EE2022 Electrical Energy Systems

Generators

Lecturer : Dr. Sangit Sasidhar (elesang)
Slides prepared by Dr. Panida Jirutitijaroen
Department of Electrical and Computer Engineering

Detailed Syllabus

Topic 1	**Transformer**: Principle of transformer. Ideal transformer. Reflected load. Impedance matching. Practical transformer. Examples
Topic 2	**Renewable Energy Sources:** Sustainable and clean energy sources; Solar Photovoltaic, Wind Energy; Examples
Topic 3	**Per unit analysis**: Single-phase per unit analysis. Three-phase transformer, Three-phase per unit analysis. Examples.
Topic 4	**Generator**: Simple generator concept. Equivalent circuit of synchronous generators. Operating consideration of synchronous generators, i.e. excitation voltage control, real power control, and loading capability. Examples.
Topic 5	Electric energy market operation; Cost of Electricity

Outline

- A basic operation of power plants
- A simple generator
- An equivalent circuit of synchronous generators

Learning Outcomes

- Use electrical engineering principles to explain the **basic operation of the electrical generator**, transmission line and transformer in an electrical energy system and **able to identify and construct their equivalent circuits** appropriately.

Outline

- A basic operation of power plants
- A simple generator
- An equivalent circuit of synchronous generators

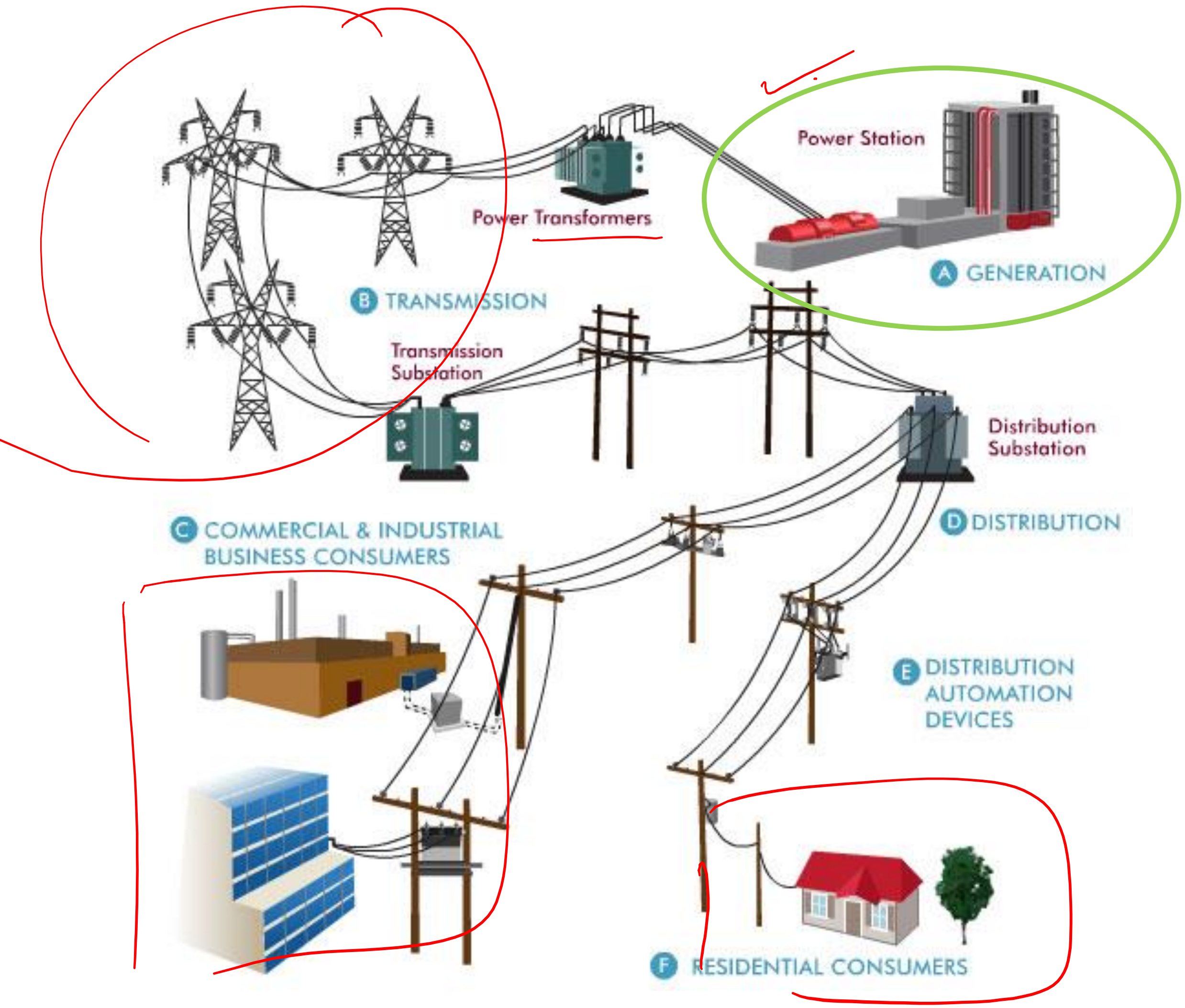
How electricity is generated

Different types of power plants

Main components of a power plant

BASIC OPERATIONS OF A POWER PLANT

Generation, Transmission and Distribution



Question: How to represent the power station by an equivalent circuit?

Answer: Three-phase voltage sources, but why?

Source: http://venturebeat.com/2010/10/29/super-grid-introduction/

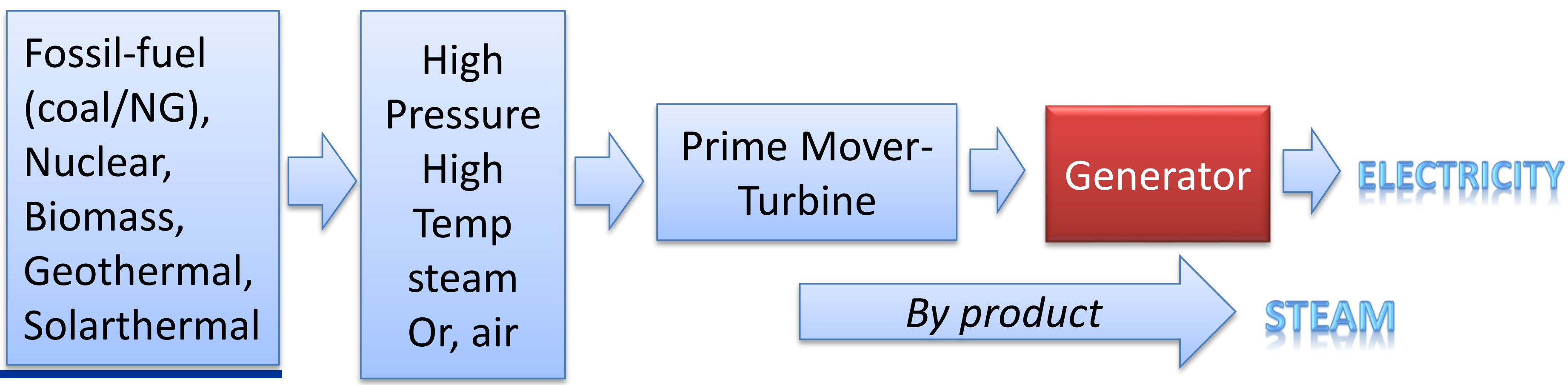
How Electricity is Generated

- Electricity is generated from other forms of energy to electricity through the energy conversion process.
- The most common conversion process to generate electricity is to convert mechanical energy using a generator.
- This process is called "Electromagnetic induction".
- The mechanical energy comes from turning the turbine (prime mover).

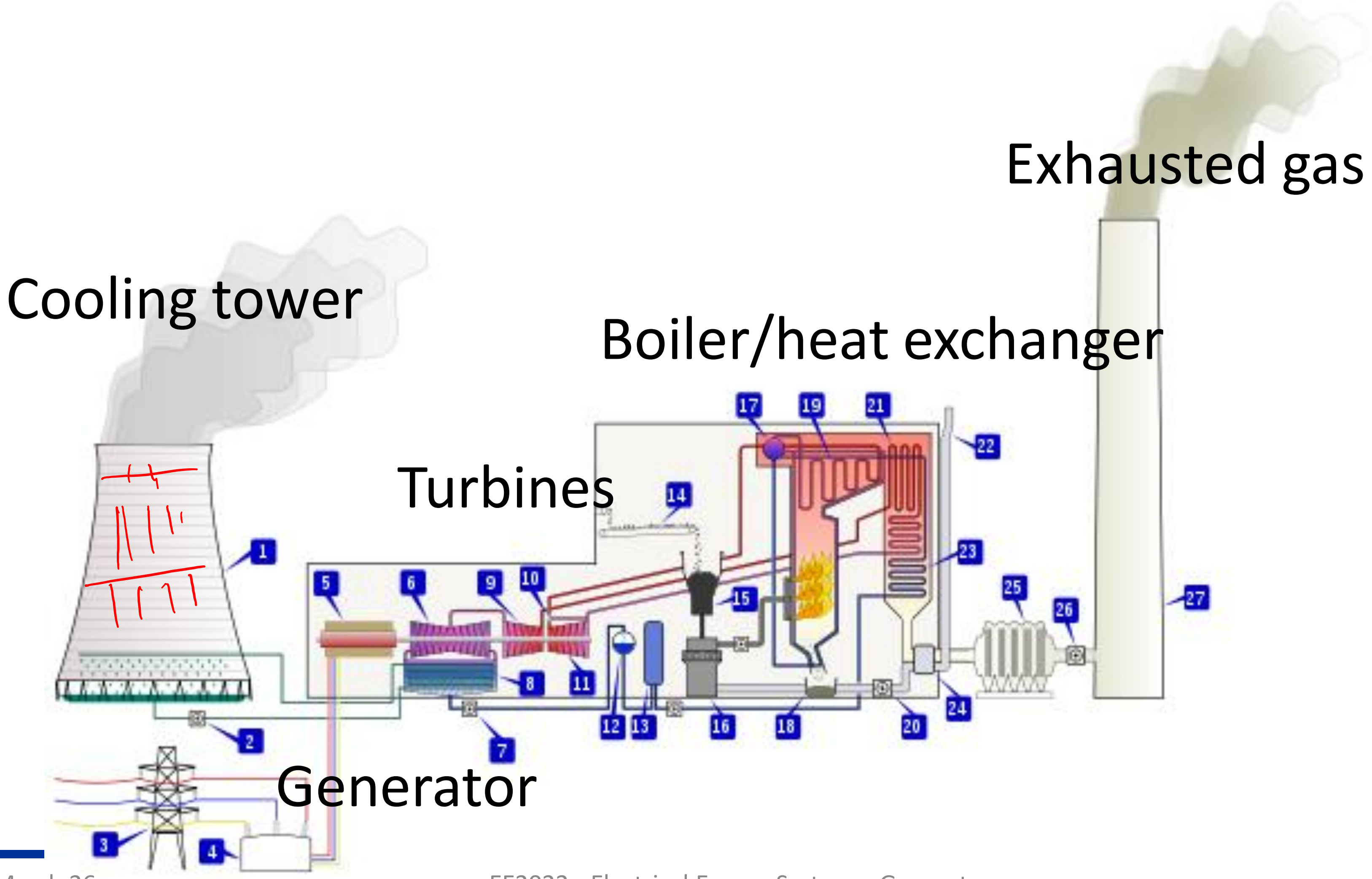
Prime Mover-Turbine → Generator → ELECTRICITY

Energy Conversion Process

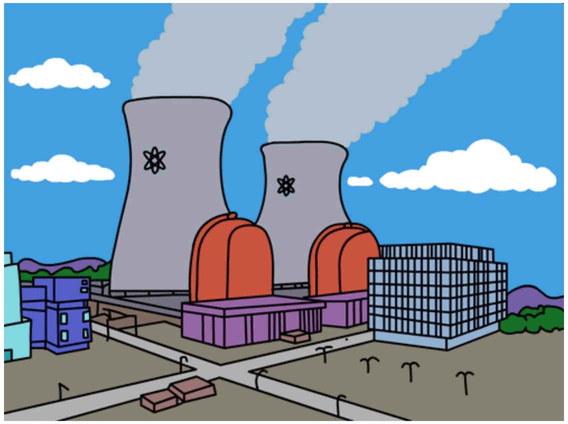
- Turbine is usually moved by high pressure and high temperature steam or hot air.
- The steam is created from boiling water in a closed loop system to reduce impurities that may affect the turbine efficiency.
- The source of heat depends on fuel types.
- Heat energy is usually measured in ‘British Thermal Unit’ or ‘BTU’.

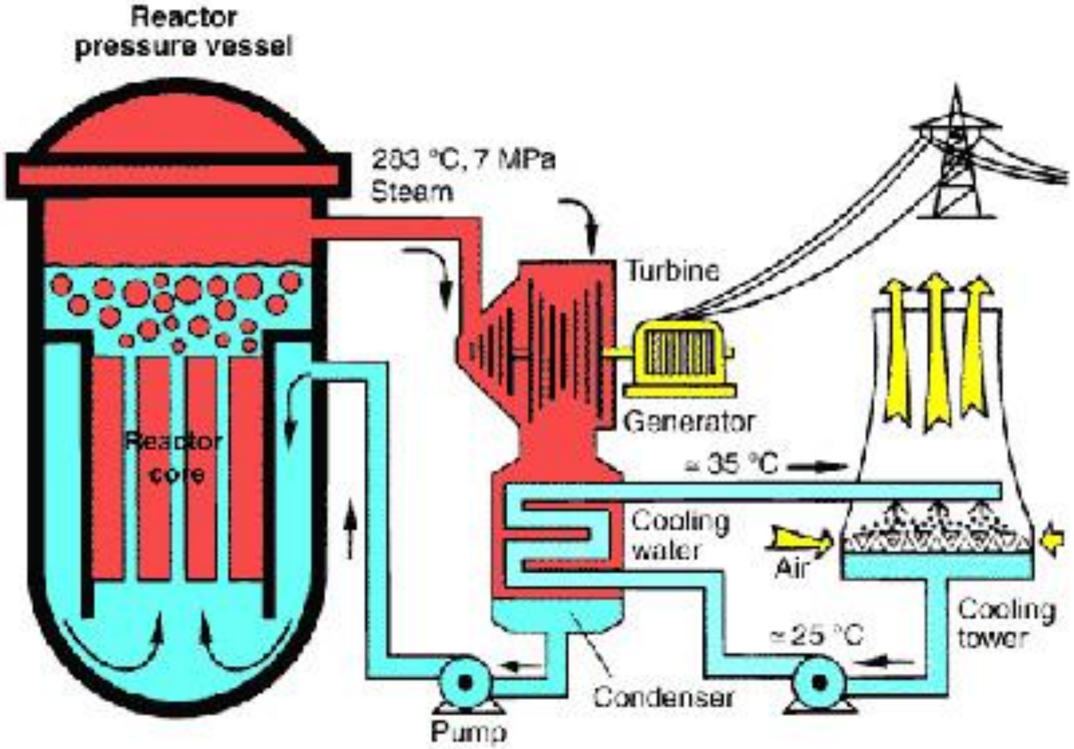


An Example of Power Plants



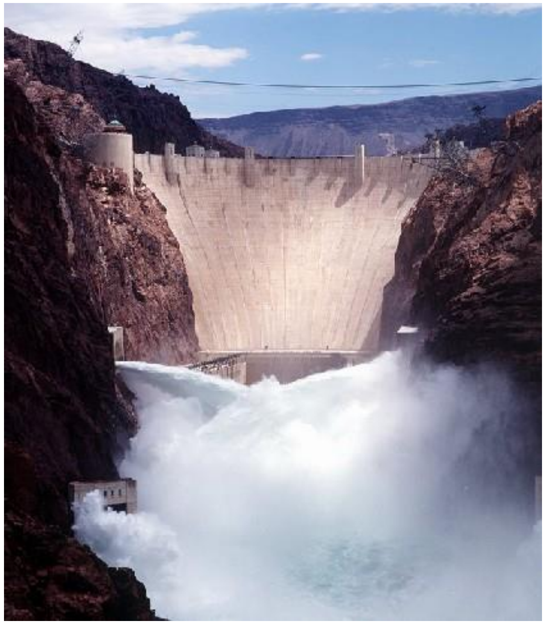
Nuclear Power Plant



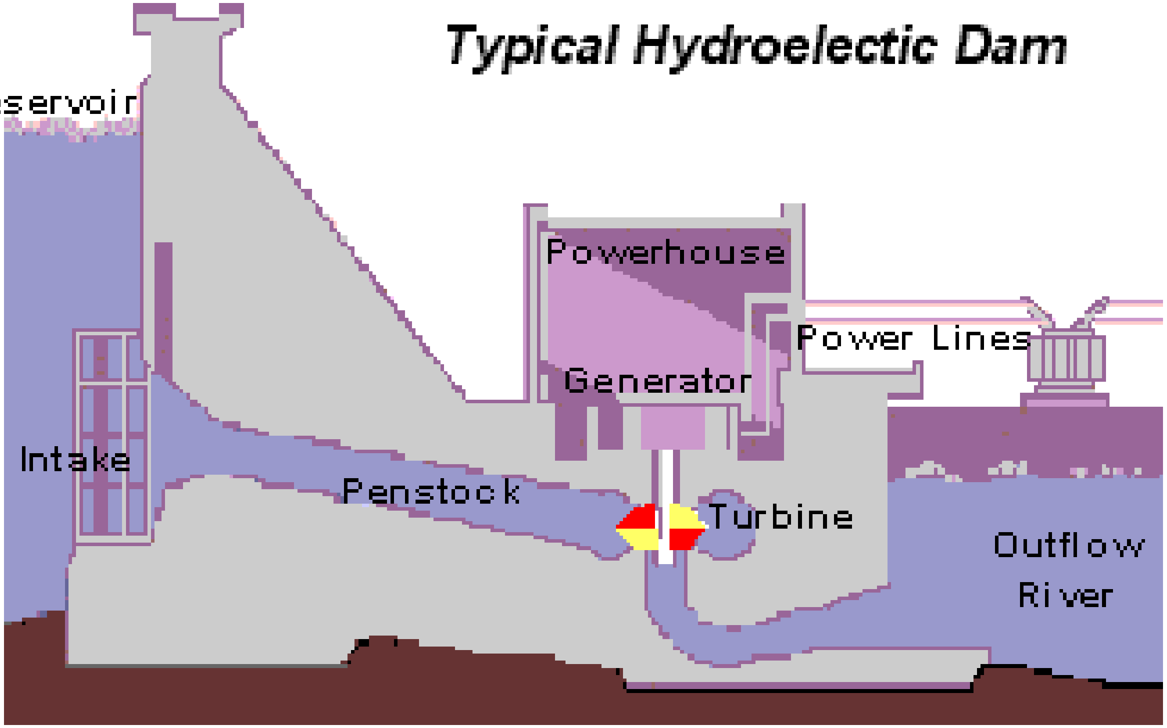


Source: http://www.euronuclear.org/info/energy-uses.htm

Hydroelectric Power Plant

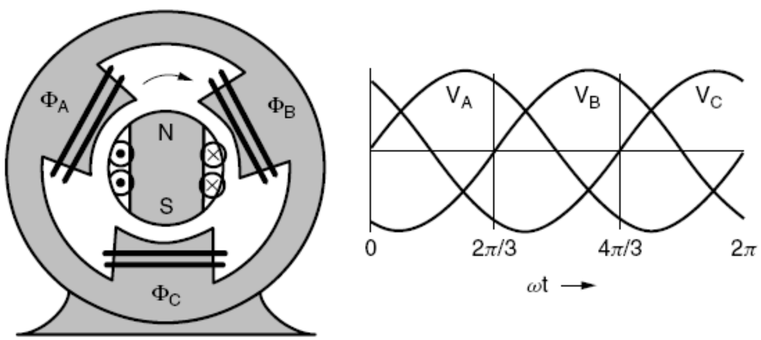


Source: http://static.howstuffworks.com/gif/hydropower-plant-usbr-hoover.jpg



Source: http://ga.water.usgs.gov/edu/hyhowworks.html

Main Components of a Power Plant

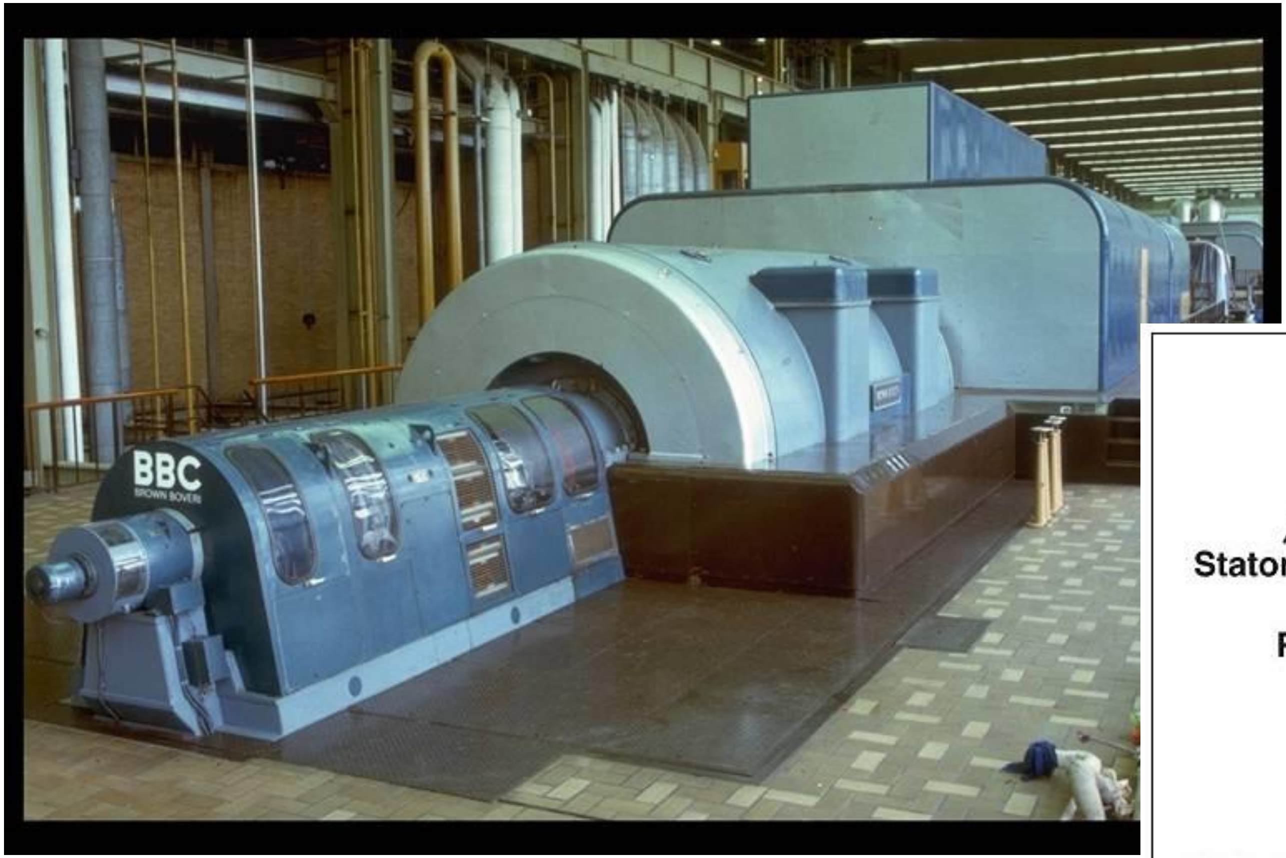


Fossil-fuel (coal/NG), Nuclear, Biomass → High Pressure& Temp steam Or, hot air → Prime Mover- Turbine → Generator → ELECTRICITY

Wind, Tidal, Hydro → Prime Mover- Turbine

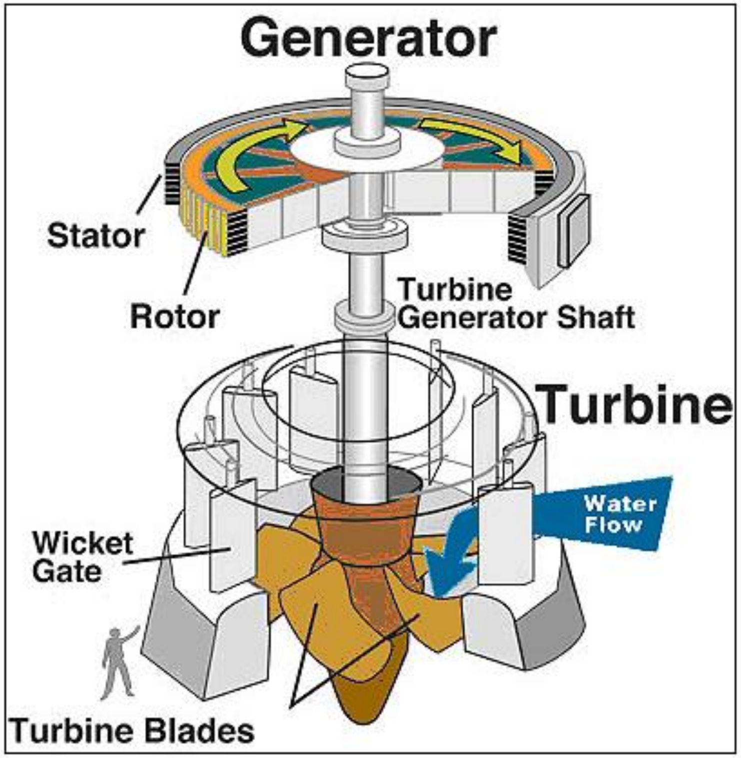
Q: How to represent a generator in the circuit diagram?

A Synchronous Machine



Source: Electrical Power System Essentials

Source: http://archive.powerauthority.on.ca/Page.asp?PageID=924&SiteNodeID=233



Electromagnetic induction

A simple generator

Main components of a generator

Types of rotor

Rotor synchronous speed

SIMPLE GENERATOR CONCEPT

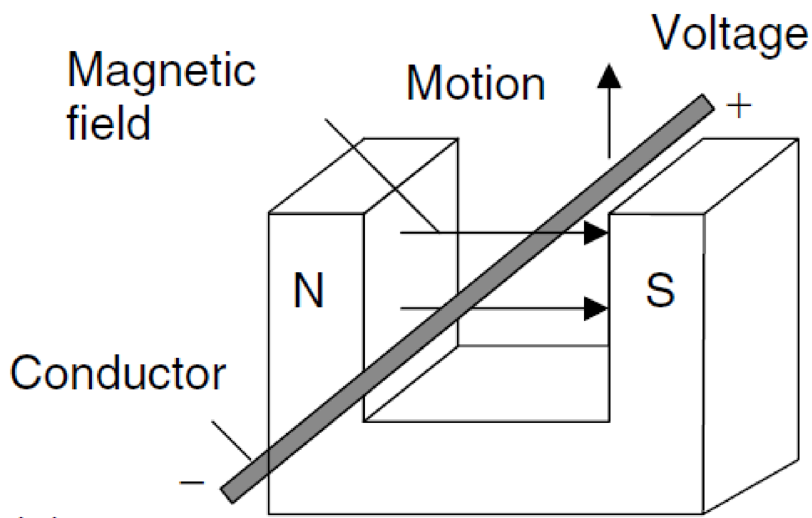
Electromagnetic Induction

- **Moving** a *conductor* through a *magnetic field*.
- Induced electromotive force (EMF), voltage generated by the magnetic force across wire.
- Faraday's law:

$$e = N\frac{d\phi}{dt}$$

Electricity rocks!

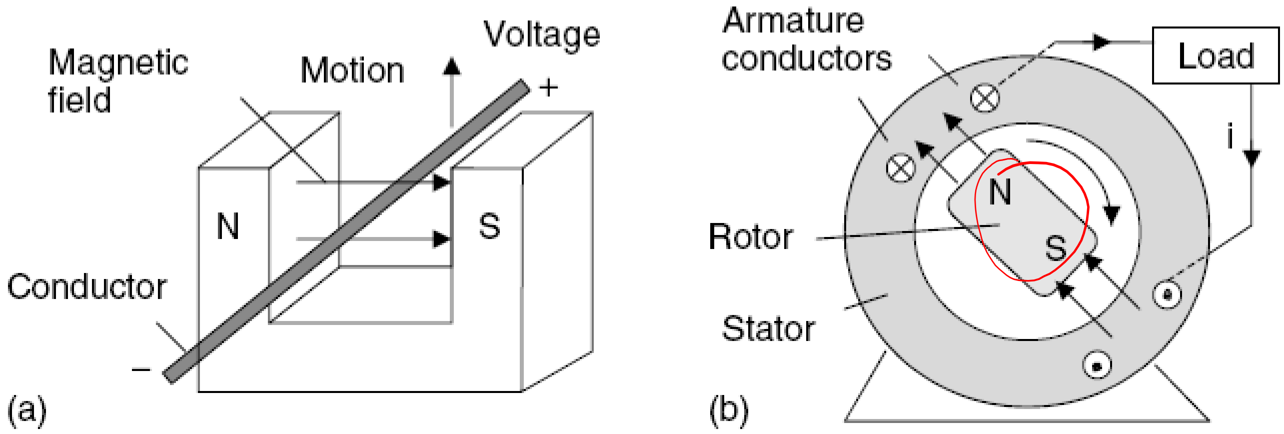
Michael Faraday,
English chemist and physicist, 1791-1867.



A Simple Generator

- Need **mechanical force** to move the magnetic field to generate *“Relative motion”* between a conductor and a magnetic field.
- Key concept:

Mechanical Input → Electrical Output



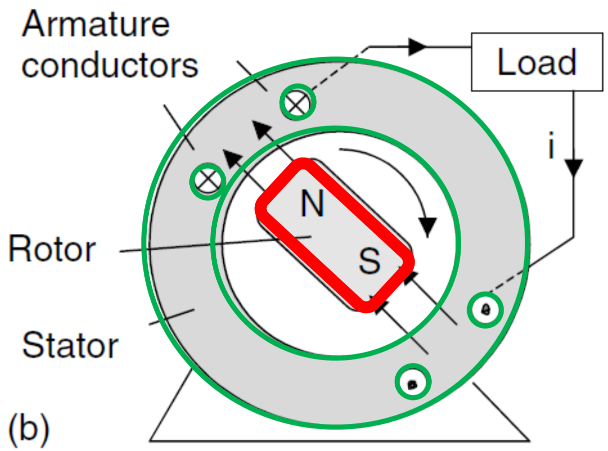
Main Components of a Generator

Rotor

- Moving part that is usually made of electromagnet materials.

Stator

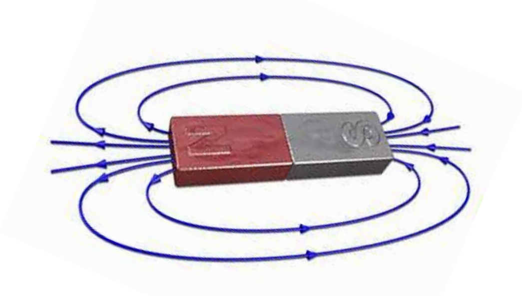
- Stationary part that contains a set of conductors called ‘armature winding’.



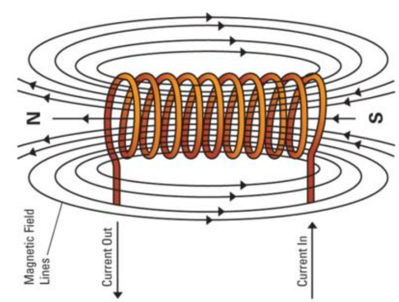
● indicates the positive current is directed out of plane of the paper.
× indicates the positive currents is directed into the plane of the paper.

Constant Magnetic Fields at Rotor

- We can produce constant magnetic fields at the rotor by two methods.
  1. Using permanent magnet. This is only suitable for small generators.
  2. Create magnetic fields using DC current supplied through coil. The DC power source is called ‘exciter’. The coil is called ‘field winding’.

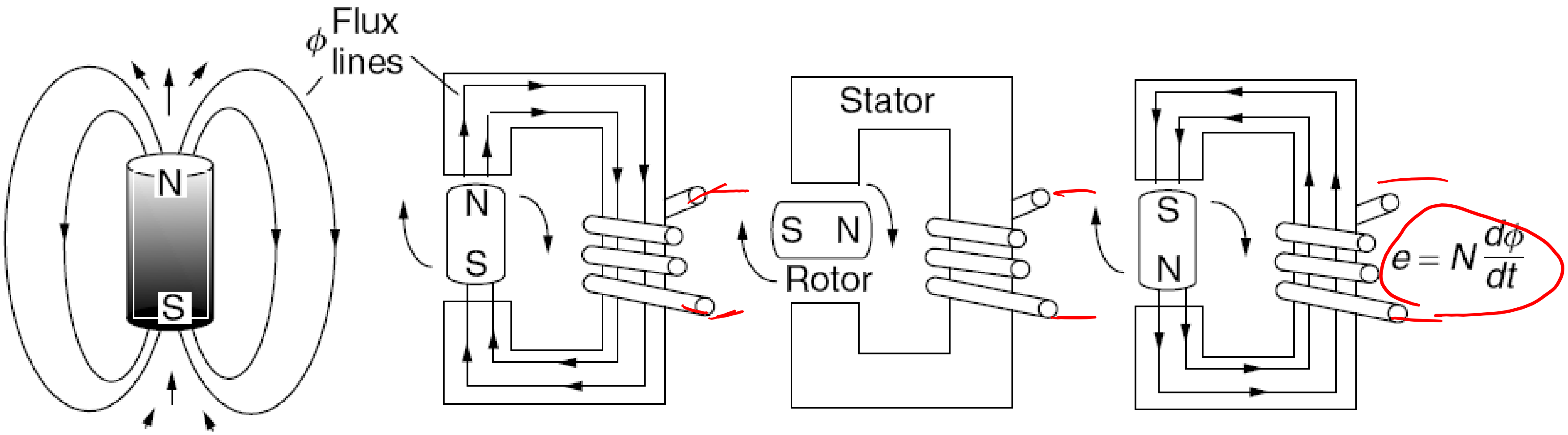


Source: http://www.magnet.fsu.edu/education/tutorials/magnetminute/permanent.html

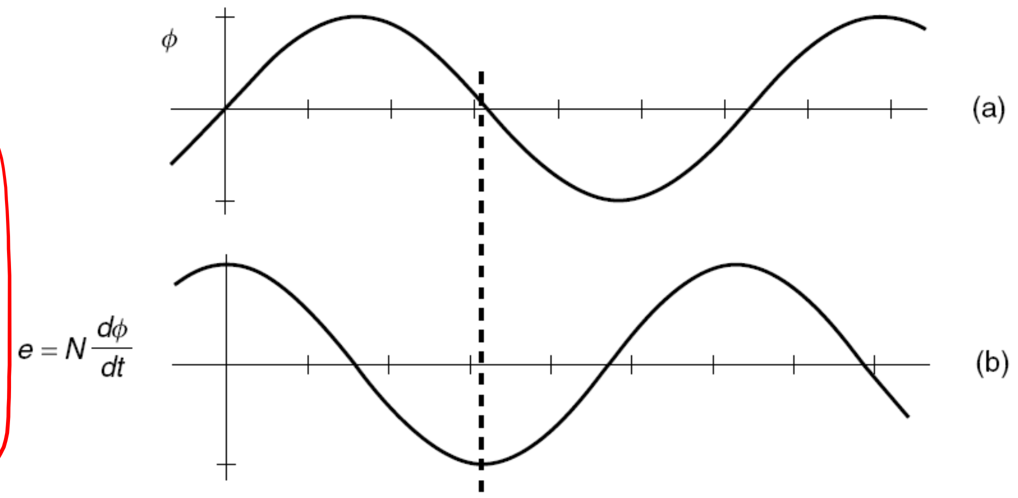


Source: http://www.lanl.gov/news/index.php/fuseaction/1663.article/d/20085/id/13276

Electromagnetic Induction at Stator

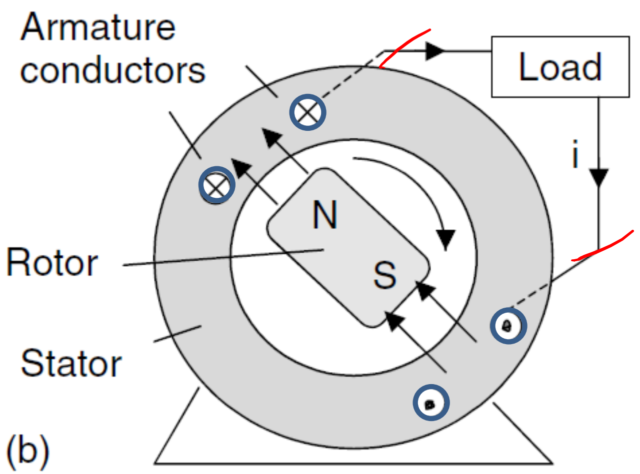


$$e = N\frac{d\phi}{dt}$$

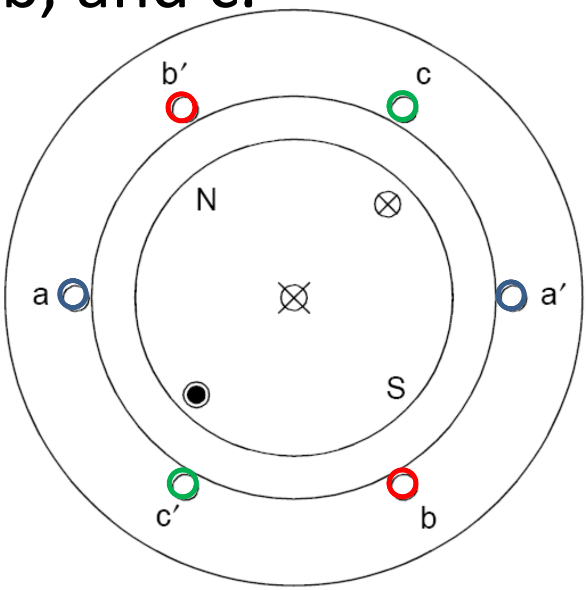


Three-Phase AC Generators

For a three-phase AC generator, the stator contains three sets of coils for phase a, b, and c.



Single-Phase AC generator

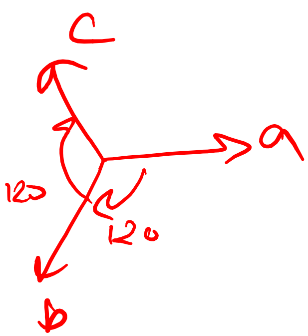


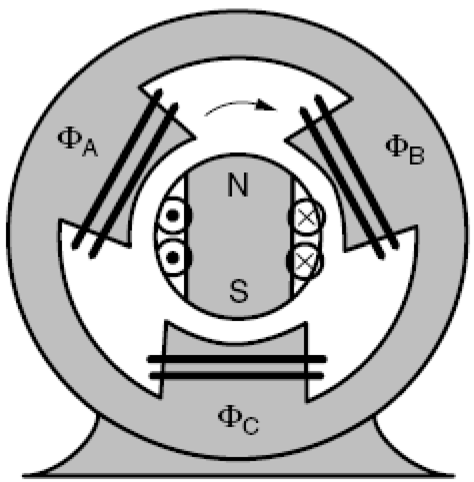
Three-Phase AC generator

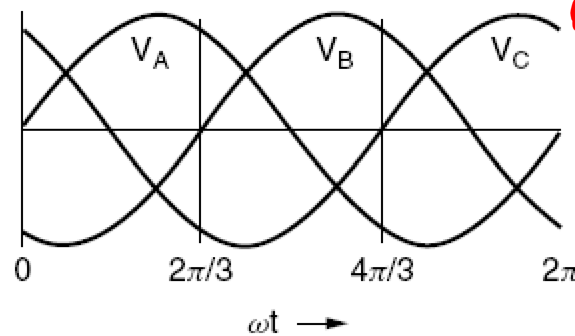
See this web course for a good animation of a three-phase generator: http://www.wisc-online.com/objects/ViewObject.aspx?ID=IAU14008

Positive VS Negative Sequence

- Positive and negative sequences can be achieved by **how we label the conductors** at the stator.





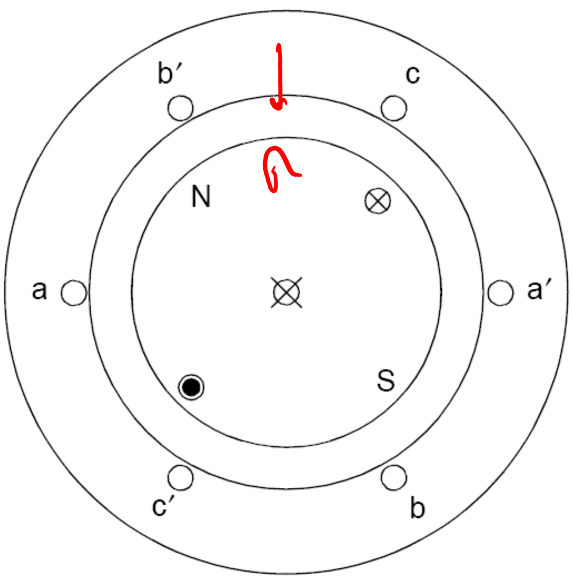


By swapping b to c, the voltage source will produce negative sequence.

Types of Rotor

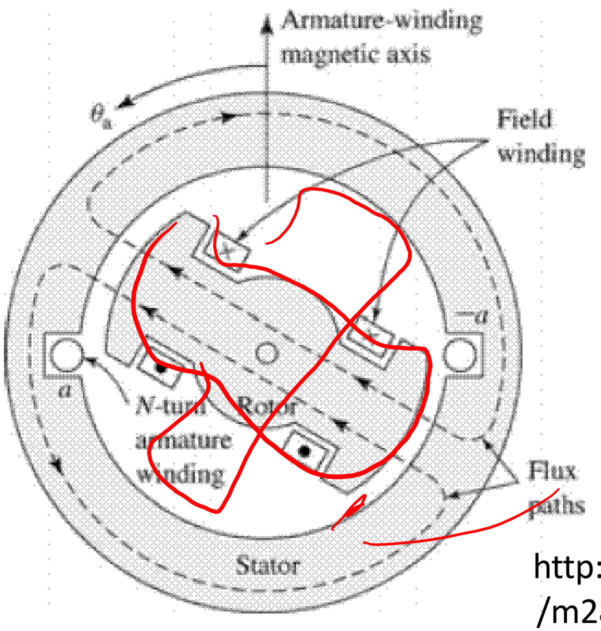
Cylindrical (Round) Rotor

- High speed application such as steam turbine at 3600 or 1800 rpm



Salient Rotor

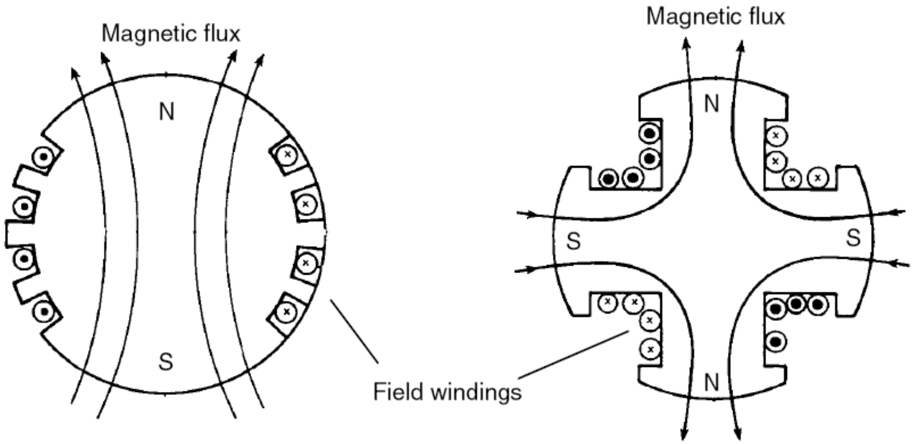
- Low speed hydro turbines at a few hundred rpm.



Source: http://cnx.org/content/m28323/latest/?collection=col10767/latest

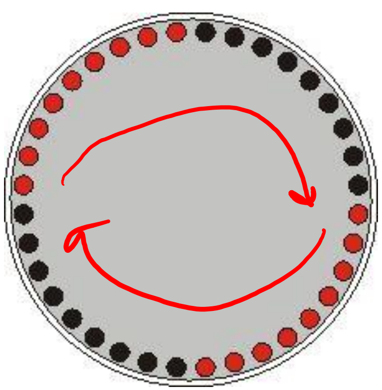
NUS
National University of Singapore

Multi-Pole Rotor

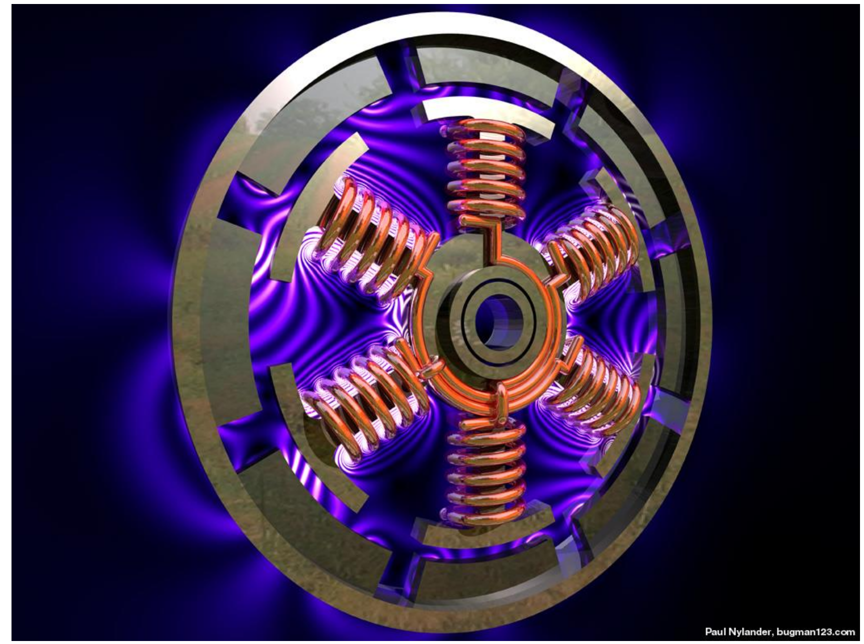


2-pole round rotor

4-pole salient-pole rotor



4-pole round rotor

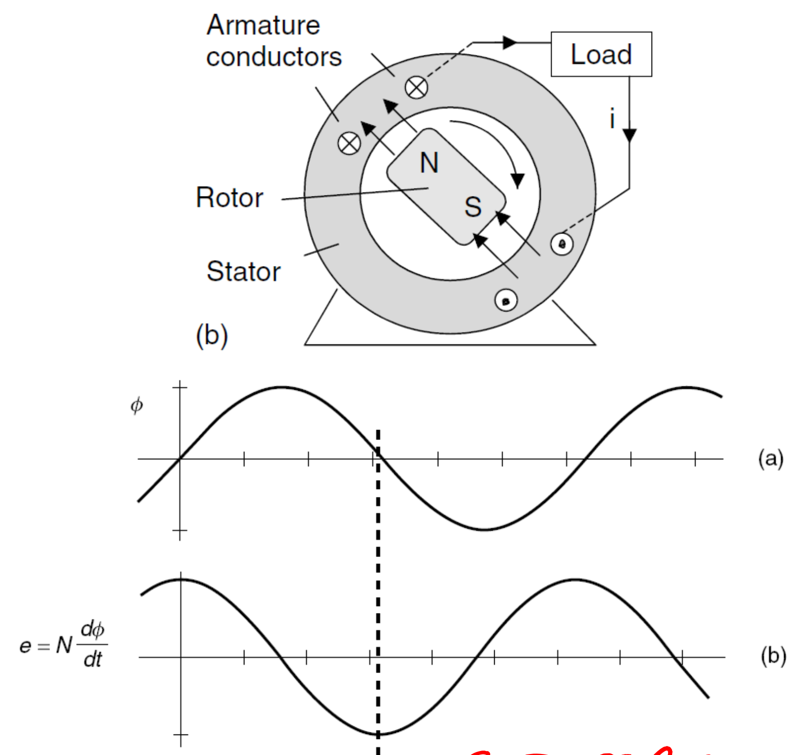


6-pole salient-pole rotor

Source: http://www.bugman123.com/Engineering/Motor-large.jpg

Rotor Speed for 2-Pole Generators

- The speed of the rotor shaft (n) is given in revolution per minute (rpm).
- For example, consider a two-pole single-phase generator on the right, the frequency of induced AC voltage is the same as the speed of rotor.
- Assume 60 Hz voltage, we can find the rotation speed by simply changing the unit from 'Hz' to 'rpm'.



3000 rpm

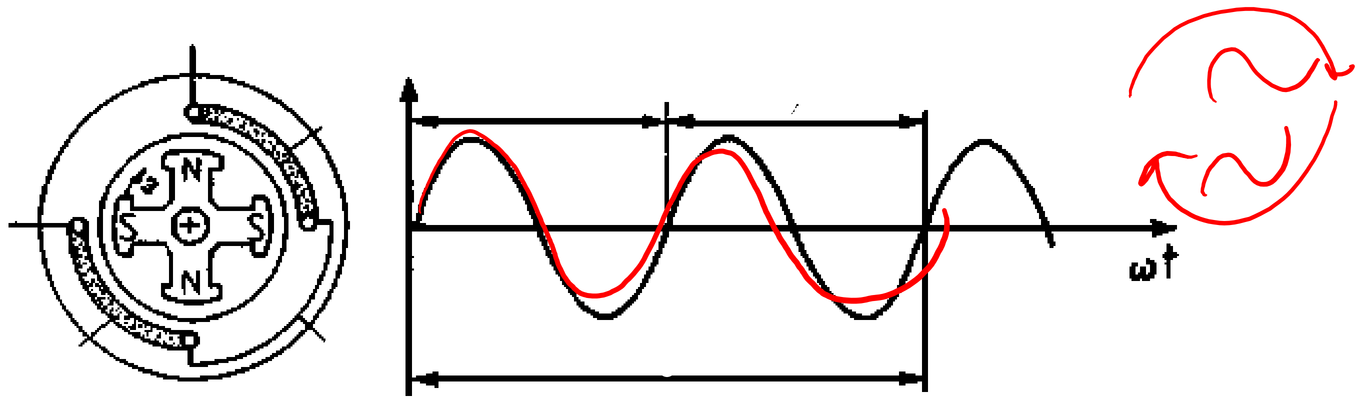
50

$$n\,(\text{rpm}) = \left(\frac{1\ \text{revolution}}{\text{cycle}}\right) \times f\,(\text{cycles/sec}) \times \frac{60\ \text{sec}}{\text{min}} = 3600\ \text{rpm}$$

2 poles

Rotor Speed for 4-Pole Generators

Source: http://www.fastonline.org/CD3WD_40/CD3WD/ELECTRIC/GTZ021E/EN/B309_6.HTM



When the machine rotate for **1 revolution**, the induced voltage has **2 cycles**.

$$n\,(\text{rpm}) = \frac{1\,\text{revolution}}{\underbrace{2\,\text{cycle}}_{4\text{ poles}}} \times \overset{50\,\text{Hz}}{f\,(\text{cycles/sec})} \times \frac{60\,\text{sec}}{\text{min}} = 1500\,\text{rpm}$$

If the frequency is 60 Hz, the rotor speed is 1800 rpm.

Rotor Speed for Multi-Pole Generators

- For p-pole generators, when the machine rotate for 1 revolution, the induced voltage has p/2 cycles.
- Then,

$$n\,(\text{rpm}) = \frac{1\,\text{revolution}}{\left(\frac{p}{2}\right)\text{cycles}} \times f\,(\text{cycles/sec}) \times \frac{60\,\text{sec}}{\text{min}}$$

$$n = \frac{120f}{p}$$

- We can relate the voltage frequency (Hz) to rotor speed (rpm) using,

$$f = \frac{np}{120}$$

f: voltage frequency (Hz)
n: rotor speed (rpm)
p: number of poles

Frequency (Hz) VS Rotor Speed (rpm)

$$\boxed{f = \frac{np}{120}}$$

f: voltage frequency (Hz)
n: rotor speed (rpm)
p: number of poles

Number of Poles	50 Hz	60 Hz
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600

Synchronous Speed

- All generators connected to the system must produce AC voltage at the same frequency, f_e.
- This implies that a generator must run at a constant speed.
- We refer to this rotor speed as 'synchronous speed', n_{sync}.
- A synchronous speed is found from:

$$n_{sync} = \frac{120 f_e}{p}$$

Connecting a generator to the grid

Excitation voltage

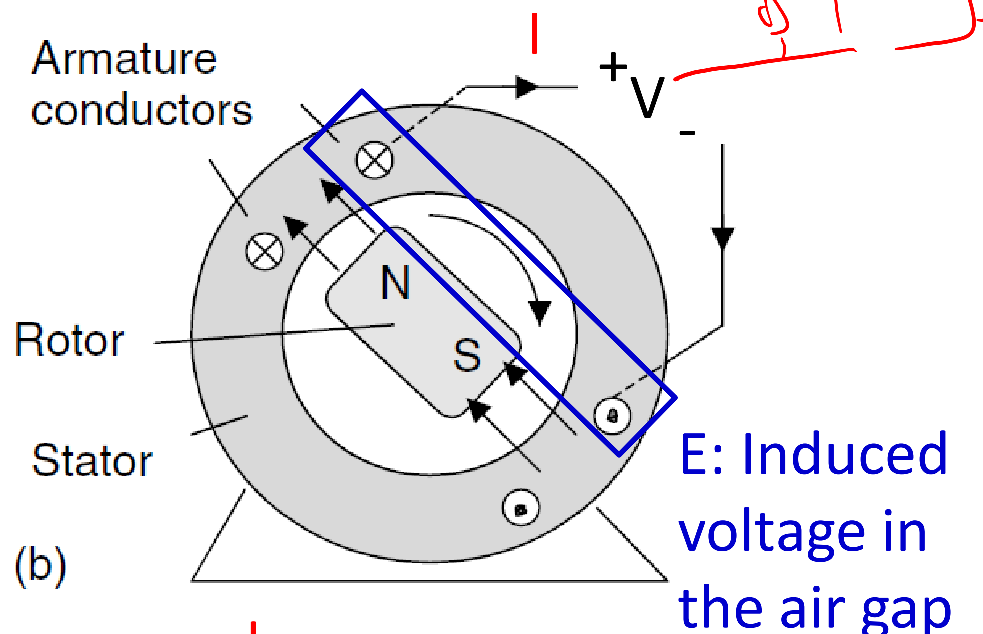
Armature reaction

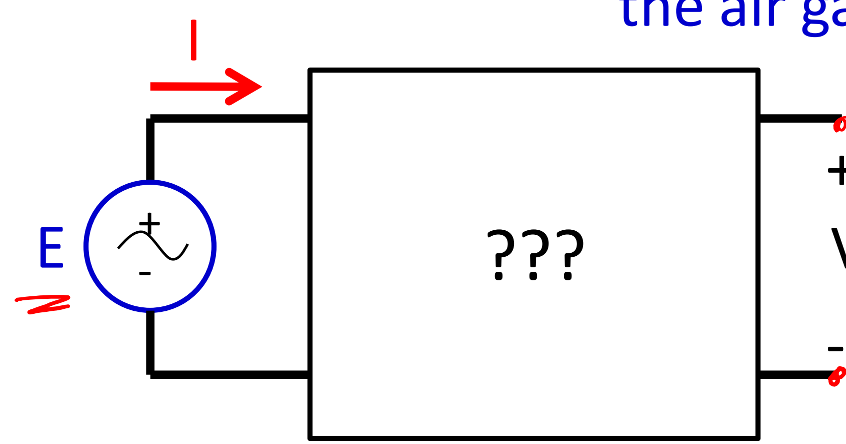
Equivalent circuit of a generator

A SYNCHRONOUS GENERATOR

Equivalent Circuit of a Generator

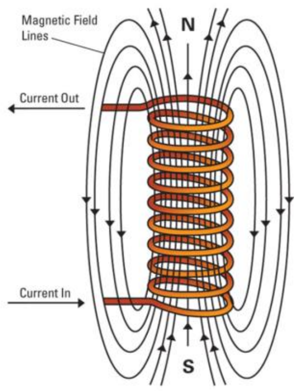
- An equivalent circuit of a generator is given in ***per-phase*** representation.
  - E = “Excitation” voltage i.e. internal Electromotive force (EMF) voltage (line-to-neutral value).
  - V = “Grid” voltage i.e. terminal voltage (line-to-neutral value). We usually use this voltage angle as a reference angle.
  - I = Armature current or load current.



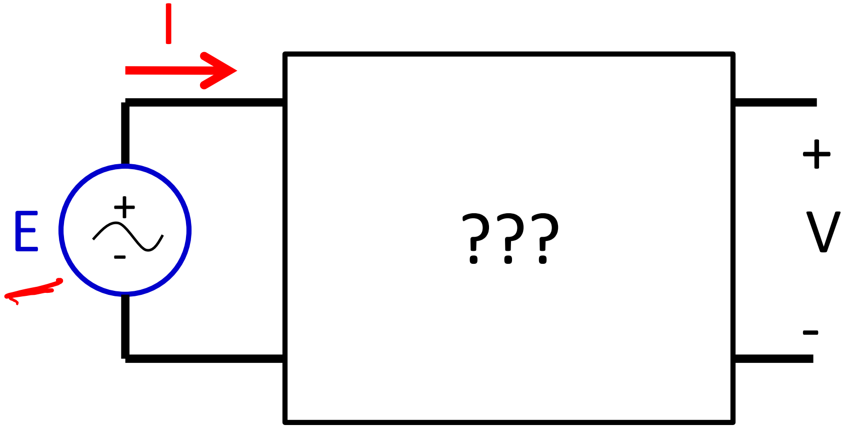


Excitation Voltage (E)

- Excitation voltage (E) or induced EMF is caused by an induced magnetic flux in the air-gap.
  - The magnetic flux on the rotor is created by a field winding at the rotor.



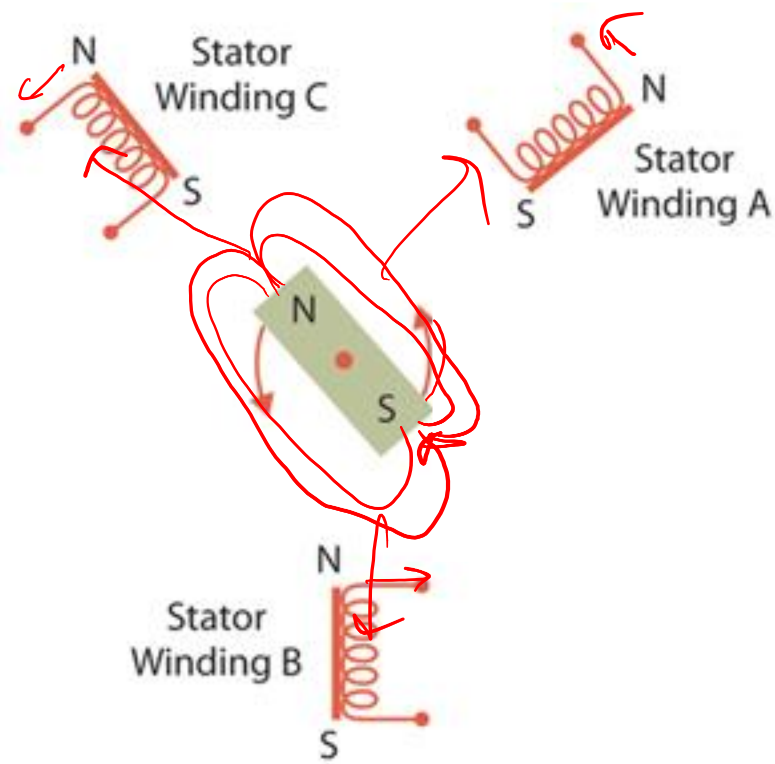
Rotating a constant magnetic field produces E.



Source: http://www.lanl.gov/news/index.php/fuseaction/1663.article/d/20085/id/13276

Magnetic Flux in the Air Gap

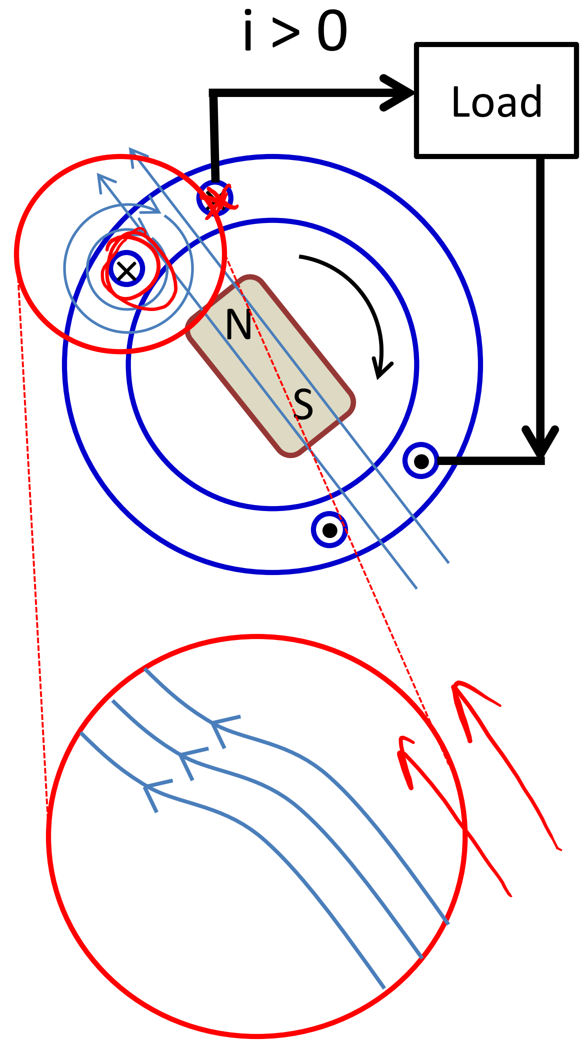
- Magnetic Flux in the air gap comes from two parts.
  1. Field current in the rotor circuit creates a constant magnetic field around the rotor.
  2. When the rotor turns, there will be induced voltage at the stator winding. After we connect stator winding to load, there will be stator (armature) currents in the stator (armature) circuit. Armature current will also create another magnetic field around it too!!



Source: http://www.ecnmag.com/article-brushless-dc-motor-control-111609.aspx

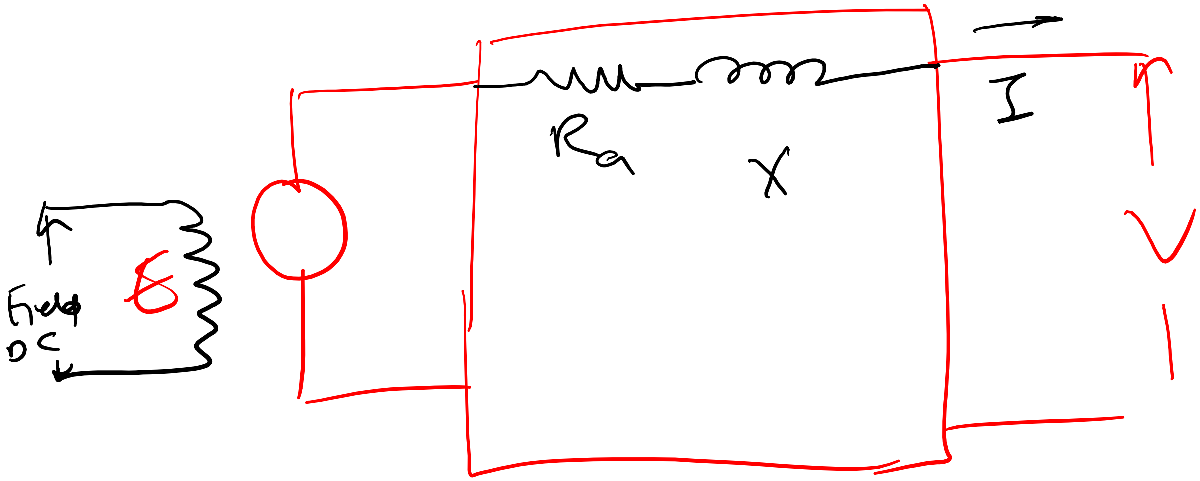
Armature Reaction

- Magnetic flux created from stator(armature) currents opposes the magnetic flux from field current.
- Flux linkage losses as a result of armature reaction are represented by an inductance called **armature reactance, Xa**.
- *Note that you can learn more about this topic in EE4502: Electric Drive and Control*



An Equivalent Circuit

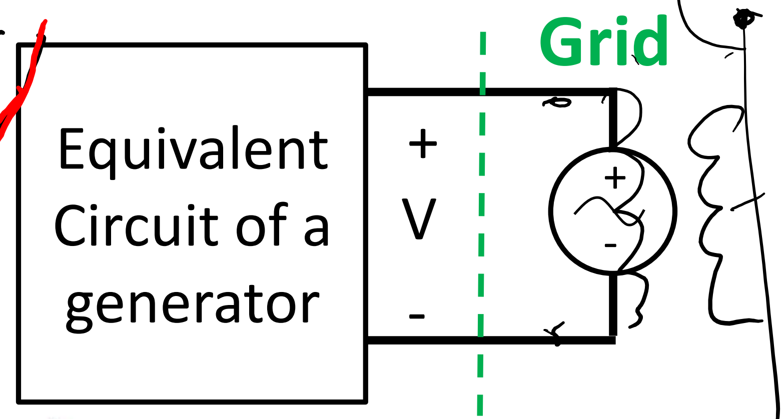
- R = <u>resistance</u> in the armature winding.
- X = synchronous <u>reactance</u>, representing flux linkage losses with a leakage reactance in the airgap, X_l and the armature reaction, X_a.

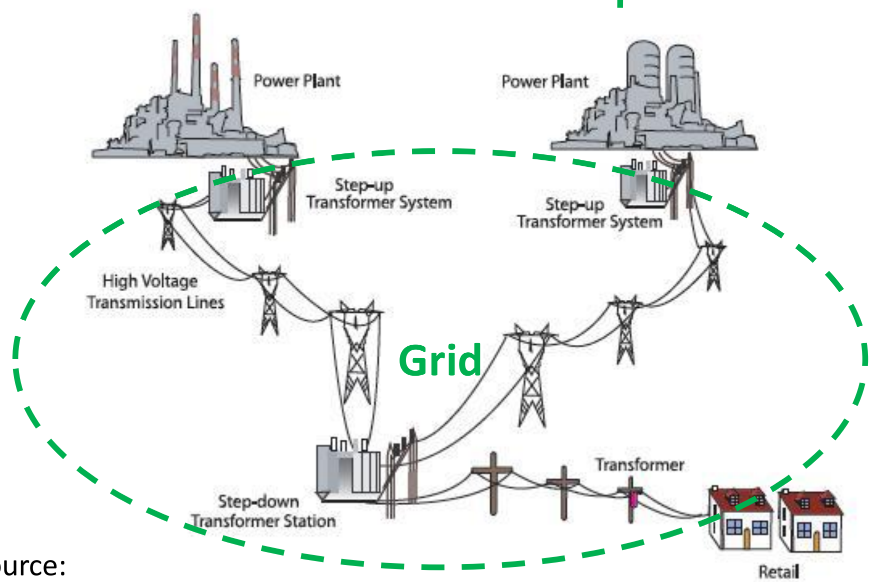


$$E = V + I(R_a + jX)$$

Connecting A Generator to the Grid

- Four conditions need to be met before connecting a generator to the grid:
    1. The three-phase voltage must have the same **frequency** as the grid.
    2. The three-phase voltage must have the same **amplitude** at its terminals as the one of the grid voltage.
    3. The three-phase voltage must have the same **phase sequence** as the grid voltage.
    4. The three-phase voltage must be **in phase** with the grid voltage.





Source: http://www.thermalfluidscentral.org/encyclopedia/index.php/Generation,_Transmission,_and_Distribution_of_Electricity

Summary

→ Power Plants

→ Generators

→ Simple Equivalent circuit

→ Electromagnetic Induction

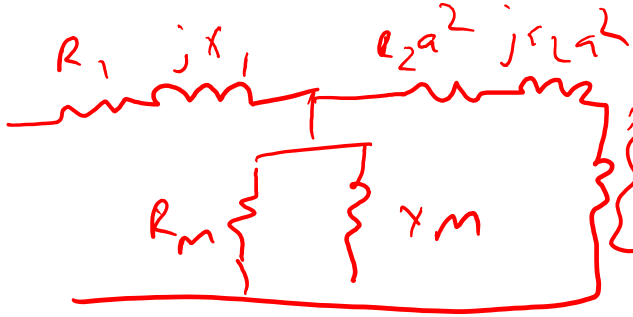
Reminder:2nd Mid-term Test @ LT5

- Monday, March 30th 5:00pm to 5:45pm **@ LT5**
- 10%
- Materials (Lectures 11-17, Tutorials 5-6):
  - Transformers
  - Renewable Energy
  - Per Unit Analysis
- Format:
  - Closed book.
  - 45 minutes.

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1} = a$$

a1

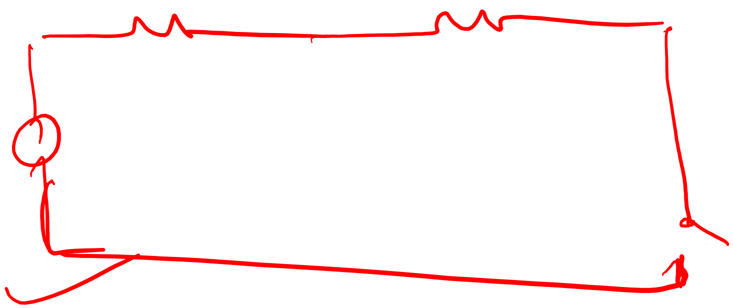
Transformers $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1} = a$



$$Z_1' = a^2 Z_2$$

Per unit = $\frac{\text{Actual value}}{\text{Base value}}$

$$Z_B = \frac{V_B^2}{S_B} \quad I_B = \frac{S_B}{V_B}$$



$$I_d = I_0 \left(e^{38.9V} - 1\right)$$

$$V_0 = 0.0257 \ln\left(\frac{I_{sc}}{I_0} + 1\right)$$

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

$$\frac{V}{V_0} = \left(\frac{H}{H_0}\right)^2$$