23-Charge Controllers & Diversion Load Controllers

*Off-Grid Electrical Systems in Developing Countries*

Chapter 9.5, 10.1-10.5

Learning Outcomes

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

✓ describe purpose and functions of solar charge controllers and diversion load controllers

✓ understand basic circuit topologies for solar battery charging

✓ describe methods for preventing over-discharge of batteries

✓ understand three-stage charging and how voltage is regulated

✓ interpret charge controller specification sheets

Charge Controllers

- Recall that charge controllers are used in off-grid systems to prevent over-charge of batteries
- Chargers are also used to charge batteries from AC sources
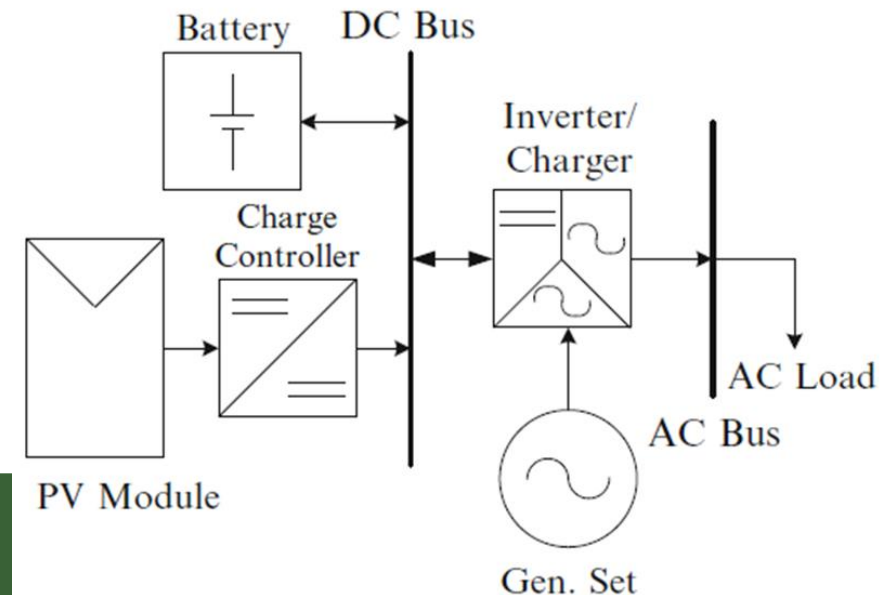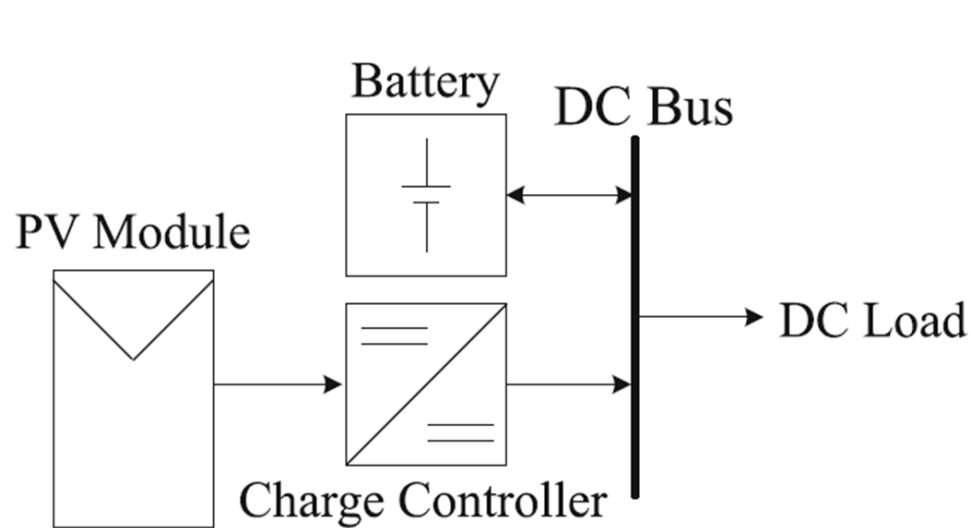
Solar Battery Charging

- 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
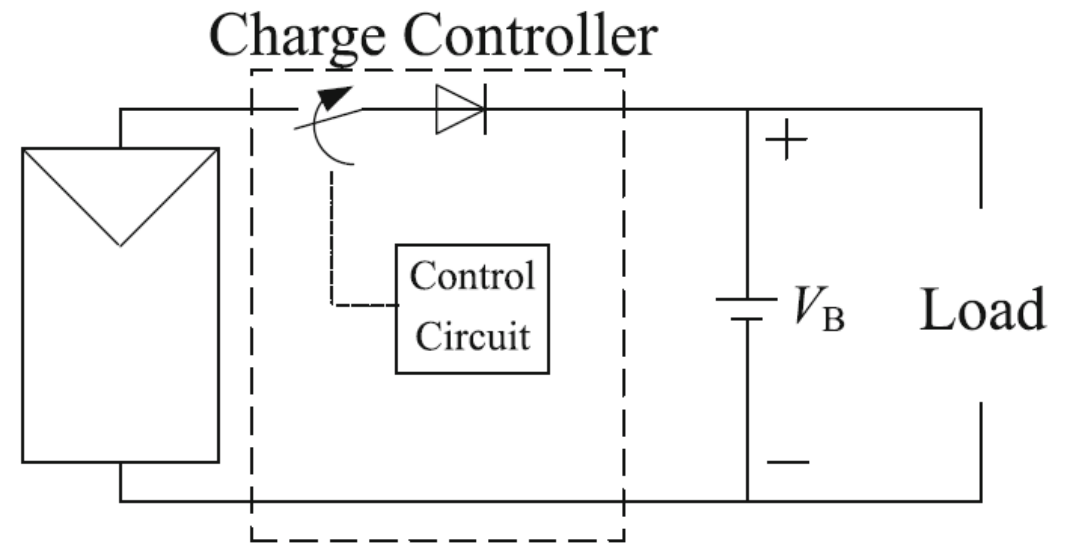
Shunt-Type Charge Controller

- 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

Charge Controller
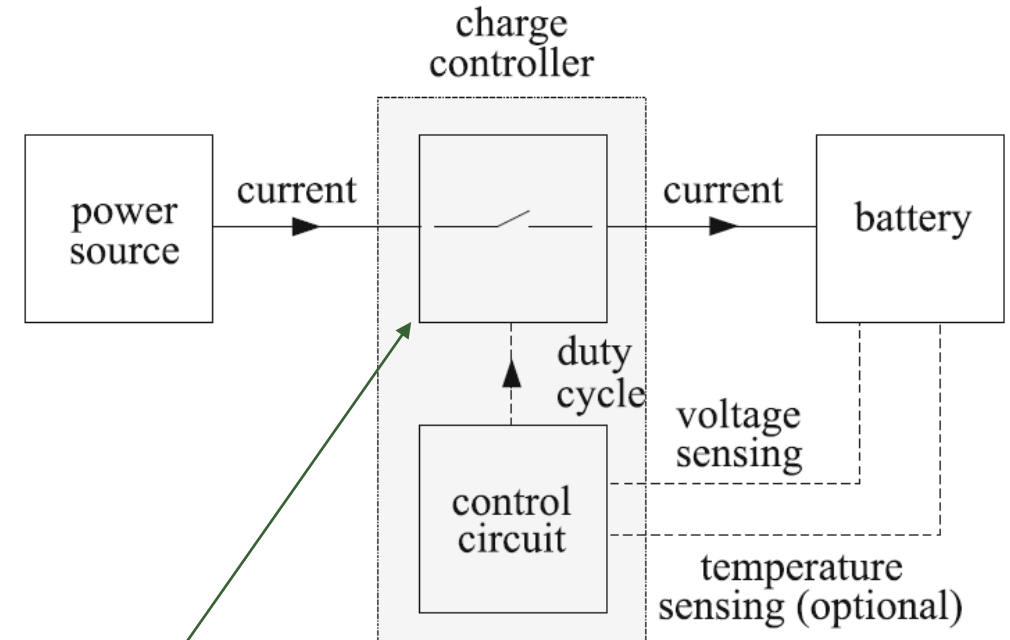
Control Circuit

V_B Load
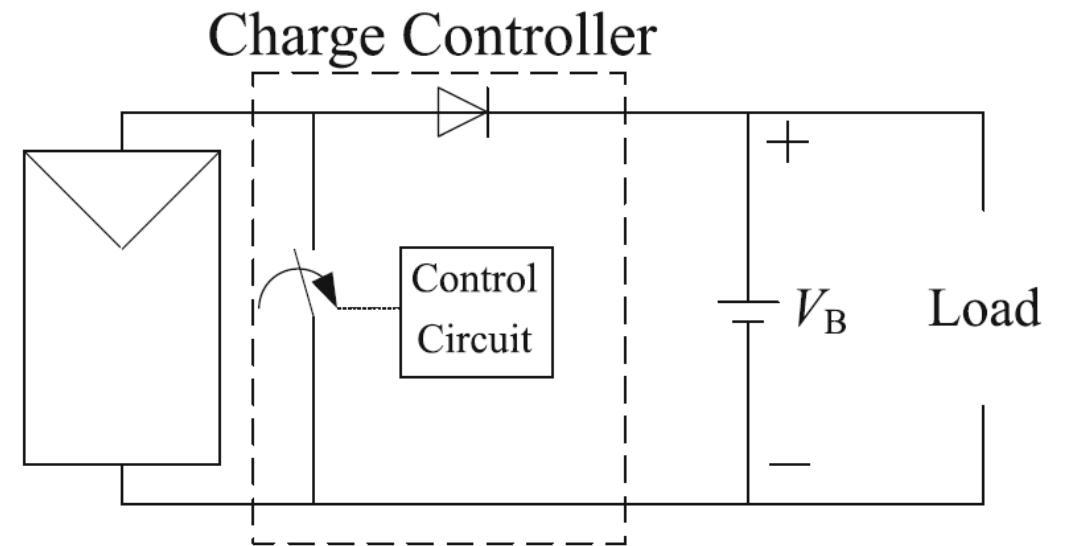
Series-Type Charge Controller

- 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)

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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

- Higher duty cycle: power source is connected longer, and more current on average is provided

- Allows for more sophisticated battery charging algorithms to be used, prolonging life and shortening charging time
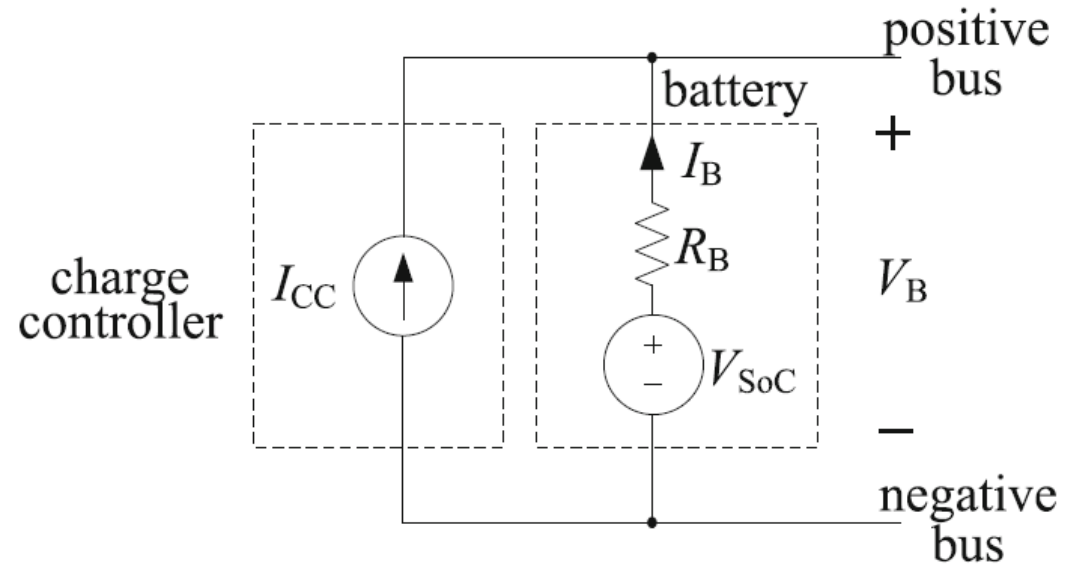

sometimes called a "DC chopper" circuit

Charge Controller circuit Model

- A PWM charge controller can control the current from the power supply (e.g. a PV module) within the limits of the power supply

- Model the charge controller as a current source

- From a KCL:

  $I_{CC} = -I_B$

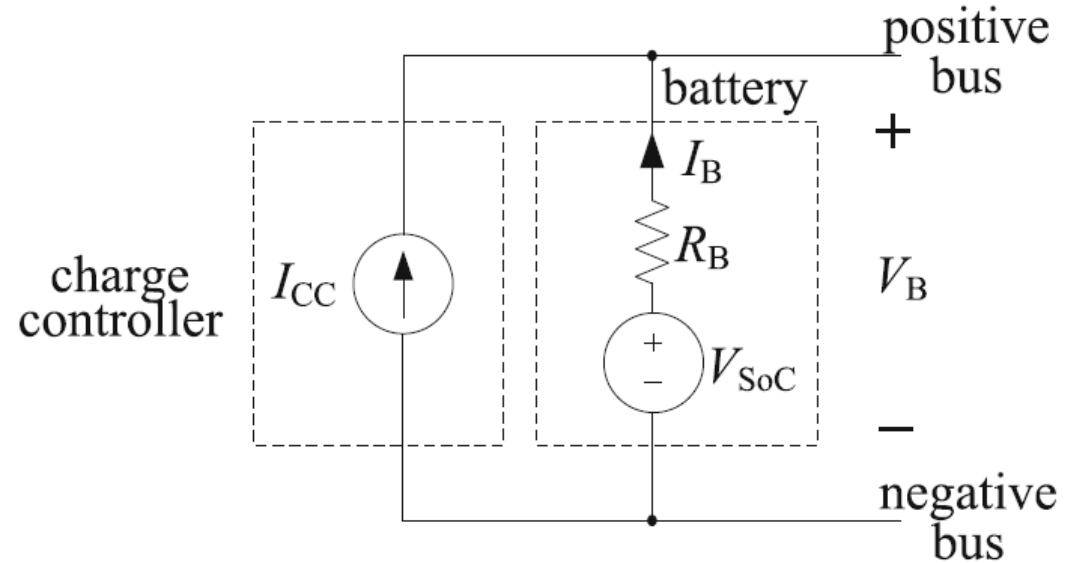Model of DC bus with charge controller and battery

Charge Controller circuit Model

- Battery terminal voltage:

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

- The battery terminal voltage depends on the charge controller current
  - Higher I_{CC} results in higher V_B
  - Recall that R_B and V_{SoC} vary based on state-of-charge, temperature, etc.

Model of DC bus with charge controller and battery

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

Example

Consider a 100Ah, 12V AGM lead-acid battery whose open-circuit voltage is 12.45V. 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.

Example

Consider a **100Ah**, 12V AGM lead-acid battery whose open-circuit voltage is 12.45V. 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 100Ah, which we assume is the 20-hour (C_{20}) capacity. So, the bulk stage current should not exceed 0.20 x 100 = 20 A.

Example

Consider a 100Ah, 12V AGM lead-acid battery whose open-circuit voltage is 12.45V. 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.

What is the battery voltage when the bulk stage starts?

Example

Consider a 100Ah, 12V AGM lead-acid battery whose open-circuit voltage is 12.45V. 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.

What is the battery voltage when the bulk stage starts?

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

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

Exercise

Consider the same 100Ah, 12V 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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Consider the same 100Ah, 12V 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?

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

The battery voltage will rise during the bulk stage

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 12V 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

- Battery is approx. full at the end of the absorption stage

Example

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.

Example

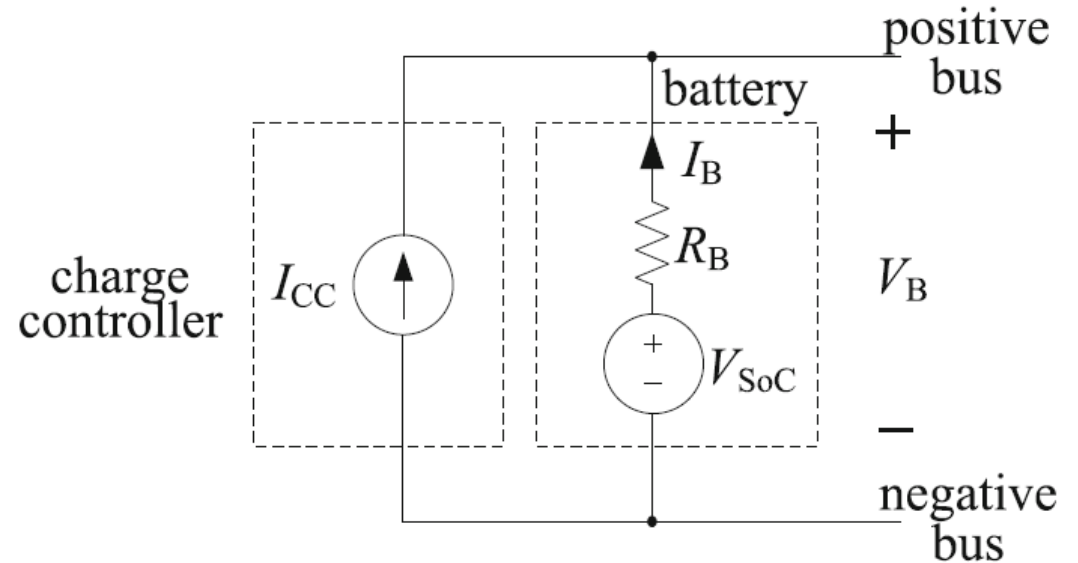$$V_B = 14.4 \text{ V}$$

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

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

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

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

Exercise

A battery is connected to solar panel through a charge controller and is being charged in the absorption stage. The V_{SoC} has risen to 12.95V and $R_B = 0.2\ \Omega$. Compute the current that should be provided to the battery to achieve the absorption voltage set-point of 14.4 V.

Exercise

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

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

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

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

$$\frac{-14.4 + 12.95}{0.2} = I_B = -7.5 \text{ A (7.5 A of charging)}$$
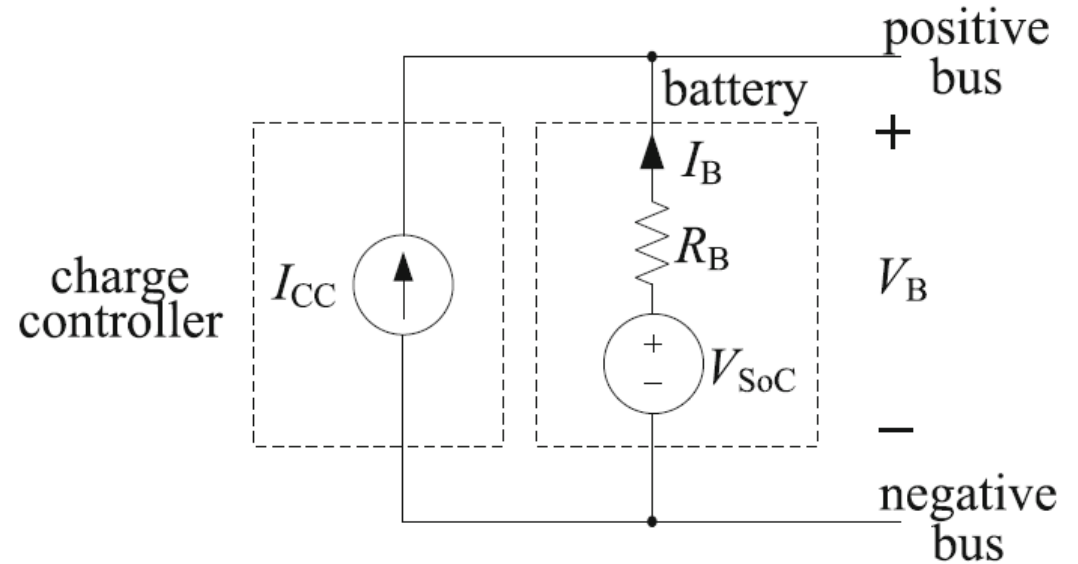
The battery current decreases as the absorption stage progresses

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

Example

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

Example

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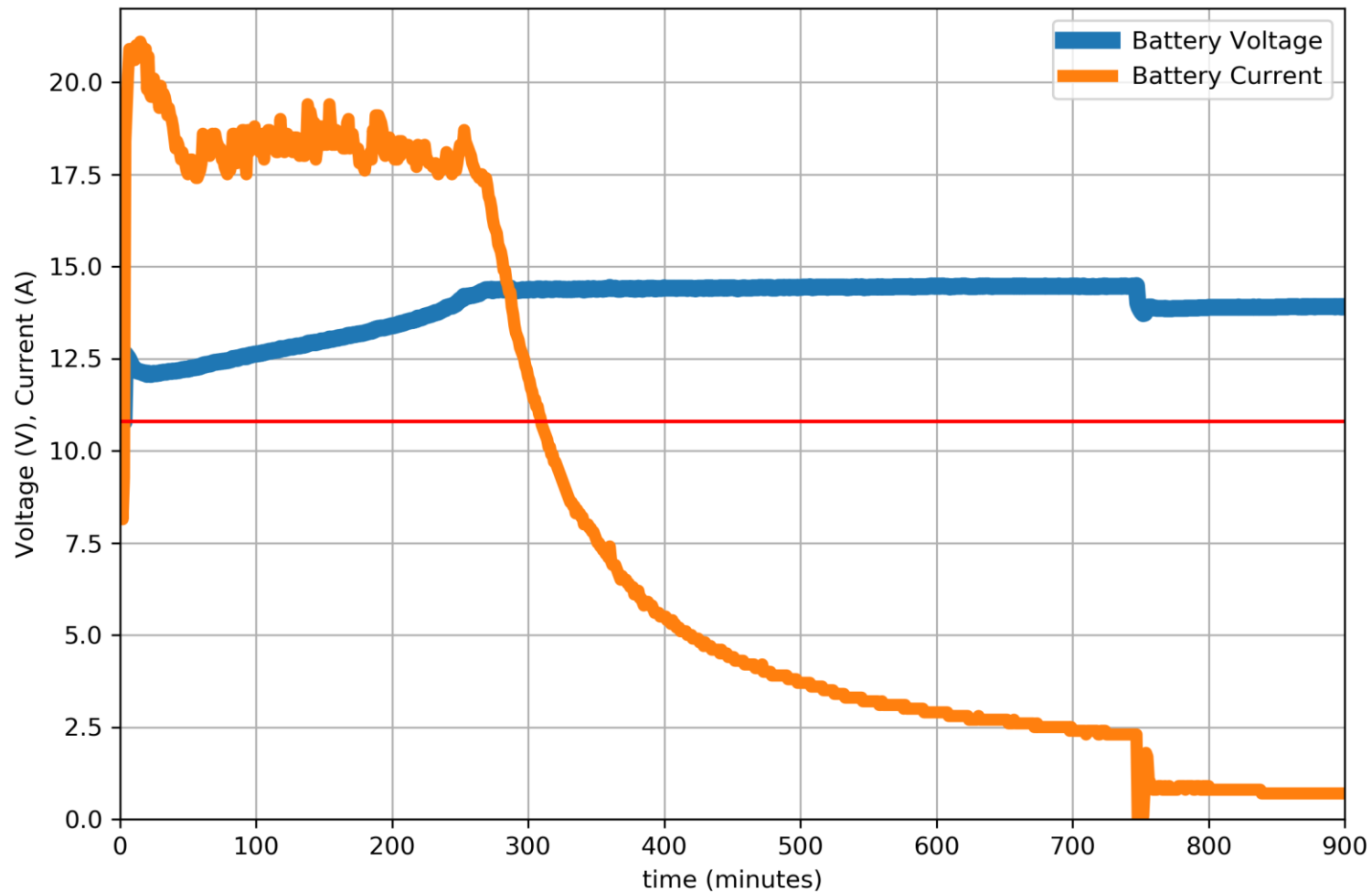
$$V_B = 13.8 \text{ V}$$

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

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

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

The current drops once float stage is entered

Three-Stage Charging
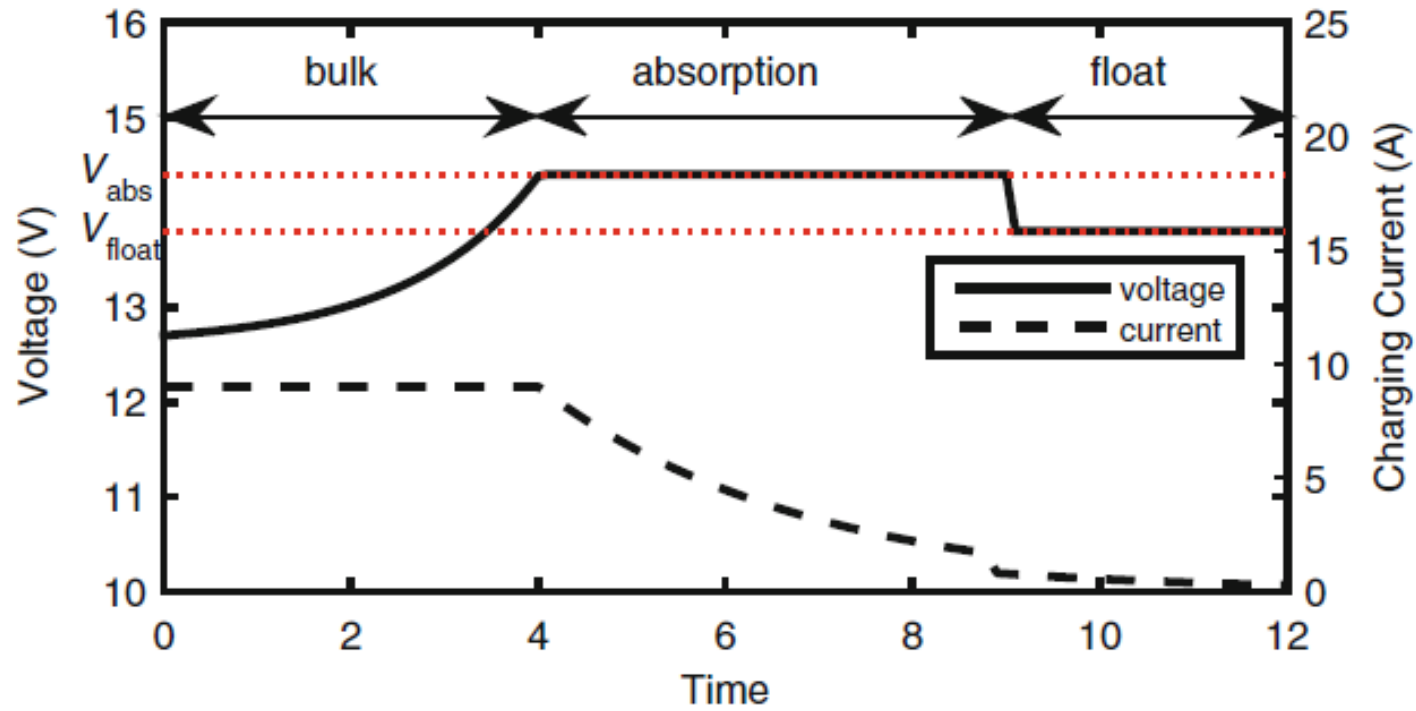
Input current limit by charger: 20A

Absorption set-point: 14.4V
Float set-point: 13.8V
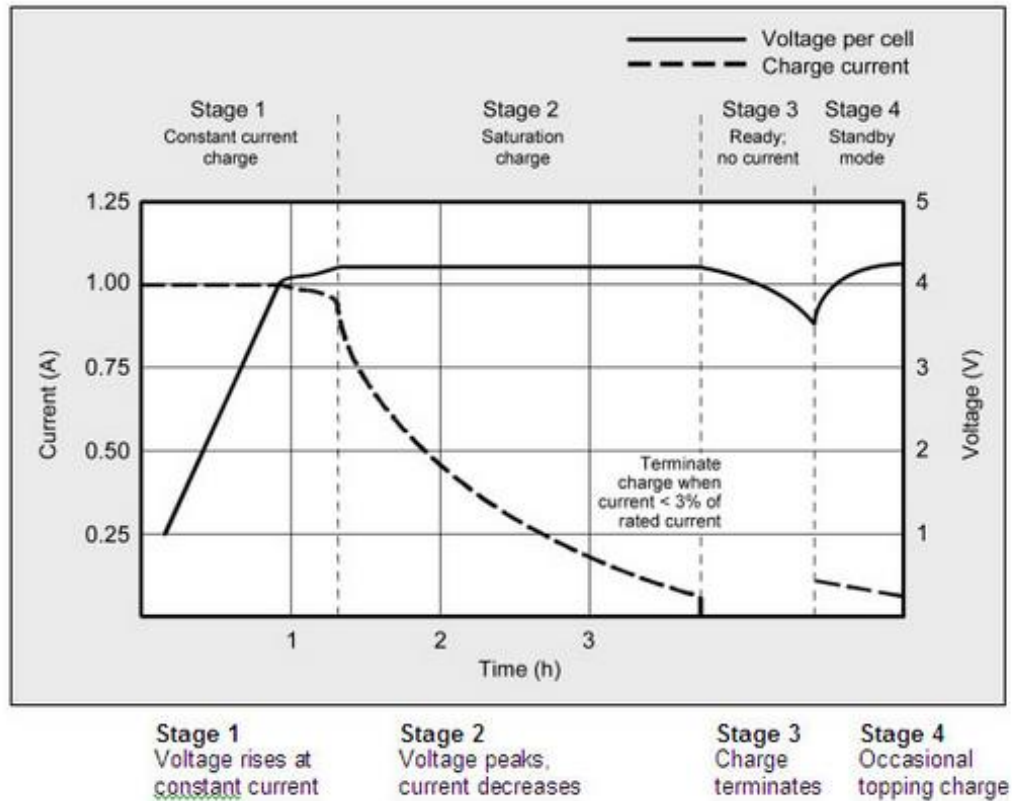
(12V, 100 Ah, AGM Battery)

Charging Li Batteries

Figure 1: Charge stages of lithium-ion. Li-ion is fully charged when the current drops to a set level. In lieu of trickle charge, some chargers apply a topping charge when the voltage drops.
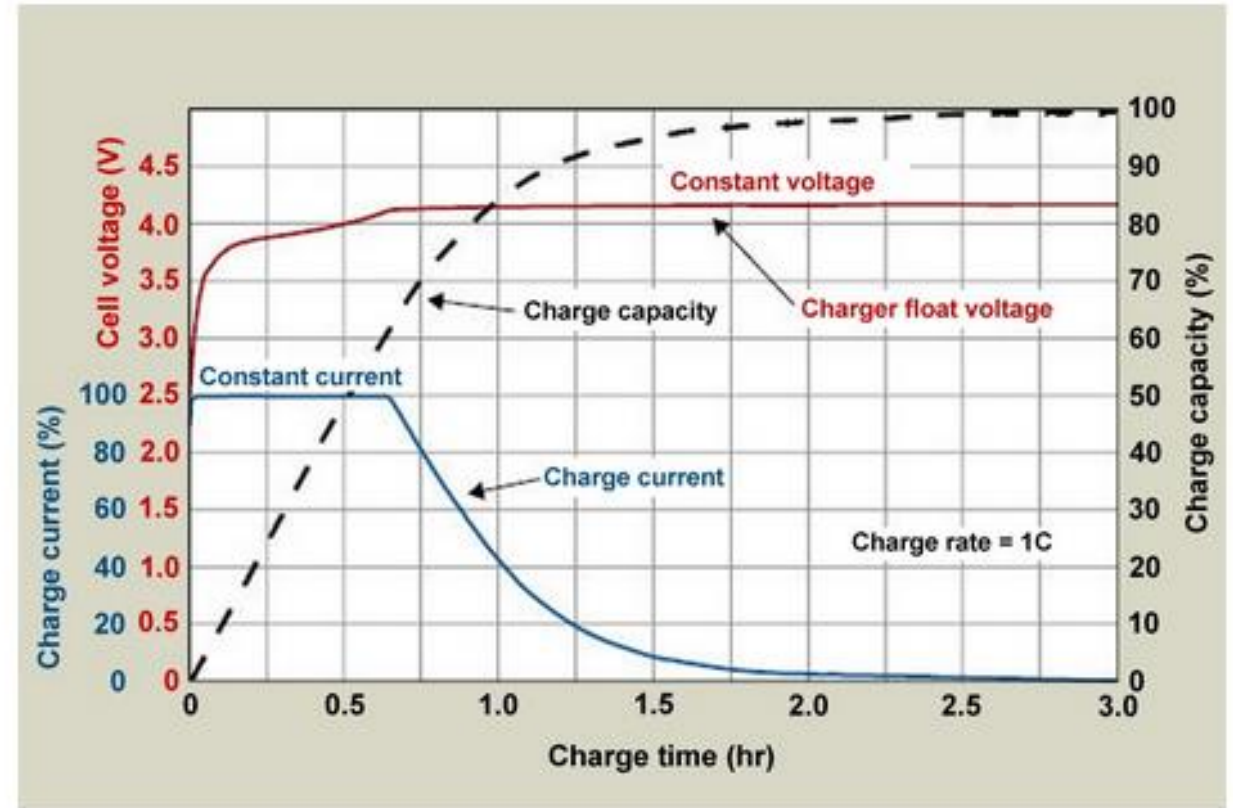
Courtesy of Cadex

Figure 3: Volts/capacity vs. time when charging lithium-ion. The capacity trails the charge voltage like lifting a heavy weight with a rubber band.

Courtesy of Cadex

Other Considerations

- Equalization Charge: maintenance charge, a temporary (1-2 hours) 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

Charging with Load
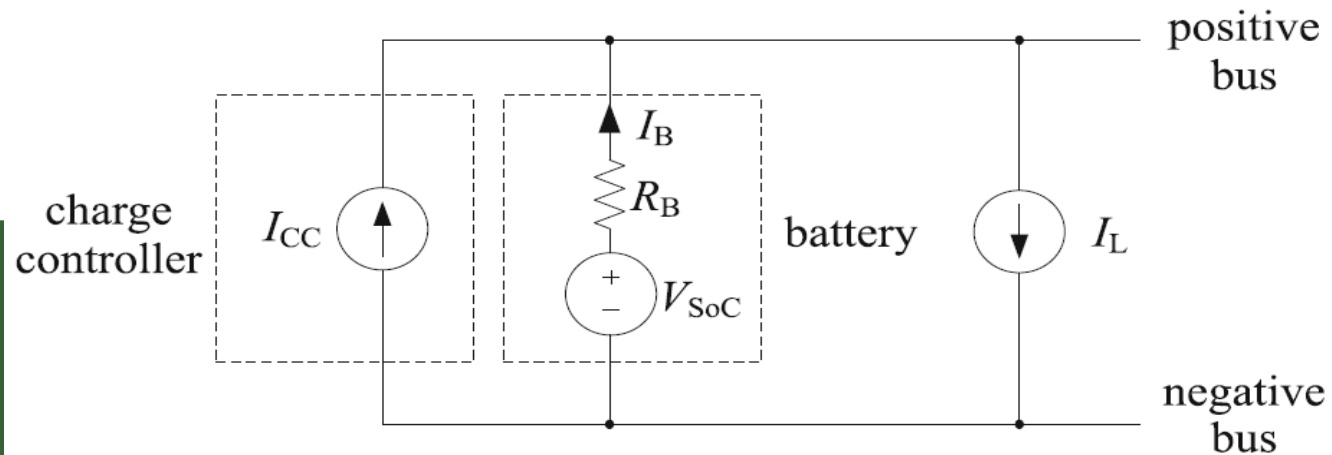

Model load as current source (note the direction)
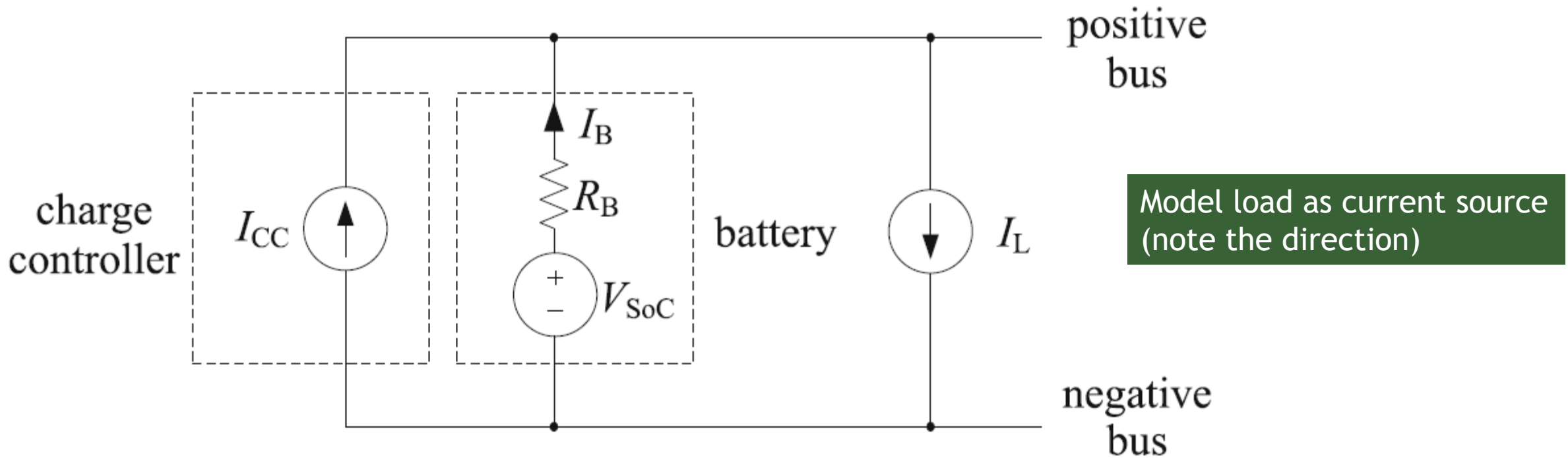
Charging with Load

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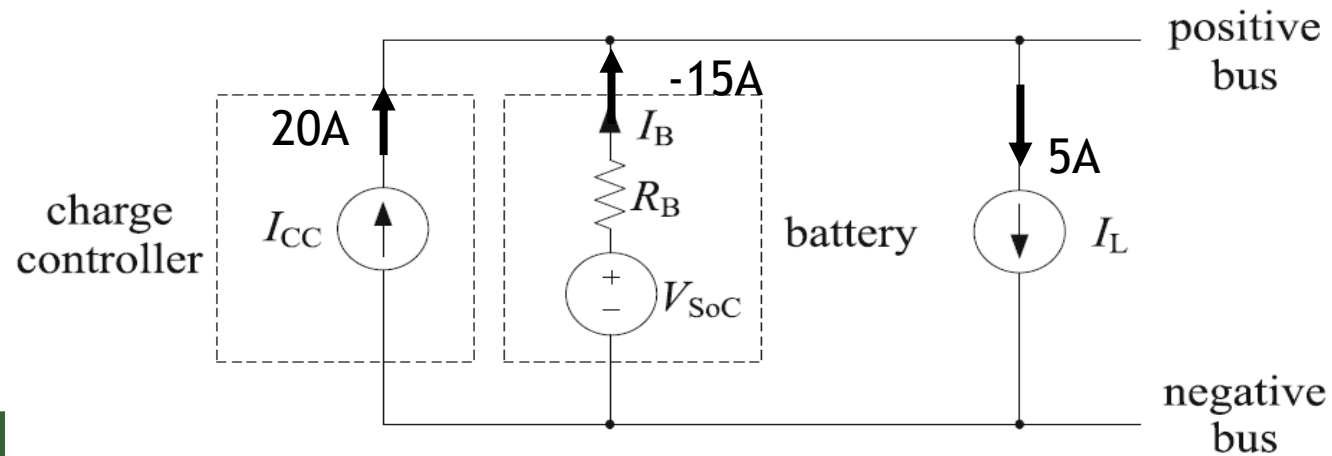
- From KCL at the positive bus:

$I_{cc} + I_B = I_L$

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

Example

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

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
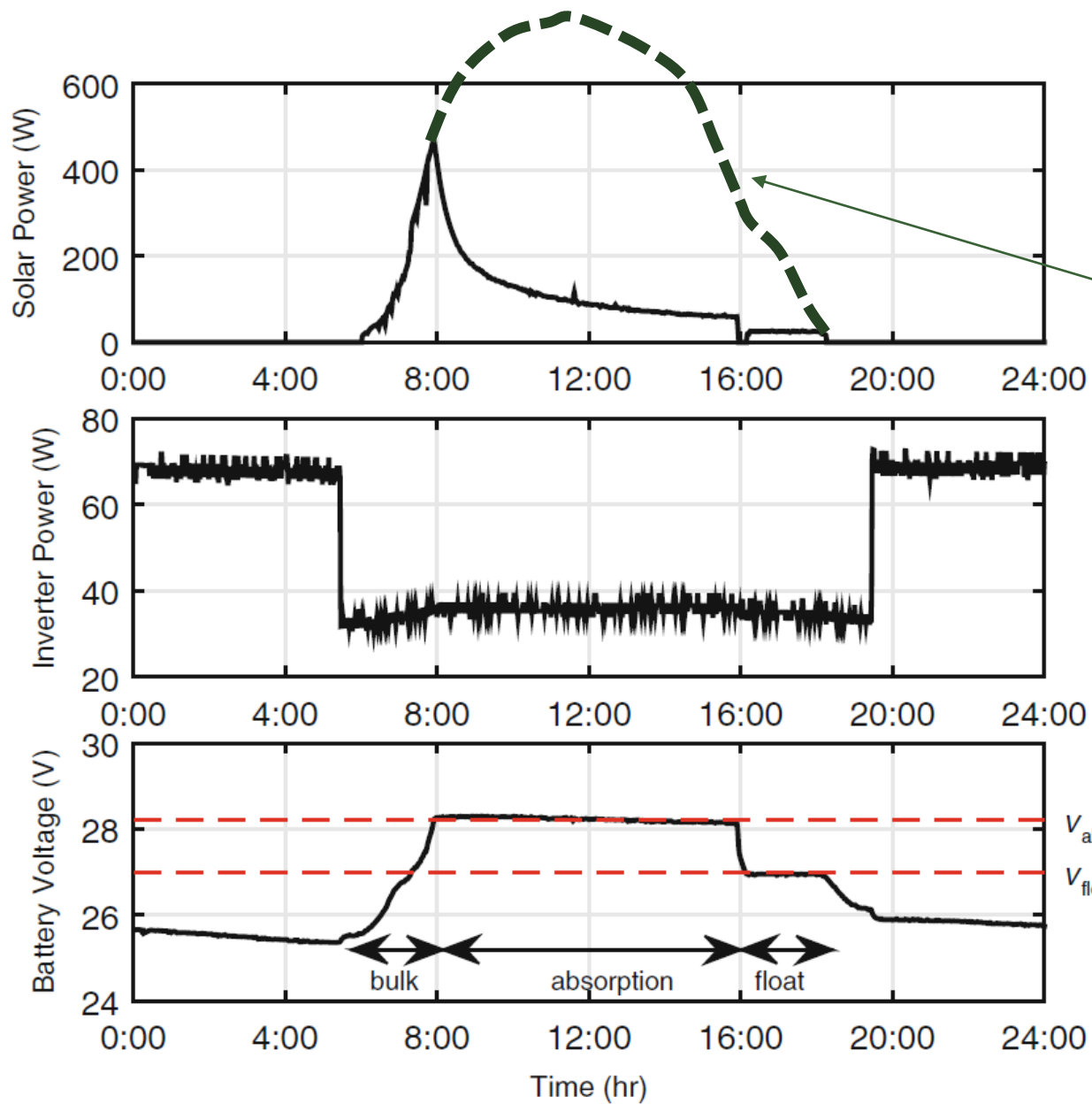
PV array could produce additional power, but the load is low and the charge controller is limiting current
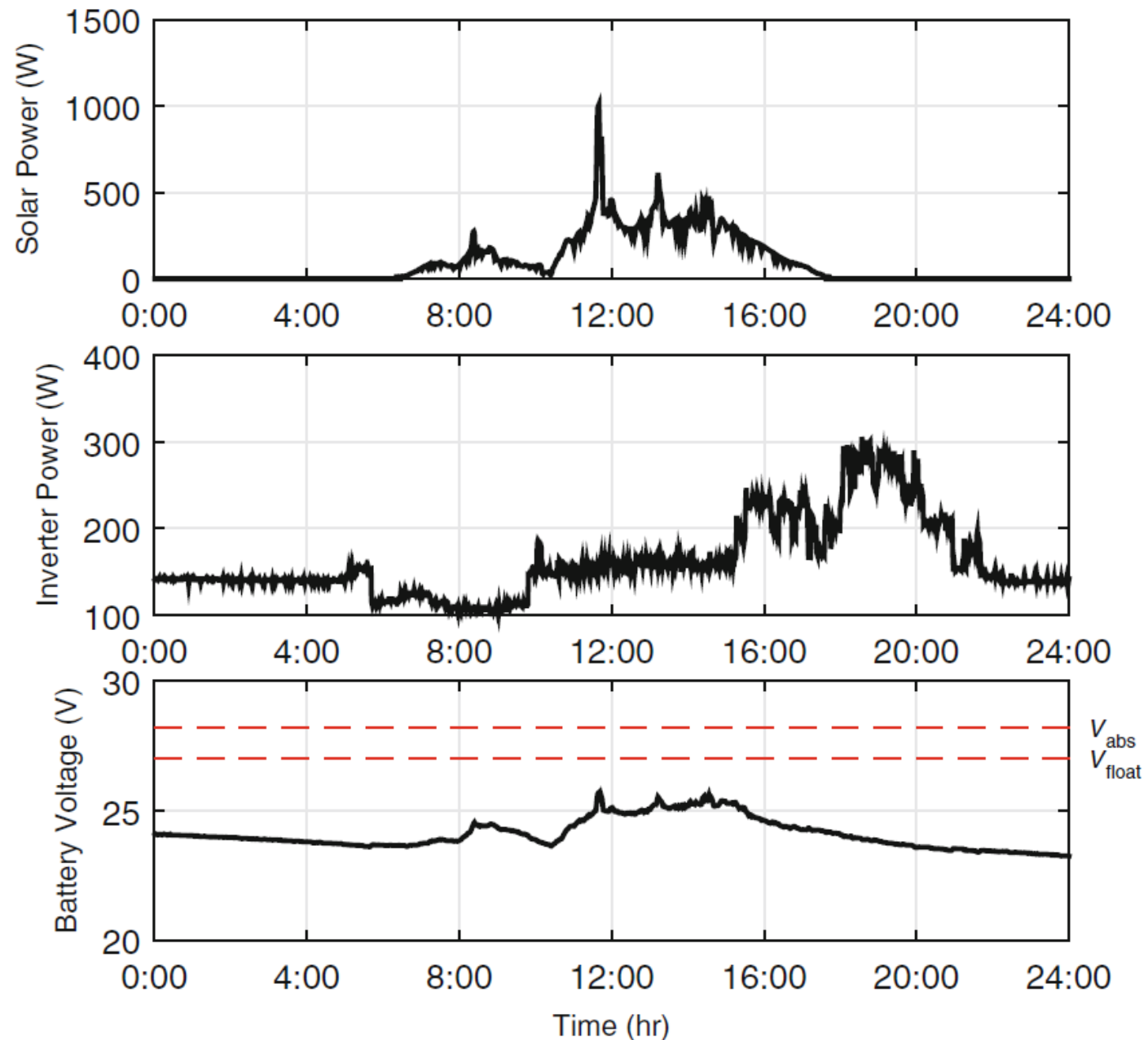
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Power-Constrained Charging
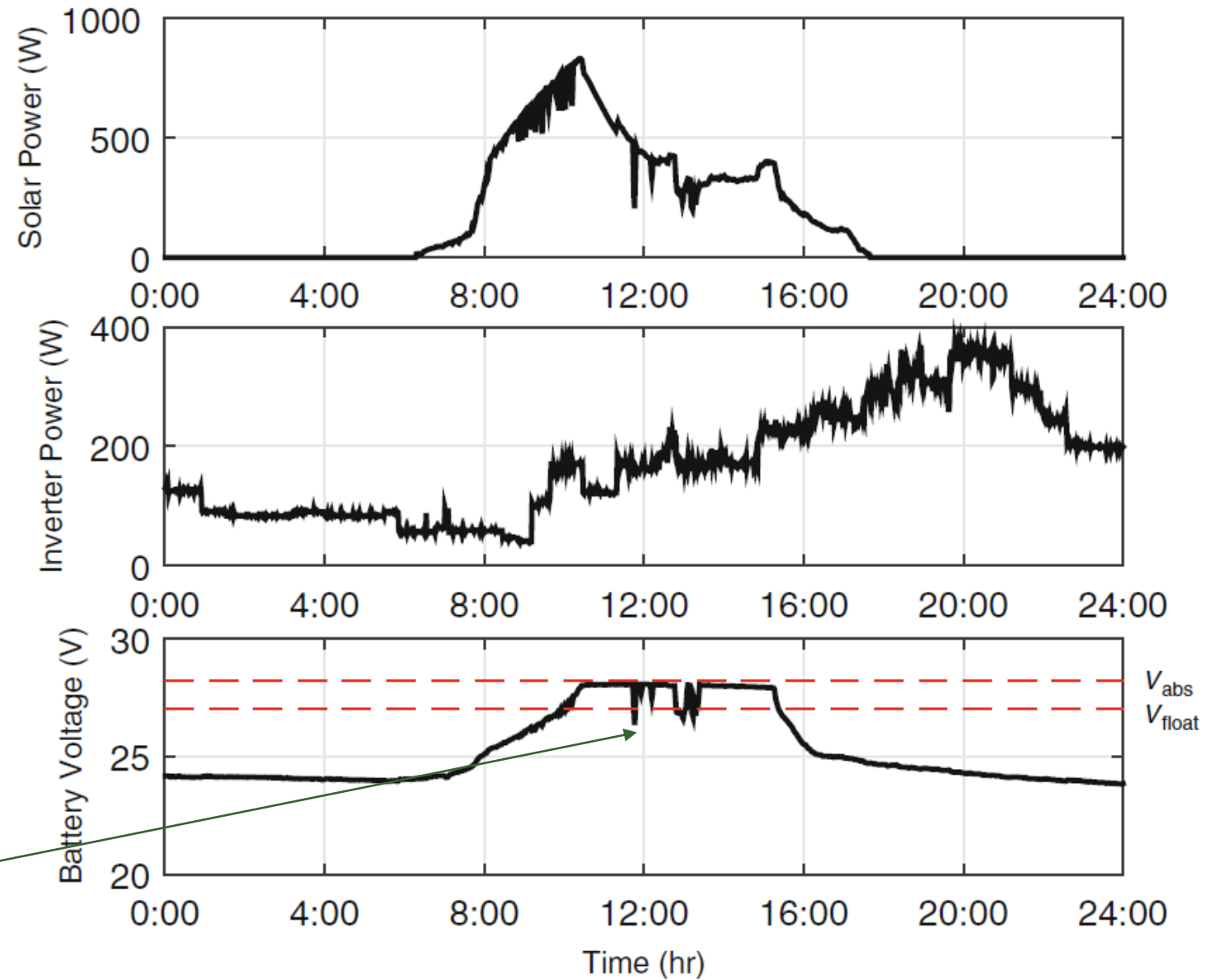
Absorption set-point voltage cannot be maintained due to load spikes

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
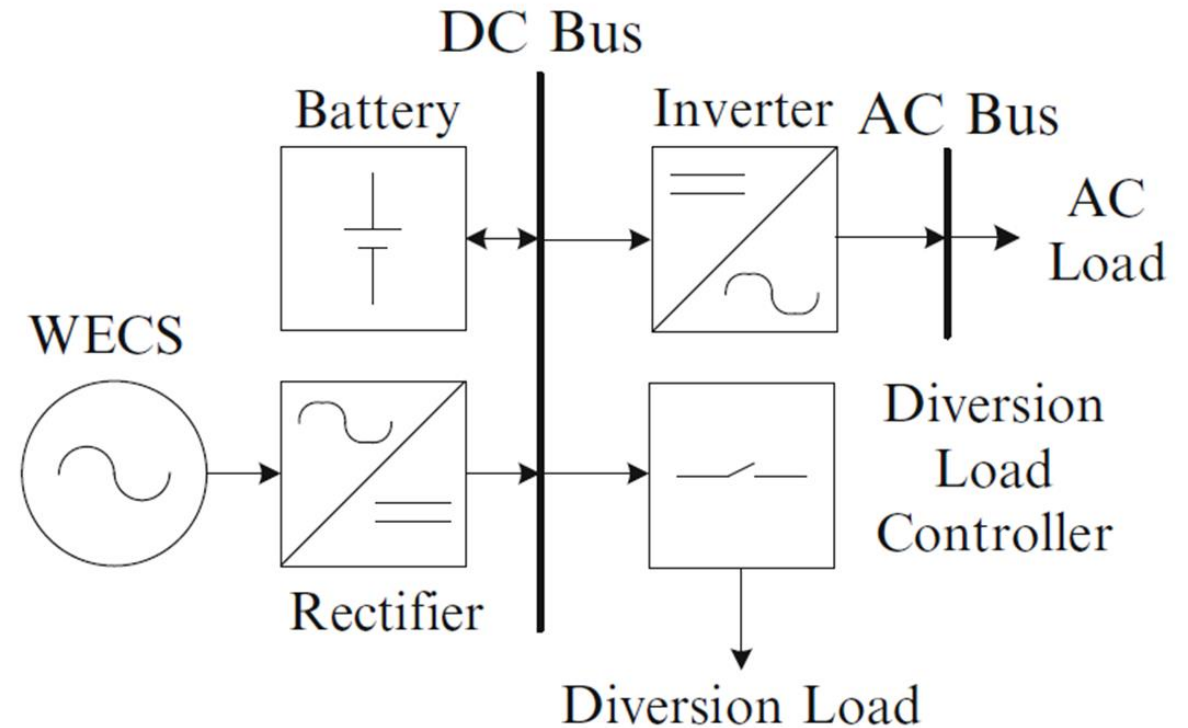
Charge Controller with Additional Generator

- Hybrid systems have other energy conversion systems capable of supplying power to the DC bus

- Model them as a generic generator connected to the DC bus

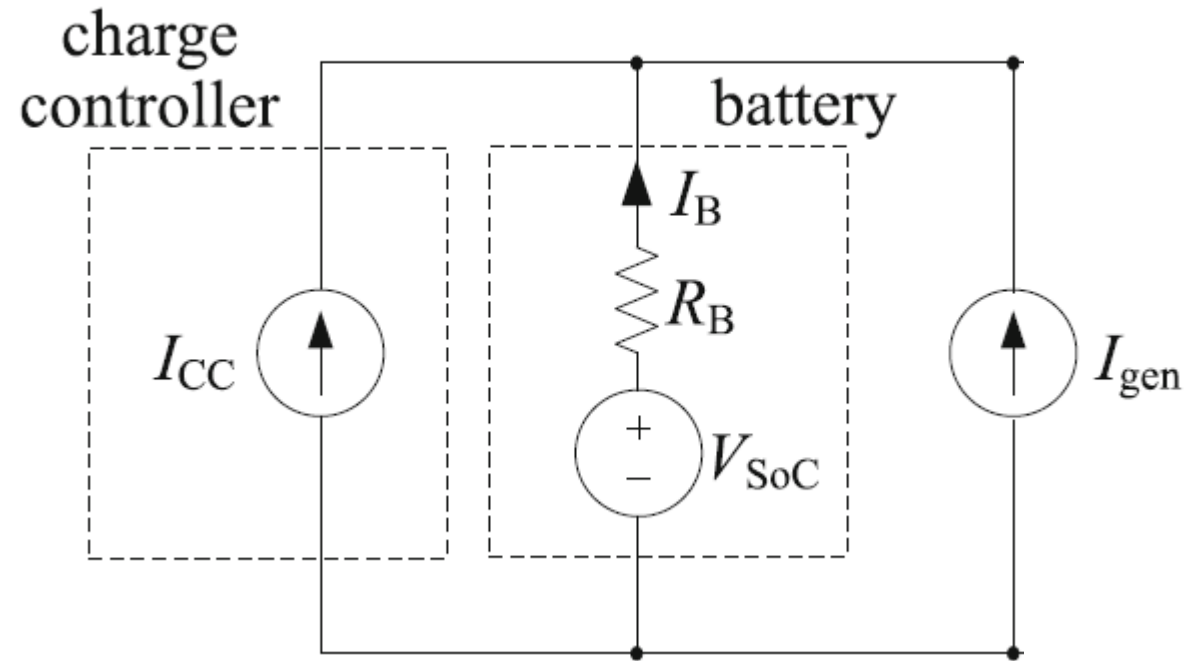- Charge controller cannot directly control this generator's output
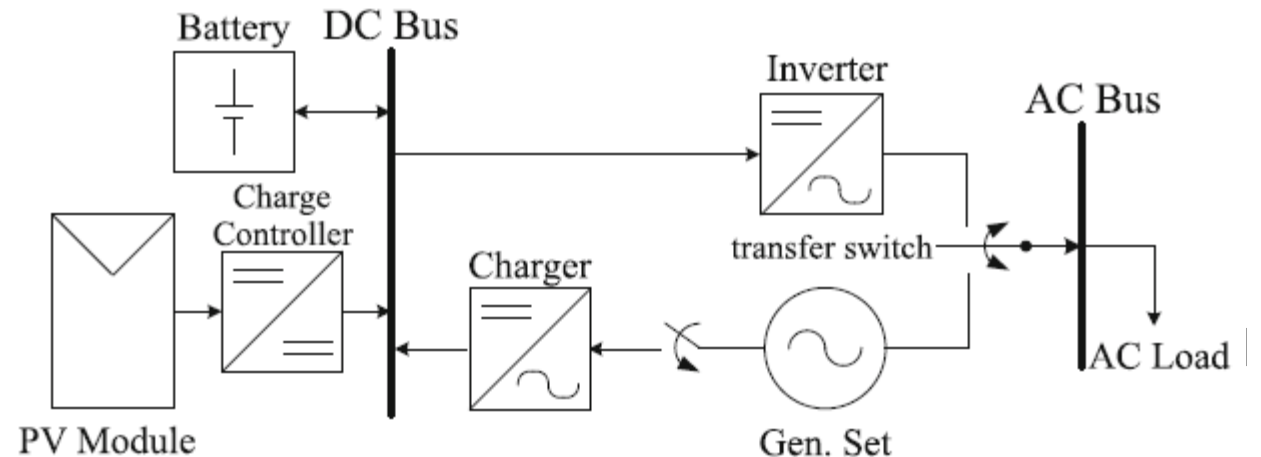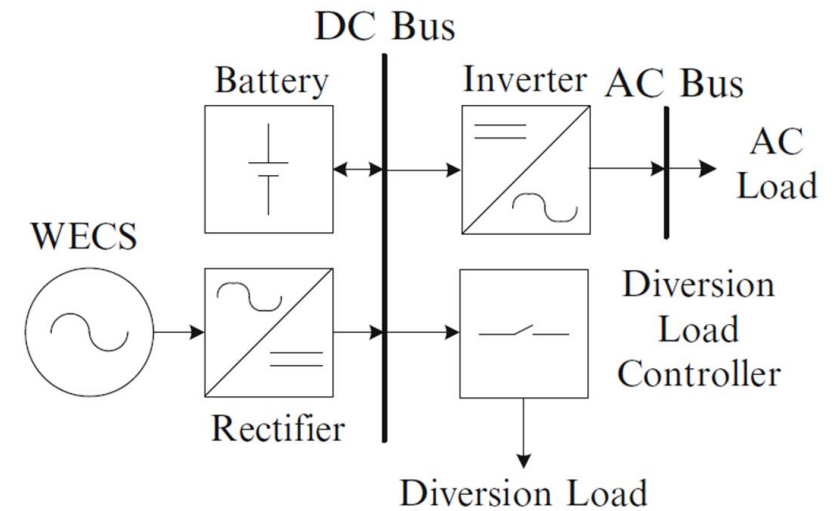
Charge Controller with Additional Generator

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

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

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

Example

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 5A. The V_{SoC} is 12.95V and R_B = 0.2 Ω. Compute the current required by the charge controller to maintain an absorption voltage set-point of 14.4 V.

Example

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

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

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

$$\frac{-V_B + V_{SoC}}{R_B} = I_B$$
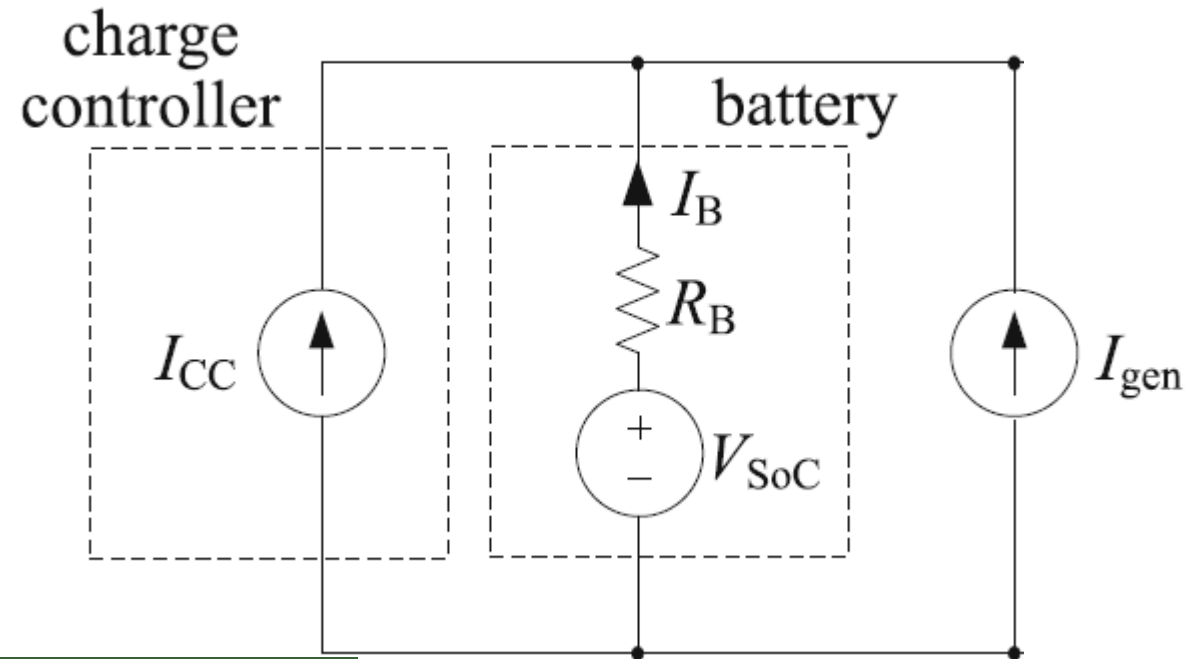
$$\frac{-14.4 + 12.95}{0.2} = I_B = -7.5 \text{ A}$$

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

This is the current from the charge controller without the wind turbine

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

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

Charge controller only needs to supply 2.5 A

charge controller

battery

I_B

R_B

I_{CC}

V_{SoC}

I_{gen}

Example

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 10A. The V_{SoC} is 12.95V and $R_B = 0.2 \, \Omega$. Compute the current required by the charge controller to maintain an absorption voltage set-point of 14.4 V.

Example

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

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

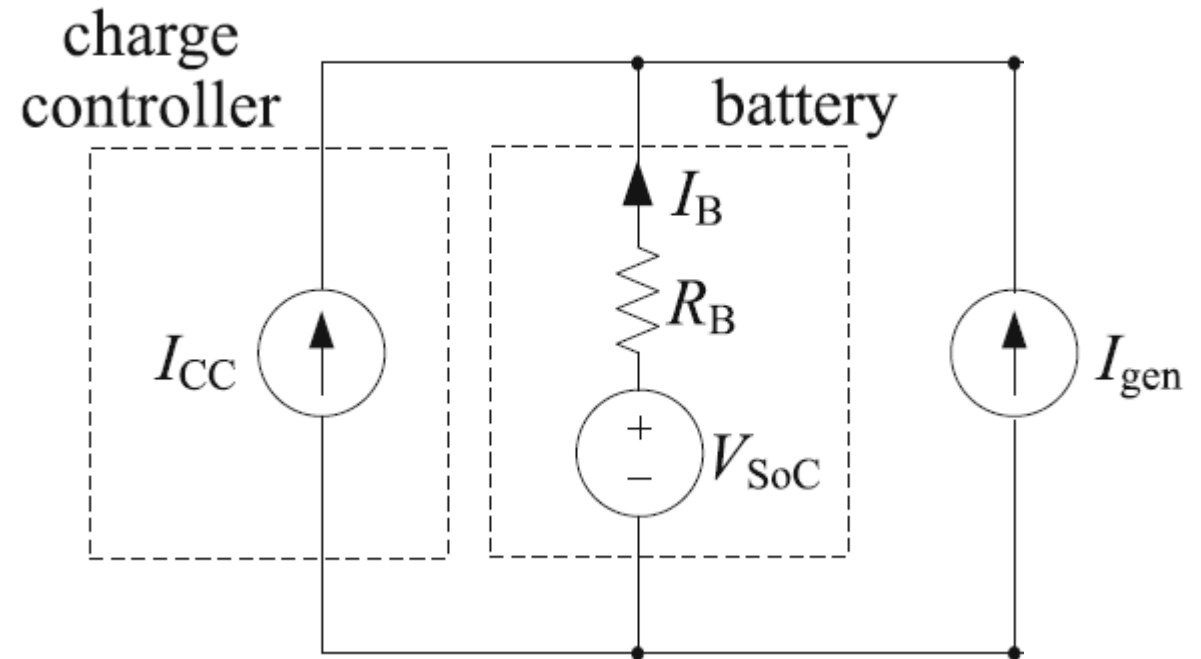$$\frac{V_B - V_{SoC}}{R_B} = -I_B$$

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

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

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

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

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

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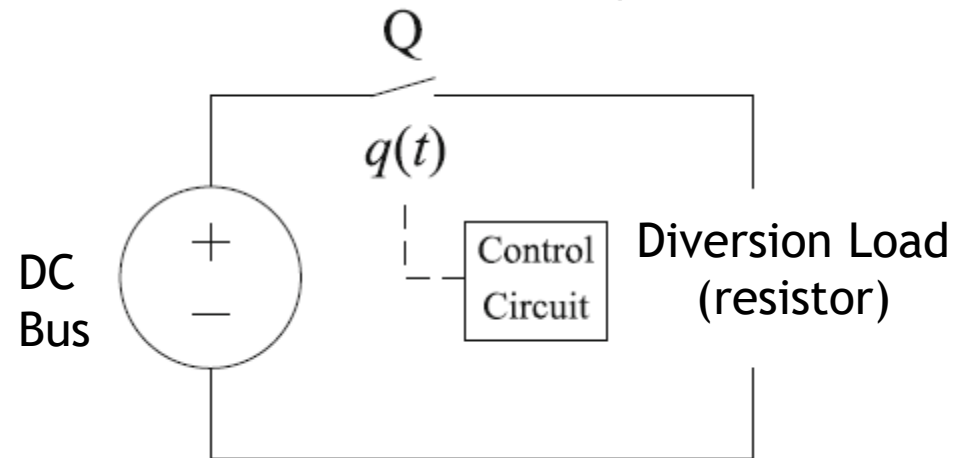
Diversion Load Controller (DLC)

- Previous example highlights the need for another controller for systems with other uncontrollable generation (wind turbines, some hydro turbines)

- Charge controller can only act as a current source (cannot supply negative current)

- Solution: add a controllable current sink

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
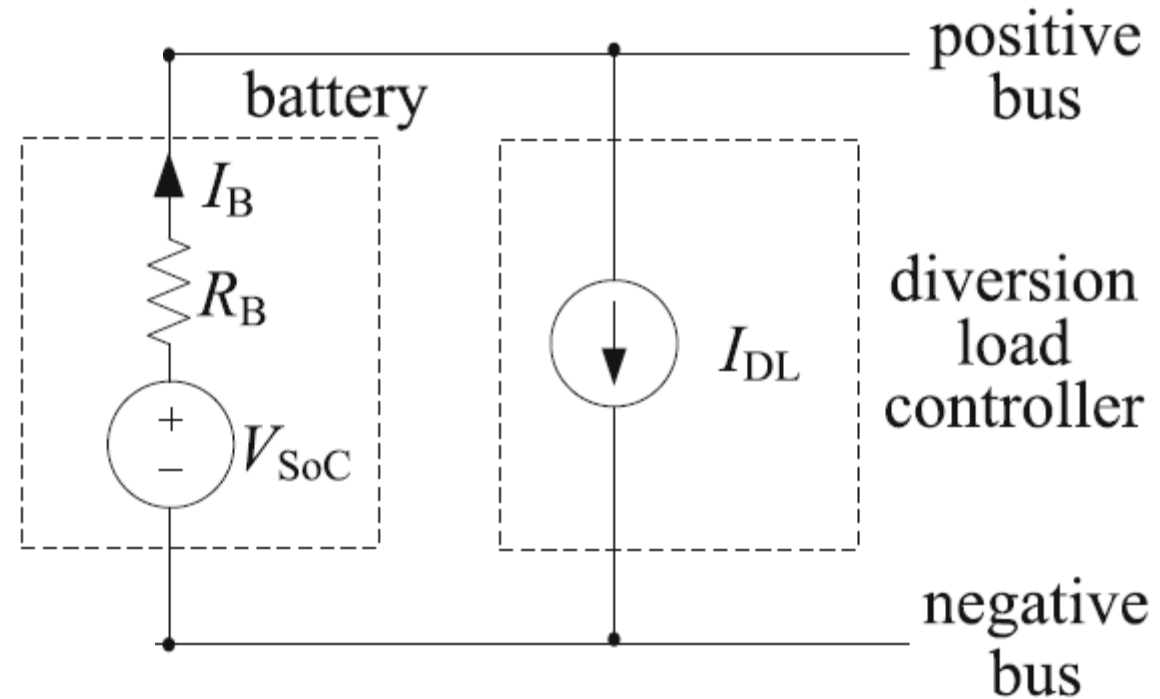
Diversion Load Controller

- 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

DC Bus with Diversion Load Controller

Note: I_{DL} must be non-negative
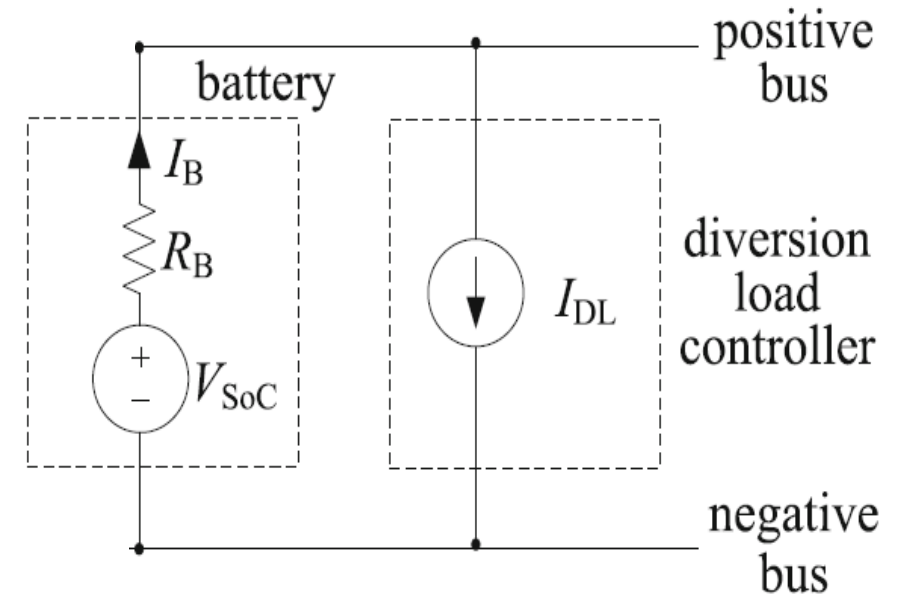
DC Bus with Diversion Load Controller

- From KCL at positive bus:

$I_B = I_{DL}$

- Battery terminal voltage:

$V_B = V_{SoC} - I_B R_B = V_{SOC} - I_{DL} R_B$

- The battery terminal voltage depends on the diversion load current

- Diversion load can control battery voltage

Example

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 10A. A diversion load controller is connected to the DC bus.

The V_{SoC} is 12.95V and $R_B = 0.2\ \Omega$. Compute the current required by the charge controller and diversion load controller to maintain an absorption voltage set-point of 14.4 V.

Example

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

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

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

$$\frac{-V_B + V_{SoC}}{R_B} = I_B$$
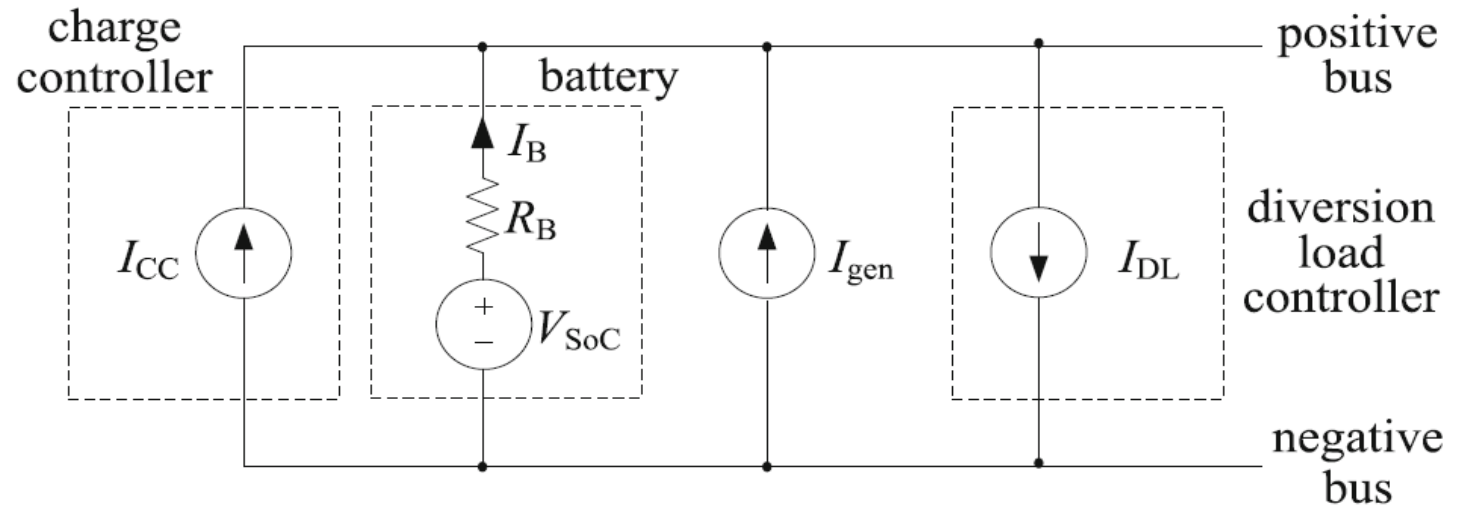
$$\frac{-14.4 + 12.95}{0.2} = I_B = -7.5 \text{ A}$$

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

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

$$I_{CC} = 0A$$

$$I_{DL} = 2.5A$$

KCL:
$I_{CC} + I_B + I_{gen} = I_{DL}$

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

DC Bus with Multiple Components

- If the power associated with DC bus components is known instead of current, convert to current by dividing the power by nominal battery bank voltage (approximation)

- Multiple charge controllers, batteries, loads (including inverters), generators, diversion loads, etc. can be modeled and analyzed in this fashion

DC Bus with Multiple Components
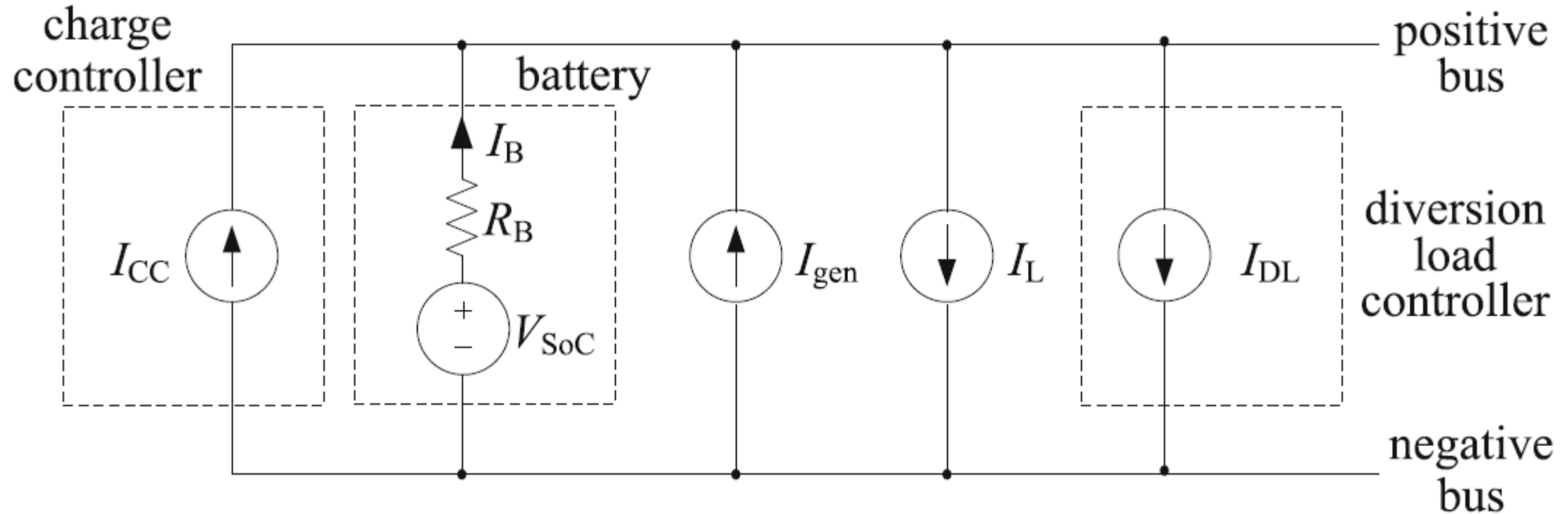
Low Voltage Disconnect

- 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 <u>some</u> 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
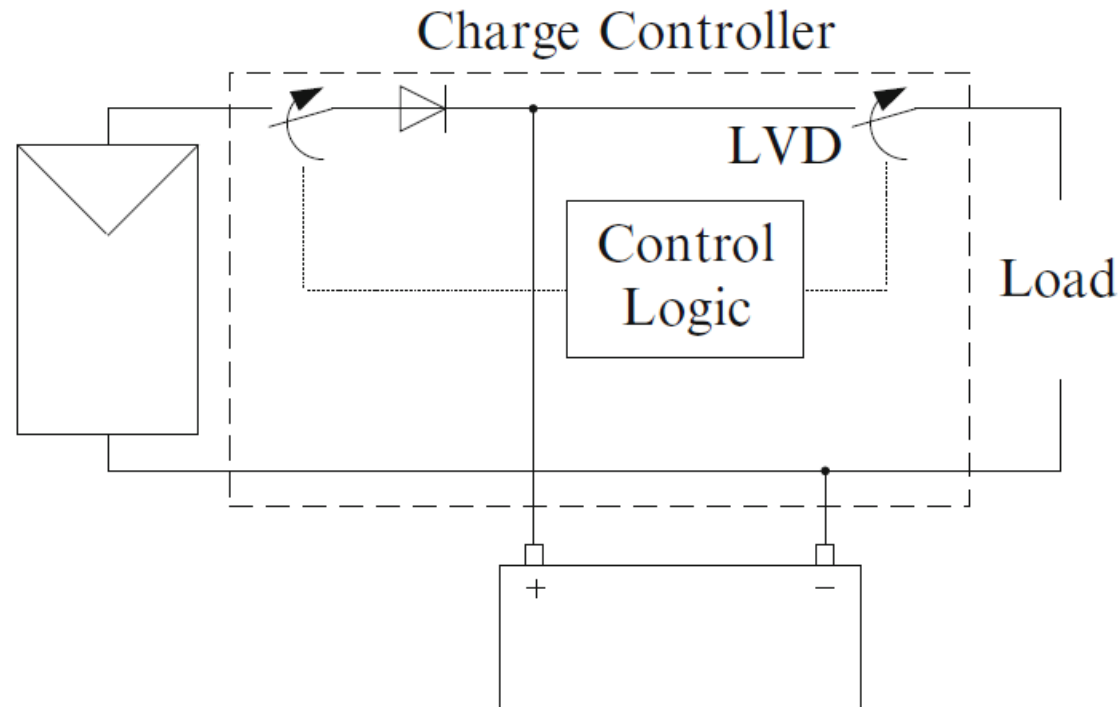
Low Voltage Disconnect Set-Points

- 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
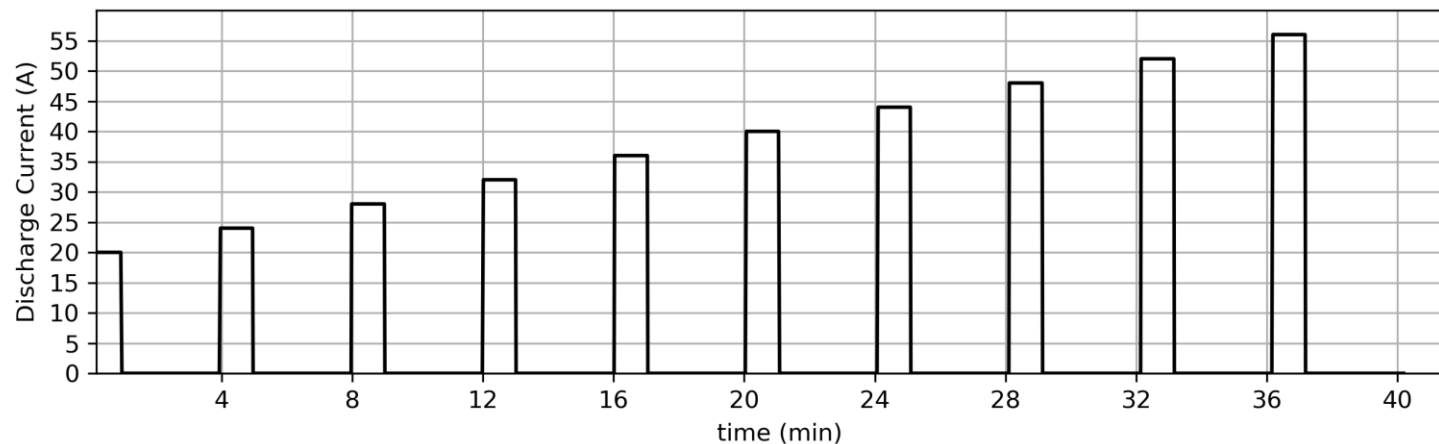
Low Voltage Disconnect

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

- $V_{LD,con}$: low voltage disconnect reconnect set-point
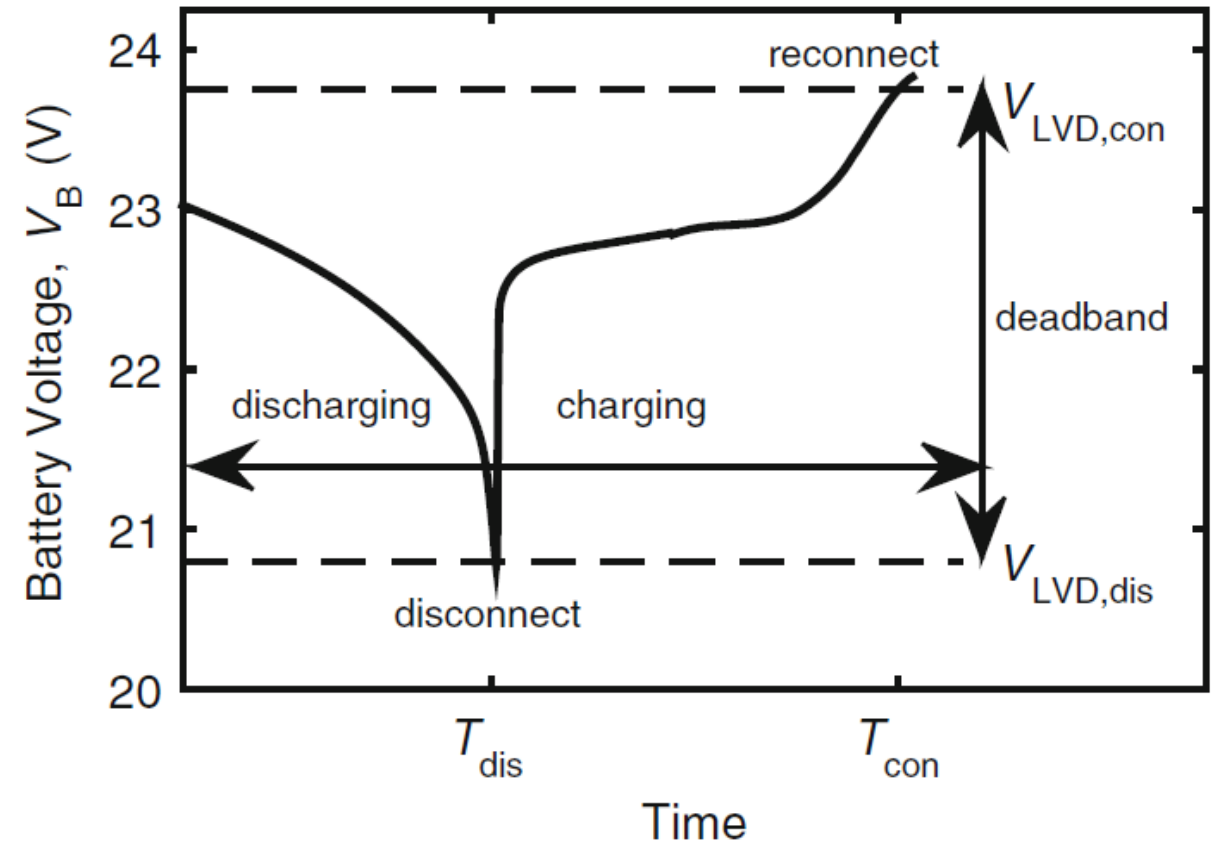
Why is a dead band needed?
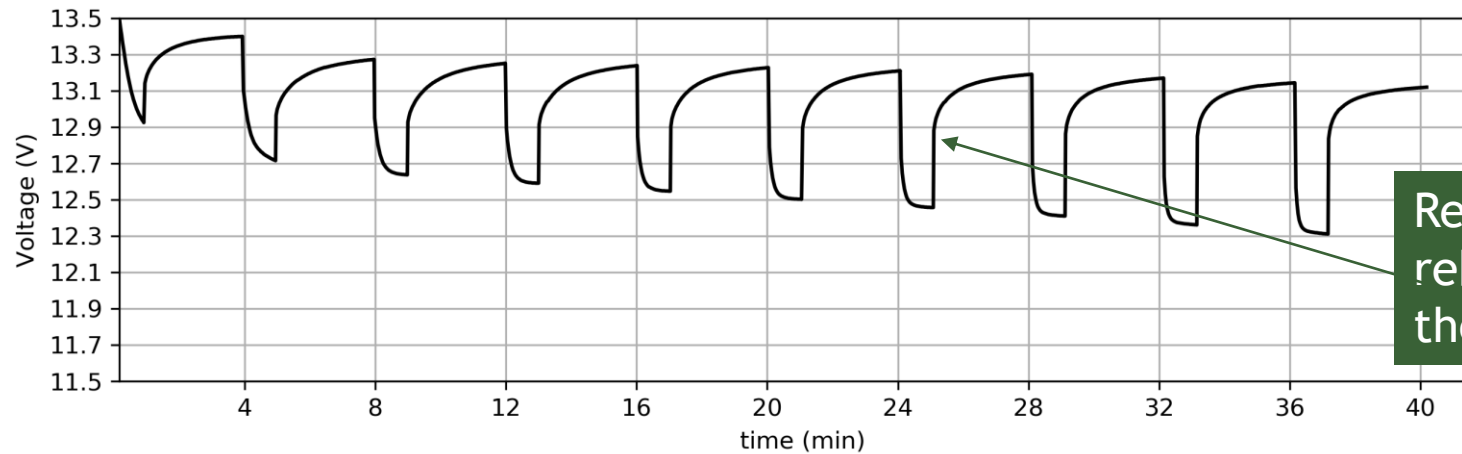
Recall that the voltage rebounds as soon as the load is removed.

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

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Proper Dead Band Behavior
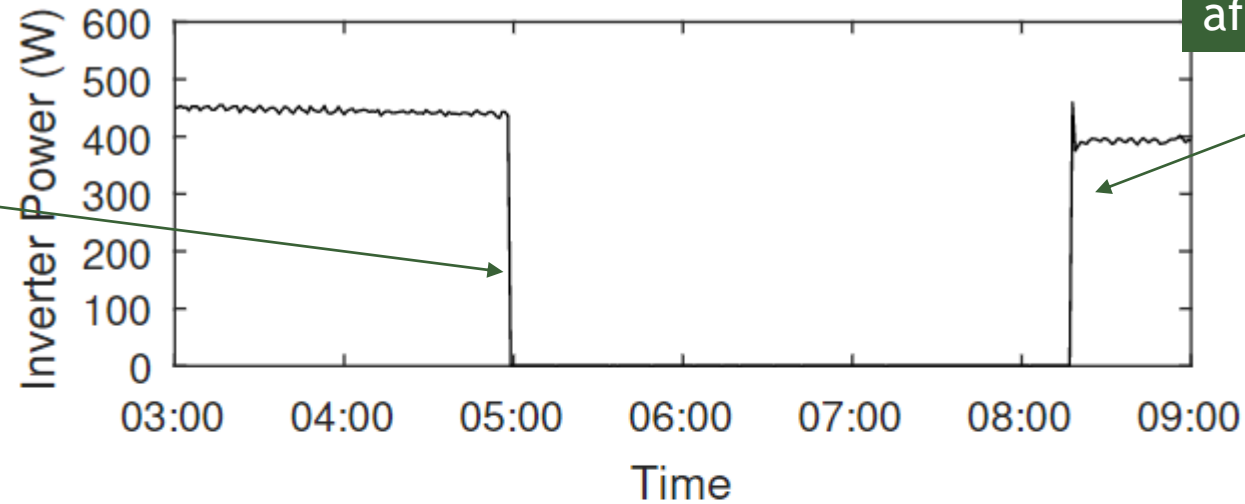
LVD re-connects only after PV recharges the battery after sunrise

LVD disconnects

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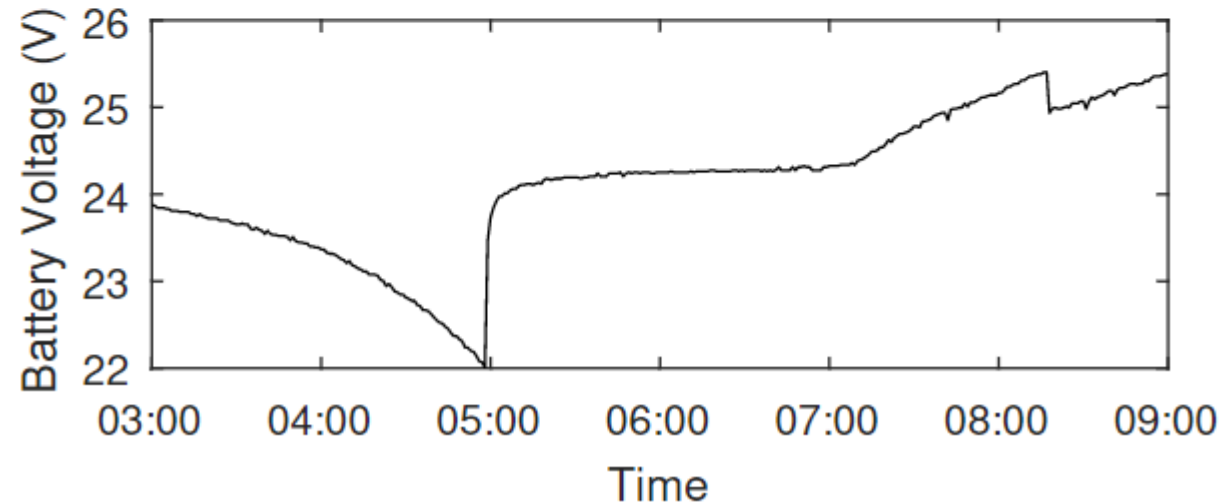
Dead Band Not Large Enough

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!)

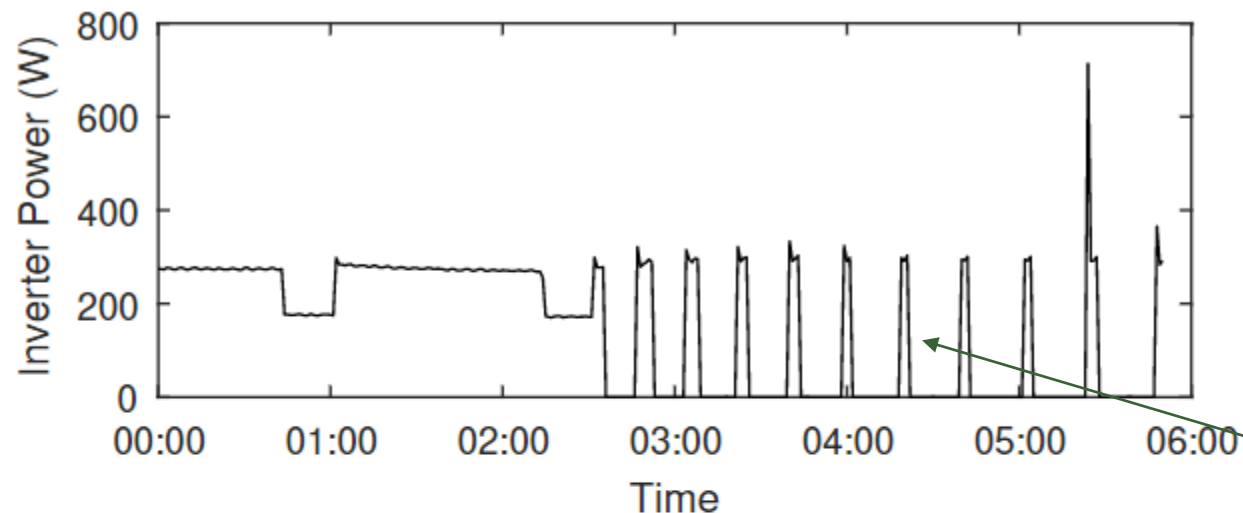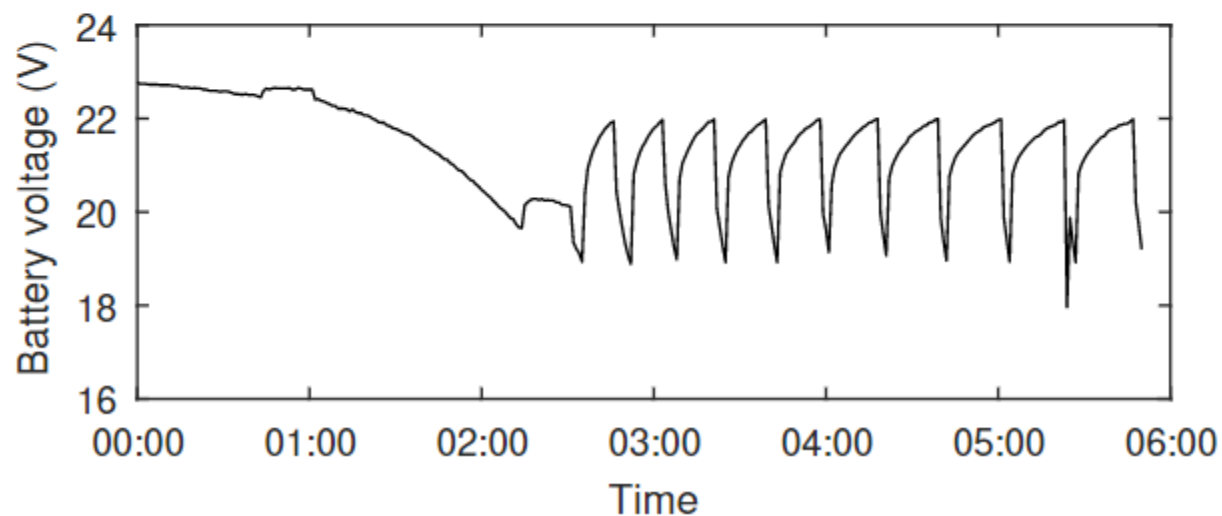Rated continuous PV input power (note that the higher the battery bank voltage, the higher the rated power). Some charge controllers will limit the power from the PV array to this level if it this level would otherwise be exceeded

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	

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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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Humidity	95 %, non-condensing	
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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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