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Fundamentals of

BATTERIES

NNSE 397; Spring 2022

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Classification of batteries: *by rechargeability*

- Primary Battery-This is a battery that can't be recharged once used
  - Primaries are helpful in applications when recharging is impractical such as military combat for example
  - The alkaline battery is one of the most common primary batteries due to its high specific energy (capacity) and cost effectiveness
- Secondary Battery-This is a battery that can be recharged once used. The most common sub-categories for secondaries include:
  - *Lead Acid*- The original secondary battery. Commonly used in "wheelchairs, golf cars, personnel carriers, emergency lighting and uninterruptible power supply (UPS)"-Battery University
  - *Nickle-Cadmium (NiCd)*- Allows ultra-fast charging with minimized stress (this is one of very few batteries capable of this). This does have environmental concerns and so it is being replaced with other electrochemical designs.
  - *Nickle-metal-hydride (NiMH)* - A common replacement of NiCd batteries. Has milder toxicity in its composition and offers higher specific energy. Available in AA and AAA cells for consumers.
  - *Lithium-ion*- This battery has the lightest metal and is low maintenance. Replacing many Pb and Ni based batteries. It does require a protection circuit due to safety concerns. It has a high initial price, but it does have a low cost per cycle which balances out.
    - More details on the Lithium-ion battery will be presented later in this presentation.

C-Rate of a battery

- The C-rate is a quantization of how fast or slow a battery will recharge or discharge (Charging Rates)
- The C-rate shows the charge and discharge rates relative to the marked Ampere-hours (Ah) rating of the battery
  - 1C is indicative that the battery's charging rates are on par with the Ah rating
  - C rates between 0 and 1 are indicative that the battery's charging time is longer, and current is less. Some examples:
    - C/2 shows time is doubled and current is halved
    - C/3 shows time is tripled and current is reduced a third
  - C rates greater than 1 are indicative that the battery's charging time is lower, and current is higher. Some examples:
    - 2C shows the time is halved and current is doubled
    - 3C shows the time is reduced a third and current tripled
    - 5C shows the time is reduced a fifth and current quintupled
  - C rates can't be negative

Sample of Battery Applications

- Batteries are applicable to any system requiring energy storage. Here's a few common applications:
  - Power tools: Commonly use Nickel-Cadmium batteries
  - Video Cameras: Nickel-cadmium is the largest used battery with other types used as well
  - Medical Technology: Currently uses various Lead-Acid batteries predominantly, but moving towards Li-ion batteries
  - Electric Cars: Has high energy demand to function on par with current gas-powered cars. Li-ion is an attractive battery for this application
  - Large scale solar: Lithium-ion batteries are popular for these due to the high energy demand houses, buildings, and electrical grids require
    - Note:
      - » More details on the Li-ion battery will be presented shortly
      - » Lead-Acid batteries will be discussed later in the presentation

The Lithium[-ion] Battery

- In modern designs of batteries, electrochemistry is an essential science.
  - Lithium is the lightest metal and has the most electrochemical potential and it is very low maintenance
  - The chemistry of this has shown itself to be the most promising
- The Li battery consists of an anode (-), cathode (+), and electrolyte
  - Cathode is a Li transition metal oxides and Anode is a porous carbon
- Graphite is used as an anode due to it yielding flatter discharge curves
  - It takes 6 atoms of carbon (graphite) to bind with single Li ion
  - Although Si can store 10x more energy, its expansion makes it impractical
  - Si/Graphite composite anode is gaining popularity

Lithium-based Batteries: Pros vs. Cons

Advantages	High specific energy and high load capabilities with Power Cells Long cycle and extend shelf-life; maintenance-free High capacity, low internal resistance, good coulombic efficiency Simple charge algorithm and reasonably short charge times Low self-discharge (less than half that of NiCd and NiMH)
Limitations	Requires protection circuit to prevent thermal runaway if stressed Degrades at high temperature and when stored at high voltage No rapid charge possible at freezing temperatures (<0°C, <32°F) Transportation regulations required when shipping in larger quantities

Lithium-based Batteries Information. Lithium-based Batteries Information – Battery University. (n.d.). https://batteryuniversity.com/learn/article/lithium_based_batteries.

Common type of Li batteries

- Lithium Cobalt Oxide($LiCoO_2$) — LCO
- Lithium Manganese Oxide (LiMn2O_4) — LMO
- Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) — NMC
- Lithium Iron Phosphate($LiFePO_4$) — LFP
- Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$) — NCA
- Lithium Titanate (Li_2TiO_3) — LTO

Charging

- Most batteries, charging is a chemical reaction.
- In the case of Li-ion batteries, scientists interpret it as energies flowing in and out of the battery.
- Li-ion chargers are voltage limiting devices.
  - Unlike lead acid systems, differences in the Li-ion charges involve "higher voltage per cell, tighter voltage tolerances and the absence of trickle or float charge at full charge." –Battery University
- Increasing charge current in a Cobalt blended Li-ion battery will not make it much faster to achieve full charge state as saturation will take longer.
  - The more saturation, the longer the battery upholds high voltage

Discharging

- Charge & Discharge rates are yielded with C-rates
- Note: A battery can be briefly overloaded, but the longer this is the case the endurance of the battery will decrease.
- Discharging basics:
  - Lead acid discharges to 1.75V/cell
  - Nickel-based system discharges to 1.0V/cell
  - Most Li-ions discharges to 3.0V/cell
  - At these levels, ~95% of the energy is spent, and the voltage would drop rapidly if the discharge were to continue.
- There's no standard definition of discharge cycle.
  - Typically refers to full discharge or nearly full discharge ~20% (smart batteries ~15%) then consecutive recharge.
  - Recall avoiding full discharges will be beneficial to battery's lifespan.

Discharge Curves

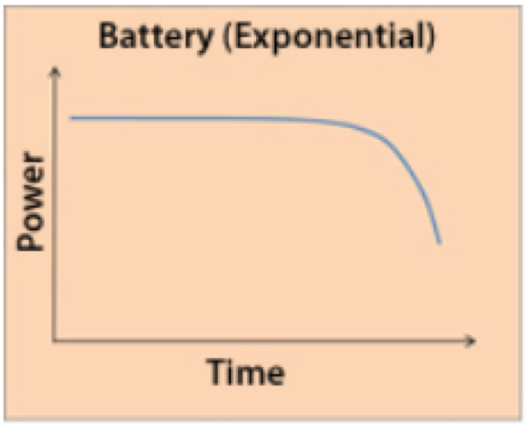

Figure 1: Discharge curve of Battery. Eponential discharge provides steady power to the end.

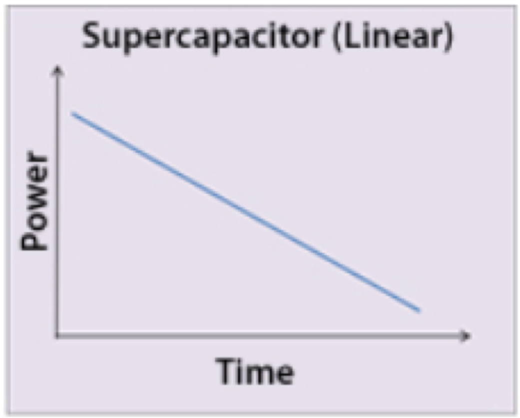

Figure 2: Discharge curve of supercapacitor. Linear discharge prevents the full use of energy.

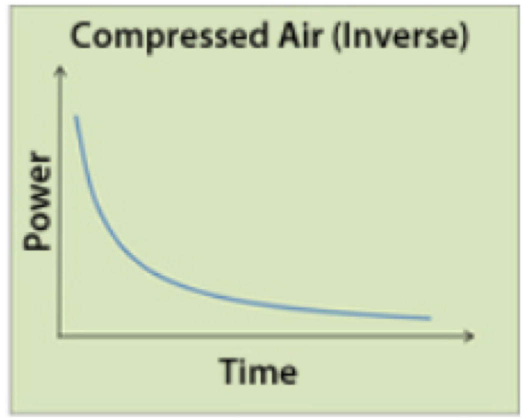

Figure 3: Discharge curve of compressed air. Inverse. Best performance at beginning

BU-501: Basics about Discharging. Battery Discharge Methods – Battery University. (n.d.). https://batteryuniversity.com/learn/article/discharge_methods.

How do Lithium batteries work?

- Recall: Lithium has the greatest specific energy and electrochemical potential than other metals
  - This is due to Lithium being lighter than most metals
  - Lithium itself is unstable when charging, so Li-ions are commonly used instead now
- On the anode and cathode of the battery, Lithium is stored
- In the electrolyte, positively charged Li-ions are carried between the anode and cathode (either direction) through the separator
- This movement causes free electrons in the anode yield charge on the positive current collector
- The current then flows from the + current collector, to the device being powered, then terminates at the – current collector.

How Does a Lithium-ion Battery Work? Energy.gov. (n.d.). https://www.energy.gov/eere/articles/how-does-lithium-ion-battery-work.

How do Lead-Acid batteries work?

- This is the first rechargeable (secondary) battery commercially used and was the standard battery for the solar systems before Lithium-ion batteries.
- Lead is mixed with other metals, commonly antimony, calcium, tin and selenium
  - "Adding antimony and tin improves deep cycling but this increases water consumption"-Battery University
  - Calcium reduces self-discharge. The trade off, the positive Pb-Ca plate will grow due to grid oxidation when over charged
- Doping agents are also used in modern lead-acid batteries
  - » Note: These batteries are heavily stressed when fully discharged and loses a bit of capacity each recharge
- Voltage limits are very important to acknowledge in these batteries

Lead-Acid batteries: Pros vs. Cons

Advantages	Inexpensive and simple to manufacture; low cost per watt-hour
	Low self-discharge; lowest among rechargeable batteries
	High specific power, capable of high discharge currents
	Good low and high temperature performance
Limitations	Low specific energy; poor weight-to-energy ratio
	Slow charge; fully saturated charge takes 14-16 hours
	Must be stored in charged condition to prevent sulfation
	Limited cycle life; repeated deep-cycling reduces battery life
	Flooded version requires watering
	Transportation restrictions on the flooded type
	Not environmentally friendly

Table 4: Advantages and limitations of lead acid batteries. Dry systems have advantages over flooded but are less rugged.

Battery University. (2020, March 4). *BU-201: How does the Lead Acid Battery Work?* Battery University. https://batteryuniversity.com/article/bu-201-how-does-the-lead-acid-battery-work.

Graphite Anodes

- Graphite is the most stable allotrope of carbon
- This is a useful material for anodes in Li-ion batteries especially
- Graphite can be come in two general forms:
  - Natural Graphite which comes from mines
    - Natural Graphite is cheaper and more environmentally friendly relatively
  - Synthetic Graphite which can be chemically engineered
    - Synthetic Graphite tends to be the preferred form due to its consistency
    - Less environmentally friendly due to it's production requiring strong acids
- Green manufacturing technology is emerging for graphite purification such as hydroelectricity

https://batteryuniversity.com/article/bu-309-how-does-graphite-work-in-li-ion

Graphene

- Graphene is another allotrope of carbon that has a 2-dimensional hexagonal lattice and can be one atom thick when in a sheet of carbon
- Graphene in theory is said to hold energy better than graphite, however Graphene hasn’t been used commercially yet
- When vanadium oxide is added to the cathode, graphene functions better in experimental batteries
- Graphene is also being explored in supercapacitors

https://batteryuniversity.com/article/bu-309-how-does-graphite-work-in-li-ion

$LIPF_6$

- $LIPF_6$ represents Lithium hexafluorophosphate
- This is commonly used in secondary batteries; especially Li-ion batteries
- This material has a very high solubility in non aqueous solutions

https://www.sciencedirect.com/science/article/pii/S2405829718311048?via%3Dihub

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SCANNING TECHNOLOGY

- X-Ray Tomography is a contemporary technique used to analyze the physical microstructural topography of materials
- This especially comes in use with analyzing electrodes and looking for any anomalies using x-rays
- Utilizing this, the microstructure of the materials can be modeled with high precision; sometimes in 3D
- One of X-Ray tomography's strongest suits is modeling the surface of a material

https://www.sciencedirect.com/topics/engineering/x-ray-tomography

- Electron Microscopes are capable of taking high resolution images of sample materials at microscopic and/or nanoscopic sizes
- There's two major types of electron microscopes
  - Scanning Electron Microscope (SEM)
  - Transmission Electron Microcope (TEM)
- TEMs are useful for studying very thin materials, and finds many applications in biology
- SEMs are capable of greater depth and find many applications in materials sciences (and electrochemistry)

https://www.purdue.edu/ehps/rem/laboratory/equipment%20safety/Research%20Equipment/sem.html

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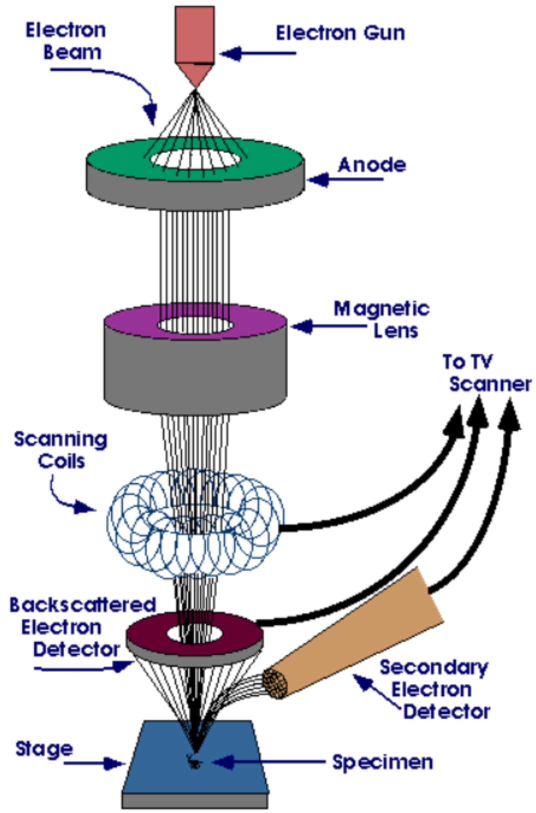
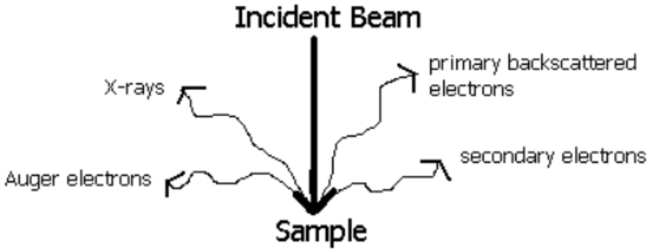
Diagram of Electron Microscope





https://www.purdue.edu/ehps/rem/laboratory/equipment%20safety/Research%20Equipment/sem.html

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TOPICS TO BE ADDED:

-PHOTOS OF UTICA NANO LAB

SPECIFIC ABILITIES OF EACH MACHINE

-RESULTS FROM SAMPLES

THIS WILL BE ADDED WHEN THE LAB REOPENS

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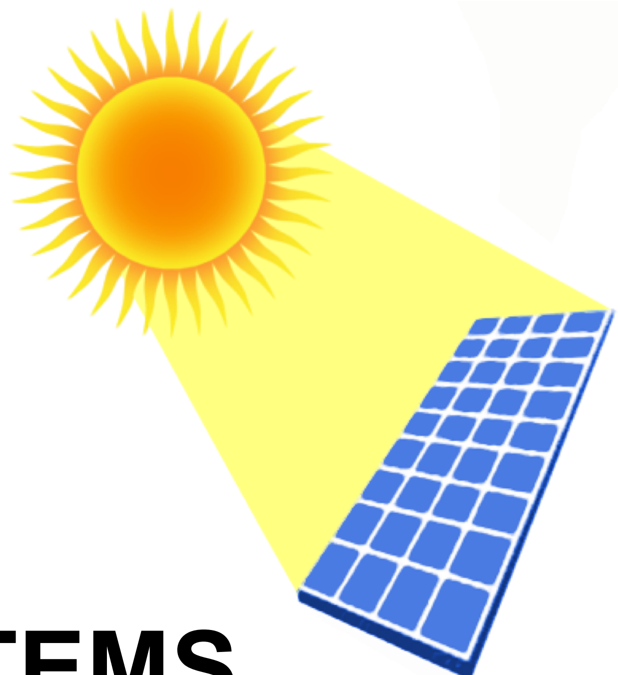


Fundamentals of

PHOTOVOLTAIC SYSTEMS

NNSE 397; Summer 2021

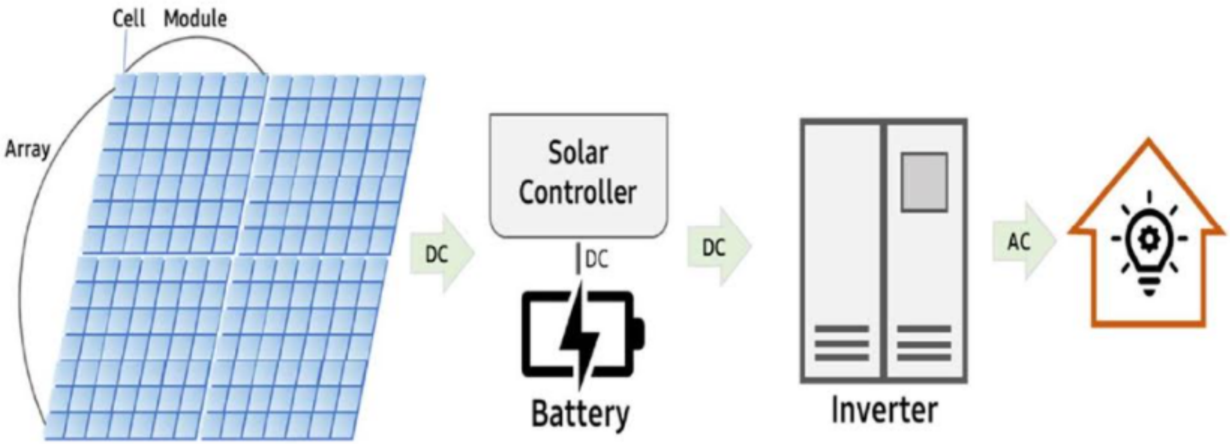
Daniel J. Macdonald

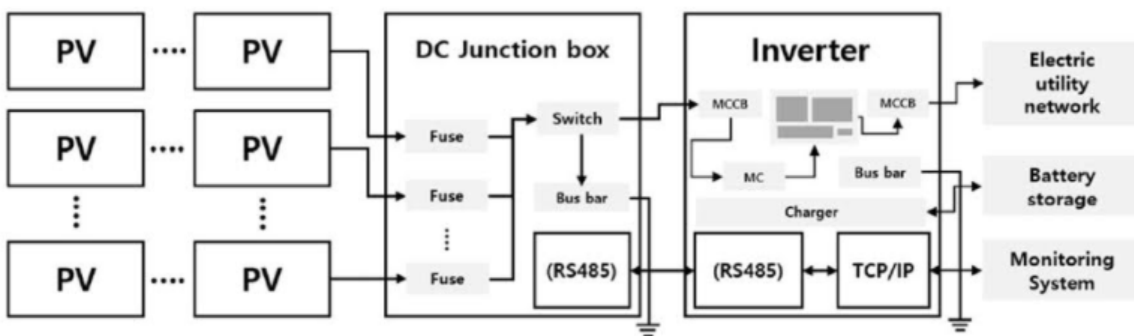
Advisor: Dr. Harry Efstathiadis

Basics of Photovoltaic Systems in Power Grids

- Photovoltaic energy utilizes energy from the sun to create electric power.
- In a power grid, solar systems will deliver DC power to a Power Conditioning Unit (PCU) which converts that DC power to AC.
  - The PCU will ultimately keep electric demands satisfied.
    - When sufficient energy from the solar panels is present it will depend on those
    - When insufficient energy is from the solar panels, it will tap into the utility grid to keep energy demands in the house/building it's powering
      - » The utility grid is usually in AC by default, so the PCU won't convert it
- PCUs also optimizes the photovoltaic system's operations on its I-V curve
- It is worth noting, PCUs don't just power houses and buildings, it can also power devices like water pumps

General Diagram of a Photovoltaic System





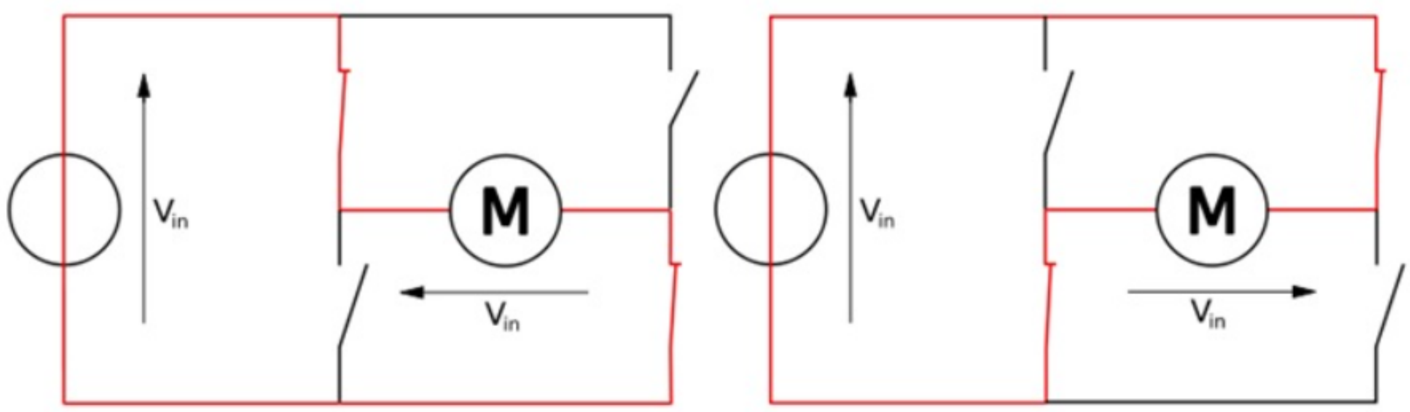
Park, C.-Y., Hong, S.-H., Lim, S.-C., Song, B.-S., Park, S.-W., Huh, J.-H., & Kim, J.-C. (2020, October 1). *Inverter Efficiency Analysis Model Based on Solar Power Estimation Using Solar Radiation*. MDPI. https://www.mdpi.com/2227-9717/8/10/1225/htm.

Inverters

Basics of Solar Inverters

- An inverter is a device that will convert Direct Current to Alternating Current
- In the case of a photovoltaic system, it will collect DC from the solar array, and will output AC so it can be used for electronics requiring AC
- The way an inverter works is it depends on solid state devices (semiconductors)
  - One example:
    - Insulated Gate Bipolar Transistors (IGBTs) can be used
    - When IGBTs are connected to form a H-bridge, it will oscillate causing the DC to convert to AC

H-bridge circuit of an inverter



Inverters. PVEducation. (n.d.).
https://www.pveducation.org/pvcdrom/inverters.

Engineering Requirements

Inputs and Outputs

Inverters have to be designed to be able to withstand the maximum amount of voltage, current, and power that can be produced by the photovoltaic modules. When sizing inverters an engineering analysis needs to occur to meet the following requirements:

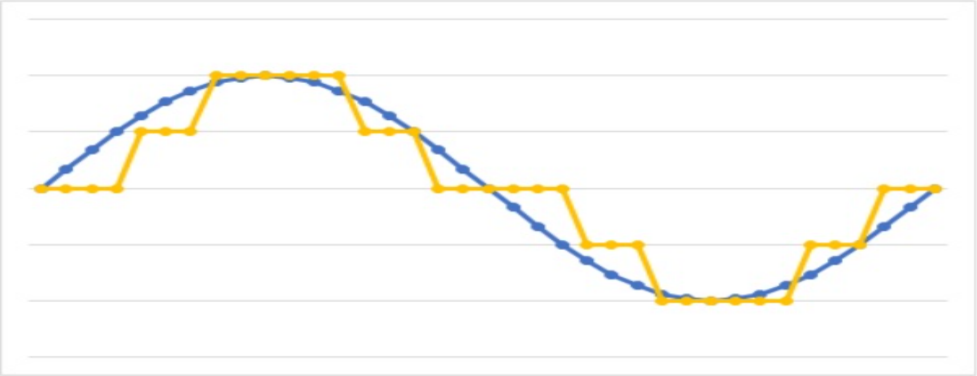
1) The maximum open circuit voltage of the system does not exceed the voltage requirements.

2) The minimum voltage requirement of the inverter will be met by the system to function correctly.

3) The maximum power output of the modules is less than the inverters rating.

4) The maximum current at the point of operation is less than the inverters rating.

The output current of the inverter resembles a sine wave with a frequency near the grid's power requirements. However, an inverter can only imitate a sine wave and the resultant output is a square wave.



Inverters. PVEducation. (n.d.). https://www.pveducation.org/pvcdrom/inverters.

Common Types of Inverters

- String Inverter
- Central Inverters
- Microinverter
- Battery Based Inverter
- Hybrid Inverter

Pros of Solar Inverters

- Pros:
  - Solar energy decreases the greenhouse effect, as well as abnormal weather change.
  - By using solar products, we can save money by reducing electricity bills
  - The solar inverter is used to change Direct Current to Alternating Current and this is a reliable source of energy.
  - These inverters empower businesses around the globe by reducing their energy requirements & needs.
  - These are “multifunctional devices” as they are preprogrammed to alter DC to AC which assists large energy consumers.
  - Easy to set up and a better alternative compared to gas powered generators
    - » This is a big help during power outages
  - Maintenance is easy

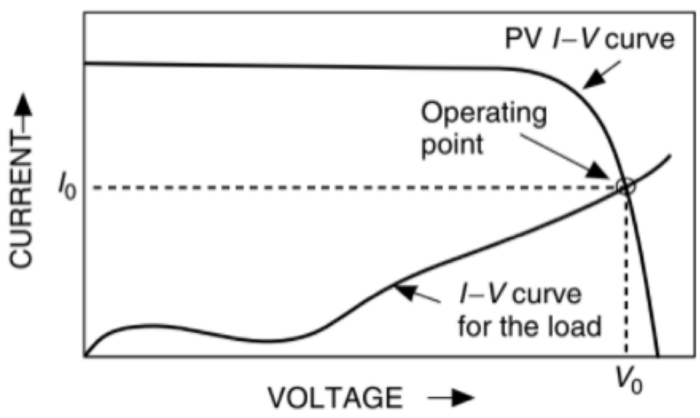
Cons of Solar Inverters

- Inverters can be expensive to afford.
- Sufficient electricity requires sufficient sunlight
- Installation requires a lot of space
- This requires a battery to work at nighttime to provide proper electricity to the home, commercial, etc.

Selected Photovoltaic Equations

$$R_m = \frac{V_m}{I_m}$$

To find resistance that maximizes power
V_m = Voltage at max power
I_m = Current at max power
based on Ohm's Law



$$V = I R_a + k\omega$$

DC Motor I-V relationship:
R_a = armature resistance
kw = electromotive force (e)

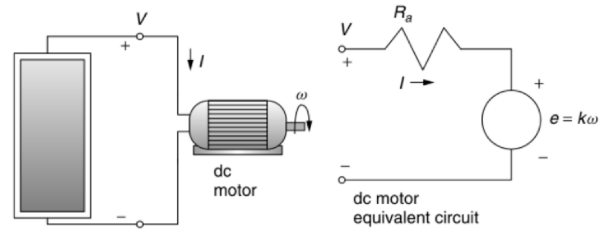


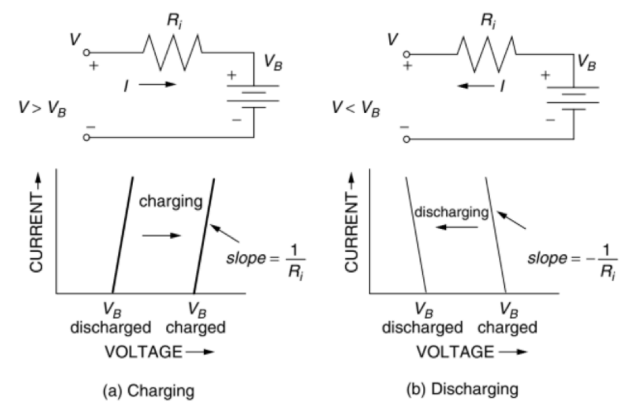
Figure 9.7 Electrical model of a permanent magnet dc motor.

$$V = V_B + R_i I$$

Battery I-V relationships:
R_i = Internal resistance
V_B = Battery Voltage

NOTE: This diagram models real batteries: an ideal battery in series with a resistor

Ideal batteries only exist in theory



Masters, G. M. (2013). In *Renewable and Efficient Electric Power Systems* (pp. 510–513). essay, Wiley.

Fundamentals of

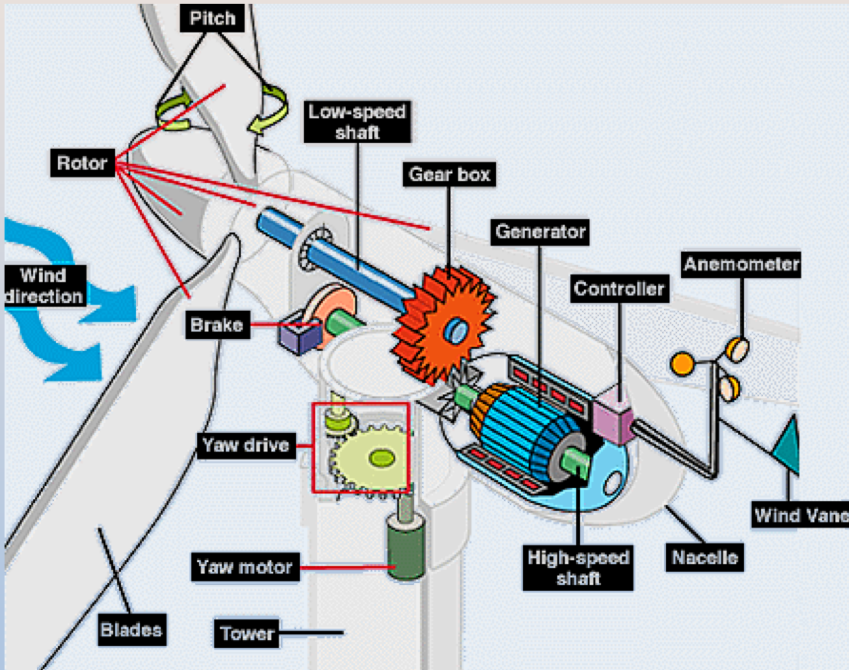
WIND POWER

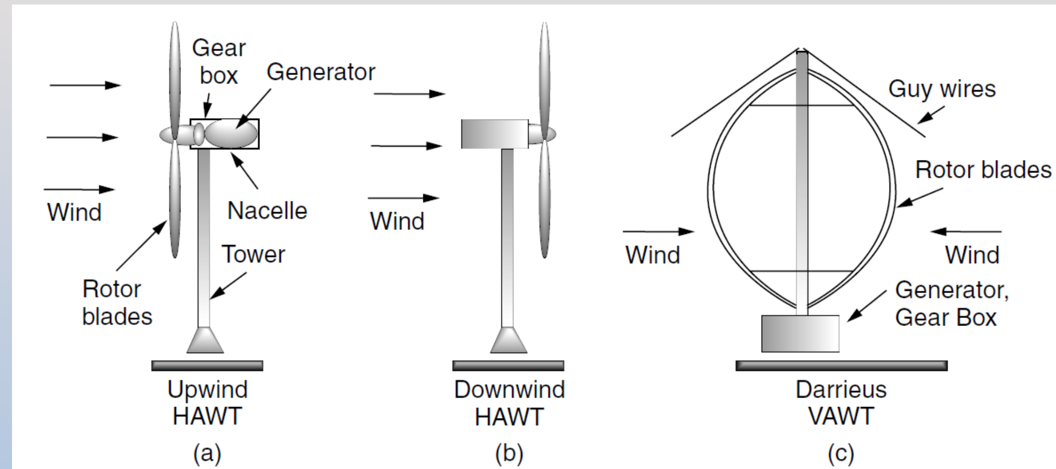
Introduction

- Wind Turbines have been a traditional means of pumping water and grinding grain into flour.
  - Wind turbines have been in existence in Europe since the 12th century
- Wind power has risen and fallen in popularity throughout it's existence, although it is of interest to many energy engineers due to the appeal of green energy.
- As the wind blows on the turbines, the spinning of the turbines produces usable electricity.

Masters, G. M. (2013). In *Renewable and Efficient Electric Power Systems*

Wind Turbine Anatomy





The vertical axis wind turbine (VAWT)

- Wind turbines can be classified based on whether its axis is vertical or horizontal.
- The Darrieus Rotor, named after its engineer, GM Darrieus, is the most common vertical axis wind turbine design used.
  - This is one of the only designs that's seen widespread commercial use.
- This turbine spins vertically and has rotor blades arced like an eggbeater to spin around
- Guy wires are optional but can be attached to the top of the turbine to make the poll holding up the blades lighter and cheaper

Masters, G. M. (2013). In *Renewable and Efficient Electric Power Systems*

Vertical Axis Image

VAWTs Pros vs Cons

- Advantages:
  - There is no control system needed to keep the whole machine facing the wind (biggest advantage)
  - The [heavy] machinery inside the nacelle can be on the ground. This is easy to maintain
    - Consequently, the tower upholding the turbine doesn't have to be as structurally strong
  - VAWT's are cheaper to build
- Disadvantages:
  - The blades must be lower to the ground than HAWTs. Faster wind speeds occur higher off the ground
  - Winds lower to the ground tend to be more turbulent which can put more stress on the VAWT system.
  - VAWTs have very low starting torque than HAWTs in low winds
  - In high winds, the system doesn't spill as easily as pitch controlled HAWTs
    - NOTE: In high winds all turbines will have to have output power restricted to protect the generator

Masters, G. M. (2013). In *Renewable and Efficient Electric Power Systems*

HAWT

- Horizontal Axis Wind Turbines (HAWT) on the other hand are the most common type of wind turbine.
- HAWTs essentially provide many advantages where VAWTs are disadvantageous and vice versa.

Masters, G. M. (2013). In *Renewable and Efficient Electric Power Systems*

Power produced in a Wind Turbine

$$P_w = \frac{1}{2}\rho A v^3$$

P_w = Power Outputted
ρ = Air Density (kg/m^3)
A = X-section where wind passes (m^2)
v = Wind Velocity (m/s)
[v is wind speed normal to A]

*This equation is derived from the kinetic energy equation, where: $\dot{m} = \rho A v$

Masters, G. M. (2013). In *Renewable and Efficient Electric Power Systems*

Impact of Tower Height/Location

- Within the first few 500 meters from earth's surface, wind speeds generally are slower than they are at higher altitude.
  - This is due to irregularities around earth's surface such as forests and buildings.
- Smooth surfaces like above a calm sea tend to have milder impacts on the wind's speed

$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha}$$

$$\left(\frac{v}{v_0}\right) = \frac{\ln(H/z)}{\ln(H_0/z)}$$

v is wind velocity as height H
v_0 is wind velocity at height H_0
α = Friction Coefficient
z = roughness

Masters, G. M. (2013). In *Renewable and Efficient Electric Power Systems*

TABLE 6.3 Friction Coefficient for Various Terrain Characteristics

Terrain Characteristics	Friction Coefficient α
Smooth hard ground, calm water	0.10
Tall grass on level ground	0.15
High crops, hedges and shrubs	0.20
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.30
Large city with tall buildings	0.40

Masters, G. M. (2013). In *Renewable and Efficient Electric Power Systems*

TABLE 6.4 Roughness Classifications for Use in (6.16)

Roughness Class	Description	Roughness Length $z(m)$
0	Water surface	0.0002
1	Open areas with a few windbreaks	0.03
2	Farm land with some windbreaks more than 1 km apart	0.1
3	Urban districts and farm land with many windbreaks	0.4
4	Dense urban or forest	1.6

Masters, G. M. (2013). In *Renewable and Efficient Electric Power Systems*

Environmental Impacts of Wind Power

- The primary benefit of wind power is the energy produced is green and clean
  - It is not producing smoke or other pollutants bothersome to the environment and people living in the vicinity
  - Air quality in regions implementing wind power replacements do statistically increase
- Some draw backs include:
  - Birds fly into blades (although stats show this isn't a substantial issue)
  - Aesthetically, wind turbines can be obstructive
  - Sound pollution

Masters, G. M. (2013). In *Renewable and Efficient Electric Power Systems*

SUNY POLY Sources for further reading

- https://batteryuniversity.com/articles
- https://www.energy.gov/eere/articles/how-does-lithium-ion-battery-work
- Masters, G. M. (2013). In *Renewable and Efficient Electric Power Systems.* essay, Wiley.
- https://www.mdpi.com/2227-9717/8/10/1225/htm
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- https://www.pveducation.org/pvcdrom/inverters
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- https://www.mdpi.com/2227-9717/8/10/1225/htm