# ELEC 342
# Electromechanical Energy Conversion and Transmission

2025-26 Winter Term 2

Lecture 18

March 17, 2026

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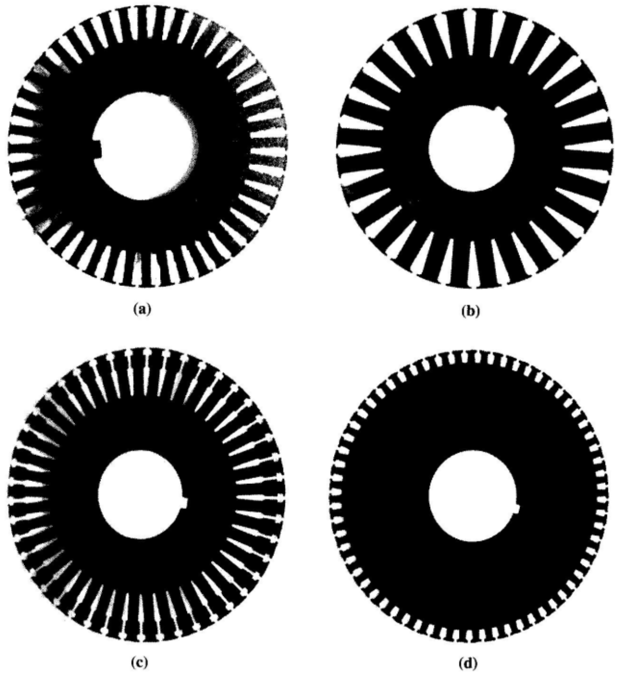
# Course Logistics

- Quiz 3 will take place on March 20
  - Detailed information already announced on Canvas
    - Beginning of tutorial and you will be given 20 minutes
    - Closed book and notes, calculators allowed
    - Coverage: Module 5
- SEI survey: March 28 – April 13
- Final exam: Apr. 19 @ 12 PM in IRC 4

# National Electrical Manufactures Association (NEMA) Design Classes/Types

### Rotor laminations

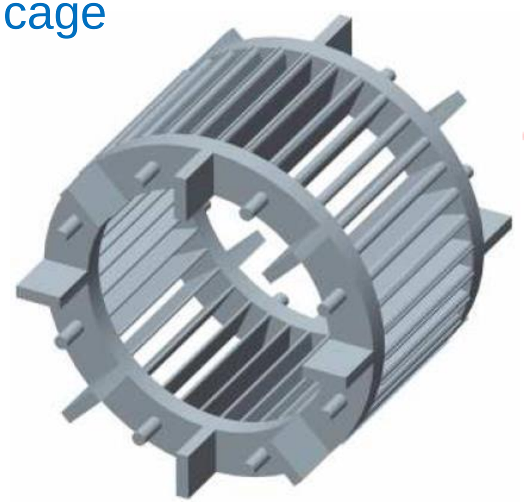



Recall the Skin Effect → $f \uparrow$ → current on outer part of conductor

Effective rotor resistance changes with frequency (which is the slip frequency) and therefore depends on the rotor speed ⇒ Different torque-speed characteristics can be designed by shaping the rotor winding slots

↳ change $R_2''$

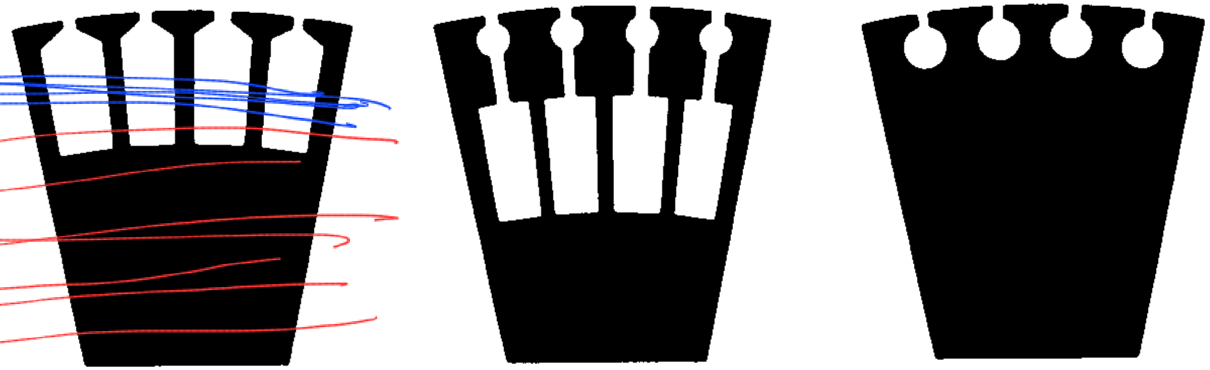
### Rotor cage



❖ Practical rotor laminations for different NEMA Design Classes

→ high f → large start-up torque

low f



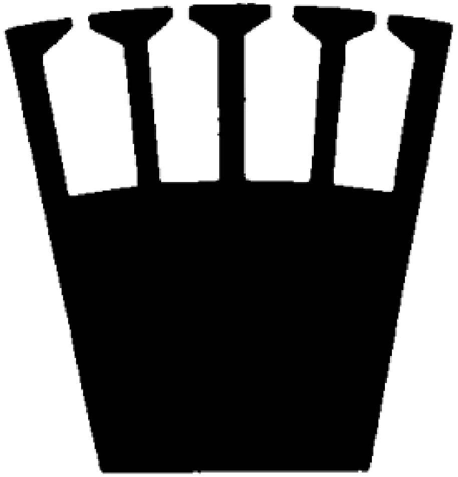
Design *B* Design *C* Design *D*

Start up: $s = 1$, steady-state: $s \sim 0.05$

# Deep Bars Rotor Design

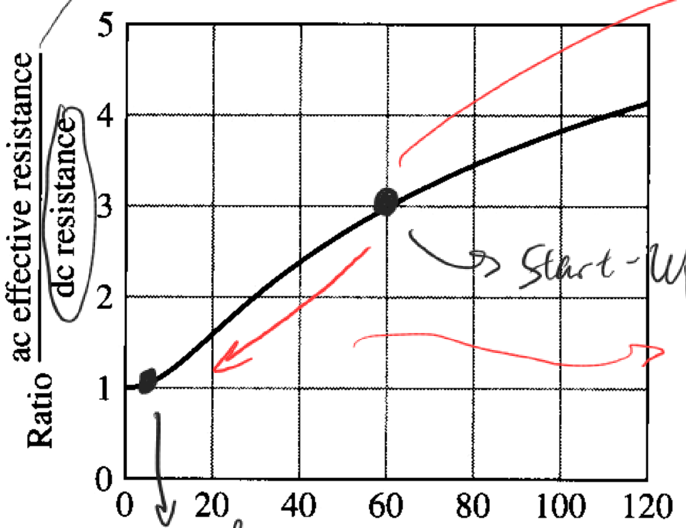
Effect of changing the effective values of rotor resistance

deep



DC resistance is smallest resistance possible

normalized resistance



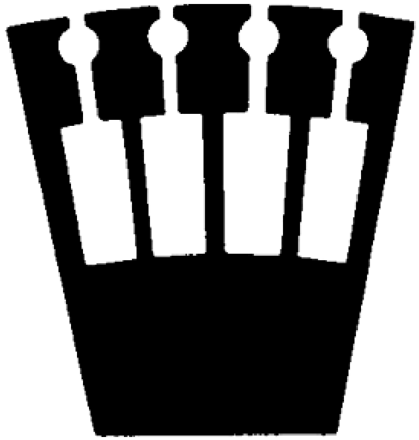

high start-up torque

Start-Up

$R_2'$ reduces by 3

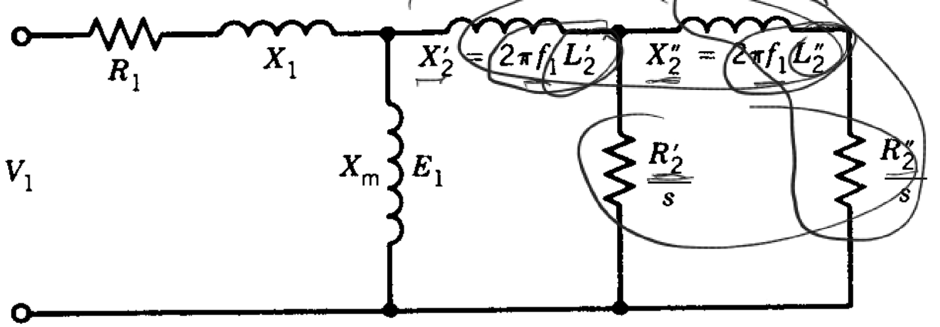
steady-state

Accurate modelling of such rotors requires higher-order circuit

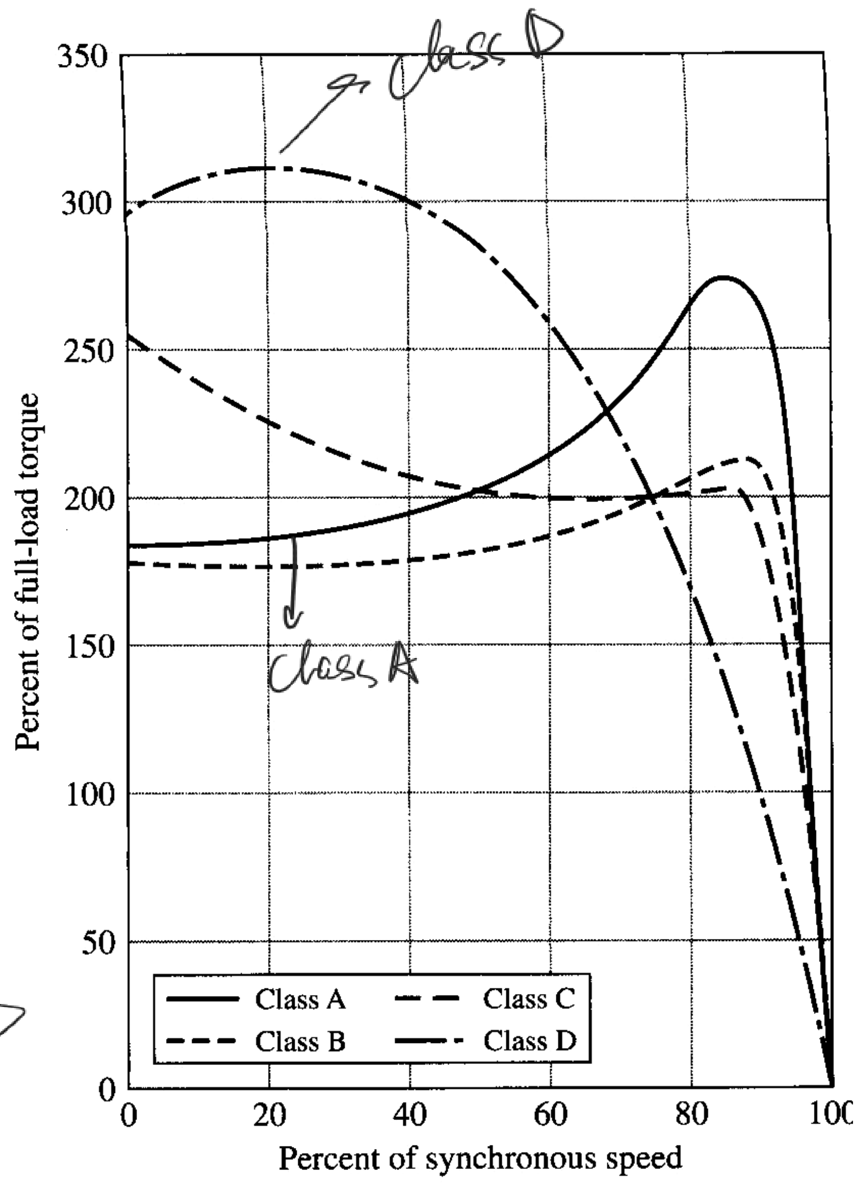


Not covered in this class

multiple branches



# NEMA Design Classes




Similar

**Class A:** normal starting torque, high starting current, low operating slip (0.5% < s < 1.5%), low rotor resistance, high operating efficiency (*special needs for starting*)

↳ Smallest slip → fastest speed
↳ Smallest losses
↳ Lowest possible start-up torque

**Class B:** normal starting torque, low starting current (~75% of class A), low operating slip, higher leakage reactance, lower maximum torque, efficiency as high as A, (*general purpose motors, fans, blowers, pumps, etc*.)

**Class C:** high starting torque, low starting current, higher rotor resistance, higher operating slip, lower efficiency than A&B (*compressors, crushers, conveyors, etc*.)

→ cutting tools, chainsaws

**Class D:** high starting torque, low starting current, high operating slip (8-15%), high rotor resistance, low efficiency (*rapid acceleration, high impact loads*)

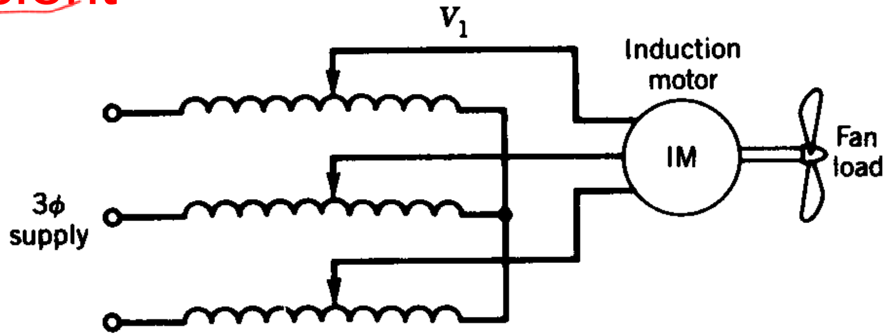
↳ highest starting torque
↳ highest slip

# Speed & Torque Control

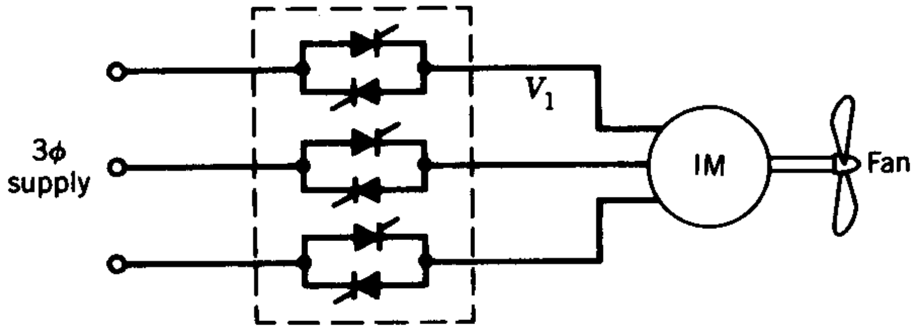
## 1) Line Voltage Control (AC voltage control)

- Narrow speed control region for motors Class A, B, C
- Inefficient

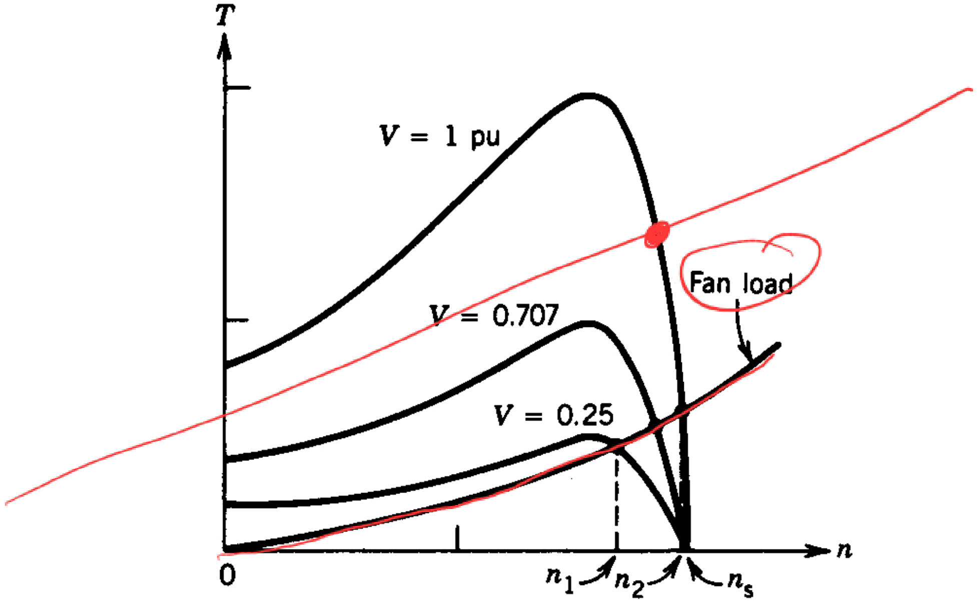
Fans

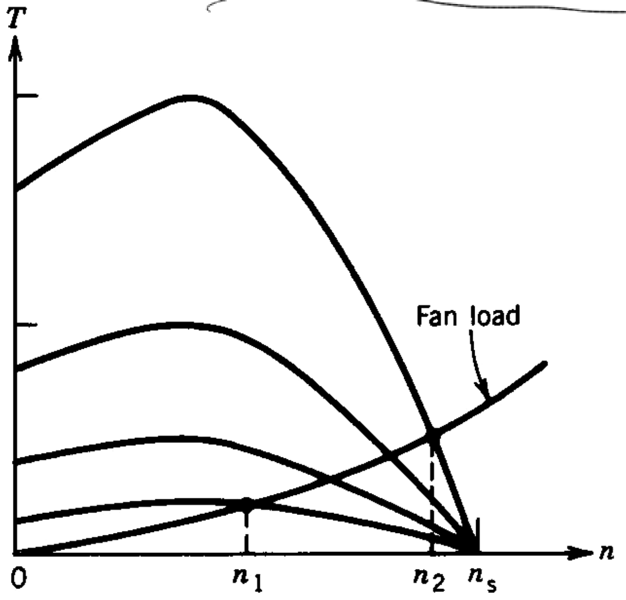



Variac voltage control




Thyristor voltage control

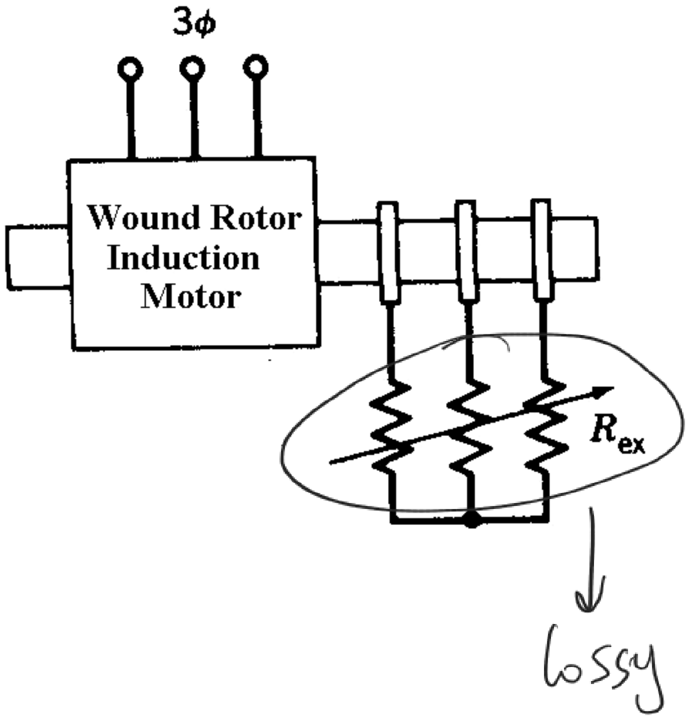


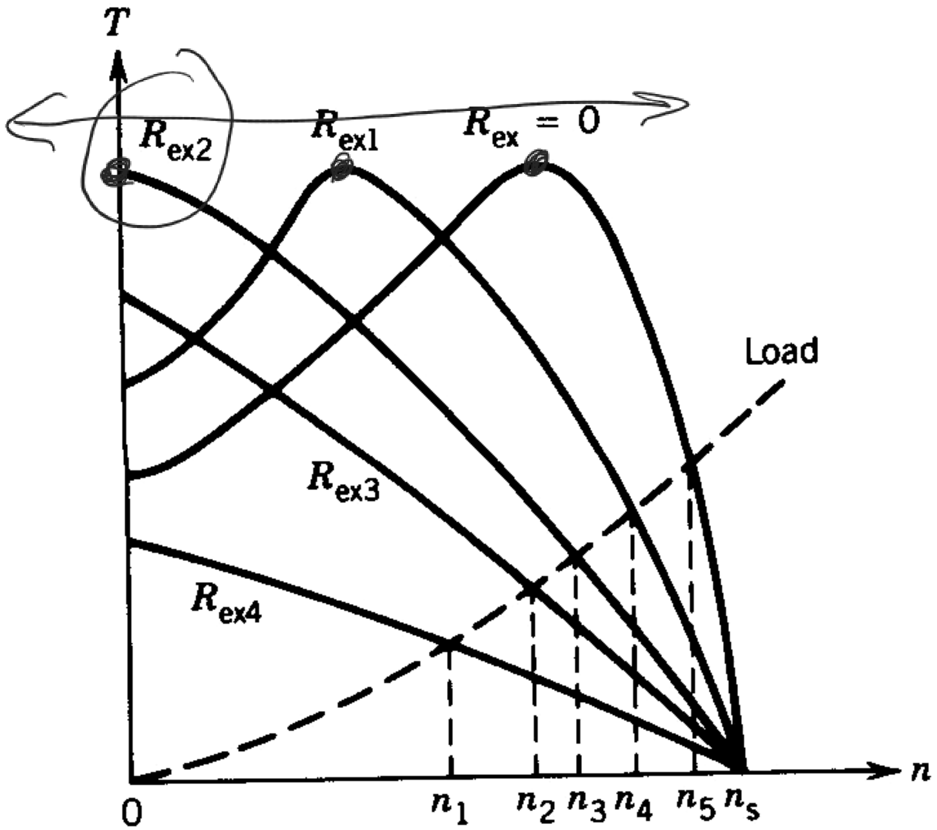



# Speed & Torque Control

## 2) Changing Rotor Resistance (only for wound-rotor IM)

- Energy loss

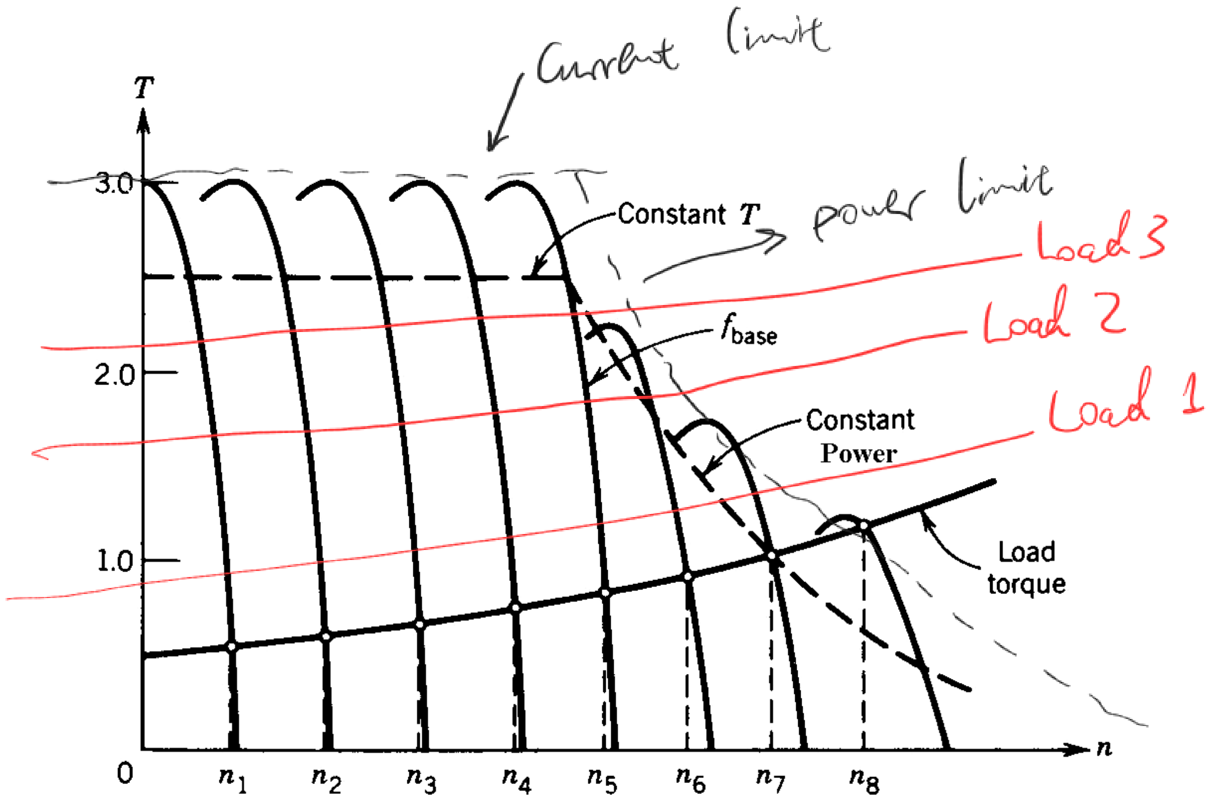

$$T_e = 3\frac{P}{2}\frac{V_{1,th}^2}{\omega_e} \cdot \frac{R_2'/s}{(R_{1,th}+R_2'/s)^2+(X_{1,th}+X_2')^2}$$

$$s_{T\max} = \pm\frac{R_2'}{\sqrt{R_{1,th}^2+\left(X_{1,th}+X_2\right)^2}}$$

# Speed & Torque Control

## 3) Variable Frequency & Voltage

→ Best
→ V/f




$$T_e = 3\frac{P}{2}\frac{V_{1,th}^2}{\omega_e}\cdot\frac{R_2'/s}{(R_{1,th}+R_2'/s)^2+(X_{1,th}+X_2')^2}$$

Synchronous speed $\omega_{syn} = \frac{2}{P}\omega_e$

- Large range of speeds
- High efficiency
- Need power electronics to vary V and $f_e$

$$\Phi_{peak} = \frac{\sqrt{2}V_{1,rms}}{N_1\omega_e}$$

# Speed & Torque Control

change the speed of magnetic field

## 3) Variable Frequency & Voltage

- Large range of speeds, High efficiency
- Need power electronics to vary V and $f_e$ simultaneously
- Best and most practical method

### Variable Frequency Drives (VFDs)

❖ **Classification**

Lab 4

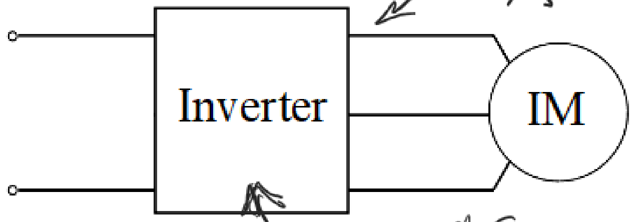
a) Scalar Controls (Volts/Hz, Constant slip, Maximum efficiency (ME), Maximum Torque Per Ampere (MTPA), etc.)

Assume steady-state equivalent circuit. Control: $|I_s|$ $|v_{as}|$ $\omega_e$

b) Vector Controls (Field-oriented control (FOC), Direct torque control (DTC), and variations thereof)

Assume dynamic *qd* equivalent circuit. Control: $I_s\angle\theta_e$ $V_s\angle\theta_e$ $\mathbf{i}_{qds}$ $\mathbf{v}_{qds}$

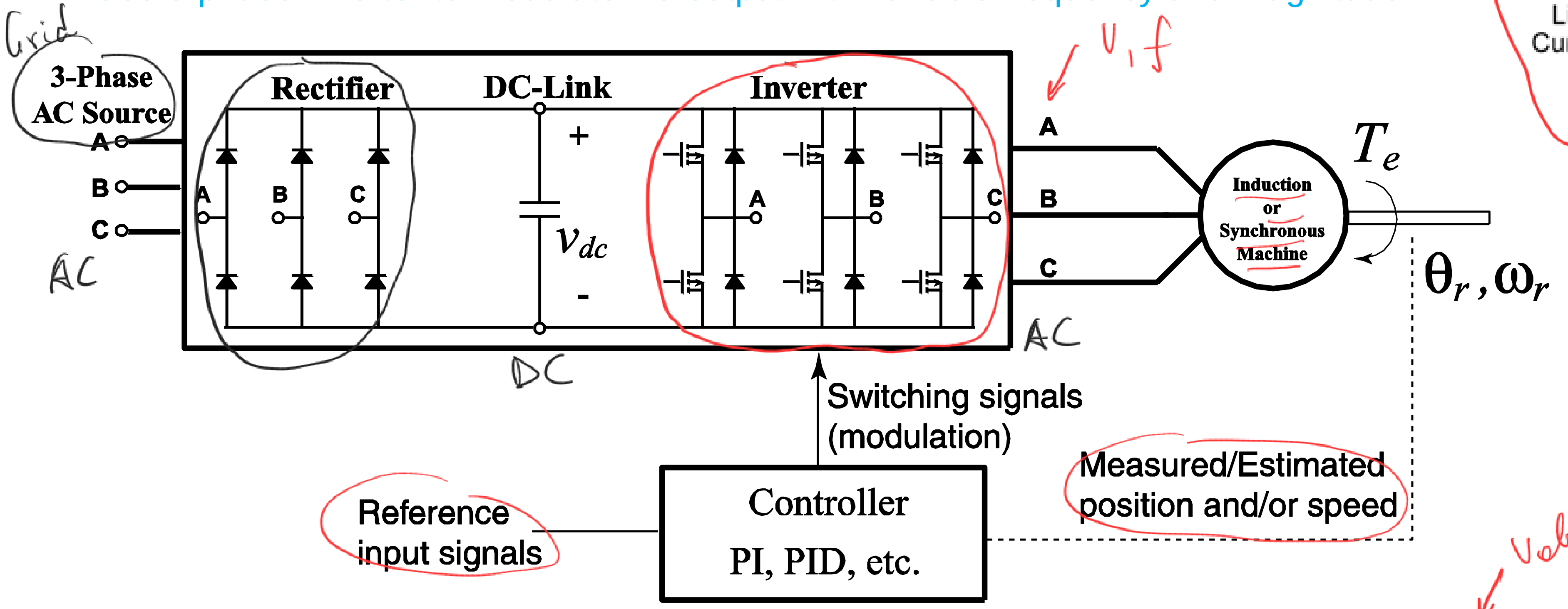
v, f

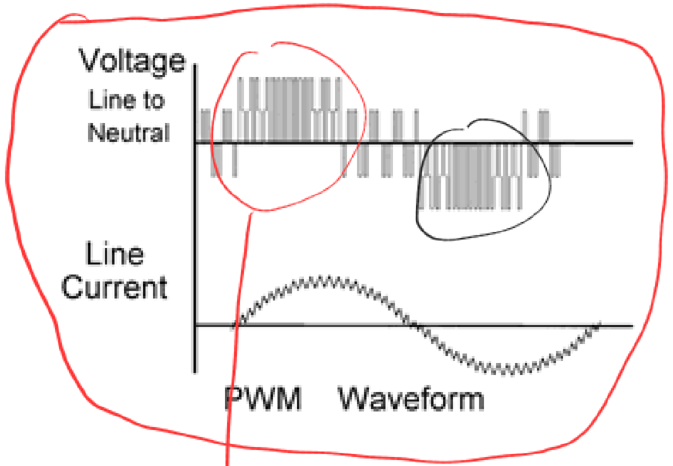



DC-AC or AC-AC converter

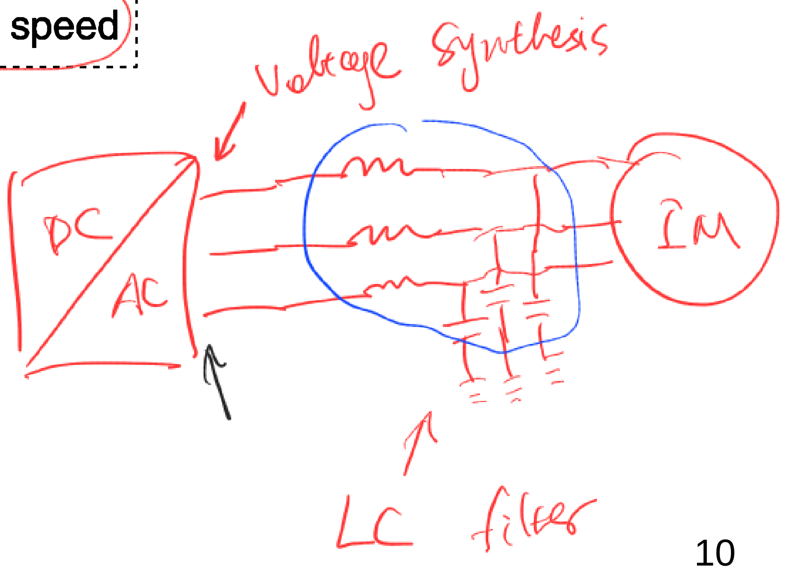
# Variable Frequency Drives (VFDs)

1. Use 3-phase rectifier to obtain DC from 60Hz input
2. Use 3-phase inverter to modulate AC output with variable frequency and magnitude




EMI
interfere with digital meters




**Typical operation** under nominal flux: Volts/Hertz (V/f)

$$v_{1a} = \sqrt{2}\cdot V_{rms}\cos(\omega_e t) = R_1 i_{1a} + \frac{d\lambda_{1a}}{dt}$$

$$\lambda_{1a} \approx \frac{\sqrt{2}\cdot V_{rms}}{\omega_e}\sin(\omega_e t) \Rightarrow |\lambda_{1a}| = \frac{\sqrt{2}\cdot V_{rms}}{\omega_e} = \frac{\sqrt{2}}{2\pi}\cdot\frac{V_{rms}}{f_e}$$

# Variable Frequency Drives (VFDs)

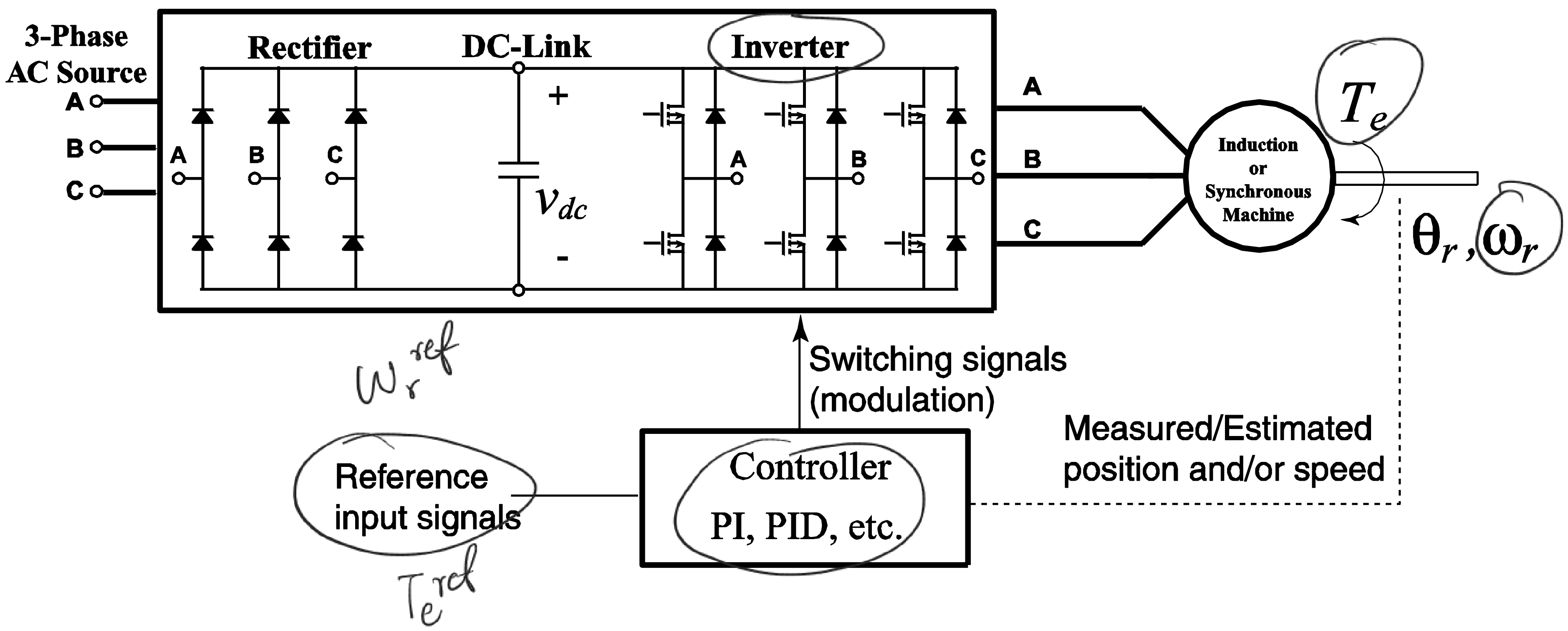
## ➢ Typical Control Modes (achieved by outer control loop)

**Controlled (Constant) Speed Operation** → Elevators

- Control tries to keep the speed at specified value no matter what the load is doing ⇒ so torque is changing

**Controlled (Constant) Torque Operation** → Tools

- Control tries to keep the torque at specified level no matter what the load is doing ⇒ so speed is changing



# Variable Frequency Drives (VFDs)



0.2 - 3 kW



10 kW



MW

# Module 6: AC Synchronous Machines

# Objectives & important concepts

- Applications of synchronous machines
- Types and construction of typical synchronous machines, types of rotor, excitation, etc
- Direct & quadrature magnetic axes
- Principle of operation, rotor angle, motoring, generating
- Steady state equivalent circuit
- Determination of parameters, OS and SC tests
- Basic phasor diagrams
- Torque (power) – angle characteristic, real & reactive power, V-characteristic
- Salient-rotor machines, phasor diagrams
- Torque (power) – angle characteristic, real & reactive power
- Principle of speed control
- Principle of reluctance and brushless dc motors

- Must read **Chapter 6** → Lab 5

# Electrical Motors & Generators

## Electrical Energy Generation → SM → Generation

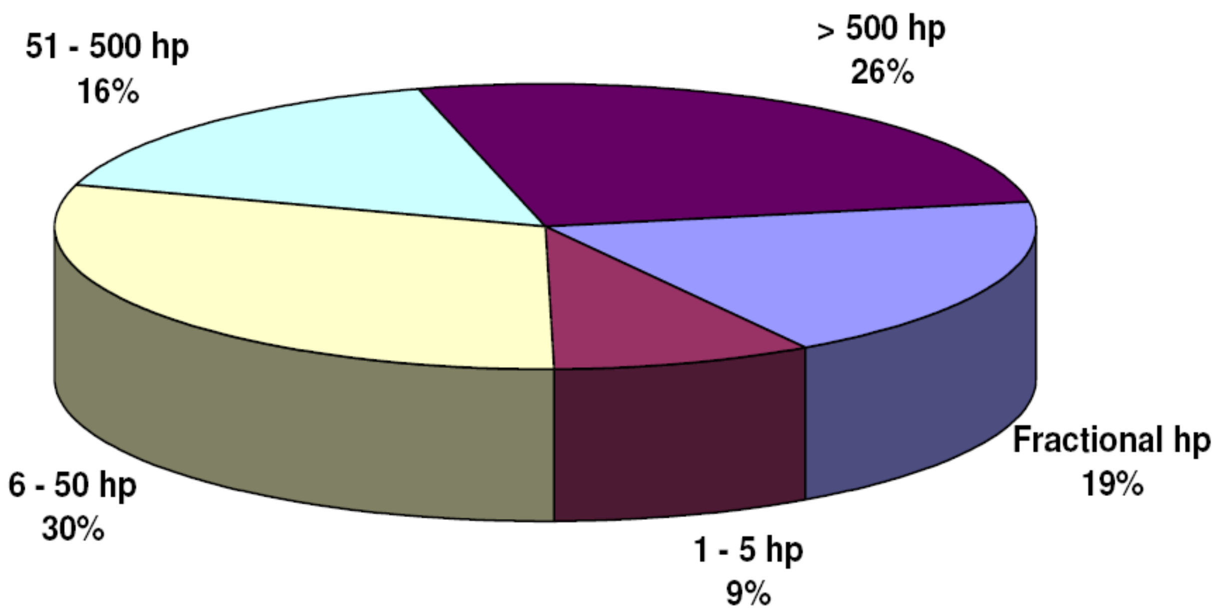
- Almost all electricity produced in BC (10 ~12GW) is produced by **Synchronous Generators**

## Electrical Energy Utilization → IM → Consumption

- About 65% of all electricity is consumed by motors: mostly induction, few synchronous, etc.
- For industry it is about 85%

## Electromechanical Energy Conversion Devices

- Predominant way of generating and consuming electrical energy



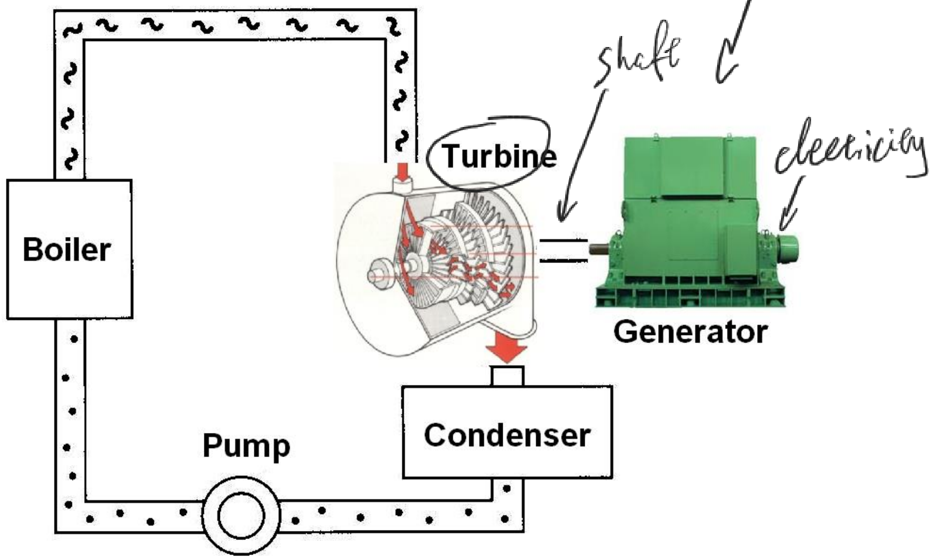

SM: scales well
↳ high $\eta$ even at
high power

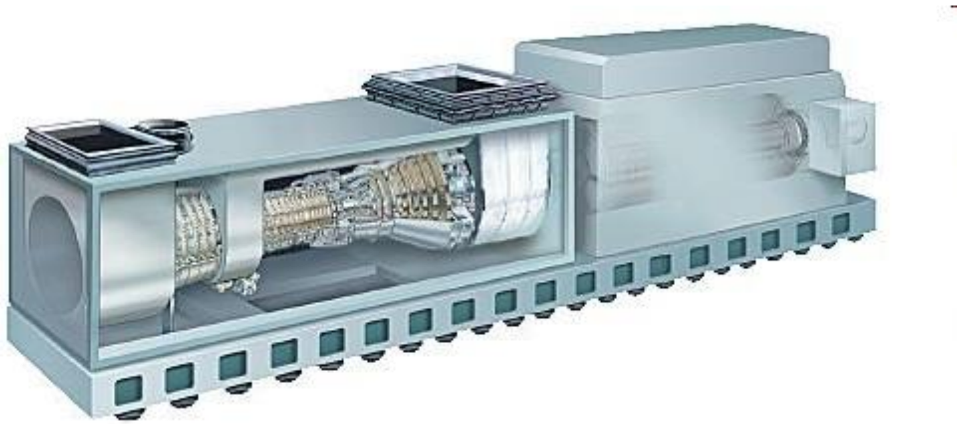
# Generation of Electricity - Thermal

## Electromechanical Energy Conversion – Big Scale

- Gas/Steam turbines have high speed
- Generator shaft will also have high speed
- Gearbox is not practical – additional losses
- The generator is typically synchronous machine
- The AC power must be at 60Hz grid frequency

# of poles



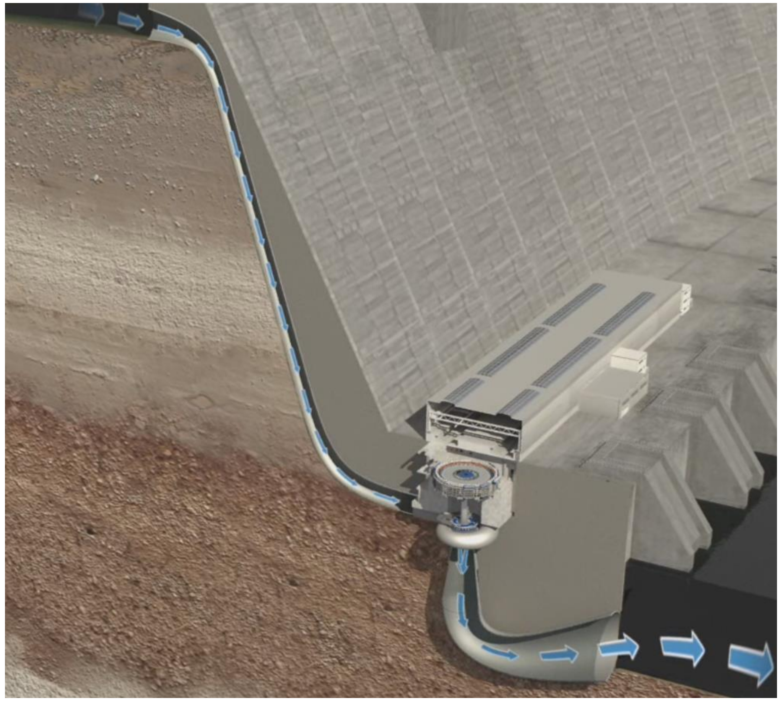



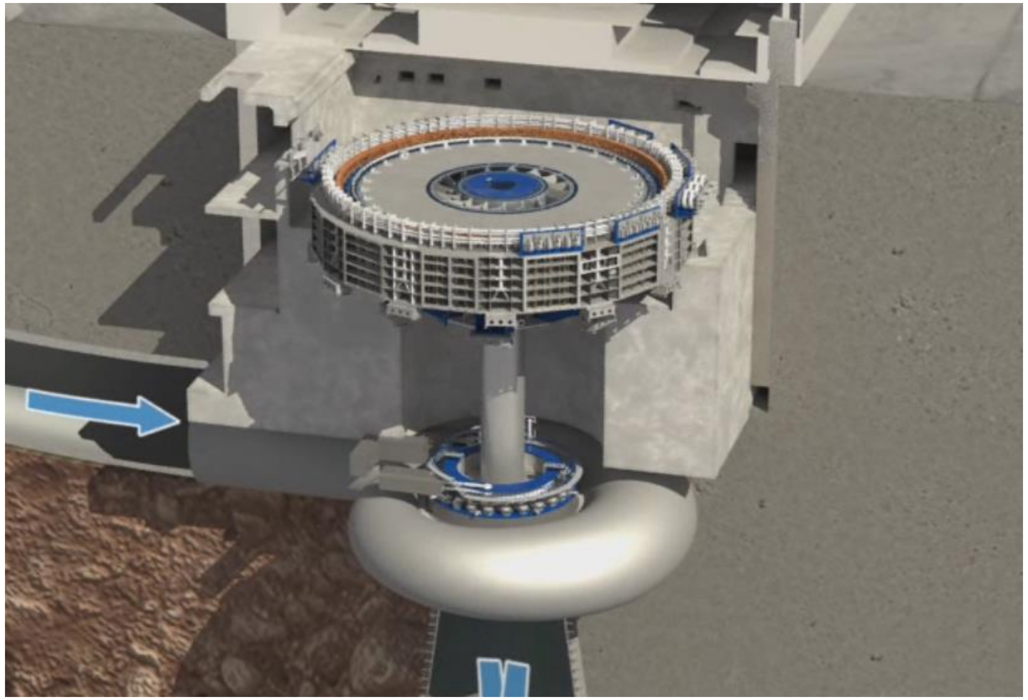
# Generation of Electricity – Hydro Power

most electricity in BC / Canada

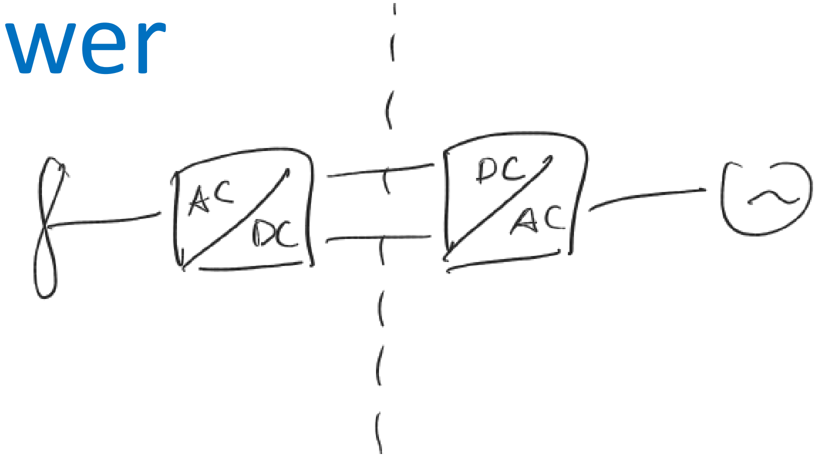
**Electromechanical Energy Conversion – Big Scale**

- Falling water has low speed
- Generator shaft will also have low speed
- Because the generator is synchronous, its speed must be constant for the 60Hz grid frequency





# Generation of Electricity – Wind Power



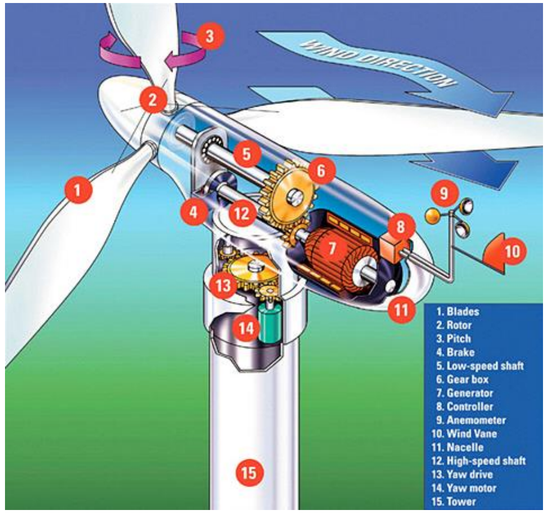

## Electromechanical Energy Conversion

- Blowing wind has low speed
- Generator shaft will also have low speed
- Gearbox may be used to increase the shaft speed
- The generator may be asynchronous or synchronous
- The AC power must be at 60Hz grid frequency
- Power electronic converters are used to decouple the speed/frequency
- DC could be used for HVDC transmission of wind power

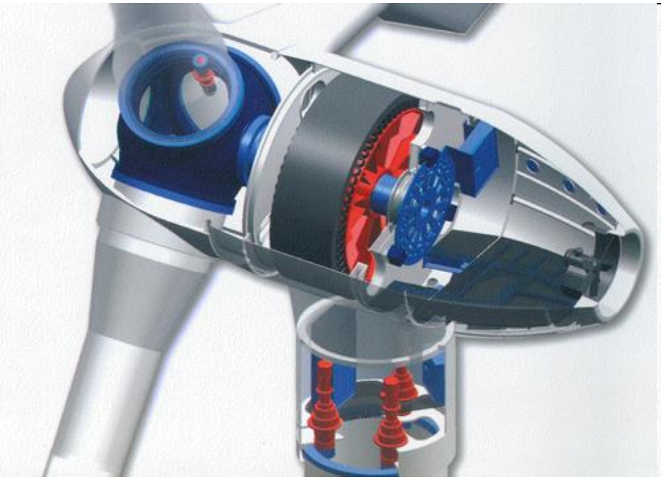
< 5 MW → IM

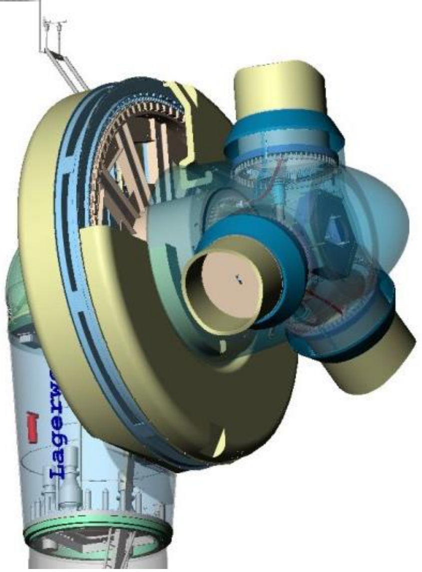
20 MW → SM

**Induction Generator Turbine**




**Direct Drive Synchronous Generator Turbine**





UBC : 40 - 60 MW

# Synchronous Machines

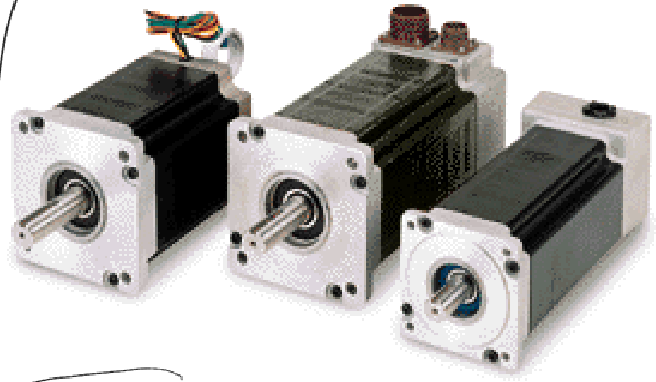
Portable Diesel Generators

0.5 . . . 10 kW

Car Alternators

DC — DC/AC = SM

Small motors



Brushless DC and Servo Motors

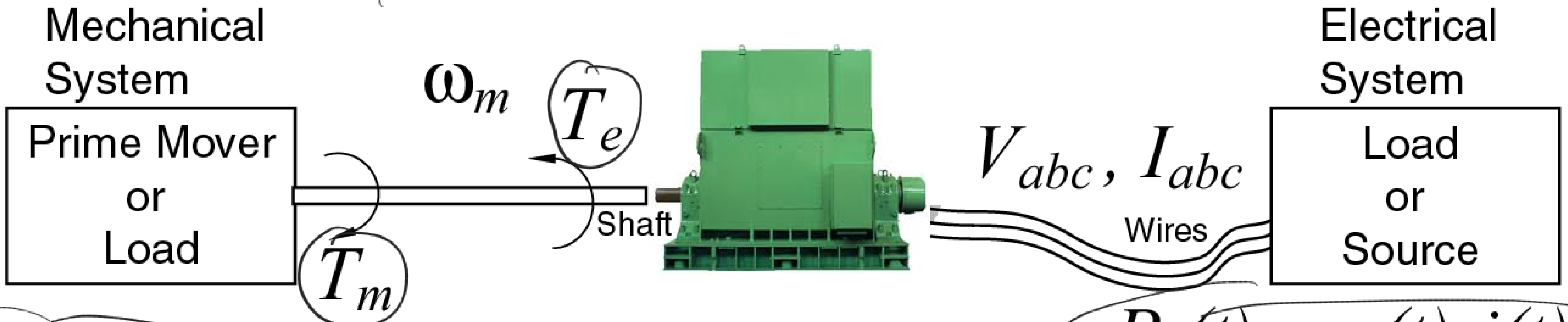
↳ scooters, drones

# Electromechanical Energy Conversion

Mechanical System (Prime Mover, Turbine, etc.) or (Load, plant ) ⟷ Mechanical Energy ⟷ Conversion Device ⟷ Electrical Energy ⟷ Electrical System (Transmission, load, etc.) or (Substation, feeder, source, etc.)

SM

Power Flow => Generator




$$P_m = \omega_m * T_m$$

$$P_e(t) = v(t) * i(t)$$

Motor <= Power Flow

Can the energy flow in both directions in the same device? Yes

Can the energy flow into the device from both sides? Yes

Can the energy flow out of the device from both ends? Yes

What is inside that devices that can store energy? Magnetic field, inertia (mechanical)

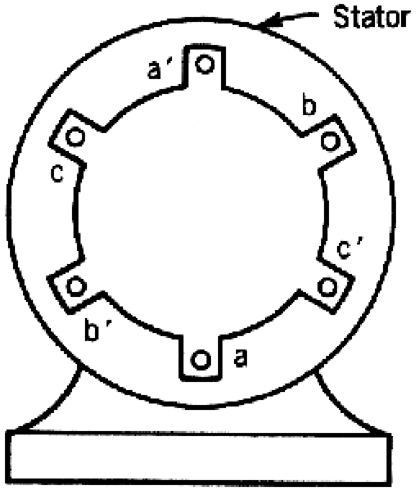
How does the energy gets converted? magnetic field <=> mechanical system (100% efficient)

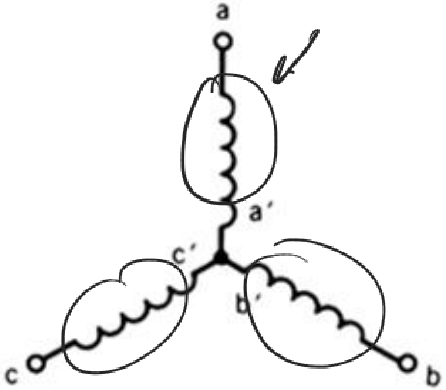
# Stator Windings → similar to IM

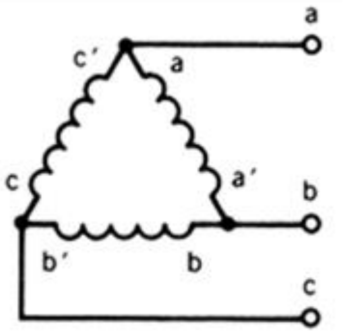
- ✓ A typical stator would have 3-phases, which may be Y or Δ connected
- ✓ Windings may have multiple sections with parallel and/or series connection
- ✓ The actual winding will be typically distributed as to better utilize stator volume and approximate smooth "sinusoidal" distribution











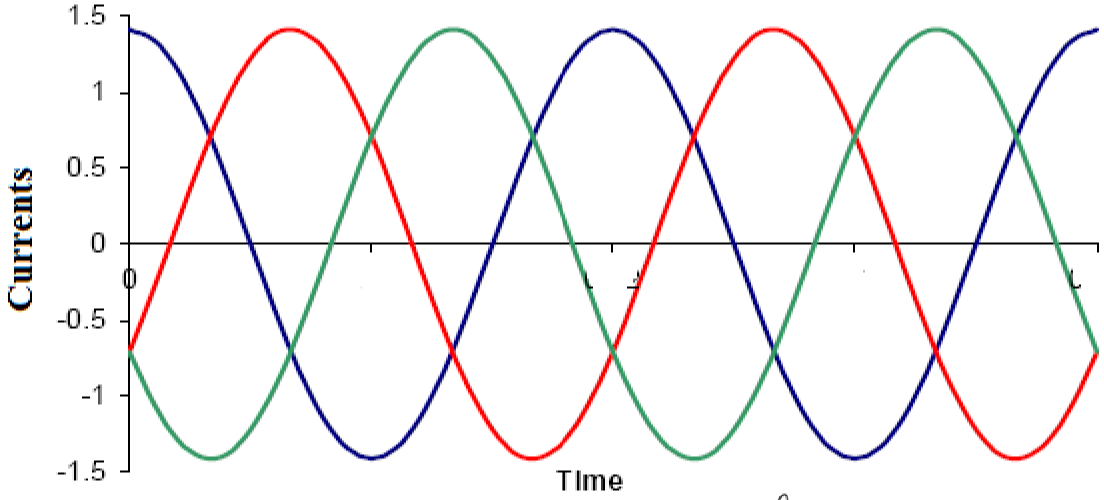

For simplicity, we can assume concentrated winding

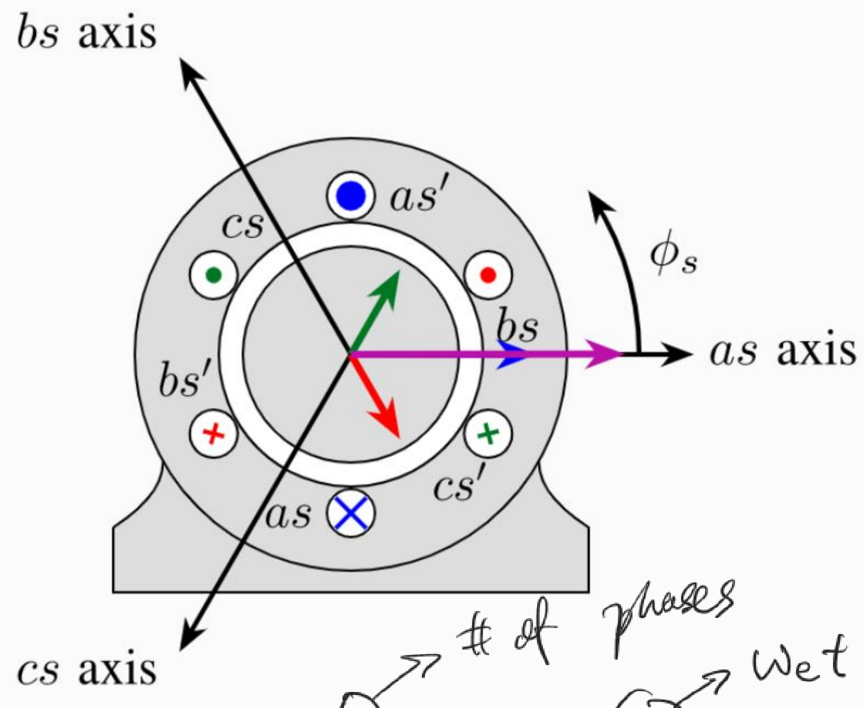
# Rotating Magnetic Field

## ➢ How to produce rotating magnetic field:

need a minimum of 2 phases

1. Given a balanced set of ac currents shifted in time →
2. Apply these currents to windings symmetrically shifted in space ⇒ Produce vector $\mathbf{F}_s$ that
   - Has constant magnitude
   - Rotates in space → $f_e$




# of phases

$\omega_e t$

$$\mathbf{F}_s = (3/2)\, F_m \angle \theta_e$$

Inc. # of phases

↓

dec. current to keep same MMF → less likely to have saturation

# Looking ahead…

- Continue **Module 6**