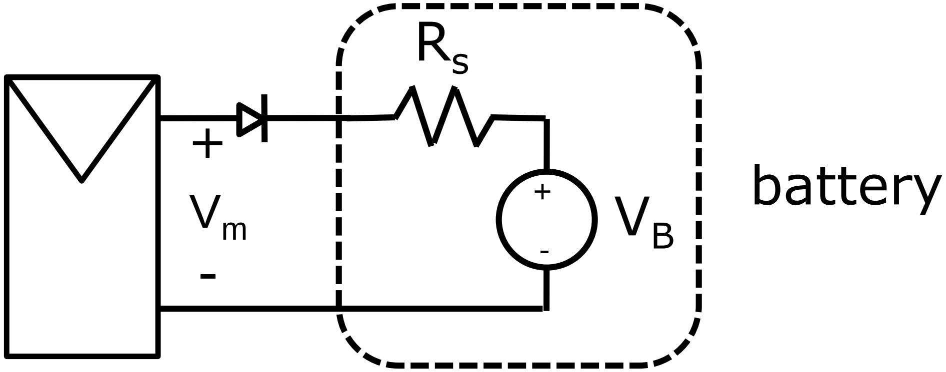
- Consider a PV panel connected to a battery
- What happens at night?
  - $I_L = 0$
  - Diode can be forward biased
    - depends on number of cells in series in the module
  - Battery discharges through PV
  - How can we prevent this?





Battery Charging

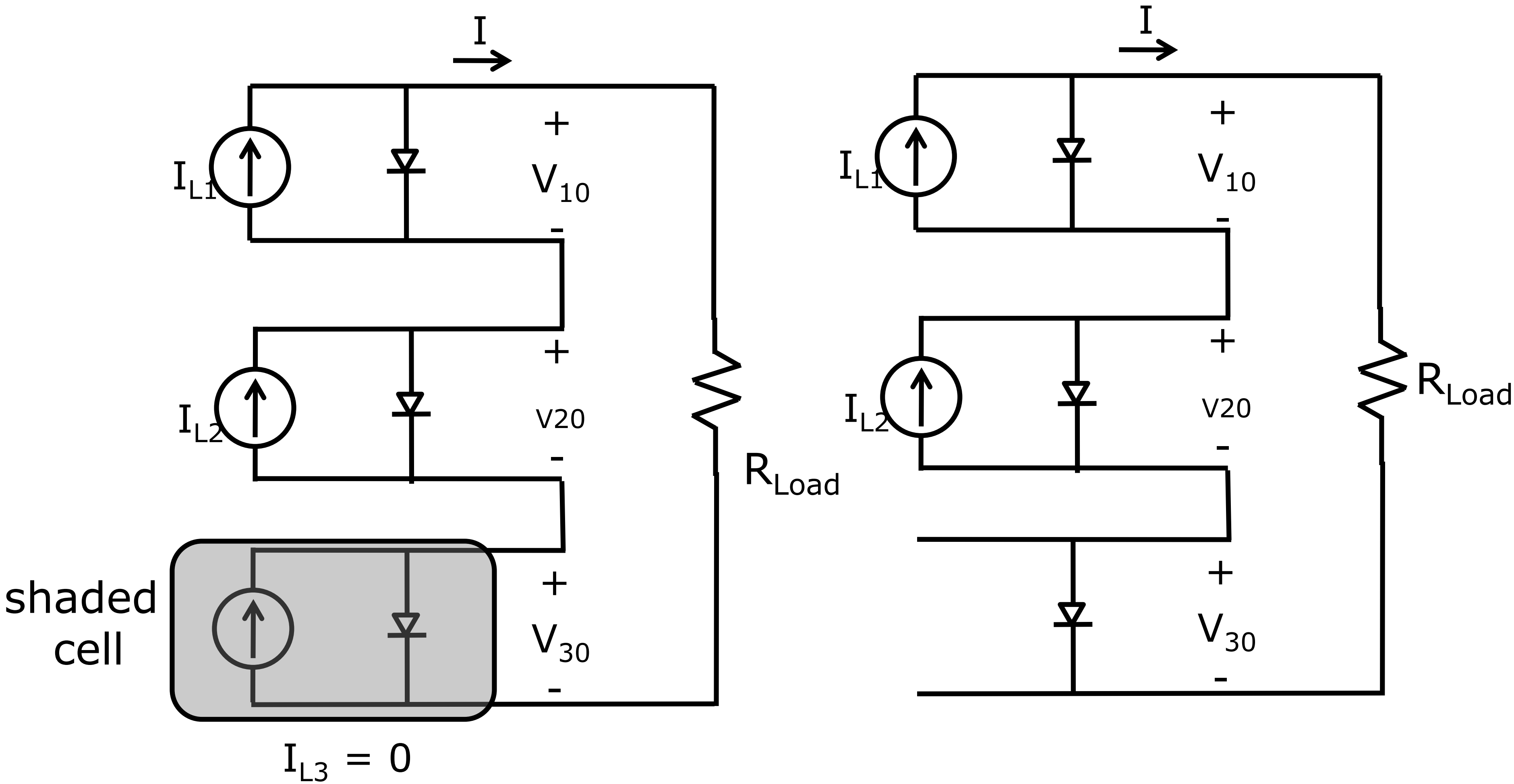
- Add a blocking diode
- Less efficient operation during charging
  - Power loss due to diode voltage drop
- Prevents discharging when $V_m < V_B$



Shading

- What happens when a portion of a PV module is shaded?

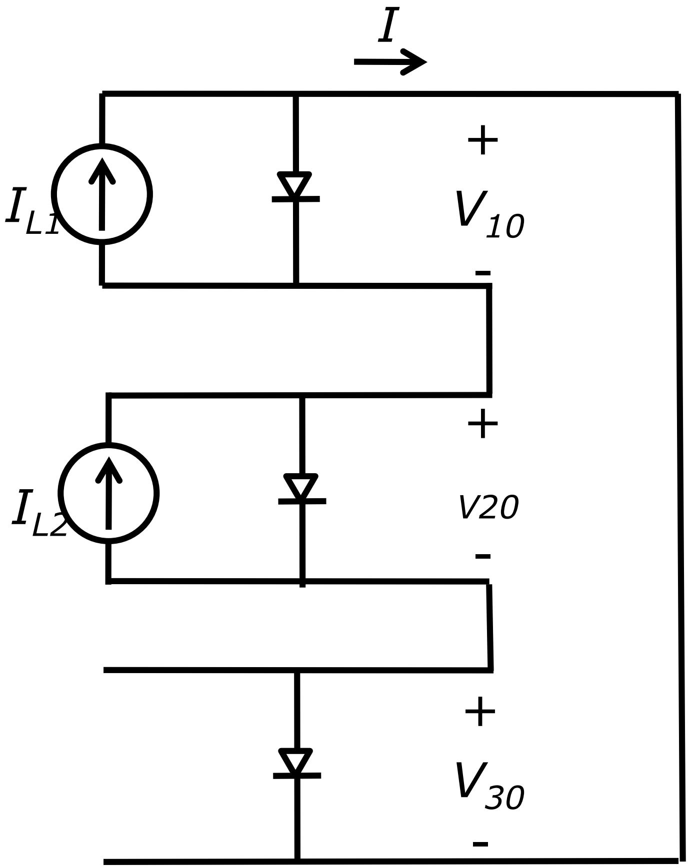
Shading



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

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