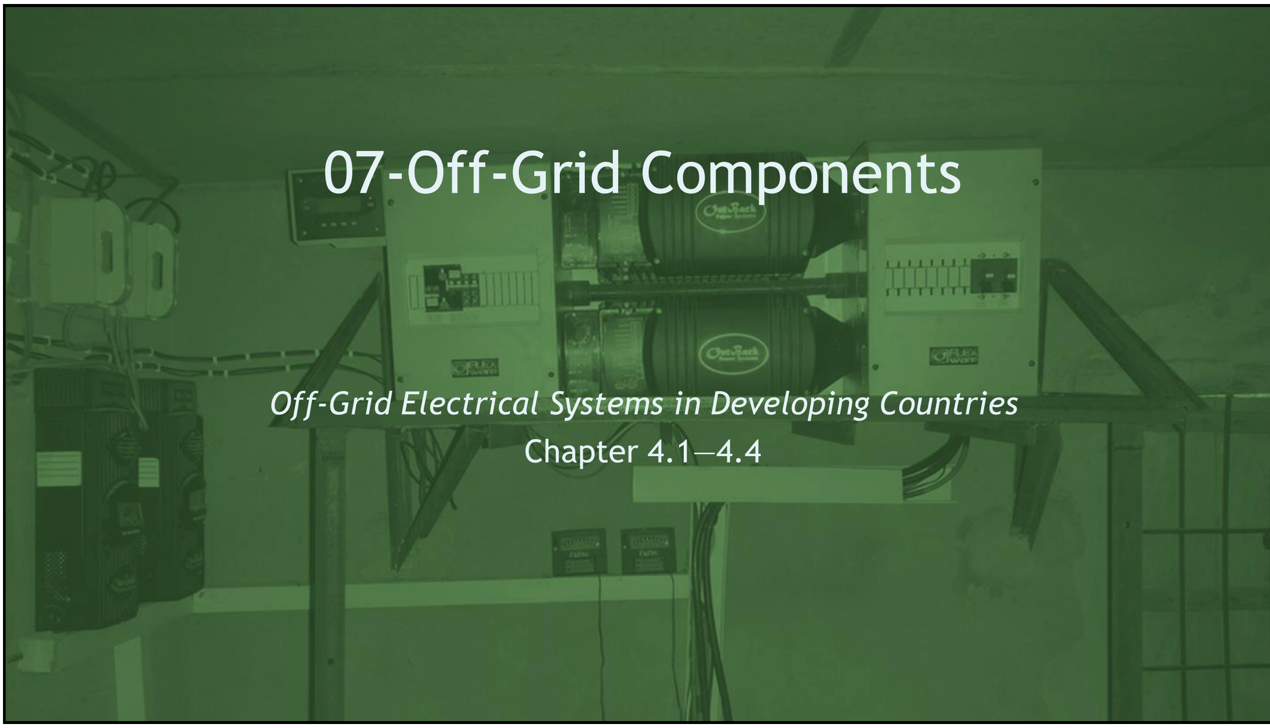

07-Off-Grid Components

Off-Grid Electrical Systems in Developing Countries

Chapter 4.1—4.4

1

Learning Outcomes

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

- ✓describe the building blocks of off-grid system
- ✓draw and interpret a one-line schematic of an off-grid system
- ✓Describe the frequency, voltage and battery charging requirements of AC and DC buses
- ✓develop a one-line schematic, including the required components, for for an off-grid system

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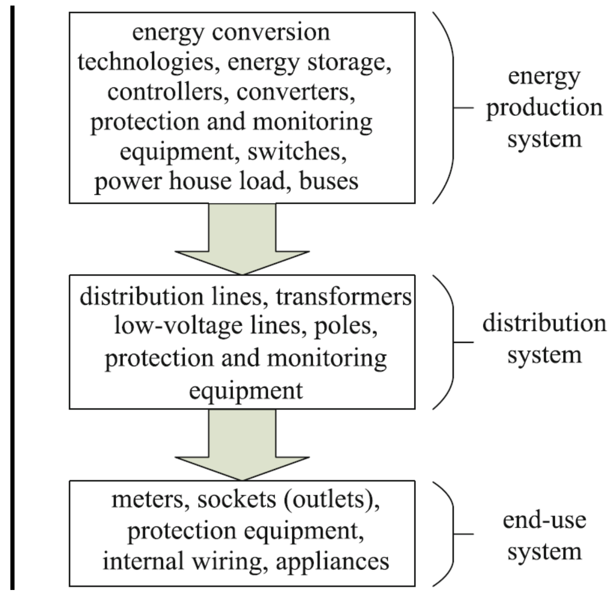
Mini-Grid Sub-Systems



Terminology

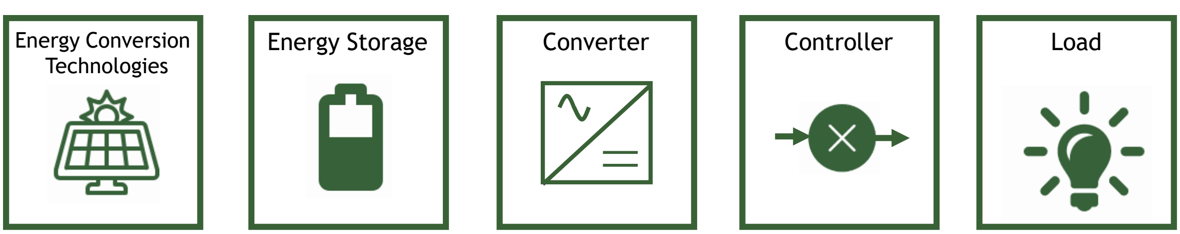
Terminology in use is inconsistent and ambiguous

- *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.
- *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 Cont…

- *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 user such as a solar home system or solar lantern, typically rated at less than 1 kW.
- *Mini-grid*: an off-grid system that serves multiple users, typically rated at less than 100 kW and often less than 10 kW

Building Blocks of Off-Grid Systems



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

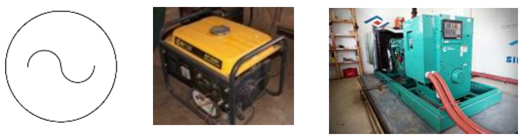
Wind Turbine

Hydro Turbine

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

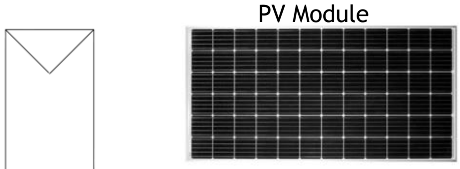
Energy Conversion Technologies

Gen. Set (Fossil-fuel/biomass)



Wind Energy Conversion System (WECS)

PV Module

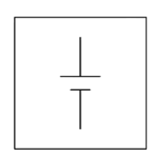


(*courtesy Itek Energy*)

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 (see zinc-air battery by Nant Energy)



Battery Symbol

Batteries

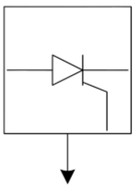
- Must be connected to a DC bus
- Should at least one pathway to be charged and discharged
- Cannot supply AC load directly
- Over-charging must be prevented
- Over-discharging must be prevented

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

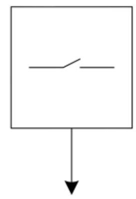
Controllers

Electronic Load Controller



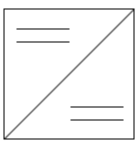
Controls power to a ballast load.
Used to regulate frequency in micro hydro power systems

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

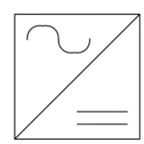


Prevents battery from being over-charged; may contain maximum power point tracking capability

Converter

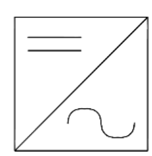
- Used in controllers and to facilitate flow of power between AC and DC buses in a mini-grid
- Common Applications
  - DC/DC converters (increase/decrease voltage)
  - DC/AC inverter
  - AC/DC rectifier

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

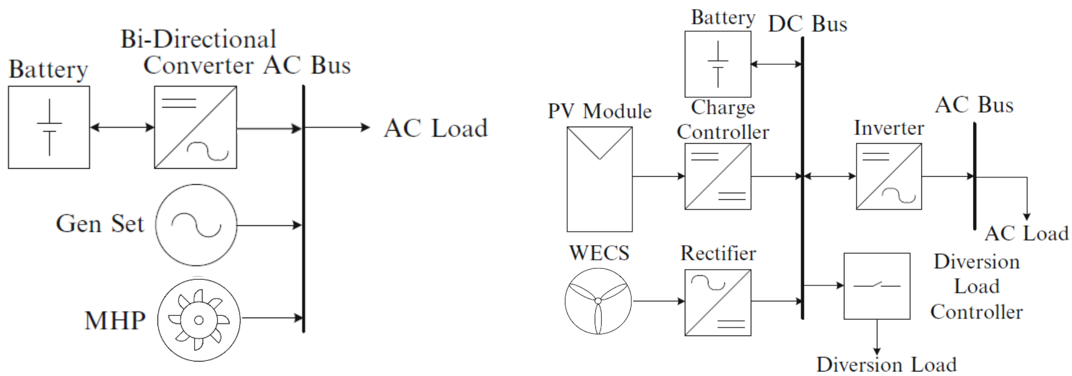
What is it?

- Graphical representation of the major components of a system
- Describes the architecture of the system---what components are included and how they are connected
- 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



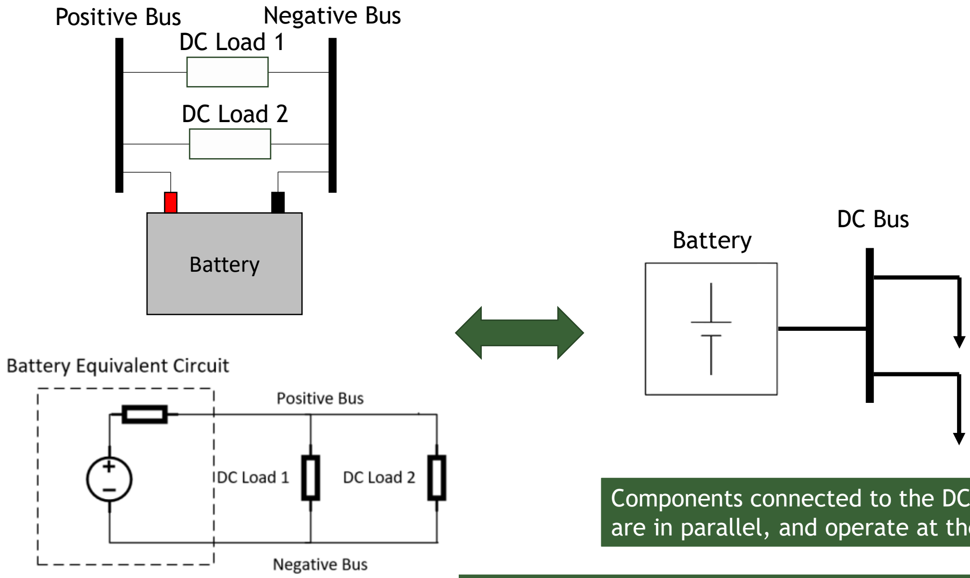
Electrical Buses

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, frequency and phase

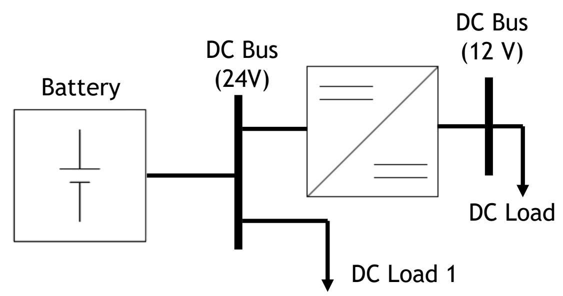
Assume the bus is lossless with zero impedance



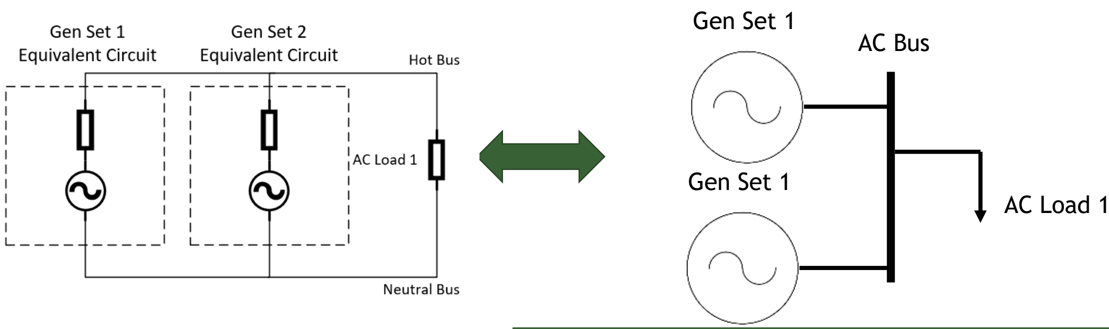
Components connected to the DC Bus
are in parallel, and operate at the same voltage

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

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One-Line Schematic Rules

1. A functioning system will have at least one load and one energy conversion technology (source), and there must be at least one path from the source to the load
2. An AC load can only be connected to an AC Bus; a DC load can only be connected to a DC bus
3. A source whose output is AC can only be connected to an AC Bus; a source whose output is DC can only be connected to a DC Bus
4. Only inverters and rectifiers can be simultaneously connected to an AC bus and DC bus

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One-Line Schematic Rules Continued

5. Multiple sources can only be connected to the same AC bus if the sources are capable of synchronizing with each other, staying synchronized (through voltage and frequency control)
6. AC bus must include at least one component (usually generator with AVR and governor, inverter, or electronic load controller) capable of regulating the frequency and voltage
7. DC bus with a battery must include at least one component (usually charge controller or diversion load controller) that can regulate the charging of the battery

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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
MHPS	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

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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)

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Low Voltage Disconnect

- In systems with batteries and DC loads, it is important that the load does not deeply discharge the battery
- The most common way to prevent deep discharge is to include a "low voltage disconnect" that disconnects the load when the battery voltage drops below a threshold (battery voltage is related to its charge level)
- We will assume that inverters and DC loads have low voltage disconnect functionality (it is also common to have a controller connected between the DC bus and DC load that has low voltage disconnect functionality)

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Example

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

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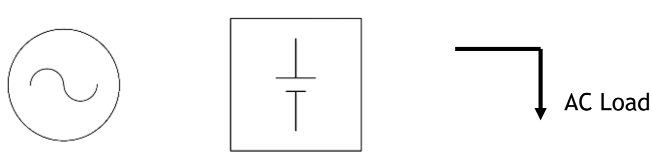
Example

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

Here are the components described in the problem



Standard assumption is that the gen set supplies AC voltage

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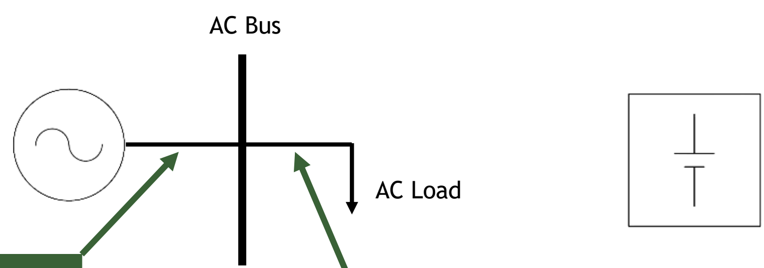
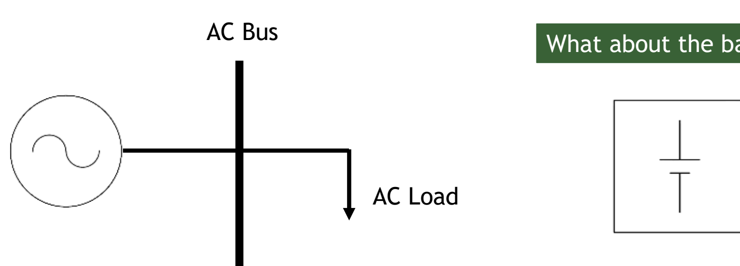
Example



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

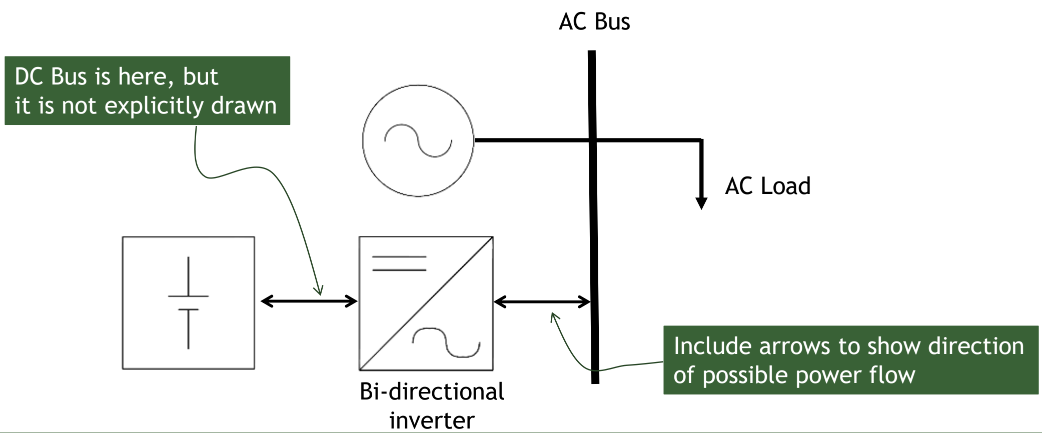
Example



What about the battery?

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

Example



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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 back-up.

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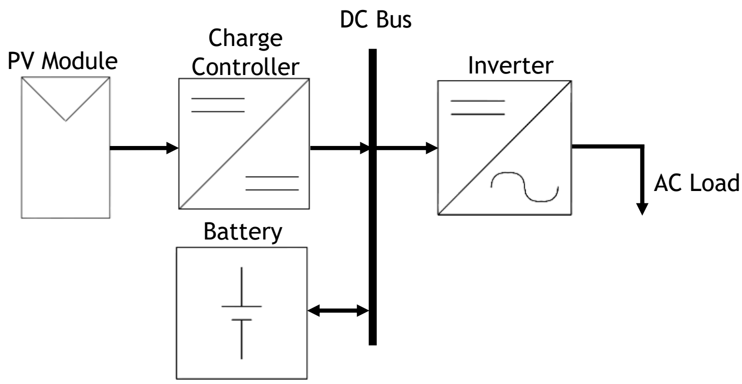
Exercise



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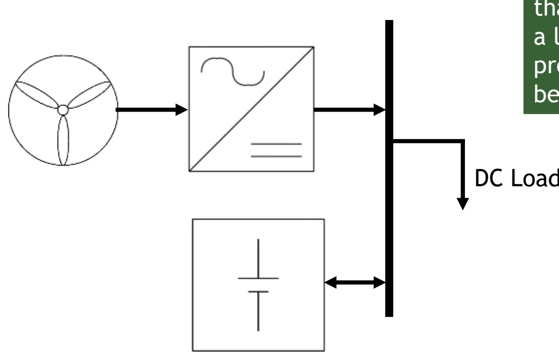
What is wrong with this design?

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



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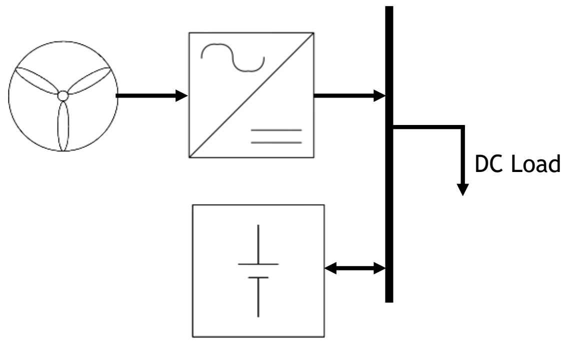
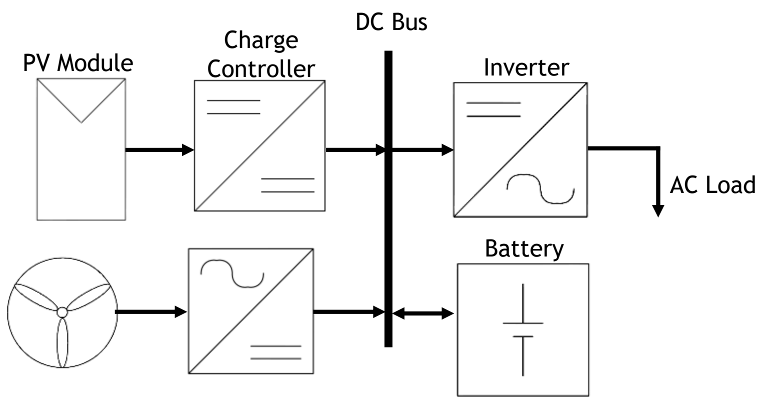
What is wrong with this design?

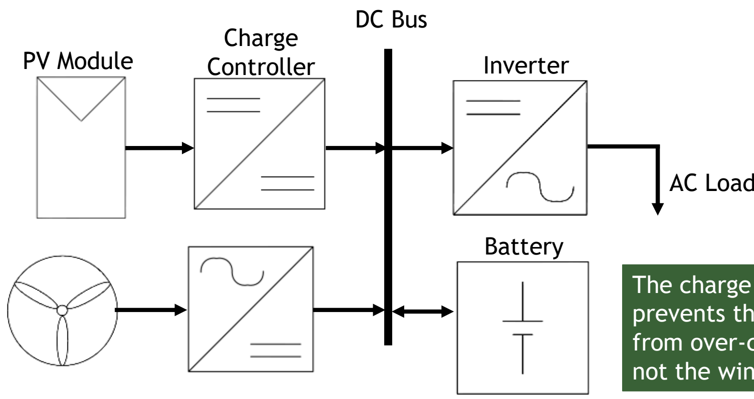


There is nothing to manage the charging of the battery. The system would function, but the battery is at risk of being over-charged and damaged

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

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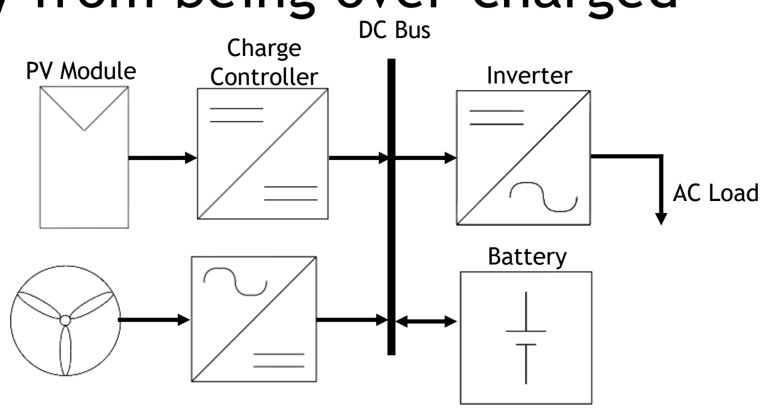
Re-design the system to prevent the battery from being over-charged



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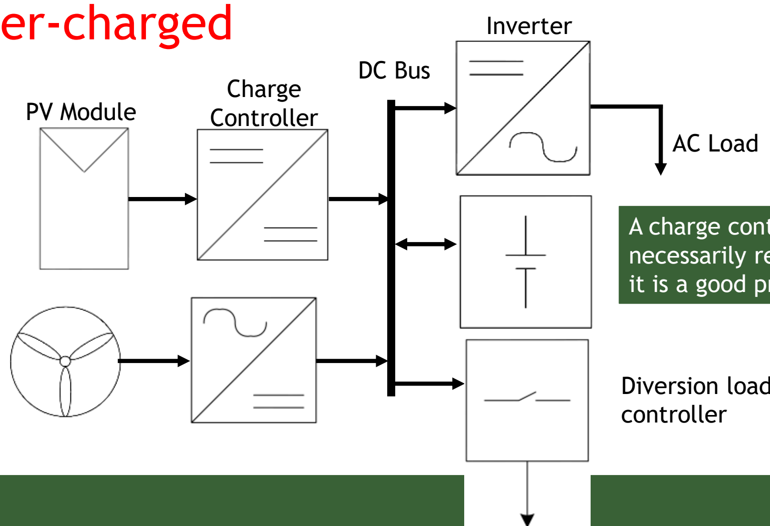
Re-design the system to prevent the battery from being over-charged



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

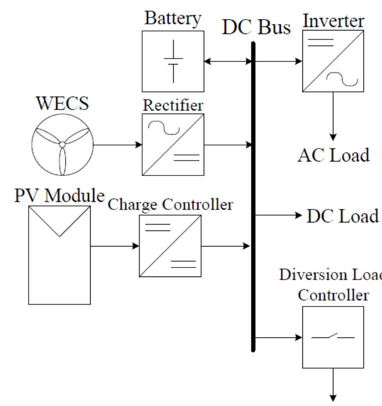
System Coupling

- 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

DC Coupling

Example of DC-coupled System



- 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

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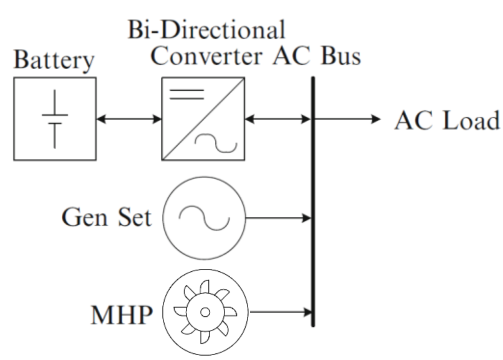
AC Coupling

Example of AC-coupled System



- All energy sources connected to AC bus
- Sources must be synchronized (same frequency)
- One source "forms" AC bus
- Voltage frequency and magnitude must be regulated and allow for coordinated control of real and reactive power allocation among sources

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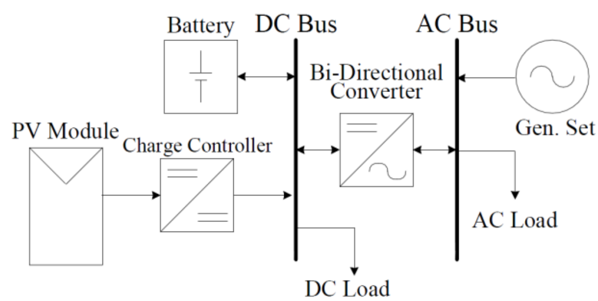
AC—DC-Coupling

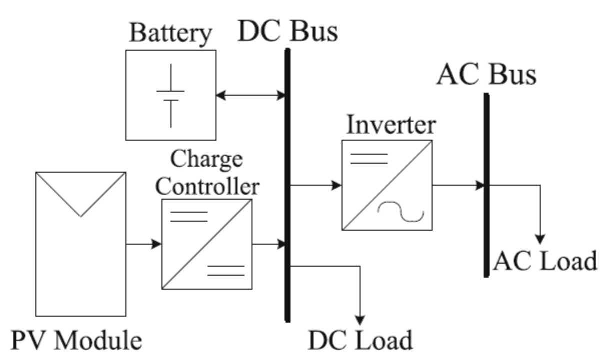
- Flexible architecture
- At least one DC-coupled and one AC-coupled source
- Power flow can be bi-directional or uni-directional (AC to DC bus, or DC to AC bus)

Example of AC—DC-coupled System



Exercise

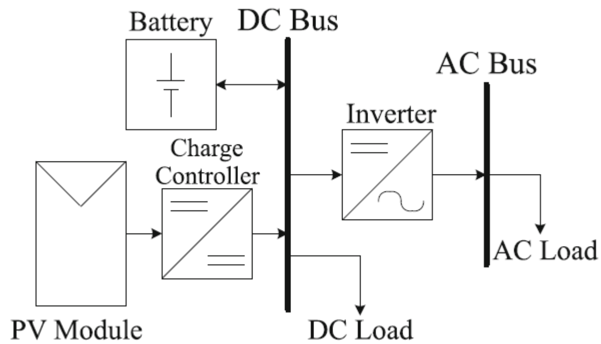
Is this system AC-coupled, DC-coupled or AC—DC coupled? Why?



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



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)

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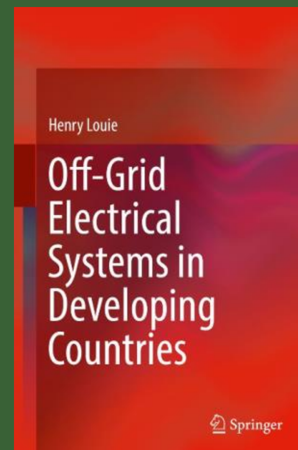

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