13-Off-Grid System Battery Operation and Control

Off-Grid Electrical Systems in Developing Countries, 2nd Edition

Chapter 13

Preface

- These lectures slides are intended to accompany the textbook *Off-Grid Electrical Systems in Developing Countries, 2nd Edition, 2025* written by Dr. Henry Louie and published by SpringerNature
- Additional content, explanations, derivations, examples, problems, errata, and other materials are found in the book and on www.drhenrylouie.com
- To request solutions, explanations, permissions to use author-supplied images, or if you notice an error, please email the author at hlouie@ieee.org
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- If you want to support work in electricity access, consider donating to KiloWatts for Humanity or IEEE Smart Village

Learning Outcomes

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

- ✓Describe the stages in lead-acid and lithium-ion battery charging algorithms and typical current and voltage patterns in each stage
- ✓Interpret battery voltage profiles to assess the general energy balance in off-grid systems
- ✓Formulate and analyze circuit models to determine the DC bus voltage and currents under different operating conditions
- ✓Explain how maximum power point tracking algorithms are able to locate the maximum power point of a photovoltaic (PV) module or array to increase their power production

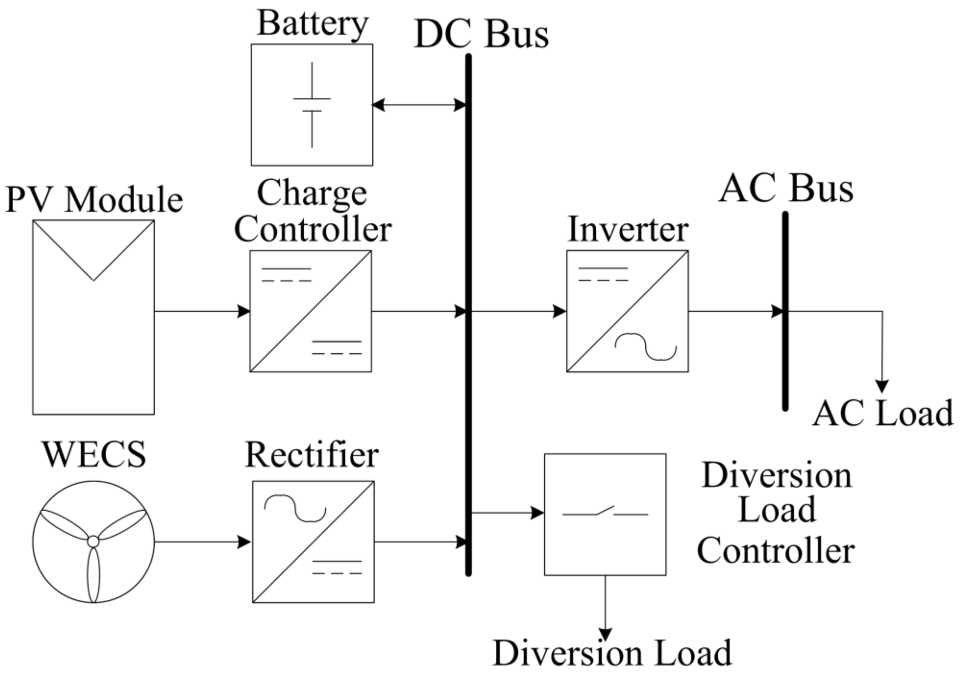
Introduction

- Off-grid system operation: how the components interact with each other to maintain an acceptable and desirable state
- DC bus operation (this lecture): focuses on how the components connected to the DC bus are controlled to maintain an acceptable DC bus voltage
  - emphasis on battery charging and discharging
- AC bus operation (next lecture): how components connected to the AC bus are controlled to maintain an acceptable AC bus voltage frequency and magnitude

DC Bus Components

Off-grid system DC bus components

- battery bank: stores energy, establishes DC bus voltage
- charge controller: prevents PV array from damaging the battery during charging
- rectifier: converts AC to DC
- diversion load controller: diverts power from DC bus to prevent over-charging
- inverter: converts DC to AC



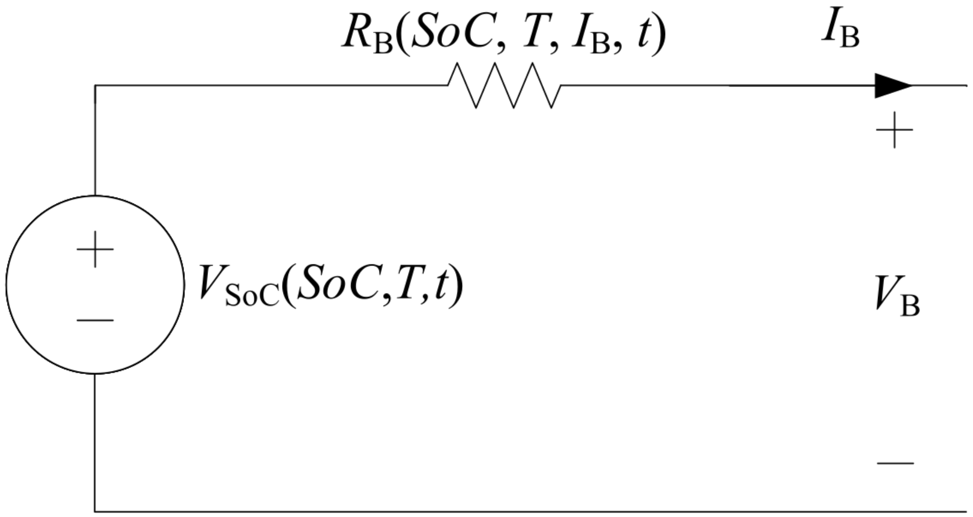
Battery Charging

- DC bus components are managed to prevent over-charging or over-discharging the battery
- Goal: charge and discharge the battery in a way to prolong its lifespan
  - batteries are expensive
  - batteries often the first component to require replacement

(*courtesy H. Louie*)

Battery Circuit Model

- Circuit model of a battery (or battery bank) introduced in Chap. 10
- V_{soc} varies with state of charge (SoC), temperature, and time
- R_B depends on SoC, temperature, time, and magnitude and direction of the battery current (see Chap. 10 for how to interpret R_B)



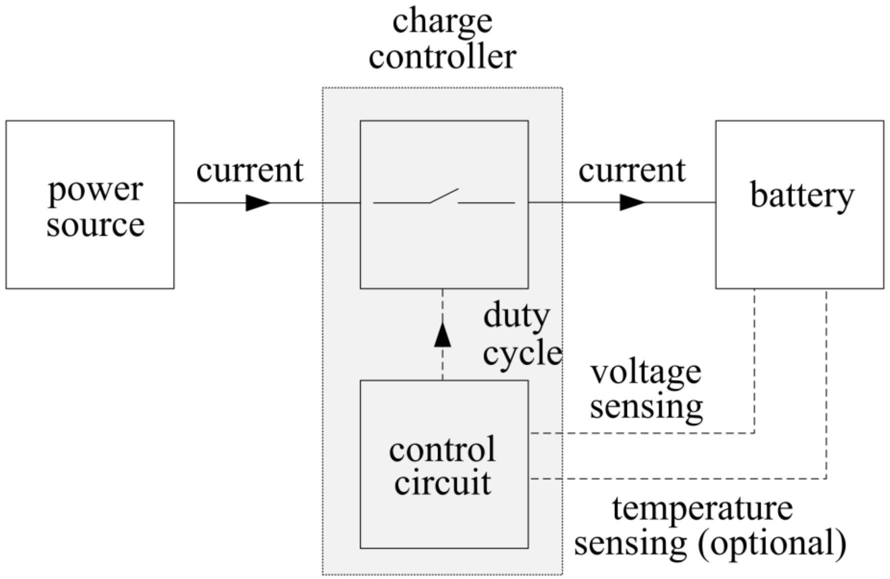
battery voltage V_B depends on V_{SoC} and battery current I_B

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 vs lithium-ion)

Charge Controller

- High quality charge controllers can regulate the current into the battery through Pulse Width Modulation (PWM)
- Battery voltage is measured and duty cycle is adjusted to decrease current to prevent over-charging battery



Lead-Acid Battery Charging

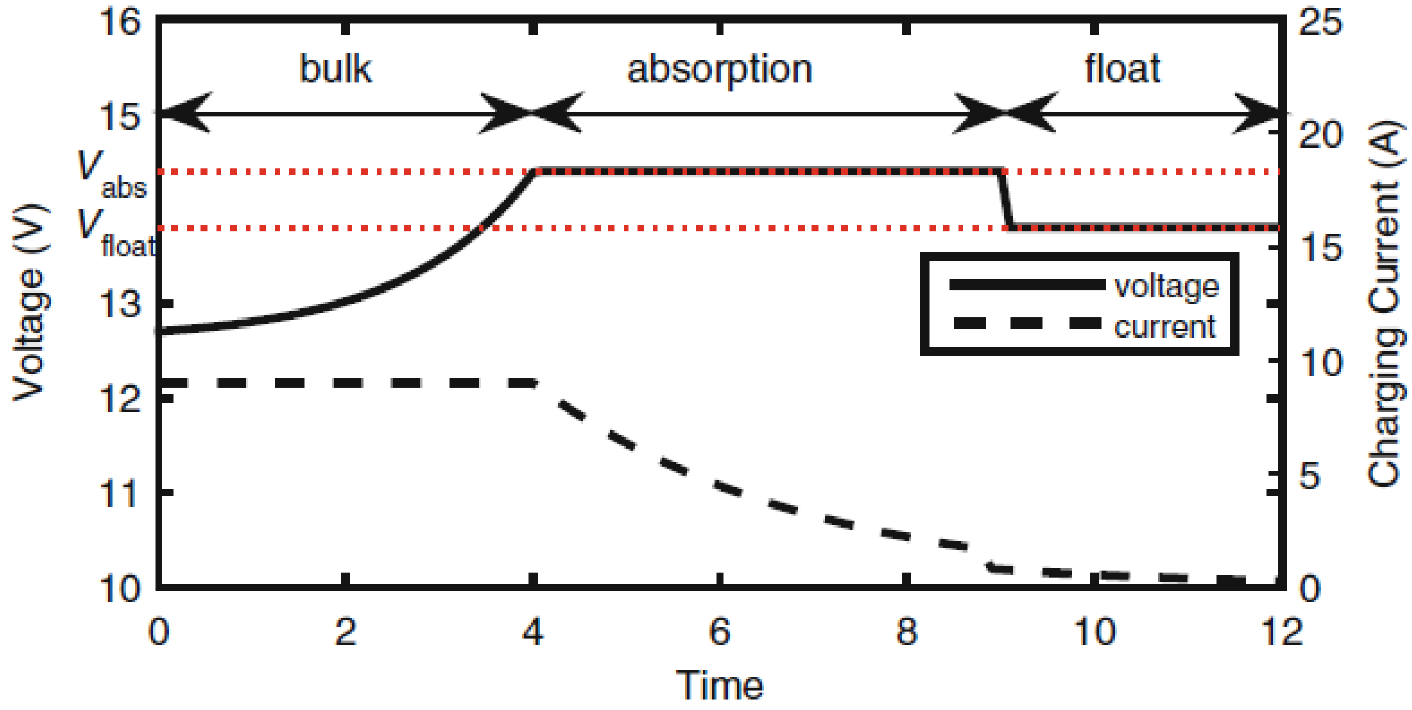
Lead-acid batteries are usually charged following a three-stage approach

Stage 1: Bulk Charge

Stage 2: Absorption Charge

Stage 3: Float Charge

Three-Stage Charging



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”
  - 14.2 V – 14.6 V for a 12 V battery
- Battery state-of-charge is 70-90% at end of Bulk stage

Exercise

Consider a 100 Ah, 12 V AGM lead-acid battery whose open-circuit voltage is 12.45 V. In its present state, the battery resistance is 0.04 Ω. A charge controller is now connected to the battery and begins charging it in its bulk stage.

Compute the maximum bulk stage charge current if the battery manufacturer recommends a charge current no greater than 20% of its C_{20} capacity.

Exercise

Consider a 100 Ah, 12 V AGM lead-acid battery whose open-circuit voltage is 12.45 V. In its present state, the battery resistance is 0.04 Ω. A charge controller is now connected to the battery and begins charging it in its bulk stage. Compute the maximum bulk stage charge current if the battery manufacturer recommends a charge current no greater than 20% of its C_{20} capacity.

The capacity is given as 100 Ah, which we assume is the 20-hour (C_{20}) capacity. So, the bulk stage current should not exceed 0.20 x 100 = 20 A.

Stage 2: Absorption Charge

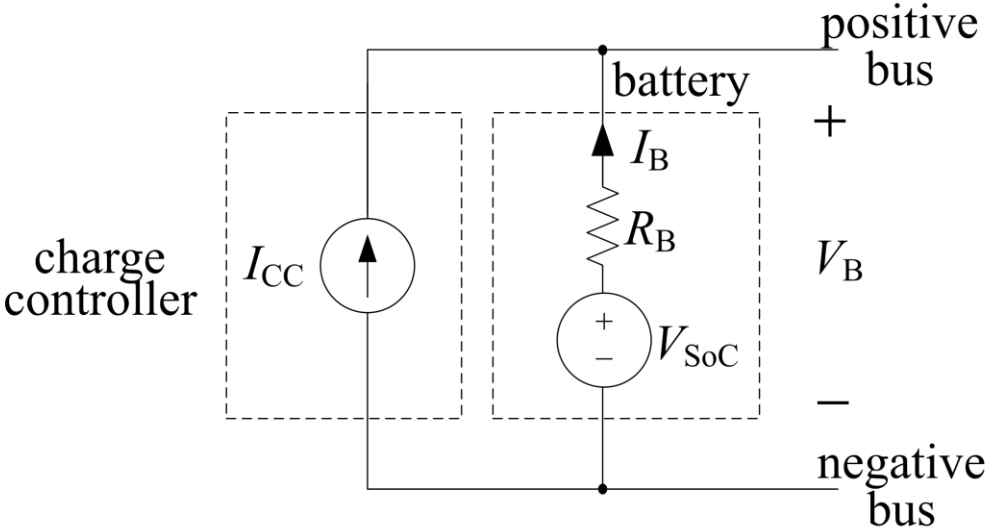
- Carefully charge the battery so that its voltage does not exceed the absorption charge set-point (14.2 to 14.4 for 12 V nominal battery)
- Voltage is regulated to be approximately constant
- Current will decrease during this period as the battery state-of-charge increases
- Stage ends either after 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, or after the current becomes small enough
- 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 12 V 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

Circuit Model

- How do we determine the current from each component on the DC bus for a given charging stage?
- Start with simple model of charge controller and battery
- Add components one at a time



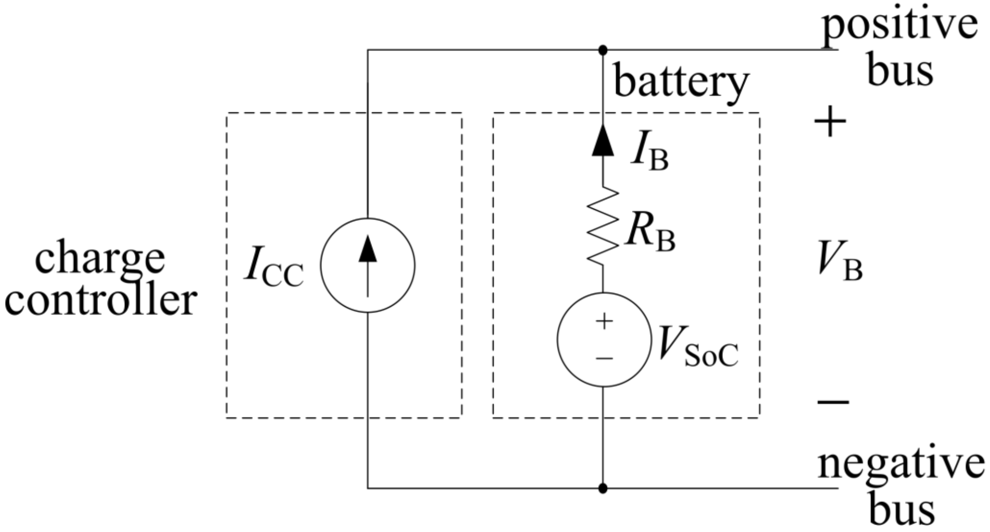
Circuit Model

- KCL at the positive bus

$$I_{CC} = -I_B$$

- KVL

$$V_B = V_{SoC} - I_B R_B = V_{SoC} + I_{CC} R_B$$

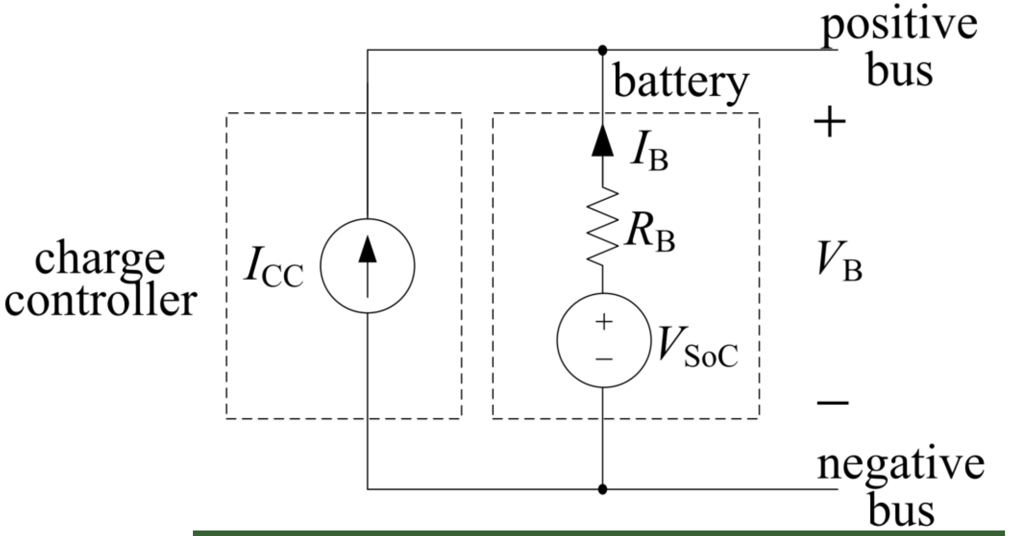


Circuit Model: Bulk Stage

- Let I_{CC}^{*} be the current setpoint of the charge controller
- Battery voltage during bulk stage (assuming charge controller can supply I_{CC}^{*})

$$V_B = V_{SoC} + I_{CC}^{*} R_B$$

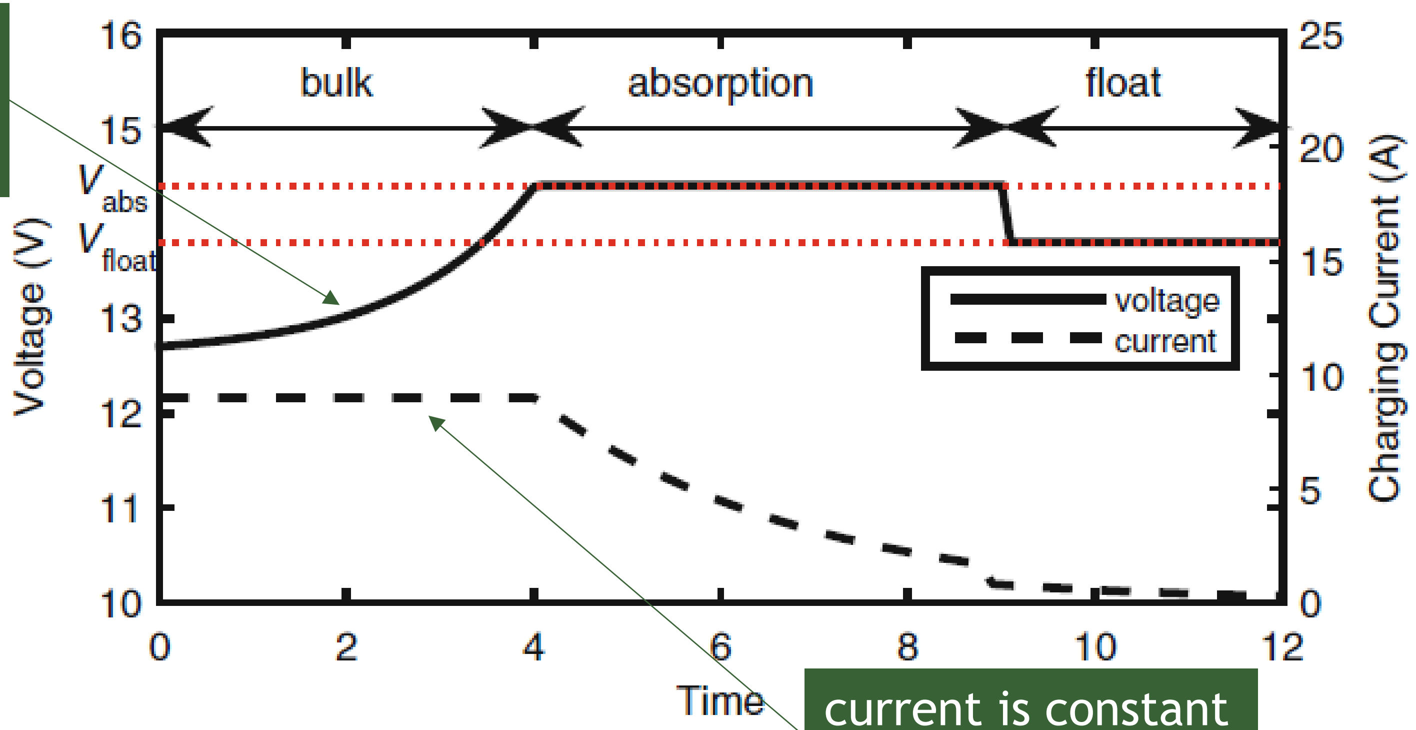
- As charging progresses, V_{SoC} increases and R_B changes
  - battery voltage V_B increases



charge controller can only measure V_B, not V_{SoC}

Three-Stage Charging

battery voltage increases during bulk stage



current is constant during bulk stage

Exercise

Consider a 100 Ah, 12 V AGM lead-acid battery whose open-circuit voltage is 12.45 V. In its present state, the battery resistance is 0.04 Ω. A charge controller is now connected to the battery and begins charging it in its bulk stage at a current of 20 A.

What is the battery voltage when the bulk stage starts?

Exercise

Consider a 100 Ah, 12 V AGM lead-acid battery whose open-circuit voltage is 12.45 V. In its present state, the battery resistance is 0.04 Ω. A charge controller is now connected to the battery and begins charging it in its bulk stage at a current of 20 A.

What is the battery voltage when the bulk stage starts?

$V_B = V_{SoC} - I_B R_B = V_{SOC} + I_{CC} R_B = 12.45 + 20 \times 0.04 = 13.25$ V

note that V_{SOC} is equal to the open circuit voltage

Exercise

Consider the same 100 Ah, 12 V AGM lead-acid battery. Thirty minutes into the bulk stage, the V_{SOC} rises to 12.65 V, and the battery resistance changes to 0.05 Ω. What is the battery voltage now?

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$$V_B = V_{SOC} + I_{CC}R_B = 12.65 + 20 \times 0.05 = 13.65 \text{ V}$$

the battery voltage V_B rises during the bulk stage

Circuit Model: Absorption Stage

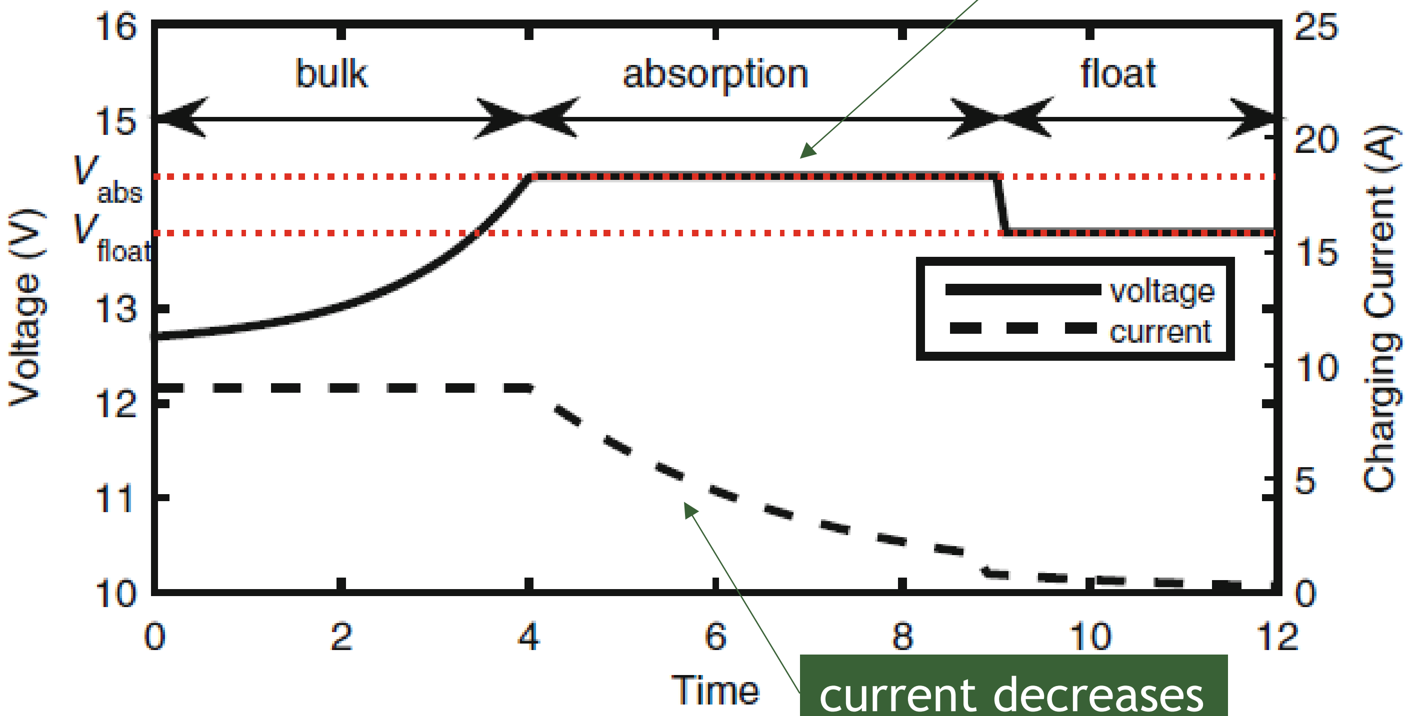
- Voltage rise cannot continue indefinitely without risking damage to battery
- Charge controller current adjusted (decreased) to avoid voltage increasing past absorption voltage setpoint V_{abs} (~2.40 V/cell)
- Charge controller current required for V_{B} = V_{abs} is

$$V_{\text{abs}} = V_{\text{B}} = V_{\text{SoC}} + I_{\text{CC}} R_{\text{B}}$$

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

Three-Stage Charging

battery voltage kept constant during absorption stage



current decreases

Exercise

A battery is connected to solar panel through a charge controller and is being charged in the absorption stage. Let V_{SoC} = 12.8 V and R_{B} = 0.1 Ω. Compute the current that should be provided to the battery to achieve the absorption voltage set-point of 14.4 V.

Exercise

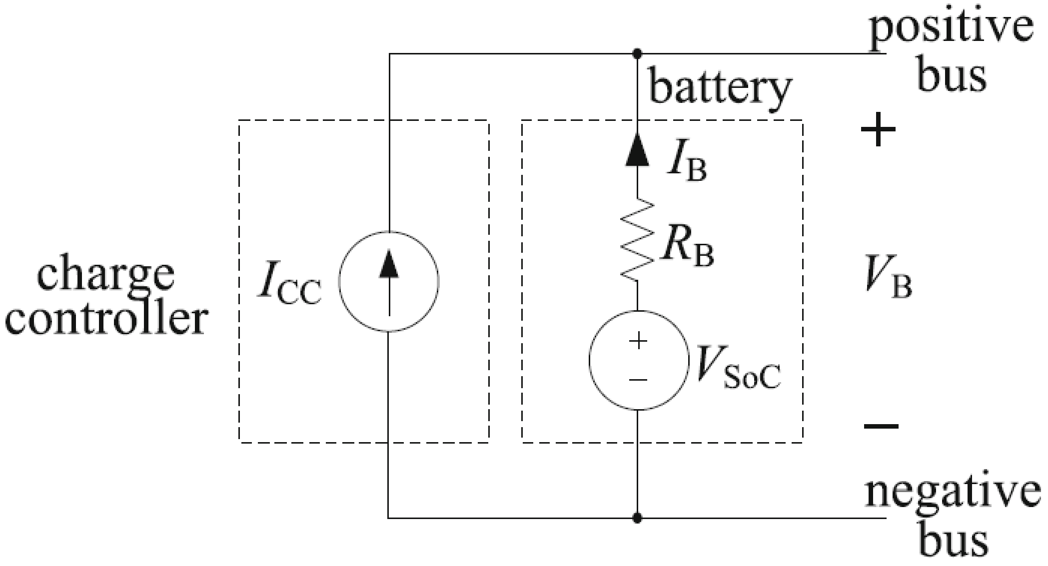
$$V_B = 14.4 \text{ V}$$

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

$$\frac{V_B - V_{SoC}}{R_B} = -I_B$$

$$\frac{-V_B + V_{SoC}}{R_B} = I_B$$

$$\frac{-14.4 + 12.8}{0.1} = I_B = -16 \text{ A (16 A of charging)}$$



Exercise

Consider the same battery as before. The V_{SoC} has risen to 12.95 V and R_{B} = 0.2 Ω. Compute the current that should be provided to the battery to achieve the absorption voltage set-point of 14.4 V.

Exercise

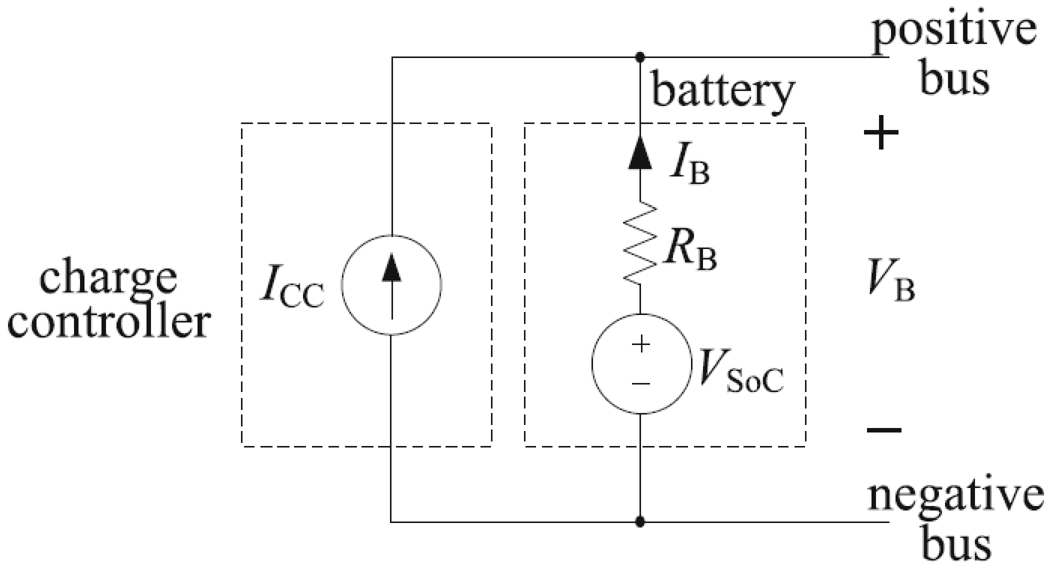
$$V_B = 14.4 \text{ V}$$

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

$$\frac{V_B - V_{SoC}}{R_B} = -I_B$$

$$\frac{-V_B + V_{SoC}}{R_B} = I_B$$

$$\frac{-14.4 + 12.95}{0.2} = I_B = -7.5 \text{ A (7.5 A of charging)}$$



the battery current decreases as the absorption stage progresses

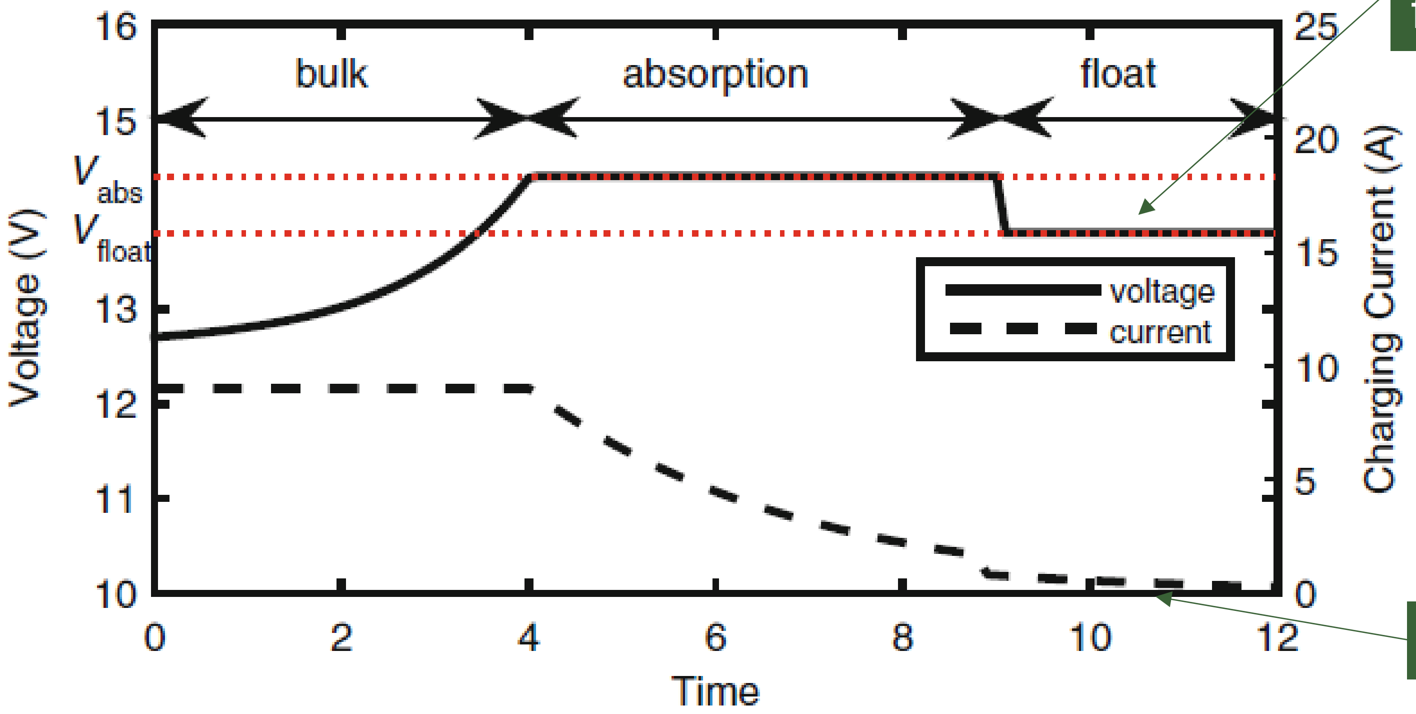
Circuit Model: Float Stage

- Elevated voltage of the absorption stage can harm battery if it lasts for extended periods
  - battery approx. 100% SoC at end of absorption stage
- Voltage is reduced to the float setpoint V_{float} (~2.23 V/cell)
  - current controlled (reduced) to keep voltage at setpoint value
  - goal is offset losses and keep battery fully charged

$$V_{\text{float}} = V_{\text{B}} = V_{\text{SoC}} + I_{\text{CC}} R_{\text{B}}$$

$$I_{\text{CC}} = \frac{V_{\text{float}} - V_{\text{SoC}}}{R_{\text{B}}}$$ charge controller current required to maintain float voltage

Three-Stage Charging



battery voltage kept constant during float stage

current decreases

Exercise

At the end of the absorption stage, a 12 V battery has a terminal voltage of 14.4 V and is being charged by 2.5 A. The V_{SoC} is 13.15V. Determine how much current is drawn by the battery to achieve the float voltage set-point of 13.8 V? Assume the battery resistance is 0.5 Ω.

Exercise

At the end of the absorption stage, a 12 V battery has a terminal voltage of 14.4 V and is being charged by 2.5 A. The V_{SoC} is 13.15V. Determine how much current is drawn by the battery to achieve the float voltage set-point of 13.8 V? Assume the battery resistance is 0.5 Ω.

$$V_B = 13.8 \text{ V}$$

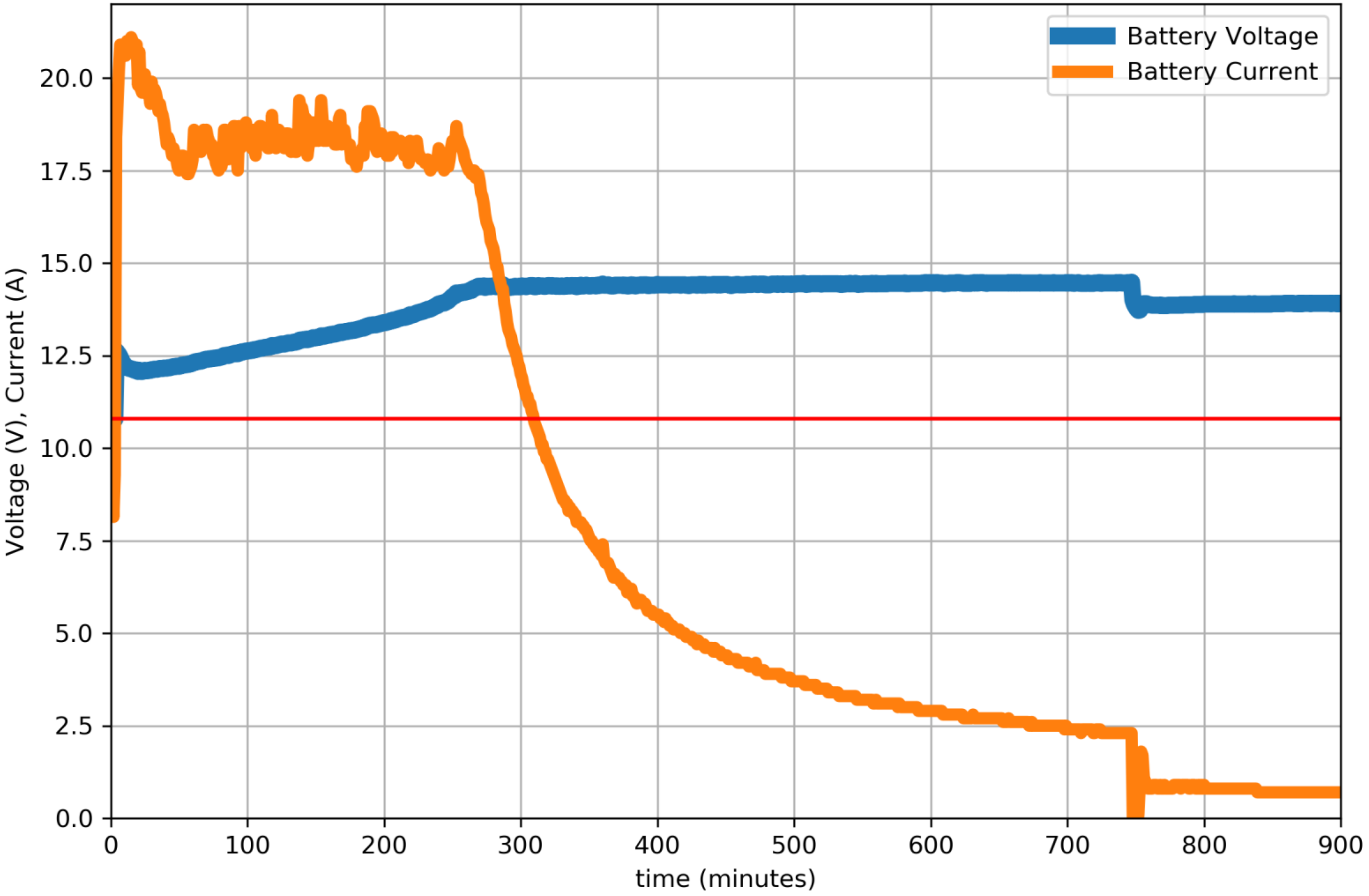
$$V_B = V_{SoC} - I_B R_B$$

$$\frac{-V_B + V_{SoC}}{R_B} = I_B$$

$$\frac{-13.8 + 13.15}{0.5} = I_B = -1.3 \text{ A (1.3 A of charging)}$$

the current drops once float stage is entered

Actual Three-stage Charging



Input current limit by charger: 20A

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

(12V, 100 Ah, AGM Battery)

Power-Constrained Charging

- Charger/charge controller may be supplied by a variable generation source such as WECS or PV array
- Current output might be limited by generation source (e.g. clouds) in which case

efficiency of
charge controller

maximum power input to the charge
controller at a particular moment

maximum current that can
be provided by charge
controller at
a particular moment

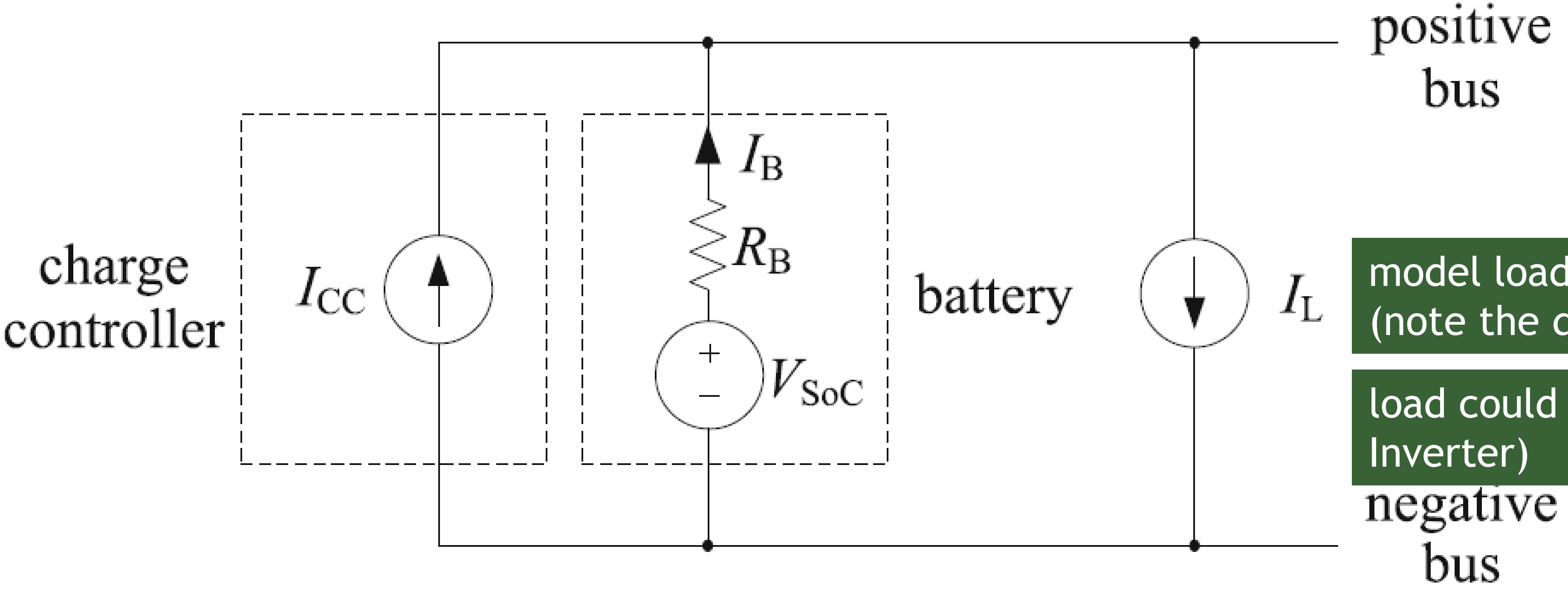
$$I_{\mathrm{CC}}^{\max} = \min\left\{ I_{\mathrm{CC}}^{*}, \frac{\eta_{\mathrm{CC}} P_{\mathrm{CC,in}}^{\max}}{V_{\mathrm{B}}} \right\}$$

charge controller maximum current
setpoint

Battery Charger Circuit Analysis

- Now consider realistic off-grid architectures with additional components connected to the DC bus
- Basic approach
  - model generation sources and loads as current sources
  - apply KCL and KVL to understand voltage and current relationship at different charging stages

Charging with Load



model load as current source (note the direction)

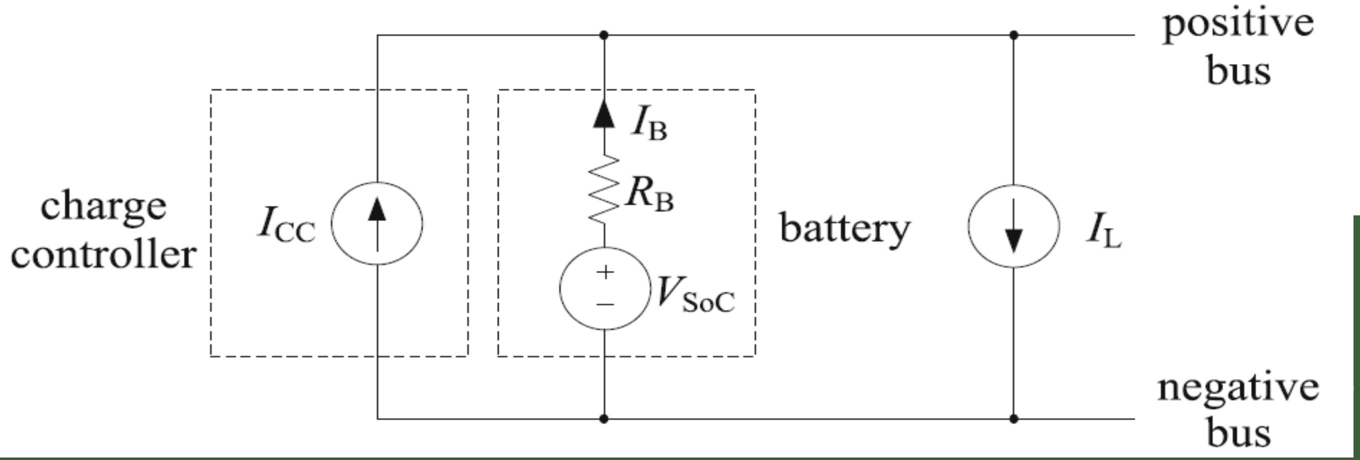
load could be DC or AC (modeling Inverter)

Charging with Load

- Load diverts a portion of the charge controller current from the battery
- From KCL at the positive bus:

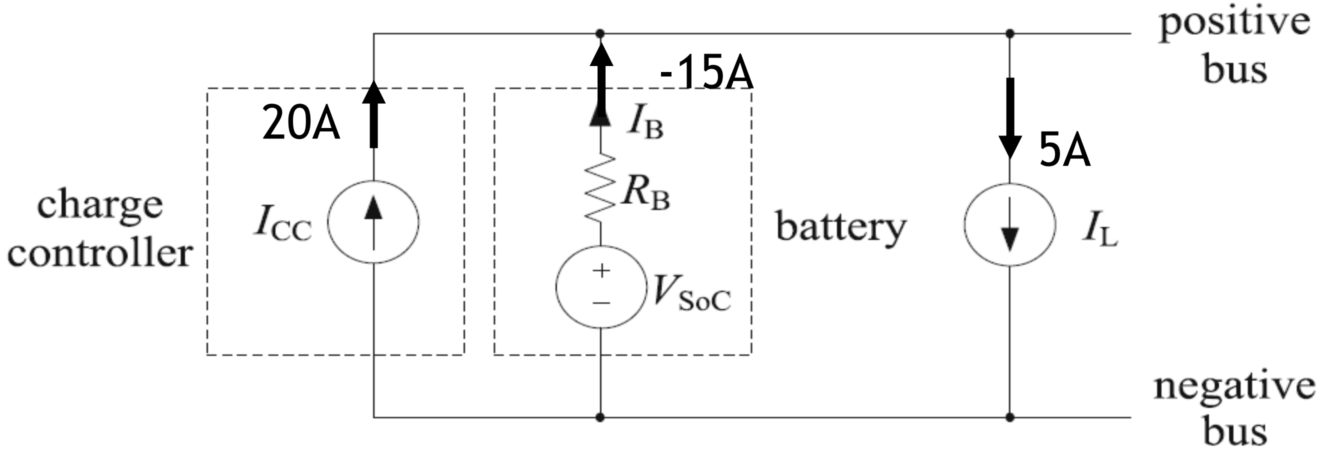
$$I_{cc} + I_B = I_L$$

$$V_B = V_{SoC} - I_B R_B = V_{SOC} + (I_{CC} - I_L)R_B$$



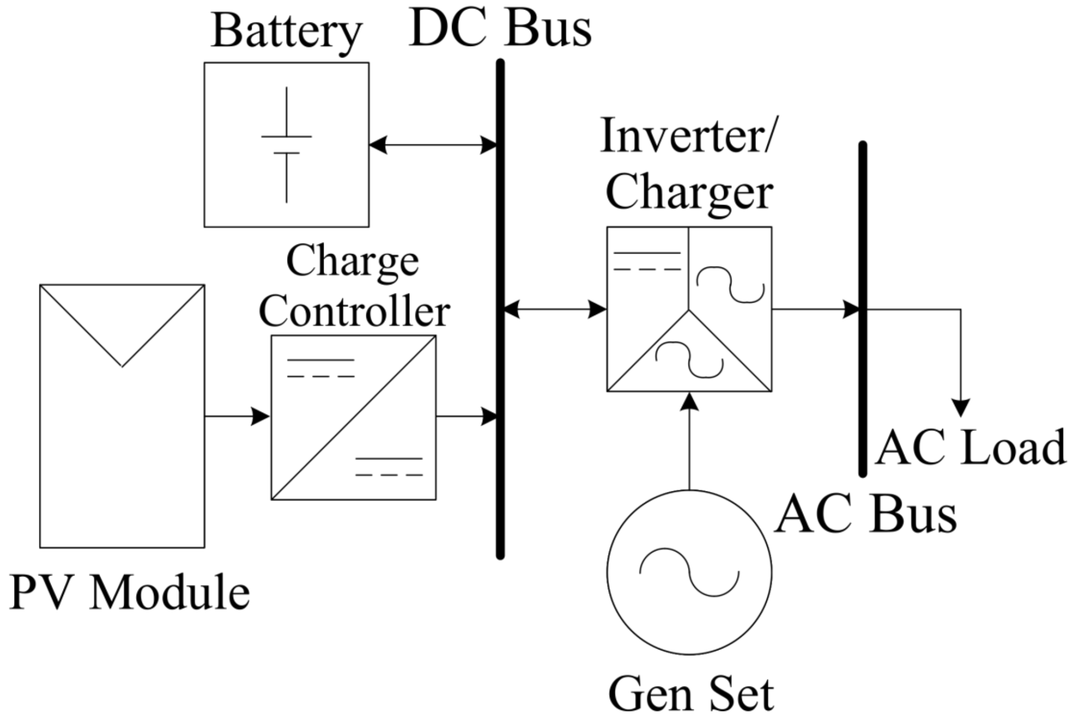
Charging with Load

A charge controller providing 20 A of current to the DC bus where there is a load drawing 5 A, will only provide 15 A to the battery and hence the battery will charge less quickly



Charge Controller with Additional Generation Sources

- Hybrid systems have other energy conversion systems capable of supplying power to the DC bus
- Model them as a generic generation source connected to the DC bus
- Charge controller cannot directly control this generation source's output



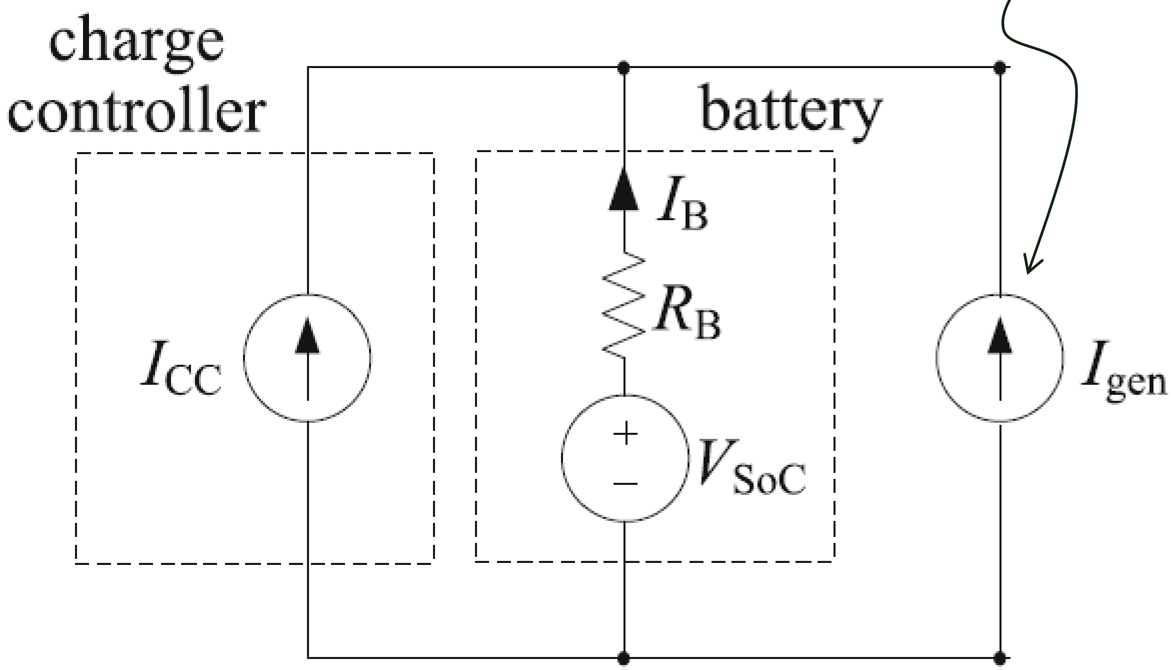
Charge Controller with Additional Generation Sources

could be a WECS, MHP, or gen set

- Generator is modeled as a current source
- Current direction is the same as the charge controller
- From KCL at the positive bus:

$I_{cc} + I_B + I_{gen} = 0$

$V_B = V_{SoC} - I_B R_B = V_{SOC} + (I_{CC} + I_{gen}) R_B$



Exercise

A battery is connected to solar panel through a charge controller and is being charged in the absorption stage. A WECS is connected to the DC bus through a rectifier. The WECS outputs 5 A. The V_{SoC} is 12.95 V and R_{B} = 0.2 Ω. Compute the current required by the charge controller to maintain an absorption voltage setpoint of 14.4 V.

Exercise

$$V_B = 14.4 \text{ V}$$

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

$$\frac{V_B - V_{SoC}}{R_B} = -I_B$$

$$\frac{-V_B + V_{SoC}}{R_B} = I_B$$

$$\frac{-14.4 + 12.95}{0.2} = I_B = -7.5 \text{ A}$$

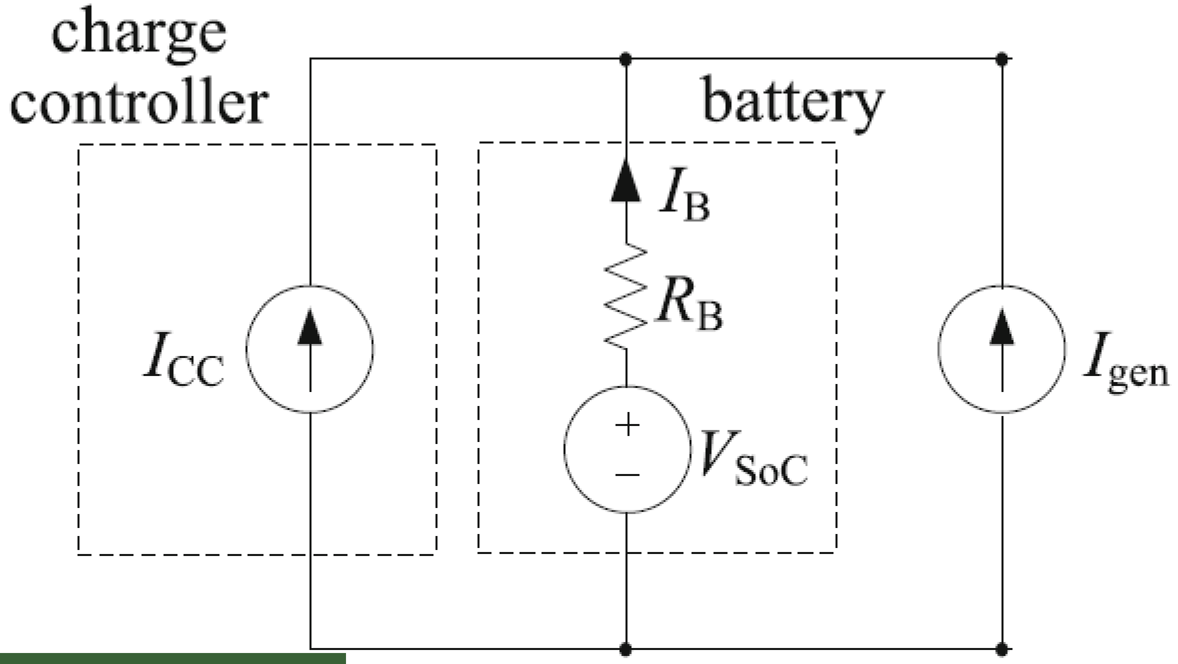
$$I_{CC} + I_{gen} = -I_B$$

$$I_{CC} + 5 = 7.5$$

$$I_{CC} = 2.5\text{A}$$

this is the current from the charge controller without the WECS

charge controller only needs to supply 2.5 A



Exercise

A battery is connected to solar panel through a charge controller and is being charged in the absorption stage. A wind turbine is connected to the DC bus through a rectifier. The wind turbine outputs 10 A. The V_{SoC} is 12.95 V and R_B = 0.2 Ω. Compute the current required by the charge controller to maintain an absorption voltage setpoint of 14.4 V.

Exercise

$$V_B = 14.4\text{ V}$$

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

$$\frac{V_B - V_{SoC}}{R_B} = -I_B$$

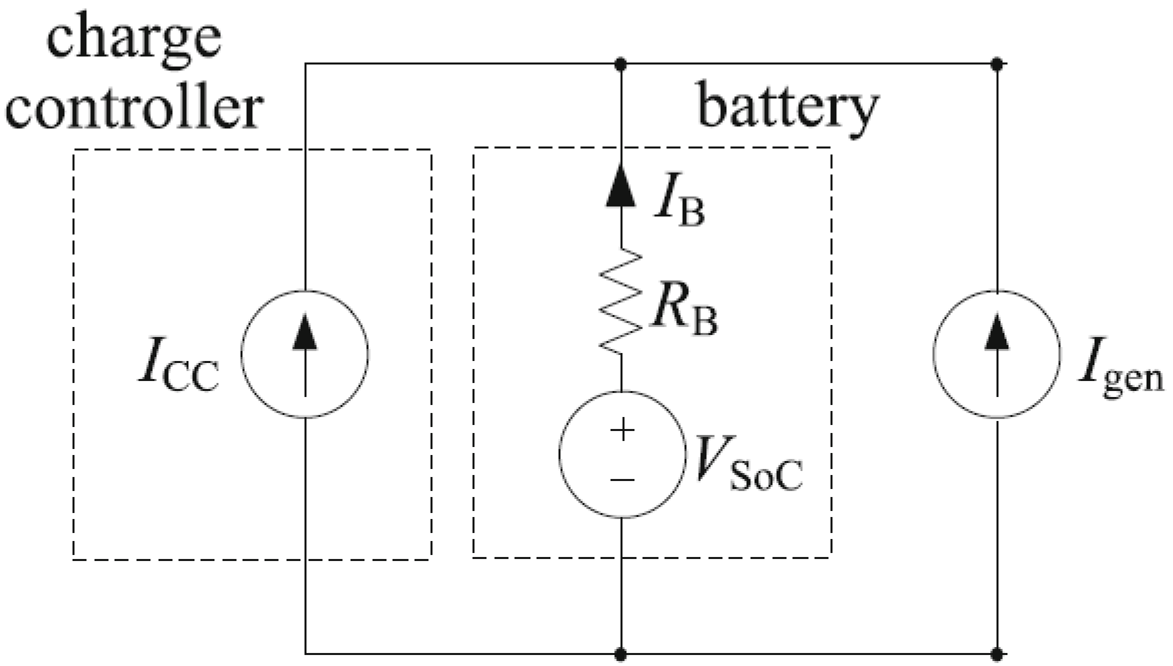
$$\frac{-V_B + V_{SoC}}{R_B} = I_B$$

$$\frac{-14.4 + 12.95}{0.2} = I_B = -7.5\text{ A}$$

$$I_{CC} + I_{gen} = -I_B$$

$$I_{CC} + 10 = 7.5$$

$$I_{CC} = -2.5\text{A}$$



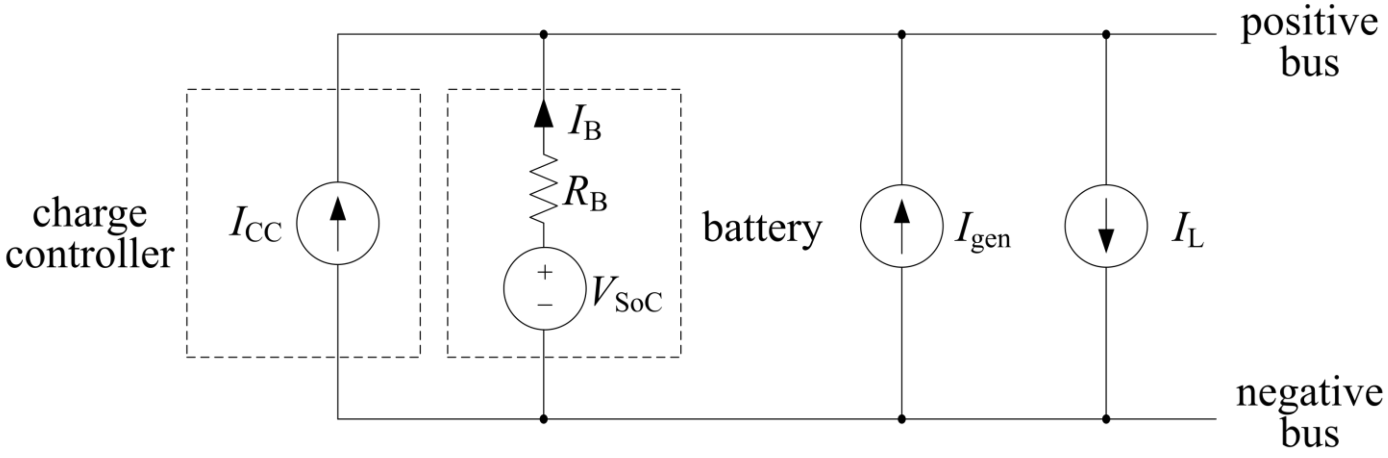
This is a problem. The charge controller cannot supply negative current! The charge controller will reduce its current to 0 A, but the battery voltage will not be 14.4 V (it will be 12.95 + 10x0.20 = 14.95 V, an over-voltage!)

Battery Charger Circuit Analysis: Load and Generation

Battery current and voltage

$$I_B = -I_{CC} - I_{gen} + I_L$$

$$V_B = V_{SoC} - I_B R_B = V_{SoC} - \left(-I_{CC} - I_{gen} + I_L\right) R_B$$



Circuit Analysis: Bulk Stage

- Charge controller current is set to its maximum value (either its set point or the maximum current it can provide given its input power)
- Battery current and voltage found from

$$I_{\text{B}} = -I_{\text{CC}}^{\text{max}} - I_{\text{gen}} + I_{\text{L}}$$

$$V_{\text{B}} = V_{\text{SoC}} - I_{\text{B}} R_{\text{B}} = V_{\text{SoC}} - \left(-I_{\text{CC}}^{\text{max}} - I_{\text{gen}} + I_{\text{L}}\right) R_{\text{B}}$$

recall: $I_{\text{CC}}^{\text{max}} = \min\left\{ I_{\text{CC}}^{*}, \dfrac{\eta_{\text{CC}} P_{\text{CC,in}}^{\text{max}}}{V_{\text{B}}} \right\}$

Circuit Analysis: Absorption Stage

Charge controller balances changes in net load and generation to maintain battery voltage at the absorption setpoint

targeted charge controller current

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

$$\hat{I}_{\mathrm{CC}} = \frac{V_{\mathrm{abs}} - V_{\mathrm{SoC}}}{R_{\mathrm{B}}} + I_{\mathrm{L}} - I_{\mathrm{gen}}$$

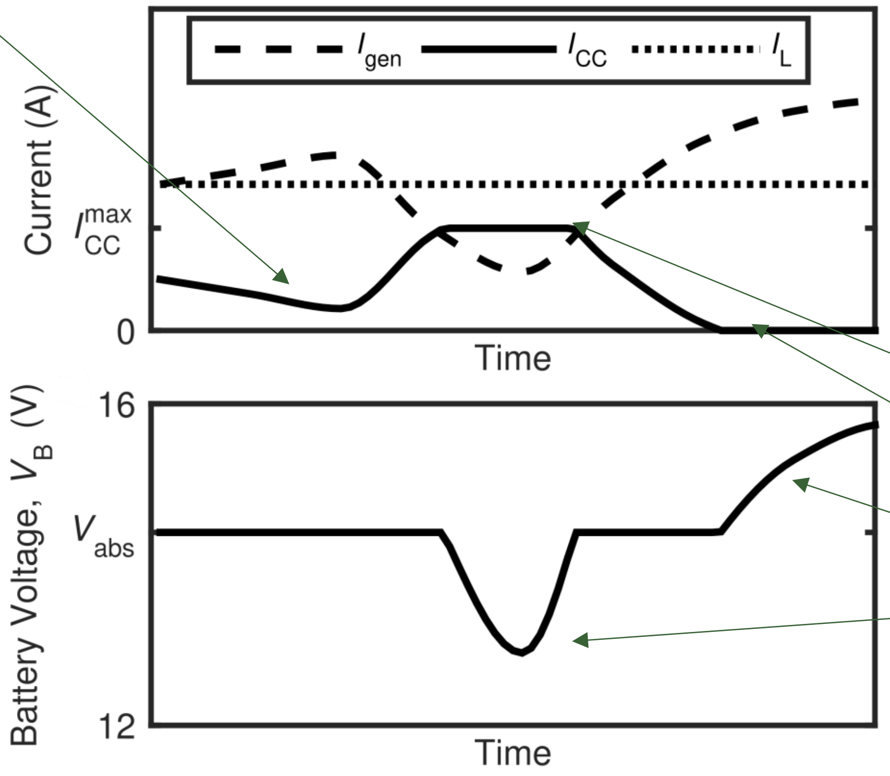
Circuit Analysis: Absorption Stage

- Possible for targeted charge controller current to beyond its capabilities (too high or negative) as was shown in the past Exercise
- Battery voltage will not be at absorption setpoint (too high or too low)

$$I_{CC} = \begin{cases} 0 : \hat{I}_{CC} \leq 0 \quad \text{(over-voltage)} \\ \hat{I}_{CC} : 0 < \hat{I}_{CC} < I_{CC}^{max} \\ I_{CC}^{max} : \hat{I}_{CC} \geq I_{CC}^{max} \quad \text{(under-voltage)} \end{cases}$$

Circuit Analysis: Absorption Stage

charge controller current balances change in generation



when charge controller current targeted value exceeds its limits (high or low), battery voltage deviates from absorption setpoint

Circuit Analysis: Float Stage

Analysis is similar to absorption stage

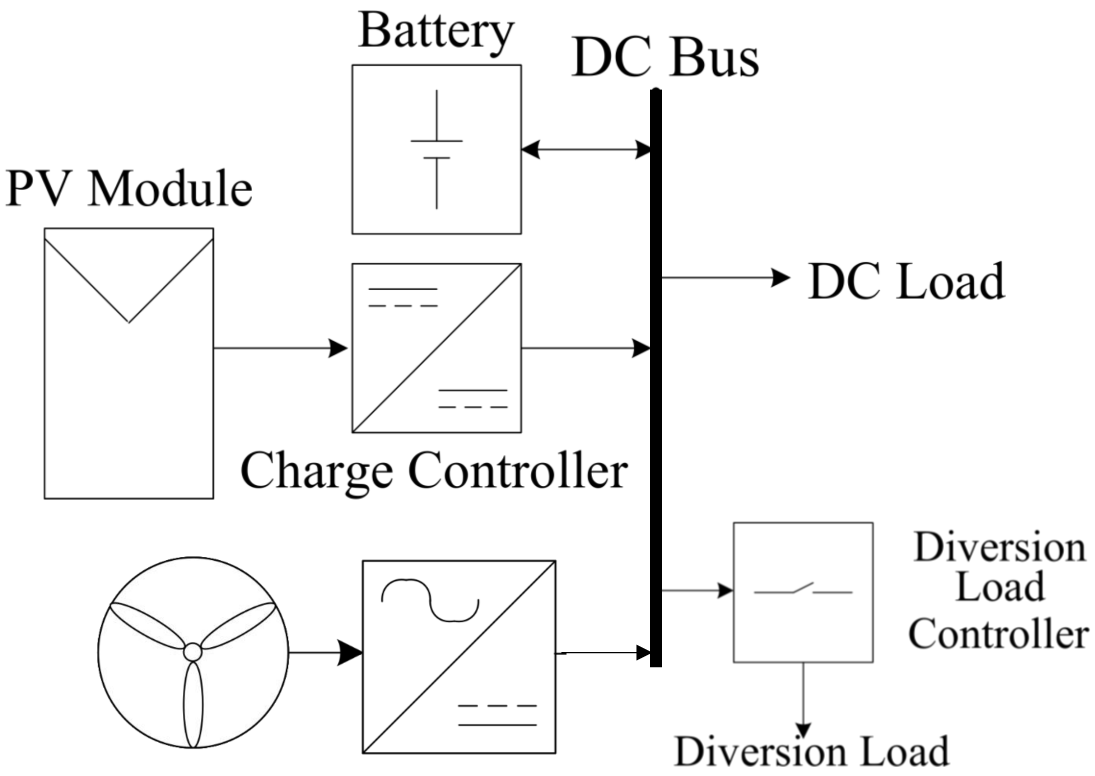
$$V_{\mathrm{B}} = V_{\mathrm{float}}$$

$$\hat{I}_{\mathrm{CC}} = \frac{V_{\mathrm{float}} - V_{\mathrm{SoC}}}{R_{\mathrm{B}}} + I_{\mathrm{L}} - I_{\mathrm{gen}}$$

$$I_{\mathrm{CC}} = \begin{cases} 0 : \hat{I}_{\mathrm{CC}} \leq 0 \quad \text{(over-voltage)} \\ \hat{I}_{\mathrm{CC}} : 0 < \hat{I}_{\mathrm{CC}} < I_{\mathrm{CC}}^{\mathrm{max}} \\ I_{\mathrm{CC}}^{\mathrm{max}} : \hat{I}_{\mathrm{CC}} \geq I_{\mathrm{CC}}^{\mathrm{max}} \quad \text{(under-voltage)} \end{cases}$$

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 battery

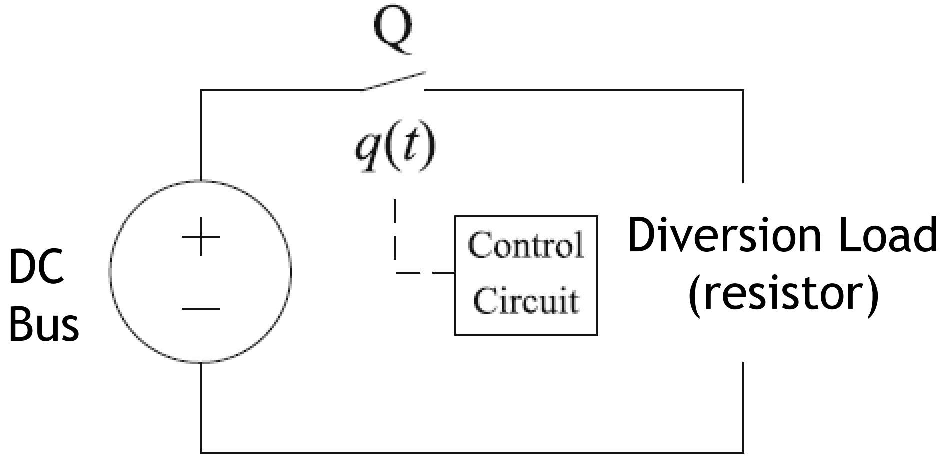


Diversion Load Controller (DLC)

- When $\hat{I}_{cc}$ is negative, it means that a current sink is needed to maintain absorption (or float) setpoint, otherwise an over-voltage will occur
  - charge controllers can only supply power
  - situation occurs with WECS and some MHP
- Solution: add a controllable current sink
  - diversion load

Recall Diversion Load Controller (DLC)

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

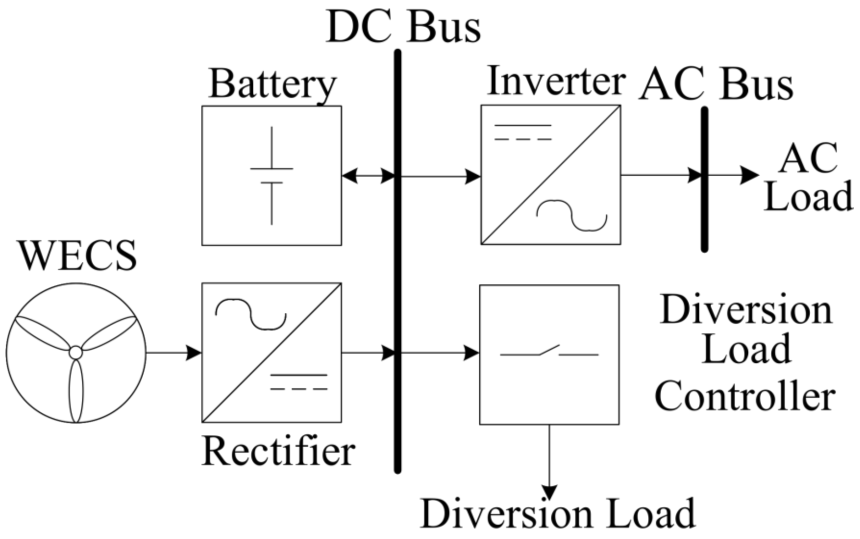


Diversion Load Controller

- 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. (lower/zero Q)
- Absorption Stage: duty cycle is reduced to maintain constant DC bus (battery) voltage at absorption set point (higher Q)
- Float Stage: duty cycle is further reduced to maintain constant DC bus voltage at float set point

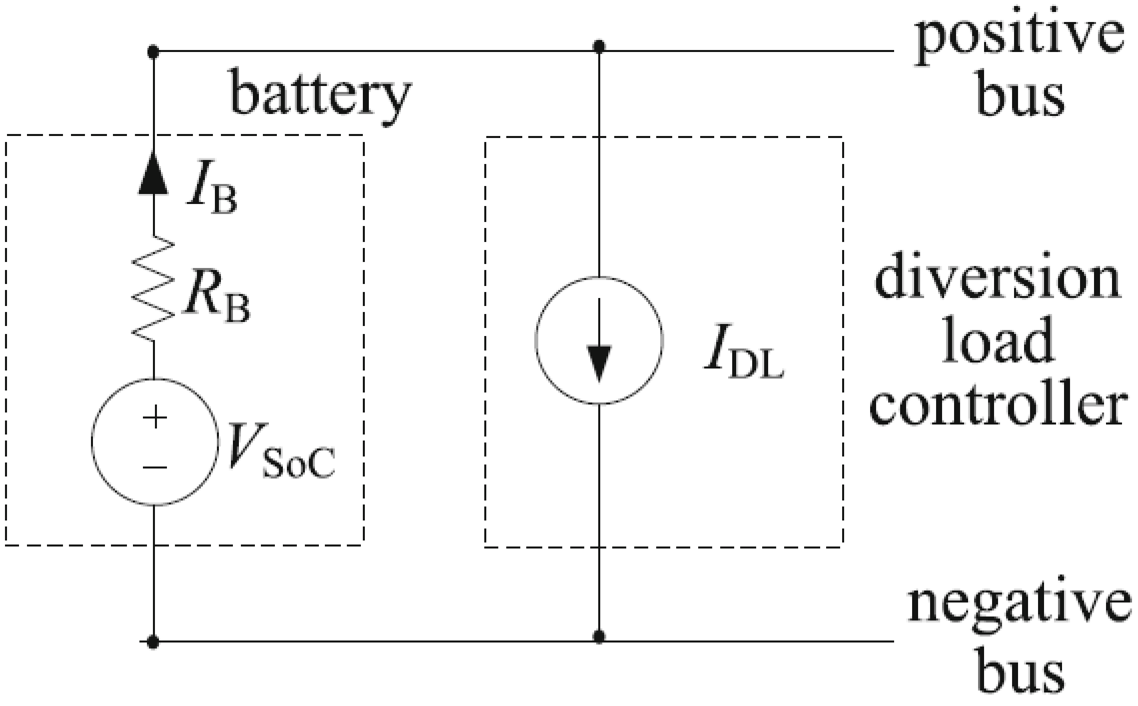
Diversion Load Controller

Diversion load controllers do not need a charge controller



DC Bus with Diversion Load Controller

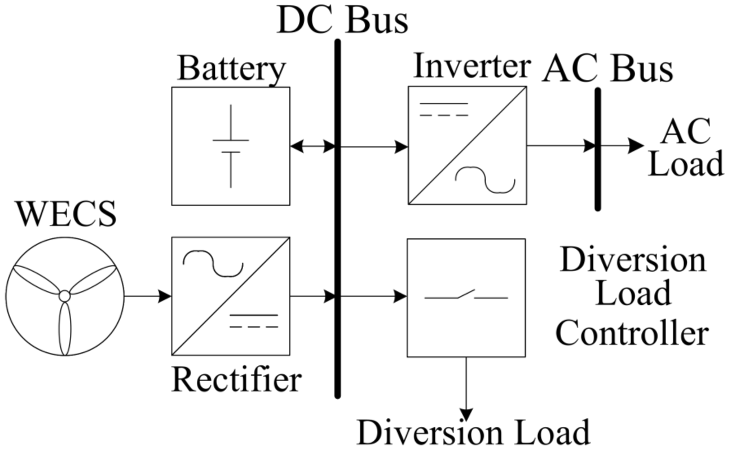
Note: I_{DL} must be non-negative



Exercise

A battery is connected to solar panel through a charge controller and is being charged in the absorption stage. A WECS is connected to the DC bus through a rectifier. The WECS outputs 10A. A diversion load controller is connected to the DC bus.

The V_{SoC} is 12.95 V and R_B = 0.2 Ω. Compute the current required by the charge controller and diversion load controller to maintain an absorption voltage setpoint of 14.4 V.



Exercise

$$V_B = 14.4 \text{ V}$$

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

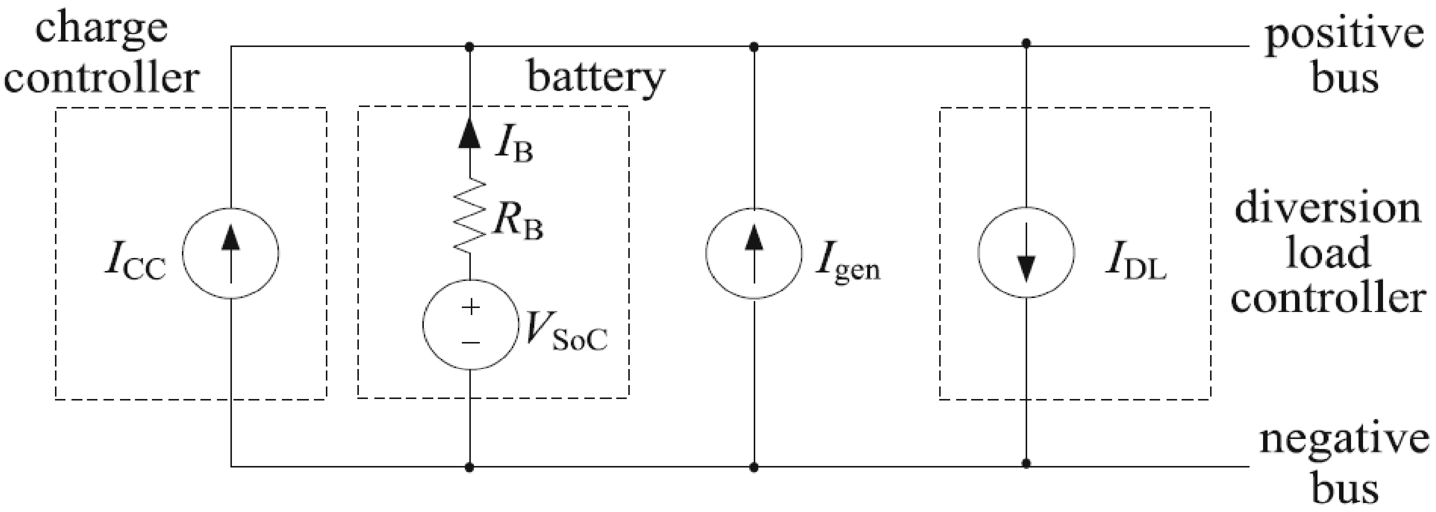
$$\frac{V_\mathrm{B} - V_\mathrm{SoC}}{R_\mathrm{B}} = -I_\mathrm{B}$$

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

$$\frac{-14.4 + 12.95}{0.2} = I_\mathrm{B} = -7.5 \text{ A}$$

$$I_{CC} + I_{gen} - I_{DL} = -I_B$$

$$I_{CC} + 10 - I_{DL} = 7.5$$



KCL:
$I_\mathrm{CC} + I_\mathrm{B} + I_\mathrm{gen} = I_\mathrm{DL}$

$$\left.\begin{aligned} I_{CC} &= 0\text{A} \\ I_{DL} &= 2.5\text{A} \end{aligned}\right\}$$

Any combination of I_{cc} and I_{DL} that equals -2.5 A would work (both must be non-negative). But the preferred solution would be to set the charge controller current to 0 A.

Diversion Load Setpoint

- Absorption and float setpoints for diversion load should be somewhat higher than for the charge controller
  - usually better to "throttle" generation than to send to diversion load (smaller diversion load capacity is needed this way)

$$V_{\text{abs,DL}} = V_{\text{abs}} + \Delta$$
$$V_{\text{float,DL}} = V_{\text{float}} + \Delta$$

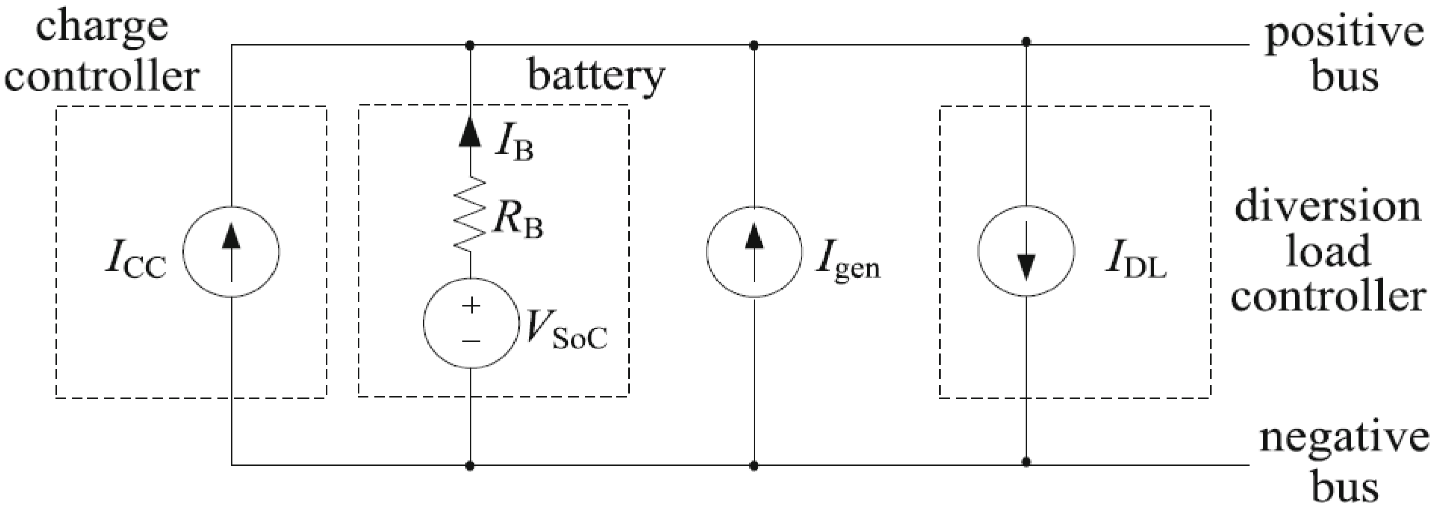
Δ around 0.1 to 0.2 V

- Diversion load controller current is only non-zero when charge controller targeted current $\hat{i}_{\text{CC}}$ is negative (over-voltage)

Charging Stages with Diversion Load

Target diversion load controller current to maintain battery voltage at diversion load absorption set point is

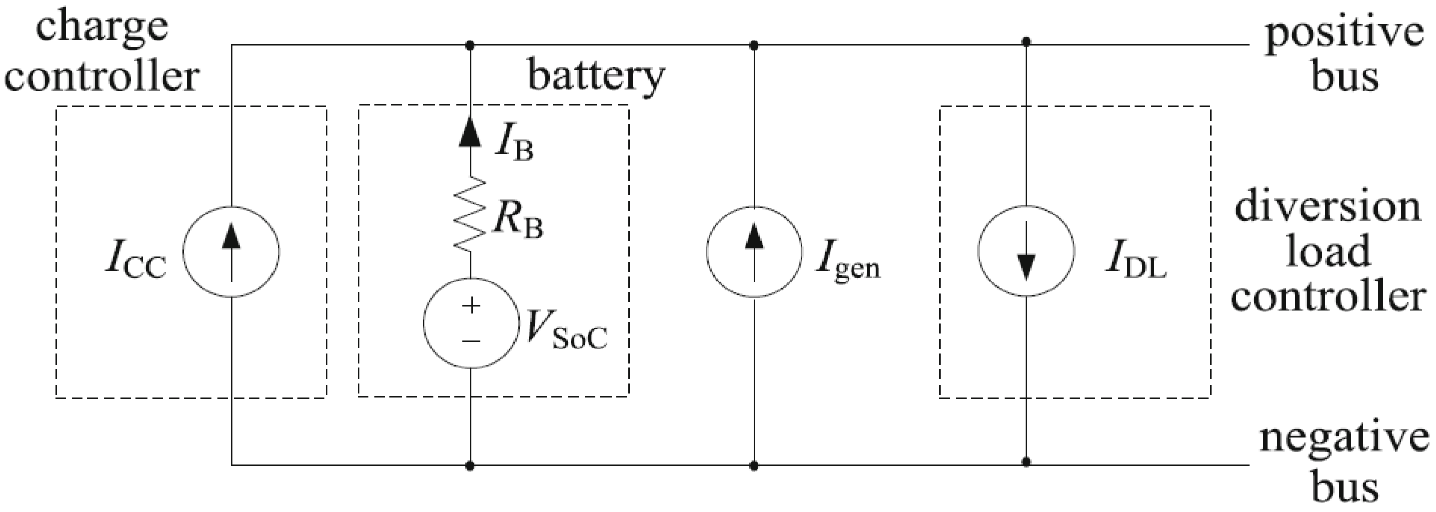
$$\hat{I}_{DL} = -\frac{V_{abs,DL} - V_{SoC}}{R_B} - I_L + I_{gen} + I_{CC}$$



Charging Stages with Diversion Load

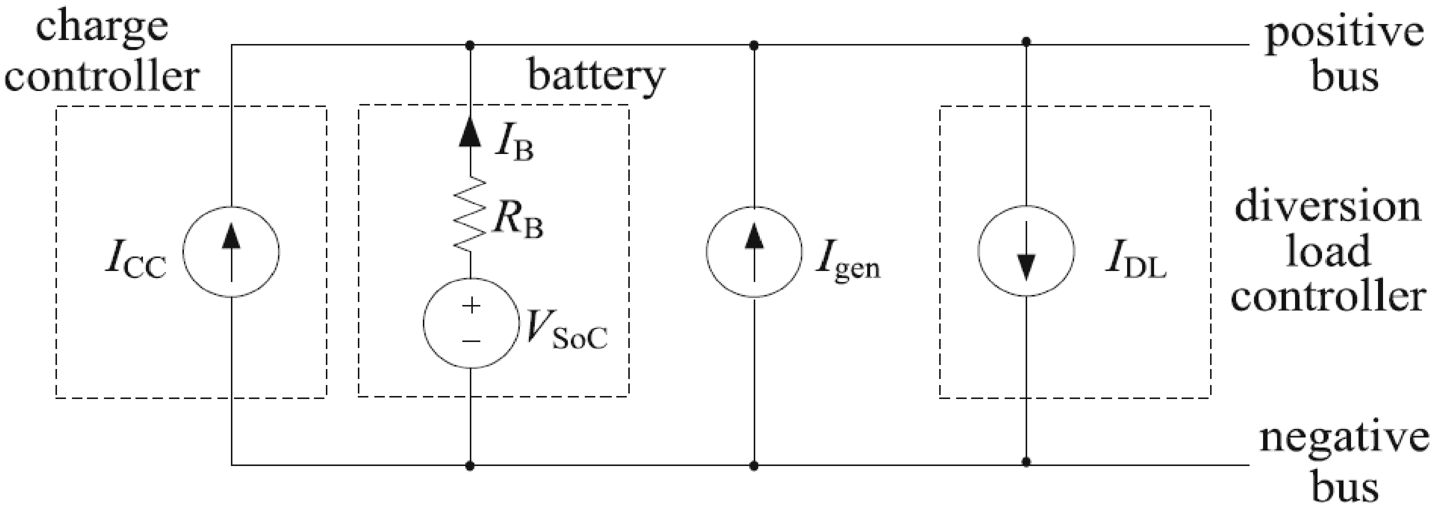
As with charge controller, diversion load controller is limited so that

$$I_{DL} = \begin{cases} 0 : \hat{I}_{DL} \le 0 & \text{(under-voltage)} \\ \hat{I}_{DL} : 0 < \hat{I}_{DL} < I_{DL}^{max} & \\ I_{DL}^{max} : I_{DL}^{max} \le \hat{I}_{DL} & \text{(over-voltage)} \end{cases}$$



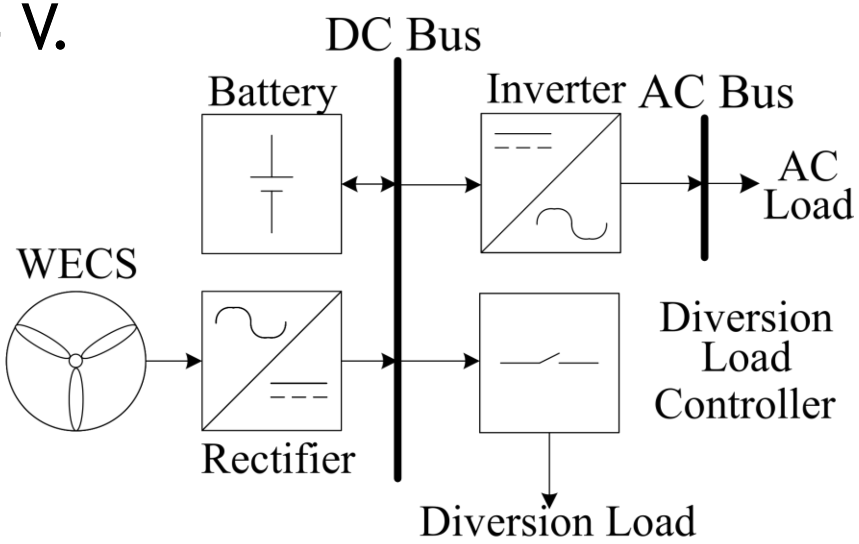
Charging Stages with Diversion Load

If setpoints are specified correctly, then there should never be current from the charge controller and to the diversion load at the same time



Example 13.4

Consider a mini-grid with a DC-coupled WECS, battery, DC load, and diversion load controller. Let $V_{abs,DL}$ = 56.8 V and R_B = 0.8 Ω. The load is 6 A. The current from the WECS is 19 A. The diversion load controller is rated at 50 A. Compute the absorption stage diversion load controller current when V_{SoC} = 54 V.



Example 13.4

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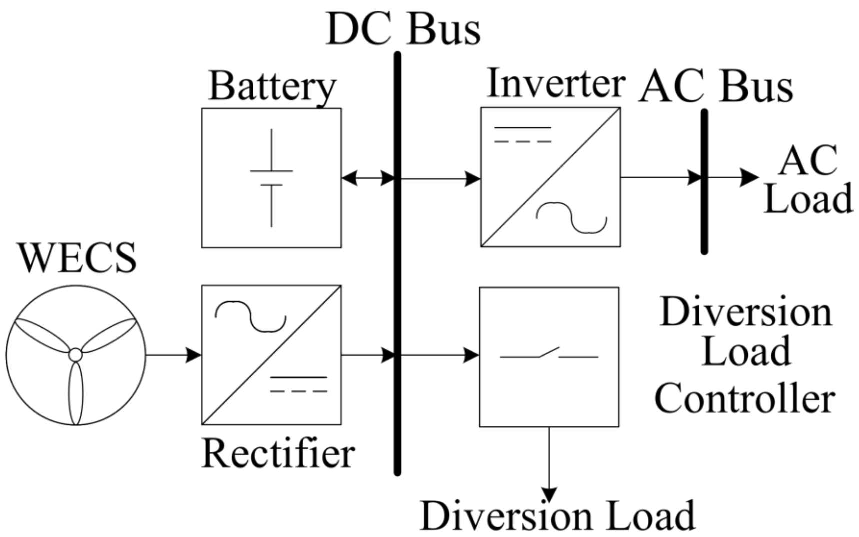
The load is only 6 A compared to a WECS current of 19 A.

The required diversion load current is

$$\begin{aligned}\hat{I}_{\text{DL}} &= -\frac{V_{\text{abs,DL}} - V_{\text{SoC}}}{R_B} - I_L + I_{\text{gen}} \\ &= -\frac{56.8 - 54}{0.8} - 6 + 19 \\ &= 9.5\,\text{A}\end{aligned}$$



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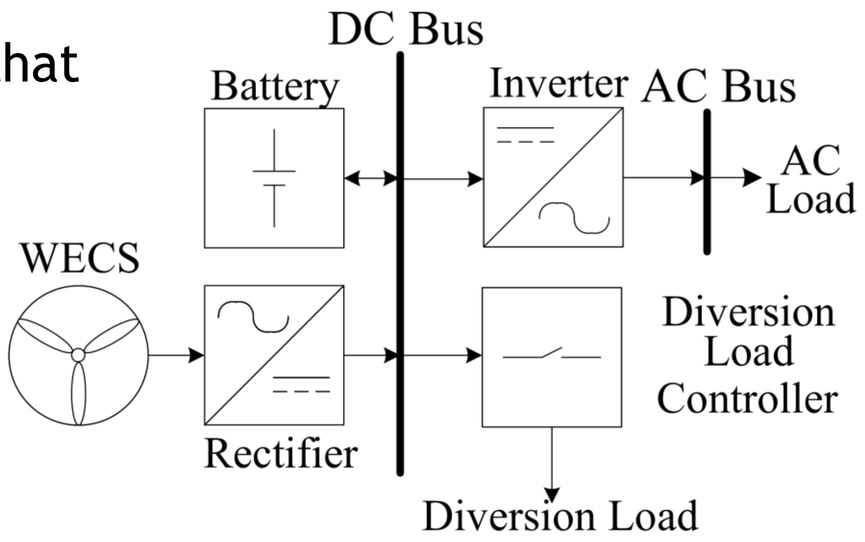
Target diversion load current is less than its rating (50 A) so that

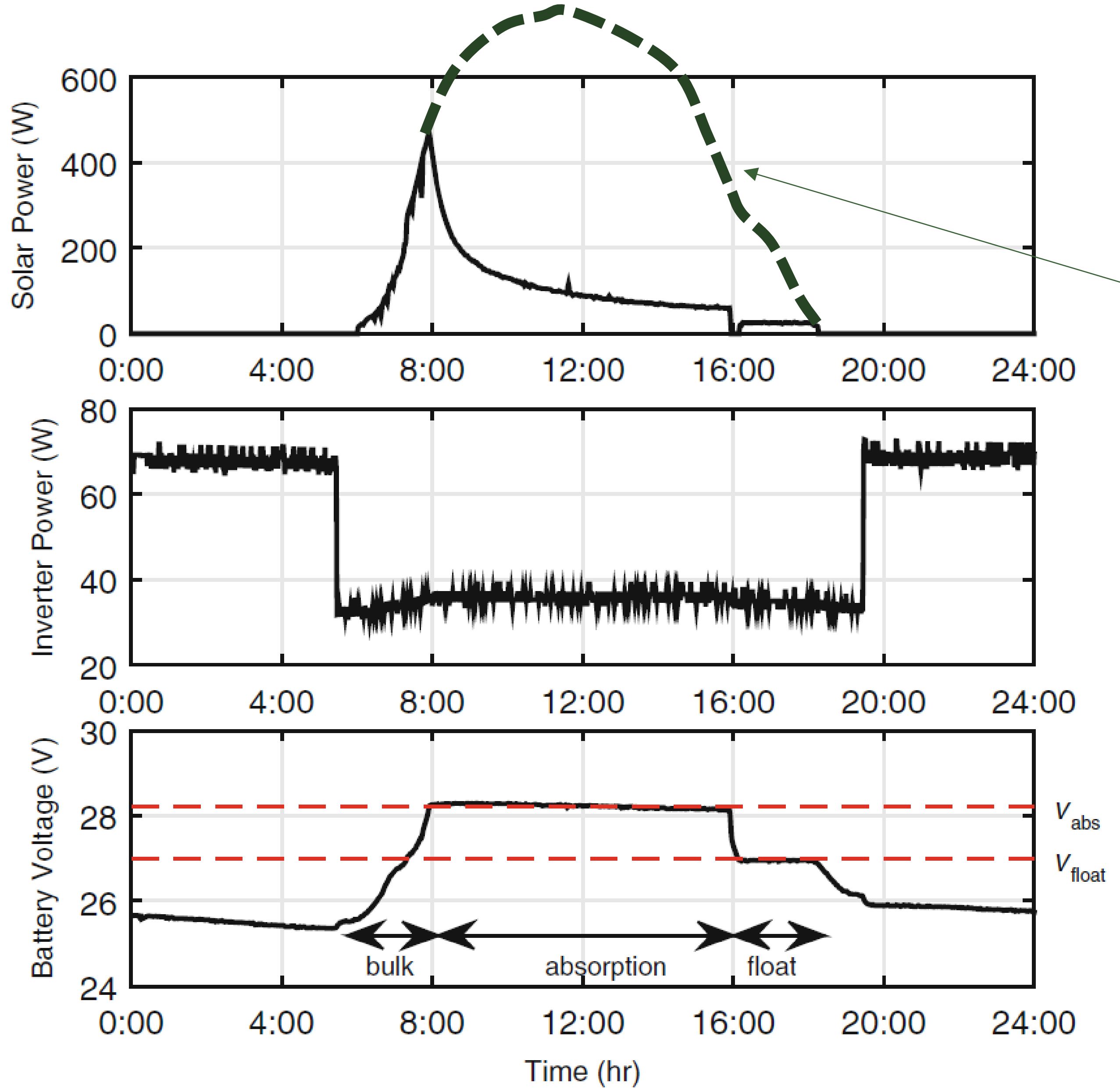
$$I_{DL} = \hat{I}_{DL}$$

The absorption setpoint voltage is maintained at 56.8 V.



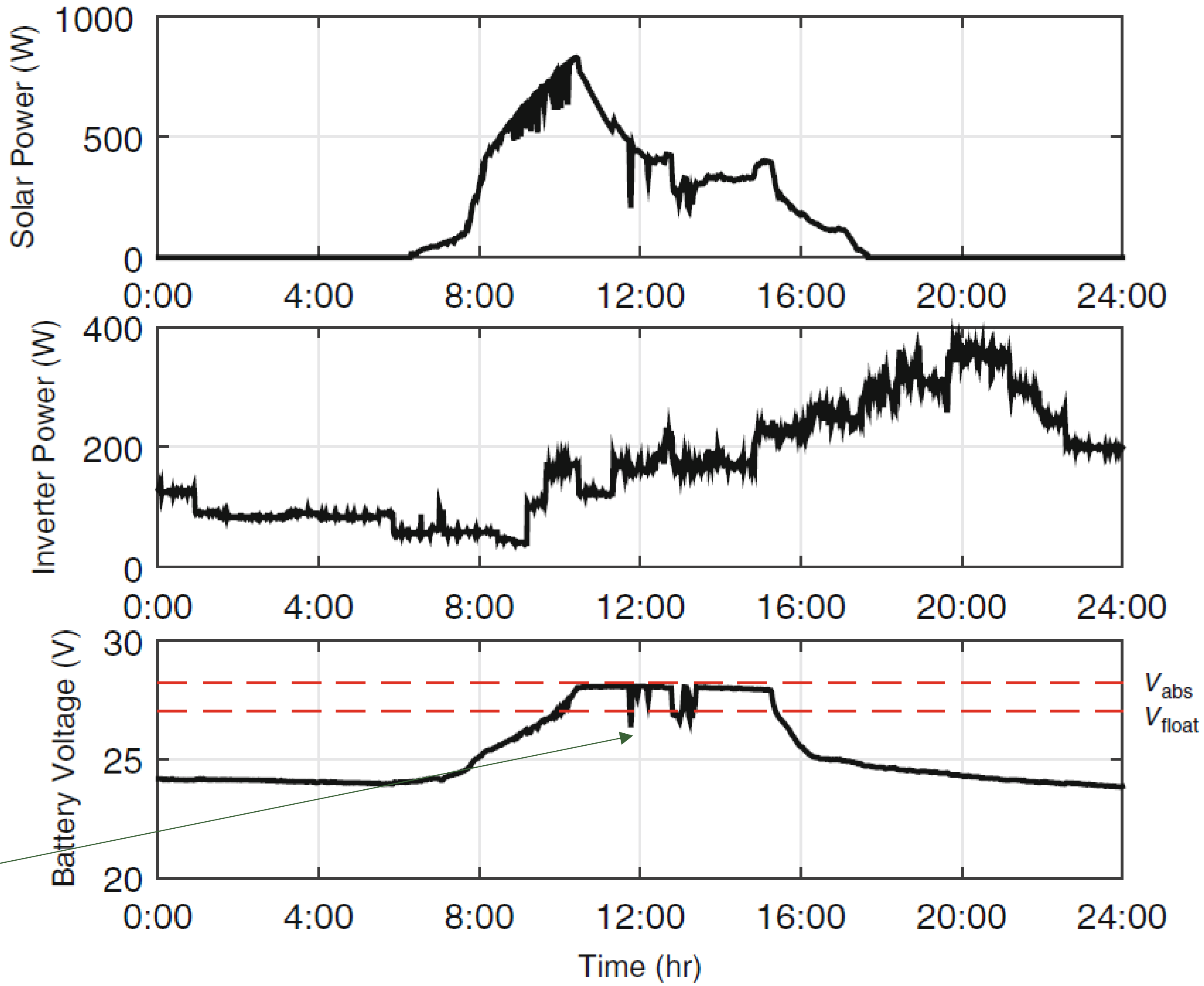
Three-Stage Charging in PV Systems

- 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

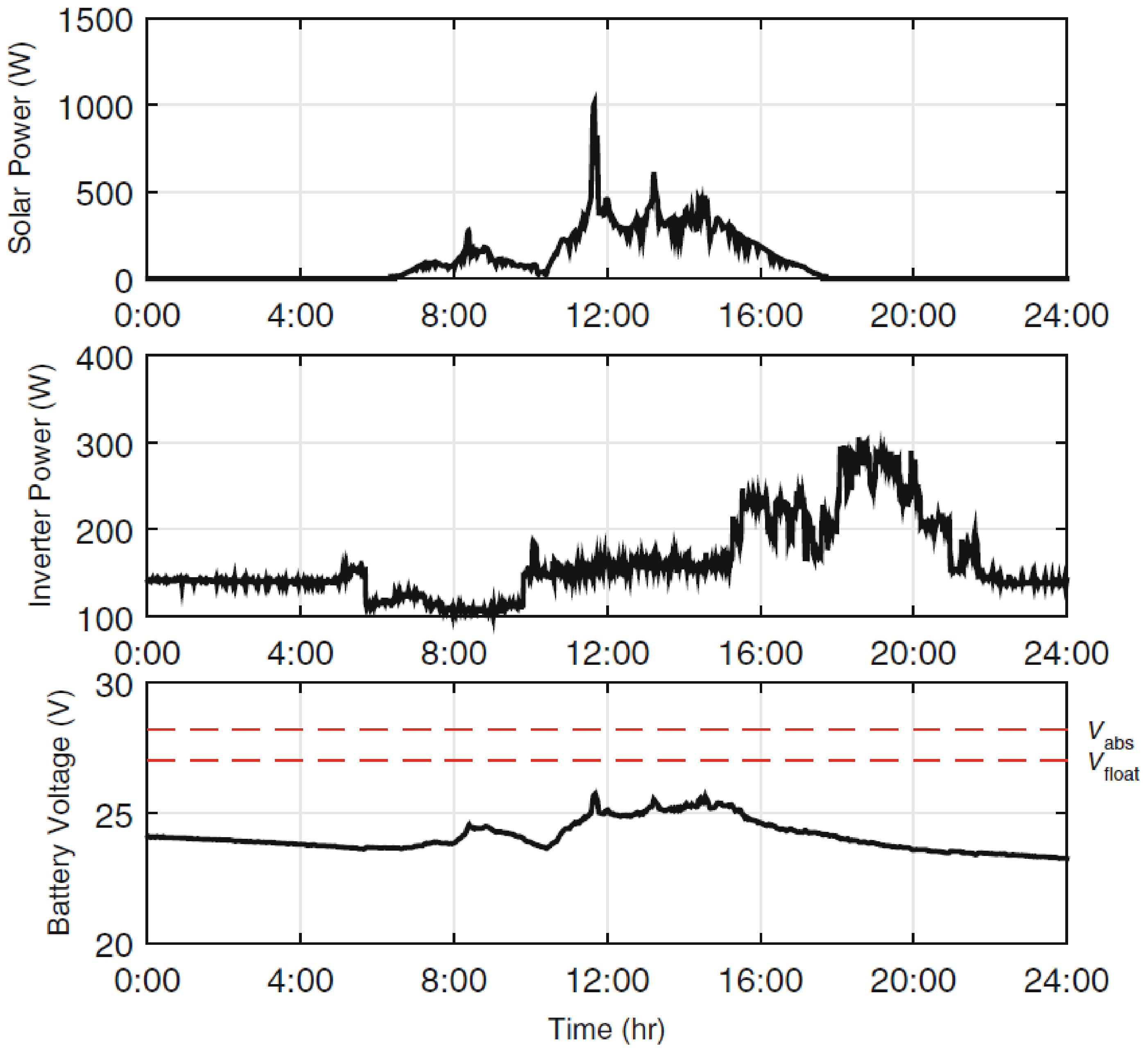
Power-Constrained Charging



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

Power-Constrained Charging

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

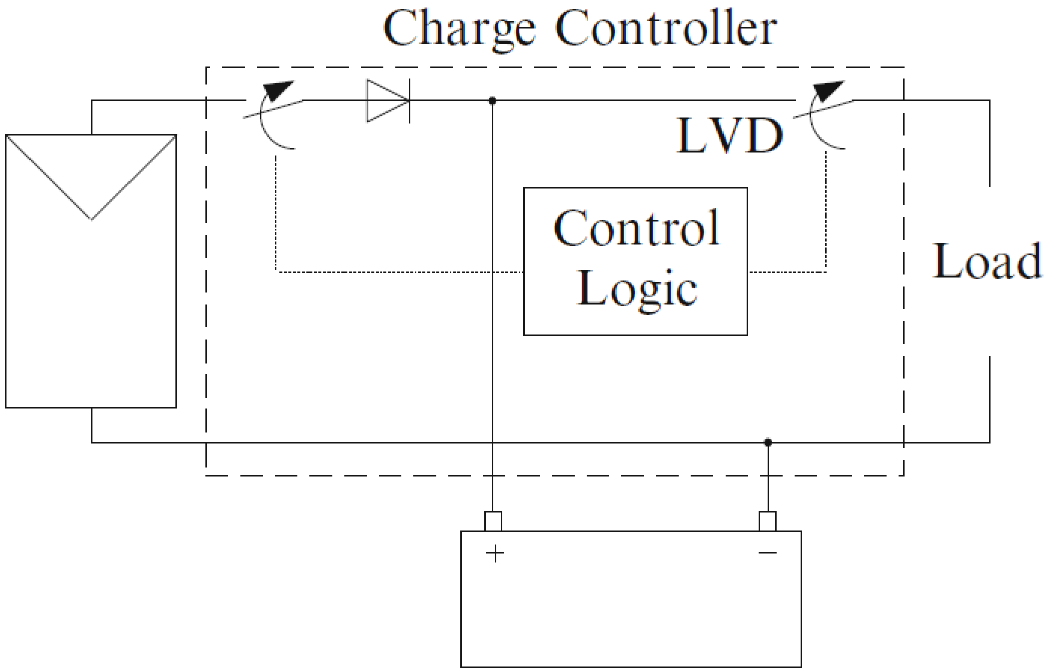


Battery Discharging Control

- 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 if the battery is discharging)
- Inverters 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

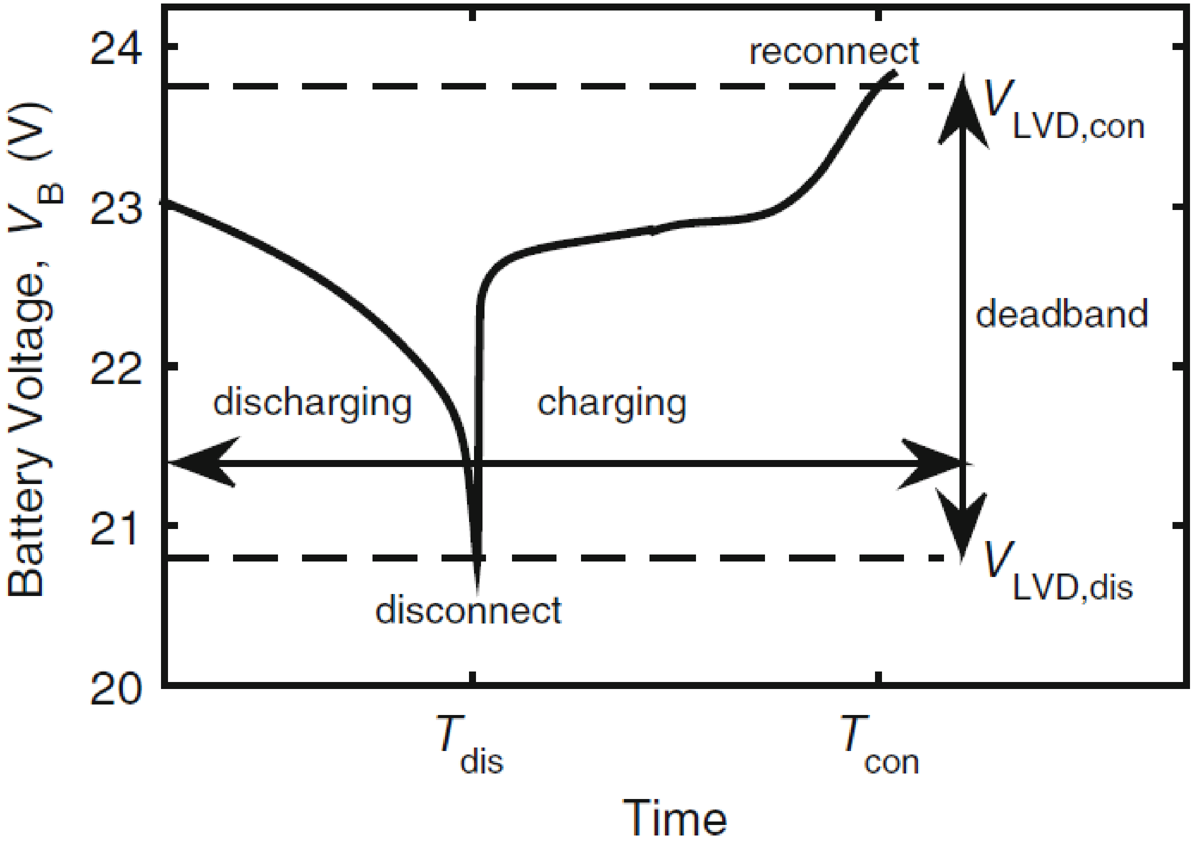


Low Voltage Disconnect Setpoints

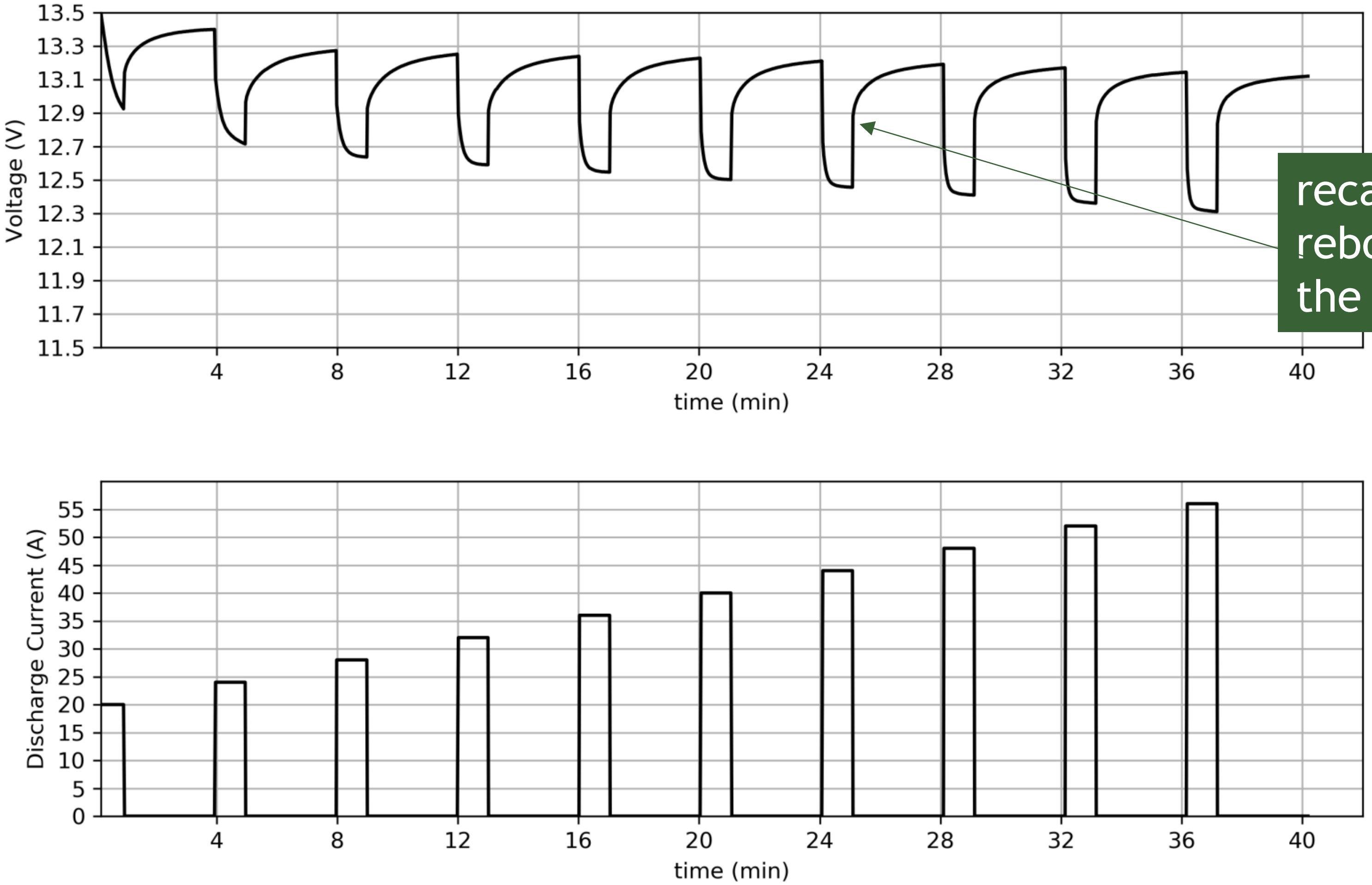
- Disconnect Setpoint: battery terminal voltage at which the load is disconnected
- Reconnect Setpoint: battery terminal voltage at which the load is re-connected
- Difference between Disconnect and Reconnect set-points is known as the "deadband"
- Determining these setpoints can be difficult since terminal 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 setpoint
- $V_{LD,con}$: low voltage disconnect reconnect setpoint



Why is a dead band needed?



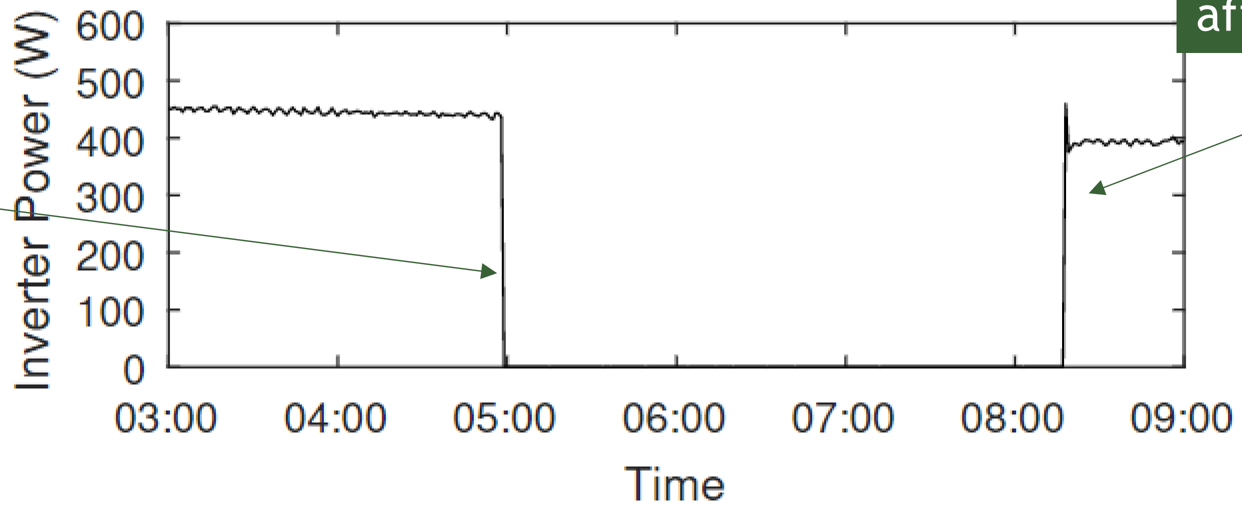
recall that the voltage rebounds as soon as the load is removed.

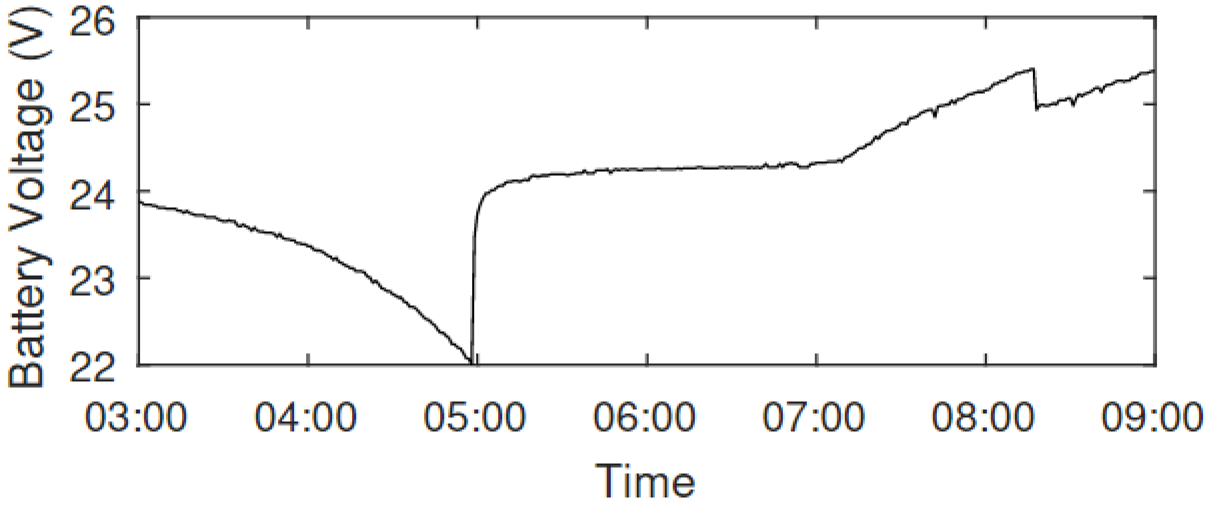
Without a large enough deadband, the LVD can be tricked into thinking the battery has been recharged, and it would connect the load

Proper Deadband Behavior

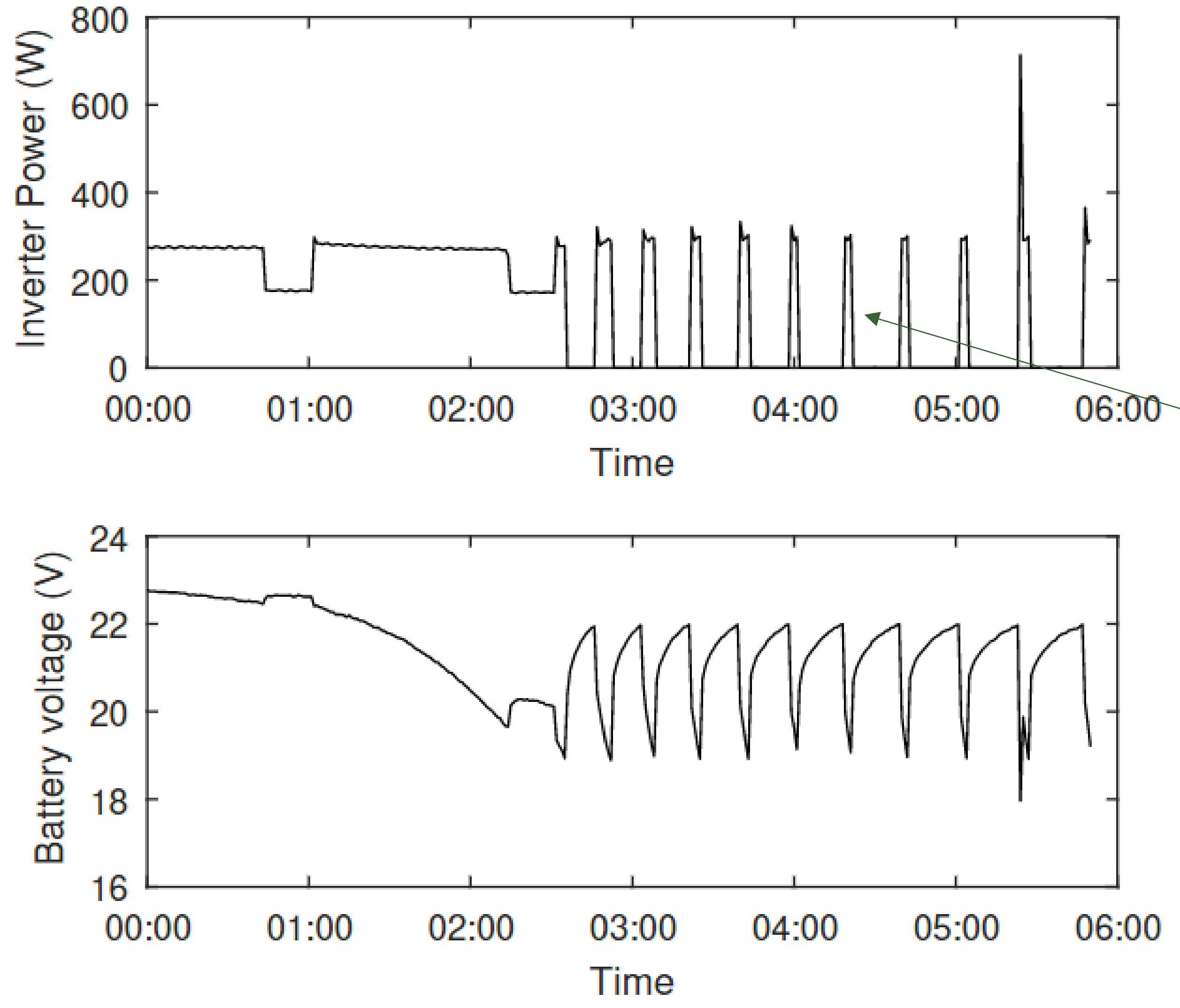
LVD re-connects only after PV recharges the battery after sunrise

LVD disconnects





Deadband Not Large Enough



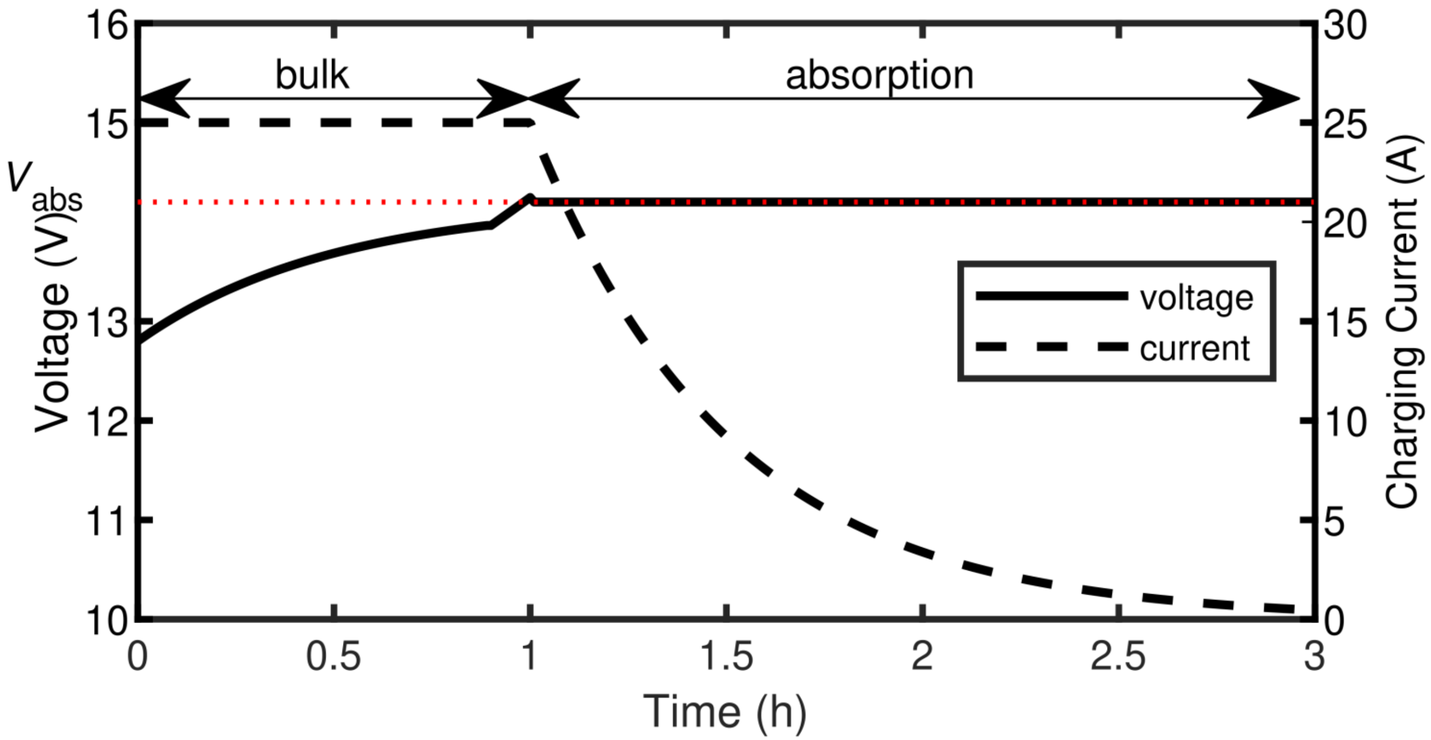
inverter reconnects and
quickly disconnects. (this is early
in the morning when there is no PV power)

oscillation is undesirable
and results in a deeply discharged
battery

Charging Lithium-Ion Batteries

- $LiFePO_4$ (lithium iron phosphate) are increasingly used in off-grid systems
- Charging of LI batteries similar to but different than from lead-acid batteries
  - higher current during bulk stage
  - no float stage (little self-discharge, better to keep voltage lower)

LI Charging Algorithm

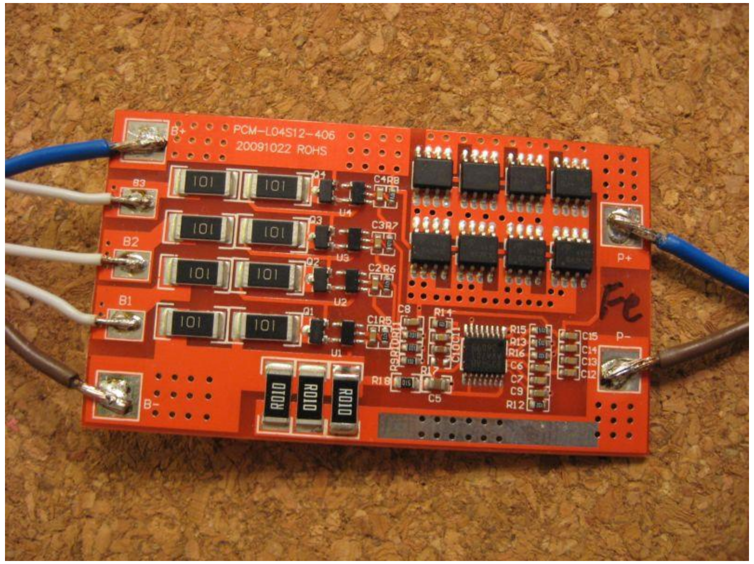


similar to lead-acid three-stage charging

two-stage charging (bulk, absorption) without float

Battery Management Systems (BMS)

- BMS: circuitry and control systems that monitor, protect, and manage the state of cells in an LI battery pack
- BMS provides additional protection to mitigate hazards of LI batteries (see Chap. 10)
- BMS prolongs LI battery life by preventing abnormal operating conditions
- BMS may be internal or external to battery



(Source Hadhuey - Own work CC BY-SA 3.0)

BMS Core Functions

- Protection
- Cell Balancing
- Monitoring and Communication

BMS: Protection

Internally disconnect cells during abnormal or hazardous conditions

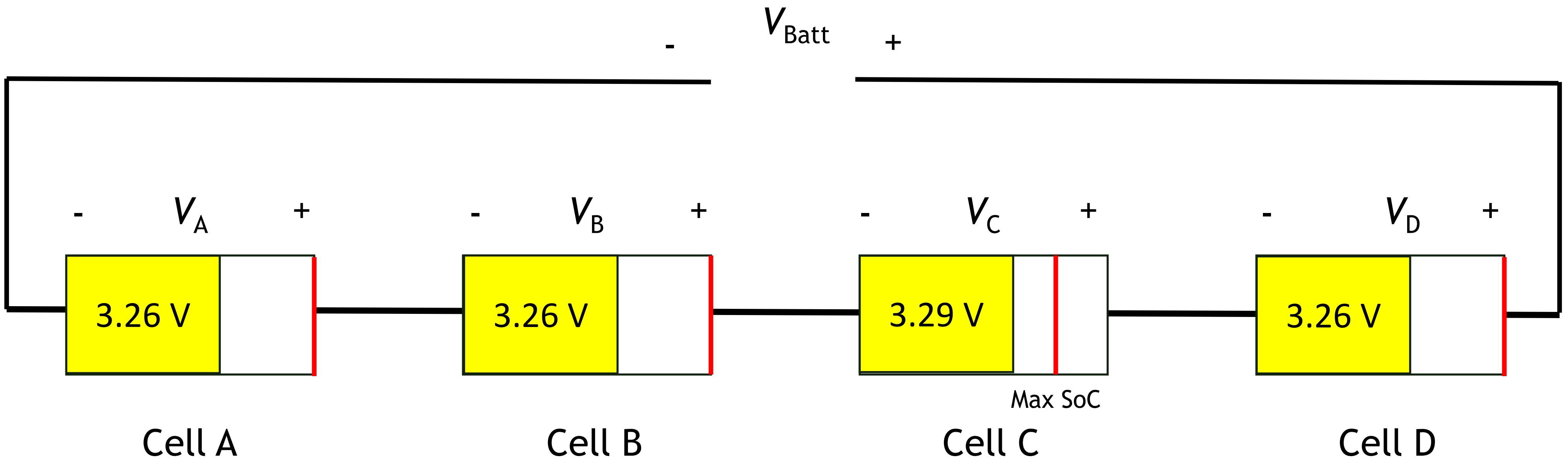
- Over-charge: prevents damage from an over-voltage condition
- Over-discharge: prevents damage from an under-voltage condition
- Thermal: prevents the cell or battery from operating at extreme hot and cold temperatures
- Over-current: prevents the cell or battery from excessive charge, discharge or internal short circuits

Cell Imbalance

- Series connected cells can become imbalanced
- Types of imbalance
  - states of charge
  - maximum charge
  - battery resistance
- Causes
  - minor manufacturing variations
  - non-uniform degradation over time or use
- Effects
  - limited capacity
  - shortened lifespan
  - lower output voltage and current
  - heating and failure

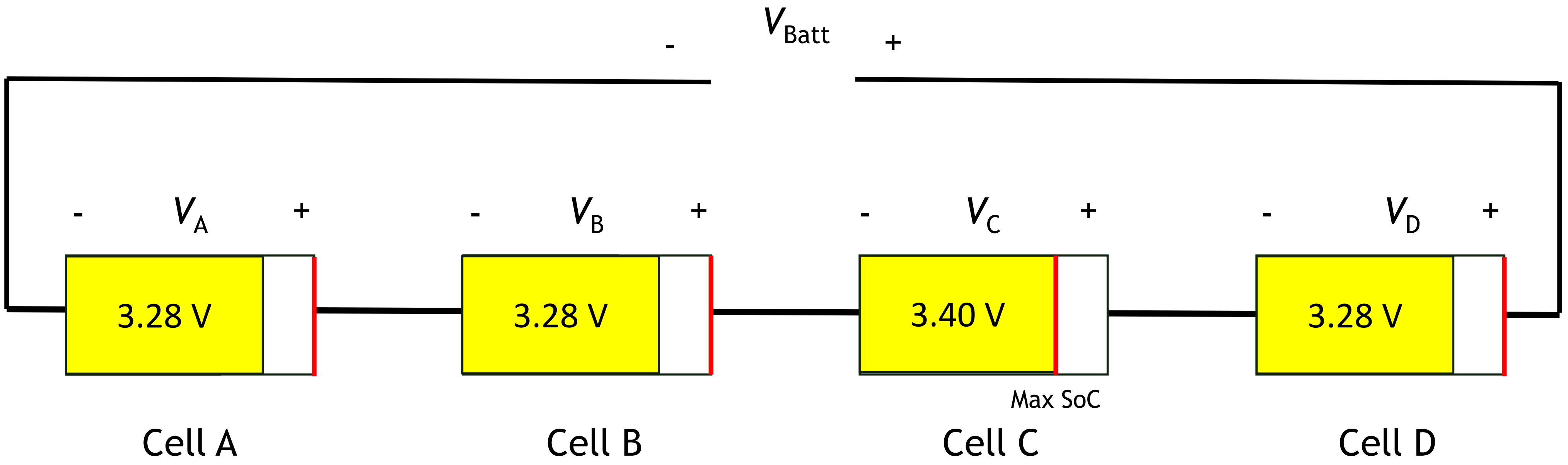
BMS: Cell Balancing

Consider 4 series connected LI cells. Cell C has a lower maximum SoC due to accelerated aging. All cells have same charge (yellow area), but Cell C has a higher voltage since it is closer to its maximum SoC



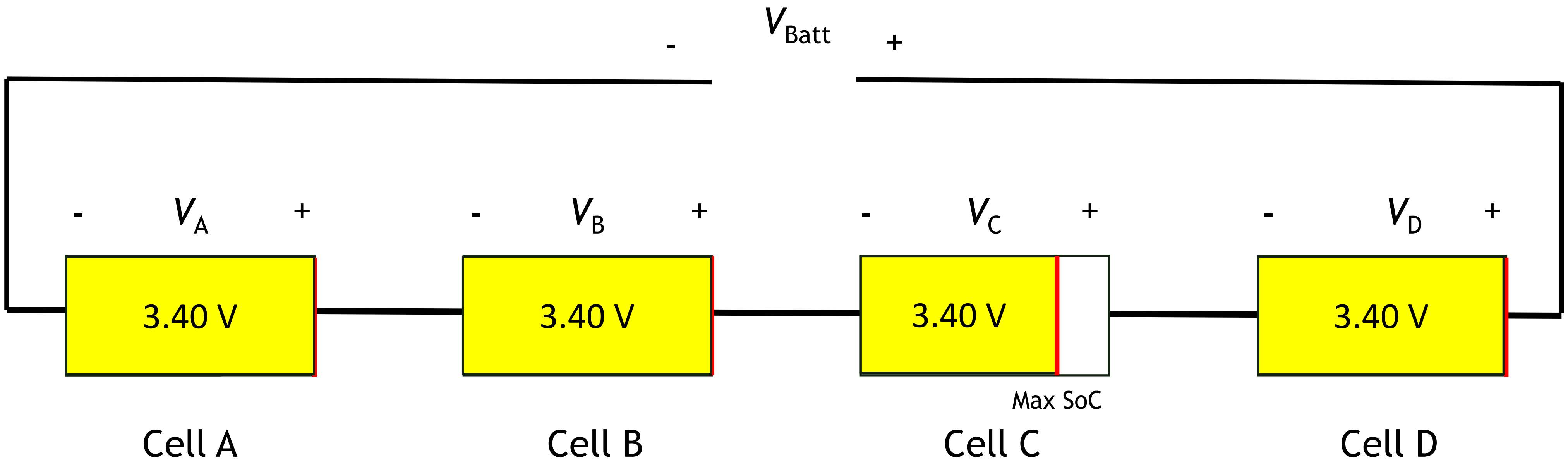
BMS: Cell Balancing

As the battery charges, Cell C reaches its maximum SoC and voltage before the others. BMS senses that Cell C is at its maximum voltage and will signal for charging to stop. However, the other cells are not fully charged. The battery's charge capacity is limited by one cell.



BMS: Cell Balancing

Cell balancing can allow Cells A, B, and D to be charged to their full SoC, increasing the overall charge capacity of the battery. This is just one example of the benefit of cell balancing



Cell Balancing Approaches

- Passive: each cell has resistor connected in parallel with it; solid-state switch connects resistor to cell when cell reaches its maximum voltage (effectively bypassing the cell from charge current)
  - inexpensive
  - simple
  - slow to balance
  - low efficiency
- Active: transfer charge from higher-voltage cells to lower-voltage cells using switched capacitors, inductors, or charge controllers
  - more expensive
  - more complicated
  - faster balancing
  - higher efficiency

BMS: Monitoring & Communication

- BMS continuously measure battery’s electrical and thermal characteristics at each cell
- Collected data can be stored/shared with other components and data acquisition system
- BMS can communicate with other components (e.g. charge controllers, chargers, inverters) to signal end of charging stages, low voltage disconnect and more

Setpoint Selection

- Components require setpoints to be specified by the user
- Careful coordination needed to achieve desired operation

(*courtesy D. Nausner*)

Typical Charging/Discharge Setpoints

Battery	Nominal (V/cell)	Bulk (C-rate)	Absorption (V/cell)	Float (V/cell)	Equalization (V/cell)	LVD[1] (V/cell)
AGM Lead-acid	2.0-2.1	0.1-0.20	2.35-2.45	2.23-2.30	2.65[2]	1.85-1.95
Flooded Lead-acid	2.0	0.1-0.20	2.40-2.50	2.23-2.30	2.70	1.85-1.95
Gel Lead-acid	2.0-2.2	0.1-0.20	2.35-2.40	2.23-2.30	—[2]	1.85-1.95
$LiFePO_4$	3.2	0.5-1.0	3.55	3.4[2]	—	3.10-3.20

[1] Note this is the cell voltage while being discharged,not the open-circuit voltage

[2] Not normally done. Consult battery specification sheet to see if recommended

setpoints should be adjusted for temperature, decreasing setpoint value as temperature increases

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)

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Rated charge current	30 A	50 A
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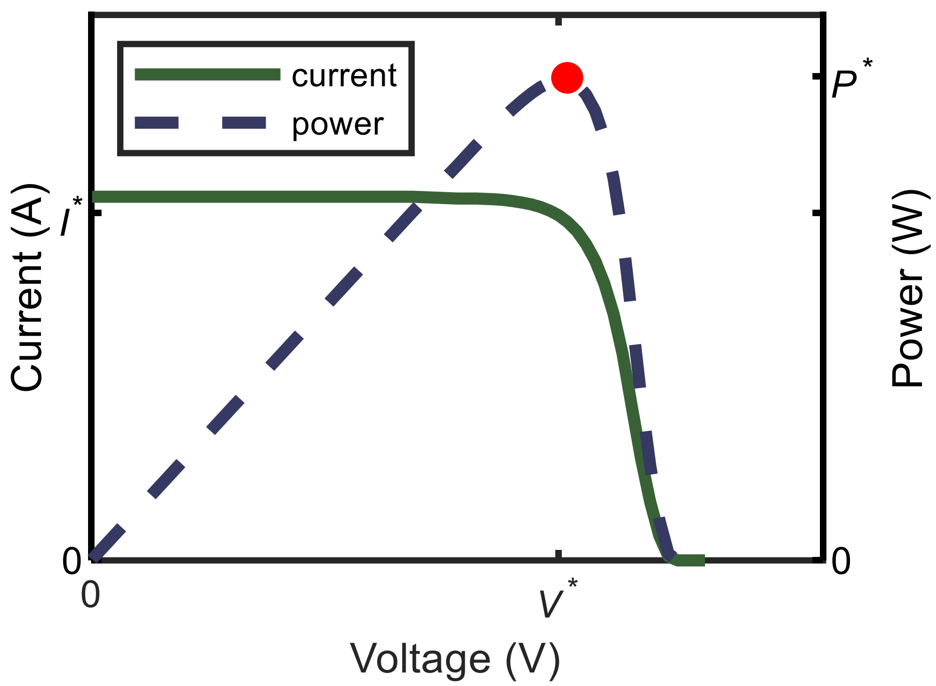
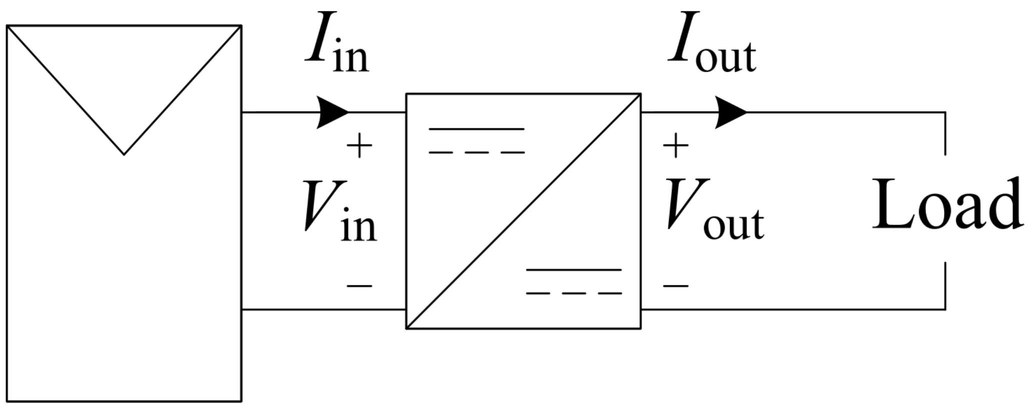
Maximum Power Point Tracking

- 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?



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 using a DC-DC converter (Maximum Power Point Tracker)
- Several types: series, shunt, optimization-based

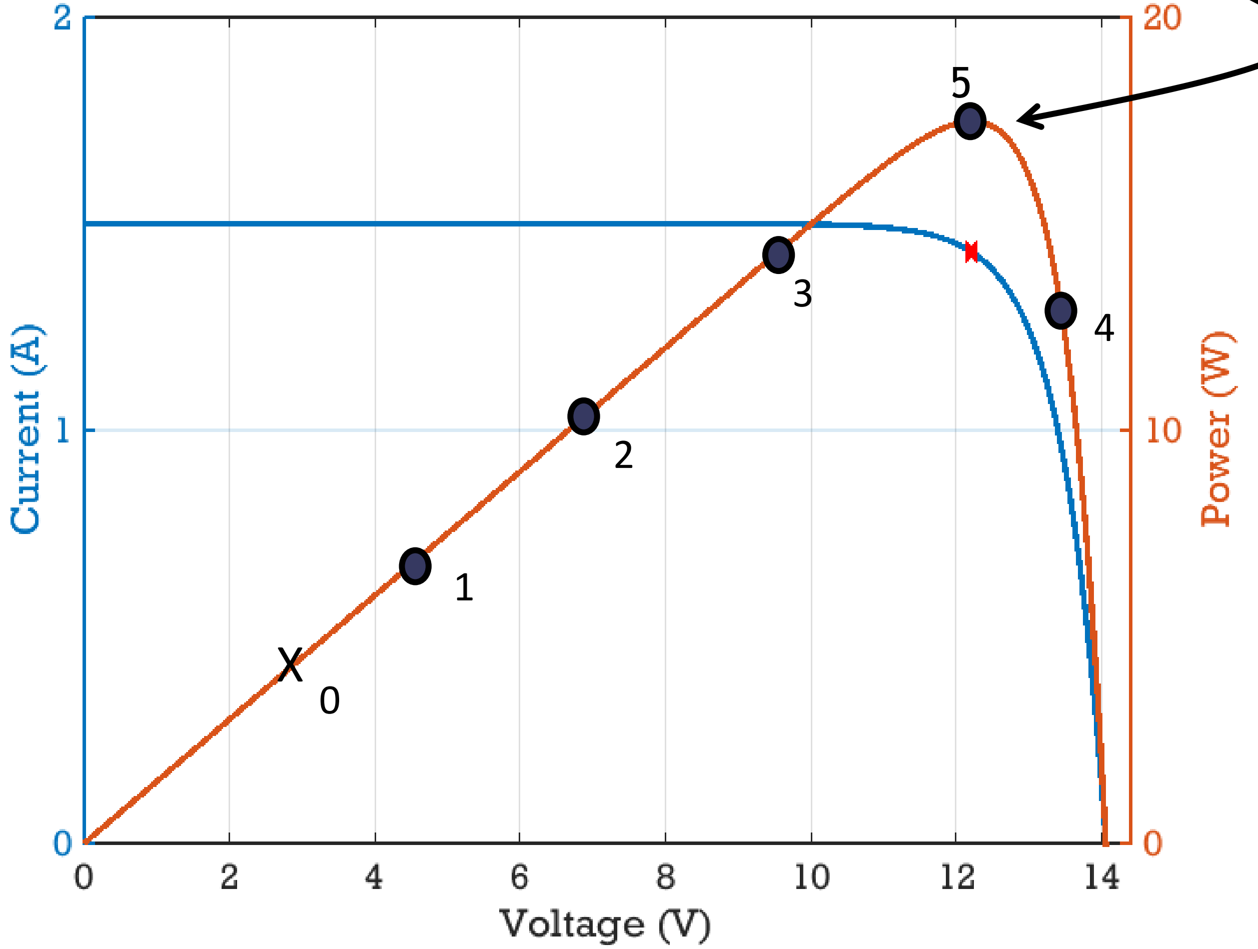


Maximum Power Point Trackers

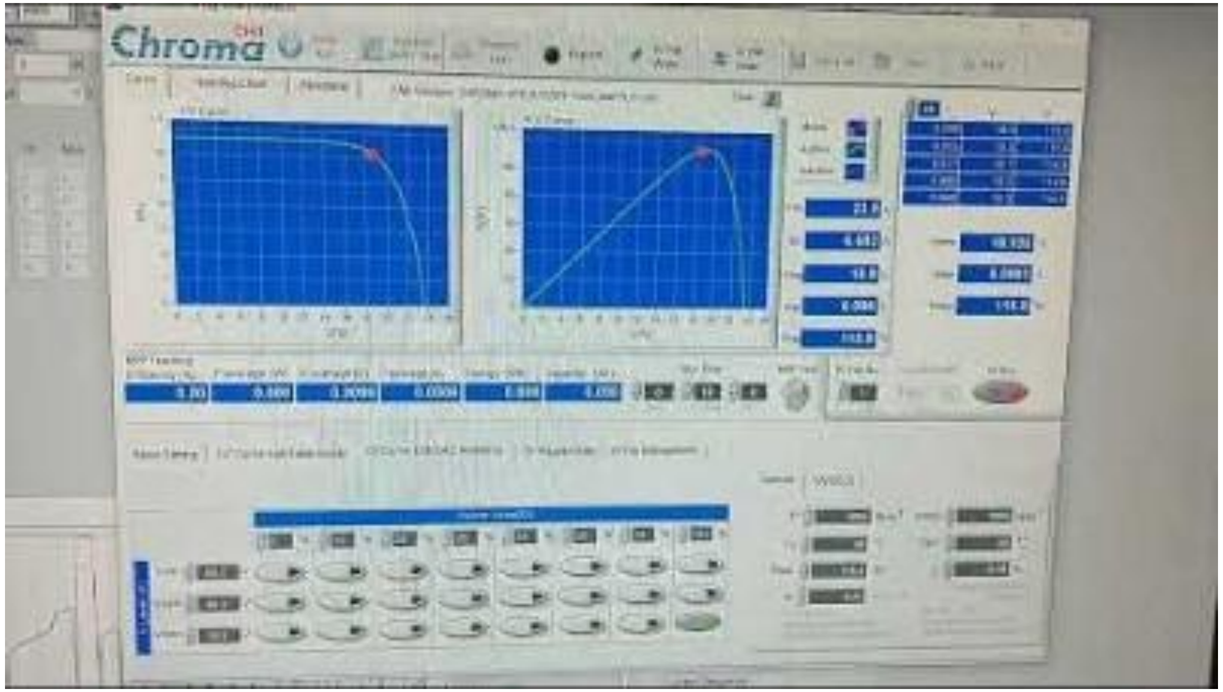
- Maximum power tracker control requires PV voltage and current sensing to control the duty ratio (irradiance and perhaps the load are constantly changing)
- Common methods:
  - Perturb and Observe (P&O)
  - Incremental Conductance (IC)
- Both methods are non-model methods (meaning you do not need to 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)



Hill-Climbing Algorithm

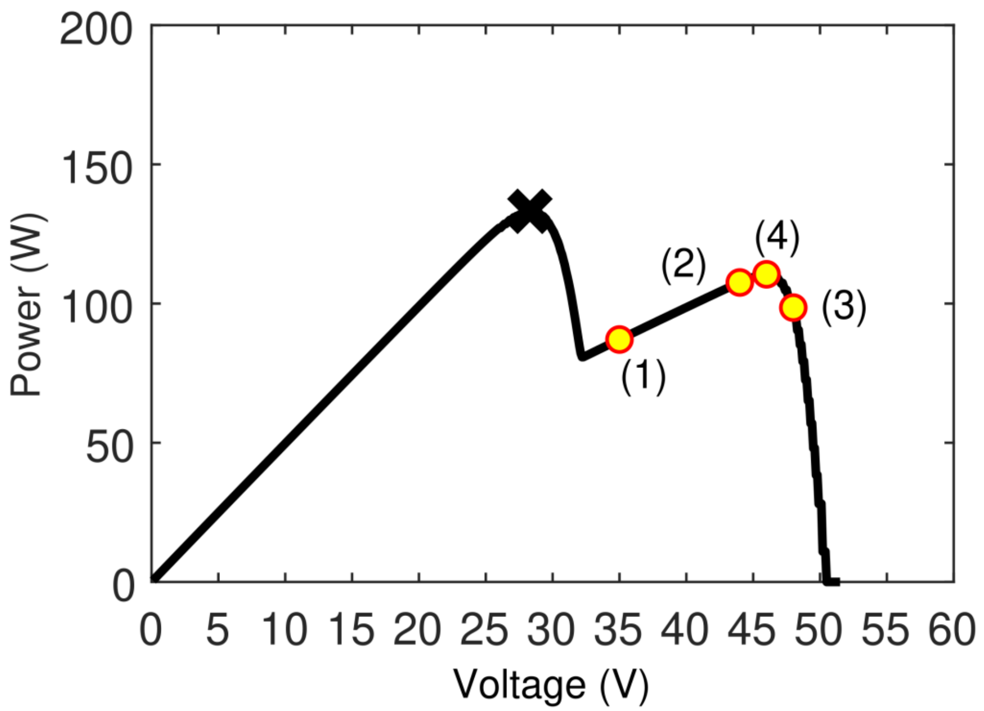


https://www.youtube.com/watch?v=qTTVjIdiz0s

MPPT operating as the load changes every 3 seconds

Hill-Climbing Algorithms

Can become “stuck” at local maxima (for example, when a PV array or module is partially shaded)



Perturb and Observe (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

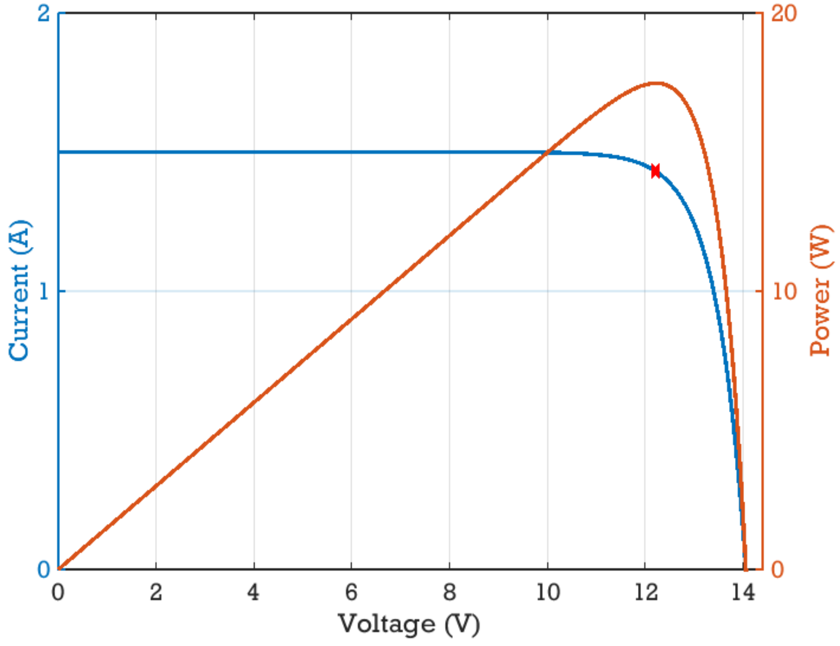
- Basic idea: at MPP, the derivative of power with respect to voltage is zero (it is a maximum point)
- Conductance $G = I/V$ (inverse of resistance)

don't confuse with irradiance

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

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

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



IC Method

$$P = I(V)V$$

$$\frac{\mathrm{d}P}{\mathrm{d}V} = \frac{\mathrm{d}I(V)V}{\mathrm{d}V} = \frac{\mathrm{d}I}{\mathrm{d}V}V + 1I(V) = 0$$

at the maximum

Applying the product rule for derivatives

$$\frac{\mathrm{d}I}{\mathrm{d}V}V = -1I(V)$$

$$\frac{\mathrm{d}I}{\mathrm{d}V} = \frac{-I(V)}{V}$$

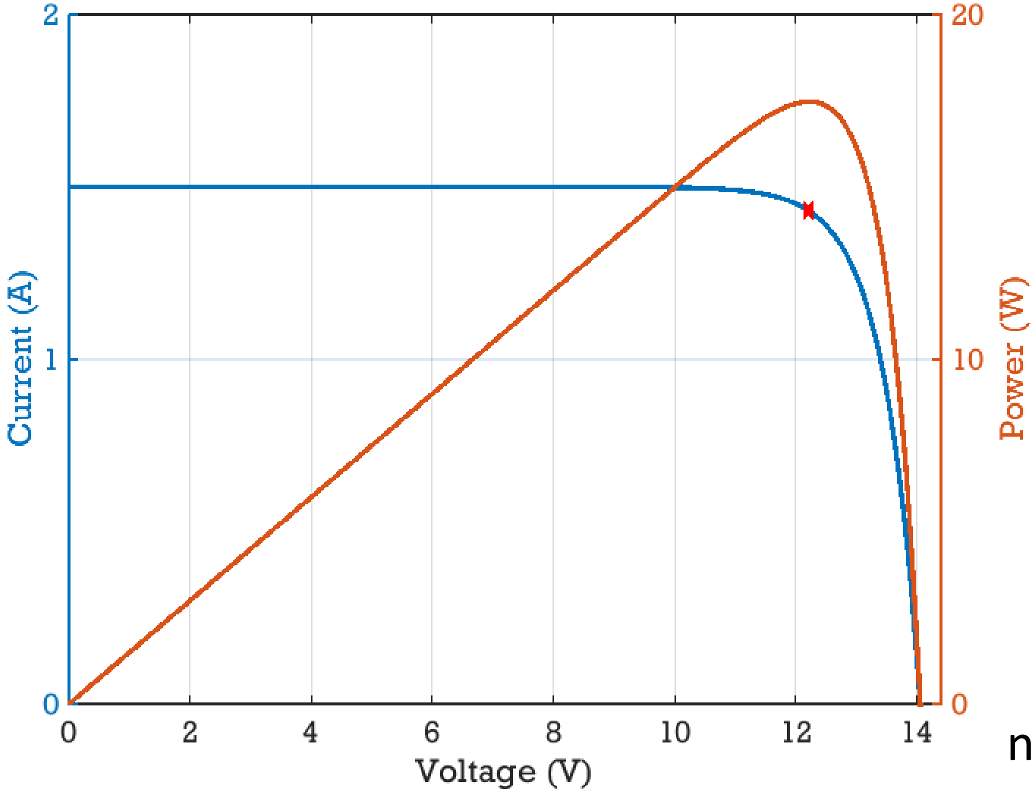
IC Method

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

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

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

Example



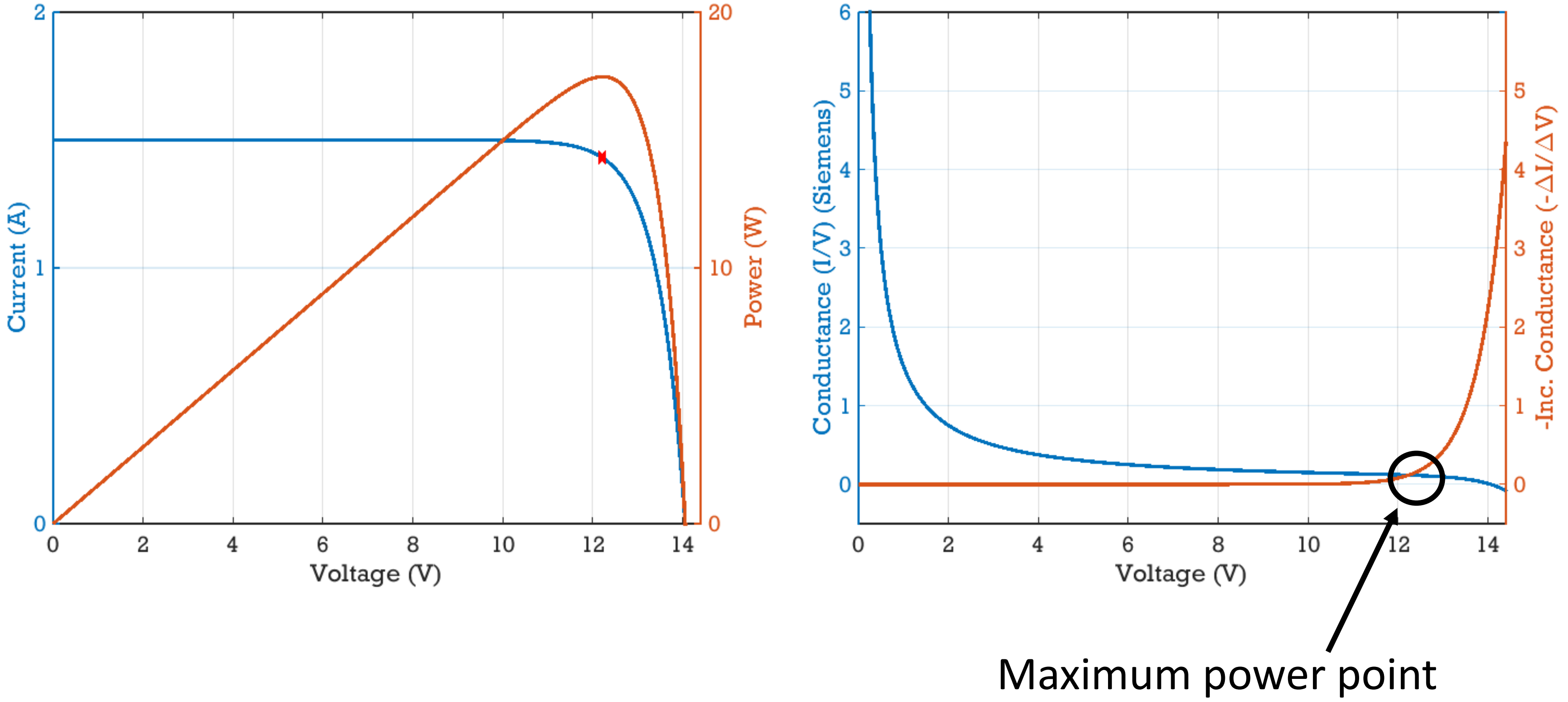
V^* = 12.22V
I^* = 1.40A

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

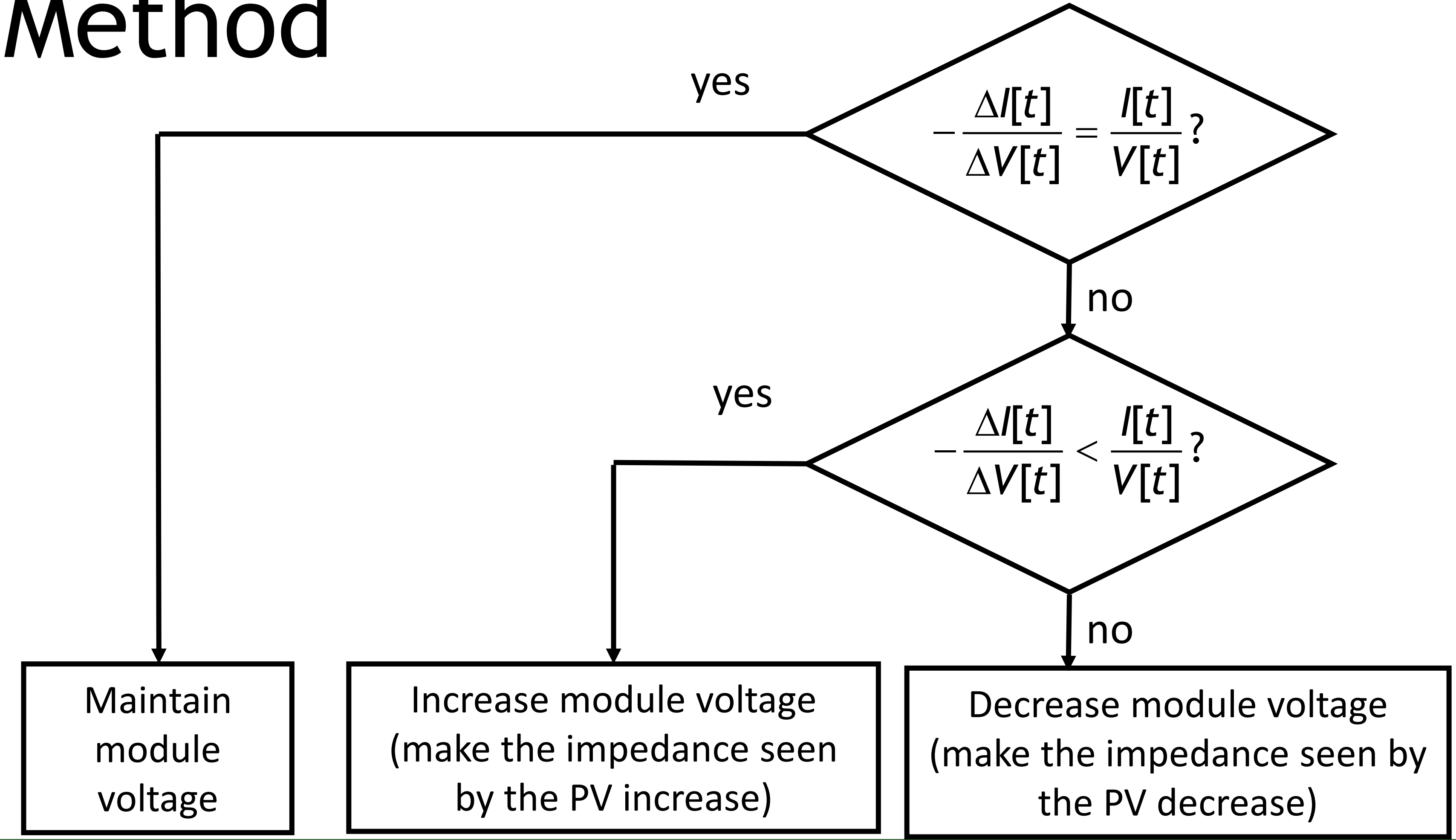


Current (A)
Power (W)
Voltage (V)
Conductance (I/V) (Siemens)
-Inc. Conductance (-ΔI/ΔV)
Voltage (V)
Maximum power point

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:
  - $\Delta I/\Delta V = (I[t] - I[t\text{-}1])/(V[t] - V[t\text{-}1])$
- 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 module voltage
Increase module voltage (make the impedance seen by the PV increase)
Decrease module voltage (make the impedance seen by the PV decrease)

Summary

- Circuit model of DC bus and connected components developed
  - model components as current sources and battery as voltage source in series with resistance, use KCL and KVL to determine relationships
- Battery charging:
  - Lead-acid battery charging: bulk (constant current), absorption (constant voltage), float (constant reduced voltage)
  - Lithium-ion battery charging: bulk and absorption only (typically)
- Maximum power point tracking can be accomplished through hill-climbing algorithms