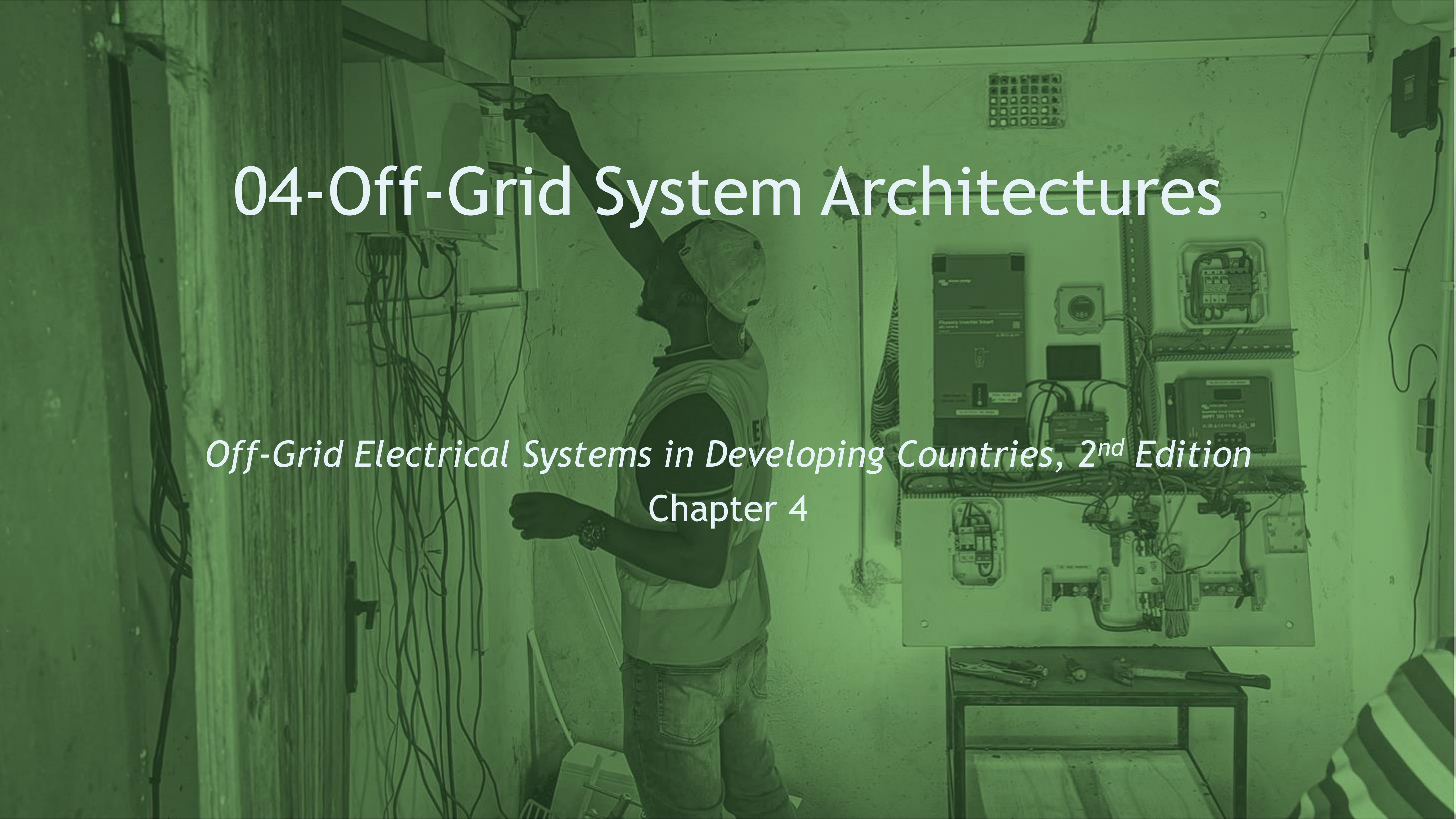


04-Off-Grid System Architectures

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

Chapter 4

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
- Inquiries about guest lectures, seminars, or trainings can be made to hlouie@ieee.org
- If you want to support work in electricity access, consider donating to KiloWatts for Humanity or IEEE Smart Village

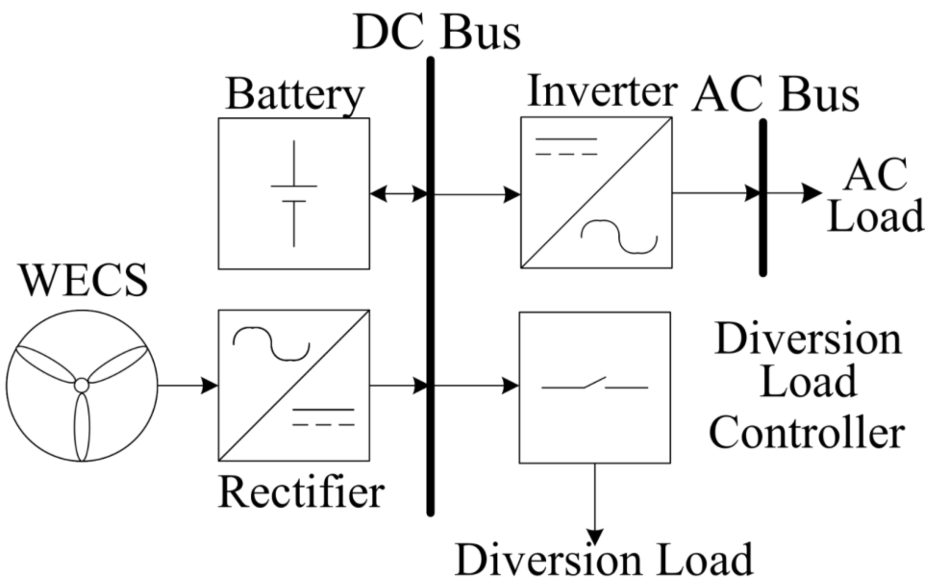
Learning Outcomes

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

- ✓Interpret symbols and schematics of off-grid systems
- ✓Describe the purpose and function of energy conversion technologies, storage, converters, controllers, and load in off-grid systems
- ✓Design valid and appropriate architectures of off-grid systems that use a variety of components and couplings

Introduction

- Off-grid systems are made up from several types of components such as generators, batteries, and controllers
- This lecture considers off-grid architectures—how the components can be connected to together to form an operational system



Terminology

Terminology in use is
inconsistent and ambiguous

- *Centralized system (national grid):* a large power system that is often a state-owned, vertically integrated and regulated monopoly with centralized control and coordination of generation, transmission, and distribution. Such systems typically serve a large geographic area and many users.

- *Decentralized system*: composed of autonomous units where generation and distribution have no centrally coordinated interaction with other units.

- *Off-grid*: an electrical system which is detached from the national grid.

Terminology Continued…

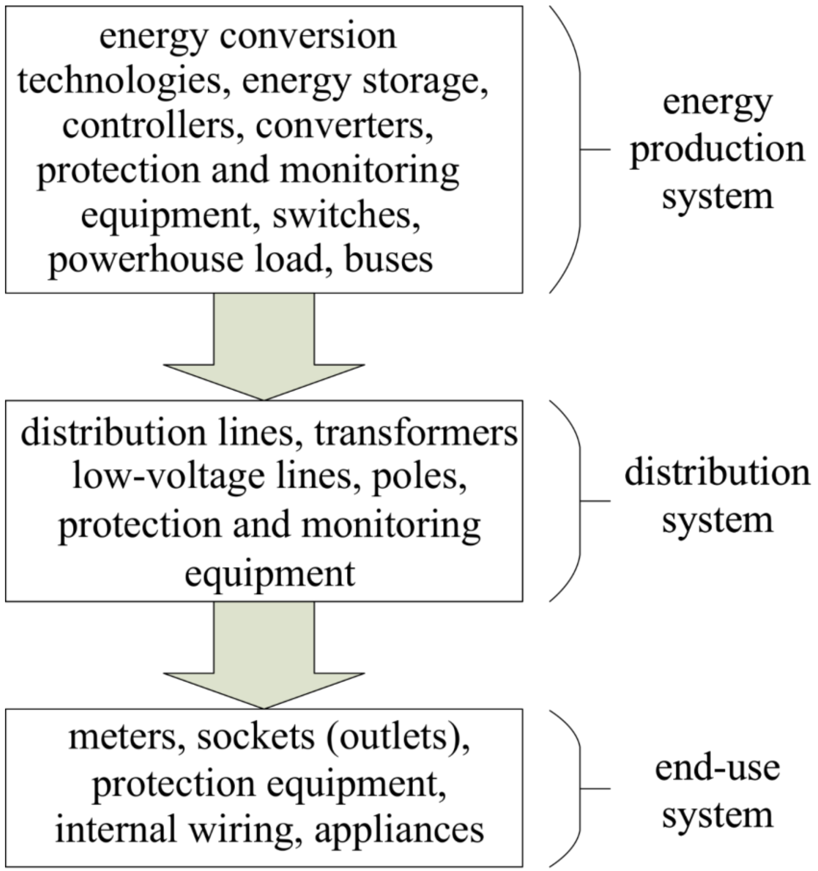
- *Small-scale*: a system whose power production rating does not exceed 5 MW (a mini-grid of this size is actually quite large—it could likely serve several thousand rural households).
- *Hybrid*: an off-grid system using two or more types of energy conversion technologies to produce electricity.
- *Conventional generation*: generators that run solely on fossil fuels (usually diesel or gasoline).
- *Stand-alone*: a system that serves a single building such as home, business, school, or medical clinic. Stand-alone systems are typically less than 1 kW but sometimes exceed 10 kW.
- *Mini-grid*: an off-grid system that serves multiple users, typically rated at less than 1MW, low-voltage distribution, and usually greater than 10 kW in capacity.
- *Metro-grid*: an emerging term for large mini-grids whose capacity is 1 MW or greater, with several thousand connections, and medium- and low-voltage distribution networks.

Example

A small-scale, decentralized, hybrid mini-grid using wind and solar power in Kenya

(*courtesy: KiloWatts for Humanity*)

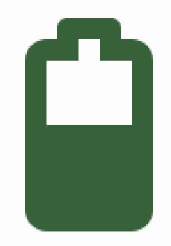
Mini-Grid Sub-Systems



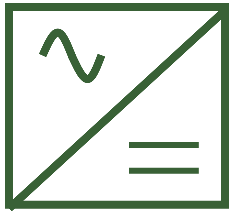
Building Blocks of Off-Grid Systems

Energy Conversion Technologies

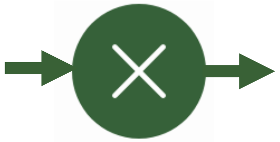
Energy Storage



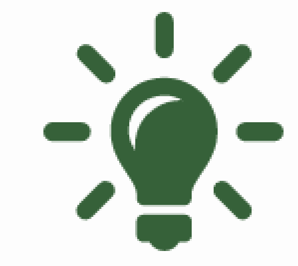
Converter



Controller



Load



Energy Conversion Systems

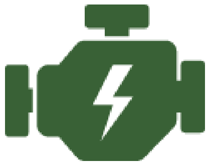
Convert energy of one form into electrical energy

- Example: wind turbine converts kinetic energy in moving air to rotational energy in a generator shaft, which produces electricity

We must take note of the type of output of an energy conversion system

- AC or DC
- frequency
- regulation (controllability) of voltage magnitude and frequency

Energy Conversion Technologies



Conventional or Biomass Gen Sets

Photovoltaic Array

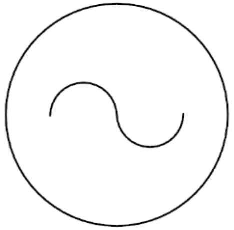
Wind Turbine

Hydro Turbine

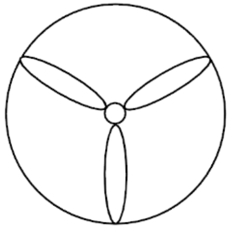
Why are geothermal, tidal, wave and concentrating solar power not used in mini-grids?

Energy Conversion Technologies

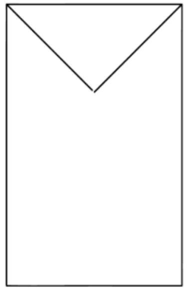
Gen. Set (Fossil-fuel/biomass)

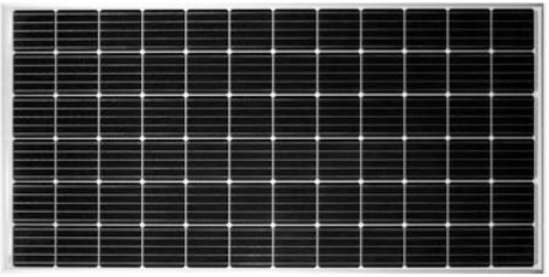


Wind Energy Conversion System (WECS)

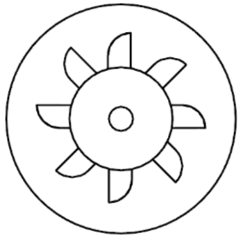


PV Module



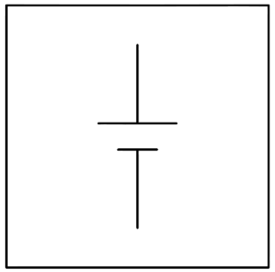


Micro Hydro Power (MHP)



Energy Storage

- Energy storage improves reliability and availability of a system
- Not required in all systems, depending on the energy conversion technology
- Common types in off-grid systems
  - Lead-acid
  - Lithium-ion (various types)
  - Many others proposed and used in pilot/limited deployment (for example zinc-air battery)



Battery Symbol

Batteries

- Must be connected to a DC bus
- Must be at least one pathway to be charged and discharged
- Cannot supply AC load directly
- Over-charging must be prevented
- Over-discharging must be prevented

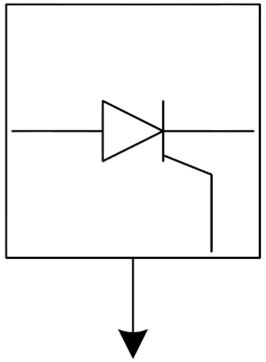
(*courtesy: KiloWatts for Humanity*)

Controllers

- Controllers affect how components operate and interact with each other
- Applications
  - battery charging
  - generator voltage regulation (Automatic Voltage Regulator)
  - generator frequency (electronic governors, electronic load controller)
  - maximize power from PV modules (maximum power point tracking)
  - synchronize generators and inverters
  - coordinate operation of different controllers
  - and more

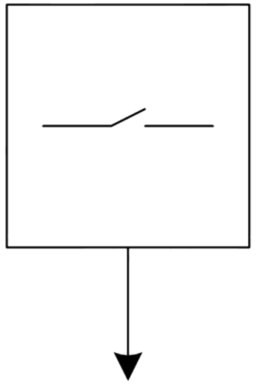
Controllers

Electronic Load Controller



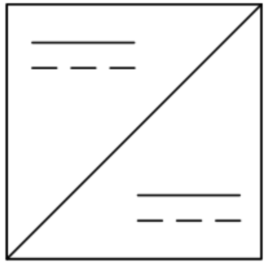
Controls power to a ballast load.
Used to regulate frequency in micro hydro power systems

Diversion Load Controller



Controls power to a resistive diversion load. Used to prevent over-charging a battery in wind and some hydro systems

Charge Controller

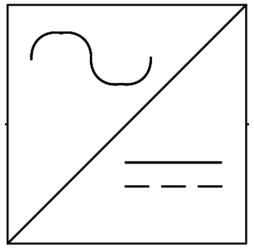


Prevents battery from being over-charged; may contain maximum power point tracking capability

Converter

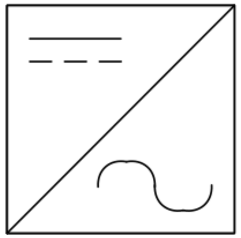
- Used in controllers and to facilitate flow of power between AC and DC buses in a mini-grid
- Common Applications
  - DC/DC converters (increase/decrease voltage)
  - DC/AC inverter
  - AC/DC rectifier

Rectifier



Converts AC to DC

Inverter



Converts DC to AC, can be bi-directional

Load

- "Load" can mean the power or energy consumed by a device, or the device itself
  - "The load is 100 W"
  - "The load is a television"
- Loads can be AC or DC (some can be supplied by either)
- Some loads are more tolerant than others to being supplied voltage or frequency outside their rating

One-Line Schematic

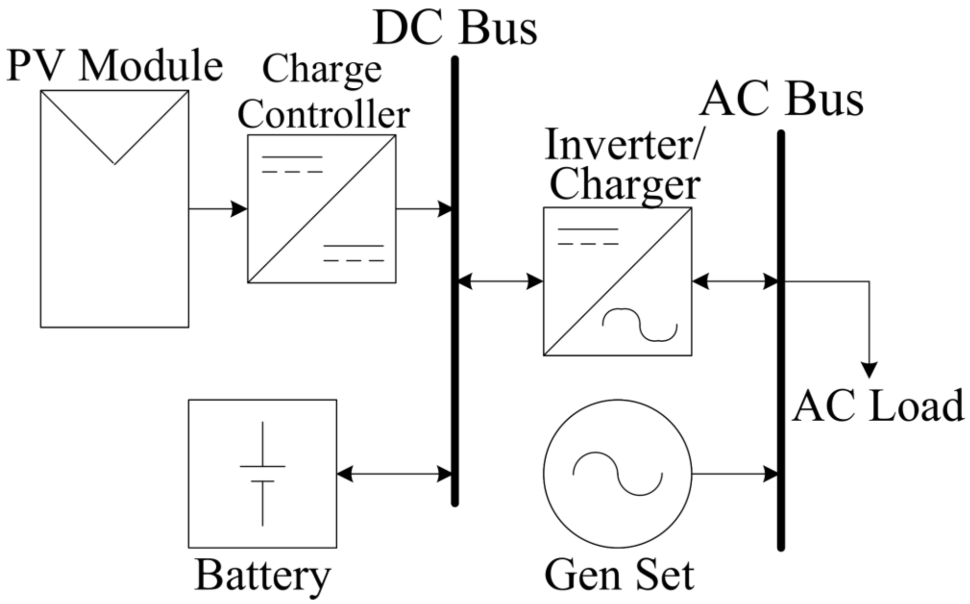
What is it?

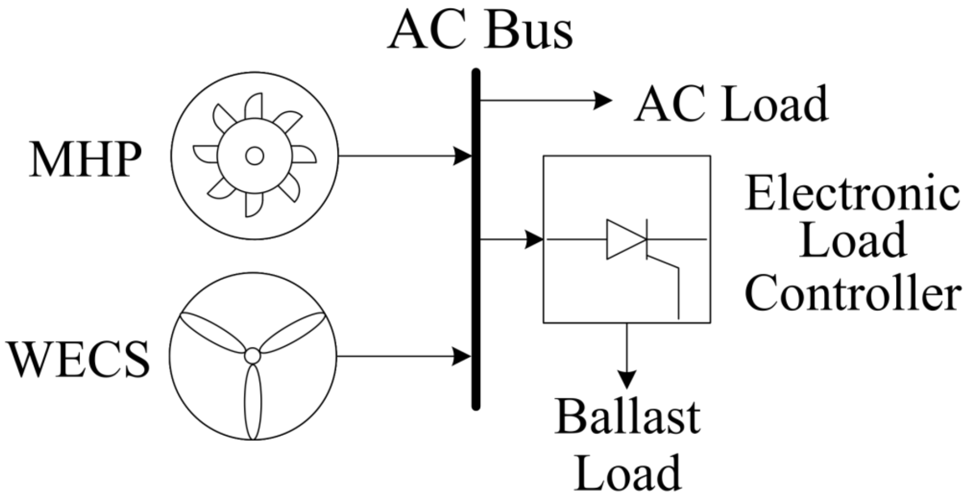
- Graphical representation of the major components of a system
- Describes the architecture of the system---what components are included and how they are connected
- Similar components are combined into one symbol (e.g. one battery for a battery bank)
- Shows the possible flow of power in the system
- Used as a first step in design of the system, allowing major components to be identified

What is it not?

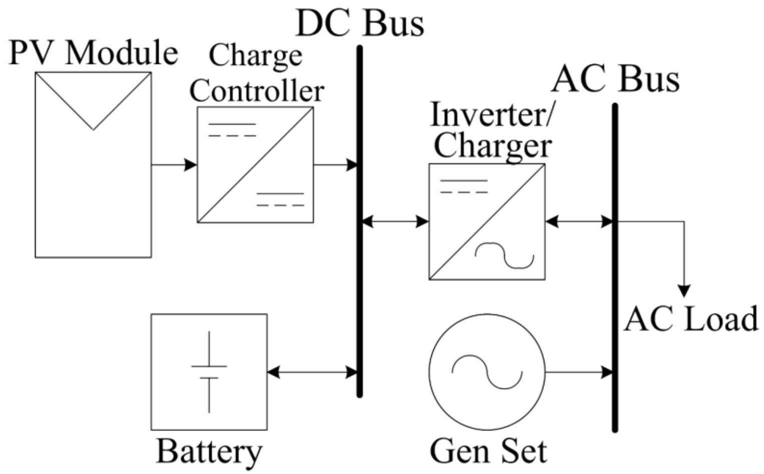
- Circuit model of the system
- Depiction of all the wires of the system
- Detailed representation of the entire system (notably omitted: protection equipment, meters, and some controllers)

Examples

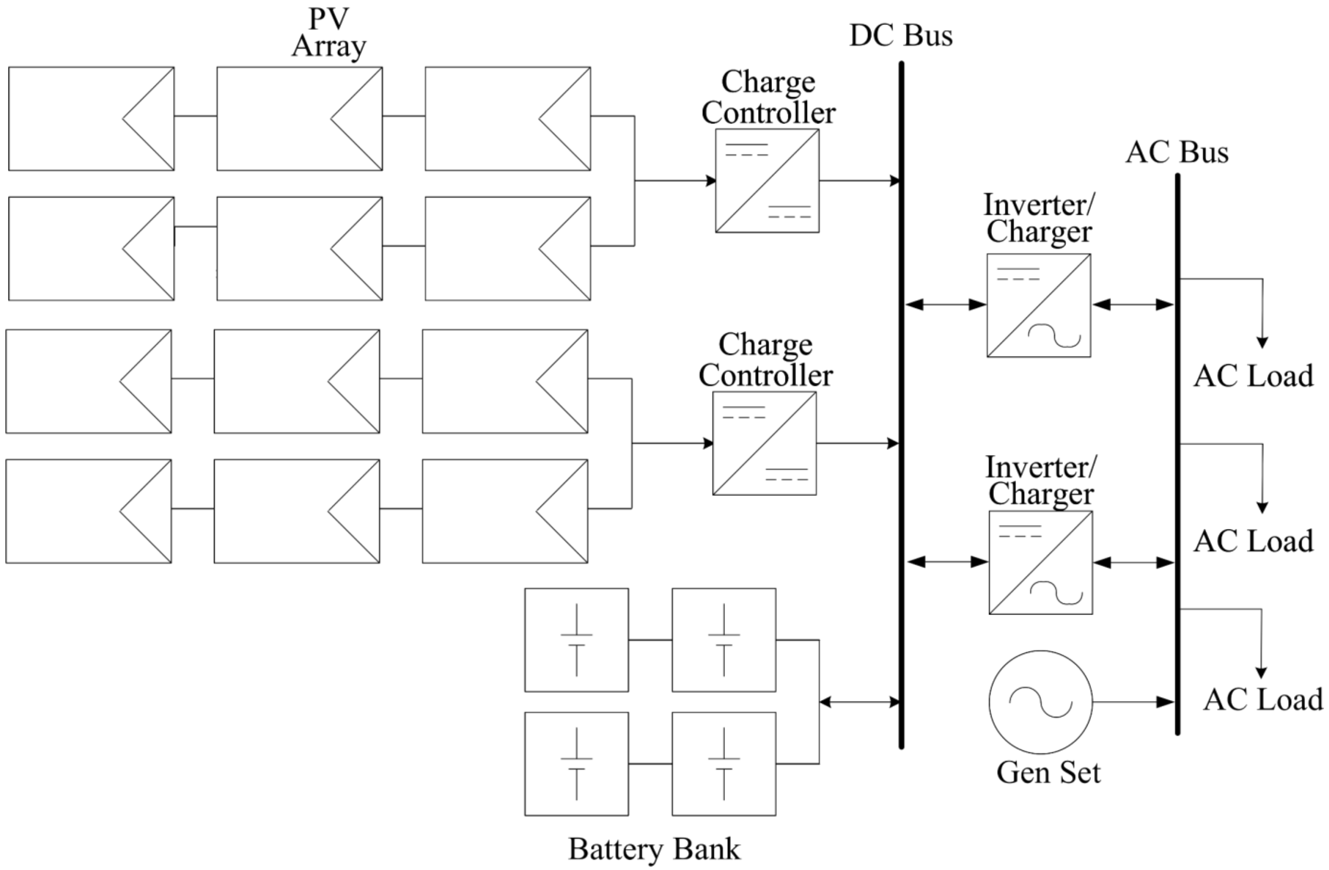

DC Bus
PV Module
Charge
Controller
AC Bus
Inverter/
Charger
AC Load
Battery
Gen Set


AC Bus
AC Load
MHP
Electronic
Load
Controller
WECS
Ballast
Load

Condensed Schematic



Full Schematic



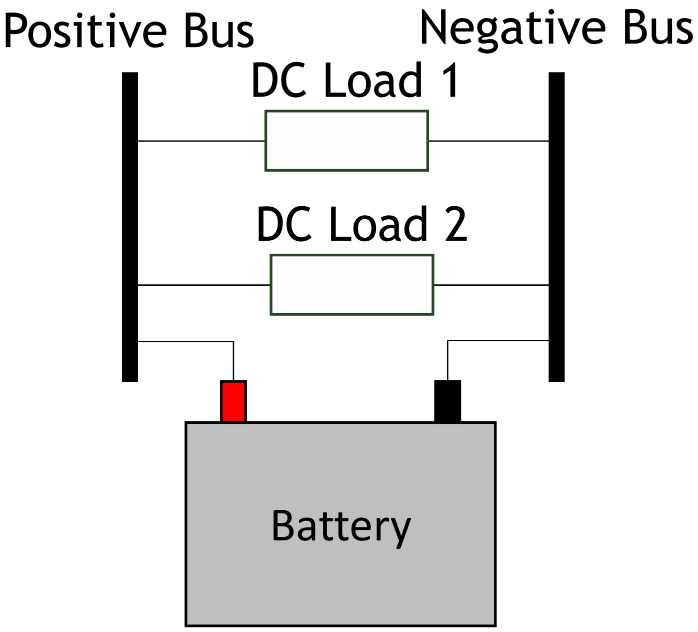
Electrical Buses

Electrical bus: point (or node) where components are connected

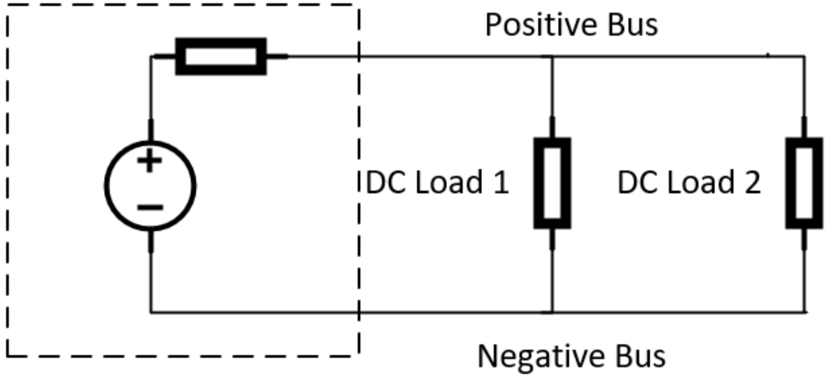
- can be a single terminal, or a busbar (metal strip with lugs attached)

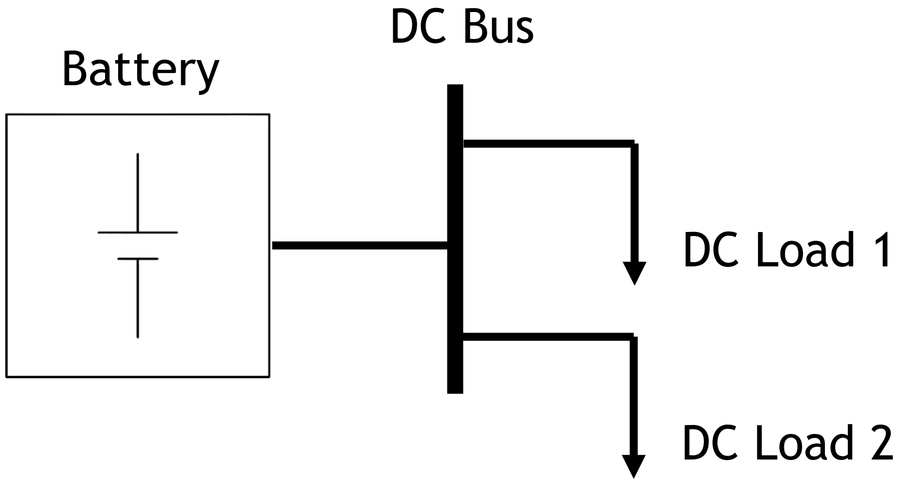
All components connected to the same bus are in parallel with each other: same voltage magnitude, polarity, frequency and phase

Assume the bus is lossless with zero impedance



Battery Equivalent Circuit

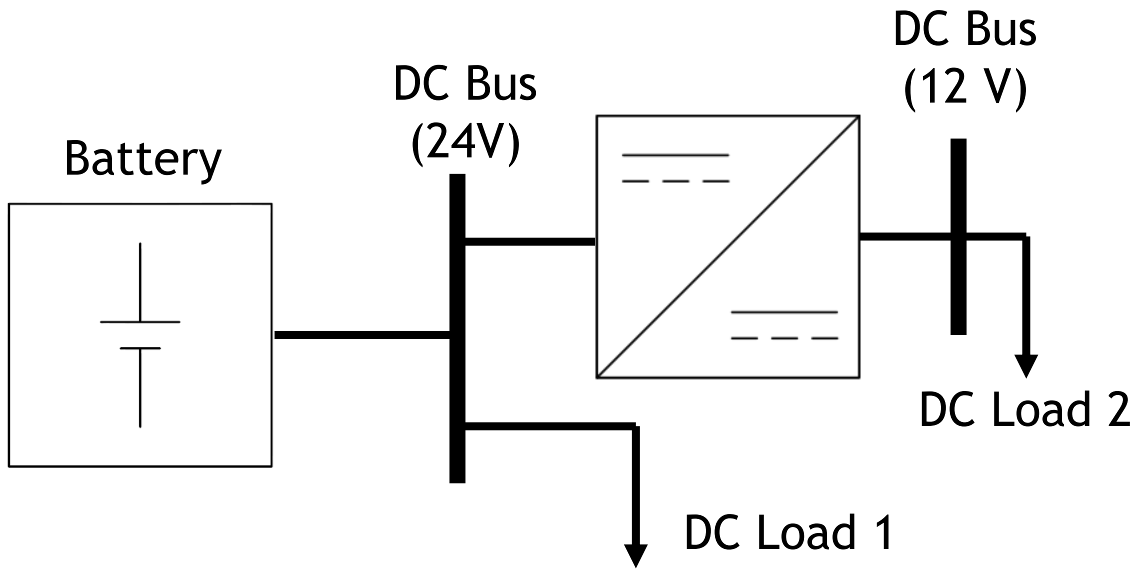




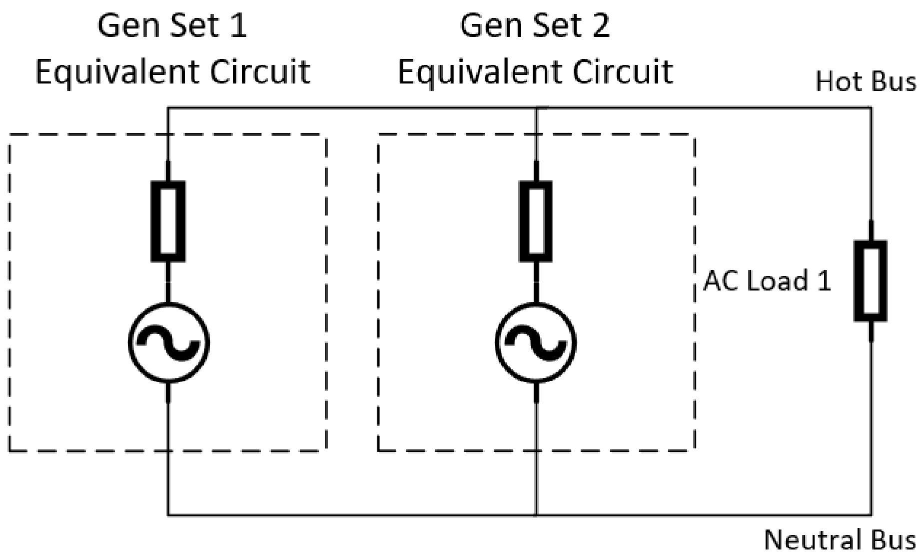
Components connected to the DC Bus
are in parallel, and operate at the same voltage

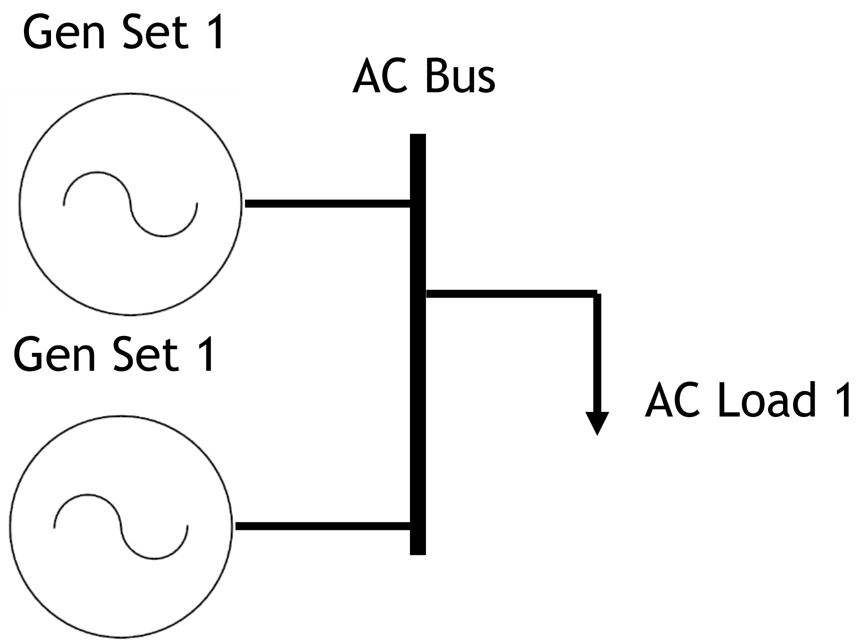
DC Bus

- DC bus voltage must be set by a component
  - Almost always a battery
  - Bi-directional inverters can be used, but not common in off-grid systems
- DC—DC converters can be used to form multiple DC buses (with different voltage levels)



AC Bus





Components connected to the AC bus
are in parallel, and operate at the same voltage
magnitude, frequency and phase. Only one phase is
showed, even if it is a three-phase system

System Coupling

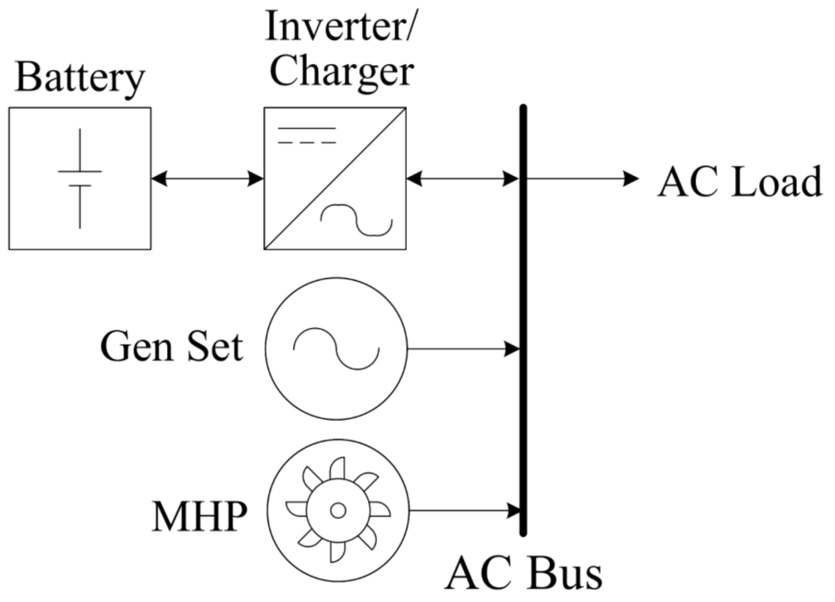
- Off-grid systems can be described by the system's *coupling*
- System coupling types:
  - DC
  - AC
  - AC—DC

Coupling determined by which bus energy sources are connected

AC Coupling

- All energy sources connected to AC bus
- Sources must be synchronized (same frequency)
- One source “forms” AC bus
  - sets and maintains voltage frequency
- Voltage frequency and magnitude must be regulated and allow for coordinated control of real and reactive power allocation among sources
- Not all generation sources can control their voltage frequency (WECS and some MHP)

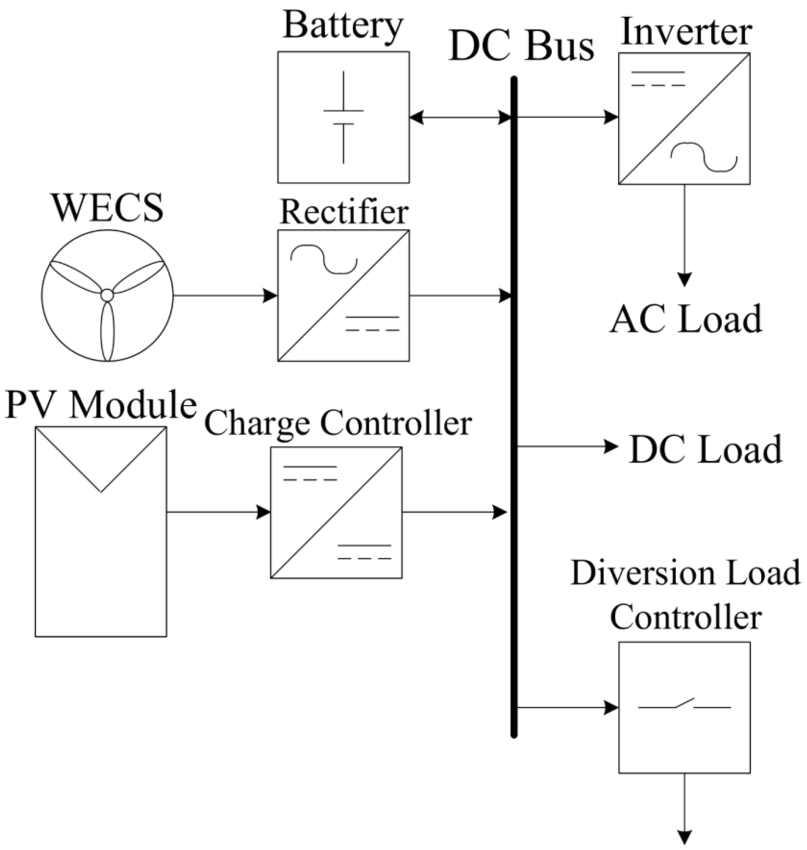
Example of AC-coupled System



DC Coupling

- All energy sources connected to DC bus
- Battery sets DC bus voltage
- Battery must be protected against over-charging and deep discharge
- Especially suitable for
  - PV systems
  - LED lighting

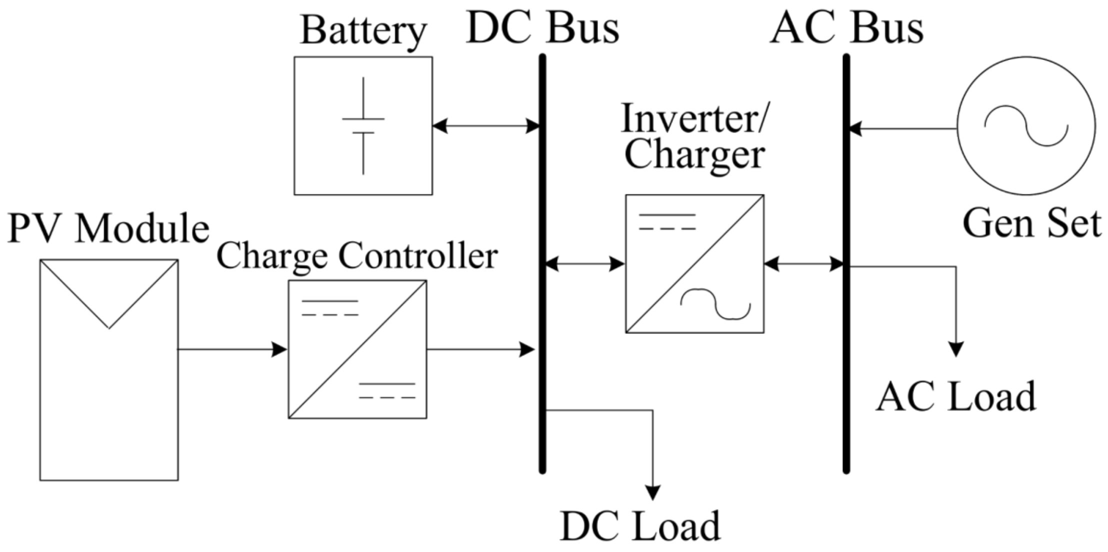
Example of DC-coupled System



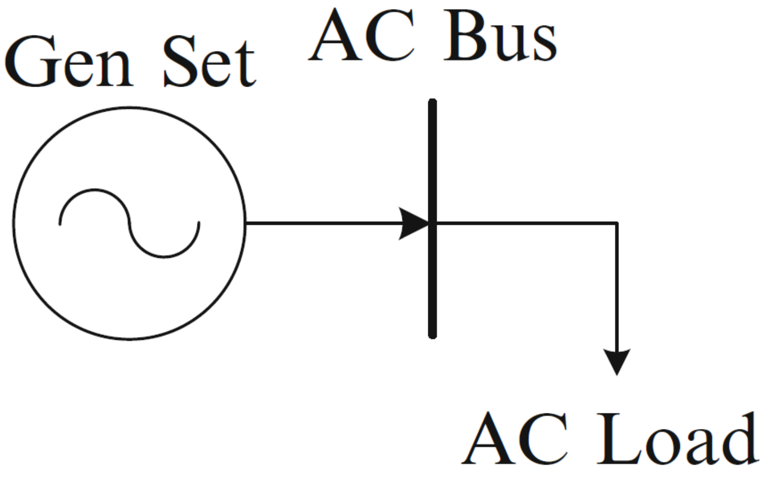
AC—DC-Coupling

- Flexible architecture
- At least one DC-coupled and one AC-coupled source
- Power flow can be bi-directional or uni-directional (AC to DC bus, or DC to AC bus)

Example of AC—DC-coupled System

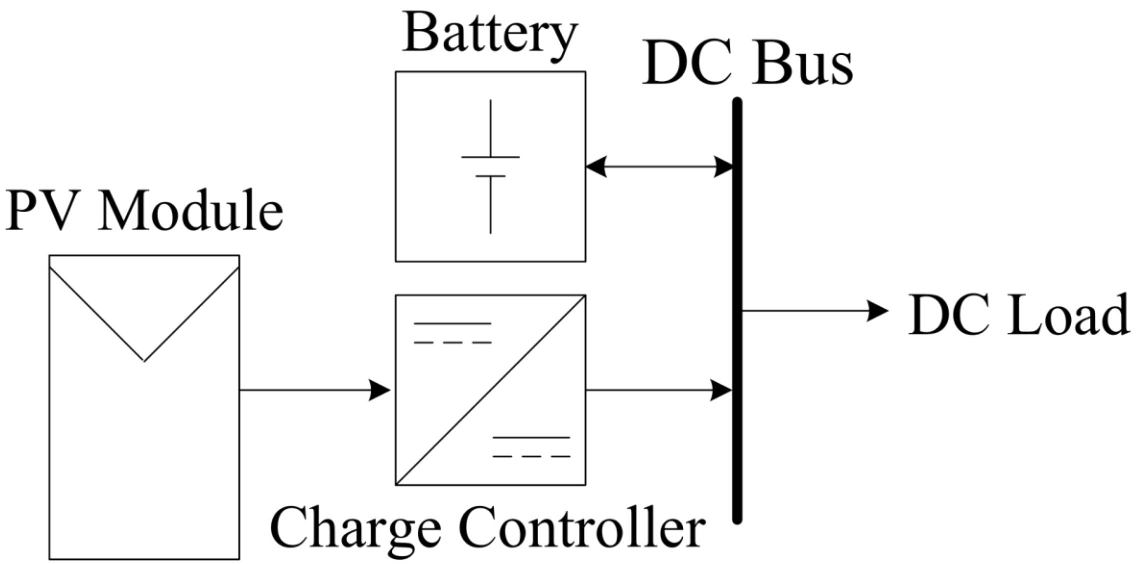


Conventional or Biomass Gen Sets



What component is responsible for voltage/freq. regulation?

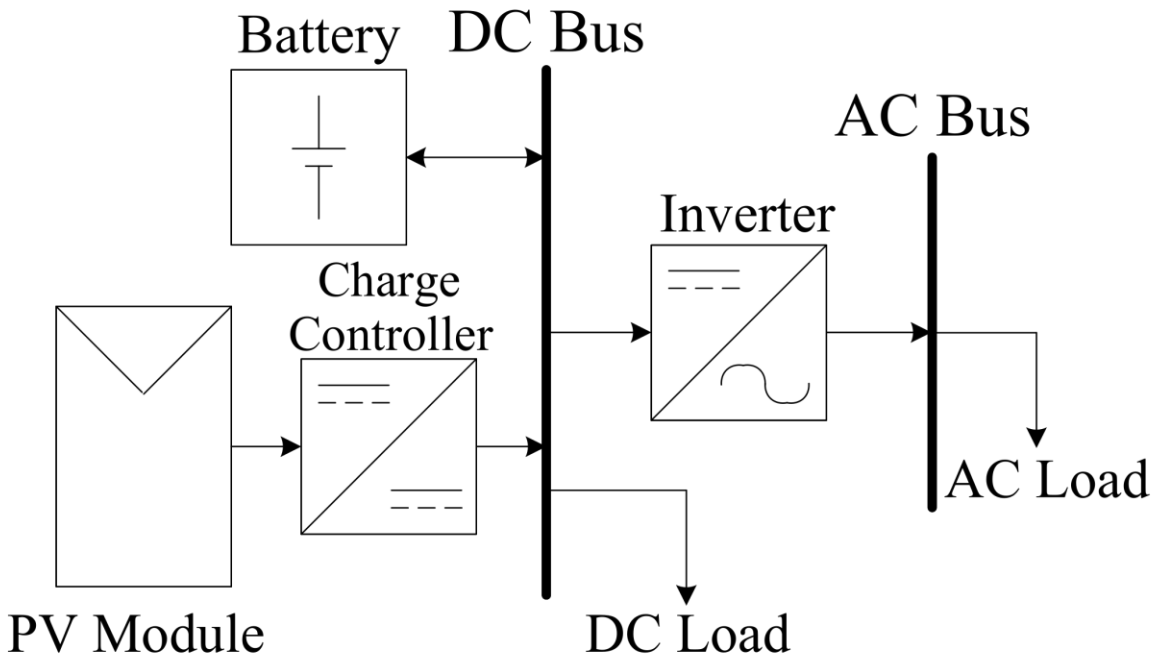
Photovoltaic System with DC Load

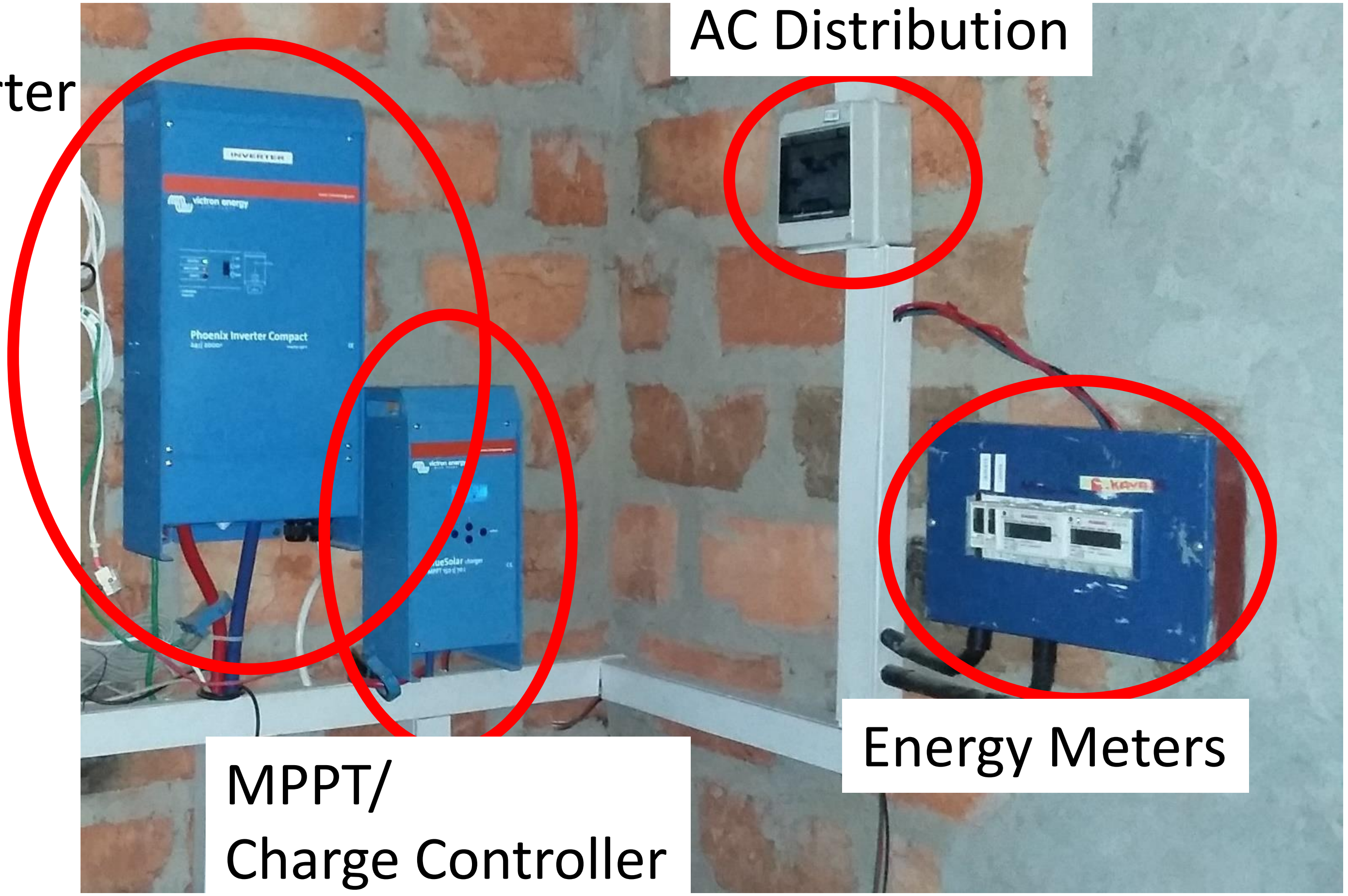


Photovoltaic System with AC Load

What component is responsible for voltage/freq. regulation?

What component(s) is responsible for battery charge management?

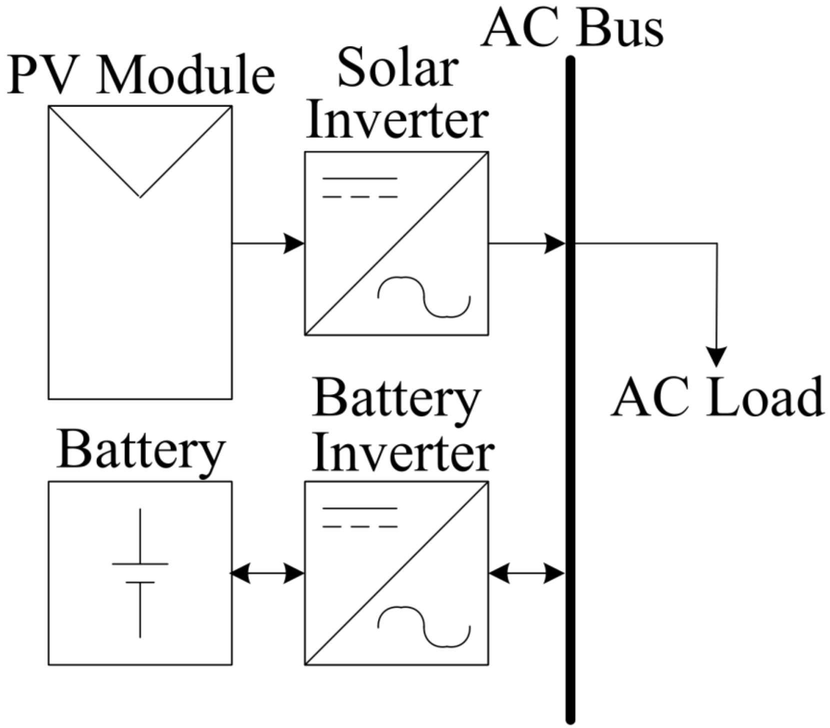




(*courtesy: H. Louie*)

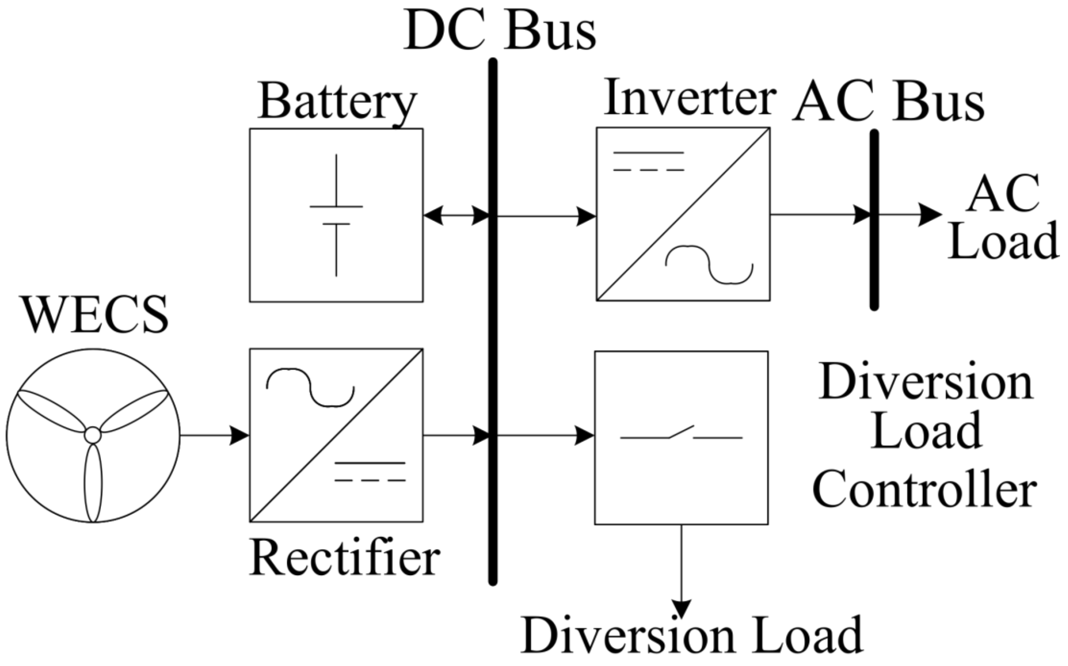
AC-Coupled PV Systems

- Solar inverters can be used to couple PV modules to the AC bus
- Battery inverter “forms” the AC bus and the solar inverters synchronize to it



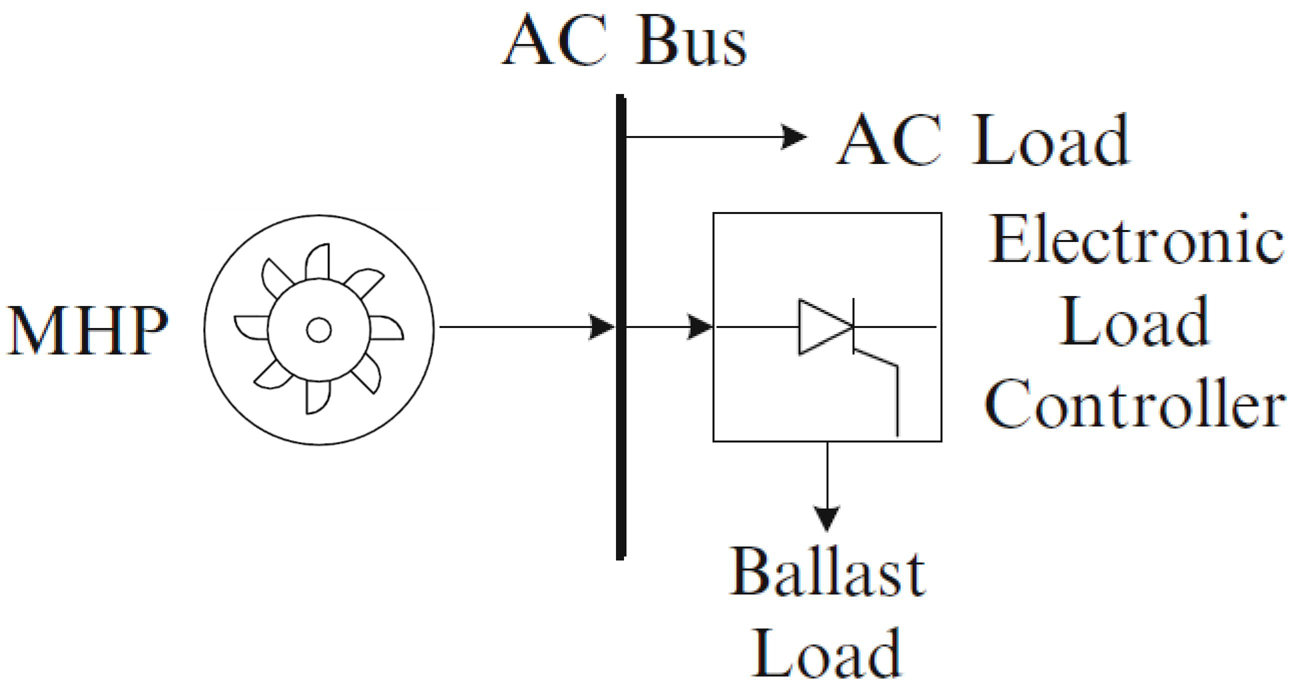
Wind Energy Conversion Systems

- DC-coupled WECS are common
- WECS can be AC coupled if connected to a Wind Inverter, which ensures the frequency output is constant



Micro Hydro Power System

What component is responsible for voltage/freq. regulation?

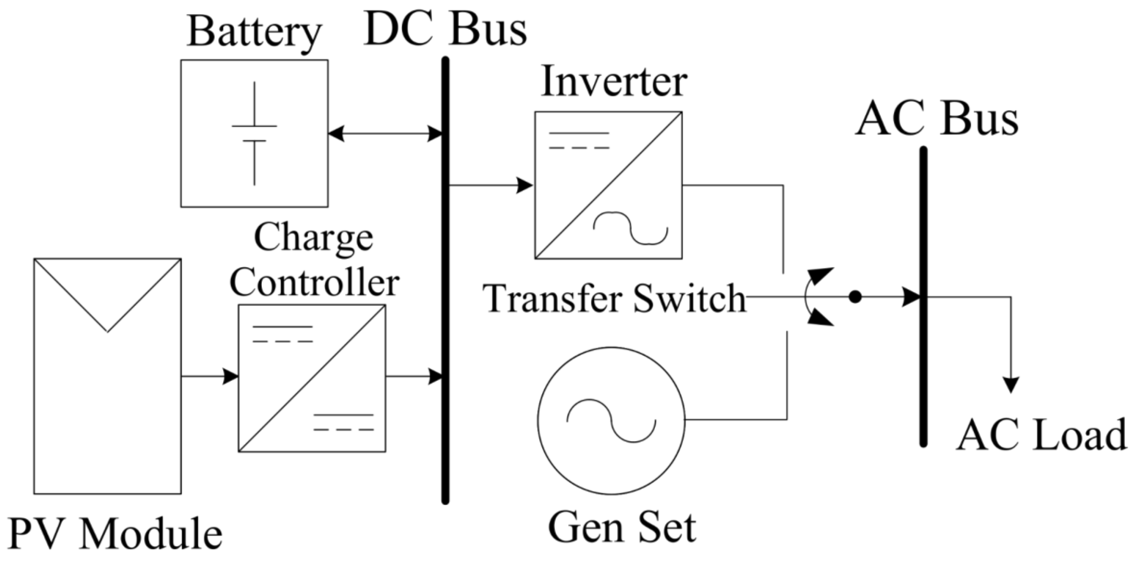


Hybrid Systems

- Recall that hybrid systems incorporate two or more different energy sources
- One source is often, but not always, a gen set

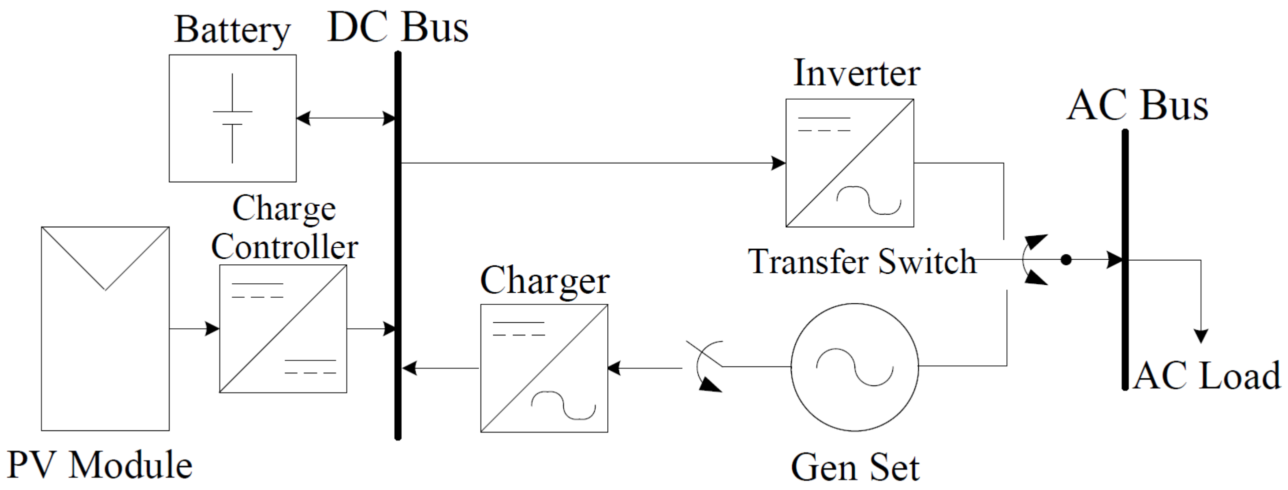
Hybrid Systems: Switched Architecture

- Gen set is used as a back-up supply in case battery state-of-charge is too low
- Load is supplied by EITHER inverter or Gen Set (not both)
    - no need to synchronize
- Inverter is not bi-directional



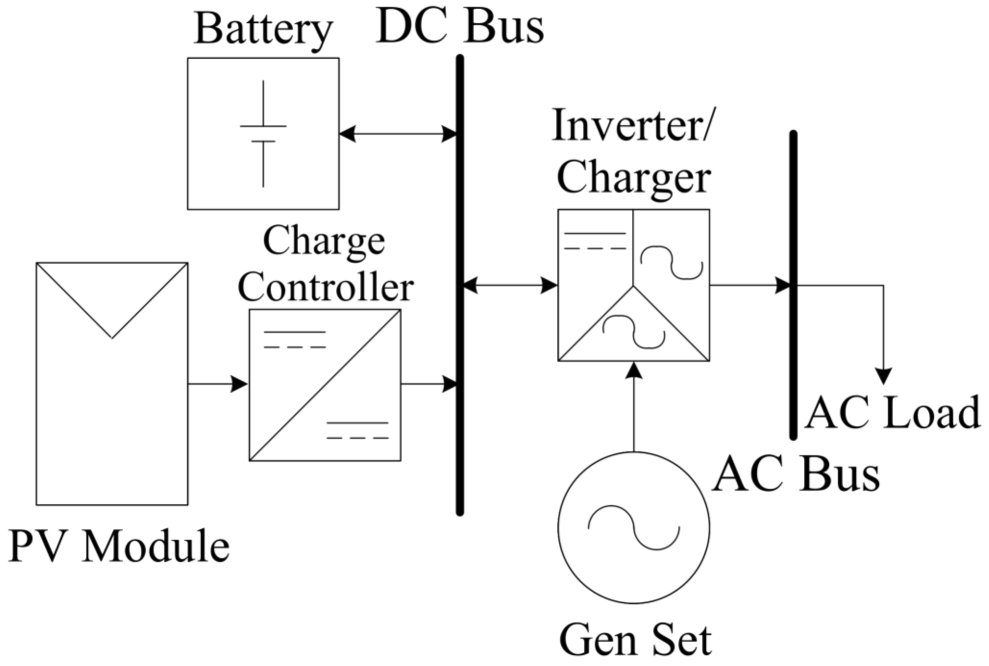
Hybrid Systems: Switched Architecture with Battery Charging

Separate AC charger enables gen set to recharge battery



Hybrid Systems: Switched Architecture with Battery Charging

- Inverter is bi-directional and can synchronize with gen set
- Gen set power to recharge battery and/or supply load
- Gen set and inverter can simultaneously supply load



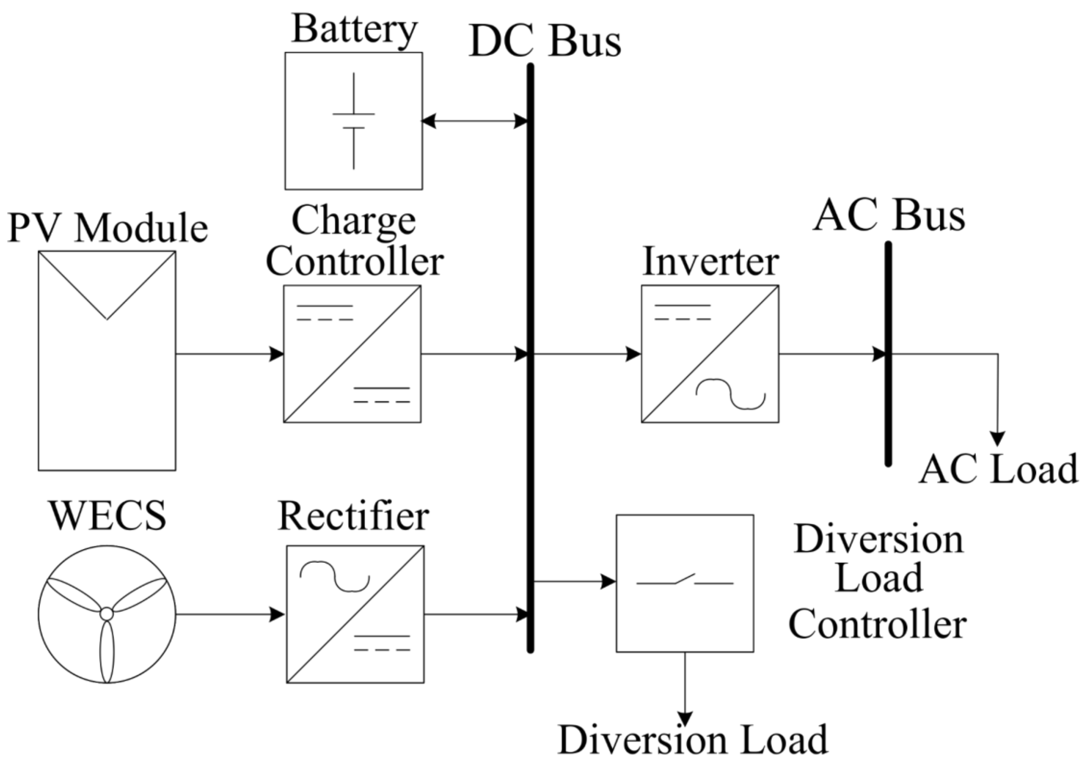
Hybrid Renewable System

- Two or more different renewable power sources
- Used when sources have complementary characteristics
- Example: sunny during the daytime and windy in the evening

(*courtesy: KiloWatts for Humanity*)

Hybrid Renewable System

- PV module and WECS are DC-coupled
- Battery managed by charge controller and diversion load controller



One-Line Schematic Rules

1. There must always be a path for power to flow to each load from at least one generation source
2. It must be possible for power to flow into and out of each bus (equivalently, there must be arrows into and out of each bus)
3. There must be a path for power to flow into and out of each battery
4. Only DC components can be connected to a DC bus; only AC components can be connected to an AC bus
5. Only converters (rectifiers, inverters, inverters/chargers) can simultaneously be connected to both an AC bus and DC bus

One-Line Schematic Rules Continued

6. All components connected to the same bus are electrically in parallel and thus must be capable of operating at that the voltage, frequency or polarity of that bus
7. An AC bus must contain at least one generation source capable of “forming” the bus voltage
8. The voltage frequency and magnitude at each AC bus must be regulated, often by a gen set, inverter, or MHP with electronic load controller or mechanical governor
9. All batteries must be protected from being over-charged, for example by using a charge controller (with PV modules), diversion load controller (with WECS and some MHP), and/or by a charger

Energy Conversion Technology

Technology	Output	Voltage Regulation?	Frequency Regulation?
Gen set	AC (assumed), can be DC	Yes, with Automatic Voltage Regulator (AVR) (assumed)	Yes, with governor (assumed)
WECS	AC (assumed), can be DC	No	No
MHP	AC (assumed), can be DC	Yes, with AVR (assumed)	Can be with governor (e.g. needle valve control), (NOT assumed)
PV Module	DC	No	N/A
Inverter	AC	Yes	Yes

Converters and Controllers

Technology	Connected To	Battery Charge Regulation?
Diversion Load	DC Bus	Yes
Electronic Load Controller	AC Bus	No
Charge Controller	PV array (input), DC Bus (output)	Yes, but only from PV array to which it is attached
Rectifier	AC source (input), DC Bus (output)	No (assumed), but can be if it is a “battery charger”
Inverter (bi-directional)	AC Bus, DC Bus	Yes, when it is a “battery charger” (assumed)

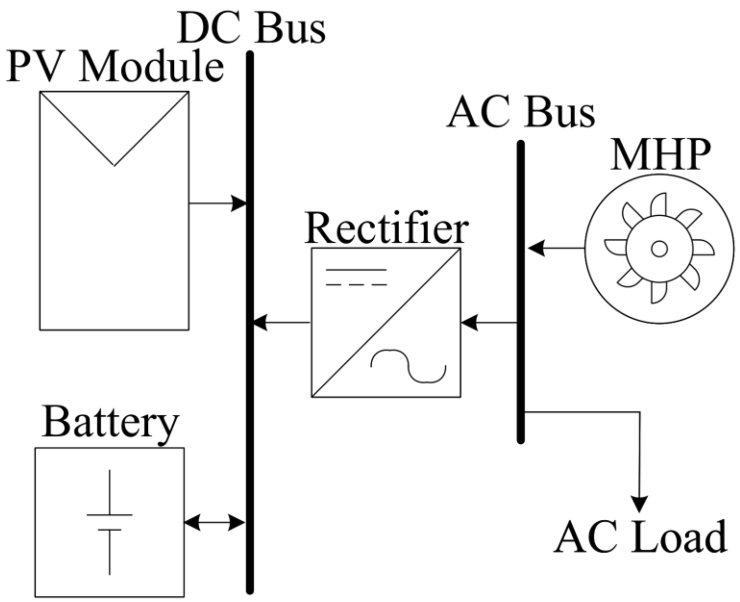
Architecture Selection

Select architecture that minimizes complexity and cost, and maximizes efficiency

- fewer conversions preferred (i.e. if load is DC, consider DC-coupled architecture)

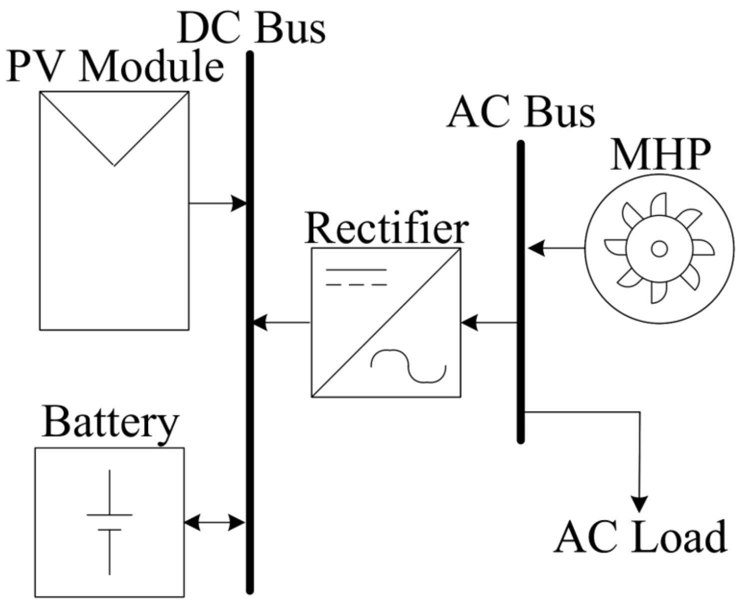
Example 4.1

Consider the proposed off-grid system shown. The MHP does not have a mechanical governor. Identify the errors in the architecture. Propose a valid off-grid system architecture and draw the corresponding schematic.



Example 4.1

Consider the proposed off-grid system shown. The MHP does not have a mechanical governor. Identify the errors in the architecture. Propose a valid off-grid system architecture and draw the corresponding schematic.



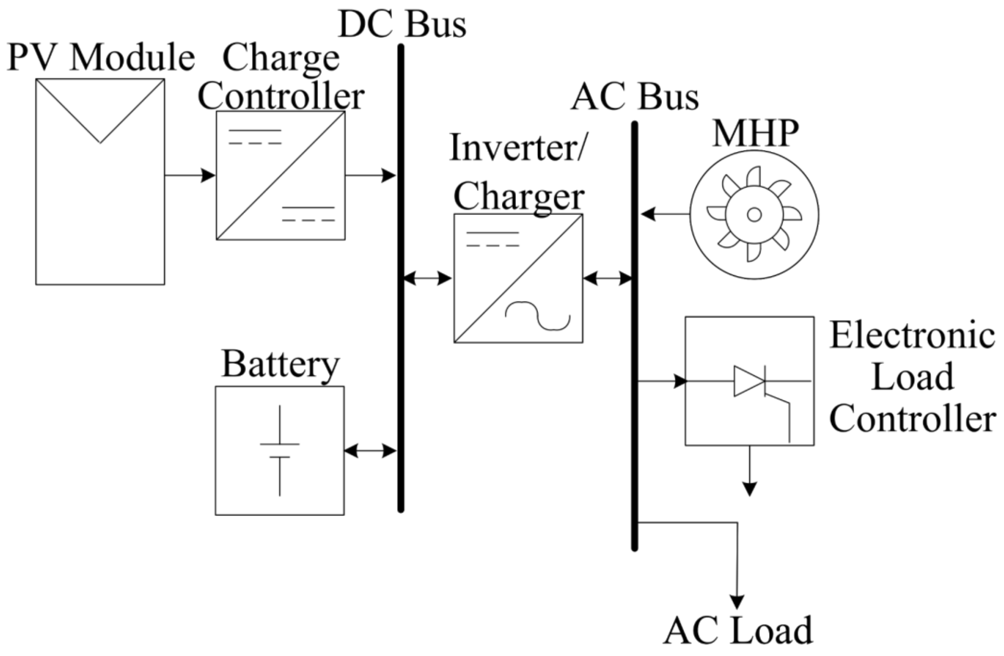
The direction of power from the rectifier is such that the battery cannot discharge (rules 2 and 3)

Without a mechanical governor or electronic load controller, there is no way to regulate the AC bus frequency (rule 8)

The battery is not protected from being over-charged from the PV module (rule 9)

Example 4.1

Consider the proposed off-grid system shown. The MHP does not have a mechanical governor. Identify the errors in the architecture. Propose a valid off-grid system architecture and draw the corresponding schematic.



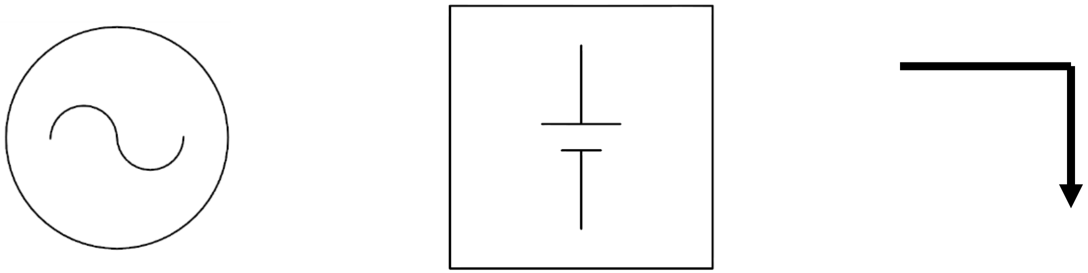
Exercise

Draw a one-line schematic of an off-grid system that uses a gen set to supply an AC load. There is a battery backup. Assume the gen set outputs a voltage that is compatible with the load.

Exercise

Draw a one-line schematic of an off-grid system that uses a gen set to supply an AC load. There is a battery backup.

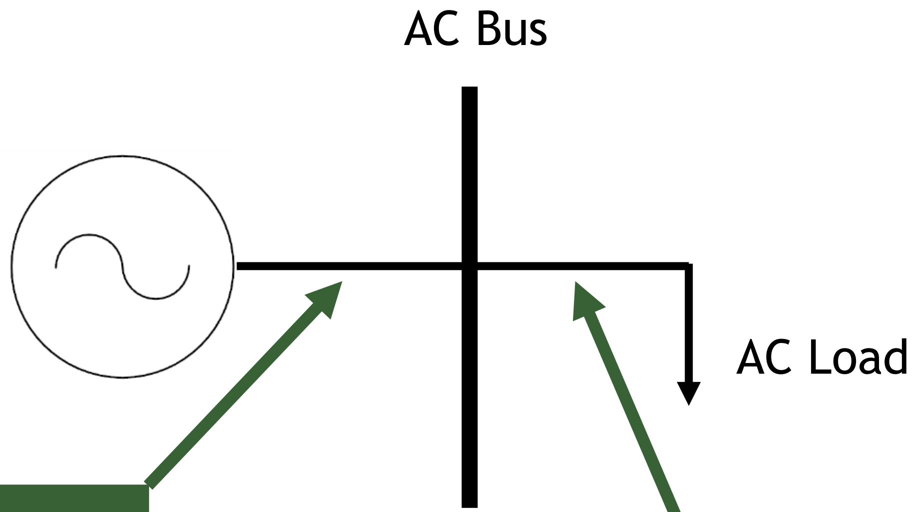
Here are the components described in the problem

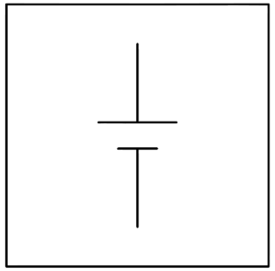


AC Load

Standard assumption is that the gen set supplies AC voltage

Exercise

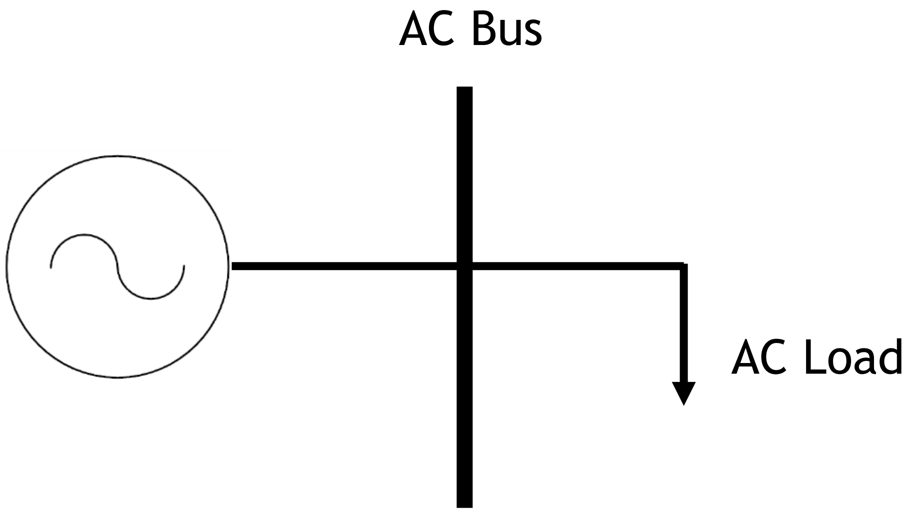




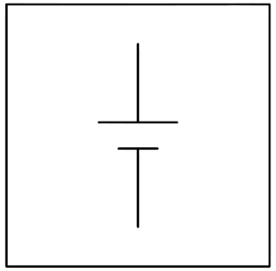
Standard assumption is that
the gen set supplies AC voltage,
so it must be coupled to the AC bus

Since the gen set outputs the desired voltage,
the AC load can be coupled to the same AC bus

Exercise

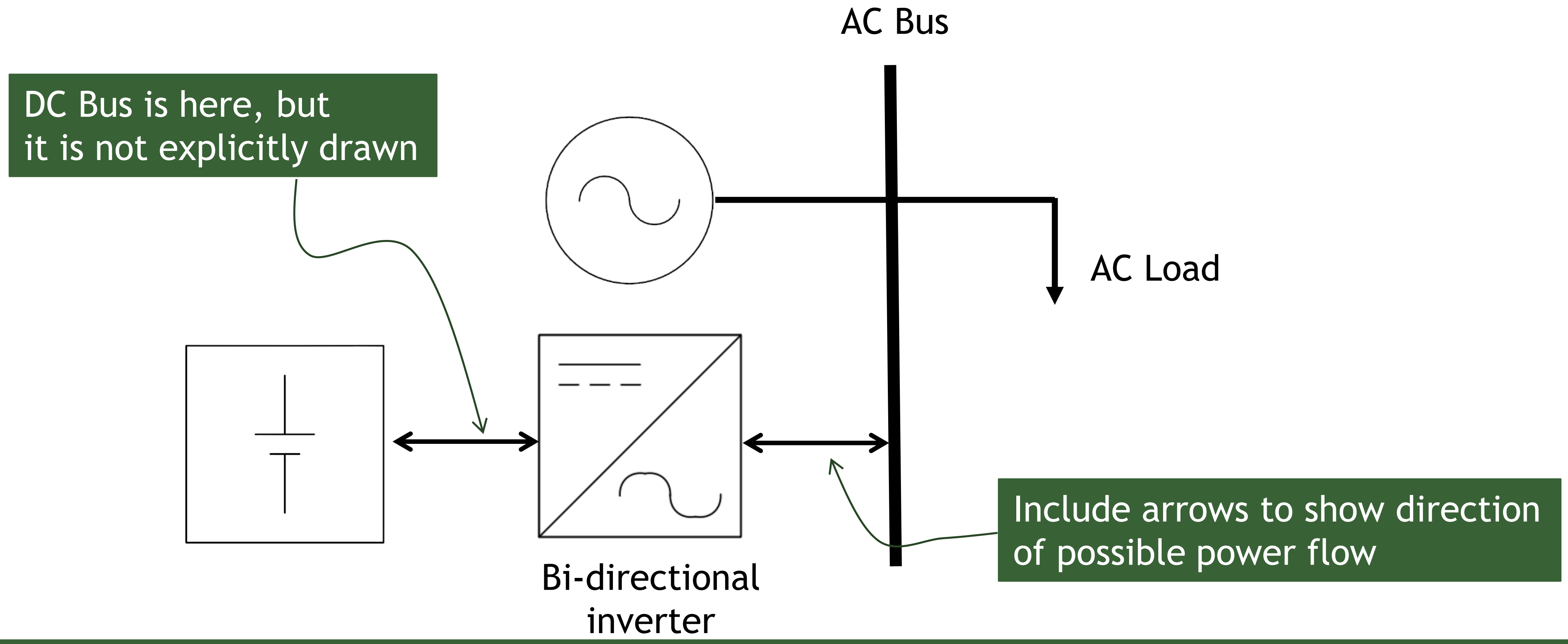


What about the battery?



Battery cannot be coupled directly to the AC Bus. Need a converter. What type?

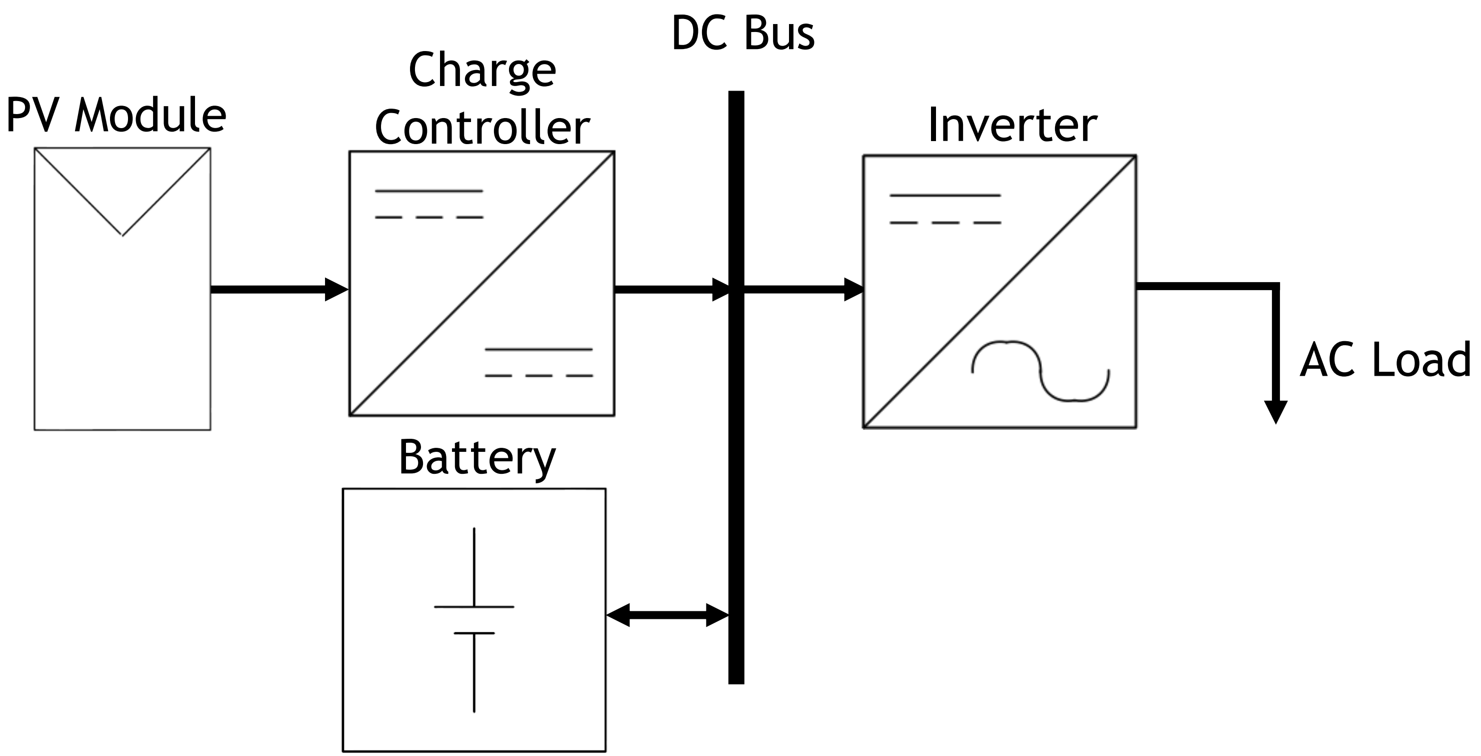
Exercise


AC Bus
DC Bus is here, but
it is not explicitly drawn
AC Load
Bi-directional
inverter
Include arrows to show direction
of possible power flow

Exercise

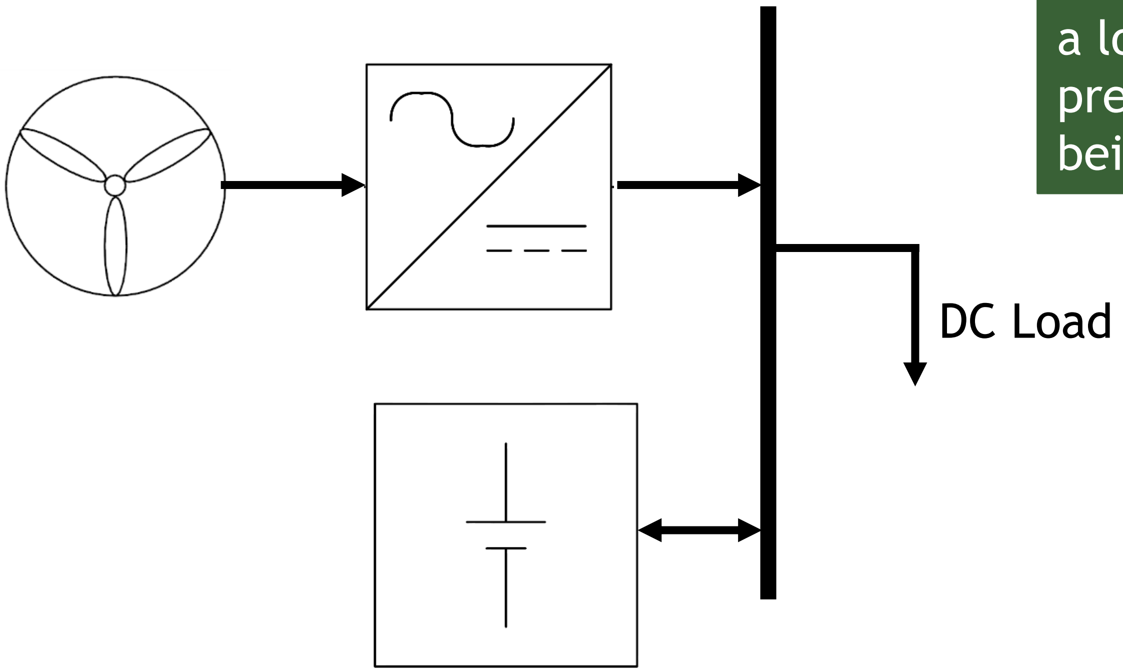
Draw a one-line schematic of an off-grid system that uses a PV module to supply an AC load. There is a battery backup.

Exercise



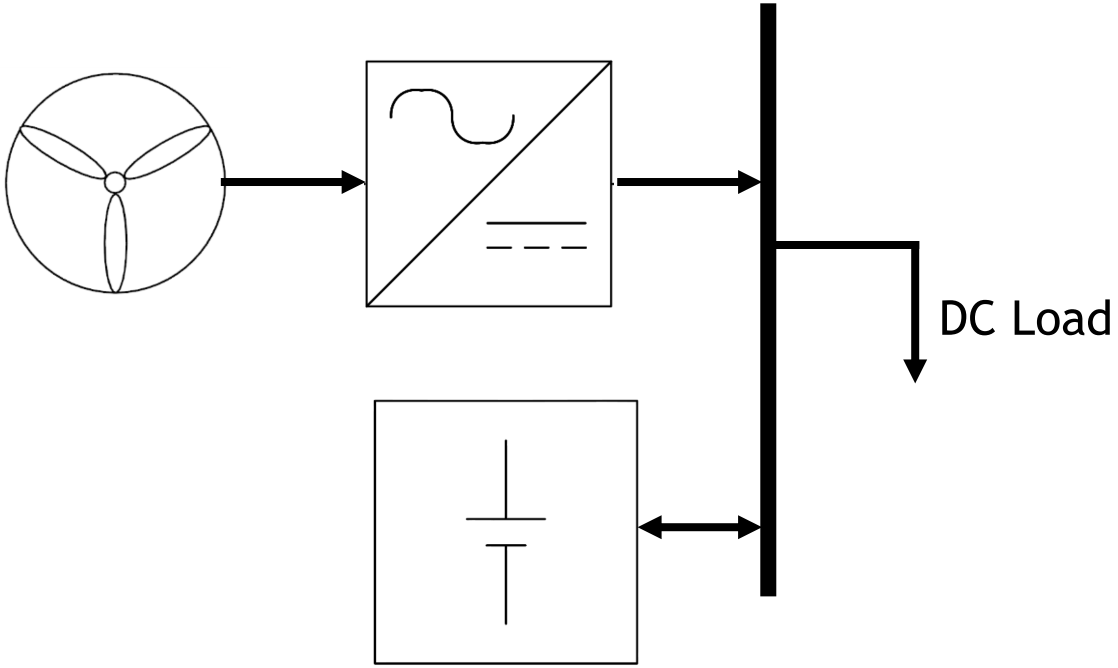
DC Bus
Charge Controller
PV Module
Inverter
AC Load
Battery

What is wrong with this design?



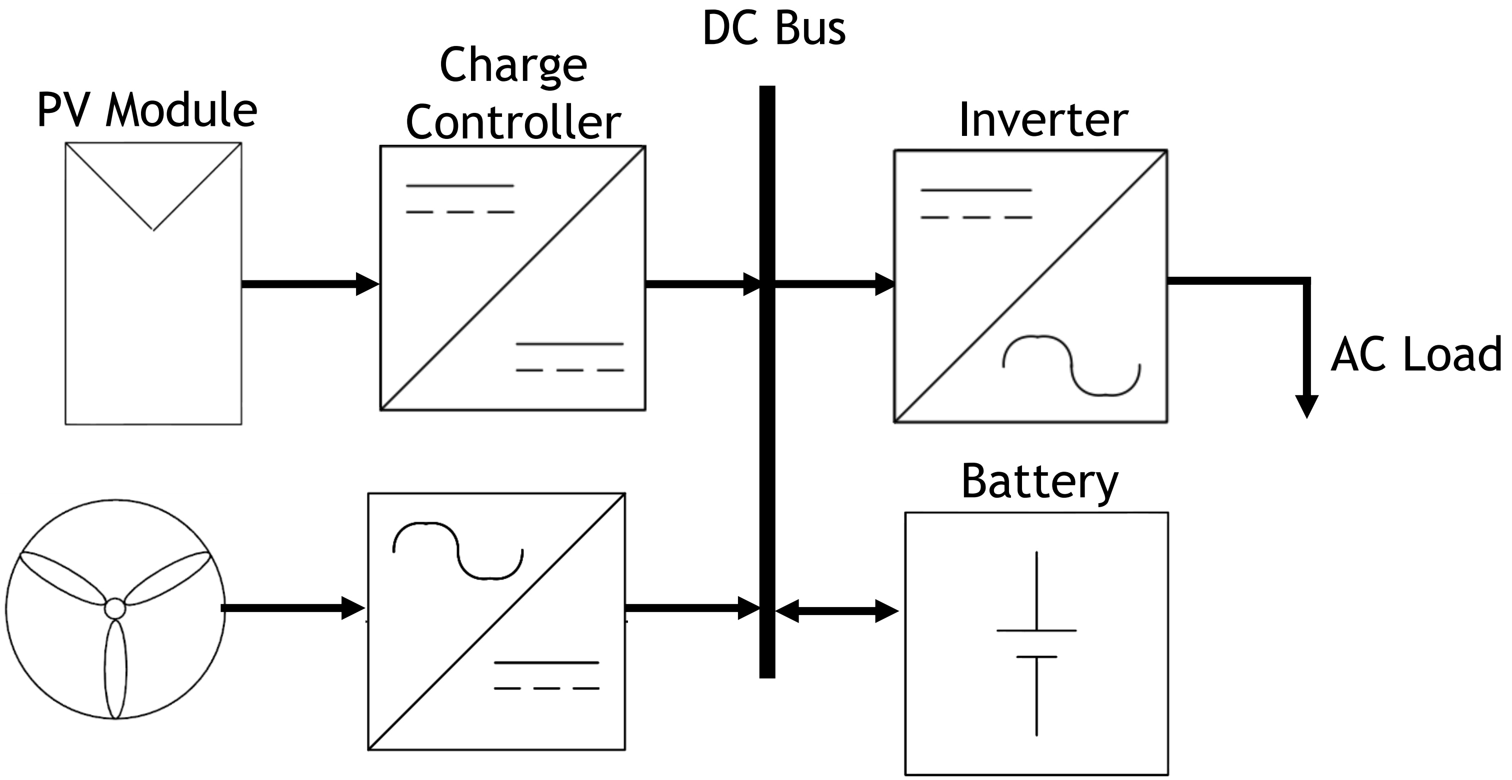
Note: we will generally assume that the DC loads will have a low-voltage disconnect that prevents the battery from being too deeply discharged.

What is wrong with this design?

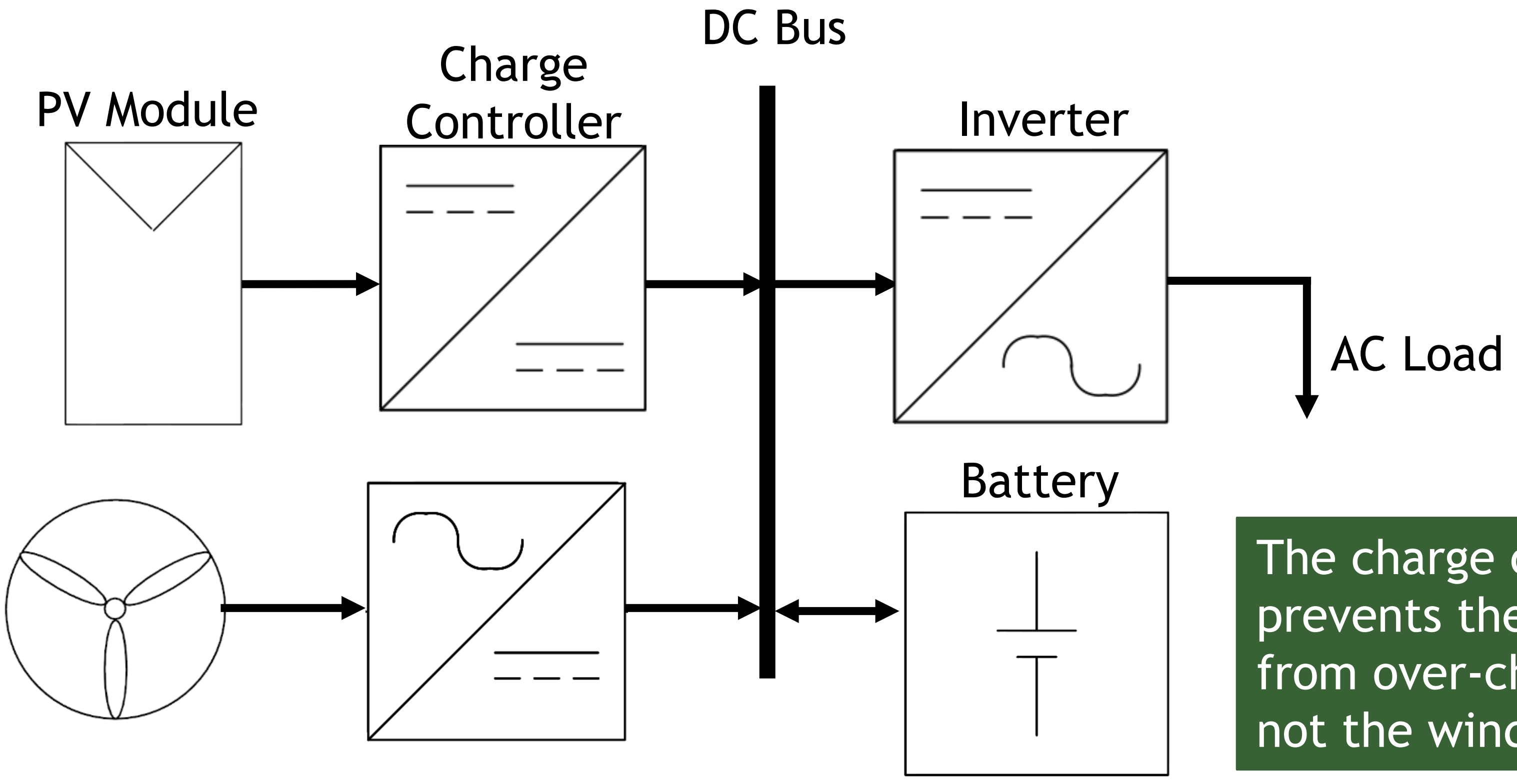


There is nothing to manage the charging of the battery. The system would function, but the battery is at risk of being over-charged and damaged

What is wrong with this design?

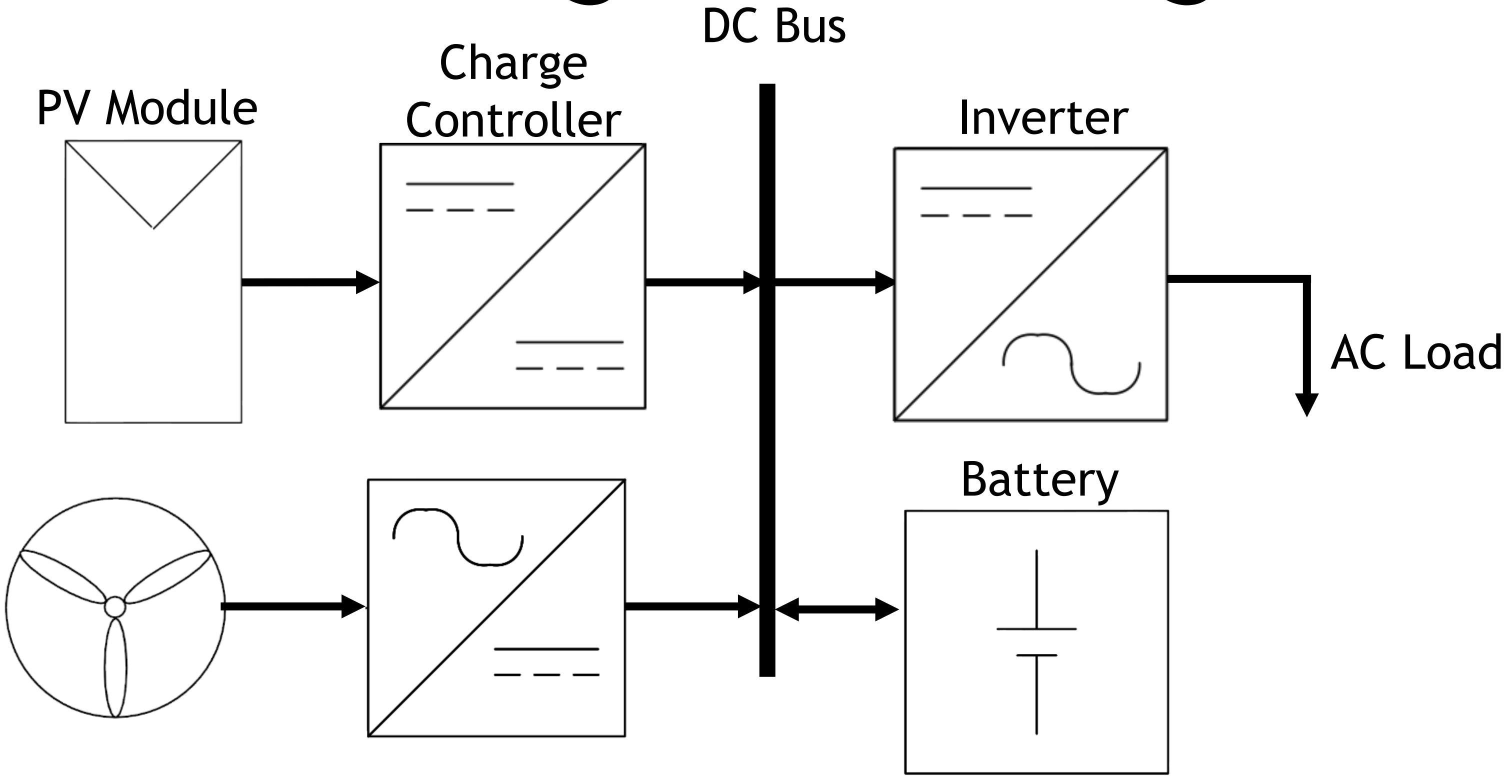


What is wrong with this design?

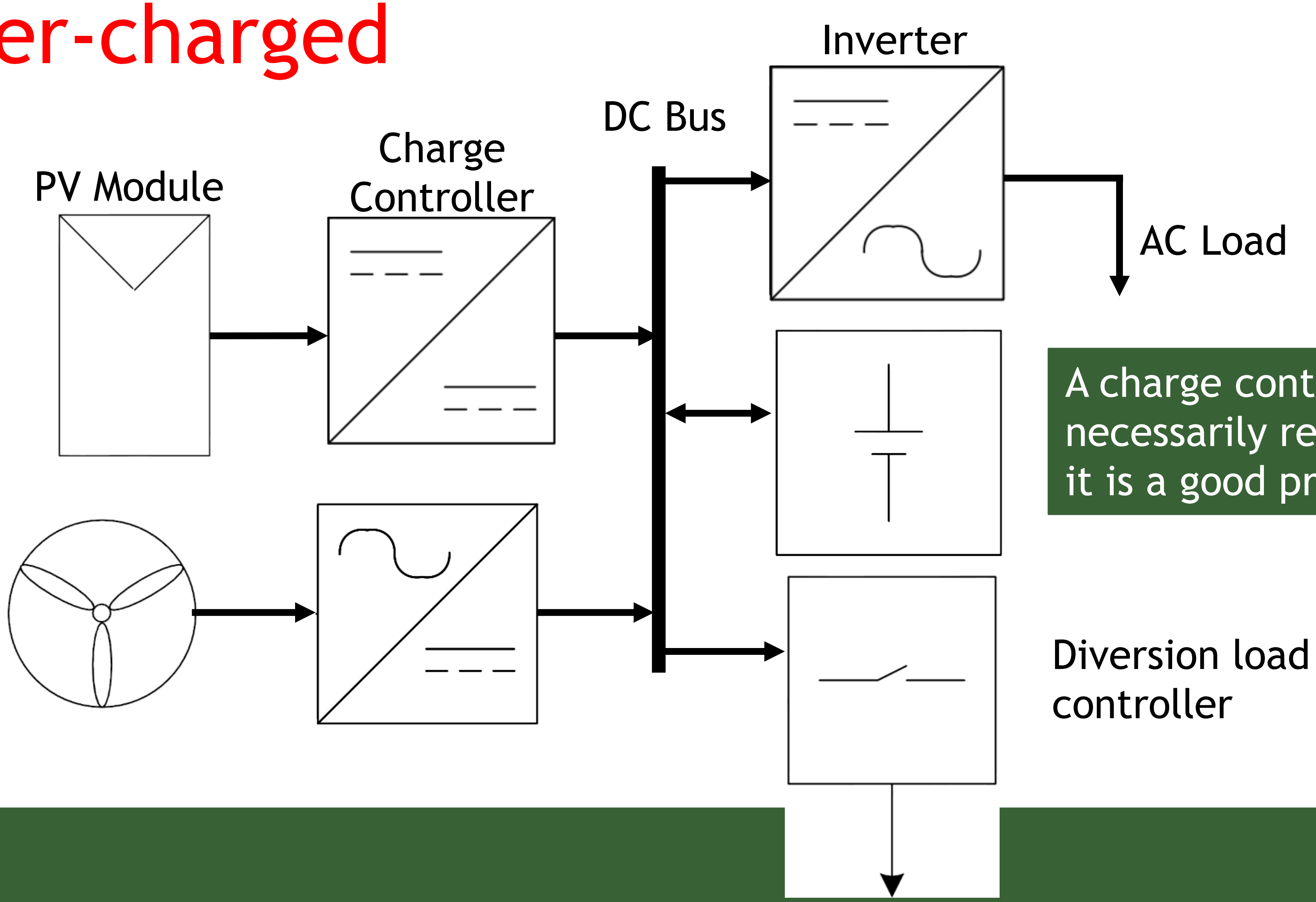


The charge controller only prevents the PV module from over-charging the battery, not the wind turbine

Re-design the system to prevent the battery from being over-charged



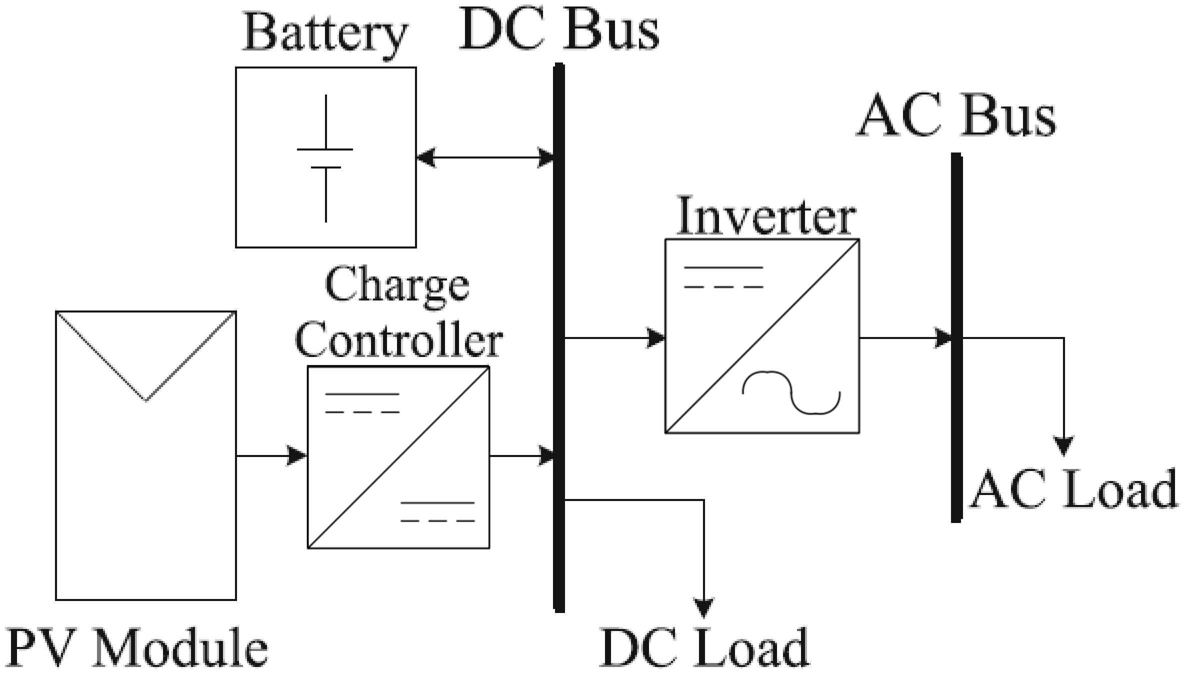
Re-design the system to prevent the battery from being over-charged



A charge controller isn't necessarily required, but it is a good practice to include it

Exercise

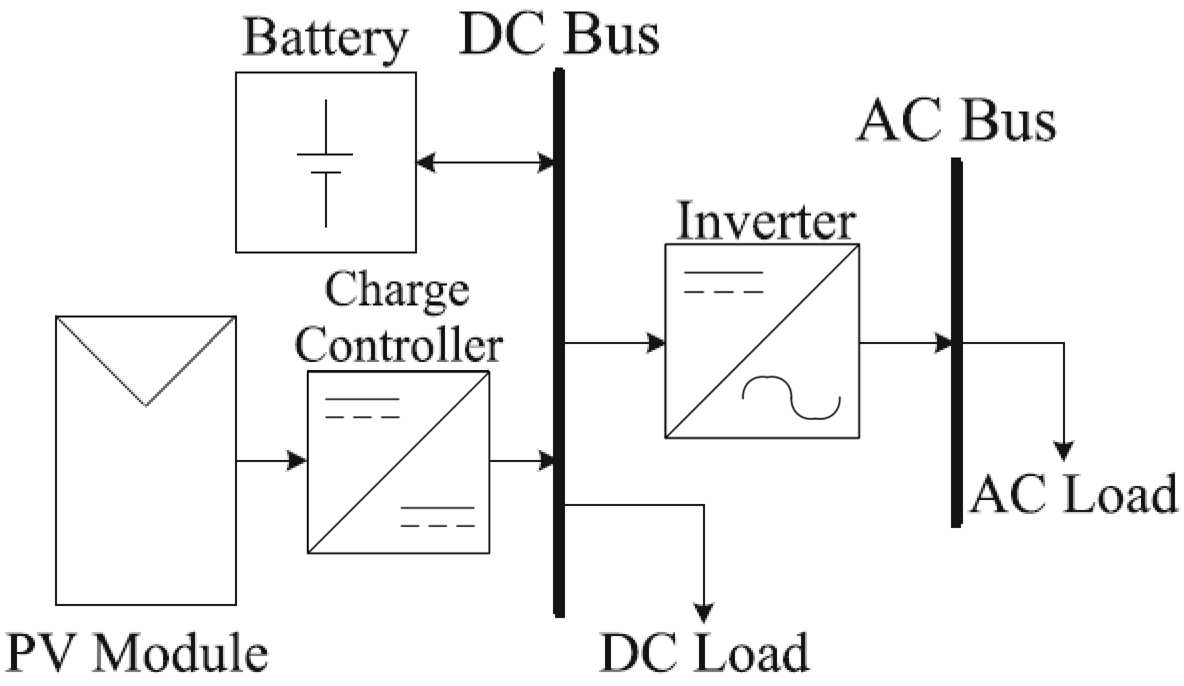
Is this system AC-coupled, DC-coupled or AC—DC coupled? Why?



Exercise

Is this system AC-coupled, DC-coupled or AC—DC coupled? Why?

System is DC coupled. The PV module is the only source, and it is connected (indirectly) to the DC bus



Summary

- Off-grid make use of energy conversion systems, controllers, converters, and energy storage to serve load
- Typical energy conversion systems: solar, gen set (conventional or biomass), wind, and hydro power
- Many valid architectures are possible
  - AC bus voltage magnitude and frequency must be regulated
  - DC bus must prevent battery from being over-charged
- System coupling is determined by which bus the energy sources are connected