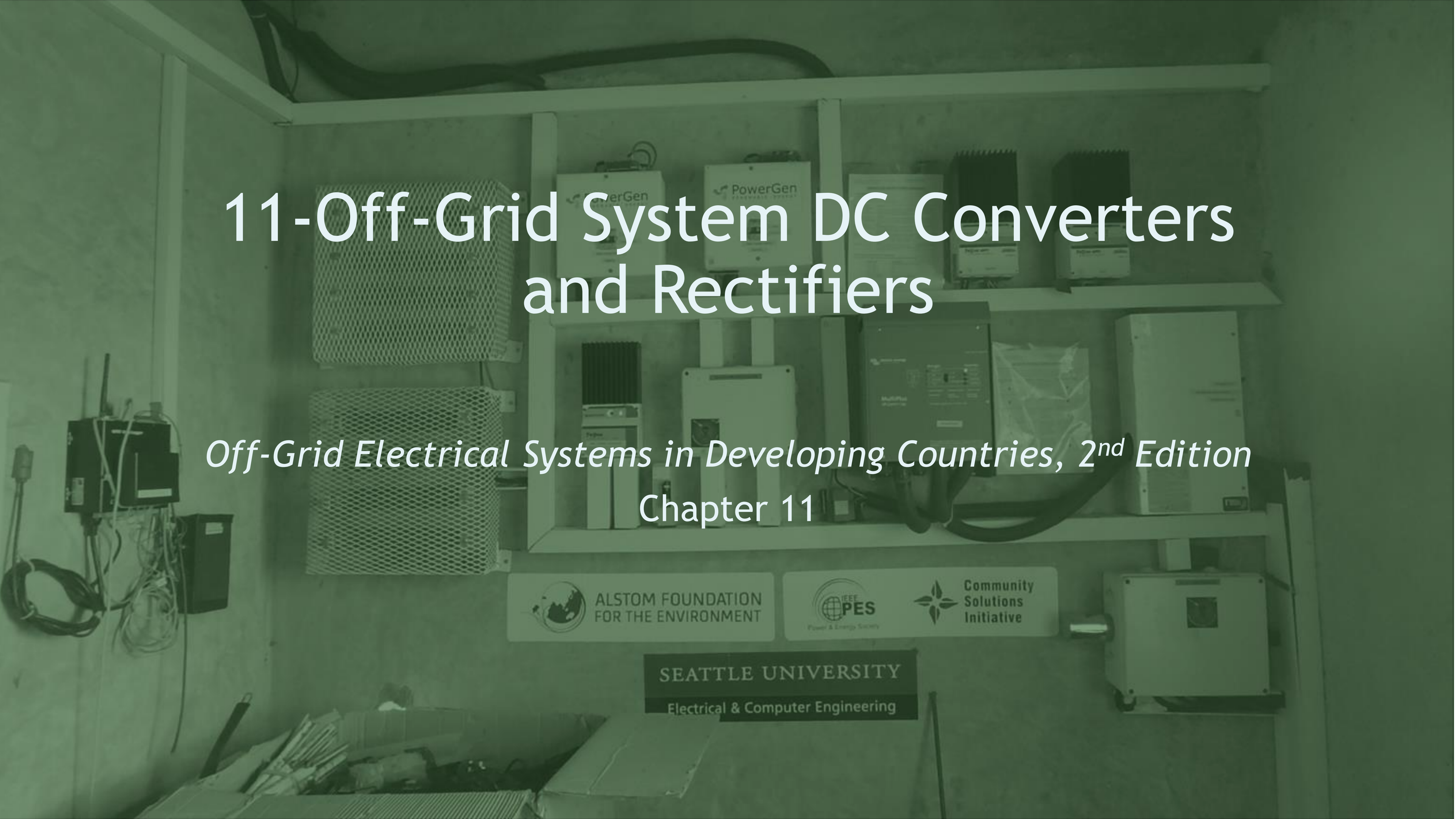
11-Off-Grid System DC Converters and Rectifiers

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

Chapter 11



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
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Learning Outcomes

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

✓Describe the basic function, operating principles, and application of DC–DC converters, maximum power point trackers, charge controllers, diversion load controllers, automatic voltage regulators, and rectifiers in off-grid systems

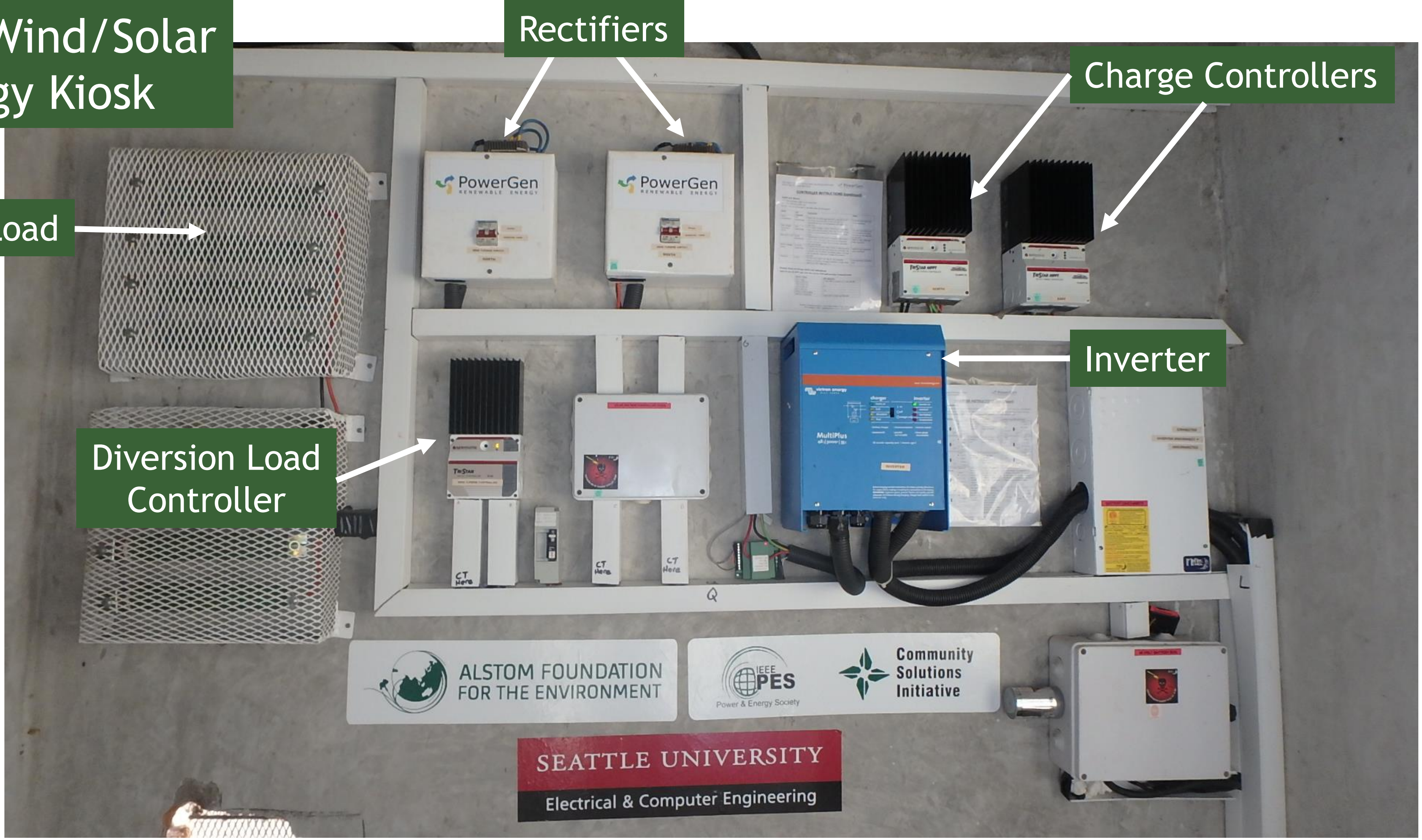
✓Demonstrate a comprehensive understanding of foundational concepts related to off-grid converters and controllers including solid-state switches, and duty cycle

✓Analyze and compute the voltages, currents, and power at the input, output, and internal stages of various DC converters and rectifiers

Introduction

- Engineered off-grid systems rely on a variety of controllers and converters
- Converters: power electronic devices that perform a variety of functions in DC and AC systems
  - AC/DC, DC/AC, DC/DC conversion
  - maximum power point tracking
  - battery charging
  - more
- Focus on DC controllers and converters in this lecture

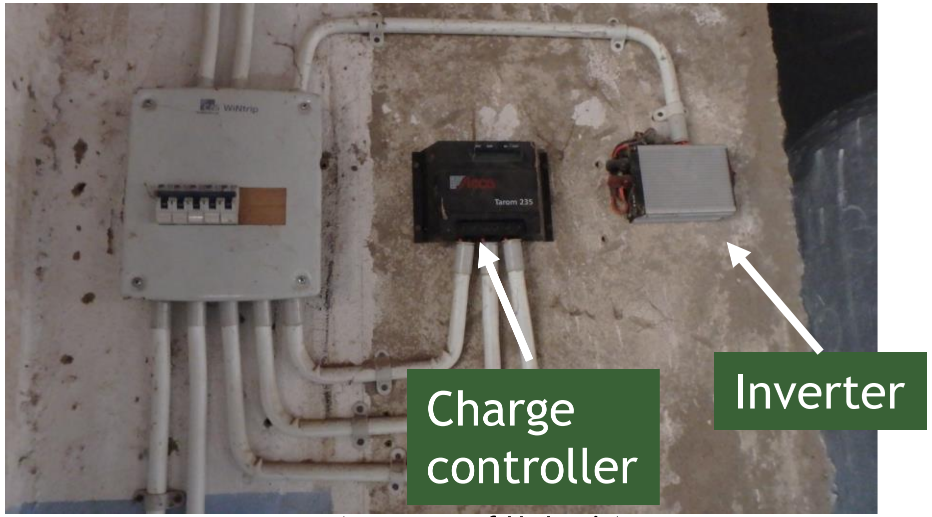
Hybrid Wind/Solar Energy Kiosk



(*courtesy of H. Louie*)

Control Components

(*courtesy of GVE Projects*)



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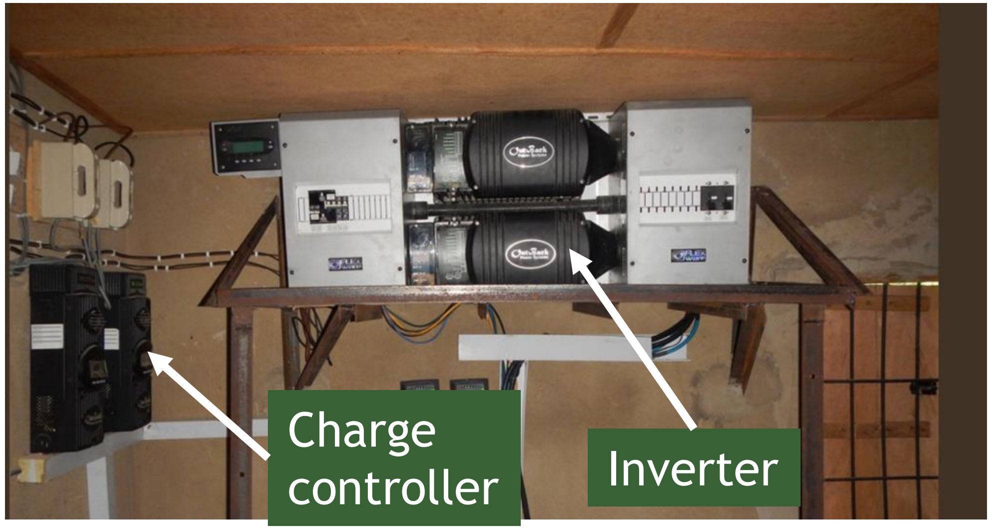


(*courtesy of GVE Projects*)

Function and Application of Converters

Converter	Function
DC-DC Converter	Increases or decreases output voltage
Maximum Power Point Tracker	Increases power produced by PV arrays or WECS
Charge Controller	Manages battery charging from DC sources
Diversion Load Controller	Manages battery charging by sending excess power to the diversion load
Rectifier	Converts AC to DC
Automatic Voltage Regulator	Adjusts excitation to synchronous generators

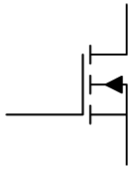
Function and Application of Converters

Converter	Function
Electronic Load Controller	Controls power to ballast load to regulate frequency
Inverter	Converts DC to AC
Solar Inverter	Converts DC from PV sources to AC
Wind Inverter	Converts DC or variable frequency AC from WECS to fixed frequency AC
Grid Tied Inverter	Converts DC to AC and synchronizes with AC bus
Bi-Directional Converter, Inverter/Charger	Allows power to be exchanged between the DC and AC Buses
Hybrid Inverter	Combines charge controller, maximum power point tracker, charger and inverter functions

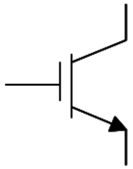
Basic Concepts: Solid-State Switching Elements

- Converters rely on solid-state switches to function
- Switching often happens 10,000 times per second or more
- Assume controlled by a signal $q(t)$
  - $q(t) = 0$ switch is “open”
  - $q(t) = 1$ switch is “closed”

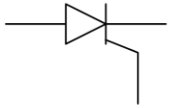
Solid-State Switches



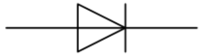
Power MOSFET



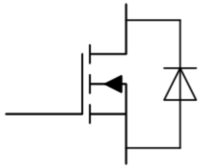
IGBT



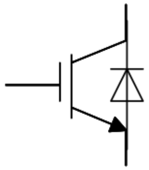
Thyristor



Diode



Power MOSFET
with antiparallel
diode



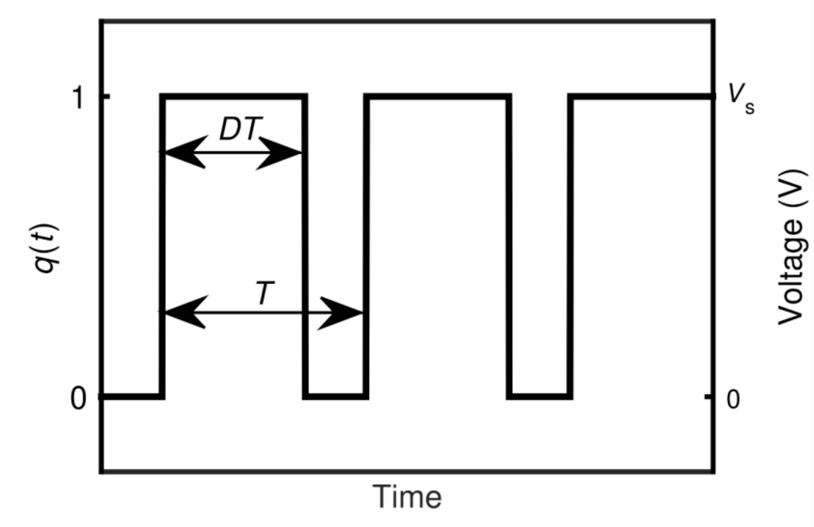
IGBT
with antiparallel
diode

Generic Switch

Basic Concepts: Pulse Width Modulation (PWM)

Pulse width modulation: width of a train of pulses is adjusted to achieve a targeted average value

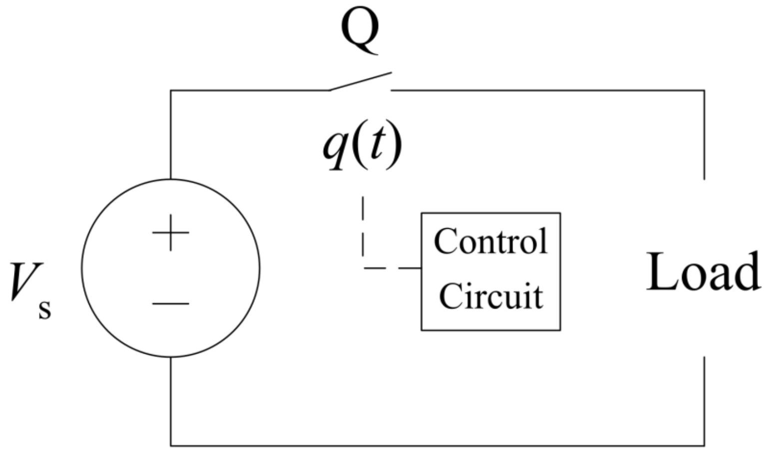
Proportion of time the switch is closed is the “duty cycle” *D*



Pulse Width Modulation (PWM)

- Consider the "chopper" circuit connected to the load
- Average voltage across the load depends on the duty cycle

$$\bar{V}_{\text{Load}} = \frac{1}{T}\int_0^T v(t)\ \mathrm{d}t = \frac{1}{T}\int_0^{DT} V_{\text{s}}\ \mathrm{d}t = DV_{\text{s}}$$



Pulse Width Modulation (PWM)

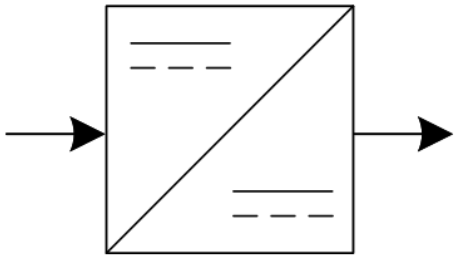
More generally, if the maximum and minimum voltage across the load are V_{max} and V_{min}, then

$$\bar{V}_{\text{Load}} = \frac{1}{T}\int_0^T v(t)\ \mathrm{d}t = \frac{1}{T}\left(\int_0^{DT} V_{\text{max}}\ \mathrm{d}t + \int_{DT}^{T} V_{\text{min}}\ \mathrm{d}t\right) = DV_{\text{max}} + (1-D)V_{\text{min}}$$

DC-DC Converters

DC-DC converter: decouple input voltage from output voltage in DC circuits

- may increase or decrease voltage
- highly efficient
- used in MPPTs, diversion load controllers, inverters
- used in solar lanterns, solar home systems to offer charging ports

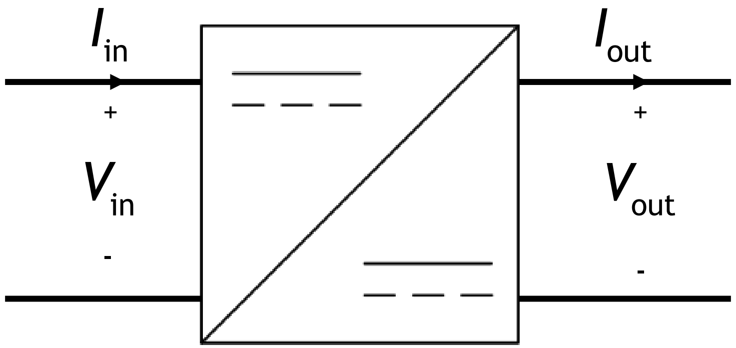


DC-DC Converters

Input power and output power

$$P = (\eta_{\text{DC-DC}}) V_{\text{in}} I_{\text{in}} = V_{\text{out}} I_{\text{out}}$$

efficiency is usually >90%



DC-DC Converters

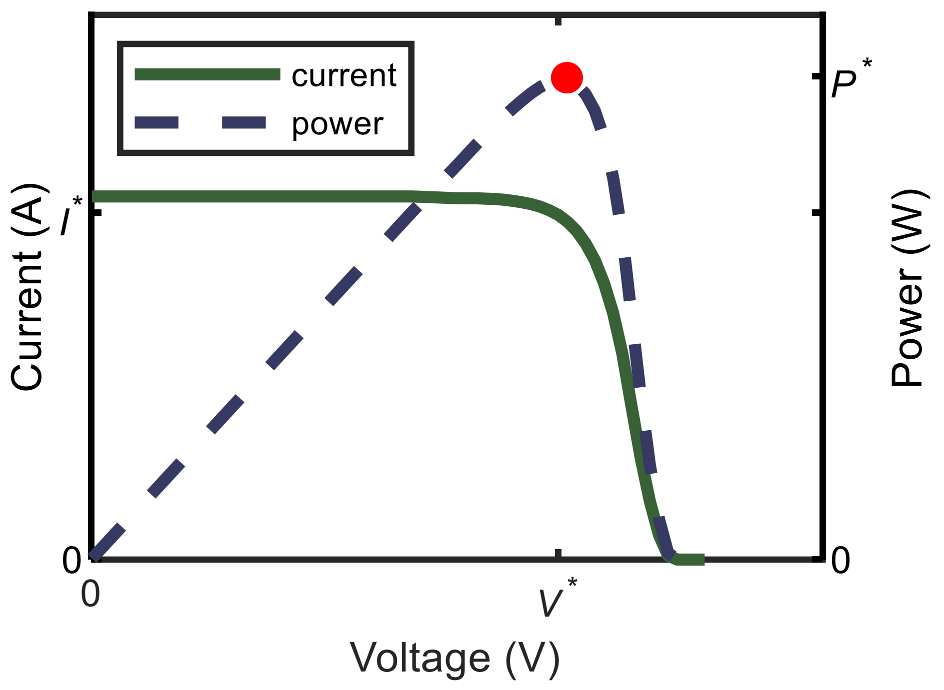
- Several types of DC-DC converters
  - boost (increase output voltage)
  - buck (decrease output voltage)
  - buck-boost (may increase or decrease output voltage)
  - many others
- Ratio of input to output voltage depends on type of converter and the duty cycle

DC-DC Converters

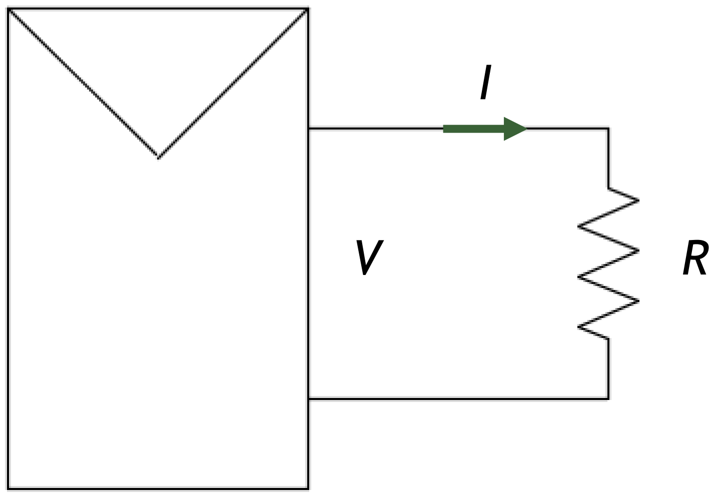
Converter	Relationship
Boost	$V_{\text{out}} = \frac{1}{1-D} V_{\text{in}}$
Buck	$V_{\text{out}} = D V_{\text{in}}$
Buck-Boost	$V_{\text{out}} = \frac{-D}{1-D} V_{\text{in}}$

Maximum Power Point Tracking

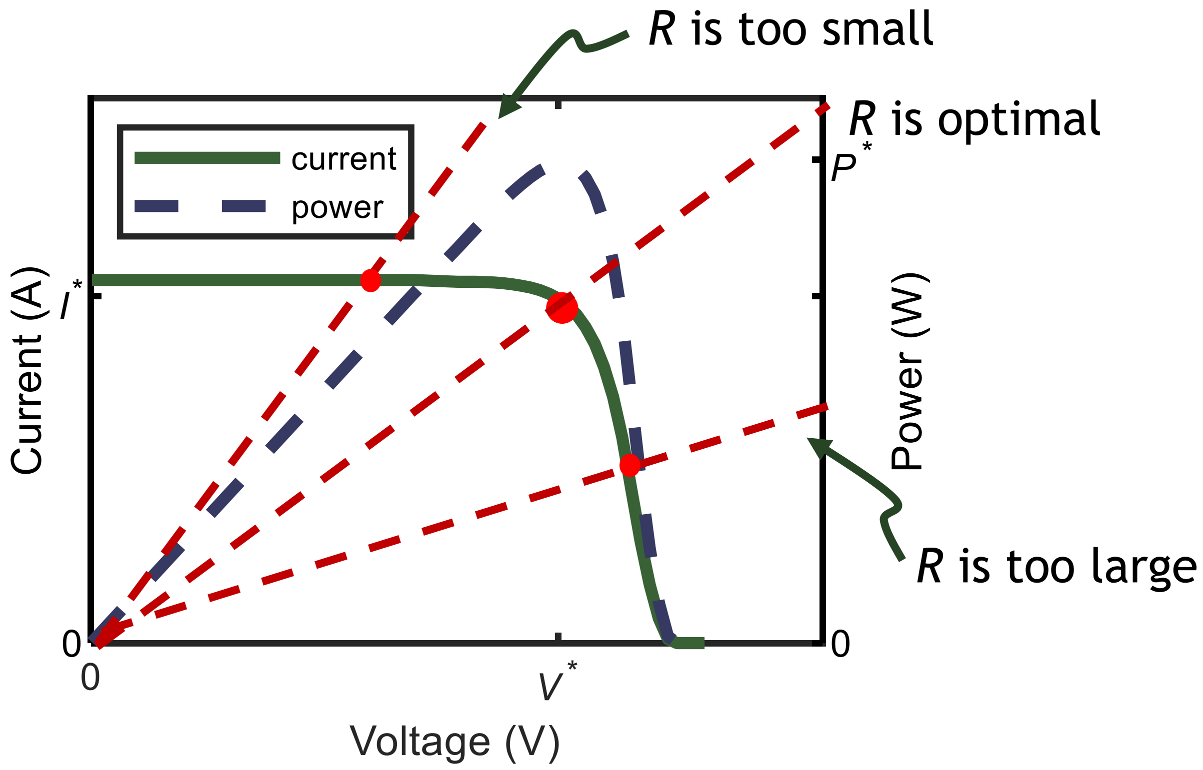
- Recall that a PV module (or array) has a unique operating point that maximizes power production for given irradiance, shading and temperature conditions
- How do we ensure the module operates at the maximum power point?



Load Matching



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

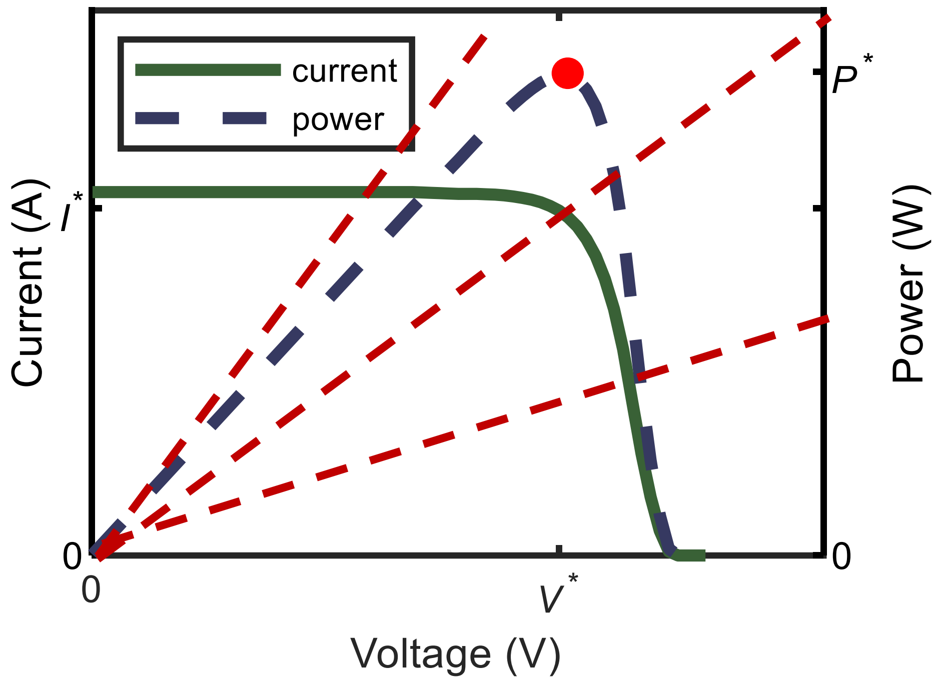


Load Matching

Solving for R^* (resistance for maximum power output)

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

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



Exercise

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

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

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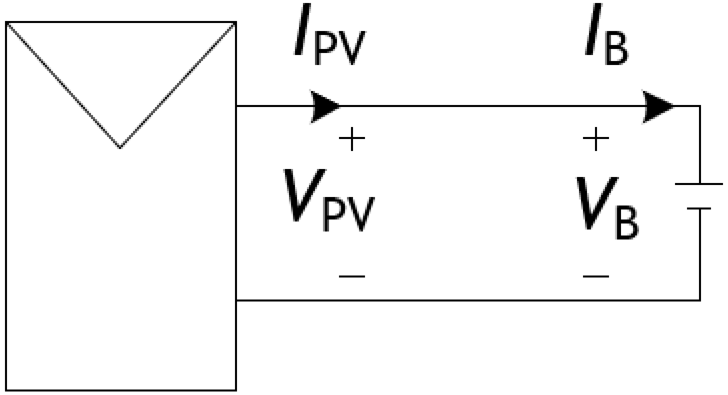
Direct Battery Connection

When a PV module is directly connected to a battery, the module voltage is “set” by the battery voltage

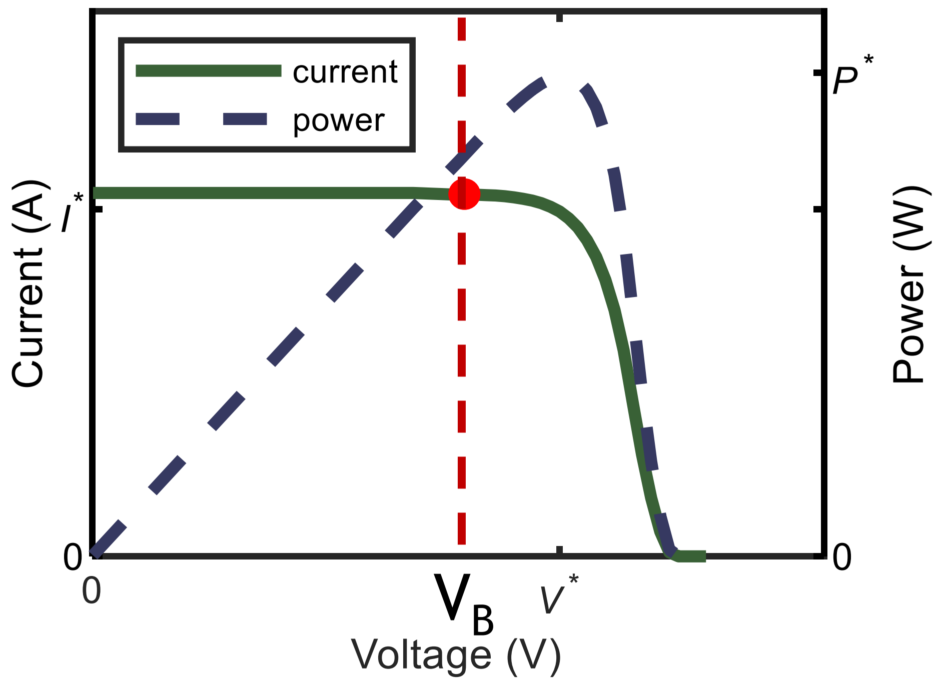
$$V_{\mathrm{PV}} = V_{\mathrm{B}}$$

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



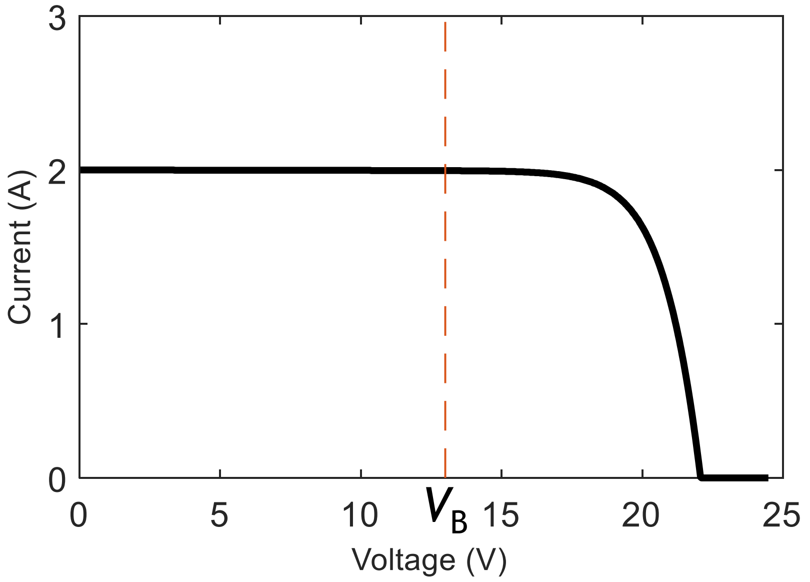
Direct Battery Connection

- Operating point is found by the intersection of the battery voltage the I-V curve of the PV module
  - note: terminal voltage V_B 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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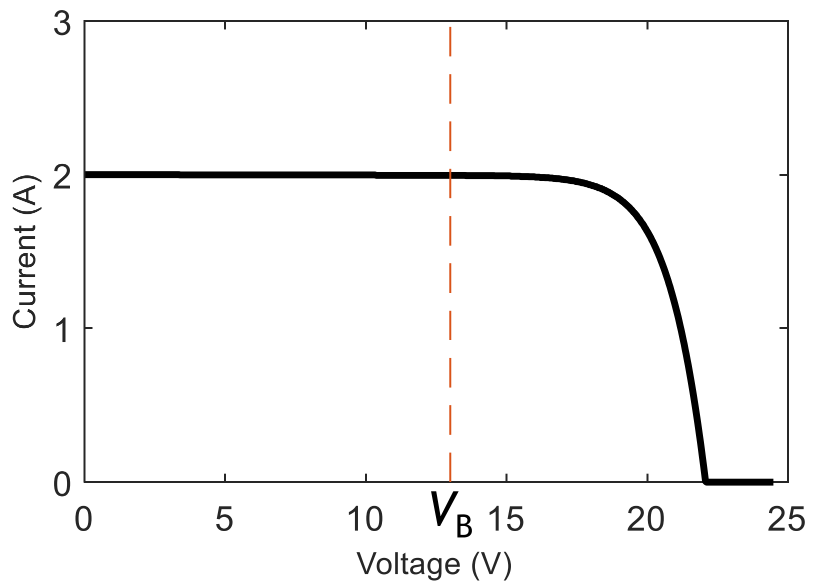
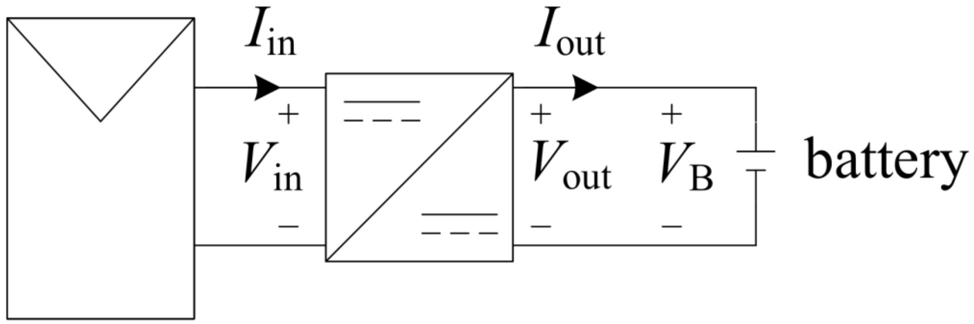


The terminal voltage of the battery “sets” the voltage of the PV module. The power therefore is approximately P = 13 V x 2 A = 26 W

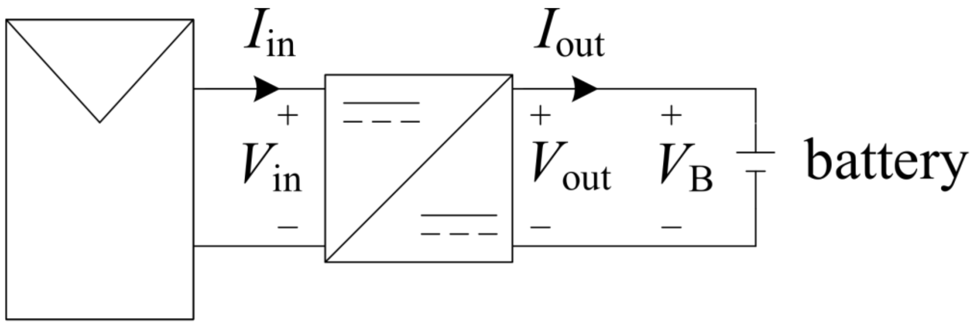
Maximum Power Point Tracking

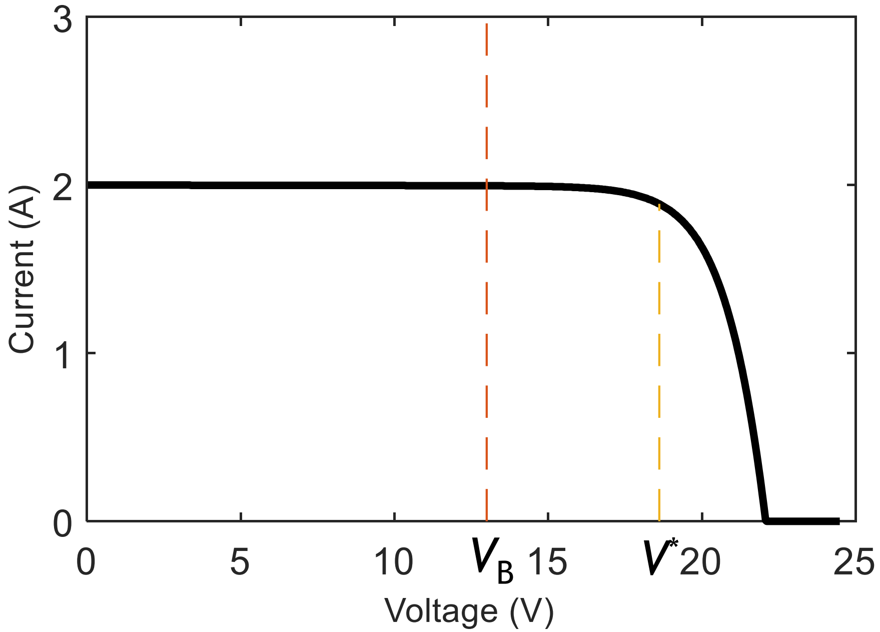
- Direct connection of PV module to battery does not optimize production
- Better approach: de-couple battery voltage from PV module voltage with a DC/DC converter



Exercise

Next, consider the scenario in which the off-grid 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.





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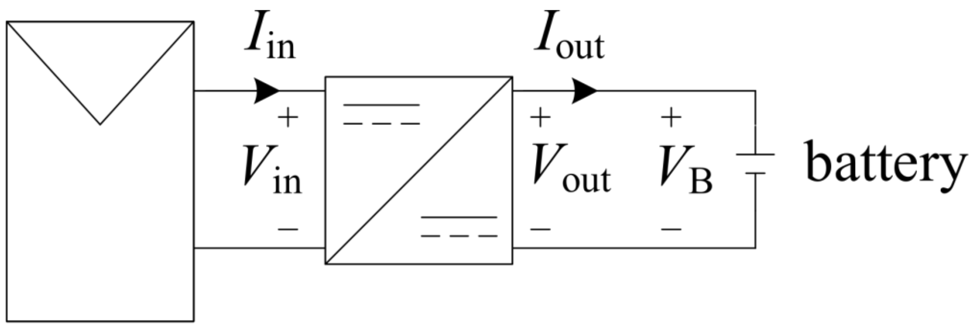
$$V_{\text{out}} = \frac{1}{1-D} V_{\text{in}}$$

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

$$D = 0.3048$$

Exercise



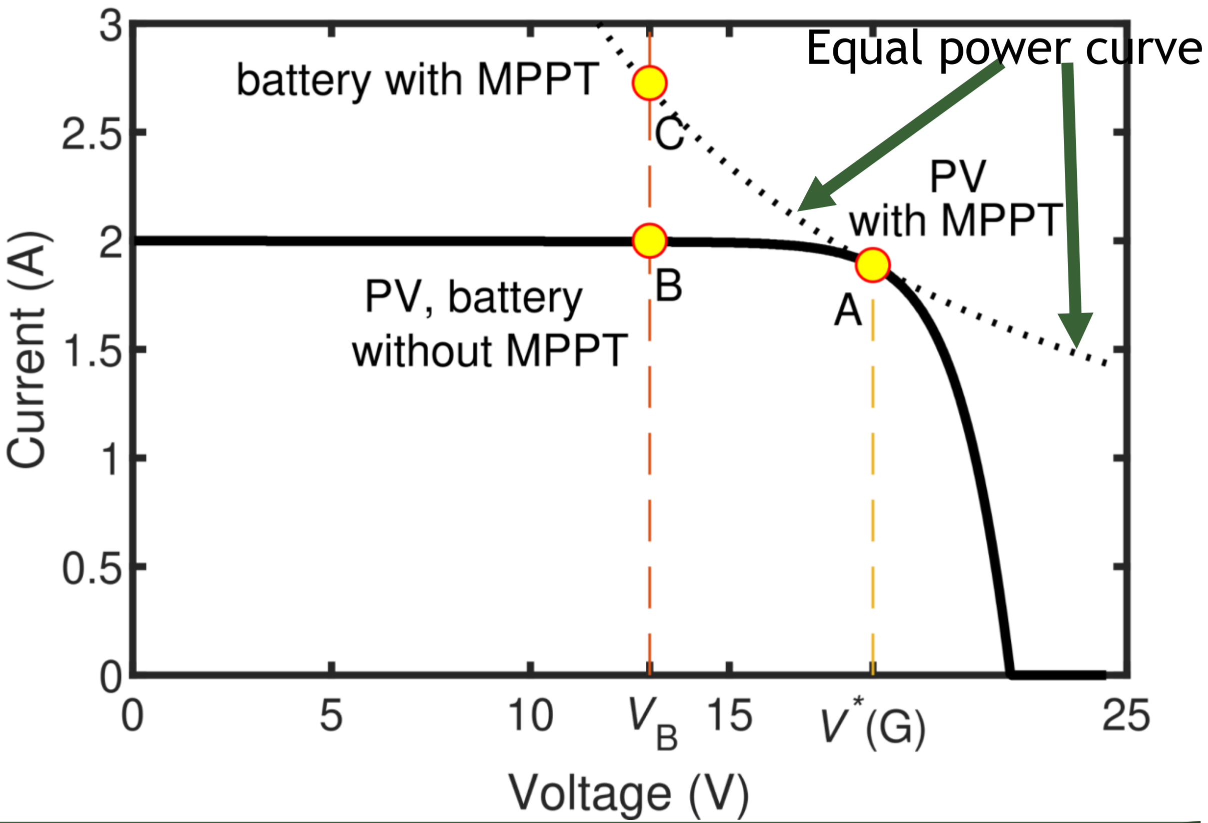
Battery Voltage: 13 V
PV Voltage: 18.7 V
Battery Current: 1.89 A
PV Current: 2.74 A

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

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

Maximum Power Point Tracking

- Operating points with MPPT
  - Battery: point C
  - PV array: point A
- Without MPPT both PV array and battery a operate at point B
- Duty cycle adjusted to track MPP as irradiance and other factors change

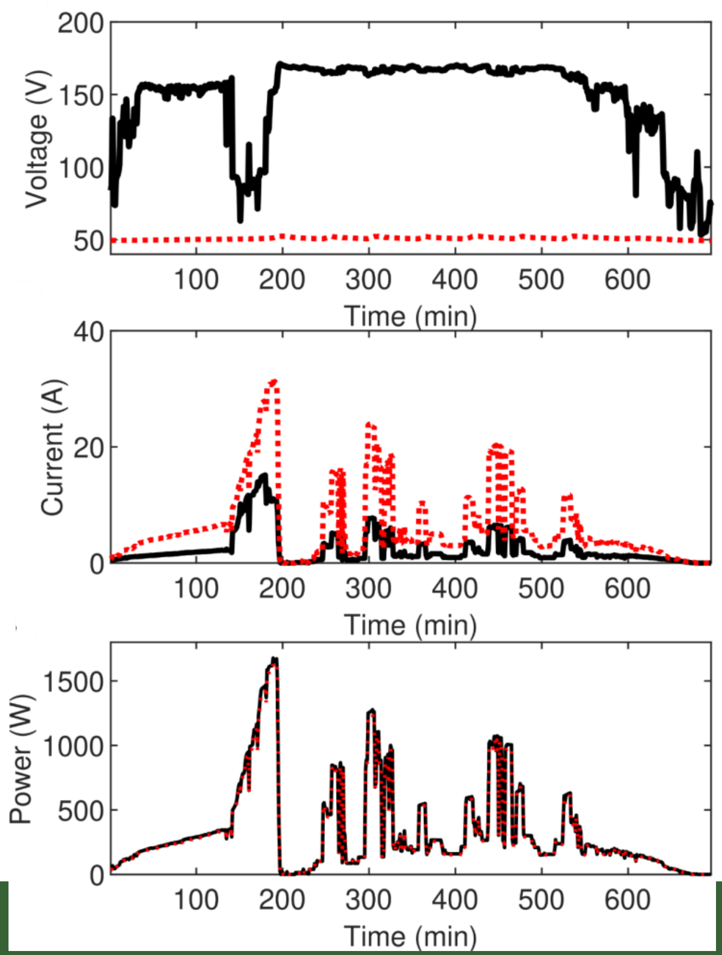


MPPT: Practical Considerations

- 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)
- Control algorithms discussed in Chap. 13

Maximum Power Point Tracking Example

Solid: PV side
Dashed: battery side



note how battery side remains close to nominal voltage (48 V), but PV side varies

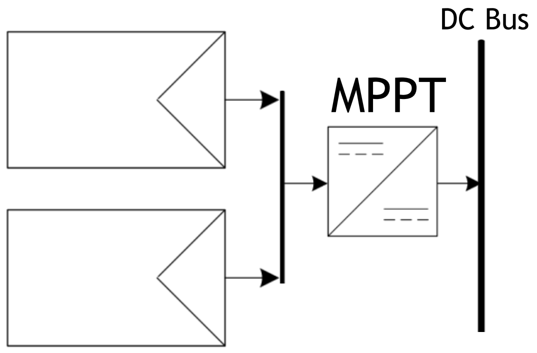
since PV voltage is higher, the PV current is lower than the battery current

power into the MPPT is nearly the same as out

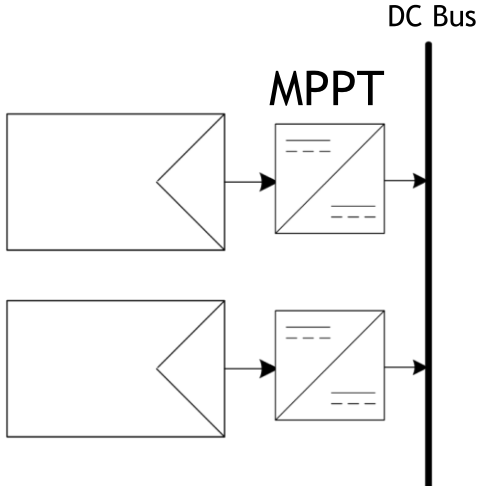
Mismatch Losses

- Multiple modules can be connected to the same MPPT
  - paralleled strings and modules operate at same voltage
  - series strings and modules operate at same current
- Optimal operating point may not be the same for all due to differences in irradiance and temperature (see Chap. 5)
- More MPPTs generally leads to improved overall power production (but higher cost)

Mismatch Losses



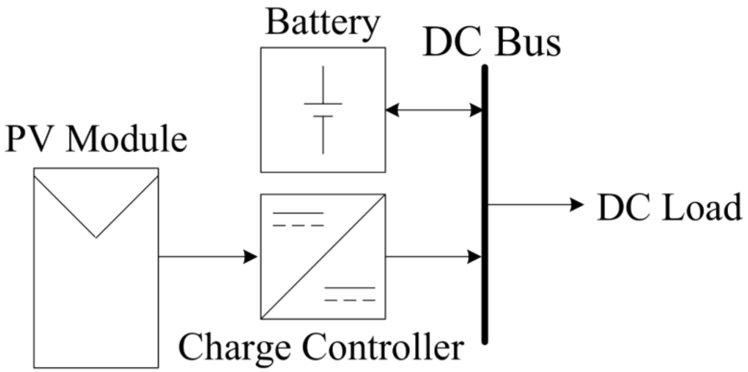
higher mismatch losses

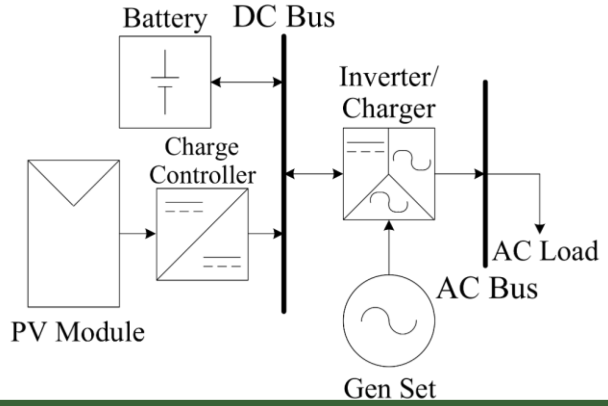


lower mismatch losses

Charge Controllers

- Recall that charge controllers are used in off-grid systems to prevent over-charge of batteries
  - often have MPPT built-in
- Chargers are also used to charge batteries from AC sources



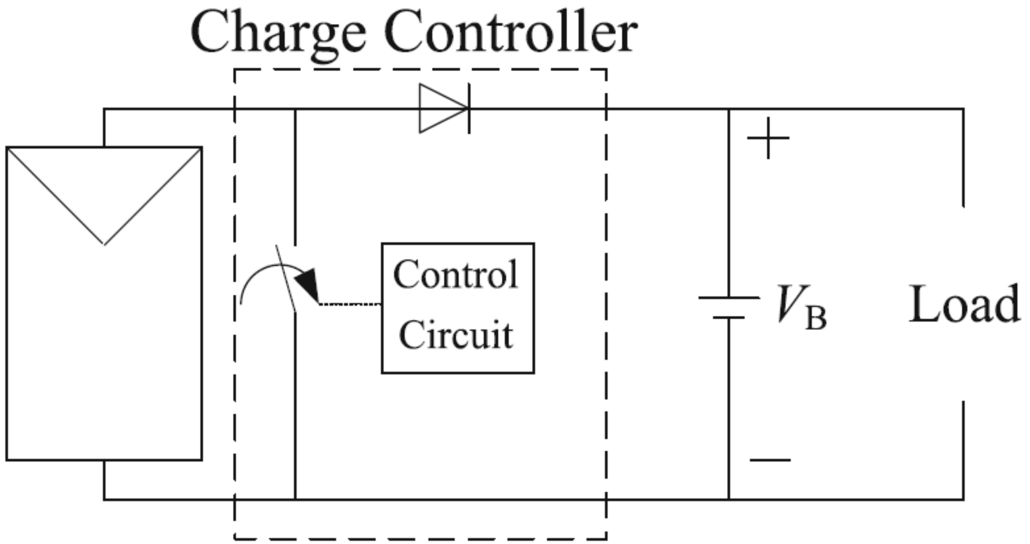


Charge Controllers

- Three general types of solar chargers
  - Shunt
  - Series
  - Pulse Width Modulation
- All have general goal of preventing damage to battery while charging

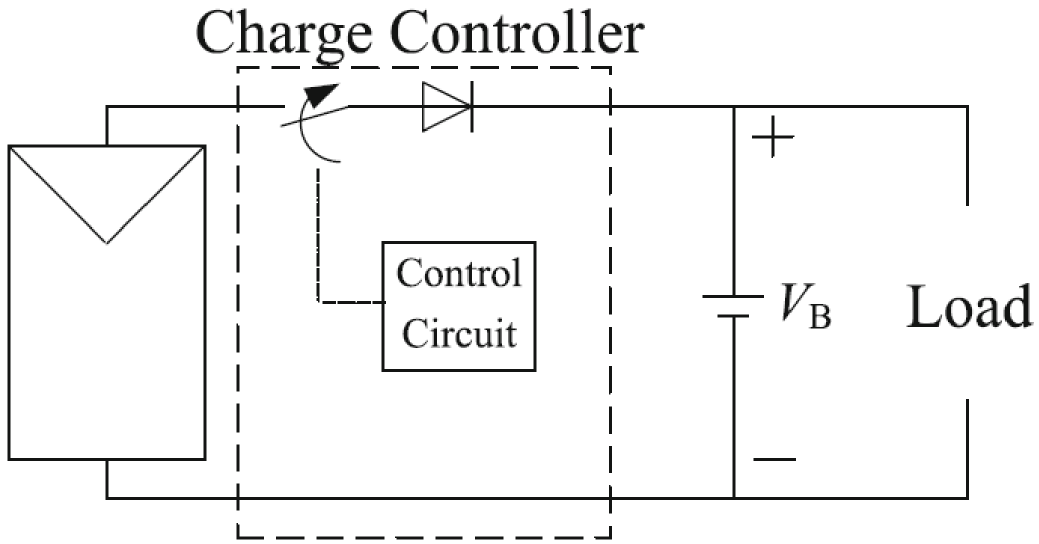
Shunt-Type Charge Controller

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



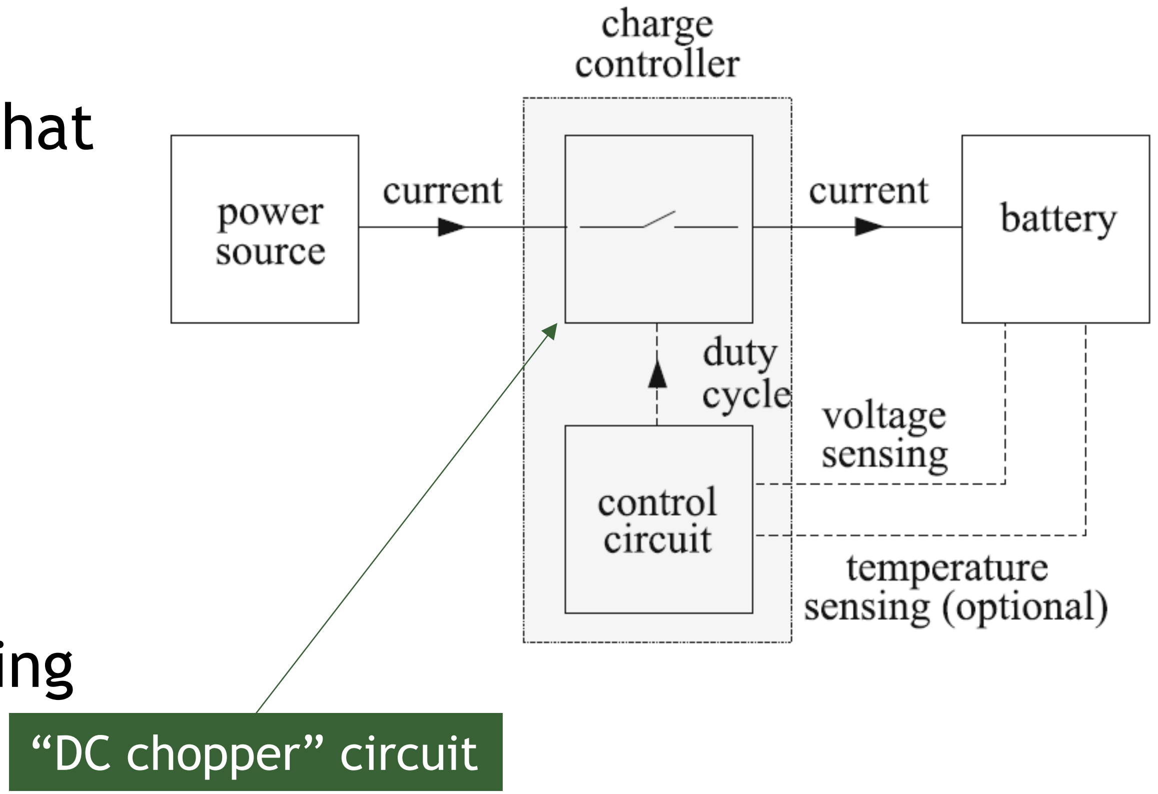
Series-Type Charge Controller

- 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
- 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



Example 11.3

Consider a series-type charge controller with PWM. The PV module is modeled as a constant voltage source V_{PV} whose value is 16 V. The battery state-of-charge (SoC) voltage is V_{SoC} = 12.8 V and its resistance R_B = 0.1 Ω. Determine the duty cycle D needed for the battery current to have an average value of 1.5 A.

Example 11.3

Consider a series-type charge controller with PWM. The PV module is modeled as a constant voltage source V_{PV} whose value is 16 V. The battery state-of-charge (SoC) voltage is V_{SoC} = 12.8 V and its resistance R_B = 0.1 Ω. Determine the duty cycle D needed for the battery current to have an average value of 1.5 A.

$$I_{max} = \left(\frac{V_{PV} - V_{SOC}}{R_B}\right) = \left(\frac{16 - 12.8}{0.1}\right) = 32\,\text{A}$$

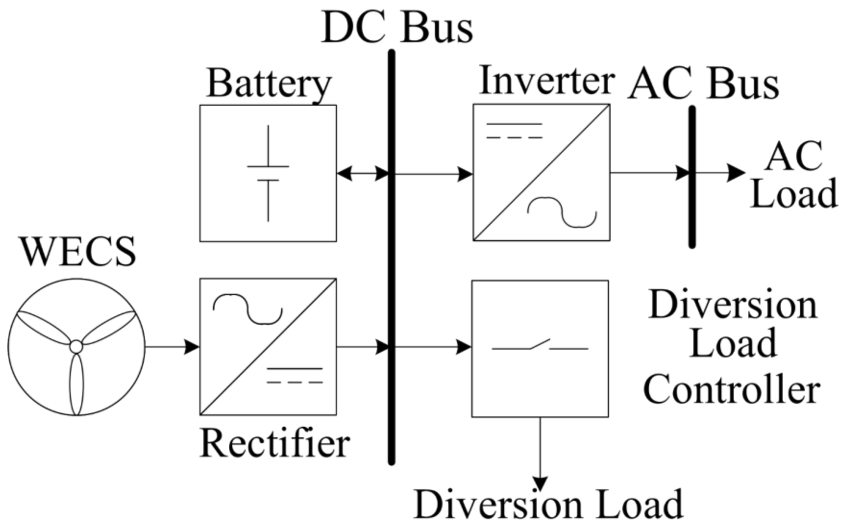
$$I_B = DI_{max} + (1-D)I_{min} = D\left(\frac{V_{PV} - V_{SOC}}{R_B}\right) + (1-D)0 = \left(\frac{V_{PV} - V_{SOC}}{R_B}\right)D$$

Solving for D

$$D = I_B\left(\frac{R_B}{V_{PV} - V_{SOC}}\right) = 1.5\left(\frac{0.1}{16 - 12.8}\right) = 0.0469$$

Diversion Load Controllers

- Specialty type of charge controller typically used with WECS and some DC-coupled MHP
- Used to divert power from battery to prevent overcharging
- Diverted power goes to Diversion Load (high-power resistor or water heater)



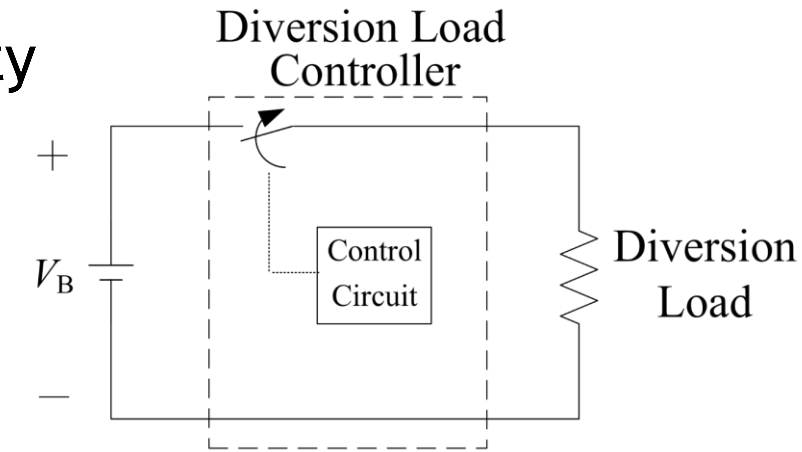
Diversion Load Controllers

- Duty cycle of switch controlled to regulate power to diversion load
- Current and power to diversion load depends on duty ratio and diversion load resistance

$$I_{DL} = D\frac{V_B}{R_{DL}}$$

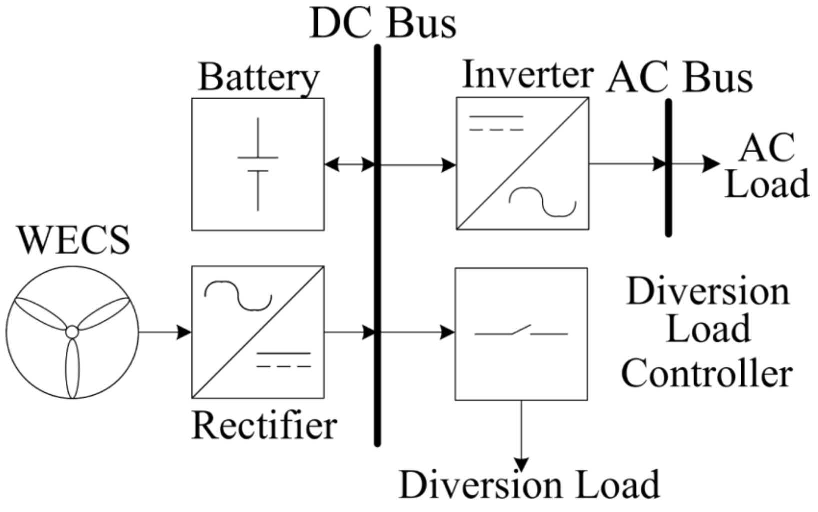
$$P_{DL} = I_{DL}^2 R_{DL} = \frac{V_B^2}{R_{DL}} D^2$$

- Diversion load must be sized to consume maximum power produced by generation sources coupled to DC bus (that are not already connected to a charge controller)



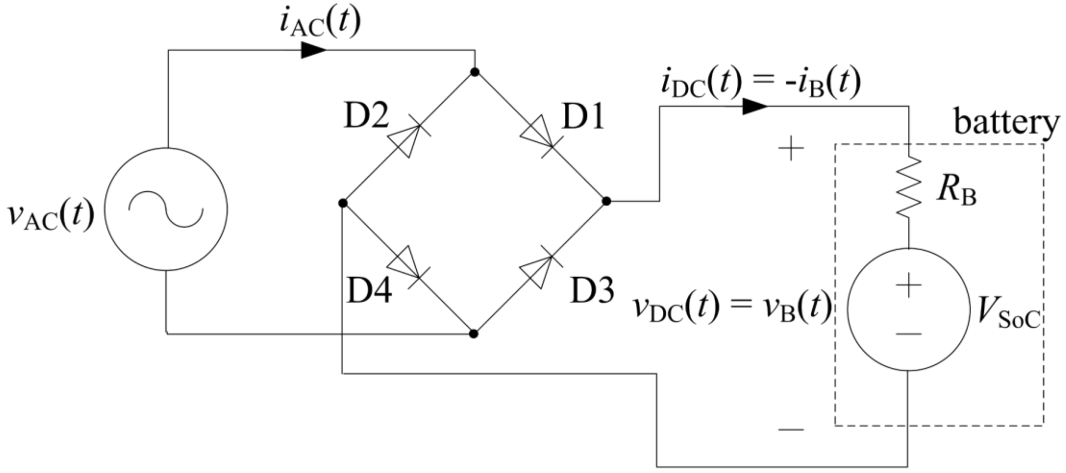
Rectifiers

- Converts AC to DC
- Used in DC-coupled WECS and MHP systems, also in some controllers such as battery chargers and Automatic Voltage Regulators
- Several types:
  - single-phase half- and full-bridge
  - three-phase full-bridge
  - phase-controlled

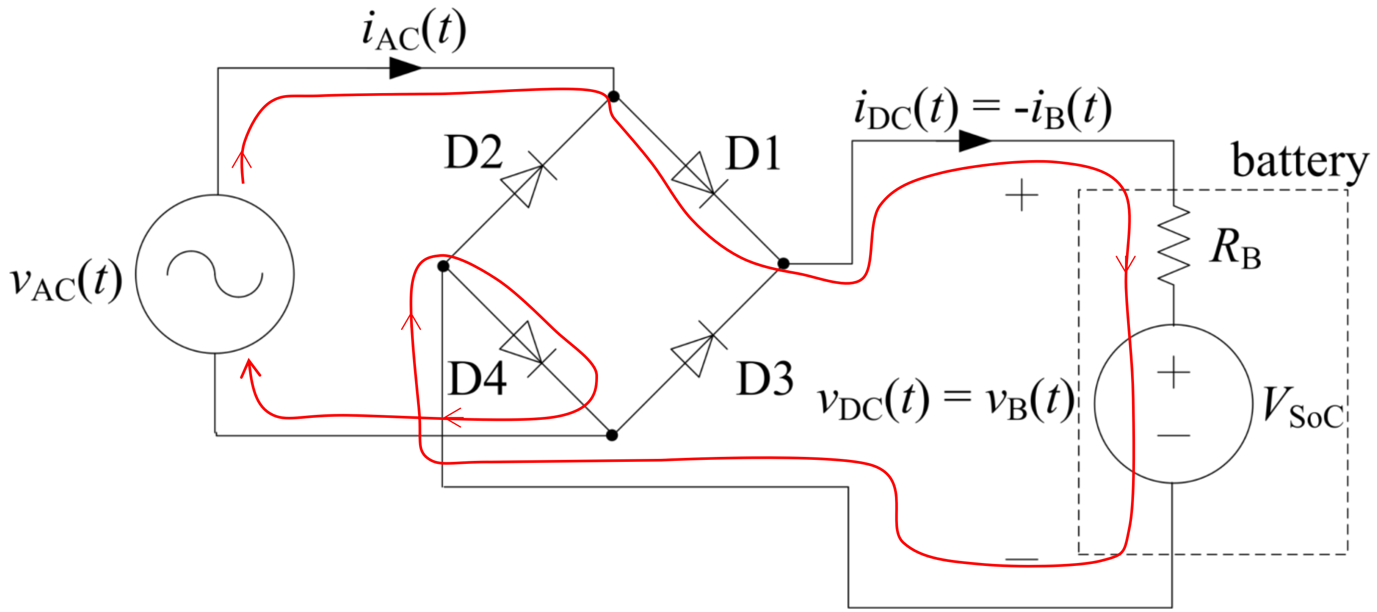


Single-Phase Full Bridge Rectifier

- Four diodes connected as bridge
  - no external control required
  - diodes conduct when forward biased
  - D1 and D4 conduct together, then D2 and D3
- Voltage across output is not constant, but its polarity does not change

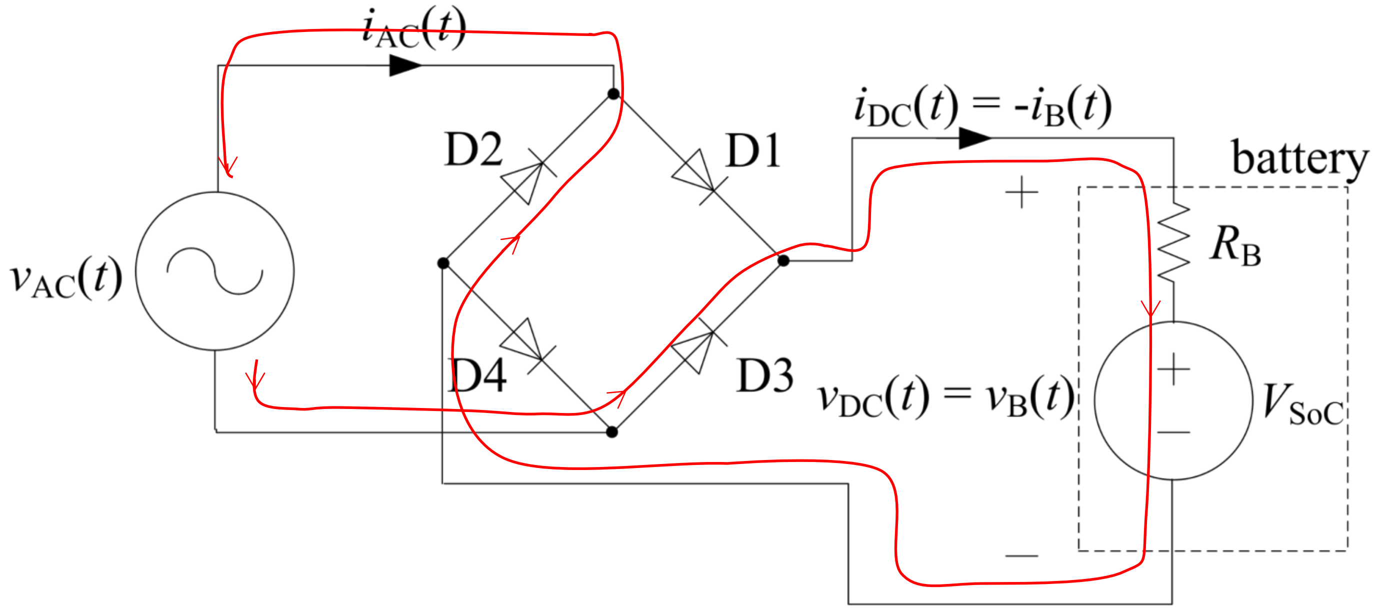


Single-Phase Full Bridge Rectifier



D1, D4 forward-biased during positive half-cycle

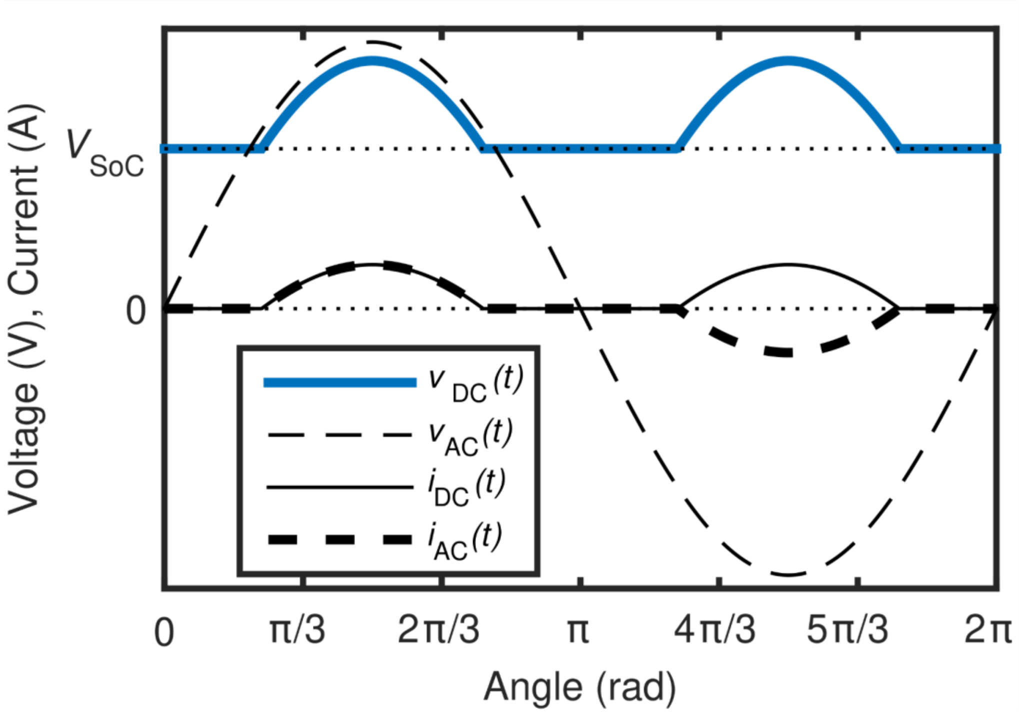
Single-Phase Full Bridge Rectifier



D2, D3 forward-biased during negative half-cycle

notice the direction of current to the battery does not change between positive and negative half-cycles

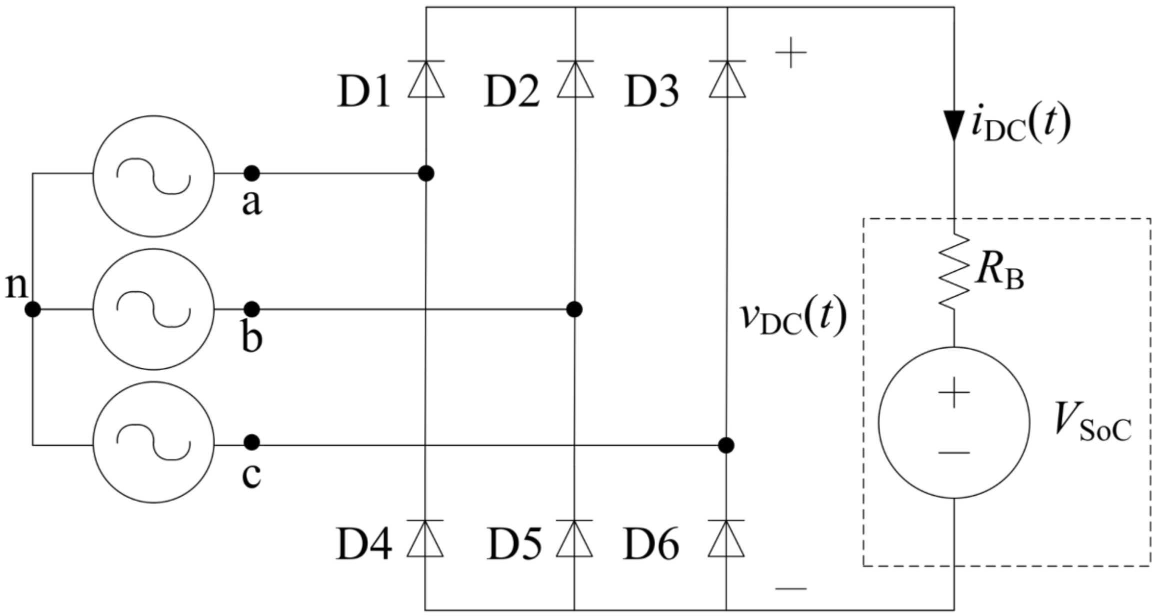
Single-Phase Full Bridge Rectifier



dc voltage pulsates

current and voltage from AC source are in phase (unity PF)

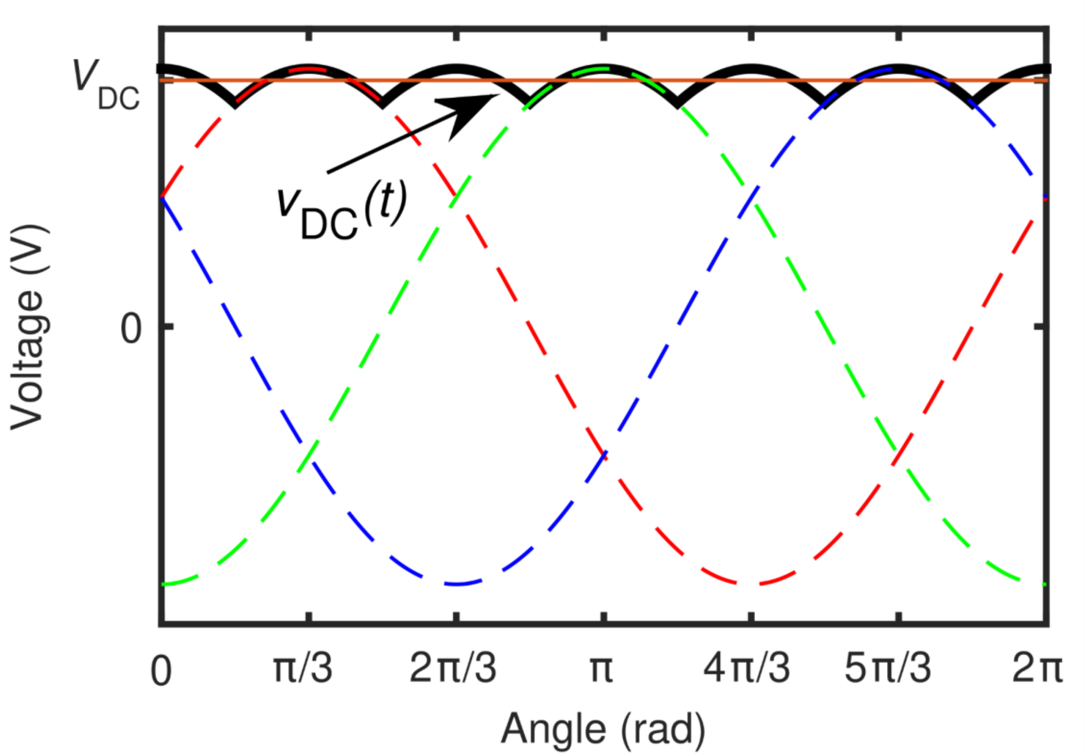
Three-Phase Full Bridge Rectifier



two diodes conducting at a time

line-line voltage applied across battery

Three-Phase Full Bridge Rectifier



dc voltage pulsates at period of $\pi/3$ (60^o)

average dc voltage almost equal to peak line-line voltage

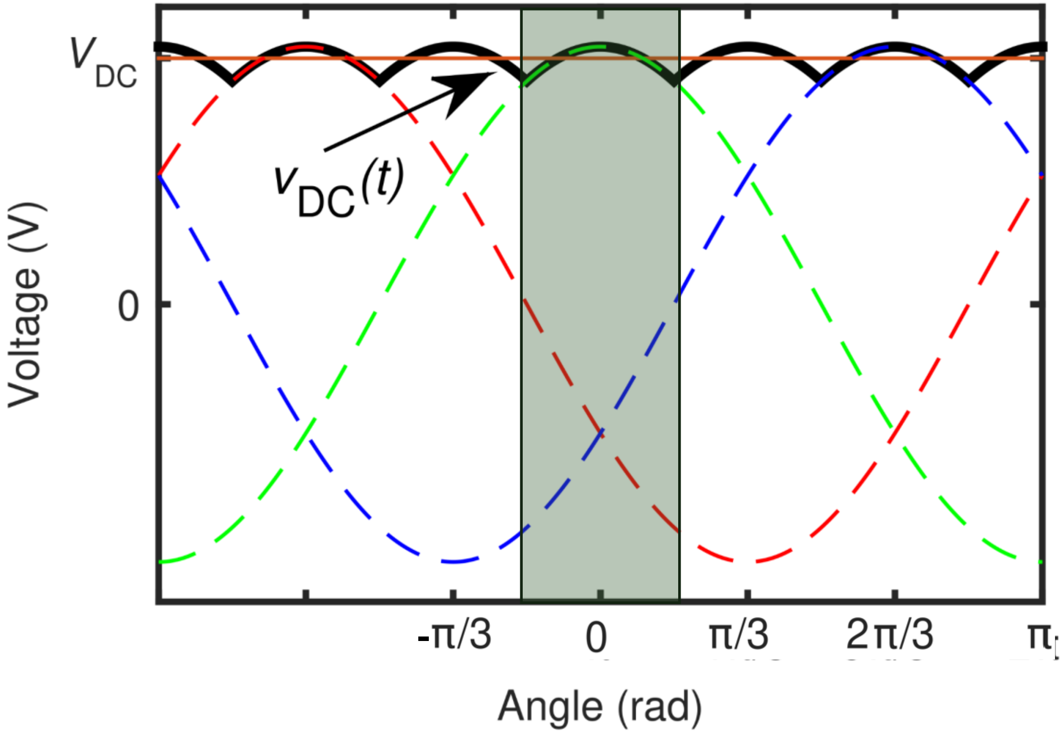
Three-Phase Full Bridge Rectifier

Voltage during one "hump"

$$v_{DC}(t) = V_{\ell\ell}^{\max} \cos(\theta) : -\pi/6 \le \theta \le \pi/6$$

$$i_{DC}(t) = \frac{V_{DC}(t) - V_{SoC}}{R_B} = \frac{V_{\ell\ell}^{\max} \cos(\theta) - V_{SoC}}{R_B}$$

voltage drop across diodes ignored (usually small compared to AC voltage)



Three-Phase Full Bridge Rectifier

Average value of dc voltage and current

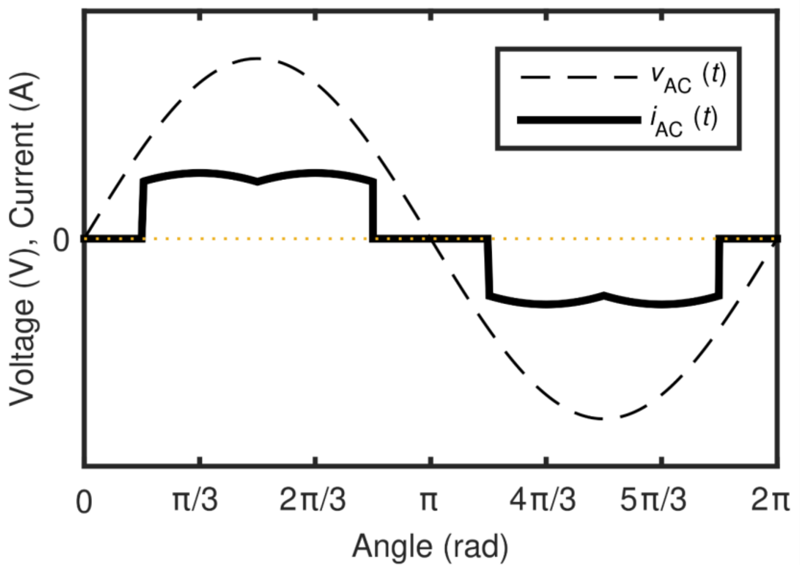
$$V_{\mathrm{DC}} = \frac{3}{\pi}\int_{-\pi/6}^{\pi/6} V_{\ell\ell}^{\max}\cos(\theta)\,\mathrm{d}\theta = \frac{3}{\pi}V_{\ell\ell}^{\max} \approx 0.955V_{\ell\ell}^{\max}$$

$$I_{\mathrm{DC}} = \frac{3}{\pi}\int_{-\pi/6}^{\pi/6} i_{\mathrm{DC}}\,\mathrm{d}\theta = \frac{3}{\pi}\int_{-\pi/6}^{\pi/6} \frac{V_{\ell\ell}^{\max}\cos(\theta) - V_{\mathrm{SoC}}}{R_{\mathrm{B}}}\,\mathrm{d}\theta = \frac{V_{\mathrm{DC}} - V_{\mathrm{SoC}}}{R_{\mathrm{B}}}$$

average dc voltage is approx. 96% of the maximum line-line voltage,
this matches our observation from before

Three-Phase Full Bridge Rectifier

current and voltage from a single phase of the AC source



current is non-sinusoidal

current and voltage are in phase

Three-Phase Full Bridge Rectifier

Instantaneous power to the battery

$$p(t) = V_{\mathrm{DC}} i_{\mathrm{DC}}(t) = \frac{V_{\ell\ell}^{\max} \cos(\theta)\left(V_{\ell\ell}^{\max} \cos(\theta) - V_{\mathrm{SoC}}\right)}{R_{\mathrm{B}}}$$

$$p(t) = \frac{1}{R_{\mathrm{B}}}\left(\left(V_{\ell\ell}^{\max}\right)^2 \cos^2(\theta) - V_{\ell\ell}^{\max} V_{\mathrm{SoC}} \cos(\theta)\right)$$

Three-Phase Full Bridge Rectifier

Average (real) power to the battery

$$P_B = \frac{3}{\pi}\frac{1}{R_B}\int_{-\pi/6}^{\pi/6}\left(V_{\ell\ell}^{\max}\right)^2 \cos^2(\theta) - V_{\ell\ell}^{\max}V_{\mathrm{SoC}}\cos(\theta)\mathrm{d}\theta$$

only need to average across one hump

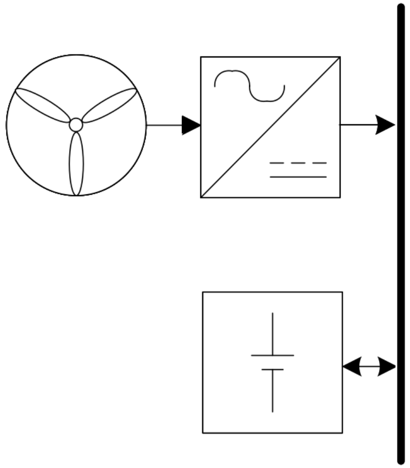
$$= \frac{3}{\pi}\frac{1}{R_B}\left(\left(V_{\ell\ell}^{\max}\right)^2\left(\frac{\pi}{6}+\frac{\sqrt{3}}{4}\right) - V_{\ell\ell}^{\max}V_{\mathrm{SoC}}\right)$$

$$= \frac{3}{\pi}\frac{1}{R_B}\left(0.957\left(V_{\ell\ell}^{\max}\right)^2 - V_{\ell\ell}^{\max}V_{\mathrm{SoC}}\right)$$

power to battery increases with AC voltage,
but decreases with state-of-charge voltage

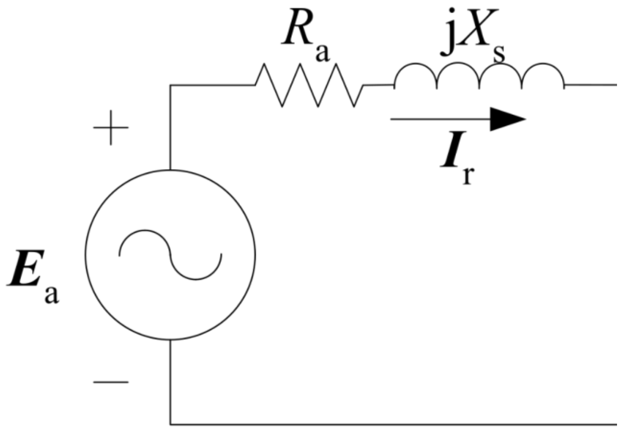
Rectification of Variable AC Generation

- Consider an off-grid system in which a WECS is used for battery charging
  - voltage and frequency of AC voltage varies with wind speed
- How can we determine power to the battery while modeling the generator?



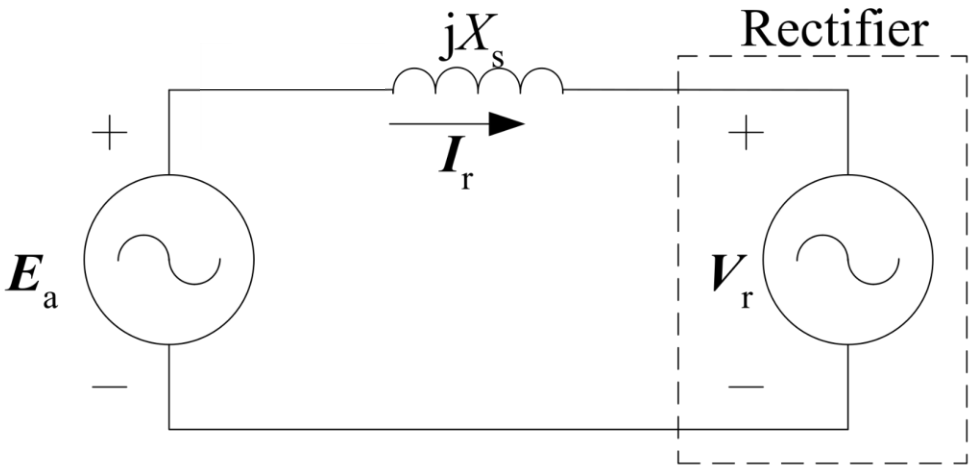
Rectification of Variable AC Generation

- Recall from Chap. 6 the model of a single phase of a synchronous generator
- X_s and $\boldsymbol{E}_a$ (induced voltage) are frequency dependent (depend on rotational speed of WECS)



Phasor-Domain Model

- Cannot represent rectifier in phasor domain (non-linear, non-sinusoidal characteristics)
- Phasor circuit model based on these assumptions
  - voltage drop across diode is negligible
  - battery is continuously being charged (always current from generator)
  - armature resistance is negligble
  - rectifier is lossless
- Basic idea: model rectifier as a voltage source
  - model is approximate only



Phasor-Domain Model

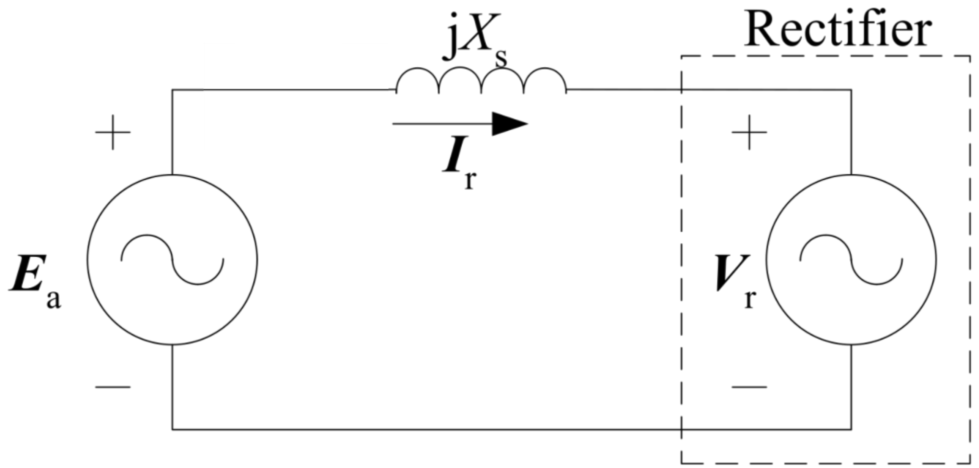
- Voltage and current into rectifier are in phase, so PF is 1.0

  $\boldsymbol{V}_{\mathrm{r}} = |\boldsymbol{V}_{\mathrm{r}}| \angle 0^{\circ}$ set as reference

  $\boldsymbol{I}_{\mathrm{r}} = |\boldsymbol{I}_{\mathrm{r}}| \angle 0^{\circ}$

- Lossless rectifier assumption

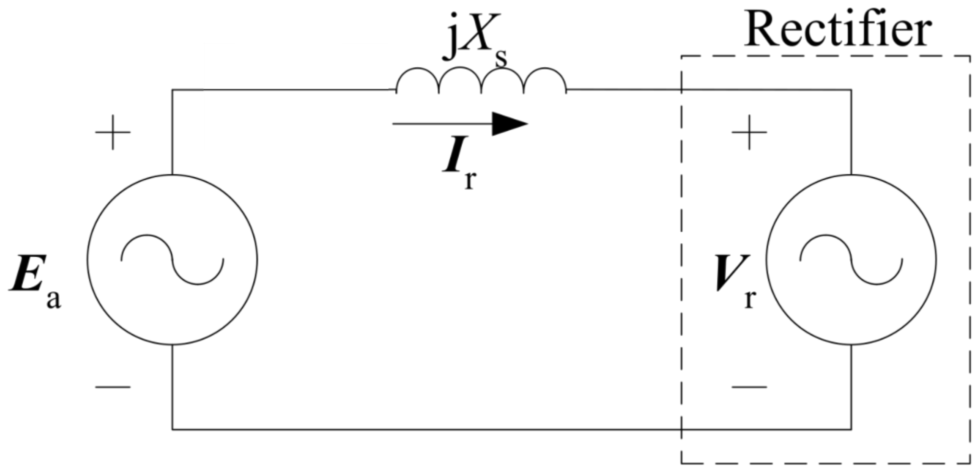
$$P_{\mathrm{B}} = 3\mathrm{Re}\left\{\boldsymbol{V}_{\mathrm{r}}\boldsymbol{I}_{\mathrm{r}}^{*}\right\} = 3\left|\boldsymbol{V}_{\mathrm{r}}\right|\left|\boldsymbol{I}_{\mathrm{r}}\right|$$



Phasor-Domain Model

Set V_r to the line-neutral RMS voltage on the AC-side of the rectifier

$$\left|\boldsymbol{V}_r\right| = \frac{V_\phi^{max}}{\sqrt{2}} = \frac{V_{\ell\ell}^{max}}{\sqrt{2}\sqrt{3}} = \frac{V_{\ell\ell}^{max}}{\sqrt{6}}$$



Phasor-Domain Model

Recall battery power from rectifier is:

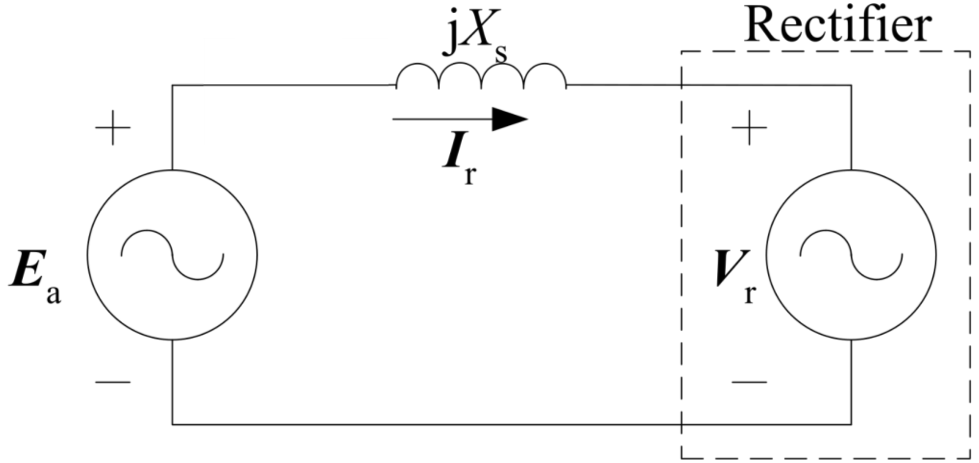
$$P_{\mathrm{B}} = \frac{3}{\pi}\frac{1}{R_{\mathrm{B}}}\left(0.957\left(V_{\ell\ell}^{\max}\right)^2 - V_{\ell\ell}^{\max}V_{\mathrm{SoC}}\right)$$

Current therefore is:

$$\left|\boldsymbol{I}_{\mathrm{r}}\right| = \frac{P_{\mathrm{B}}}{3\left|\boldsymbol{V}_{\mathrm{r}}\right|} = \frac{1}{3\left|\boldsymbol{V}_{\mathrm{r}}\right|}\left(\frac{3}{\pi}\frac{1}{R_{\mathrm{B}}}\left(0.957\left(V_{\ell\ell}^{\max}\right)^2 - V_{\ell\ell}^{\max}V_{\mathrm{SoC}}\right)\right)$$

$$= \frac{1}{3\left|V_{\mathrm{r}}\right|}\left(\frac{3}{\pi}\frac{1}{R_{\mathrm{B}}}\left(0.957\left(\sqrt{6}\left|V_{\mathrm{r}}\right|\right)^2 - \sqrt{6}\left|V_{\mathrm{r}}\right|V_{\mathrm{SoC}}\right)\right)$$

$$= \frac{6}{\pi}\frac{1}{R_{\mathrm{B}}}\left(0.957\left|V_{\mathrm{r}}\right| - \frac{1}{\sqrt{6}}V_{\mathrm{SoC}}\right)$$

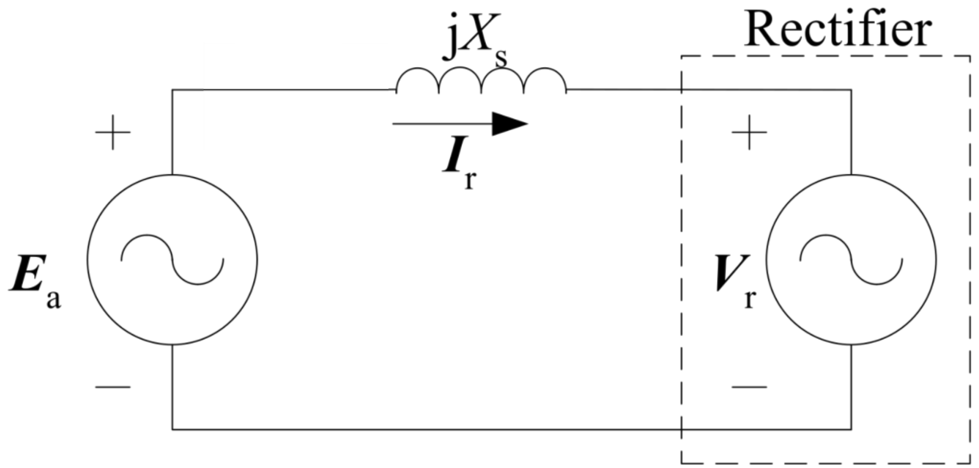


Phasor-Domain Model

Simplifying further

$$\left|\boldsymbol{I}_\mathrm{r}\right| = \frac{6}{\pi}\frac{1}{R_\mathrm{B}}\left(0.957\left|\boldsymbol{V}_\mathrm{r}\right| - \frac{1}{\sqrt{6}}V_\mathrm{SoC}\right)$$

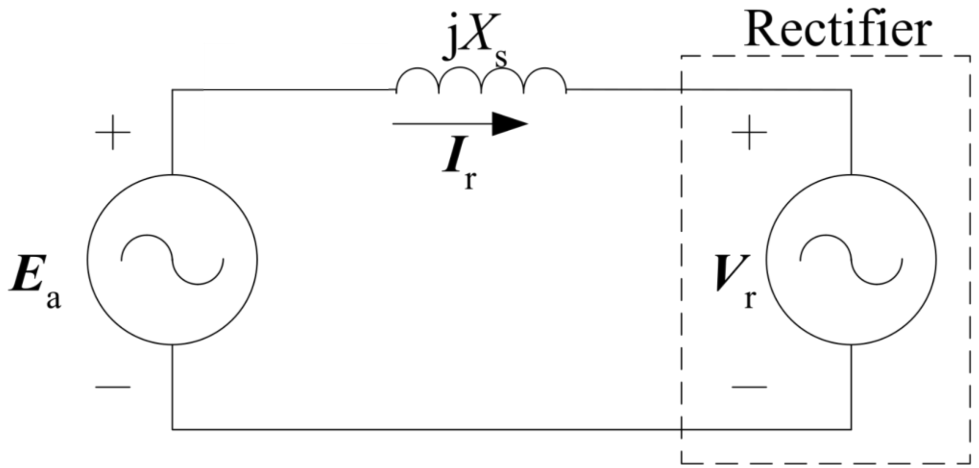
$$= \frac{1.8277}{R_\mathrm{B}}\left(\left|\boldsymbol{V}_\mathrm{r}\right| - 0.4268V_\mathrm{SoC}\right)$$



Phasor-Domain Model

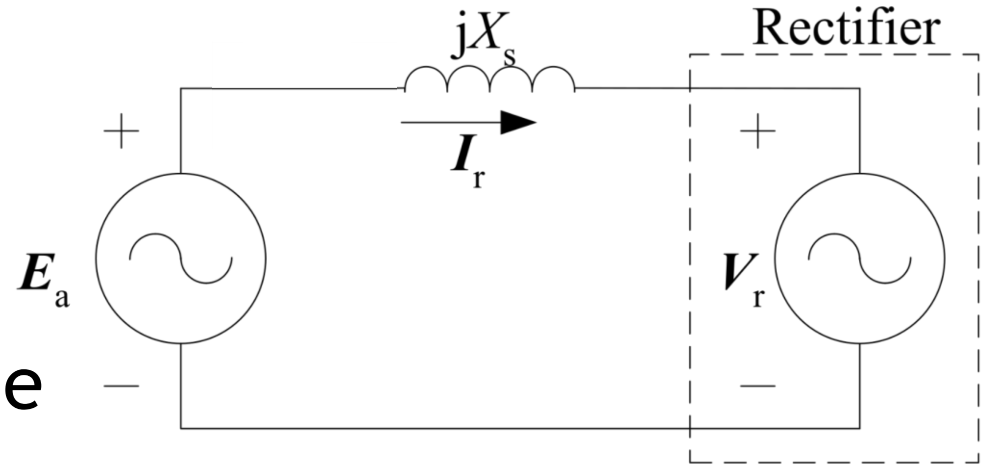
Applying KVL

$$\boldsymbol{E}_{\mathrm{a}} = \mathrm{j}X_{\mathrm{s}}\boldsymbol{I}_{\mathrm{r}} + \boldsymbol{V}_{\mathrm{r}} = \mathrm{j}X_{\mathrm{s}}\left|\boldsymbol{I}_{\mathrm{r}}\right| + \left|\boldsymbol{V}_{\mathrm{r}}\right|$$



Phasor-Domain Model

- Given parameters
  - R_B (battery resistance)
  - V_{SoC} (battery state-of-charge voltage)
  - X_s (generator synchronous reactance)
- Power to battery can determined if the induced voltage is known by solving



$$\left|\boldsymbol{I}_{r}\right| = \frac{1.8277}{R_{B}}\left(\left|\boldsymbol{V}_{r}\right| - 0.4268V_{SoC}\right)$$

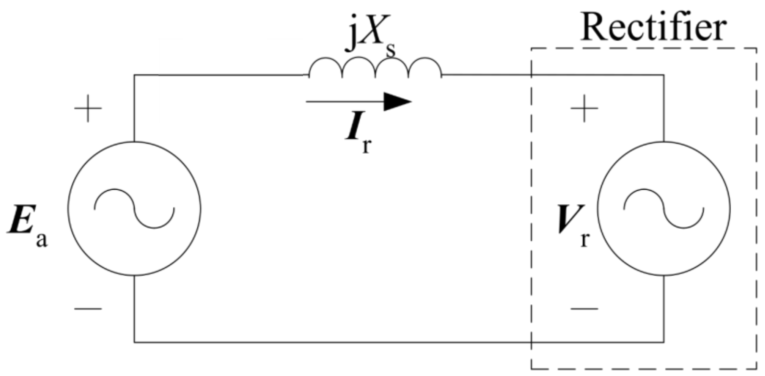
$$\boldsymbol{E}_{a} = jX_{s}\left|\boldsymbol{I}_{r}\right| + \left|\boldsymbol{V}_{r}\right|$$

$$P_{B} = 3\left|\boldsymbol{V}_{r}\right|\left|\boldsymbol{I}_{r}\right|$$

see Example 11.5 for details

Power to Battery

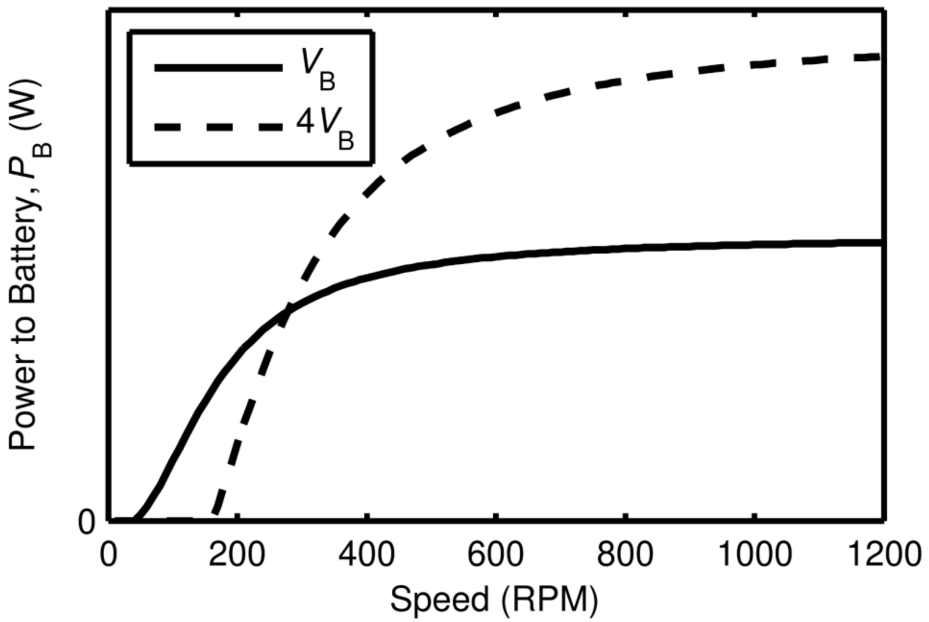
- As WECS speed increases:
  - frequency and magnitude of $\boldsymbol{E}_a$ increases
  - X_s increases due to increased frequency
- Higher $\boldsymbol{E}_a$ should increase power to battery, BUT…
- Higher X_s reduces current to battery
- Which wins out?



Power to Battery

- Power to battery tends to increase with WECS (synchronous generator) speed
- Power increase tapers off at higher speeds
- Power to battery increases with battery voltage
- Battery charging only begins after generator produces high enough voltage to forward bias the diodes

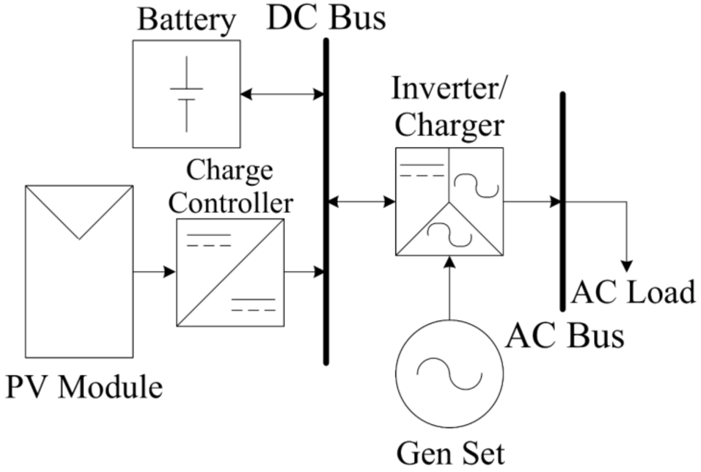
power to 12 V and 48 V battery

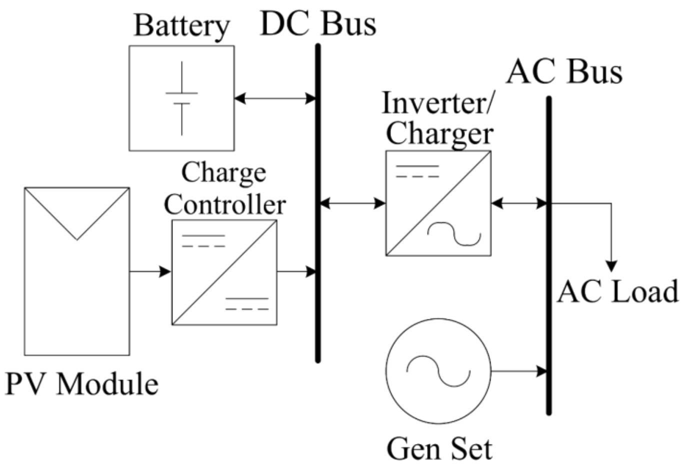


Battery Chargers

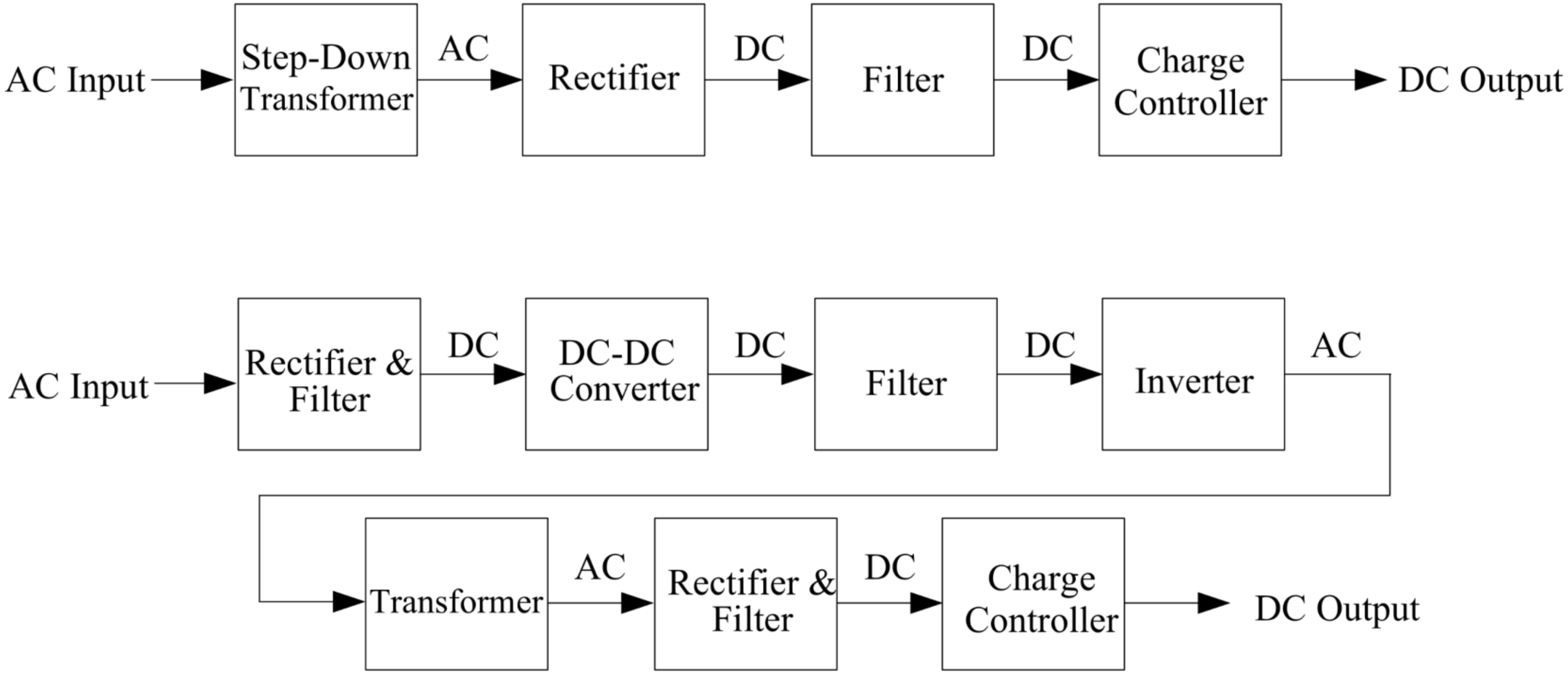
Off-grid systems are often charged from an AC source

- gen set-connected chargers
- inverter/chargers



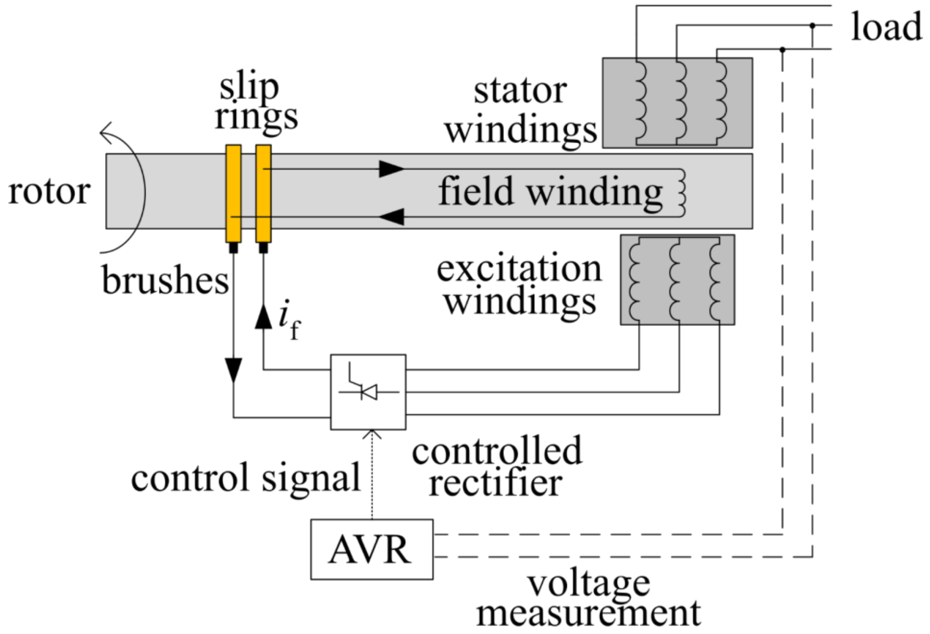


AC Battery Charging



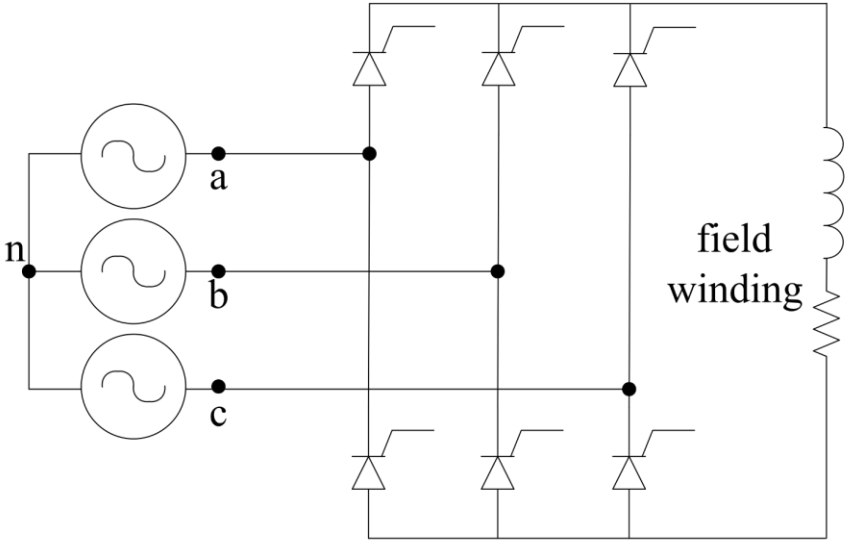
Automatic Voltage Regulator (AVR)

- Special application of rectifier
- Used in synchronous generators to control (regulate) the output voltage (see Chap. 6)
- Adjust dc current to generator rotor's field winding to achieve desired generator output voltage
- Use a controlled rectifier

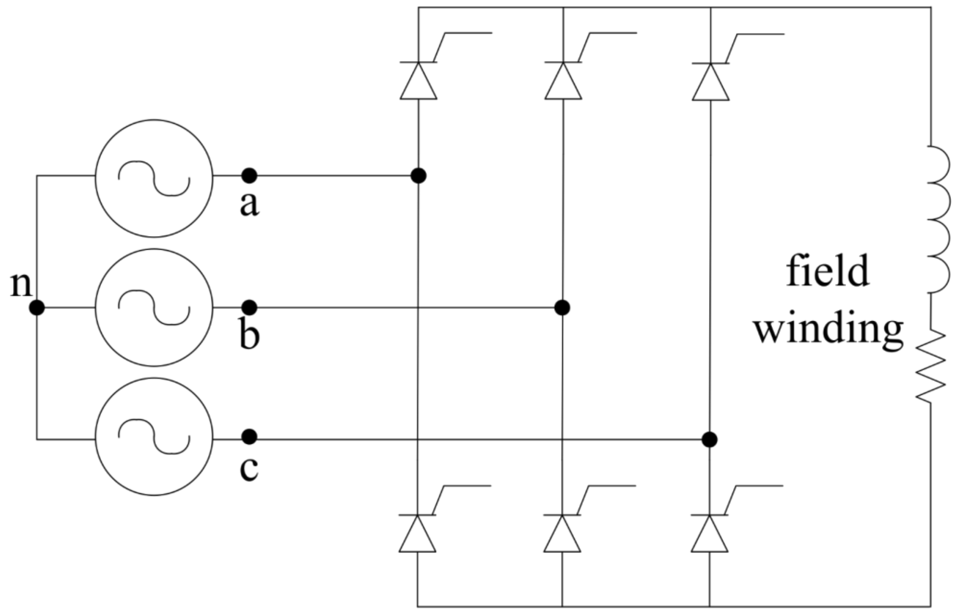


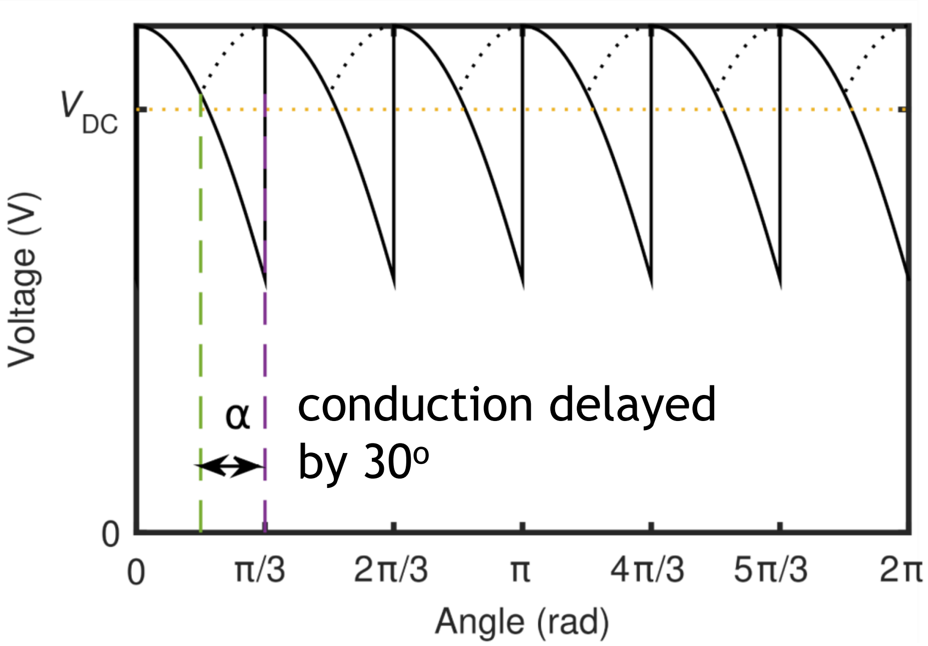
Automatic Voltage Regulator (Phase-Controlled Rectifier)

- Three-phase rectifier using thyristors instead of diodes
- Thyristor: conduction begins when forward biased AND "firing" signal received (α)
- Delay conduction to reduce average voltage and current output



Phase-controlled Rectifier





Phase-controlled Rectifier

Average DC output voltage depends on firing angle

$$V_{\text{DC}} = \frac{3V_{\ell\ell}^{\max}}{\pi}\left(\sin(\pi/6+\alpha) - \sin(-\pi/6+\alpha)\right)$$

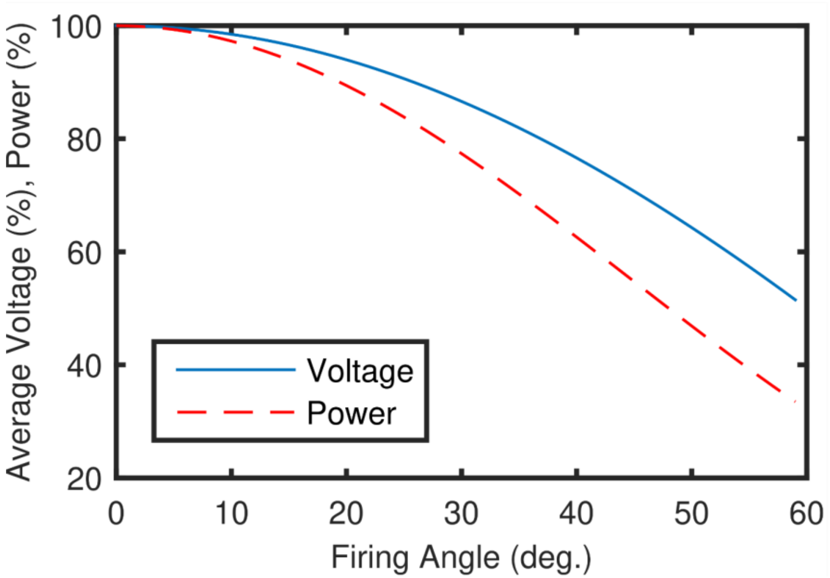
$$= \frac{3V_{\ell\ell}^{\max}}{\pi}\left(\sin(\pi/6)\cos(\alpha) + \cos(\pi/6)\sin(\alpha) - \sin(-\pi/6)\cos(\alpha) - \cos(-\pi/6)\sin(\alpha)\right)$$

$$= \frac{3V_{\ell\ell}^{\max}}{\pi}\left(0.5\cos(\alpha) + \frac{\sqrt{3}}{2}\sin(\alpha) + 0.5\cos(\alpha) - \frac{\sqrt{3}}{2}\sin(\alpha)\right)$$

$$V_{\text{DC}} \approx 0.955 V_{\ell\ell}^{\max}\cos(\alpha)$$

Phase-controlled Rectifier

Voltage and power to a resistive load as firing angle changes



Example 11.6

A hybrid off-grid system uses a three-phase biogas-fueled gen set. The gen set includes a three-phase phase-controlled AVR. The generator's field winding resistance is 150 Ω. Determine the firing angle needed to produce an average steady-state field winding current of 0.5 A when the generator's output voltage is 200 V.

Example 11.6

A hybrid off-grid system uses a three-phase biogas-fueled gen set. The gen set includes a three-phase phase-controlled AVR. The generator's field winding resistance is 150 Ω. Determine the firing angle needed to produce an average steady-state field winding current of 0.5 A when the generator's output voltage is 200 V.

From Ohm's Law, the required DC voltage is

$$V_{\text{DC}} = 0.5 \times 150 = 75\,\text{V}$$

Solving for firing angle:

$$\alpha = \cos^{-1}\left(\frac{V_{\text{DC}}}{0.955 V_{\ell\ell}^{\max}}\right) = \cos^{-1}\left(\frac{75}{0.955 \times 200 \times \sqrt{2}}\right) = 73.9^{\circ}$$

Summary

- **DC-DC Converters**: increase/decrease DC input voltage. Used in MPPTs and chargers.
- **MPPT**: allow PV arrays to operate at maximum power point by decoupling PV array voltage from battery voltage
- **Charge Controllers**: prevent battery from being overcharged by disconnecting or regulating the input DC source
- **Diversion Load Controller**: same purpose as a charge controller, but instead of interrupting a generation source, they send power to a dedicated diversion load
- **Automatic Voltage Regulators**: adjust the current to a synchronous generator’s field winding by using a phase-angle controlled rectifier