ELEC 343 Electromechanics

Module 8:

Part 1: Induction Motors (Chap. 6), Lab-5
Part 2: Single-Phase Motors (Chap. 10)

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Class Webpage:
http://courses.ece.ubc.ca/elec343

Important Concepts and Objectives:

- Types and construction of commonly used Induction Motors
- Asynchronous speed, slip & principle of torque production
- Steady-state equivalent circuit
- Power conversion, torque-speed characteristic
- Deep-rotor-bar, Standard Motors NEMA Classes
- Single-phase induction motors, principle & types
- Universal motor

Electromechanics Devices

Electrical Energy Generation

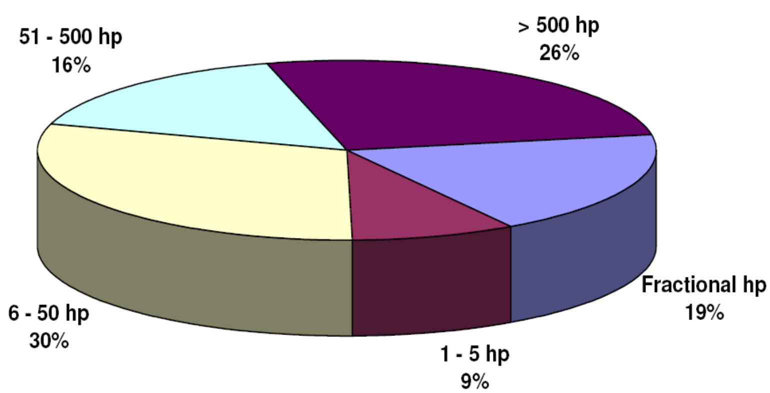
- Almost all electricity produced in BC (10 ~12GW) is produced by Synchronous Generators

Electrical Energy Utilization

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

Electromechanical Energy Conversion Devices

- Predominant way of generating and consuming electrical energy



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.)

Power Flow => Generator

$$P_m = \omega_m * T_m \qquad P_e(t) = v(t) * i(t)$$

Motor <= Power Flow

Can the energy flow in both directions in the same device?
Can the energy flow into the device from both sides?
Can the energy flow out of the device from both ends?
What is inside that devices that can store energy?
How does the energy gets converted?

Fundamentals of Energy Conversion

Fundamentals: Maxwell's Equations (1870s)

1) Faraday's Law: **E**lectro**M**otive **F**orce (emf)

The line integral of electric field around a closed contour *C* is equal to the negative of the rate of change of the magnetic flux through that contour

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt}\int_S \mathbf{B} \cdot d\mathbf{a} = -\frac{d\Phi}{dt}$$

For winding with N turns

$$e = N\frac{d\Phi}{dt} = \frac{d\lambda}{dt} = EMF$$

2) Ampere's Law for static electric field: **M**agneto**M**otive **F**orce (mmf)

The line integral of the magnetic field *B* around a closed contour *C* is proportional to the net electric current flowing through that contour *C*

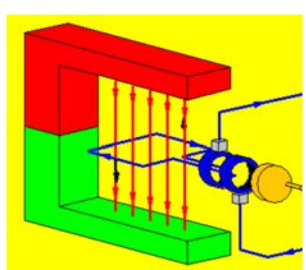
$$\oint_C \mathbf{B} \cdot d\mathbf{l} = \mu_0 \int_S J \cdot da = \mu_0 I_{net}$$

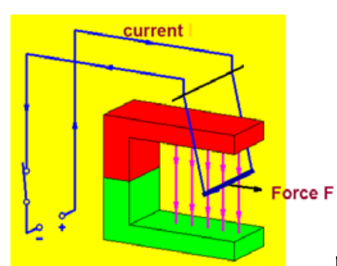
Lorentz Force $F = lBi$

For winding with *N* turns

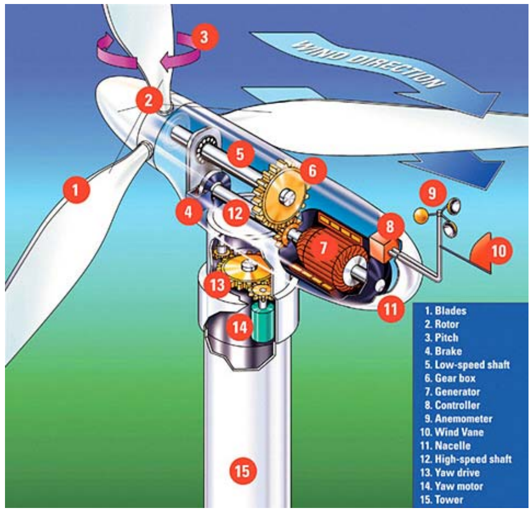
$$\oint_C \mathbf{H} \cdot d\mathbf{l} = I_{net} = N \cdot i = MMF$$

How "clean" and "efficient" is this energy conversion?





Induction Generators

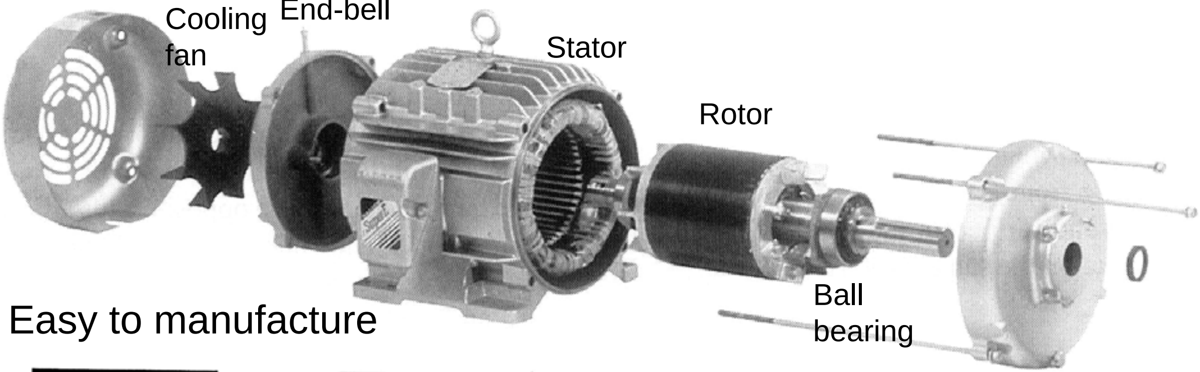


- Speed of the shaft changes
- Range from 100W to 2MW
- Efficient
- Reliable
- Low maintenance
- Often used with power electronic inverters

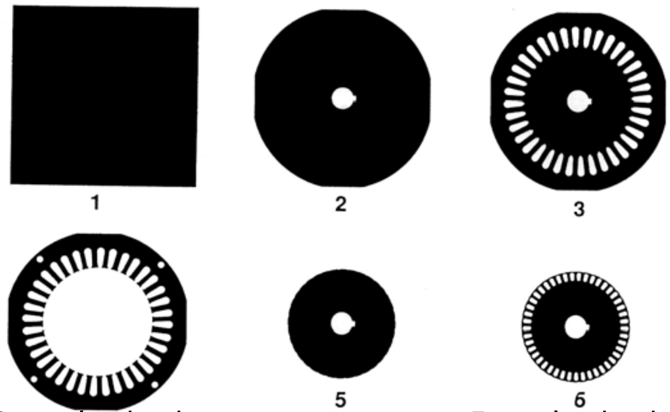
Part 1: Typical AC Induction Motors (IM)

Most commonly used AC motor in industrial applications
- Efficient
- Reliable
- Low (or no) maintenance
- Inexpensive to produce
- Often used with power-electronic (variable-speed) drives

Construction of a Typical IM



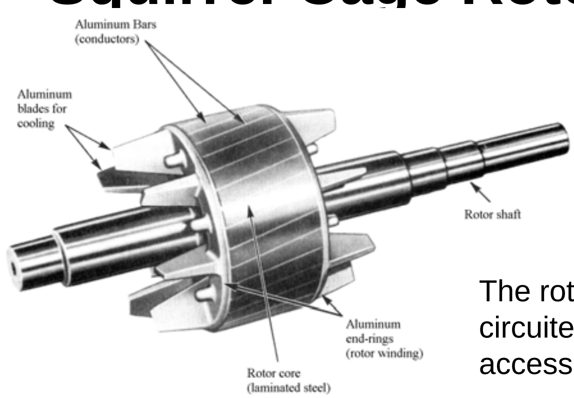
Easy to manufacture



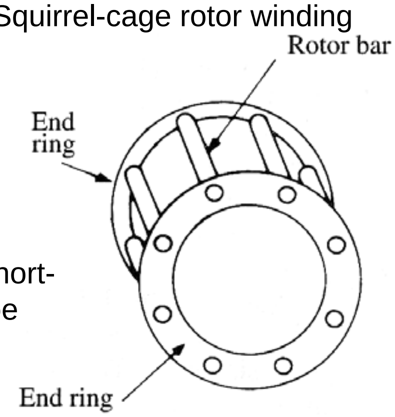
Stator lamination

Rotor lamination

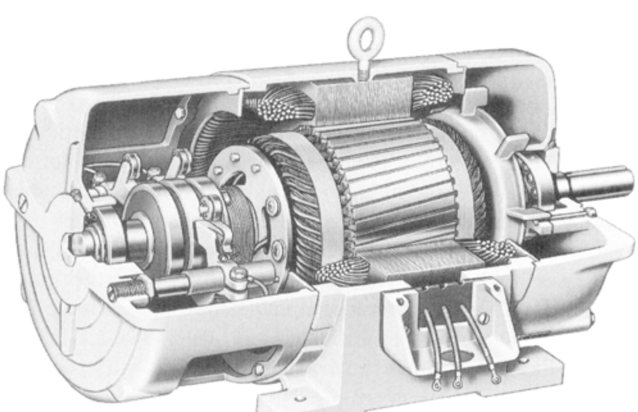
Squirrel-Cage Rotor or Wound Rotor



Squirrel-cage rotor winding



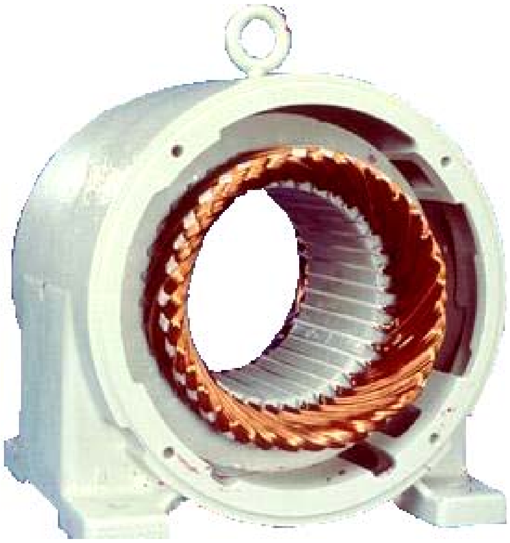
The rotor winding is short-circuited and cannot be accessed!

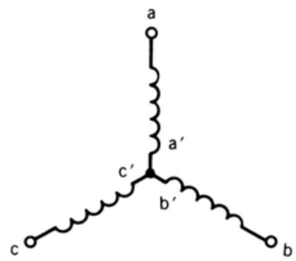


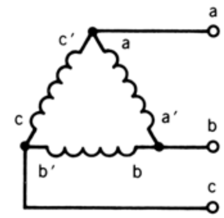
The rotor winding is connected to the slip-rings and can be accessed from outside => Doubly-Fed Induction Machine (DFIM)

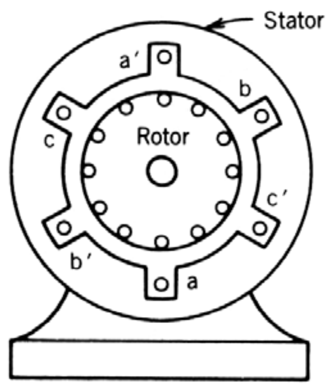
Stator Winding

Winding may be Y or Δ connected









The actual winding is distributed to approximate sinusoidal distribution of magnetic field inside, and to maximize the use of magnetic core

We can assume concentrated winding for simplicity of analysis and easy understanding

Speed of a *P*-Pole Motor

Recall *P*-pole Stator System (*P* – number of magnetic poles)

$$\theta_e = \omega_e t$$ Electrical displacement

Electrical (stator) speed for f_e = 60 Hz

$$\omega_e = 2\pi f_e \approx 377 \,[\mathrm{r/s}]$$

Synchronous speed is 2/*P* of the electrical speed

$$\omega_{syn} = \frac{2}{P}\omega_e \,[\mathrm{r/s}]$$

$$n_{syn} = \frac{120}{p} \cdot f_e \quad [\mathrm{rpm}]$$

P	ω_{syn} rad/sec	n_{syn} rpm	Typical speed, n rpm
2	120π	3600	3570
4	60π	1800	1750
6	40π	1200	1160
8	30π	900	830

a little less than sync

Referred speed & position $$\omega_r = \frac{P}{2}\omega_{rm} \qquad \theta_r = \frac{P}{2}\theta_{rm}$$

We can always "convert" a *P*-pole motor into an equivalent 2-pole motor using the *P*/2 factor !

Speed of a *P*-Pole Motor

P – denoted number of poles (*P* = 2, 4, 6, …)

$\theta_e = \omega_e t$ Electrical displacement

Electrical (stator) speed for f_e = 50 Hz

$$\omega_e = 2\pi f_e \approx 314\,[\mathrm{r/s}]$$

Synchronous speed is 2/*P* of the electrical speed

$$\omega_{syn} = \frac{2}{P}\omega_e\,[\mathrm{r/s}]$$

$$n_{syn} = \frac{120}{P}\cdot f_e \quad [\mathrm{rpm}]$$

P	ω_{syn} rad/sec	n_{syn} rpm	Typical speed, n rpm
2	100π	3000	
4	50π	1500	
6	33.3π	1000	
8	25π	750	

We can always “convert” a *P*-pole motor into an equivalent 2-pole motor using the *P*/2 factor !

Equivalent 2-pole motor seed $\omega_r = \frac{P}{2}\omega_{rm}$ Actual mechanical speed

a little less

Actual mechanical speed is not constant and depends on the mechanical load!

Slip & Asynchronous Speed

Induction Machine = Asynchronous Machine

⇒ Speed of the rotor is different from the speed of the stator magnetic field / poles

⇒ Slip – difference between the synchronous field speed and the rotor speed

Fractional Slip $$s = \frac{n_{syn} - n}{n_{syn}} = \frac{\omega_{syn} - \omega_{rm}}{\omega_{syn}} = \frac{\omega_e - \omega_r}{\omega_e}$$

Percent Slip $$s = \frac{n_{syn} - n}{n_{syn}}100\%$$

Rotor speed relative to the stator magnetic field (poles) =>

Slip frequency $$\omega_s = \omega_e - \omega_r = s\cdot\omega_e$$

Rotor mechanical speed $$\omega_{rm} = (1-s)\omega_{syn} \qquad n = (1-s)n_{syn}$$

Frequency of Rotor Currents

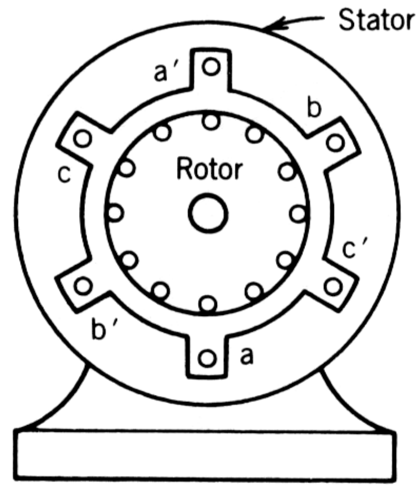
Slip frequency $\omega_s = \omega_e - \omega_r = s \cdot \omega_e$

Rotor electrical speed relative to the stator magnetic field

$$f_r = \frac{\omega_s}{2\pi} = \frac{s\omega_e}{2\pi} = s \cdot f_e$$

$$n_{syn} = \frac{2}{P} 60 f_e$$

$$f_r = \frac{P}{120} s \cdot n_{syn} = \frac{P}{120}\left(n_{syn} - n\right)$$



Rotor winding (circuit) operates at different frequency !

This frequency is proportional to slip *S*

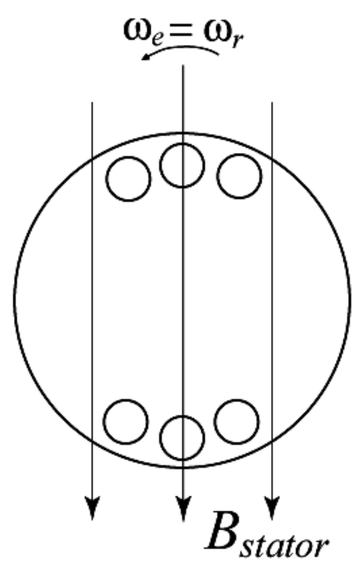
Principle of Operation

a) Assume synchronous speed $\omega_r = \omega_e$

$s = \dfrac{\omega_e - \omega_r}{\omega_e} = 0$ and

$\omega_s = \omega_e - \omega_r = 0$

- No flux crosses the rotor bars
- No current induced
- No torque produced

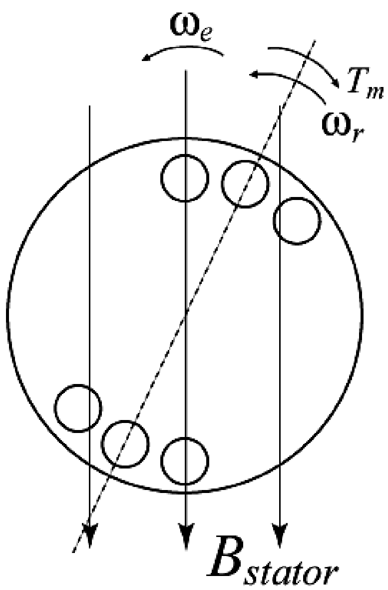


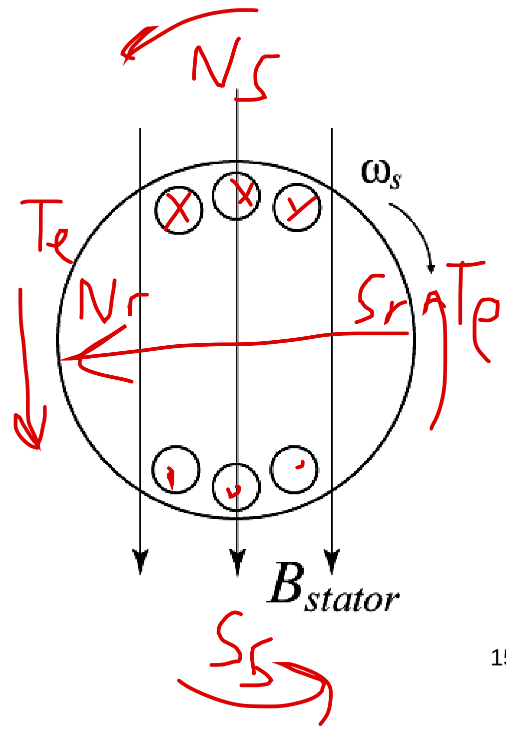
Principle of Operation (motoring)

b) Assume T_m in CW, and $\omega_r < \omega_e$

$s = \dfrac{\omega_e - \omega_r}{\omega_e} > 0 \qquad \omega_s = \omega_e - \omega_r$

Relative to the stator field!



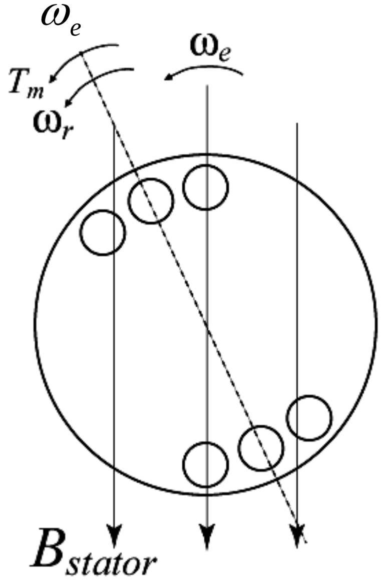


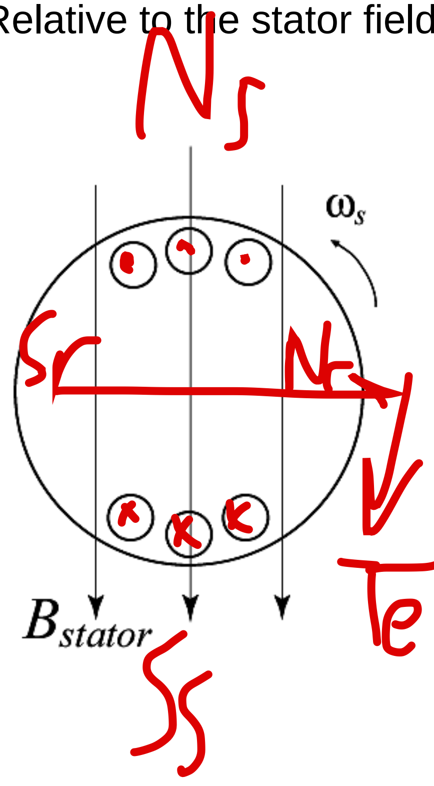
Principle of Operation (generating)

c) Assume T_m in CCW, and $\omega_r > \omega_e$

$s = \dfrac{\omega_e - \omega_r}{\omega_e} < 0 \qquad \omega_s = \omega_e - \omega_r$

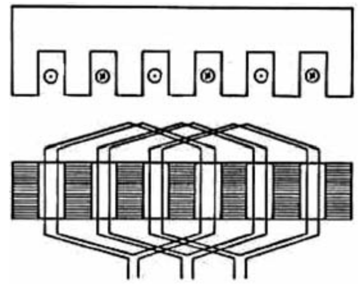
Relative to the stator field!



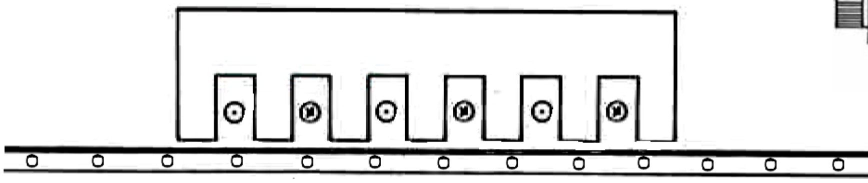


Principle of Linear Induction Machine

Recall Running Magnetic field

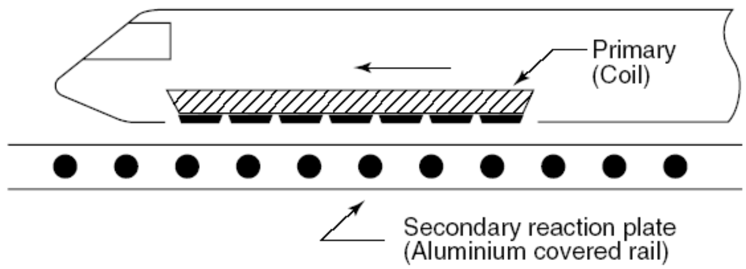


Movable platform – what used to be “Stator”



Stationary rail – what used to be “Rotor”

Train Propulsion System



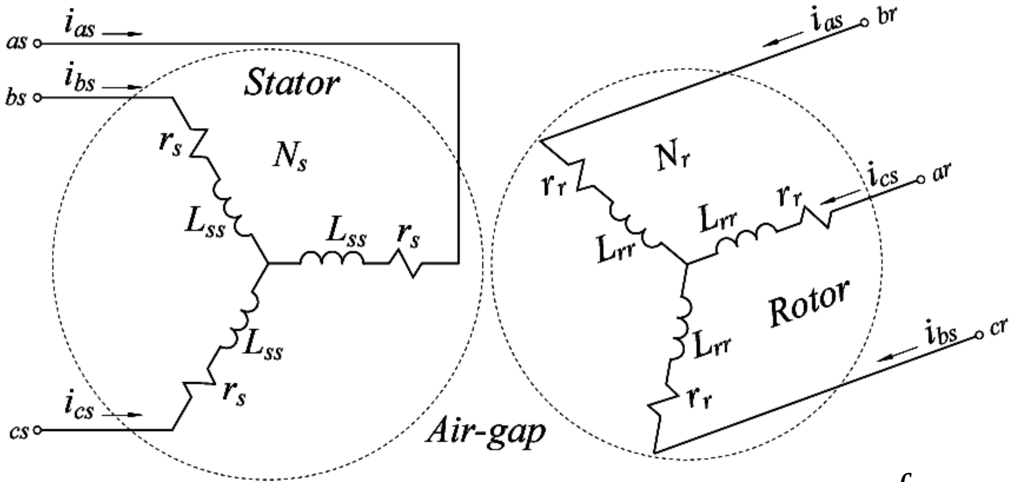
Linear Induction Motors (LIM)

Millennium Line

- Propulsion System
- Motors react with aluminum-capped steel rail on the guideway
- LIM provide both propulsion and regenerative braking
- No moving parts
- Reduced maintenance and risk of mechanical failure

Steady-State Equivalent Circuit

- Assume rotor has the same number of phases as stator (3-ph)



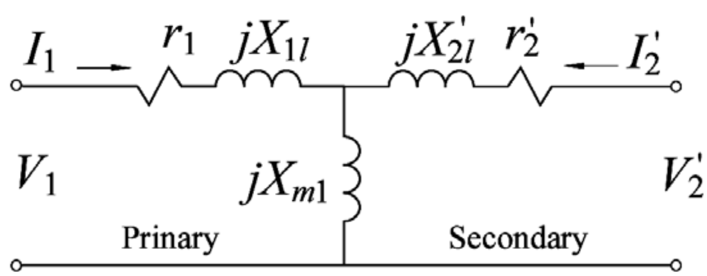
$$f_r = s \cdot f_e = s \cdot f_s$$
$$= \frac{p}{120}\left(n_{syn} - n\right)$$

- Rotor winding (circuit) operates at different frequency
- Rotor circuit is typically shorted (squirrel-cage)
- At $\omega_r = 0$, motor looks like 3-phase transformer
- Develop equivalent circuit per-phase
- Extend the results to 3-phase

Steady-State Equivalent Circuit

- Recall equivalent circuit for transformer

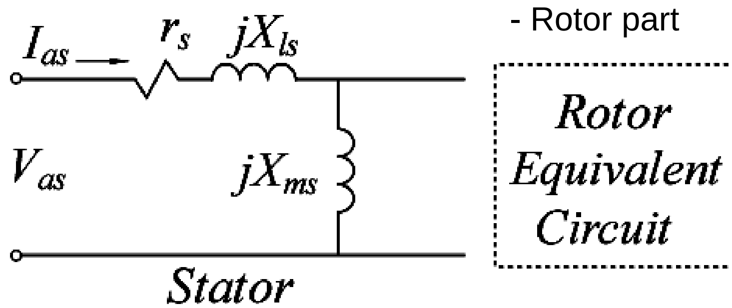
$$X_{11} = X_{1l} + X_{m1}$$



- Stator part

$$X_{ss} = X_{ls} + X_{ms}$$
$$= \omega_e L_{ls} + \omega_e L_{ms}$$

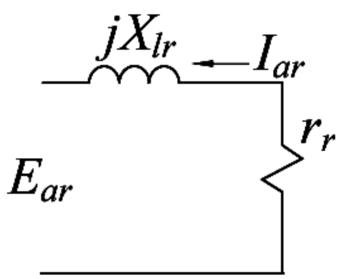
- Rotor part



- What about rotor part ?

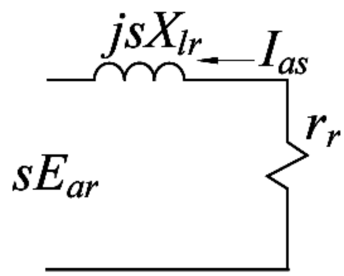
Rotor Equivalent Circuit

At stall, $\omega_r = 0$



$$X_{lr} = \omega_s L_{lr} = s\omega_e L_{lr}$$
$$= 2\pi f_e s L_{lr}$$

When rotor moves, ω_r



$$\omega_s L_{lr} = s\omega_e L_{lr} = sX_{lr}$$

Slip dependent circuit !

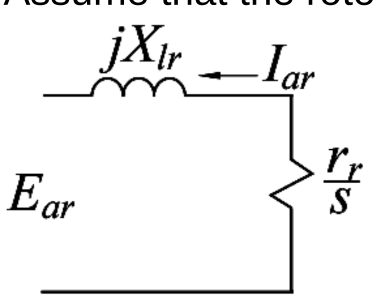
$E_{ar} =$ per-phase induced voltage in the rotor at $\omega_r = 0$

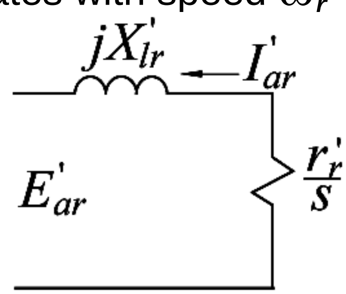
$X_{lr} =$ per-phase rotor winding leakage reactance

$L_{lr} =$ per-phase rotor winding leakage inductance

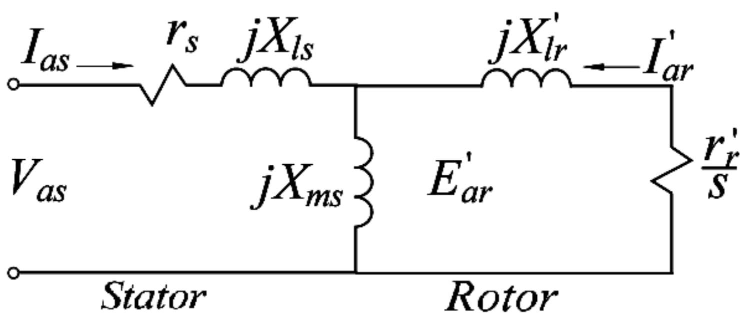
Equivalent Circuit

Assume that the rotor rotates with speed ω_r





Slip dependent rotor resistance !



Final circuit for the short-circuited rotor !

Use stator-to-rotor turns-ration $a = N_s/N_r$

Refer rotor variables to the Stator side

$$E'_{ar} = a \cdot E_{ar}$$

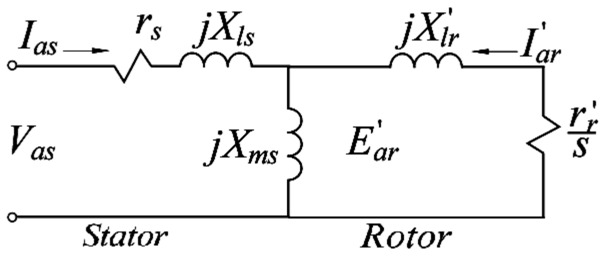
$$I'_{ar} = I_{ar} / a$$

$$X'_{lr} = a^2 \cdot X_{lr}$$

$$r'_r = a^2 \cdot r_r$$

Determining Machine Parameters

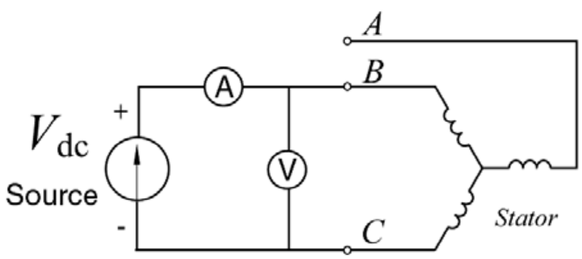
Consider Equivalent Circuit



Tests to determine circuit parameters:

1. DC Measurement of winding resistance
2. No Load Test (like Open-Circuit in transformer)
3. Blocked Rotor Test (like Short-Circuit in transformer)

1. DC Measurement of winding resistance (use DC source or Multi-meter)

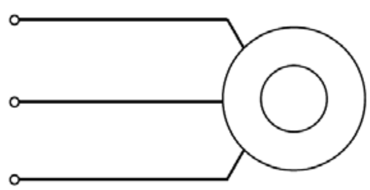


$$r_s = \frac{V_{dc}}{2I_{dc}}$$

Determining Machine Parameters

2. No-Load (NL) Test

Apply rated voltage $V_{ph,NL}$

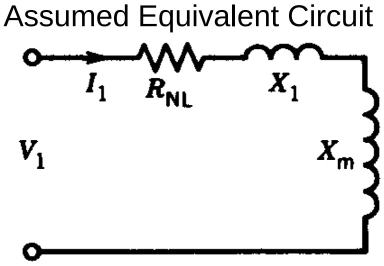


Measure

$$V_{ph}, P_{nl}, I_{nl}$$

Rotational losses $P_{rotational} = P_{NL} - 3r_s I_{NL}^2$

Assumed Equivalent Circuit



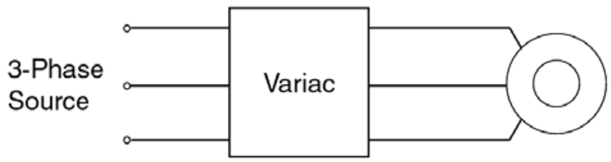
Combined reactance $X_{ls} + X_m = X_{NL} = \dfrac{Q_{NL}}{3I_{NL}^2}$

where reactive power

$$Q_{NL} = \sqrt{S_{NL}^2 - P_{NL}^2} = \sqrt{(3I_{NL}V_1)^2 - P_{NL}^2}$$

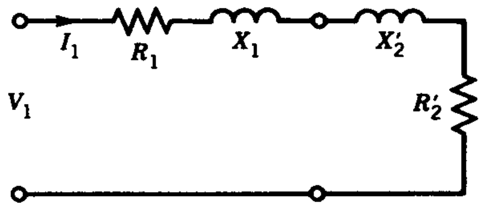
Determining Machine Parameters

3. Blocked-Rotor (BR) Test



Apply reduced voltage $V_{ph,BR}$
(this test may be performed at reduced frequency)

Assumed Equivalent Circuit



Measure $V_{ph-BR}, P_{BR}, I_{BR}$

Combined resistance $r_s + r_r' = R_{BR} = \dfrac{P_{BR}}{3I_{BR}^2}$

Combined reactance

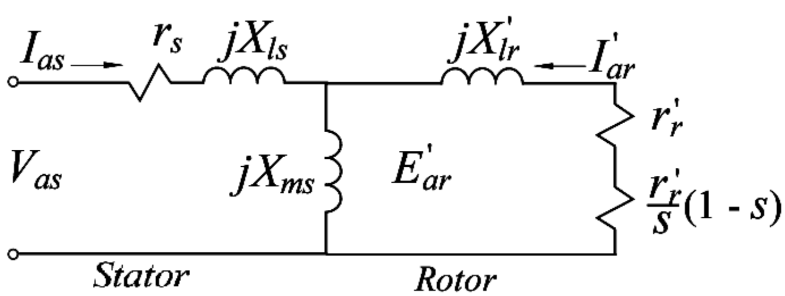
$$X_{BR} = \sqrt{Z_{BR}^2 - R_{BR}^2} = \sqrt{(V_1 / I_{BR})^2 - R_{BR}^2}$$

Leakage reactance $X_{ls} \approx X_{lr}' = \dfrac{X_{BR}}{2}$

Magnetizing reactance $X_m = X_{NL} - X_{ls}$

Rotor resistance $r_r' = R_{BR} - r_s$

Power Conversion



Split rotor resistance

$$\frac{r_r'}{s} = r_r' + \frac{r_r' - s r_r'}{s}$$

Input Power $P_{in} = 3|V_{as}| \cdot |I_{as}| \cos(\varphi) = 3V_{s,ph} I_{s,ph} \cos(\varphi)$

Stator resistance loss $P_{s,loss} = 3I_s^2 r_s$

Air-gap power $P_{ag} = 3I_r'^2 \dfrac{r_r'}{s}$

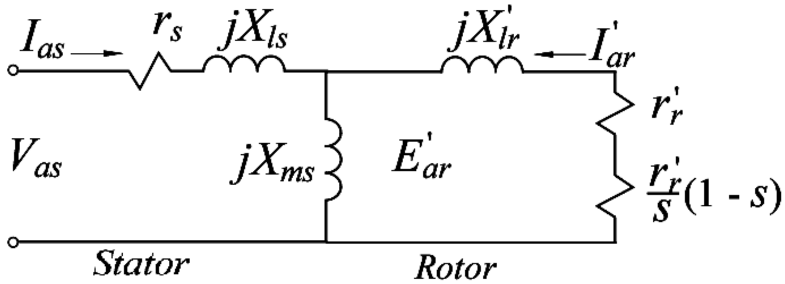
Rotor resistance loss $P_{r,loss} = 3I_r'^2 r_r'$

Conversion power

$$P_{conv} = 3I_r'^2 r_r' \left(\frac{1-s}{s}\right)$$

$$= P_{ag}(1-s)$$

Power Conversion - Torque



Split rotor resistance

Electromagnetic torque $$T_e = \frac{P_{conv}}{\omega_{rm}} = \frac{(1-s)P_{ag}}{\omega_{rm}} = \frac{P_{ag}}{\omega_{syn}}$$

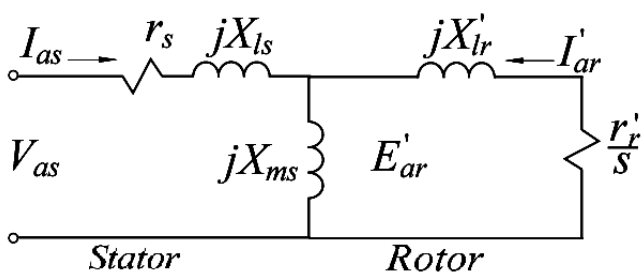
Recall the air-gap power $$P_{ag} = 3I_r'^2 \frac{r_r'}{s}$$

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

The expression for the torque becomes

$$T_e = 3\frac{P}{2} \cdot \frac{I_r'^2 r_r'}{s \cdot \omega_e}$$

Electromagnetic Torque



Electromagnetic torque

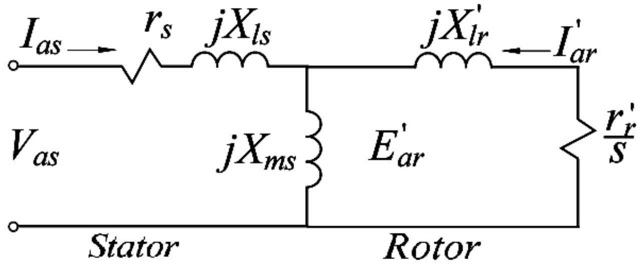
$$T_e = 3\frac{P}{2} \cdot \frac{|I_r'|^2 r_r'}{s \cdot \omega_e}$$

$$I'_{ar} = -\frac{E'_{ar}}{r'_r/s + jX'_{lr}} \qquad E'_{ar} = \frac{jX_{ms}(jX'_{lr} + r'_r/s)}{jX_{ms} + jX'_{lr} + r'_r/s} I_{as}$$

$$I'_{ar} = -\frac{jX_{ms}}{r'_r/s + jX'_{rr}} I_{as} \qquad |I'_r|^2 = \frac{X_{ms}^2}{(r'_r/s)^2 + X'^2_{rr}} |I_s|^2$$

$$T_e = 3\frac{P}{2} \cdot \frac{r'_r}{s \cdot \omega_e} \cdot \frac{X_{ms}^2}{(r'_r/s)^2 + X'^2_{rr}} |I_s|^2 = 3\frac{P}{2} \cdot \frac{(X_{ms}^2/\omega_e)(r'_r/s)}{(r'_r/s)^2 + X'^2_{rr}} |I_s|^2$$

Electromagnetic Torque



Use per-phase equivalent circuit with shorted rotor

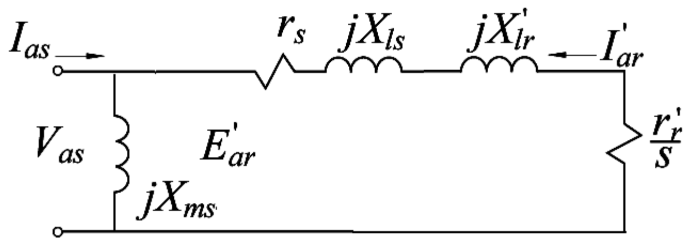
Stator current $I_s = \dfrac{V_{as}}{Z_{eq}}$

$$Z_{eq} = r_s + jX_{ls} + \frac{jX_{ms}\left(jX'_{lr} + r'_r/s\right)}{jX'_{rr} + r'_r/s}$$

$$= \frac{r_s\left(r'_r/s\right) + \left\{X_{ms}^2 - X_{ss}X'_{rr} + j\left[\left(r'_r/s\right)X_{ss} + r_s X'_{rr}\right]\right\}}{jX'_{rr} + r'_r/s}$$

$$T_e = 3\frac{P}{2}\cdot\frac{\left(X_{ms}^2/\omega_e\right)r'_r s}{\left[r_s r'_r + s\left(X_{ms}^2 - X_{ss}X'_{rr}\right)\right]^2 + \left(r'_r X_{ss} + s r_s X'_{rr}\right)^2}\left|V_s\right|^2$$

Approximate Equivalent Circuit



Use per-phase equivalent circuit with shorted rotor

Electromagnetic torque

$$T_e = 3\frac{P}{2}\cdot\frac{\left|I'_r\right|^2 r'_r}{s\cdot\omega_e}$$

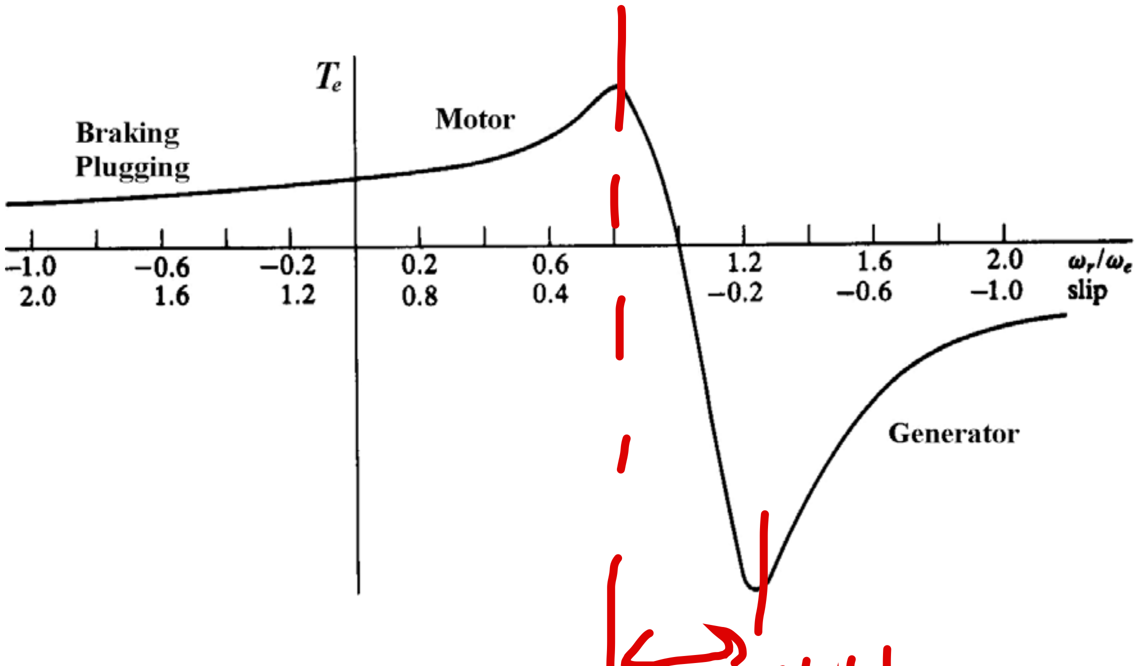
$$I'_{ar} = -\frac{V_{as}}{r_s + r'_r/s + j\left(X_{ls} + X'_{lr}\right)}$$

$$\left|I'_r\right|^2 = \frac{1}{\left(r_s + r'_r/s\right)^2 + \left(X_{ls} + X'_{lr}\right)^2}\left|V_s\right|^2$$

$$T_e = 3\frac{P}{2}\cdot\frac{\left|V_s\right|^2}{\omega_e}\cdot\frac{\left(r'_r/s\right)}{\left(r_s + r'_r/s\right)^2 + \left(X_{ls} + X'_{lr}\right)^2}$$

Electromagnetic Torque

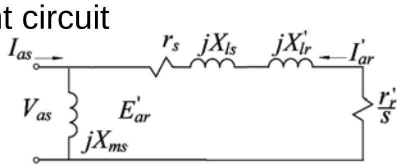
$$T_e = 3\frac{P}{2}\cdot\frac{\left(X_{ms}^2/\omega_e\right)r_r's}{\left[r_sr_r' + s\left(X_{ms}^2 - X_{ss}X_{rr}'\right)\right]^2 + \left(r_r'X_{ss} + sr_sX_{rr}'\right)^2}|V_s|^2 \qquad T_e = 3\frac{P}{2}\cdot\frac{|V_s|^2}{\omega_e}\cdot\frac{(r_r'/s)}{(r_s + r_r'/s)^2 + (X_{ls} + X_{lr}')^2}$$



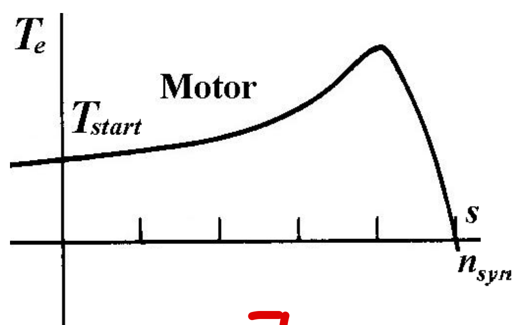
stable op

Approximate Starting Torque / Current

Equivalent circuit



Torque-speed characteristic



$$T_e = 3\frac{P}{2}\cdot\frac{|V_s|^2}{\omega_e}\cdot\frac{(r_r'/s)}{(r_s + r_r'/s)^2 + (X_{ls} + X_{lr}')^2}$$

Starting torque (set slip s = 1) =>

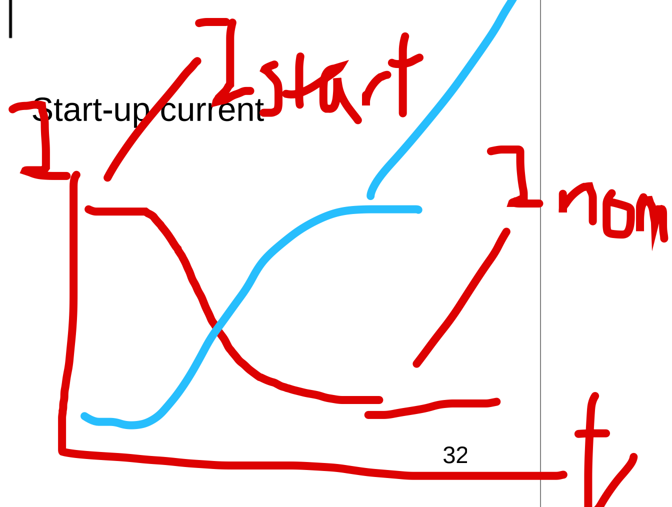
$$T_{start} = 3\frac{P}{2}\cdot\frac{|V_s|^2}{\omega_e}\cdot\frac{r_r'}{(r_s + r_r')^2 + (X_{ls} + X_{lr}')^2}$$

Starting current (set slip s = 1) =>

$$I_{as,start} = \frac{V_{as}}{jX_{ms}} + \frac{V_{as}}{r_s + r_r' + j(X_{ls} + X_{lr}')}$$

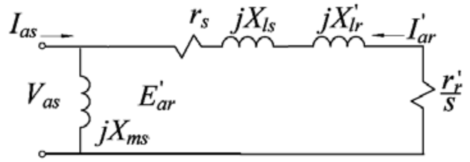
ω_r

Start-up current

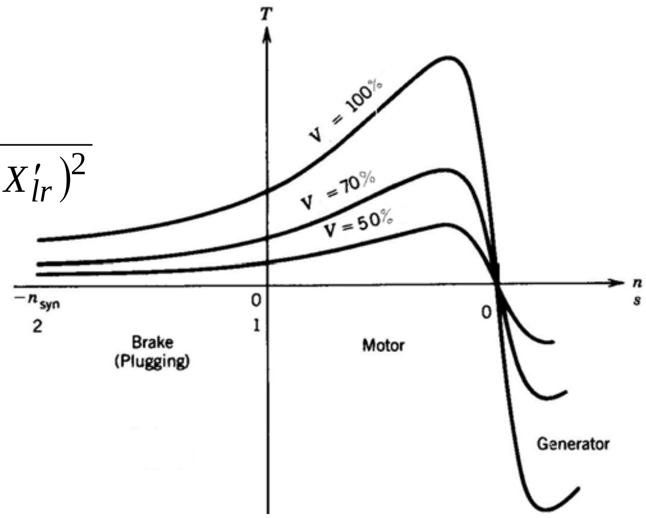


Istart >> Inominal
5-10 times

Torque Speed Characteristic



Changing the input voltage



$$T_e = 3\frac{P}{2}\cdot\frac{|V_s|^2}{\omega_e}\cdot\frac{(r'_r/s)}{(r_s + r'_r/s)^2 + (X_{ls} + X'_{lr})^2}$$

$$T_{\max} = 3\frac{P}{2}\frac{V_s^2}{2\omega_e}\cdot\frac{1}{r_s + \sqrt{r_s^2 + (X_{ls} + X'_{lr})^2}}$$

$$s_{T\max} = \pm\frac{r'_r}{\sqrt{r_r'^2 + (X_{ls} + X'_{lr})^2}}$$

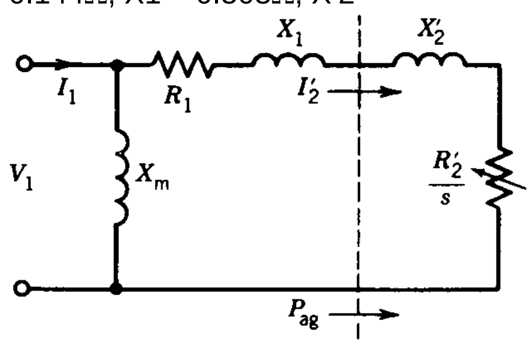
$$\frac{dT}{ds} = 0$$

Example

Consider a Y-connected 7.5kW, 220V (line-line), 60Hz, 6-pole, Squirrel-cage motor with the following parameters: R1 = 0.294Ω, R'2 = 0.144Ω, X1 = 0.503Ω, X'2 = 0.209Ω, Xm = 13.5Ω

a) Compute the starting current I_{1start}
b) Compute the starting torque T_{start}

Assume Approximate Equivalent Circuit



$V_1 = \frac{220}{\sqrt{3}} = 127.01\,V$ - phase voltage

At start $s = 1$, $\omega_{rm} = 0$

$I_{2,start} = \frac{V_1}{R_1 + R_2 + j(X_1 + X_2)} = \frac{127.01}{0.294 + 0.144 + j(0.503 + 0.209)}$

$= 79.6 - j129.4$

$|I_{2,start}| = 151.92\ A$

$I_\phi = \frac{V_1}{jX_m} = \frac{127.01}{j\cdot 13.25} = -j\,9.59$

$I_{1,start} = I_\phi + I_{2,start} = 79.6 - j138.99 =$

$|I_{1,start}| = 160.19\ A$

Starting Torque: $T = 3\frac{I_2^2 R_2}{s\cdot\omega_{syn}}$

$\omega_{syn} = \left(\frac{2}{P}\right)\omega_e = \left(\frac{2}{P}\right)2\cdot\pi\cdot 60 = 125.66\,r/s$

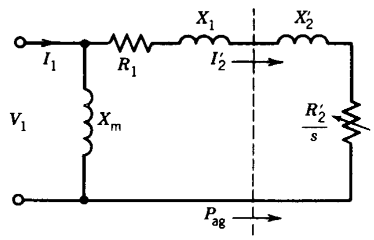
$T = 3\cdot\frac{(151.92)^2\cdot 0.144}{125.66\,r/s} = 79.4\ N\cdot m$

Example

Consider a Y-connected 7.5kW, 220V (line-line), 60Hz, 6-pole, Squirrel-cage motor with the following parameters: R1 = 0.294Ω, R'2 = 0.144Ω, X1 = 0.503Ω, X'2 = 0.209Ω, Xm = 13.5Ω. Assume motor operates under load with slip s = 0.03 (3%)

c) Compute the torque T_e
d) Compute starter current I_1

Assume Approximate Equivalent Circuit
Assume no friction or rotational losses



Under load, $S = 0.03$ $(S=3\%)$

$$I_2 = \frac{V_1}{R_1 + \frac{R_2}{s} + j(X_1+X_2)} = \frac{127.01}{0.294 + \frac{0.144}{0.03} + j(0.505 + 0.209)} =$$

$$= 24.45 - j3.42 = |24.69|\ A$$

$$I_1 = I_\varphi + I_2 = 24.45 - j13.6 = |27.69|\ A$$

$$T_e = T_m = 3 \cdot \frac{I_2^2 R_2}{S \cdot \omega_{syn}} = \frac{24.69^2 \cdot 0.144}{0.03 \cdot 125.66} = 69.88\ N\cdot m$$

Example

Consider a Y-connected 7.5kW, 220V (line-line), 60Hz, 6-pole, Squirrel-cage motor with the following parameters: R1 = 0.294Ω, R'2 = 0.144Ω, X1 = 0.503Ω, X'2 = 0.209Ω, Xm = 13.5Ω. Assume motor operates under load with slip s = 0.03 (3%)

e) Compute mechanical speed and power

Mechanical speed under load

$$n_{syn} = \frac{120}{p} \cdot f_e = \frac{120}{6} \cdot 60 = 1200\ rpm$$

$$n = n_{syn}(1-s) = 1200 \cdot 0.97 = 1164\ rpm$$

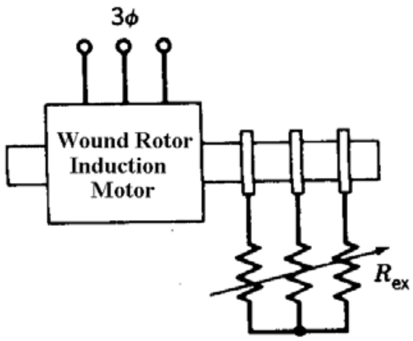
$$\omega_{rm} = \omega_{syn} \cdot (1-S) = 125.66 \cdot 0.97 = 121.89\ r/s$$

$$P_m = T_m \cdot \omega_{rm}$$

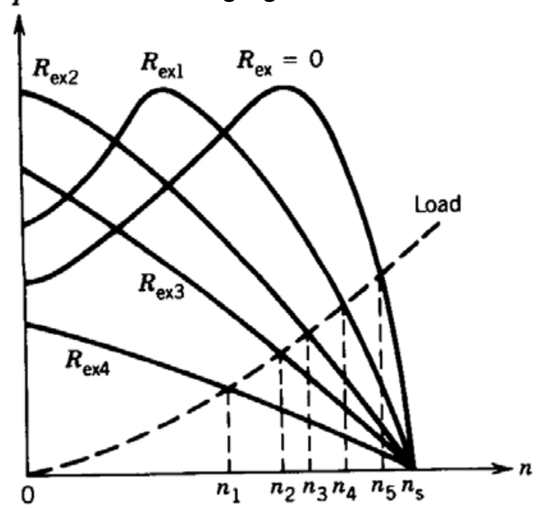
Assume No Friction $T_{fric} = 0 \Rightarrow T_e = T_m$

$$P_m = 65.41 \cdot 121.89 = 7.9\ kW = \frac{7.9kW}{746W} = \underline{10.69\ Hp}$$

Torque Speed Characteristic & Rotor Type



Changing the rotor resistance

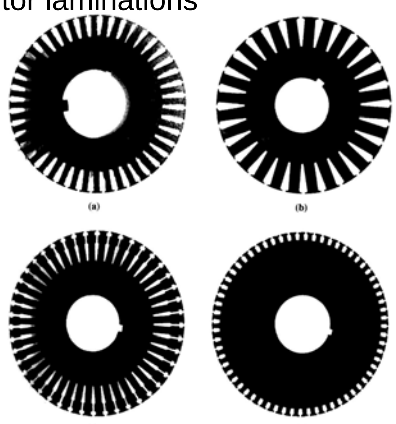


$$T_{\max} = 3\frac{P}{2}\frac{V_s^2}{2\omega_e}\cdot\frac{1}{r_s + \sqrt{r_s^2 + (X_{ls} + X'_{lr})^2}}$$

$$s_{T\max} = \pm\frac{r'_r}{\sqrt{r_r'^2 + \left(X_{ls} + X'_{lr}\right)^2}}$$

National **E**lectrical **M**anufactures **A**ssociation (NEMA) Design Classes/Types

Rotor laminations

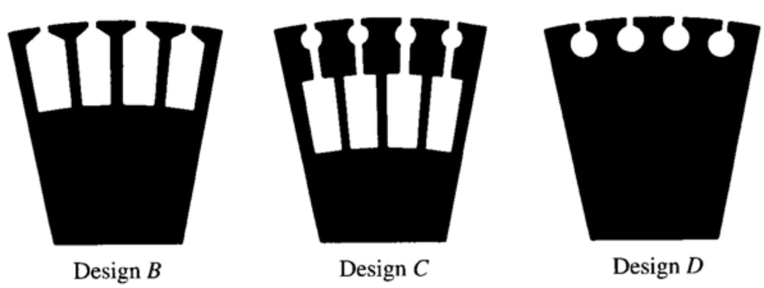


Effective rotor resistance changes with frequency (which is the slip frequency) and therefore depends on the rotor speed =>

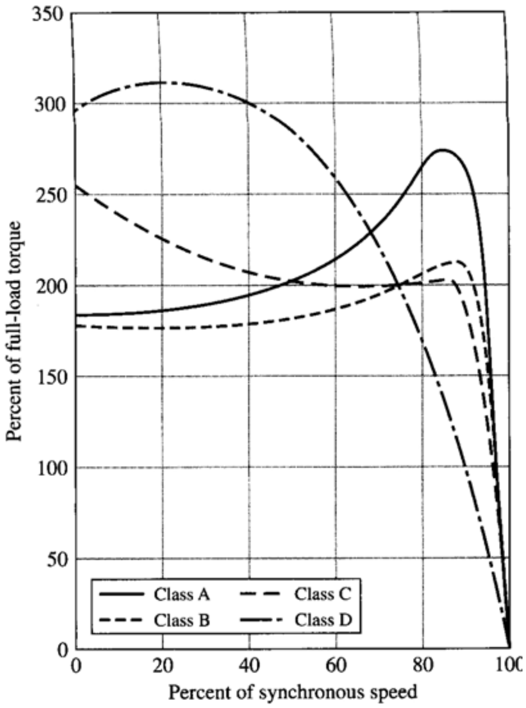
Different torque-speed characteristics can be designed by shaping the rotor winding slots! Recall the Skin Effect!

Practical rotor laminations for different NEMA Design Classes

Rotor cage



NEMA Design Classes



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*)

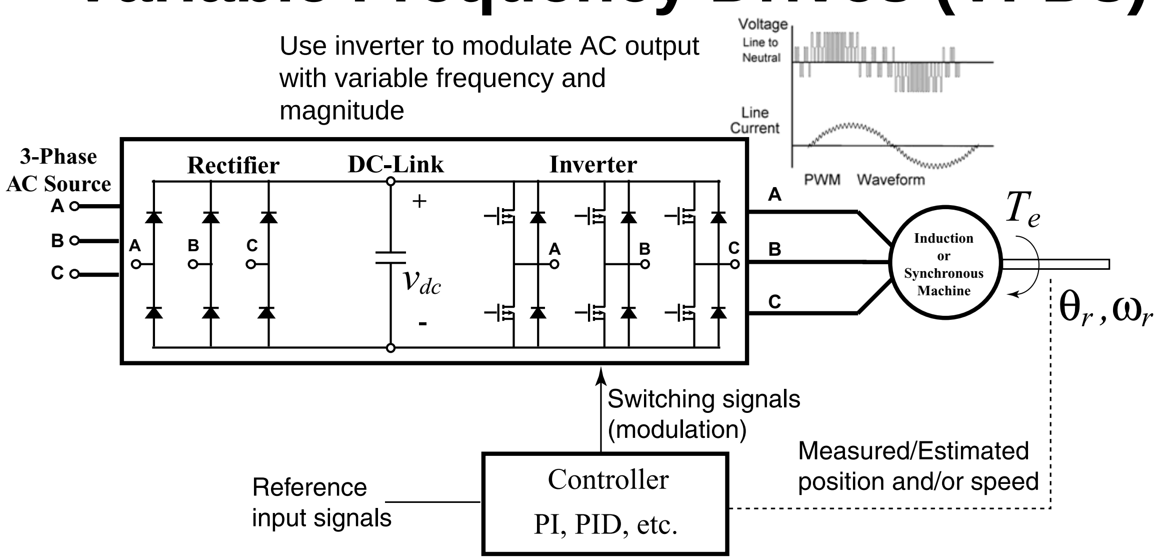
Class B: normal starting torque, low starting current (75% of class A), low operating slip, higher leakage reactance, lower maximum torque (*general purpose motors, fans, pumps, etc*.)

Class C: high starting torque, low starting current, higher rotor resistance, higher operating slip (*compressors, crushers, conveyors, etc*.)

Class D: high starting torque, low starting current, high operating slip (8-18%), low efficiency (*high acceleration, high impact loads*)

Variable Frequency Drives (VFDs)

Use inverter to modulate AC output with variable frequency and magnitude

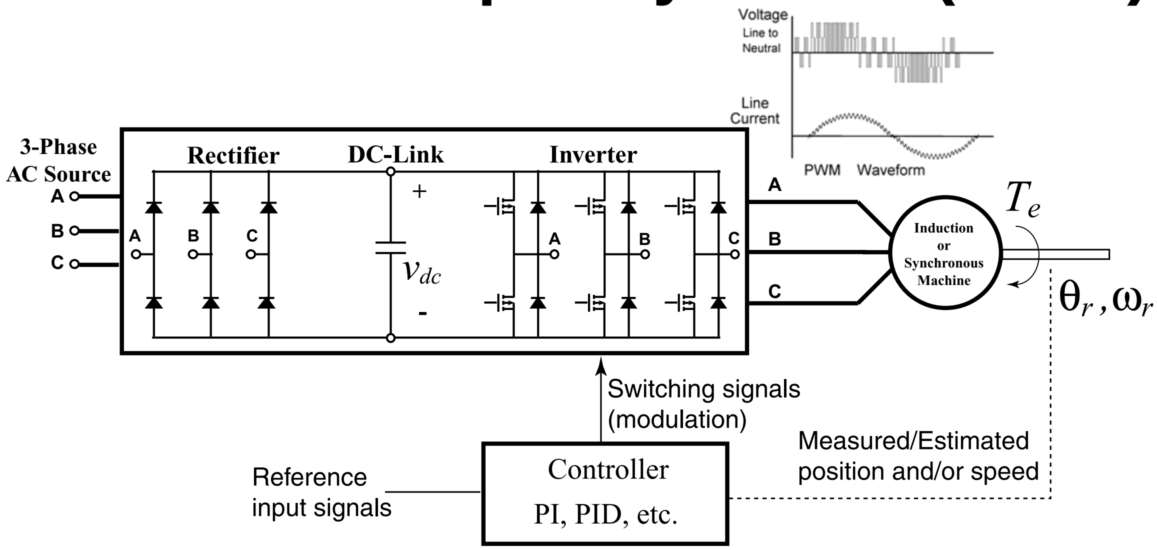


Typical operation under nominal flux: Volts/Hertz (V/f)

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

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

Variable Frequency Drives (VFDs)



Typical Control Modes

Constant Speed Operation

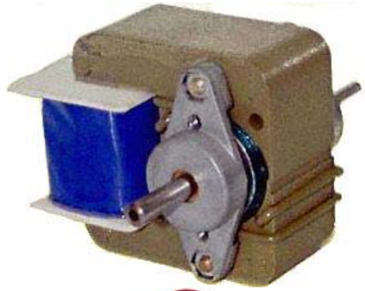
- Control tries to keep the speed at specified value no matter what the load is doing => so torque is changing

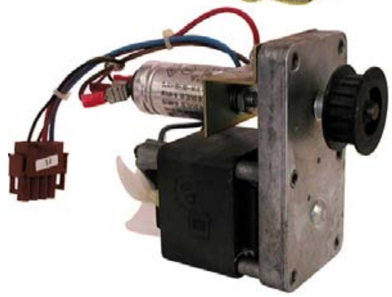
Constant Torque Operation

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

Variable Frequency Drives (VFDs)

Part 2: Single-Phase Induction Motors

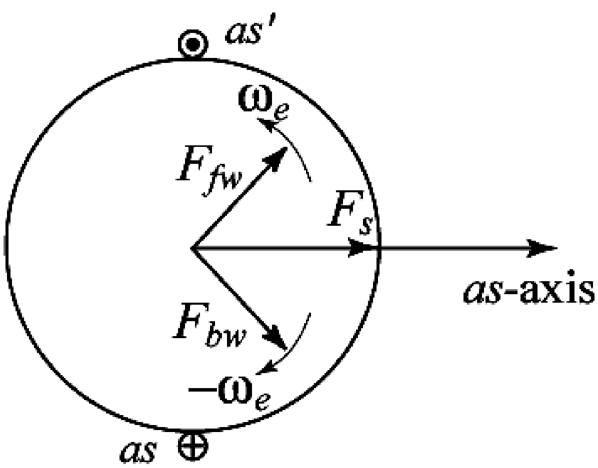




- Less efficient
- Low power
- Low maintenance
- Very inexpensive
- Often used capacitors & gearheads

Single-Phase Induction Motors

Pulsating magnetic field $\mathbf{F}_s = \mathbf{F}_{fw} + \mathbf{F}_{bw}$



Pulsating field $\mathbf{F}$s can be viewed as two magnetic fields $\mathbf{F}_{fw}$ and $\mathbf{F}_{bw}$ of ½ strength and rotating in opposite directions

Forward component

$$\mathbf{F}_{fw} = \frac{1}{2} F_m \angle \theta_e$$

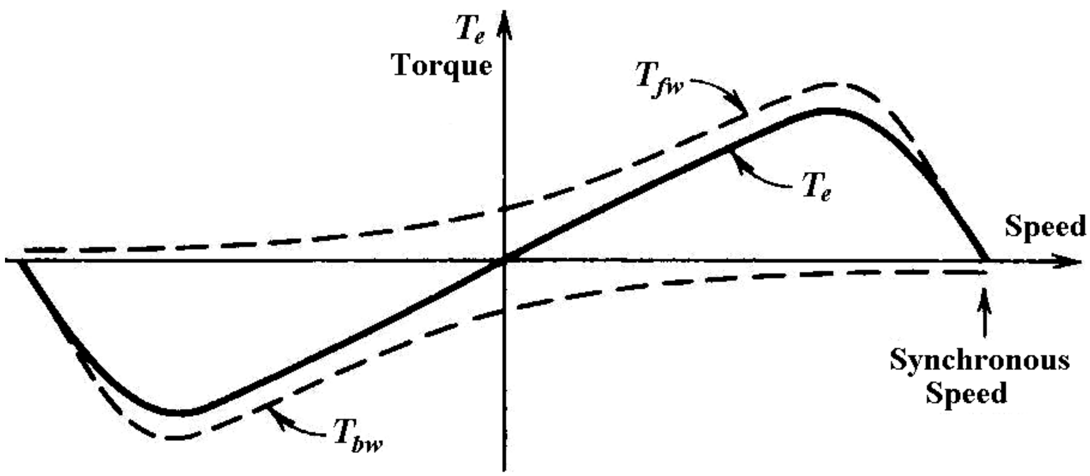
Backward component

$$\mathbf{F}_{bw} = \frac{1}{2} F_m \angle -\theta_e$$

Torque–Speed (Slip) Characteristic

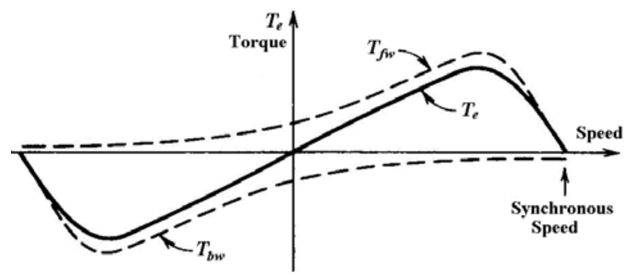
Recall 3-phase IM $$T_e = 3\frac{P}{2}\cdot\frac{|V_s|^2}{\omega_e}\cdot\frac{(r_r'/s)}{(r_s + r_r'/s)^2 + (X_{ls} + X_{lr}')^2}$$

Recall single-phase IM $$T_{e,net} = T_{fw} - T_{bw}$$ (Forward - Backward)

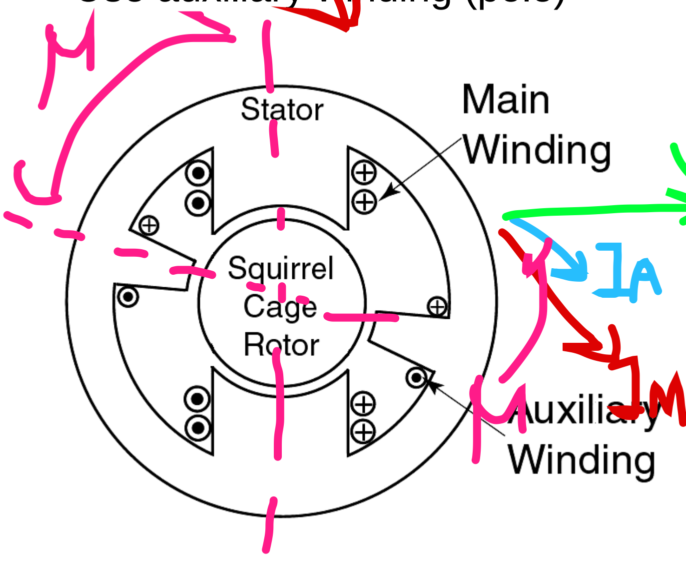


Split-Phase Induction Motors

Recall single-phase IM with
one stator winding
No starting torque !

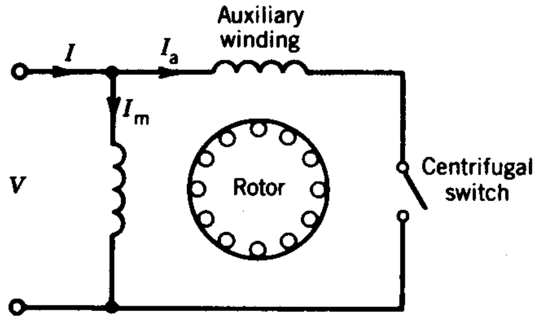


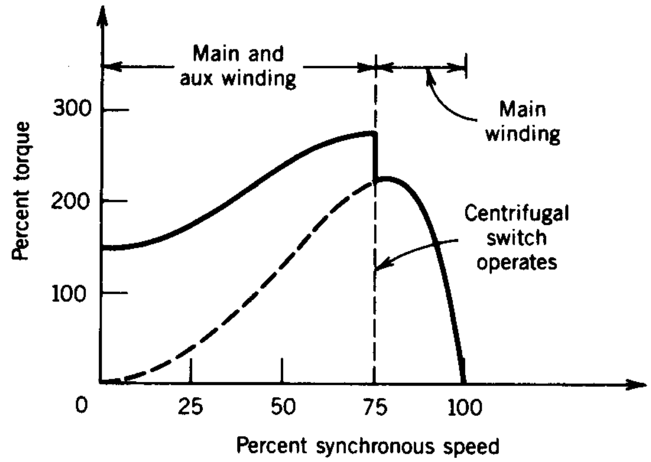
Use auxiliary winding (pole)



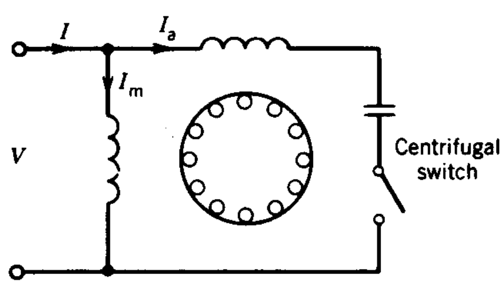
Shift phase of the current in
auxiliary winding

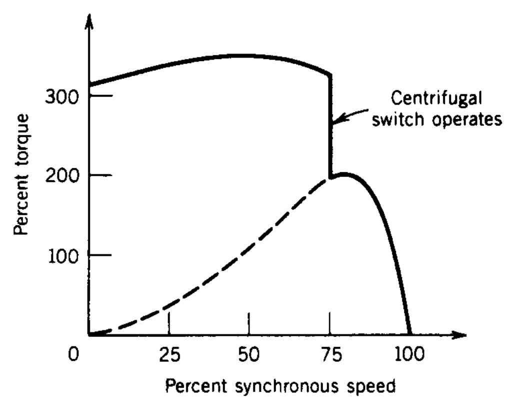
Split-Phase Motors

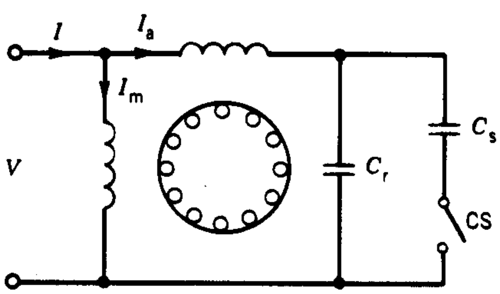


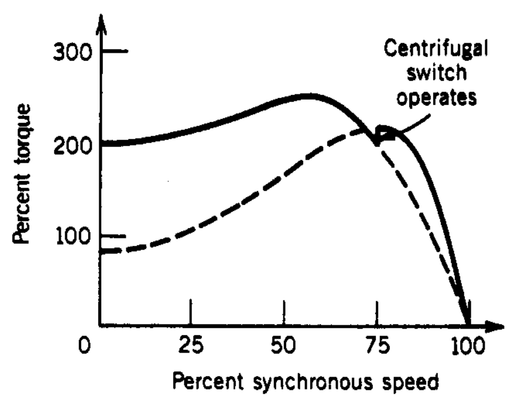


Capacitor-Start/Run Motors



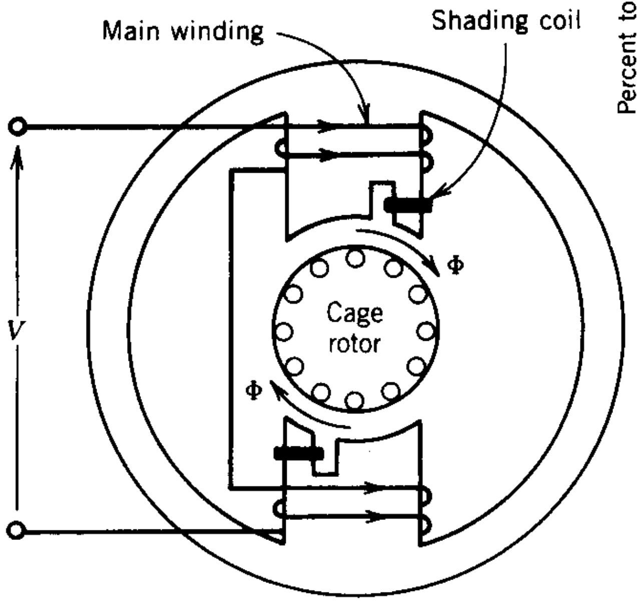


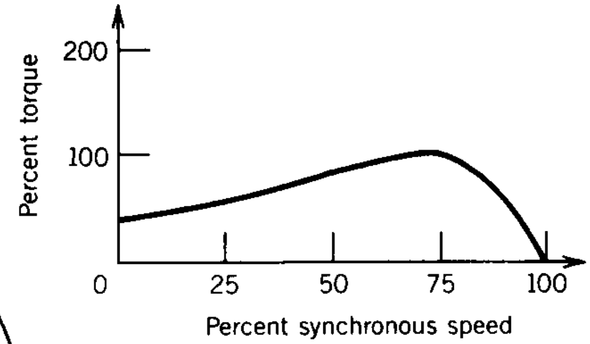




Shaded-Pole Motors

In very small applications, under 50 W
Very inexpensive
High slip, Low efficiency





ϕ_M

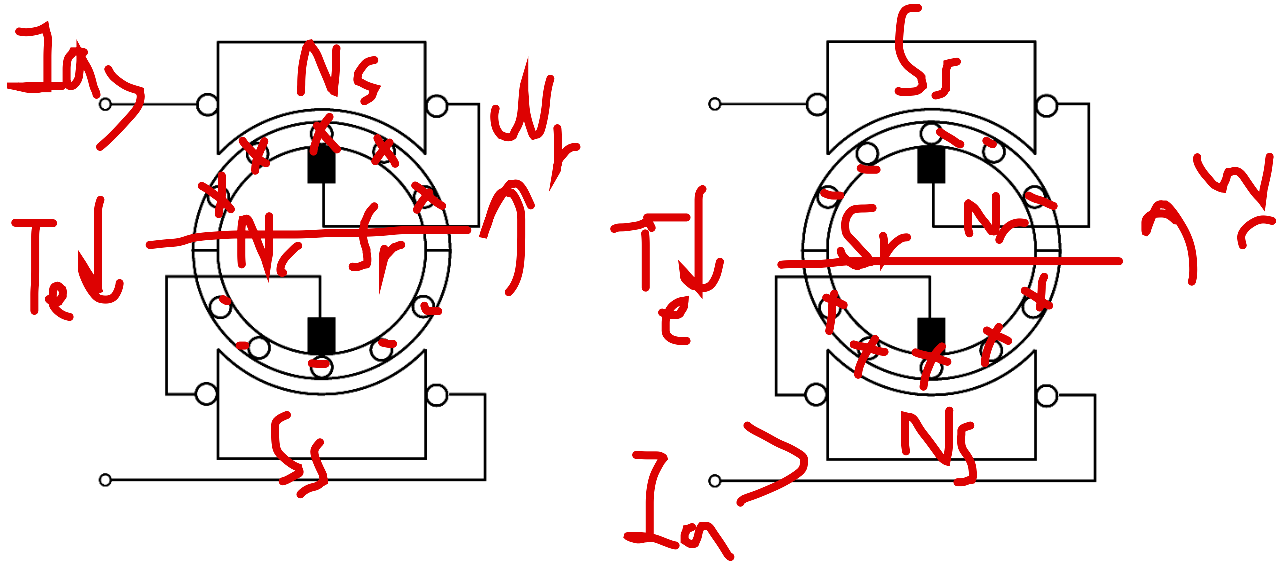
ϕ_{SH}

Single-Phase Induction Motors

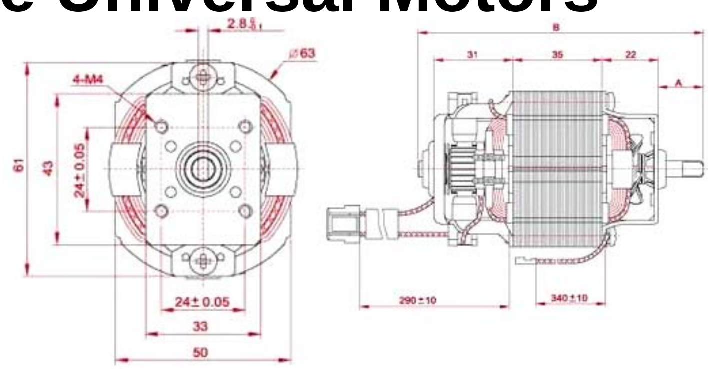
Type of Motor	Torque as % of Rated Torque: Starting	Torque as % of Rated Torque: Breakdown	Rated Load: Power Factor	Rated Load: Efficiency	Horsepower Range
Split-phase (resistance-start)	100–250	Up to 300	50–65	55–65	1/20–1
Capacitor-start	250–400	Up to 350	50–65	55–65	1/8–1
Capacitor-run	100–200	Up to 250	75–90	60–70	1/8–1
Capacitor-start, capacitor-run	200–300	Up to 250	75–90	60–70	1/8–1
Shaded-pole	40–60	140	25–40	25–40	1/200–1/20

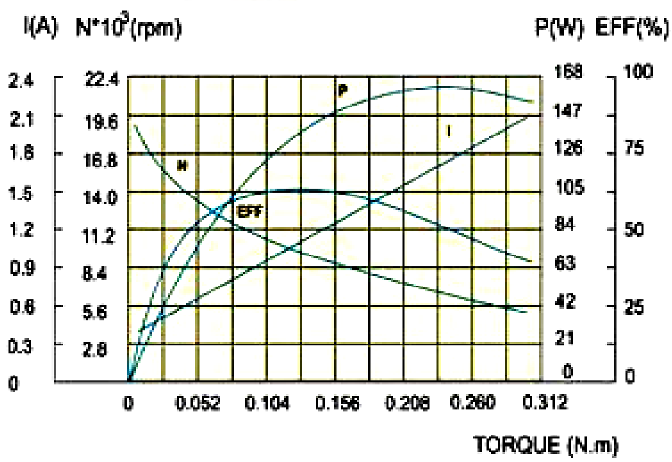
Single-Phase Universal Motors

Recall Series DC Motor



Single-Phase Universal Motors





- Fractional horsepower applications
- Domestic appliances such as:
  - Portable tools, drills, mixers, blenders, vacuum cleaners, etc
- Operate at high speeds (1500 – 20,000 rpm)