11-Maximum Power Point Tracking

ECEGR 452

Renewable Energy Systems

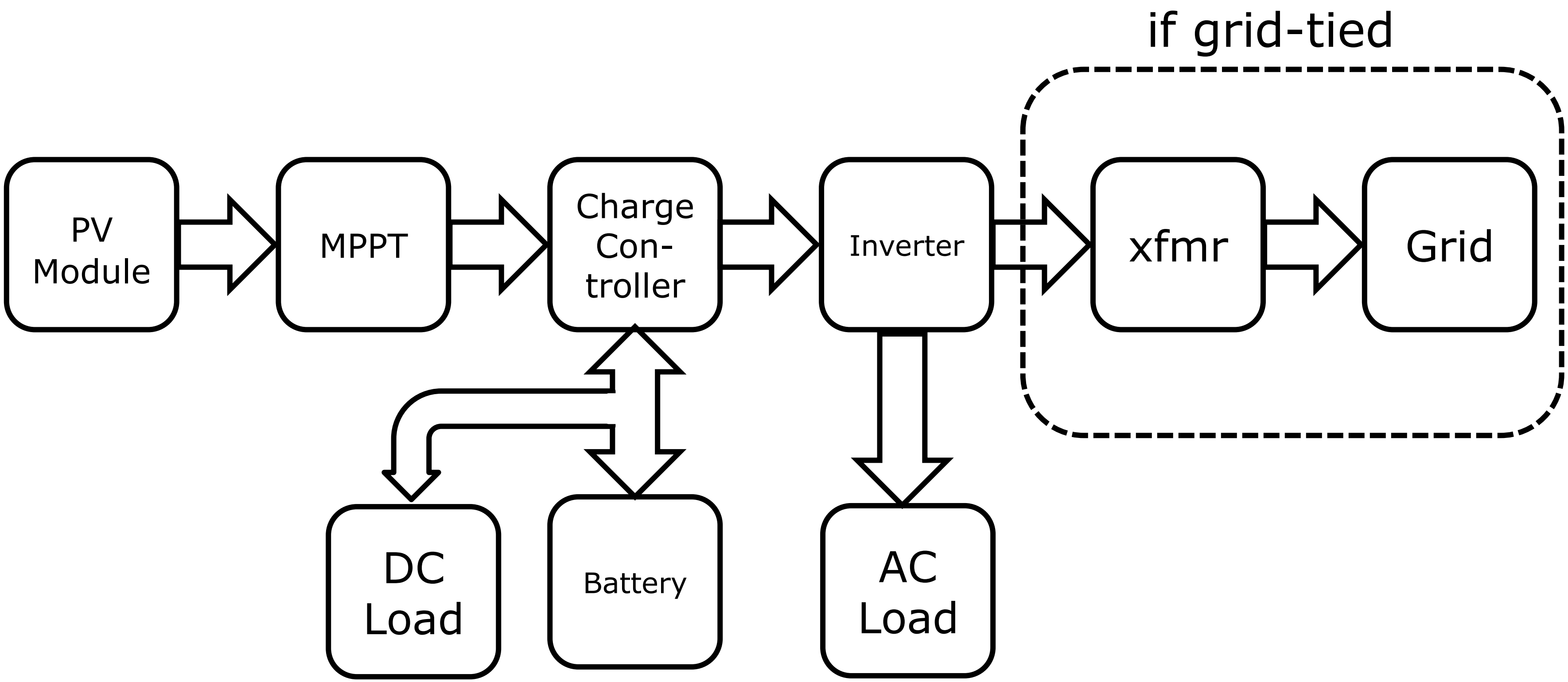
Overview

- PV Applications
- Maximum Power Point
- Boost Converter
- Illustrative Simulation

PV Applications

- Stand-Alone: all energy supplied to load originates from PV
  - remote applications
- Grid Connected: energy from PV may serve local load or be exported to the electric grid. Import of energy from the grid possible
  - PV power plants
  - urban applications
- Hybrid: PV + one or more generation sources (such as diesel generator), may be connected to the grid

Common PV System Elements

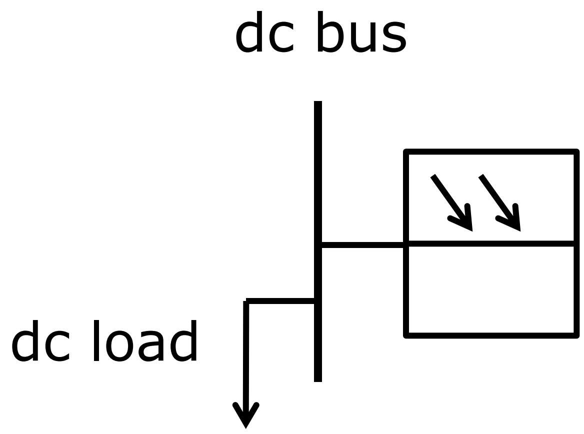


PV System Elements

- Generation
  - PV module(s)
  - diesel
  - other
- Power electronic converters
  - DC/AC (inverters)
  - DC/DC (buck, boost, buck boost)
- Load
  - AC
  - DC
- Storage
  - battery
  - hydrogen
- Transformer

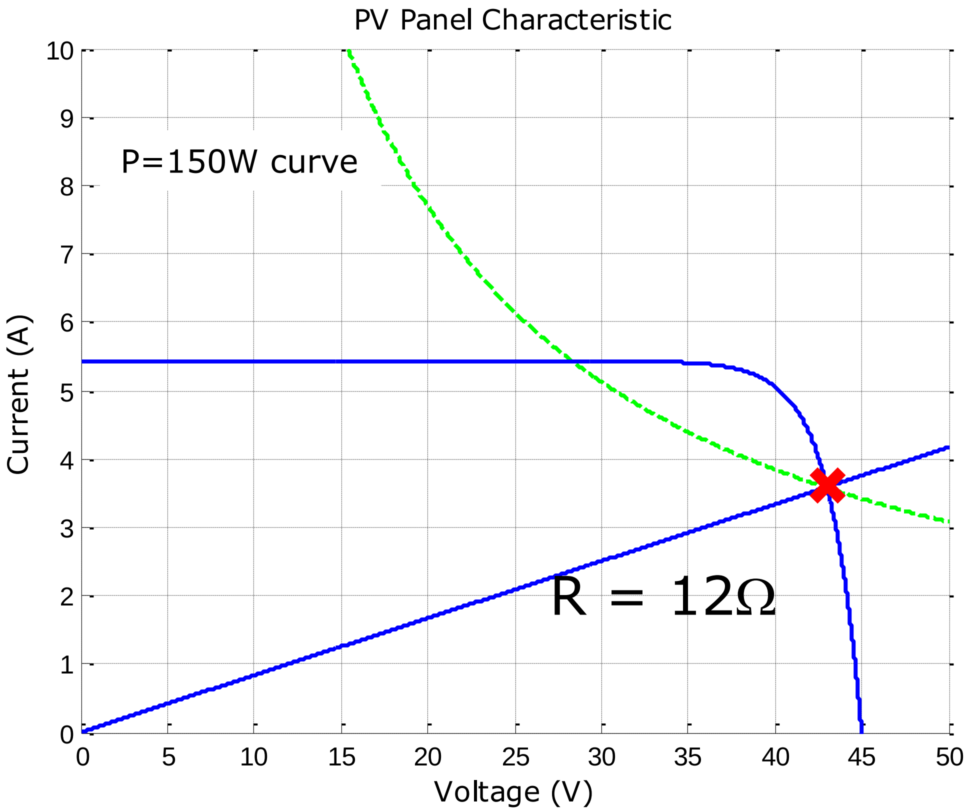
Stand Alone PV System

- Simple dc system
  - one PV module
  - one 12 Ohm resistive load (a heater)



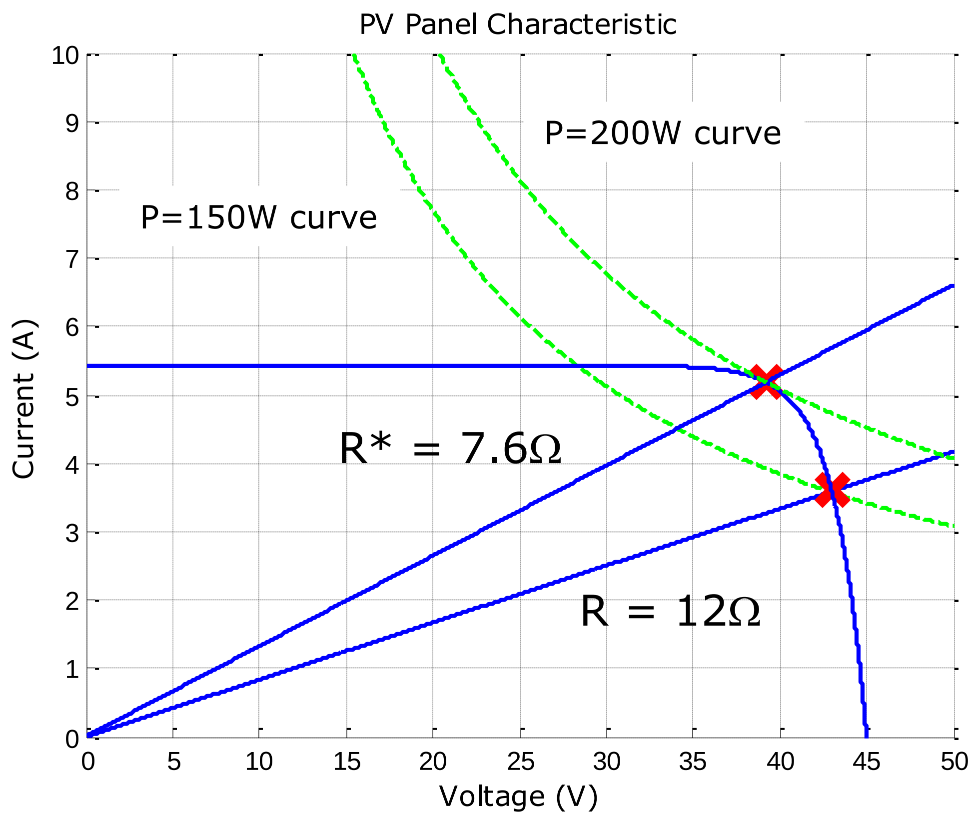
Stand Alone PV System

- With 12 Ohm load
  - P = 150 W
- Module Characteristics
  - P* = 200 W
  - Power output is not maximized



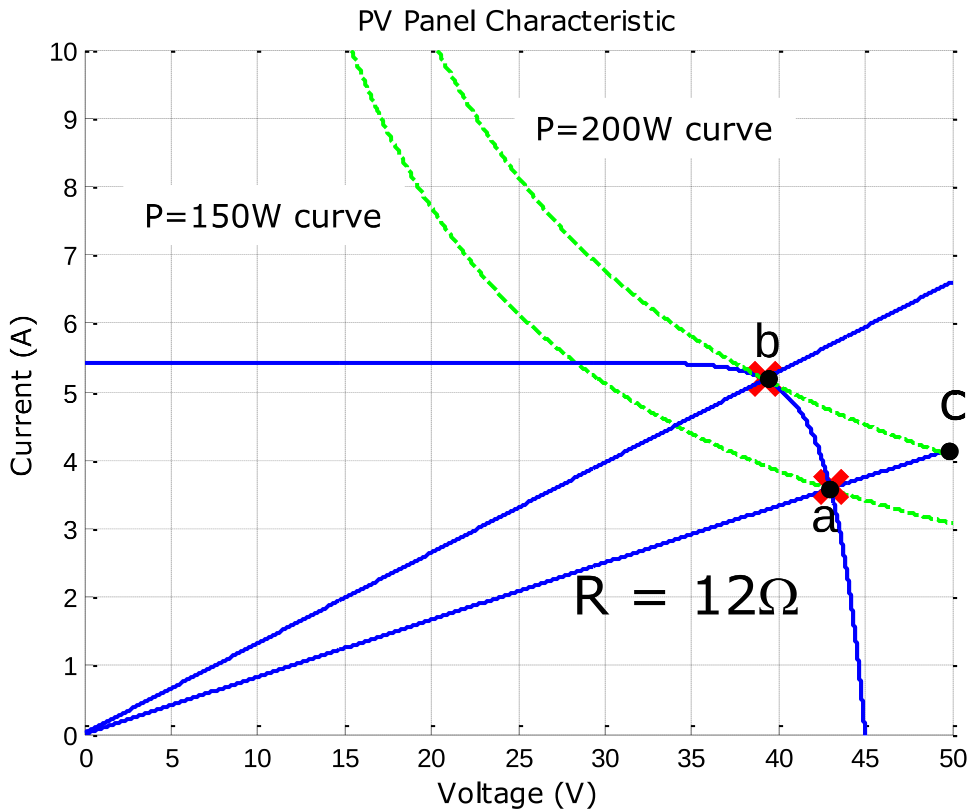
Stand Alone PV System

- At optimal operating point R = 7.6Ω



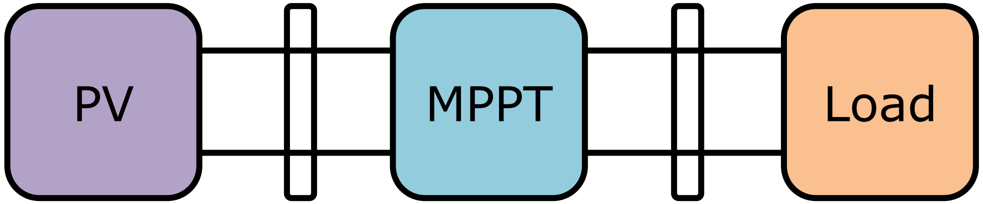
Stand Alone PV System

- Need to "move" operating point of the PV from a to b
- Need to move operating point of the load from a to c (increase voltage)
- Need an interface between PV panel and load



Maximum Power Point Trackers

- Use Maximum Power Point Tracker (MPPT): dc-dc converter
- HOMER assumes that the design has a MPPT in the converter

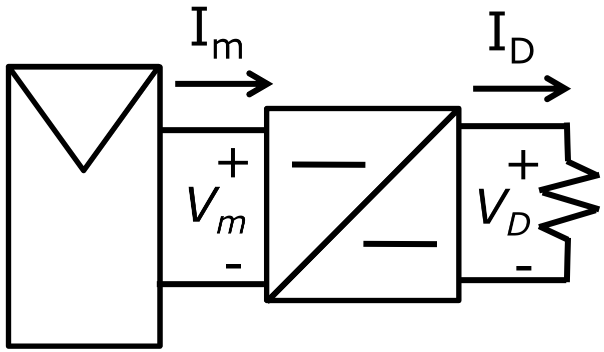


Operate at point "a"

Operate at point "c"

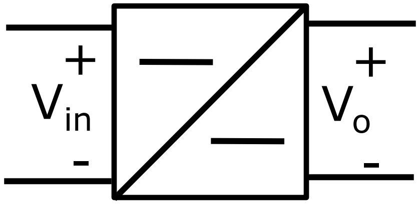
Maximum Power Trackers

- DC-DC converter
  - controls output voltage
  - ideal (no losses)
  - power is conserved $(V_m \times I_m) = (V_D \times I_D)$



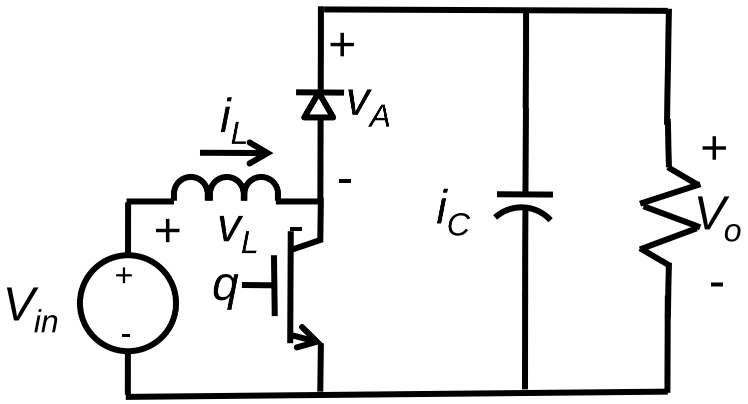
Maximum Power Trackers

- In most cases, the voltage at the load must be greater than the PV module voltage for maximum power transfer
- Voltage must be “boosted”
  - $V_o > V_{in}$
- Use a Boost Converter



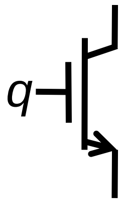
Boost Converter

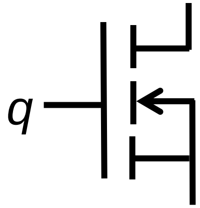
- Used to efficiently produce output voltage that is greater than input voltage
- First analyze assuming input is a voltage source



Boost Converter

- Power electronic components
  - IGBT (Insulated Gate Bipolar Transistor)
  - MOSFETs
- Behave like controllable switches
  - q = 1; switch is closed
  - q = 0; switch is open





Inductor Model

- Recall:
  - L: inductance (H)
  - current through inductors cannot change instantaneously
- Behavior is described as:

$$v_L = L\frac{di}{dt} \Rightarrow i_L(t)\frac{1}{L}\int_{\tau} v_L d\tau$$

$$i_L(t) = i_L(0) + \frac{1}{L}\int_0^t v_L d\tau$$

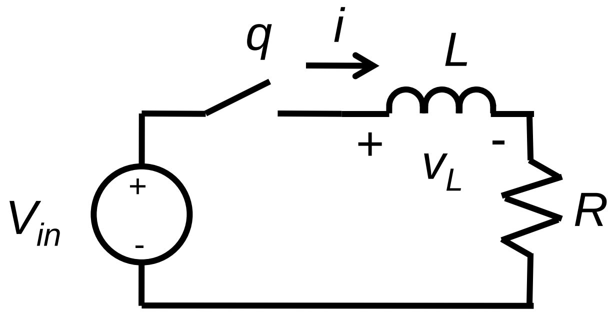
$$E = \frac{1}{2}Li_L^2$$

Inductor Model

- Switch q closes at t = 0
- Response of the circuit is computed as

$$V_{in} = Ri + L\frac{di}{dt}$$

$$\frac{di}{dt} = \frac{V_{in} - Ri}{L} = \frac{-R}{L}\left(i - \frac{V_{in}}{R}\right)$$



L = 100µH, V_{in} = 10 V,
R = 5Ω

Inductor Model

$$V_{in} = Ri + L\frac{di}{dt}$$

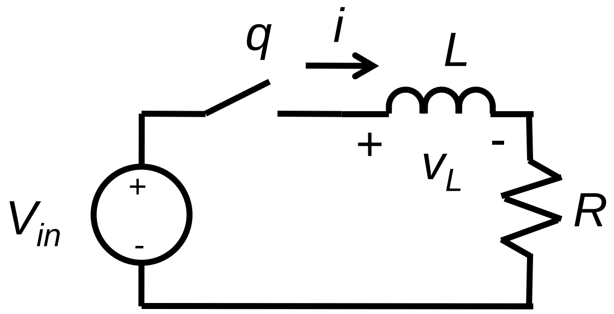
$$\frac{di}{dt} = \frac{V_{in} - Ri}{L} = \frac{-R}{L}\left(i - \frac{V_{in}}{R}\right)$$

- Solving the differential equation gives:

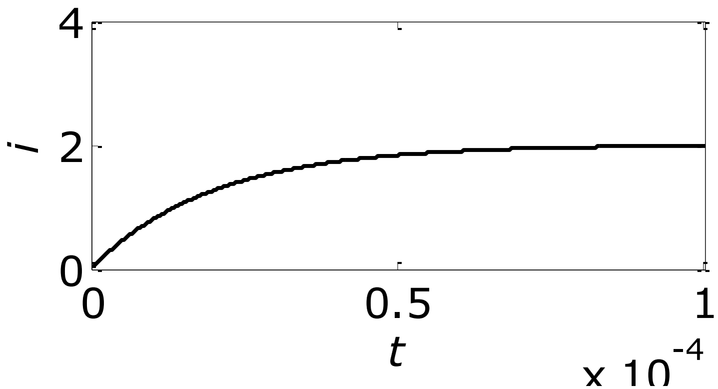
$$i(t) = \frac{V_{in}}{R} - \frac{V_{in}}{R}e^{-\left(R/L\right)t}$$

time constant L/R

- Note the dependence of the time constant, τ, on L and R



L = 100μH, V_{in} = 10 V,
R = 5Ω

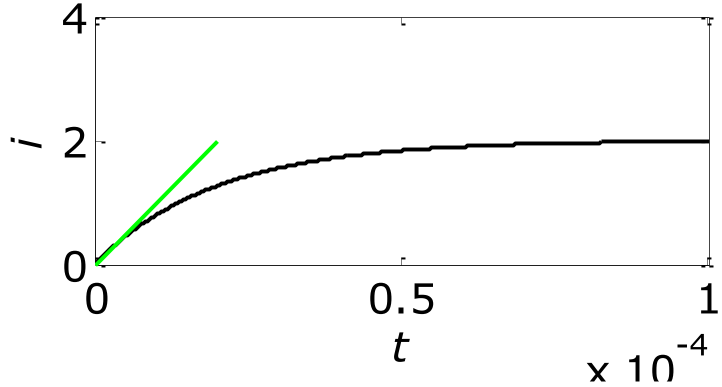


Response of R-L Circuit

- If we are only interested in $t < \tau$, then we can use a linear approximation

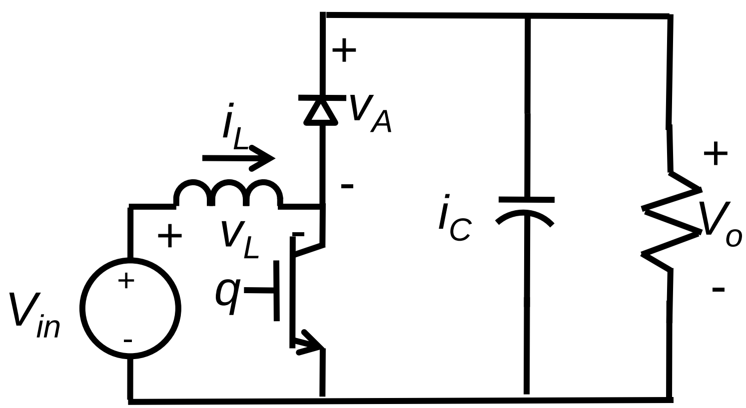
$$v_L = L\frac{\Delta i}{\Delta t}$$

- We will use linear approx. hereafter (fast switching time, large inductances)

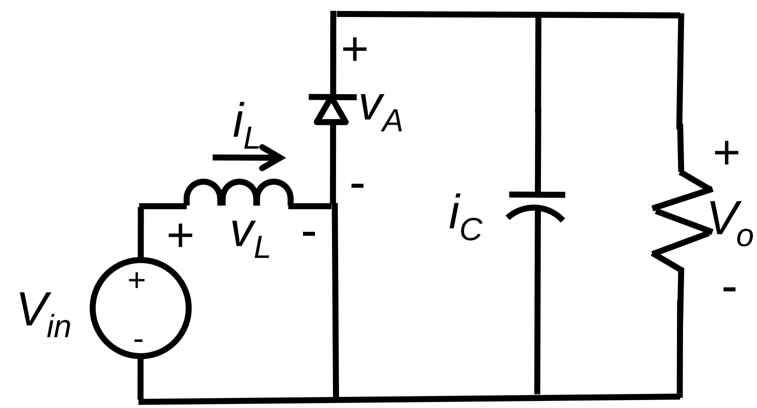


Boost Converter

- Assume q = 1
- transistor is in the on-state
- Is the diode conducting?



(switch closed)



Boost Converter (q=1)

- Diode is in the off-state

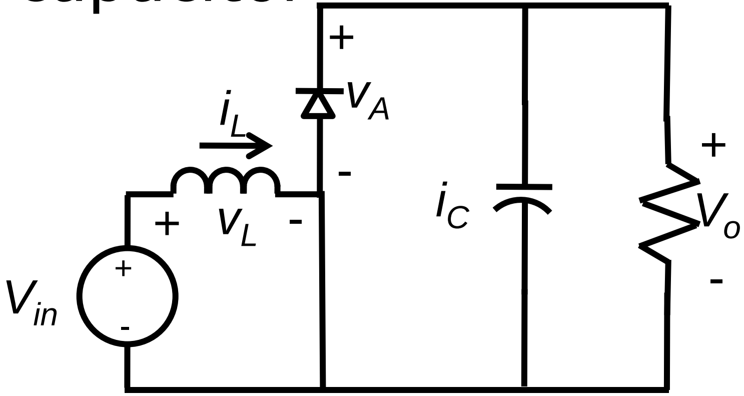
  $$v_A = v_o > 0$$

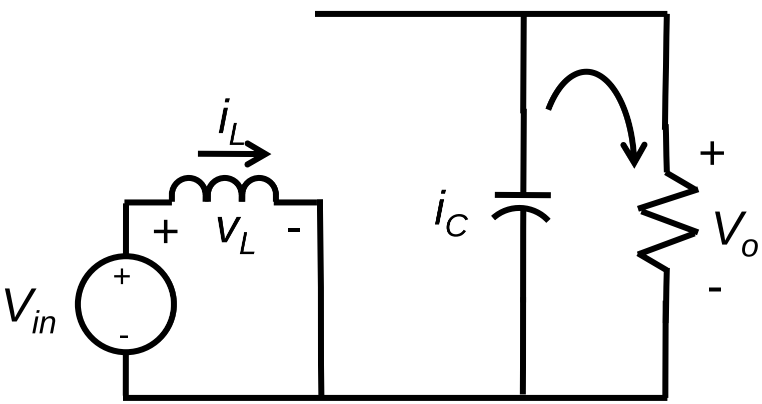
- Observations

  $$v_L = V_{in}$$

  $$i_{in} = i_L$$

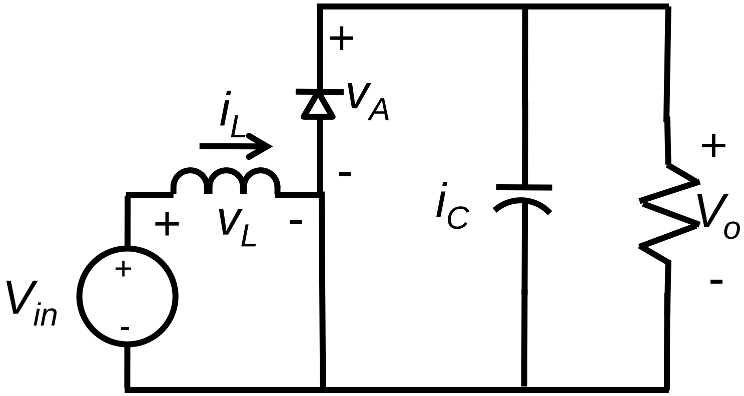
- Load current is supplied by discharging the capacitor

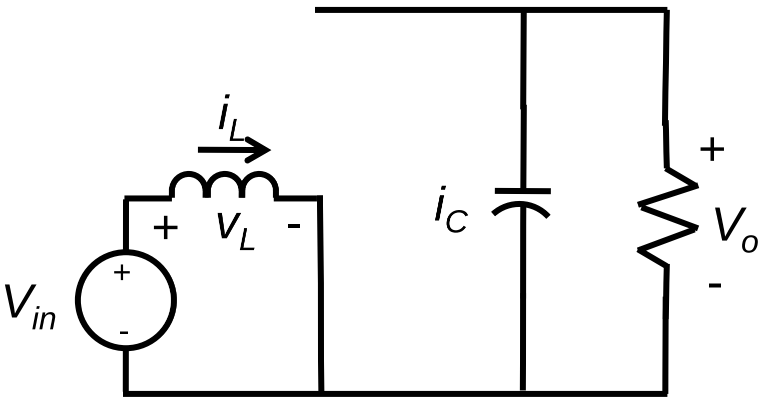




Boost Converter (q=1)

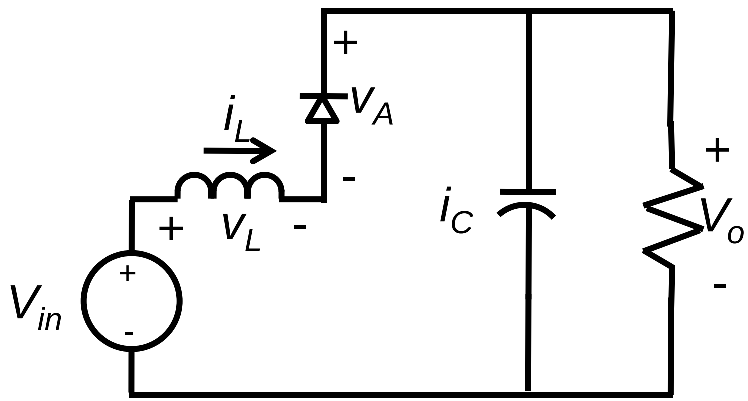
- Voltage across inductor is positive
  - Inductor current increases (assumed linear)



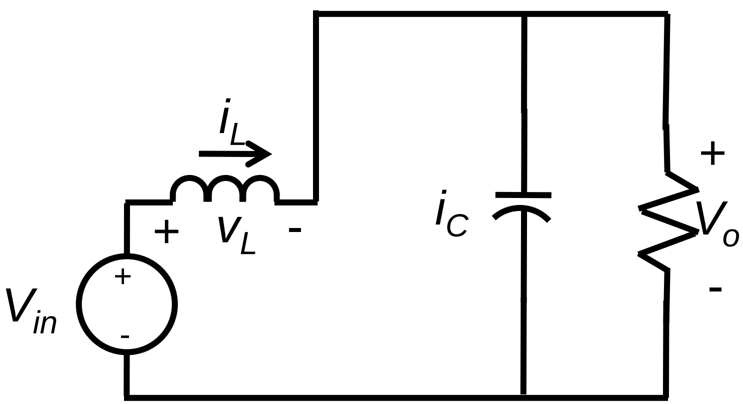


Boost Converter (q=0)

- Now assume q = 0
- Transistor is in the off-state
- Is the diode conducting?
  - diode is in the on-state (inductor current must flow)



(switch open)



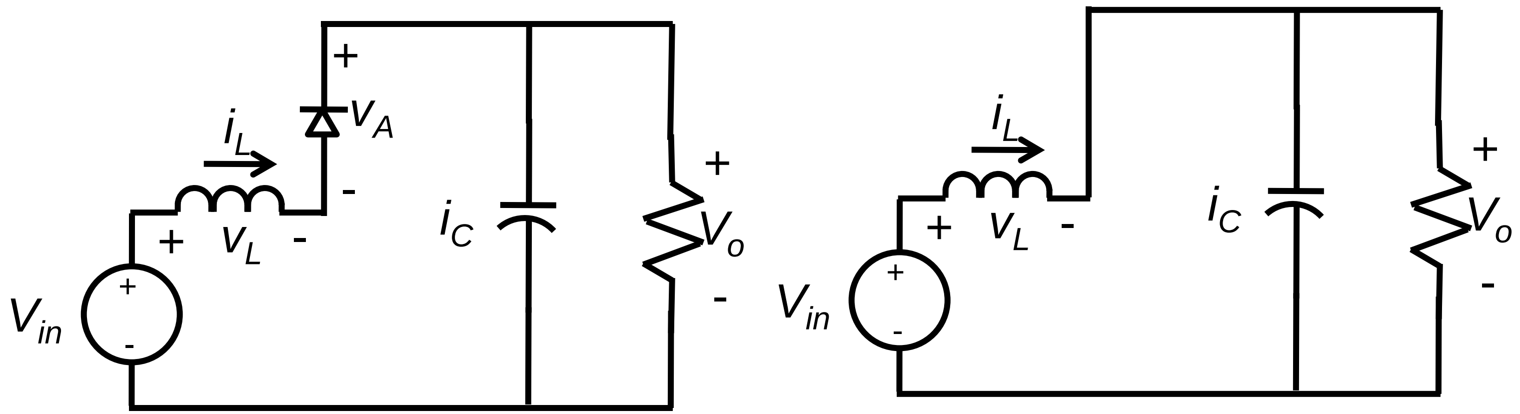
Boost Converter (q=0)

- Observations

  $v_L = V_{in} - V_o$ (ignoring diode voltage drop)

  $i_{in} = i_L$

- If $V_o > V_{in}$, then V_L is negative
  - inductor current decreases (assumed linear)



Boost Converter Inductor Voltage

- If q = 1, then

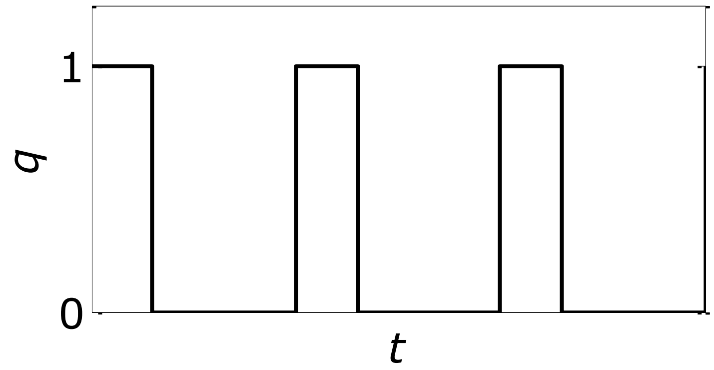
$$v_L = V_{in}$$

- If q = 0, then

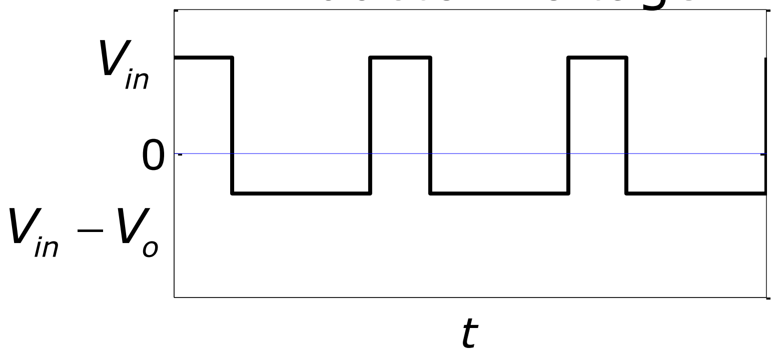
$$v_L = V_{in} - V_o$$

- What is the average output voltage?

Switching Signal

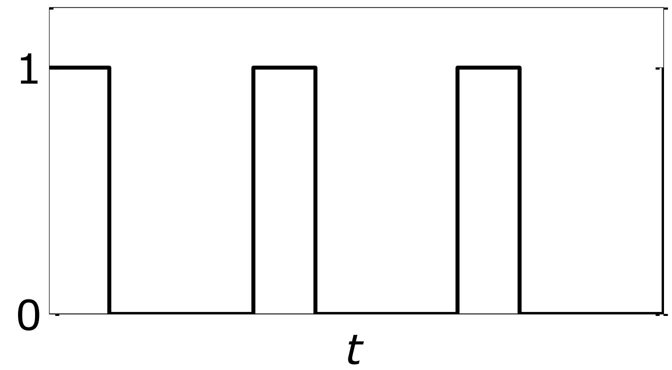


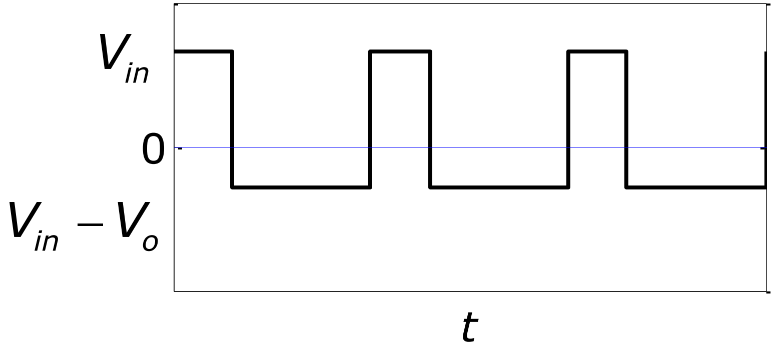
Inductor Voltage



Boost Converter Inductor Voltage

- What is the average output voltage?
  - average inductor voltage must equal zero
  - otherwise the current (and energy) increases





Boost Converter Inductor Voltage

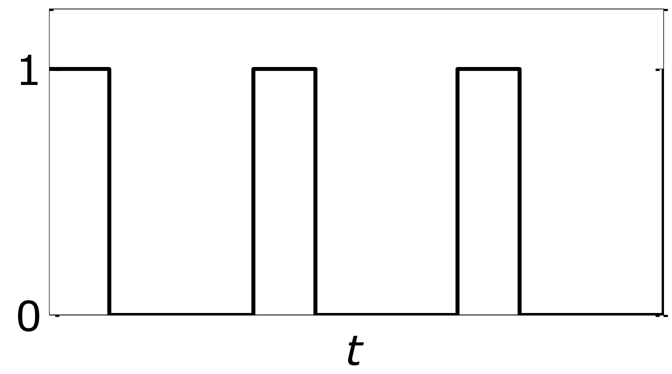
- Let the duty ratio D be the percent of time that q = 1
- Then:

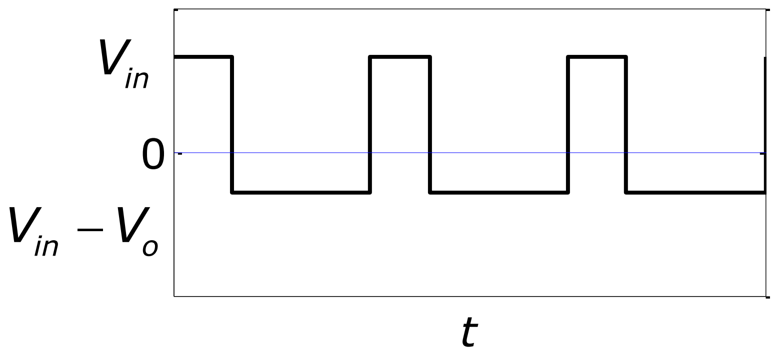
$$D\left(V_{in}\right) + (1 - D)\left(V_{in} - V_o\right) = 0$$

$$\Rightarrow DV_{in} + V_{in} - V_o - DV_{in} + DV_o = 0$$

$$\Rightarrow V_o\left(-1 + D\right) + V_{in}\left(D + 1 - D\right) = 0$$

$$\Rightarrow V_o = \frac{1}{1 - D} V_{in} \quad \text{important result!}$$





Boost Converter Inductor Current

- If $v_L > 0$, then

$$\Delta i_{L,pos} = \frac{1}{L}(V_{in}) D T_S$$

- If $v_L < 0$, then

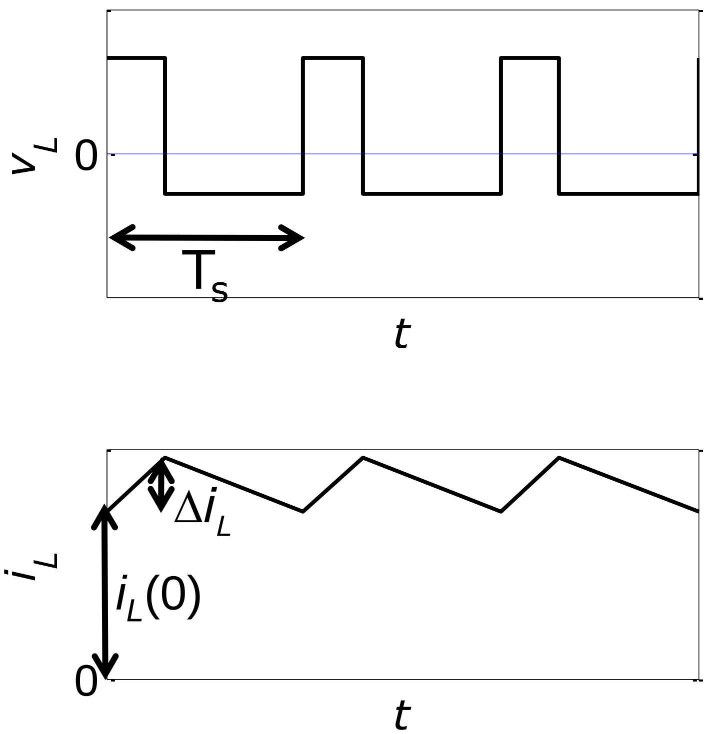
$$\Delta i_{L,neg} = -\frac{1}{L}(V_o - V_{in})(1-D)T_S$$

- and

$$\Delta i_L = \Delta i_{L,pos} = \Delta i_{L,neg}$$

- Average inductor current:

$$I_L = I_{in} = \frac{V_o}{V_{in}} I_o = \frac{1}{1-D}\left(\frac{V_o}{R}\right)$$



Boost Converter Input Current

- If q = 1, then

  $i_{in} = i_L$

- If q =0, then

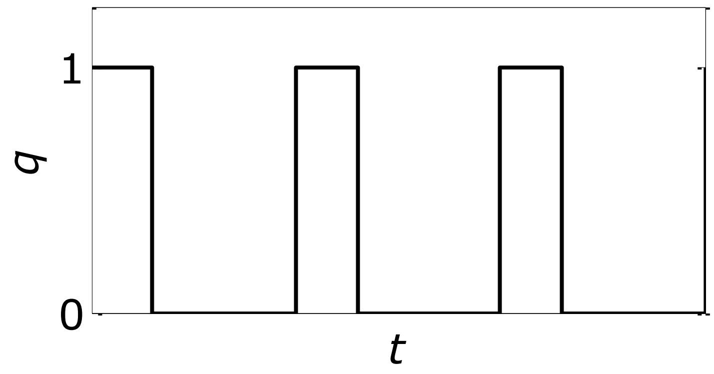
  $i_{in} = i_L$

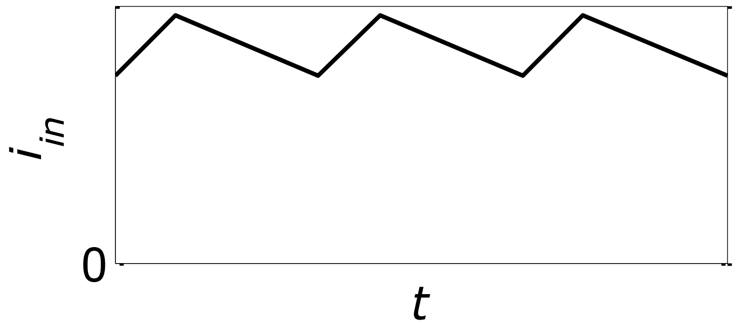
- Average input current is

  $I_{in} = I_L$

- Power in equals power out

  $V_{in} I_{in} = V_o I_o$





Boost Converter Capacitor Current

- If q = 1, then

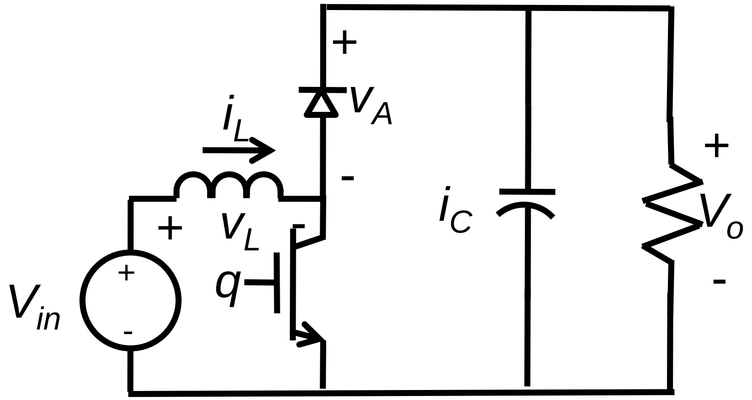
$$i_c = -I_o$$

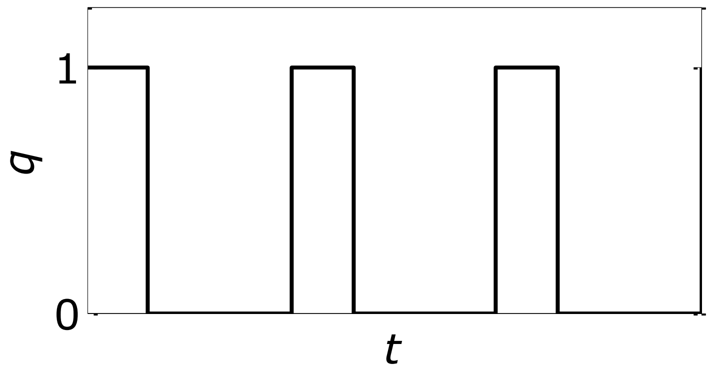
- If q =0, then

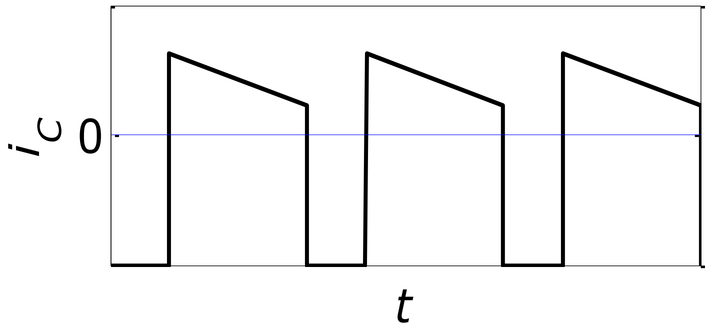
$$i_c = i_{rip}$$

- Output voltage has ripple

$$\Delta v_o = \frac{i_c \Delta t}{C}$$







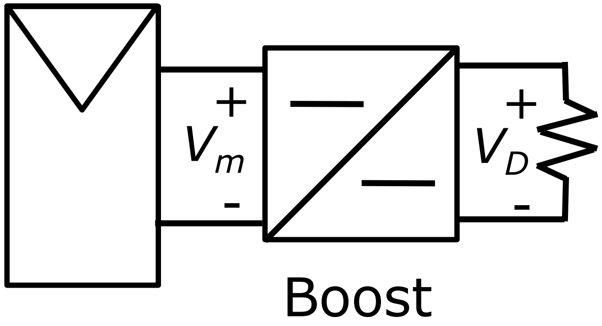
Boost Converter Capacitor Current

- Must find D that maximizes the power output

$$V_o = \frac{1}{1-D} V_{in}$$

$$D = 1 - \frac{V_{in}}{V_o}$$

- V_{in} is not a voltage source, so D cannot be made arbitrarily large



Maximum Power Trackers

- What should the voltage at the load be to ensure maximum power transfer?

$$P^* = V^* I^*$$

Recall: P* is the maximum power under the given conditions

$$P_D = V_D I_D = \frac{V_D^2}{R} = P^*$$

$$V_D^* = \sqrt{P^* R}$$

- Therefore: $D = 1 - \frac{V_{STC}^*}{V_D^*} = 1 - \frac{V_{STC}^*}{\sqrt{P^* R}}$
- The duty ratio should not exceed this value

Maximum Power Trackers

- Find D of a boost MPPT if:
  - load resistance is 12 Ohms
  - $V^* = 38$ V
  - $P^* = 200$ W

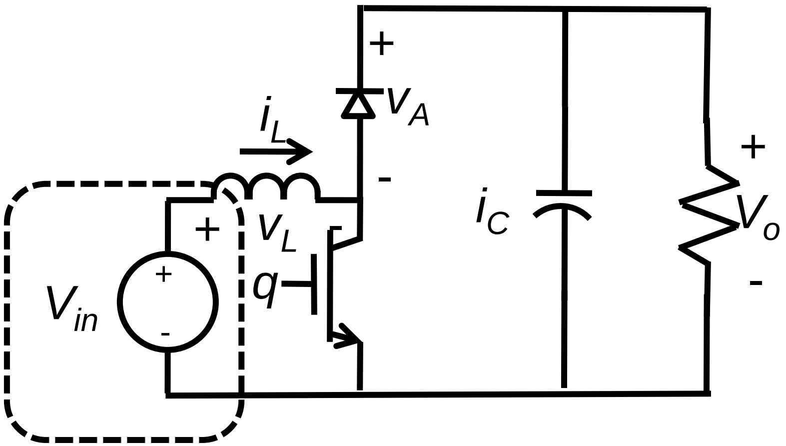
Maximum Power Trackers

- Find D of a boost MPPT if:
  - load resistance is 12 Ohms
  - $V^* = 38$ V
  - $P^* = 200$ W

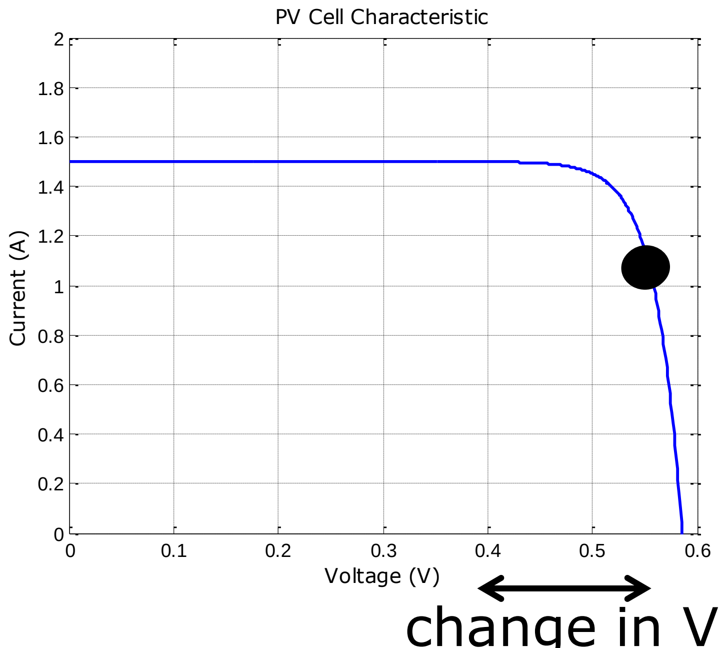
$$D = 1 - \frac{V^*}{V_D^*} = 1 - \frac{V^*}{\sqrt{P^* R}} = 0.224$$

Maximum Power Trackers

- Note: PV panels cannot be modeled as independent voltage sources
  - As I_{in} increases, the voltage decreases

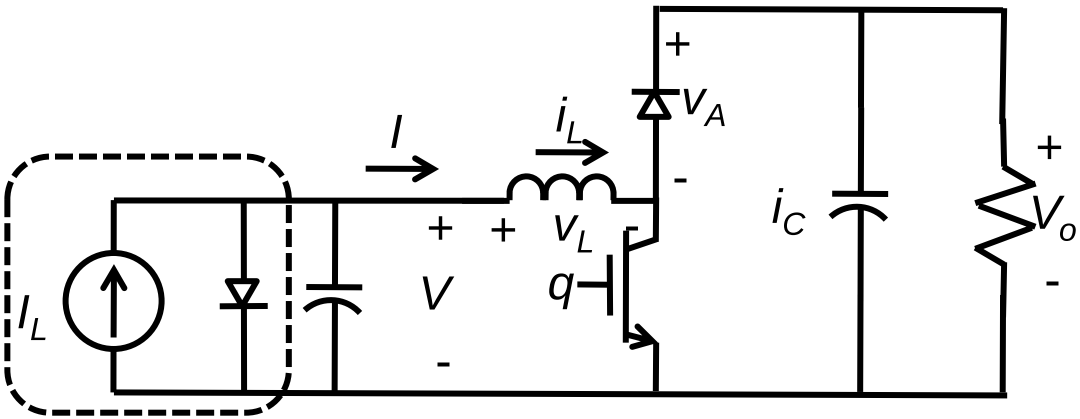


Inappropriate PV model

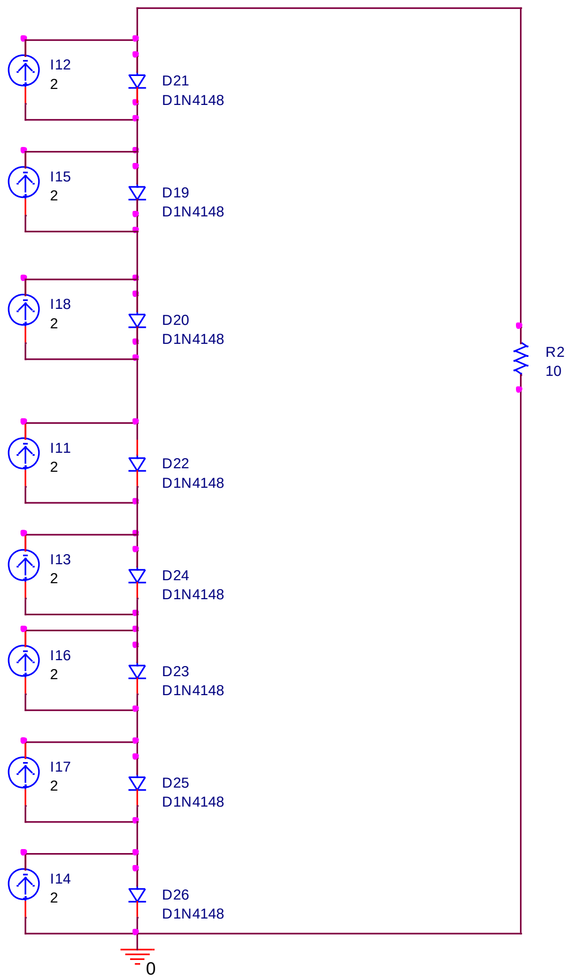


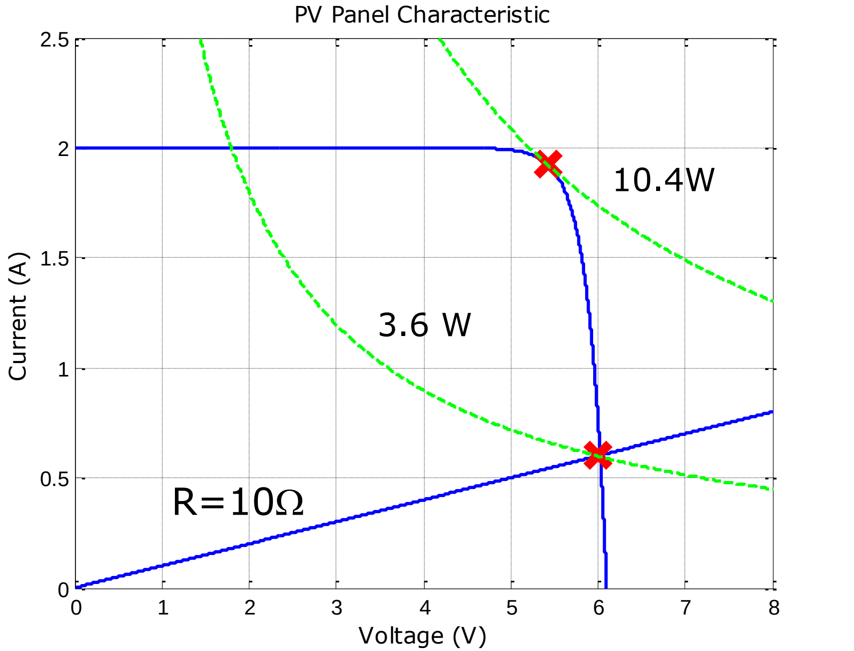
Maximum Power Trackers

- Include input capacitor to steady voltage



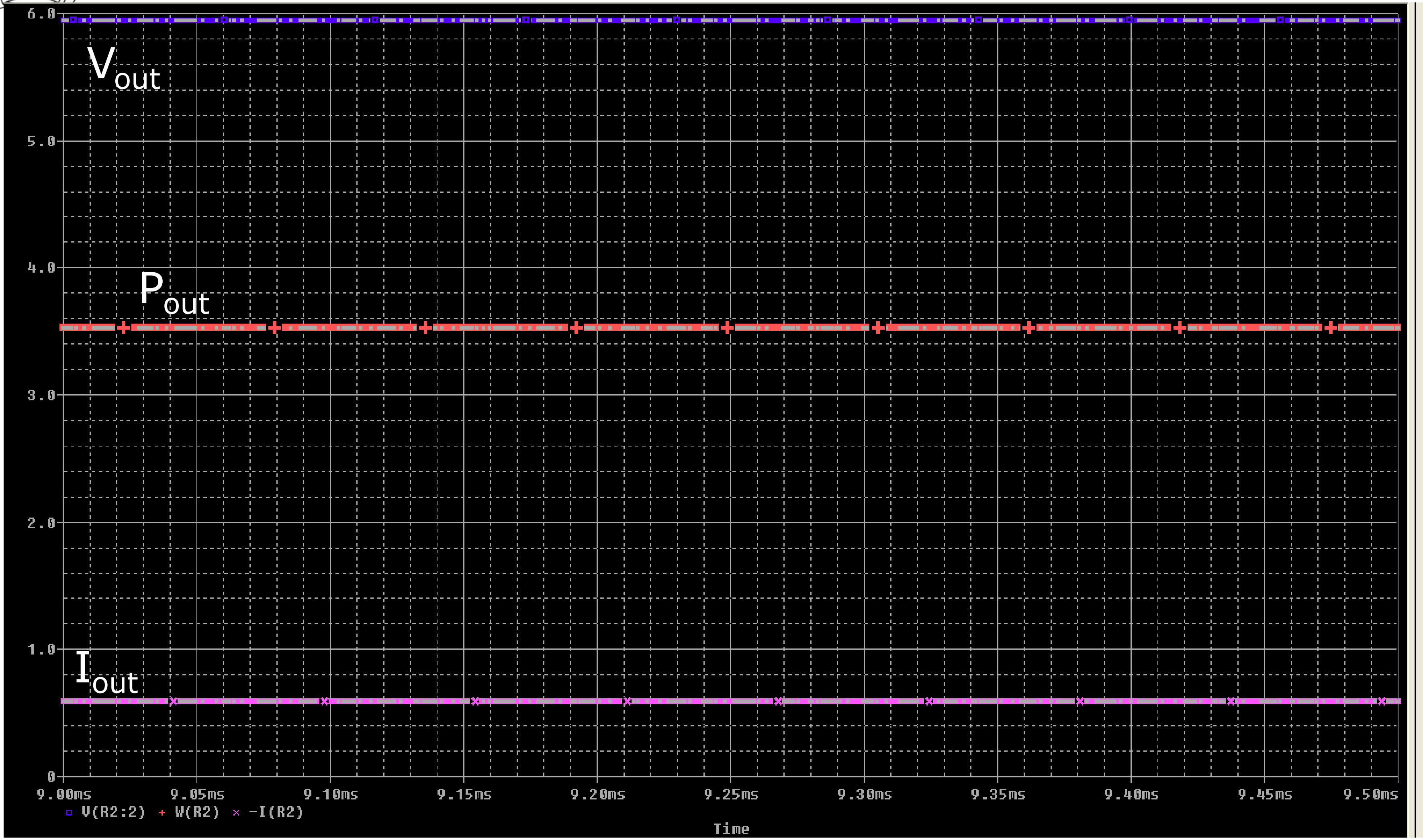
Maximum Power Trackers





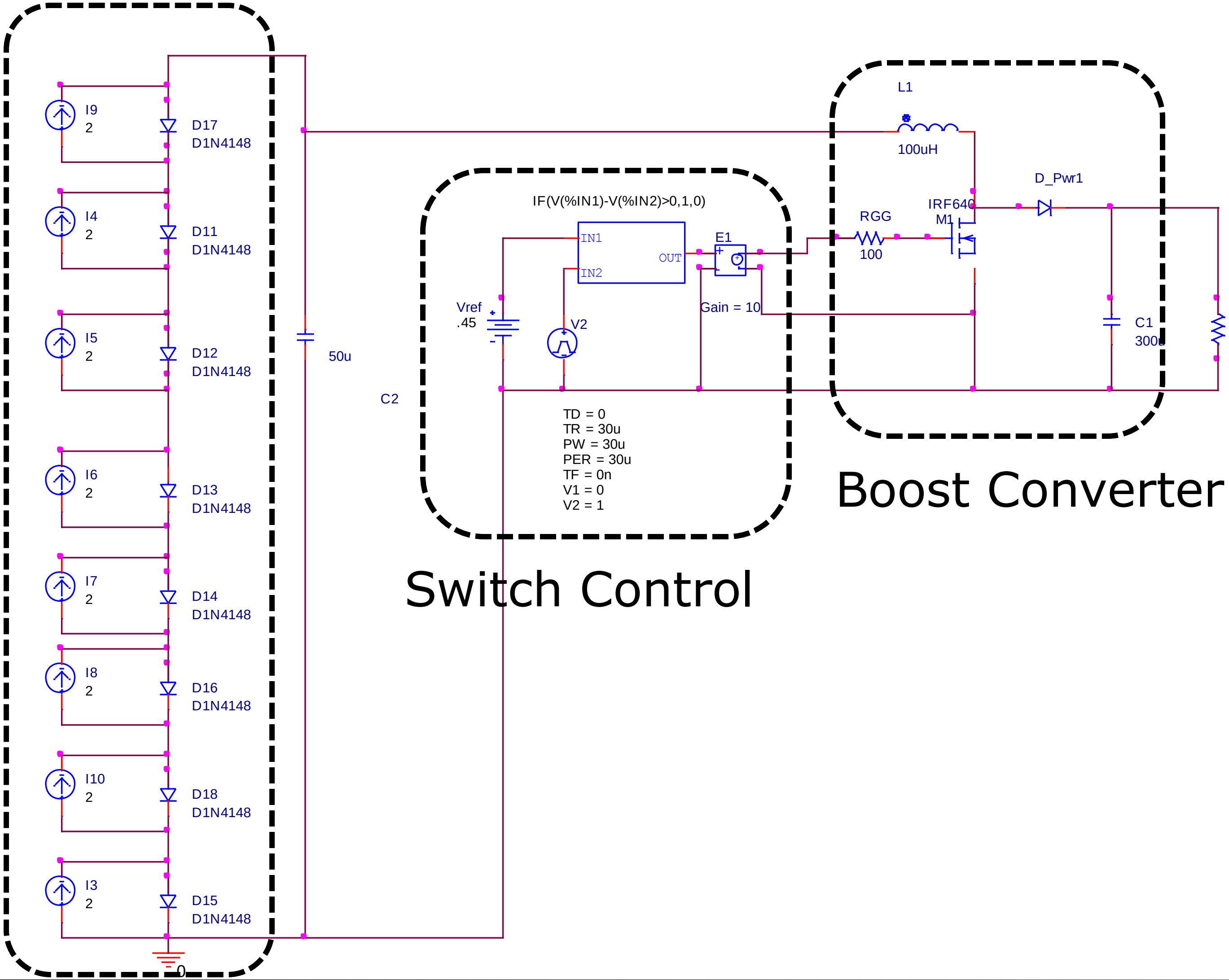
$$D = 1 - \frac{V_{STC}^*}{\sqrt{P_{STC}^* R}} = 1 - \frac{5.42}{\sqrt{10.4 \times 2.8}} = 0.47$$

Maximum Power Trackers



Maximum Power Trackers

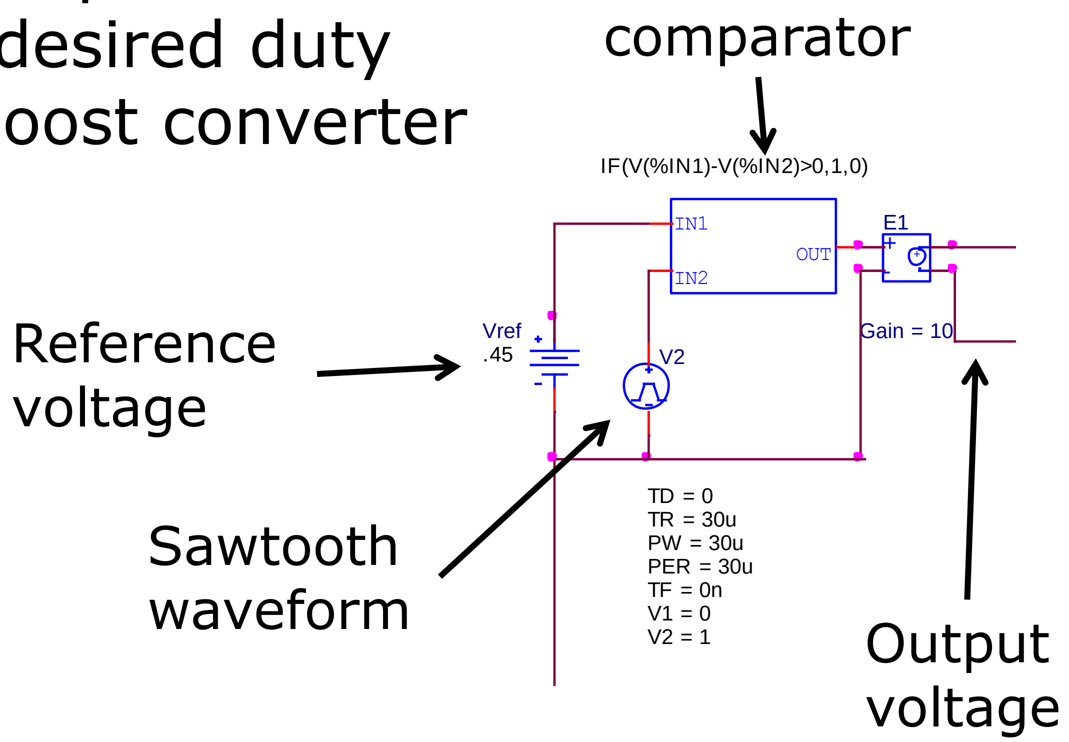
PV Module



load

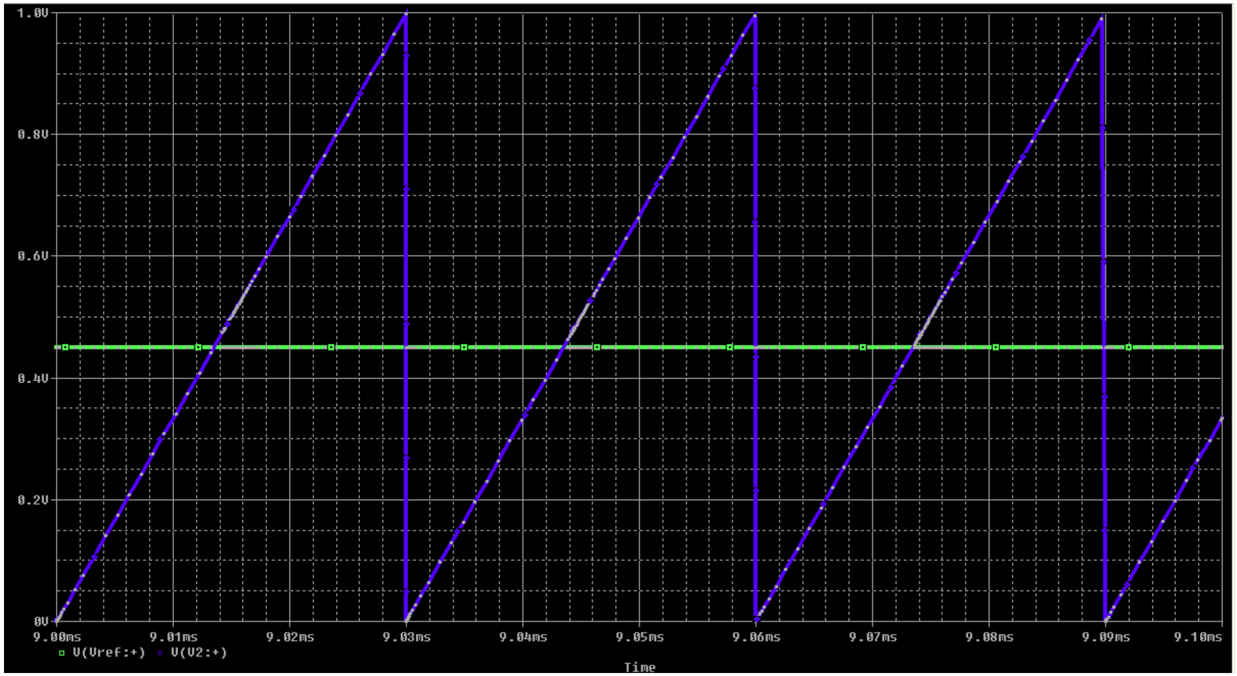
Switch Control

- Function: output square voltage wave of desired duty ratio to control boost converter MOSFET or IGBT

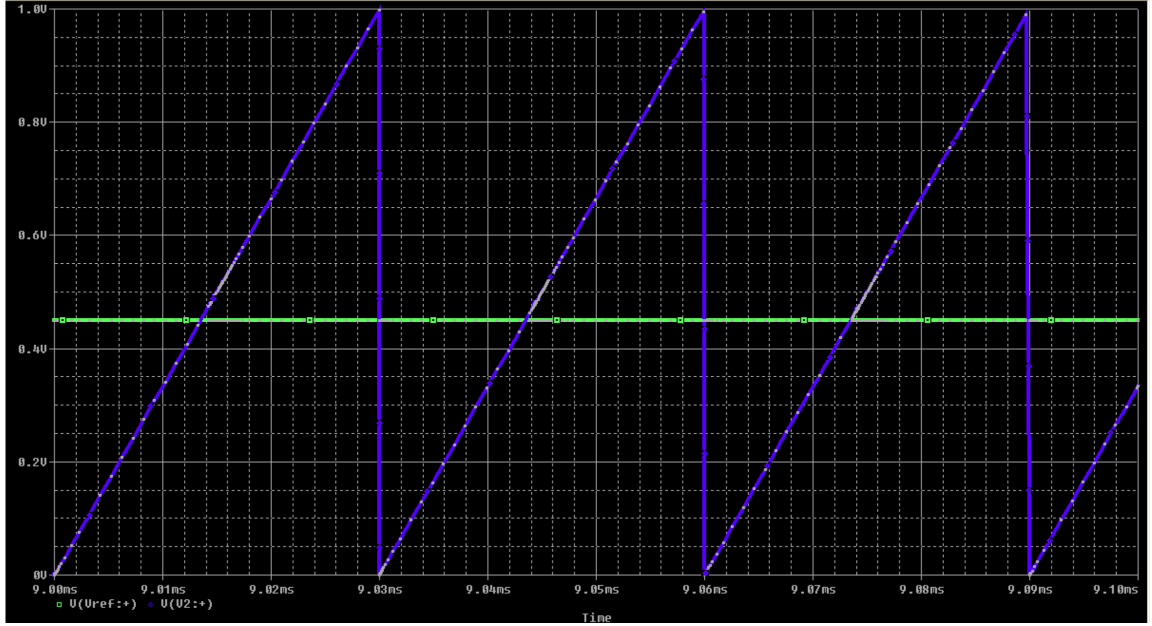


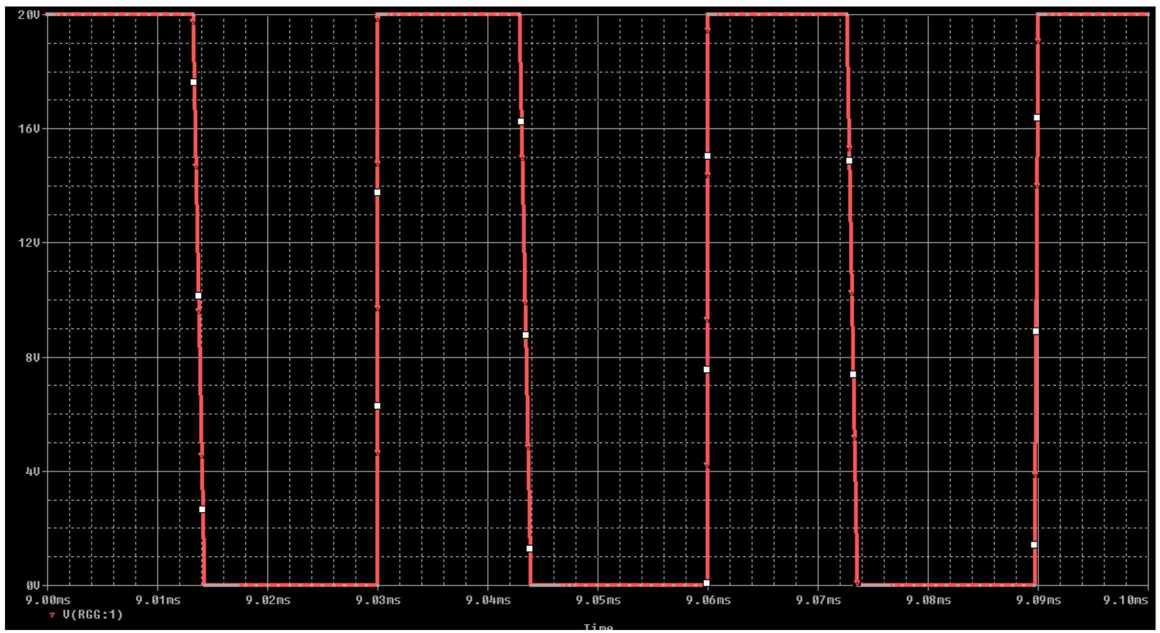
Switch Control

Set reference voltage to desired duty ratio
If $V_{ref} > V_{saw}$, q = 1
else, q =0

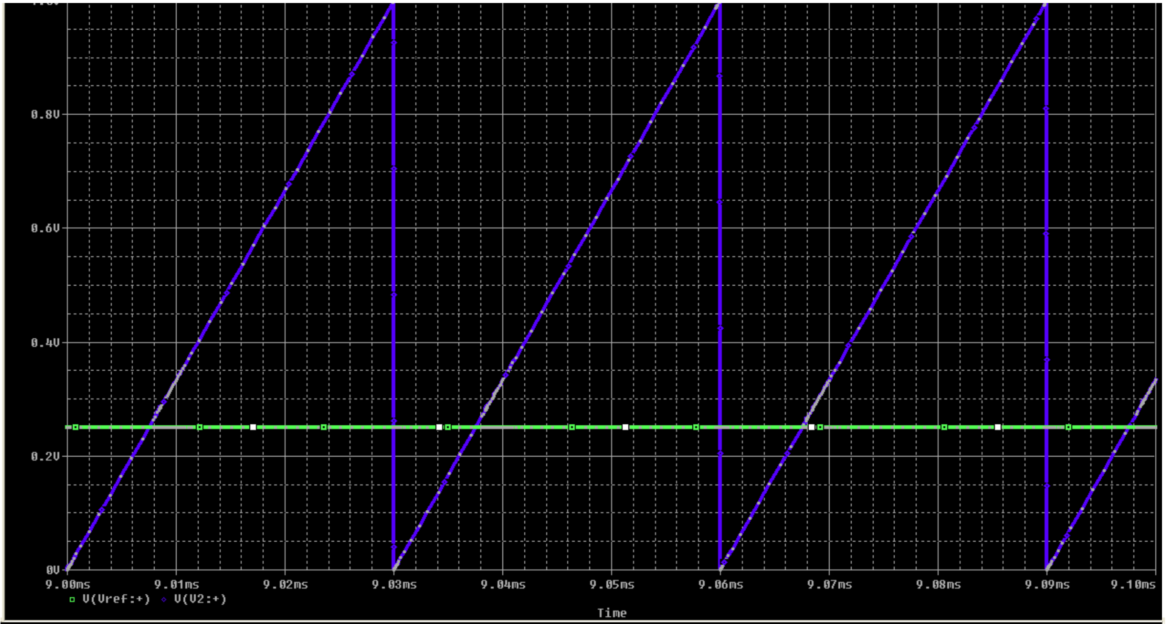


D = 0.45

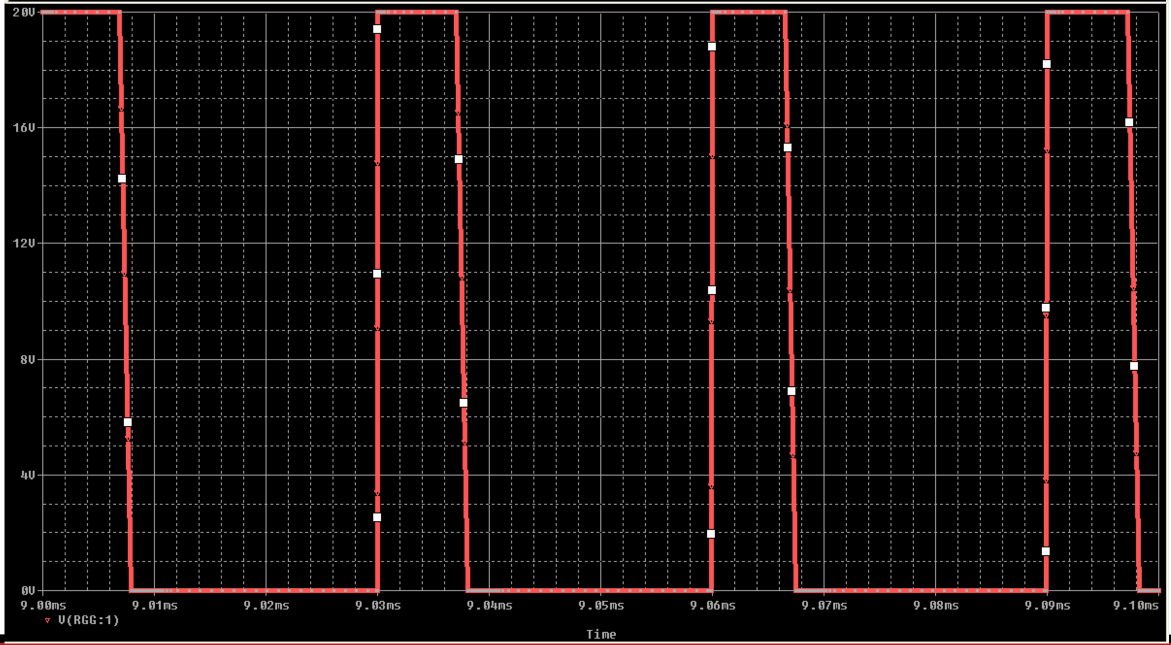

1.0V
0.8V
0.6V
0.4V
0.2V
0V
9.00ms
9.01ms
9.02ms
9.03ms
9.04ms
9.05ms
9.06ms
9.07ms
9.08ms
9.09ms
9.10ms
V(Vref:+)
V(V2:+)
Time


20V
16V
12V
8V
4V
0V
9.00ms
9.01ms
9.02ms
9.03ms
9.04ms
9.05ms
9.06ms
9.07ms
9.08ms
9.09ms
9.10ms
V(RGG:1)

D = 0.25

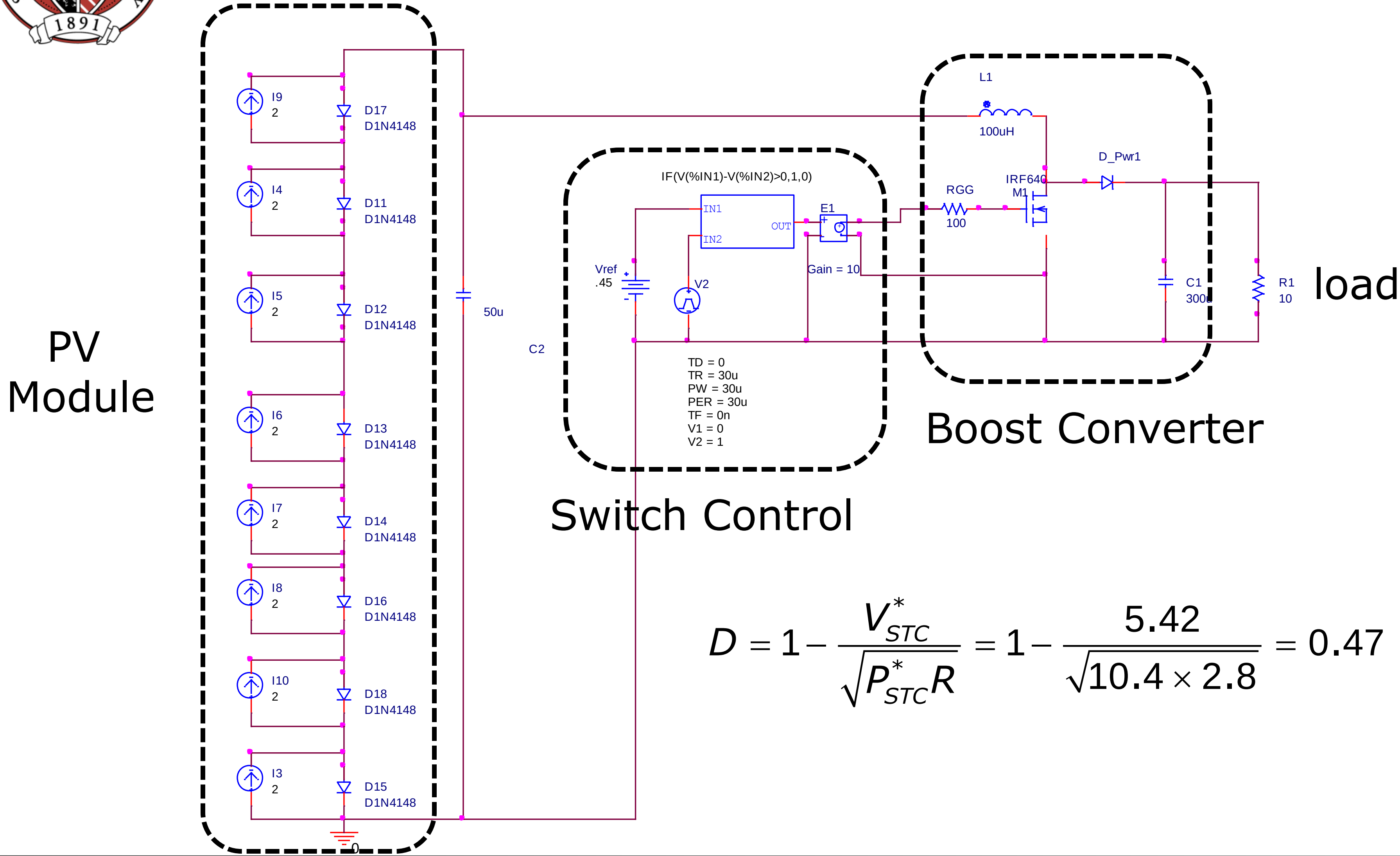


0.8V
0.6V
0.4V
0.2V
0V
9.00ms
9.01ms
9.02ms
9.03ms
9.04ms
9.05ms
9.06ms
9.07ms
9.08ms
9.09ms
9.10ms
V(Vref:+) V(V2:+)
Time



20V
16V
12V
8V
4V
0V
9.00ms
9.01ms
9.02ms
9.03ms
9.04ms
9.05ms
9.06ms
9.07ms
9.08ms
9.09ms
9.10ms
V(RGG:1)
Time

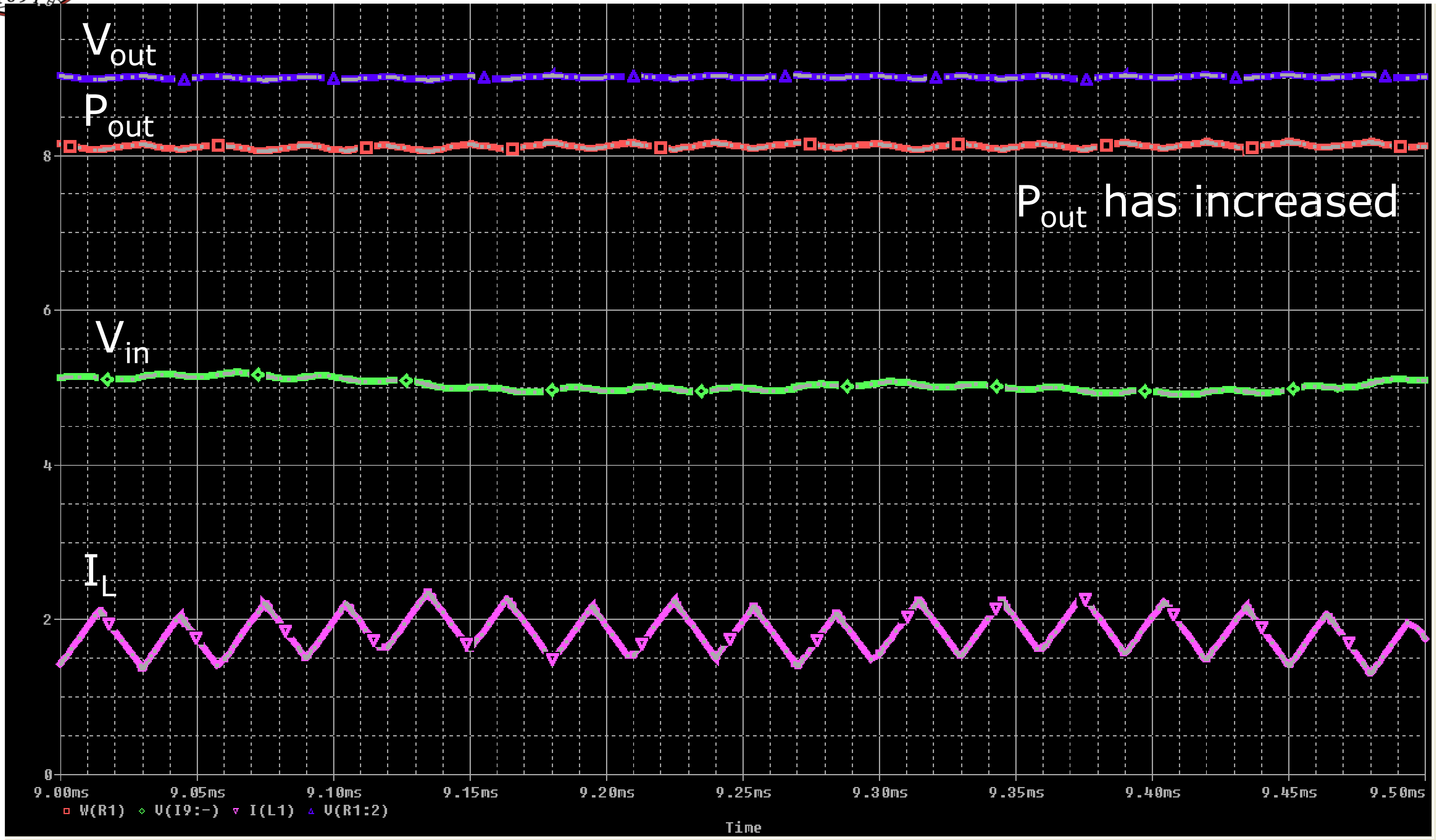
Maximum Power Trackers



$$D = 1 - \frac{V^*_{STC}}{\sqrt{P^*_{STC} R}} = 1 - \frac{5.42}{\sqrt{10.4 \times 2.8}} = 0.47$$

Without MPPT

With MPPT



V_{out}
P_{out}
P_{out} has increased
V_{in}
I_L
8
6
4
2
0
9.00ms
9.05ms
9.10ms
9.15ms
9.20ms
9.25ms
9.30ms
9.35ms
9.40ms
9.45ms
9.50ms
W(R1) V(I9:-) I(L1) V(R1:2)
Time

MPPT

- For a given irradiance level, the optimal MPPT duty ratio is 0.45. If the irradiance decreases, how should the duty ratio be adjusted?
  - A. it should decrease
  - B. it should increase
  - C. it should stay the same

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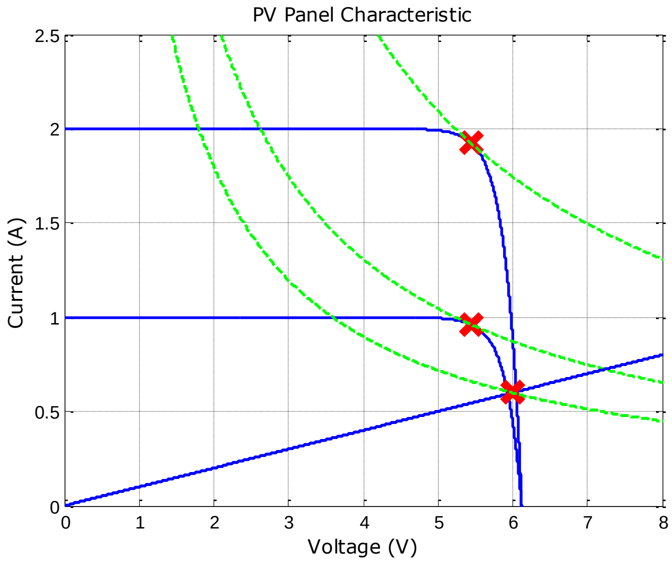
Input voltage is nearly constant, but output voltage must decrease, so D must decrease



Maximum Power Point Trackers

- Maximum power tracker control requires PV voltage and current sensing to control the duty ratio
- Control aspects are beyond the scope of this class
  - ECEGR 440: Controls
  - ECEGR 424: Power Electronics

Maximum Power Point Trackers

- Other power electronic converters may be used
  - Buck
  - Buck-Boost
  - Others
- Efficiencies in the range of 90% are possible
- MPPTs are very important for motors and pumps
  - Increases power output
  - Prolongs life