Lecture 3 – Circuit Basics

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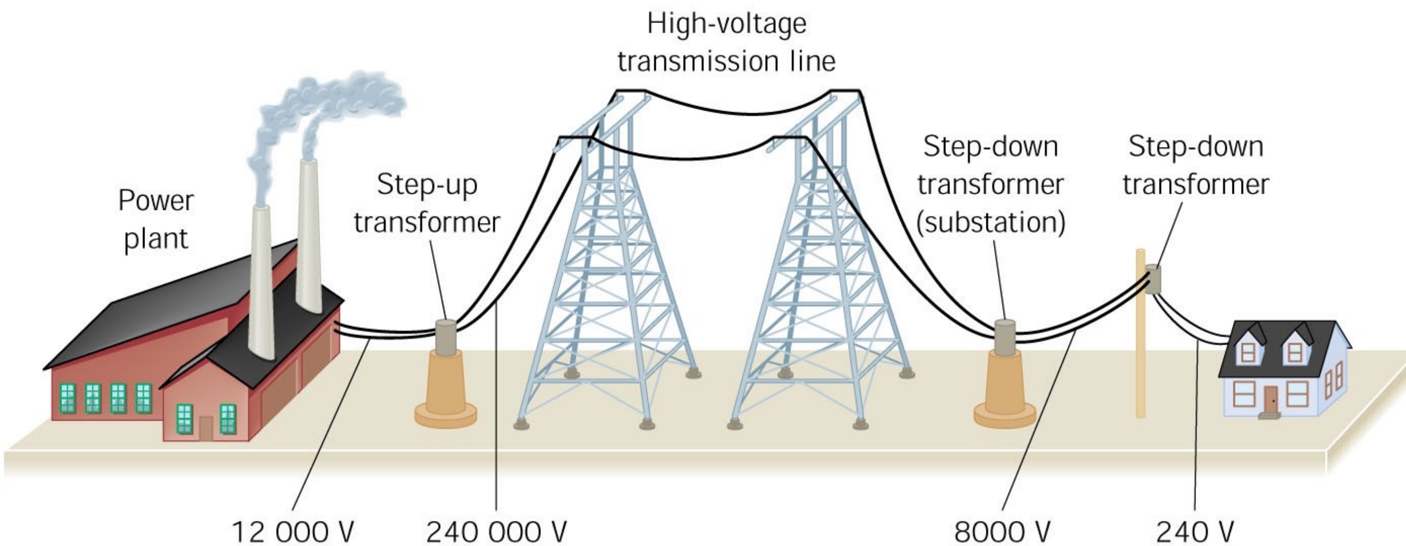
Outline

- Power Grids and Electricity Markets
- DC vis-à-vis AC
- Generators, Transformers and GFCI
- KCL and KVL
- Resistor, Inductor and Capacitor
- Power Converters

Power System Diagram

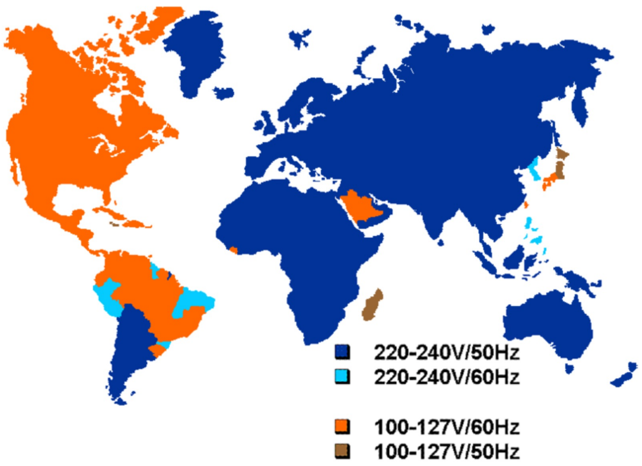


- Every large-scale power system has three major components:
  - **generation**: source of power, ideally with a specified voltage and frequency
  - **load/demand**: consumes power; ideally with a constant resistive value
  - **transmission system**: transmits power; ideally as a perfect conductor
- Additional components include:
  - **distribution system**: local reticulation of power
  - **control equipment**: coordinate supply with load

Picture source: FERC. "Final Report on the Aug. 14, 2003 Blackout in the US and Canada"

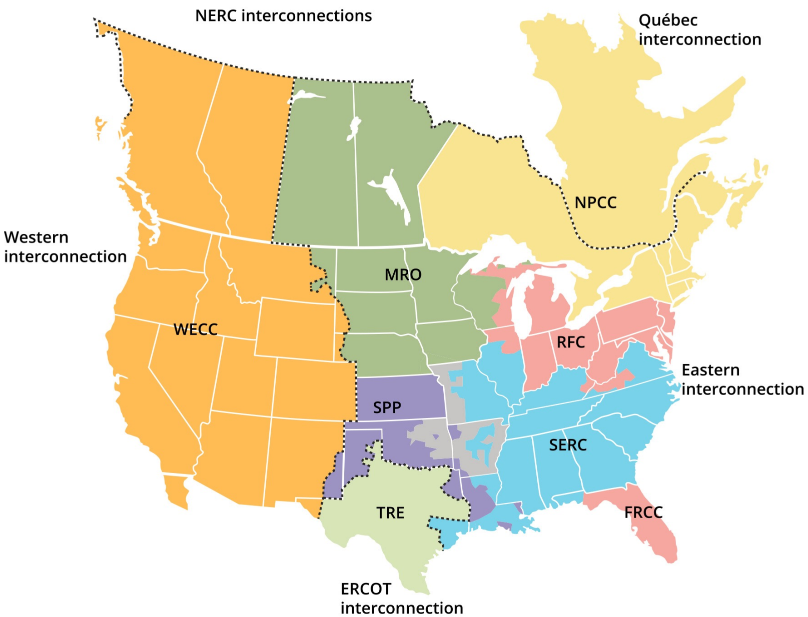
Examples of Power Systems

- Interconnection: Range from quite small (campus/town) to very large one (covering half the continent)
  - *Difference countries/regions are operated at different frequency*
  - *No great technical reason of preference*
  - *No apparent desire for complete worldwide standardization*



- Airplanes and spaceships: Reduction in weight is primary consideration; frequency is 400 Hz
- Ships and submarines
- EVs: DC with 12 volts standard and higher voltages

North America Interconnections



- Within each zone, everything is synchronized so that every circuit operates at the same frequency.
- Interconnections between the grids are made using high voltage DC (HVDC) links including rectifiers (AC-to-DC) and inverters (convert DC-to-AC).

North American Electric Reliability Corporation (NERC) has the responsibility for overseeing operations in the electric power industry and for developing and enforcing mandatory reliability standards

TABLE 1.2 NERC Regional Reliability Councils

	Council Name	Capacity (MW)	Coal (%MWh)
FRCC	Florida Reliability Coordinating Council	53,000	19
MRO	Midwest Reliability Organization	51,000	51
NPCC	Northeast Power Coordinating Council	71,000	9
RFC	Reliability First Corporation	260,000	50
SERC	Southeastern Reliability Corporation	215,000	33
SPP	Southwest Power Pool RE	57,000	33
TRE (ERCOT)	Texas Reliability Entity	81,000	19
WECC	Western Electricity Coordinating Council	179,000	18

Source: EIA/DOE, 2008.

Independent System Operators (ISO)

The role of ISOs/RTOs (regional transmission organization)

- Match power generation instantaneously with demand.
- Coordinate utilities, suppliers, consumers.
- Ensure access to affordable, reliable and sustainable power via efficient administration of independent and transparent wholesale energy markets.

Goals of Power System Operation

- Supply load with electricity at
  - specified voltage (120 V common for residential)
  - specified frequency (60 Hz)
  - minimum cost satisfying operating constraints, safety, reliability, sustainability, etc.

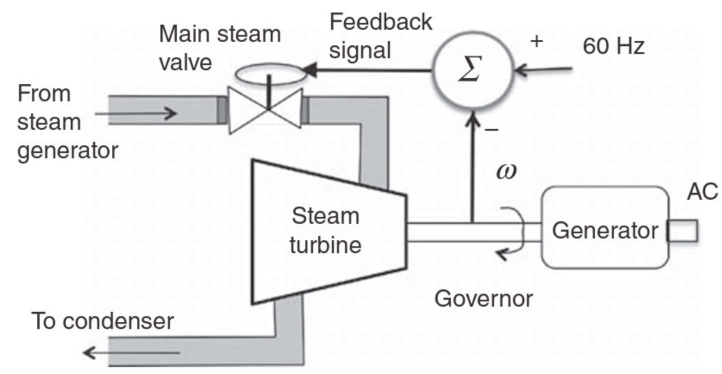


FIGURE 1.9 Frequency is often automatically controlled with a governor that adjusts the torque from the turbine to the generator.

Supply = Demand!

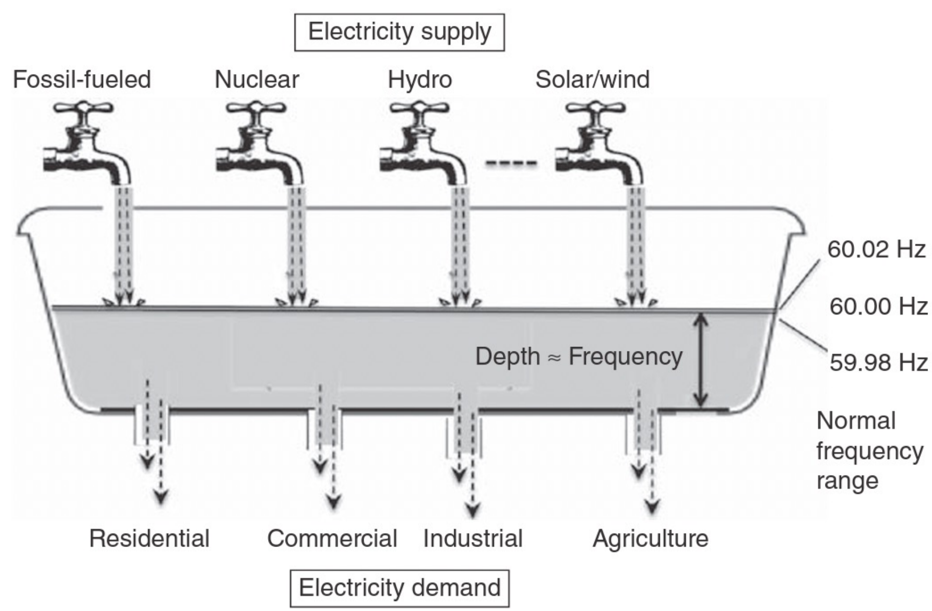
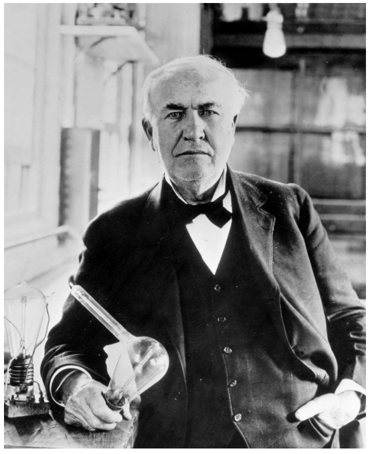
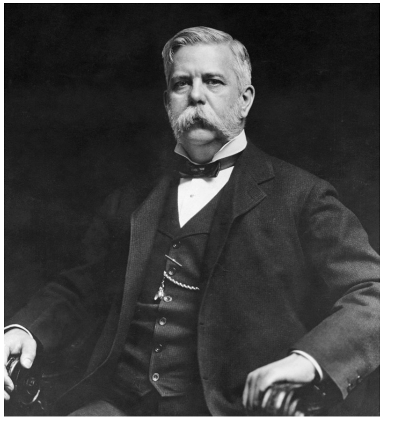


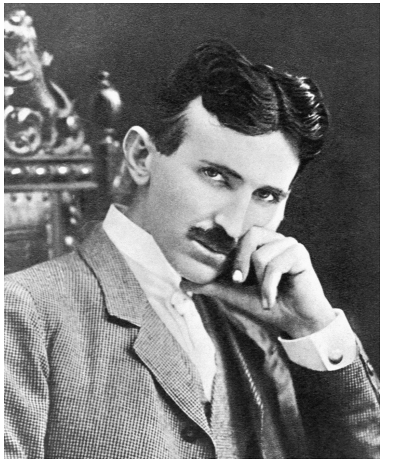
FIGURE 1.10 A simple analogy for a grid operating as a load-following system in which the supply is continuously varied to maintain a constant water level representing frequency.

Brief History of Electric Power

- 1882 – Thomas Edison introduced Pearl Street DC system in Manhattan as the nation's first IOU, powering 7200 lamps within 1 mi^2 area.
- 1883 – Frank Sprague patented self-regulated DC motor
- 1885 – William Stanley built first transformer
- 1886 – George Westinghouse built the first commercial AC power station
- 1886 – Nikola Tesla invented AC induction motor
- 1893 – First 3-phase transmission line operating at 2.3 kV
- 1896 – AC lines delivered hydrogen electricity from Niagara Falls to Buffalo, 20 miles away



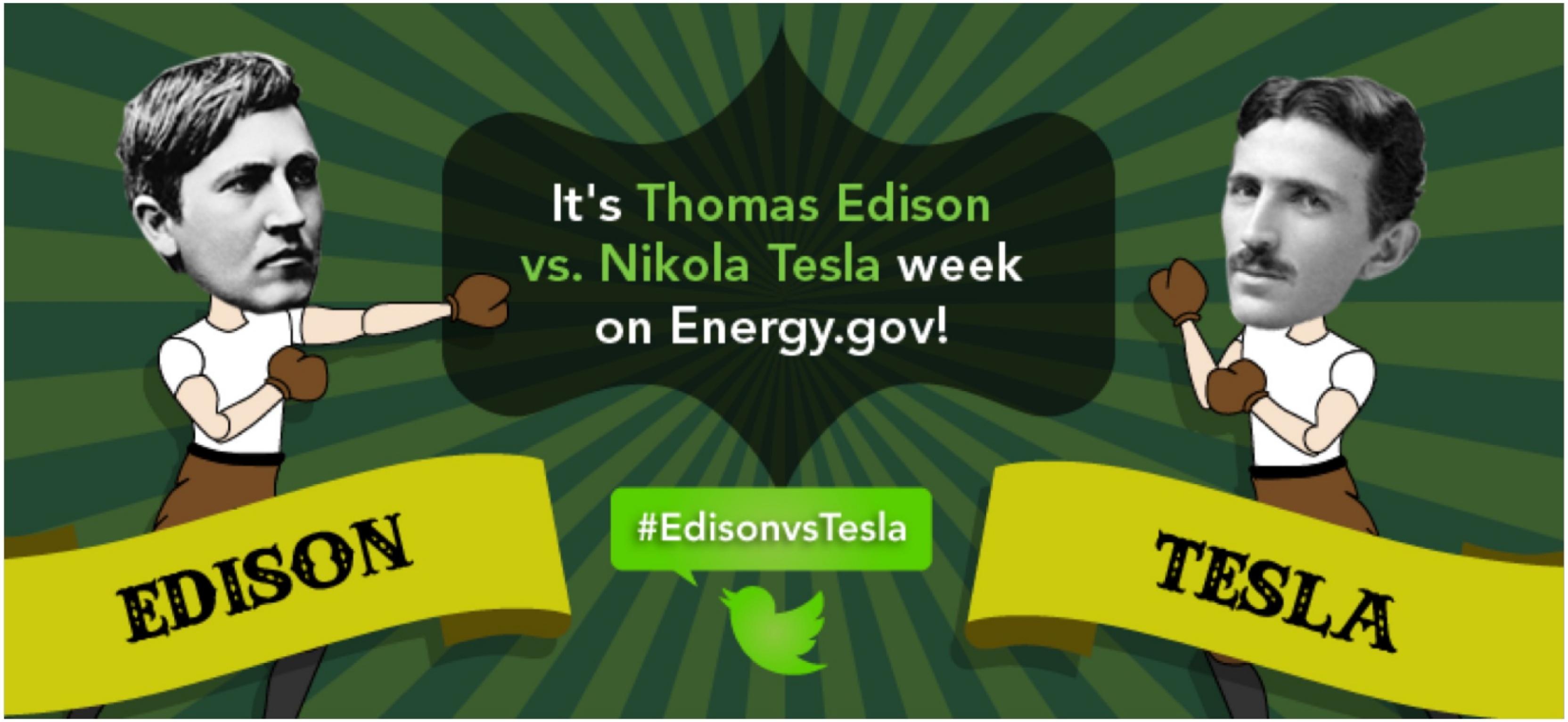




Private utilities supplied all customers in early 1900's. And large interstate holding companies controlled most electricity systems by 1920's.

See details: edisontechcenter.org/AC-PowerHistory.html

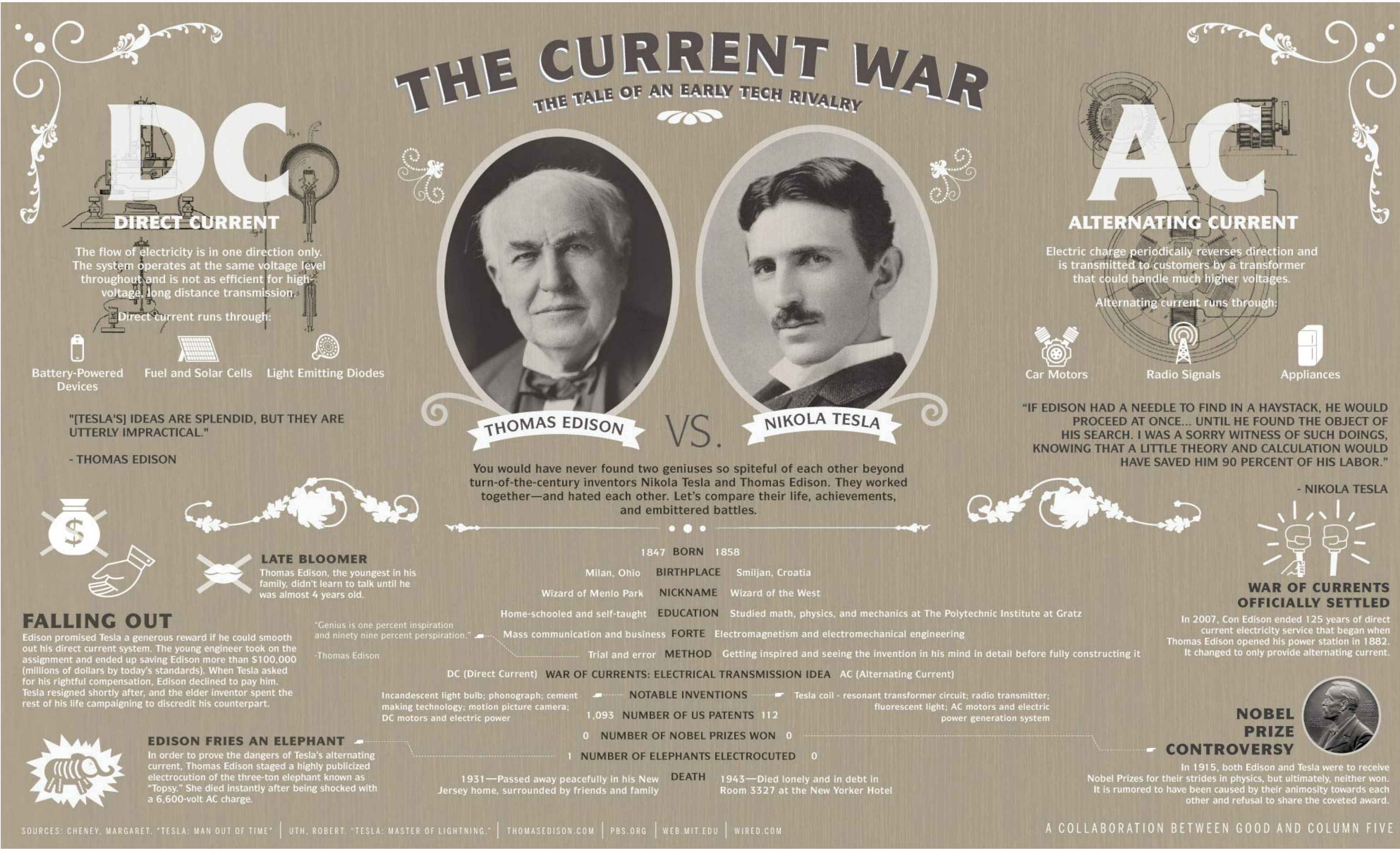
Alternating Current (AC) vs Direct Current (DC)



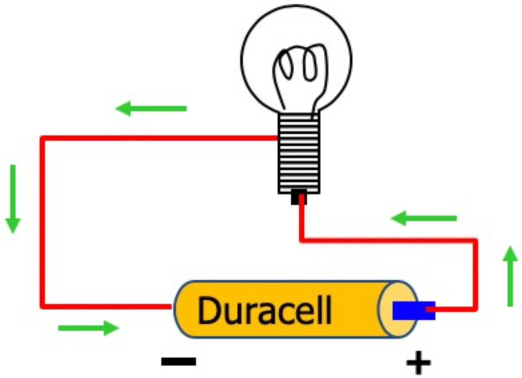
Edison "invented" the electric business, but Tesla "sealed" its future.

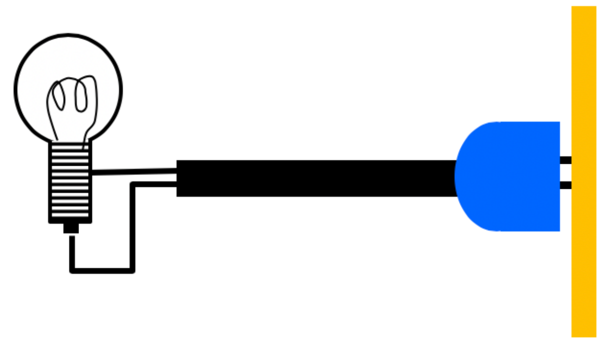
Figure: Source credit: Dr. Merwin Brown at UC Berkeley

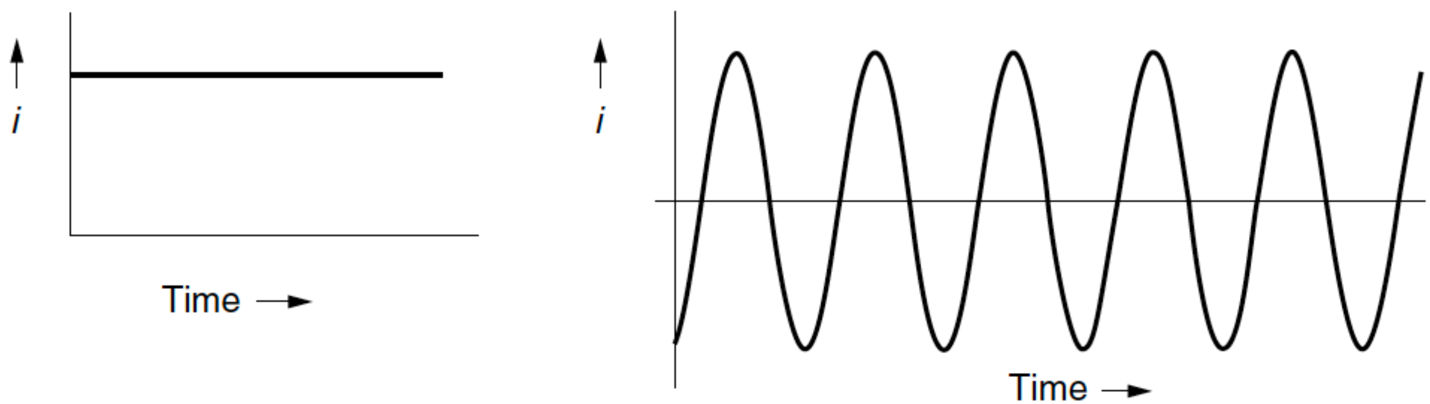
AC vs DC (cont'd)



DC vs AC







(a) Direct current (b) Alternating current

Figure 1.3 (a) Steady-state direct current (dc). (b) Alternating current (ac).

AC (cont'd)

- Voltage (current) reverses polarity (direction) 60 times/second
- Cell phone chargers convert AC to DC

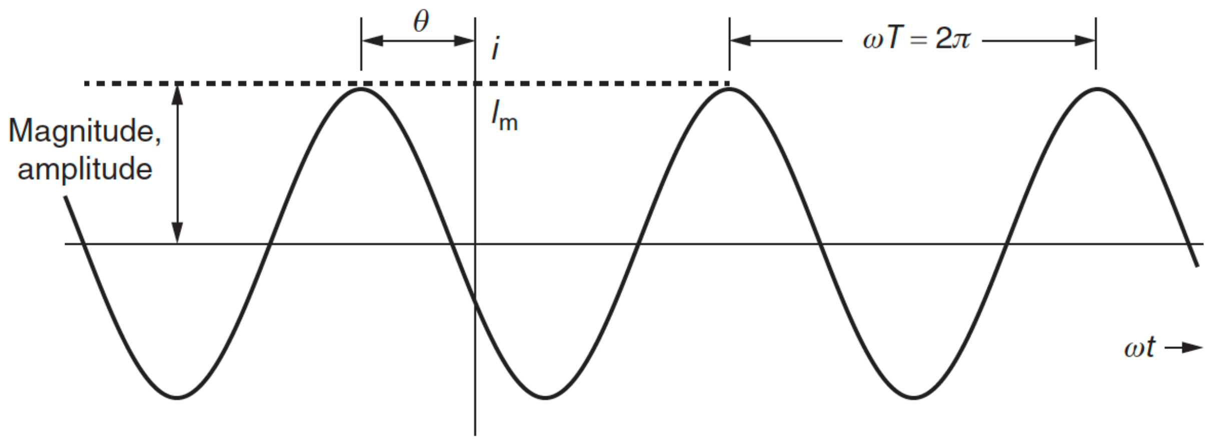


FIGURE 3.1 Illustrating the nomenclature for a sinusoidal function.

$$i = I_m \cos(\omega t + \theta) = I_m \cos(2\pi f t + \theta) = I_m \cos\left(\frac{2\pi}{T} t + \theta\right)$$

Pros/Cons of AC & DC

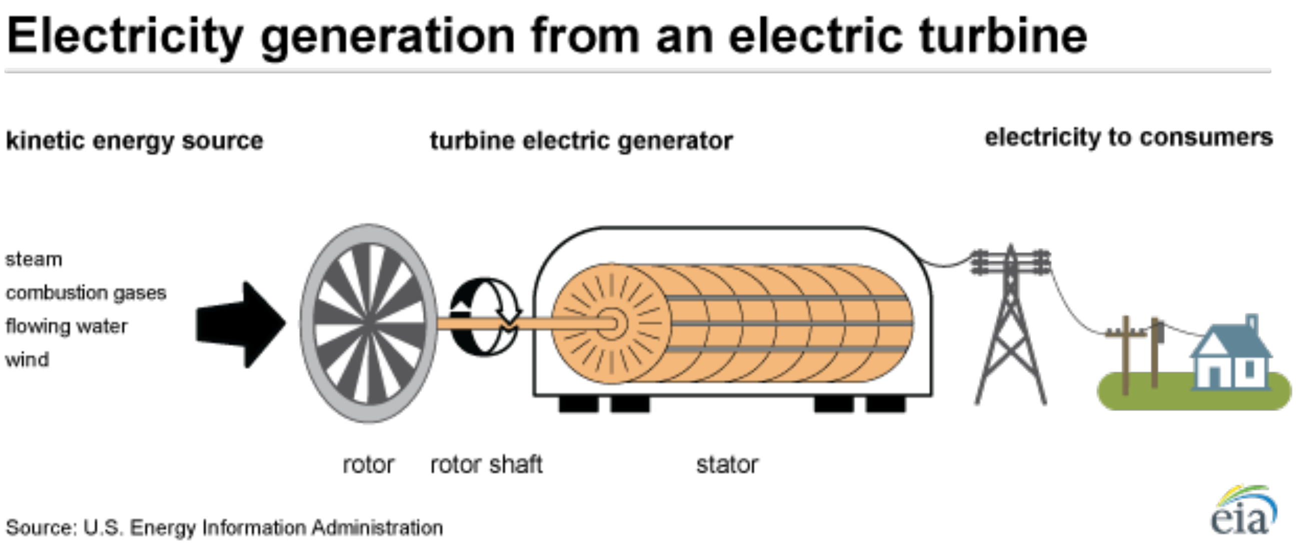
- DC power is provided at one voltage only.
- AC power is easier to generate and can be stepped up or down to provide any voltage required.

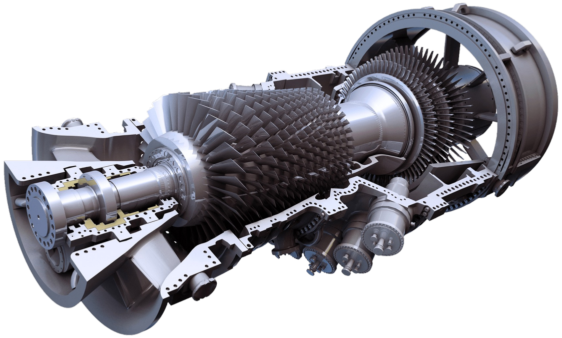
- DC is very expensive to transmit over large distances compared with AC.
- DC power plants must be close to users while AC plants can be far outside cities.

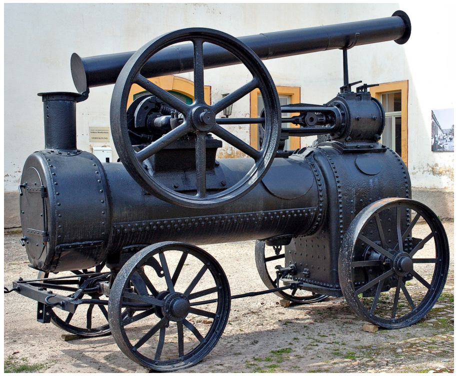
- The advantage of a DC link is that problems associated with exactly matching AC frequency, phase, and voltages from one interconnect to another are eliminated in DC.

Prime Mover

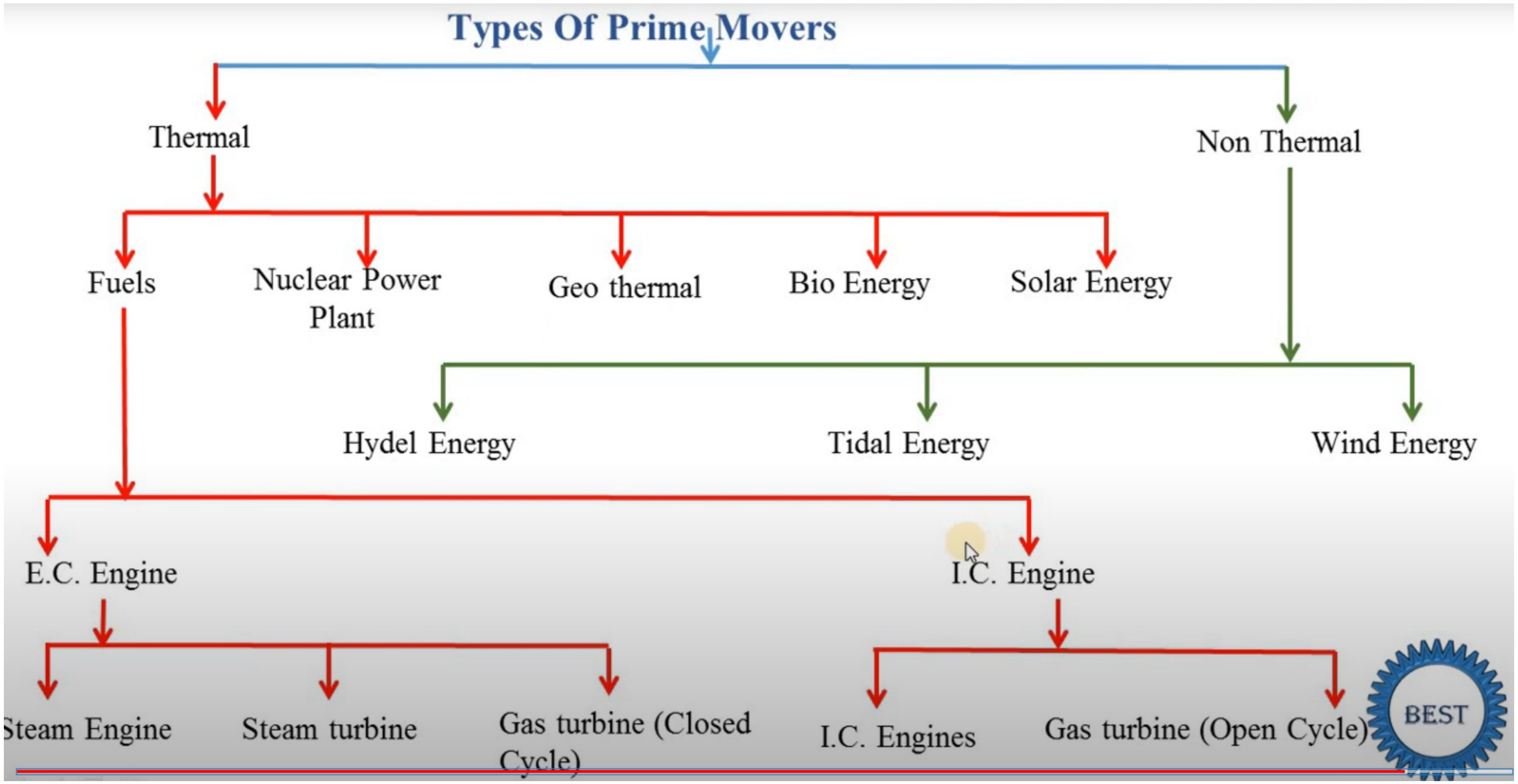
Prime mover: A device uses natural sources to convert mechanical energy into shaft work. For power systems, it can be an engine, turbine, water wheel, or similar machine that drives an electric generator.







Types of Prime Movers



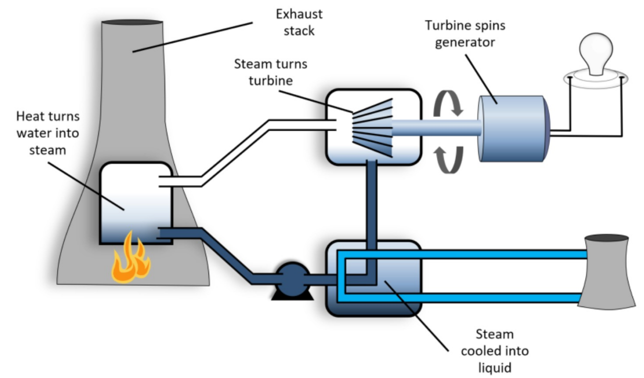
One distinguishing point between steam turbine vs steam engine:

- For steam turbine, the steam is expanded into the sets of nozzles, fixed blades, and moving blades to get the work output.
- For steam engine, the steam is expanded into the piston-cylinder assembly to get the work output.

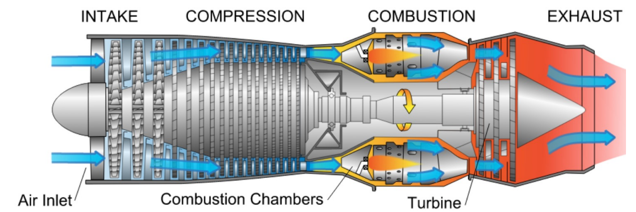
Figure credit: tinyurl.com/yv63spk9

Steam and Gas Turbines

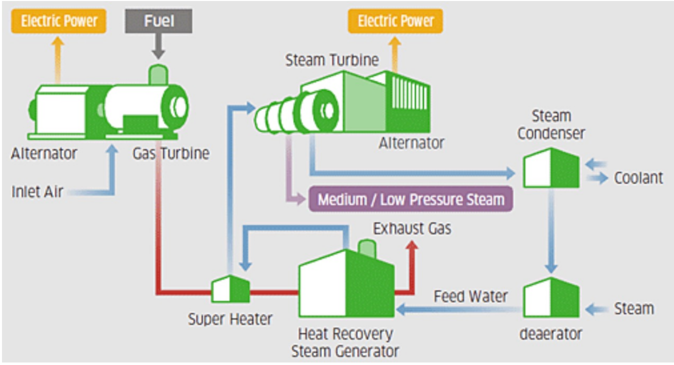
- Most steam turbines have a boiler in which a fuel is burned to produce hot water and steam in a heat exchanger, and the steam powers a turbine that drives a generator. Examples: nuclear power reactors, solar thermal/ geothermal power.



- Combustion gas turbines burn gaseous or liquid fuels to produce hot gases to turn the turbine blades.

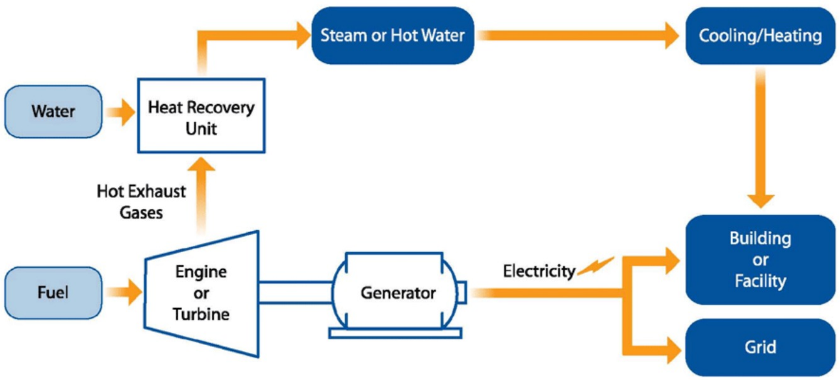


- Steam and combustion turbines can be operated as stand-alone generators in a single-cycle or combined in a sequential combined-cycle. Combined-cycle systems use combustion gases from one turbine to generate more electricity in another turbine.

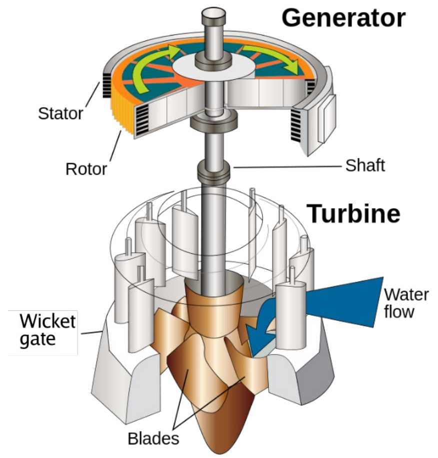


Cogenerators, Hydro/Wind Turbines

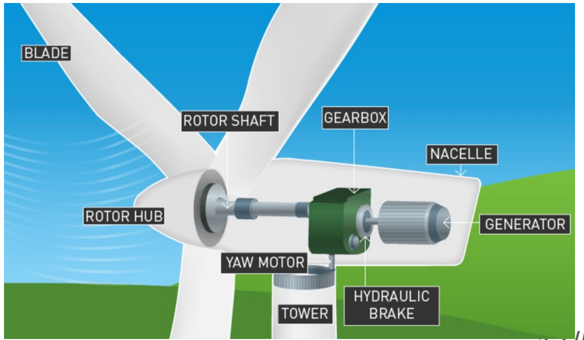
- Combined-heat-and-power (CHP) plants (a.k.a. cogenerators) use the heat that is not directly converted to electricity in a steam turbine, combustion turbine, or an internal combustion engine generator for industrial process heat or for space and water heating.



- Hydroelectric turbines use the force of moving water to spin turbine blades. Most hydropower plants use water stored in a reservoir or diverted from a river or stream.



- Wind turbines use the power in wind to move the blades of a rotor. There are two general types of wind turbines: horizontal axis (the most common) and vertical-axis turbines.



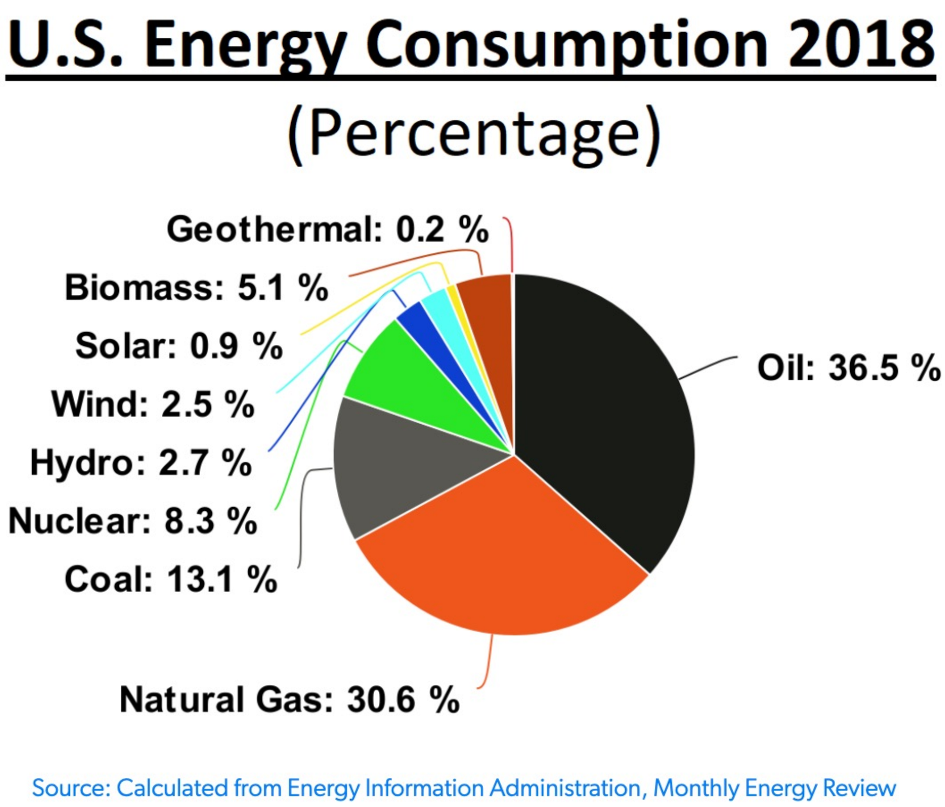
Electricity Generators by Major Type

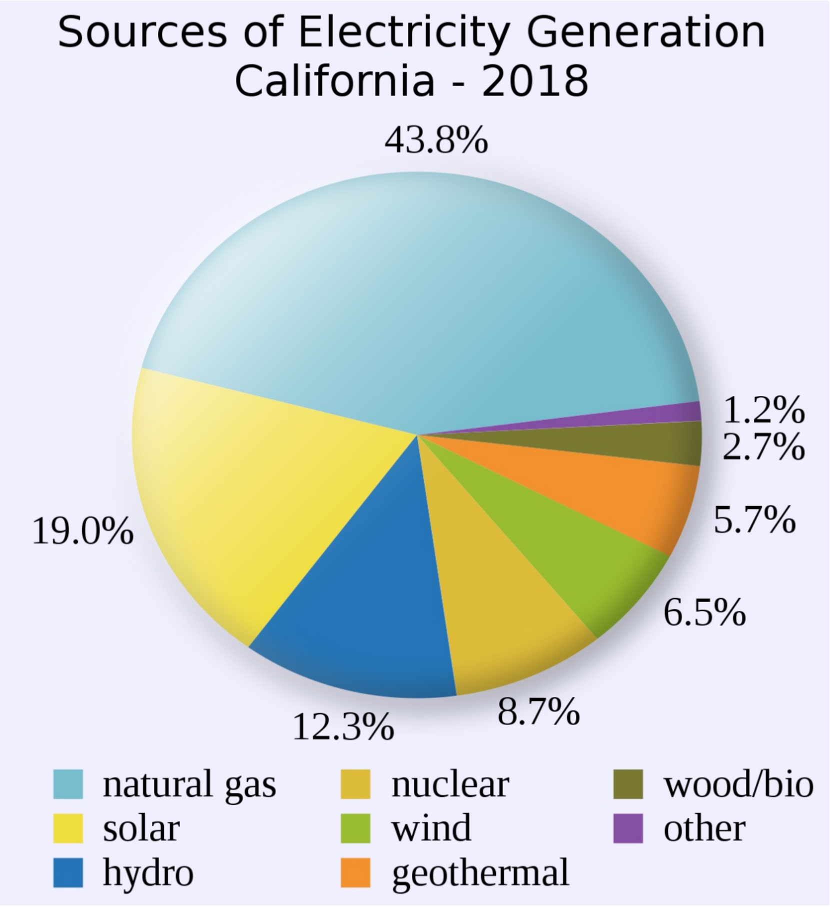
Generator	Plant type	Main fuel/energy source	Share of annual electricity generation
Steam turbine	**Single cycle**	**All sources**	**45.3%**
		Coal	21.6%
		Nuclear	18.9%
		Natural gas	2.4%
		Biomass (1.0%); Others (1.3%)	2.3%
Multiple	**Combined cycle**	**Natural gas[2]**	**32.8%**
Combustion turbine			20.7%
Steam turbine			10.5%
Dual/single shaft			1.6%
Combustion gas turbine	**Single cycle**	**Natural gas[2]**	**3.4%**
Wind turbine	**All types**	**Wind**	**9.2%**
Hydroelectric turbine	**Conventional**	**Water**	**6.1%**
Photovoltaic	**All types**	**Solar**	**2.7%**
Others[3]		**Various**	**0.5%**
Storage systems[4]		**Various**	**-0.1%**

Data source: U.S. EIA, Form EIA-923 Power Plant Operations Report, 2021

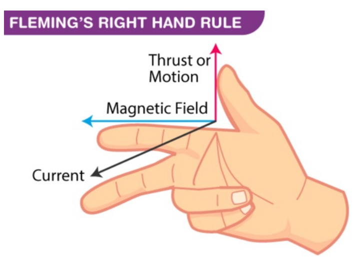
Energy Sources

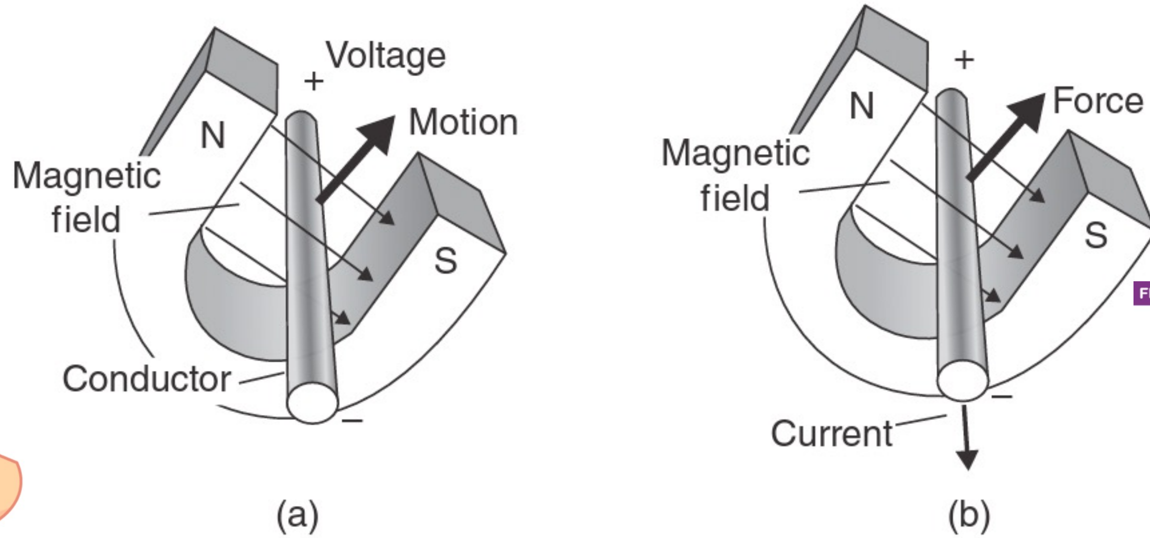
Renewable/nonrenewable energy sources are used as primary energy sources to produce useful energy such as heat or used to produce secondary energy sources such as electricity.





Wonders of Electromagnetism





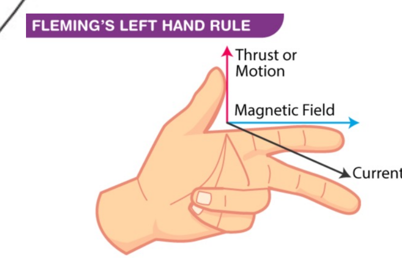
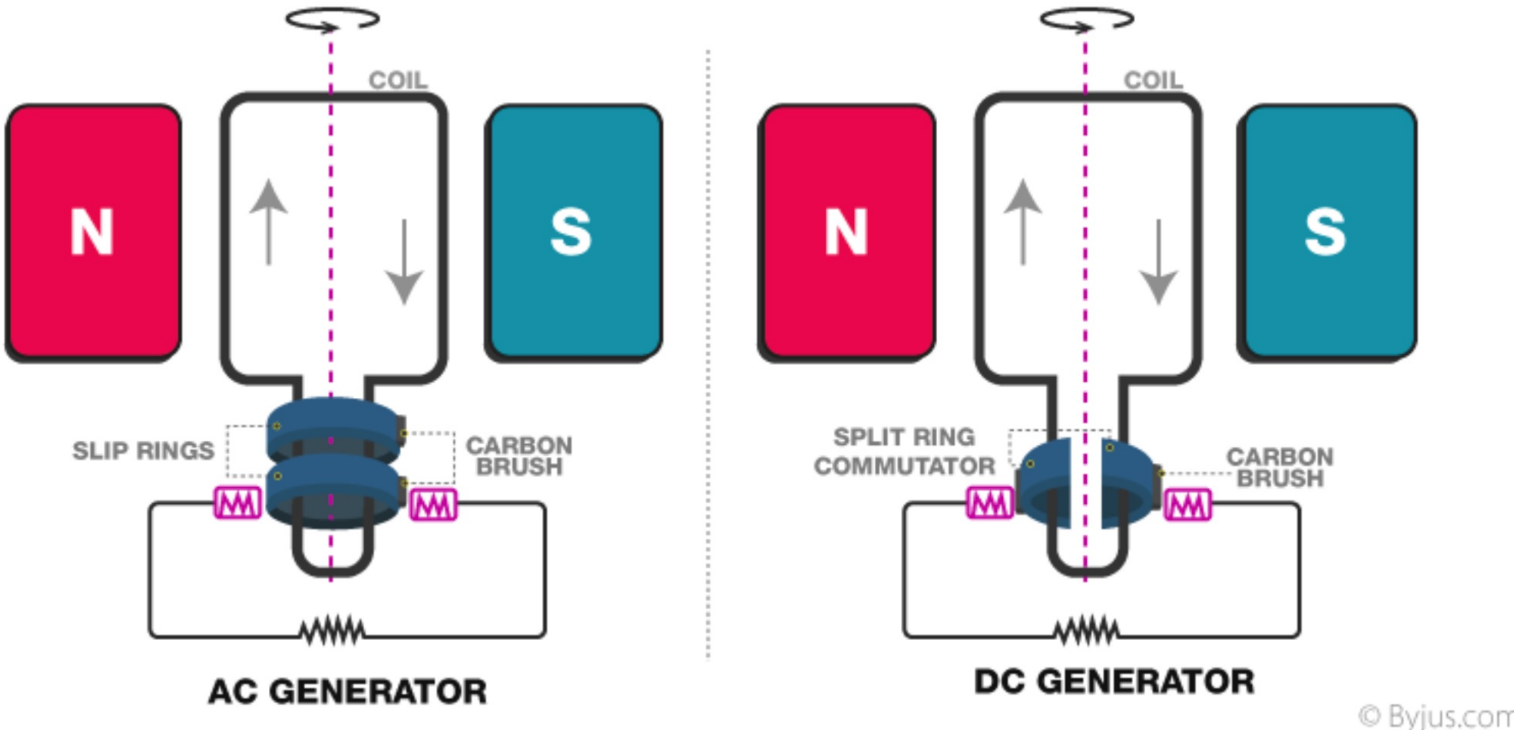


FIGURE 1.1 Moving a conductor through a magnetic field creates a voltage (a). Sending current through a wire located in a magnetic field creates a force (b).

- The interactions between electricity & magnetism make it possible for the development of generators and motors.
- Pioneers in the early 19th century: Hans Oersted, James Maxwell, and Michael Faraday.

Fig credit: Byjus.com

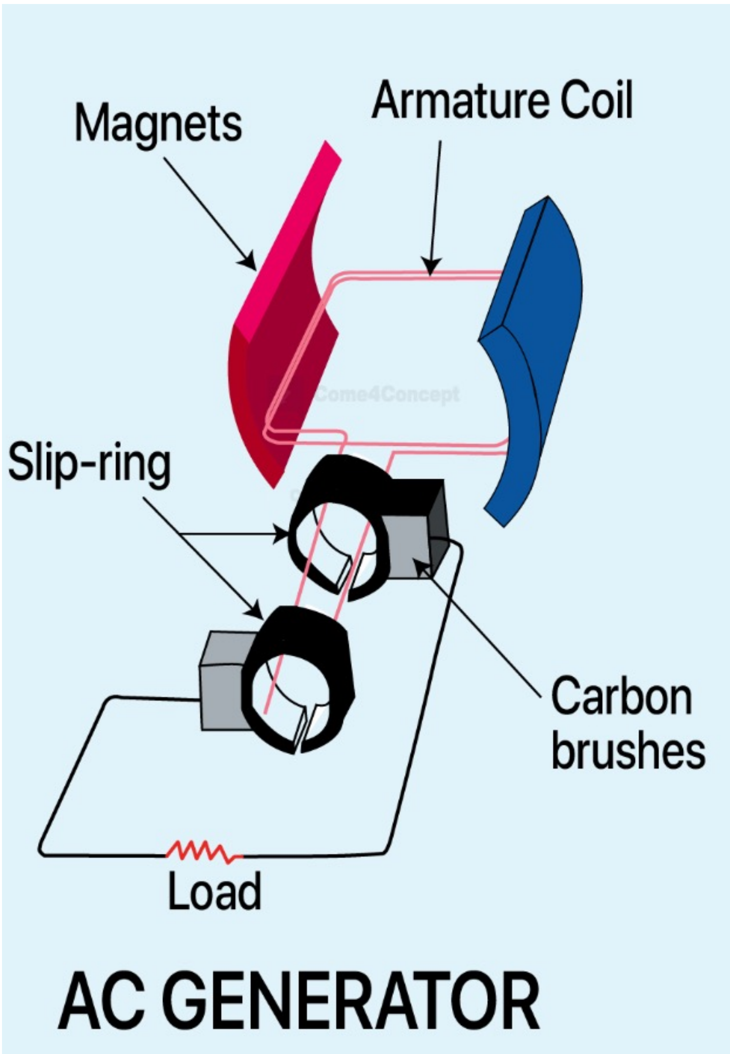
AC vs DC Generators



- Both machines operate due to the relative motion between a magnetic field and a coil.
- Both are based on the principle of Faraday's law to generate electric current.
- Both coverts mechanical energy into electricity and initially produce AC voltage.

Fig credit: Byjus.com

AC vs DC Generators (cont'd)



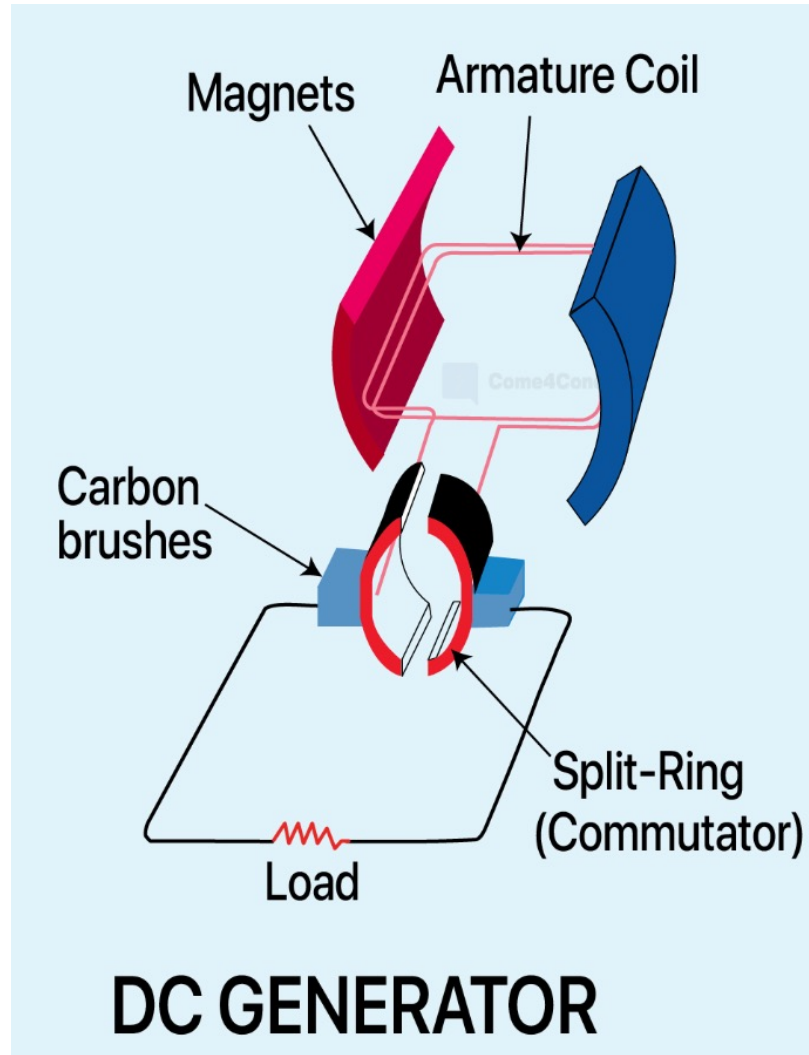
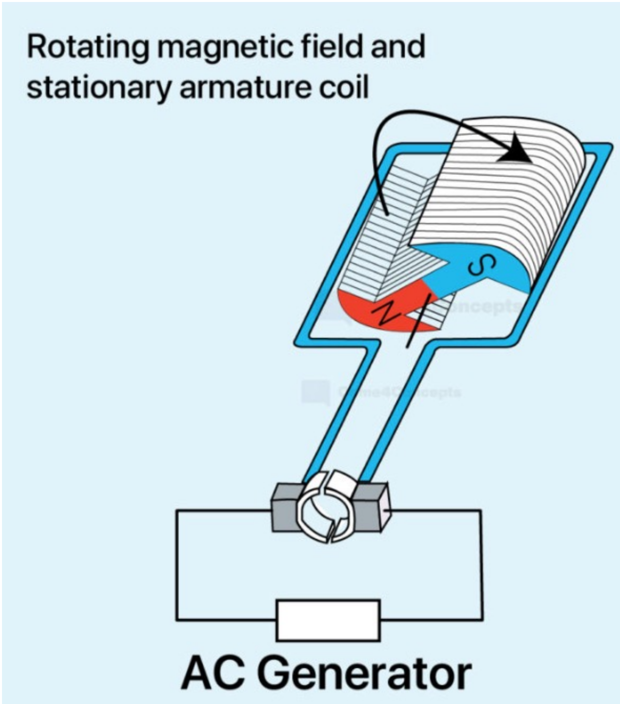
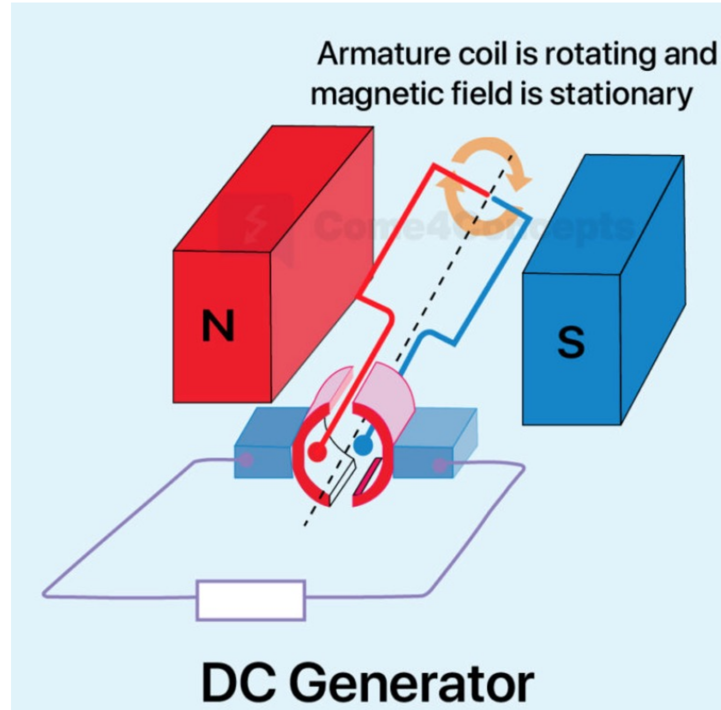


Fig credit: come4concepts.com

AC vs DC Generators (cont'd)



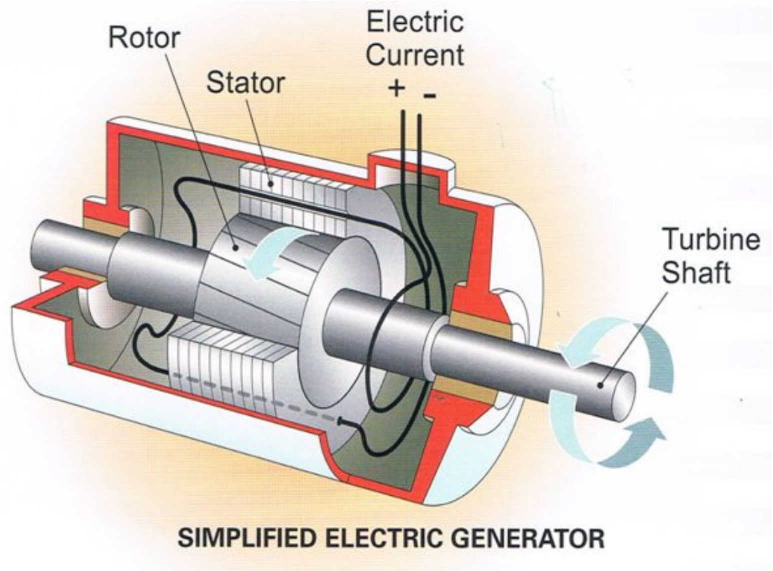


- Field winding: winding produces main magnetic field. It is installed on the rotor for AC gen while placed on the stator for DC gen.
- Armature winding: winding where voltage is induced. It is provided on the stator for AC gen while placed on the rotor for DC gen.

Fig credit: come4concepts.com

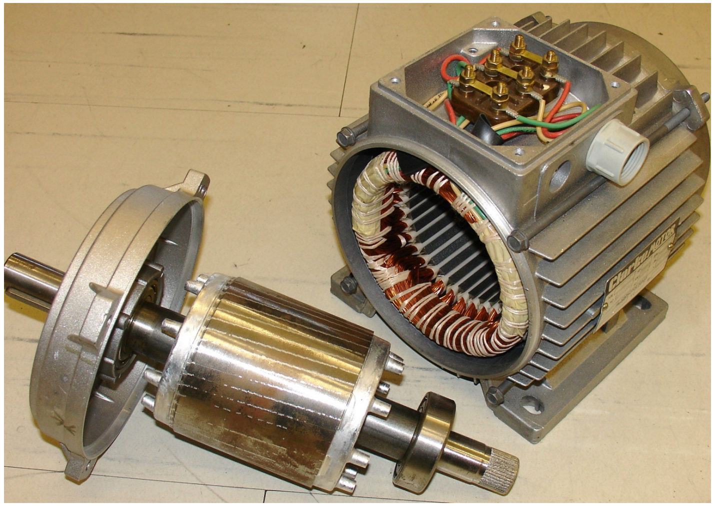
Electric Generator

- Faraday's law - Electromagnetic induction: Whenever a conductor is placed in a varying magnetic field, an electromotive force is induced. If the conductor circuit is closed, a current is induced.
- A basic electromagnetic generator has a series of insulated coils of wire that form a stationary cylinder (**stator**) surrounding an electromagnetic shaft (**rotor**).

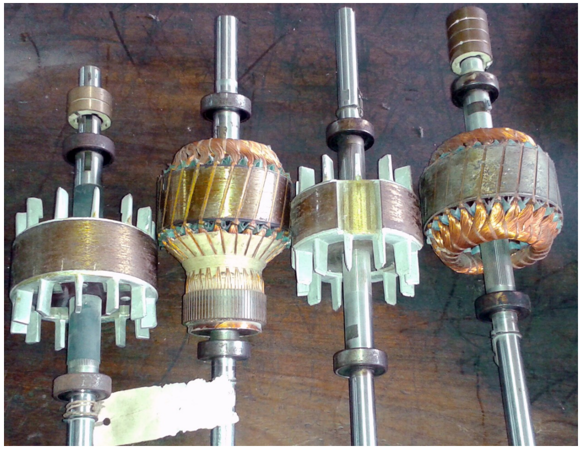


- The induced voltage depends on how many wires the coil has and how fast it is rotated.
- The frequency depends on the rotational speed of the coil and number of poles.

$$\text{Frequency} = \frac{\text{RPM} \times \text{number of poles}}{120}$$



Electric Generator



Stator is a stationary part that contains a set of metal coils. These coils are arranged in a circular pattern around the rotor.

Rotor is a rotating part that is located inside the stator. The rotor is typically made up of a metal shaft with a series of metal bars or coils wrapped around it.

A generator typically contains permanent magnets (often for very small generators) or electromagnets in the rotor to create a rotating magnetic field that induces electrical current in the stator coils.

When an external force (e.g., turbine or engine) rotates the rotor, the magnetic field it generates moves past the metal coils in the stator. This movement causes electrons in the coils to move, creating an electric current.

Construction of Alternator

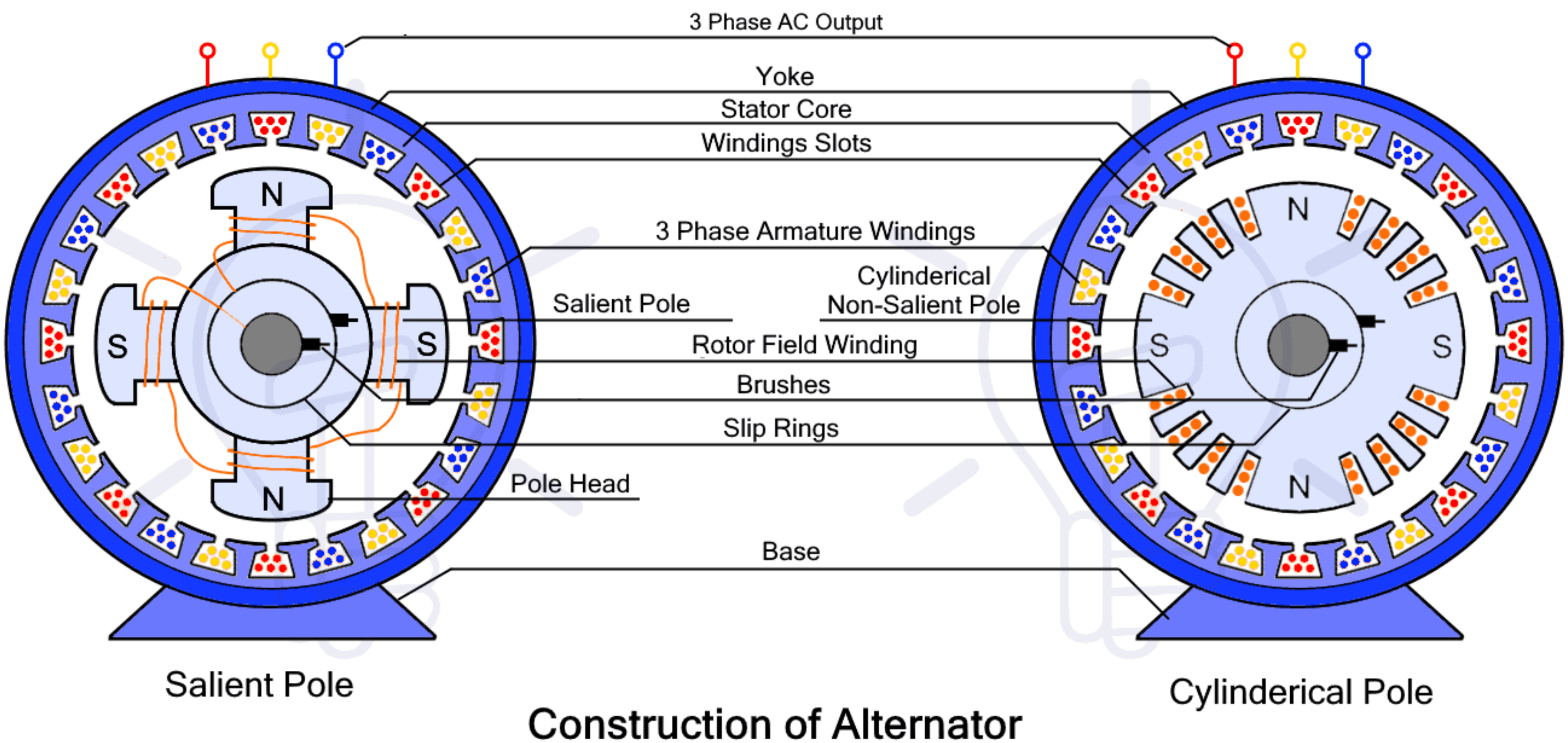


Fig credit: electricaltechnology.org

Transformers

Transformers make the voltage bigger or smaller, only work with AC!

Fig: A typical step-down transformers used to bring the line voltage down from 5 kV to 240 V.

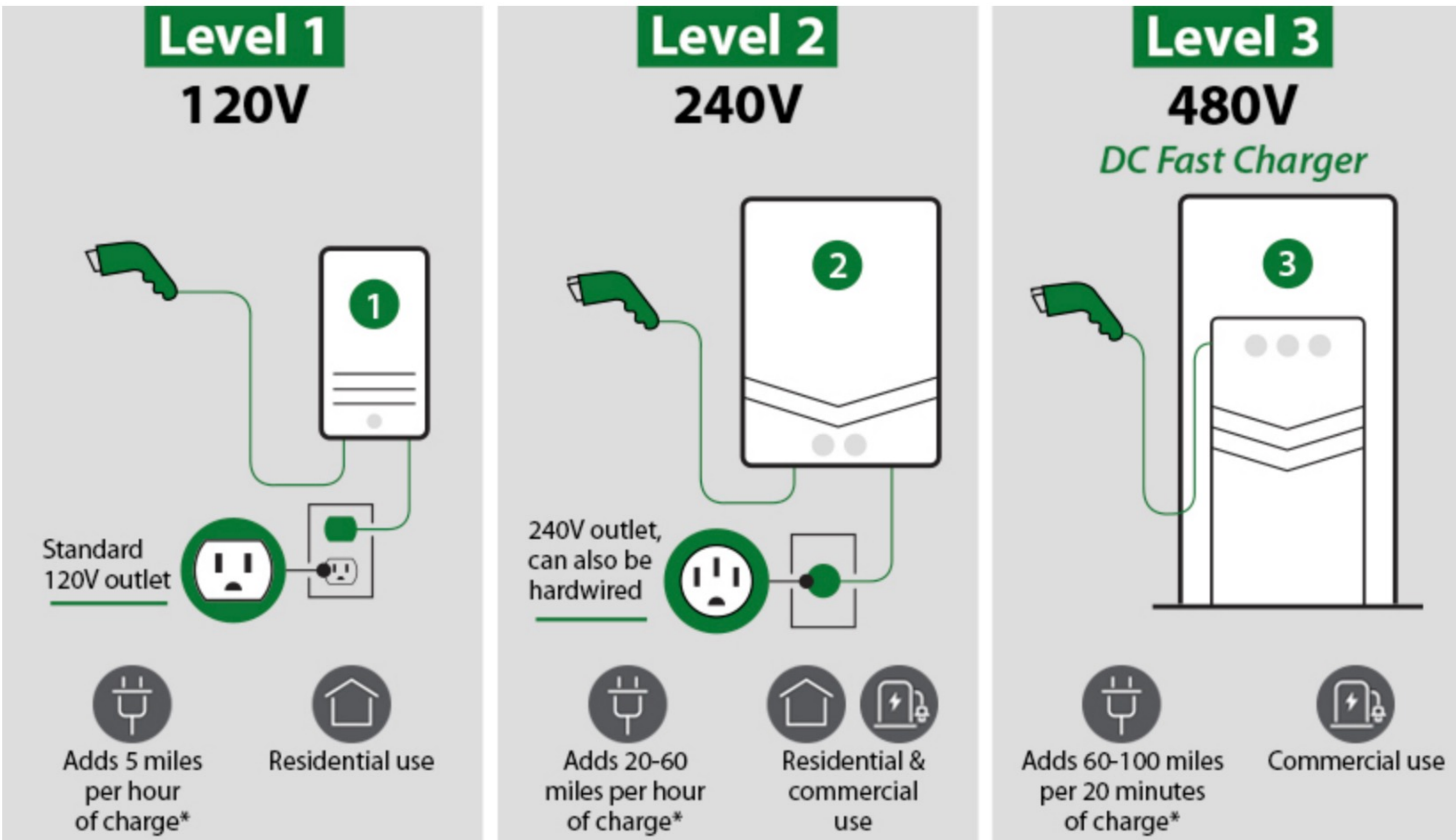
Residential voltage in the USA and Canada is 120/240V AC.

Power enters the dwelling's main electrical panel from a utility transformer as two 120V lines with phases that are 180 degrees apart.

120V and 240V (along with neutral and ground) is then distributed to outlet boxes (switch, receptacle, light fixture, etc) throughout the dwelling.

120V and 240V Outlets

- The 240V is used for the high-power appliances like the clothes dryer, range (cooktop & oven), water heater, central AC, air compressors, welding machines, etc.
- The 120 V is for most appliances.



Phase Voltage (120V) vs Line Voltage (240V)

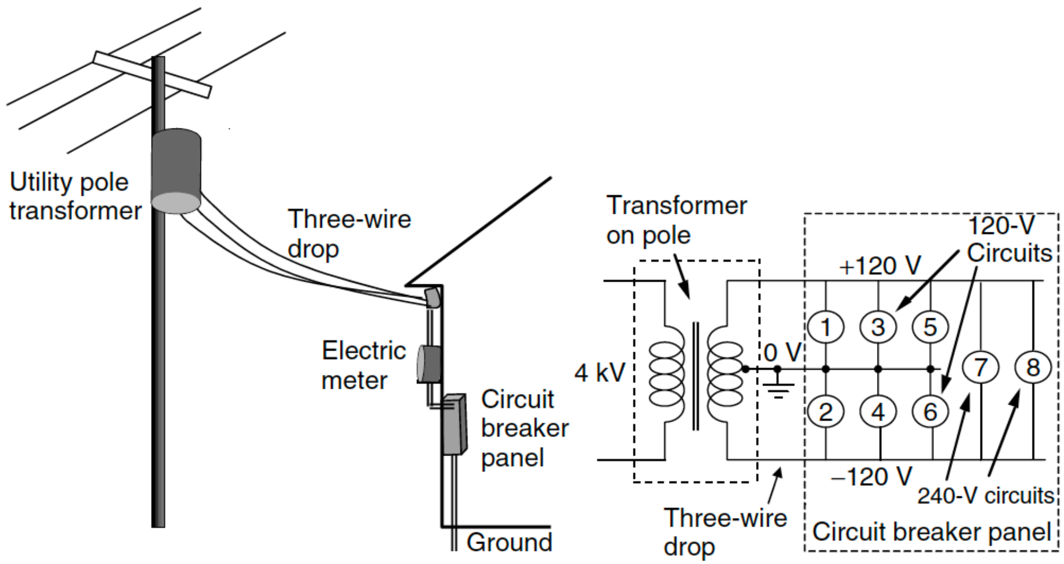
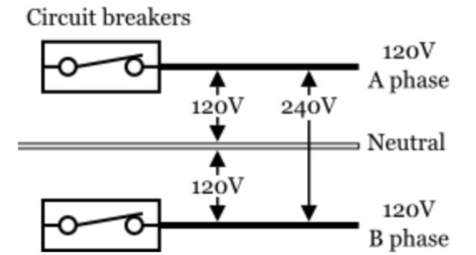
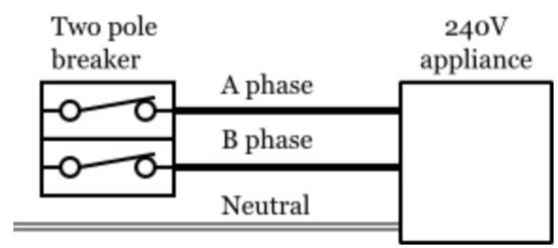


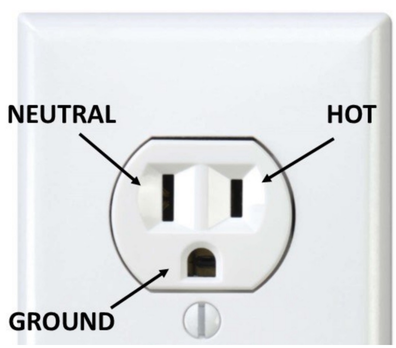
Figure 2.11 Three-wire, single-phase power drop, including the wiring in the breaker box to feed 120-V and 240-V circuits in the house.



Voltage between A and B phase is 240 Volts

240 Volts Appliance Wiring Diagram





120V outlet

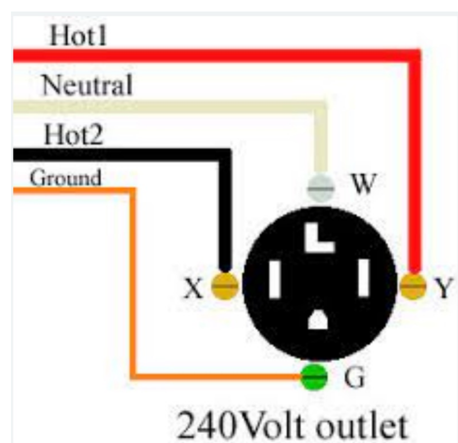


Fig source: B1

Electric Outlets and GFCI

- Normally, current from the hot line, through the appliance, is returned through the neutral wire. None with the ground wire (provides a safe path for current in the event of a short circuit).
- Equal hot and neutral currents passing through a coil, their magnetic fields cancel.
- If there is a leakage/short, current in the neutral line will slow/stop, the magnetic fields of the hot and neutral lines will no longer cancel.
- That results in a spike of magnetic flux that is detected in a comparator circuit, which sends a signal to immediately open the breaker.
- Ground-Fault Circuit Interrupter (GFCI) interrupts the circuit very quickly if current flows through anything other than the hot or neutral.

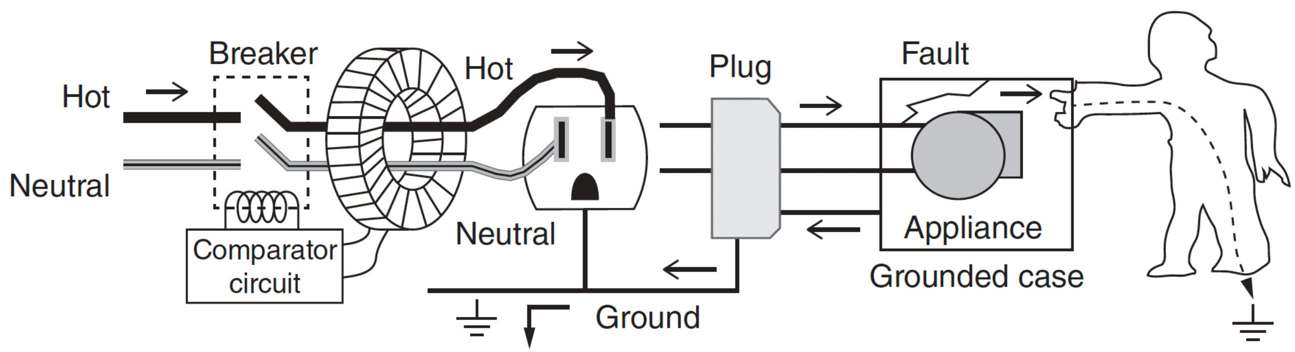
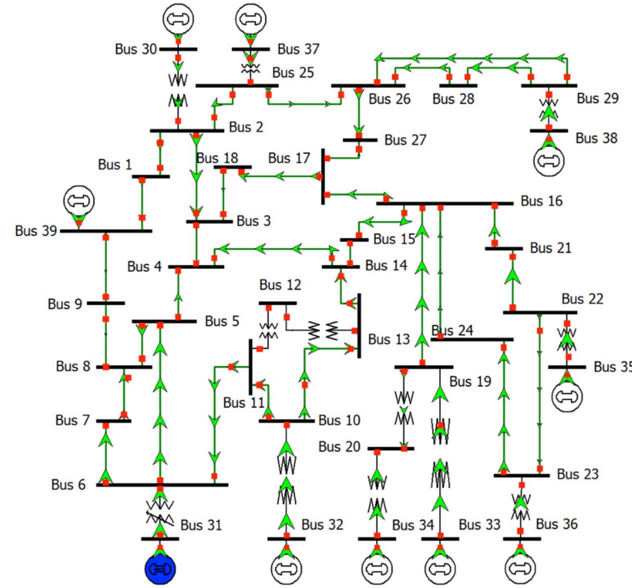
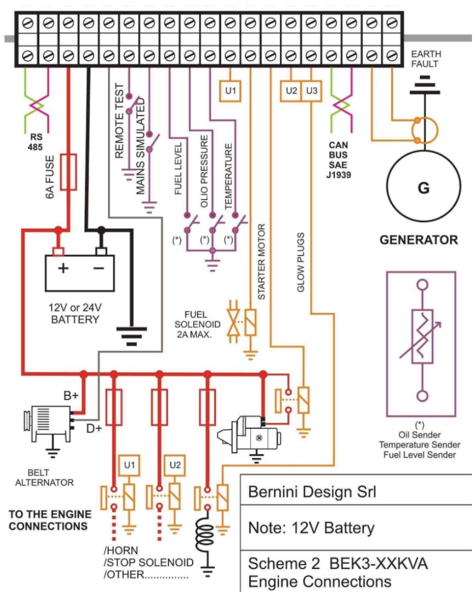
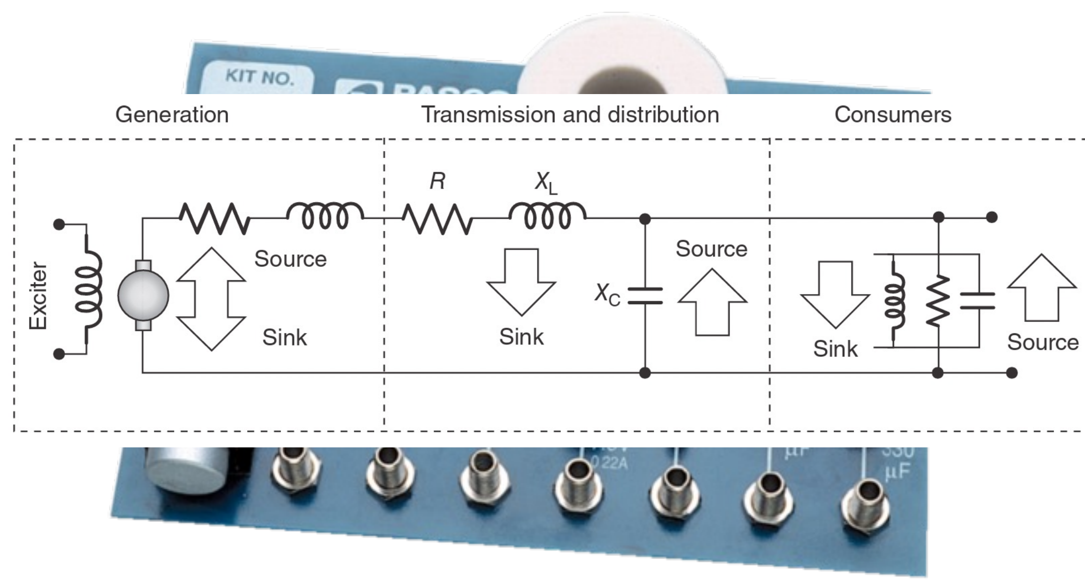


FIGURE 3.16 A ground fault interrupter (GFI) protects against dangerous faults by opening a breaker when unequal currents in the hot wire and neutral line are sensed.

Power Grid: A Big Circuit

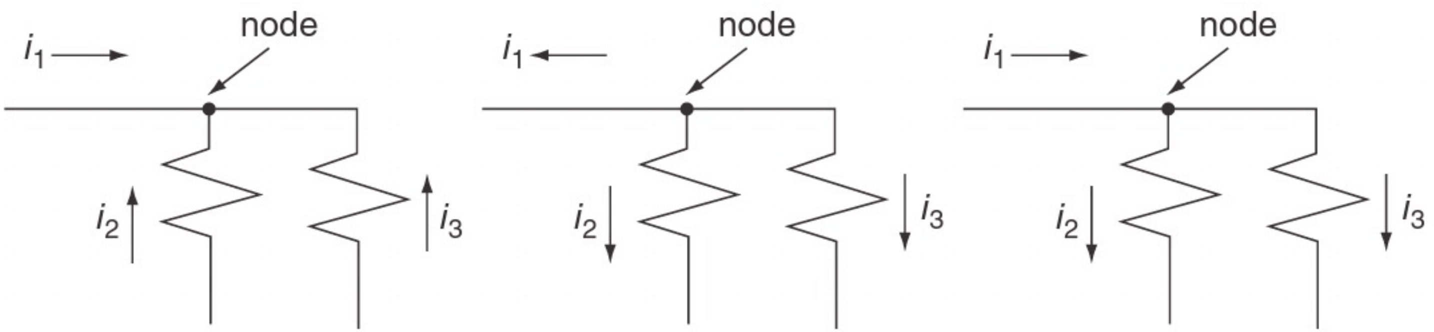






Kirchhoff's Current Law (KCL)

KCL: At any instant the sum of the currents flowing into any node of a circuit must equal the sum of the currents leaving the node (a node is any spot where two or more wires are joined); i.e., node cannot store current!

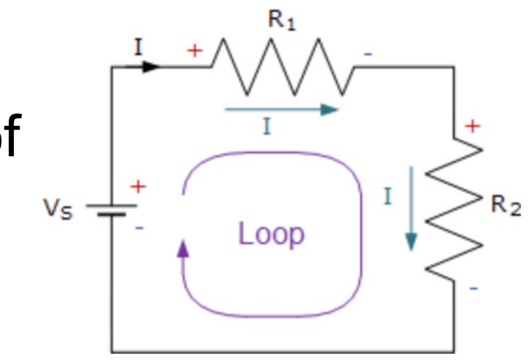


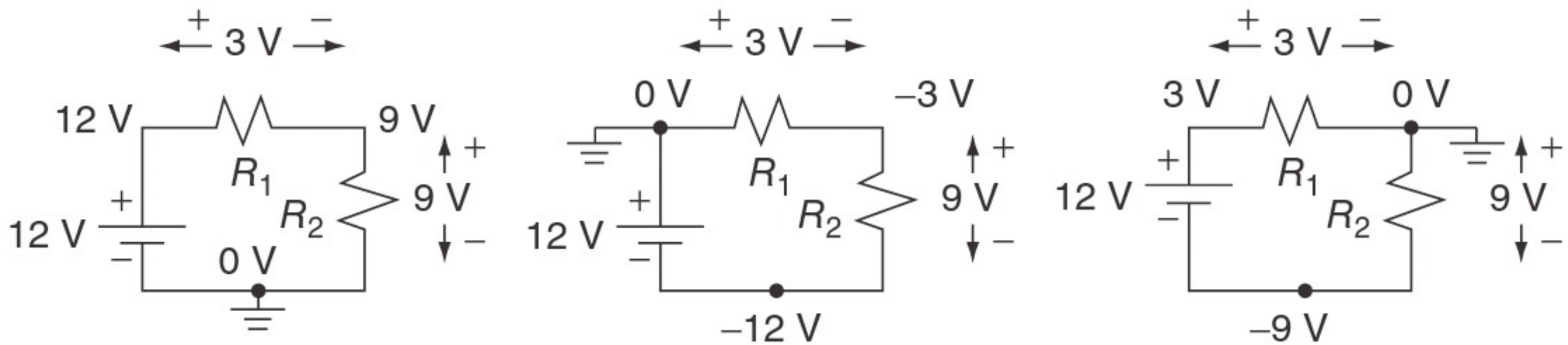
(a) $i_1 + i_2 + i_3 = 0$ (b) $i_1 + i_2 + i_3 = 0$ (c) $i_1 = i_2 + i_3$

Note: reference direction of a current arrows is arbitrary. But once drawn the arrows, the KCL must be written in a manner that is consistent with the reference arrows.

Kirchhoff's Voltage Law (KVL)

KVL: The sum of the voltages around any loop of a circuit at any instant is zero; i.e., the sum of voltage rises in that loop will equal the sum of the voltage drops in the loop (the conservation of energy around a closed-circuit path).





Note: reference sign of a voltage and the ground node can be arbitrary.

Series and Parallel Circuits

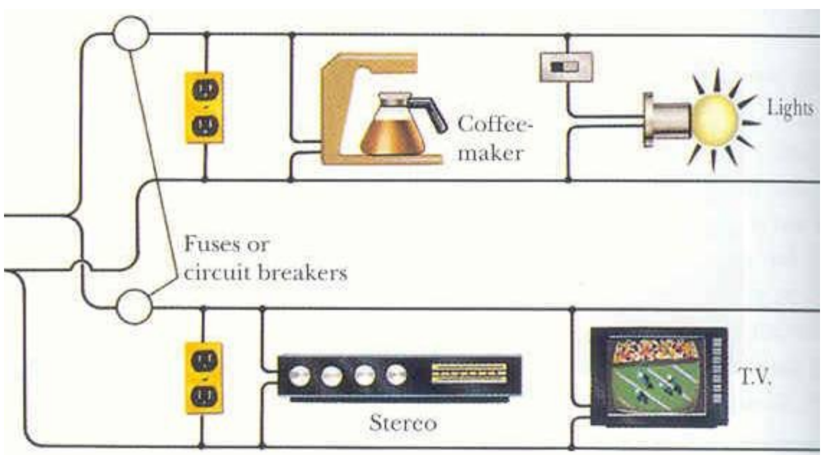
Series connection

Pros:

- less likely to overheat easily.
- easy to learn and to make.
- adding more power devices, all components carry the same current.

Cons:

- if one component breaks, the whole circuit will break.



Parallel connection

Pros:

- easy to (dis)connect a new element w/o affecting the others.
- current can pass through other paths if any fault (more robust).

Cons:

- use lot of wires.
- cannot increase the voltage.
- fails when it is required to pass exactly same amount of current through different paths.

Resistors

Modern resistors (passive two-terminal electrical component) are made out of either a carbon, metal, or metal-oxide film.

$$R = \rho \frac{l}{A} \quad \text{ohms } (\Omega)$$

where ρ is the resistivity of the material, l is the wire length, and A is the wire cross-sectional area.

Ohm's Law: $\boxed{v = Ri}$

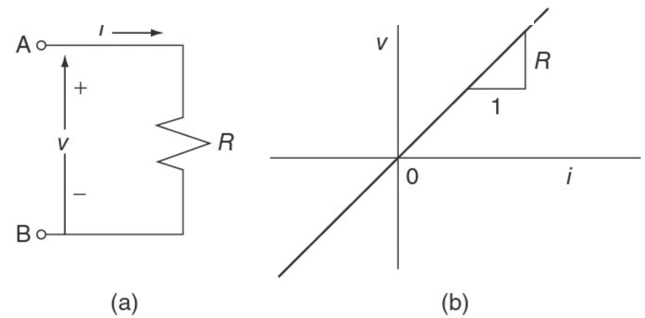
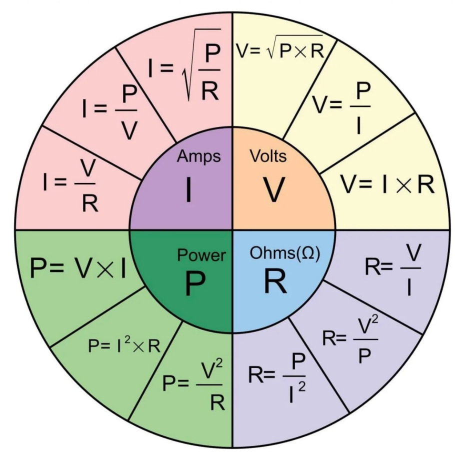


FIGURE 2.10 (a) Symbol for an ideal resistor. (b) Voltage–current relationship.

$$p = \frac{dw}{dt} = \frac{dw}{dq} \cdot \frac{dq}{dt} = vi = i^2 R = \frac{v^2}{R}$$



Series and Parallel Circuits

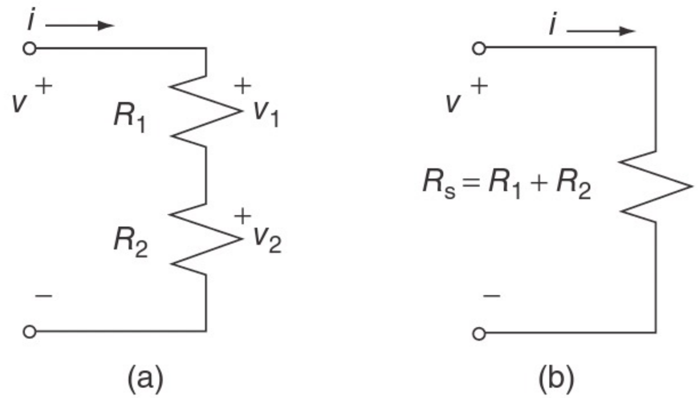


FIGURE 2.11 R_s is equivalent to resistors R_1 and R_2 in series.

$$v = iR_1 + iR_2 = iR_s$$

$$R_s = R_1 + R_2 + \cdots + R_n$$

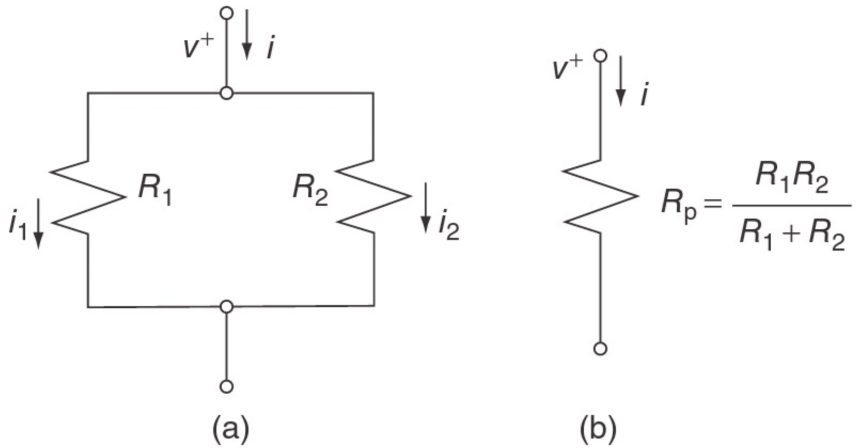
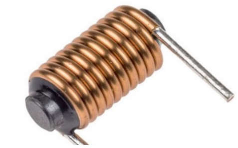


FIGURE 2.12 Equivalent resistance of resistors wired in parallel.

$$i = i_1 + i_2 = \frac{v}{R_1} + \frac{v}{R_2} = \frac{v}{R_p}$$

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}$$

Inductors



Inductor is often made from a coil of conducting material (e.g. copper wire), wrapped around a core (air or magnetic metal).

Faraday's law of electromagnetic induction: $\boxed{e = N\frac{d\phi}{dt}}$ Number of turns of wire

where e is the voltage (electromotive force, emf); ϕ the magnetic flux

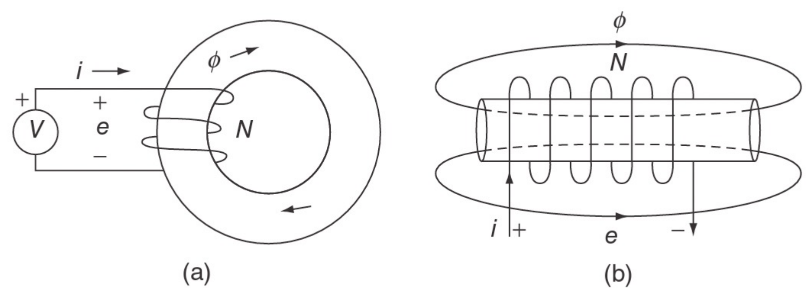


FIGURE 2.23 Flux can be increased and leakage reduced by wrapping the coils around a ferromagnetic material that provides a lower reluctance path. The flux will be much higher using the core (a) rather than the rod (b).

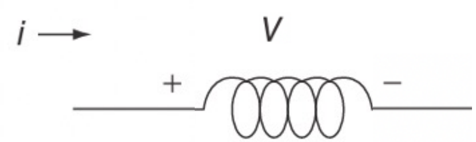
$$e = N\frac{d}{dt}\left(\frac{Ni}{\mathcal{R}}\right) = \frac{N^2}{\mathcal{R}}\frac{di}{dt} = L\frac{di}{dt} \longrightarrow L = \frac{N^2}{\mathcal{R}} \quad \text{henries (H)}$$

$$\text{Reluctance} = \mathcal{R} = \frac{l}{\mu A} \ (\text{A-t/Wb})$$

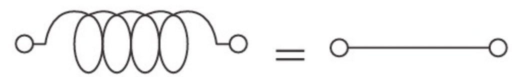
- l is the length of the circuit
- A is the cross-sectional area of the circuit
- mu is the permeability of the material

Inductors (cont'd)

$$\boxed{v = L\frac{di}{dt}}$$



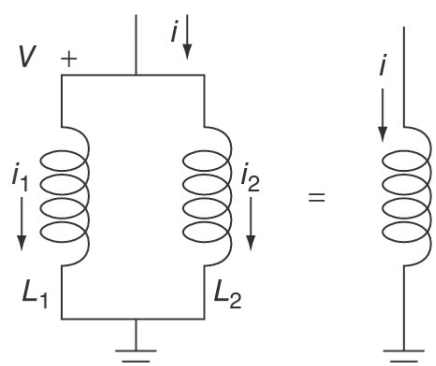
$$\mathrm{DC}: v = L\frac{di}{dt} = L \cdot 0 = 0$$



Inductor under DC is the same as a short circuit

The energy stored in the magnetic field of an inductor:

$$w_L = \int p\,dt = \int vi\,dt = \int \left(L\frac{di}{dt}\right) i\,dt = L\int i\,\mathrm{d}i = \frac{1}{2}Li^2$$



$$L_{\text{parallel}} = \frac{L_1 L_2}{L_1 + L_2}$$

FIGURE 2.24 Two inductors in parallel.

R-L Circuit

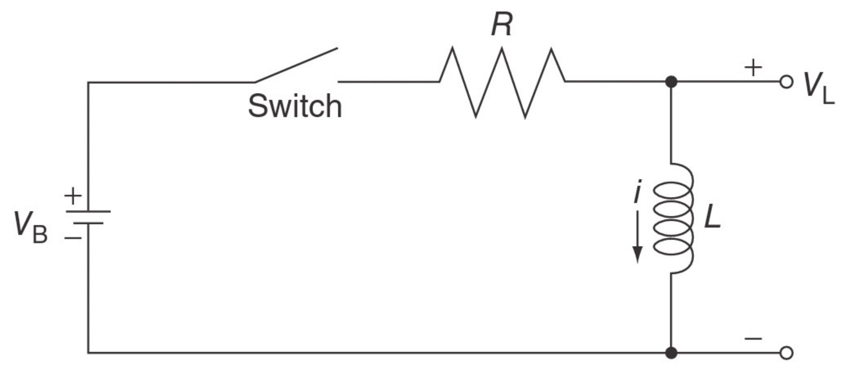
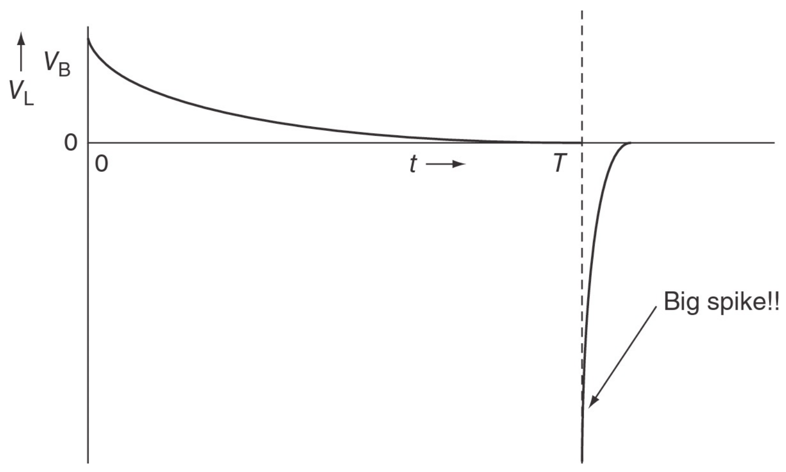
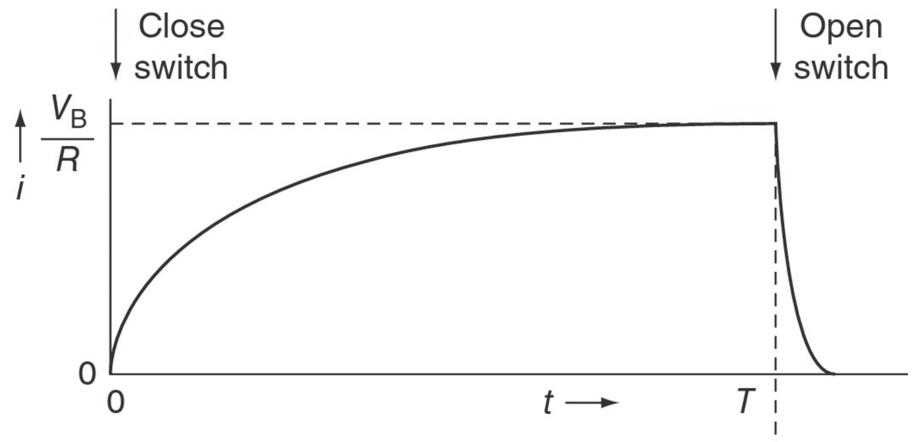


FIGURE 2.25 A simple R–L circuit with a switch.

KVL: $$V_B = iR + L\frac{di}{dt} \longrightarrow i = \frac{V_B}{R}\left(1 - e^{-\frac{R}{L}t}\right)$$





Transformer Revisited

Primary

Secondary

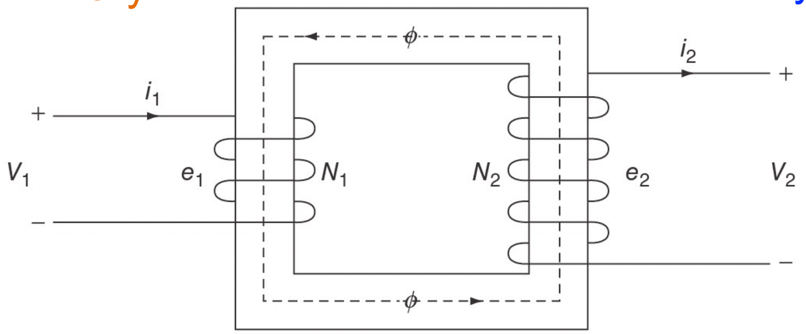


FIGURE 2.27 An idealized two-winding transformer.

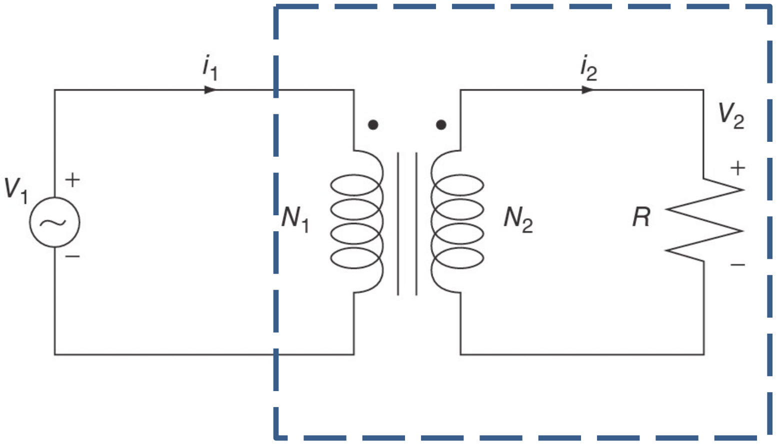
$$e_1 = N_1 \frac{d\phi}{dt}$$

$$e_2 = N_2 \frac{d\phi}{dt}$$

Turns ratio

$$\longrightarrow \quad \frac{v_2}{v_1} = \frac{e_2}{e_1} = \boxed{\frac{N_2}{N_1}}$$

Ignoring power loss: $(v_1 i_1 = v_2 i_2)$ $\longrightarrow$ $i_2 = \left(\frac{v_1}{v_2}\right) i_1 = \left(\frac{N_1}{N_2}\right) i_1$



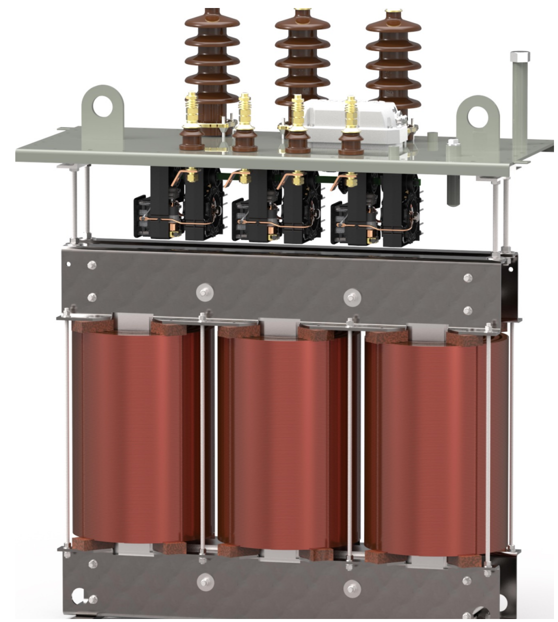
$$R_{\text{in}} = \left(\frac{v_1}{i_1}\right) = \frac{(N_1/N_2)\,v_2}{(N_2/N_1)\,i_2} = \left(\frac{N_1}{N_2}\right)^2 \cdot \frac{v_2}{i_2} = \left(\frac{N_1}{N_2}\right)^2 R$$

resistance/impedance transformation

Inductor vs Transformer

- Inductor (a single coil) is a passive two-terminal electrical component that stores energy in the form of magnetic field.

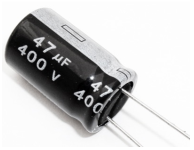
- Transformer (a set of two coils) is a system converting a voltage from one value to another. It transfers all energy instantaneously without storing any.



Transformer can be used for

1) Impedance matching
2) Voltage transformation
3) Isolation purpose

Capacitors



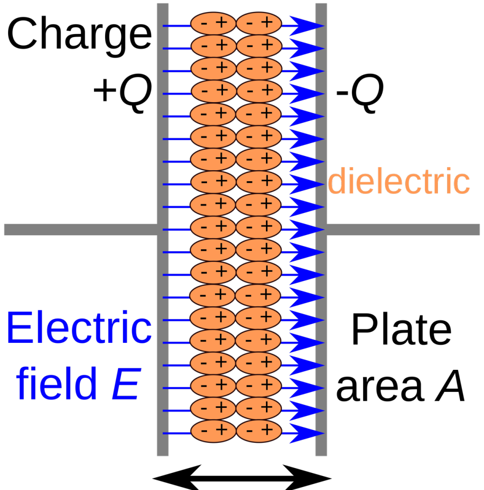


Figure: A capacitor consists of two parallel, charged plates separated by a dielectric (an electrical insulator that can be polarized by an applied electric field).

Table: Relative permittivity of different material at a frequency of 1 GHz.
Permittivity quantifies the ability of a substance to hold an electrical charge

Material	**Relative Permittivity**
Air	1
Dry Masonry	3-5
Moist Masonry	5-26
Dry Concrete	5-8
Moist Concrete	8-16
Asphalt	3-5
Granite	5-7
Basalt	8
PVC	3
Dry clay/ dry sands	4-8
Wet sands/wet clay	16-32
Ice	3-5
Water	81

$$C = \varepsilon \frac{A}{d} \quad \text{farads}$$

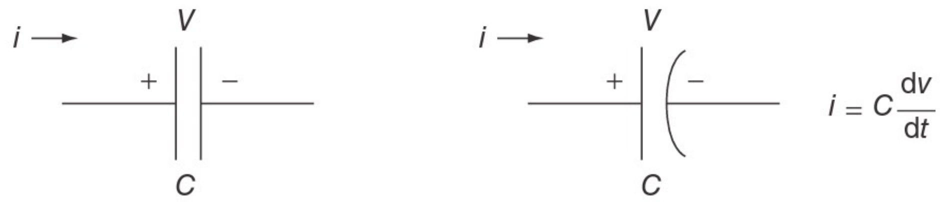
where C is capacitance (farads, F), ε is permittivity (F/m), A is the area of one plate (m^2), and d is the separation distance (m).

Capacitor vs Supercapacitor

CAPACITOR	SUPERCAPACITOR
Comprised of two metallic plates (electrodes) with dielectric in-between. Energy is stored in their electric field.	They are filled with an electrolytic solution instead of a dielectric substance. Activated carbon is used on the electrodes to enlarge the area as much as possible.
Low energy density.	High energy density.
Wider cell voltage range and higher specific power.	Higher capacitance.
Frequency selective filters, stable operation of digital electronics, blocking DC signals, store energy for applications such as pulsed lasers, radars, particle accelerators...	MP3 players, static memories (SRAM), cell phones, laptops, electric cars, solar and wind plants
Relatively cheap.	Expensive.

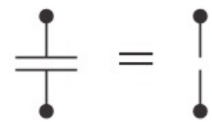
Capacitance

$$\boxed{i = \frac{dq}{dt} = C\frac{dv}{dt}}$$



(a) Common (b) Alternative

$$\text{DC}: \quad \frac{dv}{dt} = 0\,,\ \ i = 0,$$



open circuit

Capacitor under DC is the same as an open circuit

The energy stored in the electric field of a capacitor:

$$w_c = \int p\,dt = \int vi\,dt = \int vC\frac{dv}{dt}dt = C\int v\,dv \; = \frac{1}{2}Cv^2$$

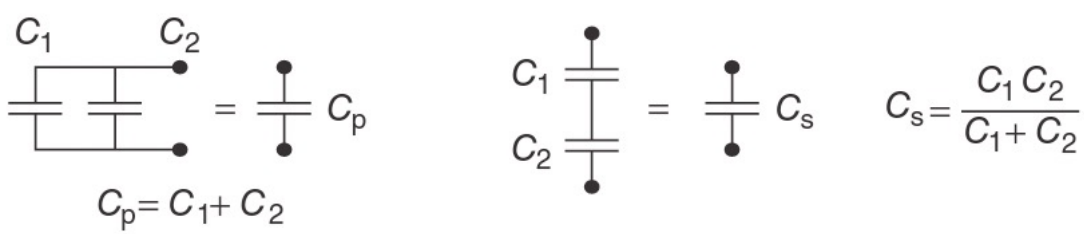
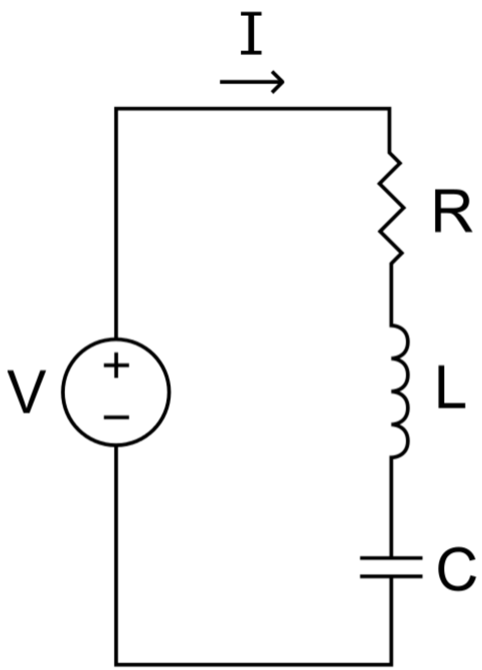


FIGURE 2.17 Capacitors in series and capacitors in parallel.

RLC Circuit

KVL: $$RI(t) + L\frac{\mathrm{d}I(t)}{\mathrm{d}t} + V(0) + \frac{1}{C}\int_0^t I(\tau)\,\mathrm{d}\tau = V(t)$$



$$\frac{d^2}{dt^2}I(t) + \frac{R}{L}\frac{\mathrm{d}}{\mathrm{d}t}I(t) + \frac{1}{LC}I(t) = 0\ .$$

This can usefully be expressed in a more generally applicable form:

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}I(t) + 2\alpha\frac{\mathrm{d}}{\mathrm{d}t}I(t) + \omega_0^2 I(t) = 0\ .$$

$$\alpha = \frac{R}{2L}$$

α : Attenuation measuring of how fast the transient response will die away

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

ω_0: Angular resonance frequency.

$$\zeta \equiv \frac{\alpha}{\omega_0} = \frac{R}{2}\sqrt{\frac{C}{L}}$$

damping factor determines the type of transient

RLC Circuit (cont'd)

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}I(t) + 2\alpha\frac{\mathrm{d}}{\mathrm{d}t}I(t) + \omega_0^2 I(t) = 0$$

Its characteristic equation: $s^2 + 2\alpha s + \omega_0^2 = 0$

Two roots in s-domain $\longrightarrow$

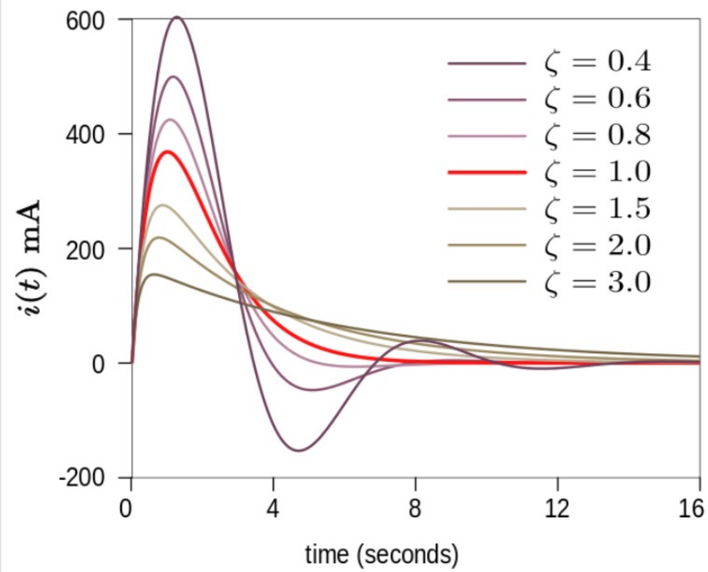
$$s_1 = -\alpha + \sqrt{\alpha^2 - \omega_0^2} = -\omega_0\left(\zeta - \sqrt{\zeta^2 - 1}\right)$$
$$s_2 = -\alpha - \sqrt{\alpha^2 - \omega_0^2} = -\omega_0\left(\zeta + \sqrt{\zeta^2 - 1}\right)$$

General solution $\longrightarrow$ $I(t) = A_1 e^{s_1 t} + A_2 e^{s_2 t}$

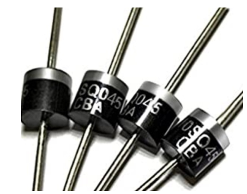
3 different types of responses:

- overdamped ($\zeta > 1$)
- underdamped ($\zeta < 1$)
- critically damped ($\zeta = 1$)

Right-side plot shows underdamped and overdamped responses of a series RLC circuit to a voltage input step of 1 V. The plots are normalized for $L = 1$, $C = 1$ and $\omega_0 = 1$.

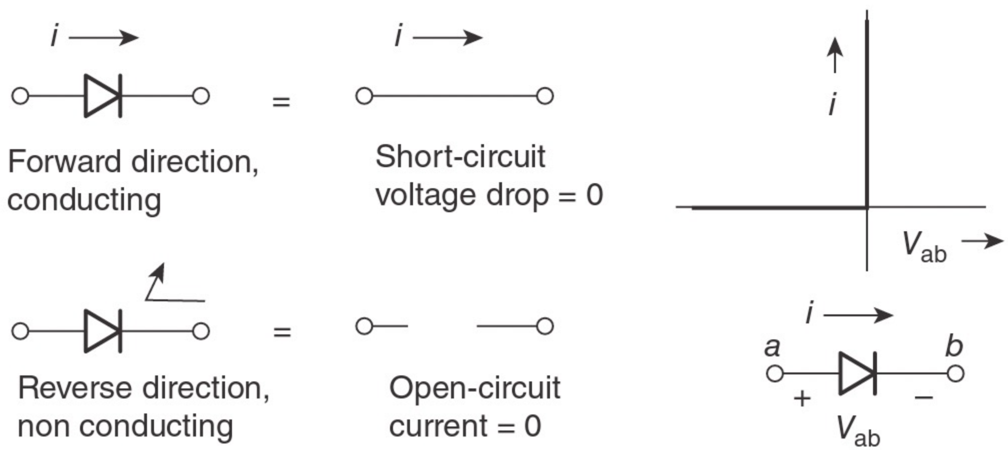


Power Converters (AC ⟷ DC)



AC-to-DC: Rectifier DC-to-AC: Inverter

Diode: one-way street for current



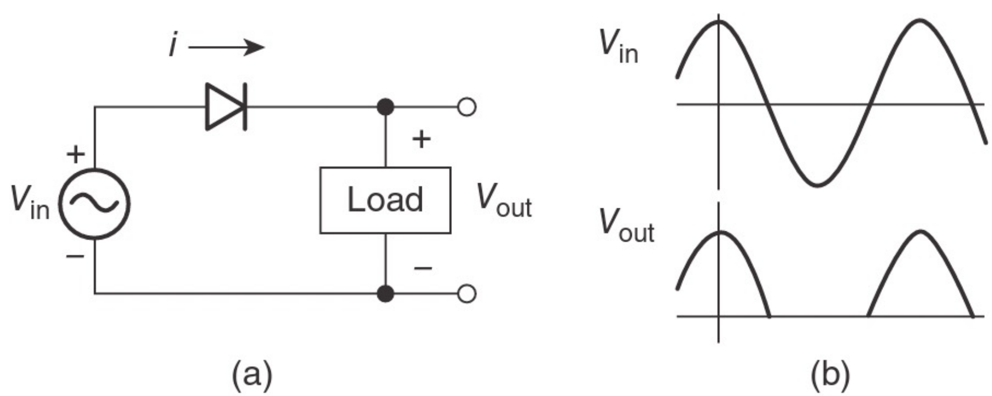
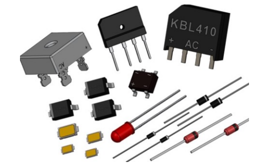


FIGURE 3.40 A half-wave rectifier: (a) The circuit. (b) The input and output voltages.

Rectifier



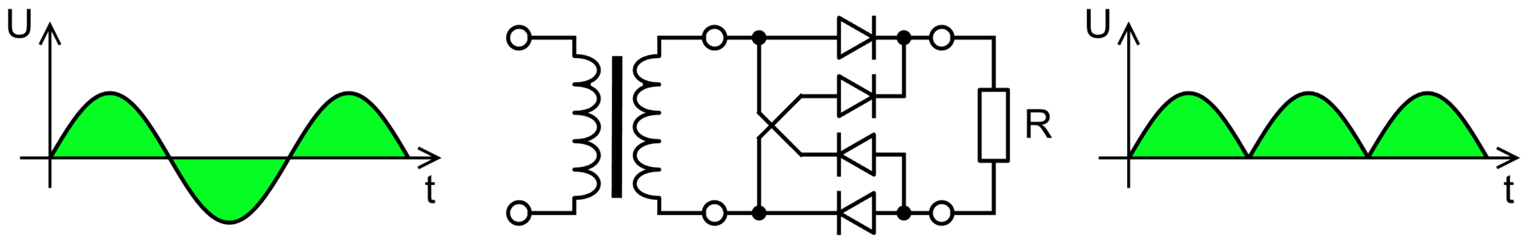


Fig (a): Full-wave bridge rectifier using four diodes

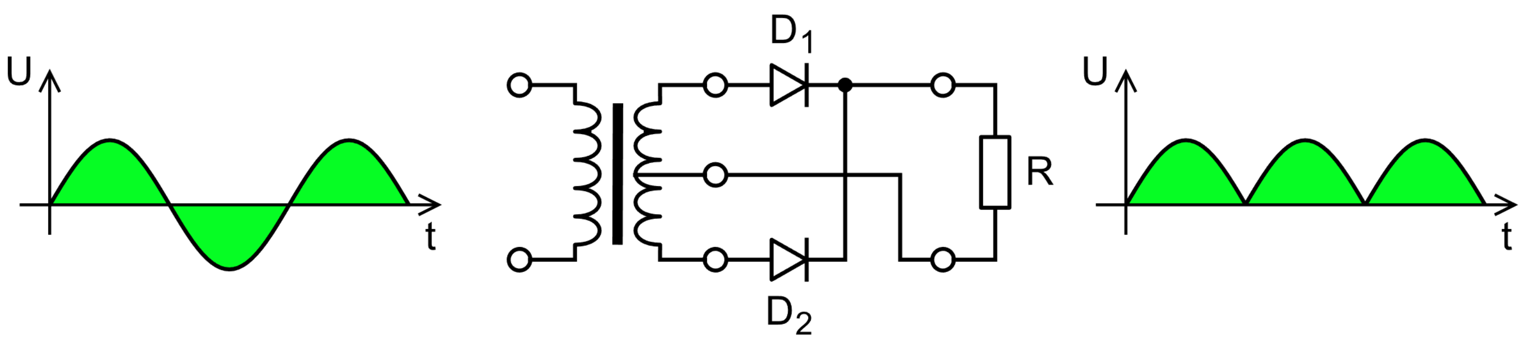
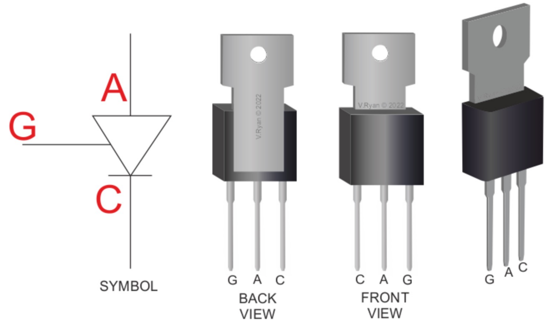


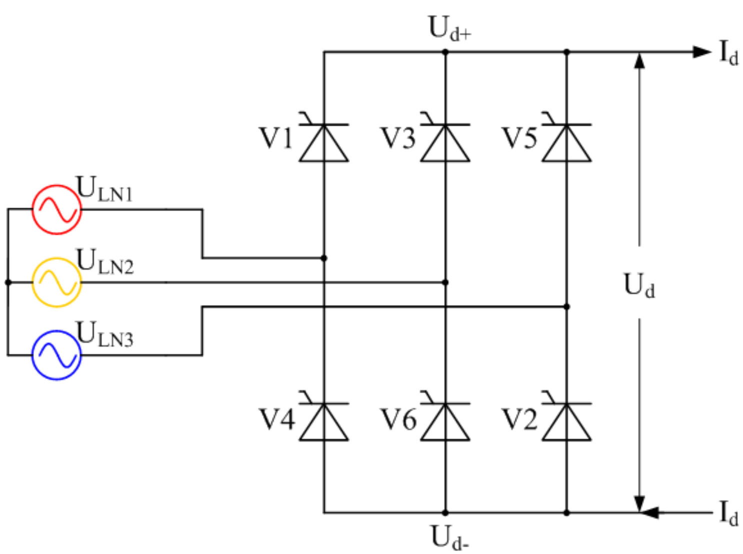
Fig (b): Full-wave bridge rectifier using a center-tapped transformer with two diodes

https://en.wikipedia.org/wiki/Rectifier

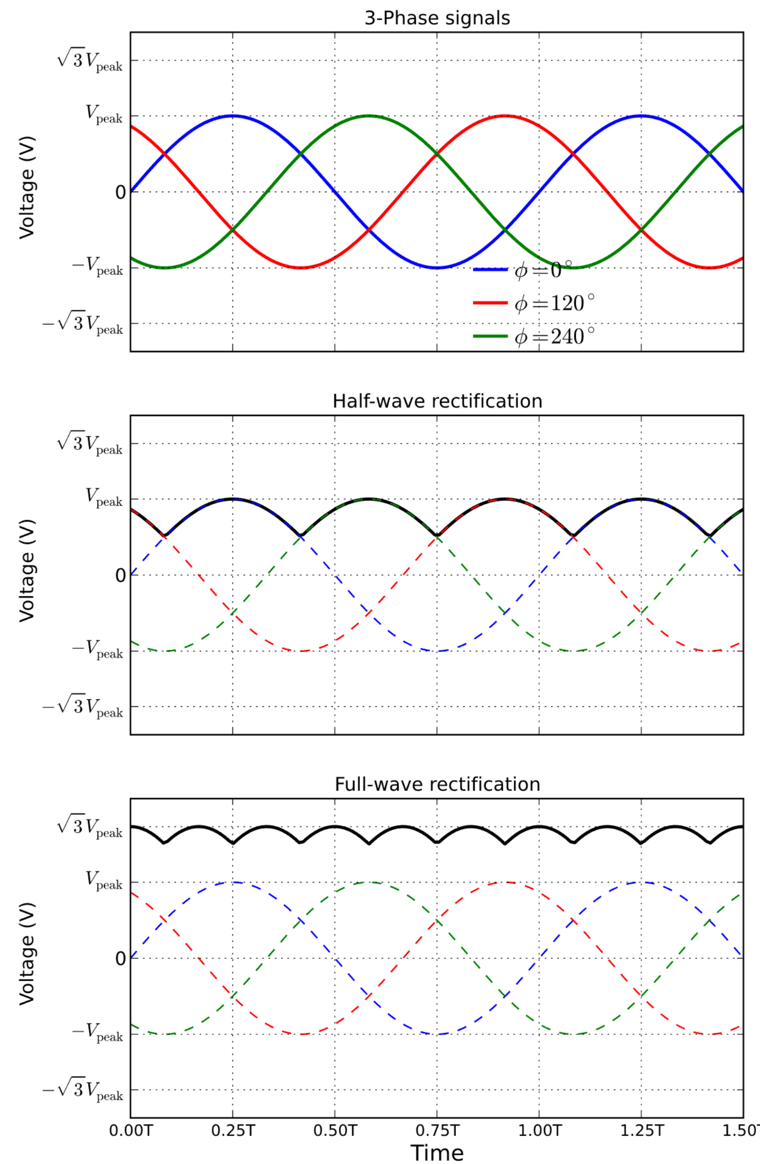
Thyristor and Three-phase Rectifier



Thyristor: When a small current flows into the GATE (G), this allows a larger current to flow from the ANODE (A) to the CATHODE (C).

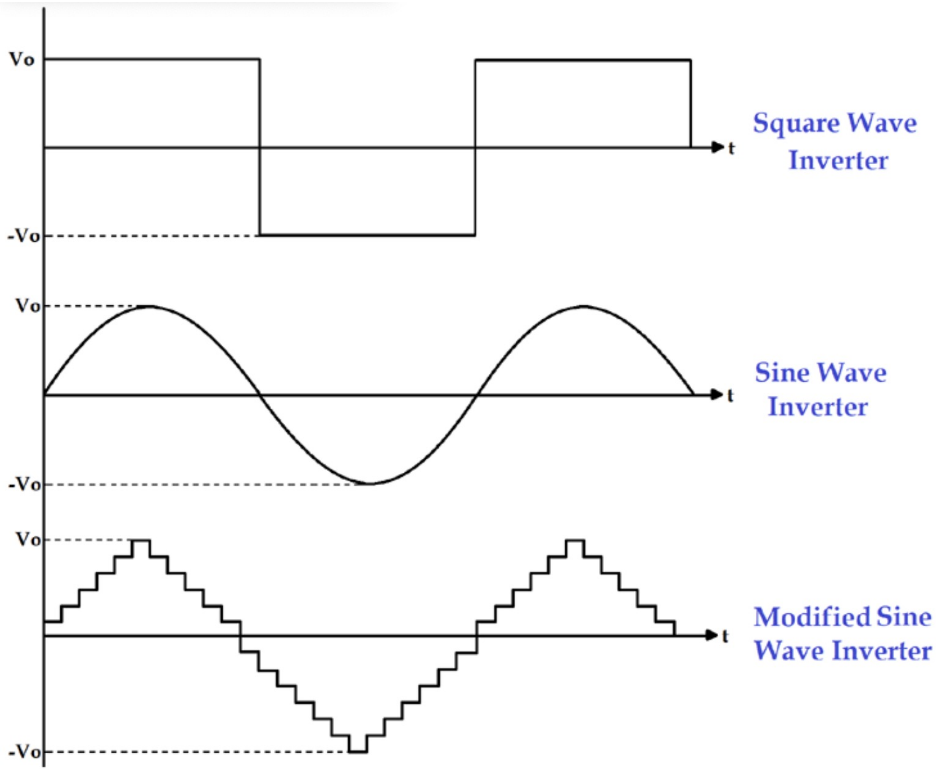


Controlled 3-phase full-wave bridge rectifier circuit using thyristors



Source: en.wikipedia.org/wiki/Rectifier

Different Types of Inverters



1) Square wave

If we supply square wave to sine wave based appliance, it may get damaged or losses are very high. The cost of this inverter is very low but the application is very rare (e.g., simple tools w/ a universal motor).

2) Sine wave

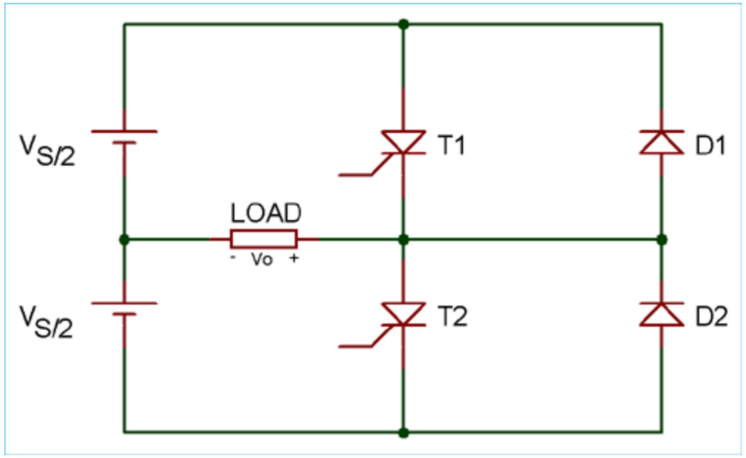
This is the perfect output and gives guarantee that equipment will work properly. It is more expensive but widely used in residential and commercial applications.

3) Modified sine wave

The construction of this type of inverter is complex than simple square wave inverter but easier compared to the pure sine wave inverter.

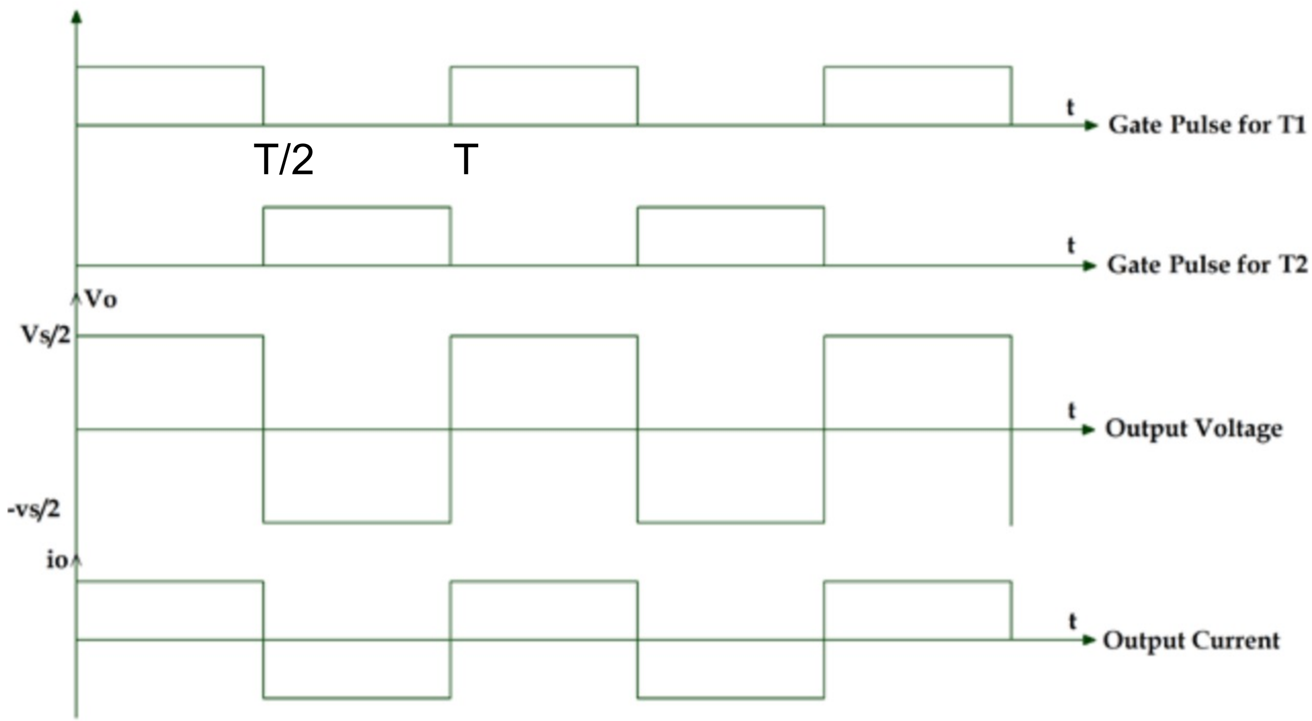
Source: circuitdigest.com/tutorial/different-types-of-inverters

Inverter using Thyristor: Half Bridge

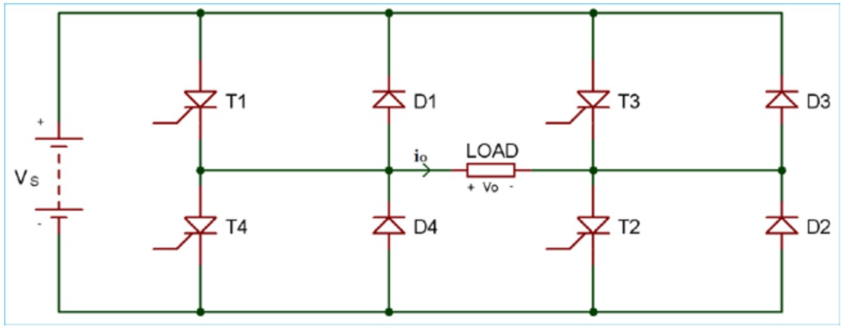


Single-phase half-bridge inverter:

- For 1st half cycle (0<t<T/2), thyristor T1 conducts. The load voltage is Vs/2 due to the upper voltage source Vs/2.
- For 2nd half cycle (T/2<t<T), thyristor T1 is commutated and T2 conducts. The load voltage is -Vs/2 due to the lower source Vs/2.

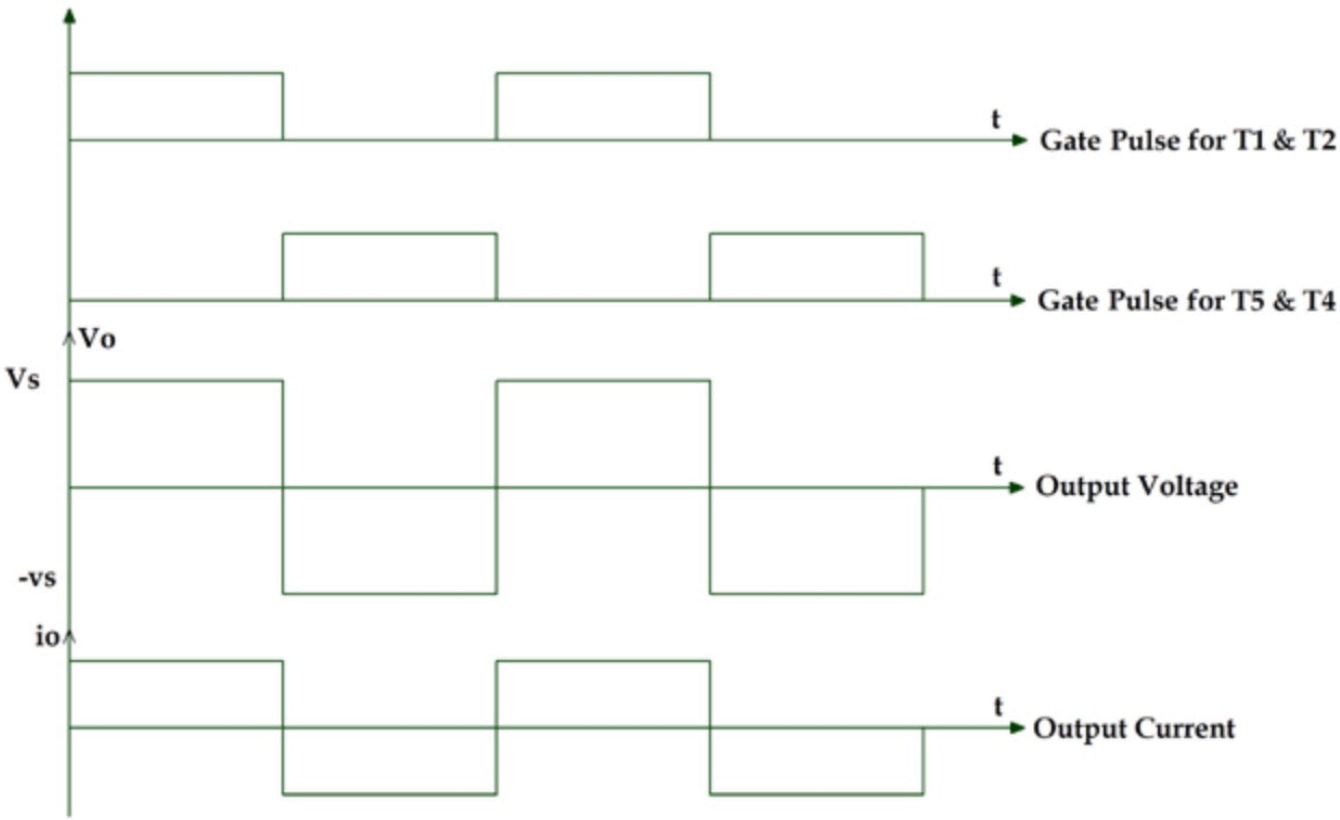


Inverter using Thyristor: Full-Bridge

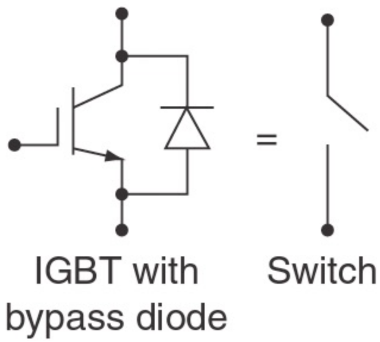


Single-phase full-bridge inverter:

- For 1st half cycle (0<t<T/2), T1 & T2 conduct. The load voltage is Vs
- For 2nd half cycle (T/2<t<T), T3 & T4 conduct. The load voltage is -Vs



Inverter using IGBT



Transistorized switches:

- Insulated-gate bipolar transistors (IGBTs) with added parallel diodes to provide a bypass path for transient currents.
- IGBTs can handle a higher amount of power and has a faster switching speed making it highly efficient.

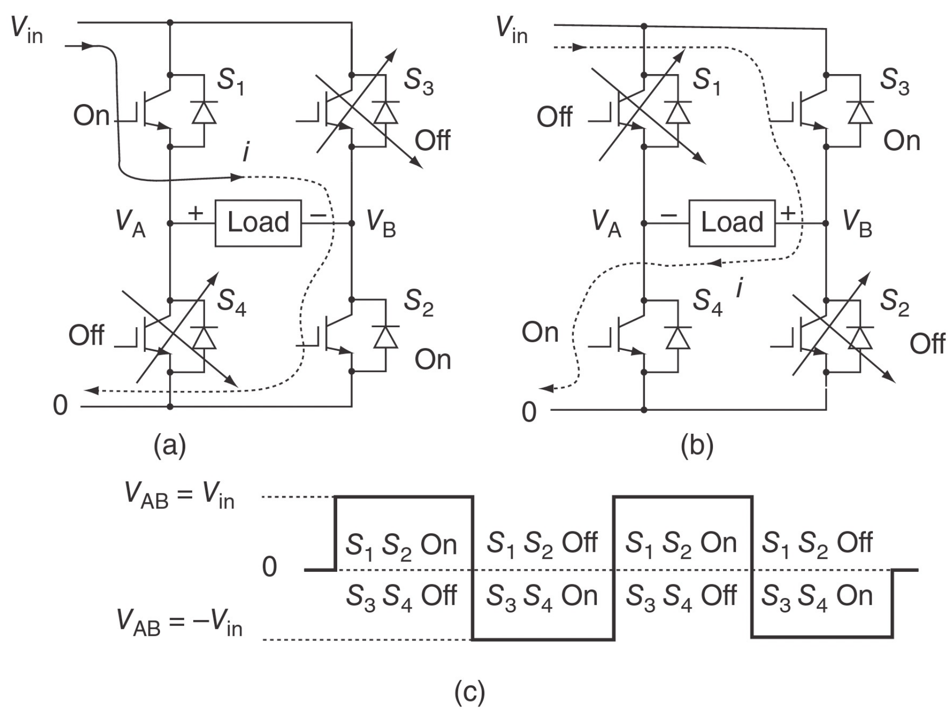
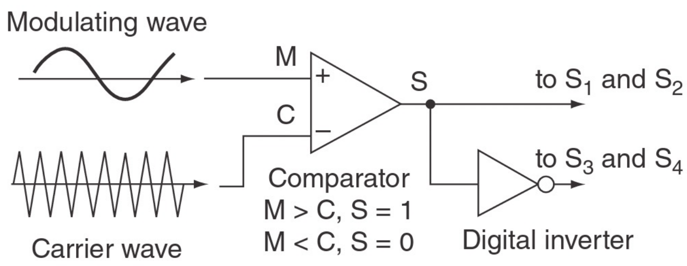


FIGURE 3.53 Showing current flow when (a) S_1 and S_2 are on and S_3 and S_4 are off, (b) after switching on/off signals and (c) the resulting square-wave output.

Pulse Width Modulation (PWM) Inverter



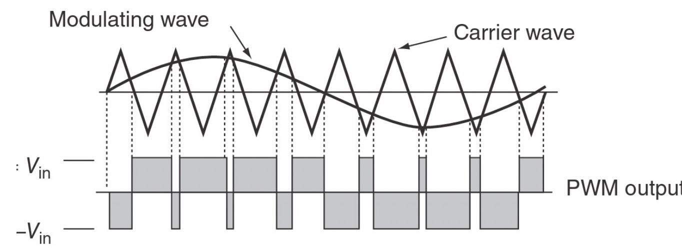
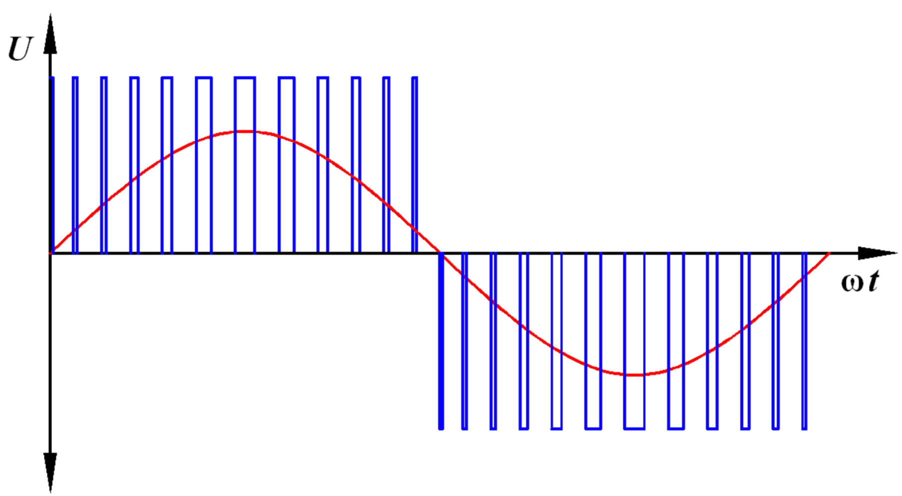


FIGURE 3.54 Switch driver for pulse-width modulation (PWM). Based on Jenkins et al. *Distributed Generation* (2010).



Basic idea: use a series of constant-amplitude, variable-width pulses of voltage to simulate a sinusoidal voltage of the desired frequency. The inductance of the motor keeps the current flowing between the pulses, resulting in an almost sinusoidal current.

Back-to-Back Voltage-Source Converter

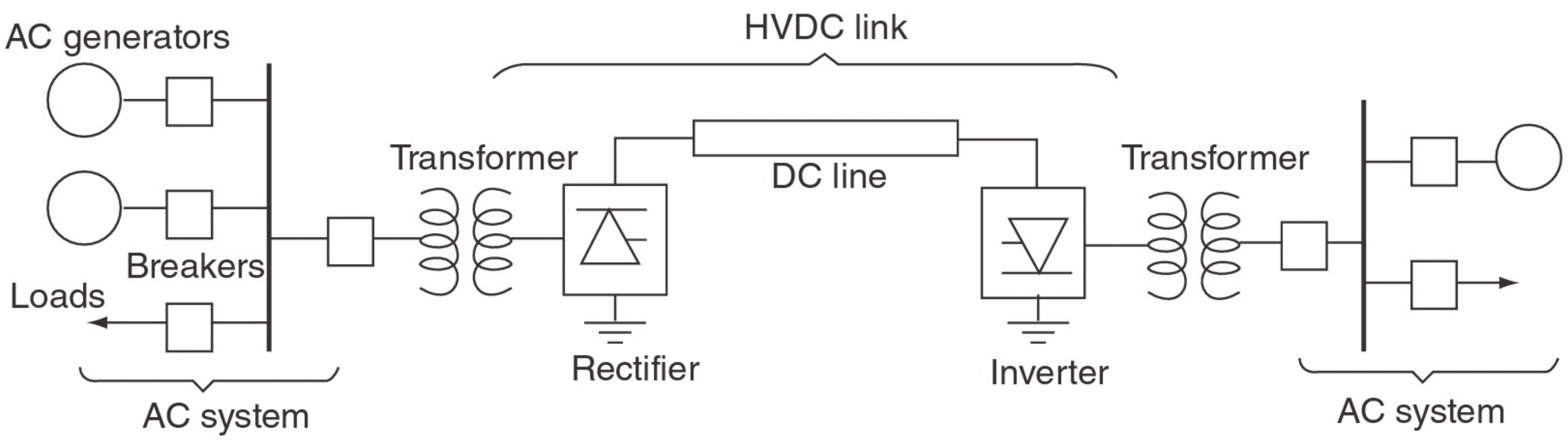


FIGURE 3.57 A one-line diagram of a DC link between AC systems. The inverter and rectifier can switch roles to allow bidirectional power flow.

DC-to-DC Conversion

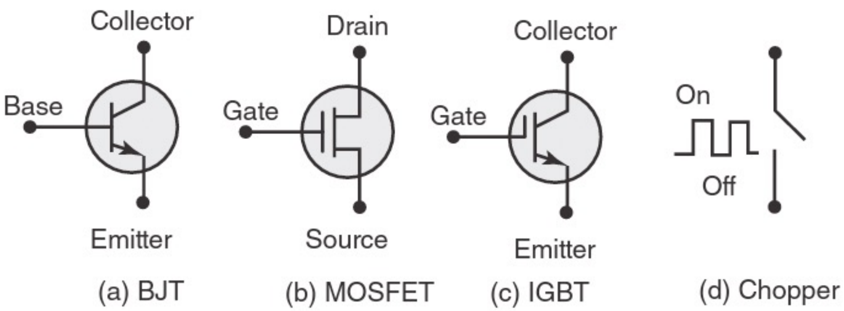


FIGURE 3.44 Symbols for various transistor switches.

Three-terminal devices acting as electrically controllable on/off switches:

- Bipolar junction transistor (BJT)
- Metal-oxide-semiconductor field-effect transistor (MOSFET)
- Insulated-gate bipolar transistor (IGBT)

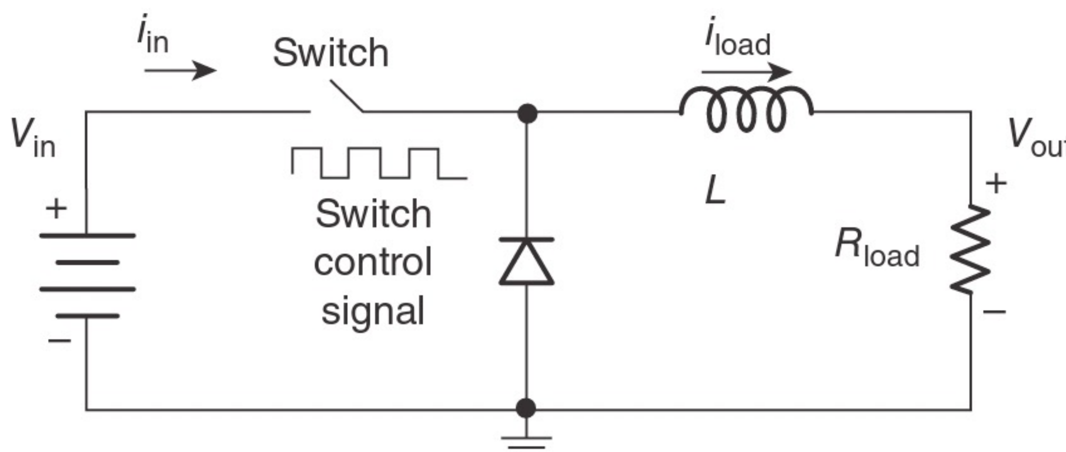
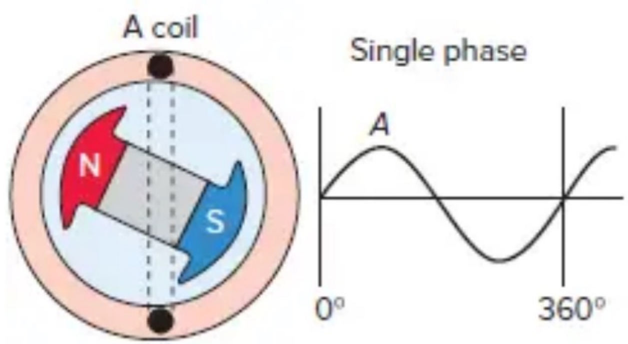
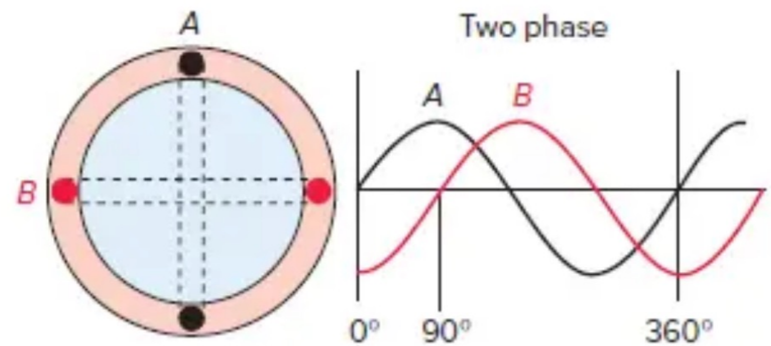
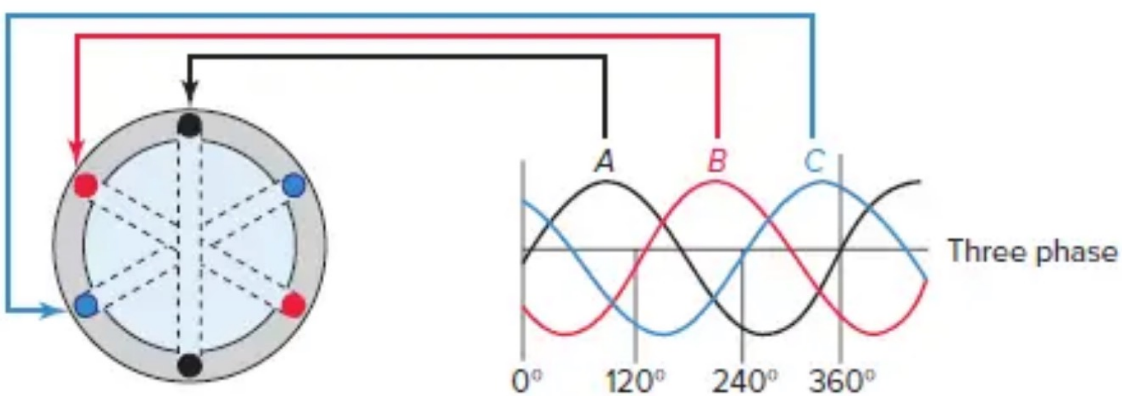


FIGURE 3.45 A DC-to-DC, step-down, voltage converter—sometimes called a *buck converter*.

Three-Phase AC Electricity







$$v_{\mathrm{a}} = V\sqrt{2}\cos(\omega t) \qquad \boldsymbol{V}_{\mathrm{a}} = V\angle 0^\circ \qquad i_{\mathrm{a}} = I\sqrt{2}\cos(\omega t) \qquad \boldsymbol{I}_{\mathrm{a}} = I\angle 0^\circ$$

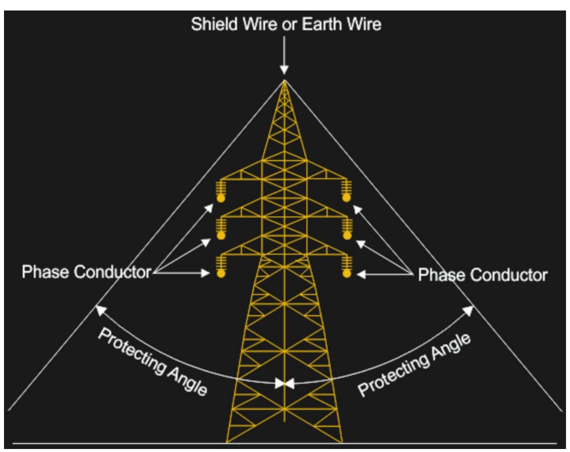
$$v_{\mathrm{b}} = V\sqrt{2}\cos(\omega t - 120^\circ) \qquad \boldsymbol{V}_{\mathrm{b}} = V\angle -120^\circ \qquad i_{\mathrm{b}} = I\sqrt{2}\cos(\omega t - 120^\circ) \qquad \boldsymbol{I}_{\mathrm{b}} = I\angle -120^\circ$$

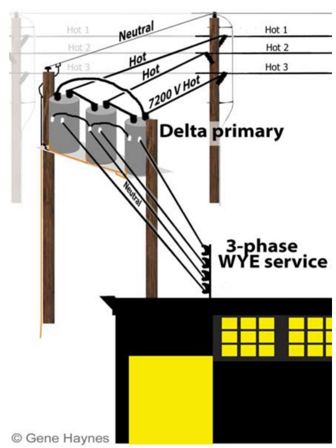
$$v_{\mathrm{c}} = V\sqrt{2}\cos(\omega t + 120^\circ) \qquad \boldsymbol{V}_{\mathrm{c}} = V\angle 120^\circ \qquad i_{\mathrm{c}} = I\sqrt{2}\cos(\omega t + 120^\circ) \qquad \boldsymbol{I}_{\mathrm{c}} = I\angle 120^\circ$$

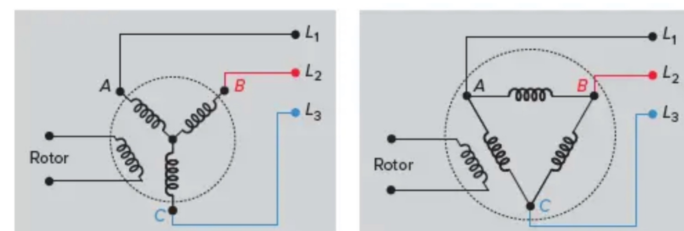
Advantage of Three-Phase Systems

A few good reasons:

- 3-phase generators are much more efficient in terms of power per unit of mass and they operate much smoother, with less vibration.
- The power delivered by a single-phase source is pulsating, whereas the power delivered by a 3-phase system is relatively constant at all times.
- 3-phase currents in motor stators create a rotating magnetic field that makes these machines spin in the right direction and at the right speed.
- Power rating of 3-phase motors and transformers are 150% greater than for single-phase counterparts.
- 3-phase transmission and distribution systems use their wires more efficiently.

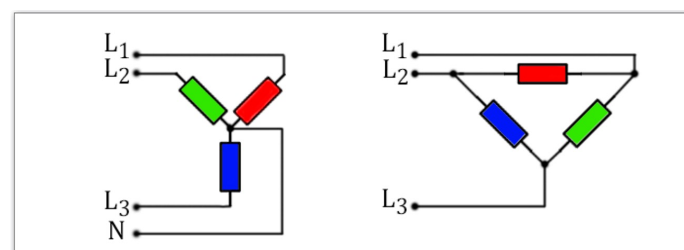






Wye alternator connection

Delta alternator connection



Wye or star (left) and delta (right) connections