DT021/3 , Electrical Machines

Three-phase Induction Machines : Torque and speed control

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Frequency of Rotor E.M.F. and Current

The frequency of the e.m.f. induced in the rotor of the induction motor, and hence the current, is dependent upon the rate at which the rotor conductors are cut by the rotating magnetic flux.

$\Downarrow$

Slip dependent

Therefore the rotor frequency can be given by:

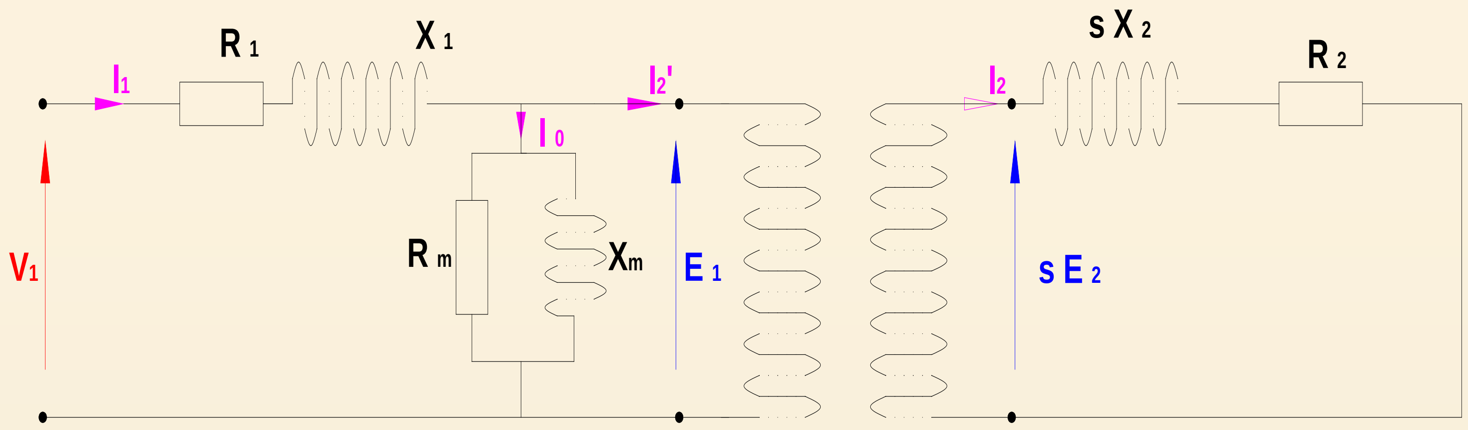
$$f_r = s.f_s$$

Rotor frequency is significant because as it varies, the rotor reactance ($X_r = 2\pi f_r L_r$) also varies, thus affecting both starting and running characteristics of the motor, as will be explained in following sections

The per-phase equivalent circuit of an induction motor

✓The induction motor may be considered as a transformer with the turns ratio dependent on the slip

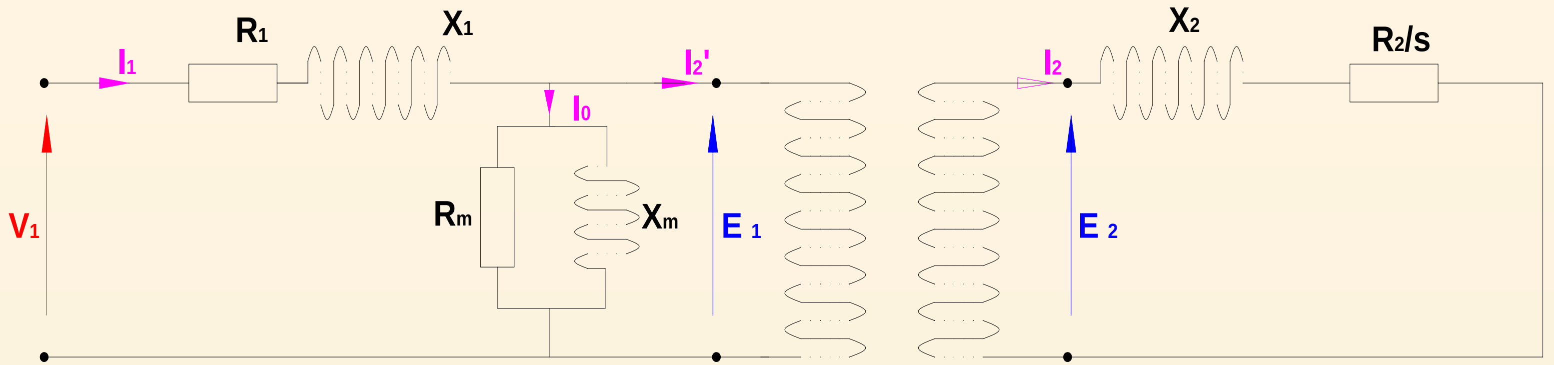
✓The motor has balanced three-phase circuits; consequently, the single-phase representation is sufficient



R_1 = Stator resistance
X_1 = Stator reactance
I_1 = Stator Phase Current
I_o = Stator no-load current
I_2^1 = Referred rotor current
I_2 = Actual rotor current

E_1 = Stator induced voltage
E_2 = Rotor induced voltage at standstill
X_2 = Rotor reactance at standstill
R_2 = Rotor resistance
s = Fractional slip = $s = \frac{N_s - N_r}{N_s}$

Note: Since the reactance is a function of frequency, the leakage reactance is proportional to the slip.

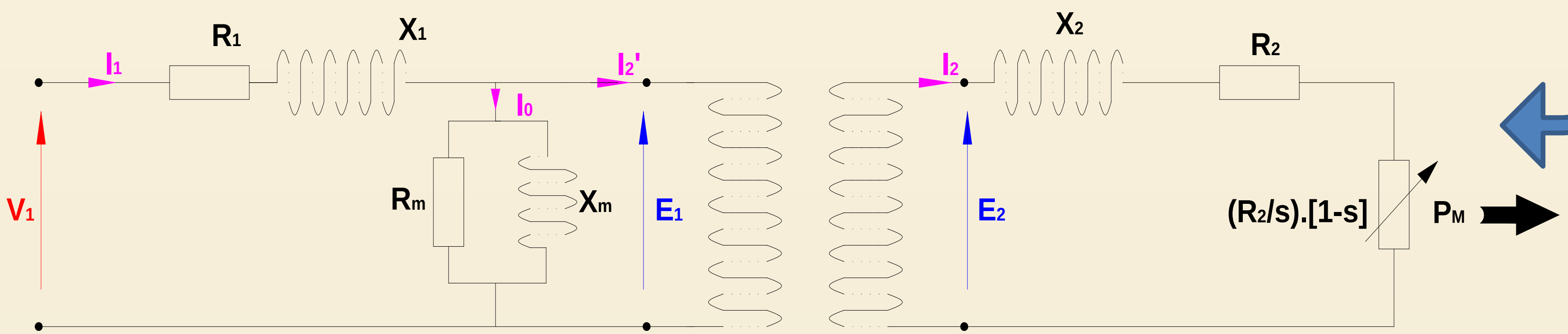


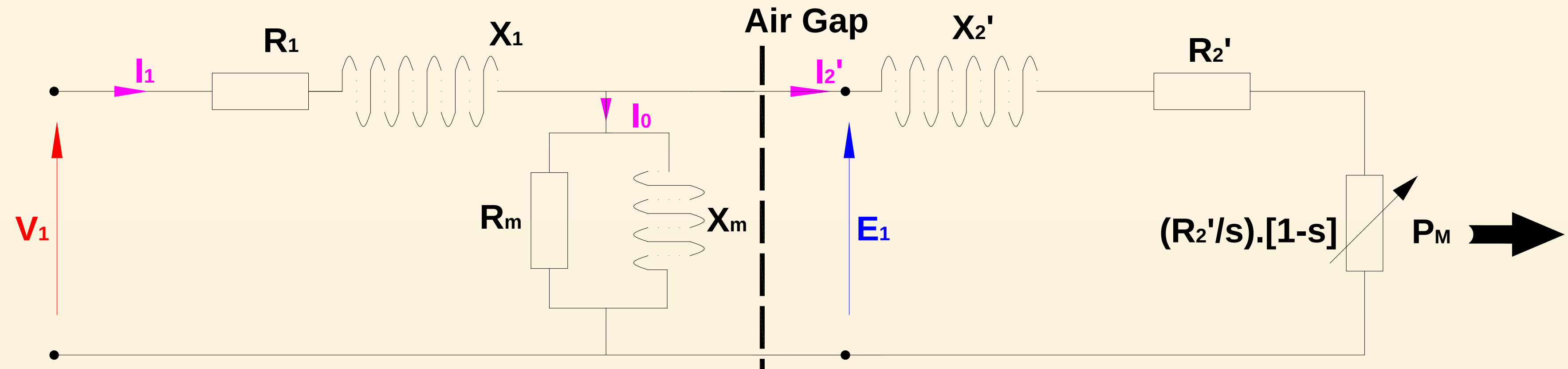
$$I_2 = \frac{sE_2}{R_2 + jsX_2} \qquad I_2 = \frac{E_2}{\frac{R_2}{s} + jX_2}$$

$$\frac{R_2}{s} = \frac{R_2}{s} - R_2 + R_2$$

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

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



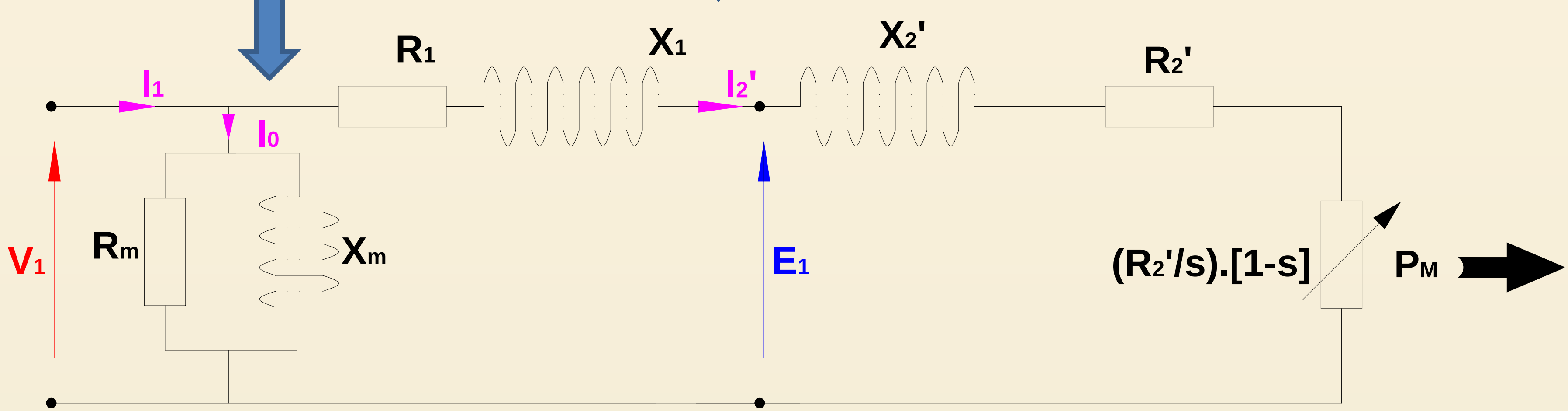


$$P_E = V_1 I_1 \cos\theta_1$$

$$P_G = \left(I_2{}'\right)^2 \cdot \frac{R_2{}'}{s}$$

$$P_M = \left(I_2{}'\right)^2 \cdot \frac{R_2{}'}{s}\left(1 - s\right)$$

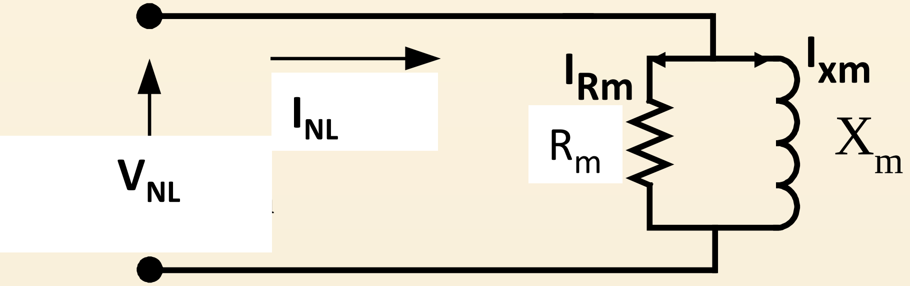
Valid for higher rated machine, more than 2hp



The equivalent circuit parameters for an induction motor can be determined using specific tests on the motor, just as was done for the transformer.

No-Load Test – comparable to the Open-circuit Test

Balanced voltages are applied to the stator terminals at the rated frequency with the rotor uncoupled from any mechanical load. Current, voltage and power are measured at the motor input. The losses in the no-load test are those due to core losses, winding losses, windage and friction. The equivalent circuit shown in the figure:



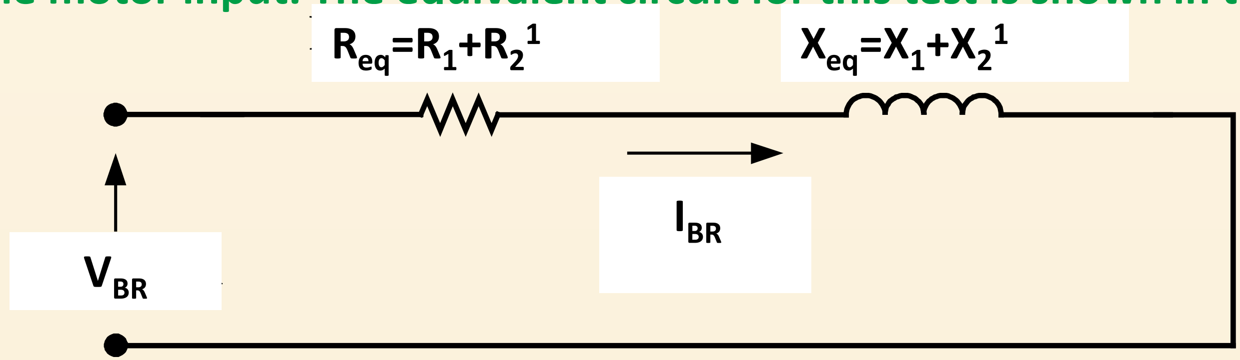
R_m represents the total no-load loss component
X_m represents magnetising component

Since the equivalent circuit is given per phase, per phase quantities should be considered in all equations

$$I_{Rm} = \frac{P_{NL}}{V_{NL}} \qquad R_m = \frac{V_{NL}}{I_{Rm}} \qquad I_{Xm} = \sqrt{I_{NL}^2 - I_{Rm}^2} \qquad X_m = \frac{V_{NL}}{I_{Xm}}$$

Blocked rotor test-comparable to short circuit test

The rotor is blocked to prevent rotation and balanced voltages are applied to the stator terminals where the rated current is achieved. Current, voltage and power are measured at the motor input. The equivalent circuit for this test is shown in the figure:



Since the equivalent circuit is given per phase, per phase quantities should be considered in all equations

$$P_{BR}=I_{BR}^2 * R_{eq} \qquad R_{eq}=\frac{P_{BR}}{I_{BR}^2} \qquad \left|Z_{eq}\right|=\frac{V_{BR}}{I_{BR}} \qquad X_{eq}=\sqrt{Z_{eq}^2-R_{eq}^2}$$

$$X_{eq}=X_1+X_2^1 \qquad R_{eq}=R_1+R_2^1$$

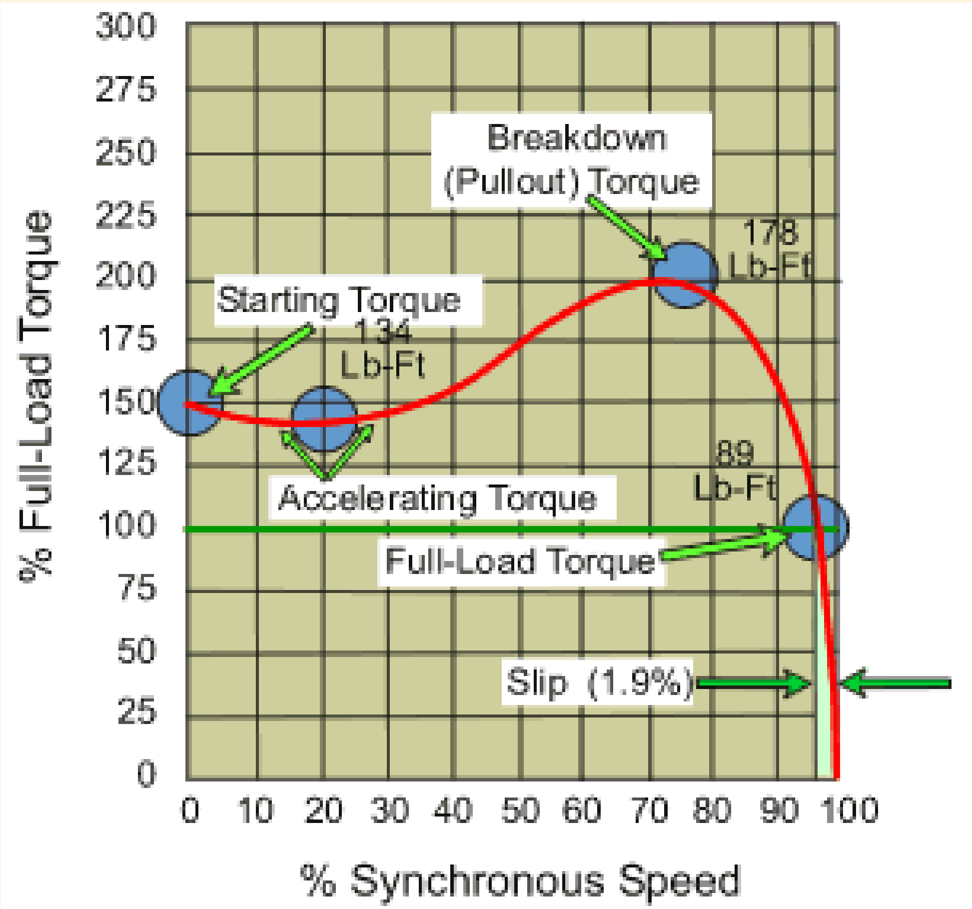
Measure stator resistance R_1 directly

$$R_2^1=R_{eq}-R_1 \qquad \frac{X_{eq}}{2}=X_1=X_2^1$$

Torque speed characteristics

- Torque is produced in an induction motor by the interaction of the stator and rotor fluxes
- Slip ensures that flux from the stator crosses the rotor conductors and a torque is produced.
- At no load, the rotor lags behind the stator flux only a small amount, since the only torque required is that needed to overcome the motor losses.
- As mechanical load is added, the rotor speed decreases. A decrease in rotor speed allows the constant-speed rotating field to sweep across the rotor conductors at a faster rate, thereby inducing larger rotor currents.
  - This results is a larger torque output at a reduced speed.
- The torque of an induction motor is due to the interaction of the rotor and stator fields and is dependent on the strength of those fields and the phase relations between them.

Typical Torque-Speed (T/N) curve



Note: the torque would be zero should the motor be rotating at synchronous speed

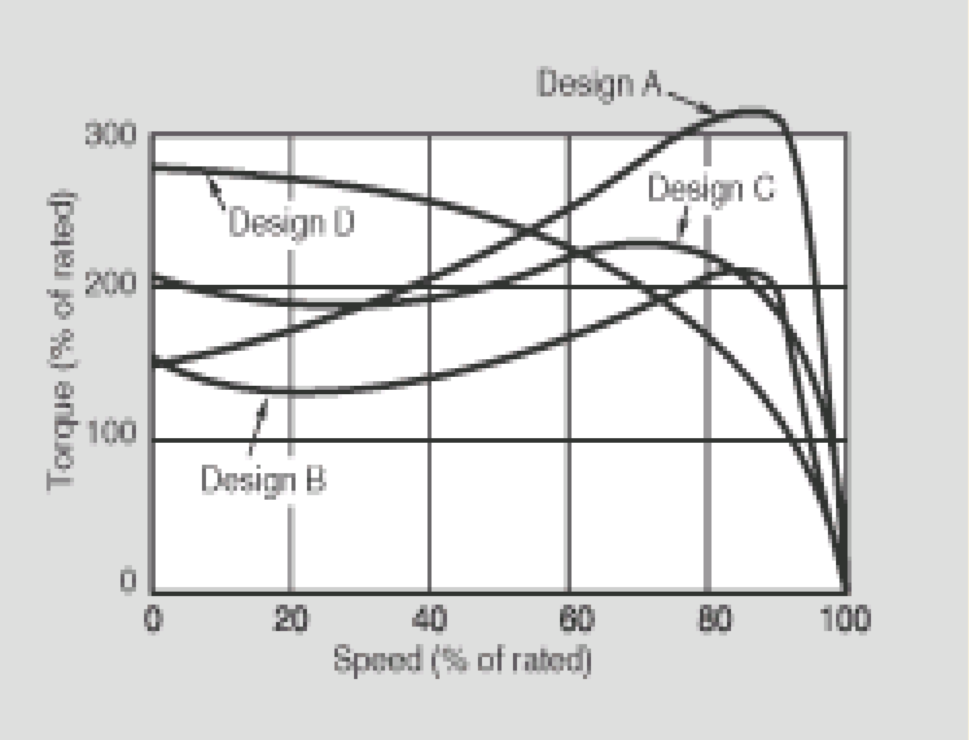
Locked rotor torque **(also known as the starting torque): is the minimum torque that the motor develops at rest for all angular positions of the rotor at rated voltage and frequency.**

Pull up torque **(also referred to as the Accelerating Torque): as the motor accelerates, the torque developed slightly decreases. Pull-up torque is the minimum torque developed by the motor in a starting process.**

Breakdown torque: **is the maximum torque that the motor develops at rated voltage and frequency, without an abrupt drop in speed.**

Full-load torque: **is the torque required to produce the rated power at the rated speed.**

NEMA (National Electrical Manufacturers Association) classifies three-phase induction motors according to locked rotor torque and current, breakdown torque, pull up torque, and percent slip.



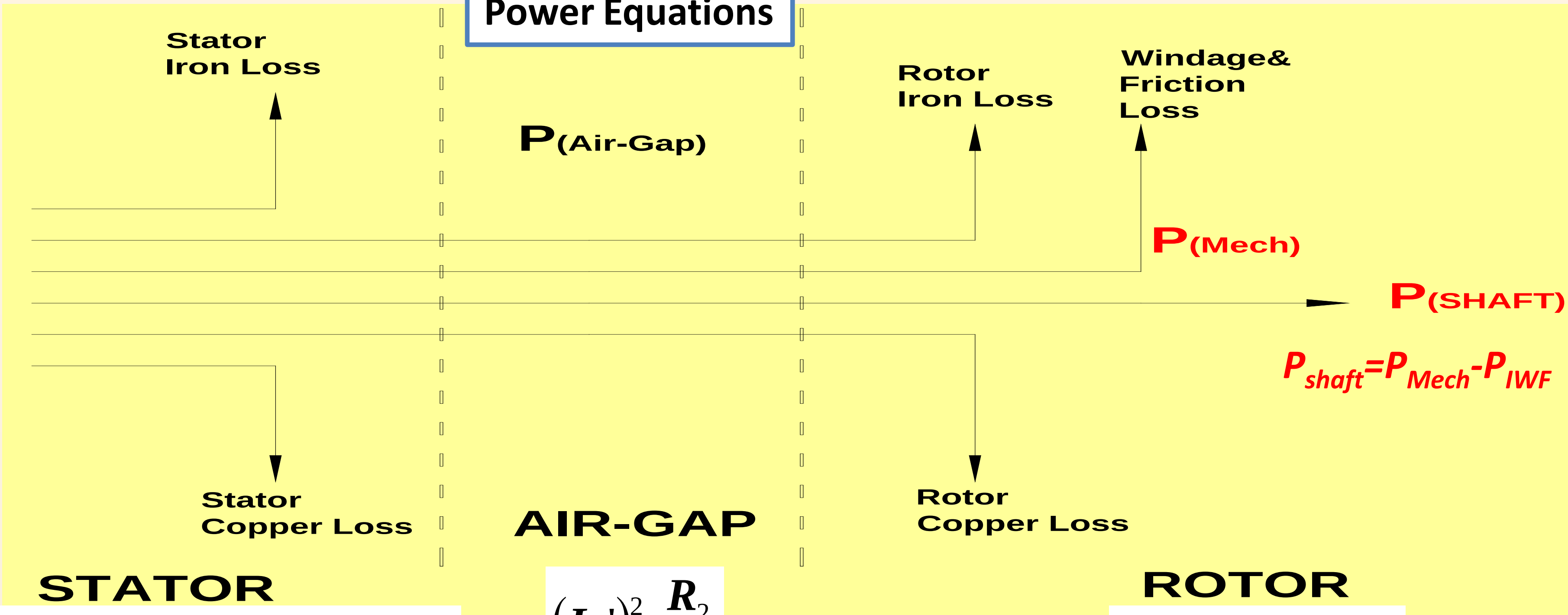
Class A: High breakdown torque, good operating characteristics at the expense of high starting current, common applications include fans, blowers, and pumps.

Class B: Accounts for most of the induction motors sold, referred to as general-purpose motors. Similar applications as class A, but low starting currents.

Class C: High starting torque, typical applications of these motors include motor conveyors, reciprocating pumps and compressors.

Class D: very high starting torque, inefficient for continuous load operation, applied for intermittent load such as a punch press

Power Equations

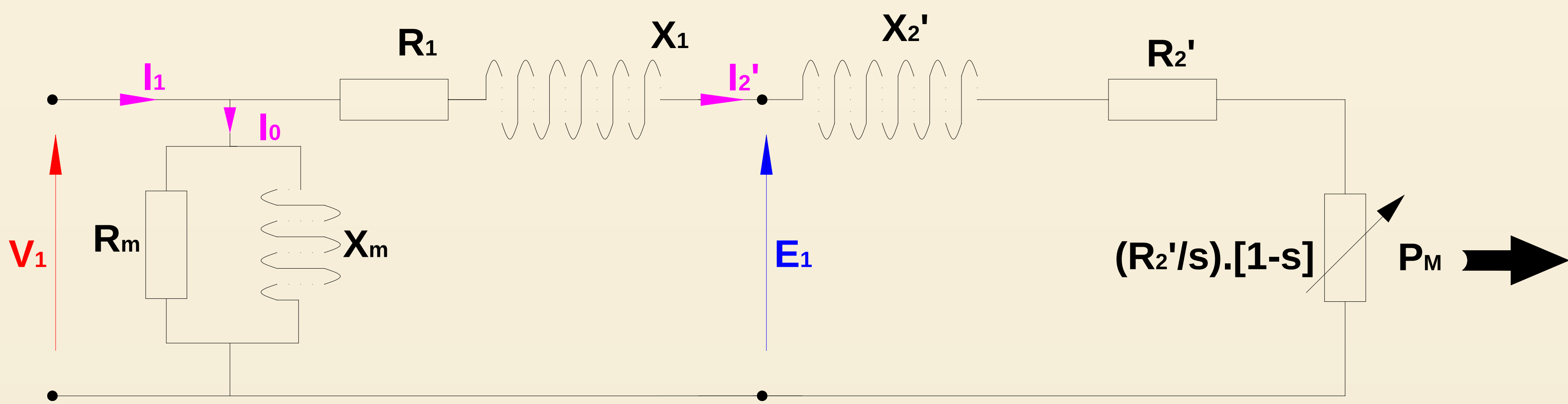


$P_{shaft}=P_{Mech}-P_{IWF}$

$$P_{IN\,/\,Phase} = V_{Ph} * I_{Ph} * \cos\theta$$

$$(I_2')^2 . \frac{R_2}{s}$$

$$(1-s)(I_2')^2 \frac{R_2'}{s}$$



$$P_{E/Phase} = V_{Ph} * I_{Ph} * \cos\theta \qquad P_g = (I_2')^2 . \frac{R_2}{s} \qquad P_M = (1-s)(I_2')^2 \frac{R_2'}{s} = (1-s) * P_g$$

P_{shaft}=P_{Mech}-P_{IWF} *where* P_{IWF} *is iron windage and friction loss*

In general Torque developed for a machine can be expressed in terms of power developed and speed

$$T_{Developed} = \frac{P_{Developed}}{\omega_{Rotor}}$$

Therefore

$$P_{Developed} = \omega_{Rotor} . T$$

In this equation, torque is in N.m (Newton meter) when power is in watts and ω is in radians per second. Therefore 3 phase torque is given by:

$$T_m = 3\frac{P_m}{\omega_r}$$

$$T_e = 3\frac{P_g}{\omega_s}$$

T_m=Mechanical torque
T_e=Electromechanical torque

Speed control of Induction Machines

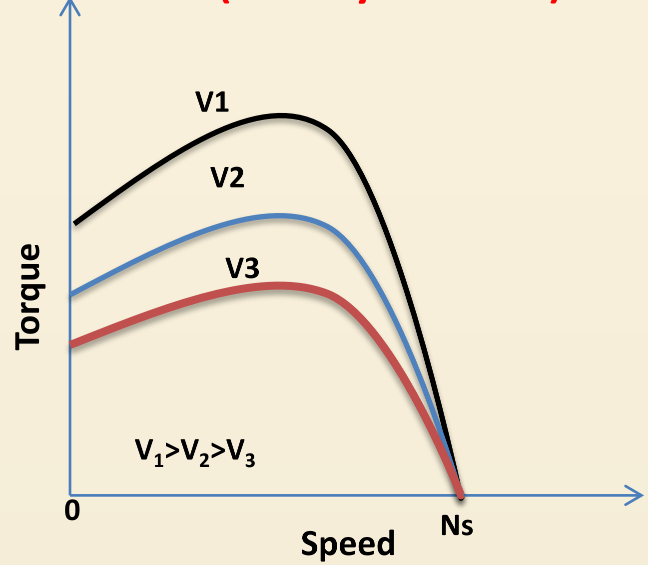
- For an induction machine in the entire loading range , the speed change is quite small.
- The machine speed is quite stiff with respect to load changes. When operating from mains is essentially a constant speed machine.
- Because of its ruggedness and a simple construction, it is a good candidate for variable speed applications if it can be achieved.

One of the following techniques can be followed to achieve speed control of an Induction machine:

- Speed control by changing applied voltage
- Rotor resistance control
- Pole changing schemes
- Stator frequency control

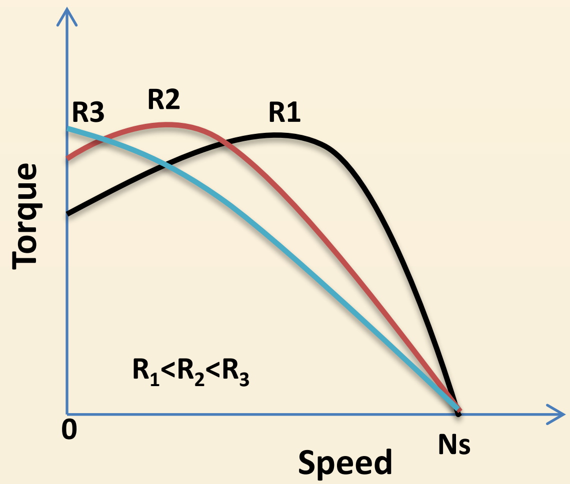
Speed control by changing the applied voltage

- The torque depends on the square of the applied voltage
- The slip at maximum torque remains same, while the value of stall torque comes down with decrease in applied voltage.
- The speed range for stable operation remains the same.
- The starting torque is also lower at lower voltages.
- This method of trying to control the speed is best suited for loads that require very little starting torque, but their torque requirement may increase with speed.
- Voltage control may be achieved by adding series resistors (a lossy, inefficient proposition), or a series inductor / autotransformer (a bulky solution) or a more modern solution using semiconductor devices.



Rotor resistance control

- The slip at maximum torque is dependent on the rotor resistance.
- the slip at which maximum torque occurs increases with increase in rotor resistance, and so does the starting torque.
- Rotor resistance control could be used as a means of generating high starting torque.
- The speed control range is more with this method.



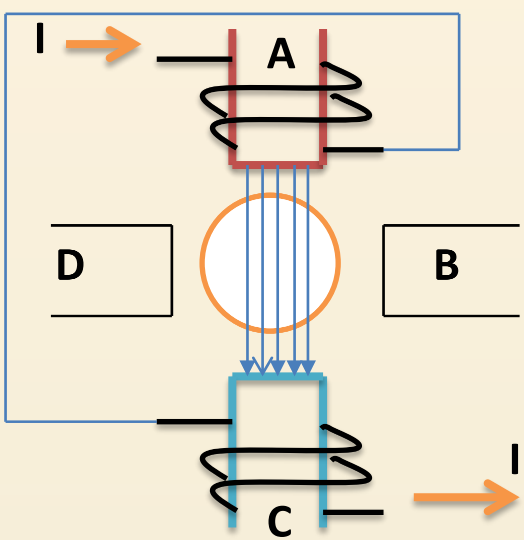
- This method of speed control can be achieved only with a slip-ring machine.
- The method is not very efficient since the additional resistance and operation at high slips entails dissipation.

A 'solid-state' alternative to a variable resistor is a chopper controlled resistance where the duty ratio control of the chopper presents a variable resistance load to the rotor of the induction machine.

Pole changing scheme

- The Synchronous speed of the induction machine is inversely proportional to the number of poles.
- If number of poles are varied, synchronous speed and hence the rotor speed can be changed.
- induction machines can be built to have a special stator winding capable of being externally connected to form two different number of pole numbers.
- This method of speed control is a stepped variation and generally restricted to two steps

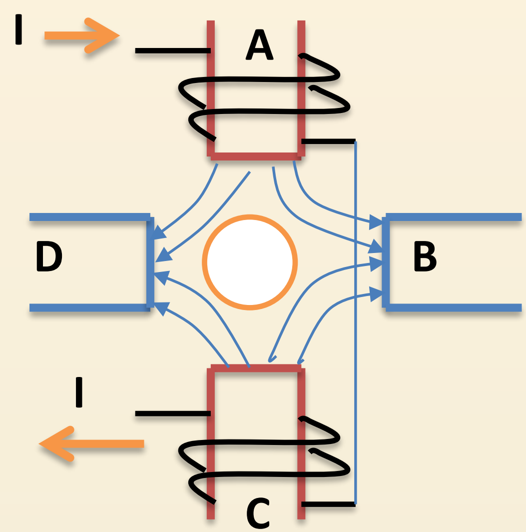
$$N_s = \frac{120 * f}{P}$$



Two pole connection

2*Ns, 2*Nr

Ns, Nr



Four pole connection

by changing the terminal connections we get either a two pole air-gap field or a four-pole field

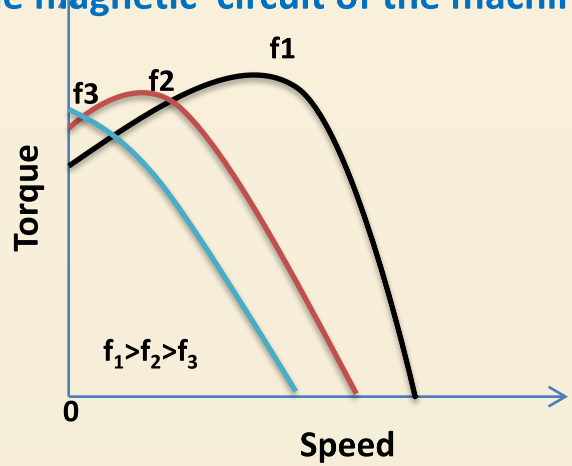
Stator frequency control

- **Synchronous speed and hence the rotor speed is directly proportional to the supply frequency.**
- **Supply frequency of the machine can be controlled by a power electronics device such as voltage source converters, current source converters or cycloconverters.**
- **The voltage and the frequency applied to the machine should be adjusted simultaneously. The V/f ratio should be held constant in order to avoid magnetic saturation .**

Reason:

Induced e.m.f in the stator is given by $E_{Stator} = 4.44N\phi_m f$

If the frequency is reduced keeping the supply voltage constant, the maximum flux developed increases proportionally to keep the induced e.m.f. inline with the supply voltage. Therefore the magnetic circuit of the machine will experience saturation.



- **At low frequencies and hence low voltages the curves show a reduction in peak torque.**
- **With this kind of control, it is possible to get a good starting torque and steady state performance.**