10-Maximum Power Point Tracking

ECEGR 4530

Renewable Energy Systems

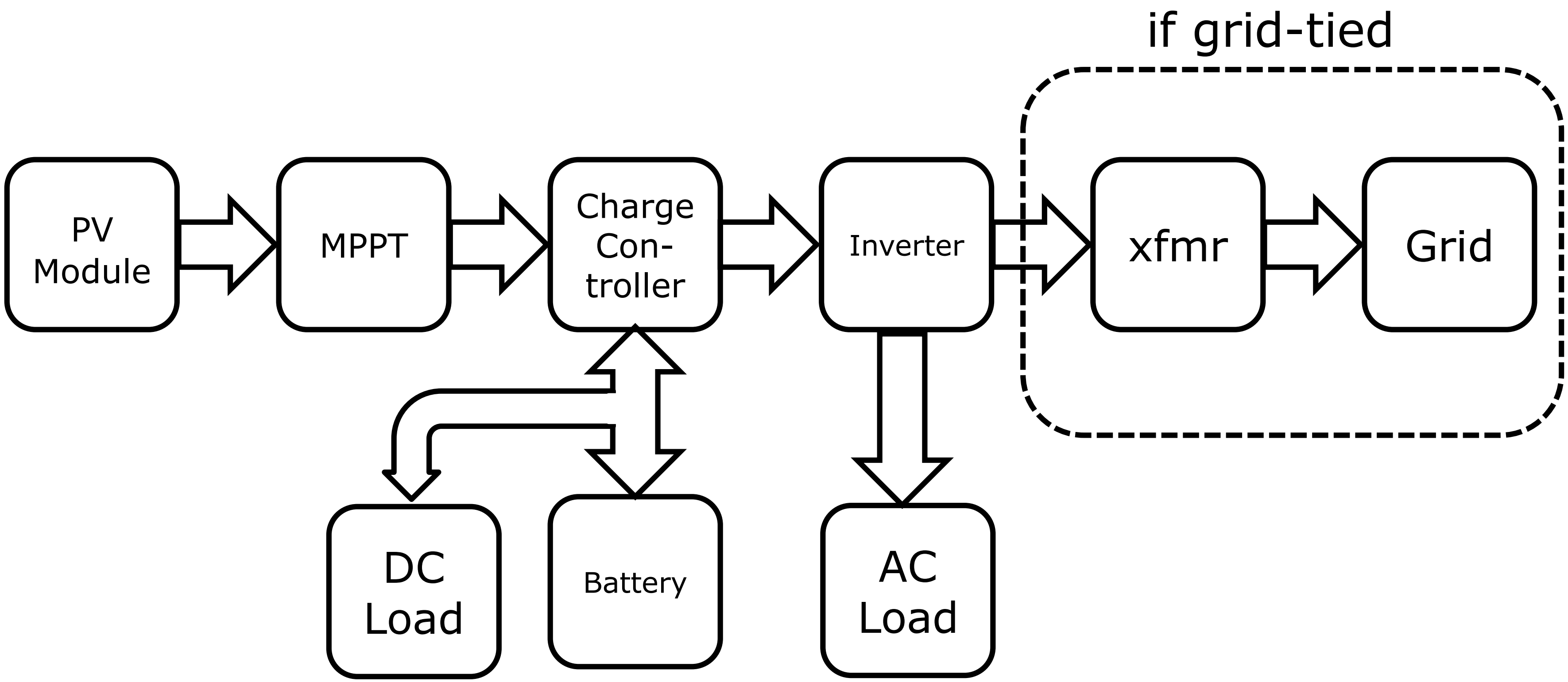
Overview

- 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

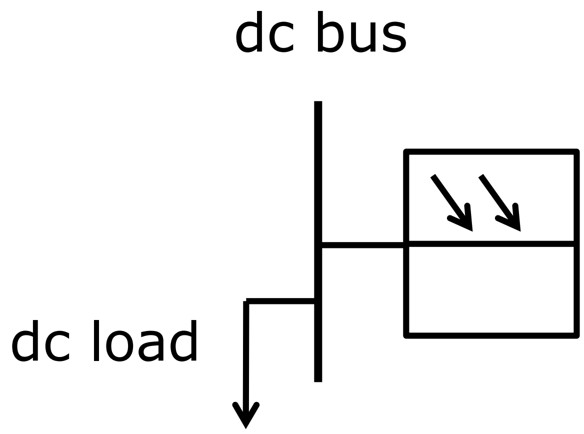


PV System Elements

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

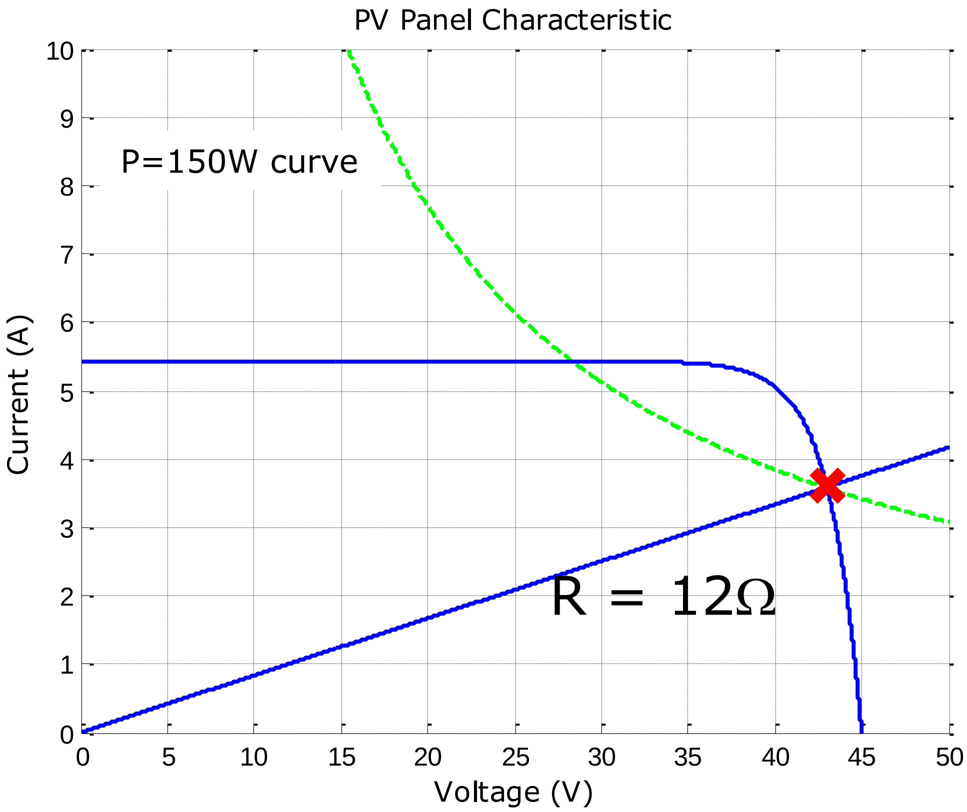
Stand Alone PV System

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



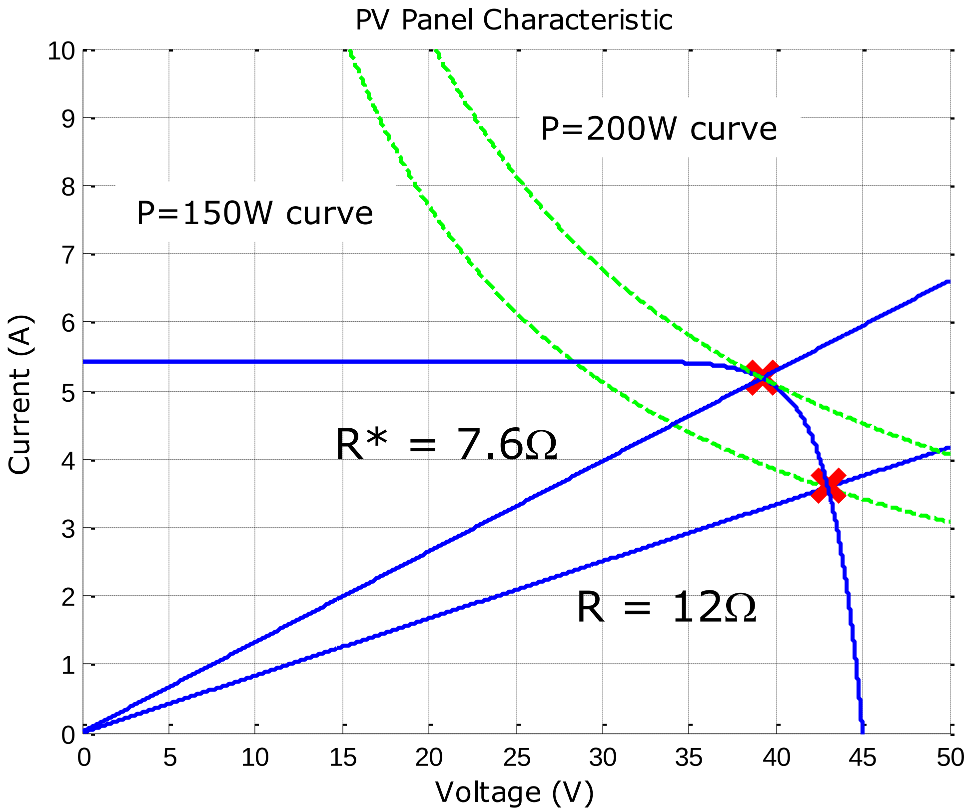
Stand Alone PV System

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



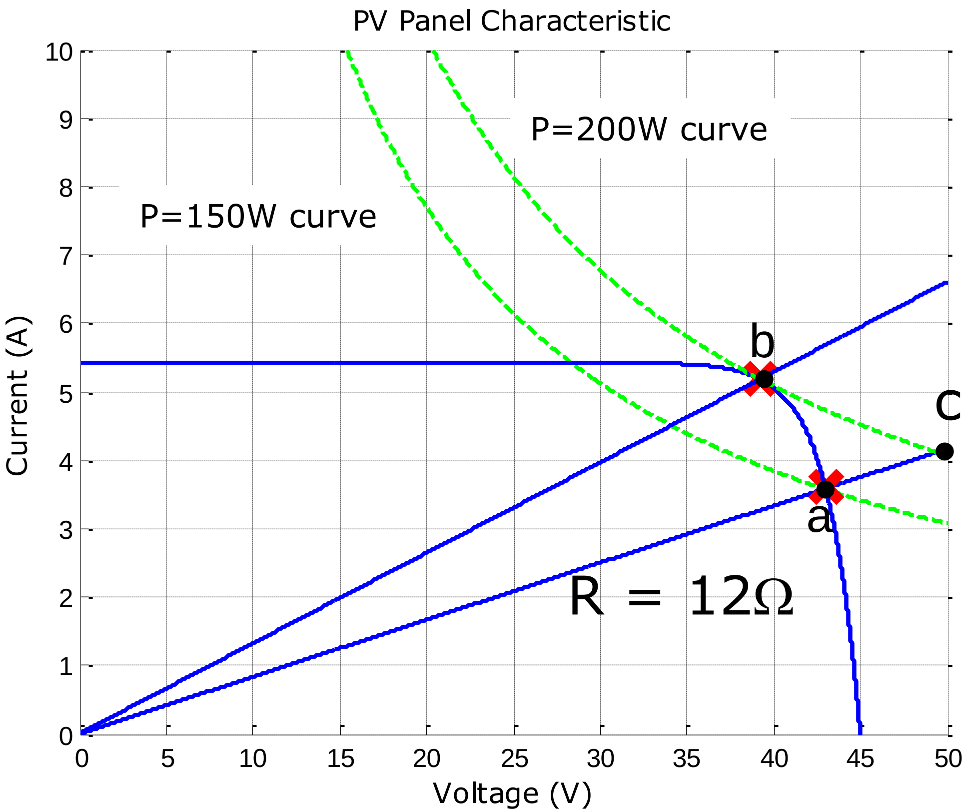
Stand Alone PV System

- At optimal operating point R = 7.6Ω



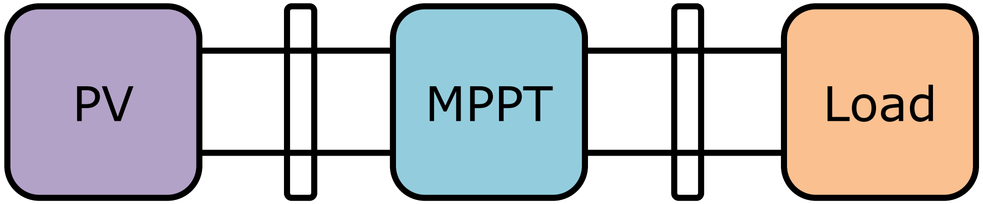
Stand Alone PV System

- 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
- MPPT changes the resistance "seen" by the PV panel
- HOMER assumes that the design has a MPPT in the converter

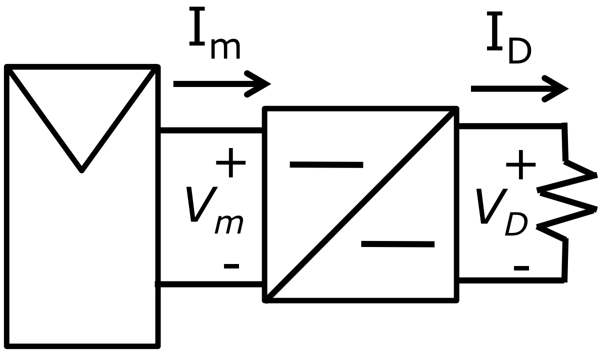


Operate at point "b"

Operate at point "c"

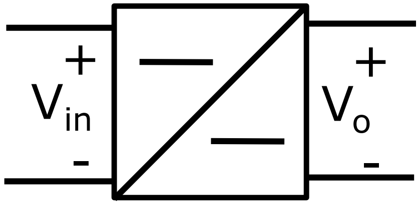
Maximum Power Trackers

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



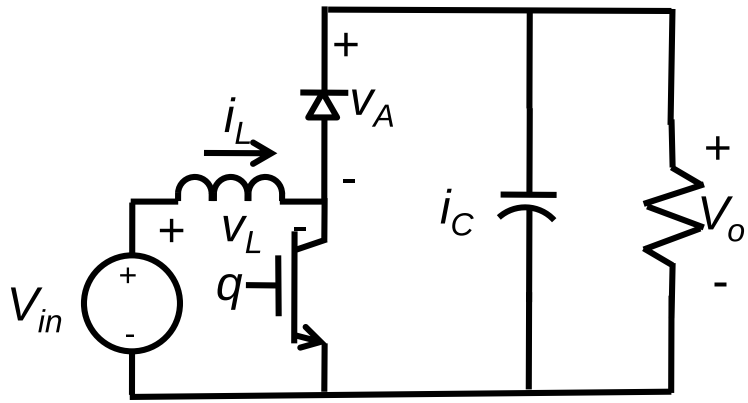
Maximum Power Trackers

- 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



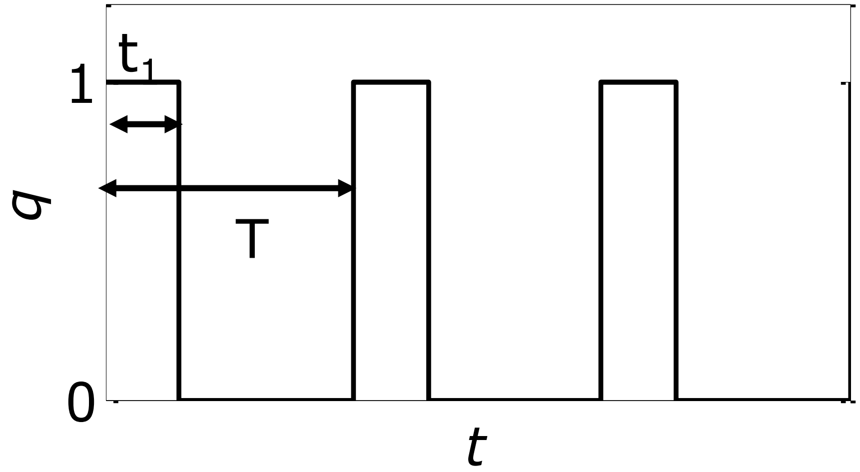
Boost Converter

- Used to efficiently produce output voltage that is greater than input voltage
- Ratio of input voltage to output voltage depends on the duty cycle of the switch “q”
- Duty cycle (D): portion of the time that q is high during one period



Duty Cycle

$$D = \frac{t_1}{T}$$



Boost Converters

- It can be shown that:

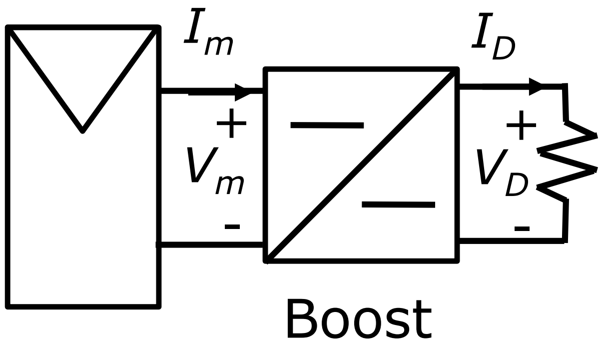
$$V_o = \frac{1}{1-D} V_{in}$$

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

Where $V_{in} = V_m$
and $V_o = V_D$

- If we assume the MPPT is lossless, then, just like a transformer, power is preserved:

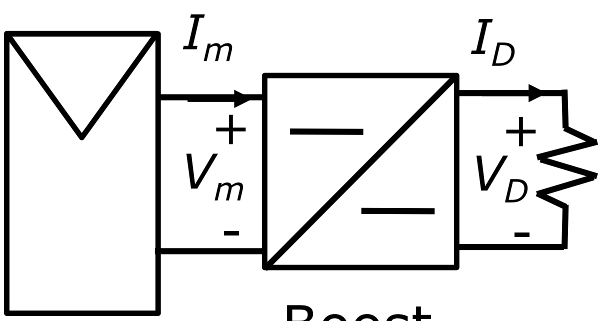
$$P_m = V_m I_m = V_D I_D = P_D$$



Duty Ratio

- For MPP tracking, we must find D that maximizes the power output
- V_m is not a voltage source, so D cannot be made arbitrarily large
- At MPP, D is such that

$$P_m^* = V_m I_m = V_D I_D$$



Maximum Power Trackers

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

$$P_m^* = V_m^* I_m^*$$

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

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

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

- 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

Exercise

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

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

$$V_D = \frac{1}{1-D} V_m = 48.96V$$

$$P_D = \frac{V_m^2}{R} = \frac{48.96^2}{12} = 200W$$

Observation

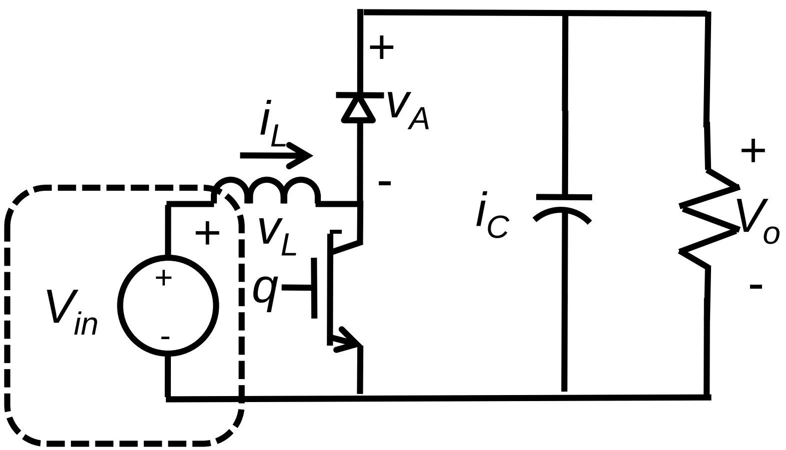
- In the previous exercise
  - Note: the voltage at load is: $V_D = \frac{1}{1-D} V_m = 48.96V$
  - And the power at the load is: $P_D = \frac{V_m^2}{R} = \frac{48.96^2}{12} = 200W$
- The power consumed by the load is equal to the maximum power of the PV panel at the given irradiance conditions
- The resistance "seen" by the PV panel is

$$R_m = \frac{38^2}{200} = 7.22\Omega$$

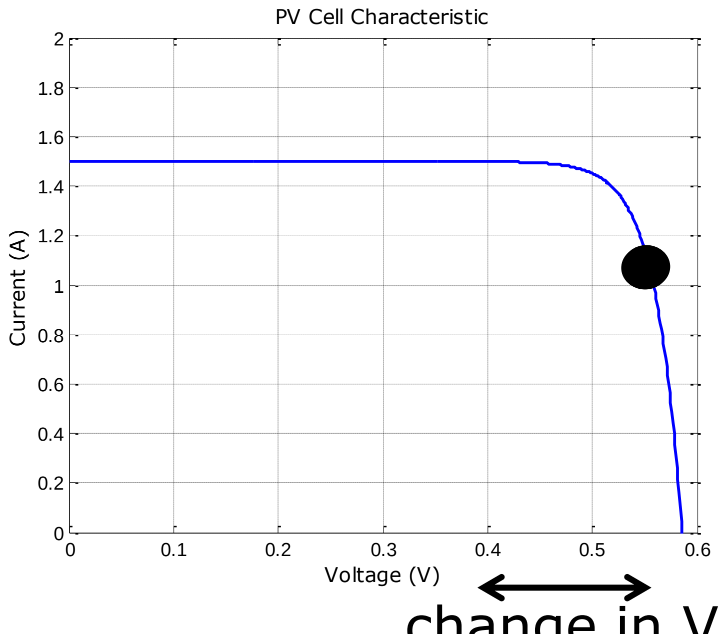
When the output voltage is boosted the resistance seen by the PV panel decreases

Maximum Power Trackers

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

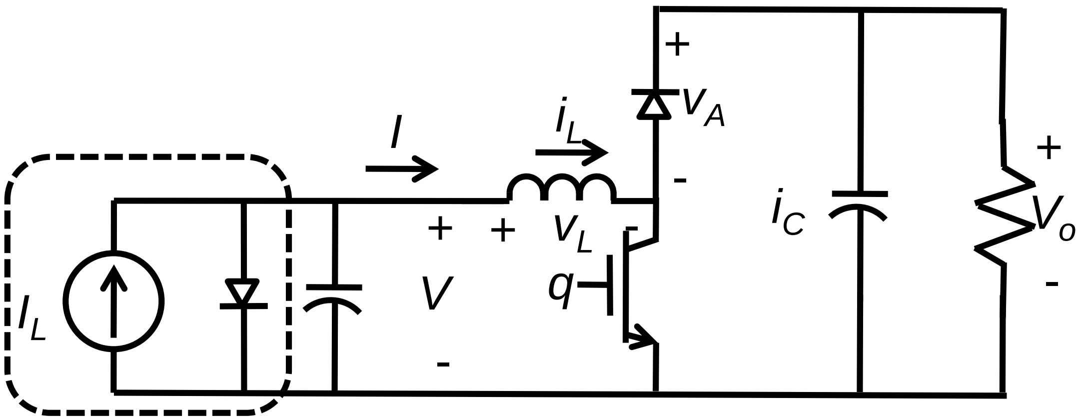


Inappropriate PV model

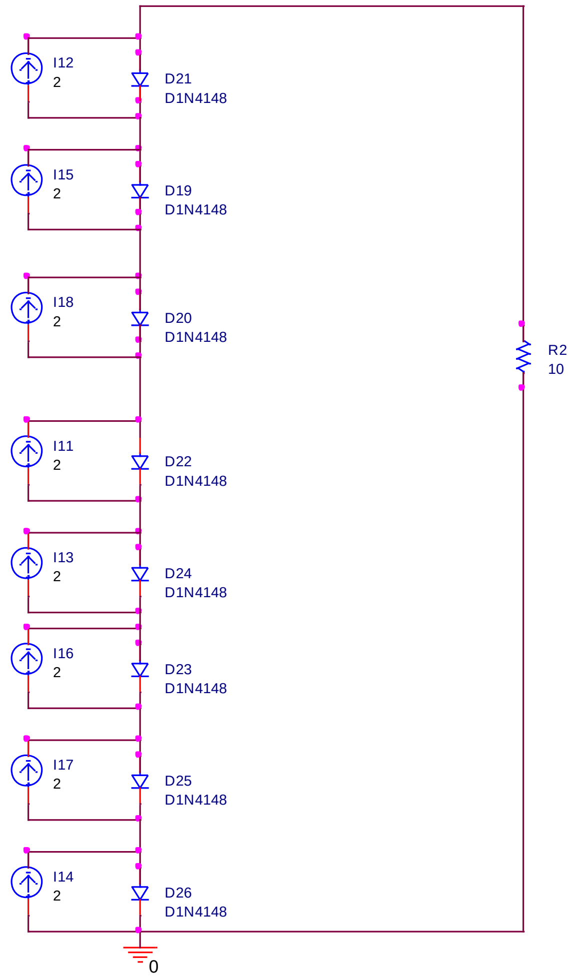


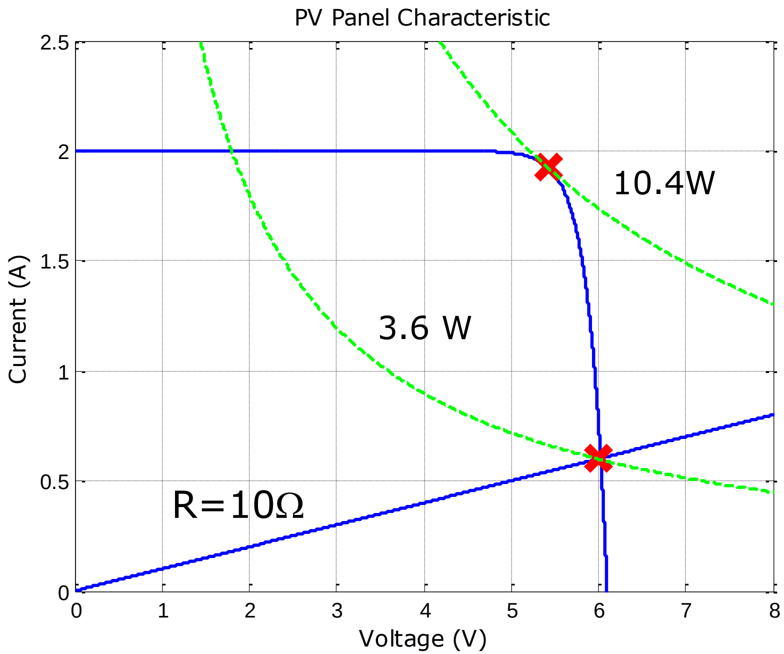
Maximum Power Trackers

- Include input capacitor to steady voltage



Maximum Power Trackers

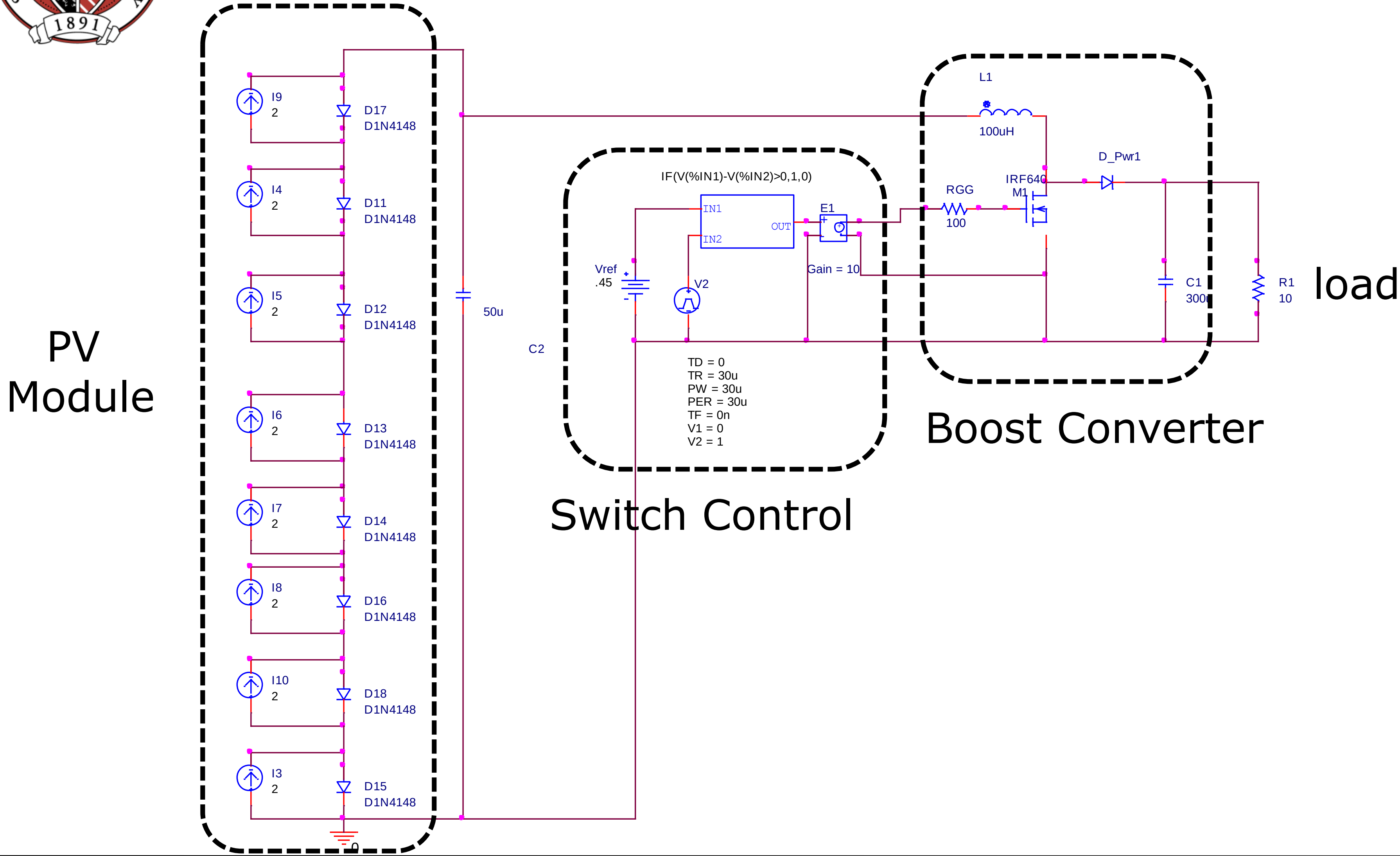




$$D = 1 - \frac{V^*_{STC}}{\sqrt{P^*_{STC} R}} = 1 - \frac{5.42}{\sqrt{10.4 \times 2.8}} = 0.47$$

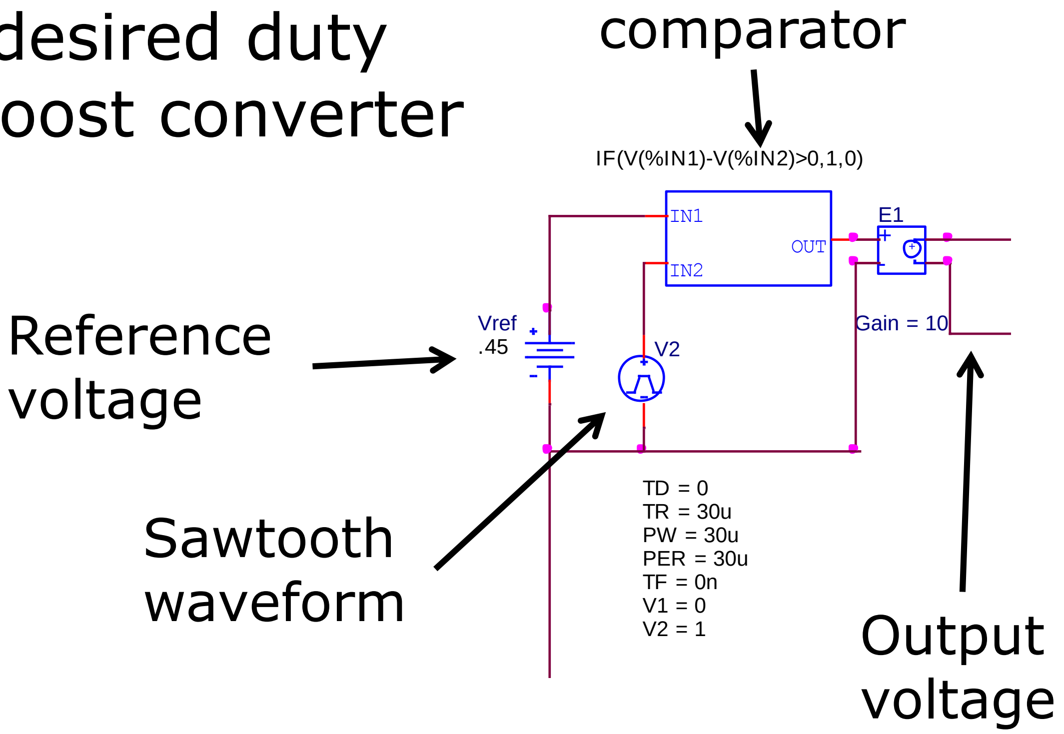
Maximum Power Trackers

Maximum Power Trackers



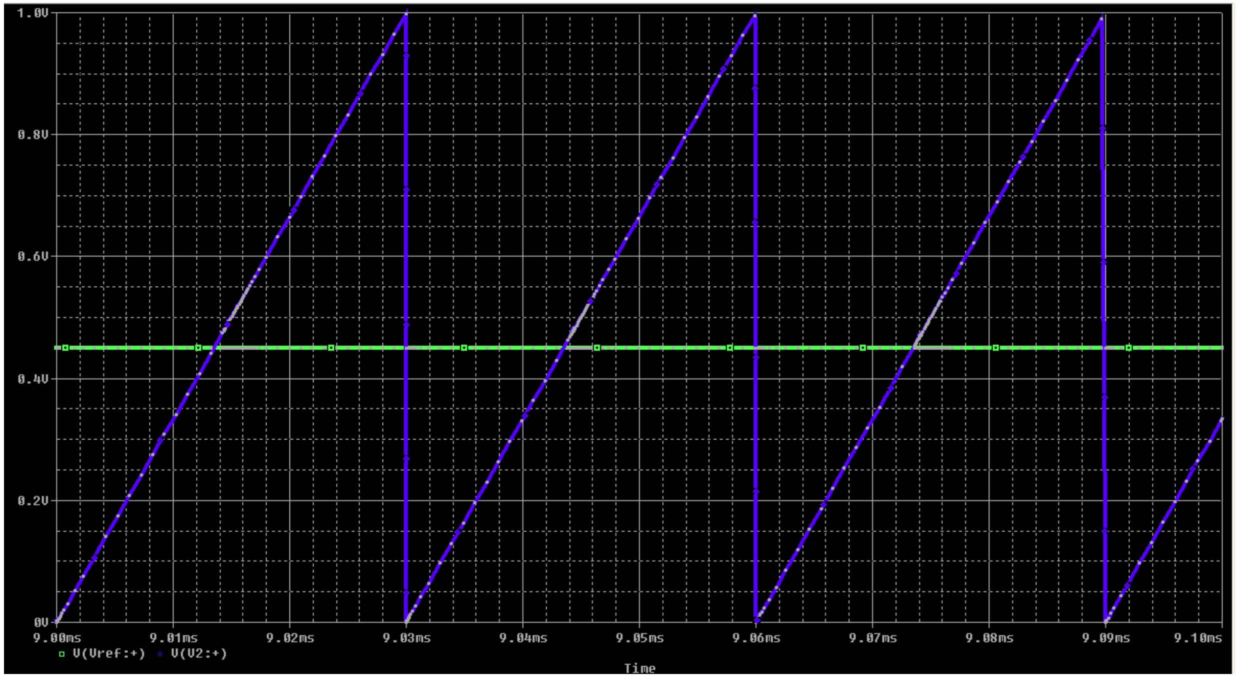
Switch Control

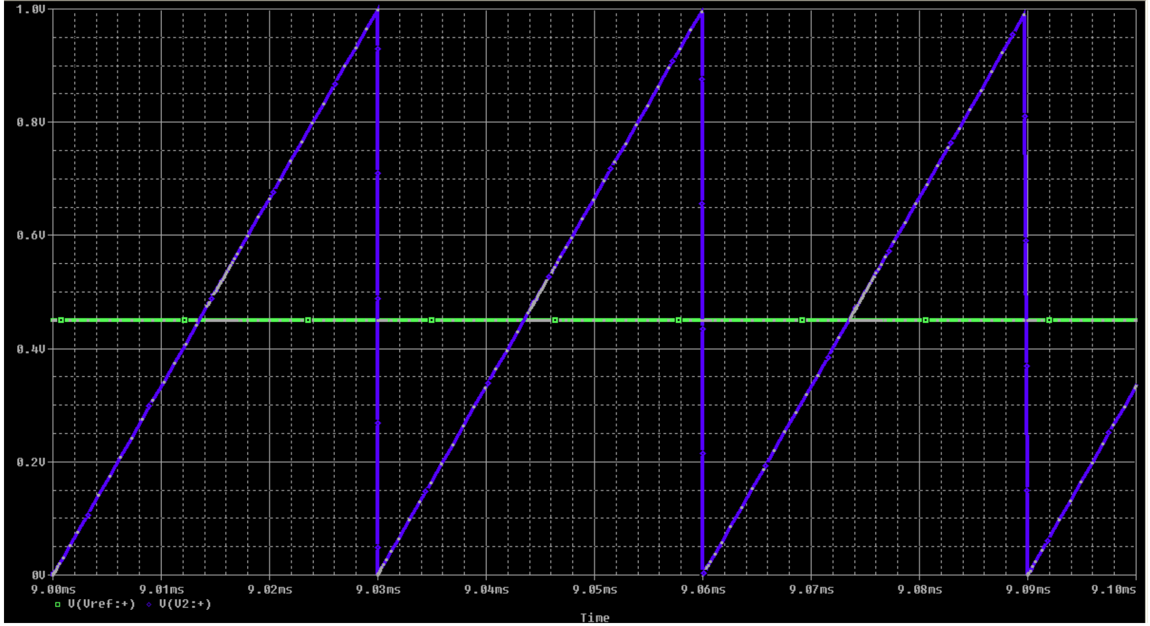
- Function: output square voltage wave of desired duty ratio to control boost converter MOSFET or IGBT



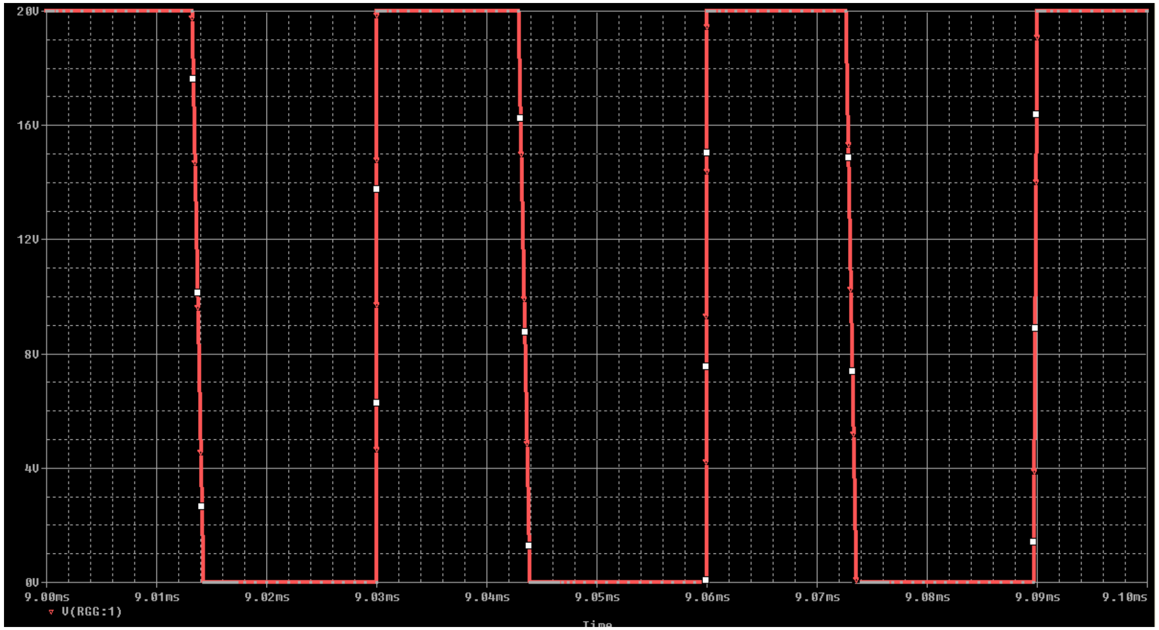
Switch Control

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

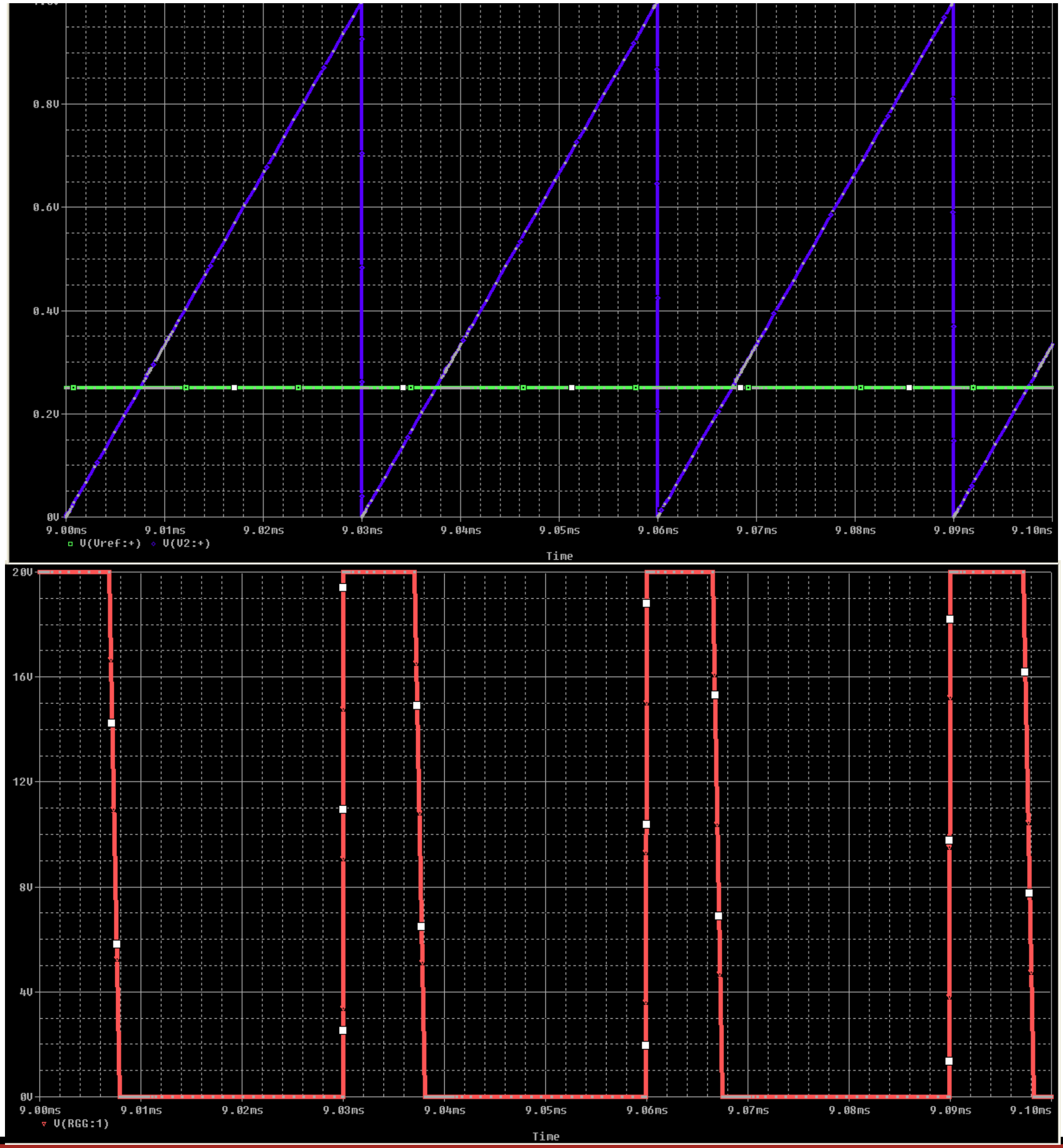



1.0V
0.8V
0.6V
0.4V
0.2V
0V
9.00ms
9.01ms
9.02ms
9.03ms
9.04ms
9.05ms
9.06ms
9.07ms
9.08ms
9.09ms
9.10ms
V(Vref:+) V(V2:+)
Time

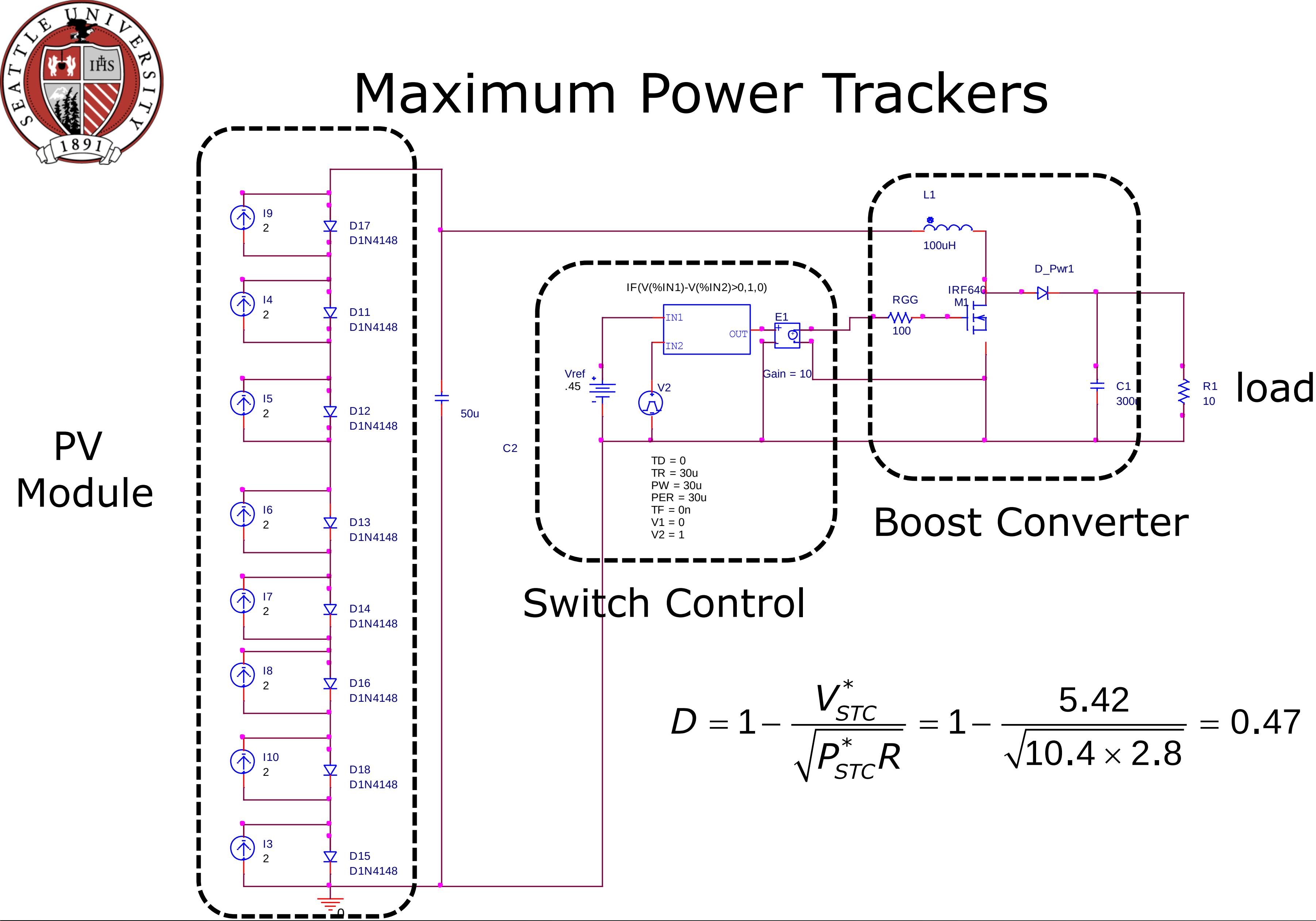
D = 0.45


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

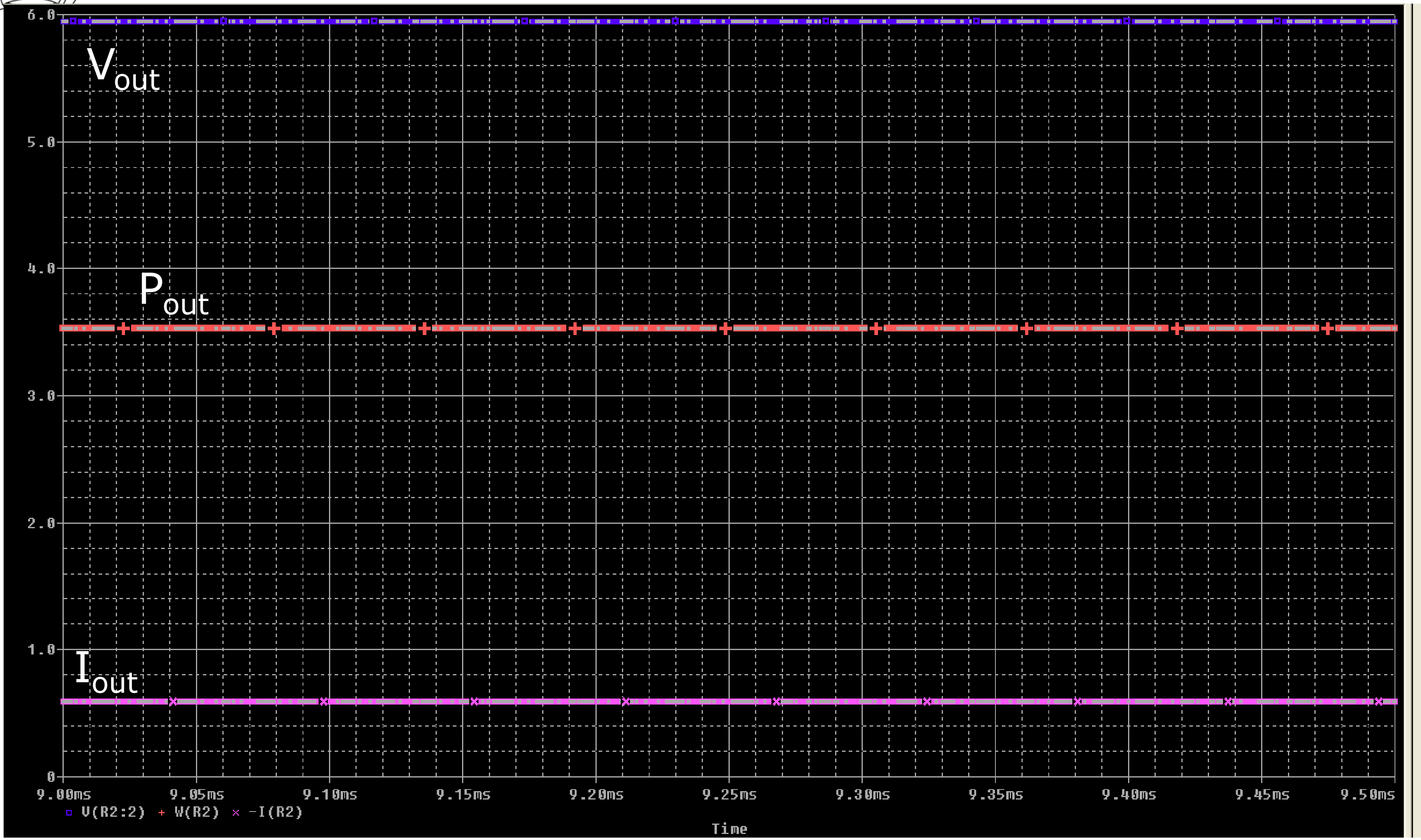

0.8V
0.6V
0.4V
0.2V
0V
9.00ms
9.01ms
9.02ms
9.03ms
9.04ms
9.05ms
9.06ms
9.07ms
9.08ms
9.09ms
9.10ms
V(Vref:+)
V(V2:+)
Time
20V
16V
12V
8V
4V
0V
9.00ms
9.01ms
9.02ms
9.03ms
9.04ms
9.05ms
9.06ms
9.07ms
9.08ms
9.09ms
9.10ms
V(RGG:1)
Time

Maximum Power Trackers

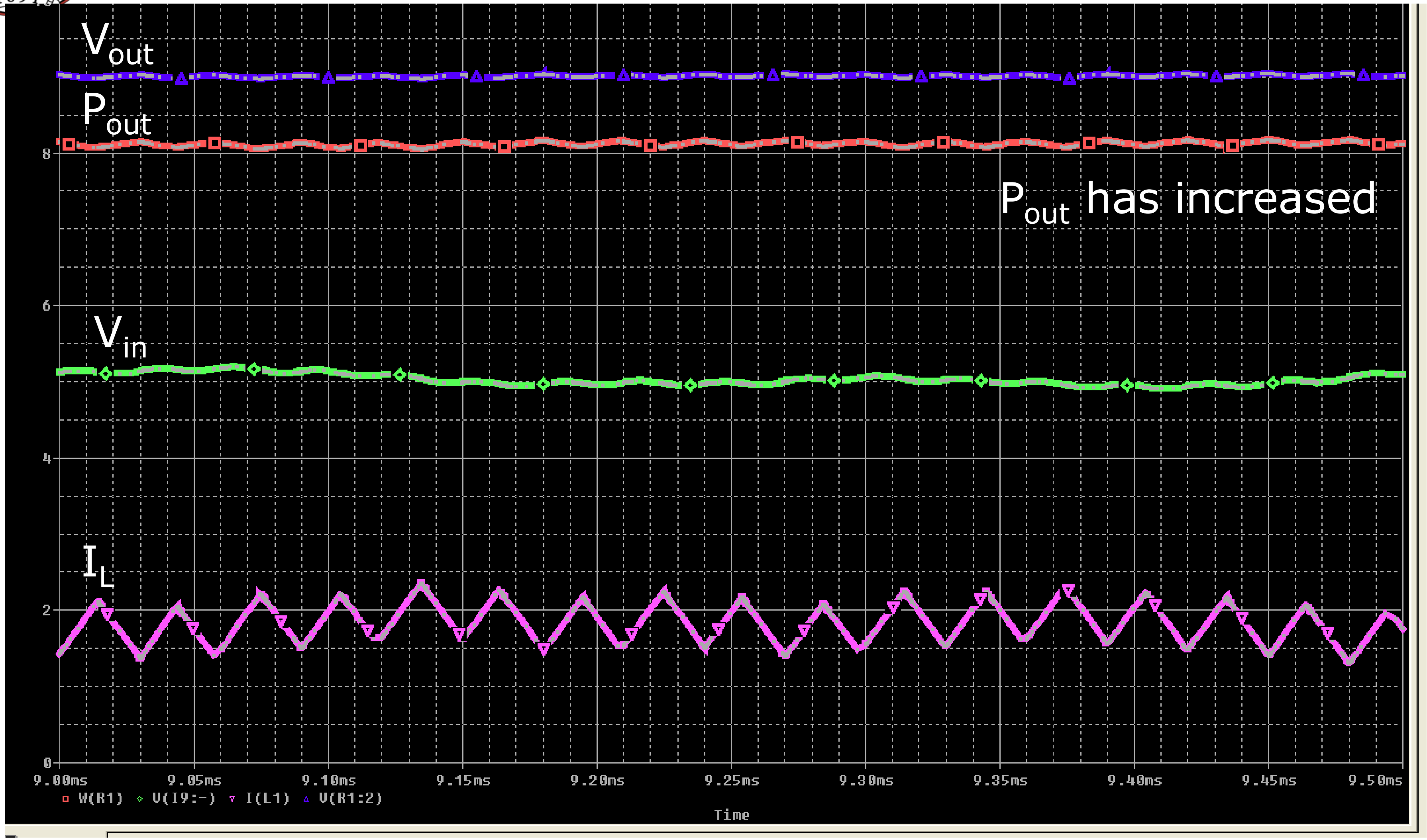


$$D = 1 - \frac{V_{STC}^{*}}{\sqrt{P_{STC}^{*} R}} = 1 - \frac{5.42}{\sqrt{10.4 \times 2.8}} = 0.47$$

Without MPPT



With MPPT



Vout
Pout
Pout has increased
Vin
IL
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

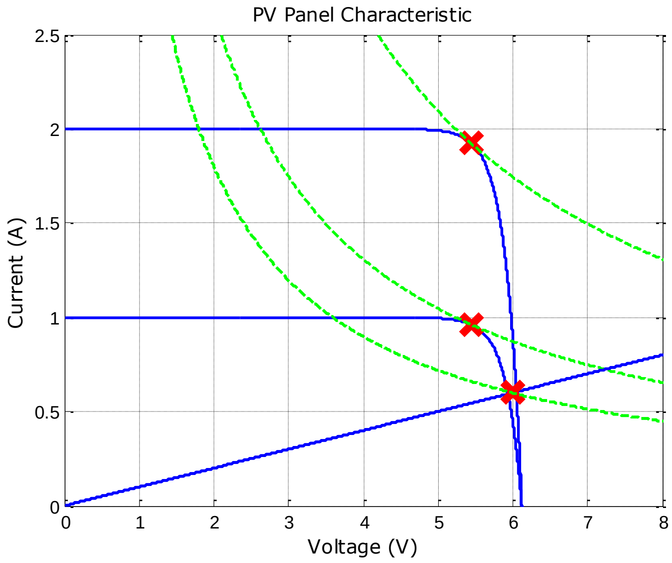
MPPT

- 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

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

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

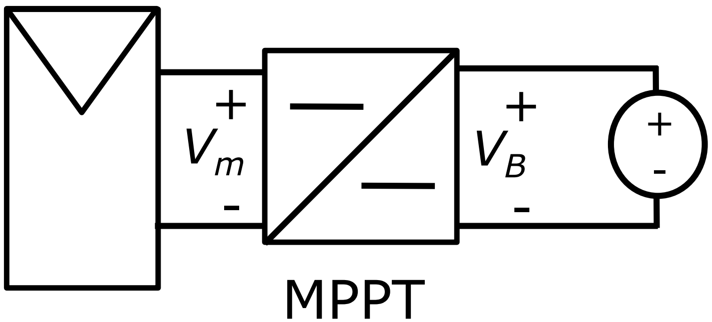


Maximum Power Point Trackers

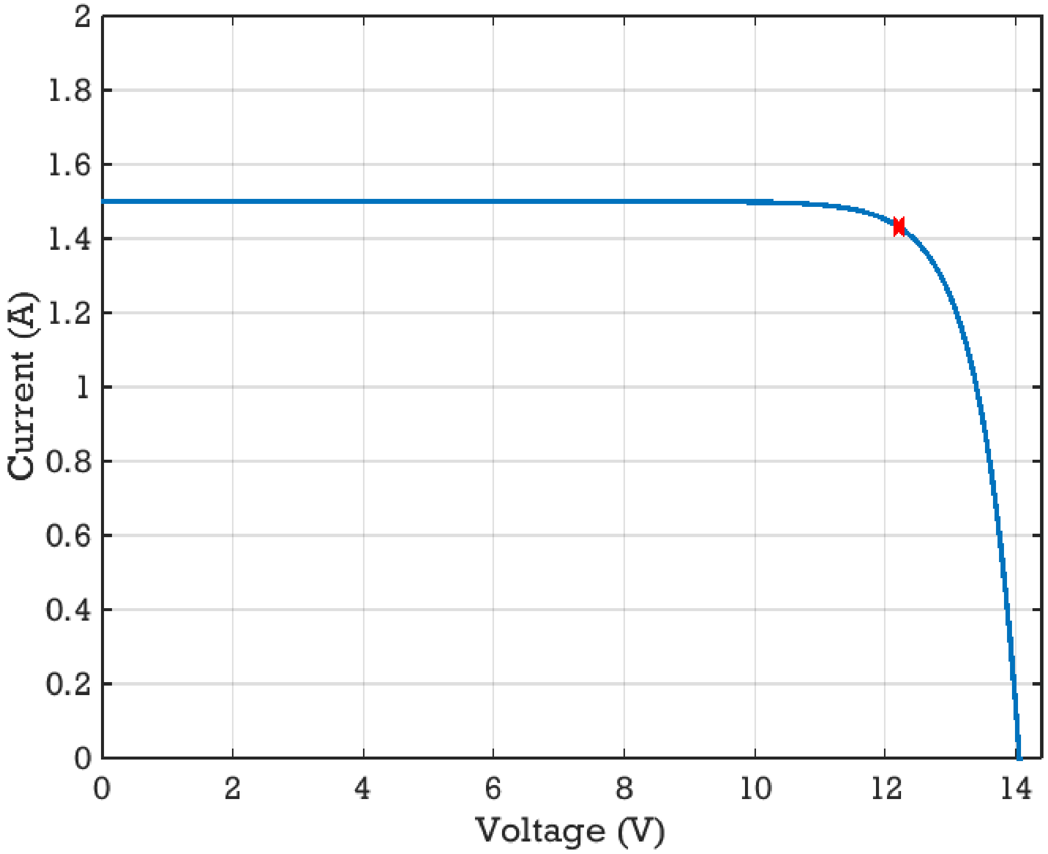
- Other power electronic converters may be used
  - Buck (decrease voltage)
  - Buck-Boost (increase or decrease voltage)
  - Others
- Efficiencies in the range of 90% are possible
- MPPTs are very important for motors and pumps
  - Increases power output
  - Prolongs life

Constant Voltage Loads

- MPPTs are often used when the PV array interfaces with a battery or inverter
- The output voltage is fixed at $V_D = V_B$



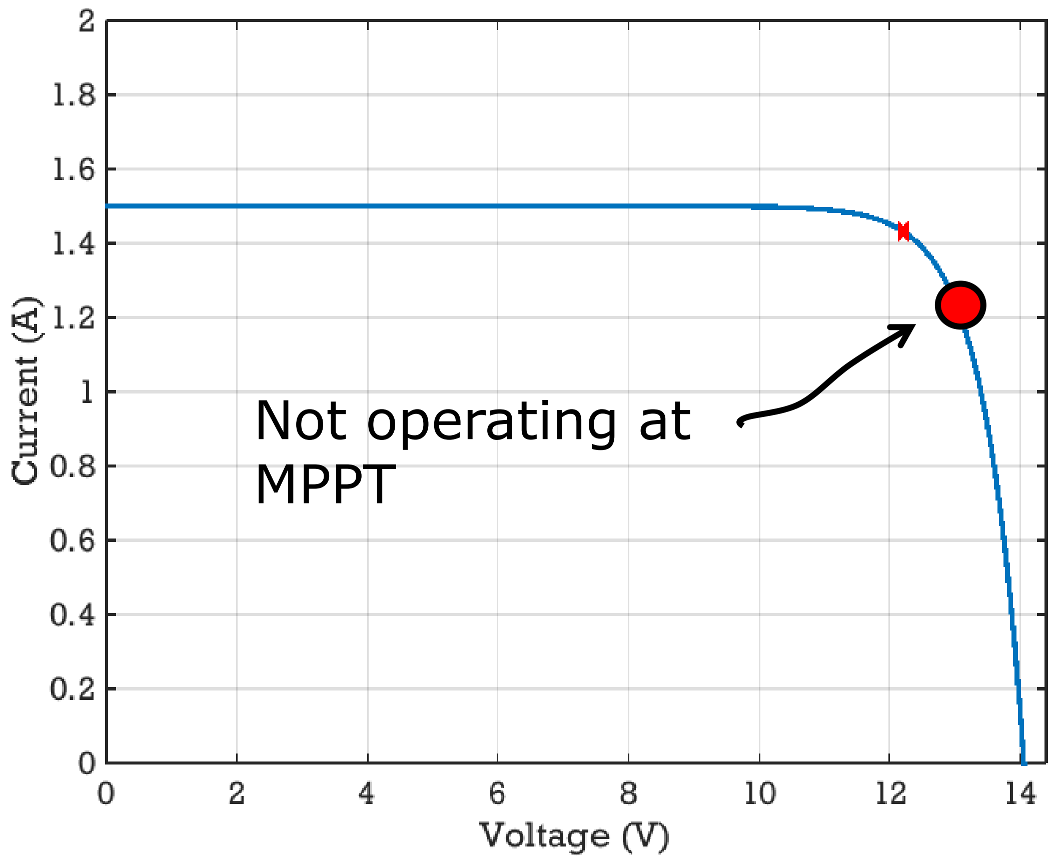
Constant Voltage Loads



V* = 12.21V
I* = 1.43 A
P* = 17.47W

"Resistance" seen by
The PV array at MPP
V^*/I^* = 8.54 Ohms

Constant Voltage Loads



Consider the case without MMPT

Let V_B = 13V, then

$V_m = V_B$

I_m = 1.24A

$P_m = P_D$ = 16.12W

"Resistance" seen by The PV array is:

V_m/I_m = 10.5 Ohms

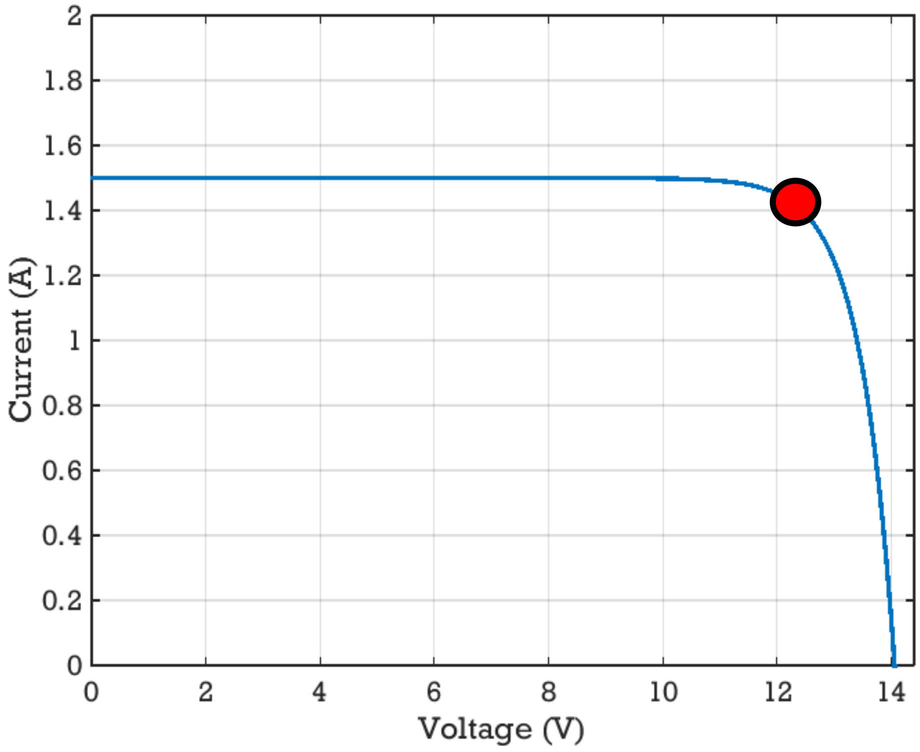
Constant Voltage Loads

- Adjust the duty cycle of MPPT so that $V_m = V^*$ given $V_D = V_B$

$$V_D = \frac{1}{1-D} V_m$$

$$13 = \frac{1}{1-D} 12.21$$

$$D = 1 - \frac{12.21}{13} = 0.061$$



- Operating at MPP
- Power to the battery

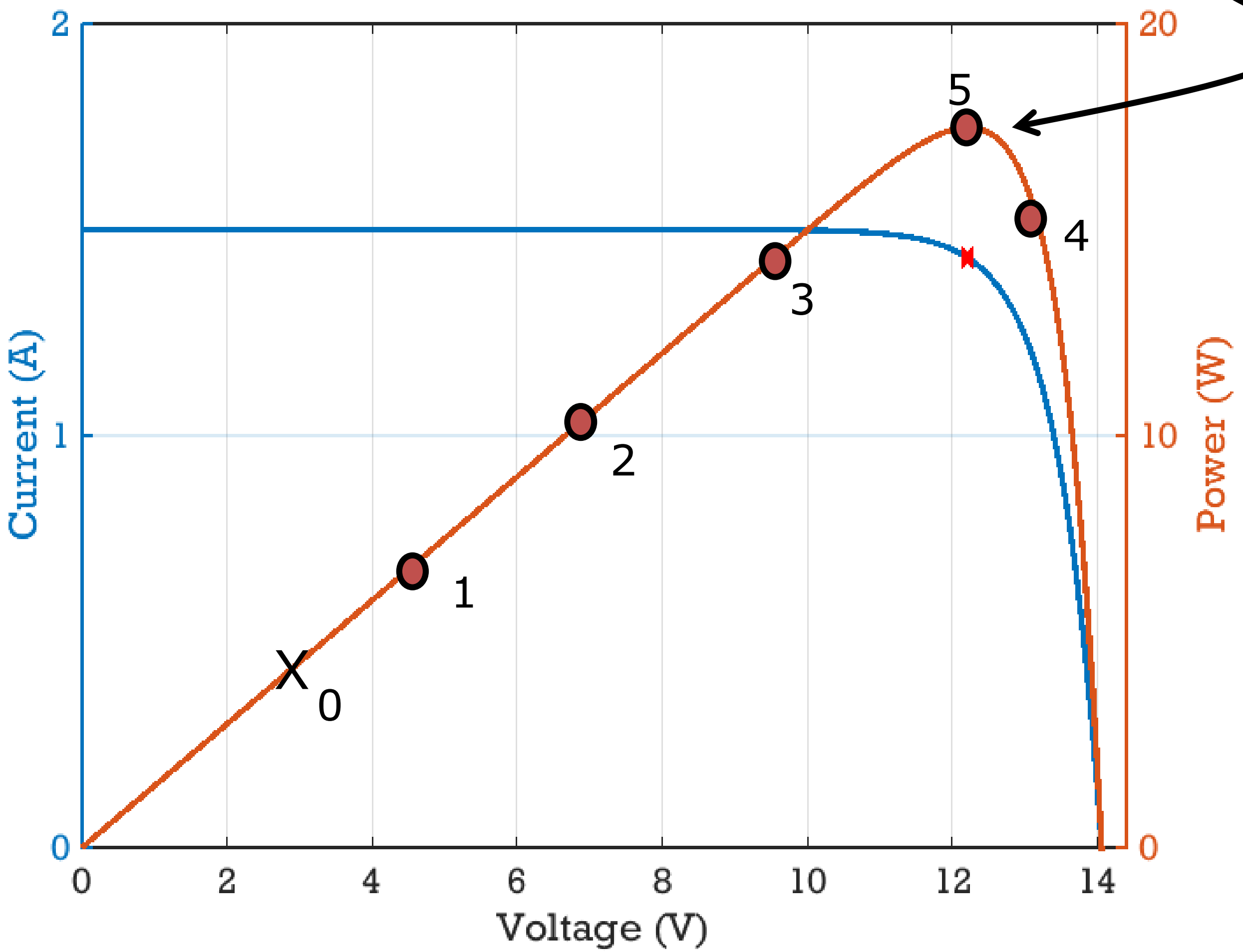
is maximized: 17.47W

Maximum Power Point Trackers

- Maximum power tracker control requires PV voltage and current sensing to control the duty ratio (irradiance and perhaps the load are constantly changing)
- Common methods:
  - Perturb and Observe (P&O)
  - Incremental Conductance (IC)
- Both methods are non-model methods (meaning you do not need to explicitly model the circuit), and both use a “hill climbing” approach

Adjust voltage by some amount until maximum is reached.

Top of the hill (MPP)



P&O

- Basic idea: perturb the duty cycle in a direction (e.g. increase it) and see if the power output increases. If power output increases, continue increasing the duty cycle; else decrease the duty cycle and repeat
- Disadvantages:
  - Oscillations around the MPP tend to occur
  - Does not rapidly converge on MPP when irradiance conditions rapidly change (compared to other methods)

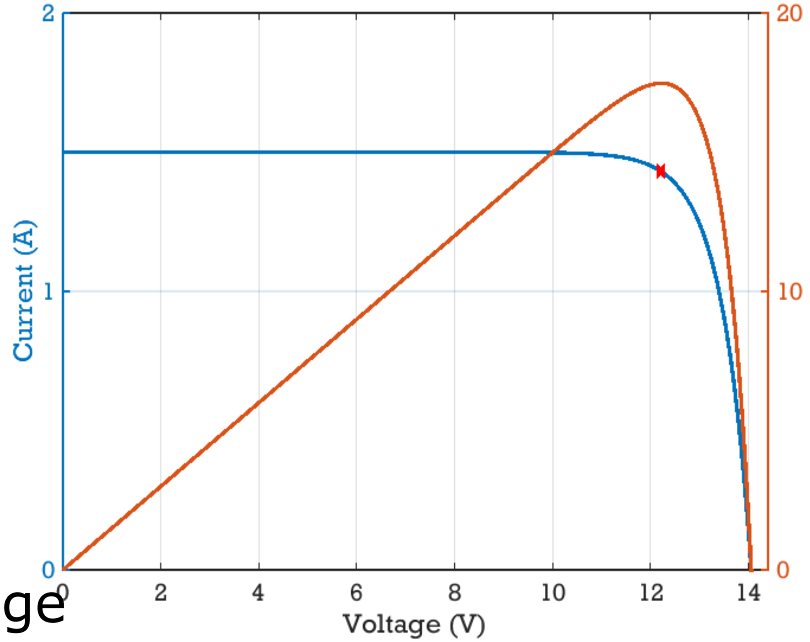
Incremental Conductance

- Basic idea: at MPP, the derivative of power with respect to voltage is zero (it is a maximum point)
- Conductance G = I/V (inverse of resistance)

$$\frac{dP}{dV} = 0 \text{ (at the MPP)}$$

$$P = IV = I(V)V$$

Recall that the current out of a PV panel is a non-linear function of voltage



IC Method

$$\frac{dP}{dV} = I(V)V$$

$$I(V)V = \frac{dI}{dV}V + 1I(V) = 0$$ ← at the maximum

Applying the product rule for derivatives

$$\frac{dI}{dV}V = -1I(V)$$

$$\frac{dI}{dV} = \frac{-I(V)}{V}$$

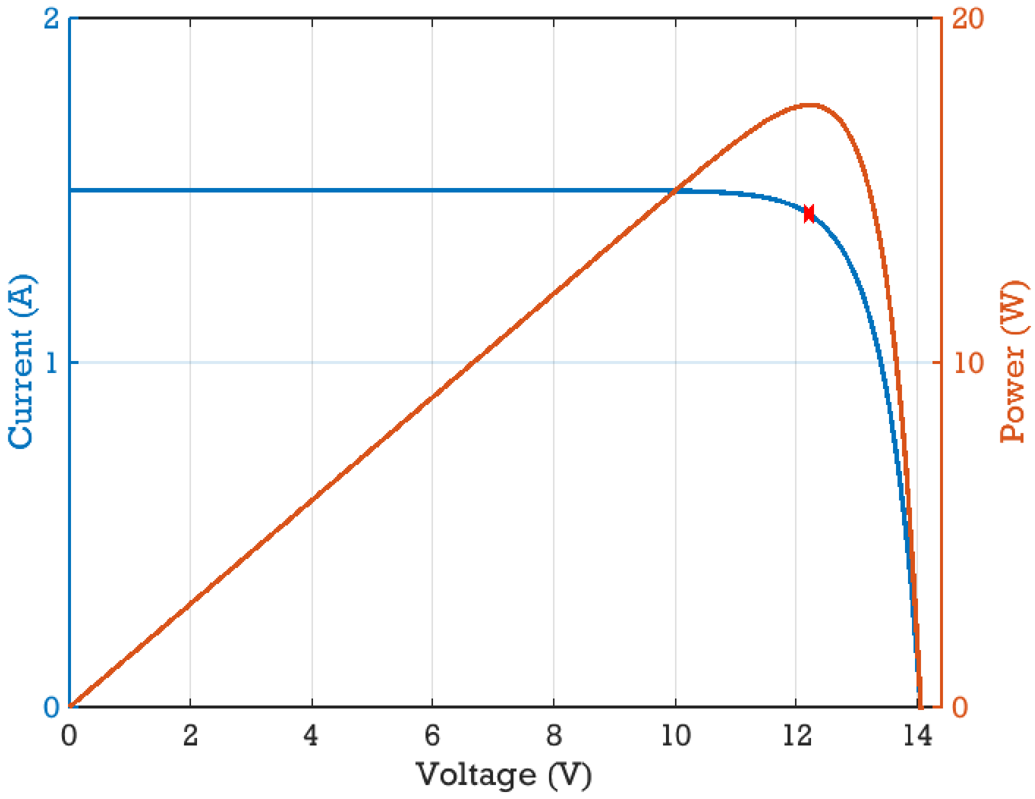
IC Method

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

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

Maximum power is achieved when
the incremental conductance is
equal to the negative of the instantaneous
conductance

Example



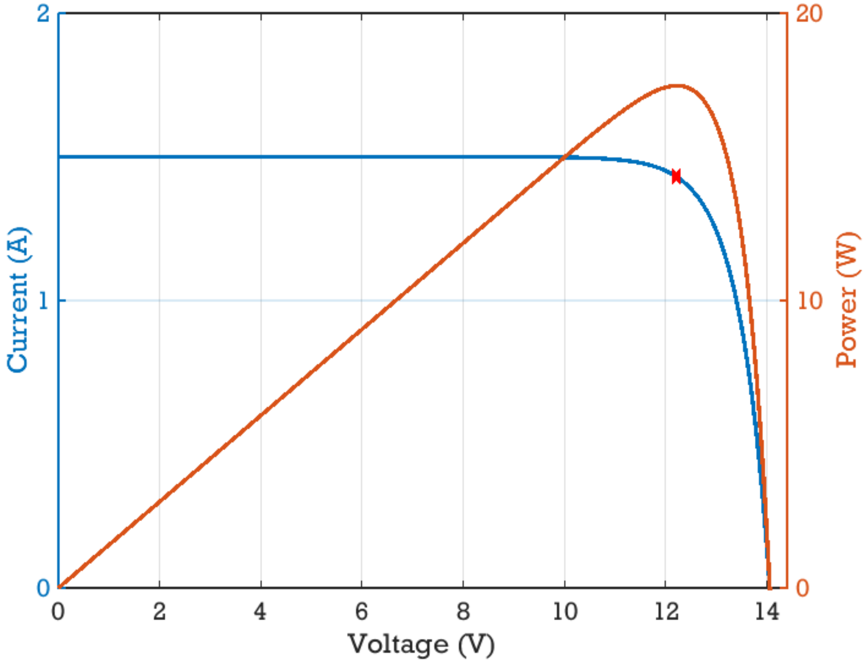
V* = 12.22V
I* = 1.40A

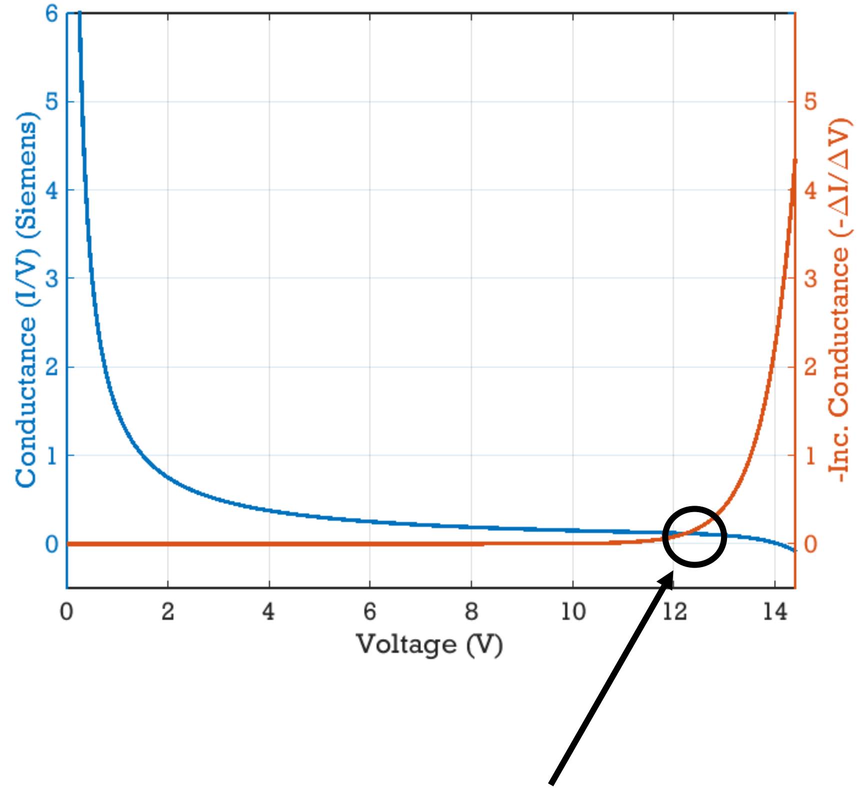
Instantaneous G at MPP
I*/V* = 0.117 Siemens

Incremental G at MPP

$$\frac{\Delta I(V^*)}{\Delta V(V^*)} = \frac{-0.0028}{0.0240} \approx -0.117$$

numerically determined



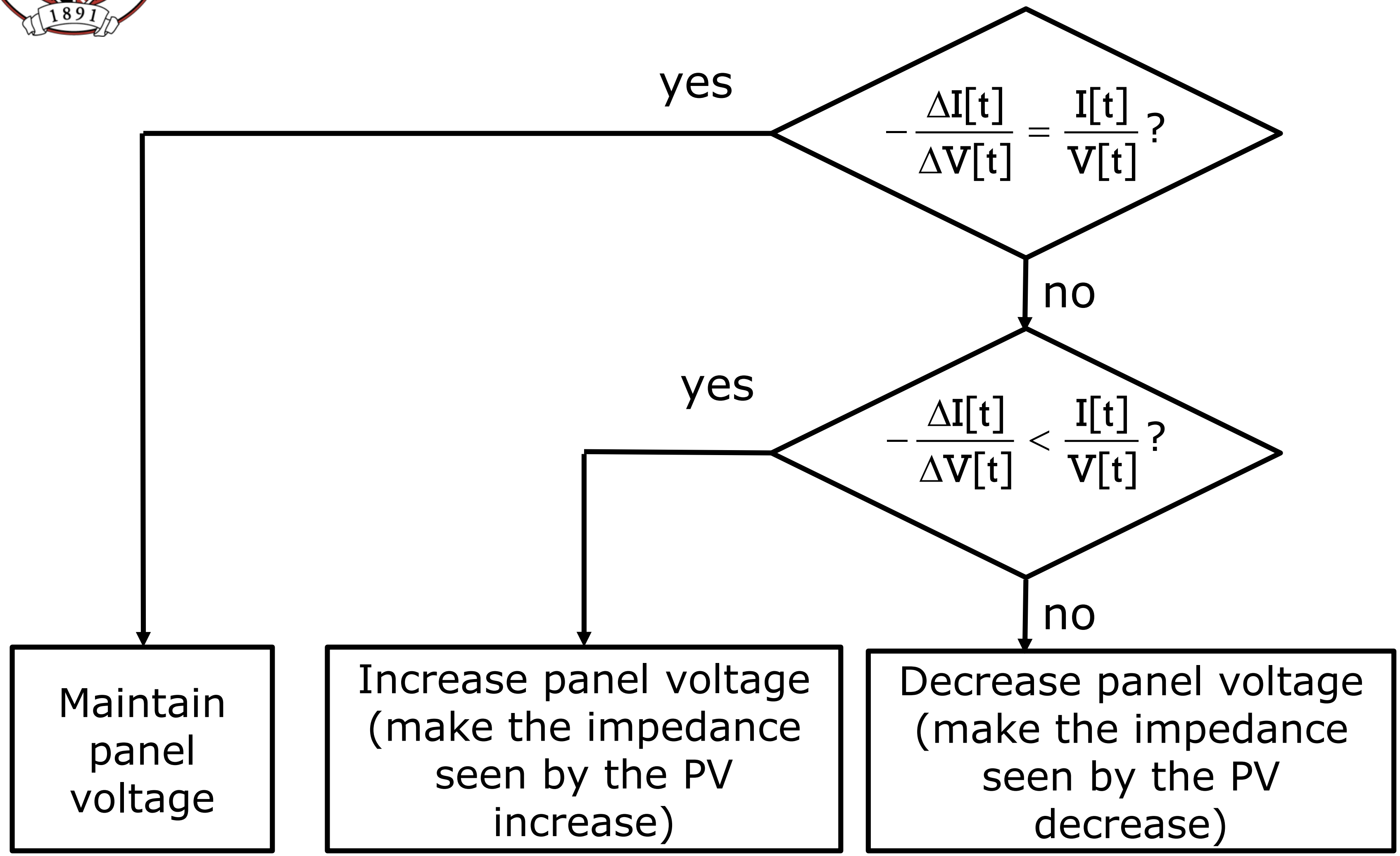


Maximum power point

IC Method

- Method is implemented by rapidly sampling the current and voltage of the PV panel:
  - I[0], I[1], … I[t], …
  - V[0], V[1],… V[t], …
- Compute incremental conductance:
  - $\Delta I/\Delta V = (I[t] - I[t-1])/(V[t] - V[t-1])$
- Compute the instantaneous conductance:
  - $I[t]/V[t]$

IC Method


yes
$-\frac{\Delta I[t]}{\Delta V[t]} = \frac{I[t]}{V[t]}$?
no
yes
$-\frac{\Delta I[t]}{\Delta V[t]} < \frac{I[t]}{V[t]}$?
no
Maintain panel voltage
Increase panel voltage (make the impedance seen by the PV increase)
Decrease panel voltage (make the impedance seen by the PV decrease)