Induction Machines: 1-phase Induction Motors

- Principle of Operation
- Equivalent Circuit
- Power and Torque
- Starting Methods and Types
- Testing

Induction Machines: 1-phase Induction Motors

- Video

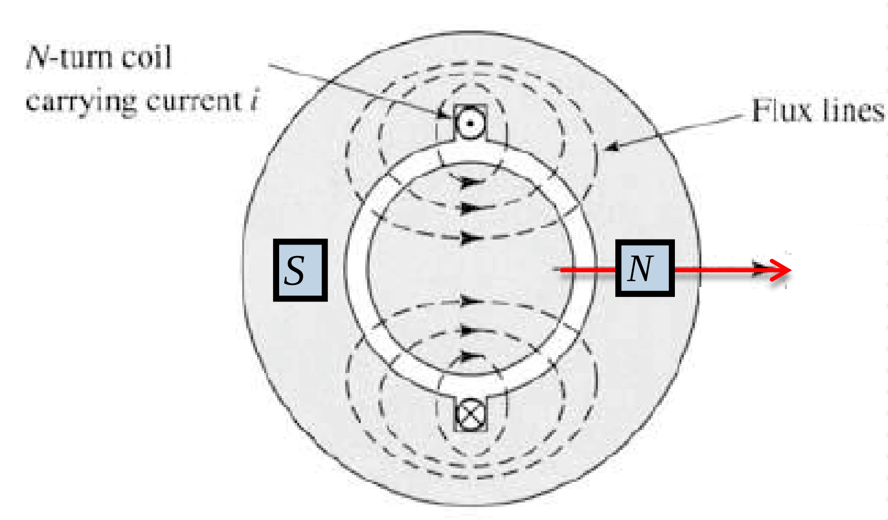
Magnetic Field Production & Distribution

$$\oint_c \underline{H}.\underline{dl} = I_{en}$$

$$\oint_c \underline{H}.\underline{dl} = Ni$$

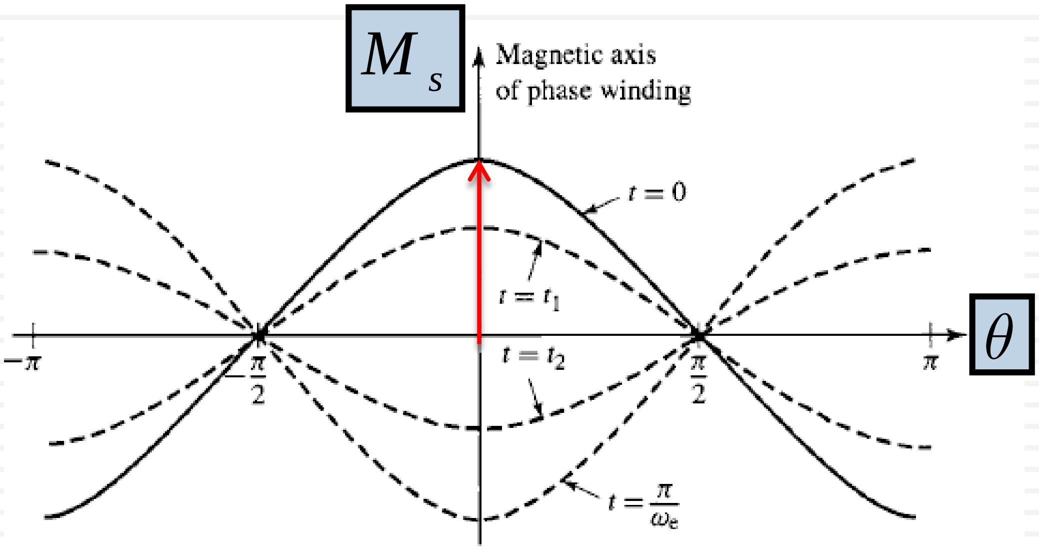
$$H \times g + H \times g \simeq Ni$$

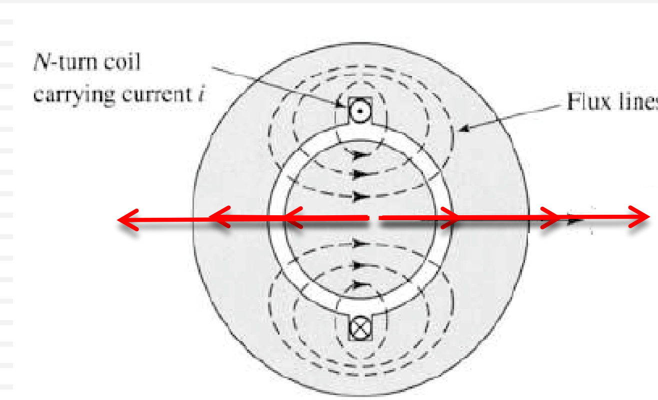
$$H_g \, g = \frac{Ni}{2} = M$$

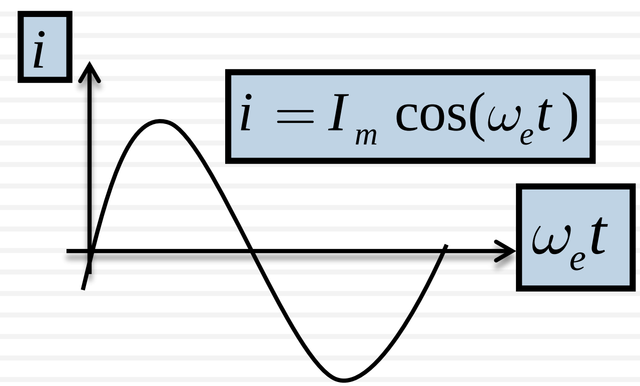


$$M = \frac{Ni}{2p}$$

Magnetic Field Production & Distribution







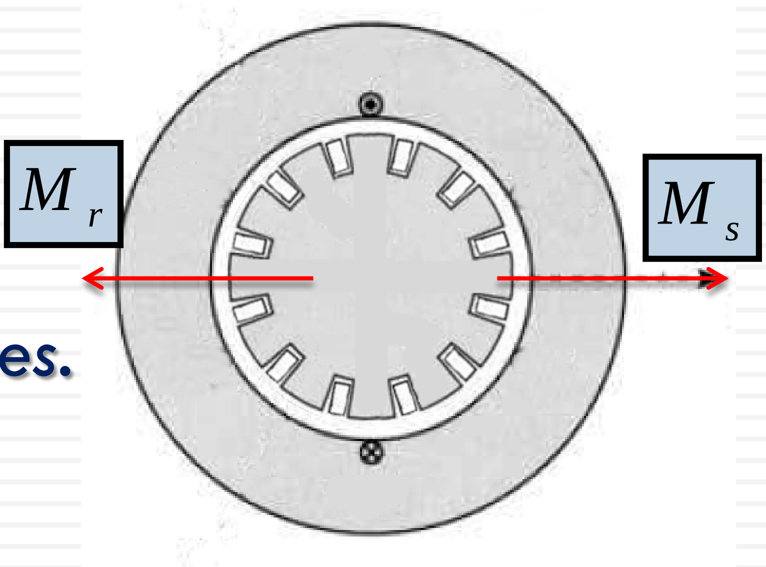
MMF Space Distribution

AC Current → **Pulsating Field**

Current Time Distribution

Rotor Reaction

At standstill, the rotor field will always be shifted by 180° from the stator field at all instances.



$$T = kB_s B_r \sin\gamma$$

$$T = kB_s B_r \sin 180^o$$

$$T = zero$$

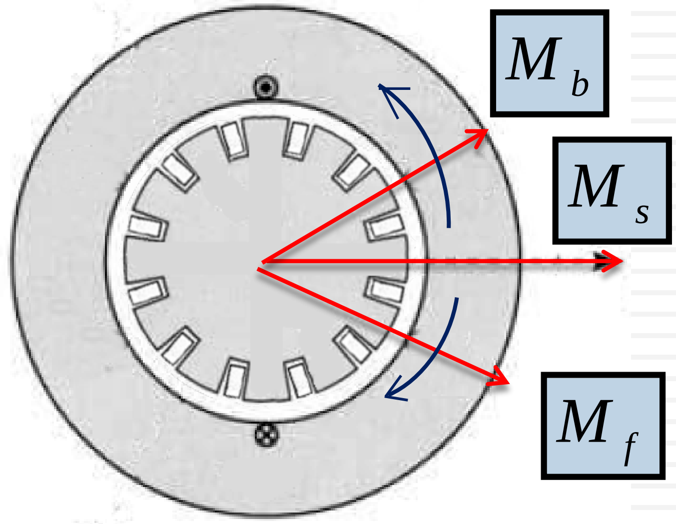
Induction Machines: 1-phase Induction Motors

Double Rotating Field Theory

$$I = I_m \cos(\omega_e t)$$

$$M = kNI \cos\theta$$

$$M = kNI_m \cos(\omega_e t)\cos p\theta$$



$$M = kN\frac{I_m}{2}[\cos(\omega_e t - p\theta) + \cos(\omega_e t + p\theta)]$$

$$M_f = kN\frac{I_m}{2}\cos(\omega_e t - p\theta)$$

Speed of Rotation

$$n_s = \frac{60f}{p}$$

Forward Field

$$M_b = kN\frac{I_m}{2}\cos(\omega_e t + p\theta)$$

Speed of Rotation

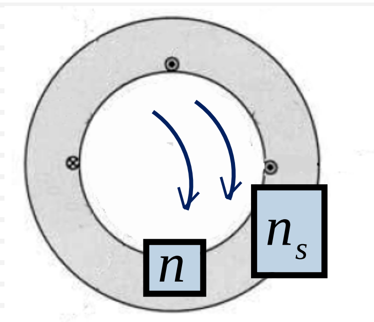
$$-n_s = -\frac{60f}{p}$$

Backward Field

Induction Machines: 1-phase Induction Motors

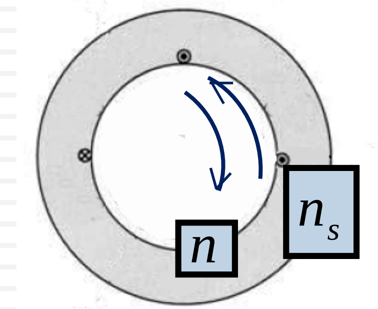
Double Rotating Field Theory

Forward Field

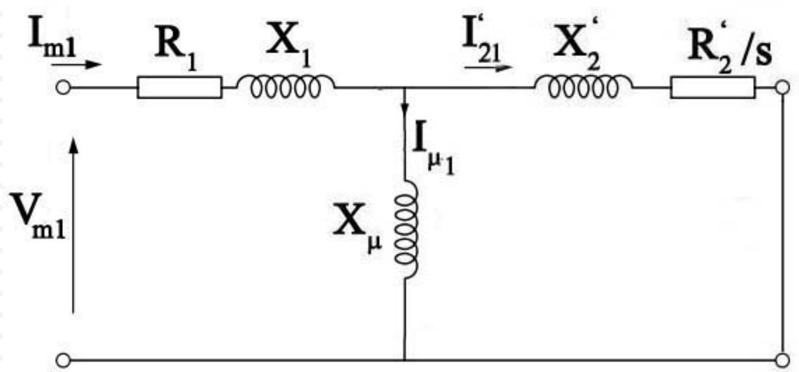


$$s_1 = \frac{n_s - n}{n_s} = s$$

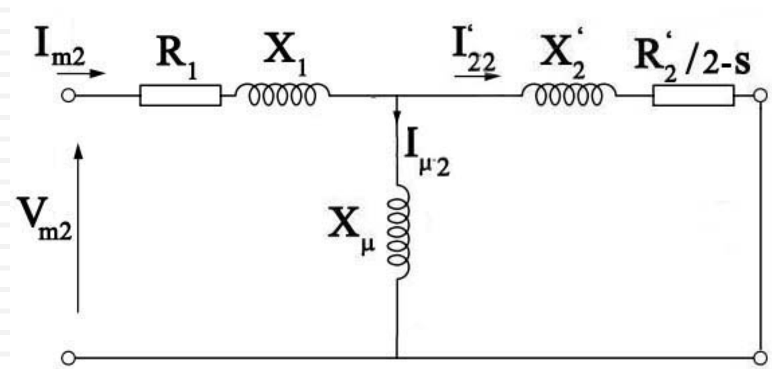
Backward Field



$$s_2 = \frac{n_s + n}{n_s} = 2 - s$$



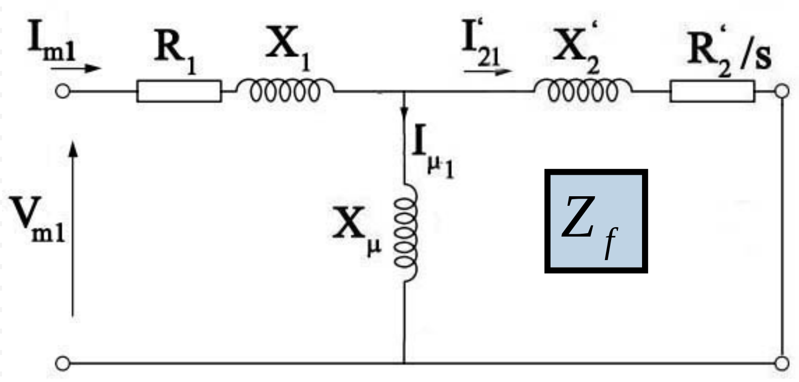
Forward



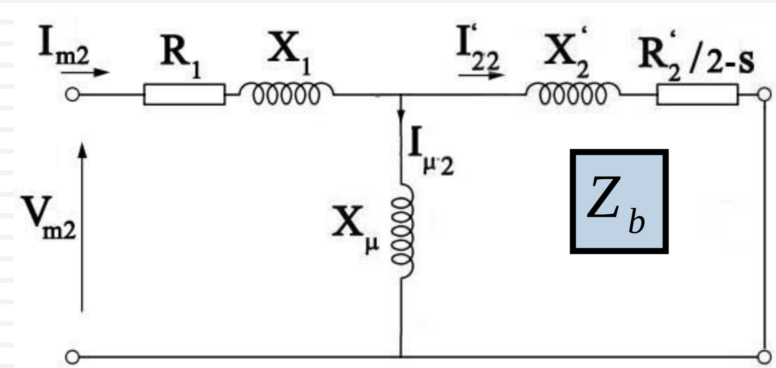
Backward

Induction Machines: 1-phase Induction Motors

Double Rotating Field Theory



Forward



Backward

$$\begin{bmatrix} V_{m1} \\ V_{m2} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix} \begin{bmatrix} V_m \\ V_c \end{bmatrix}$$

$$V_{m1} = V_{m2} = \frac{1}{2} V_m$$

At s = 1

$$Z_f = Z_b = Z$$

$$I_{m1} = I_{m2}$$

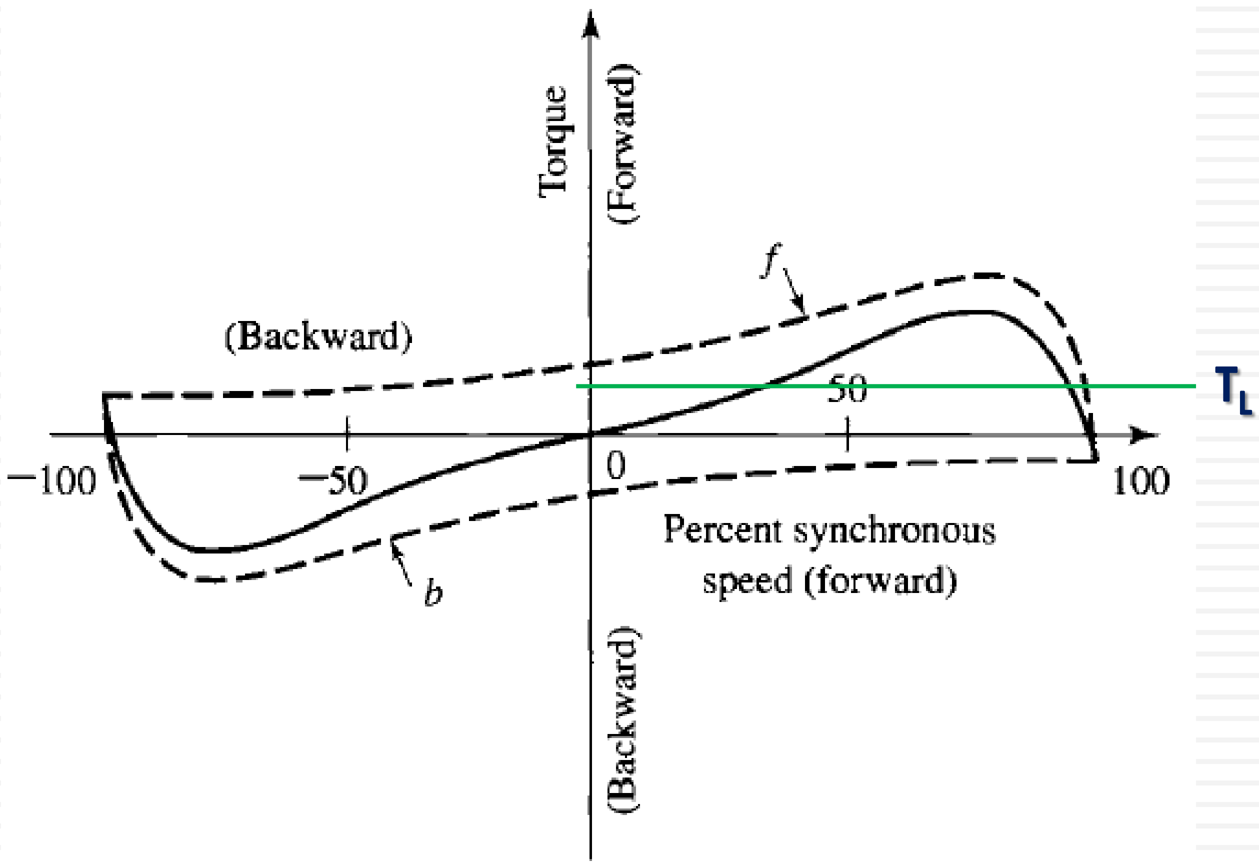
$$P_{g1} = P_{g2}$$

$$T_1 = T_2$$

$$T_{net} = T_1 - T_2 = zero$$

Induction Machines: 1-phase Induction Motors

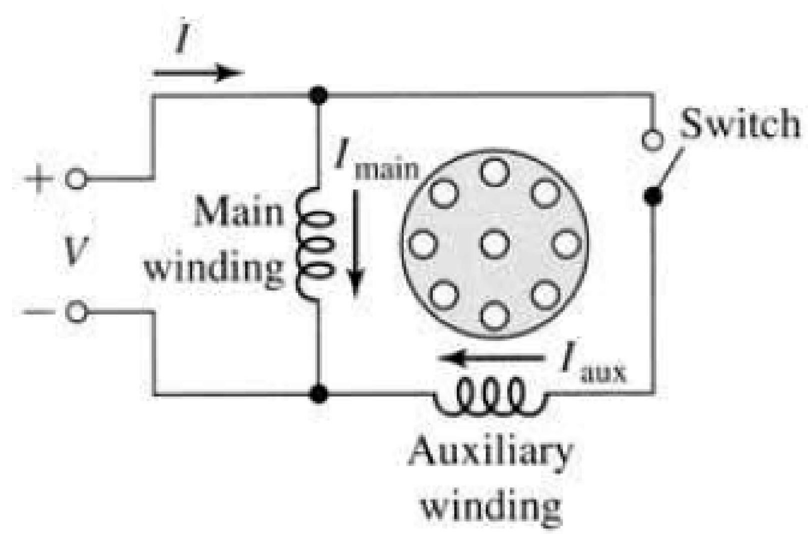
Torque-Speed Characteristics

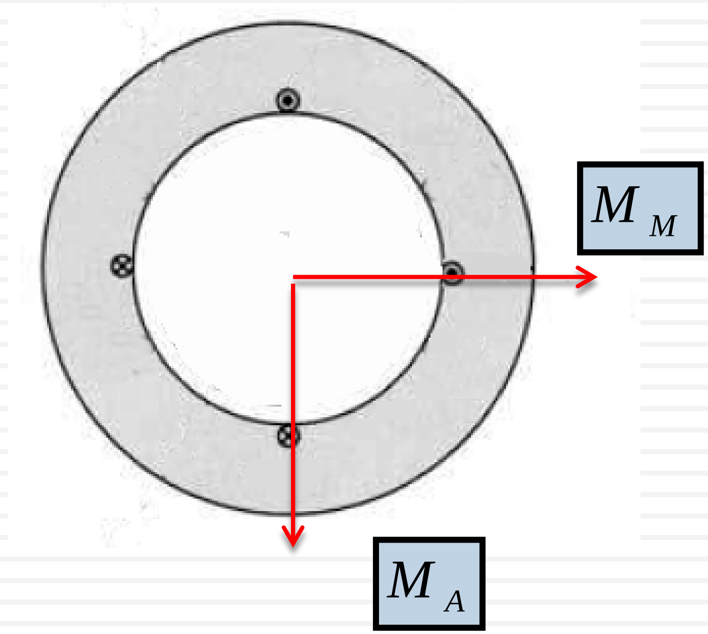


No starting torque

Induction Machines: 1-phase Induction Motors

Motor Starting



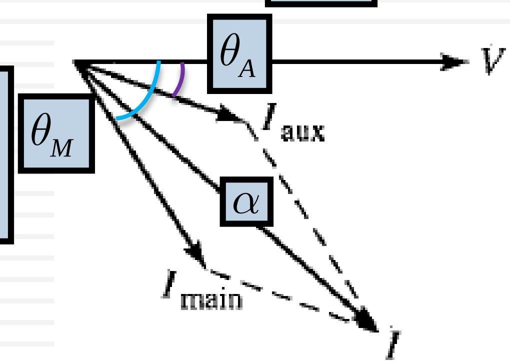


$N_M > N_A$ ⇒ $X_M > X_A$

$A_{cM} > A_{cA}$ ⇒ $R_M < R_A$

⇒ $\frac{R_A}{X_A} > \frac{R_M}{X_M}$

$$T_{st} \propto I_M I_A \sin\alpha$$



Motor Starting

$$I_M = I_{Mm}\cos(\omega_e t)$$

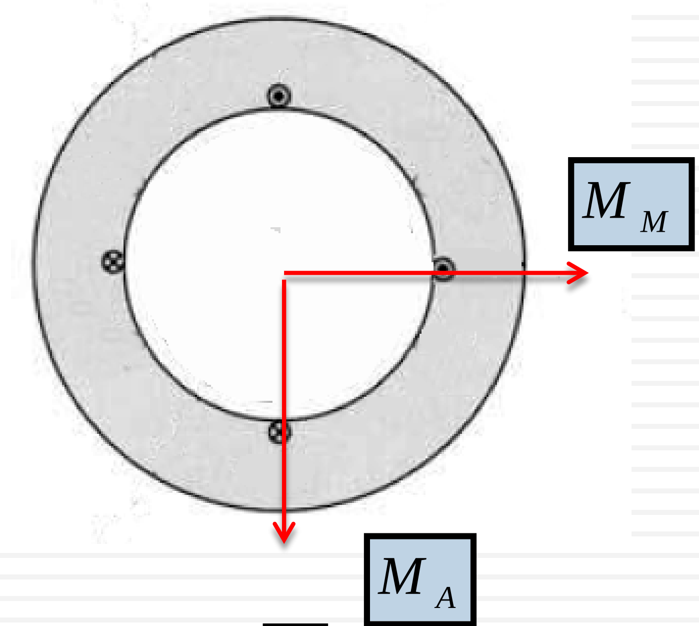
$$M_M = kN_M I_M \cos\theta$$

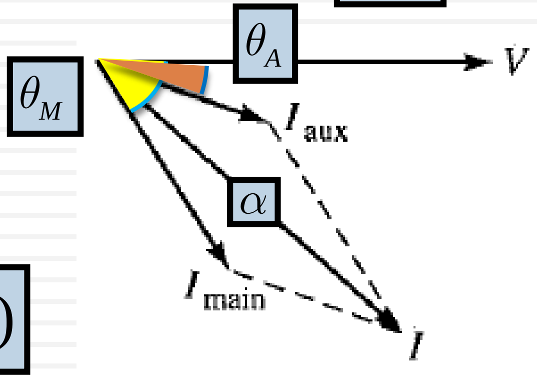
$$M_M = kN_M I_{Mm}\cos(\omega_e t)\cos p\theta$$

$$I_A = I_{Am}\cos(\omega_e t + \alpha)$$

$$M_A = kN_A I_A \cos(\theta + 90^o)$$

$$M_A = kN_A I_{Am}\cos(\omega_e t + \alpha)\cos(p\theta + 90^o)$$





Induction Machines: 1-phase Induction Motors

Motor Starting

$$M_t = kN_M I_{Mm}\cos(\omega_e t)\cos p\theta - kN_A I_{Am}\cos(\omega_e t+\alpha)\sin p\theta]$$

$$M_t = k[N_M I_{Mm}\cos(\omega_e t)\cos p\theta - N_A I_{Am}\sin p\theta[\cos(\omega_e t)\cos(\alpha) - \sin(\omega_e t)\sin(\alpha)]]$$

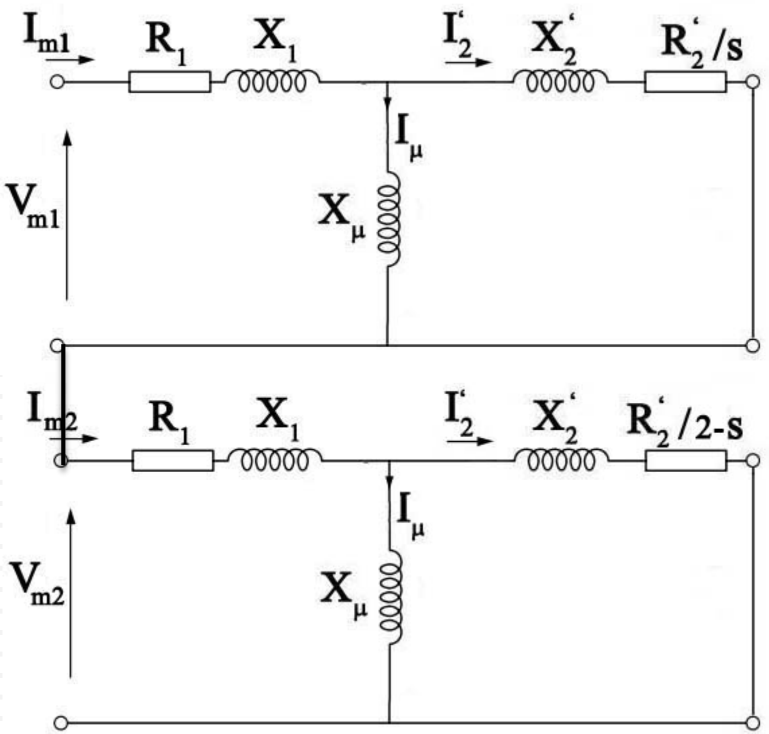
$$M_t = \frac{kN_M I_{Mm}}{2}[\cos(\omega_e t - p\theta)+\cos(\omega_e t + p\theta)] - \frac{kN_A I_{Am}}{2}\cos(\alpha)[\sin(\omega_e t + p\theta) - \sin(\omega_e t - p\theta)]$$
$$+\frac{kN_A I_{Am}}{2}\sin(\alpha)[\cos(\omega_e t - p\theta) - \cos(\omega_e t + p\theta)]$$

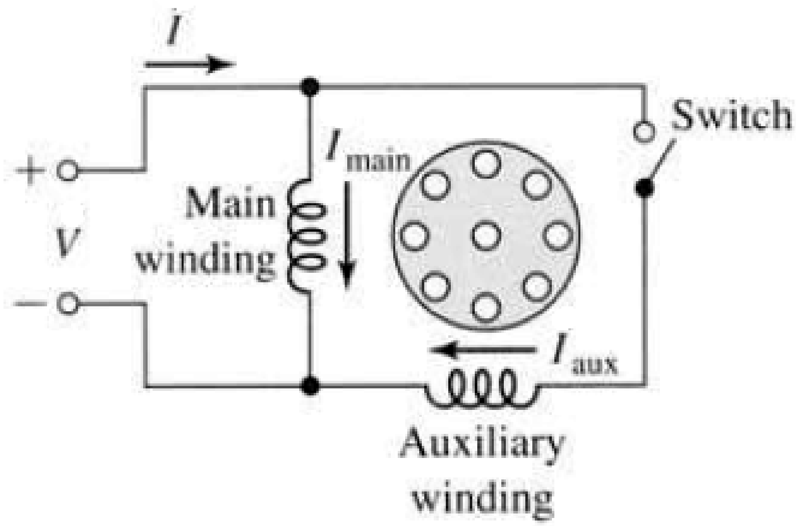
$$M_t = \frac{k}{2}[N_M I_{Mm} + N_A I_{Am}\sin(\alpha)][\cos(\omega_e t - p\theta)] + \frac{kN_A I_{Am}}{2}\cos(\alpha)\sin(\omega_e t - p\theta)$$
$$+\frac{k}{2}[N_M I_{Mm} - N_A I_{Am}\sin(\alpha)][\cos(\omega_e t + p\theta)] - \frac{kN_A I_{Am}}{2}\cos(\alpha)\sin(\omega_e t + p\theta)$$

Equivalent Circuit at running conditions

$$\begin{bmatrix} I_{m1} \\ I_{m2} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix} \begin{bmatrix} I_m \\ \not{I_a} \end{bmatrix}$$

$$I_{m1} = I_{m2} = \frac{1}{2} I_m$$

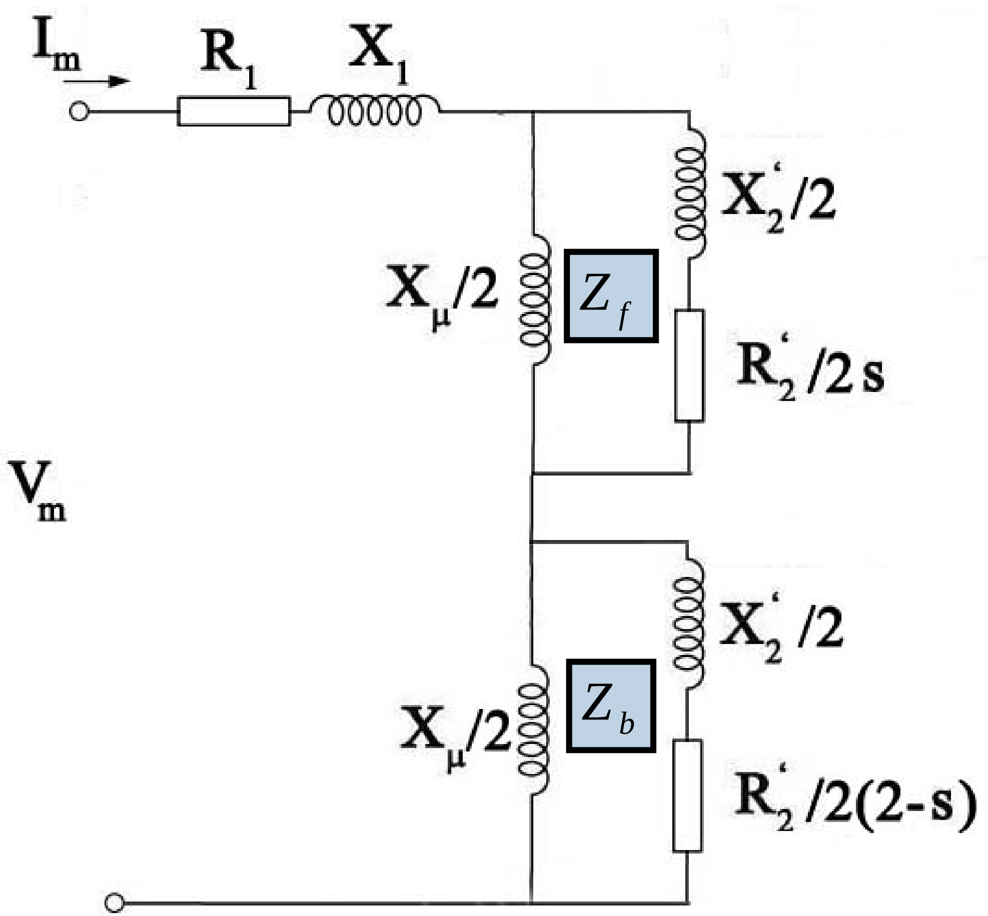


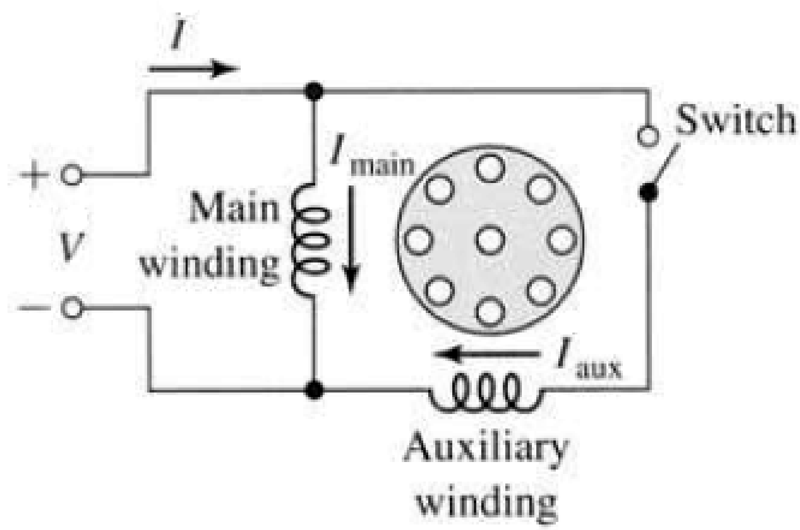


$$I_a = zero$$

$$V_{m1} = V_{m2} = \frac{1}{2} V_m$$

Equivalent Circuit at running conditions



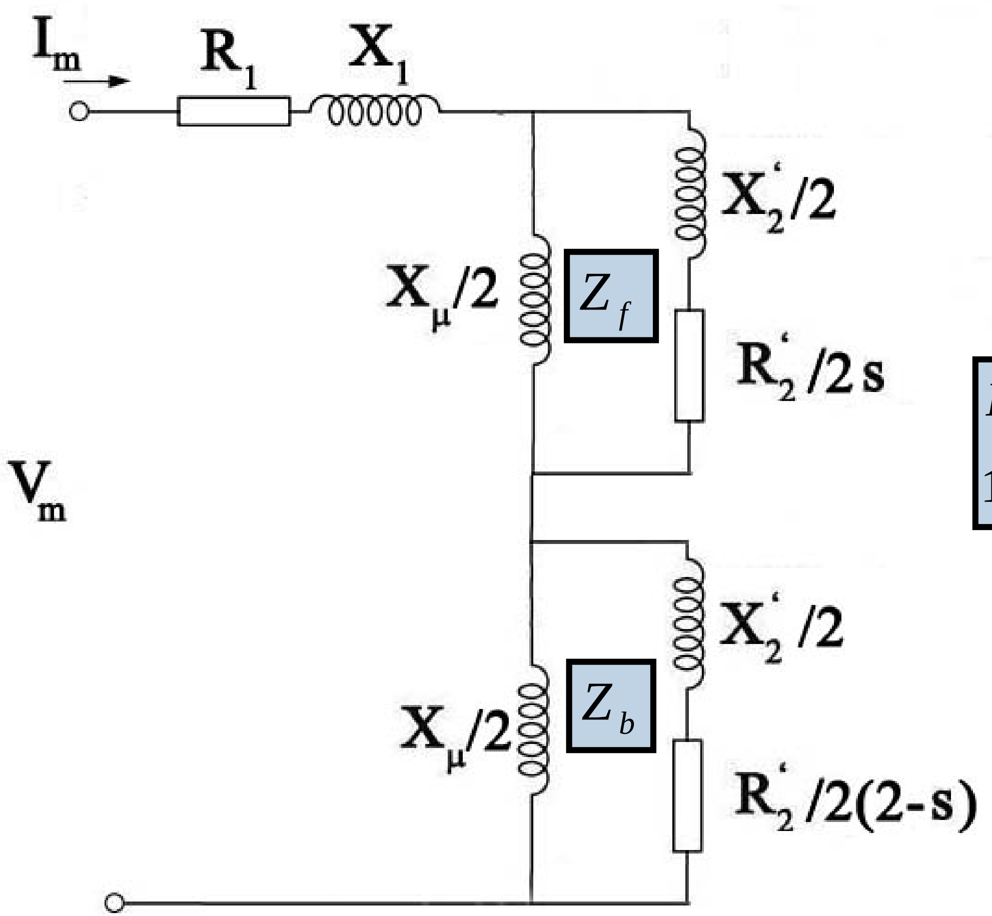


$$I_a = zero$$

$$I_m = \frac{V_m}{R_1 + jX_1 + Z_f + Z_b}$$

Induction Machines: 1-phase Induction Motors

Power Flow



$$P_{in} = V_m I_m \cos\phi_m$$

$$P_{cu1} = I_m^2 R_1$$

$$P_{gf} = I_m^2 R_f \qquad P_{gb} = I_m^2 R_b$$

$$P_{gf} : P_{cuf2} : P_{df} = 1 : s : (1-s)$$

$$P_{gb} : P_{cub2} : P_{db} = 1 : 2-s : (1-(2-s))$$

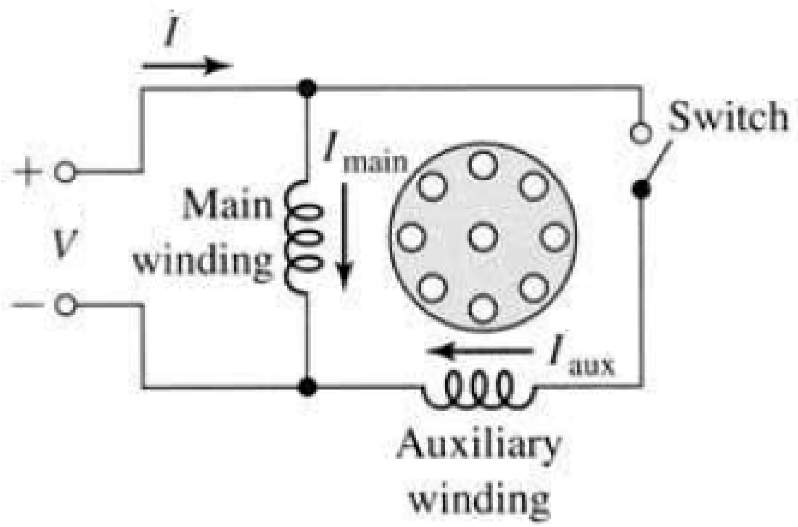
$$P_{cu2} = P_{cu2f} + P_{cu2b}$$

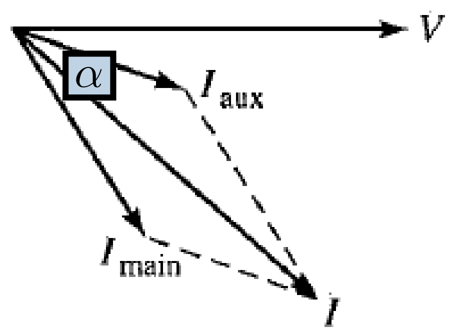
$$P_d = P_{df} + P_{db} = (1-s)(P_{gf} - P_{gb})$$

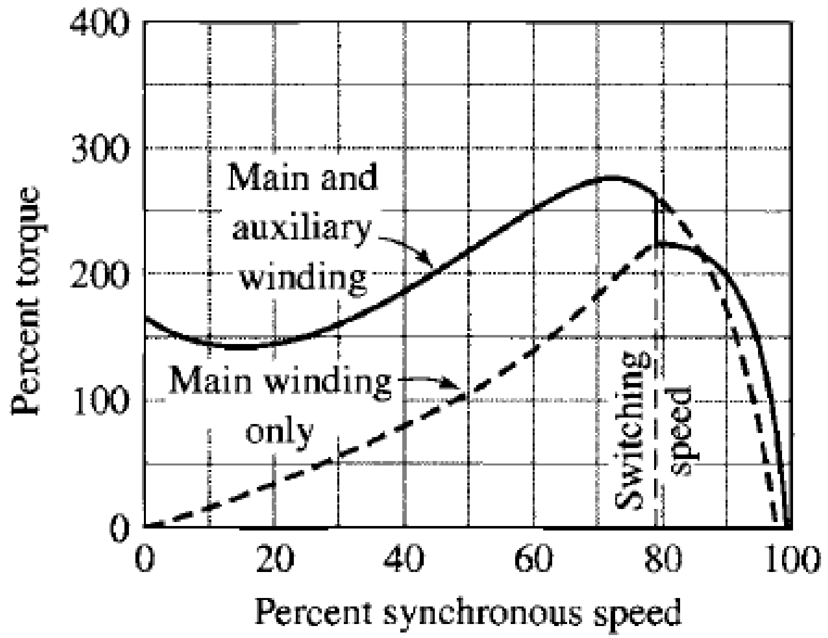
$$P_{out} = P_d - P_{mech} \qquad T_{out} = \frac{P_{out}}{\omega}$$

Motor Types

1. Split-phase (resistance-start) Motor



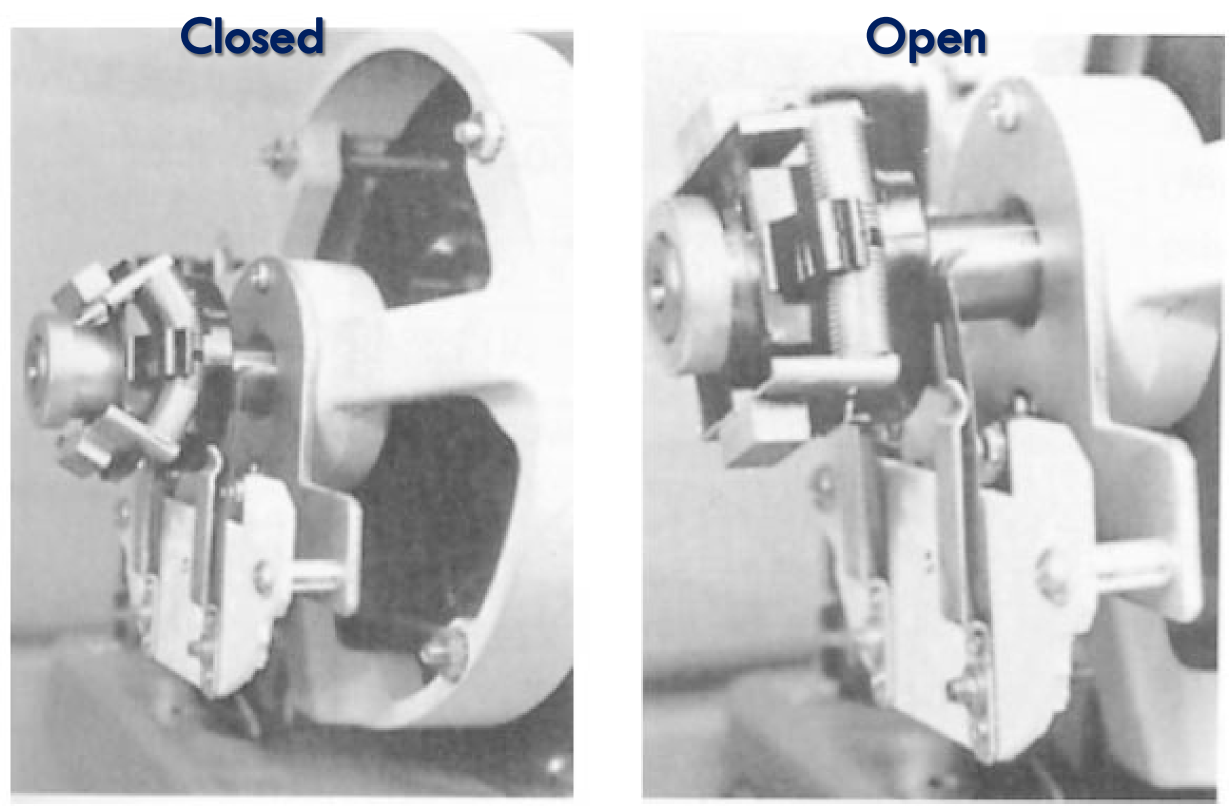




Induction Machines: 1-phase Induction Motors

Motor Types

1. Split-phase (resistance-start) Motor

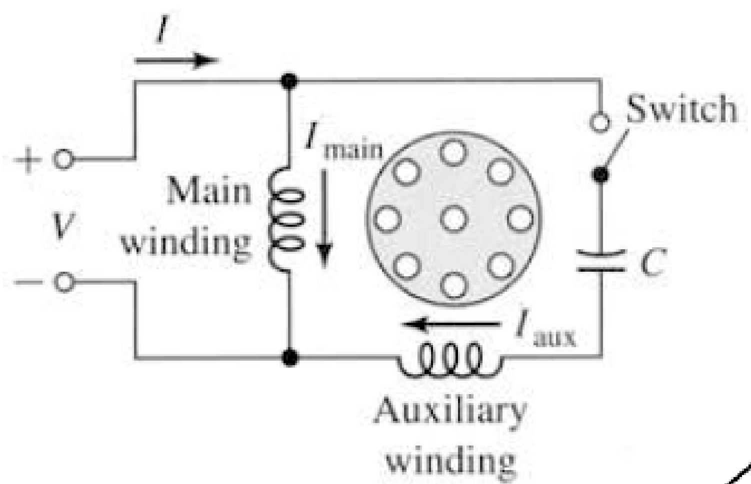


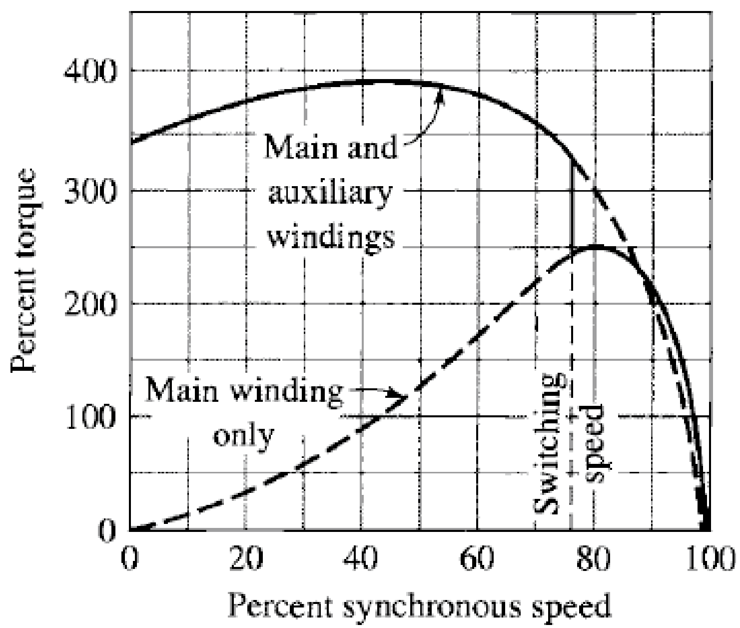
Centrifugal Switch

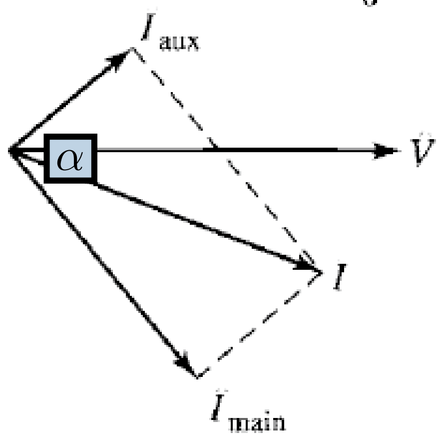
Induction Machines: 1-phase Induction Motors

Motor Types

2. Capacitor-Start Motor



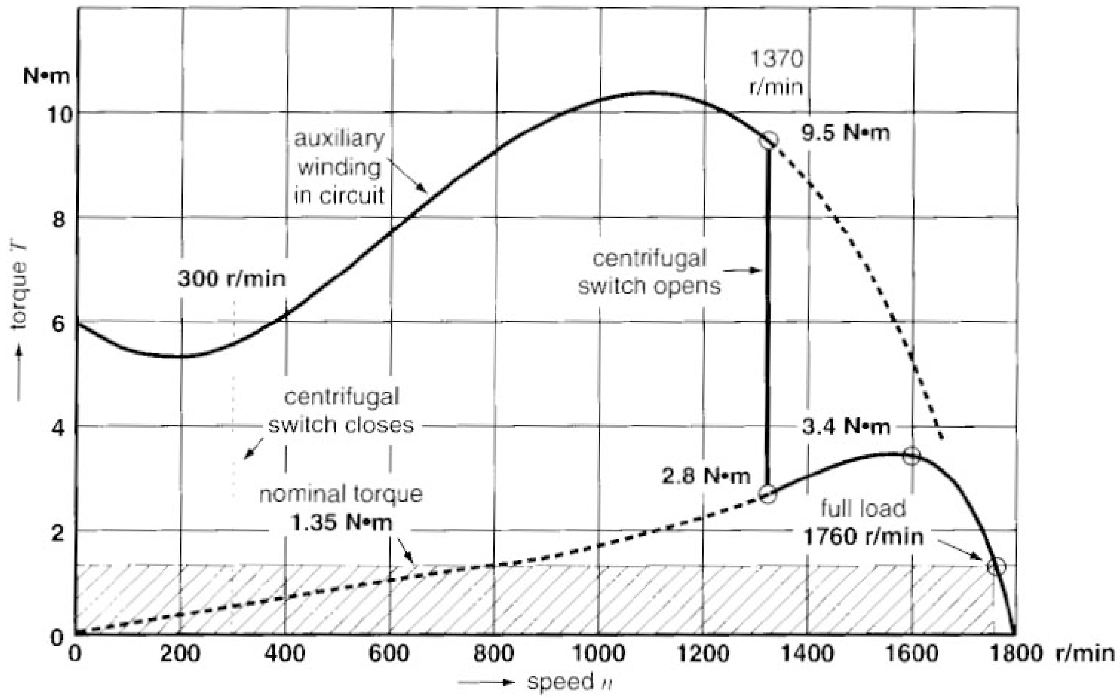




Motor Types

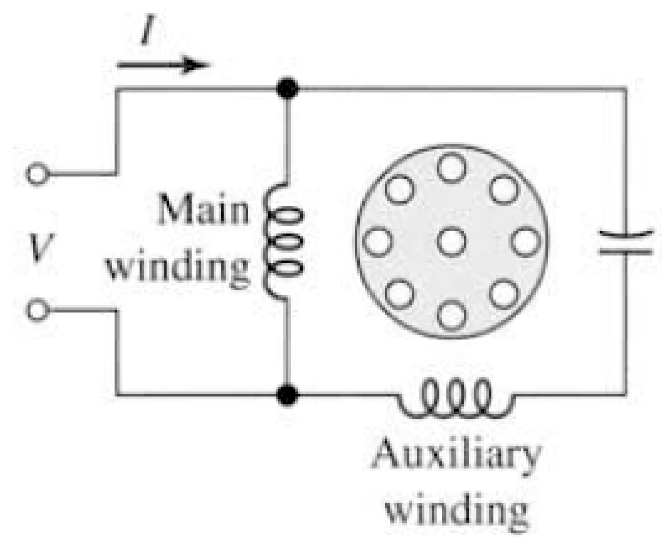
2. Capacitor-Start Motor

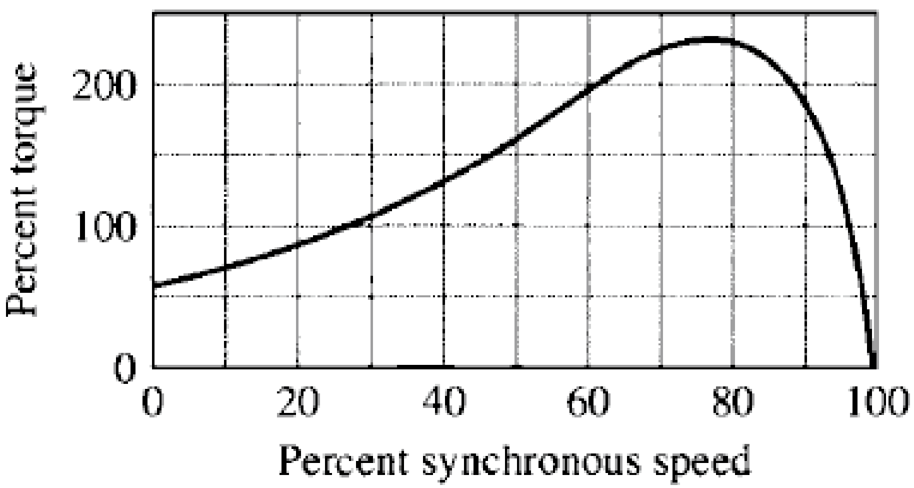
250 W (1/3 hp) motor, 4-poles, 110 V, 60 Hz



Motor Types

3. Capacitor-Run Motor

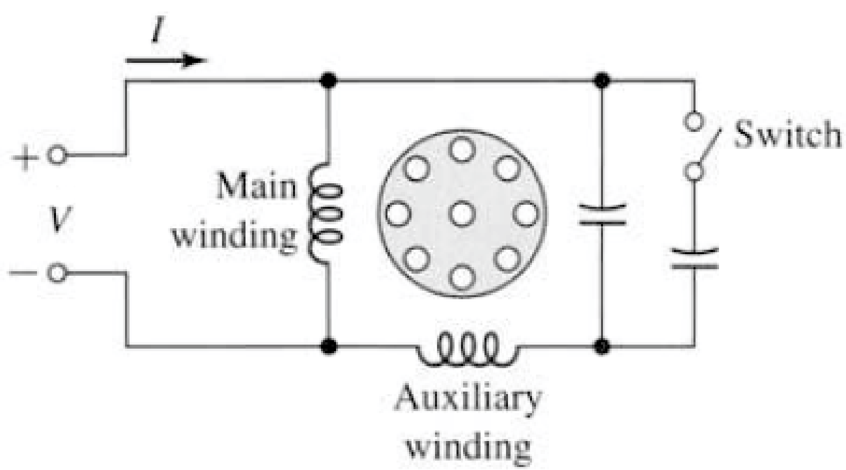


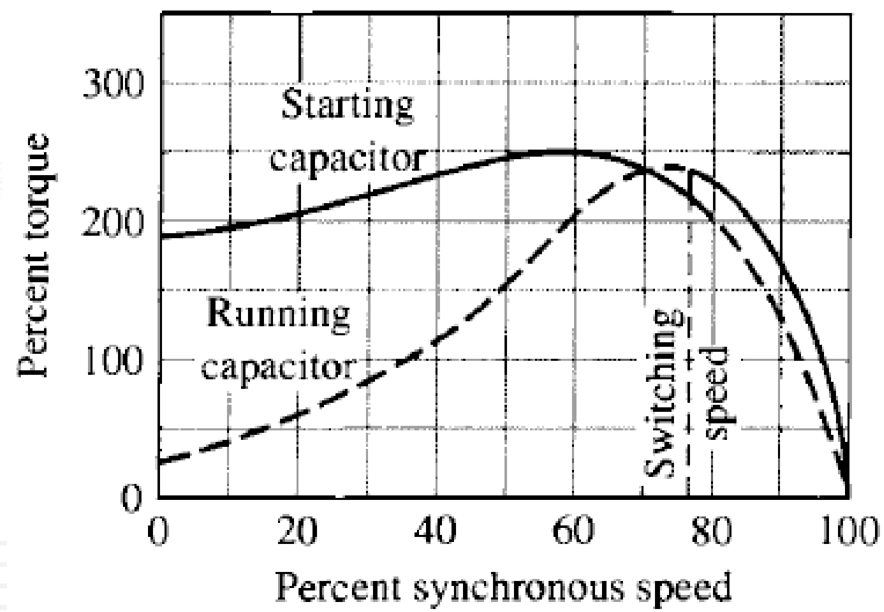


Induction Machines: 1-phase Induction Motors

Motor Types

4. Capacitor-Start, Capacitor-Run Motor

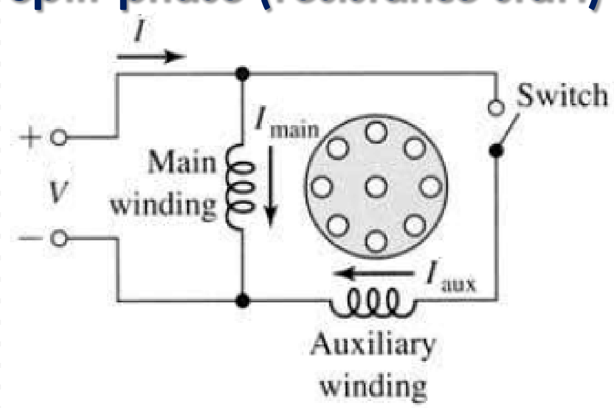




Starting Winding Design

At starting (n=0, s=1)

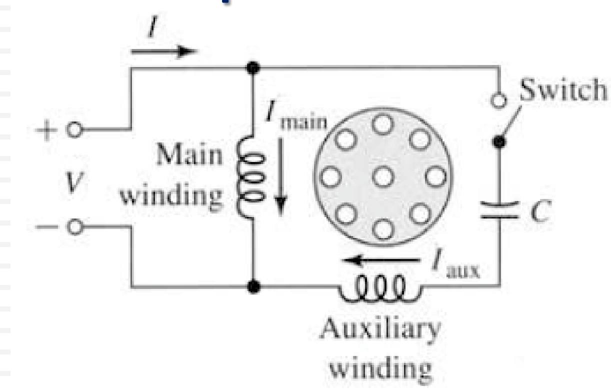
Split-phase (resistance start)



$$I_M = \frac{V}{Z_M}$$

$$I_A = \frac{V}{Z_A}$$

Capacitor-start



$$I_M = \frac{V}{Z_M}$$

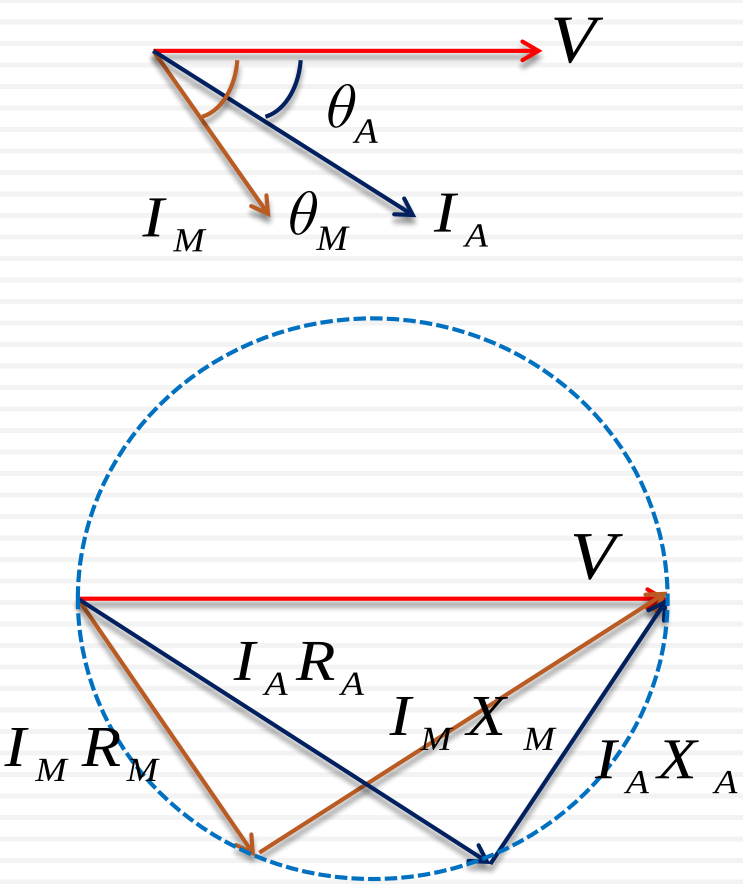
$$I_A = \frac{V}{Z_A - jX_C}$$

Z_M = standstill impedance of the main winding

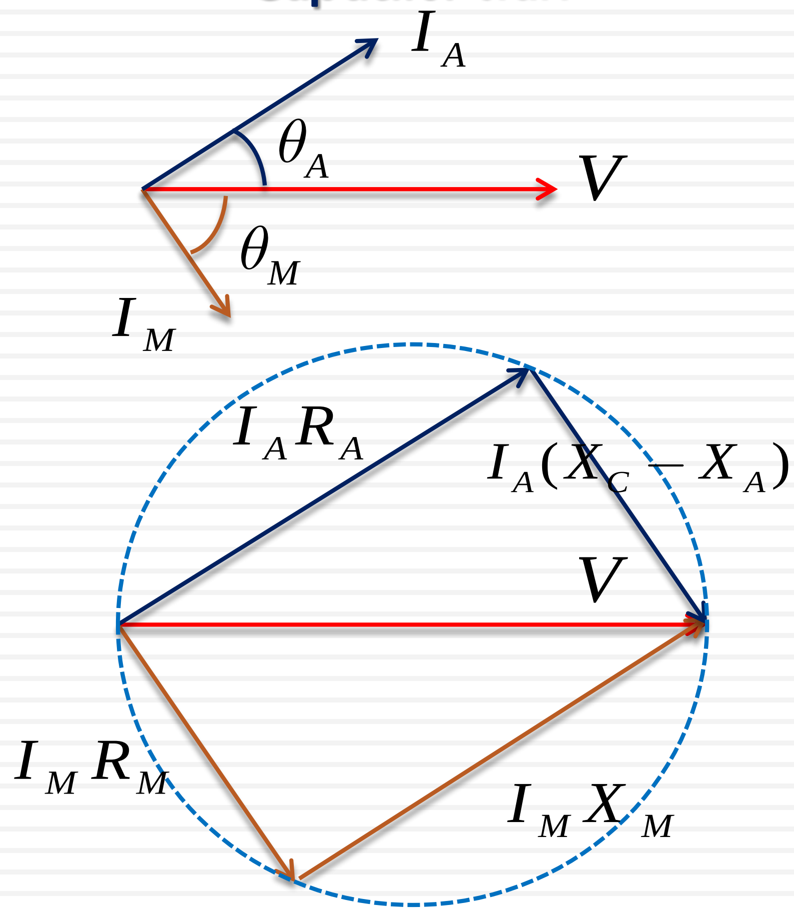
Z_A = standstill impedance of the auxiliary winding

Starting Winding Design

Split-phase (resistance start)



Capacitor-start



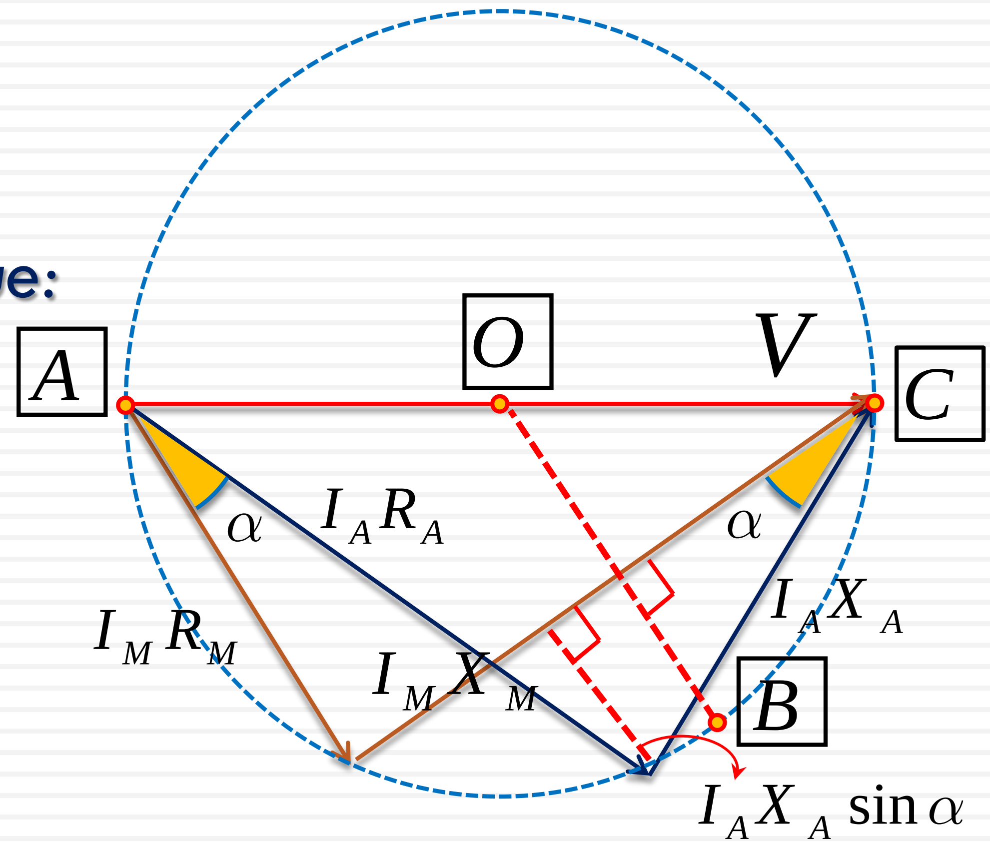
Starting Winding Design

1. Design of Resistance-Start Motors

$$T_{st} \propto I_A \sin\alpha$$

For max. starting torque:

$$\frac{AB}{BC} = \frac{R_A + R_{Add}}{X_A}$$



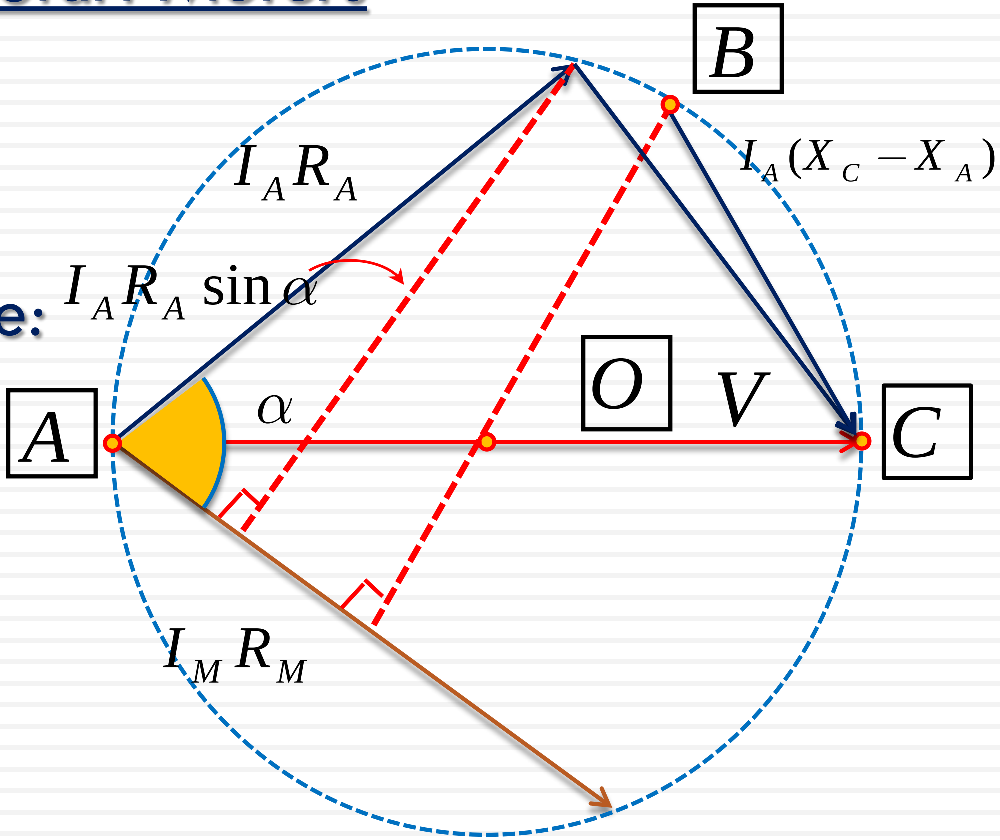
Starting Winding Design

2. Design of Capacitor-Start Motors

$$T_{st} \propto I_A \sin\alpha$$

For max. starting torque:

$$\frac{BC}{AB} = \frac{X_C - X_A}{R_A}$$



Testing: 1. Locked Rotor (Standstill) Test

Voltage is adjusted such that stator current ≤ full load current

Main winding only is connected

Reduced Voltage

m m

I_{LR}

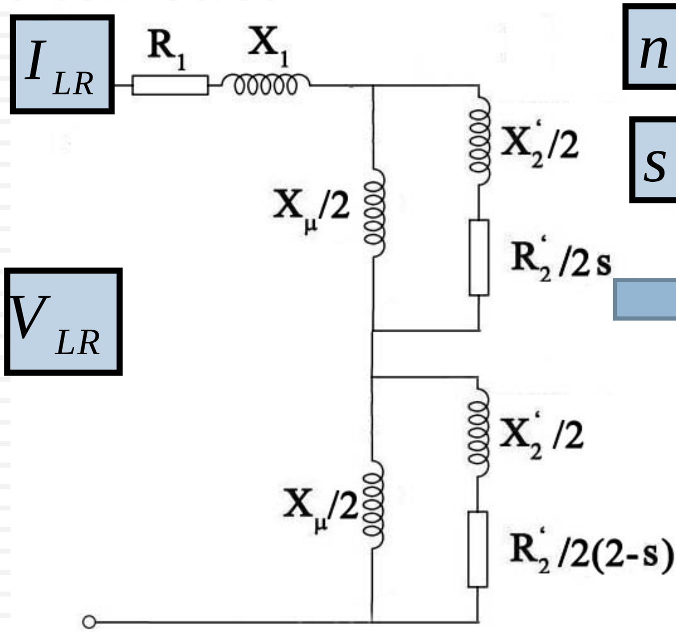
V_{LR}

W_{NL}

$$W_{LR} = P_{cu1} + P_{cu2}$$

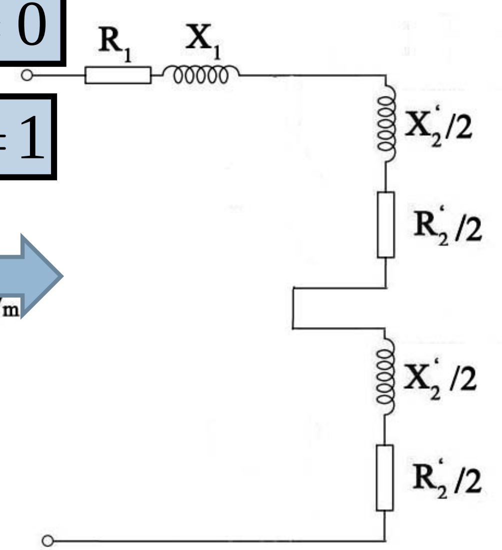
$$W = I_{LR}^2 R_{LR}$$

$$R_{LR} = R_1 + R_2^{'}$$



$$n = 0$$

$$s = 1$$



$$R_1 = R_2^{'} = \frac{R_{LR}}{2}$$

$$Z_{LR} = \frac{V_{LR}}{I_{LR}}$$

$$Z_{LR} = \sqrt{R_{LR}^2 + X_{LR}^2}$$

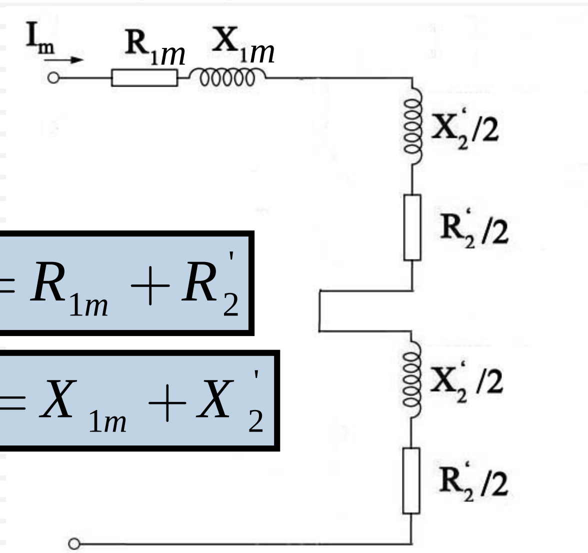
$$X_{LR} = X_1 + X_2^{'}$$

$$X_1 = X_2^{'} = \frac{X_{LR}}{2}$$

Testing: 1. Locked Rotor (Standstill) Test

To get the standstill impedances of the main and auxiliary windings, this test is performed on each winding individually.

Main Winding only connected to the supply

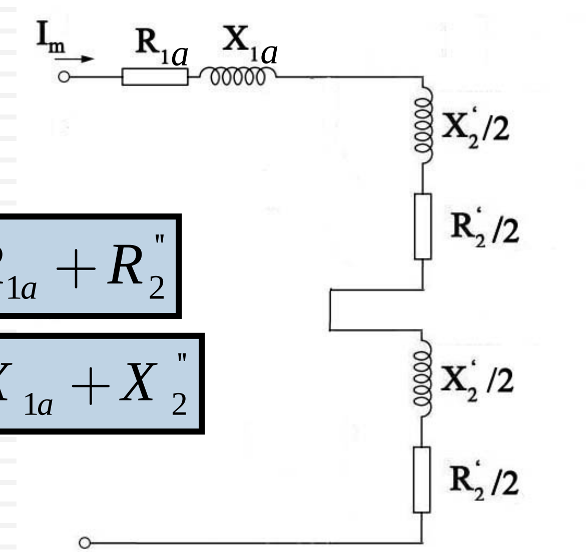


$$R_M = R_{1m} + R_2'$$

$$X_M = X_{1m} + X_2'$$

$$Z_M = R_M + jX_M$$

Aux. Winding only connected to the supply



$$R_A = R_{1a} + R_2''$$

$$X_A = X_{1a} + X_2''$$

$$Z_A = R_A + jX_A$$

Testing: 2. No-Load Test

$$W_{NL} = P_{mech} + P_{cu1}$$

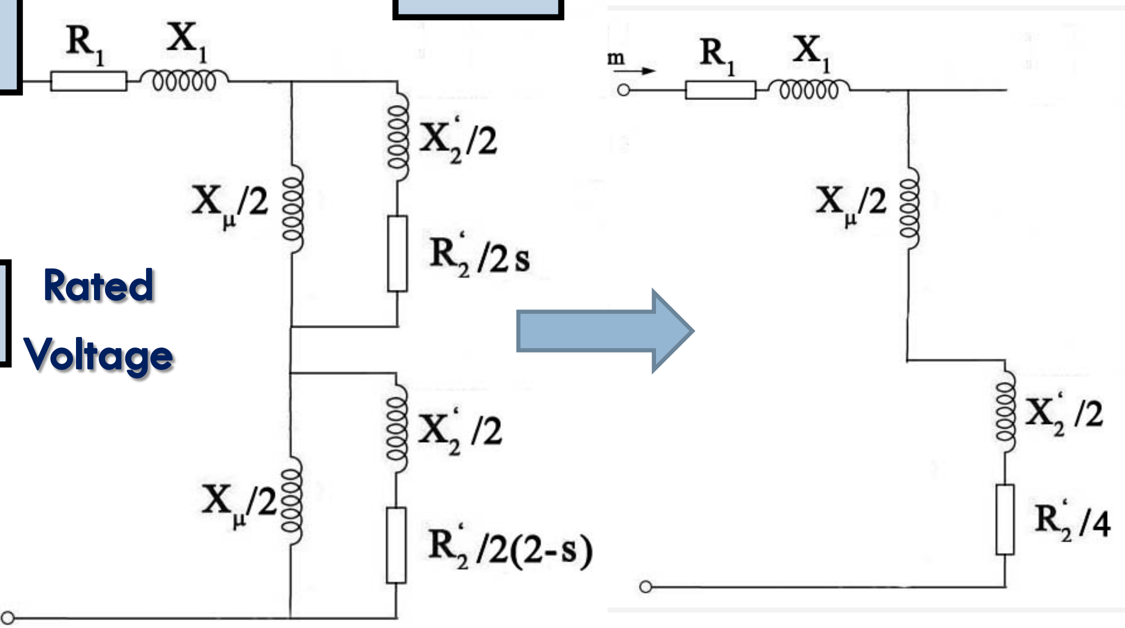
$$I_{NL}$$

$$W_{NL}$$

$$V_{NL}$$

Rated Voltage

$$s \approx 0$$



$$P_{cu1} = I_{NL}^2 (R_1 + \frac{R_2'}{4})$$

$$\rightarrow P_{mech}$$

$$Z_{NL} = \frac{V_{NL}}{I_{NL}}$$

$$Z_{NL} = \sqrt{R_{NL}^2 + X_{NL}^2}$$

$$X_{NL} = X_1 + \frac{X_2'}{2} + \frac{X_\mu}{2}$$

$$X_\mu = 2 \times (X_{NL} - X_1 - \frac{X_2'}{2})$$