Lecture-34

On

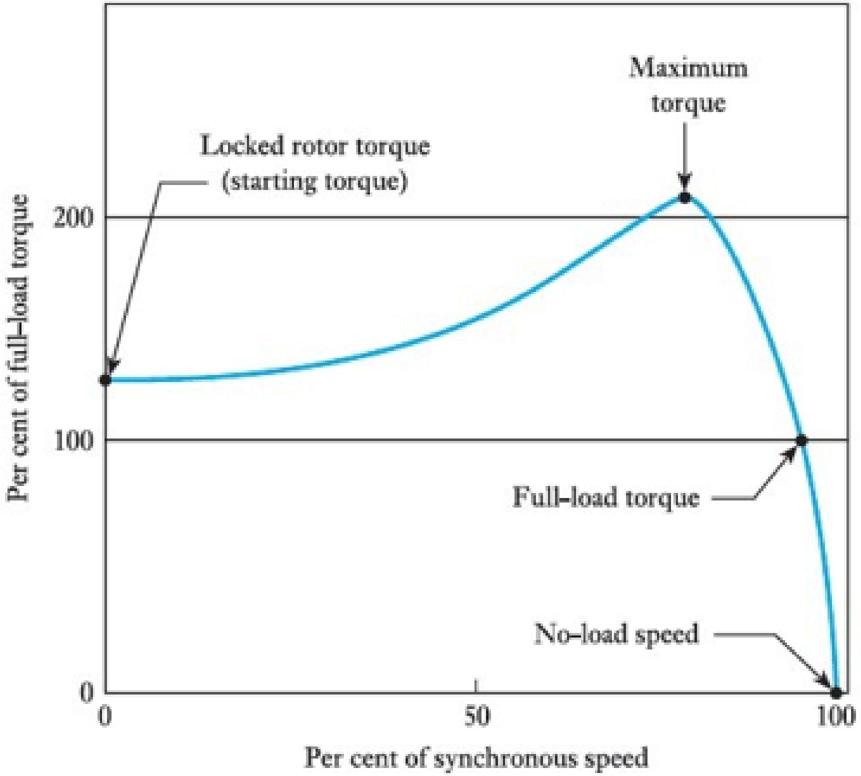
INTRODUCTION TO ELECTRICAL ENGINEERING (ESO203)

- Induction Machine.

Torque-Slip Characteristics

❑ When a motor is started with full voltage applied:

- The motor is initially stationary and develops locked-rotor torque.
- Some motors produce a slight dip in torque as these accelerate, the lowest point being called the pull-in or pull-up torque.
- As the speed increases further, the torque reaches the highest point on the curve called the pull-out or breakdown torque.
- When the motor is loaded to its full-load torque, the motor speed stabilizes.
- If the motor is not driving anything, the speed increases to the no-load or synchronous speed.



$$T = \frac{90}{\pi n_s} \times \frac{R_2'}{s} \times \frac{|V_1|^2}{\left(R_1 + \frac{R_2'}{s}\right)^2 + (X_1 + X_2')^2}$$

Torque-Slip Characteristics (Cont...)

- Induced torque is zero at synchronous speed.
- The graph is nearly linear between no load and full load (at near synchronous speeds).
- Max torque is known as pull out torque or breakdown torque, and is around 2-3 times the full-load torque.
- Starting torque is large.
- Torque for a given slip value would change to the square of the applied voltage.

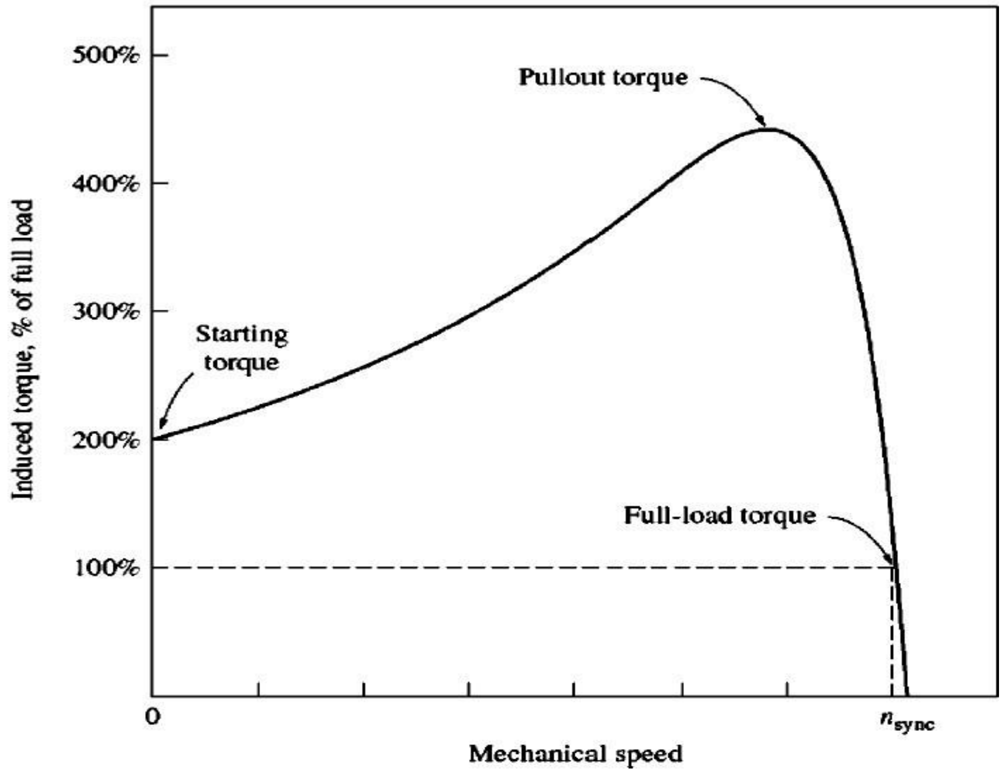


Fig: Torque-speed characteristics of a typical induction motor

$$T = \frac{90}{\pi n_s} \times \frac{R_2'}{s} \times \frac{|V_1|^2}{\left(R_1 + \frac{R_2'}{s}\right)^2 + (X_1 + X_2')^2}$$

Torque-Slip Characteristics (Cont...)

- If the rotor were driven faster than synchronous speed, the motor would then become a generator.

- If we reverse the direction of the stator magnetic field, it would produce braking action on the rotor.

- Two of the phases can be switched to create a magnetic field rotating opposite to the rotor. This is called plugging.

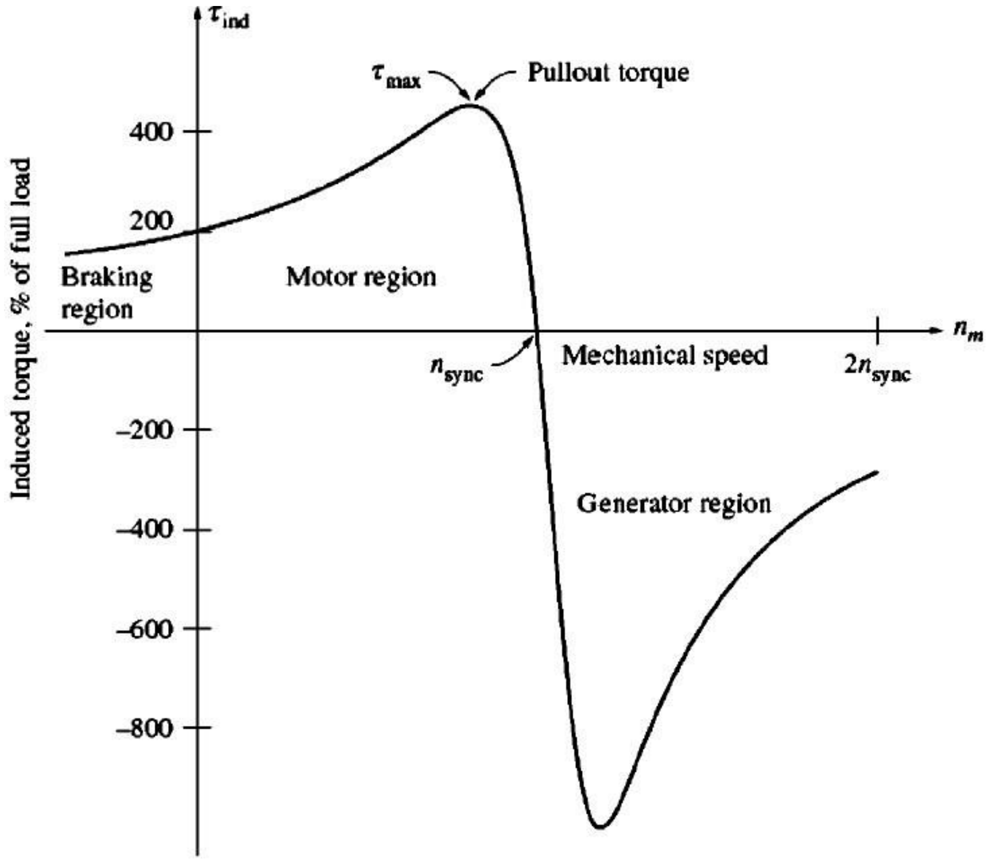


Fig: Torque-speed characteristics including braking and generator region.

Torque-Slip Characteristics (Cont...)

- Assume that the impedance of stator is assumed to be small for a given supply voltage & the value of X_2' is typically large compared with the rotor resistance.

$$T = \frac{90}{\pi n_s} \times \frac{R_2'}{s} \times \frac{|V_1|^2}{\left(R_1 + \frac{R_2'}{s}\right)^2 + (X_1 + X_2')^2}$$

$$\boldsymbol{T} = \frac{R_2'}{s} \times \frac{K}{\left(\frac{R_2'}{s}\right)^2 + (X_2')^2}$$

$$= K \times \frac{sR_2'}{(R_2')^2 + (sX_2')^2}$$

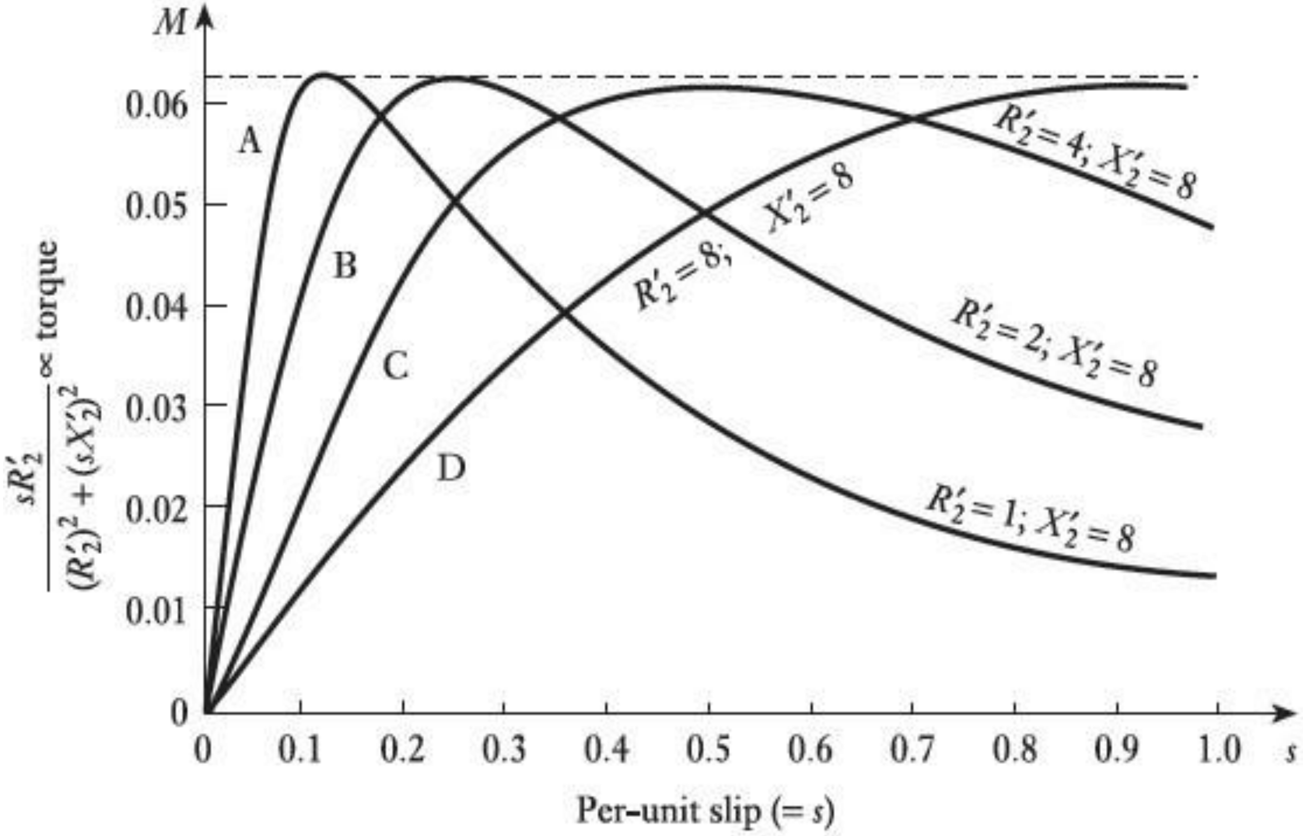
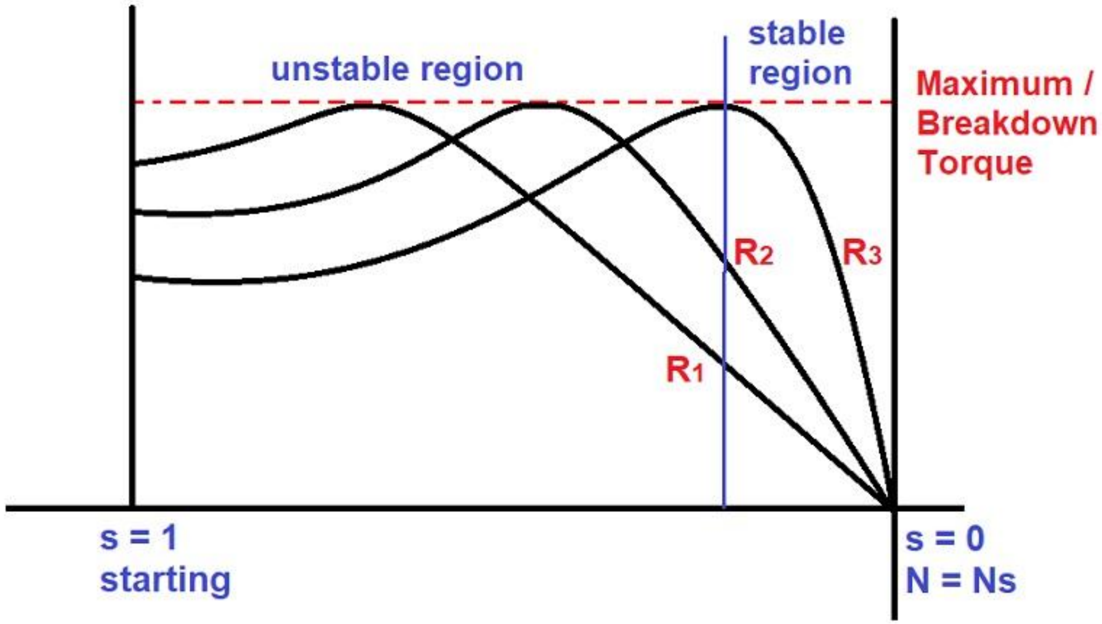


Fig: when slip is zero, speed reaches synchronous speed

Torque-Slip Characteristics (Cont...)



Effect of adding Rotor Resistance

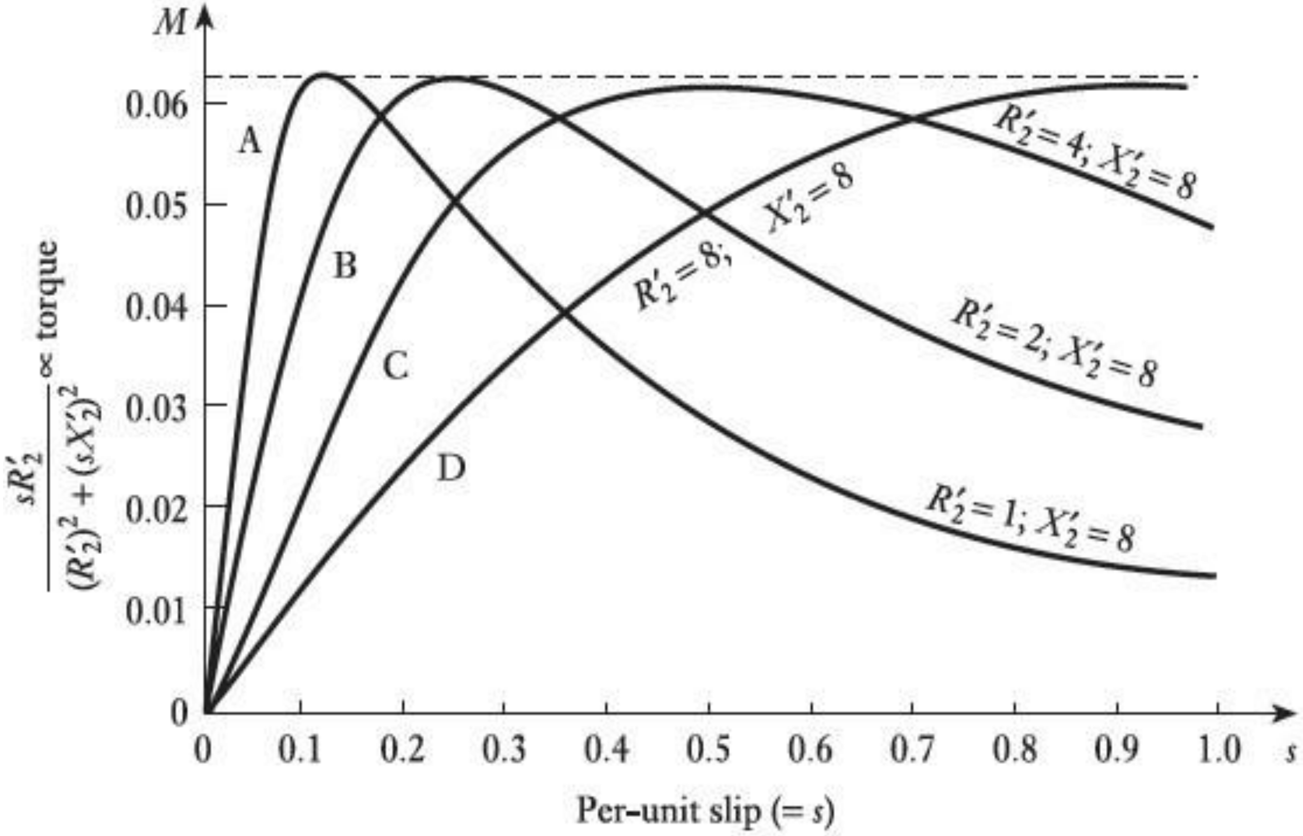


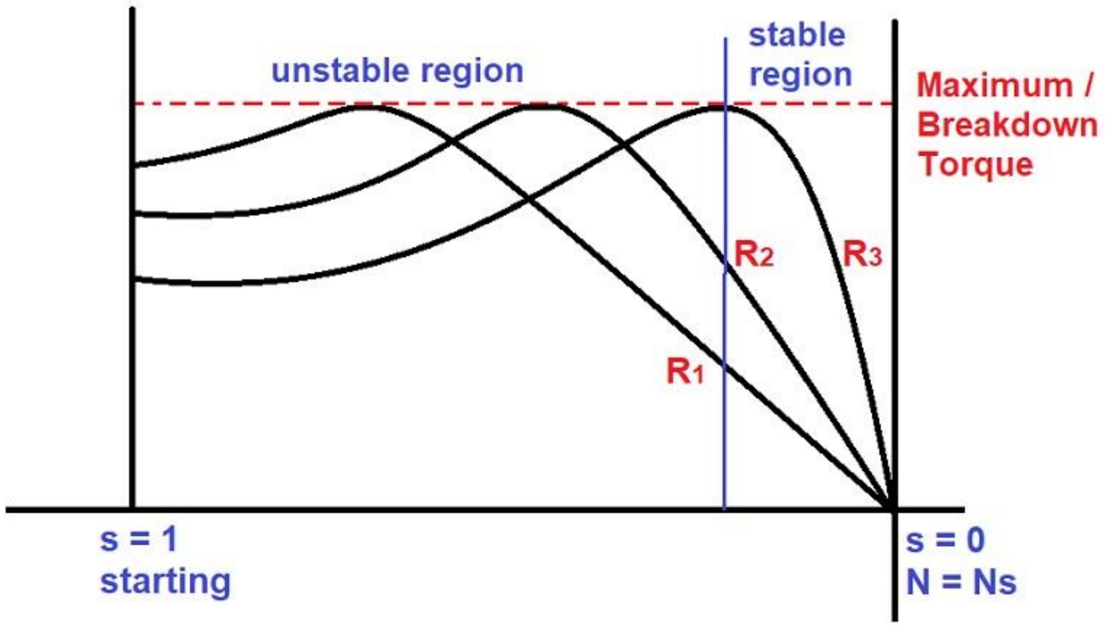
Fig: when slip is zero, speed reaches synchronous speed

Torque-Slip Characteristics (Cont...)

1. Increasing the rotor resistance moves the maximum value of torque towards higher slip values, that is, in the direction of lower speed. Thus, a higher rotor resistance gives a higher starting torque.

2. A higher rotor resistance gives a lower on-load efficiency but a higher starting torque. A lower rotor resistance gives less starting torque but higher on-load efficiency.

3. The maximum Torque is constant.



Effect of adding Rotor Resistance

Torque-Slip Characteristics (Cont...)

$$\boldsymbol{T} = \frac{R_2'}{s} \times \frac{K}{\left(\frac{R_2'}{s}\right)^2 + (X_2')^2} = K \times \frac{sR_2'}{(R_2')^2 + (sX_2')^2}$$

$$\frac{d}{ds}\left[\frac{sR_2'}{(R_2')^2 + (sX_2)^2}\right] = \frac{[(R_2')^2 + (sX_2)^2]R_2' - sR_2'2s(X_2')^2}{[(R_2')^2 + (sX_2')^2]^2} = 0$$

$$\Rightarrow (R_2')^2 + (sX_2)^2 = 2s^2(X_2')^2$$

$$\boldsymbol{T}_{max} = \frac{K}{2X_2'}$$

Note: Hence the maximum (pull out) torque is the same, whatever the value of rotor resistance.

❑ Effect of changing Rotor Circuit Resistance in Wound Rotor

- Recall that it is possible to insert resistance into the rotor circuit of wound- rotor induction motor.

- The slip at which maximum torque occurs is directly proportional to the rotor resistance.

- Value of the maximum torque is independent of the rotor resistance.

- By inserting resistance, maximum torque can be obtained at the starting. This is useful to start heavy loads.

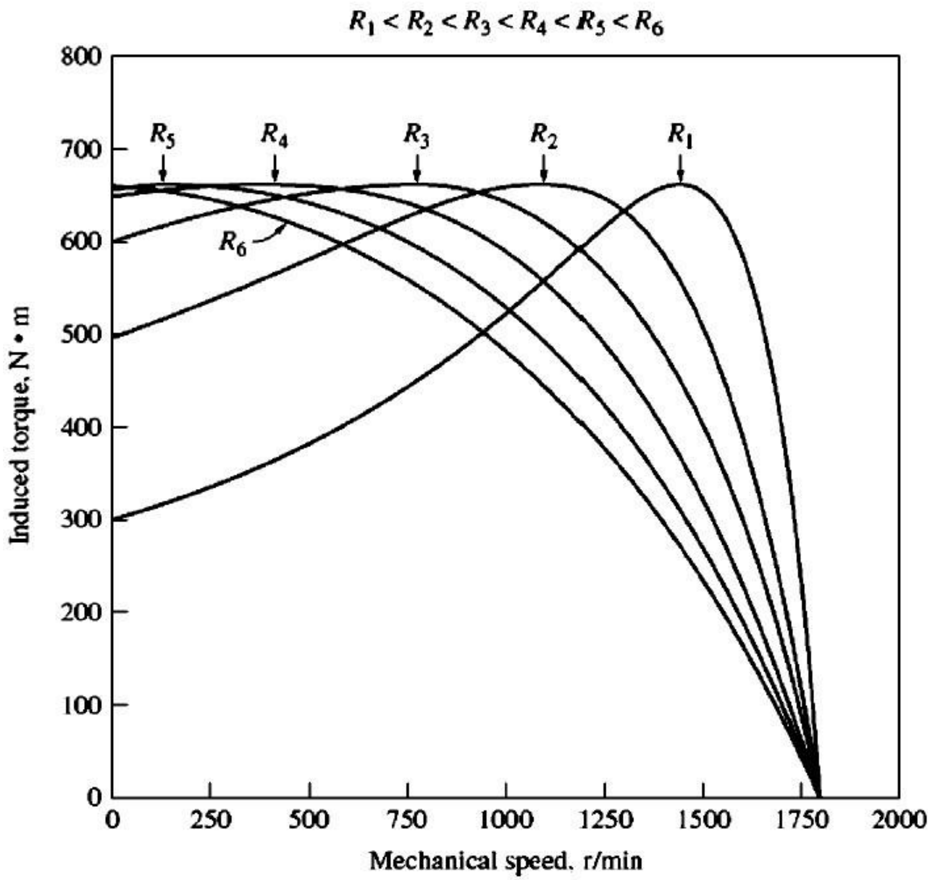


Fig: Induction-motor torque-slip curves showing effect of changing rotor-circuit resistance

Torque-Slip Characteristics (Cont...)

❑ Variations in Induction Motor Torque-Speed Characteristics

HIGH resistance rotor

↓

Starting torque HIGH Slip HIGH at normal conditions

↓

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

S increase, P_{AG} decrease, and **efficiency decrease.**

LOW resistance rotor

↓

Starting torque LOW, HIGH starting current, Slip LOW at normal conditions

↓

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

S decrease, P_{AG} increase, and **efficiency increase.**

↓

Use a wound rotor induction motor and insert extra resistance into the rotor during starting, and then removed for better efficiency during normal operations.

↓

But, wound rotor induction motors are more expensive, need more maintenance etc.

↓

Solution - utilising leakage reactance – to obtain the desired curve as shown next

❑ Desired Torque-Speed Characteristics

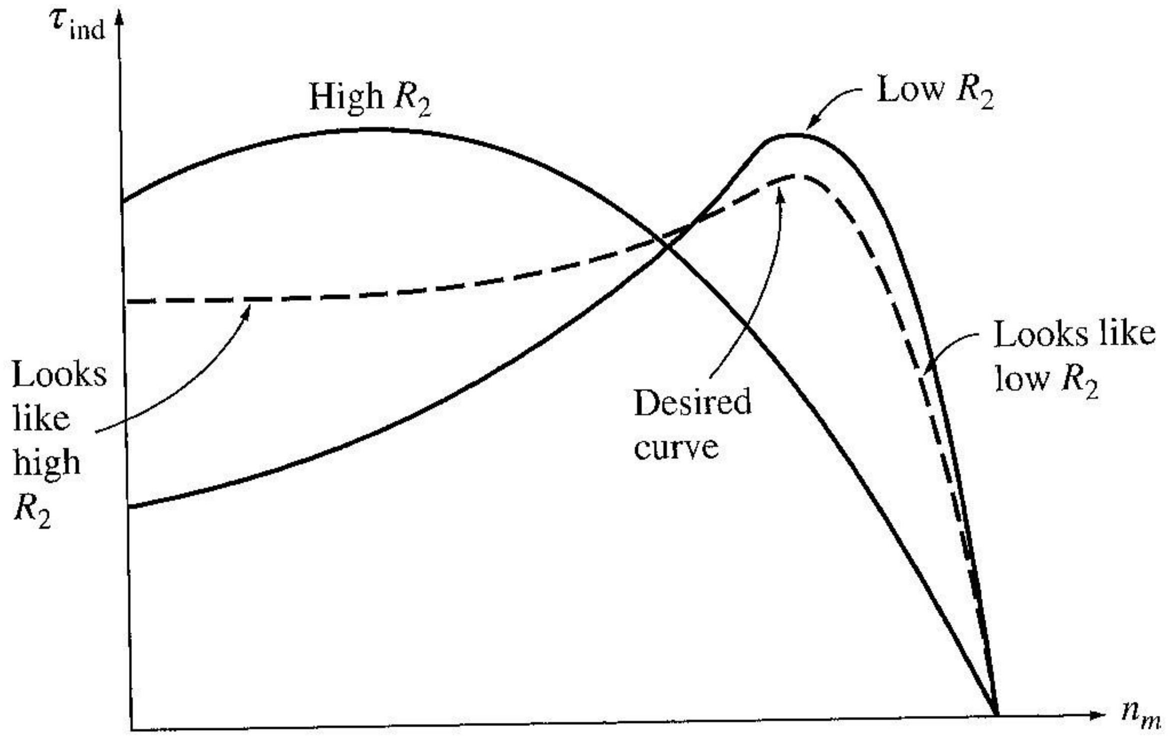


Fig: A torque-speed characteristic curve combining high-resistance effects at low speeds (high slip) with low resistance effects at high speed (low slip).

❑ Control of Motor Characteristics by Cage Rotor Design

- Leakage reactance X_2 represents the reactance due to the rotor's flux lines that do not couple with the stator windings.

- Generally, the farther away the rotor bar is from the stator, the greater its X_2, since a smaller percentage of the bar's flux will reach the stator.

- Thus, if the bars of a cage rotor are placed near the surface of the rotor, they will have small leakage flux and X_2 will be small.

- The above facts are used to carefully design the rotor slots such that the rotor resistance is high at starting, and low at normal load.

Quiz-3

Date:	**11th April 2025**
Time:	7:00 pm
Venue:	L18
Syllabus:	Till 10th April 2025

❑ Cage Rotor Designs

NEMA (National Electrical Manufacturers Association) Class A

- Rotor bars are quite large and are placed near the surface of the rotor.
- Low resistance (due to its large cross section) and a low leakage reactance X_2 (due to the bar's location near the stator).
- Motor will be quite efficient, since little air gap power is lost in the rotor resistance.
- However, since R_2 is small, starting torque will be small, and starting current will be high.
- This design is the standard motor design.
- Typical applications – driving fans, pumps, and other machine tools.

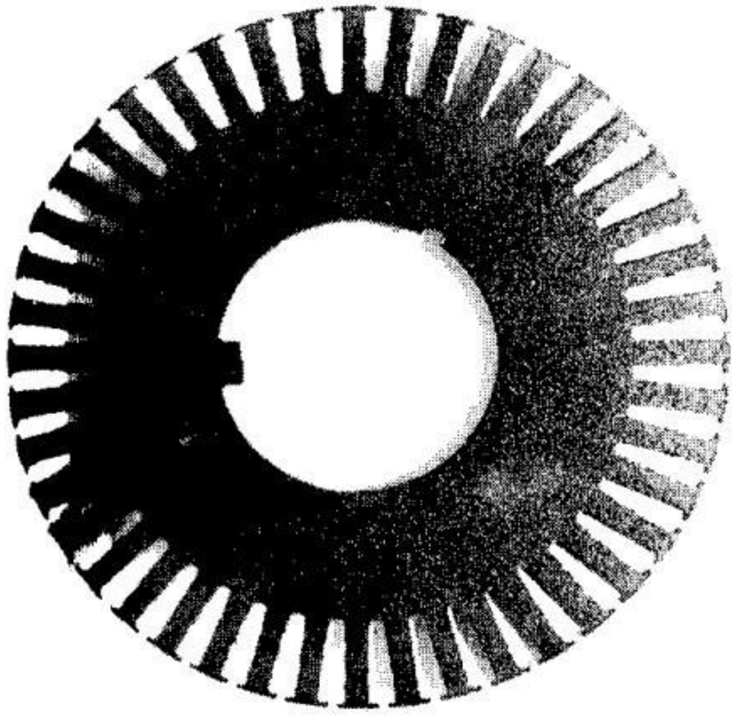


Fig: NEMA Class A rotor

❑ Cage Rotor Designs (Cont…)

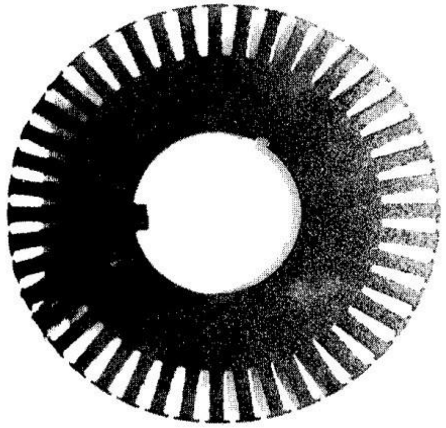


Fig: NEMA Class A rotor

Class D

- Rotor with small bars placed near the surface of the rotor (higher-resistance material).
- High resistance (due to its small cross section) and a low leakage reactance X_2 (due to the bar's location near the stator).
- Like a wound-rotor induction motor with extra resistance inserted into the rotor.
- Because of the large resistance, starting torque will be quite high, and low starting current.
- Typical applications – extremely high-inertia type loads.

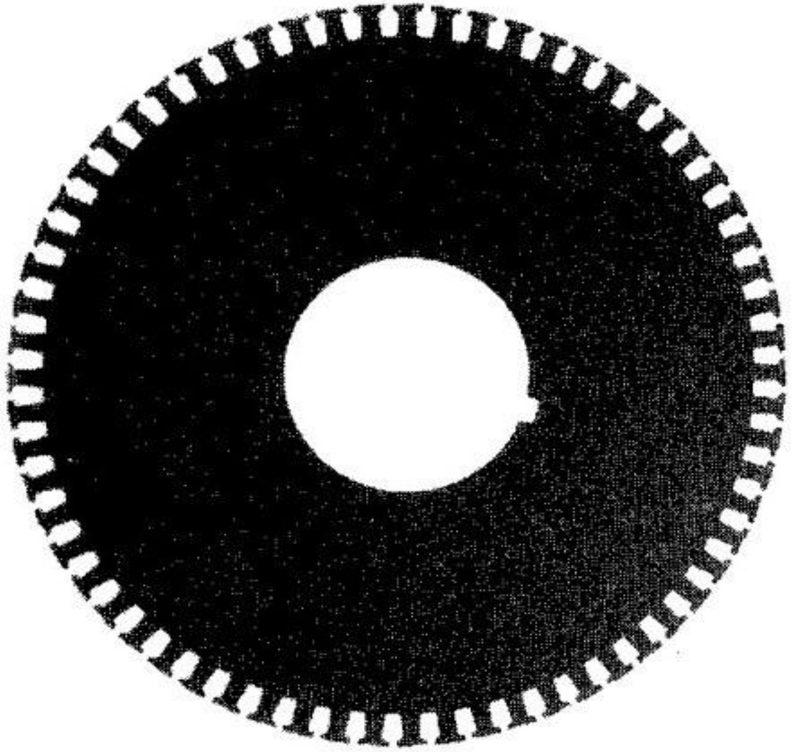


Fig: NEMA Class D rotor

❑ Cage Rotor Designs (Cont…)

Deep-Bar & Double-Cage rotor design

- For a current flowing in the top of the bar, the flux is tightly linked to the stator, and leakage L is small.

- At the bottom of the bar, the flux is loosely linked to the stator, and leakage L is large.

- Resulting equivalent circuit is with small bars placed near the surface of the rotor (higher-resistance material).

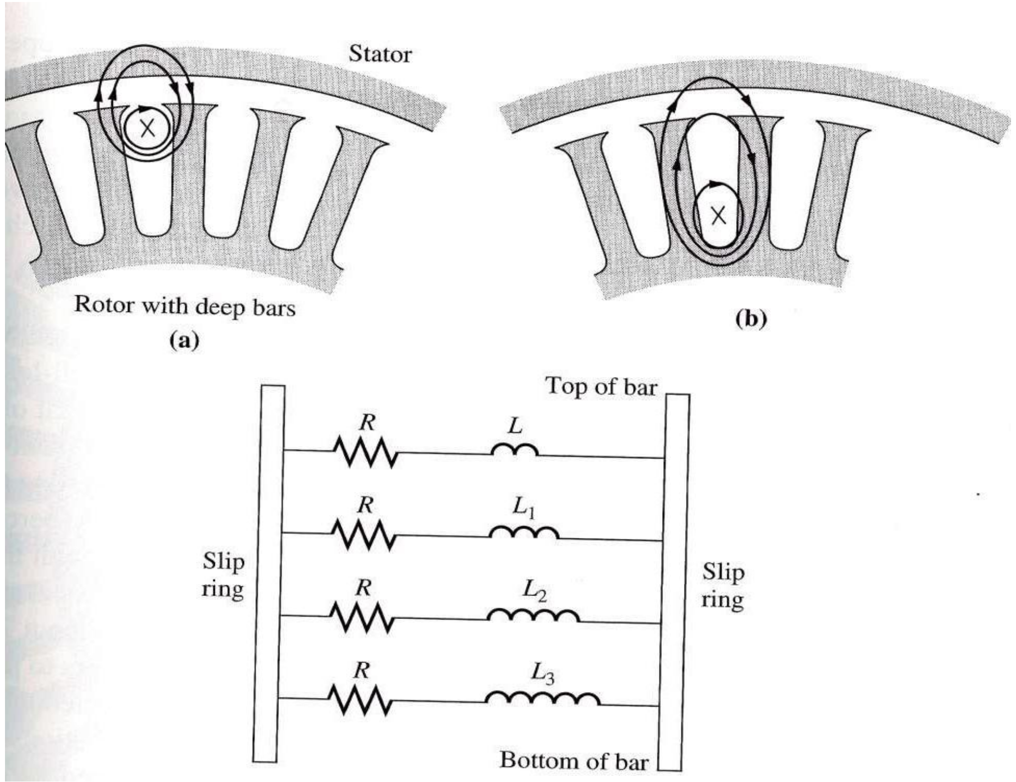


Fig: Flux linkage in deep-bar rotor and the equivalent circuit

❑ Cage Rotor Designs (Cont…)

Class B

- At low slips, the rotor's frequency is very small, and the reactances of all the parallel paths are small compared to their resistances. The impedances of all parts of the bar are approx. equal, so current flows through all the parts of the bar equally. The resulting large cross-sectional area makes the rotor resistance quite small, resulting in good efficiency at low slips.
- At high slips (starting conditions), the reactances are large compared to the resistances in the rotor bars, so all the current is forced to flow in the low-reactance part of the bar near the stator. Since the effective cross section is lower, the rotor resistance is higher.

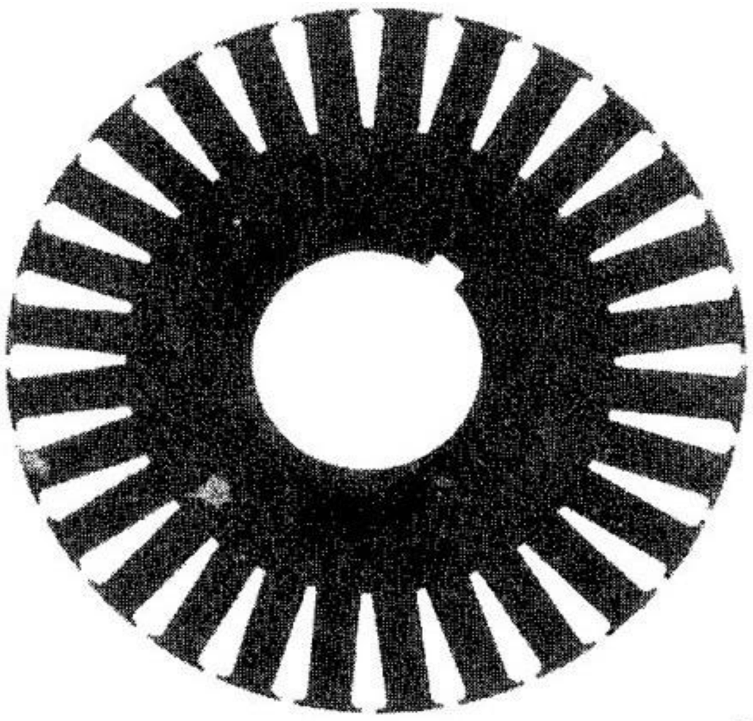


Fig: NEMA Class B rotor

❑ Cage Rotor Designs (Cont…)

Class C

- It consists of a large, low resistance set of bars buried deeply in the rotor and a small, high-resistance set of bars set at the rotor surface. It is similar to the deep- bar rotor, except that the difference between low-slip and high-slip operation.
- At starting conditions, only the small bars are effective, and the rotor resistance is high. Hence, high starting torque. However, at normal operating speeds, both bars are effective, and the resistance is almost as low as in a deep-bar rotor.
- Used in high starting torque loads such as loaded pumps, compressors, and conveyors.

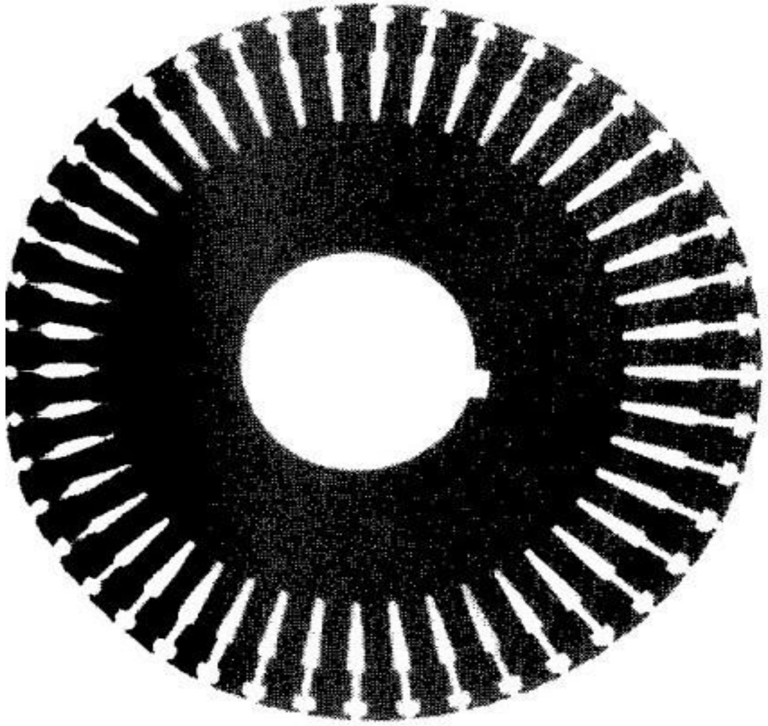


Fig: NEMA Class C rotor

Torque-Slip Characteristics (Cont...)

- Comparing NEMA- A,B,C,D

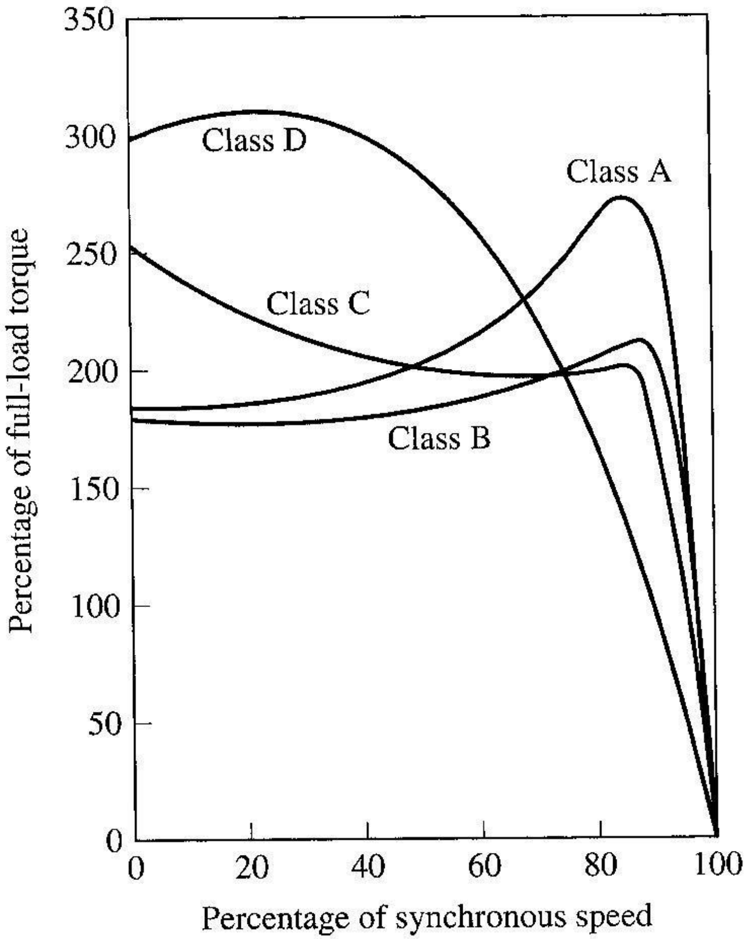


Fig: Typical torque-speed curves for different rotor designs

Torque-Slip Characteristics (Cont...)

❑ Speed Control of Induction Motors

- Induction motors are not good machines for applications requiring considerable speed control. The normal operating range of a typical induction motor is confined to less than 5% slip, and the speed variation is more or less proportional to the load.
- There are basically 2 general methods to control induction motor's speed:
  - ➢ Varying stator and rotor magnetic field speed.
  - ➢ Varying slip.
- Varying the magnetic field speed may be achieved by varying the electrical frequency or by changing the number of poles.
- Varying slip may be achieved by varying rotor resistance or varying the terminal voltage.

❑ Speed Control by Pole Changing

There are 2 approaches possible:

- Method of Consequent Poles (Old Method).
- Multiple Stator Windings Method

Method of Consequent Poles

- In the 2-pole configuration, one coil is a north pole and the other a south pole.
- When the connection on one of the 2 coils is reversed, they are both north poles, and the south poles are called consequent poles, and the windings is now a four -pole windings.
- By applying this method, the number of poles may be maintained (no changes) or doubled, hence would vary its operating speed.

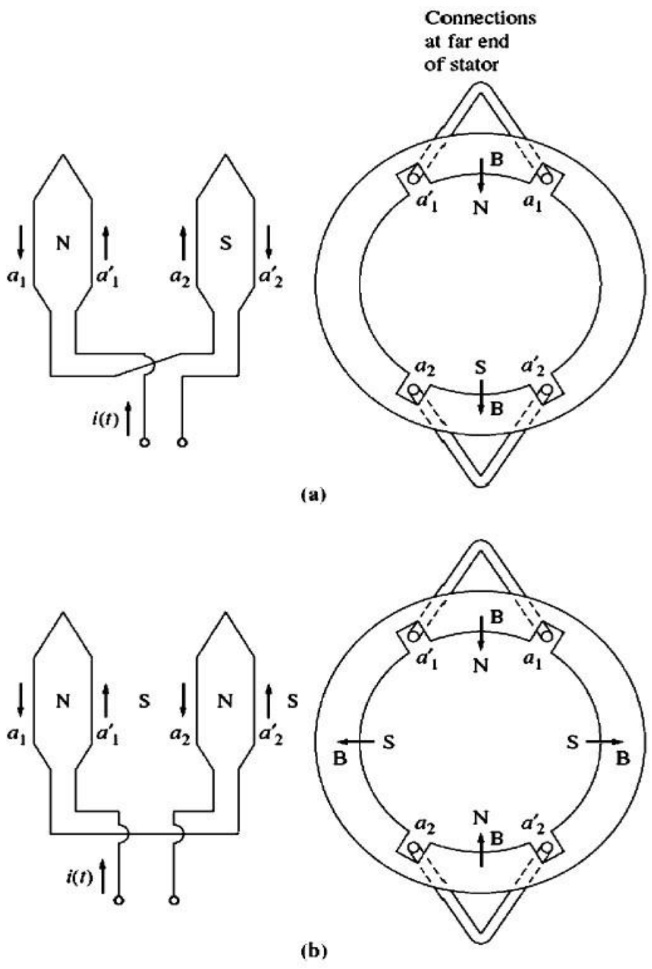


Fig: Method of consequent poles

Torque-Slip Characteristics (Cont...)

❑ Multiple Stator Windings:

- **Disadvantage of consequent pole method:**

  Speed ratio of only 2:1 is possible.

- **Solution**

  Use of multiple stator windings.

- ➢ Multiple stator windings have extra sets of windings that may be switched in or out to obtain the required number of poles.
- ➢ Unfortunately, this would an expensive alternative.

❑ Speed Control by Changing Line Frequency:

- Changing the electrical frequency will change the synchronous speed of the machine.
- Changing the electrical frequency would also require an adjustment to the terminal voltage in order to maintain the same amount of flux level in the machine core. If not the machine will experience:
  - ➢ Core saturation (non linearity effects).
  - ➢ Excessive magnetization current.

$$Es = 4.44\, k_{cs}\, k_{ds}\, f_s\, \varphi\, Ns$$

$k_{cs}\, k_{ds} = k_w$ = Winding factor of stator

- With the arrival of solid-state devices/power electronics, line frequency change is easy to achieved and it is more versatile to a variety of machines and application.

❑ Speed Control by Changing Line Voltage:

- Varying the terminal voltage will vary the operating speed but with also a variation of operating torque.
- In terms of the range of speed variations, it is not significant hence this method is only suitable for small motors only.

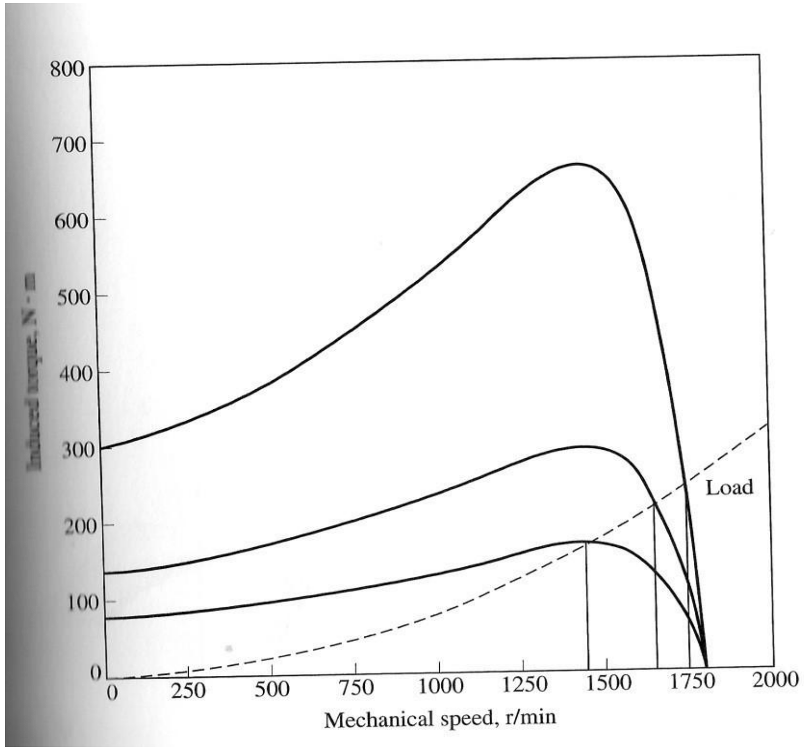


Fig: Speed control by varying line voltage

❑ Speed Control by Changing Rotor Resistance:

- It is possible only for wound-rotor induction motors.
- Inserting external resistance reduces motor efficiency. Hence it is used only for a short time.

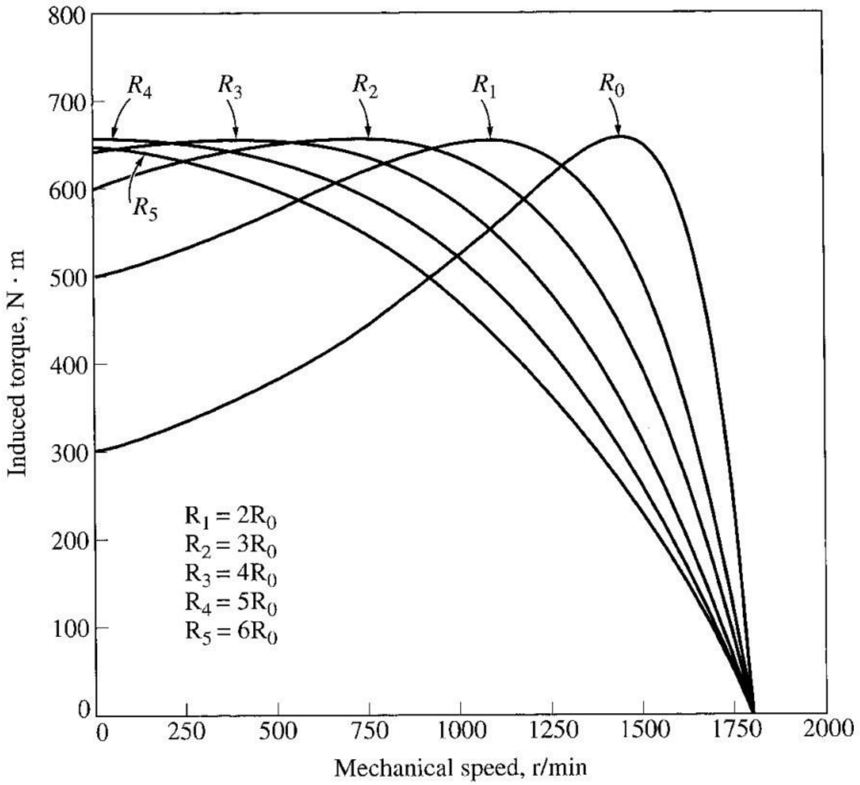


Fig: Speed control by varying rotor resistance of wound-rotor induction motor

Induction Motor Circuit Parameter

❑ Determination of Equivalent Circuit Parameters:

- There are basically 3 types of tests that can be done on an Induction motor:
  - ➢ No-load test
  - ➢ DC test
  - ➢ Locked Rotor test or Blocked Rotor test
- These tests are performed to determine the equivalent circuit elements – R_1, R_2, X_1, X_2 and X_M.

❑ DC Test:

- This is a test for R_1 independent of R_2, X_1, and X_2.

- DC voltage is applied to the terminals of the stator windings of the induction motor. Since it is DC supply, f = 0, hence no induced current in the rotor circuit. Current will flow through the stator circuit. Reactance is zero at DC. Thus, the only quantity limiting current flow in the motor is the stator resistance, and it can be determined.

- Assume we have a Y connected induction motor circuit as shown:

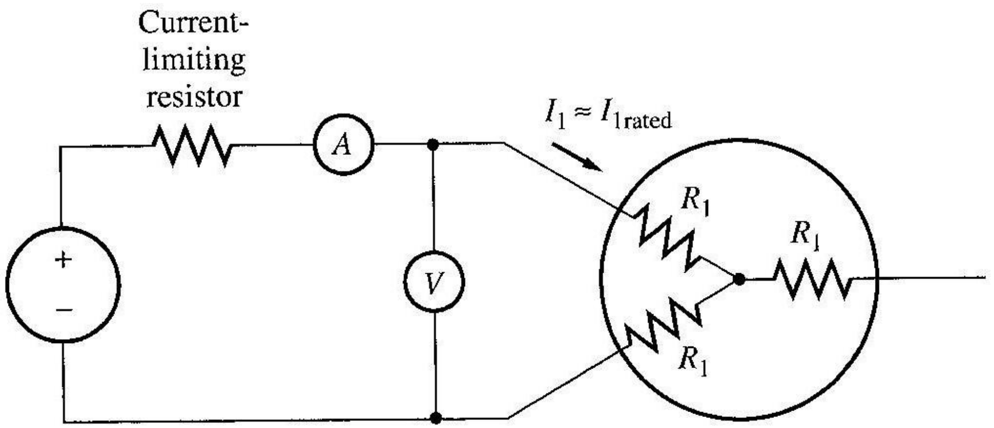
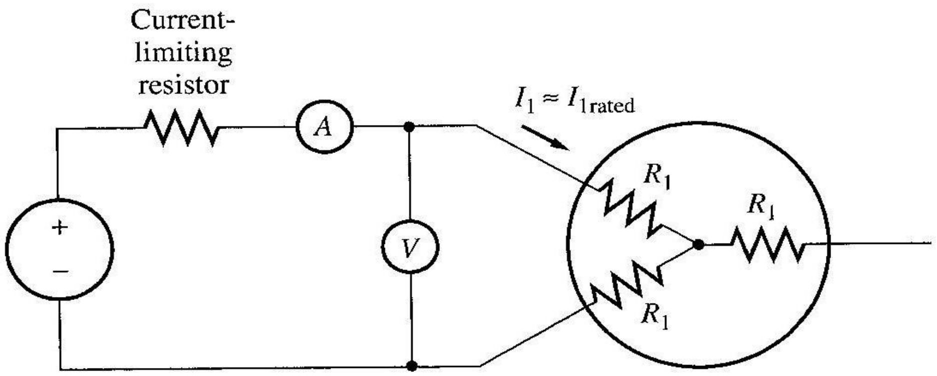


Fig: Test setup for DC test

- DC voltage is applied across the motor terminal and current flow is adjusted to rated condition.



- Voltage and current flow is noted.

- Based upon the test configuration,

$$\frac{V_{DC}}{I_{Dc}} = 2R_1 \Rightarrow R_1 = \frac{V_{DC}}{2I_{DC}}$$

- Use skin effect considerations to get the AC resistance.


THANKS
FOR YOUR
ATTENTION