Power electronic and drives: ELEC 2208

Chapter 2: Power Electronic Control of AC Motor Drives

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Overview

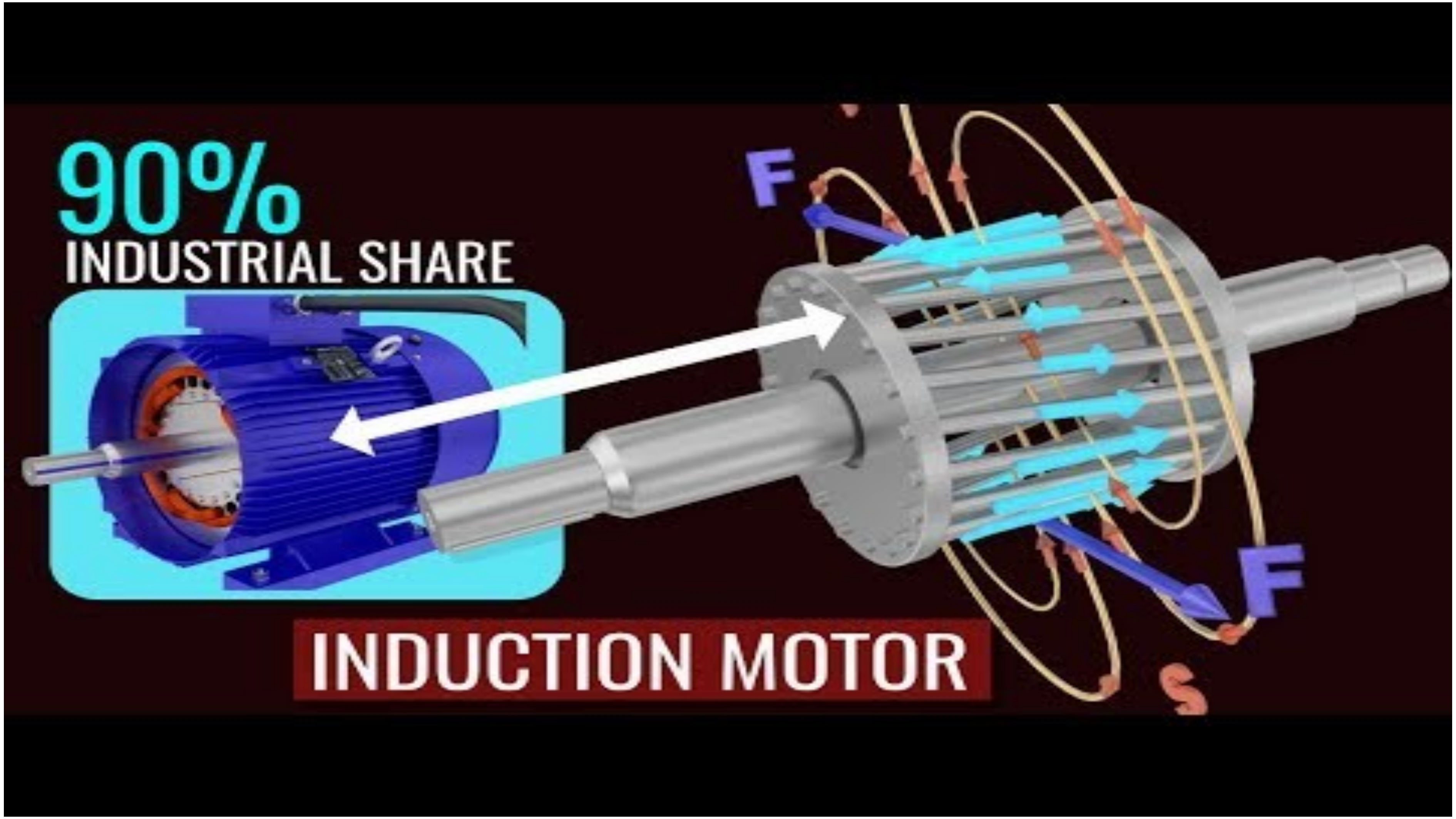
1. Chapter 3 covers the following basic definitions:
   - Introduction
   - Fundamentals of AC induction machines (general overview)
   - Speed control by simultaneous stator voltage and frequency variation
   - Inverter control of induction machines using sinusoidal PWM
   - Dynamic control of induction machines using voltage source inverters

2. Extended Summary of Chapter 3 is available on the Blackboard Shell

Learning outcomes

- Understand the key components of AC motors, in particular induction machines type.
- Appreciate the importance of the slip variable.
- Understand the different stages of energy conversion and the equations associated to them.
- Derive the mathematical expression of the torque and understand its behaviour
- Understand how speed can be controlled using V/f approach

Induction motor (IM) or asynchronous AC motor

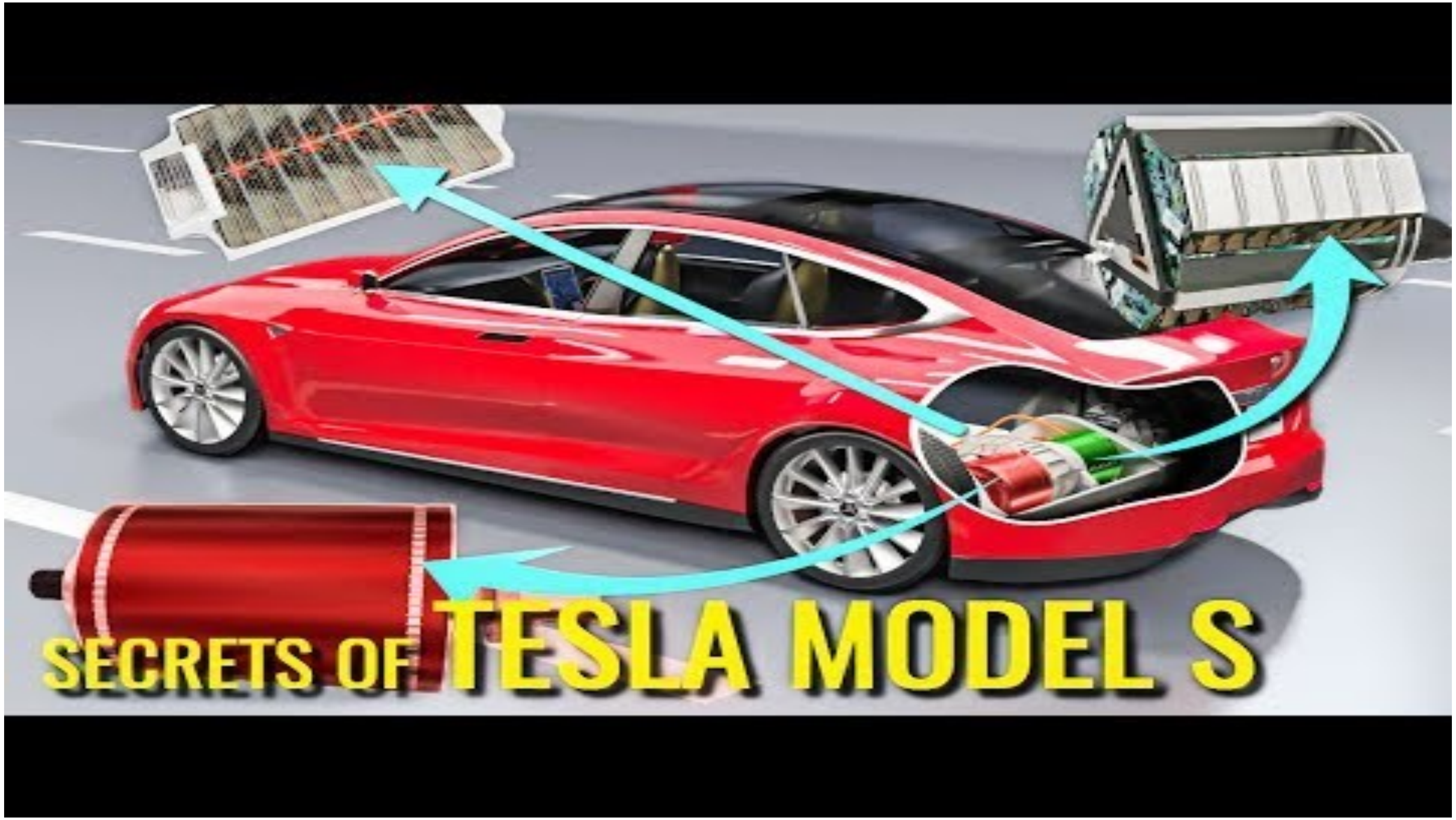


https://www.youtube.com/watch?v=AQqyGNOP_3o

Synchronous AC motor

https://www.youtube.com/watch?v=Vk2jDXxZIhs

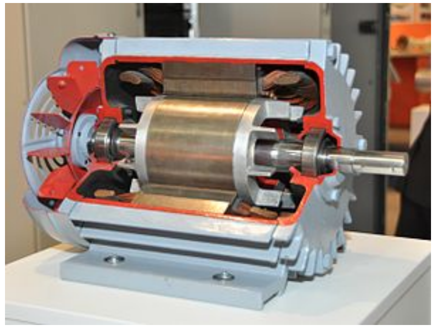
Drive train of an electric car

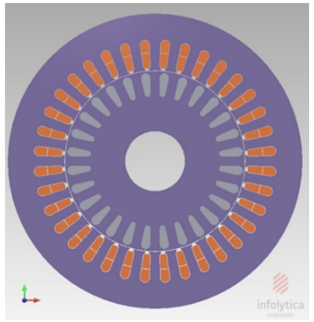


https://www.youtube.com/watch?v=3SAxXUIre28

Industrial usage

- AC motors are usually lighter than the equivalent DC motors
- Two major classes of AC machines
  - Synchronous machines
  - **Asynchronous machines (Induction machines)**
- Synchronous machines are motors and generators whose magnetic field current is supplied by a separate DC power source (or equivalent).
- Asynchronous machines, a.k.a. induction machines, are motors and generators whose field current is supplied by magnetic induction (transformer action) into their field windings.
- Both types of machines are based on the same rotating magnetic field mechanism in a three-phase machine.





IM’s synchronous speed and slip

One pole pair per phase

- One mechanical revolution per cycle of current

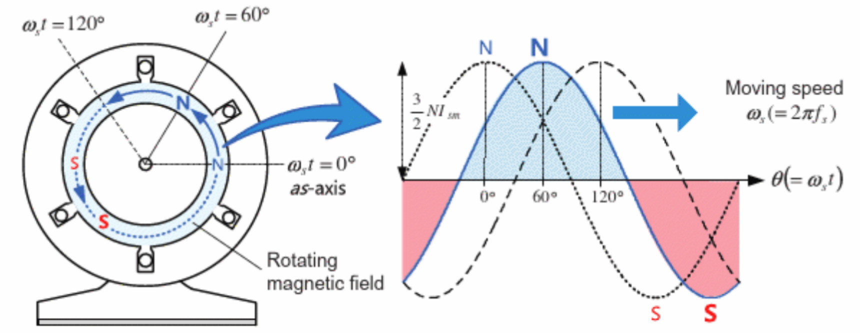
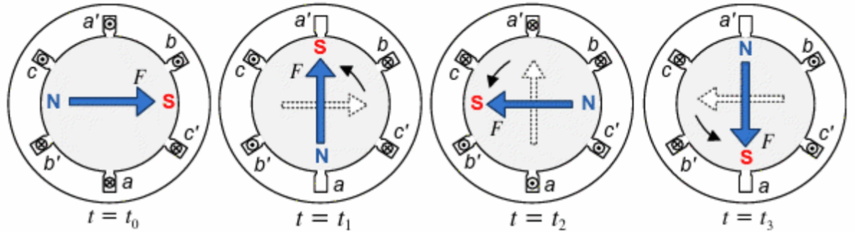


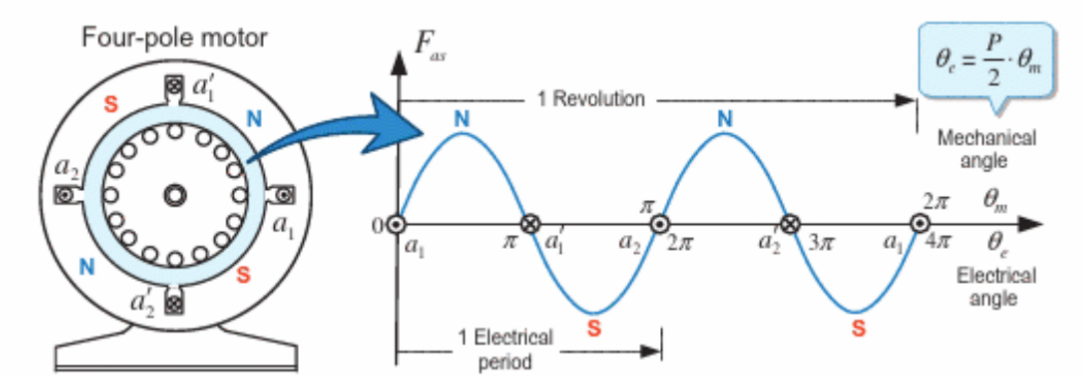
FIGURE 3.11

Resultant mmf.



Two pole pairs per phase

- 1/2 mechanical revolution per cycle of current



$$\theta_e = \frac{P}{2}\theta_m$$

$\theta_e = electrical\ angle$ P = Number of pole pairs

$\theta_m = mechanical\ angle$

IM's synchronous speed and slip, ctd.

The speed of rotation of the magnetic field due to the stator currents is known as the synchronous speed, and it is defined as:

Synchronous speed:

$$N_s = \frac{60 f_s}{P} rpm = \frac{120 f_s}{p} rpm$$

$$\omega_s = \frac{2\pi f_s}{P} rad/s = \frac{4\pi f_s}{p} rad/s$$

Slip:

$$s = \frac{\omega_s - \omega_r}{\omega_s} = \frac{N_s - N_r}{N_s} = \frac{f_s - f_r}{f_s}$$

Slip speed:

$$\text{slip speed} = \omega_s - \omega_r = s\omega_s$$

f_s= frequency Hz

P = Number of pole pairs

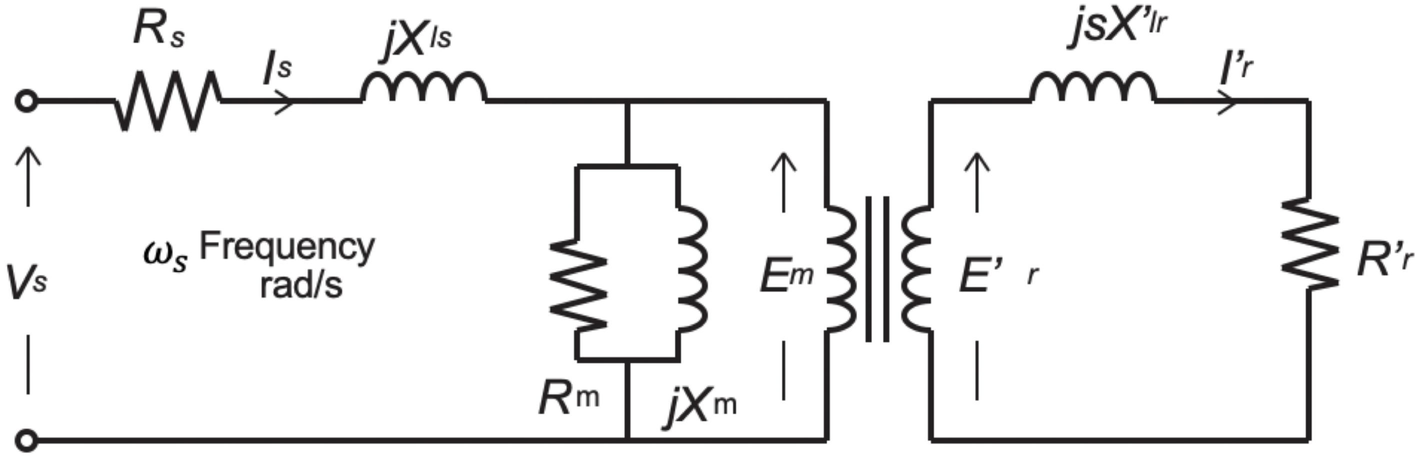
p = Number of poles

N_r = Actual speed in rpm = $(1-s)N_s$

Since rotation at synchronous speed would result in no induced rotor current, an **induction motor** always operates slightly slower than synchronous speed. The difference, or "**slip**," between actual and synchronous speed varies from about 0.5% to 5.0% for standard Design **induction motors**

Equivalent circuit of induction motor

- Induction motor operates based on the transformer's induction principle between the primary winding (stator winding) and secondary winding (rotor winding, which is now rotating spatially).
- Assume with a balanced three-phase, the per-phase equivalent circuit of an induction machine is:



E_m = back EMF

R =Core Loss

X =Magnetizing reactance

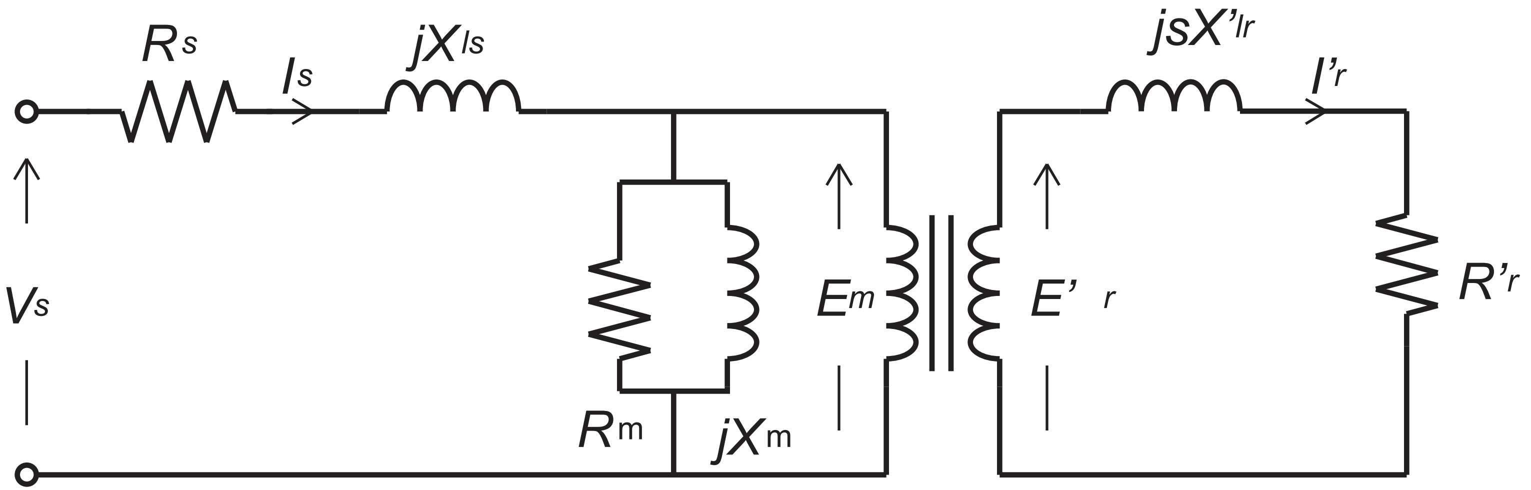
R =Winding resistance

X =Leakage reactance stator

R' =rotor resistance

X' =Leakage reactance rotor

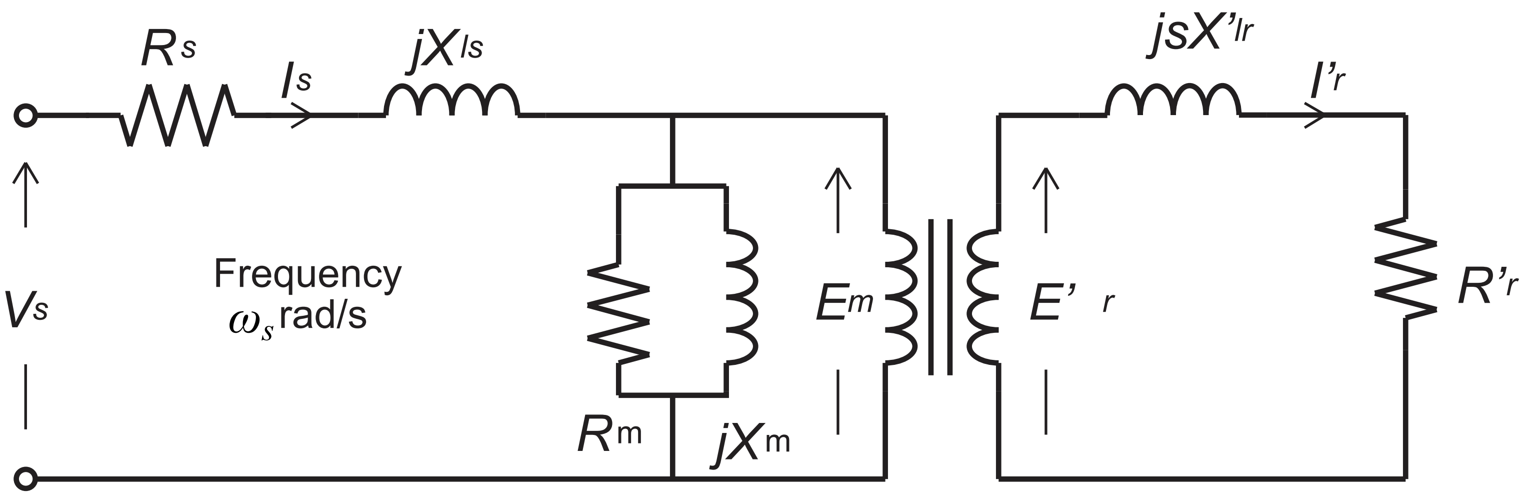
Equivalent circuit of induction motor, ctd.



- If a stator phase voltage v_s = $V_{pk}\sin\,\omega_s t$ produces steady-state magnetic flux linkage $\phi(t)$ in the rotor at a given speed ω_m:

$$\varphi(t) = \varphi_{pk}\cos(\,\omega_m t + \delta - \omega_s t)$$

Equivalent circuit of induction motor, ctd.



Then the induced back EMF at one phase of the rotor windings with an equivalent N_r turns is (assuming that ω_s and ω_m are constant):

where
N_r = number of turns on each rotor phase
ω_m = angular speed of the rotor
ω_s = synchronous speed of the motor
δ = relative position of the rotor
$E_{pk} = N_r\phi_{pk}\omega_s$ = peak value of the rotor induced back EMF
E_r = rms value of the rotor induced back EMF

$$
\begin{aligned}
e_r(t) &= \frac{d(N_r\varphi(t))}{dt} \\
&= N_r\frac{d}{dt}\left(\varphi_{pk}\cos(\omega_m t + \delta - \omega_s t)\right) \\
&= -N_r\varphi_{pk}(\omega_m - \omega_s)\sin[(\omega_m - \omega_s)t \\
&= -N_r\varphi_{pk}(\omega_s - \omega_m)\sin[(\omega_s - \omega_m)t \\
&= -s\omega_s N_r\varphi_{pk}\sin(s\omega_s t - \delta) \\
&= -sE_{pk}\sin(s\omega_s t - \delta) \\
&= -s\sqrt{2}E_r\sin(s\omega_s t - \delta)
\end{aligned}
$$

The rotor current expressed in rms phasors:

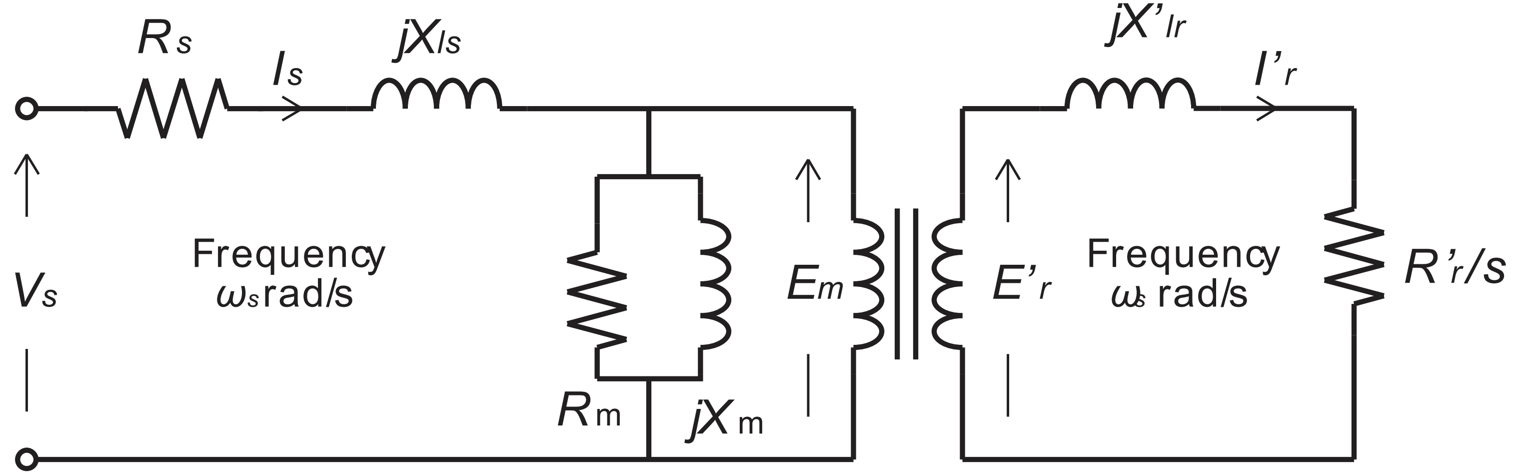
$$
\begin{aligned}
\mathrm{I}_\mathrm{r}' &= \frac{s\mathrm{E}_\mathrm{r}'}{R_r' + jsX_{lr}'} \\
&= \frac{\mathrm{E}_\mathrm{r}'}{R_r'/s + jX_{lr}'}
\end{aligned}
$$

Transforming the circuits

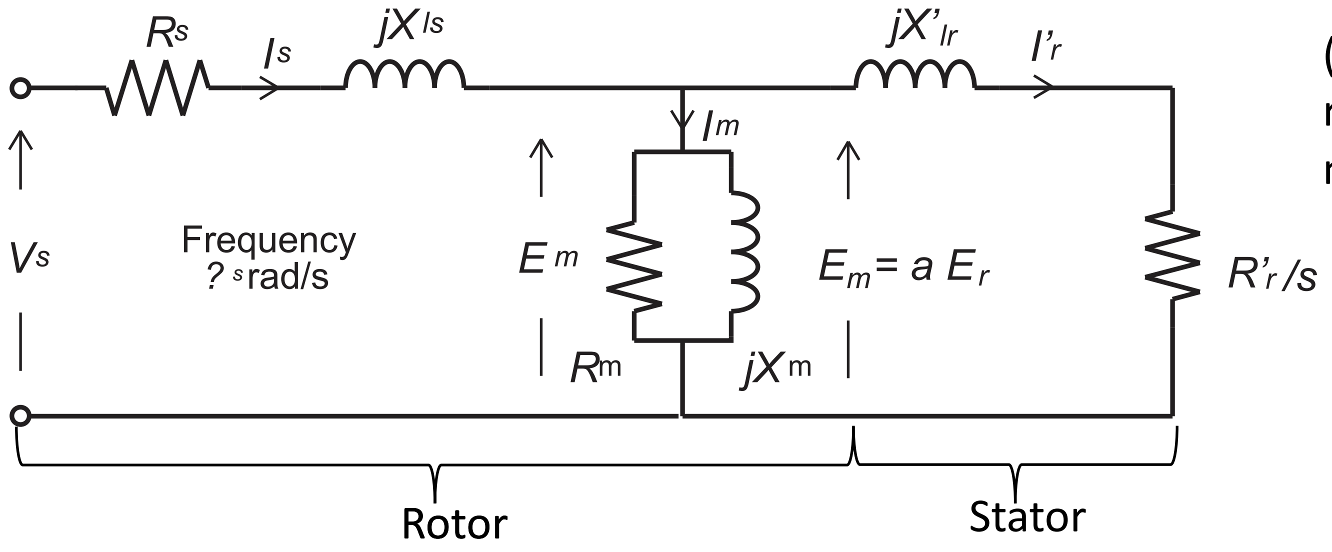
Steady-state operation of a balanced three-phase induction motor can be analyzed by simply referring to the single-phase circuitry known commonly as the per-phase equivalent circuit

stator impedance $R_s + jX_{ls}$

magnetizing reactance X_m



$E_m/E_r = a$ = Turn ratio



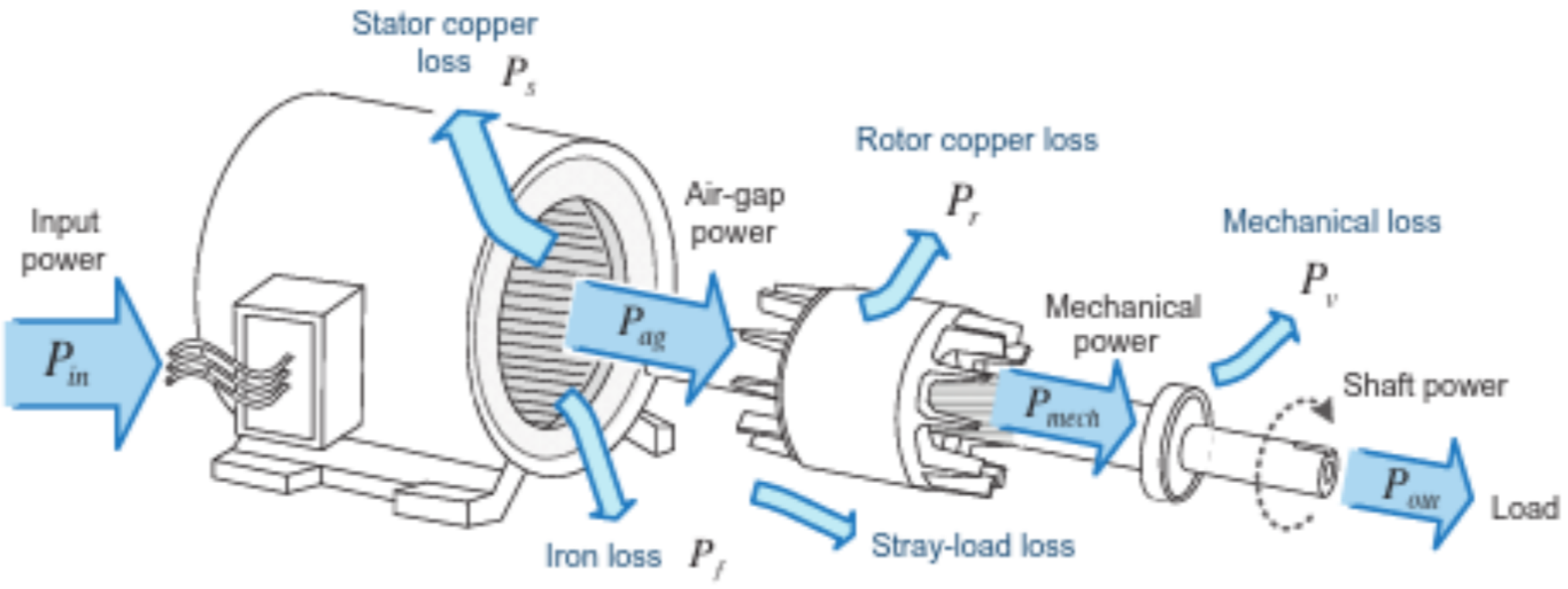
(’) are quantities reflected from the motor to the stator

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

$a^2 R_r = R'_r$

$I_r / a = I'_r$

Energy conversion stages

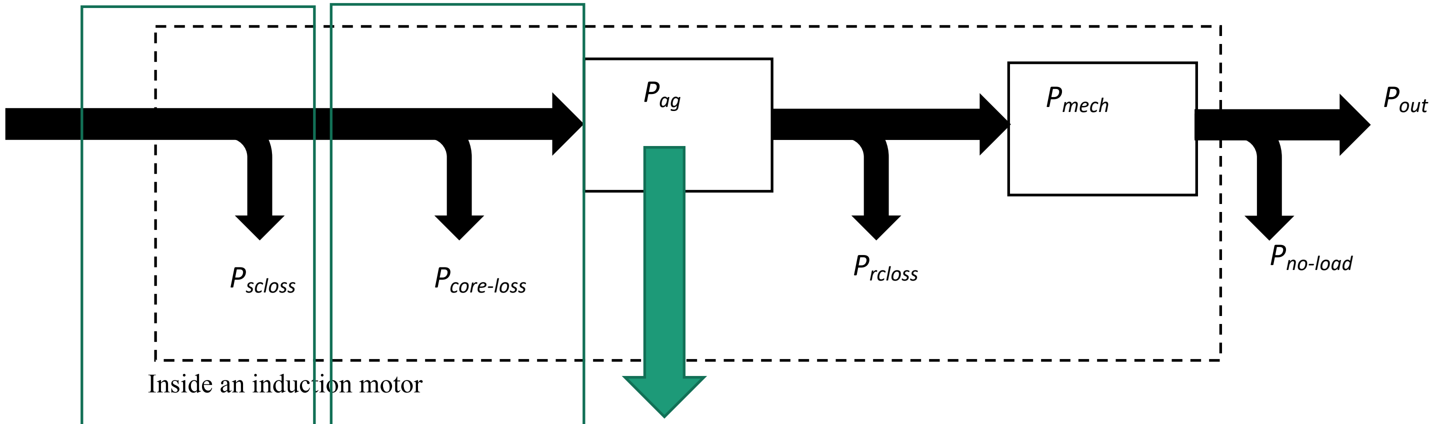


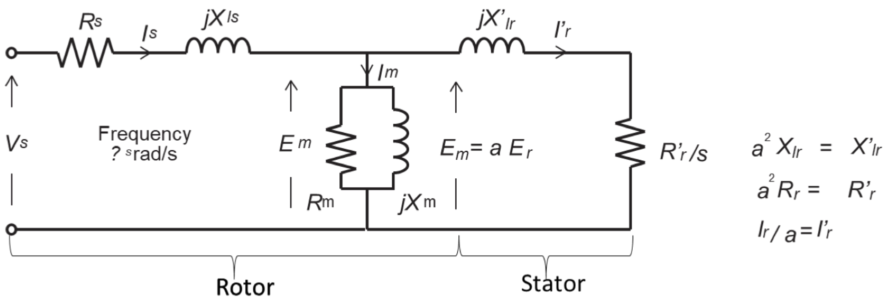
Reproduced from Kim Sang hoon - Electric motor control

Energy conversion stages, ctd.

Total Input active power

$$P_{in} = 3V_s^2 I_s \cos\theta_m$$
$$= P_{core-loss} + P_{scloss}$$





Stator copper loss

$$P_{scloss} = 3I_s^2 R_s$$

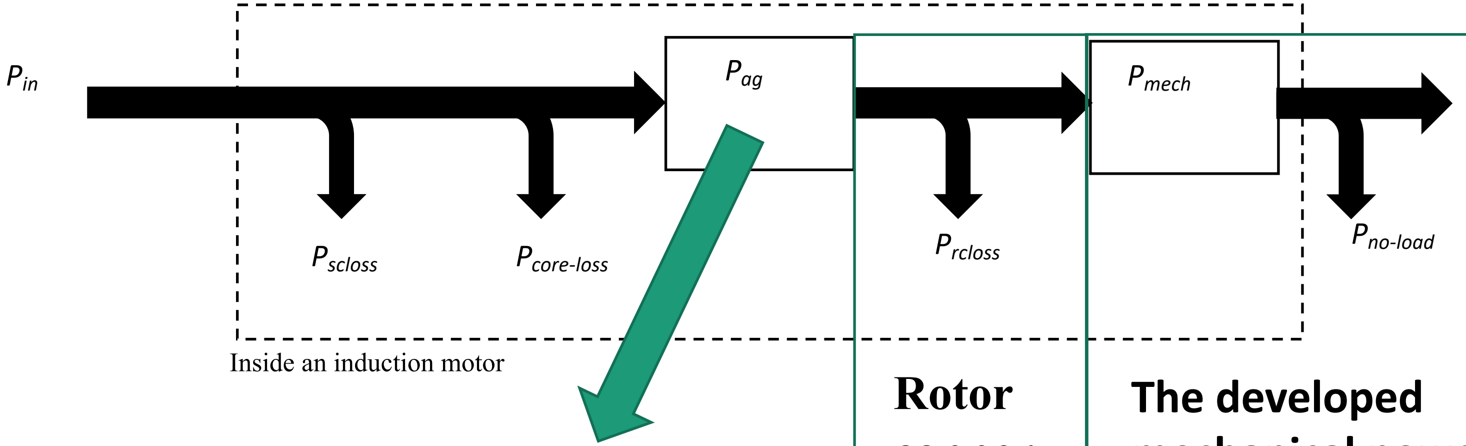
Core loss

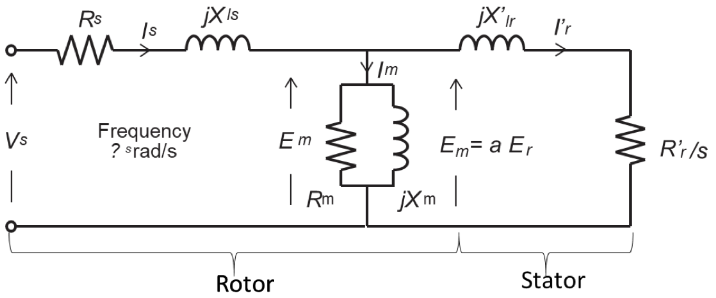
$$P_{core-loss} = \frac{3E_m^2}{R_m}$$

Air-gap power (power transferred from the stator to the rotor)

$$P_{ag} = 3I_r^2 \frac{R_r}{s}$$

Energy conversion stages, ctd.





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

$a^2 R_r = R'_r$

$I_r / a = I'_r$

Air-gap power (power transferred from the stator to the rotor)

$$P_{ag} = 3I_r^2 \frac{R_r}{s}$$

Rotor copper loss:

$$P_{rcloss} = 3I_r^2 R_r$$

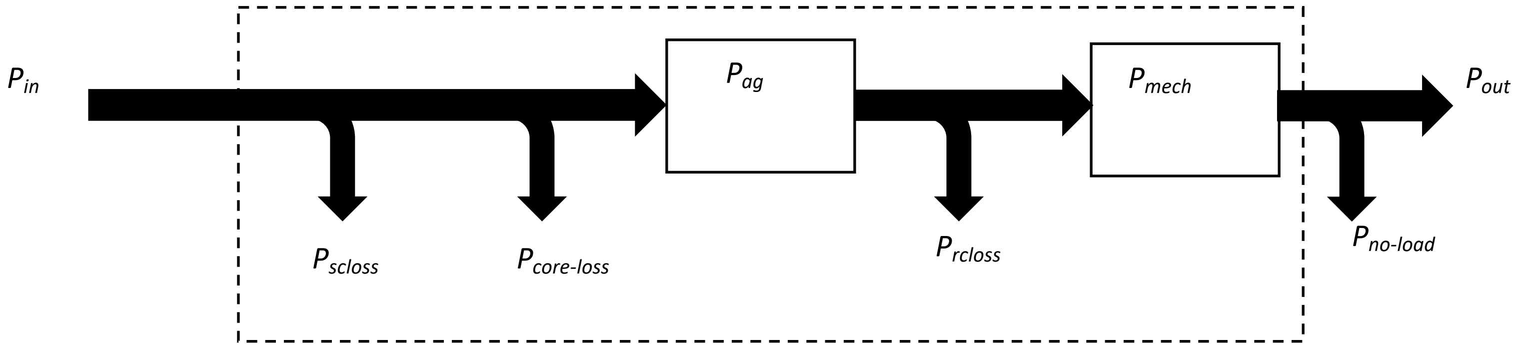
The developed mechanical power is:

$$P_{mech} = P_{ag} - P_{rcloss}$$

$$P_{mech} = 3I_r^2 R_r \frac{(1-s)}{s}$$

$$P_{mech} = P_{ag}\,(1-S)$$

Energy conversion stages, ctd.



Inside an induction motor

Useful output power: $P_{out} = P_{mech} - P_{no-load}$

The **electrical-to-mechanical power conversion efficiency** of the induction motor can be estimated from:

$$\eta = \frac{P_{mech}}{P_{in}}$$

$$= \frac{P_{mech}}{P_{core-loss} + P_{scloss} + P_{ag}}$$

By assuming:

$P_{ag} >> P_{core\text{-}loss}$

$P_{ag} >> P_{scloss}$

$$\eta \approx \frac{P_{mech}}{P_{ag}}$$

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

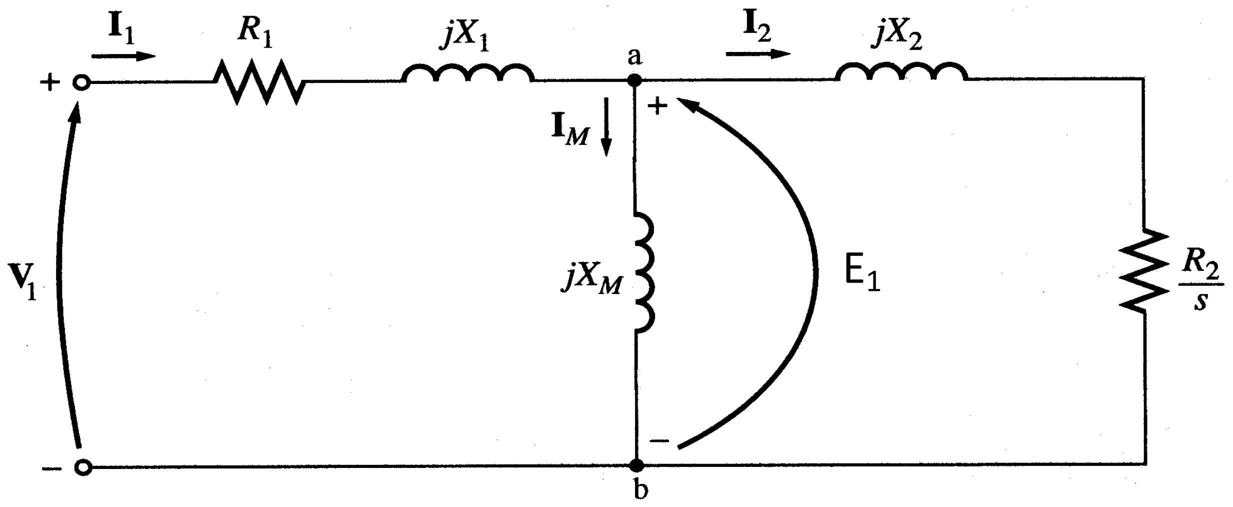
$$= (1-s)$$

Useful-power-to-input-power efficiency of the induction motor

$$\eta = \frac{P_{out}}{P_{in}}$$

Generalised expression

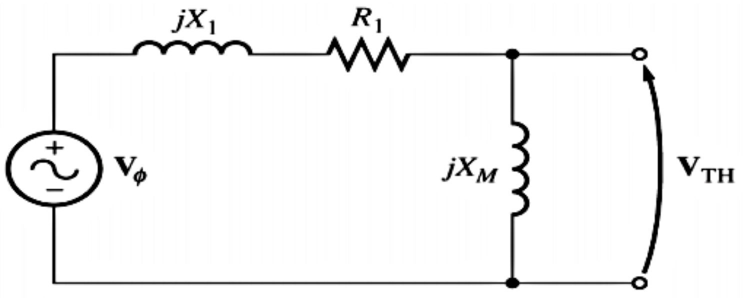
- Thevenin's theorem can be used to transform the network to the left of points 'a' and 'b' into an equivalent voltage source V_{TH} in series with equivalent impedance $R_{TH}+jX_{TH}$



- By approximating V_{TH} as V_s, and under constant supply voltage scenario (i.e. mains fed induction motor), the behaviour of the induction motor with respect to the change in its speed/slip, is clearly seen.
- Stator current can also be found from the equivalent circuit .

More info on Thevenin theorem:
https://www.youtube.com/watch?v=Vak3AkE9vYA
https://www.youtube.com/watch?v=zTDgziJC-q8

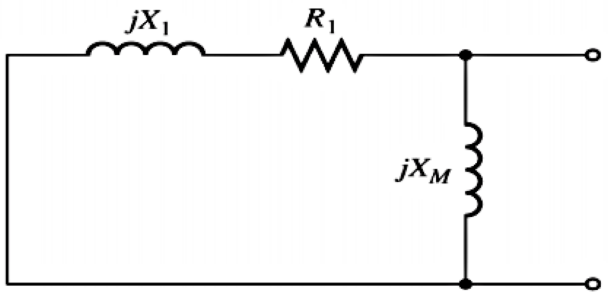
Generalised expression, ctd.



(a)

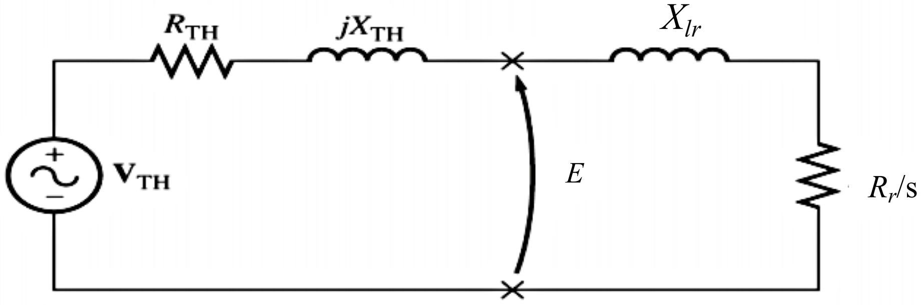
$$\mathbf{V}_{TH} = \frac{jX_M}{R_1 + jX_1 + jX_M}\mathbf{V}_\phi$$

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



(b)

$$Z_{TH} = \frac{jX_M(R_1 + jX_1)}{R_1 + j(X_1 + X_M)}$$



(c)

a) The Thevenin equivalent voltage of the stator circuit. $V_s = V_\Phi$, $X_1 = X_{ls}$ *and* $R_1 = R_s$ *(on diagram)*

$$V_{TH} = \frac{jX_m V_s}{R_s + j(X_m + X_{ls})}$$

b) The Thevenin impedance. For $R_s \ll (X_M + X_{ls})$ and $X_{ls} \ll X_m$

$$Z_{TH} = \quad R_{TH} + jX_{TH} \approx R_s\left(\frac{X_M}{X_M + X_{ls}}\right)^2 + jX_{ls}$$

a) The resulting simplified equivalent circuit of an induction motor

$$I_r = \frac{V_{TH}}{R_{TH} + R_r/s + j(X_{TH} + X_{lr})} \qquad I_r = \frac{V_{TH}}{\sqrt{(R_{TH} + R_r/s)^2 + (X_{TH} + X_{lr})^2}}$$

$$\boldsymbol{E} = \left(\frac{R_r/s + jX_{lr}}{R_{TH} + R_r/s + j(X_{TH} + X_{lr})}\right)\boldsymbol{V_{TH}}$$

Torque expression

- The mechanical power P_{mech} can expressed as the output torque times the angular frequency:

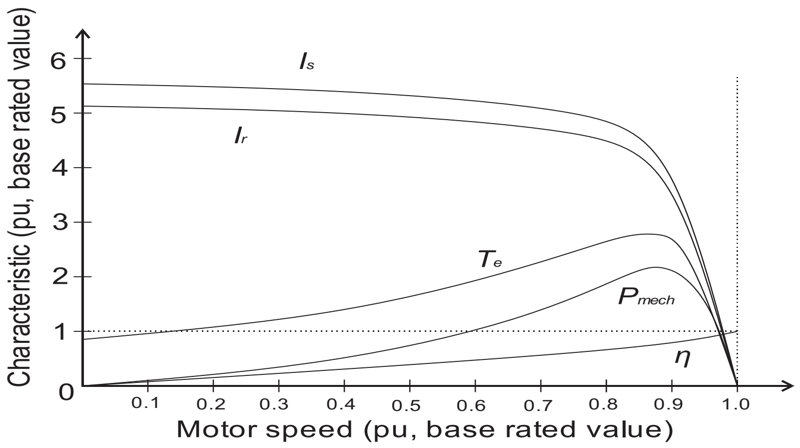
$$T_e = \frac{P_{mech}}{\omega_r} = \frac{P_{ag}\,(1-S)}{(1-S)\omega_s} = \frac{P_{ag}}{\omega_s} = \frac{3I_r^2 R_r}{S\omega_s}$$

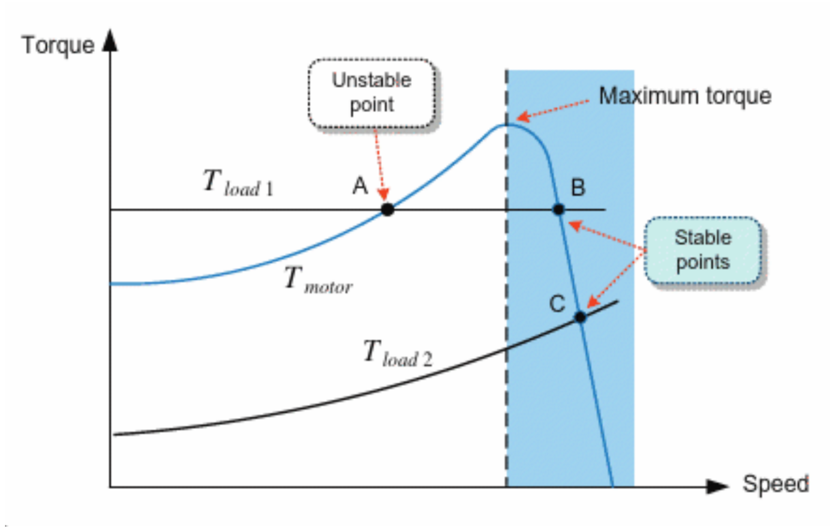
$$I_r = \frac{V_{TH}}{\sqrt{(R_{TH} + {R_r}/{S})^2 + (X_{TH} + X_{lr})^2}}$$

$$T_e = \frac{1}{\omega_s} \frac{3{V_{TH}}^2}{((R_{TH} + \frac{R_r}{S})^2 + (X_{TH} + X_{lr})^2)} \frac{R_r}{S}$$

Evolution of electrical variables with the motor speed/slip

$$P_{mech} = T_e \times \omega_r$$





$$T_e = \frac{P_{mech}}{\omega_r} = \frac{P_{mech}}{(1-S)\omega_s}$$

As s changes from 1 to 0, the motor speed ω_m changes from 0 to ω_s.

$$(1-S)\,\omega_s = \omega_m$$

1) At small slip, the torque is nearly proportional to slip.
2) As slip increases (speed decreases), stator and rotor current increase.
3) There is a slip value that corresponds to a maximum torque value (a.k.a. pull-out torque or breakdown torque). This slip value is usually only a few percent less than the full slip 1.
4) When the load torque exceeds the breakdown torque, the motor will decelerate rapidly to zero. For protection of the circuitry, supply to the machine must be disconnected immediately.

- There exists a maximum value for T_e (and hence also P_{mech}).

Maximum/Pull-out torque and the corresponding slip

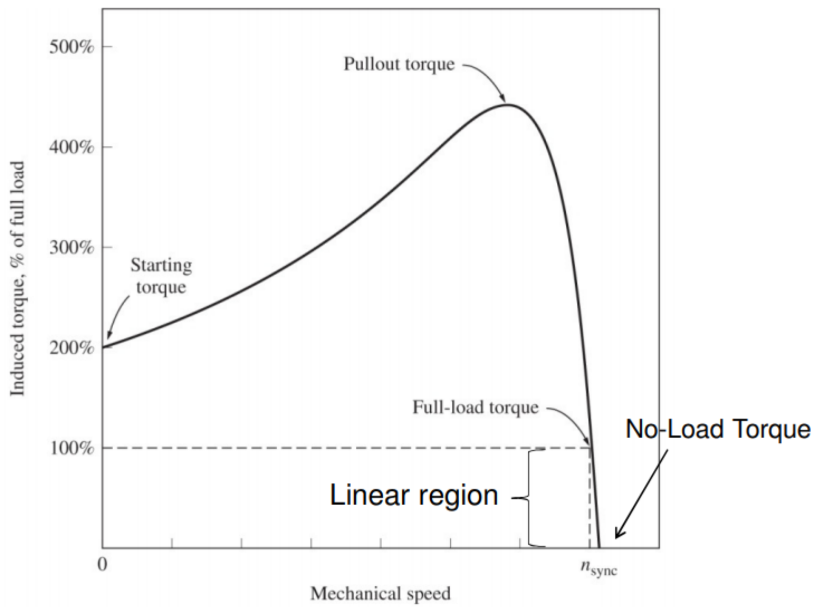
$$0 = \left.\frac{dT_e}{ds}\right|_{s=s_m}$$

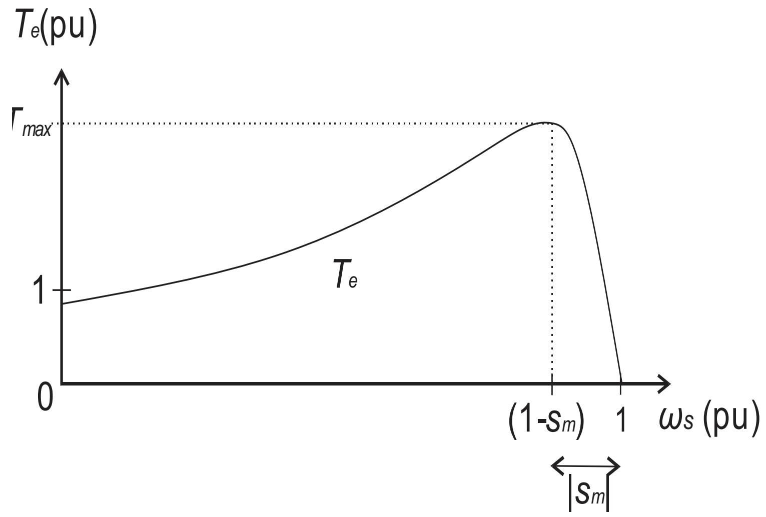
$$0 = \frac{d}{ds}\left[\frac{3R_r V_{TH}^2 \,(R_r/s_m)}{\omega_s[(R_{TH} + R_r/s_m)^2 + (X_{TH} + X_{lr})^2]}\right]$$

$$s_m = \pm\frac{R_r}{\sqrt{R_{TH}^2 + (X_{TH} + X_{lr})^2}}$$

$$T_e = \frac{3{V_{TH}}^2 R_r}{S\omega_s\,((R_{TH} + {}^{R_r}/_{S})^2 + (X_{TH} + X_{lr})^2)}$$

$$T_{\max@\,\omega_s} = \frac{3V_{TH}^2}{2\omega_s[R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_{lr})^2}]}$$





Variable-voltage-variable-frequency speed control (scalar control)

- Scalar control deals with change of only magnitude of a variable.
- Open-loop strategy that controls the synchronous speed of torque of induction machines by manipulating the stator voltage and frequency variable.
- Assume that stator frequency changes from ω_s to $\beta\omega_s, 0 < \beta \leq 1$
- The torque becomes

$$T_{e@\beta\omega_s} = \frac{3V_{TH}^2(R_r/s)}{\beta\omega_s[(R_{TH}+R_r/s)^2+(\beta X_{TH}+\beta X_{lr})^2]}$$

- And its maximum

$$T_{\max@\beta\omega_s} = \frac{3V_{TH}^2}{2\beta\omega_s[R_{TH}+\sqrt{R_{TH}^2+(\beta X_{TH}+\beta X_{lr})^2}]}$$

- By assuming R_{TH} $(i.e., R_s)$ negligible compared to reactance

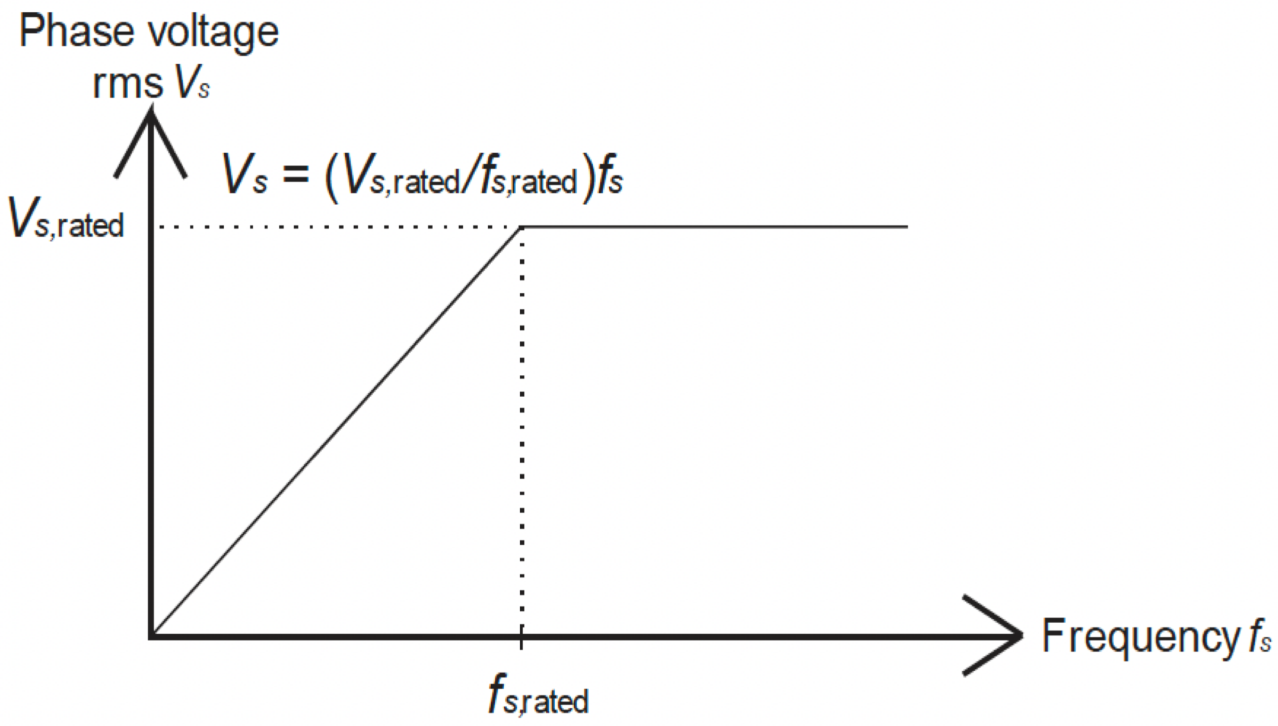
$$T_{\max@\beta\omega_s} = \frac{3V_{TH}^2}{2\beta\omega_s(\beta X_{TH}+\beta X_{lr})} = \frac{3}{2\omega_s(X_{TH}+X_{lr})}\left(\frac{V_{TH}}{\beta}\right)^2$$

If V_{TH} changes by the same β factor then the maximum torque can be maintained constant

Profile of voltage/frequency ratio

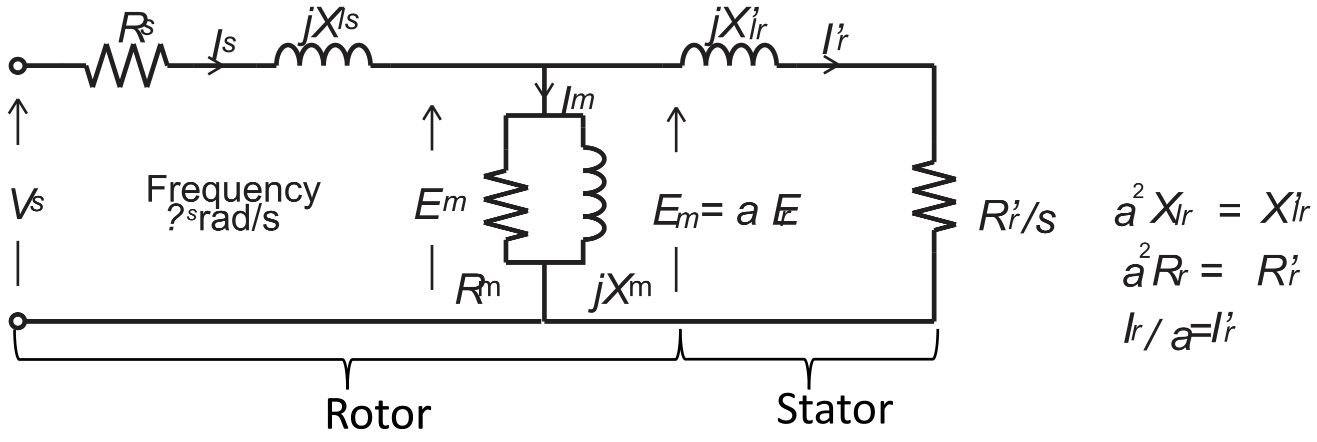
- Within the base speed region (i.e., below the rated frequency), the stator voltage should be reduced proportionally with the operating Frequency.

- Beyond the base speed region (usually known as field weakening region), the supply voltage will be kept constant and this also means that the magnetizing flux will be reduced and also the maximum torque attainable by the induction machine.



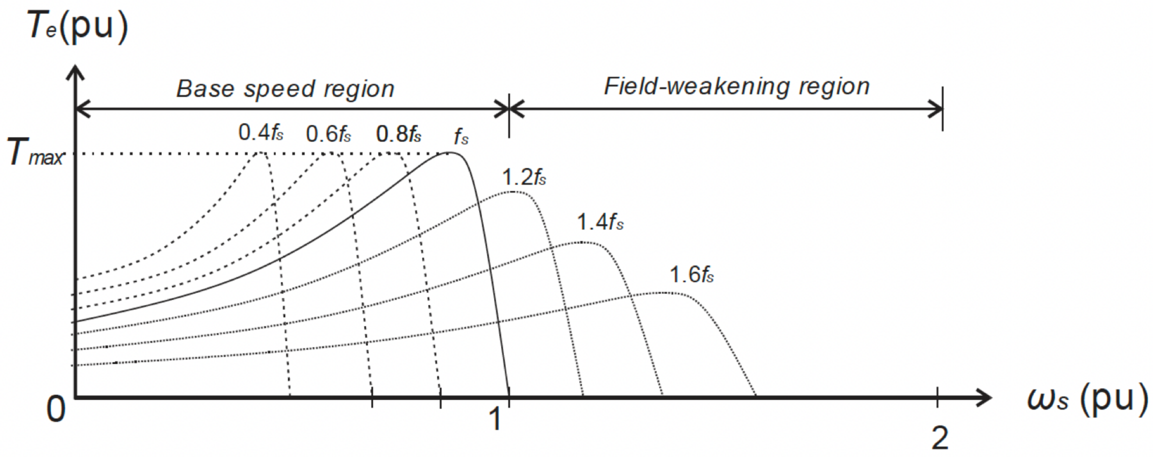
What happens to magnetizing current?

$$E_m = V_s - (R_s + jX_{ls})I_s = jX_m I_m$$
$$V_s = jX_m I_m + (R_s + jX_{ls})I_s$$



- Assumption: If $|X_m I_m| >> |R_s I_s + jX_{ls} I_s|$

$$V_s \approx X_m I_m$$
$$I_m \approx \frac{V_s}{X_m}$$
$$I_{m@\beta\omega_s} \approx \frac{\beta V_s}{\beta X_m} = \frac{V_s}{X_m} = I_{m@\omega_s}$$



- The magnetizing current I_m is kept almost constant by keeping the change in V_s and the change in ω_s to have the same ratio β. In other words, if the V_s/f_s ratio is kept constant, a constant air-gap flux as well as the pull-out torque (i.e. maximum achievable torque) can maintained about their rated values.

Practical profile of voltage/frequency ratio

- What if previous assumption is not valid?

- As speed decreases towards zero, the reactance components (X_m and X_{ls}) become smaller and the $R_s I_s$ component becomes increasingly significant compared to the decreasing Vs. In order to account for the resistive voltage drop, a voltage boost is usually introduced in practice.