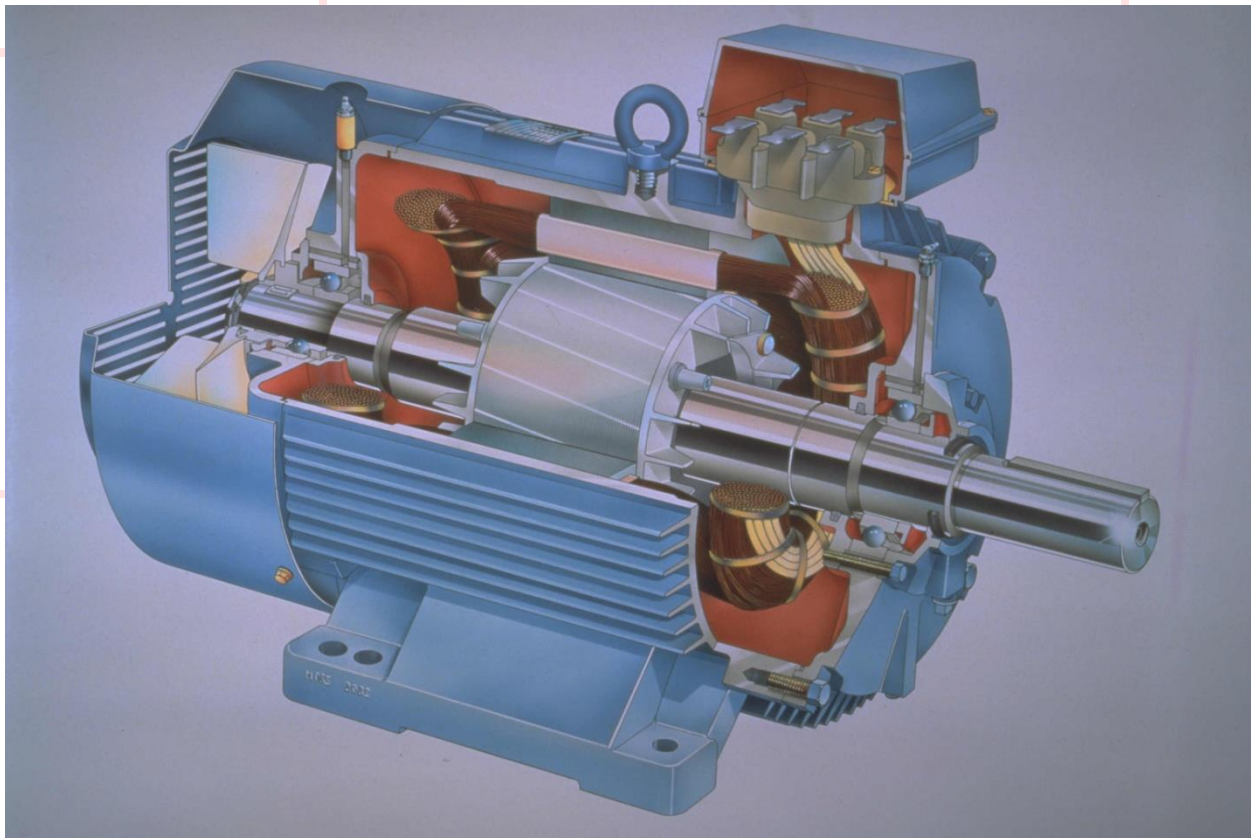
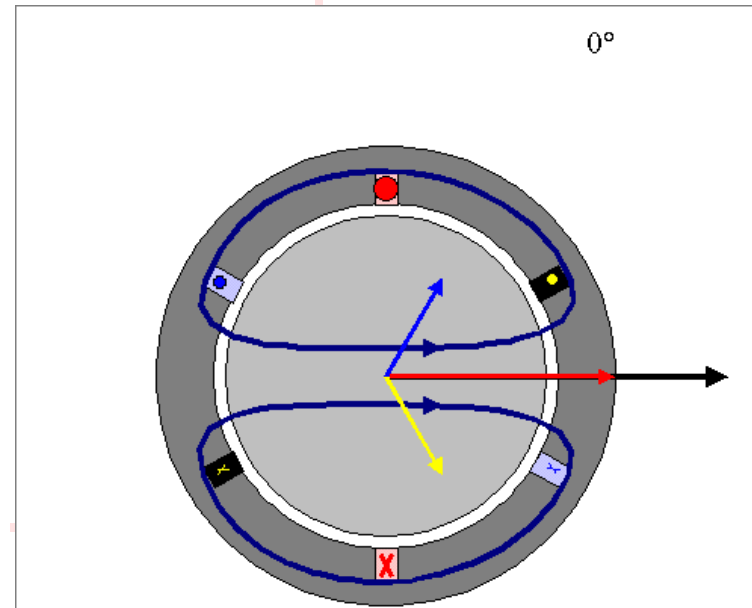
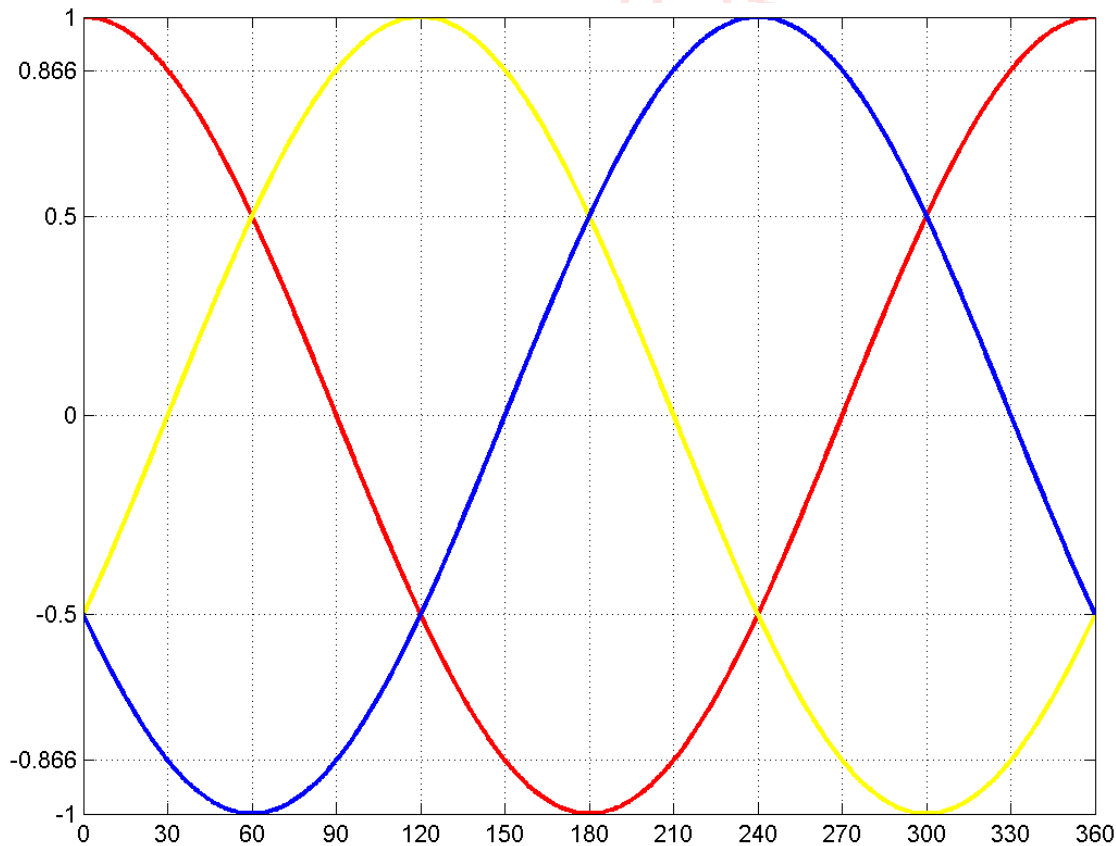


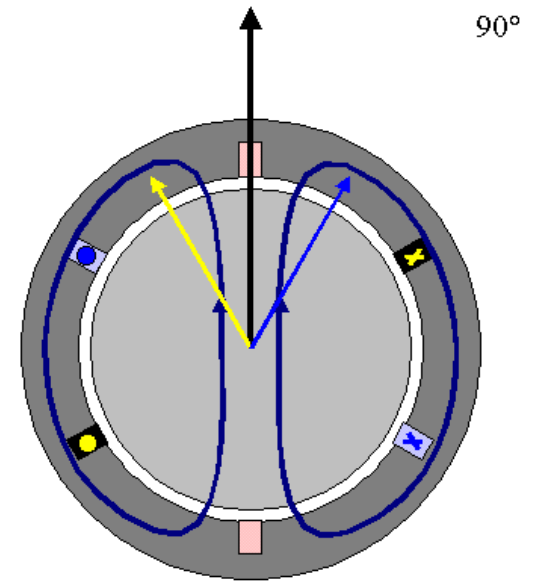
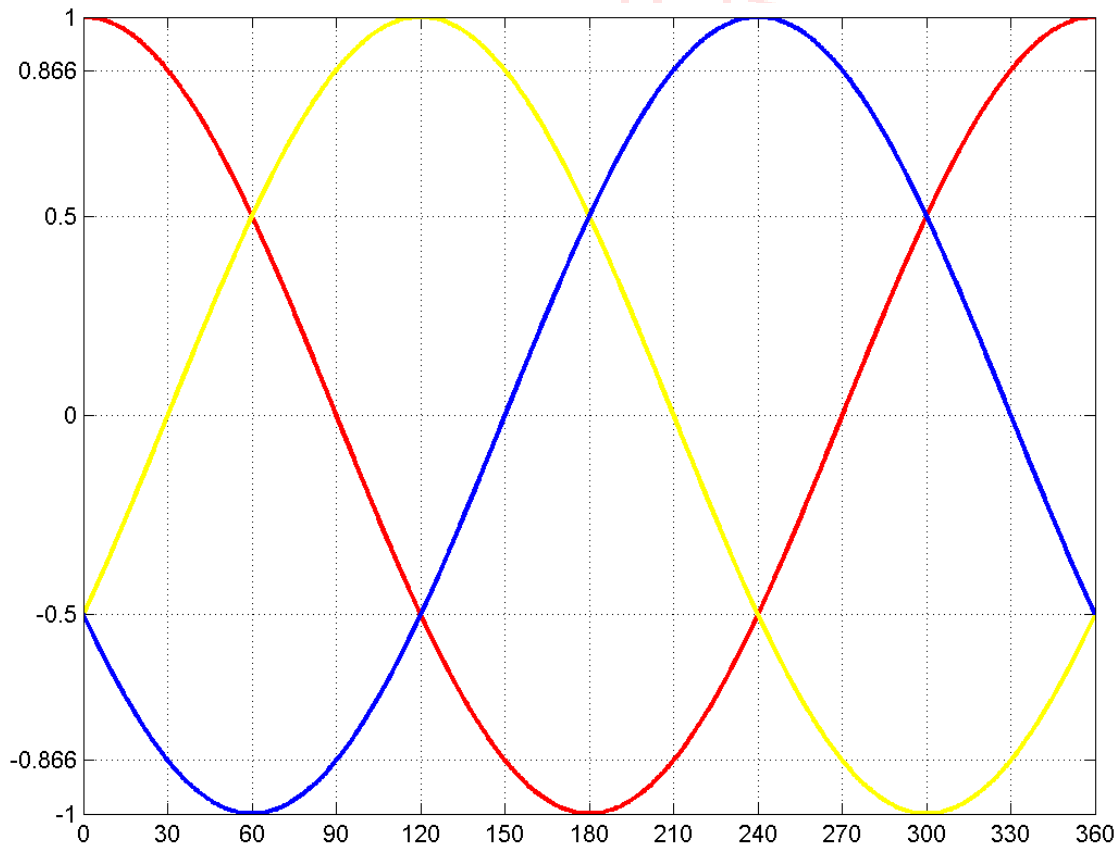
Induction Motors



Rotating Magnetic Field



Rotating Magnetic Field



Rotating Magnetic Field

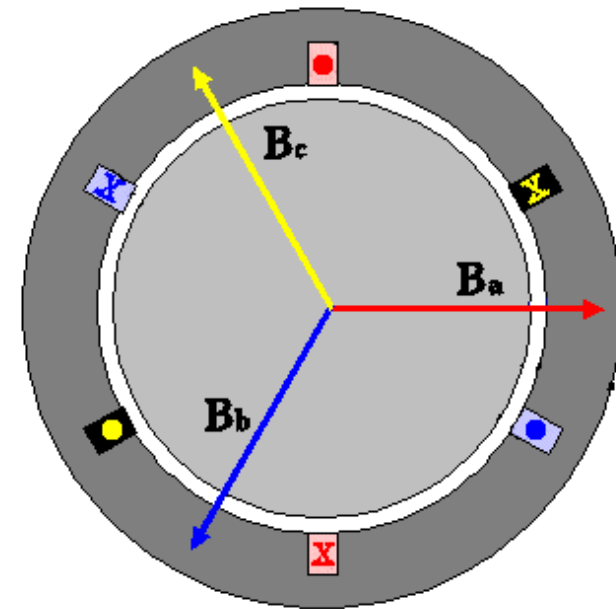
$$B_{net}(t) = B_a(t) + B_b(t) + B_c(t)$$

$$= B_M \sin(\omega t) \angle 0^\circ + B_M \sin(\omega t - 120^\circ) \angle 120^\circ + B_M \sin(\omega t - 240^\circ) \angle 240^\circ$$

$$= B_M \sin(\omega t) \hat{\mathbf{x}}$$

$$- [0.5 B_M \sin(\omega t - 120^\circ)] \hat{\mathbf{x}} - \left[\frac{\sqrt{3}}{2} B_M \sin(\omega t - 120^\circ) \right] \hat{\mathbf{y}}$$

$$- [0.5 B_M \sin(\omega t - 240^\circ)] \hat{\mathbf{x}} + \left[\frac{\sqrt{3}}{2} B_M \sin(\omega t - 240^\circ) \right] \hat{\mathbf{y}}$$

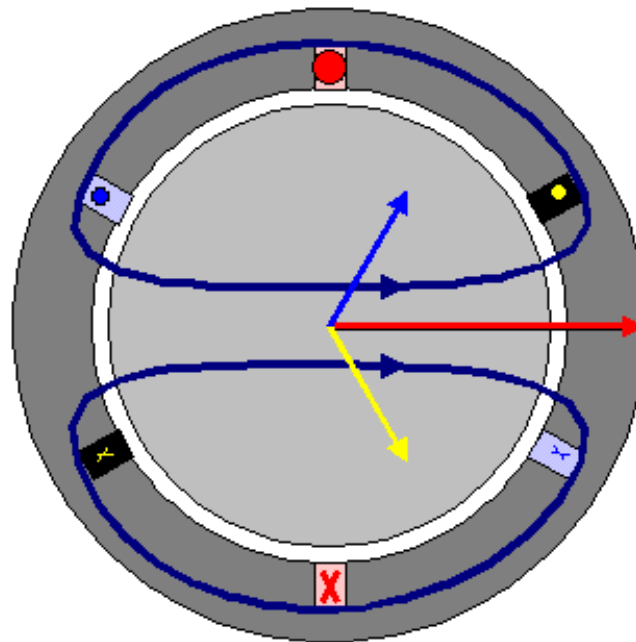


Rotating Magnetic Field

$$\begin{aligned} B_{net}(t) &= [B_M \sin(\omega t) + \frac{1}{4} B_M \sin(\omega t) + \frac{\sqrt{3}}{4} B_M \cos(\omega t) + \frac{1}{4} B_M \sin(\omega t) - \frac{\sqrt{3}}{4} B_M \cos(\omega t)] \hat{\mathbf{x}} \\ &\quad + [-\frac{\sqrt{3}}{4} B_M \sin(\omega t) - \frac{3}{4} B_M \cos(\omega t) + \frac{\sqrt{3}}{4} B_M \sin(\omega t) - \frac{3}{4} B_M \cos(\omega t)] \hat{\mathbf{y}} \\ &= [1.5 B_M \sin(\omega t)] \hat{\mathbf{x}} - [1.5 B_M \cos(\omega t)] \hat{\mathbf{y}} \end{aligned}$$

Rotating Magnetic Field

0°



Induction motor speed

- At what speed will the IM run?
 - Can the IM run at the synchronous speed, why?
 - If rotor runs at the synchronous speed, which is the same speed of the rotating magnetic field, then the rotor will appear stationary to the rotating magnetic field and the rotating magnetic field will not cut the rotor. So, no induced current will flow in the rotor and no rotor magnetic flux will be produced so no torque is generated and the rotor speed will fall below the synchronous speed
 - When the speed falls, the rotating magnetic field will cut the rotor windings and a torque is produced

Induction motor speed

- So, the IM will always run at a speed **lower** than the synchronous speed
- The difference between the motor speed and the synchronous speed is called the *Slip*

$$n_{slip} = n_{sync} - n_m$$

Where n_{slip} = slip speed

n_{sync} = speed of the magnetic field

n_m = mechanical shaft speed of the motor

The Slip

$$s = \frac{n_{sync} - n_m}{n_{sync}}$$

Where s is the *slip*

Notice that : if the rotor runs at synchronous speed

$$s = 0$$

if the rotor is stationary

$$s = 1$$

Slip may be expressed as a **percentage** by multiplying the above eq. by 100, notice that the slip is a ratio and doesn't have units

Frequency

- The frequency of the voltage induced in the rotor is given by

$$f_r = \frac{P \times n}{120}$$

Where f_r = the rotor frequency (Hz)

P = number of stator poles

n = slip speed (rpm)

$$f_r = \frac{P \times (n_s - n_m)}{120}$$

$$= \frac{P \times s n_s}{120} = s f_e$$

Frequency

- What would be the frequency of the rotor's induced voltage at any speed n_m ?

$$f_r = s f_e$$

- When the rotor is blocked ($s=1$) , the frequency of the induced voltage is equal to the supply frequency
- On the other hand, if the rotor runs at synchronous speed ($s = 0$), the frequency will be zero

Torque

- While the input to the induction motor is electrical power, its output is mechanical power and for that we should know some terms and quantities related to mechanical power
- Any mechanical load applied to the motor shaft will introduce a **Torque** on the motor shaft. This torque is related to the motor output power and the rotor speed

$$\tau_{load} \equiv \frac{P_{out}}{\omega_m} \quad N.m$$

and

$$\omega_m \equiv \frac{2\pi n_m}{60} \quad rad / s$$

Example

A 208-V, 10hp, four pole, 60 Hz, Y-connected induction motor has a full-load slip of 5 percent

1. What is the synchronous speed of this motor?
2. What is the rotor speed of this motor at rated load?
3. What is the rotor frequency of this motor at rated load?
4. What is the shaft torque of this motor at rated load?

Solution

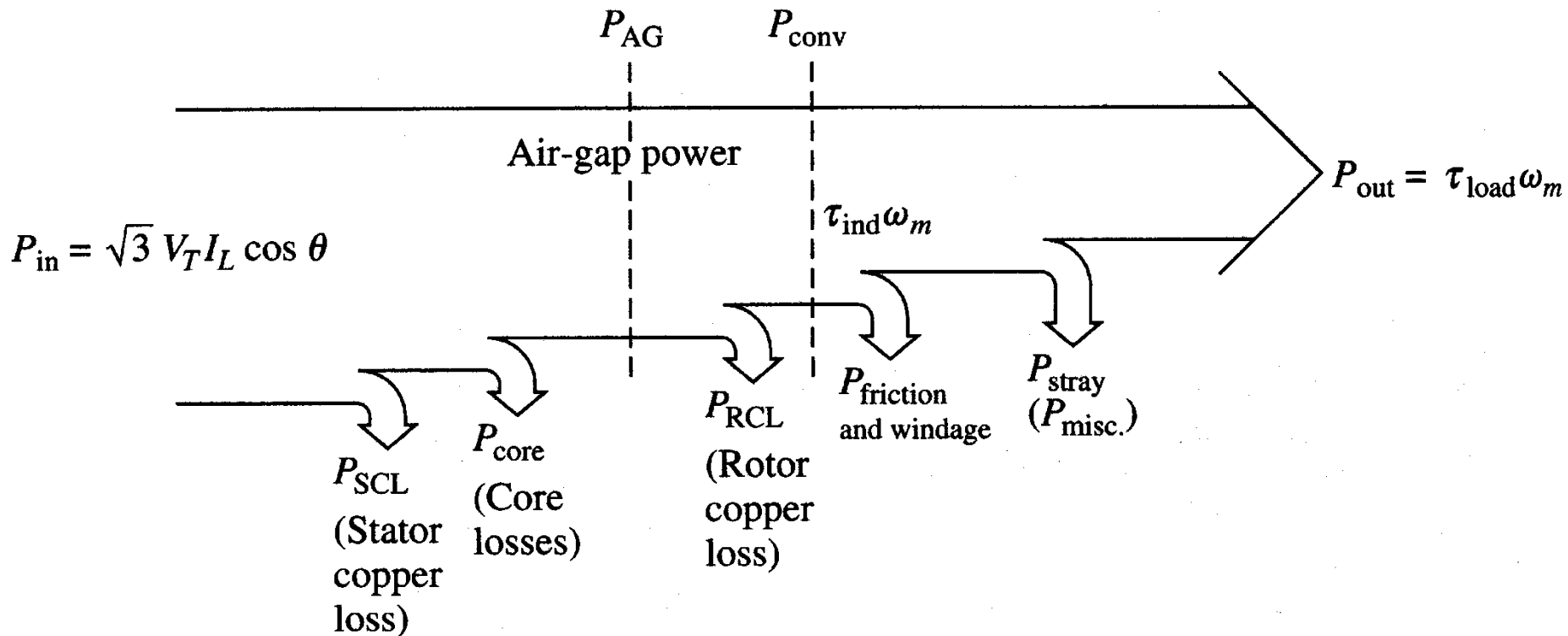
$$1. \quad n_{sync} = \frac{120 f_e}{P} = \frac{120(60)}{4} = 1800 \text{ rpm}$$

$$2. \quad n_m = (1 - s)n_s \\ = (1 - 0.05) \times 1800 = 1710 \text{ rpm}$$

$$3. \quad f_r = s f_e = 0.05 \times 60 = 3 \text{ Hz}$$

$$4. \quad \tau_{load} = \frac{P_{out}}{\omega_m} = \frac{P_{out}}{2\pi \frac{n_m}{60}} \\ = \frac{10 \text{ hp} \times 746 \text{ watt / hp}}{1710 \times 2\pi \times (1/60)} = 41.7 \text{ N.m}$$

Power flow in induction motor



Power relations

$$P_{in} = \sqrt{3} V_L I_L \cos \theta = 3 V_{ph} I_{ph} \cos \theta$$

$$P_{SCL} = 3 I_1^2 R_1$$

$$P_{AG} = P_{in} - (P_{SCL} + P_{core})$$

$$P_{RCL} = 3 I_2^2 R_2$$

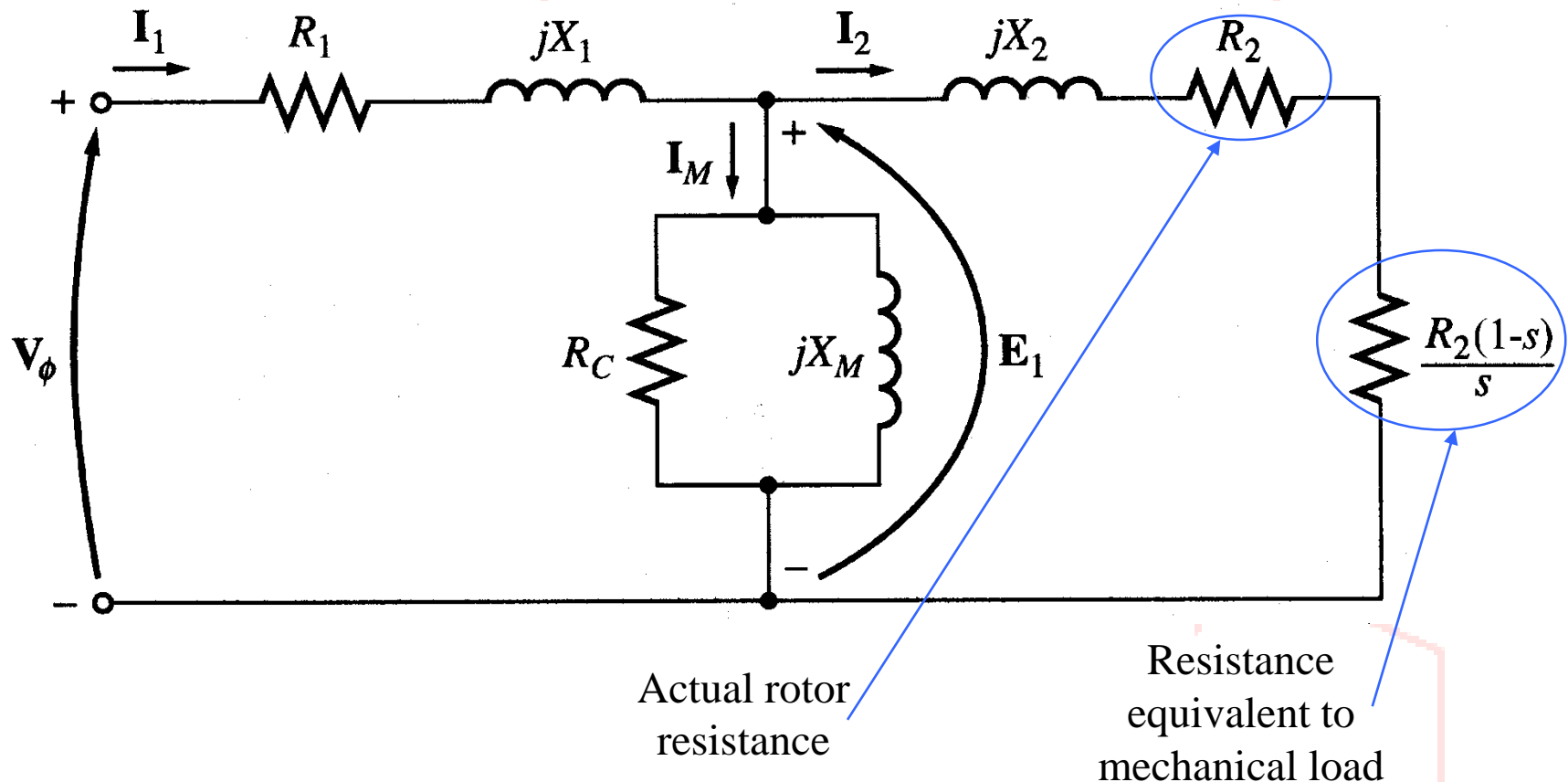
$$P_{conv} = P_{AG} - P_{RCL}$$

$$P_{out} = P_{conv} - (P_{f+w} + P_{stray})$$

$$\tau_{ind} = \frac{P_{conv}}{\omega_m}$$

Equivalent Circuit

- We can rearrange the equivalent circuit as follows



Power relations

$$P_{in} = \sqrt{3} V_L I_L \cos \theta = 3 V_{ph} I_{ph} \cos \theta$$

$$P_{SCL} = 3 I_1^2 R_1$$

$$P_{AG} = P_{in} - (P_{SCL} + P_{core}) = P_{conv} + P_{RCL} = 3 I_2^2 \frac{R_2}{s} = \frac{P_{RCL}}{s}$$

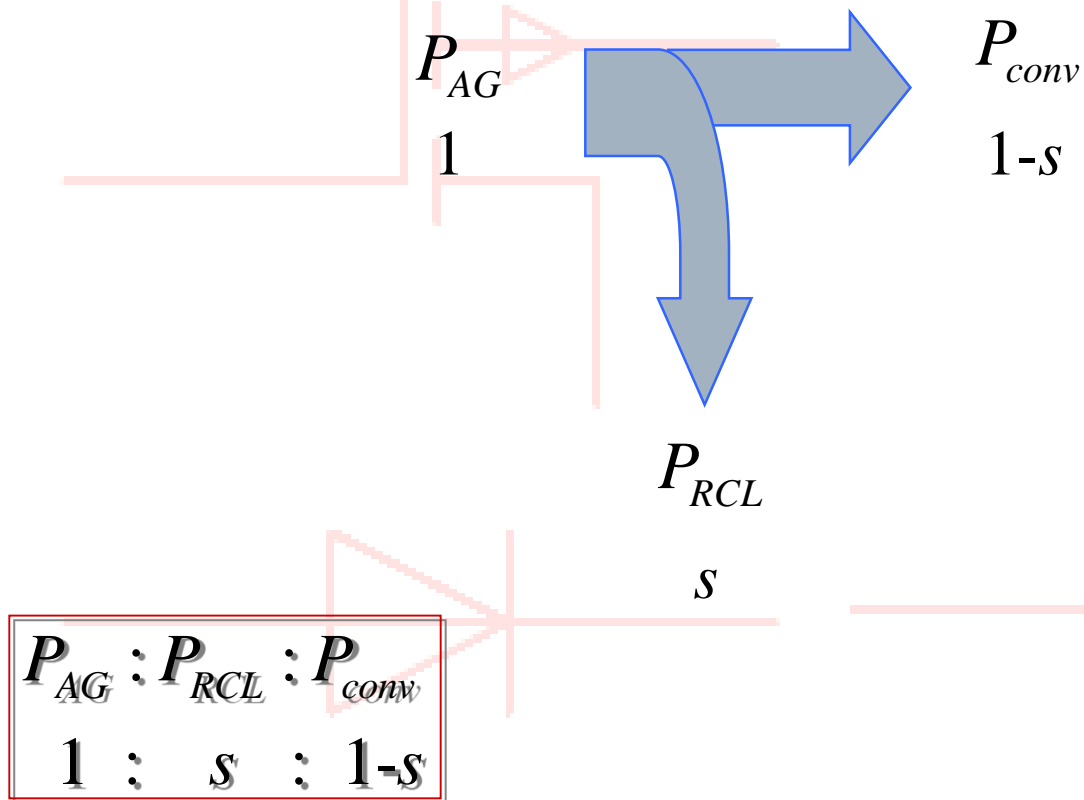
$$P_{RCL} = 3 I_2^2 R_2$$

$$P_{conv} = P_{AG} - P_{RCL} = 3 I_2^2 \frac{R_2 (1-s)}{s} = \frac{P_{RCL} (1-s)}{s}$$

$$P_{conv} = (1-s) P_{AG}$$

$$P_{out} = P_{conv} - (P_{f+w} + P_{stray}) \quad \tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{(1-s) P_{AG}}{(1-s) \omega_s}$$

Power relations



Example

A 480-V, 60 Hz, 50-hp, three phase induction motor is drawing 60A at 0.85 PF lagging. The stator copper losses are 2 kW, and the rotor copper losses are 700 W. The friction and windage losses are 600 W, the core losses are 1800 W, and the stray losses are negligible. Find the following quantities:

1. The air-gap power P_{AG} .
2. The power converted P_{conv} .
3. The output power P_{out} .
4. The efficiency of the motor.

Solution

$$\begin{aligned} 1. \quad P_{in} &= \sqrt{3} V_L I_L \cos \theta \\ &= \sqrt{3} \times 480 \times 60 \times 0.85 = 42.4 \text{ kW} \end{aligned}$$

$$\begin{aligned} P_{AG} &= P_{in} - P_{SCL} - P_{core} \\ &= 42.4 - 2 - 1.8 = 38.6 \text{ kW} \end{aligned}$$

$$\begin{aligned} 2. \quad P_{conv} &= P_{AG} - P_{RCL} \\ &= 38.6 - \frac{700}{1000} = 37.9 \text{ kW} \end{aligned}$$

$$\begin{aligned} 3. \quad P_{out} &= P_{conv} - P_{F\&W} \\ &= 37.9 - \frac{600}{1000} = 37.3 \text{ kW} \end{aligned}$$

Solution

$$P_{out} = \frac{37.3}{0.746} = 50 \text{ hp}$$

4.
$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$
$$= \frac{37.3}{42.4} \times 100 = 88\%$$

Example

A 460-V, 25-hp, 60 Hz, four-pole, Y-connected induction motor has the following impedances in ohms per phase referred to the stator circuit:

$$R_1 = 0.641 \Omega \quad R_2 = 0.332 \Omega$$

$$X_1 = 1.106 \Omega \quad X_2 = 0.464 \Omega \quad X_M = 26.3 \Omega$$

The total rotational losses are 1100 W and are assumed to be constant. The core loss is lumped in with the rotational losses. For a rotor slip of 2.2 percent at the rated voltage and rated frequency, find the motor's

1. Speed
2. Stator current
3. Power factor
4. P_{conv} and P_{out}
5. τ_{ind} and τ_{load}
6. Efficiency

Solution

$$1. \quad n_{sync} = \frac{120 f_e}{P} = \frac{120 \times 60}{4} = 1800 \text{ rpm}$$

$$n_m = (1 - s)n_{sync} = (1 - 0.022) \times 1800 = 1760 \text{ rpm}$$

$$2. \quad Z_2 = \frac{R_2}{s} + jX_2 = \frac{0.332}{0.022} + j0.464$$

$$= 15.09 + j0.464 = 15.1 \angle 1.76^\circ \Omega$$

$$Z_f = \frac{1}{1/jX_M + 1/Z_2} = \frac{1}{-j0.038 + 0.0662 \angle -1.76^\circ}$$

$$= \frac{1}{0.0773 \angle -31.1^\circ} = 12.94 \angle 31.1^\circ \Omega$$

Solution

$$\begin{aligned}Z_{tot} &= Z_{stat} + Z_f \\&= 0.641 + j1.106 + 12.94 \angle 31.1^\circ \Omega \\&= 11.72 + j7.79 = 14.07 \angle 33.6^\circ \Omega\end{aligned}$$

$$I_1 = \frac{V_\phi}{Z_{tot}} = \frac{\frac{460 \angle 0^\circ}{\sqrt{3}}}{14.07 \angle 33.6^\circ} = 18.88 \angle -33.6^\circ \text{ A}$$

3. $PF = \cos 33.6^\circ = 0.833$ lagging

4. $P_{in} = \sqrt{3} V_L I_L \cos \theta = \sqrt{3} \times 460 \times 18.88 \times 0.833 = 12530 \text{ W}$

$$P_{SCL} = 3I_1^2 R_1 = 3(18.88)^2 \times 0.641 = 685 \text{ W}$$

$$P_{AG} = P_{in} - P_{SCL} = 12530 - 685 = 11845 \text{ W}$$

Solution

$$P_{conv} = (1 - s)P_{AG} = (1 - 0.022)(11845) = 11585 \text{ W}$$

$$P_{out} = P_{conv} - P_{F\&W} = 11585 - 1100 = 10485 \text{ W}$$

$$= \frac{10485}{746} = 14.1 \text{ hp}$$

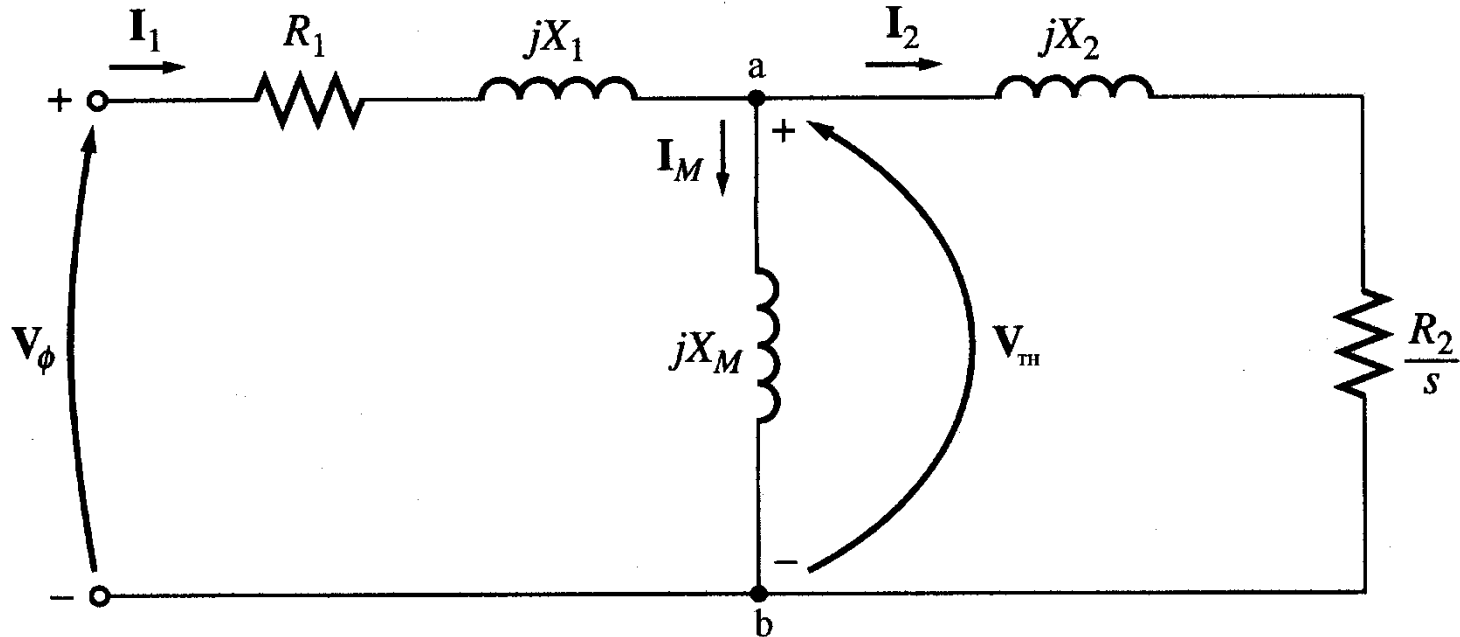
$$5. \tau_{ind} = \frac{P_{AG}}{\omega_{sync}} = \frac{11845}{2\pi \times 1800 / 60} = 62.8 \text{ N.m}$$

$$\tau_{load} = \frac{P_{out}}{\omega_m} = \frac{10485}{2\pi \times 1760 / 60} = 56.9 \text{ N.m}$$

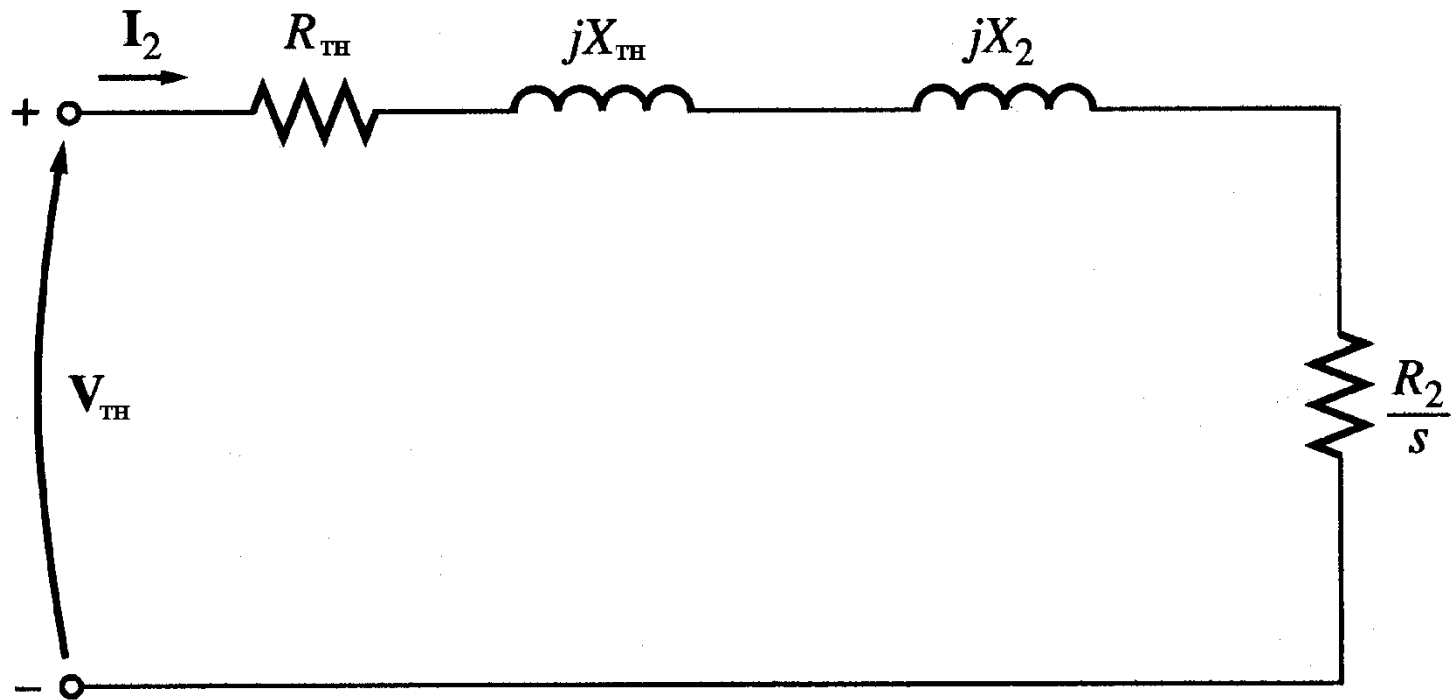
$$6. \eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{10485}{12530} \times 100 = 83.7\%$$

Torque, power and Thevenin's Theorem

- Thevenin's theorem can be used to transform the network to the left of points 'a' and 'b' into an equivalent voltage source V_{TH} in series with equivalent impedance $R_{TH} + jX_{TH}$



Torque, power and Thevenin's Theorem



$$V_{TH} = V_{\phi} \frac{jX_M}{R_1 + j(X_1 + X_M)} \quad |V_{TH}| = |V_{\phi}| \frac{X_M}{\sqrt{R_1^2 + (X_1 + X_M)^2}}$$

$$R_{TH} + jX_{TH} = (R_1 + jX_1) // jX_M$$

Torque, power and Thevenin's Theorem

- Since $X_M \gg X_1$ and $X_M \gg R_1$

$$V_{TH} \approx V_\phi \frac{X_M}{X_1 + X_M}$$

- Because $X_M \gg X_1$ and $X_M + X_1 \gg R_1$

$$R_{TH} \approx R_1 \left(\frac{X_M}{X_1 + X_M} \right)^2$$
$$X_{TH} \approx X_1$$

Torque, power and Thevenin's Theorem

$$I_2 = \frac{V_{TH}}{Z_T} = \frac{V_{TH}}{\sqrt{\left(R_{TH} + \frac{R_2}{s}\right)^2 + (X_{TH} + X_2)^2}}$$

Then the power converted to mechanical (P_{conv})

$$P_{conv} = 3I_2^2 \frac{R_2(1-s)}{s}$$

And the internal mechanical torque (T_{conv})

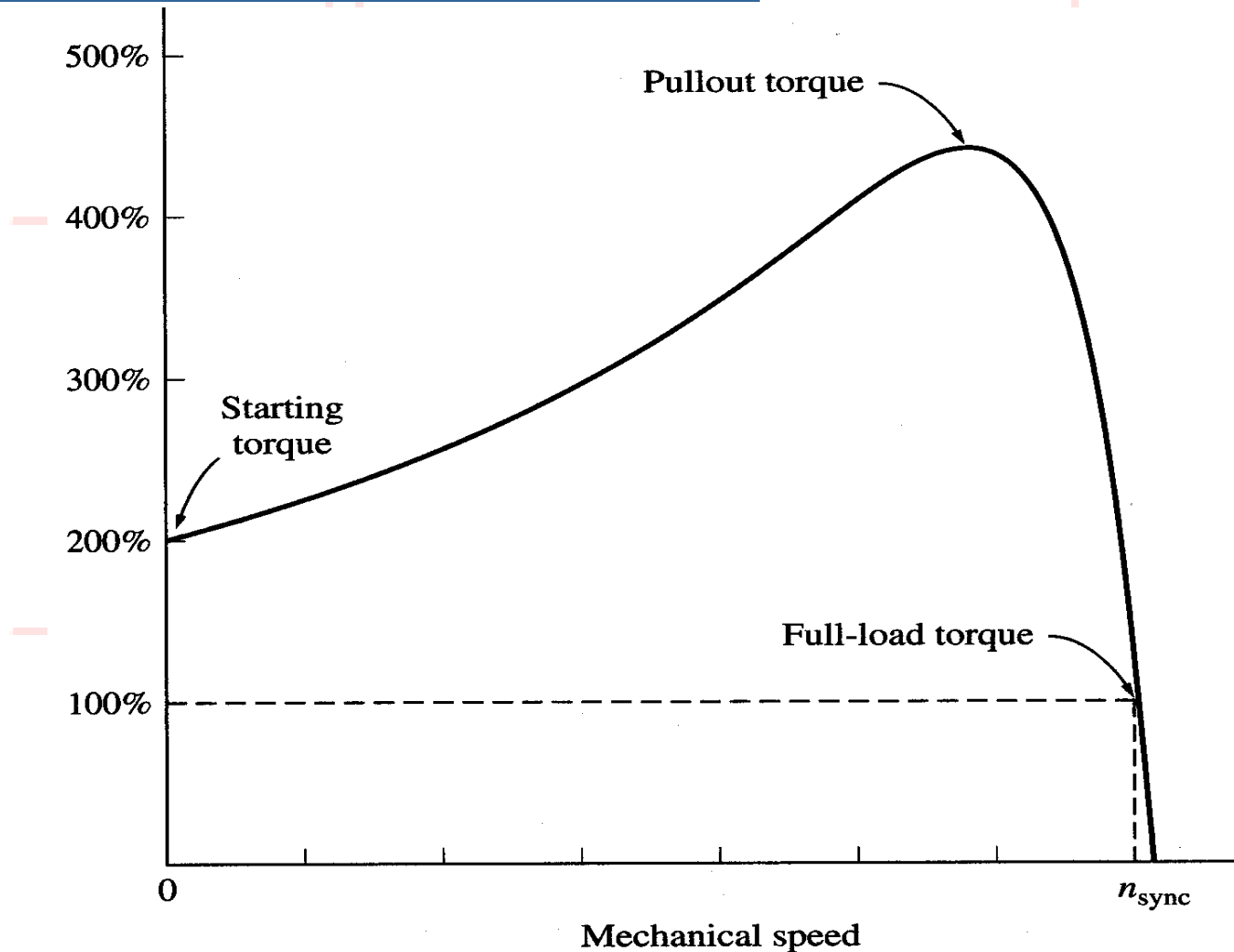
$$\tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{P_{conv}}{(1-s)\omega_s} = \frac{3I_2^2 \frac{R_2}{s}}{\omega_s} = \frac{P_{AG}}{\omega_s}$$

Torque, power and Thevenin's Theorem

$$\tau_{ind} = \frac{3}{\omega_s} \left(\frac{V_{TH}}{\sqrt{\left(R_{TH} + \frac{R_2}{s}\right)^2 + (X_{TH} + X_2)^2}} \right)^2 \left(\frac{R_2}{s} \right)$$

$$\tau_{ind} \equiv \frac{1}{\omega_s} \frac{3V_{TH}^2 \left(\frac{R_2}{s} \right)}{\left(R_{TH} + \frac{R_2}{s}\right)^2 + (X_{TH} + X_2)^2}$$

Torque-speed characteristics



Typical torque-speed characteristics of induction motor

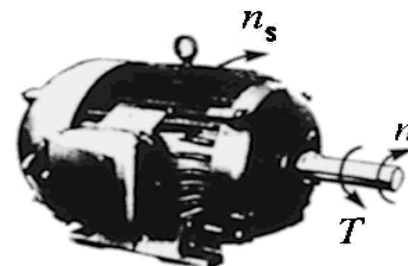
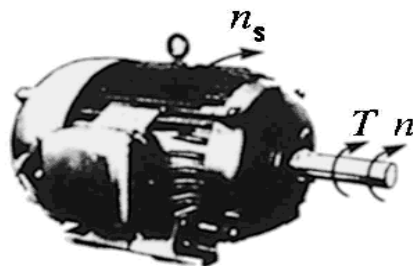
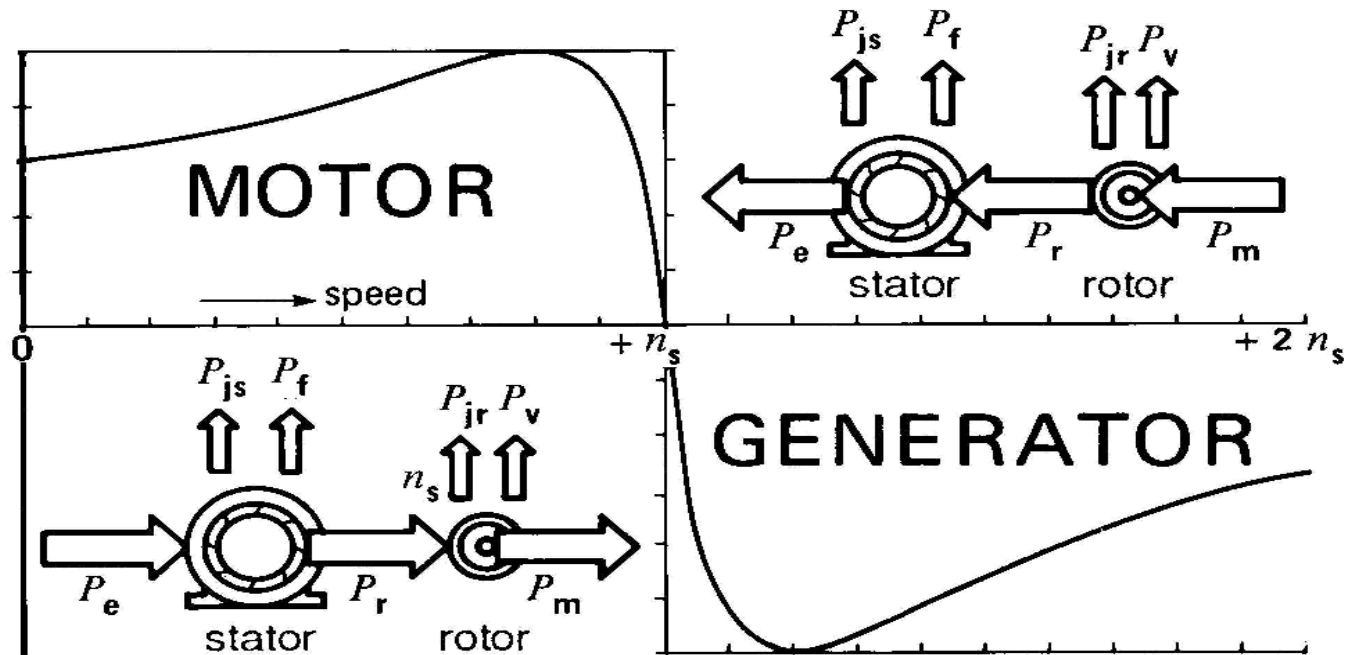
Comments

1. The induced torque is **zero** at **synchronous speed**. Discussed earlier.
2. The curve is **nearly linear** between **no-load** and **full load**. In this range, the rotor resistance is much greater than the reactance, so the rotor current, torque increase linearly with the slip.
3. There is a **maximum possible torque** that can't be exceeded. This torque is called *pullout torque* and is **2 to 3 times the rated full-load torque**.

Comments

4. The **starting torque** of the motor is slightly **higher than its full-load torque**, so the motor will start carrying any load it can supply at full load.
5. The **torque** of the motor for a given slip varies as the **square of the applied voltage**.
6. If the rotor is **driven faster than synchronous speed** it will **run as a generator**, converting mechanical power to electric power.

Complete Speed-torque c/c



Maximum torque

- Maximum torque occurs when the power transferred to R_2/s is maximum.
- This condition occurs when R_2/s equals the magnitude of the impedance $R_{TH} + j(X_{TH} + X_2)$

$$\frac{R_2}{s_{T_{\max}}} = \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}$$

$$s_{T_{\max}} = \frac{R_2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}}$$

Maximum torque

- The corresponding maximum torque of an induction motor equals

$$\tau_{\max} = \frac{1}{2\omega_s} \left(\frac{3V_{TH}^2}{R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}} \right)$$

The slip at maximum torque is directly proportional to the rotor resistance R_2

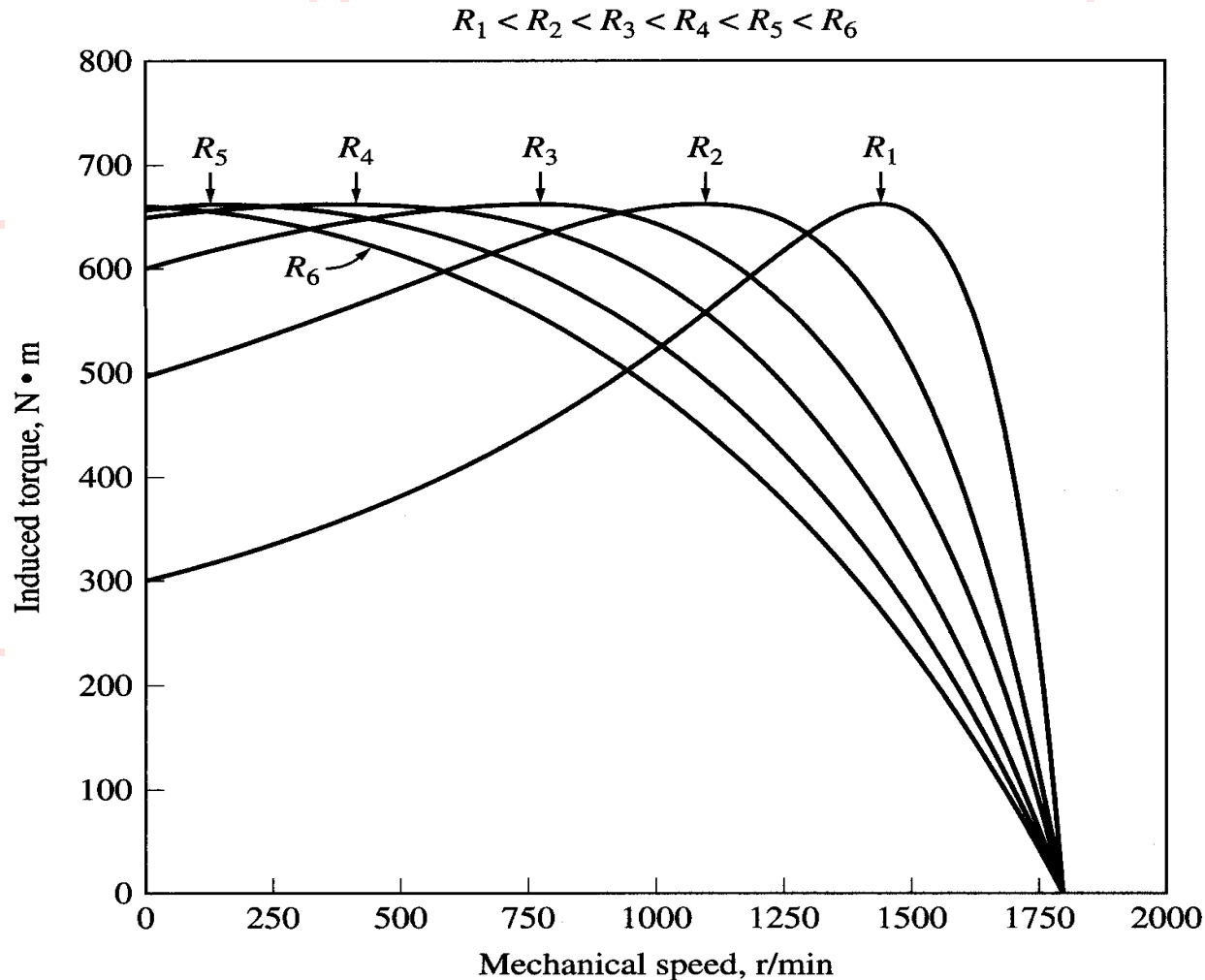
The maximum torque is independent of R_2

Maximum torque

- Rotor resistance can be increased by inserting external resistance in the rotor of a **wound-rotor** induction motor.

The
value of the maximum torque remains unaffected
but
the speed at which it occurs can be controlled.

Maximum torque



Effect of rotor resistance on torque-speed characteristic

Example

A two-pole, 50-Hz induction motor supplies 15kW to a load at a speed of 2950 rpm.

1. What is the motor's slip?
2. What is the induced torque in the motor in N.m under these conditions?
3. What will be the operating speed of the motor if its torque is doubled?
4. How much power will be supplied by the motor when the torque is doubled?

Solution

$$1. \quad n_{sync} = \frac{120 f_e}{P} = \frac{120 \times 50}{2} = 3000 \text{ rpm}$$

$$s = \frac{n_{sync} - n_m}{n_{sync}} = \frac{3000 - 2950}{3000} = 0.0167 \text{ or } 1.67\%$$

2. \because no P_{f+W} given

\therefore assume $P_{conv} = P_{load}$ and $\tau_{ind} = \tau_{load}$

$$\tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{15 \times 10^3}{2950 \times \frac{2\pi}{60}} = 48.6 \text{ N.m}$$

Solution

3. In the low-slip region, the torque-speed curve is linear and the induced torque is direct proportional to slip. So, if the torque is doubled the new slip will be 3.33% and the motor speed will be

$$n_m = (1 - s)n_{sync} = (1 - 0.0333) \times 3000 = 2900 \text{ rpm}$$

4. $P_{conv} = \tau_{ind} \omega_m$

$$= (2 \times 48.6) \times (2900 \times \frac{2\pi}{60}) = 29.5 \text{ kW}$$

Example

A 460-V, 25-hp, 60-Hz, four-pole, Y-connected wound-rotor induction motor has the following impedances in ohms per phase referred to the stator circuit

$$R_1 = 0.641\Omega \quad R_2 = 0.332\Omega$$

$$X_1 = 1.106\Omega \quad X_2 = 0.464\Omega \quad X_M = 26.3\Omega$$

1. What is the maximum torque of this motor? At what speed and slip does it occur?
2. What is the starting torque of this motor?
3. If the rotor resistance is doubled, what is the speed at which the maximum torque now occur? What is the new starting torque of the motor?
4. Calculate and plot the T - s c/c for both cases.

Solution

$$V_{TH} = V_{\phi} \frac{X_M}{\sqrt{R_1^2 + (X_1 + X_M)^2}}$$
$$= \frac{\frac{460}{\sqrt{3}} \times 26.3}{\sqrt{(0.641)^2 + (1.106 + 26.3)^2}} = 255.2 \text{ V}$$

$$R_{TH} \approx R_1 \left(\frac{X_M}{X_1 + X_M} \right)^2$$
$$\approx (0.641) \left(\frac{26.3}{1.106 + 26.3} \right)^2 = 0.590 \Omega$$

$$X_{TH} \approx X_1 = 1.106 \Omega$$

Solution

$$\begin{aligned} 1. \quad s_{T_{\max}} &= \frac{R_2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}} \\ &= \frac{0.332}{\sqrt{(0.590)^2 + (1.106 + 0.464)^2}} = 0.198 \end{aligned}$$

The corresponding speed is

$$n_m = (1 - s)n_{sync} = (1 - 0.198) \times 1800 = 1444 \text{ rpm}$$

Solution

The torque at this speed is

$$\begin{aligned}\tau_{\max} &= \frac{1}{2\omega_s} \left(\frac{3V_{TH}^2}{R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}} \right) \\ &= \frac{3 \times (255.2)^2}{2 \times (1800 \times \frac{2\pi}{60}) [0.590 + \sqrt{(0.590)^2 + (1.106 + 0.464)^2}] } \\ &= 229 \text{ N.m}\end{aligned}$$

Solution

2. The starting torque can be found from the torque eqn. by substituting $s = 1$

$$\begin{aligned}\tau_{start} = \tau_{ind} \Big|_{s=1} &= \frac{1}{\omega_s} \frac{3V_{TH}^2 \left(\frac{R_2}{s} \right)}{\left(R_{TH} + \frac{R_2}{s} \right)^2 + (X_{TH} + X_2)^2} \Big|_{s=1} \\&= \frac{3V_{TH}^2 R_2}{\omega_s [(R_{TH} + R_2)^2 + (X_{TH} + X_2)^2]} \\&= \frac{3 \times (255.2)^2 \times (0.332)}{1800 \times \frac{2\pi}{60} \times [(0.590 + 0.332)^2 + (1.106 + 0.464)^2]} \\&= 104 \text{ N.m}\end{aligned}$$

Solution

3. If the rotor resistance is doubled, then the slip at maximum torque doubles too

$$s_{T_{\max}} = \frac{R_2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}} = 0.396$$

The corresponding speed is

$$n_m = (1 - s)n_{\text{sync}} = (1 - 0.396) \times 1800 = 1087 \text{ rpm}$$

The maximum torque is still

$$\tau_{\max} = 229 \text{ N.m}$$

Solution

The starting torque is now

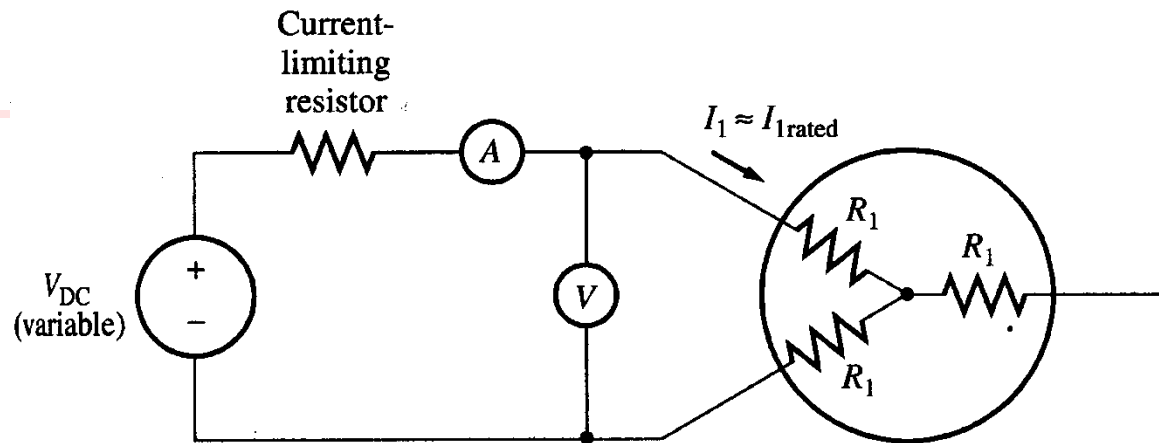
$$\begin{aligned}\tau_{start} &= \frac{3 \times (255.2)^2 \times (0.664)}{1800 \times \frac{2\pi}{60} \times [(0.590 + 0.664)^2 + (1.106 + 0.464)^2]} \\ &= 170 \text{ N.m}\end{aligned}$$

Determination of motor parameters

- Due to the similarity between the induction motor equivalent circuit and the transformer equivalent circuit, same tests are used to determine the values of the motor parameters.
 - DC test: determine the stator resistance R_1
 - No-load test: determine the rotational losses and magnetization current (similar to no-load test in Transformers).
 - Locked-rotor test: determine the rotor and stator impedances (similar to short-circuit test in Transformers).

DC test

- The purpose of the DC test is to determine R_l . A variable DC voltage source is connected between two stator terminals.
- The DC source is adjusted to provide approximately rated stator current, and the resistance between the two stator leads is determined from the voltmeter and ammeter readings.



DC test

- then

$$R_{DC} = \frac{V_{DC}}{I_{DC}}$$

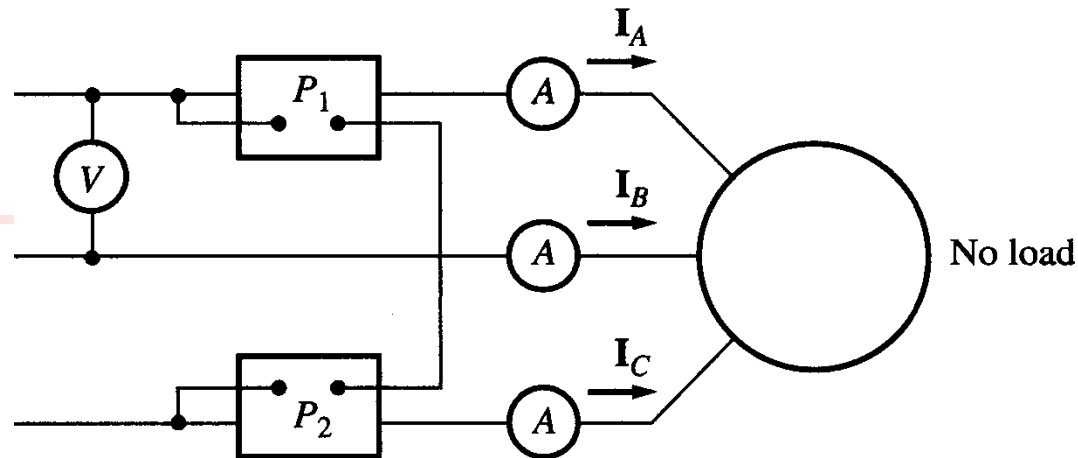
- If the stator is Y-connected, the per phase stator resistance is

$$R_1 = \frac{R_{DC}}{2}$$

- If the stator is delta-connected, the per phase stator resistance is

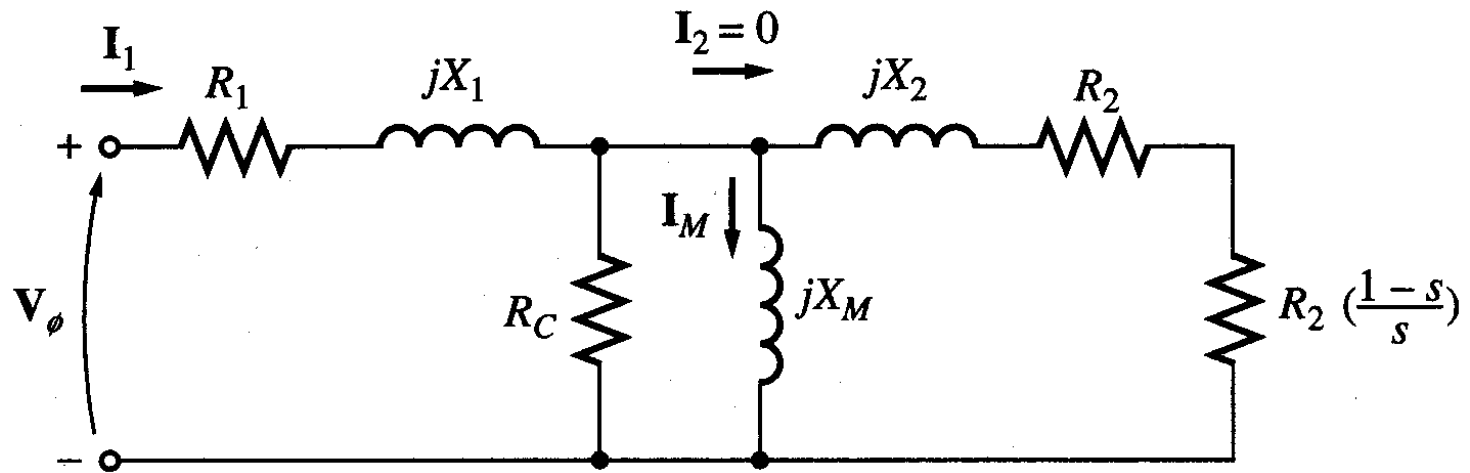
$$R_1 = \frac{3}{2} R_{DC}$$

No-load test



1. The motor is allowed to spin freely
2. The only load on the motor is the friction and windage losses, so all P_{conv} is consumed by mechanical losses
3. The slip is very small

No-load test

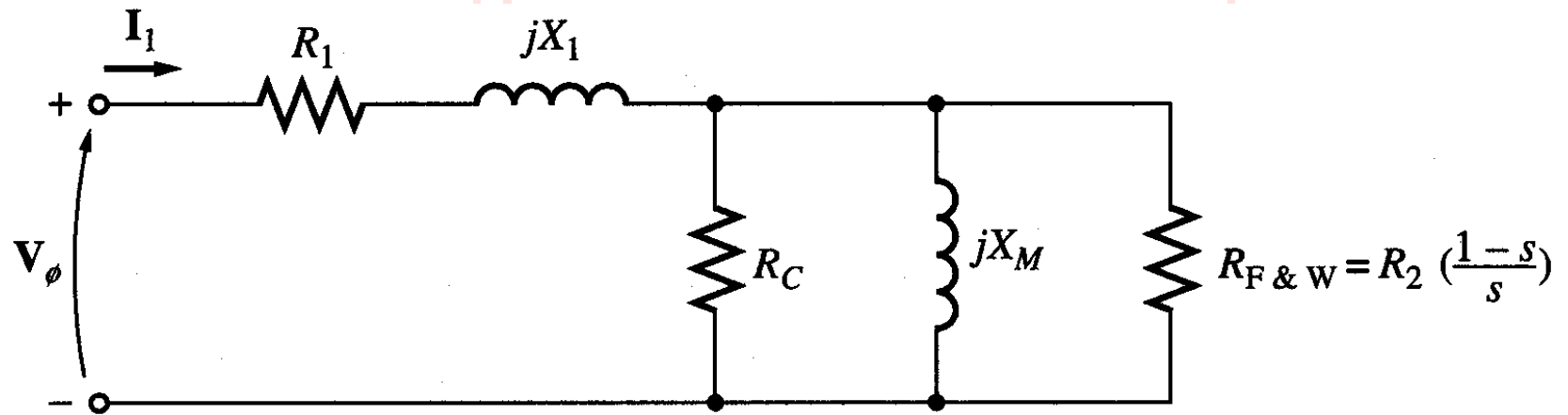


4. At this small slip

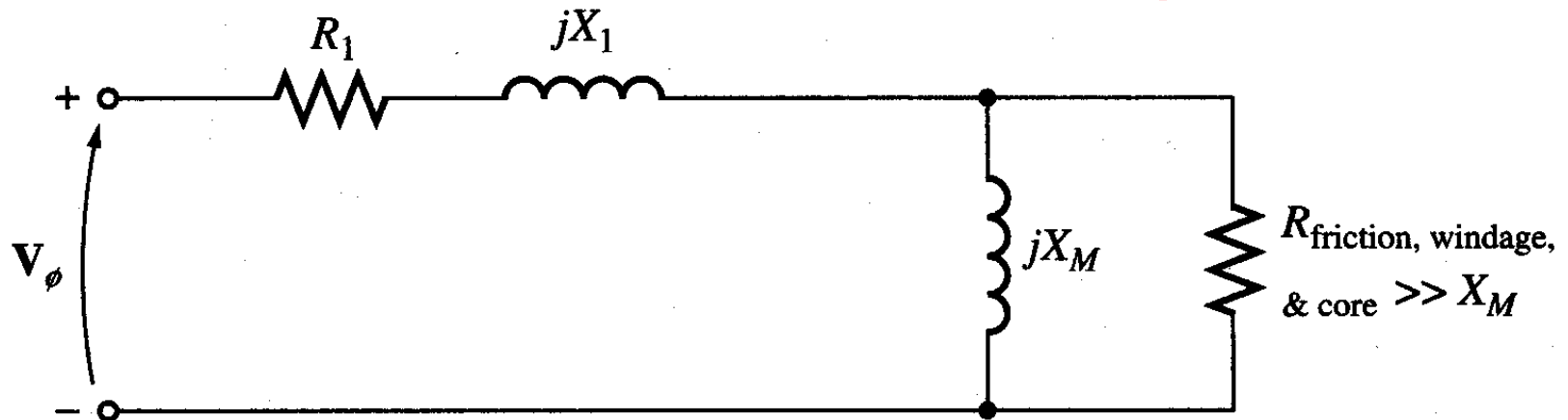
$$\frac{R_2(1-s)}{s} \approx R_2 \quad \& \quad \frac{R_2(1-s)}{s} \approx X_2$$

The equivalent circuit reduces to...

No-load test



5. Combining R_c & R_{F+W} we get.....



No-load test

6. At the no-load conditions, the input power measured by meters must equal the losses in the motor.
7. The P_{RCL} is negligible because I_2 is extremely small because $R_2(1-s)/s$ is very large.
8. The input power equals

$$\begin{aligned} P_{in} &\equiv P_{SCL} + P_{core} + P_{F\&W} \\ &\equiv 3I_1^2 R_1 + P_{rot} \end{aligned}$$

Where

$$P_{rot} = P_{core} + P_{F\&W}$$

No-load test

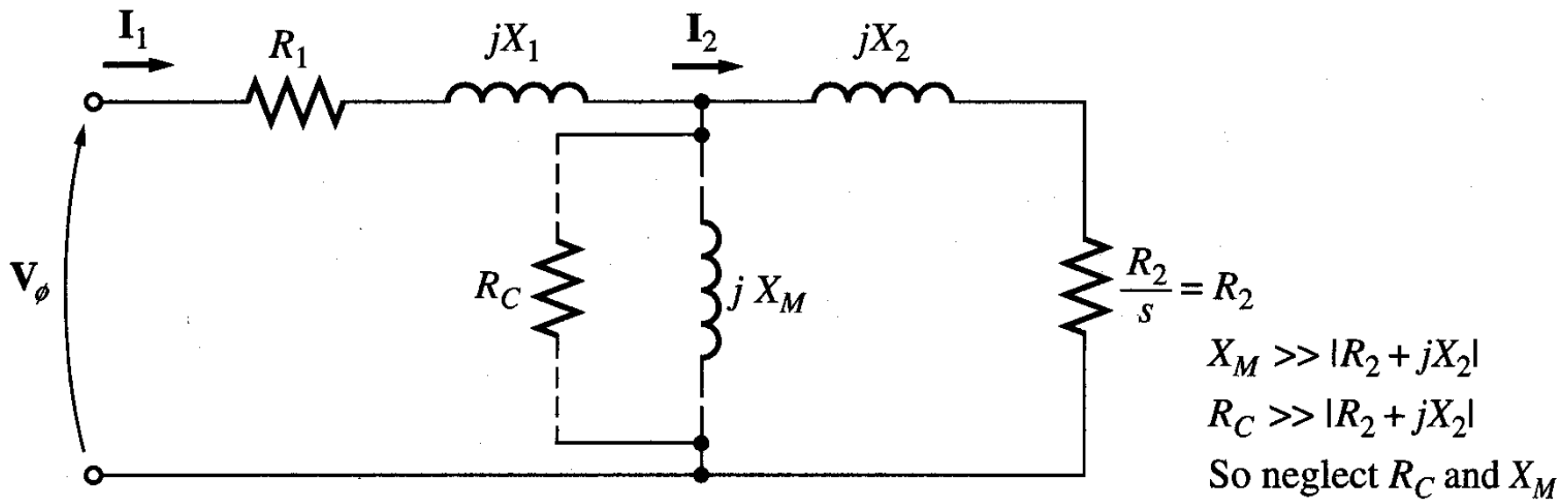
9. The equivalent input impedance is thus approximately

$$\|Z_{eq}\| = \frac{V_\phi}{I_{1,nl}} \approx X_1 + X_M$$

If X_1 can be found, in some other fashion, the magnetizing impedance X_M will be known

Blocked-rotor test

- In this test, the rotor is **locked** or **blocked** so that **it cannot move**, a voltage is applied to the motor, and the resulting voltage, current and power are measured.



Blocked-rotor test

- The AC voltage applied to the stator is adjusted so that the current flow is approximately full-load value.
- The locked-rotor power factor can be found as

$$PF = \cos \theta = \frac{P_{in}}{\sqrt{3}V_l I_l}$$

- The magnitude of the total impedance

$$\|Z_{LR}\| = \frac{V_{\phi}}{I}$$

Blocked-rotor test

$$\begin{aligned}|Z_{LR}| &= R_{LR} + jX'_{LR} \\ &= |Z_{LR}| \cos \theta + j|Z_{LR}| \sin \theta\end{aligned}$$

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

$$X'_{LR} = X'_1 + X'_2$$

Where X'_1 and X'_2 are the stator and rotor reactances at the test frequency respectively

$$R_2 = R_{LR} - R_1$$

$$X_{LR} = \frac{f_{rated}}{f_{test}} X'_{LR} = X_1 + X_2$$

Example

The following test data were taken on a 7.5-hp, four-pole, 208-V, 60-Hz, design A, Y-connected IM having a rated current of 28 A.

DC Test:

$$V_{DC} = 13.6 \text{ V}$$

$$I_{DC} = 28.0 \text{ A}$$

No-load Test:

$$V_l = 208 \text{ V}$$

$$f = 60 \text{ Hz}$$

$$I = 8.17 \text{ A}$$

$$P_{in} = 420 \text{ W}$$

Locked-rotor Test:

$$V_l = 25 \text{ V}$$

$$f = 15 \text{ Hz}$$

$$I = 27.9 \text{ A}$$

$$P_{in} = 920 \text{ W}$$

- (a) Sketch the per-phase equivalent circuit of this motor.
- (b) Find the slip at pull-out torque, and find the value of the pull-out torque.