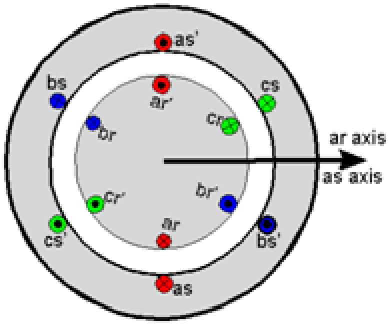
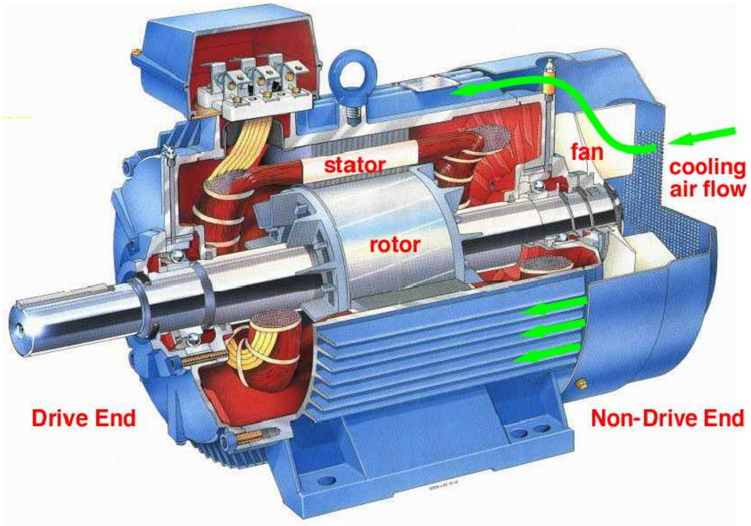
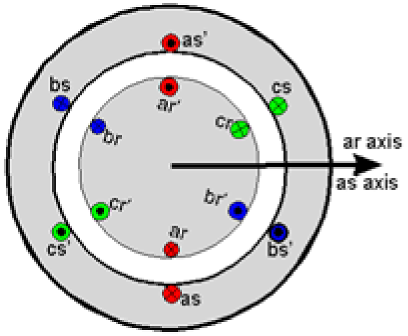
EE373-Electrical Machines

Topic 4: Three-Phase Induction (Asynchronous)

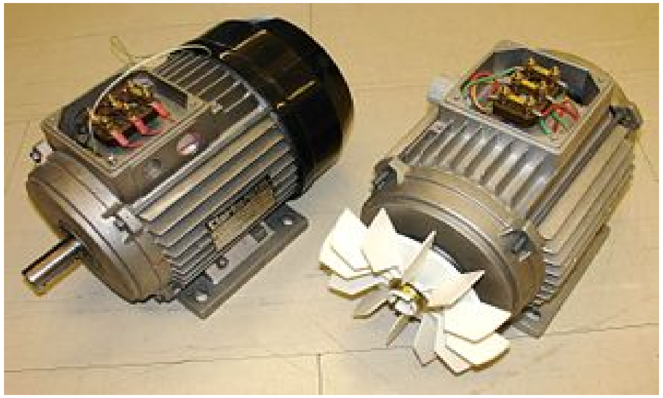




Contents



- Introduction
- Rotating Magnetic field
- Construction and Principle of Operation
- Equivalent Circuit
- Performance Characteristics
- Starting Methods
- Speed Control



Introduction: Induction Motors

- An induction motor is a singly-fed motor. Therefore, it does not require a commutator, slip-rings, or brushes. In fact, there are no moving contacts between the stator and the rotor. This results in a motor that is rugged, reliable, and almost maintenance free (Squirrel Cage type).
- The absence of brushes eliminates the electrical loss due to the brush voltage drop and the mechanical loss due to friction between the brushes and commutator or the slip-rings (Squirrel Cage type).. Thus, an induction motor has a relatively high efficiency.
- An induction motor carries alternating current in both the stator and the rotor windings.
- An induction motor is a rotating transformer in which the secondary winding receives energy by induction while it rotates.

Application

In the industrial sector alone, about 75% is consumed by motors and over 90% of them are induction machines.

- **Small single-phase induction motors are used in many household appliances, such as blenders, juice mixtures, washing machines, refrigerators, etc.**

- **Large three-phase induction motors are used in pumps, fans, compressors, paper mills, and so forth**

Simple construction, Robust, Cheap

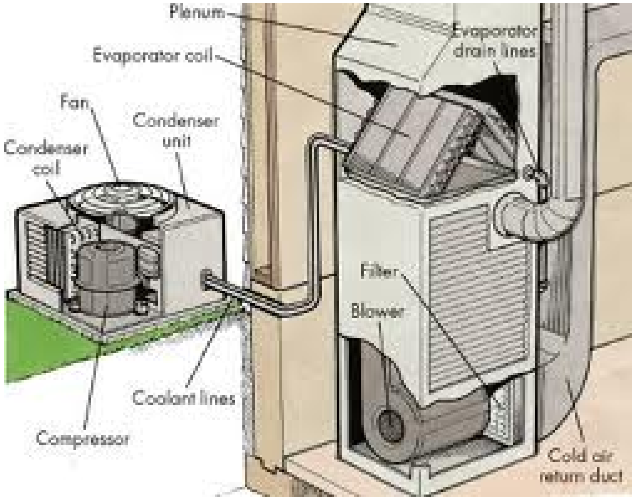
Induction Motor

Transportation Prime-mover

Induction Motor

Application Of Slip Ring Motor

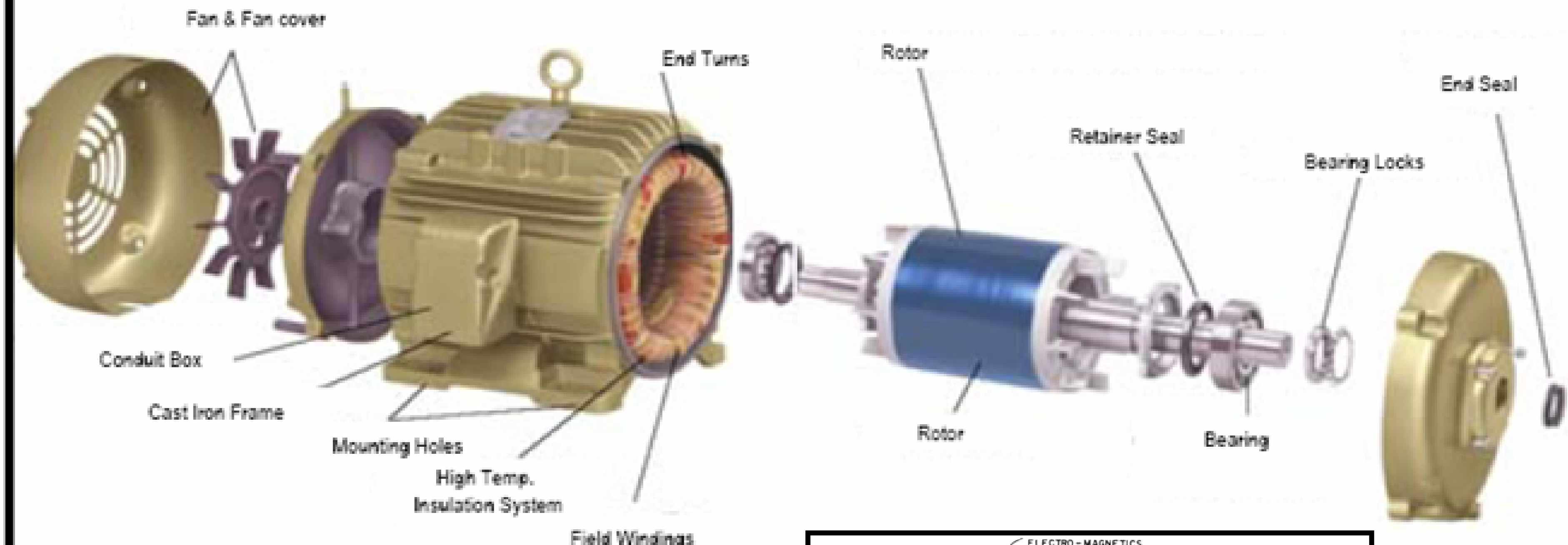
Wound rotr

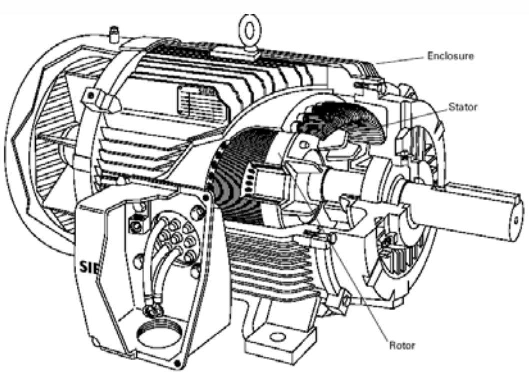


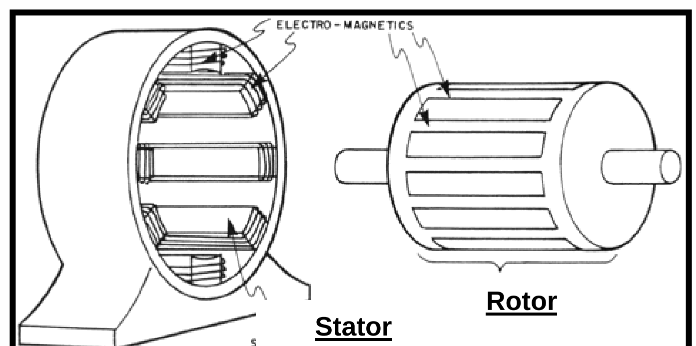
compressor

Central air conditoining

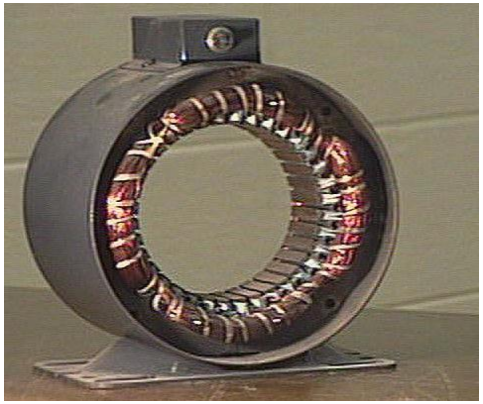
Parts of AC Motor





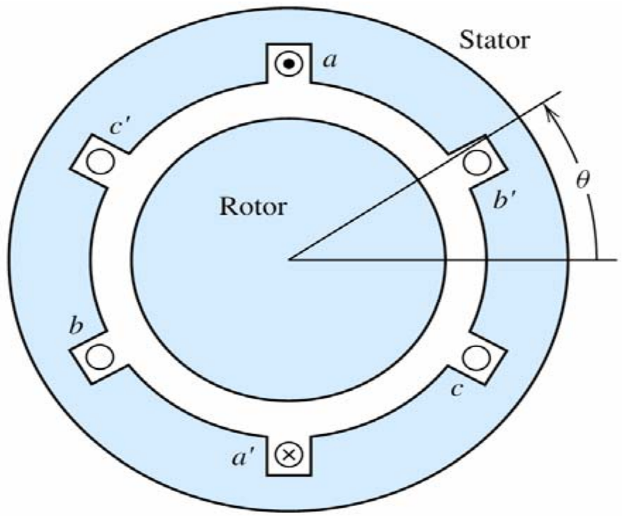


Construction

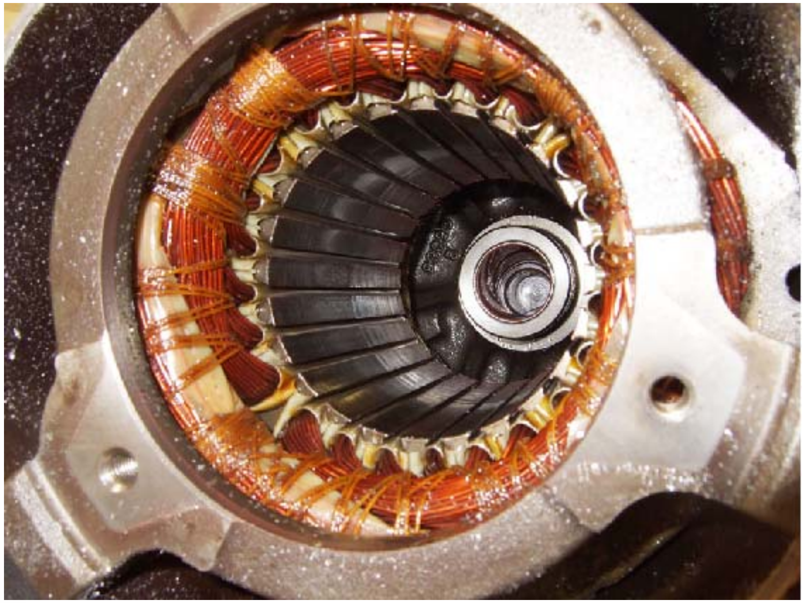


<u>1- STATOR</u>

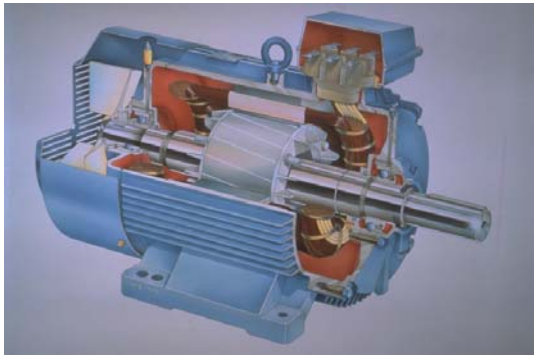
A three-phase windings is put in slots cut on the inner surface of the stationary part. The ends of these windings can be connected in star or delta to form a three phase connection. These windings are fed from a three-phase ac supply.



The stator of a two-pole machine contains three identical windings spaced 120° apart.



Construction

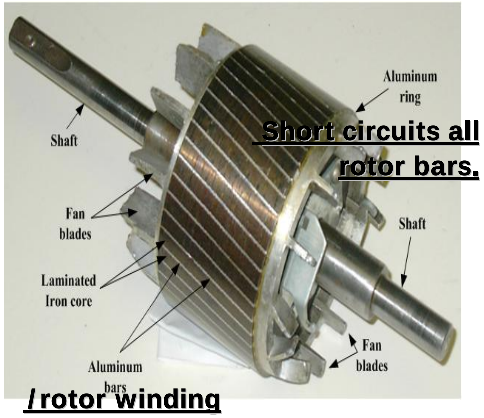


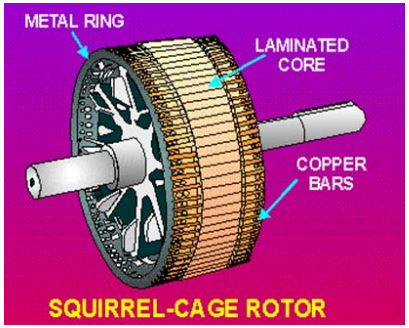
2- Rotor

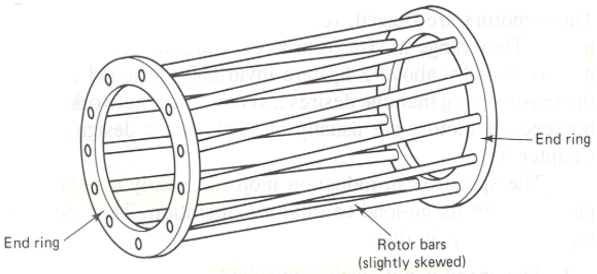
it can be either:

a- Squirrel-cage (brushless) (SCIM)

- The squirrel-cage winding consists of bars embedded in the rotor slots and shorted at both ends by end rings.
- The squirrel-cage rotor is the most common type because it is more rugged, more economical, and simpler.



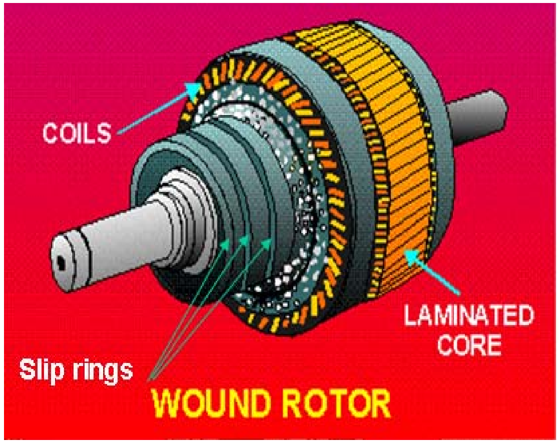


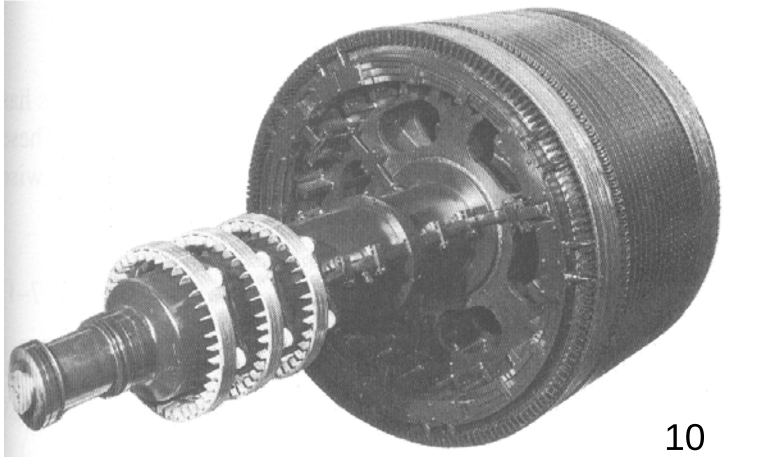


Construction

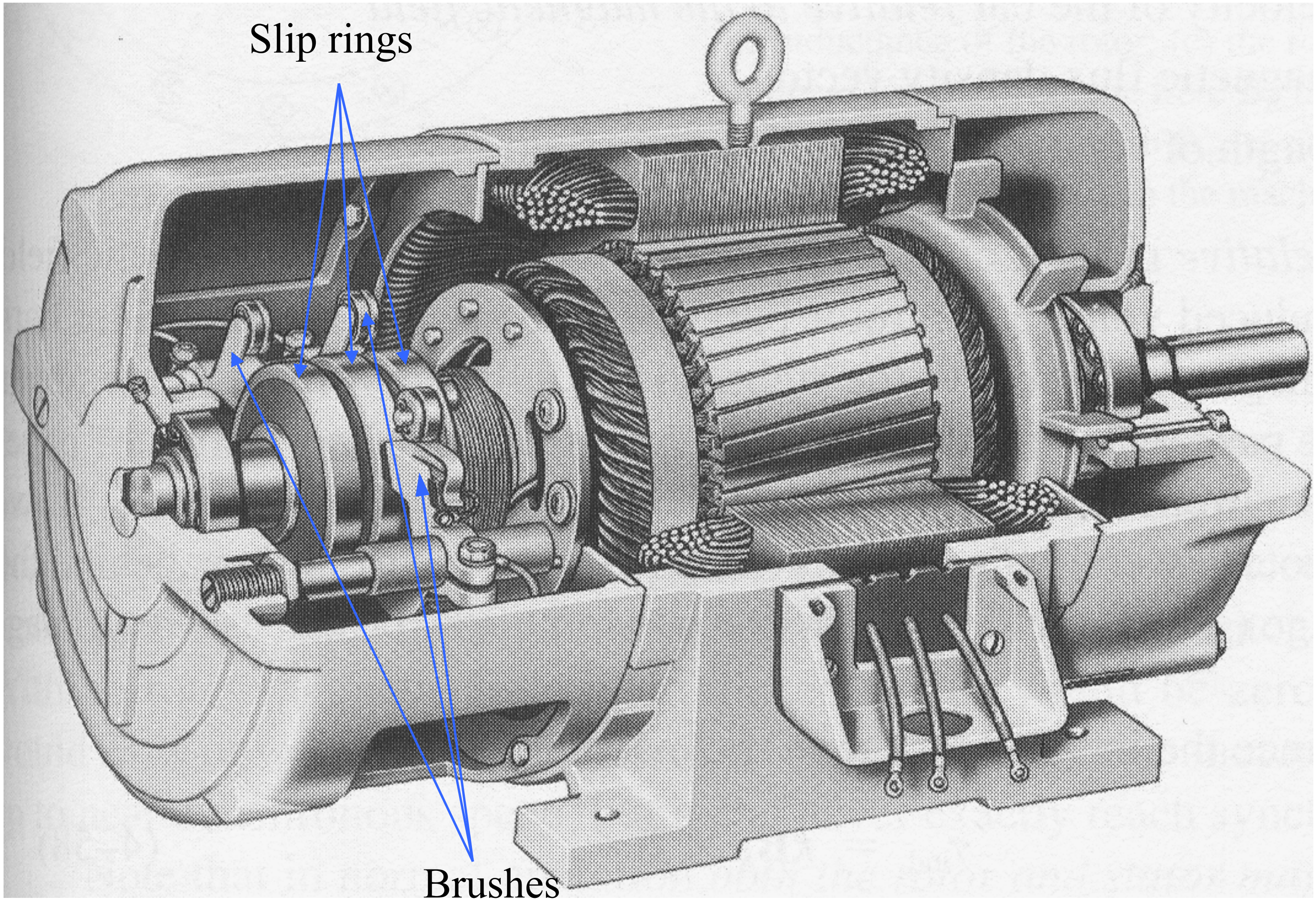
b- Slip ring (wound-rotor) (WRIM)

The wound-rotor winding has the same form as the stator winding. The windings are connected in star. The terminals of the rotor windings are connected to three slip rings. Using stationary brushes pressing against the slip rings, the rotor terminals can be connected to an external circuit.





Construction-Wound Rotor Induction Motor (WRIM)



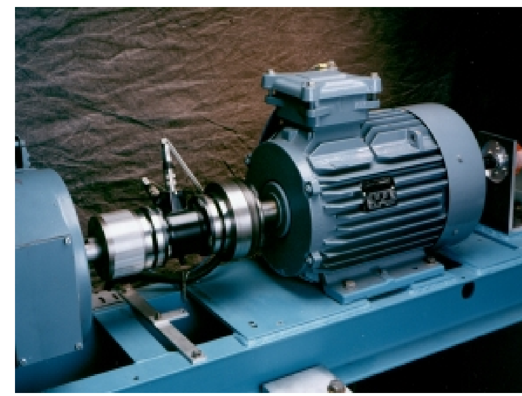
Cutaway in a typical wound-rotor IM. Notice the brushes and the slip rings

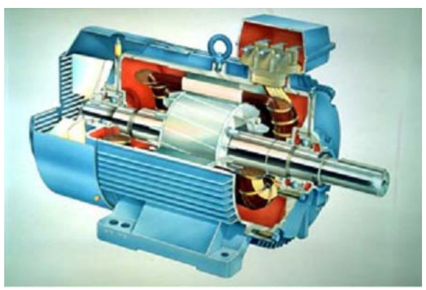
Advantages of Slip Ring and Squirrel Cage Motor

SQUIRREL CAGE	SLIP RING
cheaper and more robust slightly	the starting torque is much higher and the starting current much lower
higher efficiency and power factor	the speed can be varied by means of external rotor resistors
explosion proof, since the absence of slip-rings and brushes eliminates risk of sparking.	

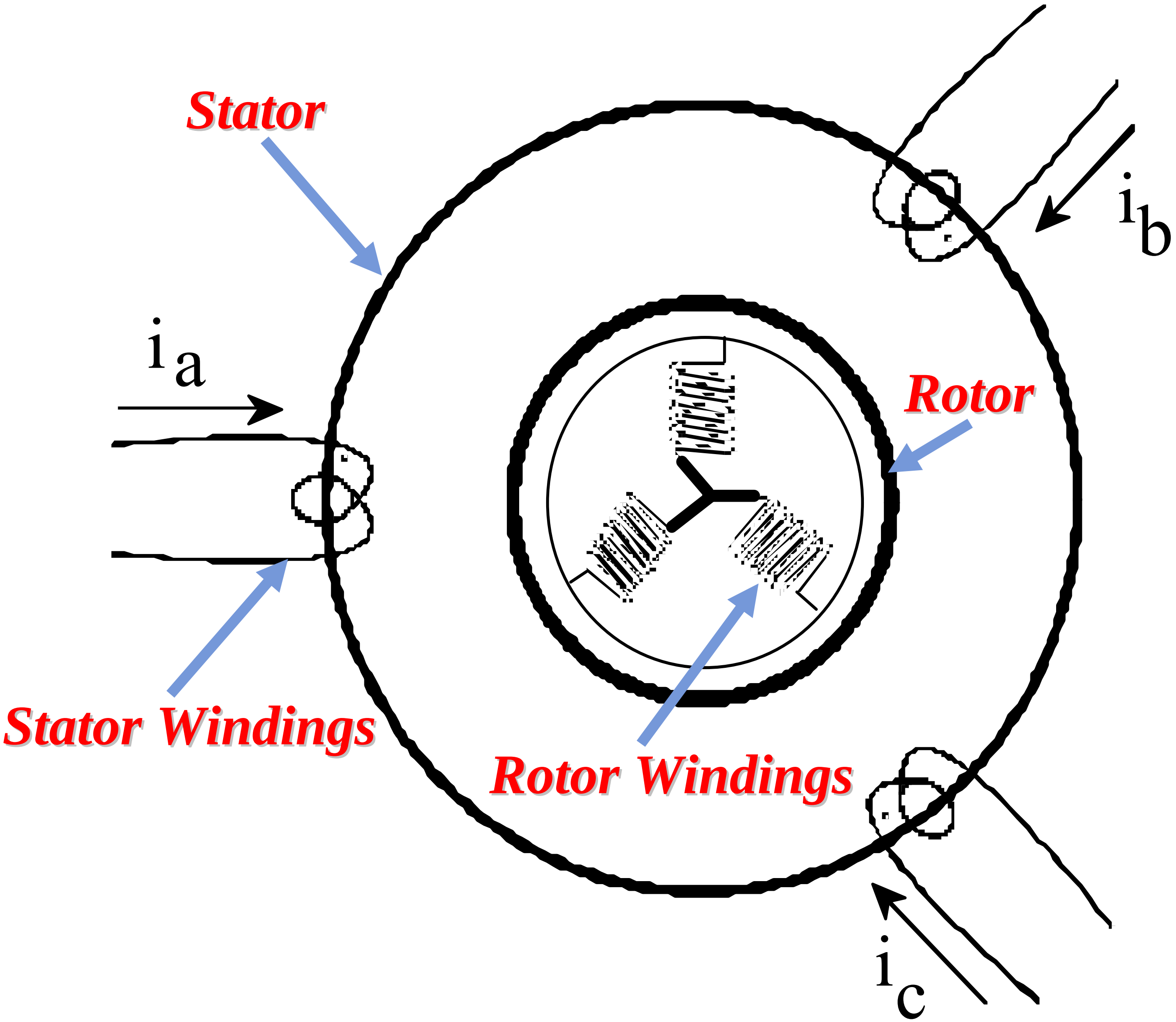
Type Of Asynchrounous Motor

- Asynchronous motor
  - 3-phase
    - Squirrel cage
      - Double poles
        - 2 separate winding
        - Dahl ender
    - Slip-ring
  - Single phase
    - Resistor start
    - Capacitor start
    - Capacitor start-run
    - Permanent capacitor
    - Commutator
      - Universal
      - Repulsion

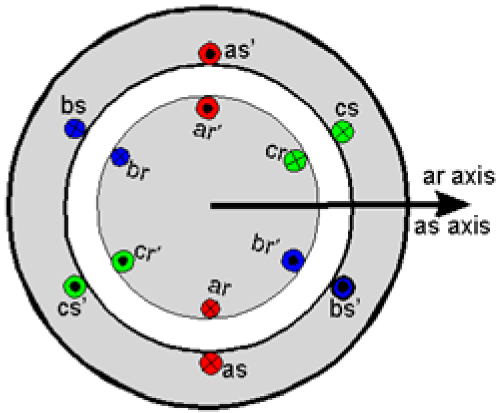




Three-Phase Induction Motor



Principle of Operation



- If the stator windings are connected to a three-phase supply; a rotating field will be produced in the air-gap. This field rotates at synchronous speed n_s. This rotating field induces voltages in the rotor windings. Since the rotor circuit is closed, the induced voltages in the rotor windings produce rotor currents that interact with the air gap field to produce torque. The rotor will eventually reach a steady-state speed n_m that is less than the synchronous speed n_s.
- The difference between the rotor speed and the synchronous speed is called the slip, s ,

$$n_s = \frac{120\ f_s}{P}$$

$$S = \frac{n_s - n}{n_s}$$

$$S = \frac{\omega_s - \omega}{\omega_s}$$

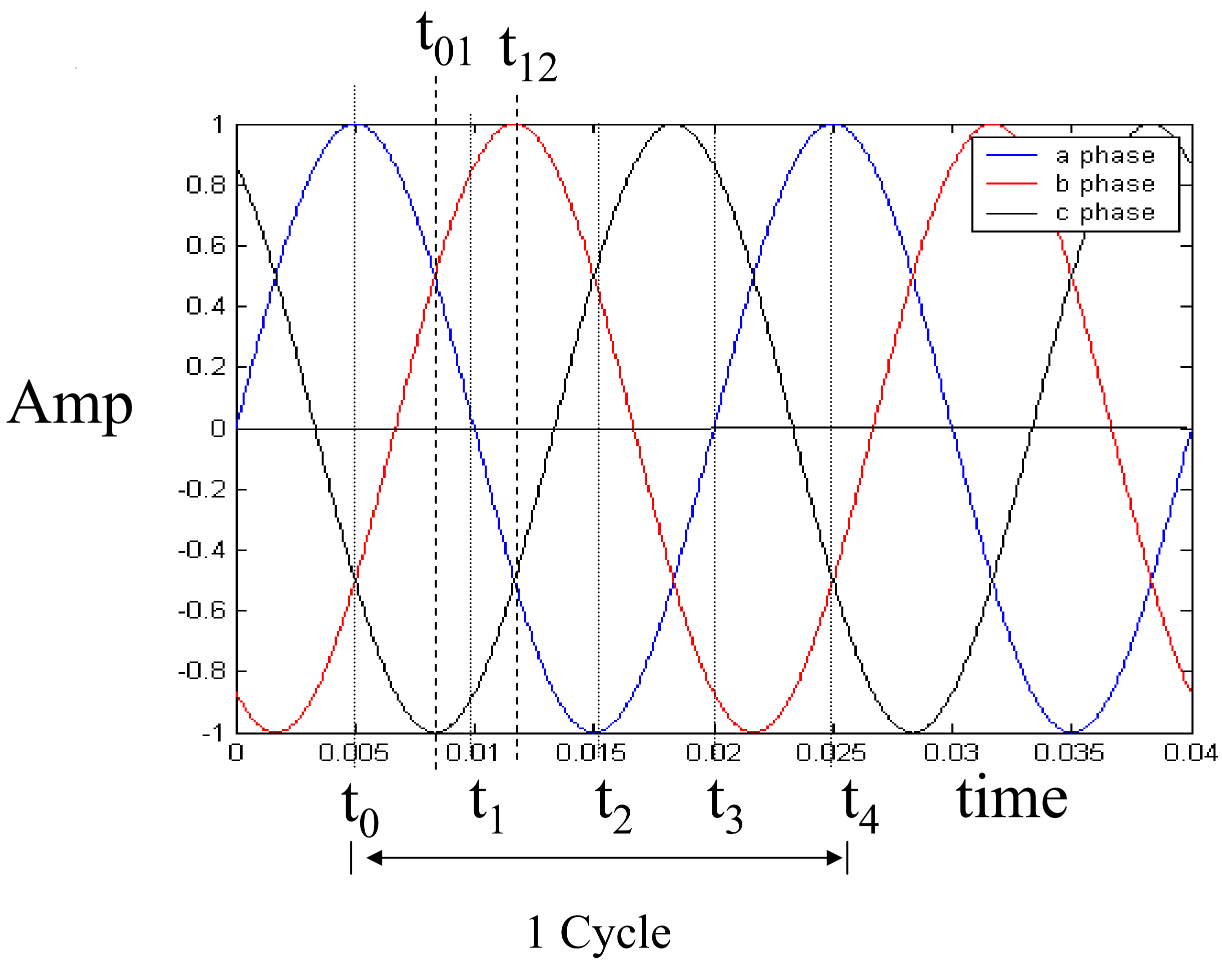
fs is the supply frequency
P is the total number of poles.

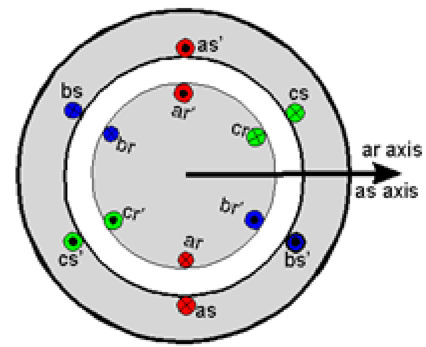
$$\omega = \frac{2\pi n}{60}$$

n in rpm
ω in rad/s

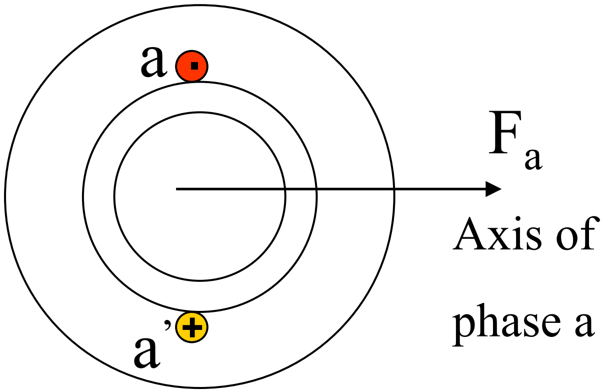
Rotating Magnetic Field

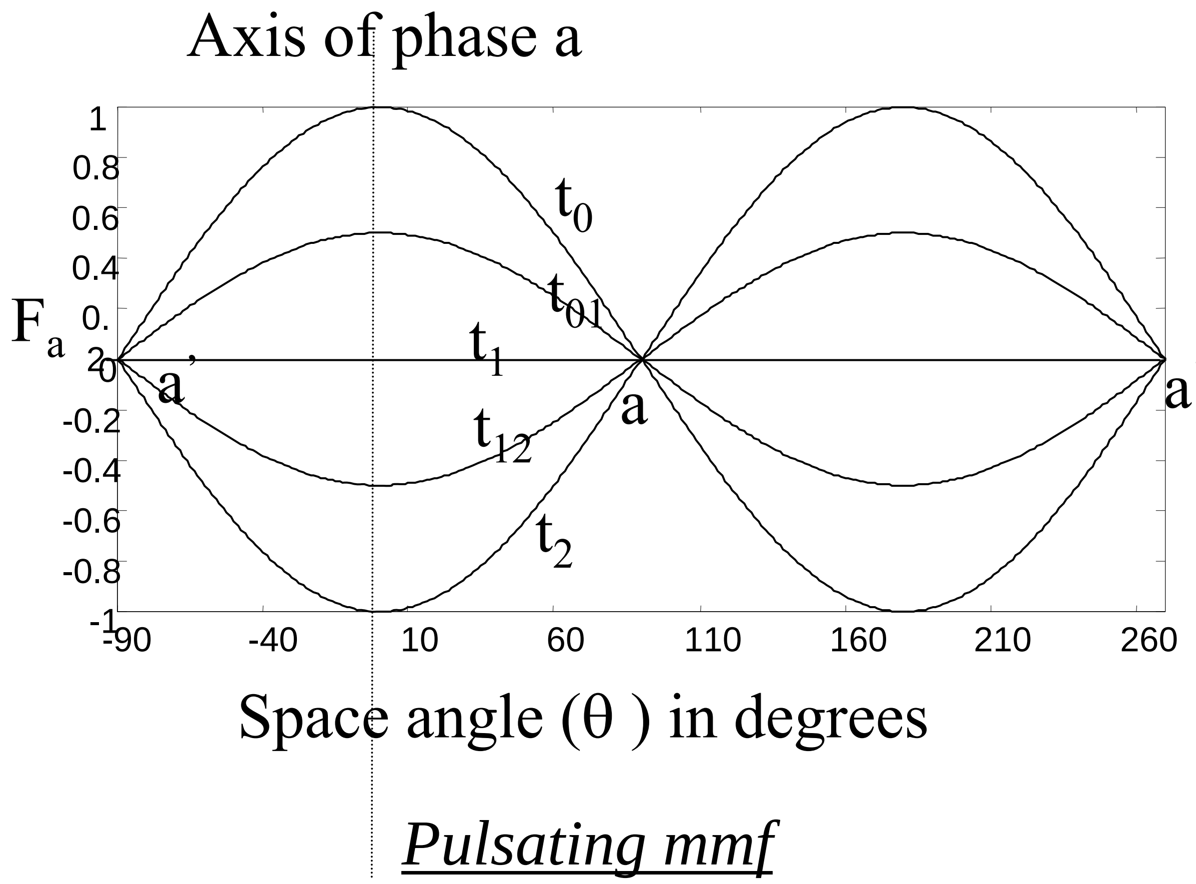
- Currents in different phases of AC Machine





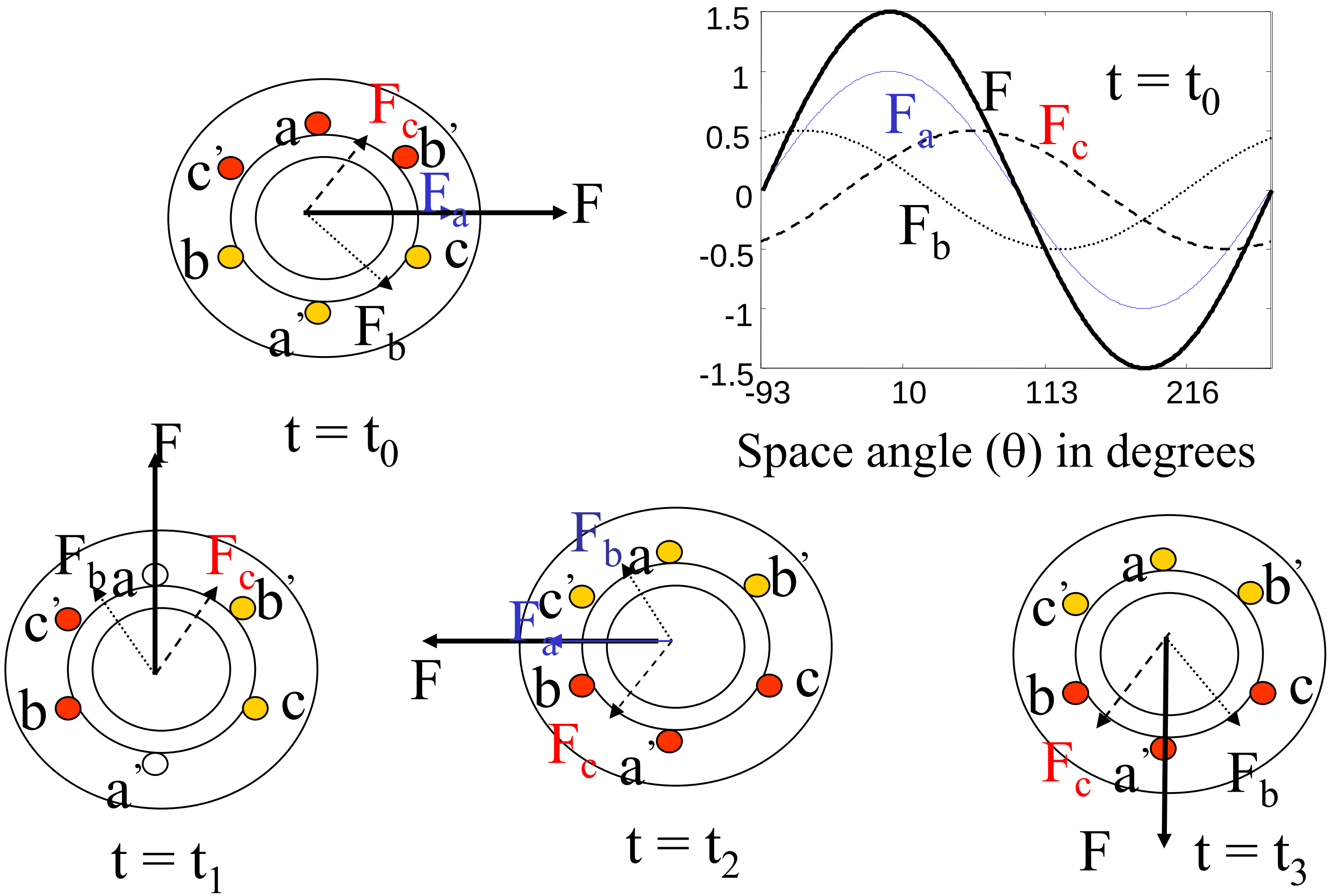
MMF due to ac current in phase "a"





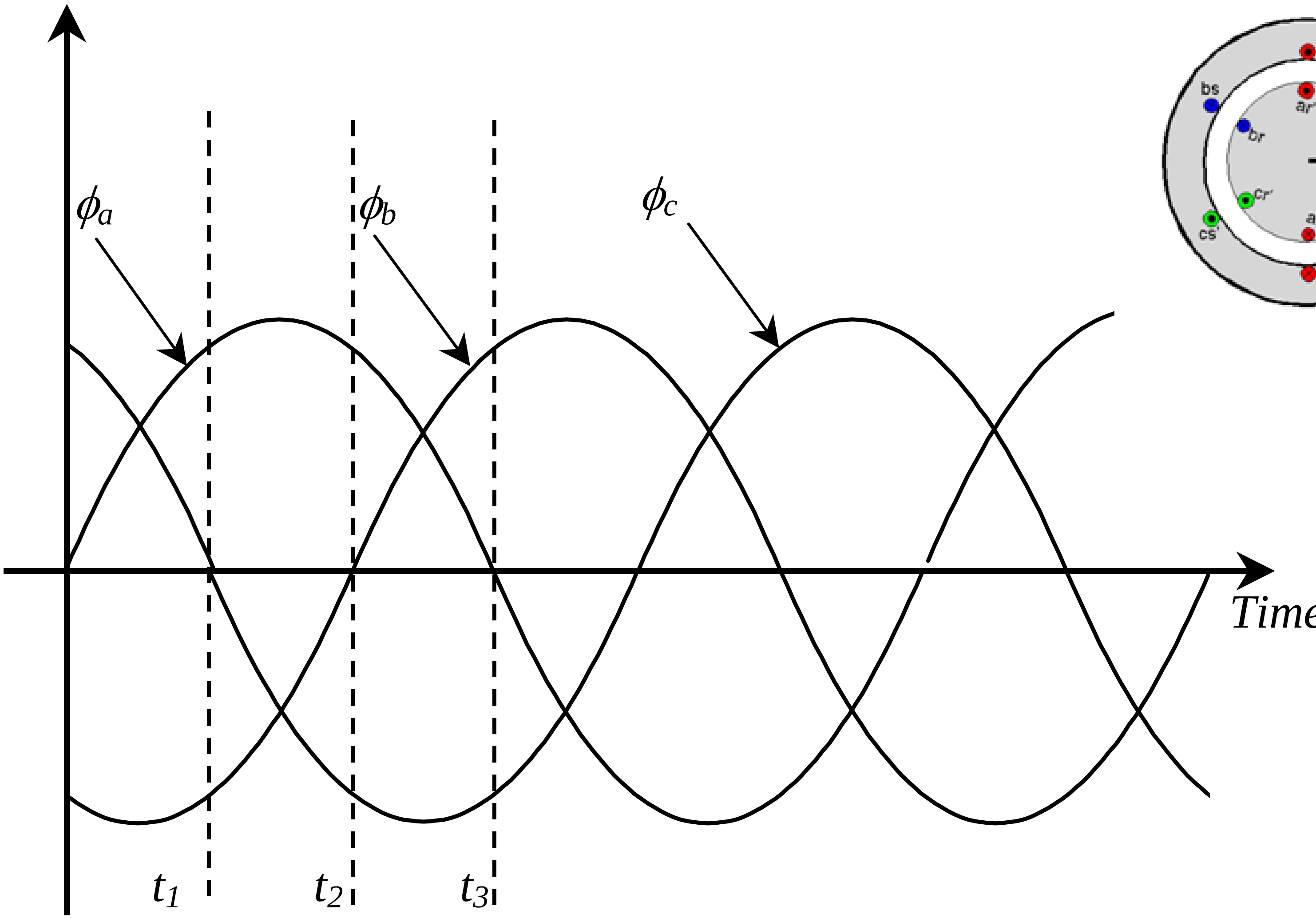
Pulsating mmf

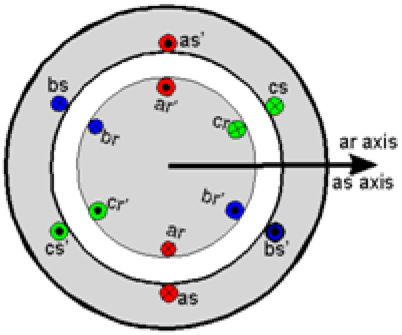
MMF due to three-phase currents in 3-ph winding



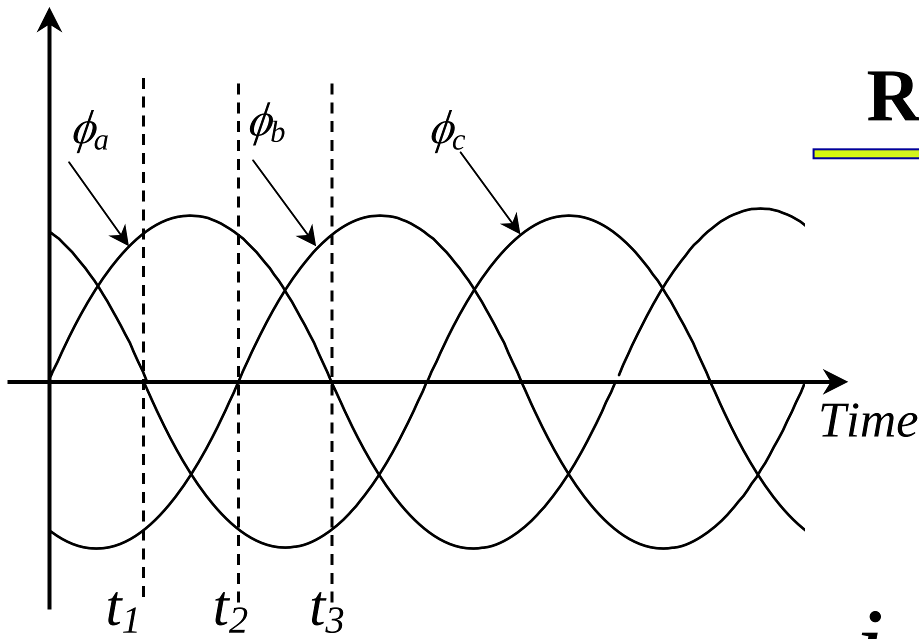
MMF's at various instant (*Rotating mmf*)

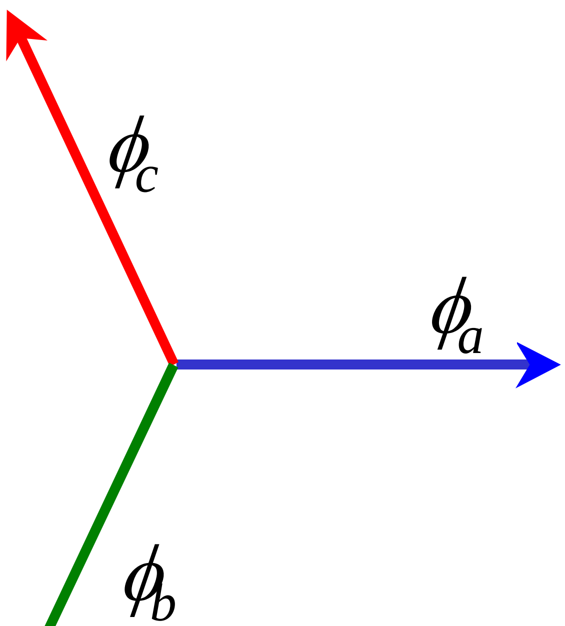
Rotating Magnetic Field

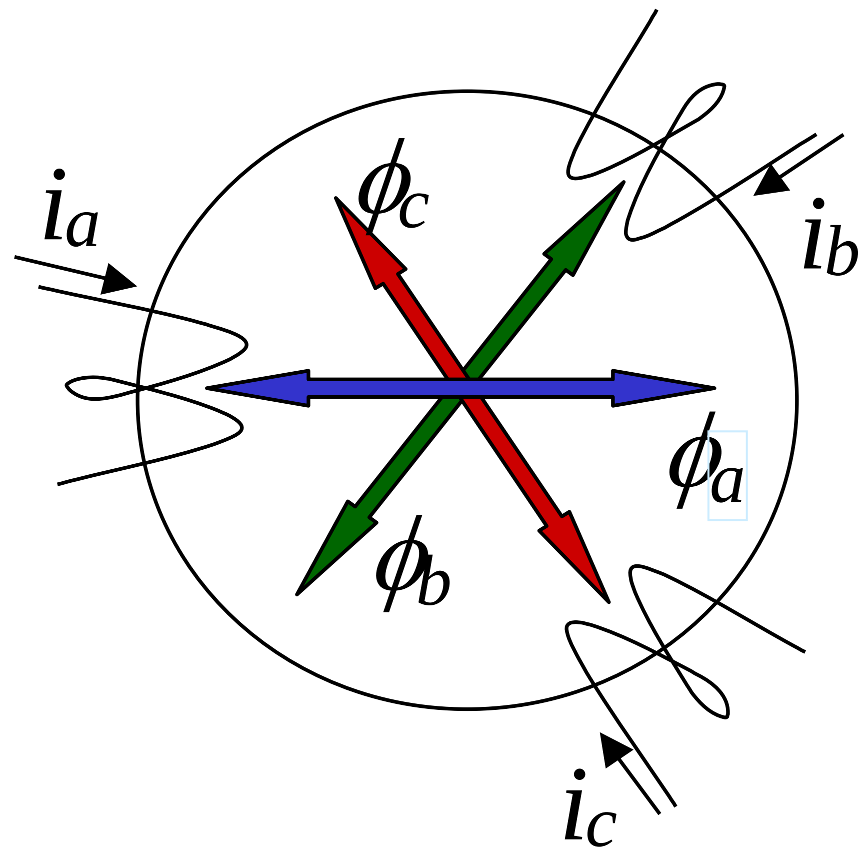




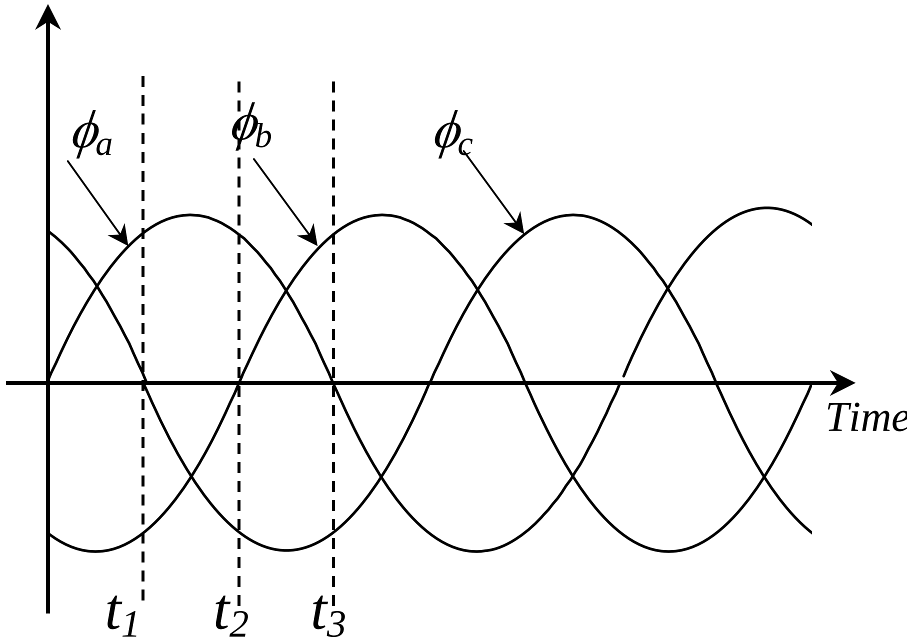
Rotating Magnetic Field

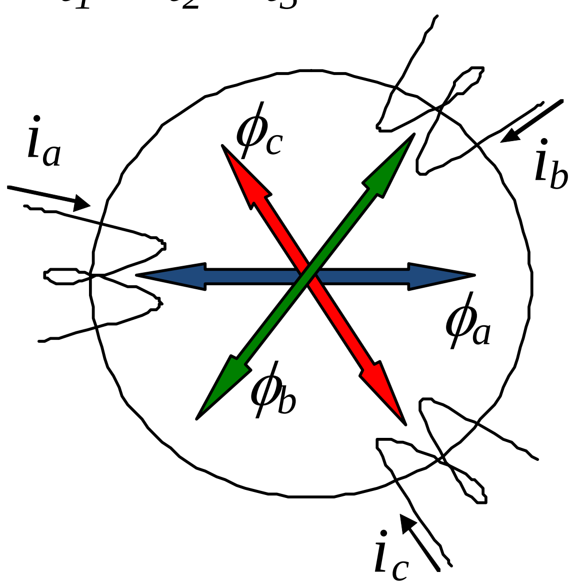


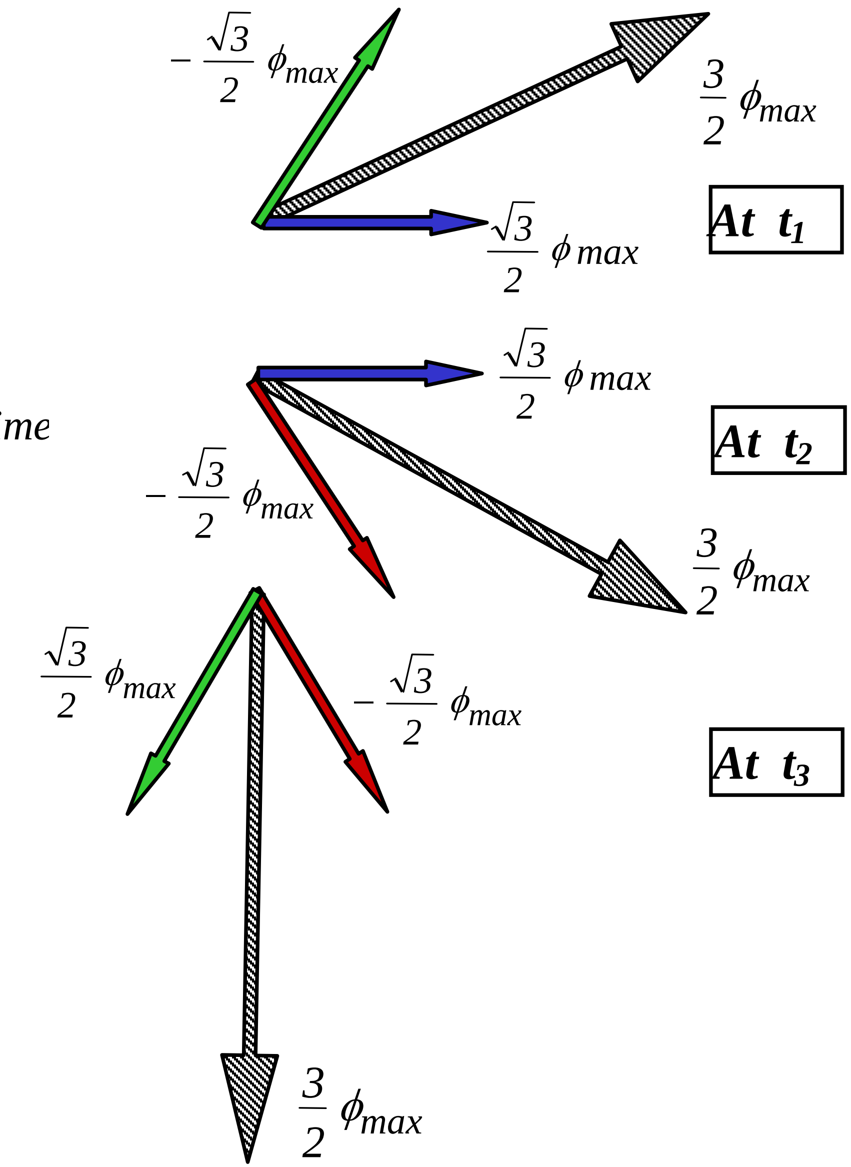




Rotating Magnetic Field







Principle of Operation: Definitions

- n_m = the rotor speed (the motor speed) w.r.t. **stator**
- n_s = the speed of stator field w.r.t. **stator** or the synch. speed
- n_r = the speed of rotor field w.r.t **rotor**
- S = the slip
- f_s = the frequency of the induced voltage in the stator (stator
- or supply frequency)
- f_r = the rotor circuit frequency or the slip frequency

$$n_r = n_s - n_m = sn_s$$

→ Slip rpm

$$f_r = \frac{p}{120}(n_r) = \frac{p}{120}(n_s - n_m) = \frac{p}{120}(S\, n_s) = S\ f_s$$

Induced EMF

The instantaneous value of the induced voltage in *N* turns coil is given by:

$$e = -N\frac{d\phi}{dt}$$

$$Let\ \ \phi = \phi_m \sin(\omega\, t)$$

$$\therefore\quad e = -N\ \omega\ \phi_m \cos(\omega\, t) = N\ 2\pi f\ \phi_m \sin(\omega\, t - 90°)$$

The r.m.s. value of the induced voltage per phase is

$$E_{rms} = 4.44\ f\ N_{ph}\ \Phi_p\ K_w$$

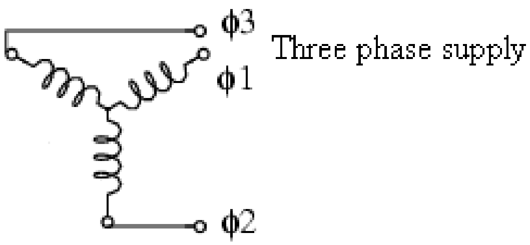
where

N_{ph} is the number of turns in series per phase

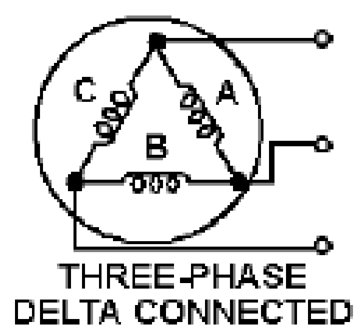
f is the frequency

ϕ_p is the flux per pole

K_w is the winding factor



phase voltage is 1/√3 of the normal voltage

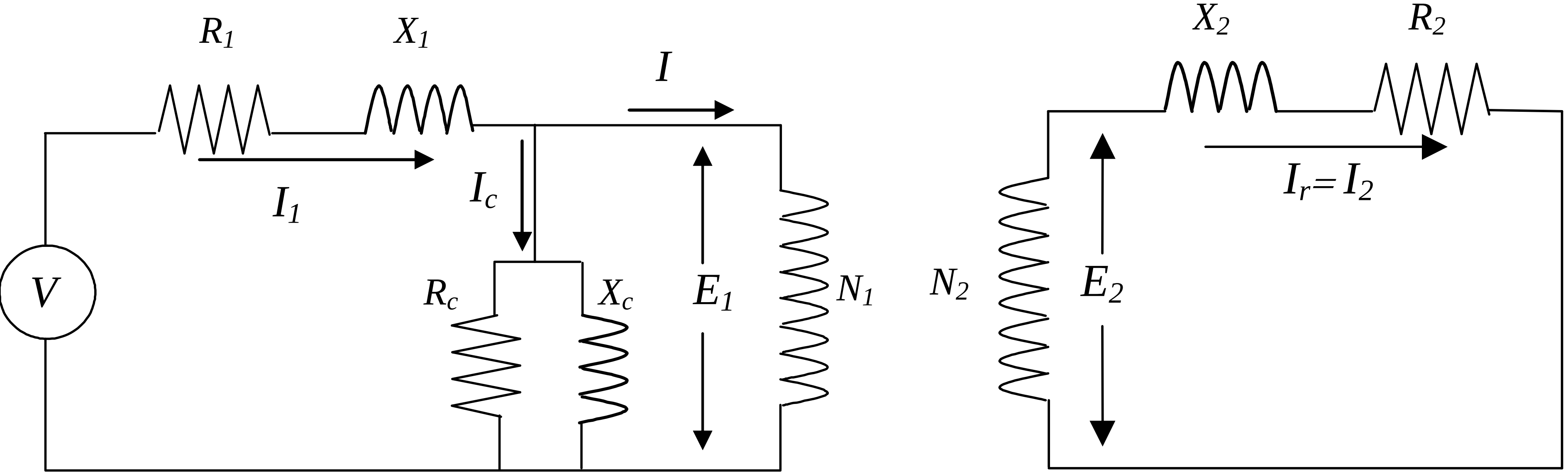


phase voltage is equal to the line voltage.

Equivalent Circuit Per Phase

- <u>At standstill</u> *($n_m = 0$, $S = 1$)*

The equivalent circuit of an induction motor at standstill is the same as that of a transformer with secondary short circuited.

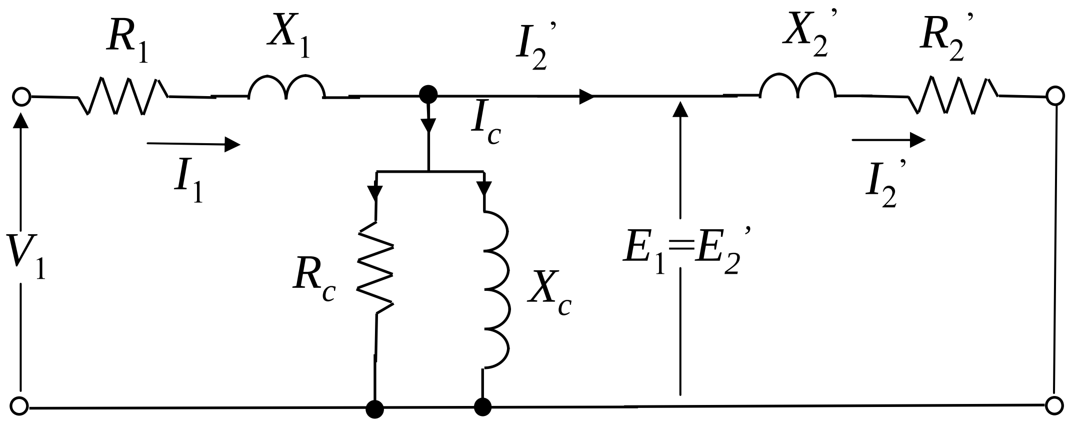


$$\frac{E_2}{E_1} = \frac{N_2}{N_1} \qquad \frac{I_2}{I} = \frac{N_1}{N_2} \cong \frac{I_2}{I_1}$$

Equivalent Circuit Per Phase

- <u>At standstill</u> $(n_m = 0\ ,\ S = 1)$

The equivalent circuit of an induction motor at standstill is the same as that of a transformer with secondary short circuited.



All values are per phase

Where

E_2 = per-phase induced voltage in the rotor at standstill

X_2 = per-phase rotor leakage reactance at standstill

Equivalent Circuit Per Phase (cont.)

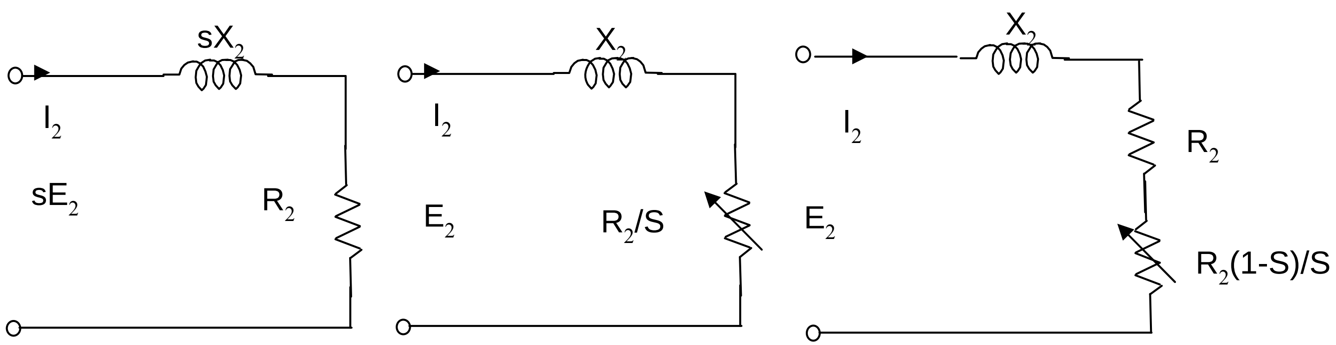
- **<u>At any slip S</u>**

When the rotor rotates with speed n_m the rotor circuit frequency will be:

$$f_r = S\ f_s$$

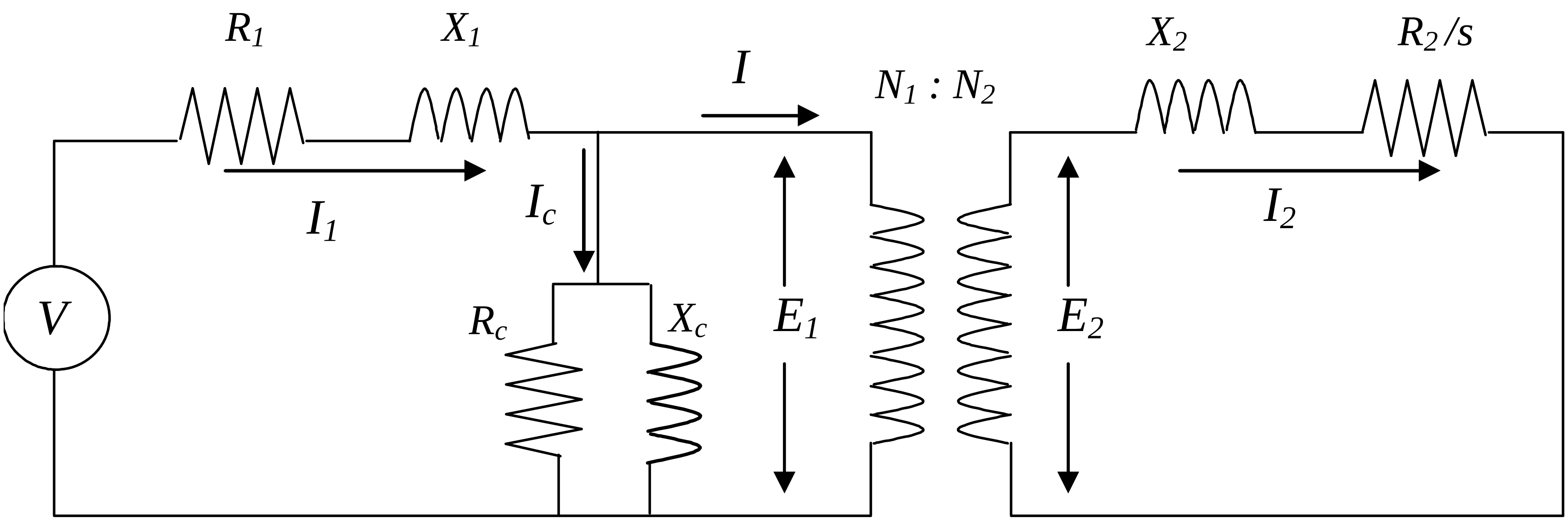
Therefore induced voltage in the rotor at any slip S will be $E_{2S} = S\ E_2$, similarly $X_{2S} = SX_2$

and the rotor equivalent circuit per-phase will be:

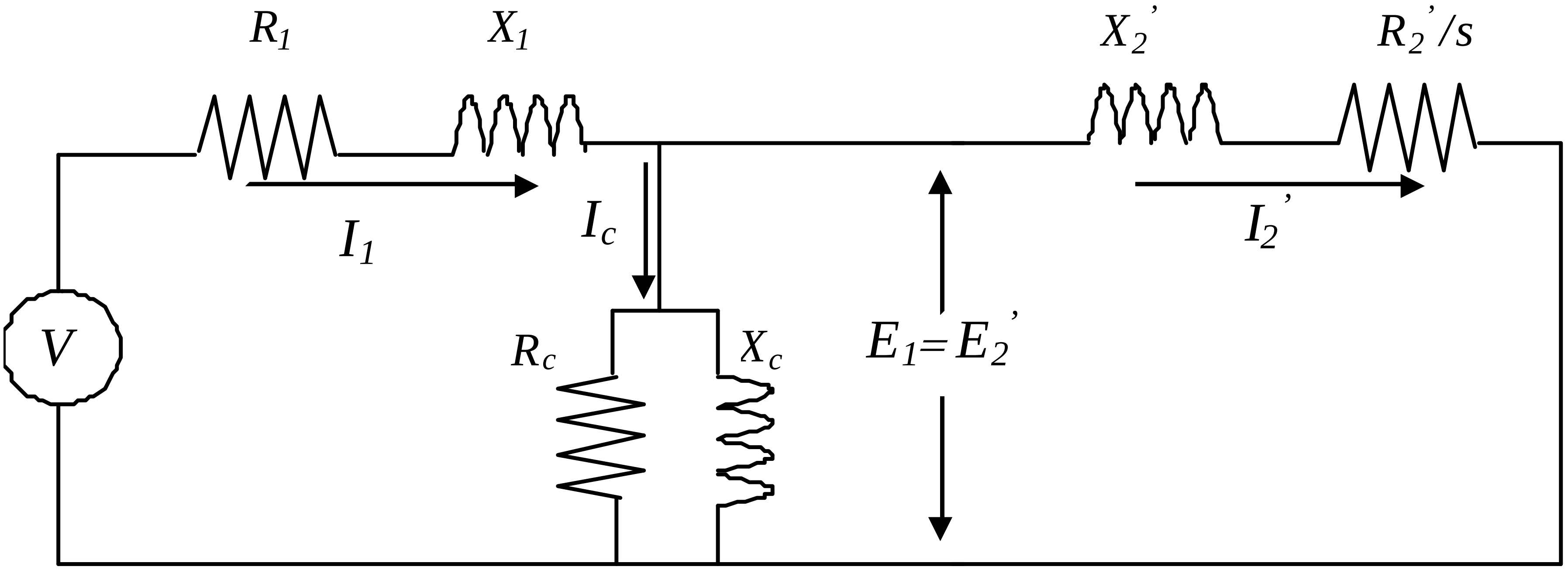


Where $$I_2 = \frac{SE_2}{R_2 + jSX_2} = \frac{E_2}{(R_2/s) + jX_2}$$

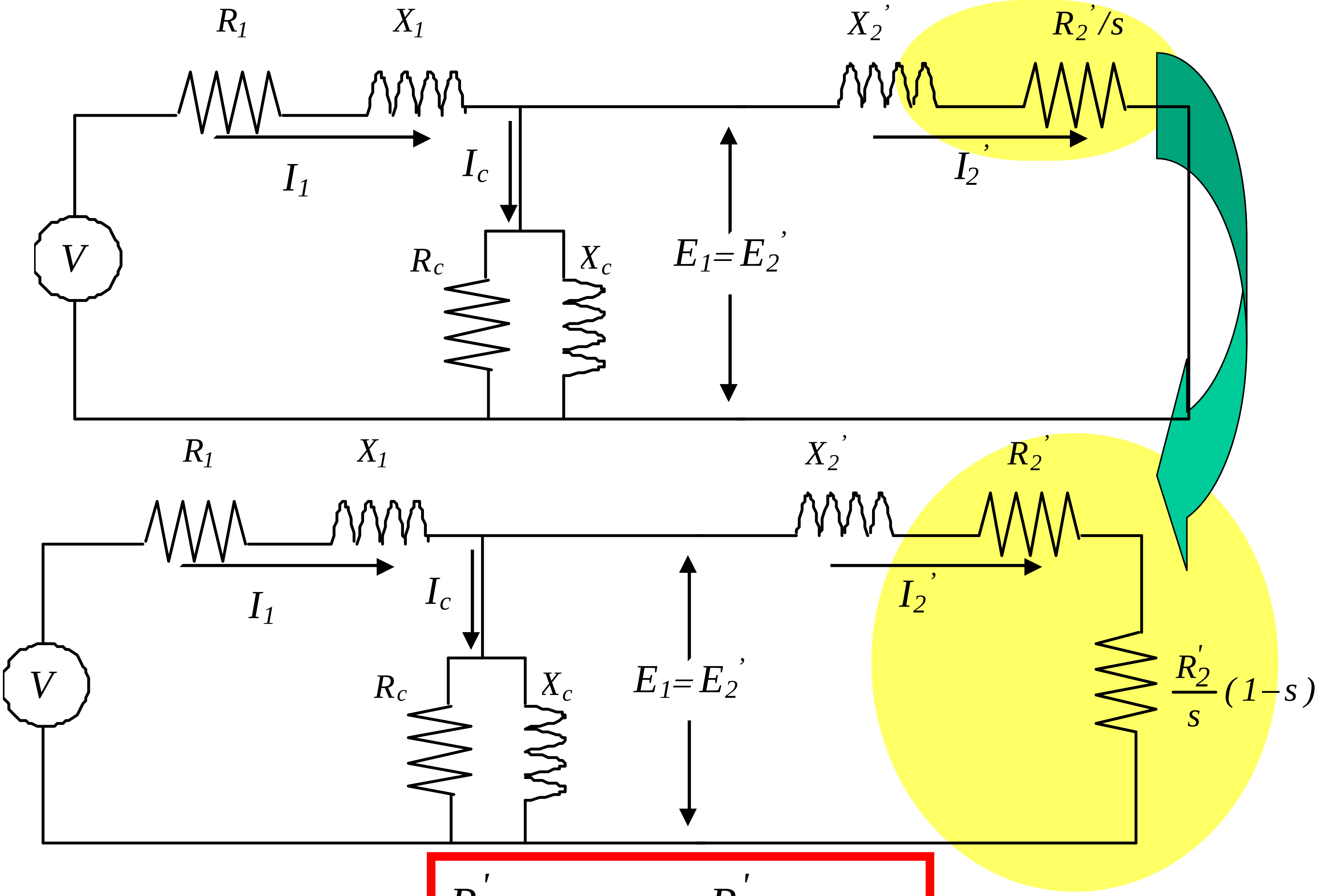
Combined Equivalent Circuit



Combined Equivalent Circuit

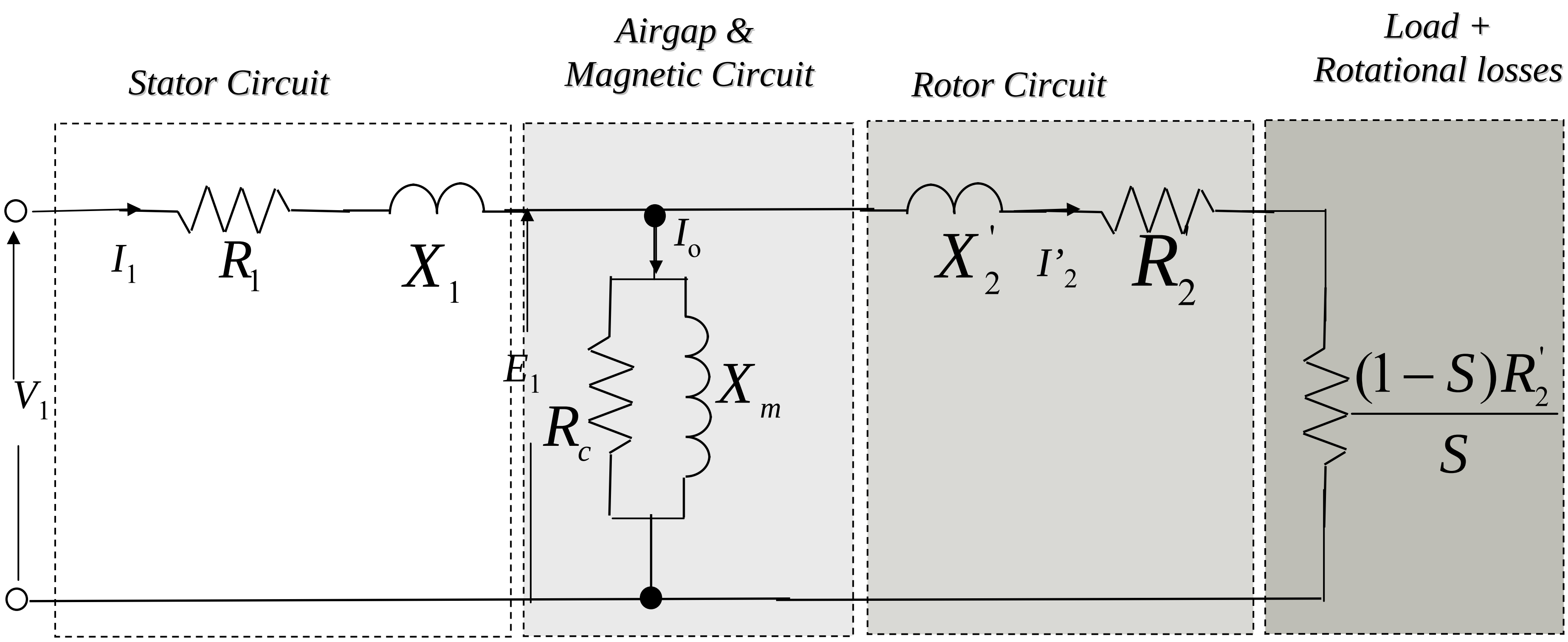


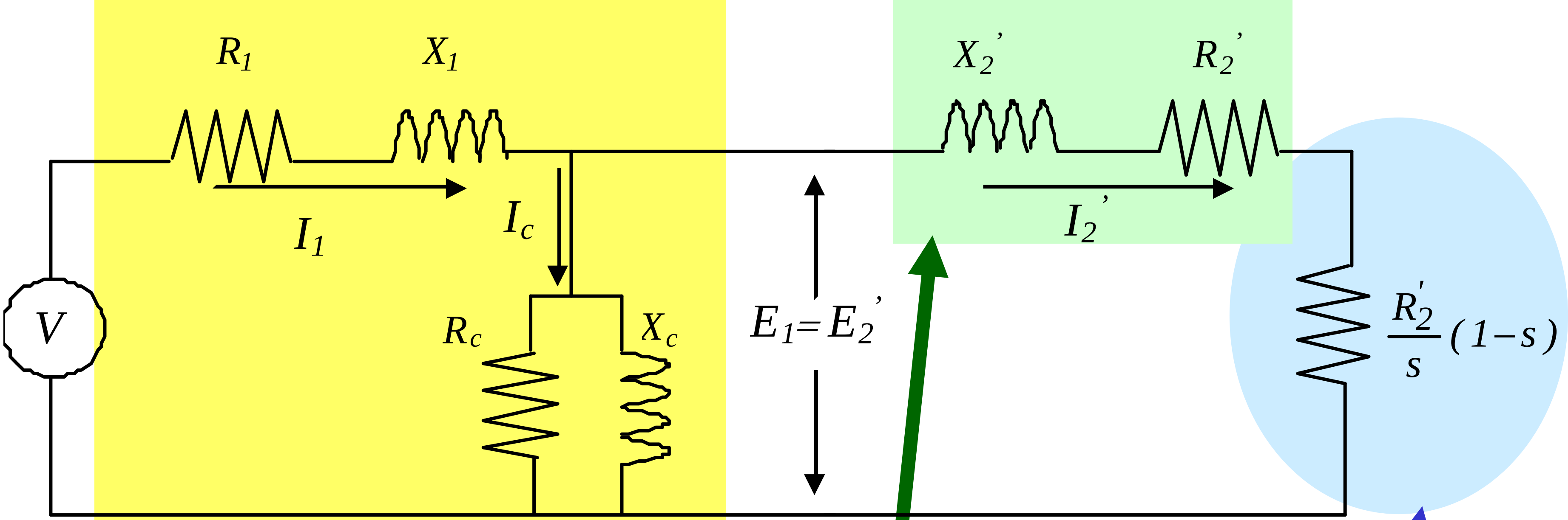
$$R_2' = R_2\left(\frac{N_1}{N_2}\right)^2 \qquad I_2' = I_2\left(\frac{N_2}{N_1}\right) \qquad X_2' = X_2\left(\frac{N_1}{N_2}\right)^2$$



$$\frac{R_2'}{s} = R_2' + \frac{R_2'}{s}(1-s)$$

Combined Equivalent Circuit

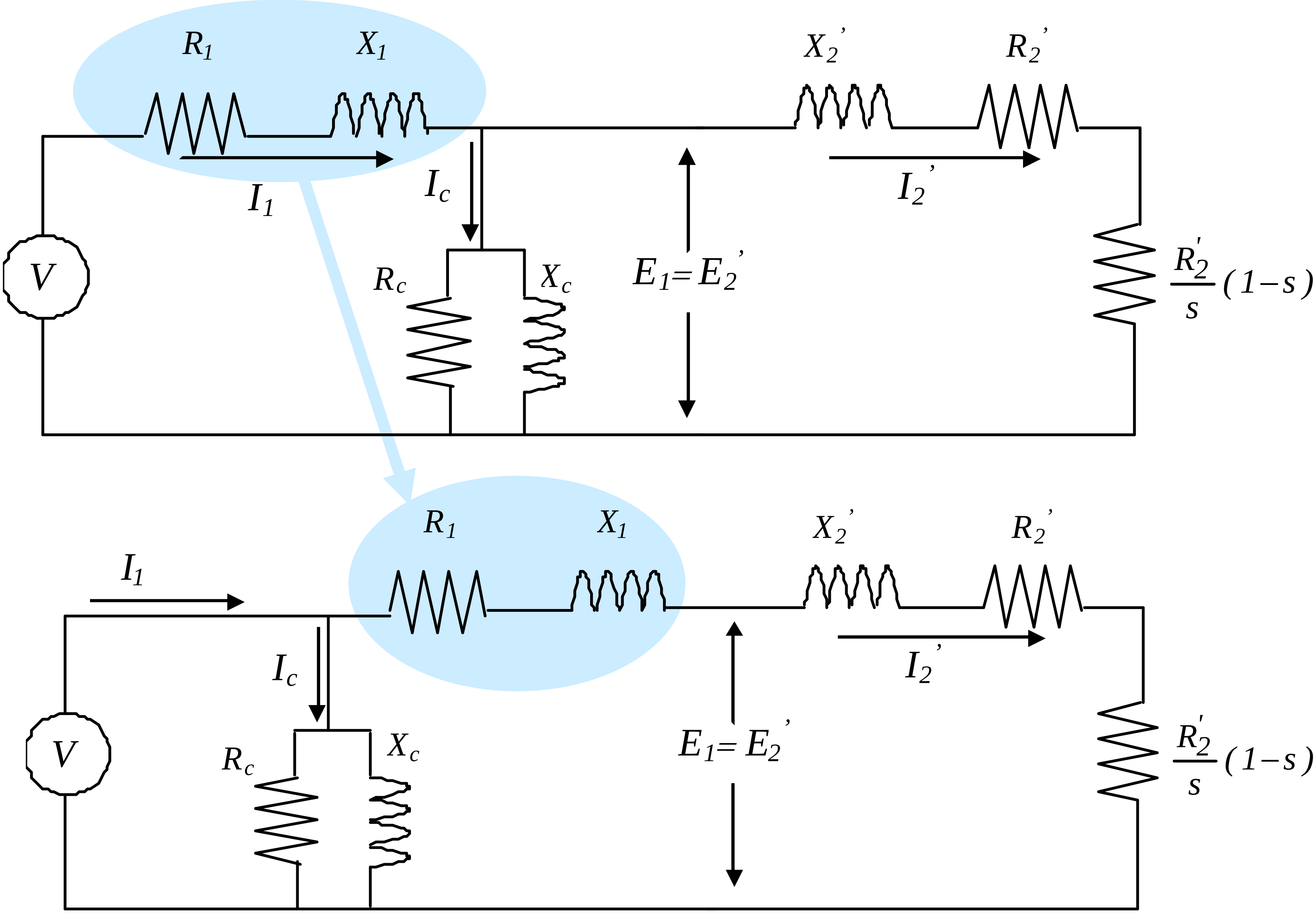




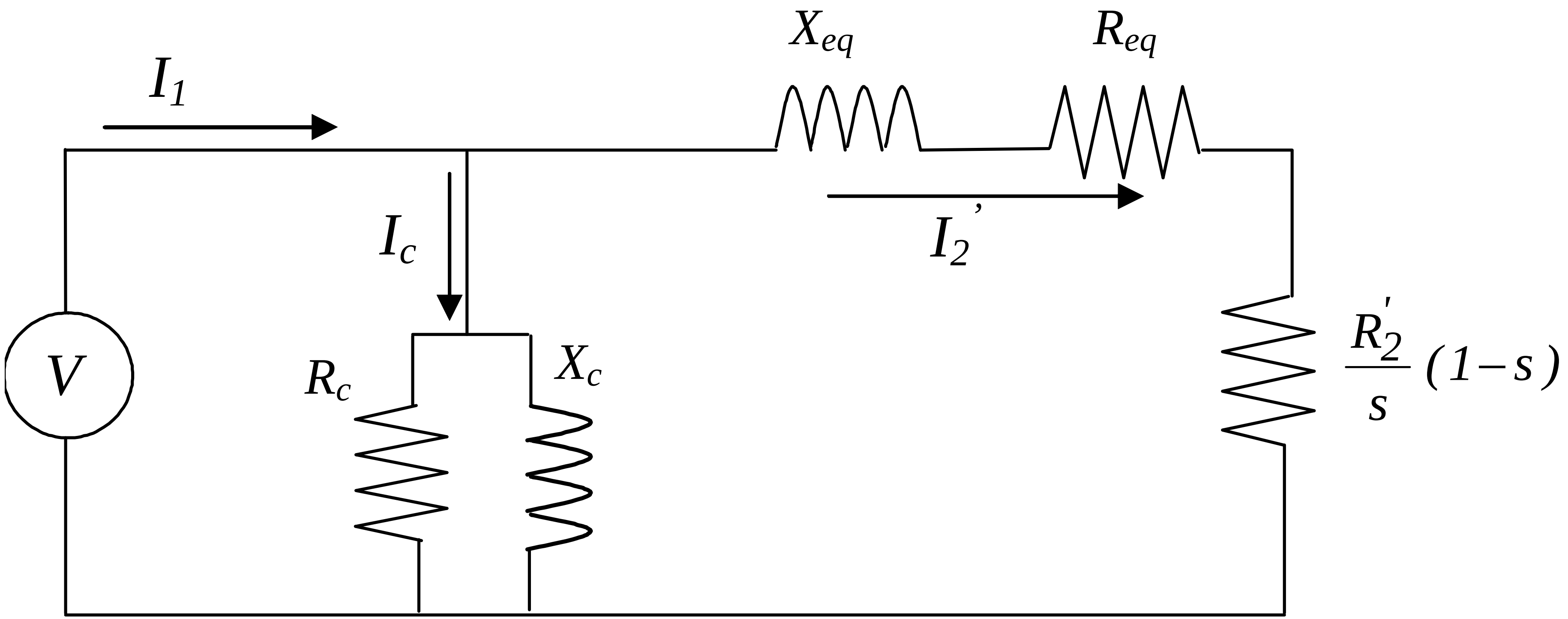
Equivalent to transformer's secondary windings

Equivalent to transformer's primary windings

Equivalent to transformer's load


R1
X1
X2'
R2'
I1
Ic
I2'
V
Rc
Xc
E1= E2'
R'2 / s (1−s)
R1
X1
X2'
R2'
I1
Ic
I2'
V
Rc
Xc
E1= E2'
R'2 / s (1−s)

Approximate Equivalent Circuit

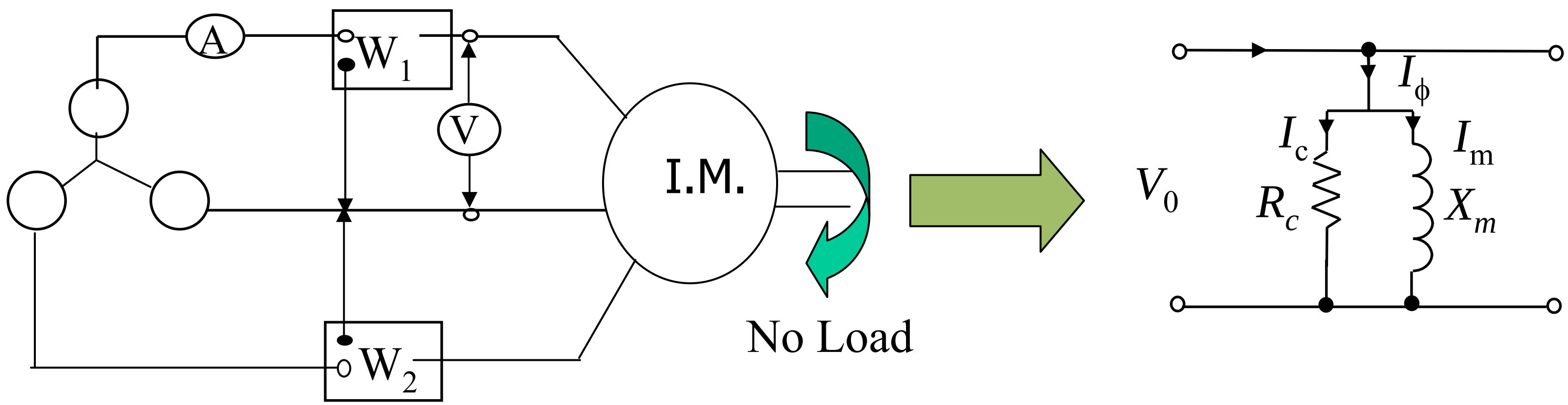


$$R_{eq} = R_1 + R_2'$$

$$X_{eq} = X_1 + X_2'$$

Determination of the Equivalent Circuit Parameters

1. No-Load Test (*S = 0*)



Measured values $V_{oL} = V_{1L}$, $I_{\phi L}$, and $P_{ot} = W_1 \pm W_2$

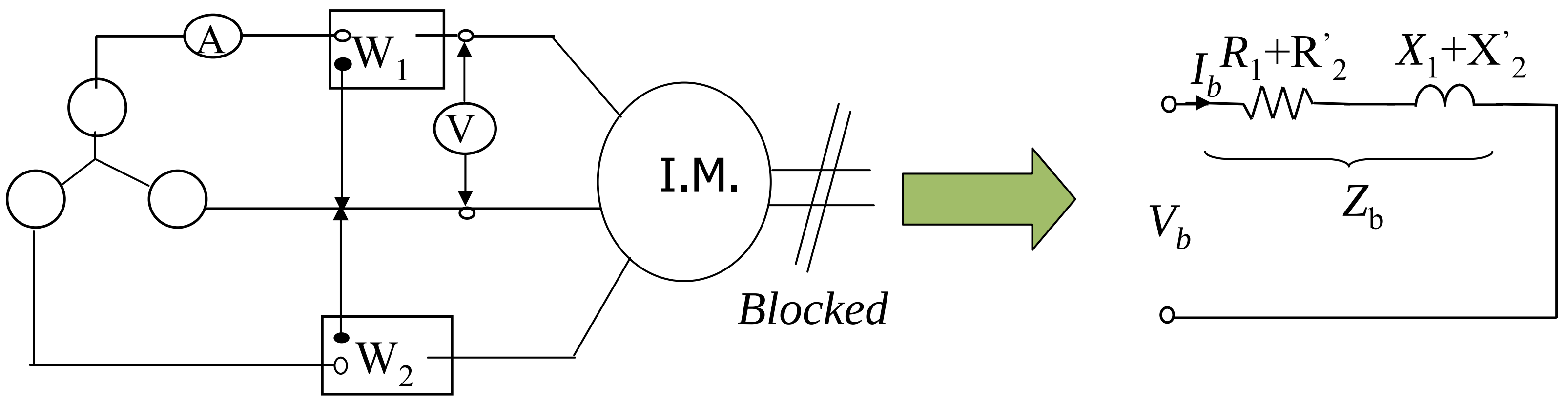
Calculate the per phase values V_0 , I_ϕ and $P_0 = P_{ot}/3$

$$\cos(\Phi_o) = \frac{P_o}{V_0 I_\phi} \qquad I_c = I_\phi \cos(\Phi_o) \qquad I_m = I_\phi \sin(\Phi_o)$$

$$R_c = \frac{V_0}{I_c} \qquad X_m = \frac{V_0}{I_m}$$

Determination of the Equivalent Circuit Parameters

2. Blocked rotor Test (*S* = *1*)



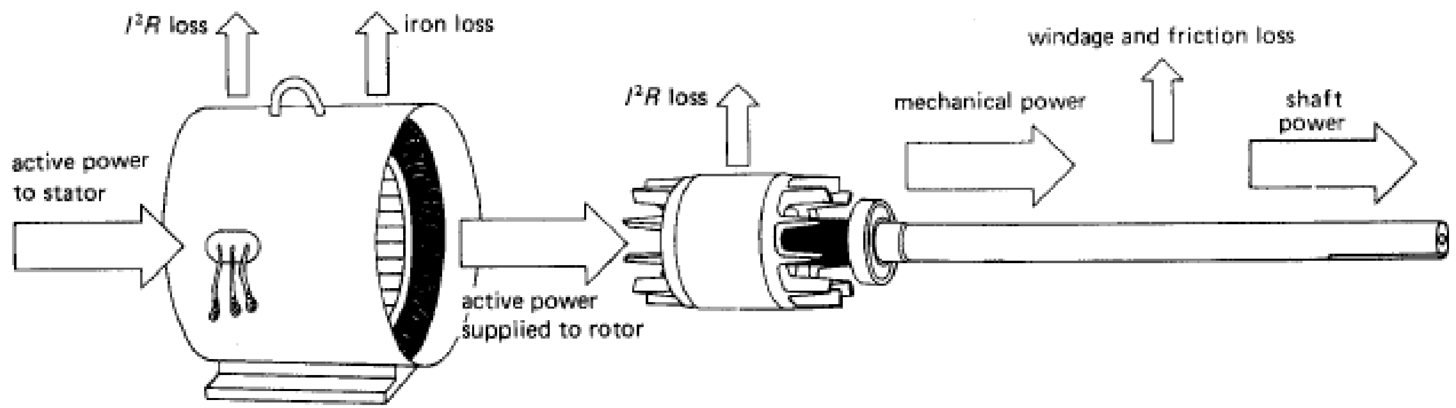
Measured values $V_{bL} < V_{1L}$, I_{bL} , and $P_{bt} = W_1 \pm W_2$

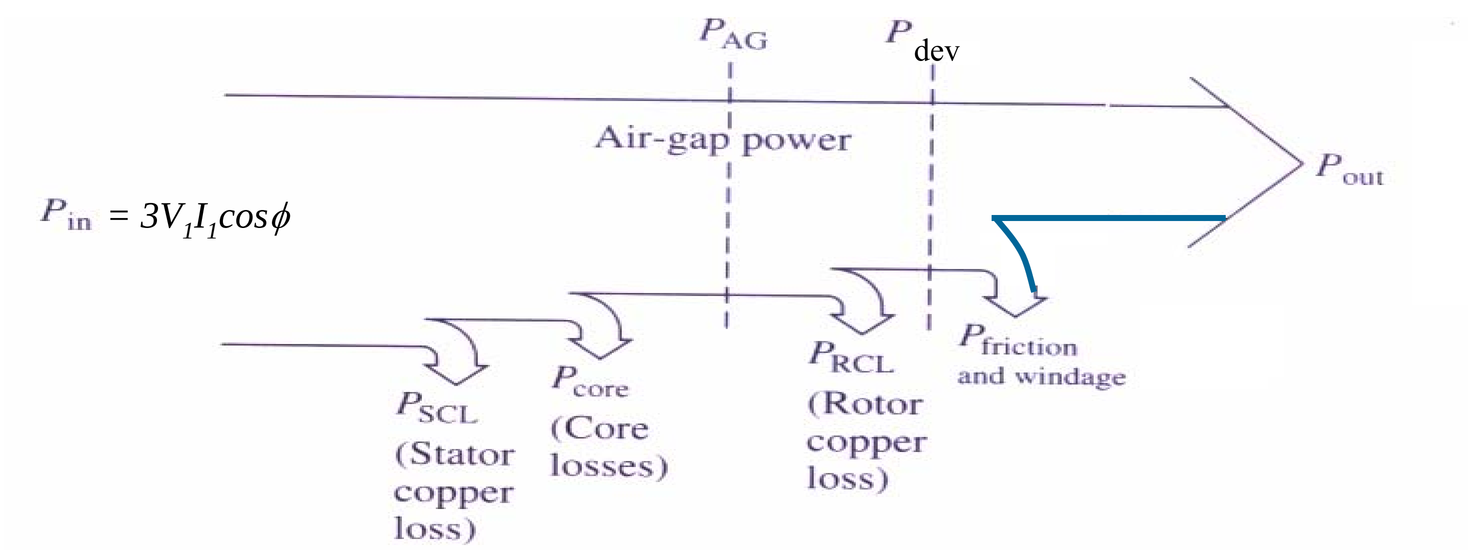
Calculate the per phase values V_b , I_b and $P_b = P_{ot}/3$

$$R_b = R_1 + R'_2 = \frac{P_b}{I_b^{\,2}}, \qquad Z_b = \frac{V_b}{I_b}, \qquad X_b = X_1 + X'_2 = \sqrt{Z_b^2 - R_b^2}$$

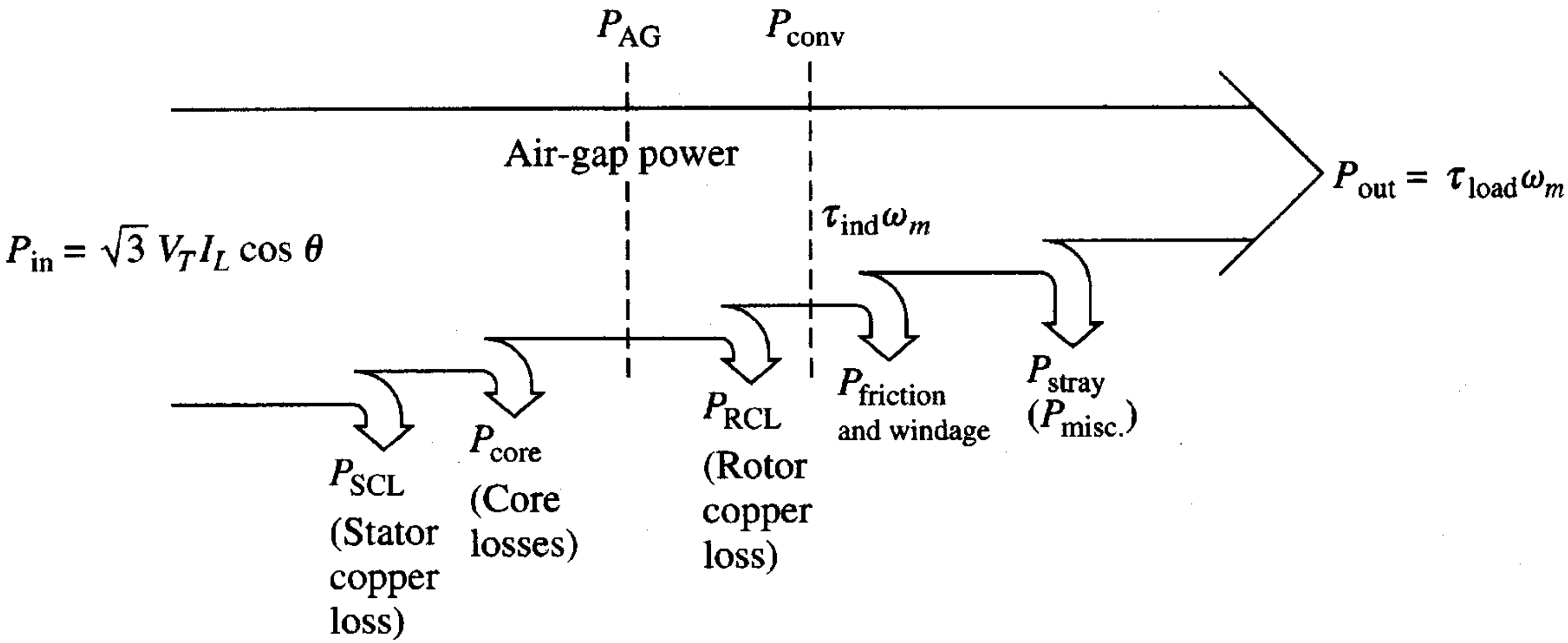
$$\therefore R'_2 = R_b - R_1 \qquad \& \qquad X_1 = X'_2 = \frac{X_b}{2}$$

Power Flow In Induction Motors





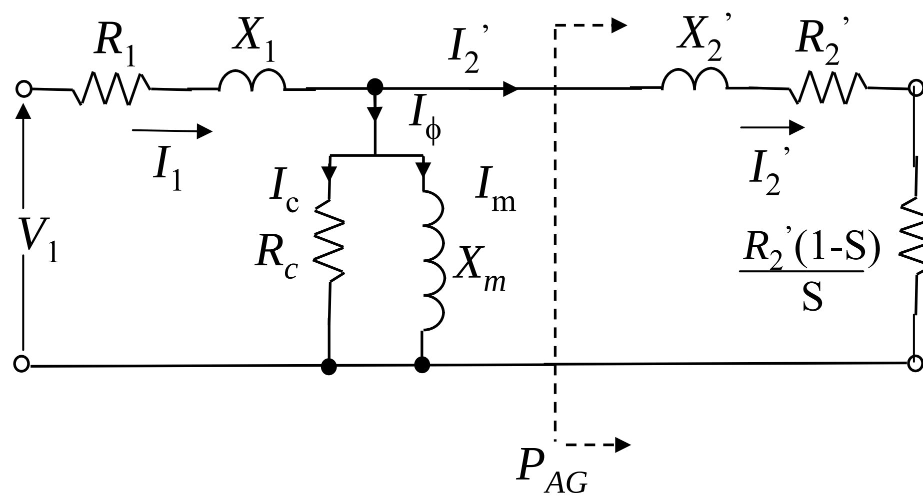
Power Flow In Induction Motors



$$P_{AG} = 3(I_2')^2 \frac{R_2'}{S}$$

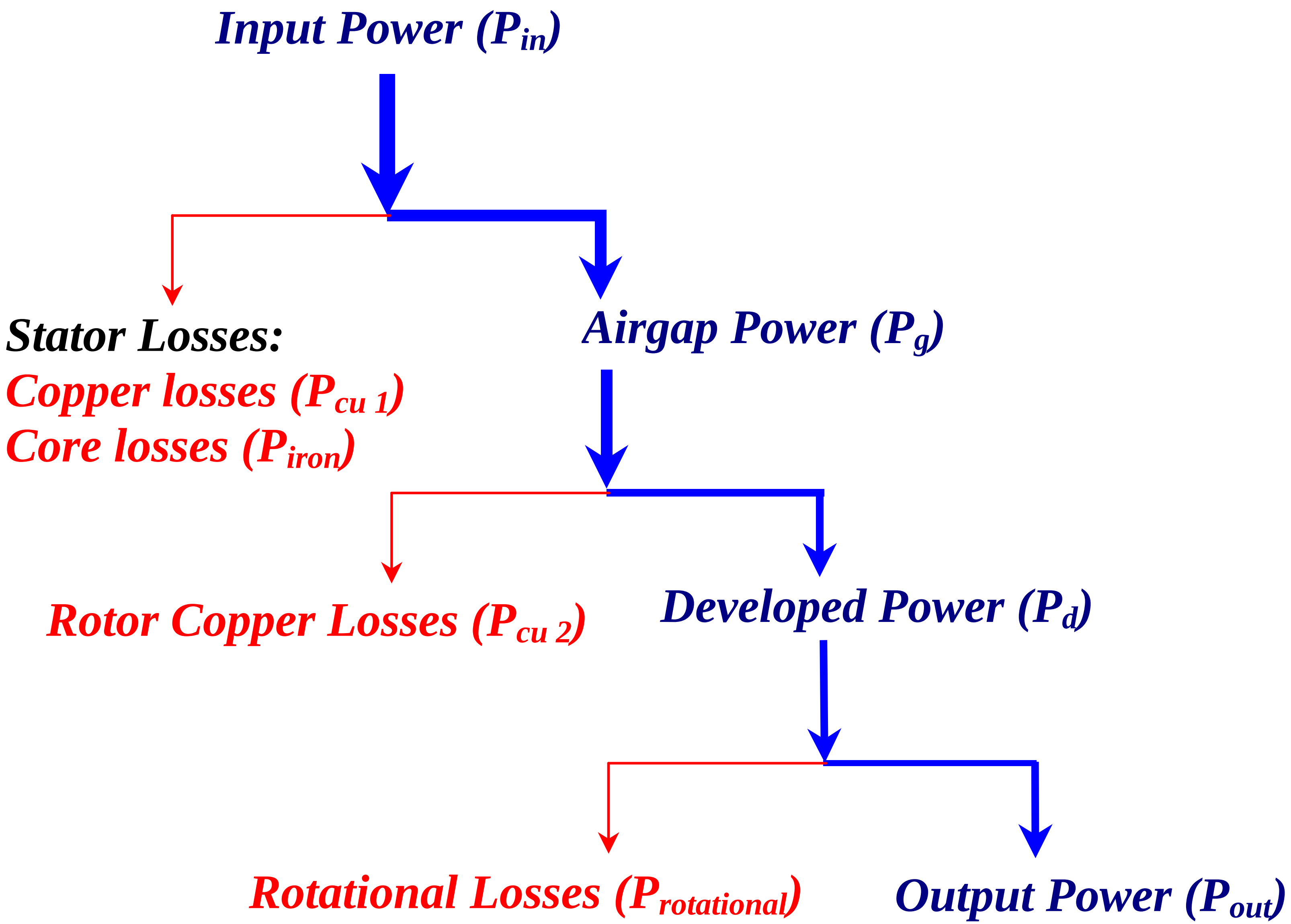
$$P_{RCL} = 3(I_2')^2 R_2'$$

$$P_{dev} = 3(I_2')^2 \frac{R_2'(1-S)}{S}$$

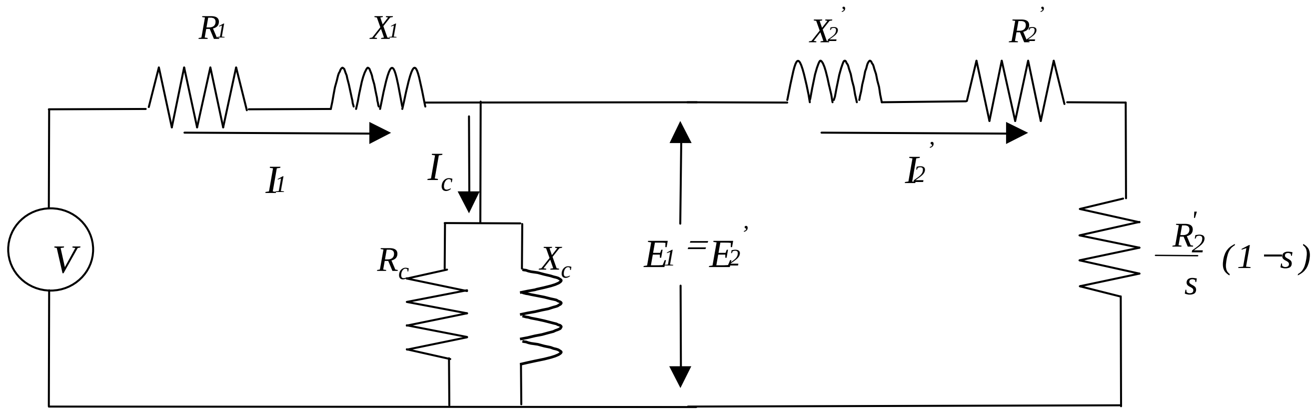


$$\therefore P_{GA} : P_{RCL} : P_{dev} = 1 : S : (1-S)$$

Power Flow In Induction Motor



Power Flow In Induction Motor



$$P_{in} = 3 V I_1 \cos\theta_1$$

$$P_{cu1} = 3\ I_1^2 R_1$$

$$P_{iron} \cong 3\frac{V^2}{R_m}$$

$$P_g = 3\ (I_2')^2 \frac{R_2'}{s} = T_d\ \omega_s$$

$$P_g : P_{cu2} : P_d = 1 : s : (1-s)$$

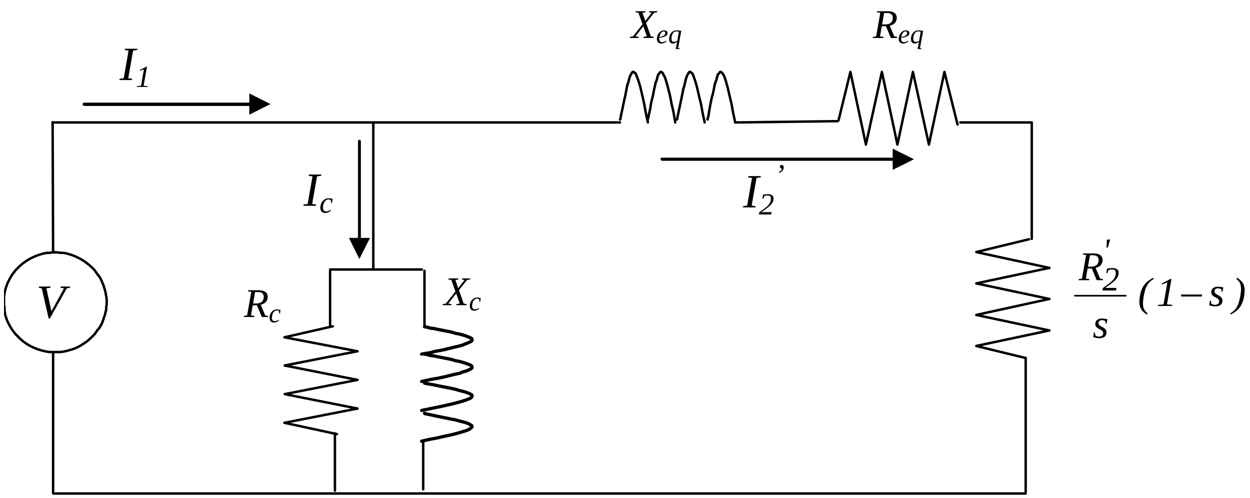
$$P_{cu2} = 3\left(I_2'\right)^2 R_2' = s\ P_g$$

$$P_d = 3\left(I_2'\right)^2 \frac{R_2'}{s}(1-s) = P_g\ (1-s)\ = T_d\ \omega$$

$$P_{rotational}$$

$$P_{out} = T\ \omega$$

Torque Characteristics

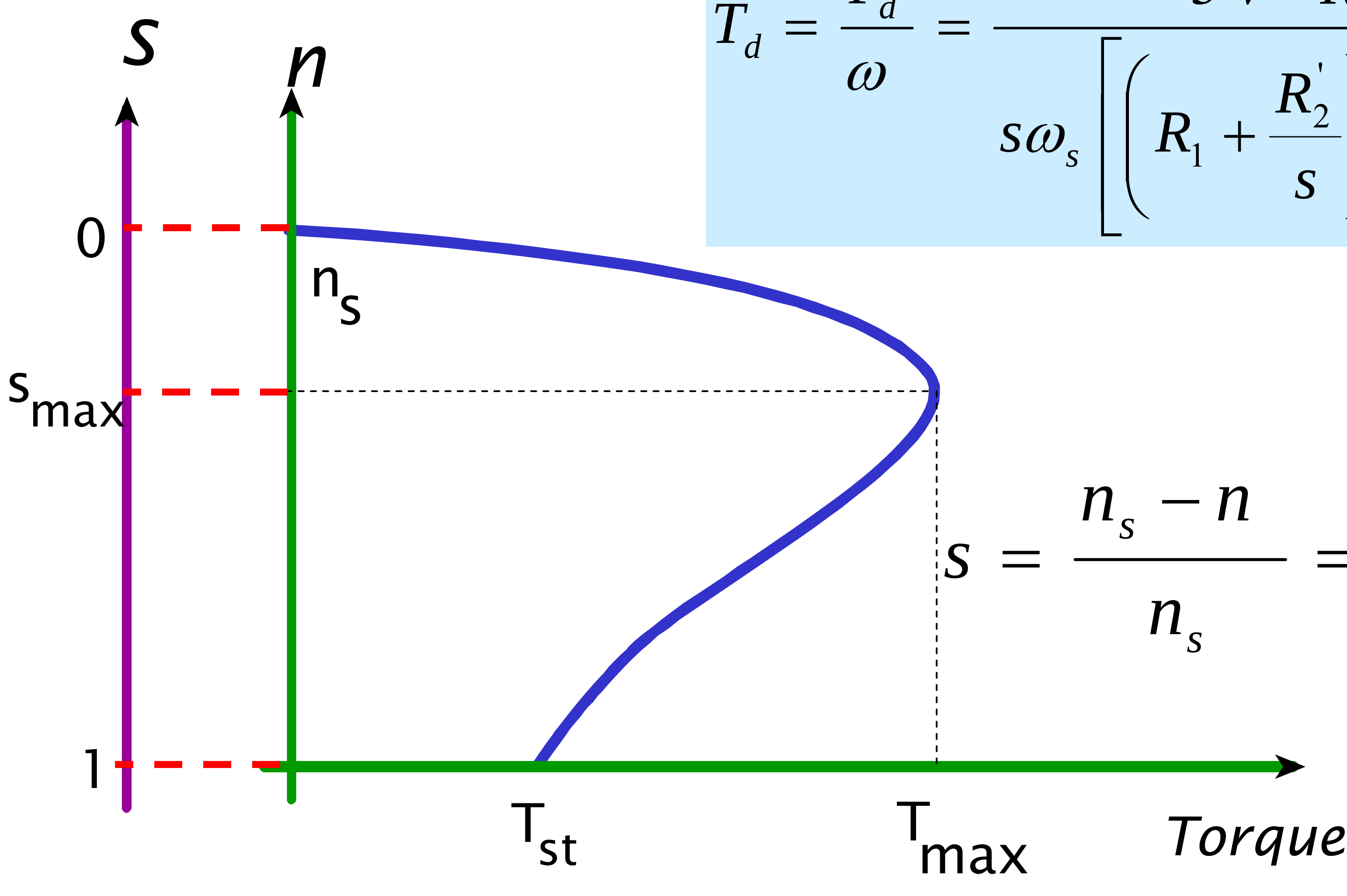


$$I_2' = \frac{V}{\sqrt{\left(R_1 + \frac{R_2'}{s}\right)^2 + X_{eq}^2}}$$

$$T_d = \frac{P_d}{\omega} = \frac{3}{\omega}(I_2')^2 \frac{R_2'}{s}(1-s) = \frac{3V^2 R_2'(1-s)}{s\omega\left[\left(R_1 + \frac{R_2'}{s}\right)^2 + X_{eq}^2\right]}$$

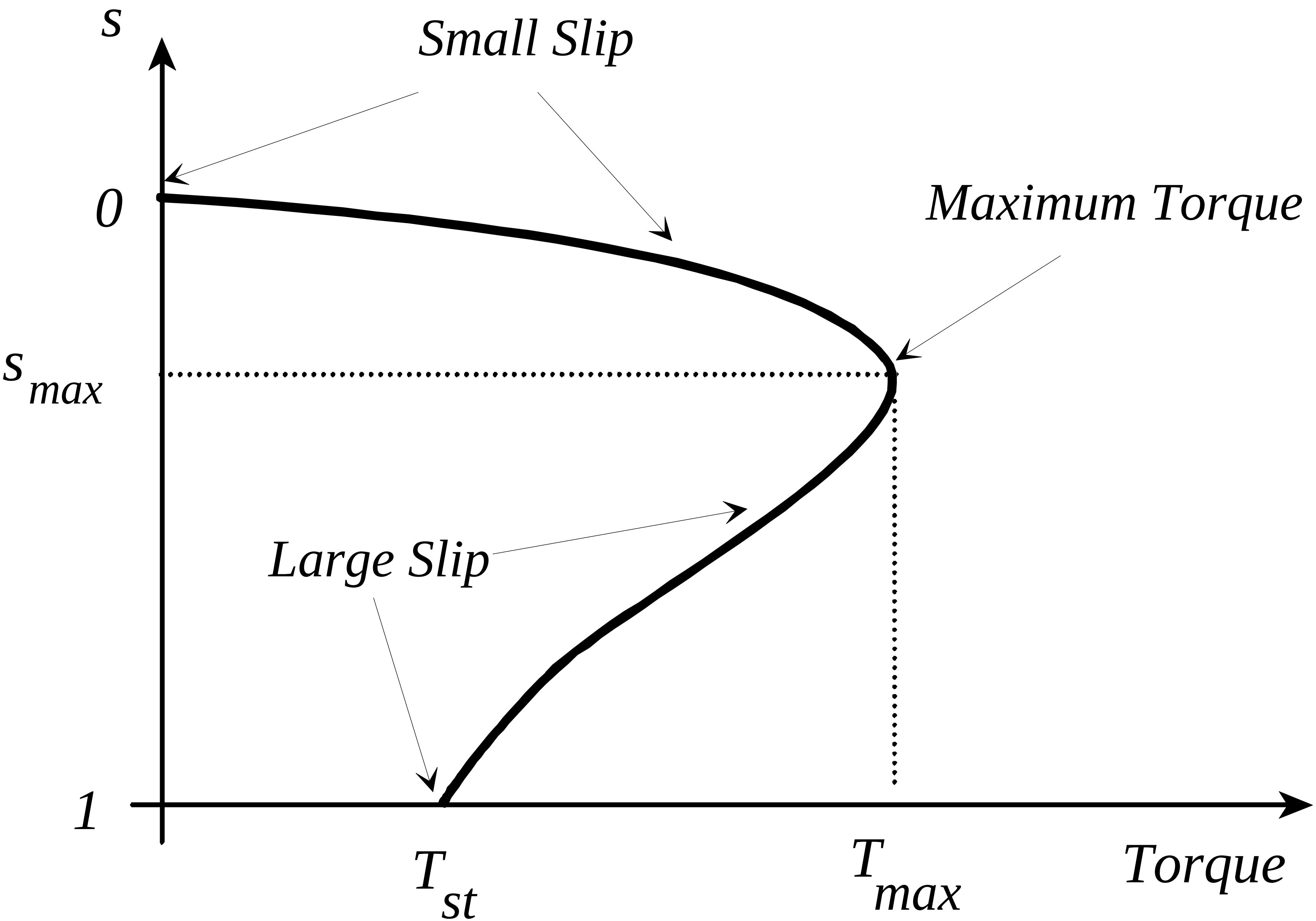
Torque Characteristics

$$T_d = \frac{P_d}{\omega} = \frac{3\,V^2\,R_2^{'}}{s\omega_s\left[\left(R_1 + \frac{R_2^{'}}{s}\right)^2 + X_{eq}^2\right]}$$



$$s = \frac{n_s - n}{n_s} = \frac{\omega_s - \omega}{\omega_s}$$

Torque Characteristics



Maximum Torque

$$T_d = \frac{P_d}{\omega} = \frac{3V^2 R_2'}{s\omega_s\left[\left(R_1 + \frac{R_2'}{s}\right)^2 + X_{eq}^2\right]}$$

Set

$$\frac{\partial T_d}{\partial s} = 0$$

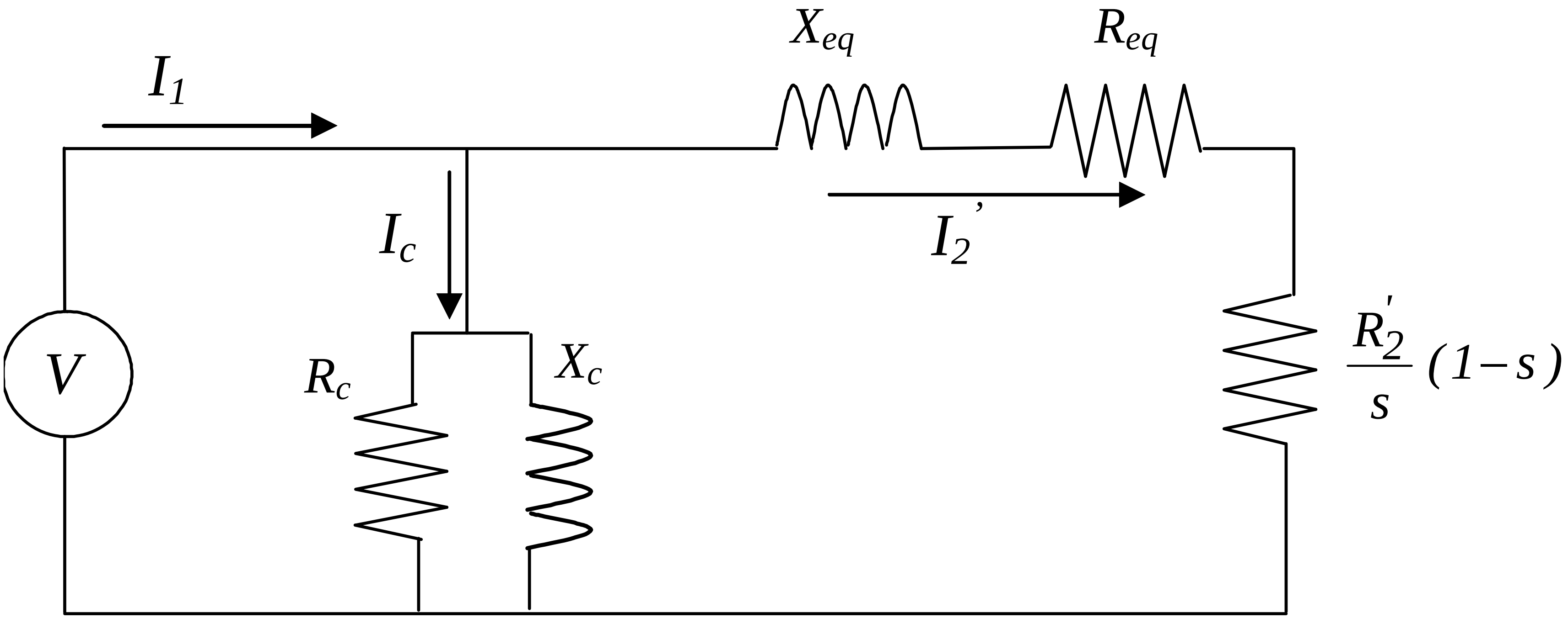
$$s_{max} = \frac{R_2'}{\sqrt{R_1^2 + X_{eq}^2}}$$

$$T_{max} = \frac{3V^2}{2\omega_s\left[R_1 + \sqrt{R_1^2 + X_{eq}^2}\right]}$$

Starting of Induction Motor

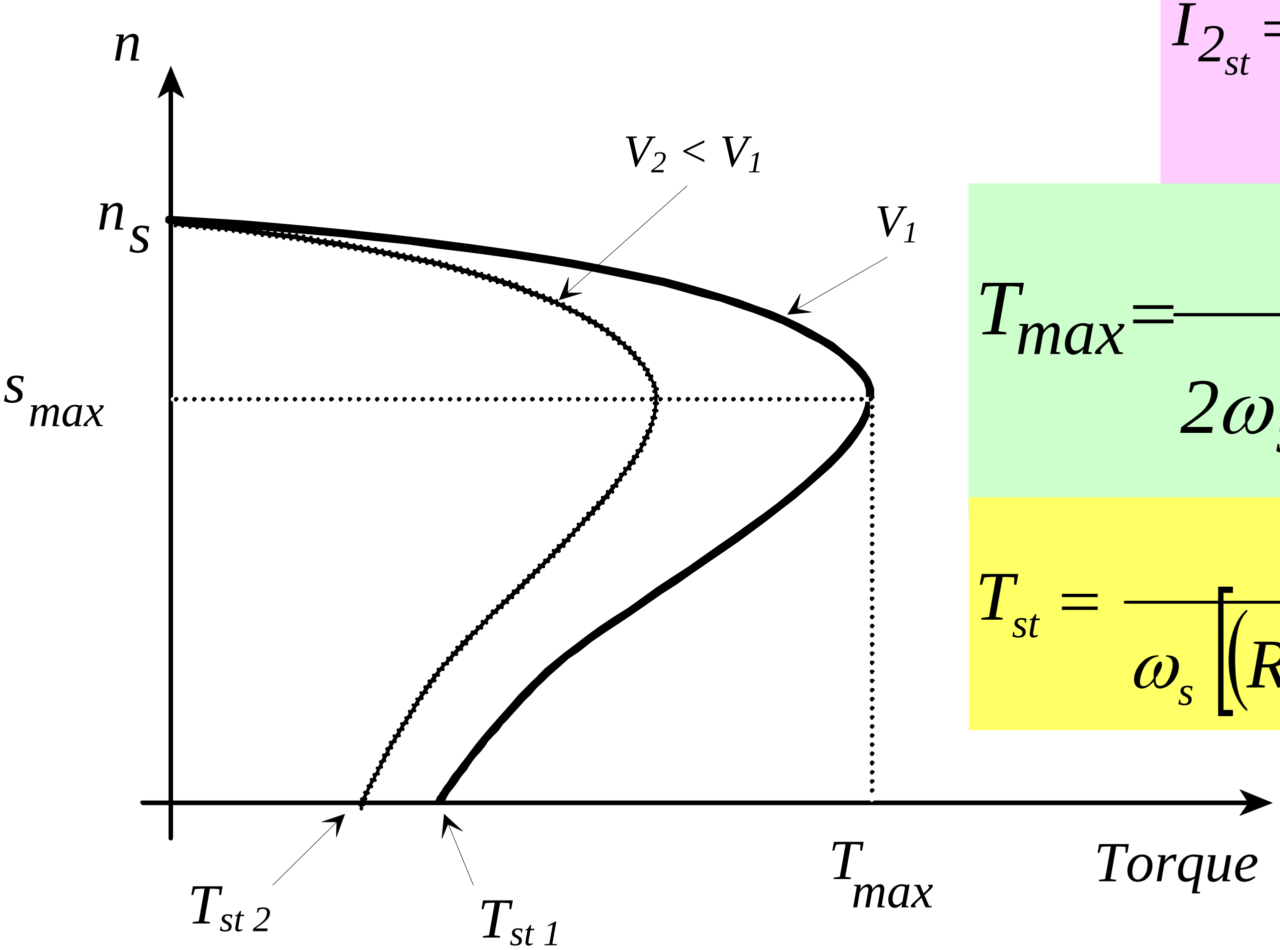
- Problems:
  - High starting current
  - Low starting torque

Starting of Induction Motor



$$I'_{2_{st}} = \frac{V}{\sqrt{\left(R_1 + R_2'\right)^2 + X_{eq}^2}}$$

Starting by Reducing Voltage



$$I'_{2_{st}} = \frac{V}{\sqrt{\left(R_1 + R'_2\right)^2 + X_{eq}^2}}$$

$$T_{max} = \frac{3\,V^2}{2\omega_s\left[R_1 + \sqrt{R_1^2 + X_{eq}^2}\right]}$$

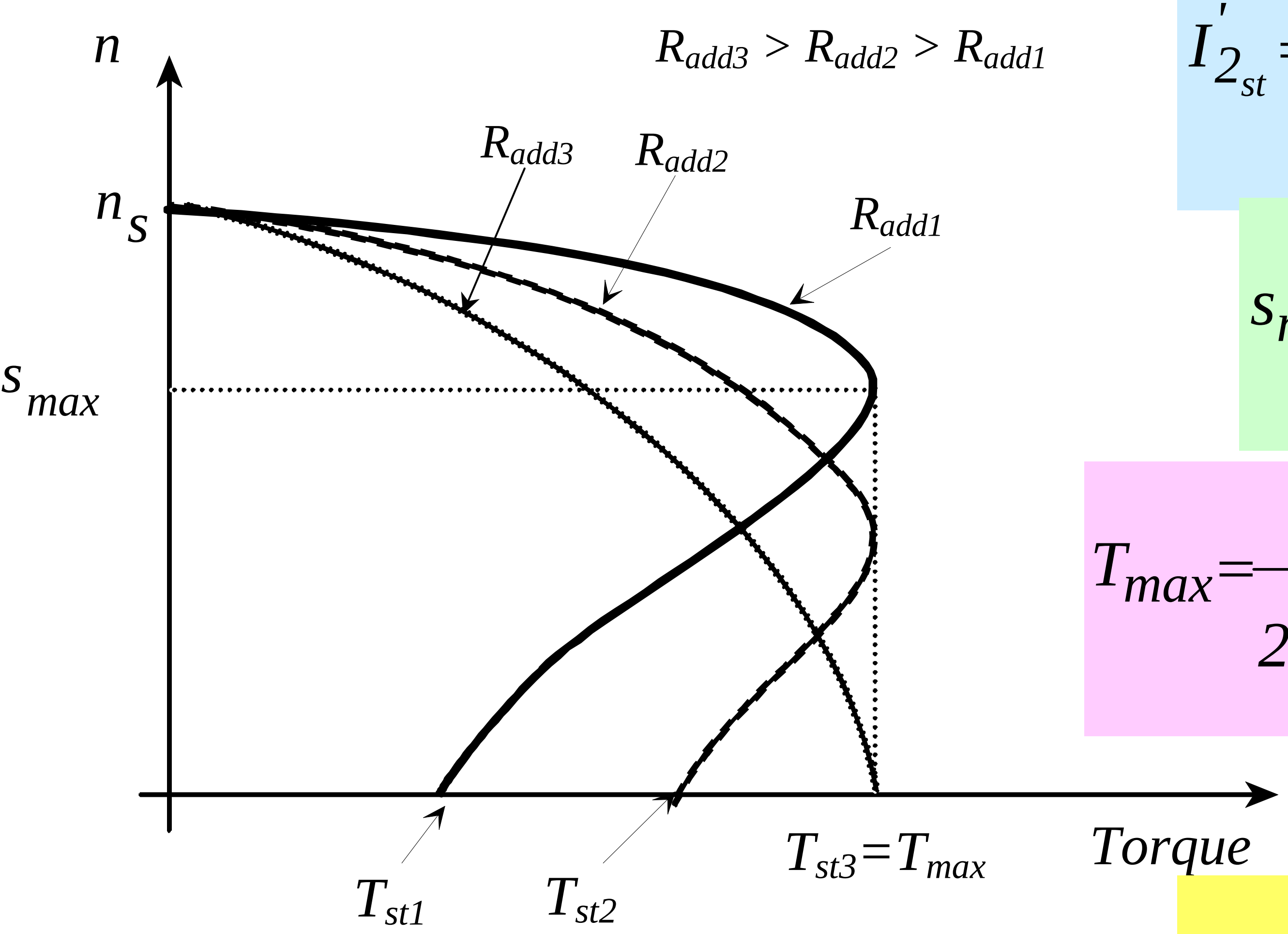
$$T_{st} = \frac{3\,V^2\,R'_2}{\omega_s\left[\left(R_1 + R'_2\right)^2 + X_{eq}^2\right]}$$

$$s_{max} = \frac{R'_2}{\sqrt{R_1^2 + X_{eq}^2}}$$

Starting by Reducing Voltage

- Starting current is reduced (good)
- Starting torque is reduced (cannot start heavy loads)
- Maximum torque is reduced (Motor acceleration is low)
- Speed at maximum torque is unchanged

Starting by Adding Rotor Resistance



$$I'_{2_{st}} = \frac{V}{\sqrt{\left(R_1 + R'_2\right)^2 + X_{eq}^2}}$$

$$s_{max} = \frac{R'_2}{\sqrt{R_1^2 + X_{eq}^2}}$$

$$T_{max} = \frac{3\,V^2}{2\omega_s\left[R_1 + \sqrt{R_1^2 + X_{eq}^2}\right]}$$

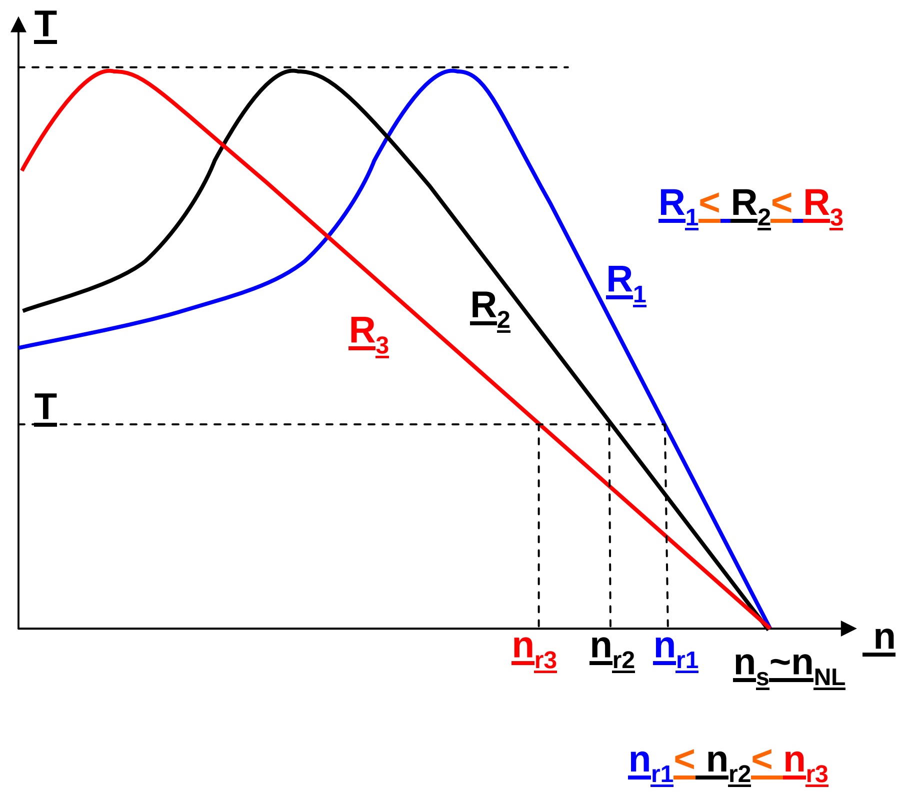
$$T_{st} = \frac{3\,V^2\,R'_2}{\omega_s\left[\left(R_1 + R'_2\right)^2 + X_{eq}^2\right]}$$

Torque/Speed Curve for varying R_2

$$T_{max} \approx \frac{3}{2\omega_S} \frac{V_{th}^2}{(X_{th} + X_2^{'})}$$

$$S_{T\max} \approx \frac{R_2^{'}}{(X_{th} + X_2^{'})}$$

- The maximum torque is independent of the rotor resistance. However, the value of the rotor resistance determines the slip at which the maximum torque will occur. The torque-slip characteristics for various values of are shown.
- To get maximum torque at starting::



$$S_{T\max} = 1 \qquad i.e. \; R_2' = (X_{th} + X_2')$$

Starting by Adding Rotor Resistance

- Starting current is reduced (good)
- Starting torque is increased (good)
- Maximum torque is unchanged (Motor acceleration is high)
- Speed at maximum torque is reduced

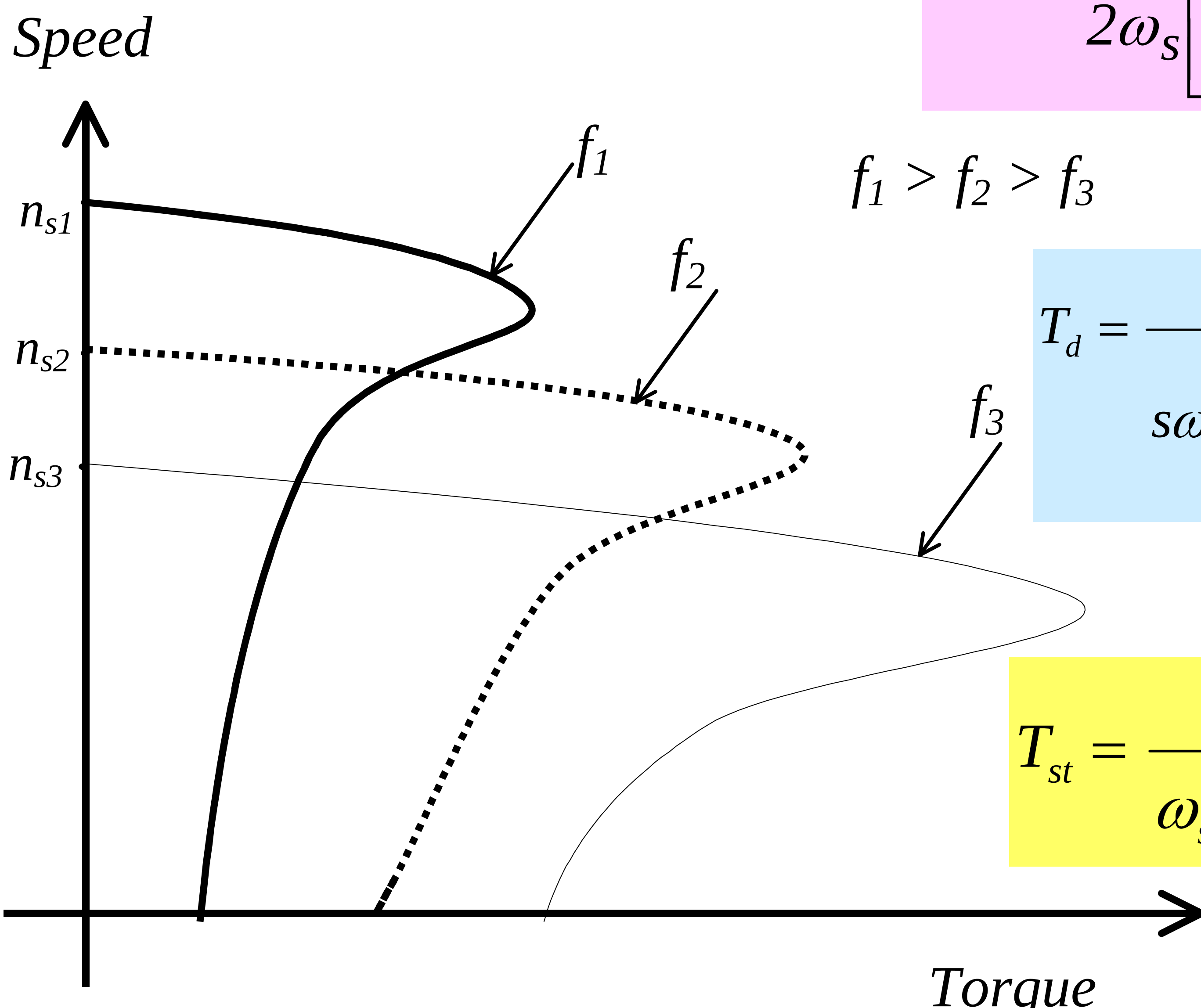
Speed Control of IM by Changing Frequency

$$n_s = 120\frac{f}{p}$$

Changing $n_s = \frac{120 f}{p}$

- Change f → Continuous variation
- Change p → Step variation

Speed Control of IM by Changing Frequency



$$T_{max} = \frac{3\,V^2}{2\omega_s\left[R_1 + \sqrt{R_1^2 + X_{eq}^2}\right]}$$

$$T_d = \frac{3\,V^2\,R_2'}{s\omega_s\left[\left(R_1 + \frac{R_2'}{s}\right)^2 + X_{eq}^2\right]}$$

$$T_{st} = \frac{3\,V^2\,R_2'}{\omega_s\left[\left(R_1 + R_2'\right)^2 + X_{eq}^2\right]}$$

Classes of squirrel-cage motors

- According to the National Electrical Manufacturing Association (NEMA) criteria, squirrel-cage motors are classified into class A, B, C or D. The torque-speed curves and the design characteristics for these classes are :

Class	Starting Current	Starting Torque	Rated Load Slip
A	Normal	Normal	< 5%
B	Low	Normal	< 5%
C	Low	High	< 5%
D	Low	Very High	8-13 %