12-Batteries and Inverters

ECEGR 452

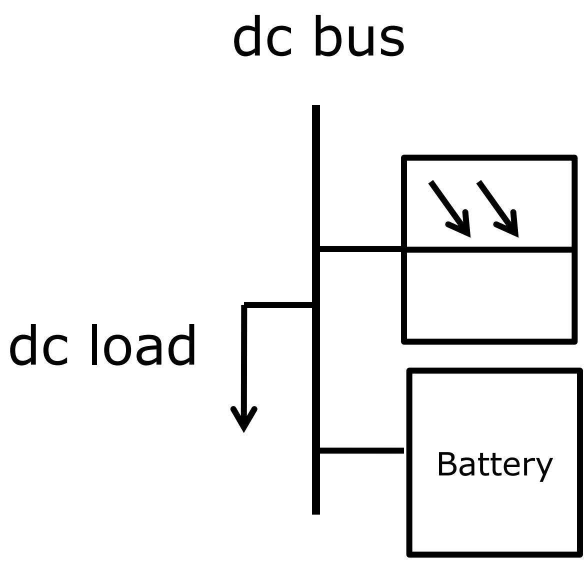
Renewable Energy Systems

Overview

- Batteries
- Lead-Acid Batteries
- Battery Specifications
- Battery Charge Controllers
- Inverters

Batteries

Incorporation of a battery is common for stand alone systems



Batteries

- Store electrical energy as chemical energy
- Nominally 6 V, 12 V or 24 V
  - series combinations used to achieve higher voltages
- Common types:
  - lead-acid
  - nickel-cadium
  - several others

Lead-Acid Batteries

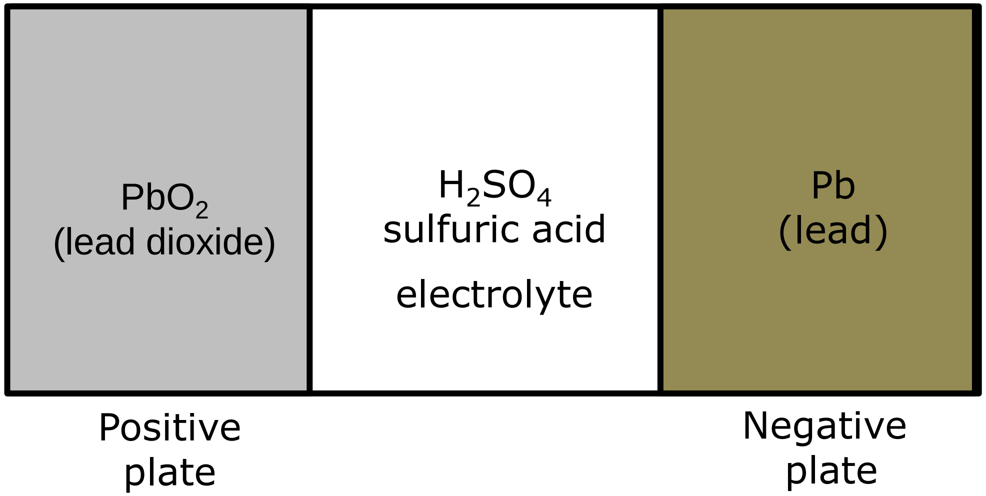
- Mature technology (invented in 1859 by Planté)
- Very common in photovoltaic systems
- Advantages:
  - Low cost ($0.15 to $0.50 per Wh)
  - High power-to-weight ratio
  - Low self-discharge
  - Good low and high temperature performance

Lead-Acid Batteries

- Disadvantages
  - Heavy
  - Low energy-to-weight ratio
  - Slow charge rate
  - Limited cycle life (<500)
  - Less durable than other batteries
  - Safety hazard (sulfuric acid)
  - Environmental hazard

Lead-Acid Batteries

Charged Battery Cell



Note: anode and cathode designation switches depending on charge or discharge

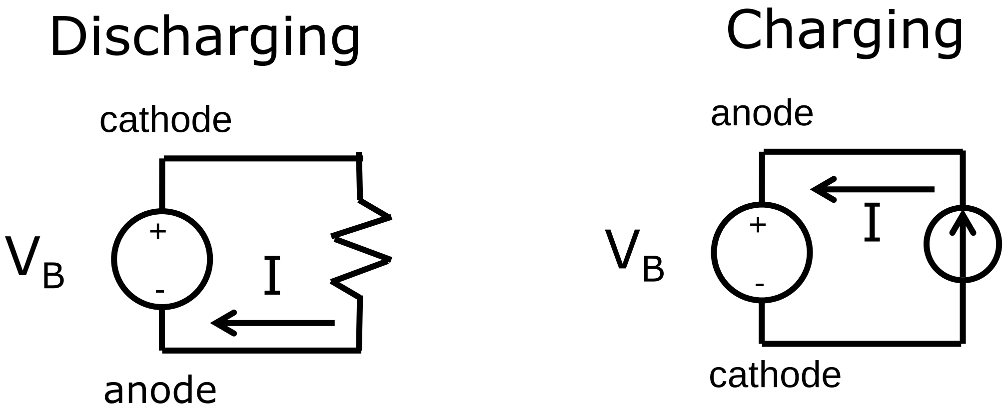
Lead-Acid Batteries

- From Chemistry class:

  An Anode is the electrode through which positive electric current flows into…

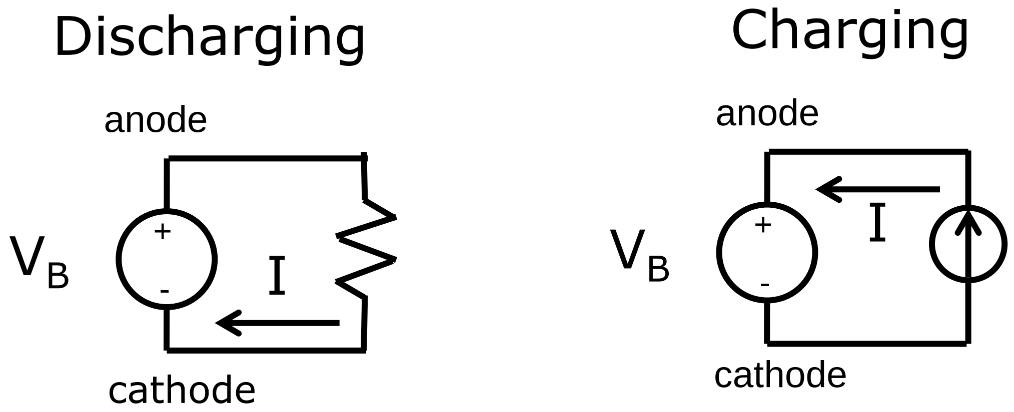
  (designation follows function not structure of device)

- anode and cathode switch terminals based on charging or discharging



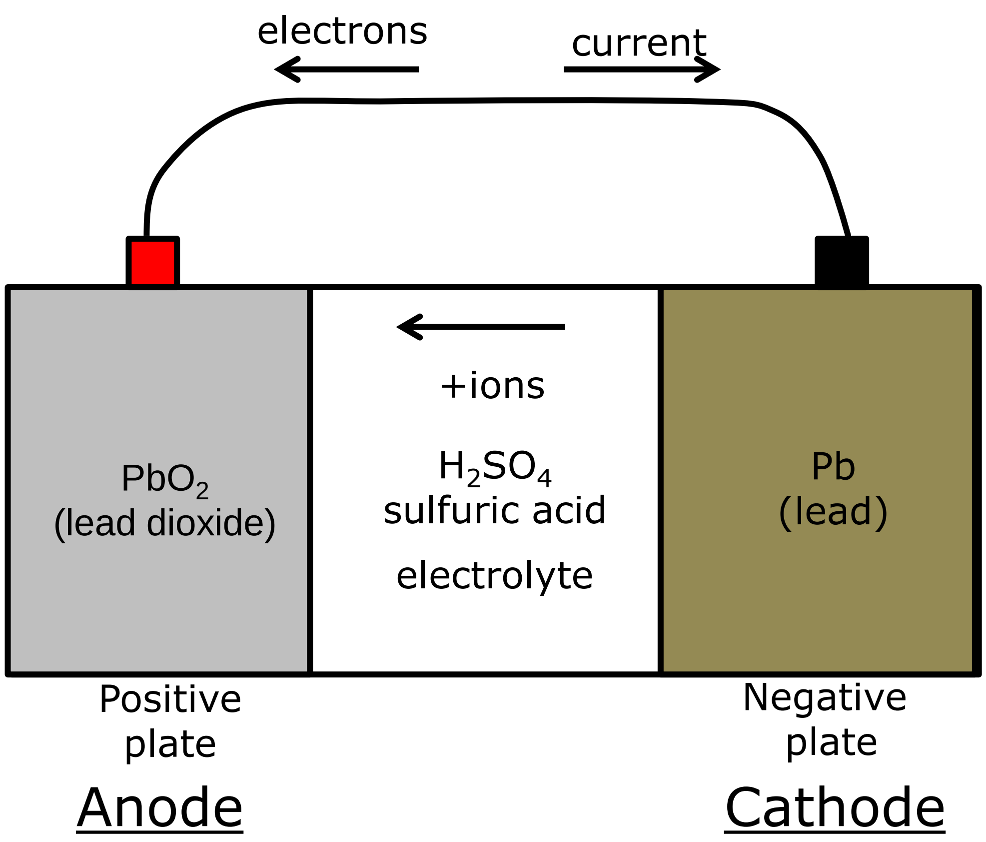
Lead-Acid Batteries

- Convention is to designate the positive plate (electrode) the anode (charging)
- We will use this convention, though not technically correct



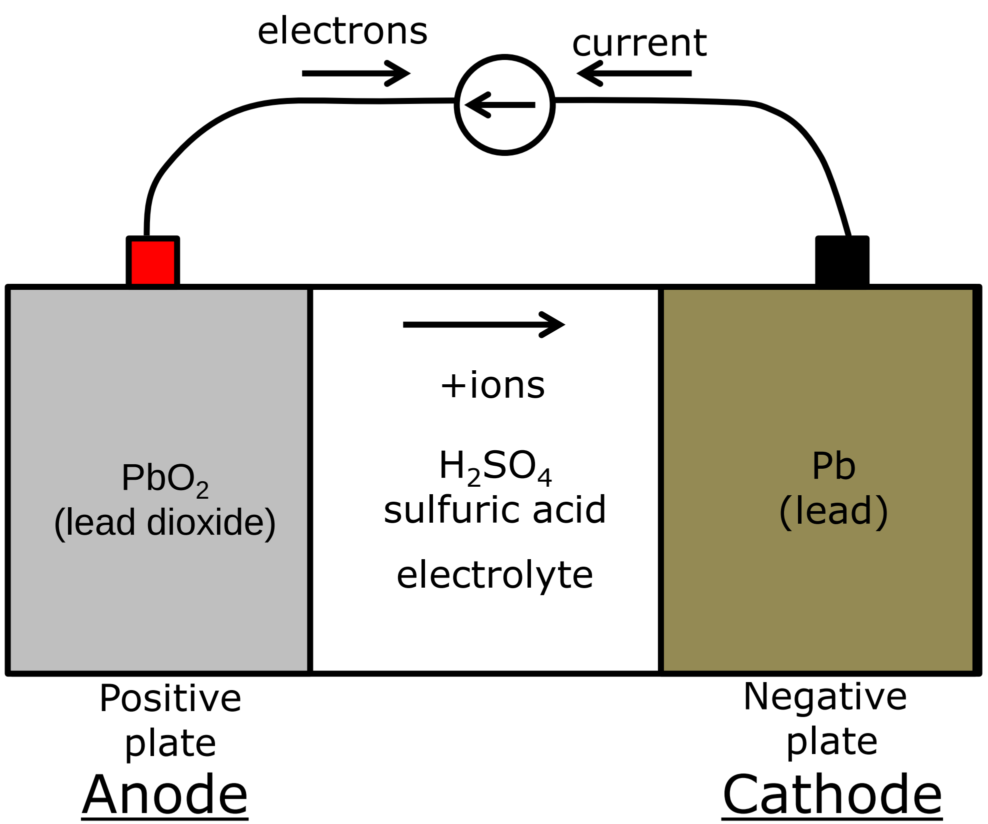
Lead-Acid Batteries

Discharging

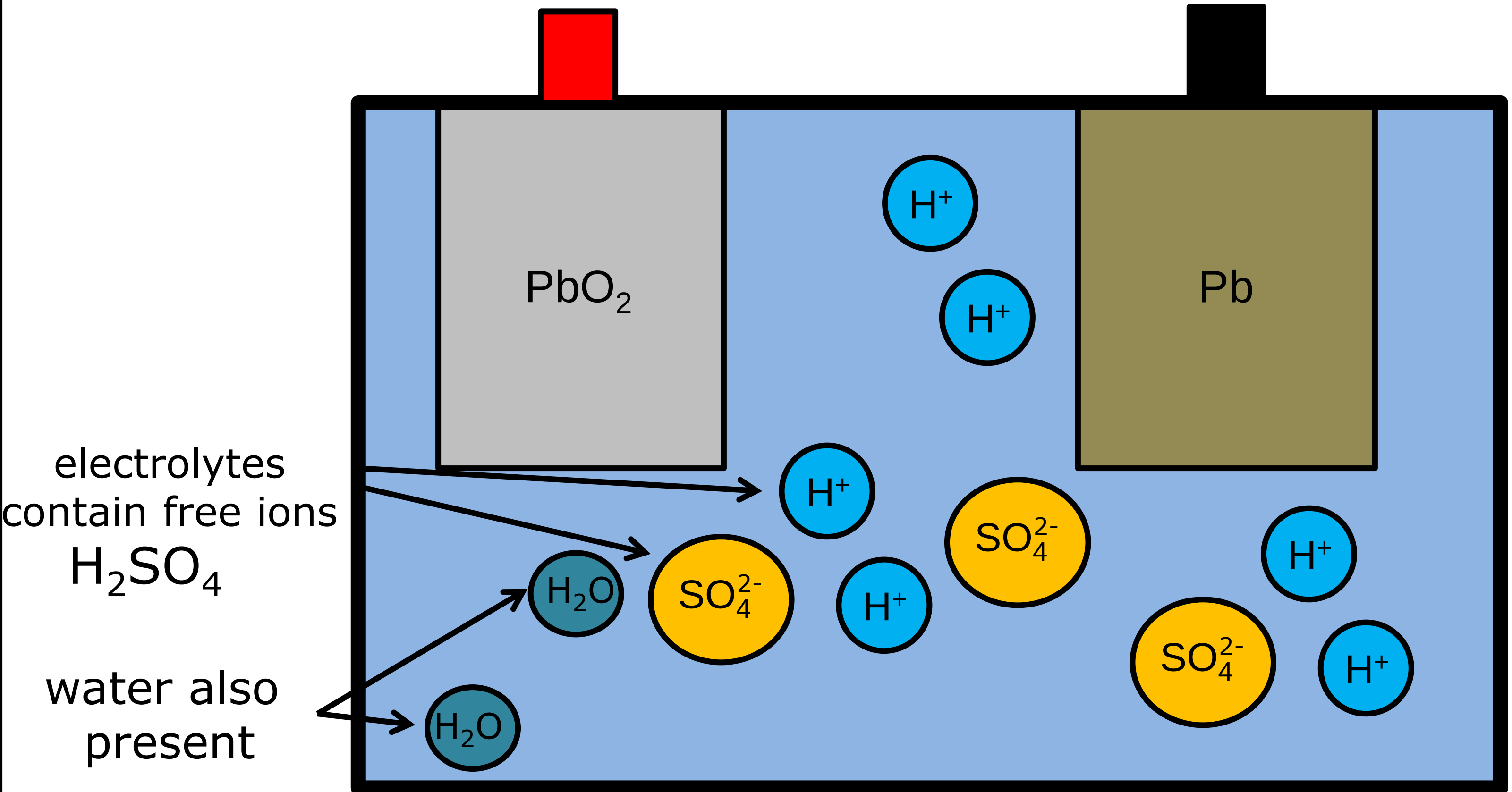


Lead-Acid Batteries

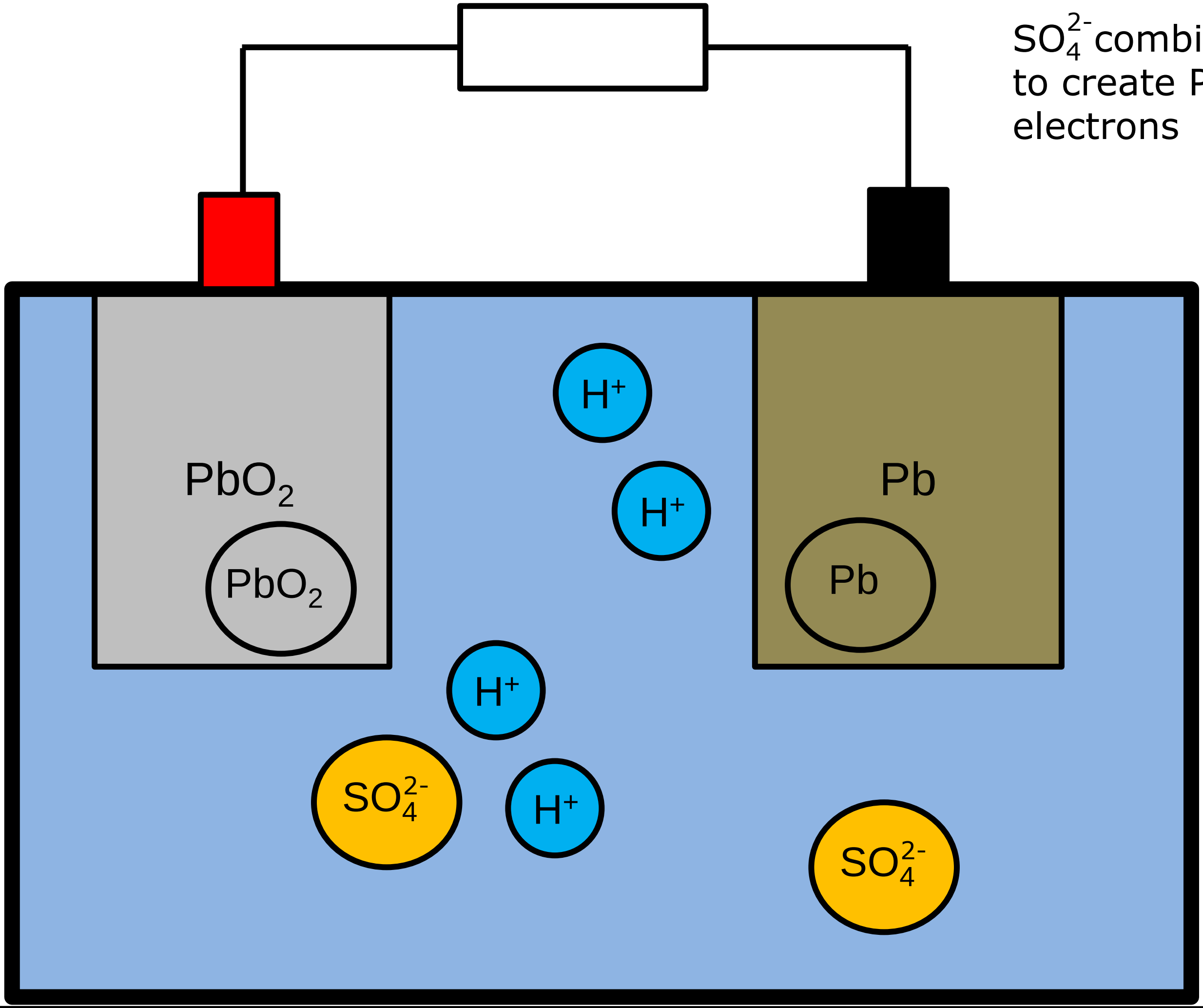
Charging



Lead-Acid Batteries

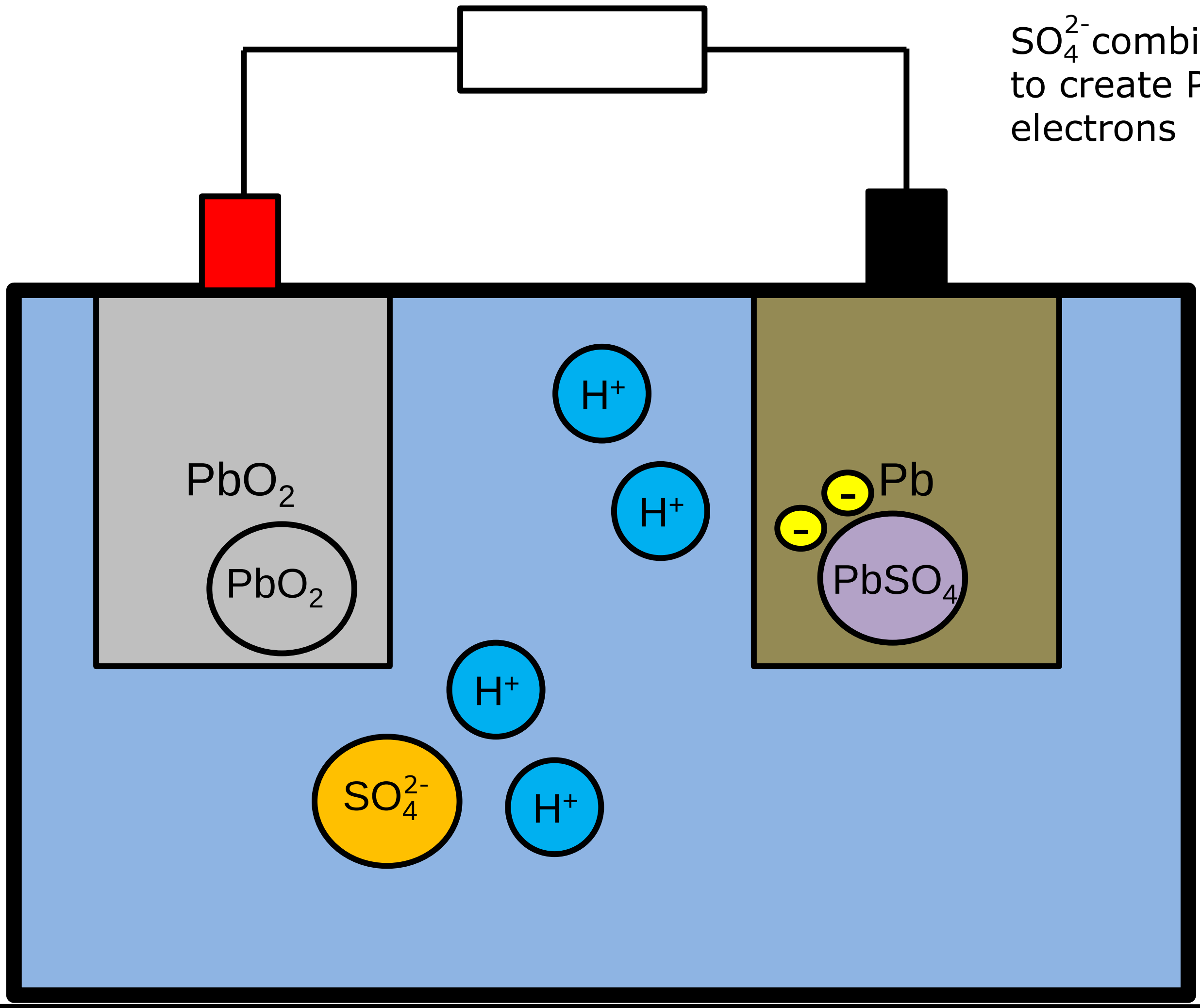


Lead-Acid Batteries



SO_4^{2-} combines with Pb to create $PbSO_4$ and 2 electrons

Lead-Acid Batteries



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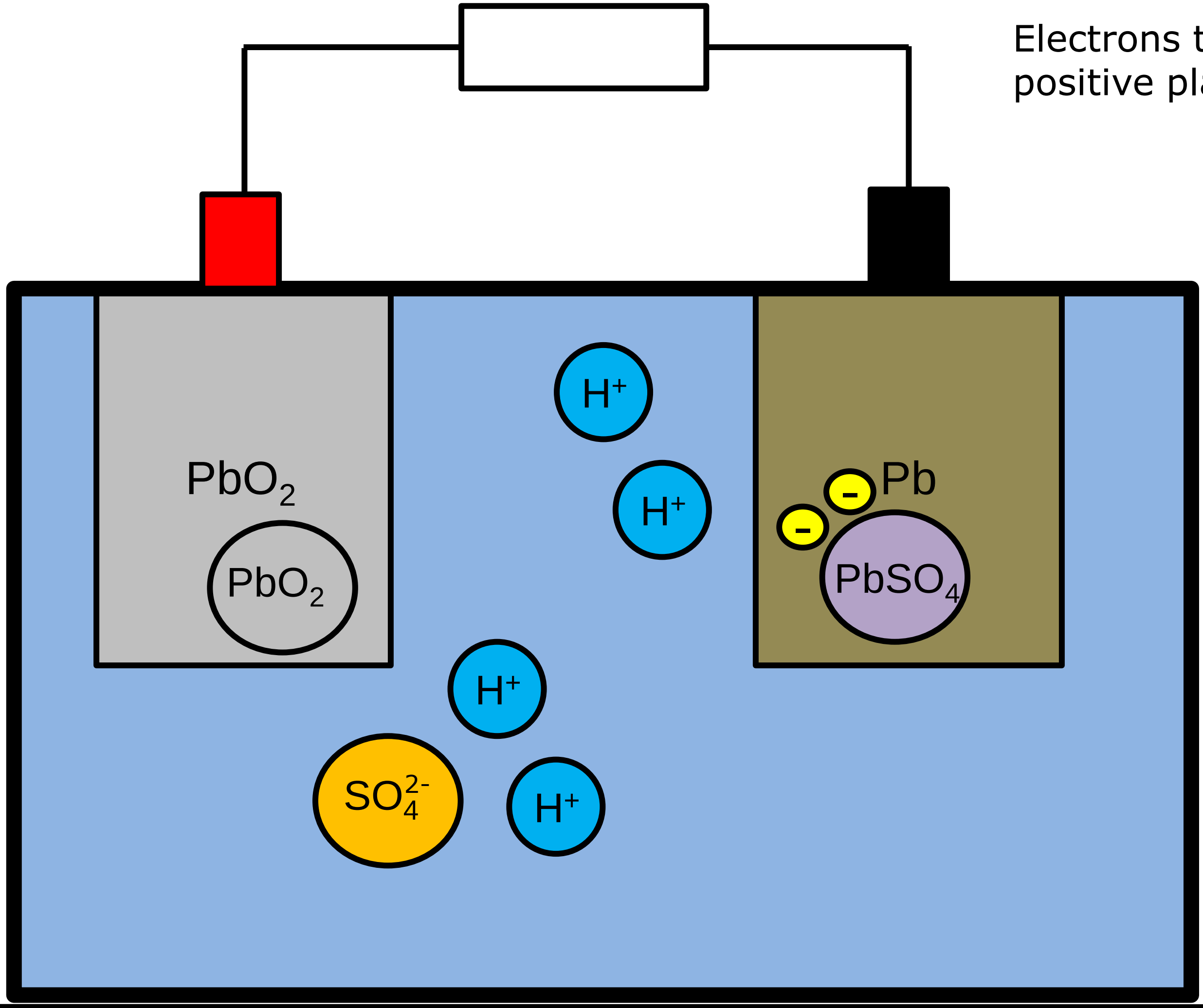
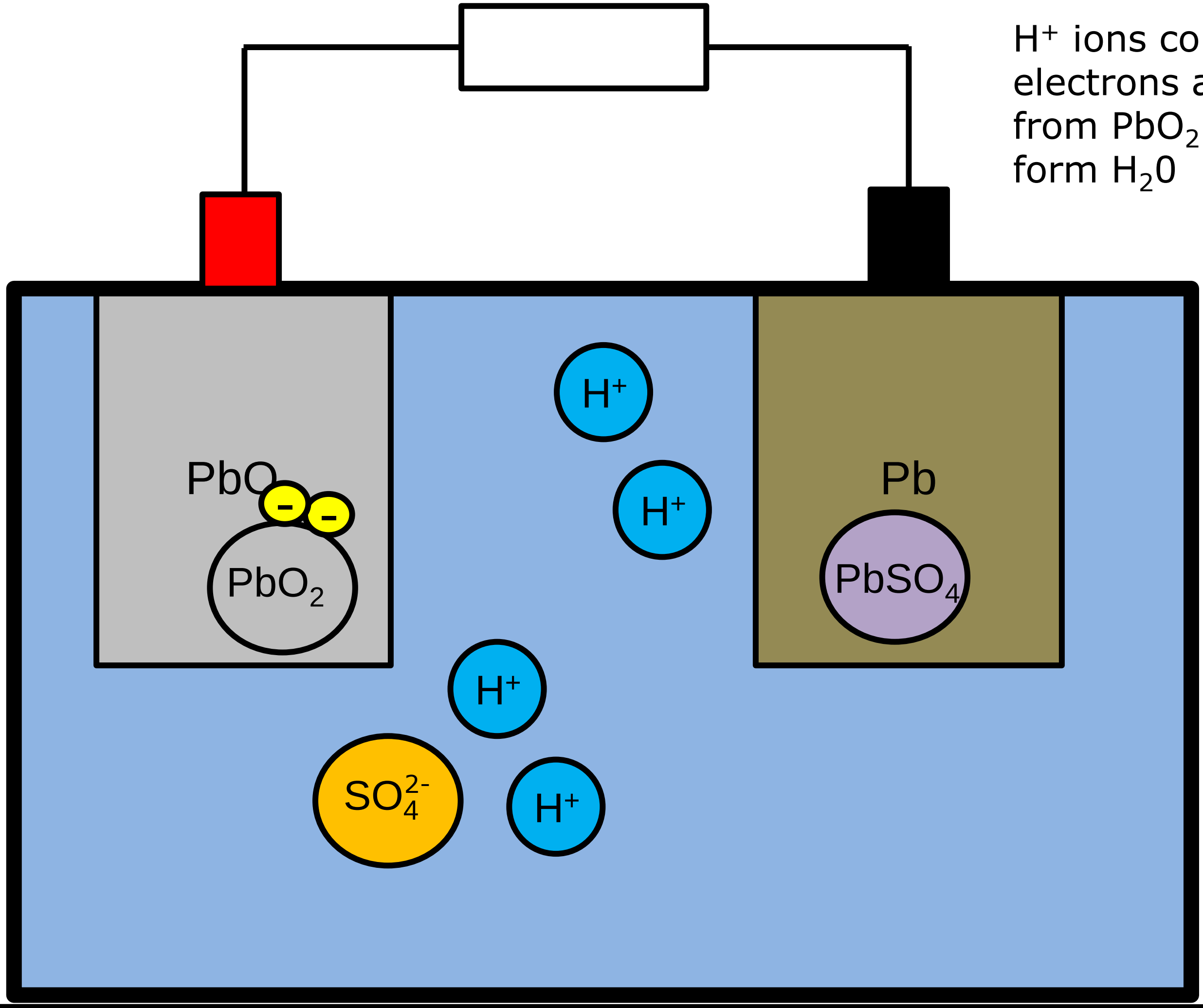
Lead-Acid Batteries



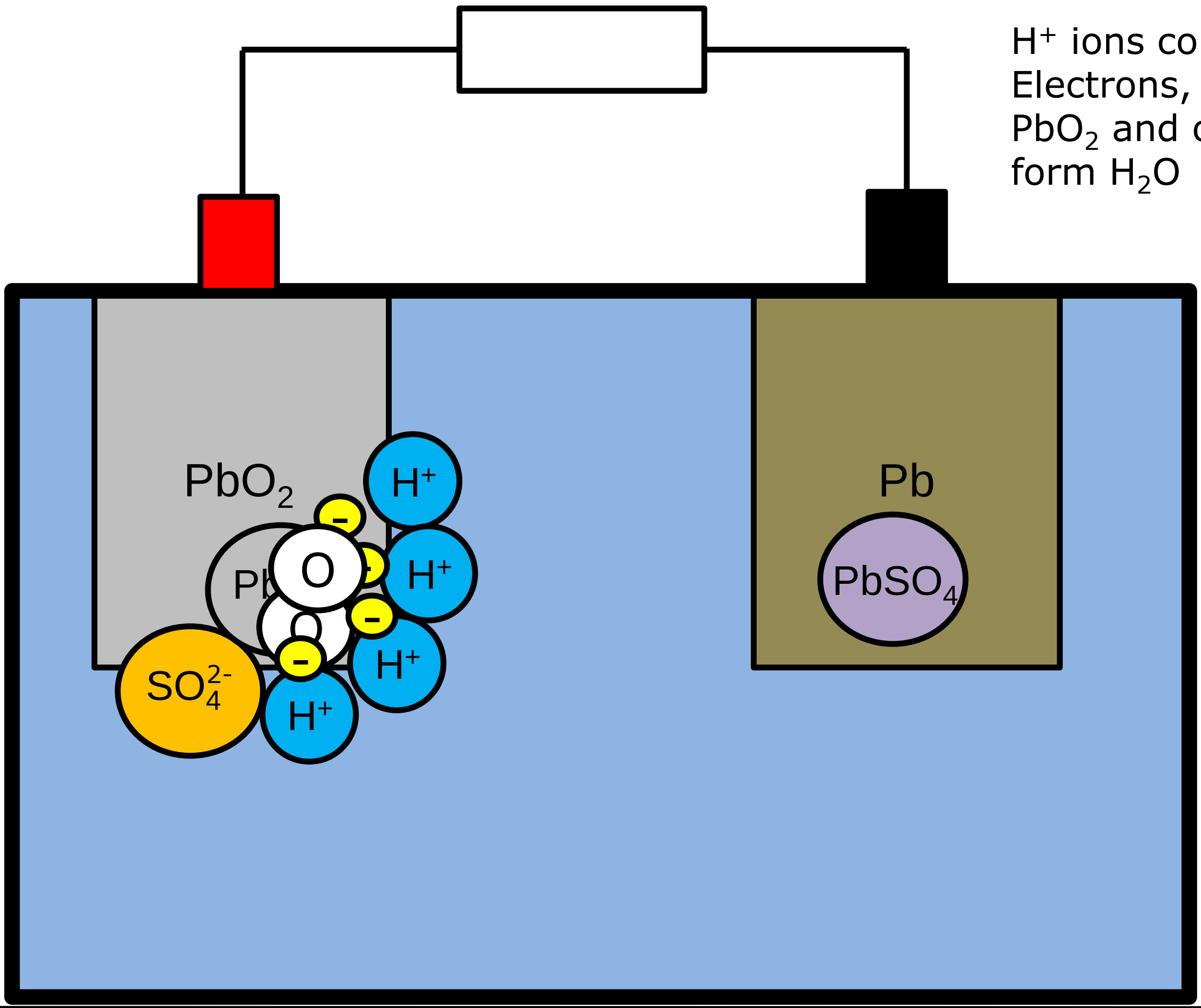
Electrons travel to the positive plate

Lead-Acid Batteries



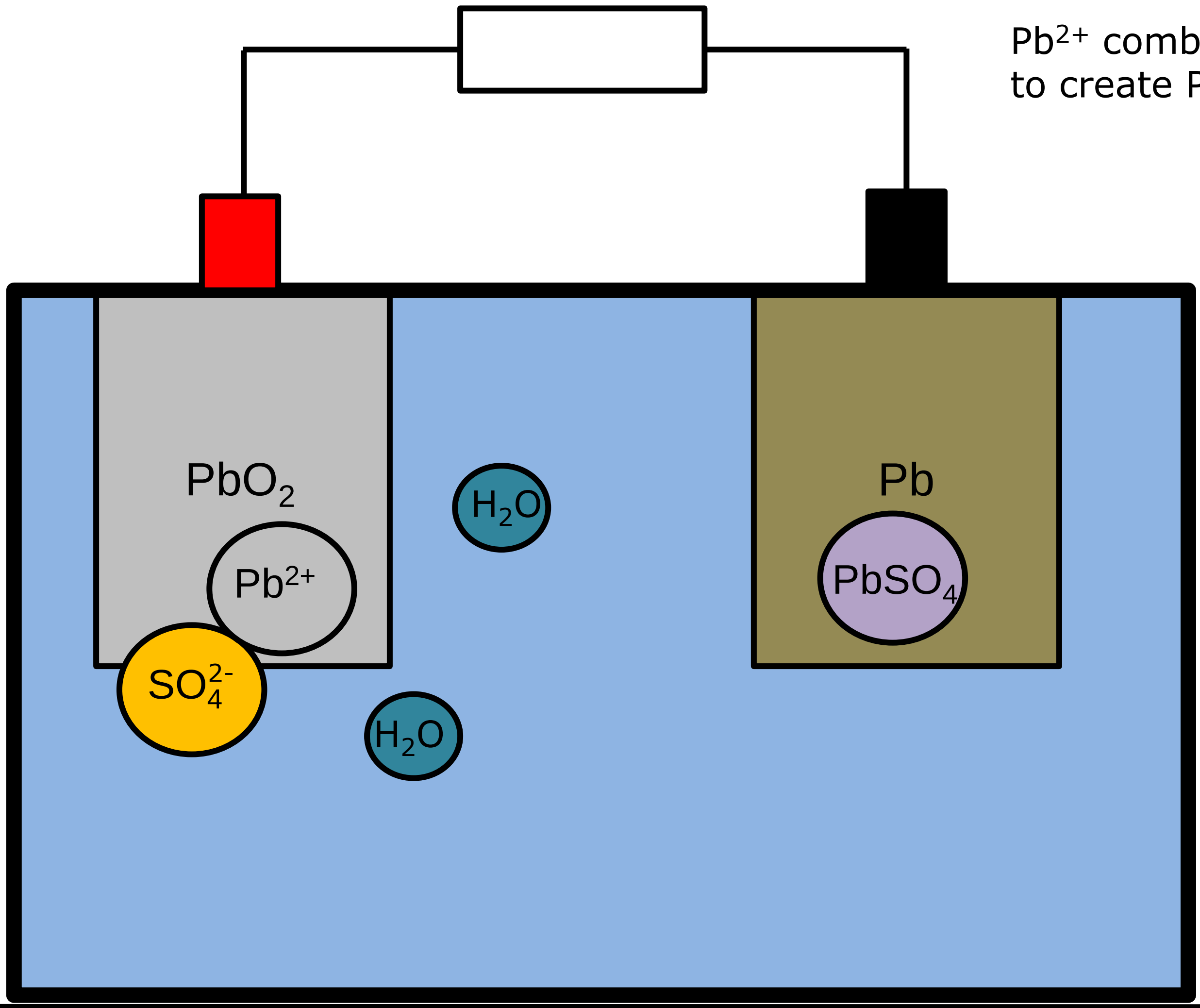
H^+ ions combine with electrons and oxygen from PbO_2 to form H_20

Lead-Acid Batteries



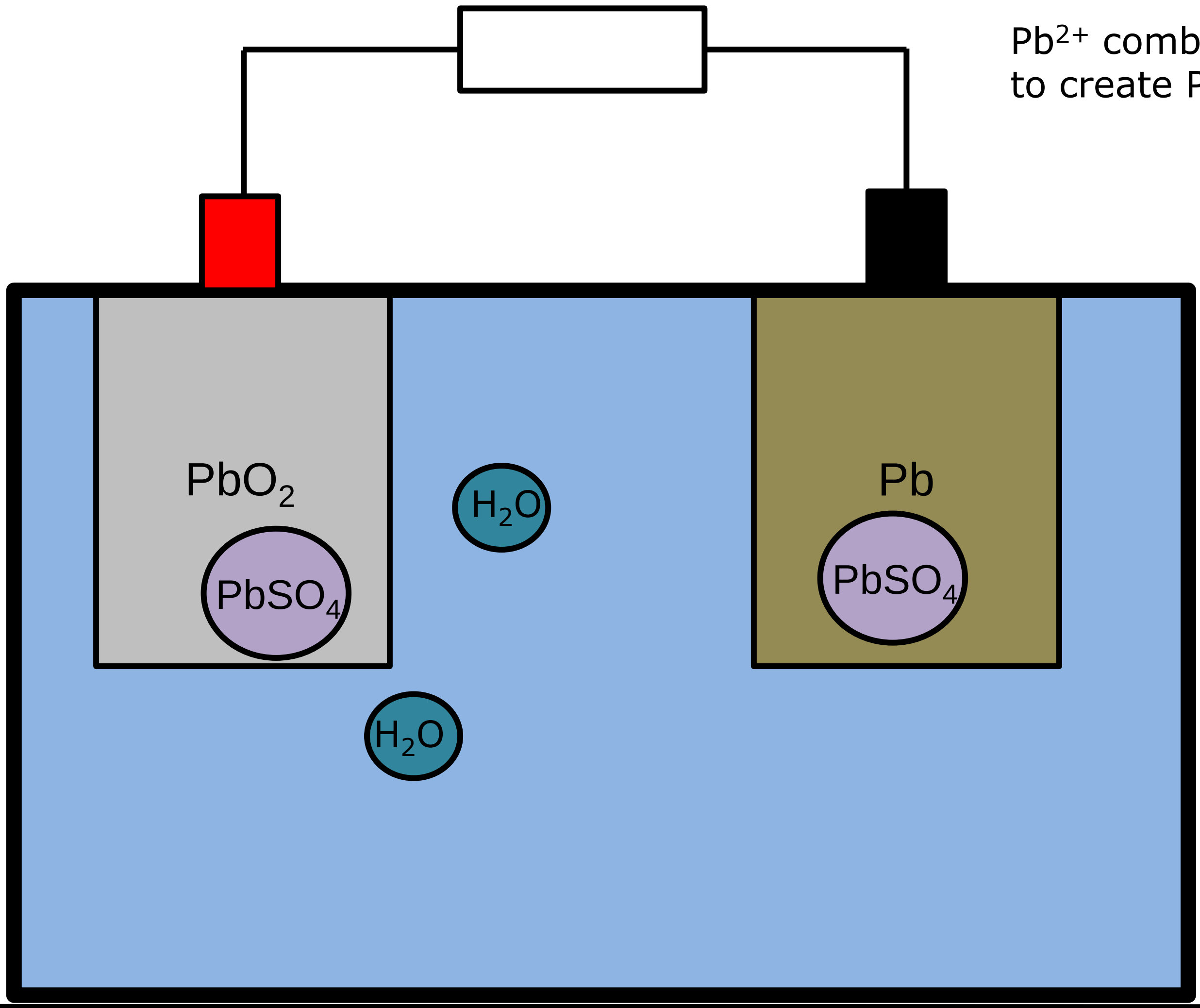
H^+ ions combine with free Electrons, electrons from PbO_2 and oxygen to form H_2O

Lead-Acid Batteries



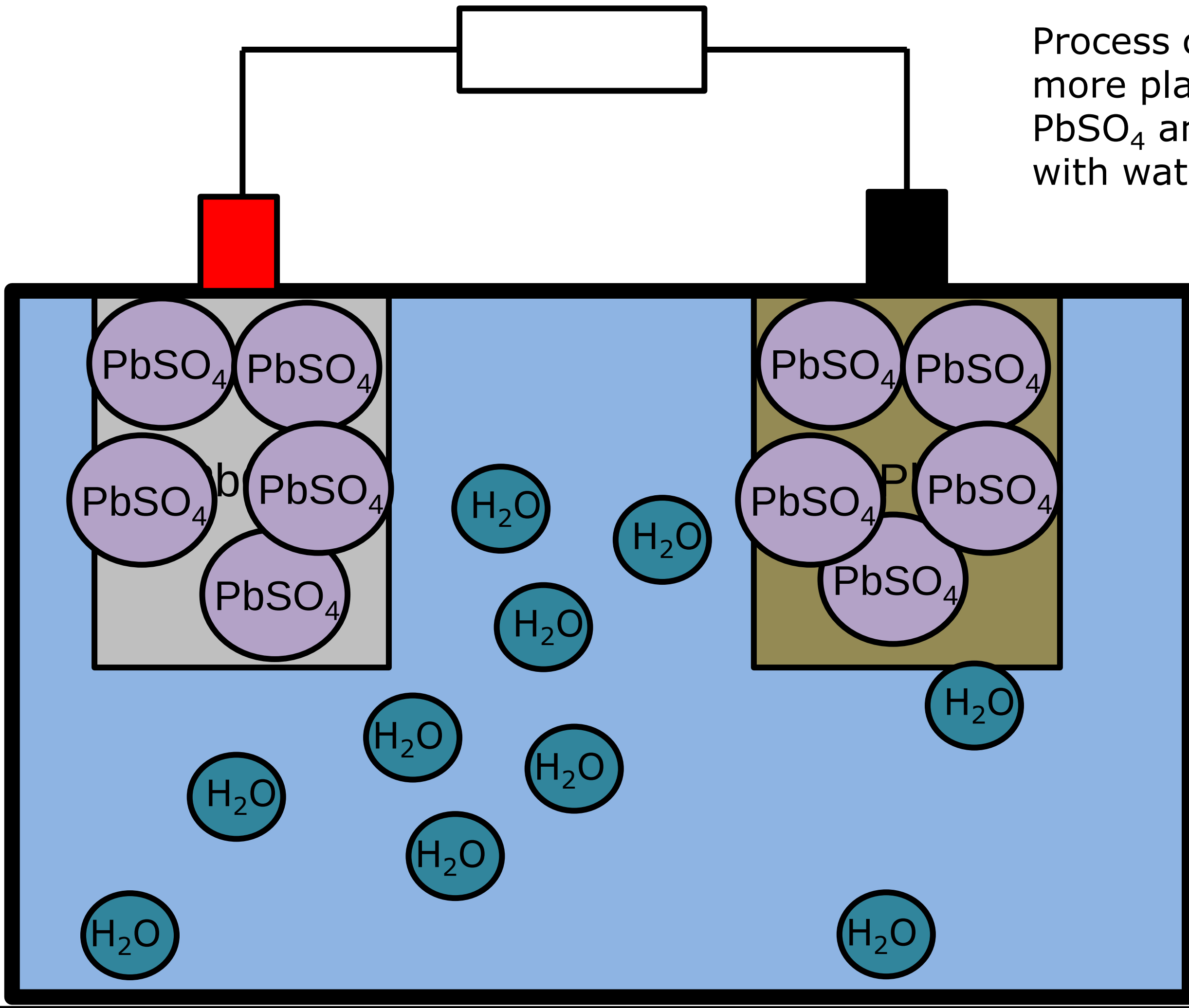
Pb^{2+} combines with SO_4^{2-} to create $PbSO_4$

Lead-Acid Batteries



Pb^{2+} combines with SO_4^{2-} to create $PbSO_4$

Lead-Acid Batteries



Process continues as more plates become $PbSO_4$ and acid is diluted with water

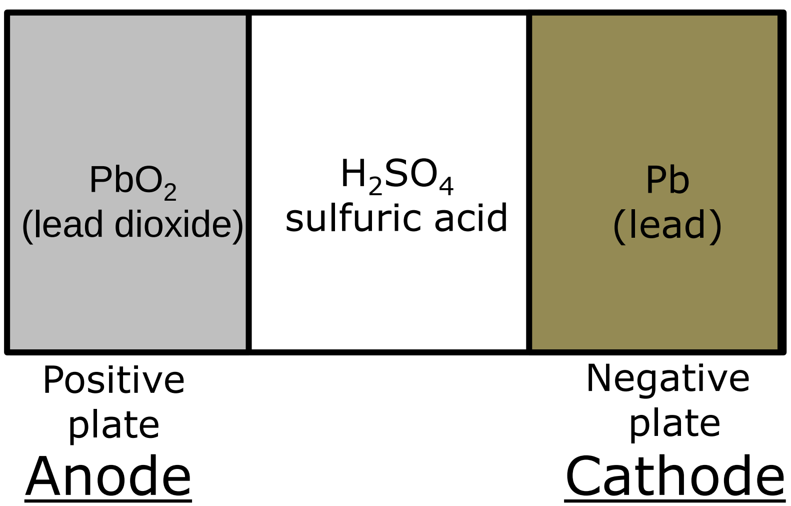
Lead-Acid Batteries

- Discharging (electrons flow into positive)
  - Anode

    $$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$$ (reduction: gains electrons)
  - Cathode

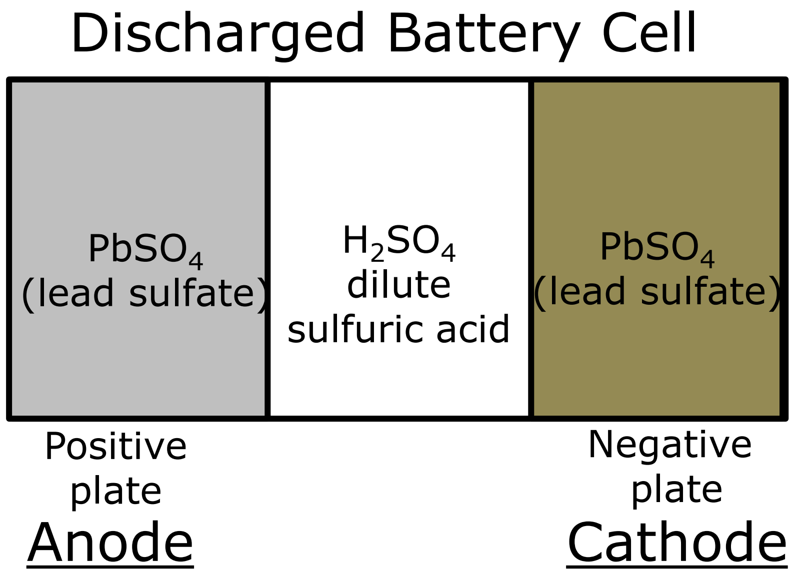
    $$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$ (oxidation: loses electrons)

Charged Battery Cell



Lead-Acid Batteries

- Result:
  - Cathode and Anode become lead sulfate
  - Acid is diluted by water



Lead-Acid Batteries

- Prolonged time in a discharged state results in sulfation
  - Lead sulfate on the negative terminal crystalizes
  - Lowers charge acceptance
  - Increases resistance
- Sulfation may be permanent—it is harder to remove the longer it has a low state of charge
- Avoid leaving batteries in low state of charge

Lead-Acid Batteries

- Charging (electrons flow into anode)
- Reactions are simply in reverse
  - Anode

    $$PbSO_4 + 2H_2O \rightarrow PbO_2 + SO_4^{2-} + 4H^+ + 2e^-$$

  - Cathode

    $$PbSO_4 + 2e^- \rightarrow Pb + SO_4^{2-}$$

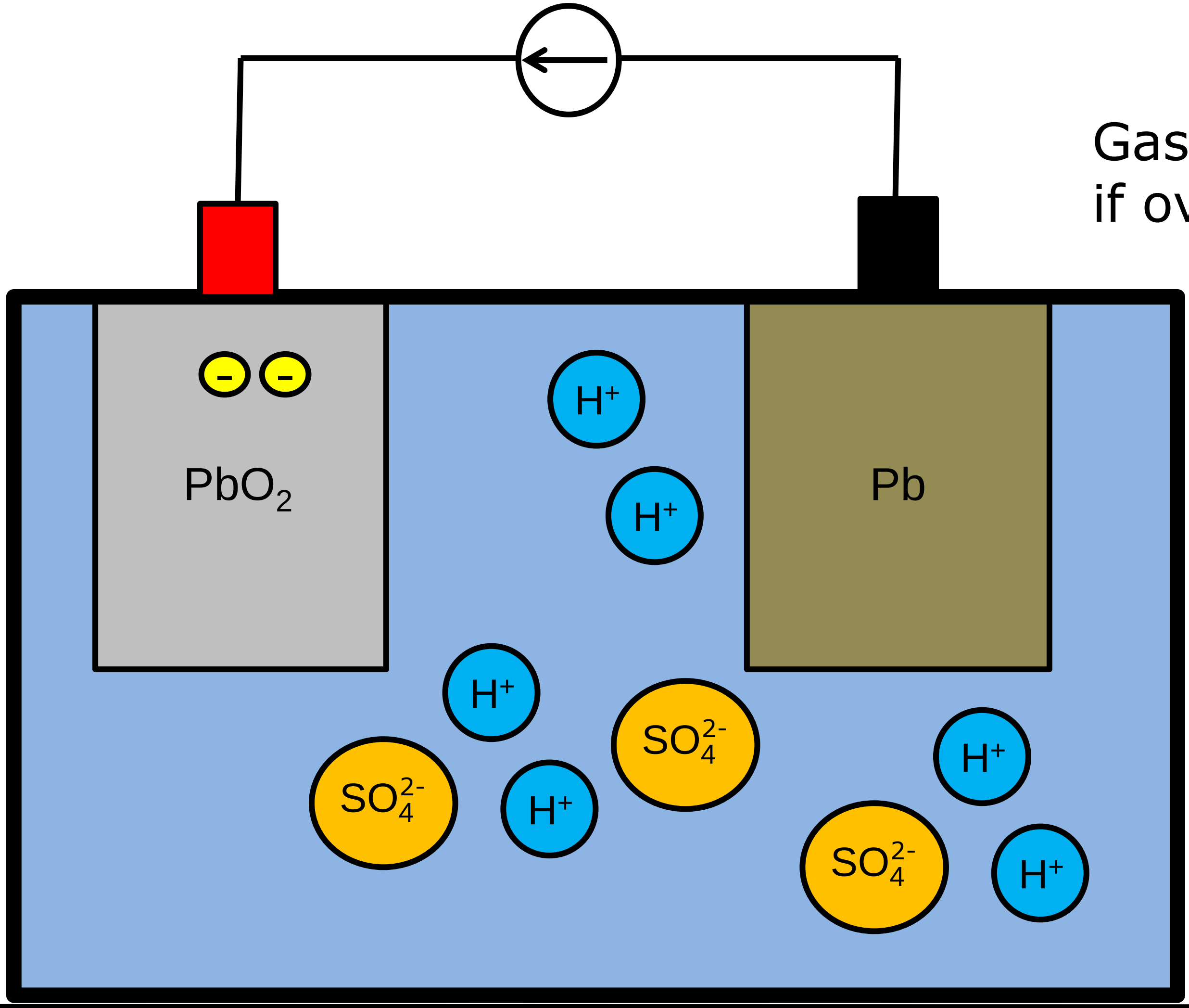
- Total Reaction:

$$PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O \quad \text{(discharge)}$$

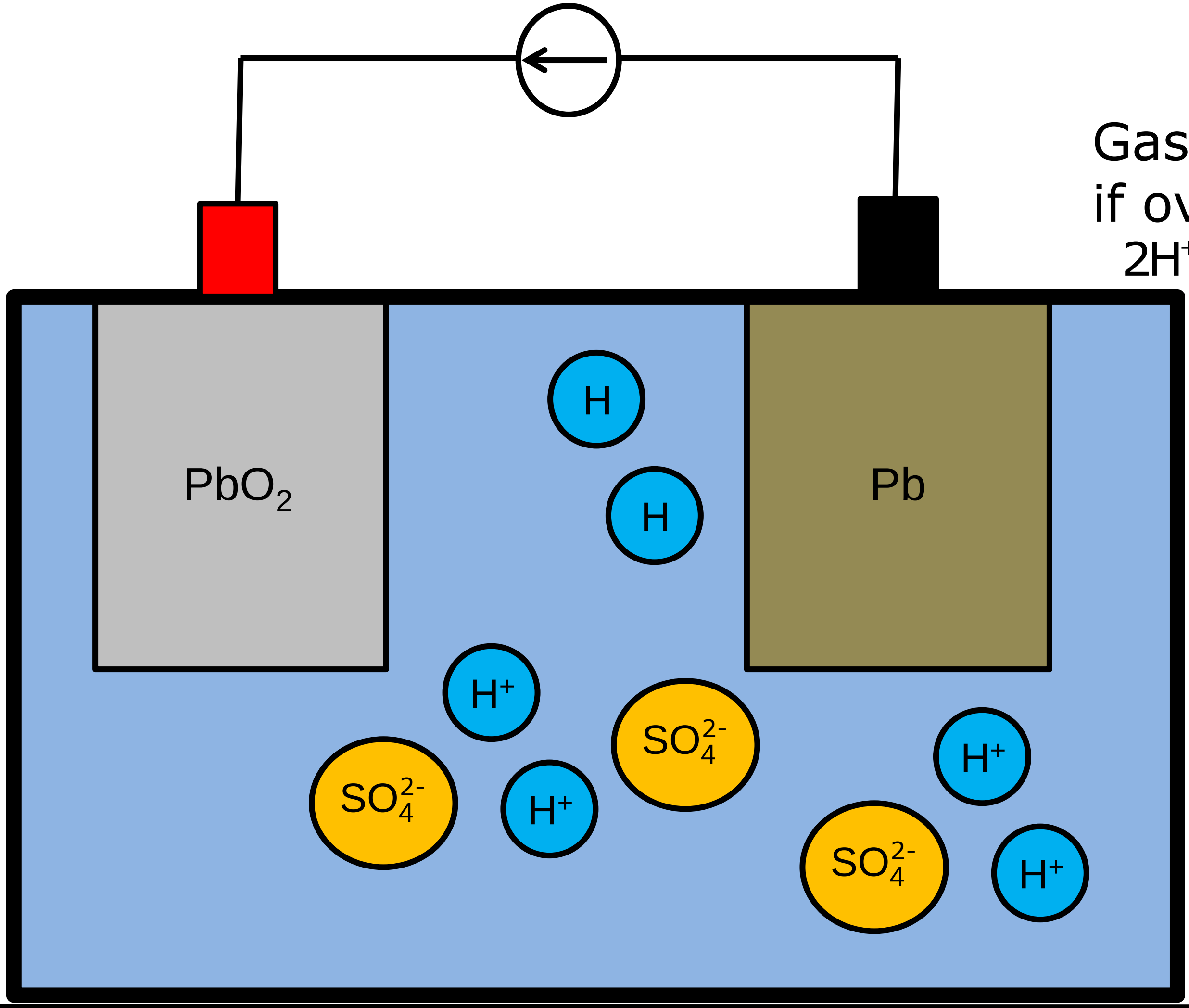
$$2PbSO_4 + 2H_2O \rightarrow PbO_2 + Pb + 2H_2SO_4 \quad \text{(charge)}$$

Lead-Acid Batteries

Gassing occurs if overcharged



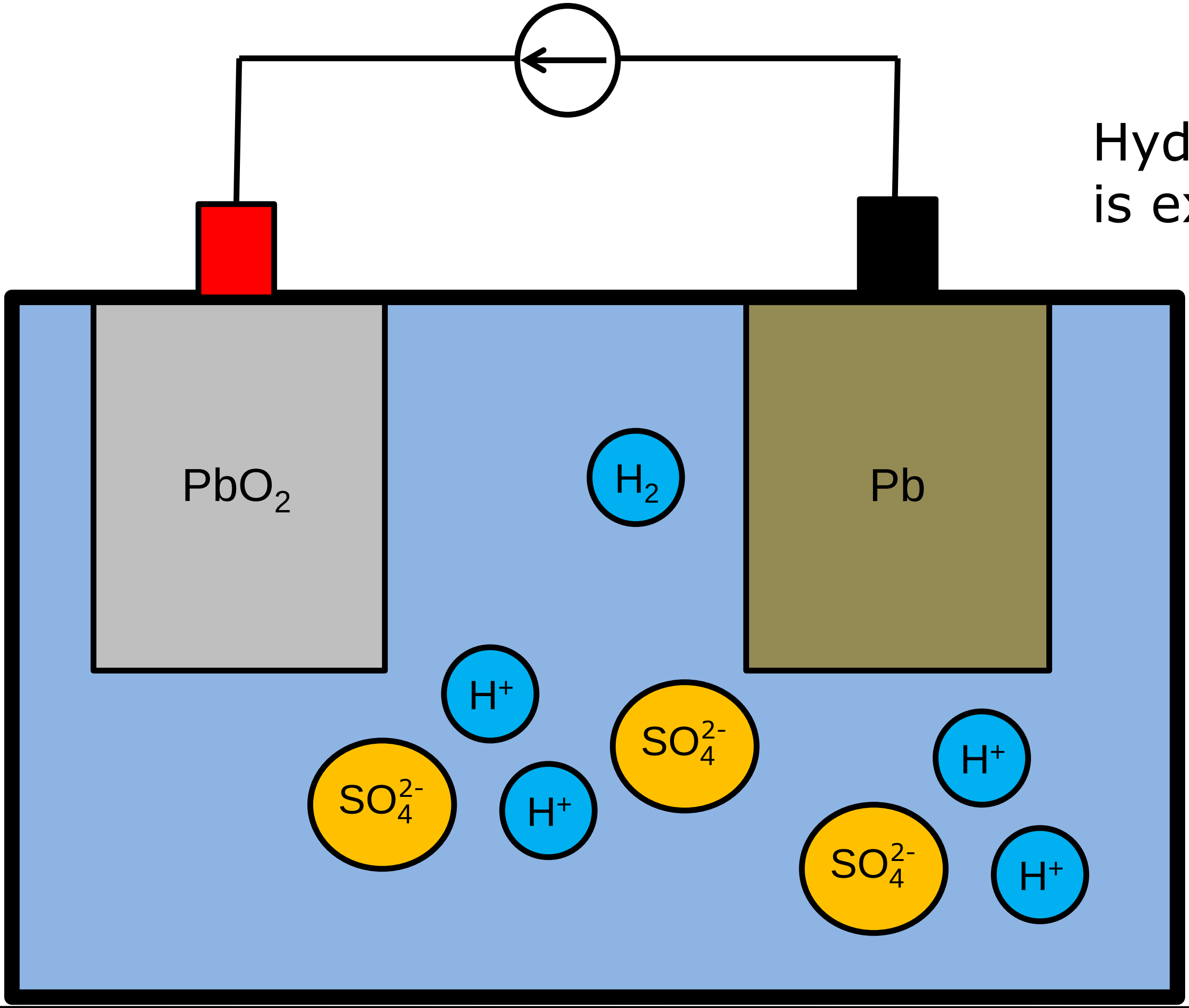
Lead-Acid Batteries



Gassing occurs if overcharged

$$2H^+ + 2e^- \rightarrow H_2$$

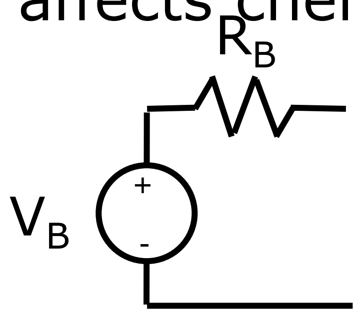
Lead-Acid Batteries



Hydrogen gas is explosive

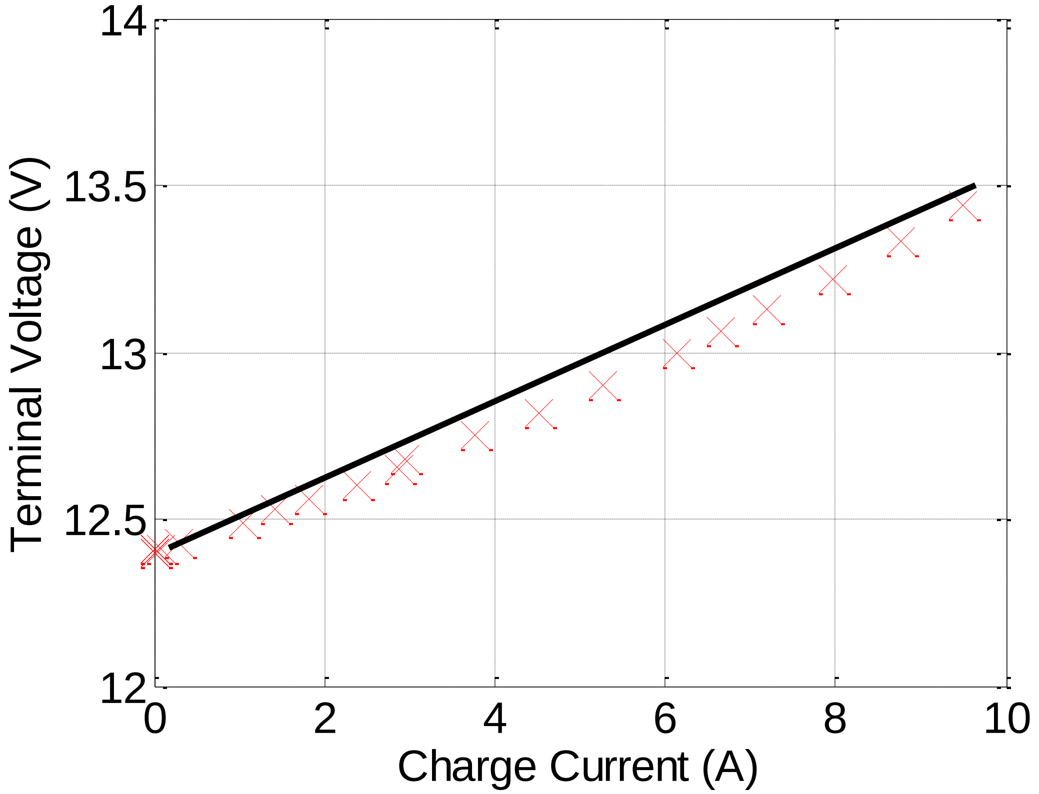
Battery Model

- Simple battery model: Thevenin equivalent voltage source
  - R_B small < 1 Ohm
  - R_B varies with state of charge (SOC)
  - Less electrolyte, greater resistance
- High charge/discharge current increases losses in R_B
  - Less meaningful energy into/out of battery
  - Heat generated affects chemical reactions (speeds them up)

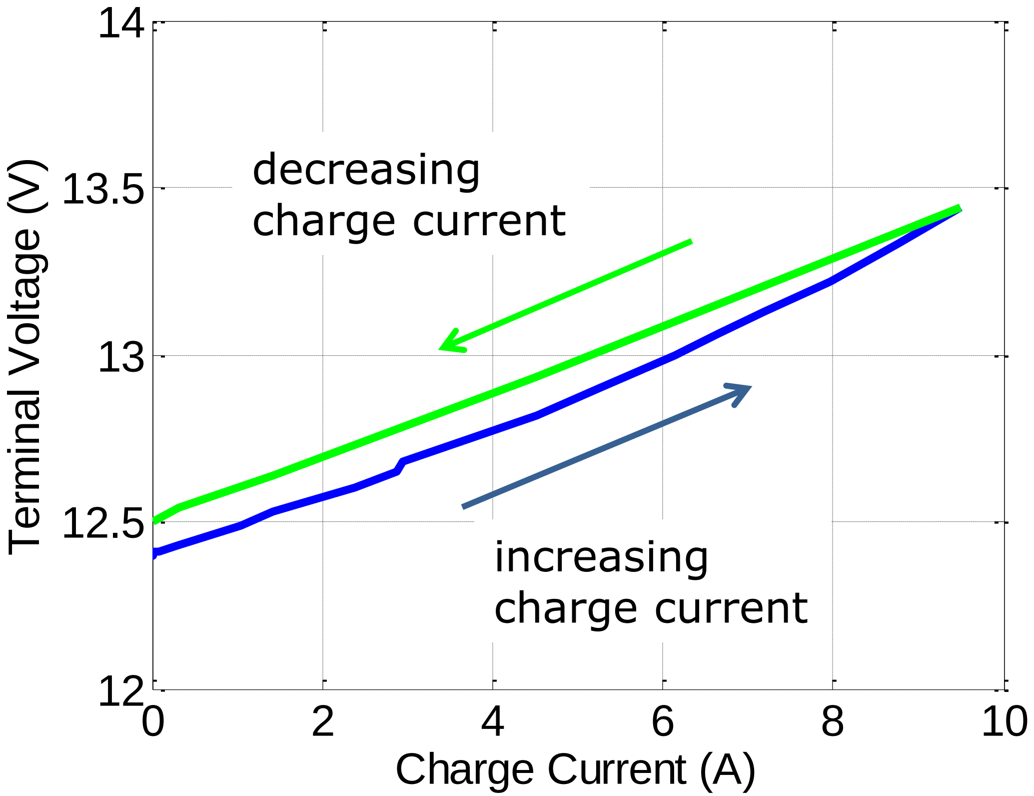


Battery Model

- Test data from 12V, 105Ah deep cycle battery (ECE 12.1)
- What is R_B?
  - ~0.096 Ohms



Battery Model



Lead-Acid Batteries

- Voltage between cells for Lead-Acid batteries: ~2.12 V
- Cells are series connected for higher voltage
  - 12V nominal battery: six cells in series (~12.6V)
  - 6V nominal battery: three cells in series (~6.3V)
  - etc

Battery Specifications

- Important technical considerations:
  - capacity
  - cycling
  - depth of charge
  - efficiency
  - temperature effects
  - other electrical characteristics
  - mechanical durability

Battery Specifications

- Battery specification challenges:
  - Non-linear device
  - Temperature dependent
  - Time dependent (degrade over time)
  - Memory (previous usage affects future performance)

Battery Specifications: Voltage

- Nominal Voltage: open circuit terminal voltage (V)
  - usually within a few volts of the nominal voltage
  - 6, 12, 24, etc

Battery Specifications: Capacity

- Capacity: energy content of battery in Amp-Hours (Ah)
  - Ah x nominal voltage = Wh
- Important caveat
  - Capacity is a function of charge or discharge current (among other factors)
  - Slower discharge: more energy extracted from battery
  - Slower charge: more energy added to battery

Exercise

A 17Ah, 12V battery contains how many Wh of energy?

A. 170 Wh

B. 204 Wh

C. 208 Wh

D. Cannot be determined

Exercise

A 17Ah, 12V battery contains how many Wh of energy?

A. 170 Wh

B. 204 Wh   17 * 12 = 204Wh

C. 208 Wh

D. Cannot be determined

Battery Specifications: C-Rate

- Important concept "C-Rate"
  - Charge rate
  - Indicates the current (Amp) value corresponding to a provided capacity rating

Battery Specifications: C-Rate

- Example: a 1.5V battery is rated at 3Ah at 1C
  - Interpretation: the battery can supply 3 x 1.5 = 4.5 Wh if discharged at a constant rate of (3 x 1) = 3 Amps

- Example: a 12V battery is rated at 7.2Ah at 0.05C
  - Interpretation: the battery can supply 7.2 x 12 = 86.4 Wh if discharged at a constant rate of (7.2 x 0.05) = 0.36 Amps

Example

- A 12V battery is rated at 105Ah at 0.05C. How many Watt-hours of energy can be supplied by the battery if it is discharged at 0.05C?

  What is the 0.05C discharge rate in Amps?

  If the battery is discharged at 10 A, will more or less than 105Ah be available?

Example

- A 12V battery is rated at 105Ah at 0.05C. How many Watt-hours of energy can be supplied by the battery if it is discharged at 0.05C?

  12 x 105 = 1.26 kWh

  What is the 0.05C discharge rate in Amps?

  105 x 0.05 = 5.25 A

  If the battery is discharged at 10 A, will more or less than 105Ah be available?

  less, since 10 > 5.25

Battery Specifications: C-Rate

- Convention:
  - lead-acid battery capacity provided at the 0.05C (or 20-hour) rate
  - Small portable batteries provided at the 1C (or 1 hour) rate

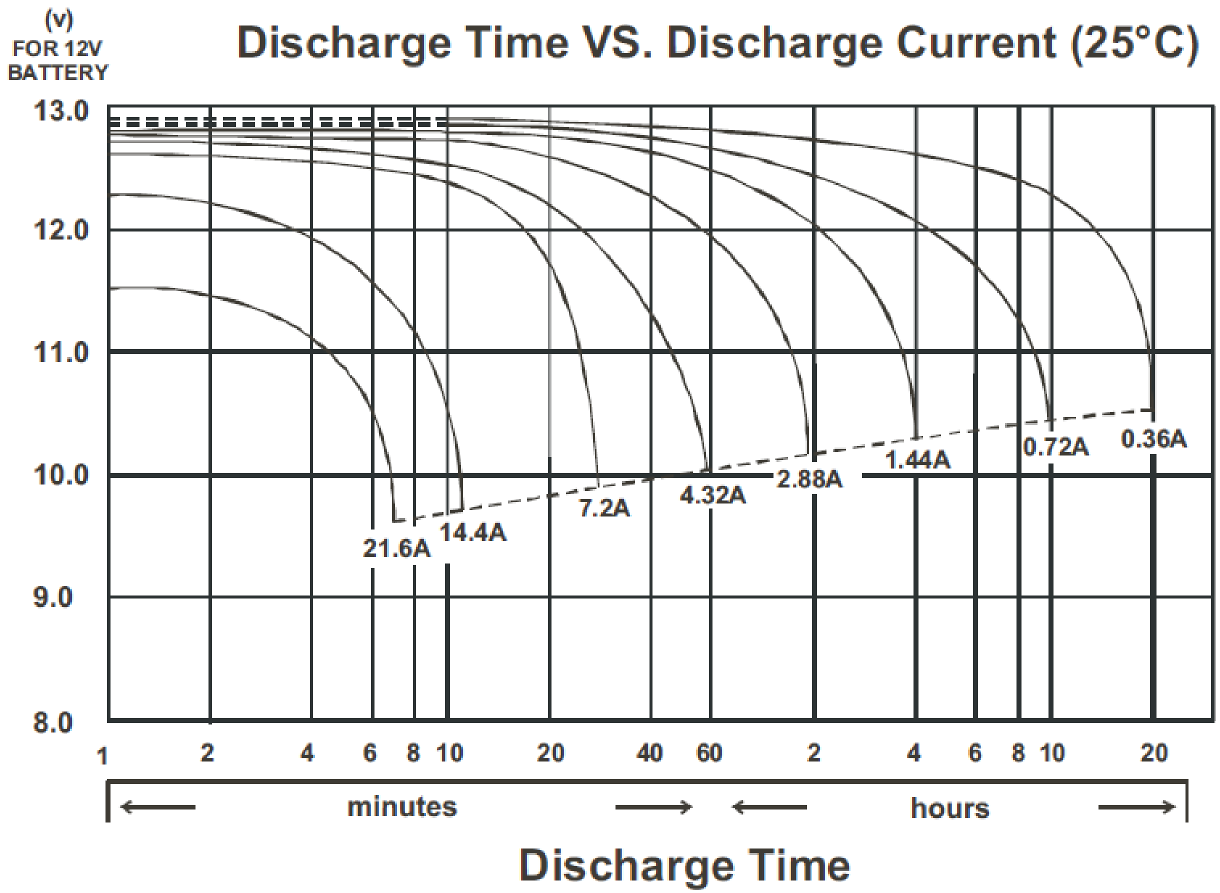
- Default assumption for this class: capacities are referenced to 0.05C

Battery Specifications

Nominal Voltage (V)	12V
Nominal Capacity	
20hour rate (0.36A to 10.50V)	7.2Ah
10hour rate (0.72A to 10.50V)	7.2Ah
5hour rate (1.22A to 10.20V)	6.12Ah
1C (7.2A to 9.60V)	3.24Ah
3C (21.6A to 9.60V)	2.59Ah

Energy decreases as current increases

Battery Specifications



Batteries

Operating Temperature Range	
Charge	0°C(32°F) to 40°C (104°F)
Discharge	-15°C(5°F) to 50°C (122°F)
Storage	-15°C(5°F) to 40°C (104°F)

self-discharge characteristic

Charge Retention (shelf life) at 20°C (68°F)	
1 month	92%
3 month	90%
6 month	80%

Charging Methods at 25°C (77°F)	
Cycle use :	Charging Voltage 14.4 to 15.0V Maximum Charging Current 2.16A
Standby use :	Float Charging Voltage 13.50 to 13.80V No current limit required

C/3 charge rate

cycling characteristic

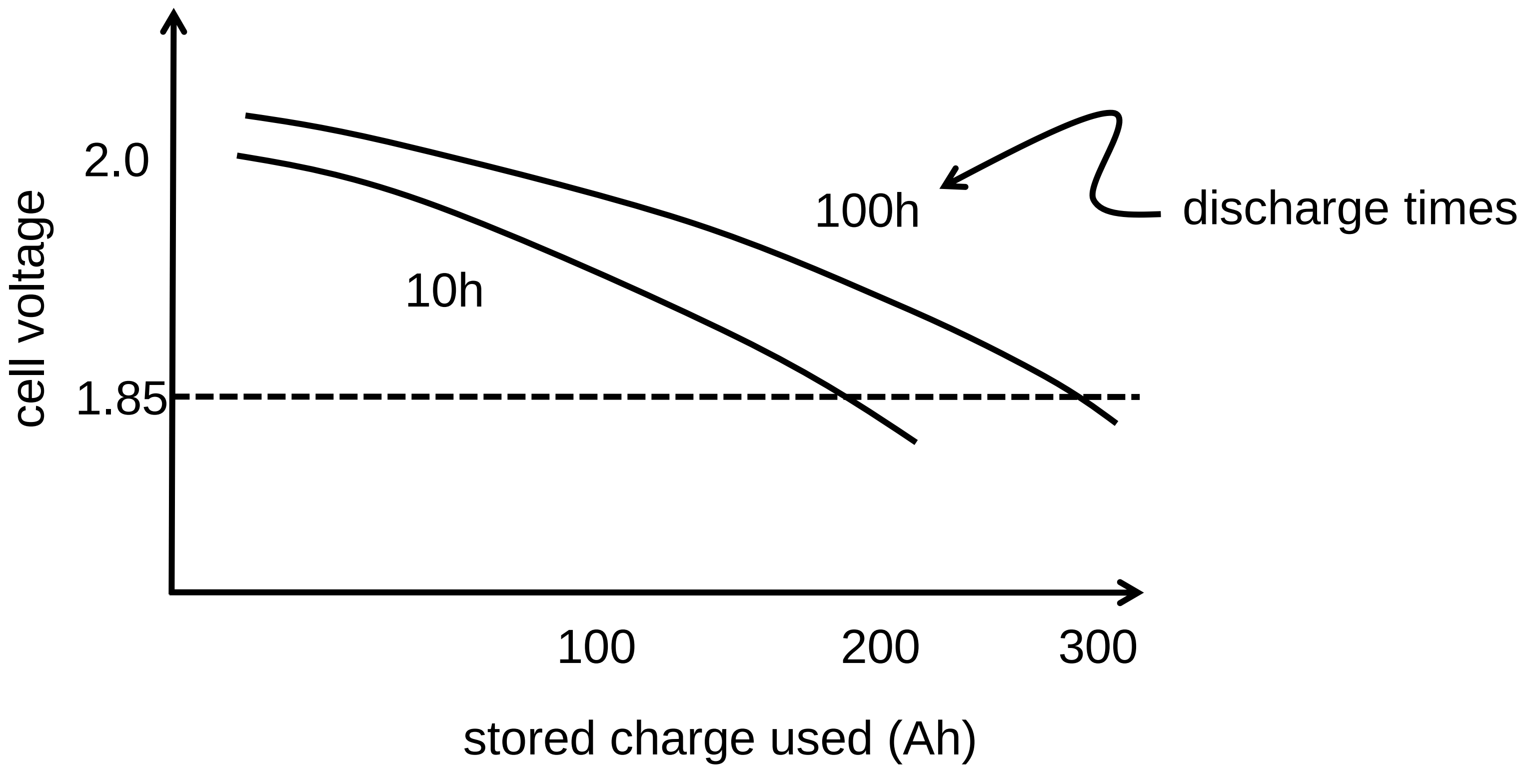
Life expectancy :	
Cycle Use :	100% depth of discharge 250 cycles 80% depth of discharge 350 cycles 50% depth of discharge 550 cycles

Batteries

- Cycling: charge and discharge cycles
  - Shortens battery life
  - PV applications cycle at least once per day
- Charge depth (amount of total energy that can be discharged without damage)
  - 25% automotive application
  - 80% PV applications, golf carts, marine vehicles

Batteries

slower discharge allows for greater energy to be utilized

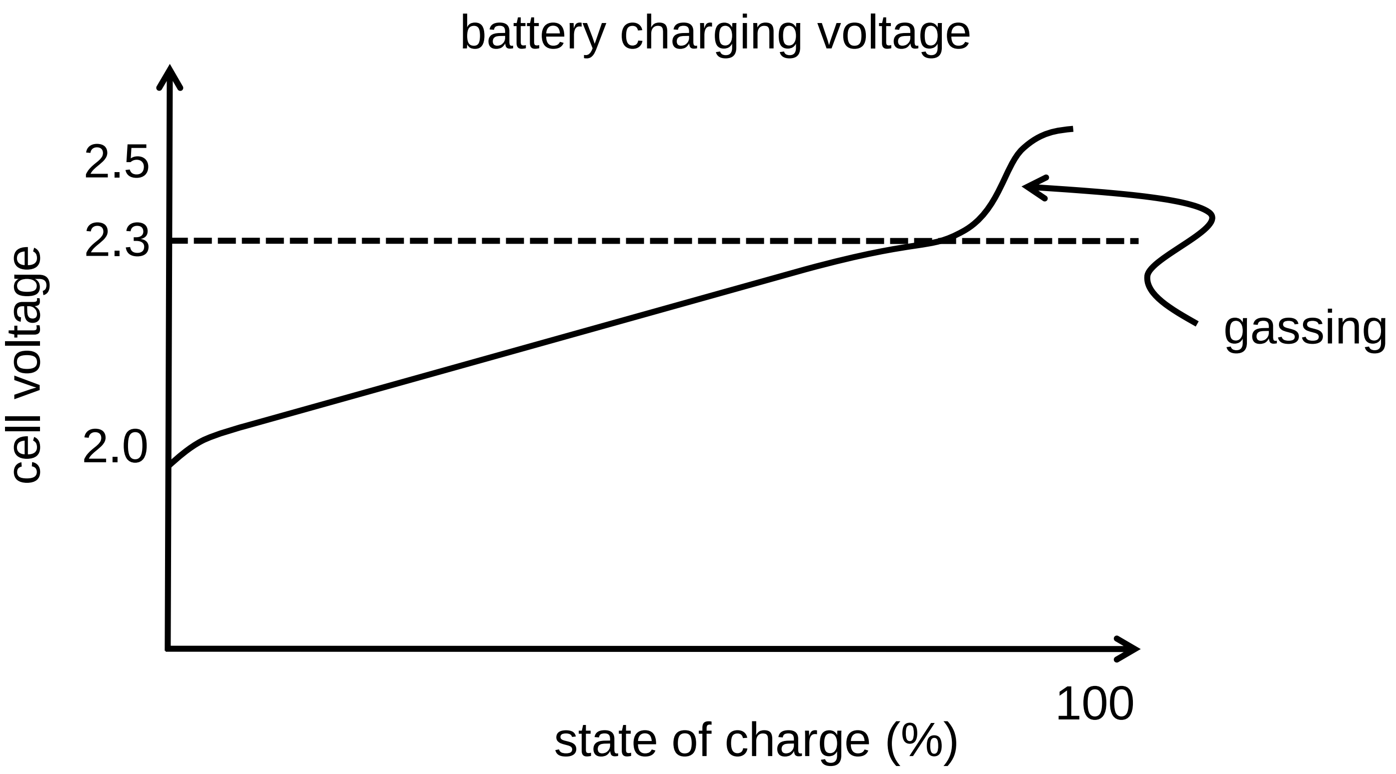


Batteries

- Other parameters of interest
- Efficiency
  - 95% charge
  - 95% discharge
  - approx 90% roundtrip
- Temperature effect
  - higher temperature increases charge capability
  - higher temperature decreases life
- Internal resistance (for lead-acid on the order of 0.050 Ω)

Energy Storage

gassing: hydrogen production, damages battery



Batteries

float voltage: open circuit battery voltage

No. of Cells	Nominal Voltage	Fully Charged Float Voltage	Fully Discharged Float Voltage	Discharge Voltage at C/20	Charge Voltage at C/5
1	2	2.15	1.9	2.0-1.7	2.1-2.30
6	12	12.9	11.4	12-10.2	12.6-13.8
12	24	25.8	22.8	24-20.4	25.2-27.6

source: xtronics.com

Exercise

You find a 12V car battery and measure it's terminal voltage to find that it reads 12.1V. The battery is:

A. Fully charged (100% state of charge)
B. Undercharged (<100% state of charge)
C. Overcharged (>100% state of charge)

Exercise

You find a 12V car battery and measure it's terminal voltage to find that it reads 12.1V. The battery is:

A. Fully charged (100% state of charge)
B. Undercharged (<100% state of charge)
C. Overcharged (>100% state of charge)

A fully charged lead acid 12V should read approximately: 6*2.15 = 12.9V

Exercise

The measured voltage on a nominal 24V battery is 18V. The battery has approximately 75% of it's energy remaining.

A. True

B. False

Exercise

The measured voltage on a nominal 24V battery is 18V. The battery has approximately 75% of it's energy remaining.

A. True

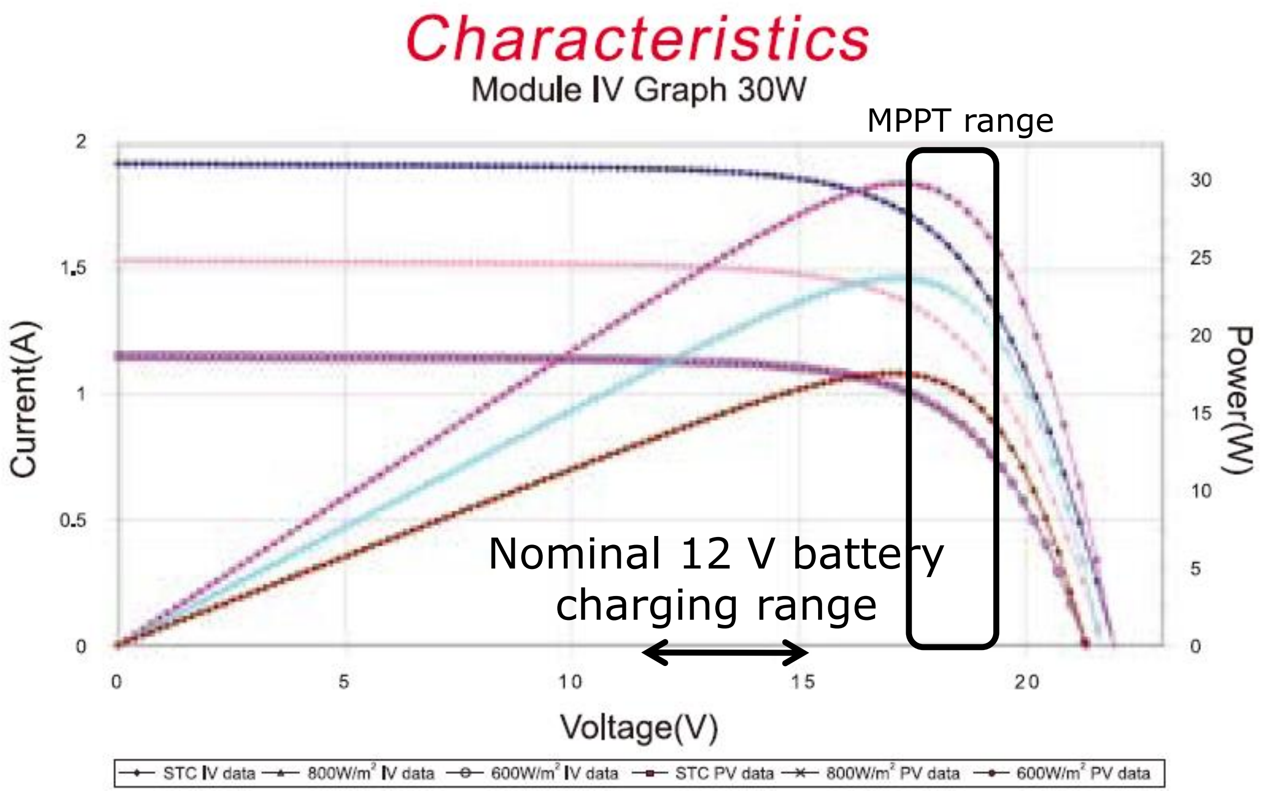
B. False

This battery is effectively "dead". 24V nominal systems should have voltages approximately between 22.8 and 26 V

Battery Charging

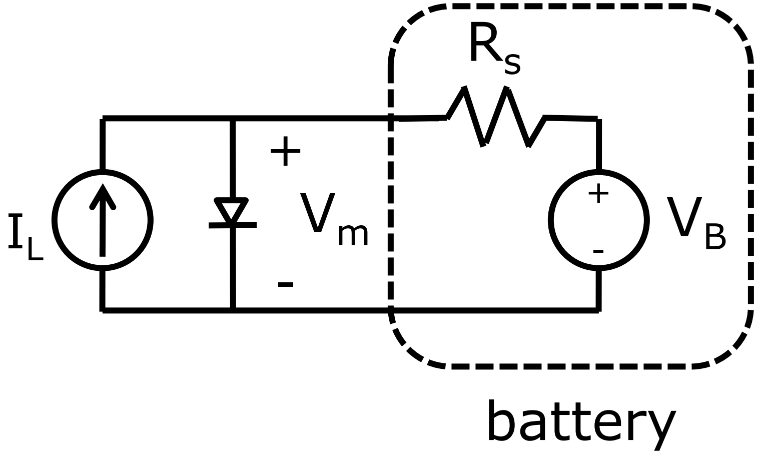
- If directly connected to the battery, the battery voltage sets the operating point of the PV module
  - Often reasonably close to the MPP
  - MPPT can also be used

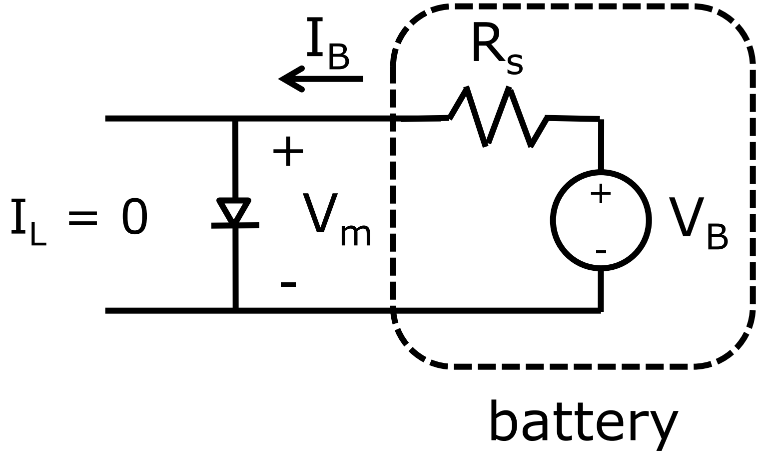
Battery Charging



Battery Charging

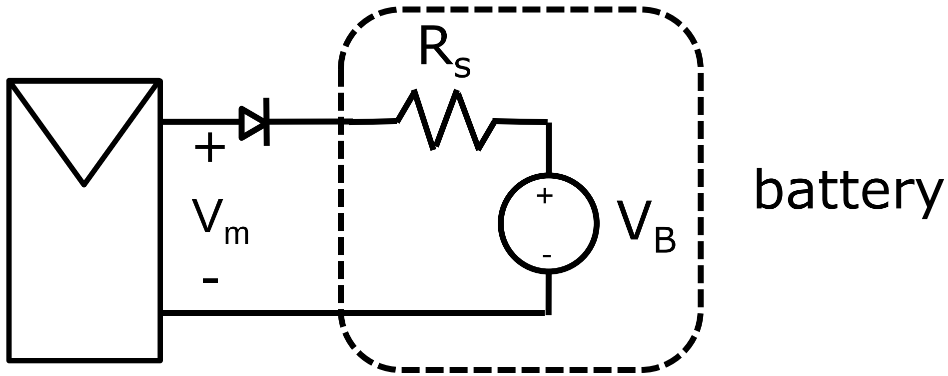
- What happens at night?
  - $I_L = 0$
  - Diode can be forward biased
    - depends on number of cells in series in the module
  - Battery discharges through PV
  - How can we prevent this?





Battery Charging

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

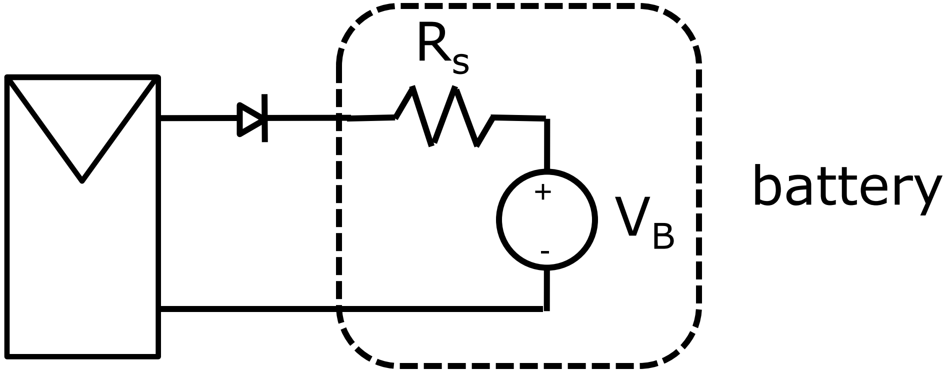


Battery Charging Control

- Control considerations:
  - prevent overcharging battery
  - prevent cycling
  - prevent excessive discharge
  - maximize power output of PV
  - prevent battery discharge through PV array

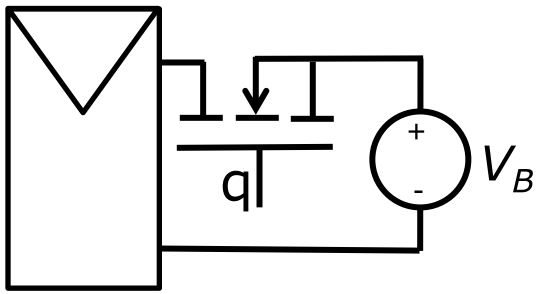
Battery Charging Application

- Blocking diode
  - self-regulated design
  - prevents battery discharge under low illumination
  - power is dissipated during charge operation
  - does not prevent overcharging of the battery
  - not recommended for most systems



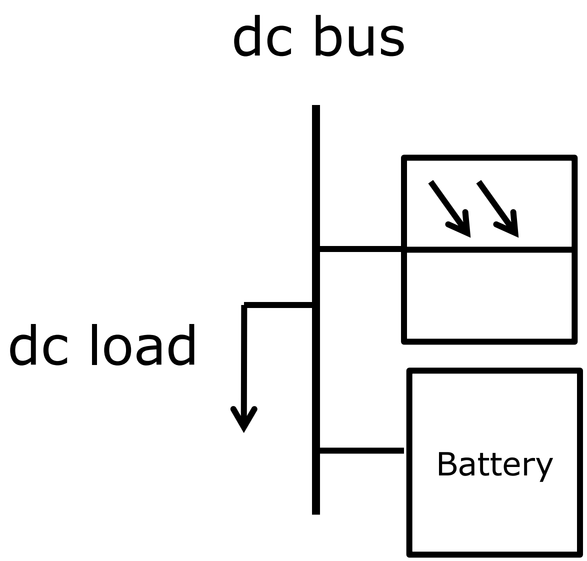
Battery Charging Application

- Improved design: series regulator
  - switching MOSFET
  - close switch when battery needs to be charged
  - open switch when battery is sufficiently charged
  - prevents battery discharge through the PV
  - low power loss
  - requires logic circuit



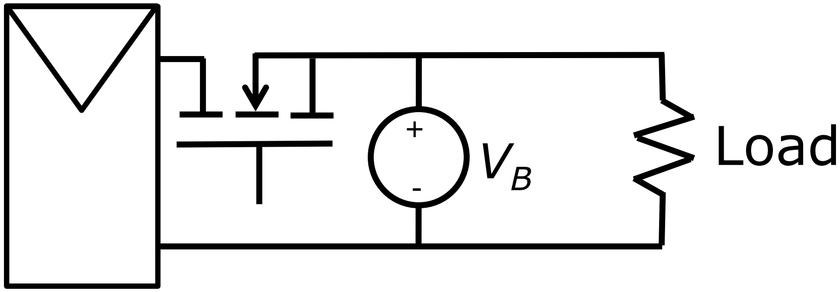
Battery Charging Application

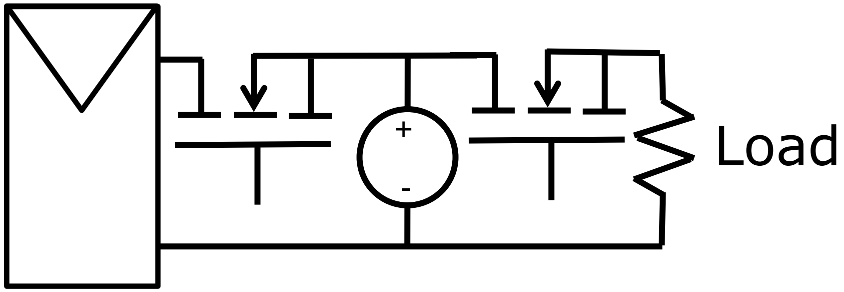
- Now add a dc load



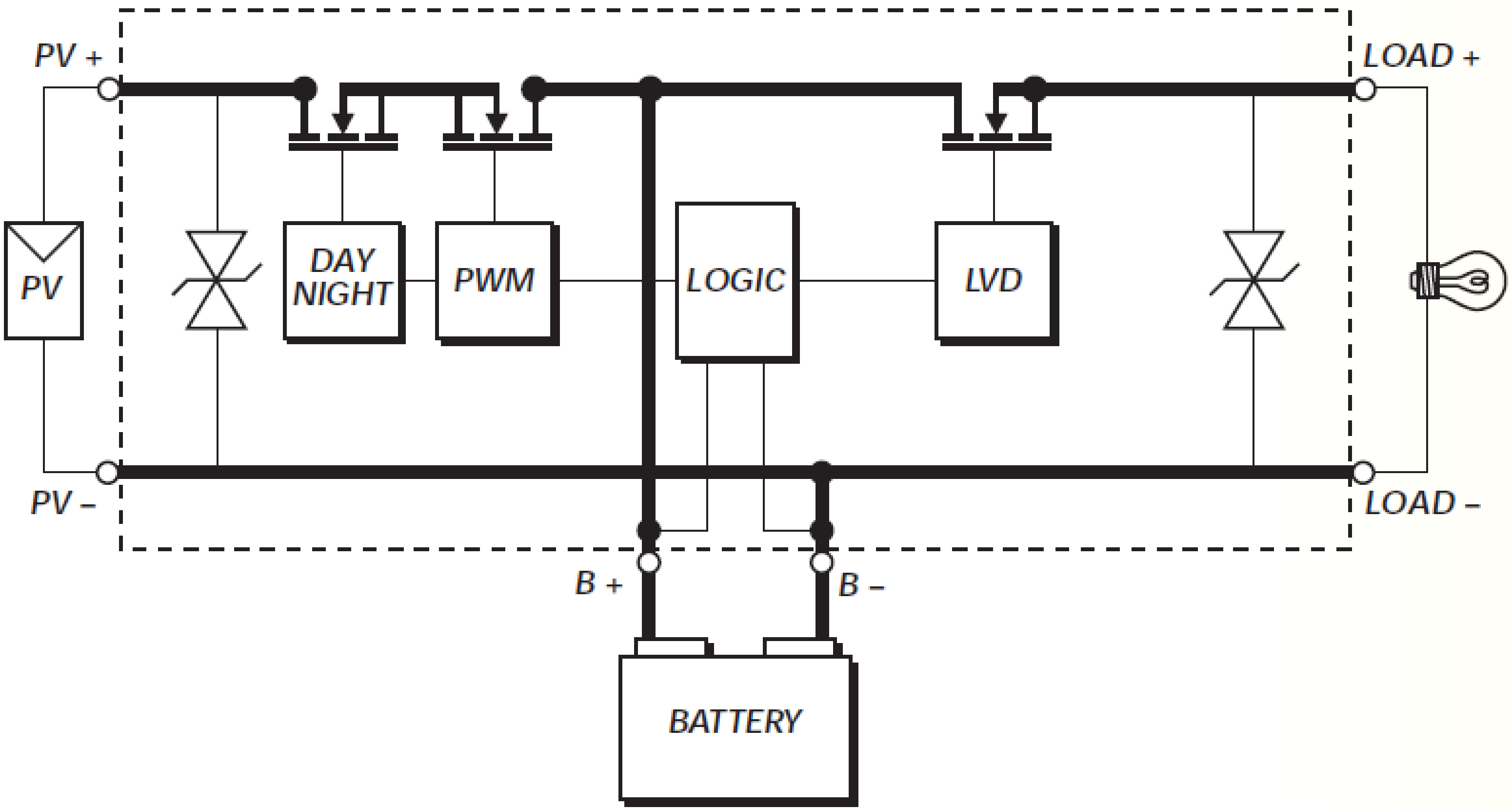
Battery Charging Application

- We often want to disconnect the load to avoid deeply discharging the battery
- Also want to avoid cycling the battery
- For example:
  - If V_b < 11.5 V, then disconnect the load (low voltage disconnect (LVD)
  - Reconnect after V_b > 12.6 V



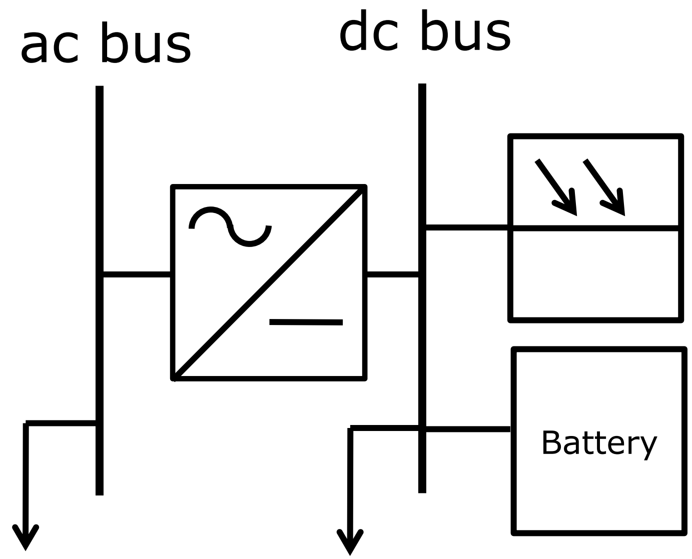


Battery Charging



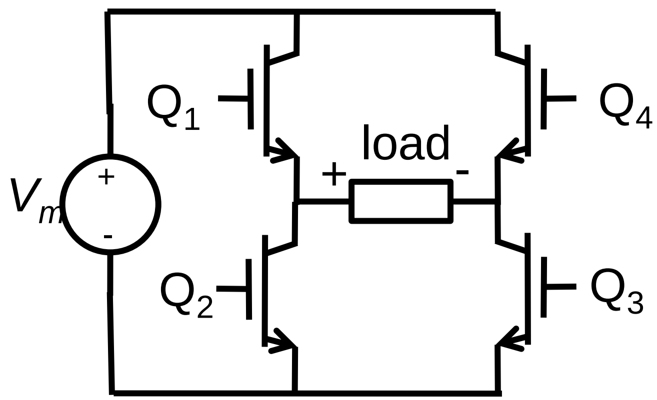
Grid Connected System

- Now add an ac load
  - ac/dc converter required



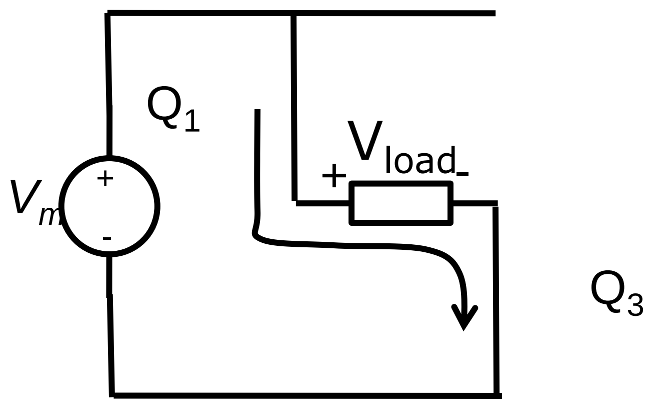
Inverter

- Power MOSFETs or SCRs 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



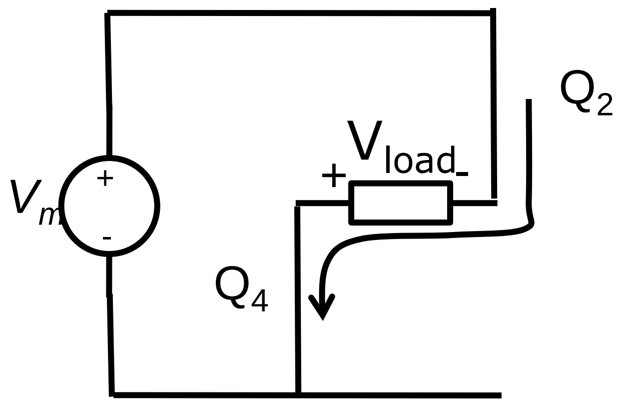
Inverter

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

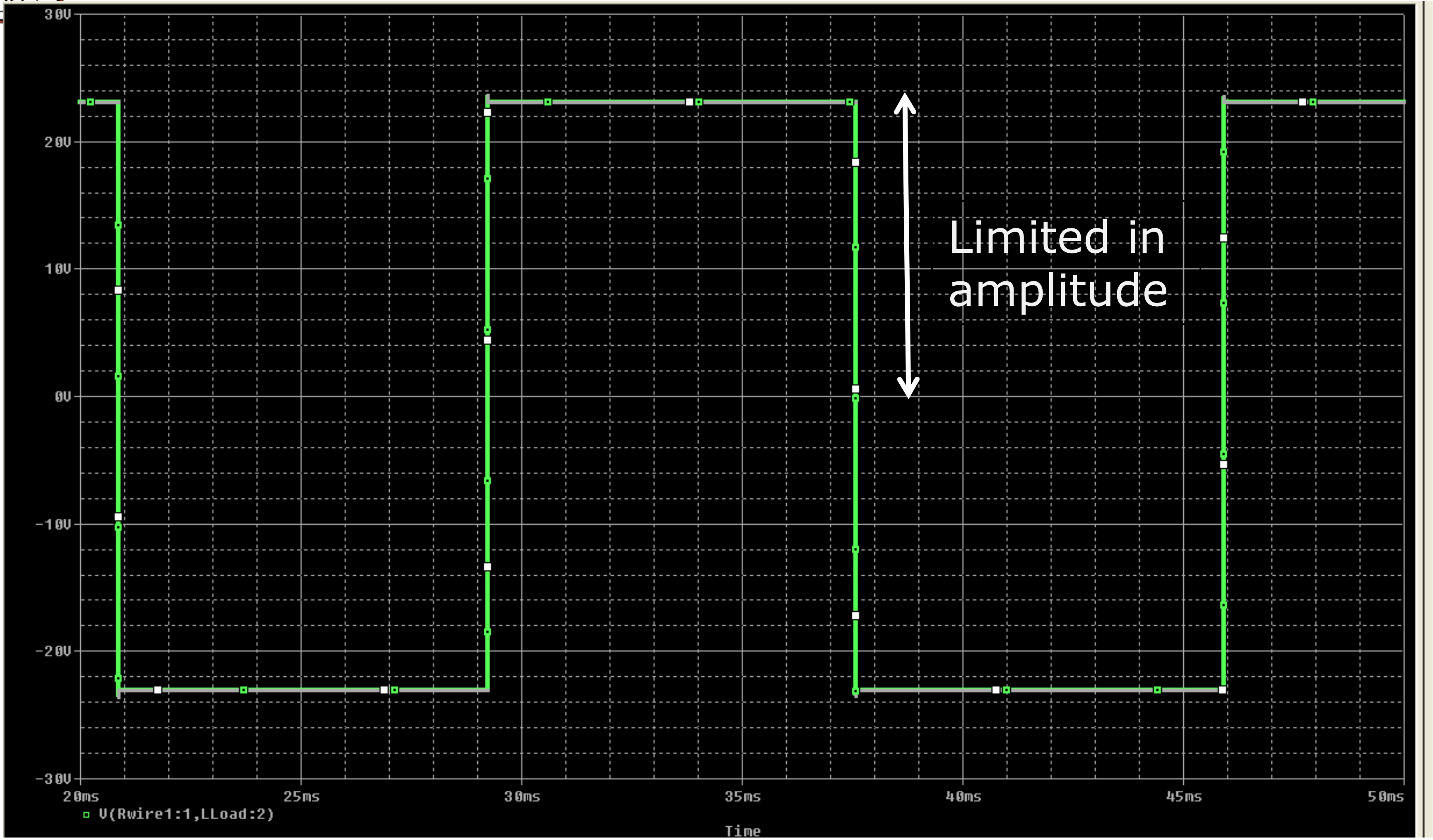


Inverter

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

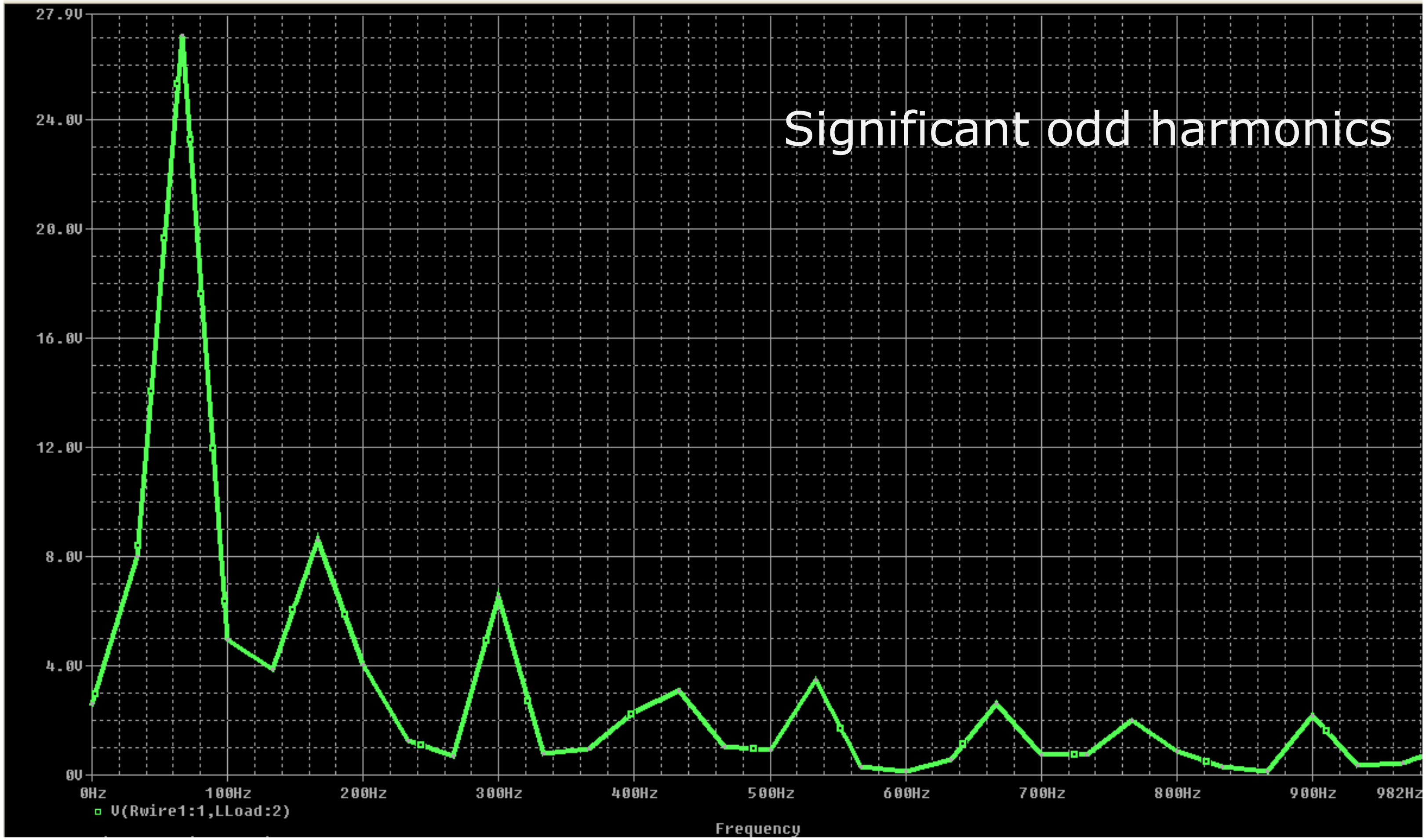


Inverter



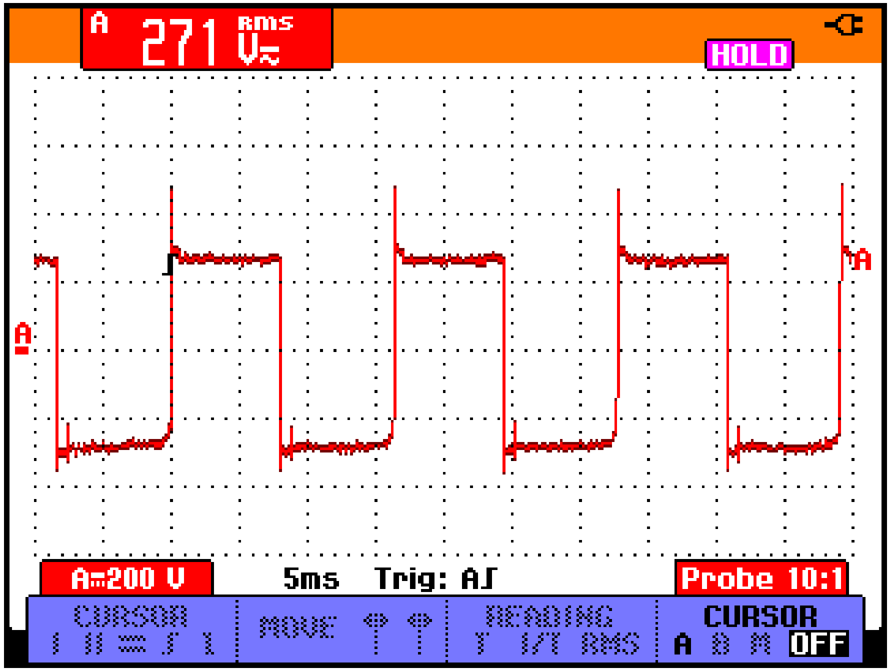
30V
20V
10V
0V
-10V
-20V
-30V
20ms
25ms
30ms
35ms
40ms
45ms
50ms
V(Rwire1:1,LLoad:2)
Time
Limited in amplitude

Inverter



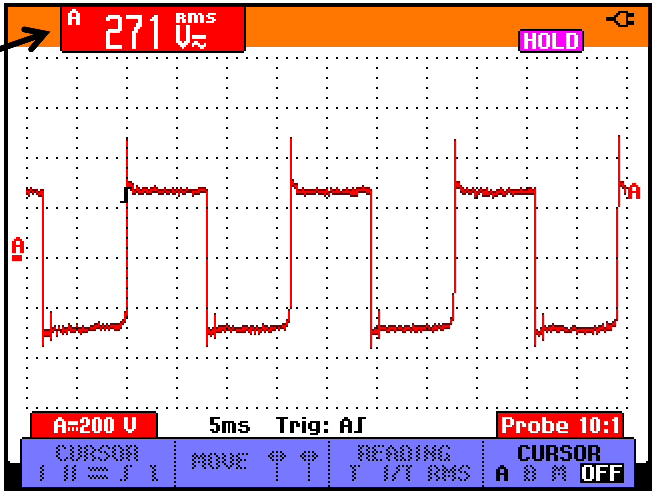
Significant odd harmonics
27.9V
24.0V
20.0V
16.0V
12.0V
8.0V
4.0V
0V
0Hz
100Hz
200Hz
300Hz
400Hz
500Hz
600Hz
700Hz
800Hz
900Hz
982Hz
V(Rwire1:1,LLoad:2)
Frequency

Squarewave Inverter

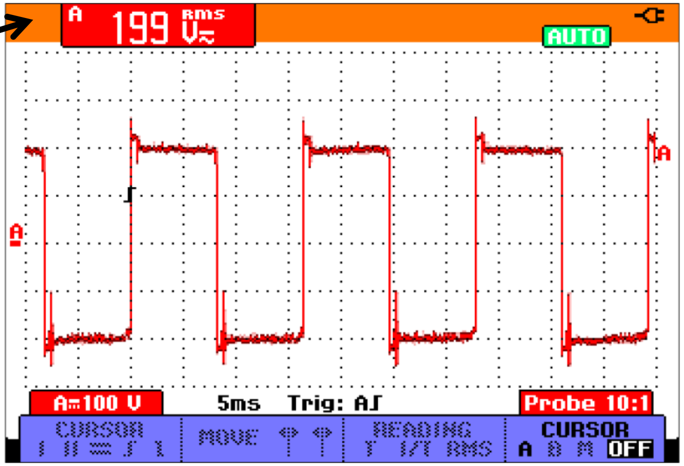


Squarewave Inverter

$V_{batt} = 12.4$



$V_{batt} = 9$



Inverter

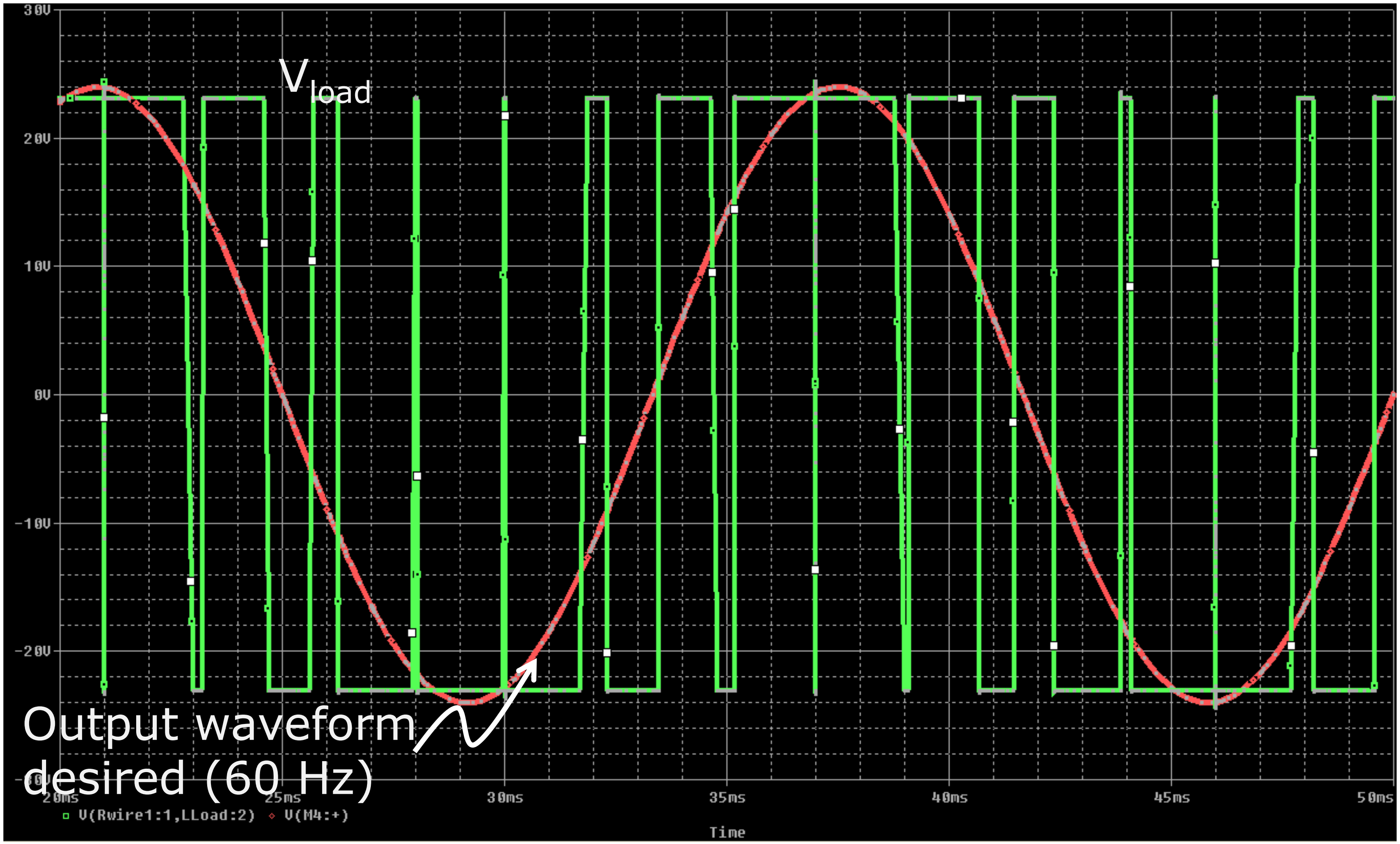
- MPPT can be used between PV and inverter
- Voltage can be stepped up to 120 Vac using a transformer
- Some ac loads can handle "dirty" power, many cannot
- Full bridge inverter output may be filtered to better approximate a sine wave
  - Significant harmonics are close to fundamental
  - Large capacitor is required
- A better approach is to use pulse width modulation to control the switches

PWM Inverter

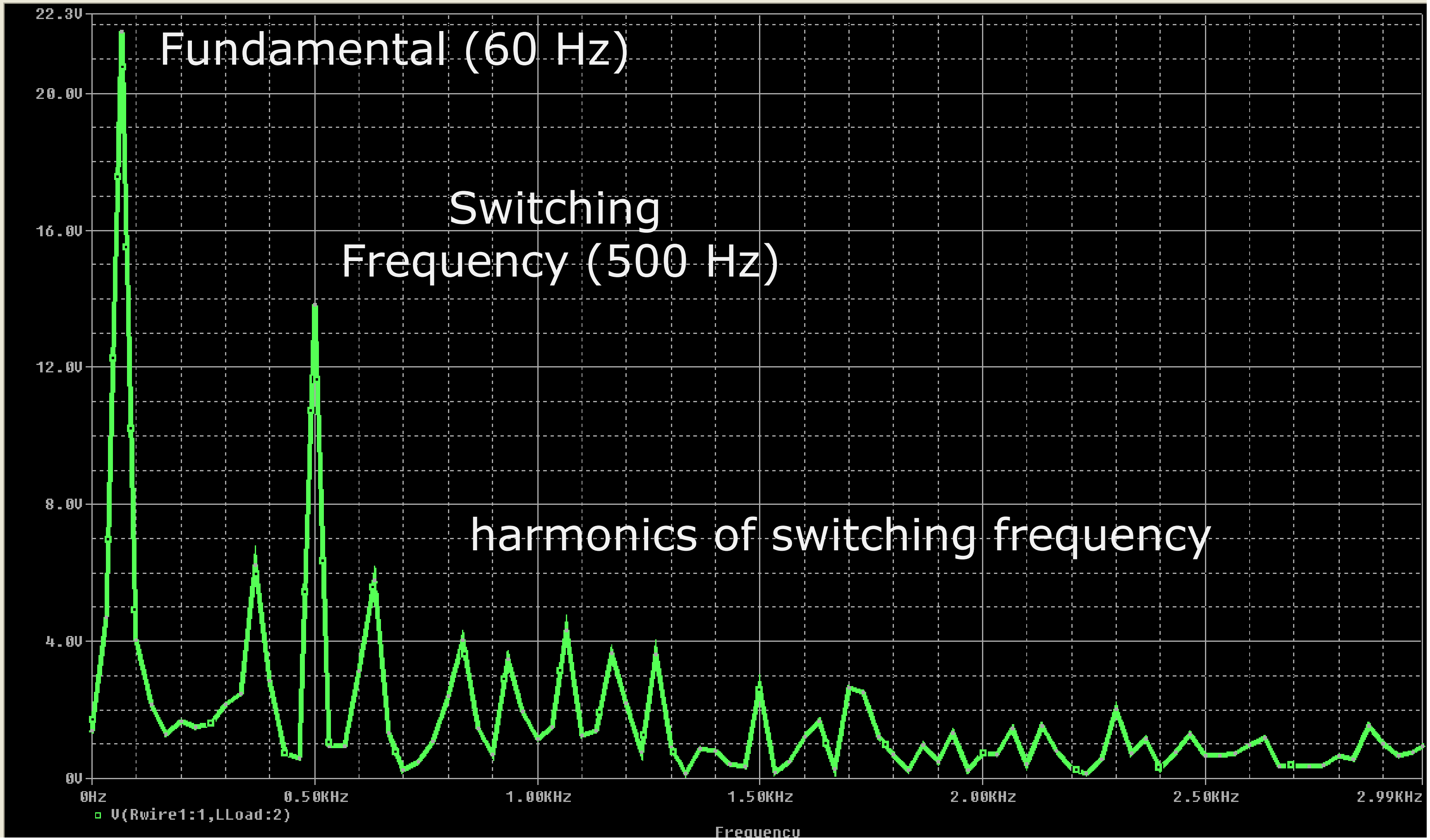
- Switching frequency should be much greater (4kHz - 10kHz) than fundamental frequency (60 Hz or 50 Hz)

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

PWM Inverter



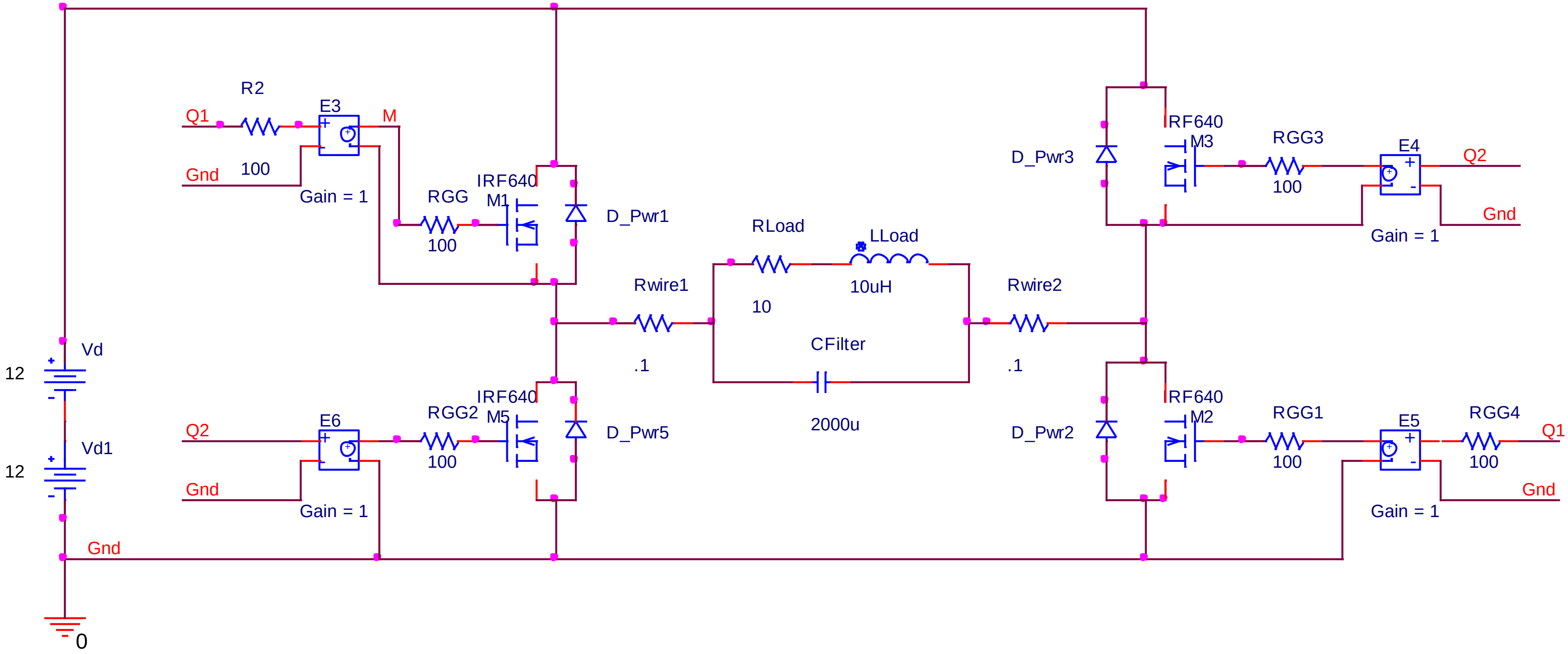
PWM Inverter



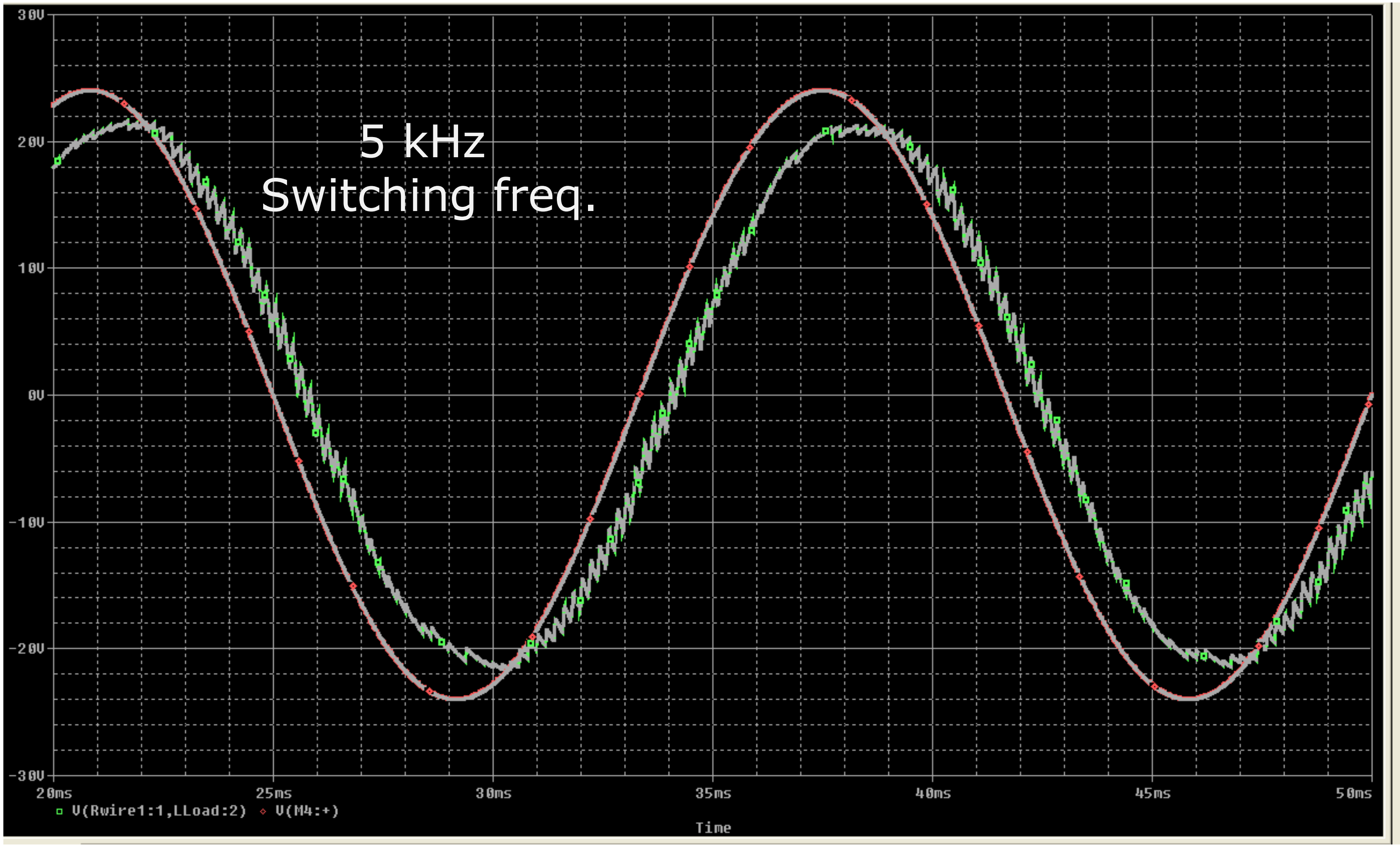
PWM Inverter

- Use a low-pass filter to remove components at switching frequency

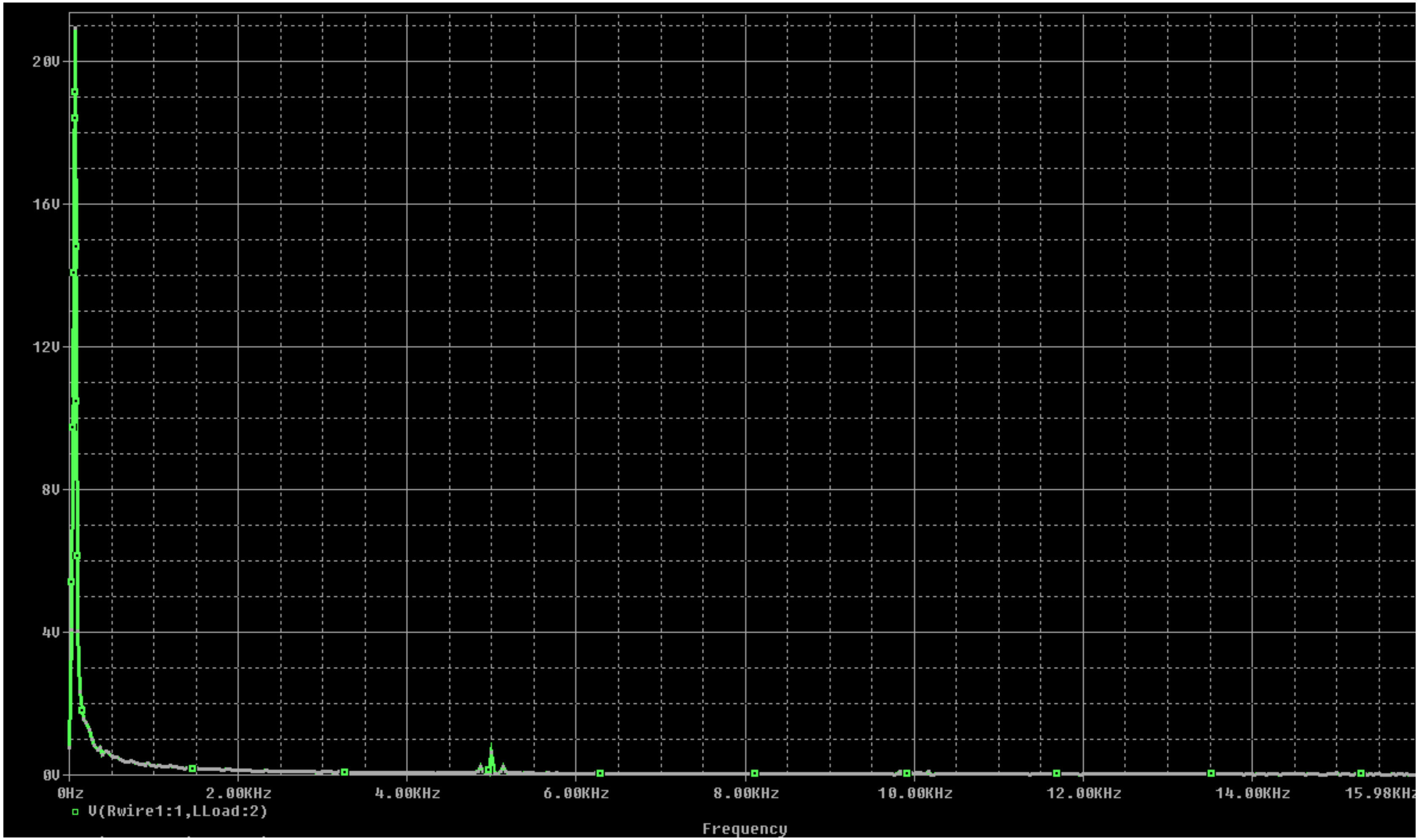
PWM Inverter



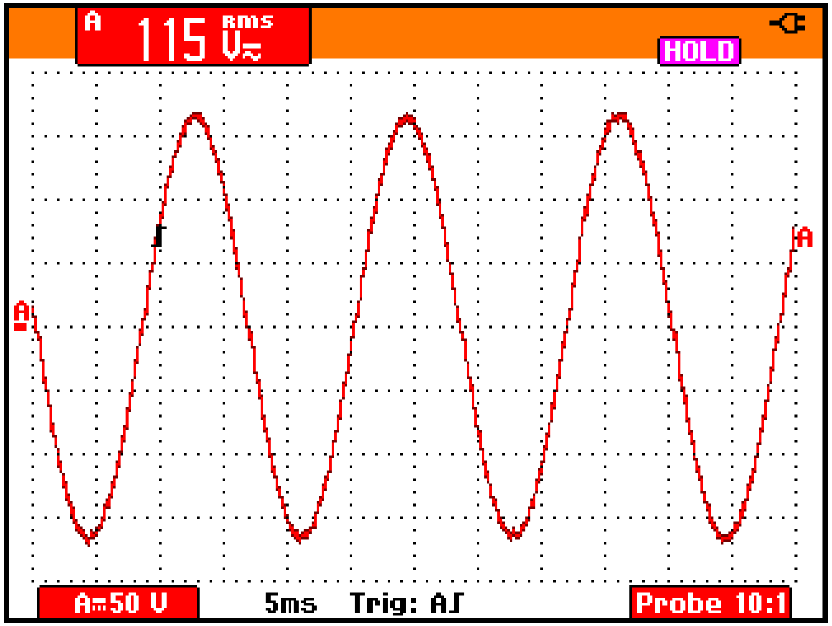
PWM Inverter



PWM Inverter

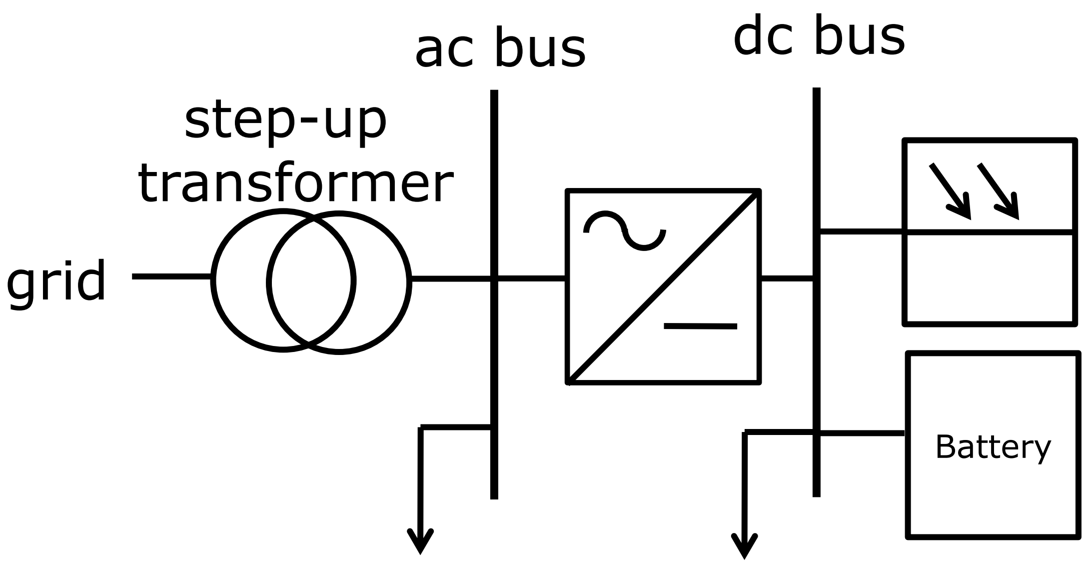


PWM Inverter



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
  - Must disconnect if the grid losses power
  - Must have acceptable power quality