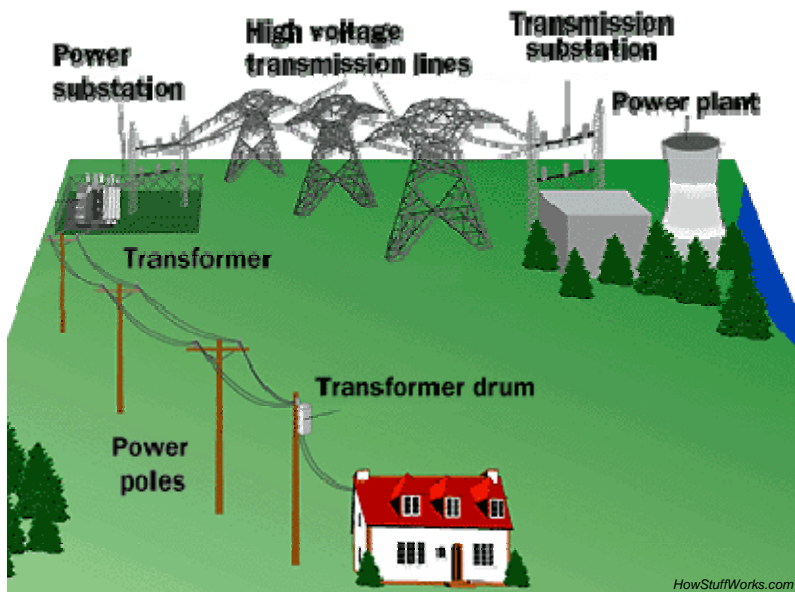




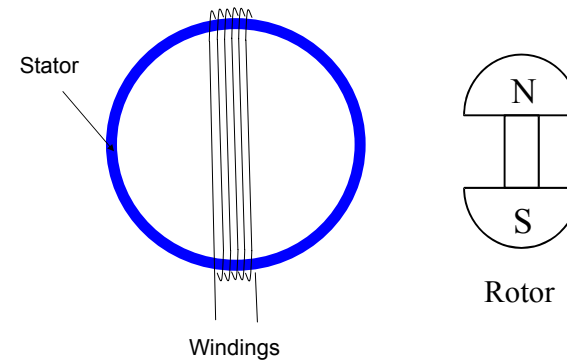
Overview

- 3-Phase Power
 - Generating 3 phase
 - Y (wye) and Delta connections
- Induction motors
 - Induced voltages and torque

2

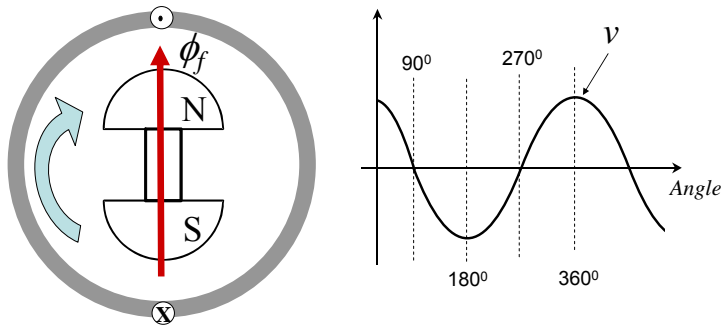


How AC is Generated



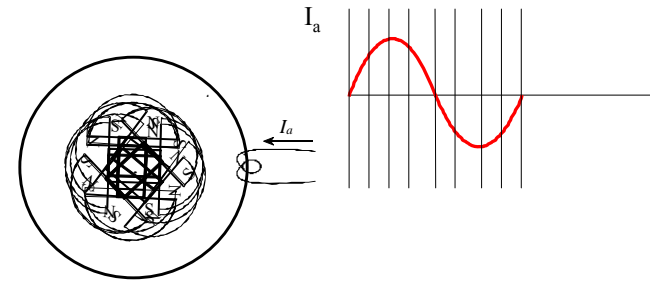
4

How AC is Generated



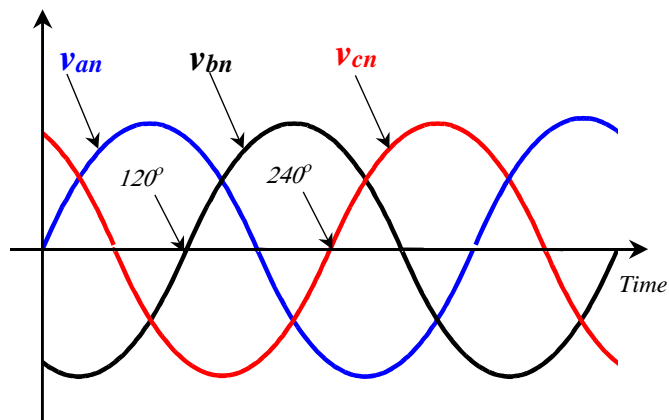
5

How AC is Generated



6

3 ϕ Power Plotted



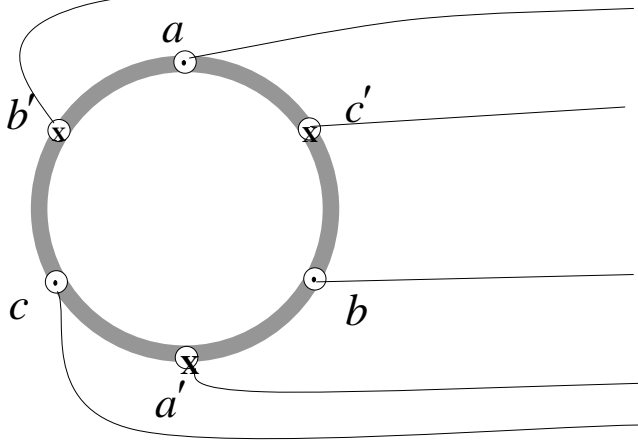
7

Why a 3-phase system?

- The instantaneous power is *nearly constant*
 - 3 ϕ better than 1 ϕ or 2 ϕ , but 4 ϕ not noticeably better than 3 ϕ
- Three-phase lines transmit more power
 - P_{avg} for 1 ϕ versus 3 ϕ
- 3 ϕ motors can start without the need for extra equipment.
- For the same physical size, a 3 ϕ generator produces more power than a 1 ϕ generator.
- 3 ϕ lines are more reliable.
 - A distribution circuit can be operated with one phase missing
- 3 ϕ eliminates the need for a return wire

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How is Three-Phase Connected?



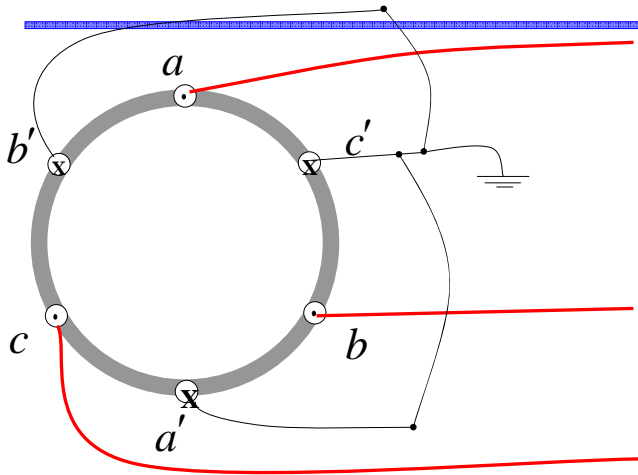
9

How is Three-Phase Connected?

- Any three-phase generator has 6 terminal wires
- Transmitting 6 wire over a long distance is expensive
- Instead, three-wire system is used by connecting the six wires as **Y** or **Delta**

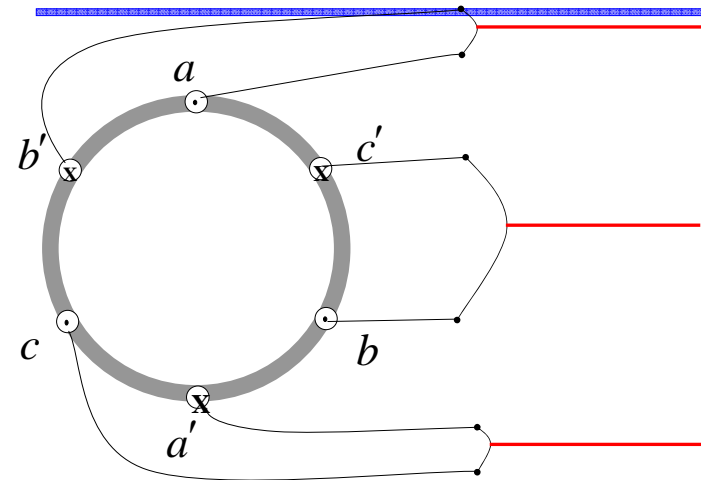
10

Y-Connection



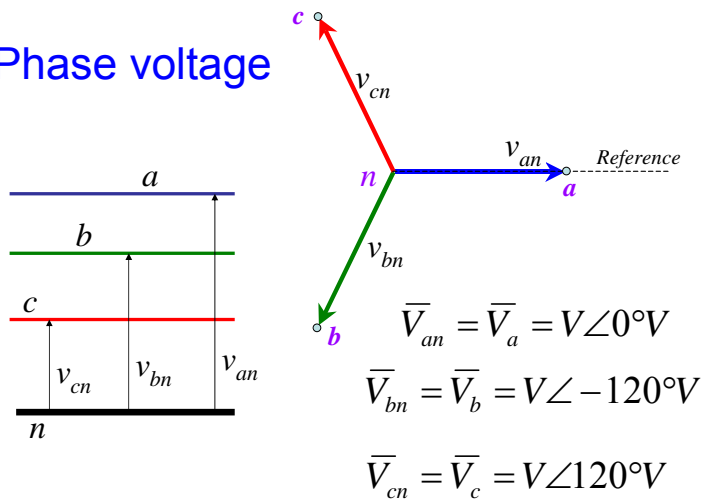
11

Delta (Δ) Connection: Source



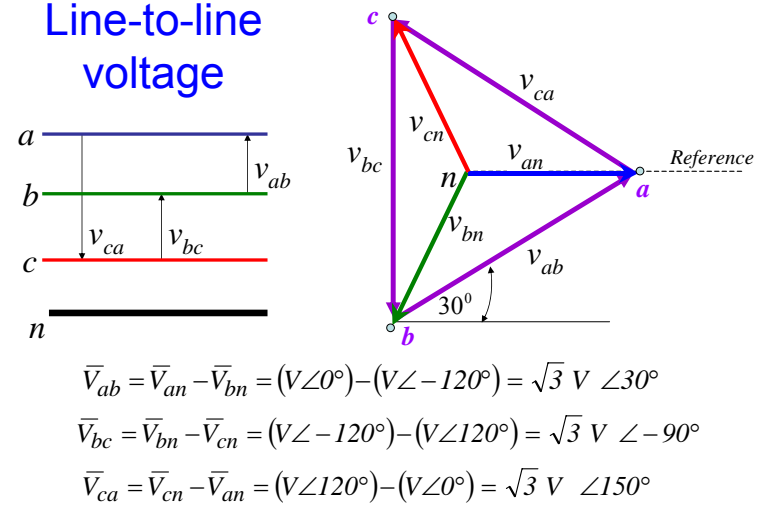
12

Phase voltage



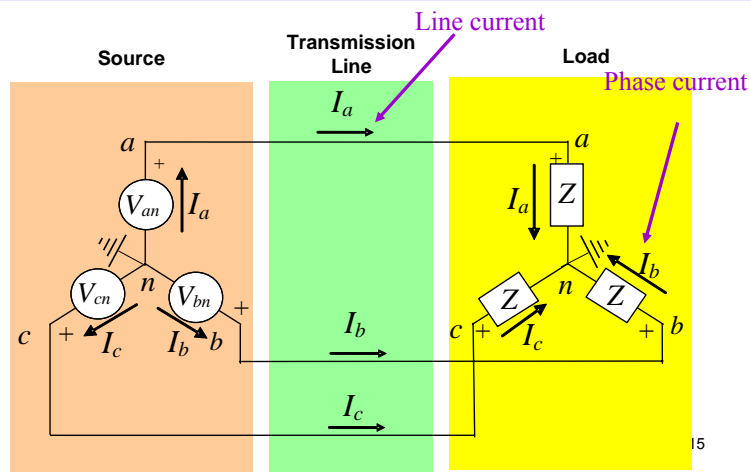
13

Line-to-line voltage



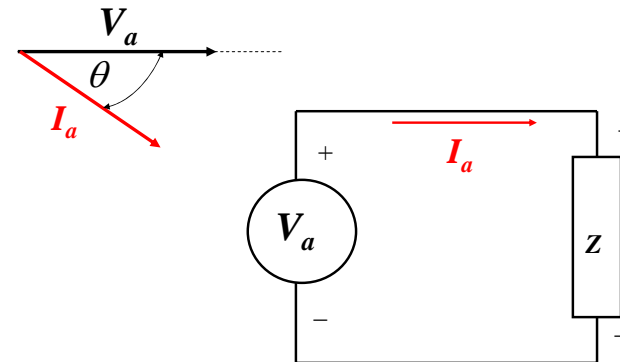
Unless stated otherwise: All voltages are line-to-line quantities 14

Y-Connected System



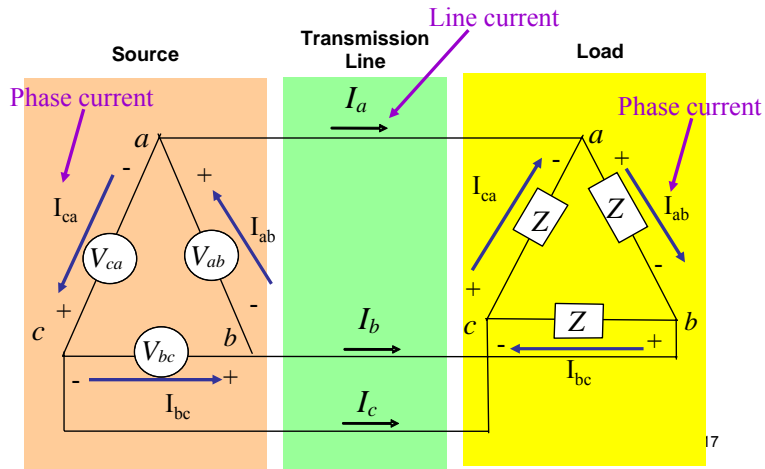
15

Single-Phase Representation

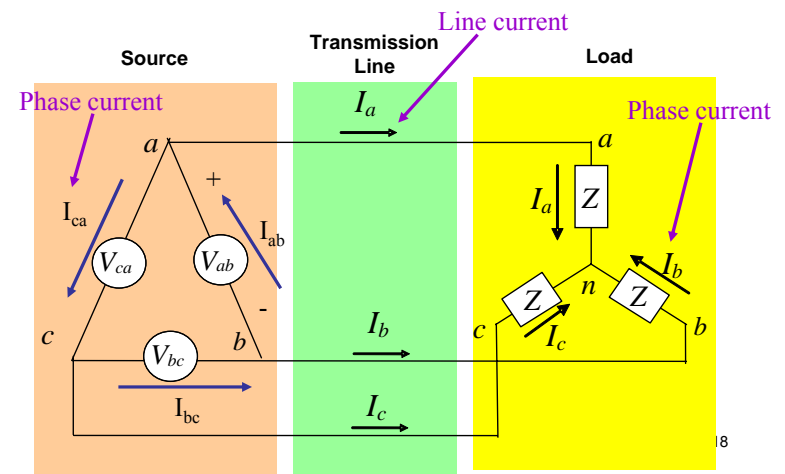


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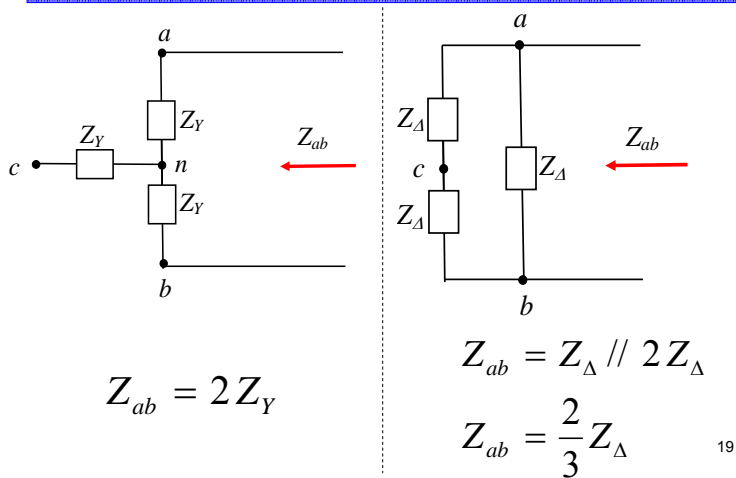
Delta-Connected System



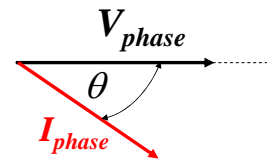
Mixed Connection System



Y-Δ Transformation



Power of 3-phase circuits



For Single phase

$$P = V_{\text{phase}} I_{\text{phase}} \cos(\theta)$$

$$Q = V_{\text{phase}} I_{\text{phase}} \sin(\theta)$$

IMPORTANT

θ is the angle between phase voltage and phase current.

Use voltage as a reference

For 3-phase

$$P = 3 V_{\text{phase}} I_{\text{phase}} \cos(\theta)$$

$$Q = 3 V_{\text{phase}} I_{\text{phase}} \sin(\theta)$$

Keep in mind

- The *pf* angle is the angle of the load impedance.
- It is the same as the angle between the phase voltage and the phase current

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Recap of 3-Phase

- Three-phase systems
 - How 3 ϕ power is generated
 - Why 3 ϕ power is generated
 - Wye and delta connections
 - Transformations between

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Rotating Machinery: Induction Motors

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Overview

- Rotating electric field
- Rotating induction motor
 - Faraday's law
 - Motor speed
 - Speed-torque relationship

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Facts about Induction Motors

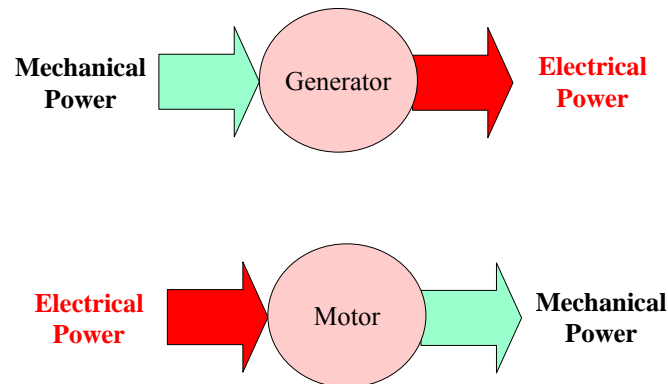
- About 65% of the electric energy in the United States is consumed by electric motors.
- In the industrial sector alone, about 75% is consumed by motors and over 90% of them are induction machines.

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Why Induction Motors are Popular

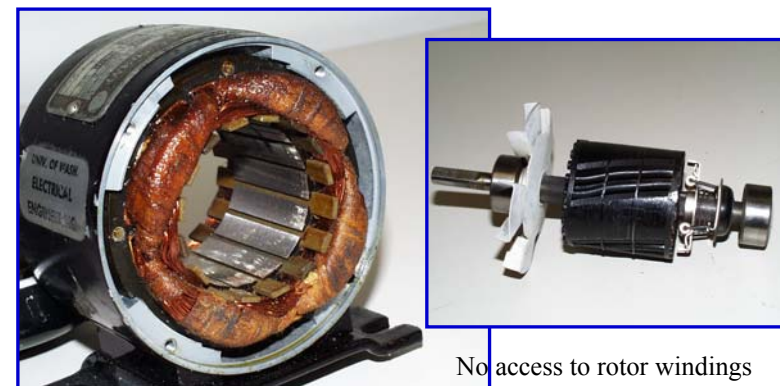
- They are rugged
- Reliable
- Easy to maintain
- Relatively inexpensive
- Their power-to-density ratios (output power to weight) are higher than some other motors

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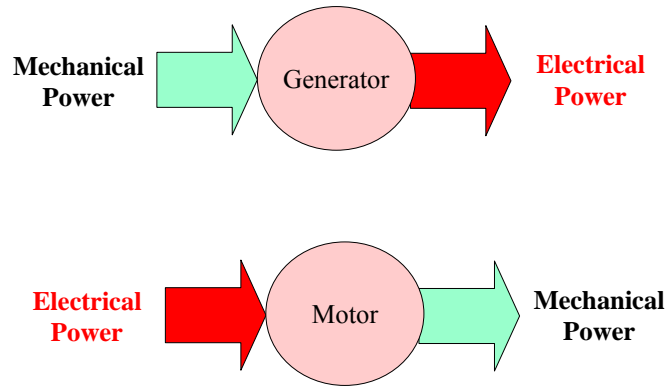


27

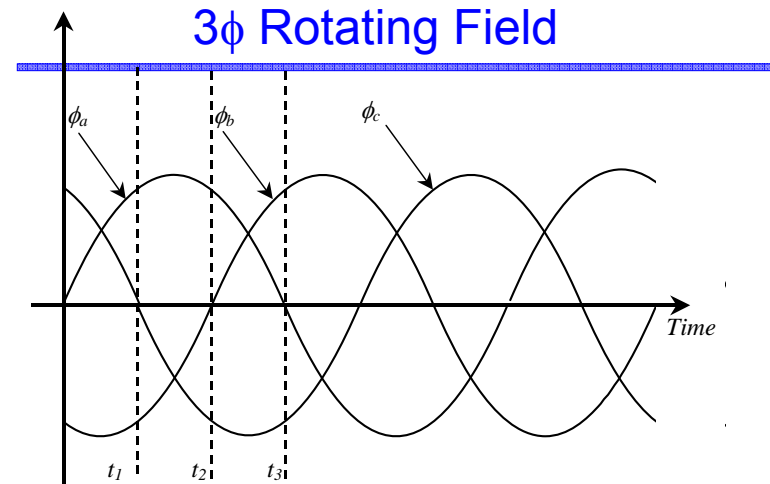
Squirrel Cage IM



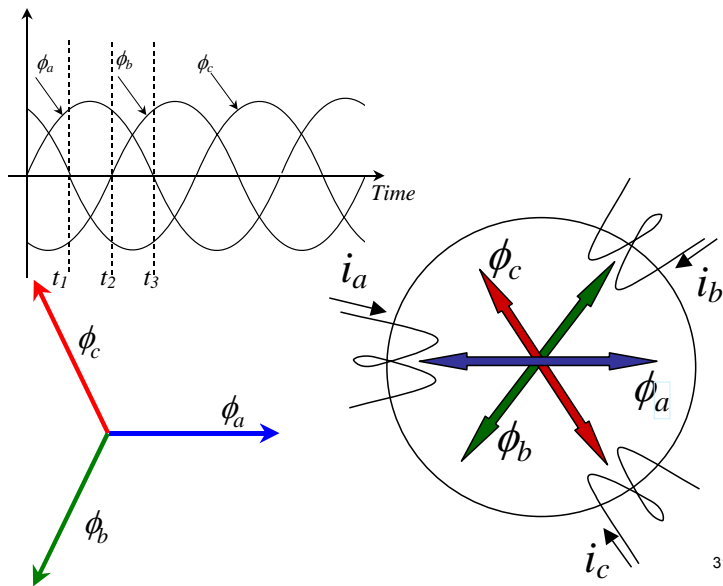
28



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Rotating Airgap Flux

- The speed of the airgap flux is one revolution per one ac cycle.
- The time of one ac cycle $\tau = \frac{1}{f}$
- The speed of the airgap flux (Synchronous Speed)

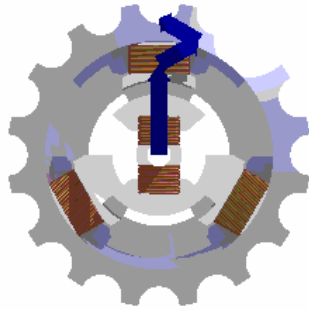
$$n_s = f \quad \text{rev/sec}$$

$$n_s = 60 f \quad \text{rev/min}$$

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Rotating Airgap Flux

<http://www.fuel-efficient-vehicles.org/images/Rotating-magnetic-field-3phase.gif>



Watch:

- Vector associated with each phase, and the rotor rotates
- Sum of all phasors – has constant amplitude

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Number of Poles

- If each phase has one coil, it is a two-pole machine
 - The rotor moves 360 degrees for one complete ac cycle.
- If each phase has two coils, it becomes 4-pole machine
 - The rotor moves 180° mechanical for every one complete ac cycle.

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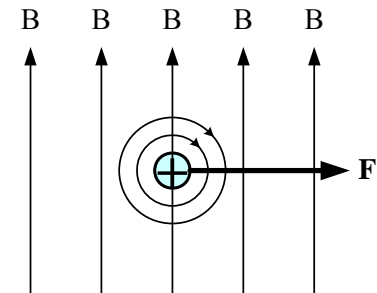
Number of Poles

$$\begin{array}{c}
 \boxed{\text{Synchronous Speed}} \\
 \downarrow \\
 n_s = \frac{60 f}{pp} = 120 \frac{f}{p} \quad \text{rev/min} \\
 \begin{array}{cc}
 \uparrow & \uparrow \\
 \boxed{\text{Number of pole pairs}} & \boxed{\text{Number of poles}}
 \end{array}
 \end{array}$$

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Induction Motors

- The interaction between the magnetic field B and the current generates a force $F = B L I$



Force direction on a current-carrying conductor placed in a magnetic field (B) (current into the page).

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Faraday's Rules

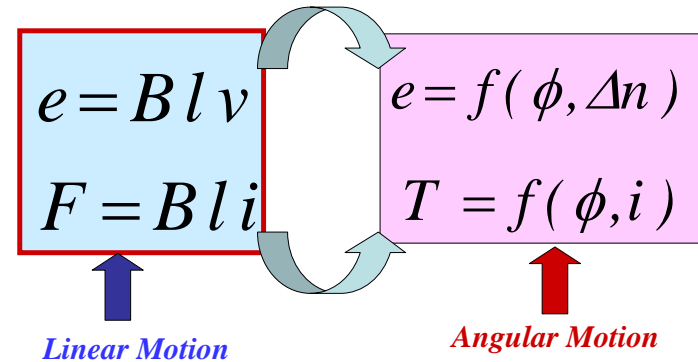
$$e = B l \Delta v$$

$$F = B l i$$

e : Voltage across a conductor
 B : Flux density seen by the conductor
 l : Length of the conductor
 Δv : Relative velocity of the conductor wrt the magnetic field
 F : Force exerted on conductor
 i : Current through conductor

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Faraday law for Rotating Motion

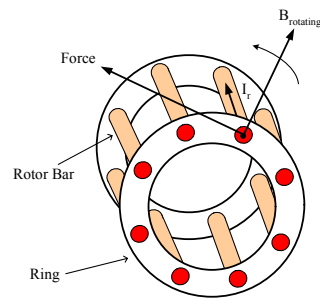


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Induction Motors

Force generation in a motor

- The three-phase winding generates a rotating field
- The rotating field induces a current in the rotor bars
- The current generation requires a speed difference between the rotor and the magnetic field
- The interaction between the field and the current produces the driving force

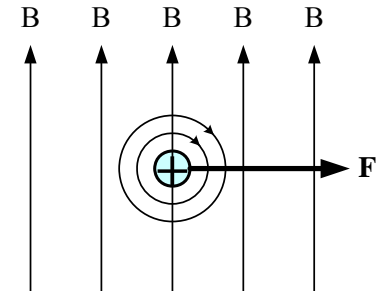


Rotating magnetic field generated driving force.

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Induction Motors

- The interaction between the magnetic field B and the current generates a force
- $$F = B L I$$



Force direction on a current-carrying conductor placed in a magnetic field (B) (current into the page).

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Motor Speed, p 337

- The relative speed, Δn , is the difference between the speeds of the rotor and the airgap flux

$$\Delta n = n_s - n$$

- If the stator is energized, a rotating flux at synchronous speed n_s is induced in the airgap
- If the rotor is stationary, then $\Delta n = n_s$

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Motor Speed con't

- Thus, the rotating field induces a voltage, e , in the rotor windings
- With the rotor windings shorted, current can flow, producing a torque on the windings (and the rotor)
- .. So the rotor spins.
- What is the steady state speed of the induction motor? ($<$, $>$, $= n_s$?)

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Summary

- Induction motors are the most common electrical load
- Faraday's law
- Next class
 - The concept of slip, speed-torque
 - Know sections 12.1 and 12.2!

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Power Flow and OPF Recap - For your own review

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Per Unit System

- Transformers step voltage up and down on either side
- Operating a power system we want to keep the voltage within 5% of its rated value
- 'per unit' \equiv normalized value
 - * 0.95 and 1.05 easier to keep track of than
 - * 727kV and 803kV for 765kV *and*
 - * 131kV and 145kV for 138kV...
- Also normalize, then, the power values

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Slack Bus

- In finding the power generation at each bus in the system...
 - We must let one generator's output 'take up the slack' after solving for
 - the generation at every bus
 - the load at every bus, and
 - the subsequent losses on the transmission lines

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Optimal Power Flow

- Economic dispatch is a form of constrained optimization
- The power flow equations (**along with line limits**) are a constraint on the use of the transmission system
- Combining these mathematical models results in an *optimal power flow*

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Optimal Power Flow

- In what way is it optimal?
- How do we frame the mathematical problem we need to solve to find the optimal power flow?

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