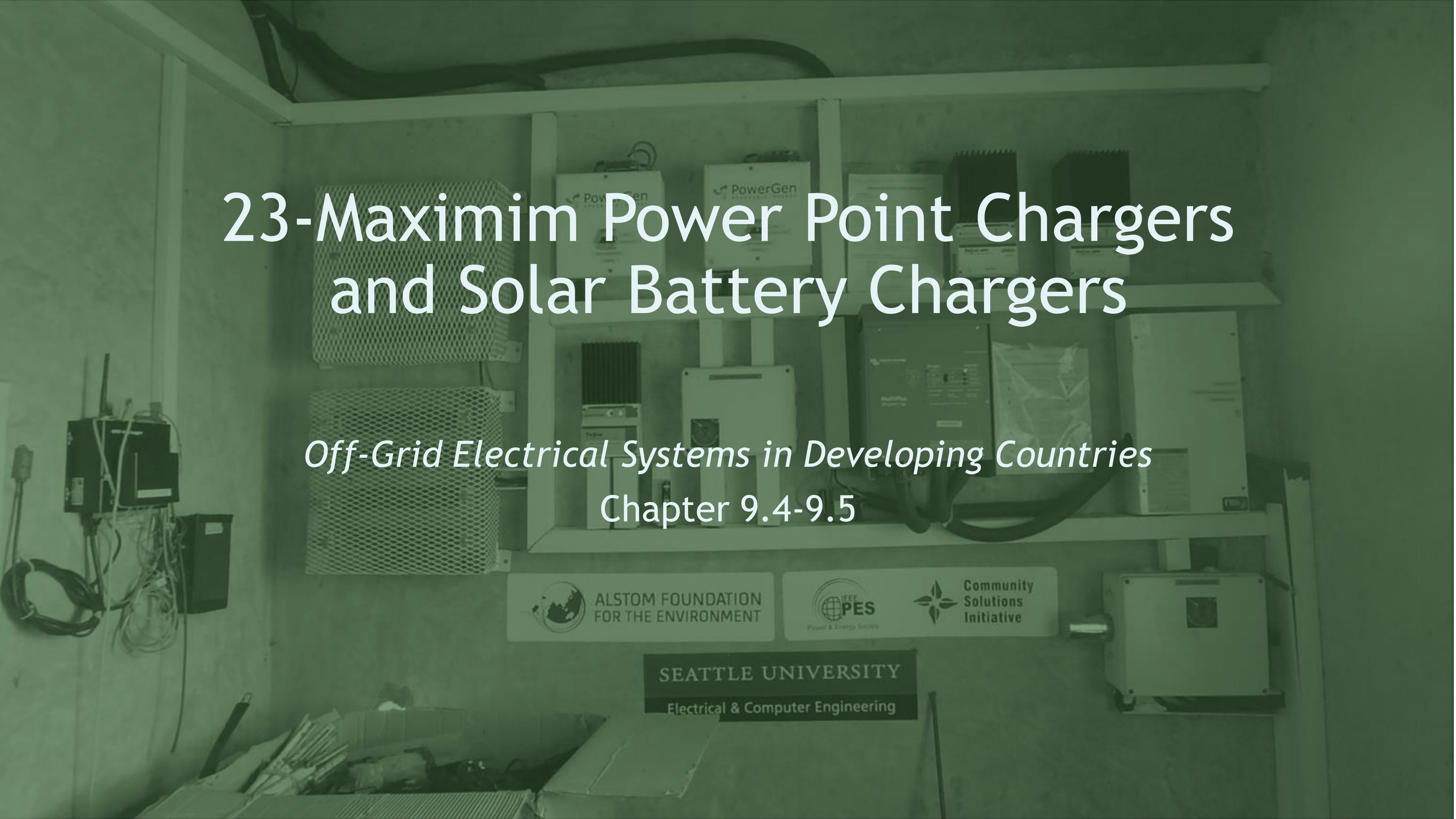
23-Maximim Power Point Chargers and Solar Battery Chargers

Off-Grid Electrical Systems in Developing Countries

Chapter 9.4-9.5



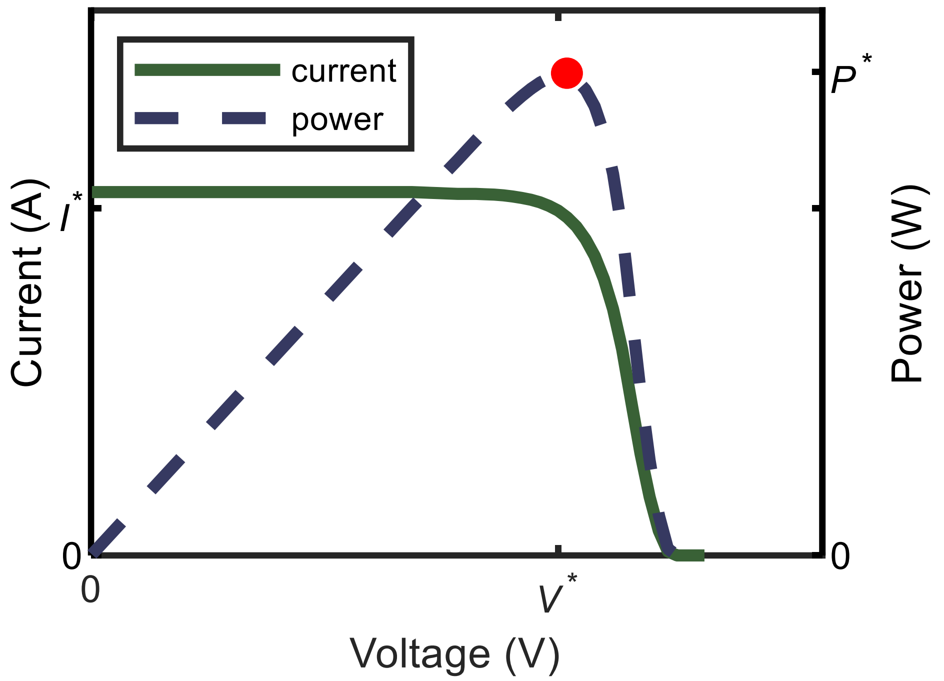
Learning Outcomes

At the end of this lecture, you will be able to:

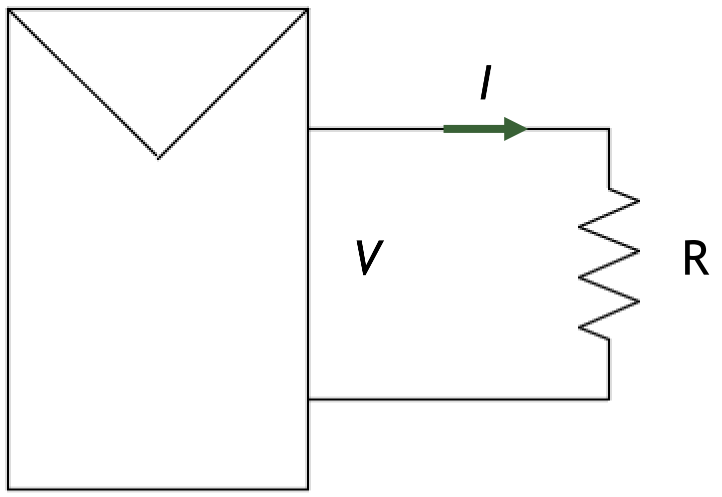
- ✓ describe the need for and application of maximum power point tracking in off-grid systems
- ✓ describe maximum power point tracking algorithms
- ✓ understand basic circuit topologies for solar battery charging

Maximum Power Point Tracking

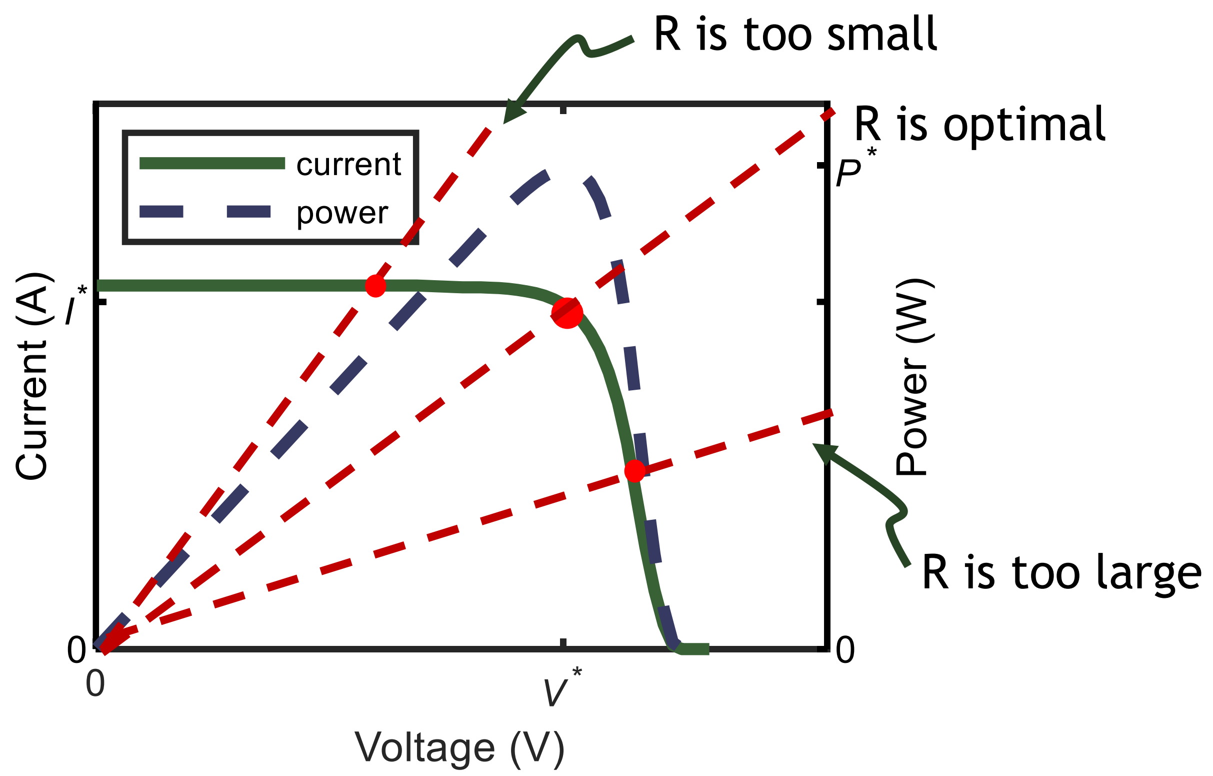
- Recall that a PV module (or array) has a unique operating point that maximizes power production for given irradiance, shading and temperature conditions
- How do we ensure the module operates at the maximum power point?



Load Matching



Operating point for a given resistance is found by the intersection of the IV curve with the line whose slope is 1/R

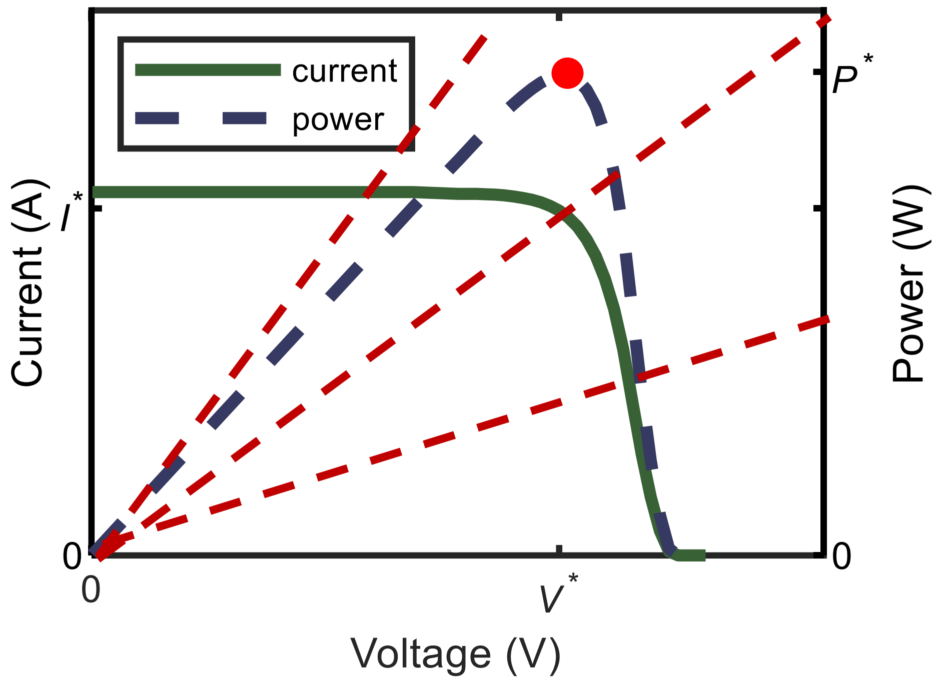


Load Matching

Solving for *R**

$$P^* = V^* I^* = I^{*2} R^*$$

$$R^* = \frac{P^*}{I^{*2}} = \frac{V^*}{I^*}$$



Exercise

What value of load resistance must be connected to the ITEK 350SE to achieve maximum power production under STC?

ELECTRICAL DATA*	350 SE
Maximum Power - P_{MAX} (Wp)	350
Maximum Power Voltage - V_{MPP} (V)	38.55
Maximum Power Current - I_{MPP} (A)	9.08
Maximum Current - I_{MAX} (A) (O,L)	12
Maximum Voltage (TS4-L only) - V_{MAX} (V)	43.57
Open Circuit Voltage - V_{OC} (V) (D,M,S,O)	47.43
Short Circuit Current - I_{SC} (A) (D,M,S)	9.49
Module Efficiency	17.54%

Exercise

What value of load resistance must be connected to the ITEK 350SE to achieve maximum power production under STC?

$$R^* = \frac{P^*}{I^{*2}} = \frac{350}{9.08^2} = 4.25\ \Omega$$

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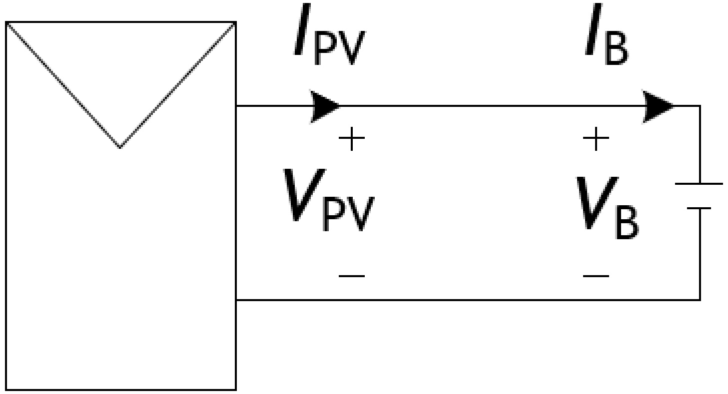
Direct Battery Connection

- When a PV module is directly connected to a battery, the module voltage is "set" by the battery voltage

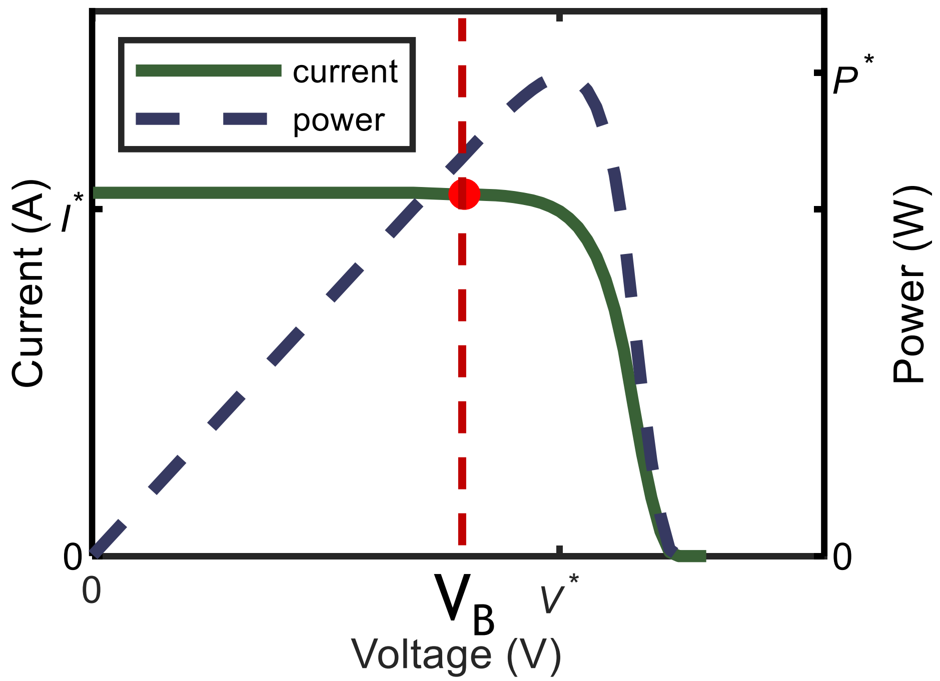
$$V_{\mathrm{PV}} = V_{\mathrm{B}}$$

$$I_{\mathrm{PV}} = I_{\mathrm{B}}$$



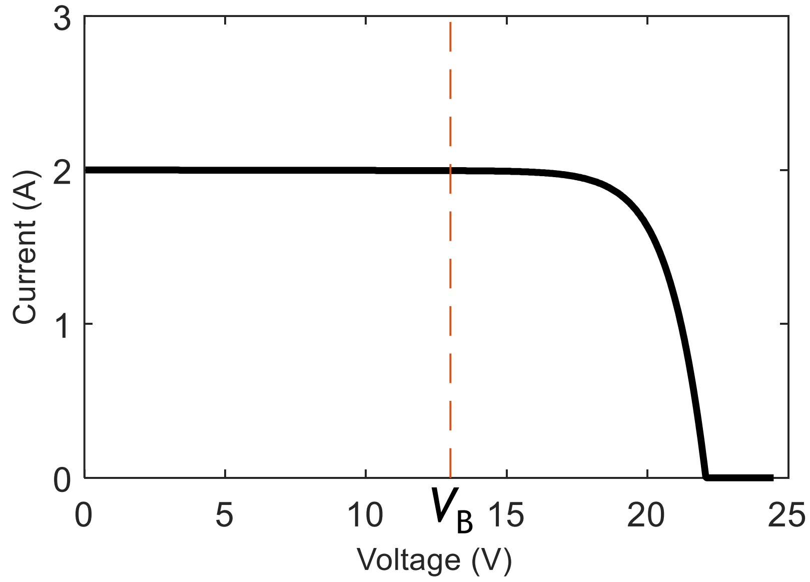
Direct Battery Connection

- Operating point is found by the intersection of the battery voltage the I-V curve of the PV module
  - Note: terminal voltage VB will change somewhat depending on the current
- The intersection generally does not correspond to the MPP (but is often reasonably close under STC)
- What happens when a battery is connected to a PV module at night (or low irradiance)?



Exercise

An off-grid house has an improvised system consisting of a PV module that is directly connected to a battery. The I–V curve of a PV module under the present irradiance and temperature conditions is shown. The PV module is used to charge a battery whose terminal voltage is 13 V. Estimate the power produced by the PV module.



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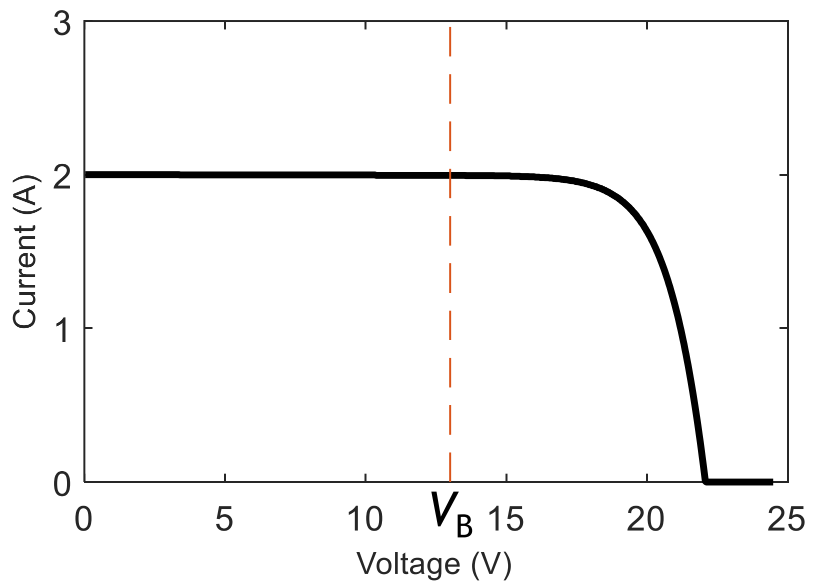
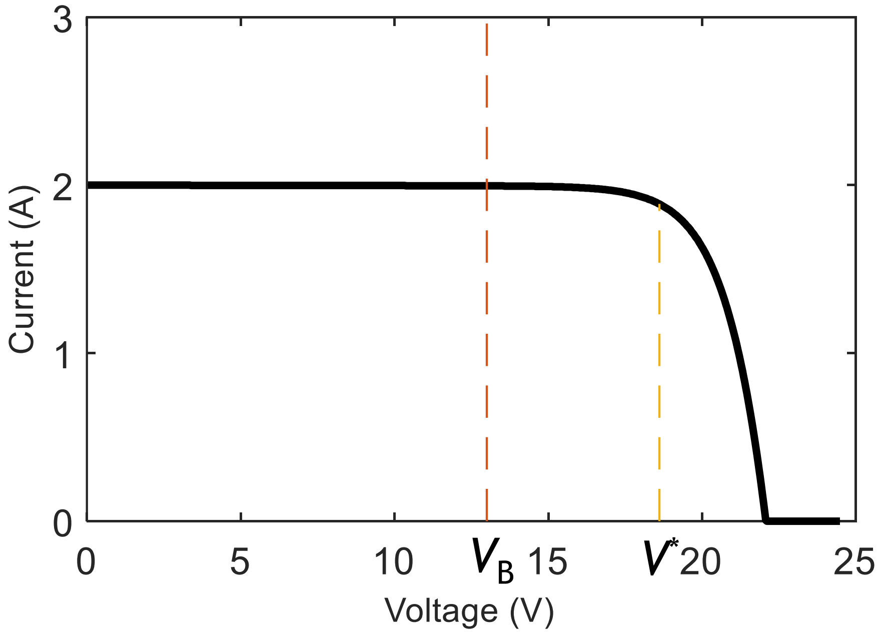
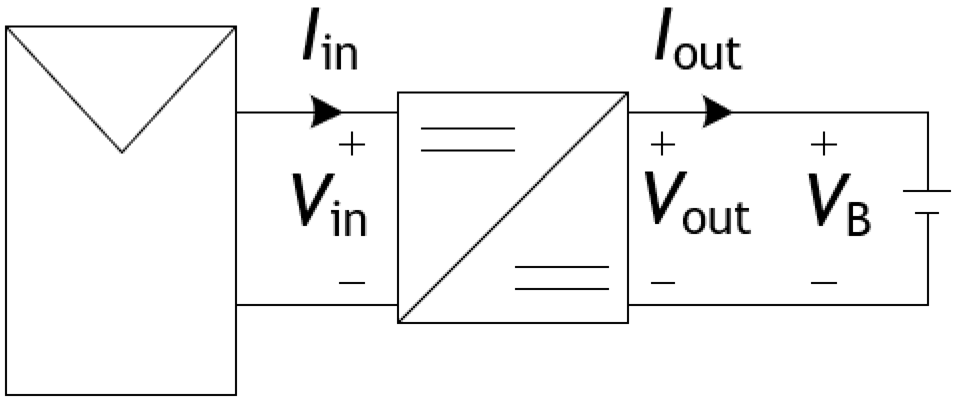


The terminal voltage of the battery "sets" the Voltage of the PV module. The power therefore is approximately P = 13 x 2 = 26 W

Example

Next, consider the scenario in which the house has an MPPT (boost converter) that is connected between the module and the battery. The voltage and current corresponding to the maximum power point are 18.7 V and 1.89 A. Compute the duty cycle so that the PV module operates at its maximum power point and the corresponding power and current into the battery.





Example

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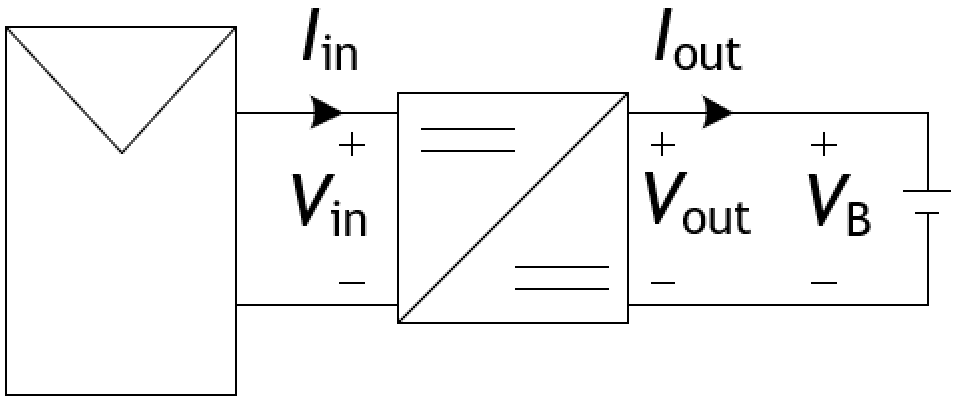
$$V_{\text{out}} = \frac{1}{1-D} V_{\text{in}} \text{ (from last lecture)}$$

$$18.7 = \frac{1}{1-D} 13$$

$$D = 0.3048$$

Example



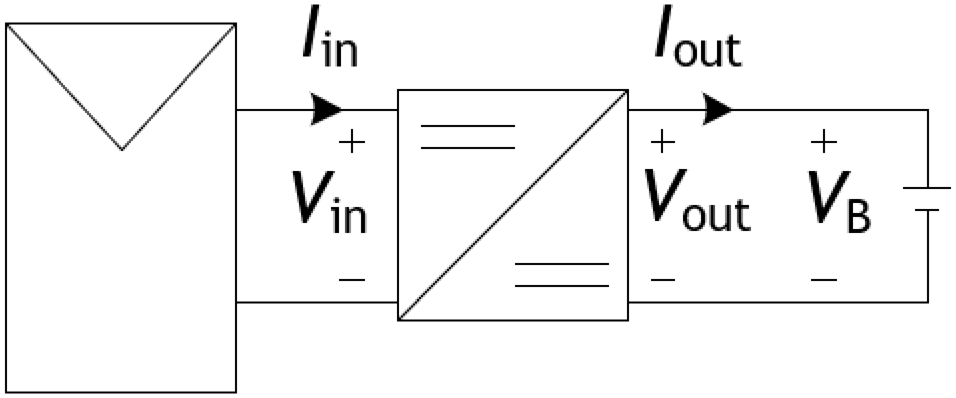
Battery Voltage: 13 V
PV Voltage: 18.7 V
Battery Current: 1.89 A
PV Current: 2.74 A

$$P = V^* I^* = 18.7 \times 1.89 = 35.32\,\text{W}$$

$$I_{out} = \frac{P}{V_{out}} = \frac{P}{V_B} = \frac{35.25}{13.0} = 2.72\,\text{A}$$

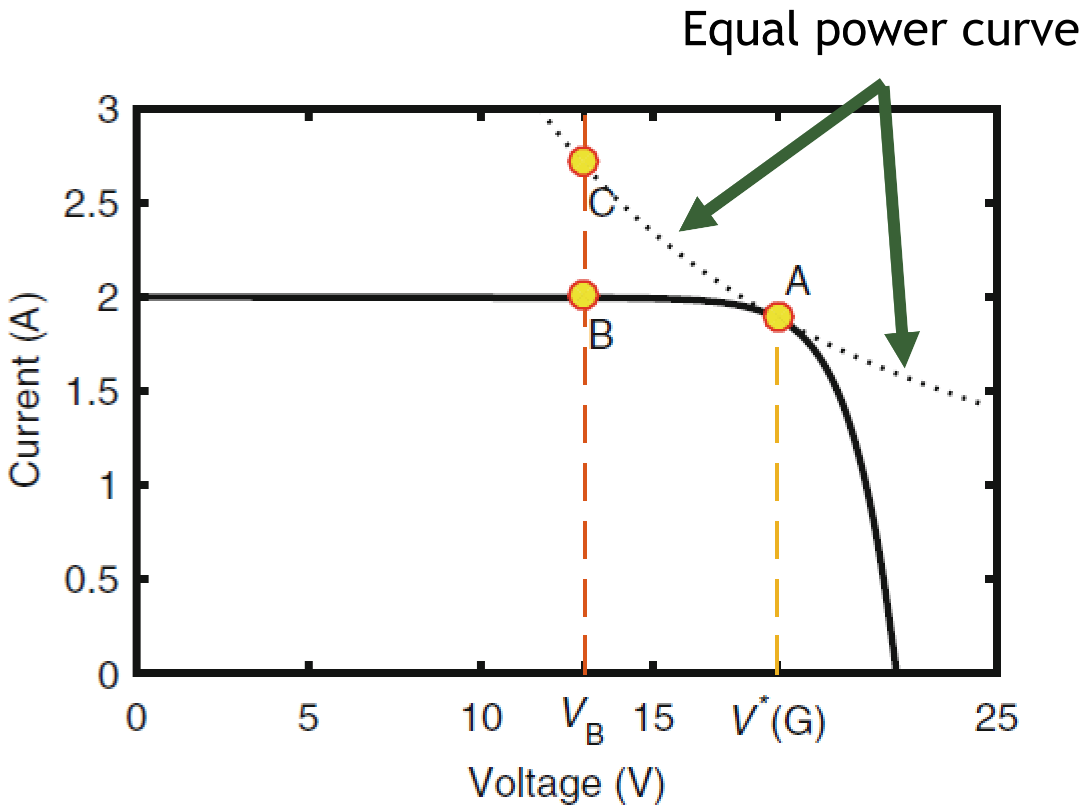
Maximum Power Point Tracking

- Direct connection of PV module to battery does not optimize production
- Better approach: de-couple battery voltage from PV module voltage



MPPT

- Operating points
  - Battery: point C
  - PV array: point A
- Without MPPT both PV array and battery a operate at point B



MPPT: Practical Considerations

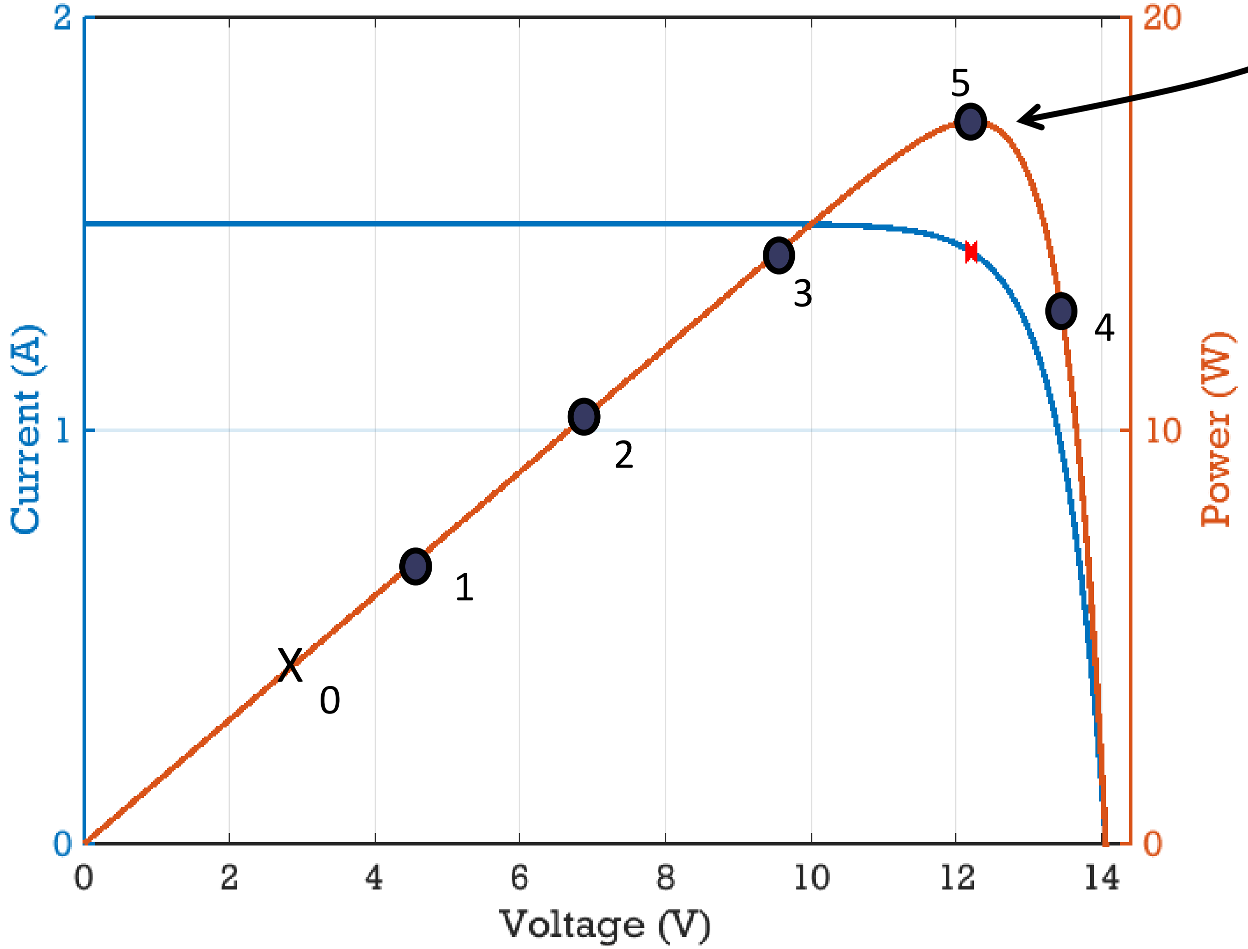
- MPPTs often increase energy production by 10-15%
- Additional cost of MPPT must be considered
- MPPT often (but not always) integrated into charge controller as a single unit
  - Charge controllers without MPPT are sometimes branded as “PWM” charge controllers (but MPPT controllers also use PWM)
- Some MPPT algorithms are better than others
  - Find MPP faster, have higher overall energy yield, less affected by shading

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)

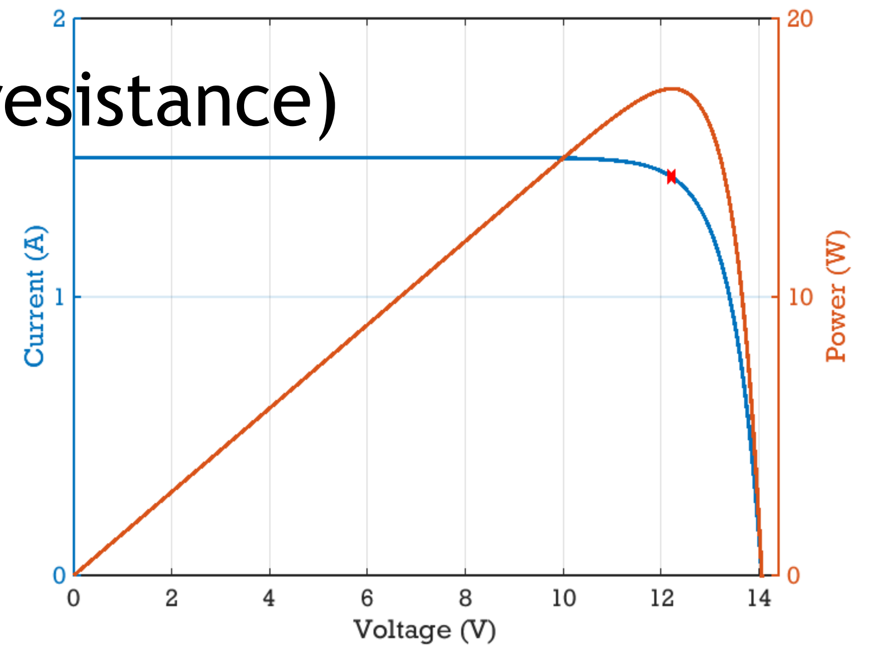
Incremental Conductance

- 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

$$P = I(V)V$$

$$\frac{dP}{dV} = \frac{dI(V)V}{dV} = \frac{dI}{dV}V + 1I(V) = 0$$

at the maximum

Applying the product rule for derivatives

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

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

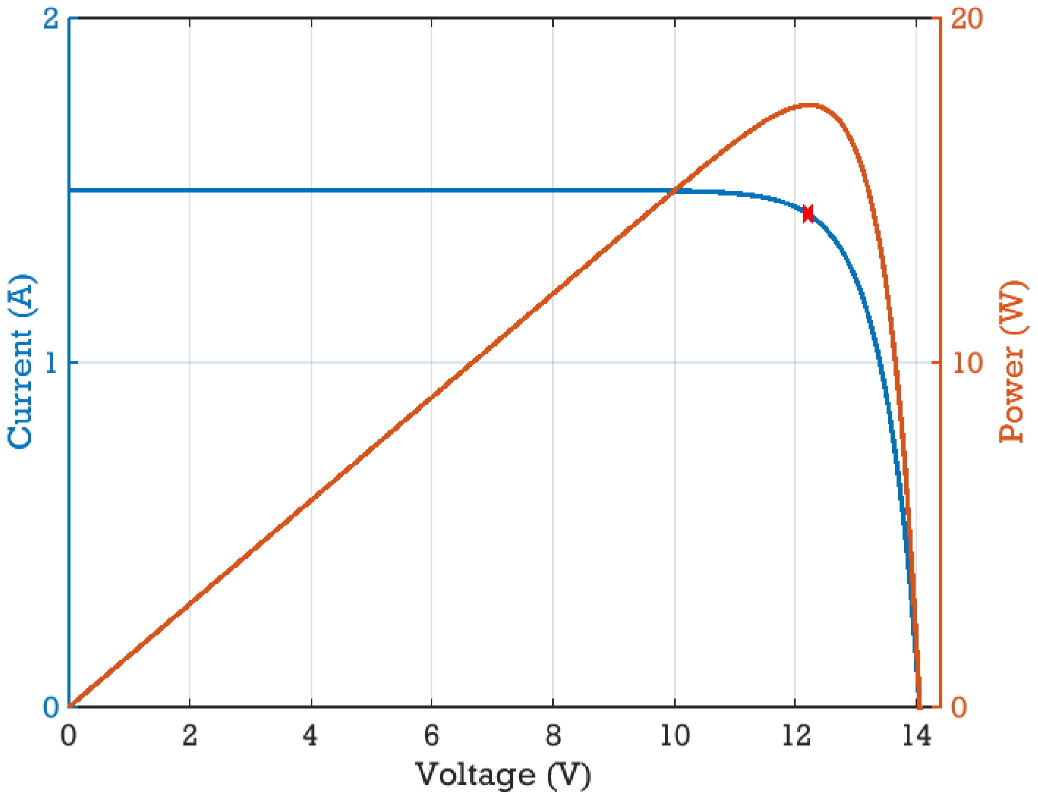
IC Method

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

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

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

Example



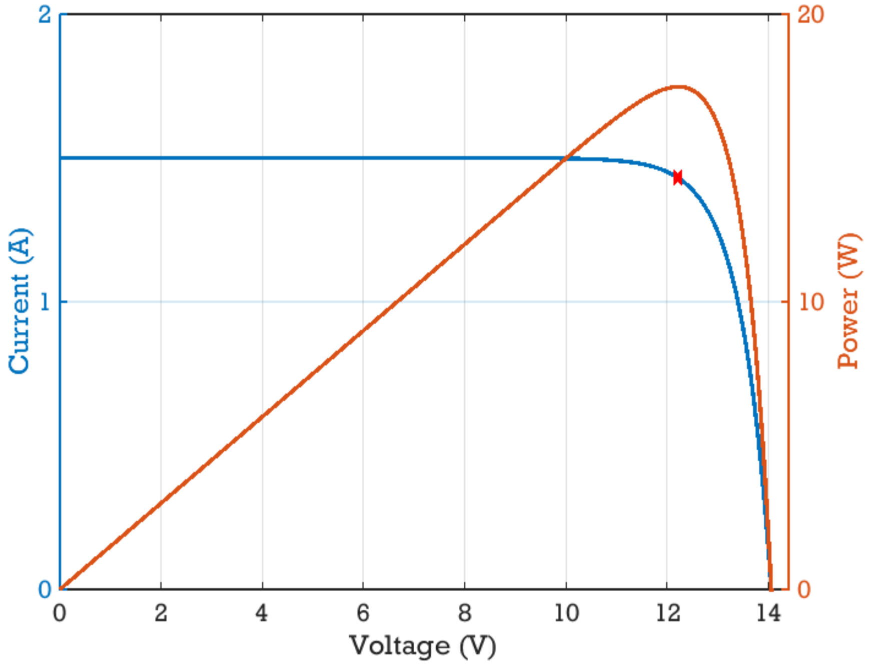
V* = 12.22V
I* = 1.40A

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

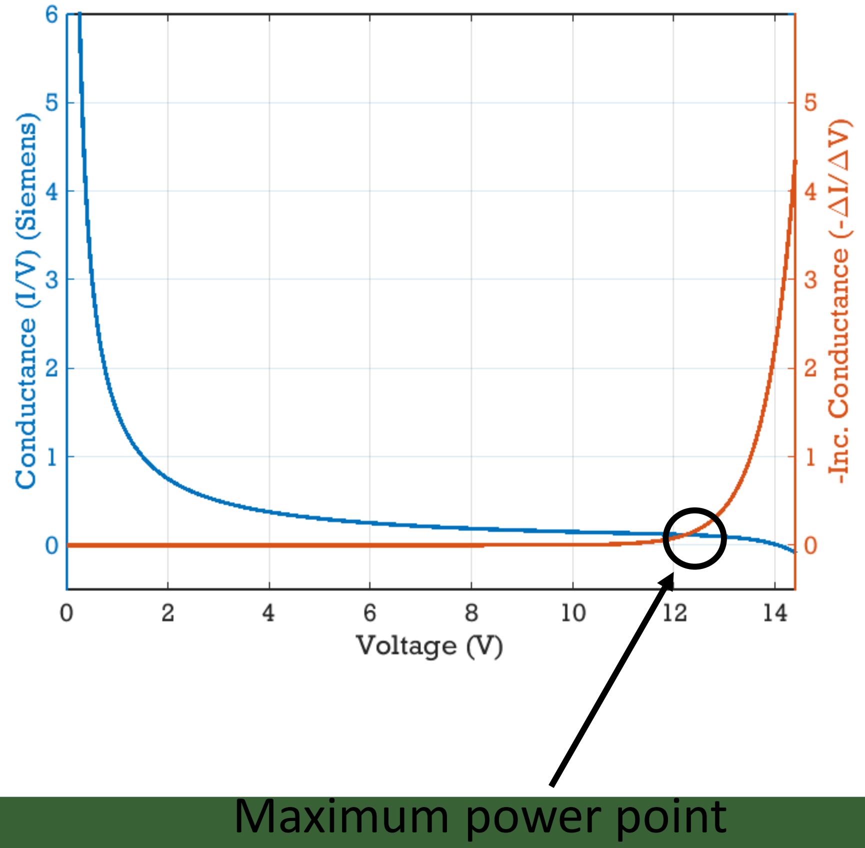
Incremental G at MPP

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

numerically determined



Current (A)
Power (W)
Voltage (V)
0
2
4
6
8
10
12
14
0
1
2
0
10
20

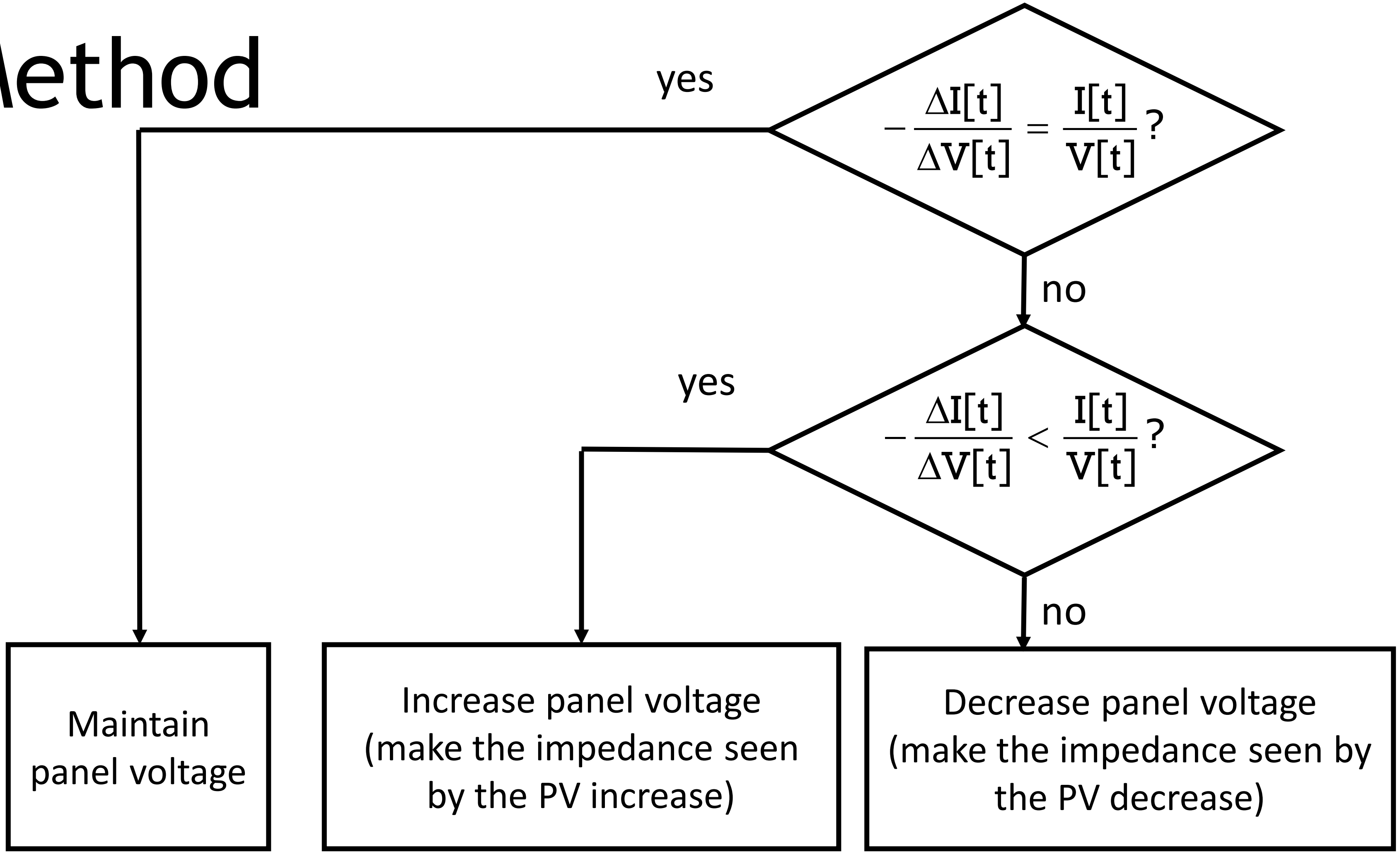


Conductance (I/V) (Siemens)
-Inc. Conductance (-ΔI/ΔV)
Voltage (V)
0
2
4
6
8
10
12
14
0
1
2
3
4
5
6
0
1
2
3
4
5
Maximum power point

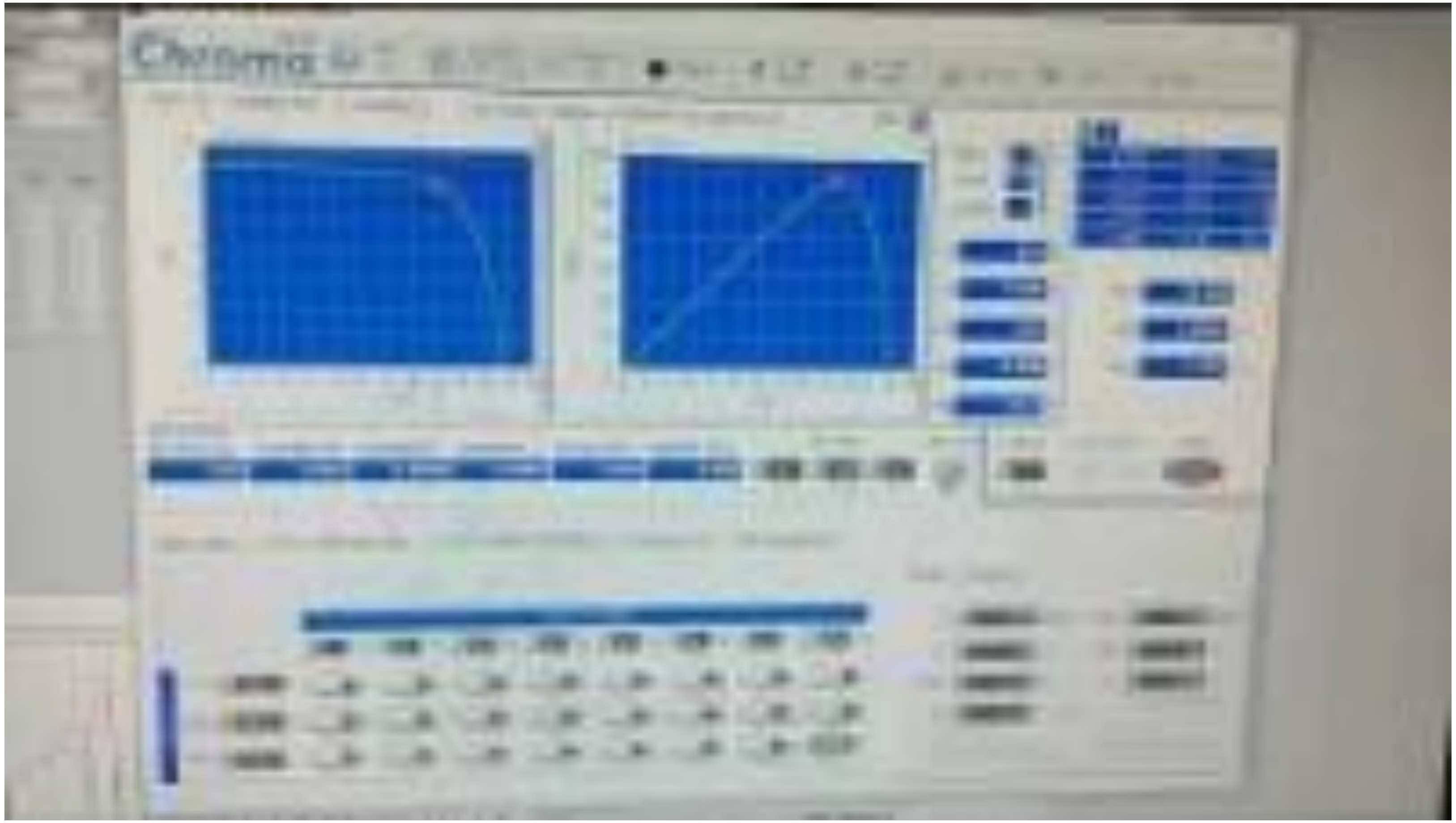
IC Method

- 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)

Red dot is the operating point. The load and PV are not changing, but the red dot still perturbs to check if it is still on the maximum power point



The load changes every 3 seconds, which exaggerates the searching of the MPPT

Solar Battery Charging

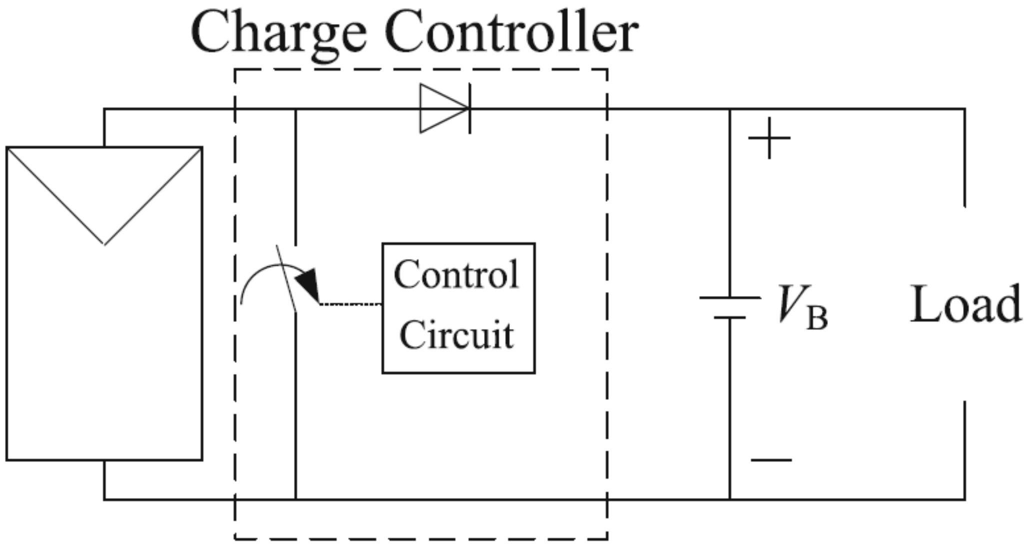
- Many off-grid systems utilize solar modules to charge batteries
  - Mini-grids
  - Solar lanterns
  - Solar home systems
- Charging of batteries via solar modules must be done in a way to prevent the battery from being damaged from over-charging

Solar Battery Chargers

- Three general types of solar chargers
  - Shunt
  - Series
  - Pulse Width Modulation
- Possible to incorporate MPPT, but we will not consider this for the sake of clarity

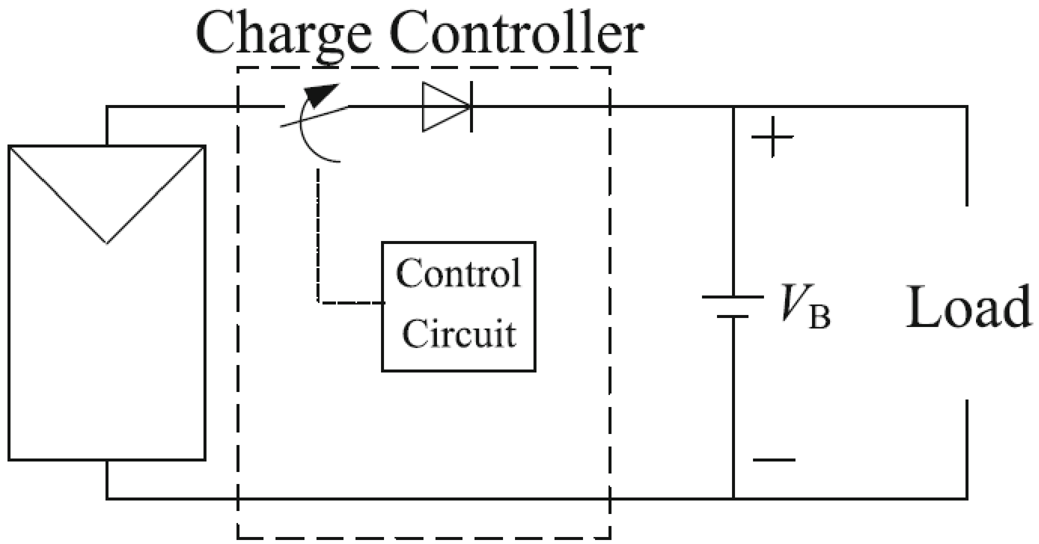
Shunt-Type Charge Controller

- Close switch when battery terminal voltage reaches a pre-defined threshold
- When switch is closed, PV module is short-circuited and no current flows to the battery
- Diode prevents battery from discharging into PV module



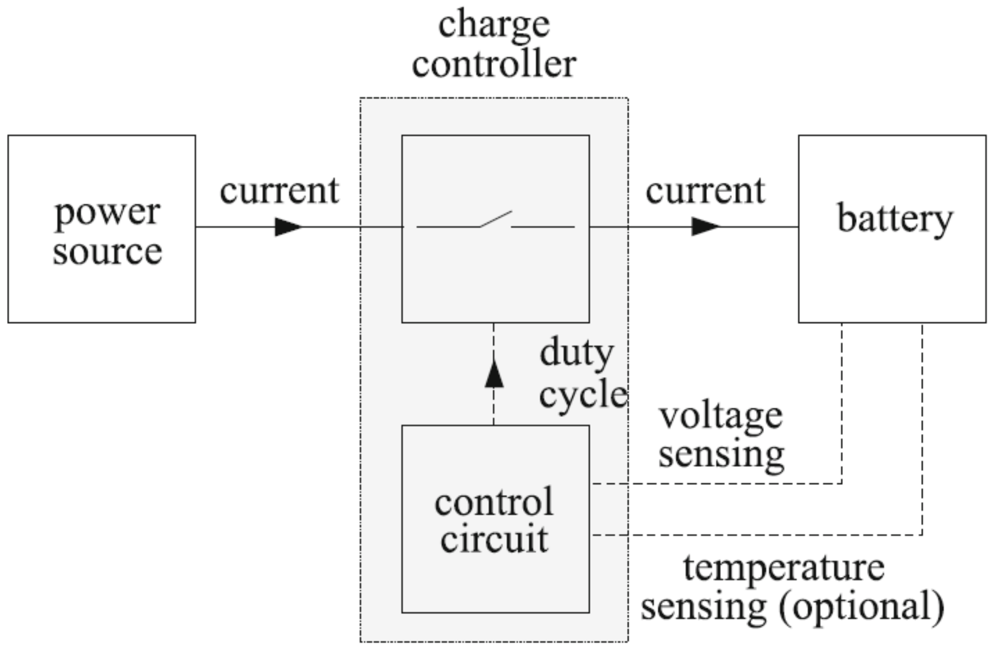
Series-Type Charge Controller

- Open switch when battery terminal voltage reaches a pre-defined threshold
- When switch is open, PV module is open-circuited and no current flows to the battery
- Diode prevents battery from discharging into PV module during the night (or low irradiance)



PWM Charge Controller

- Basic idea: operate a switch via PWM to control the current into the battery so that the battery voltage charges at a pre-defined voltage or current
- Allows for more sophisticated battery charging algorithms to be used, prolonging life and shortening charging time



Battery Charging

- Care must be taken to not damage a battery when charging it
- Avoid
  - Too large charge current (excessive heat)
  - Too high of a voltage for too long (promotes unwanted reactions that degrades the battery such as creation of hydrogen gas)
- However, we usually also want to re-charge a battery as quickly as possible
- Approach depends on the battery chemistry

Lead-Acid Battery Charging

- Lead-acid batteries are usually charged following a three-stage approach
- Stage 1: Bulk Charge
- Stage 2: Absorption Charge
- Stage 3: Float Charge

Stage 1: Bulk Charge

- Rapidly increase state-of-charge by supplying as much current as possible (usually no more than 20% of 20-hour capacity) while the battery voltage (and state-of-charge) is low
- Usually performed at constant current
- Stage 1 ends when the battery voltage reaches a pre-defined "absorption set-point"
  - Usually 14.2 V – 14.6 V for a 12V battery
- Battery state-of-charge is 70-90% full when this ends

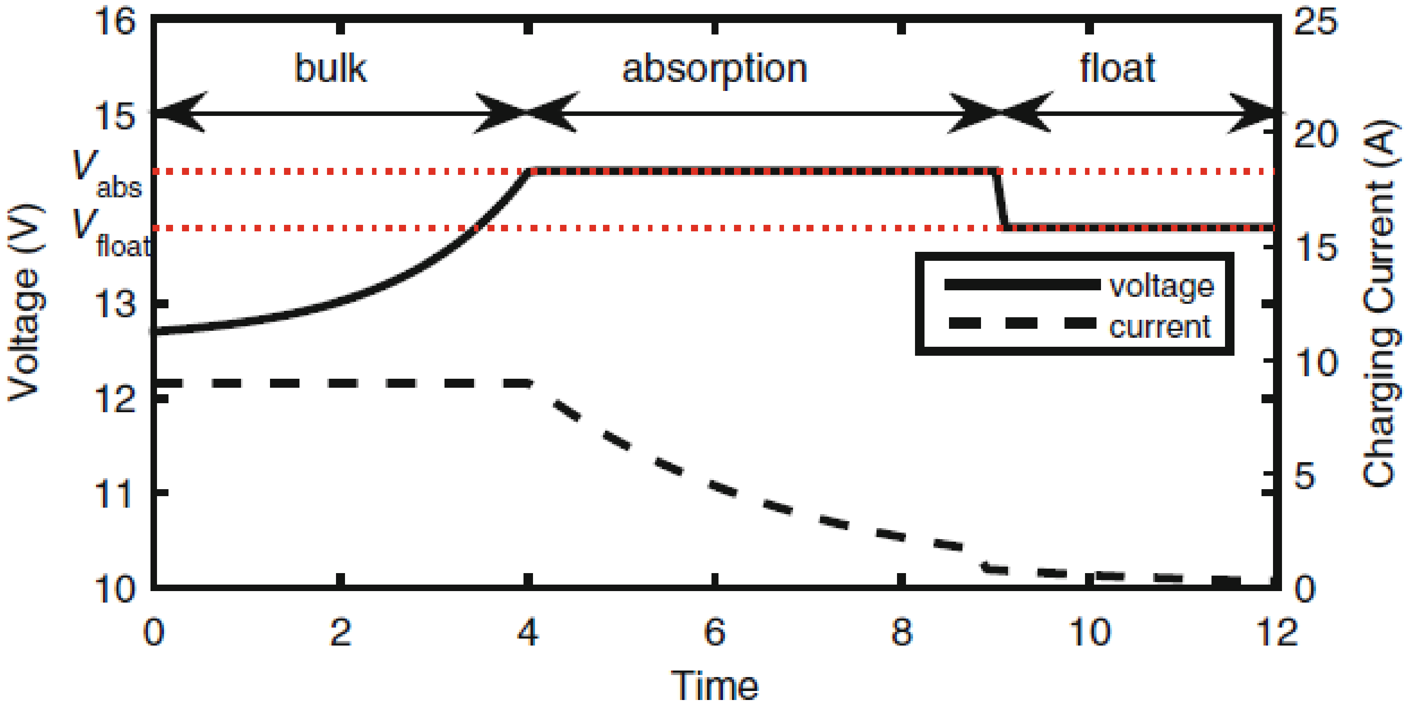
Stage 2: Absorption Charge

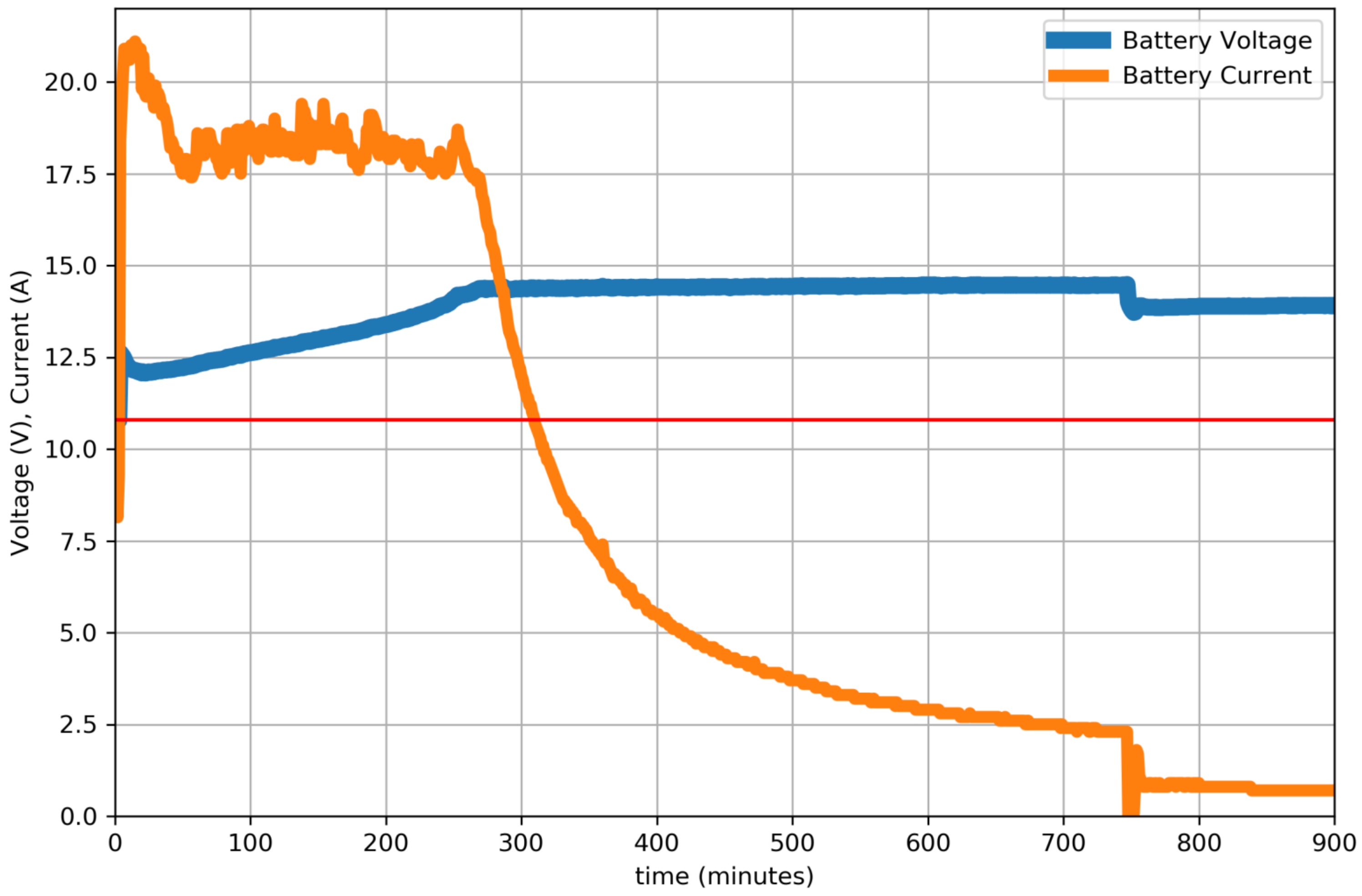
- Carefully charge the battery so that its voltage does not exceed the absorption charge set-point (voltage regulation)
- Voltage is approximately constant
- Current will decrease during this period as the battery state-of-charge increases
- Stage ends either after a pre-defined amount of time has passed (4-6 hours), or a variable amount of time depending on how long the bulk stage lasted
- Battery is approx. full at the end of the absorption stage

Stage 3: Float charge

- Maintain battery at its full state-of-charge, but at a reduced pre-defined “float” set-point voltage (13.4-13.8 V for nominal 12V battery) to reduce unwanted reactions
- Current is very low during this stage
- No definite end to this stage
  - Usually ends when PV power is insufficient to maintain float voltage

Three-Stage Charging





Input current limit by charger: 20A

Absorption set-point: 14.4V
Float set-point: 13.8V

(12V, 100 Ah, AGM Battery)

Other Considerations

- Equalization Charge: maintenance charge, a temporary over-voltage of the battery (15-16V for nominal 12V battery) that can improve life of battery by restoring lost capacity. Can be performed approximately monthly
- Standby Use: when a battery is not regularly used, lower voltage set-points are used

Three-Stage Charging Set-Points

- Battery manufacturers provide recommended absorption and float set-points
- Voltage varies based on battery type and temperature (most charge controllers can automatically adjust for temperature)
  - Higher temperature: lower set point voltage

Recommended charge voltage:

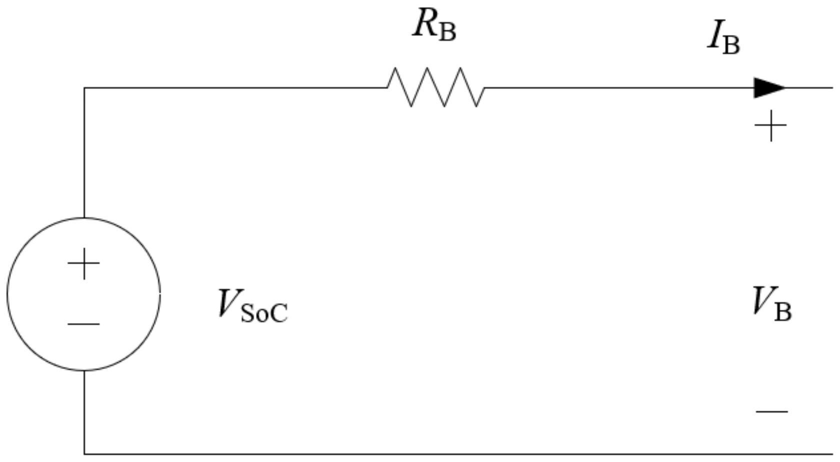
	Float Service	Cycle service Normal	Cycle service Fast recharge
Absorption		14,2 - 14,6 V	14,6 - 14,9 V
Float	13,5 - 13,8 V	13,5 - 13,8 V	13,5 - 13,8 V
Storage	13,2 - 13,5 V	13,2 - 13,5 V	13,2 - 13,5 V

Voltage Regulation

- Recall that a simple circuit model of a battery is

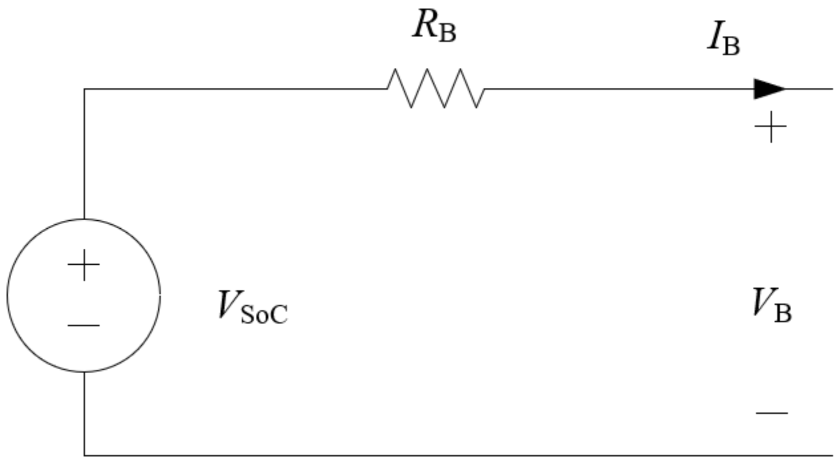
$$V_B = V_{SOC} - I_B R_B$$

- We can control the terminal voltage V_B by adjusting the battery current



Example

A battery is connected to solar panel through a charge controller. Let V_{SoC} = 12.8 V and R_B = 0.1 Ω. Compute the maximum current that can provided without the battery voltage exceeding 13.8 V.



Example

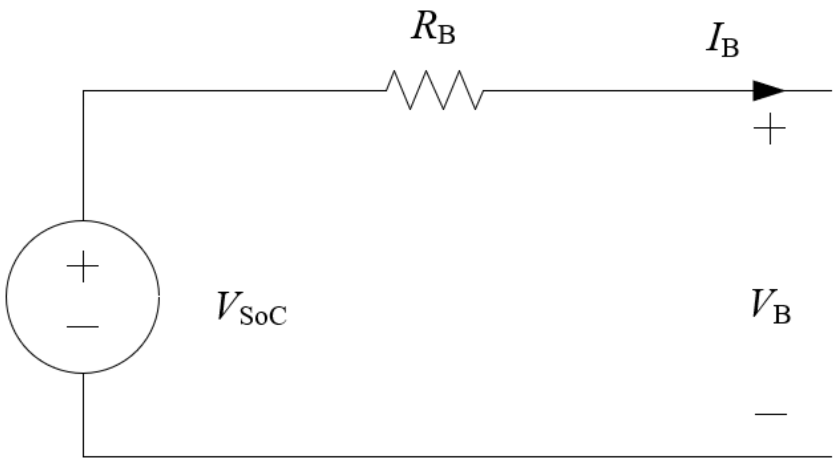
$$V_B = 13.6 \text{ V}$$

$$V_{\text{B}} = V_{\text{SoC}} - I_{\text{B}} R_{\text{B}}$$

$$\frac{V_{\text{B}} - V_{\text{SoC}}}{R_{\text{B}}} = -I_{\text{B}}$$

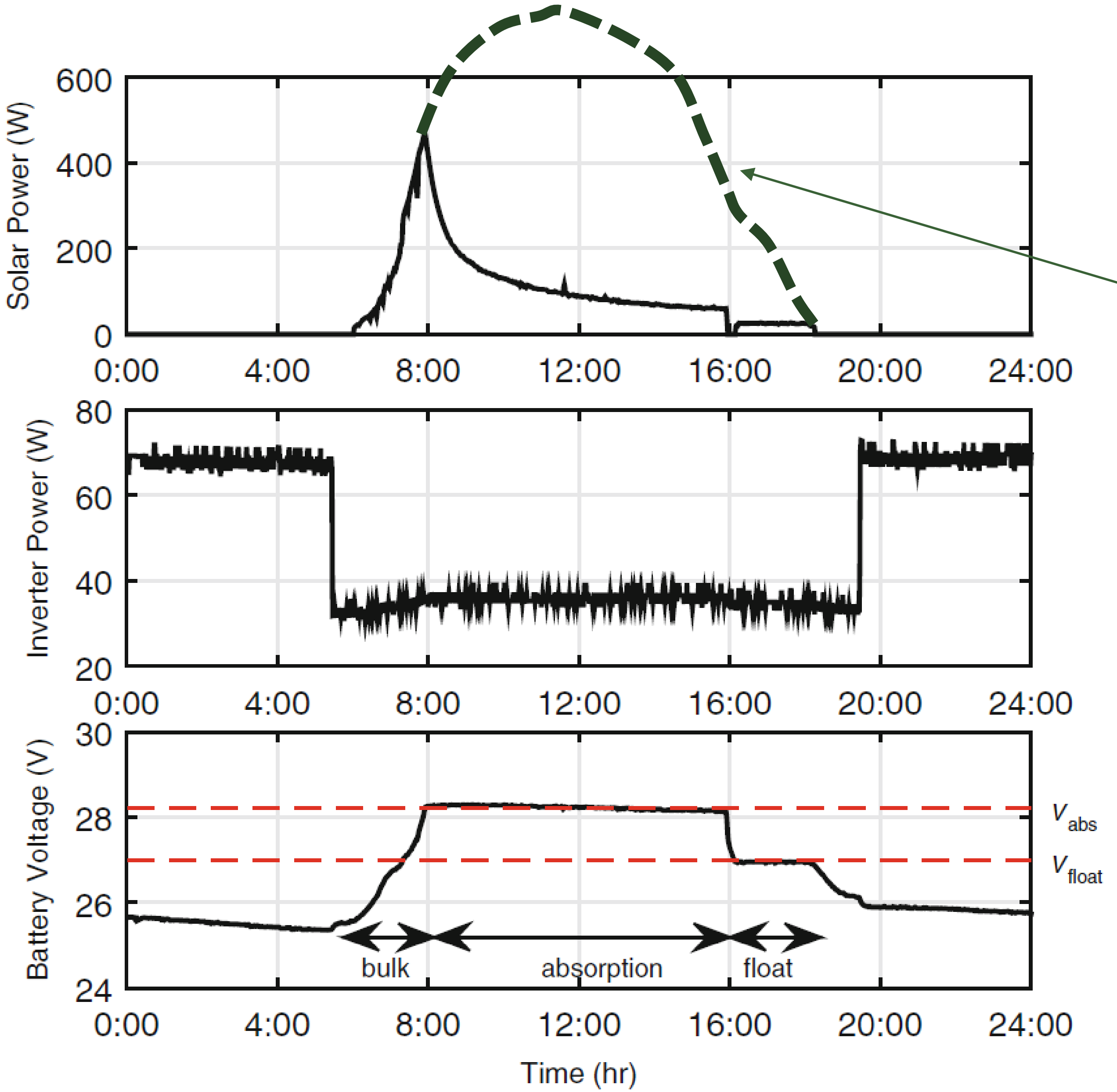
$$\frac{-V_{\text{B}} + V_{\text{SoC}}}{R_{\text{B}}} = I_{\text{B}}$$

$$\frac{-13.8 + 12.8}{0.1} = I_{\text{B}} = -10 \text{ A (10 A of charging)}$$



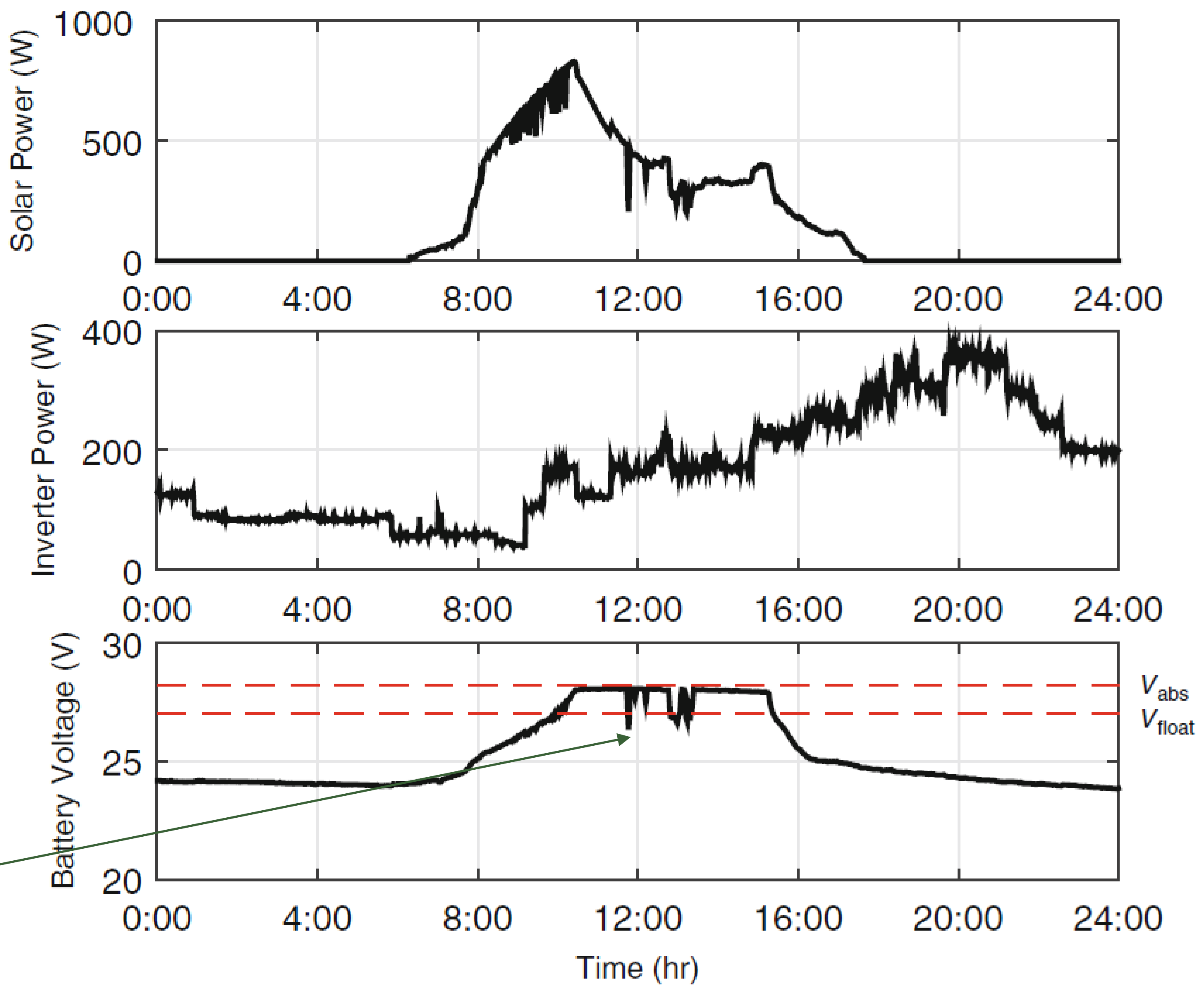
Three-Stage Charging in PV Systems

- Limited current during absorption and float charge stages may mean PV power is reduced (throttled)
- Irradiance levels and load may affect the three-stage charging process (power constrained charging)
  - PV power may be insufficient to charge battery at desired level AND supply load
  - Load is given the priority
- Battery may not be fully charged and/or absorption/float voltages may not be tightly regulated



PV array could produce Additional power, but the load is low and the charge controller is limiting current

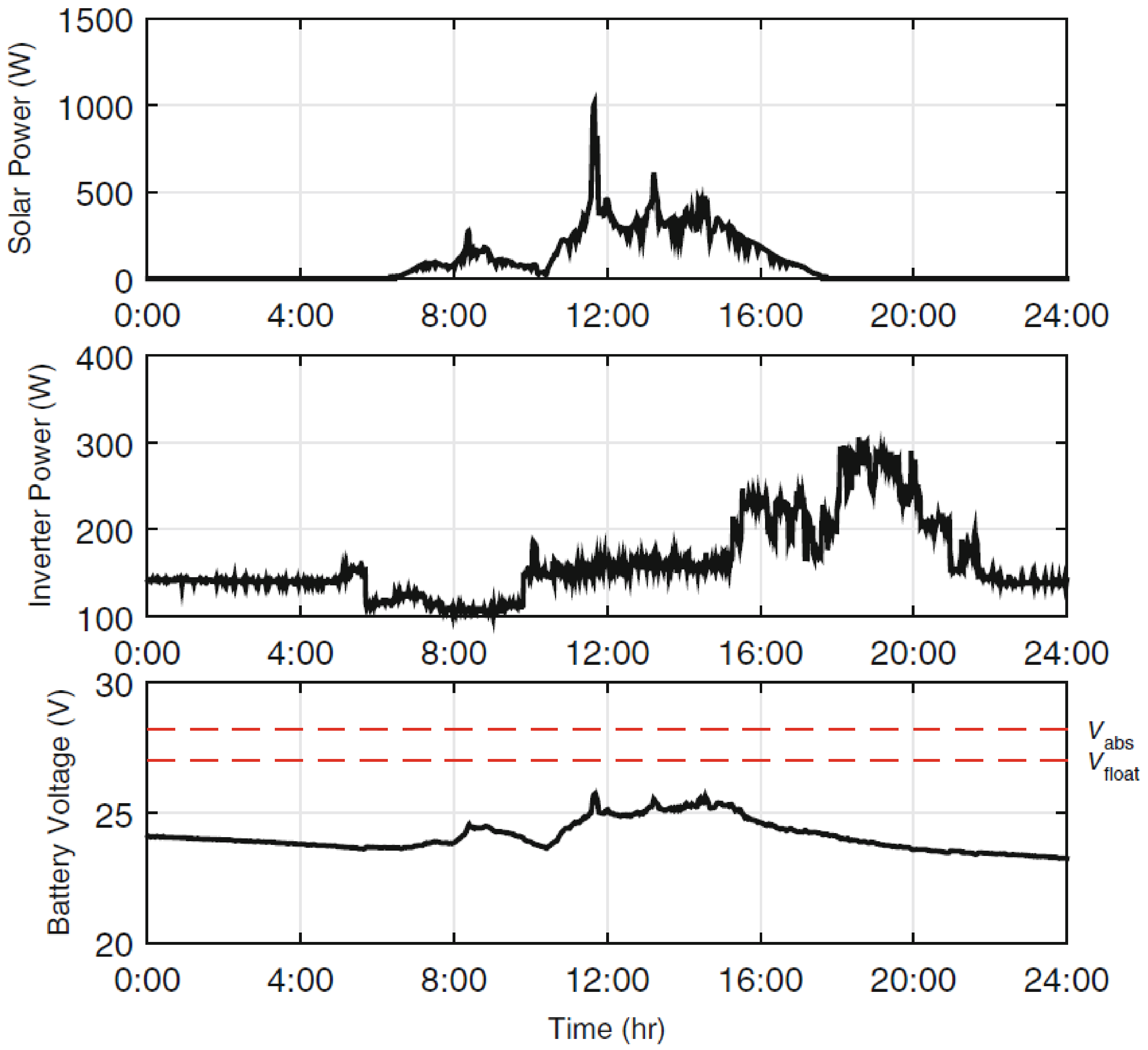
Power-Constrained Charging



Absorption set-point voltage cannot be maintained due to load spikes

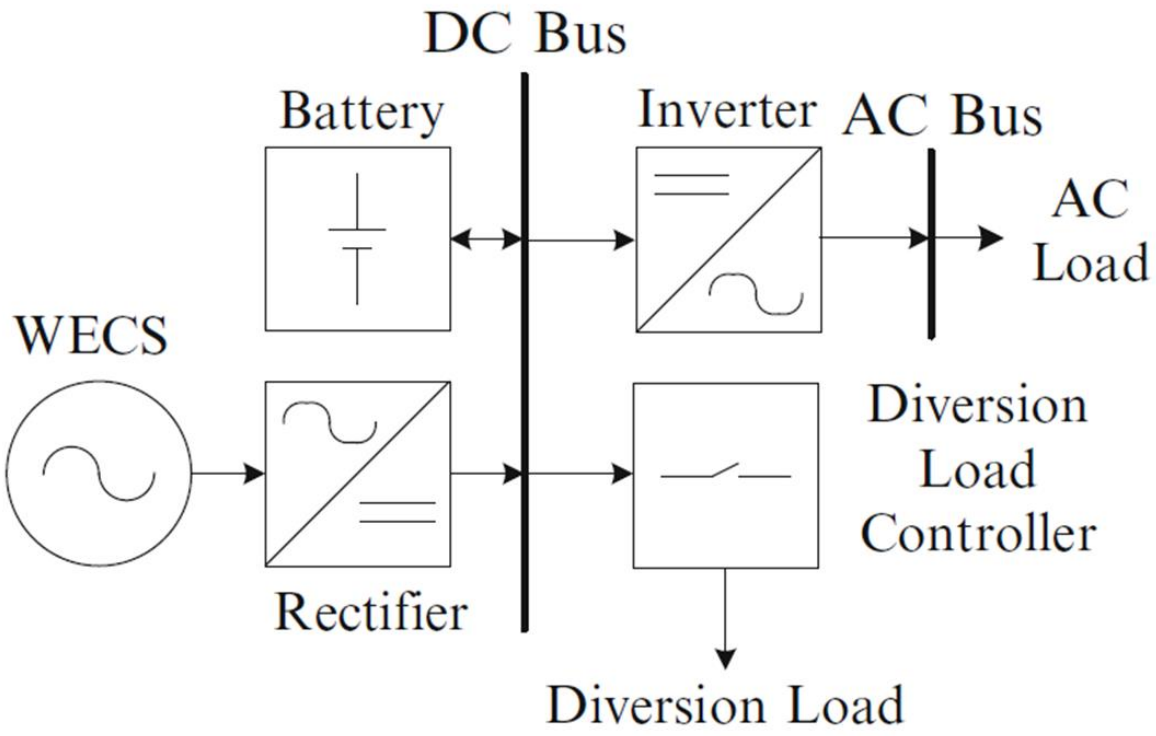
Power-Constrained Charging

- Charging on a cloudy day
- Bulk stage is never completed



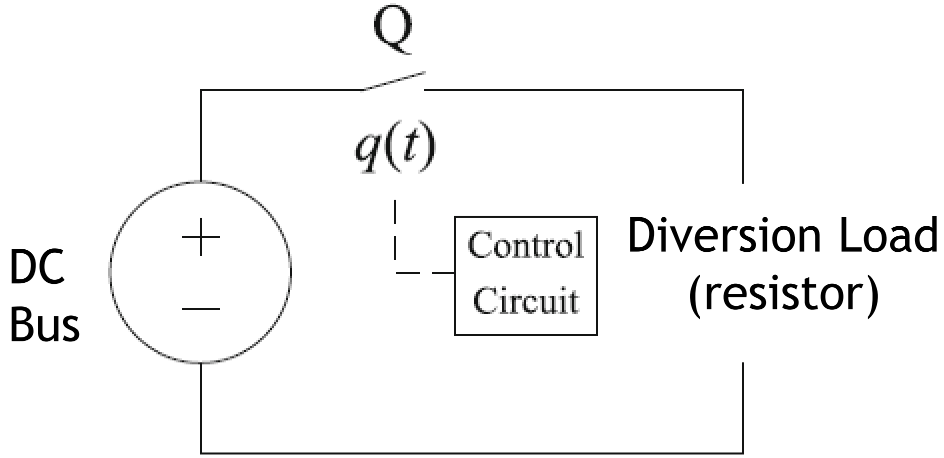
Diversion Load Controller

- Recall that some architectures require diversion load to prevent an energy source from over-charging the battery
- Diversion Load controller can also be used to implement three-stage charging of the batter



Diversion Load Controller (DLC)

- DLC can be a “chopper” circuit set between the DC bus and the diversion load (resistor bank with a high power rating)
- Switch is controlled via PWM to regulate the current to the diversion load



Diversion Load Controller

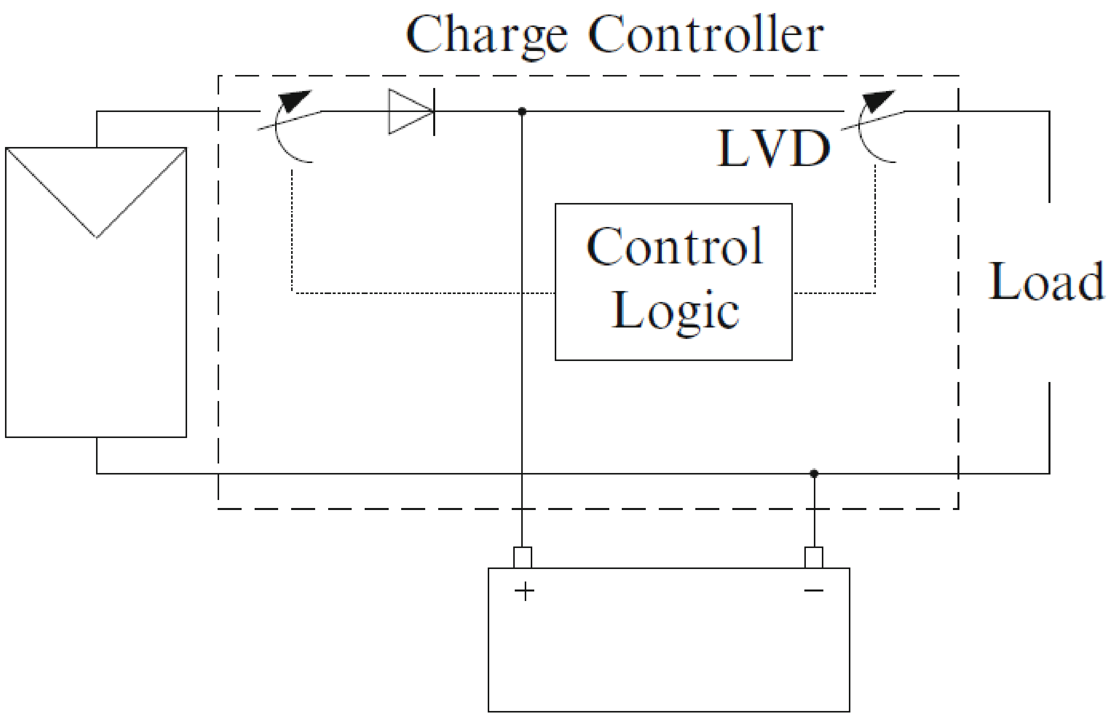
- Rather than controlling current TO the DC bus, a DLC controls the current FROM the DC bus to achieve three-stage charging
- Bulk Stage: chopper duty cycle adjusted so that current to the diversion load does not exceed the load's rated current. (higher Q)
- Absorption Stage: duty cycle is reduced to maintain constant DC bus (battery) voltage at absorption set point (lower Q)
- Float Stage: duty cycle is further reduced to maintain constant DC bus voltage at float set point

Low Voltage Disconnect

- Battery should be disconnected from a load when its state-of-charge becomes too low
- Infer state-of-charge from battery terminal voltage (this is not very accurate under load conditions)
- Inverters and some charge controllers use low voltage disconnect (LVD) to remove load from battery to prevent deep discharge

Low Voltage Disconnect

- Some smaller charge controllers have connections for load
- These usually have LVD capability

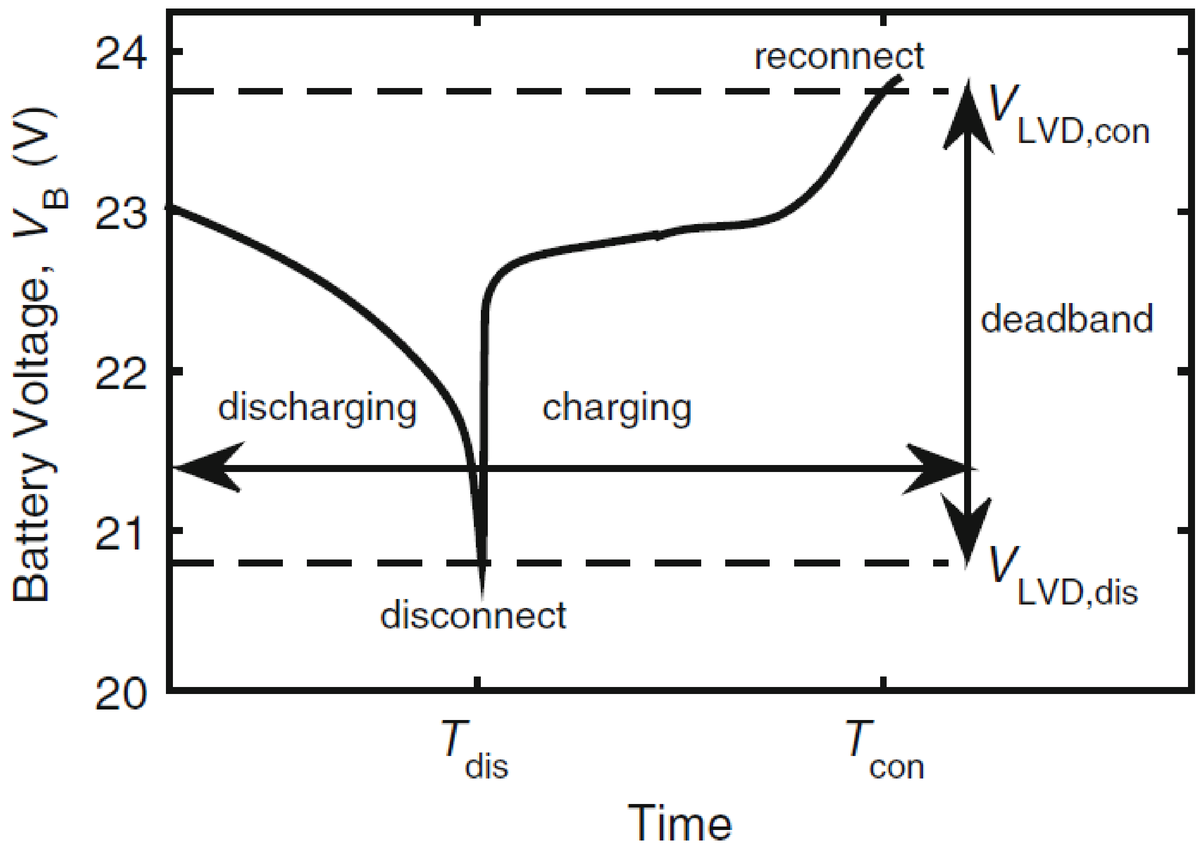


Low Voltage Disconnect Set-Points

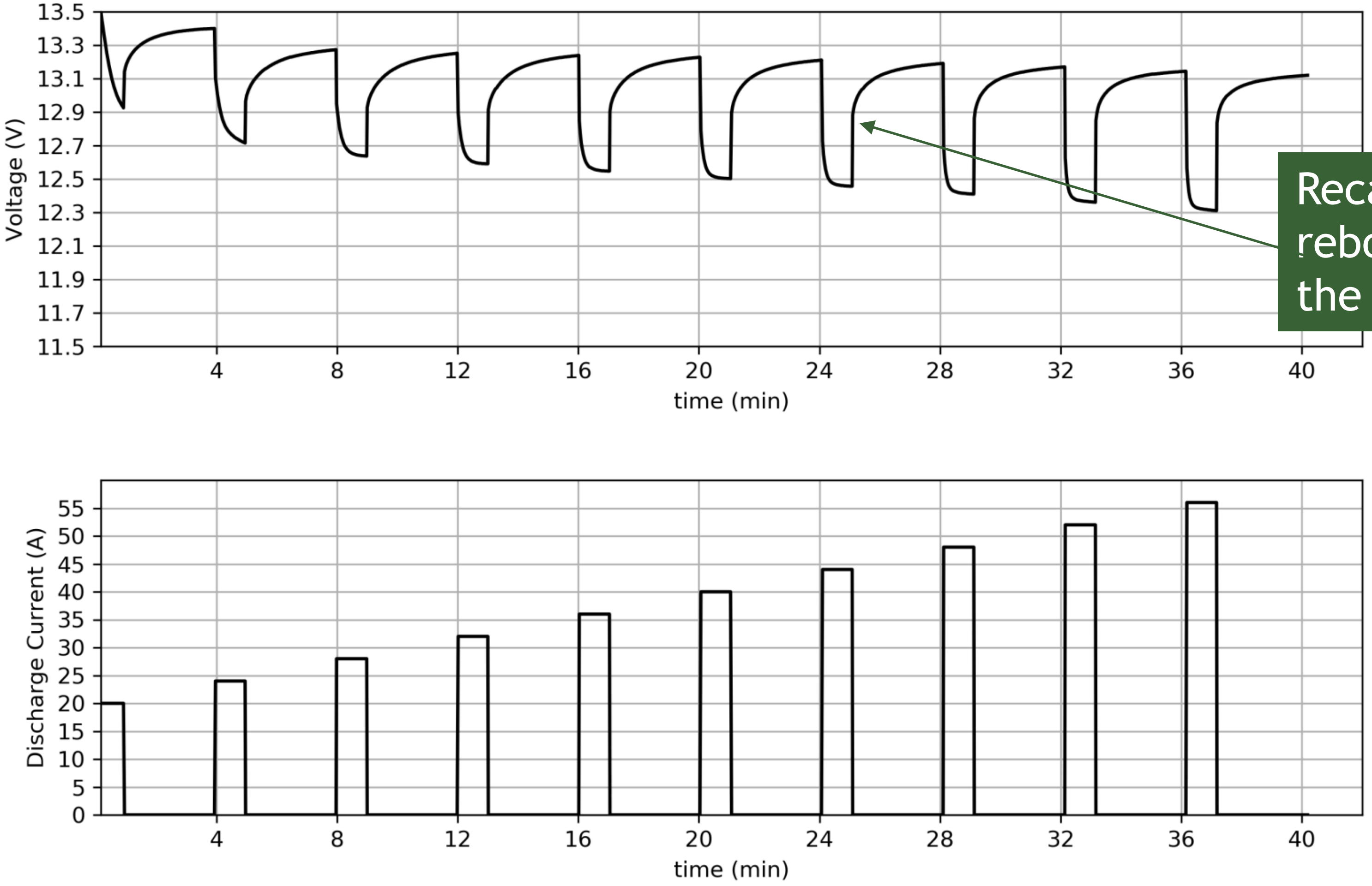
- Disconnect Set-Point: battery terminal voltage at which the load is disconnected
- Re-Connect Set-Point: battery terminal voltage at which the load is re-connected
- Difference between Disconnect and Reconnect set-points is known as the “dead bank”
- Determining these set-points can be difficult since terminal voltage does not directly map to state-of-charge AND battery voltage rebounds when load is disconnected

Low Voltage Disconnect

- $V_{LVD,dis}$: low voltage disconnect set-point
- $V_{LD,con}$: low voltage disconnect reconnect set-point



Why is a dead band needed?



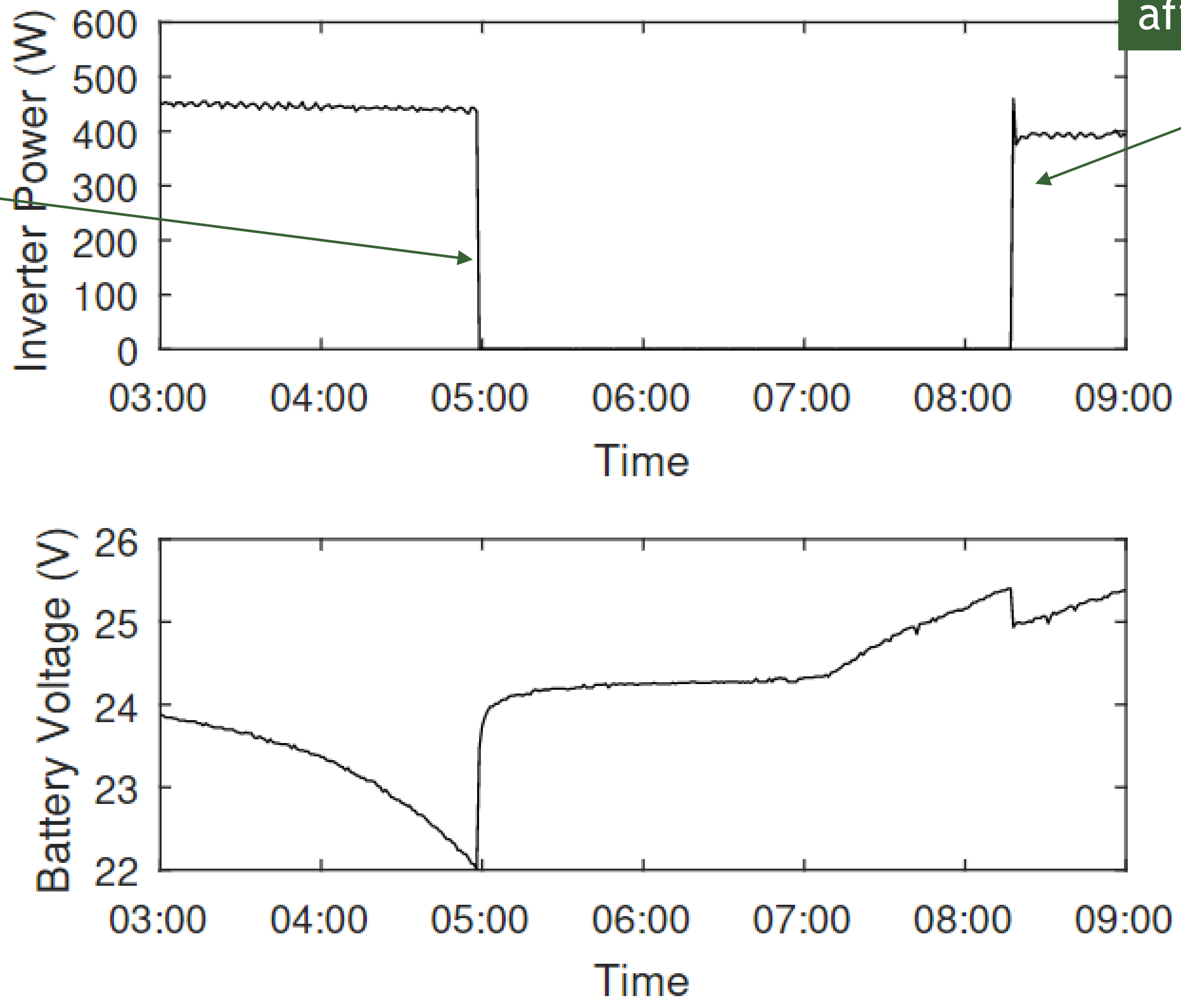
Recall that the voltage rebounds as soon as the load is removed.

Without a large enough Dead band, the LVD can be tricked into thinking the battery has been recharged, and it would connect the load

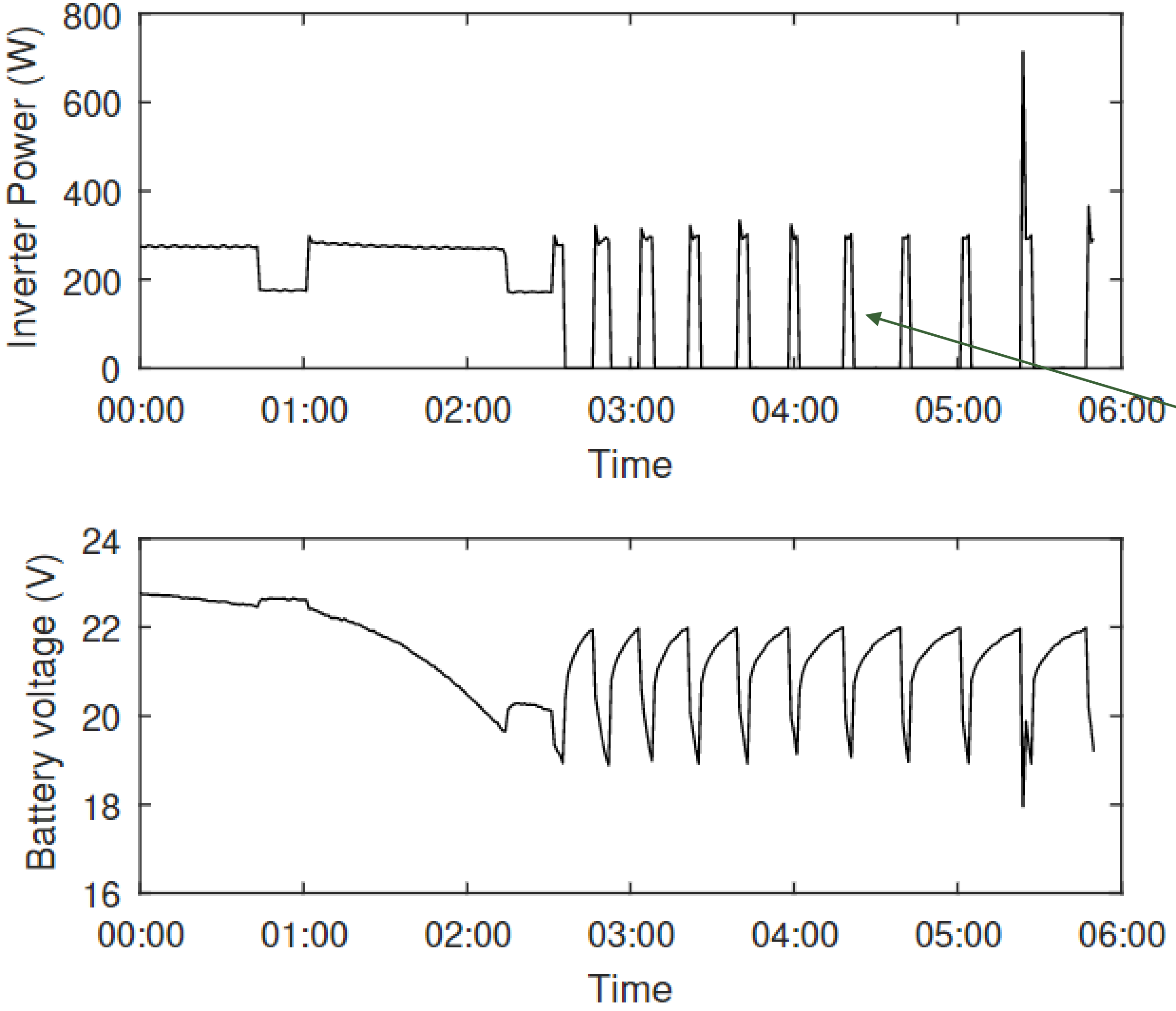
Proper Dead Band Behavior

LVD re-connects only after PV recharges the battery after sunrise

LVD disconnects



Dead Band Not Large Enough



Inverter reconnects and quickly disconnects. (this is early in the morning when there is no PV power)

This oscillation is undesirable and results in a deeply discharged battery

Specification Sheets

Battery bank nominal voltage the charge controller is compatible with

Maximum continuous current provided to the battery (if there is sufficient PV power!)

Rated continuous PV input power (note that the higher the battery bank voltage, the higher the rated power). Some charge controllers will limit the power from the PV array to this level if it this level would otherwise be exceeded

SmartSolar Charge Controller	MPPT 100/30	MPPT 100/50
Battery voltage	12/24 V Auto Select	
Rated charge current	30 A	50 A
Nominal PV power, 12 V 1a,b)	440 W	700 W
Nominal PV power, 24 V 1a,b)	880 W	1400 W
Maximum PV open circuit voltage	100 V	100 V
Max. PV short circuit current 2)	35 A	60 A
Maximum efficiency	98 %	98 %
Self-consumption	12 V: 30 mA 24 V: 20 mA	
Charge voltage 'absorption'	Default setting: 14,4 V / 28,8 V (adjustable)	
Charge voltage 'float'	Default setting: 13,8 V / 27,6 V (adjustable)	
Charge algorithm	multi-stage adaptive	
Temperature compensation	-16 mV / °C resp. -32 mV / °C	
Protection	PV reverse polarity Output short circuit Over temperature	
Operating temperature	-30 to +60 °C (full rated output up to 40 °C)	
Humidity	95 %, non-condensing	
Data communication port	VE.Direct See the data communication white paper on our website	

Specification Sheets

Maximum PV open circuit voltage the charge controller can withstand (limits the number of PV modules in series)

Maximum PV short circuit voltage the charge controller can withstand (limits the number of PV modules (strings) in parallel)

SmartSolar Charge Controller	MPPT 100/30	MPPT 100/50
Battery voltage	12/24 V Auto Select	
Rated charge current	30 A	50 A
Nominal PV power, 12 V 1a,b)	440 W	700 W
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Specification Sheets

- Is there a minimum PV voltage?
- Efficiency of the charge controller is affected by the PV voltage
- Some charge controllers will not function if the PV voltage is below (or not somewhat above) the battery voltage

1b) The PV voltage must exceed Vbat + 5 V for the controller to start.
Thereafter the minimum PV voltage is Vbat + 1 V.

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