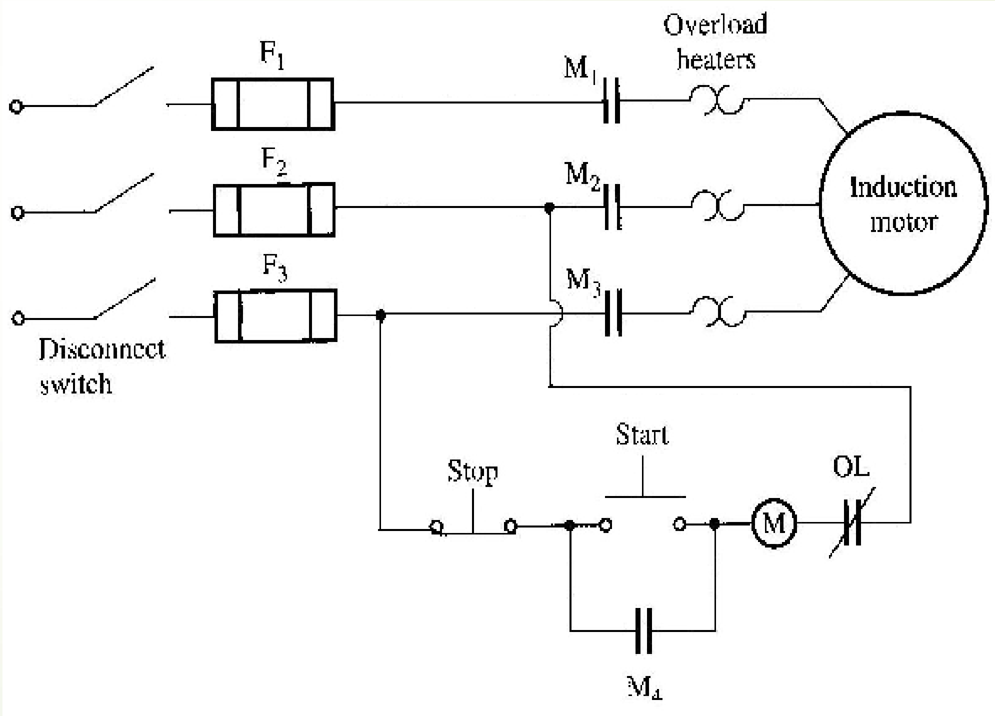
Induction Motors- Starting

- A typical full-voltage (**across-the-line**) motor magnetic starter circuit

- Start button pressed, rely coil M energized, & N.O. contacts M_1,M_2,M_3 close
- Therefore power supplied to motor & motor starts
- Contacts M_4 also close which short out starting switch, allowing operator to release it (start button) without removing power from M relay
- When stop button pressed, M relay de-energized, & M contacts open, stopping motor



Induction Motors- Starting

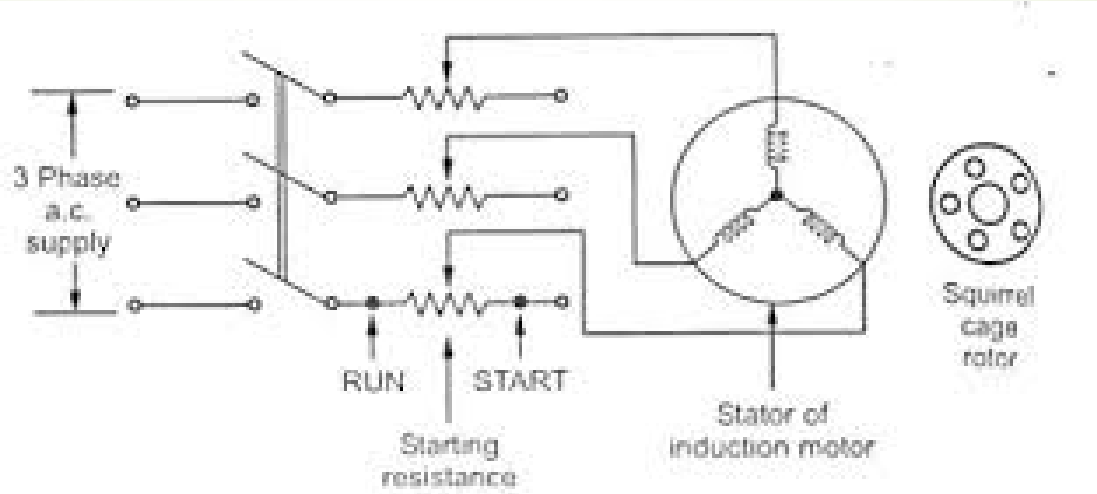
- An induction motor has the ability to start directly, however direct starting of an induction motor is not advised due to high starting currents, may cause dip in power system voltage; that across-the-line starting not acceptable
- For wound rotor, by inserting extra resistance can be reduced; this increase starting torque, but also reduces starting current
- For cage type, starting current vary widely depending primarily on motor's rated power & on effective rotor resistance at starting conditions

Induction Motors- Starting

Primary or Stator Rheostat starter:

- Voltages are drop across the resistors. Thus, low voltage is applied to the stator for the starting which causes low current. However, the torques is reduced with the square of the low supply voltages.

- **Note:** As starting current reduced proportional to decrease in voltage, starting torque decreased as square of applied voltage, therefore it is used in small motors for a smooth starting.



Induction Motors- Starting

Star-Delta starter:

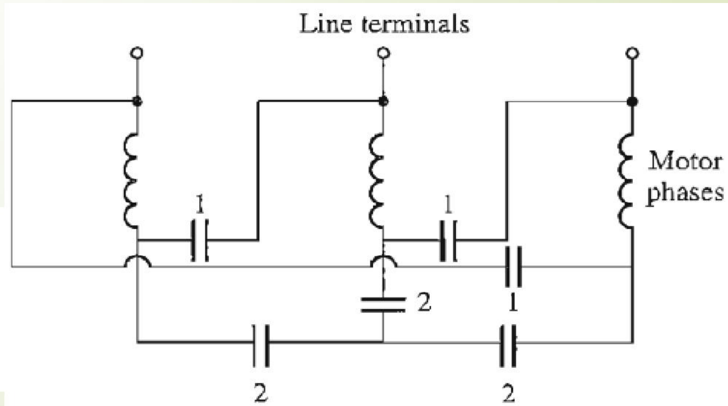
- Stator winding from the motor is switched from a star-connection to a delta-connection, then the phase voltage across the winding will decrease from V_L to $V_L/\sqrt{3}$, reducing the maximum starting current by the same ratio. When the motor accelerates to close to full speed, the stator windings can be opened and reconnected in a delta-configuration
- **Note:** As starting current reduced proportional to decrease in voltage, starting torque decreased as square of applied voltage, therefore just a certain reduction possible if motor is to start with a shaft load attached

Starting sequence:

(*a*) Close 1

(*b*) Open 1 when motor is turning

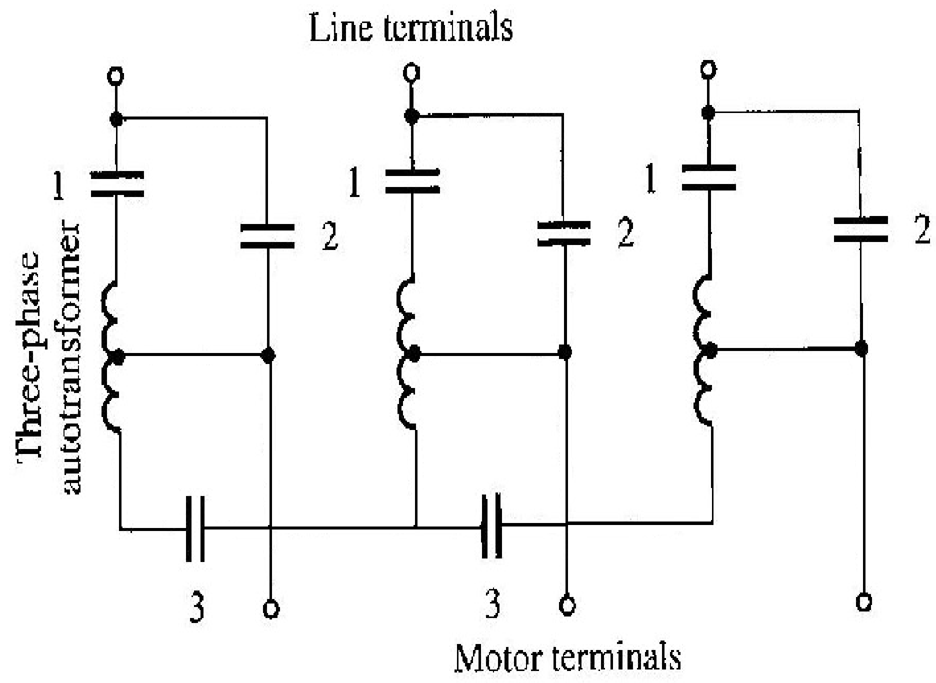
(*c*) Close 2



Induction Motors- Starting

Autotransformer starter:

- During starting, switch 1 & 3 closed, supply low voltage to motor.
- When motor is nearly up to speed; contacts 1 & 3 opened & switch 2 is closed. These contacts put full line voltage across the motor.
- **Note:** As starting current reduced proportional to decrease in voltage, starting torque decreased as square of applied voltage, therefore just a certain reduction possible if motor is to start with a shaft load attached.



Starting sequence:

(*a*) Close 1 and 3
(*b*) Open 1 and 3
(*c*) Close 2

Induction Motor- Speed Control

- 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
- Since $P_{RCL} = s\ P_{AG}$, if slip is made higher, rotor copper losses will be high as well
- There are basically 2 general methods to control induction motor's speed:

1. **Varying synchronous speed**
2. **Varying slip**

Induction Motor- Speed Control

$$n_{sync} = \frac{120 f_e}{P} \quad rpm$$

$$N_r = \frac{120 f}{p}(1-s)$$

1. **By Varying synchronous speed n_{sync}**
   A. *By changing the number of poles on the machine*
   B. *By changing the electrical frequency*

2. **By Varying Slip**
   A. *By changing terminal voltage of the motor.*
   B. *By changing Rotor resistance*

Induction Motor- Speed Control

- Speed Control by Pole Changing

Two major approaches:

(1) Method of consequent poles

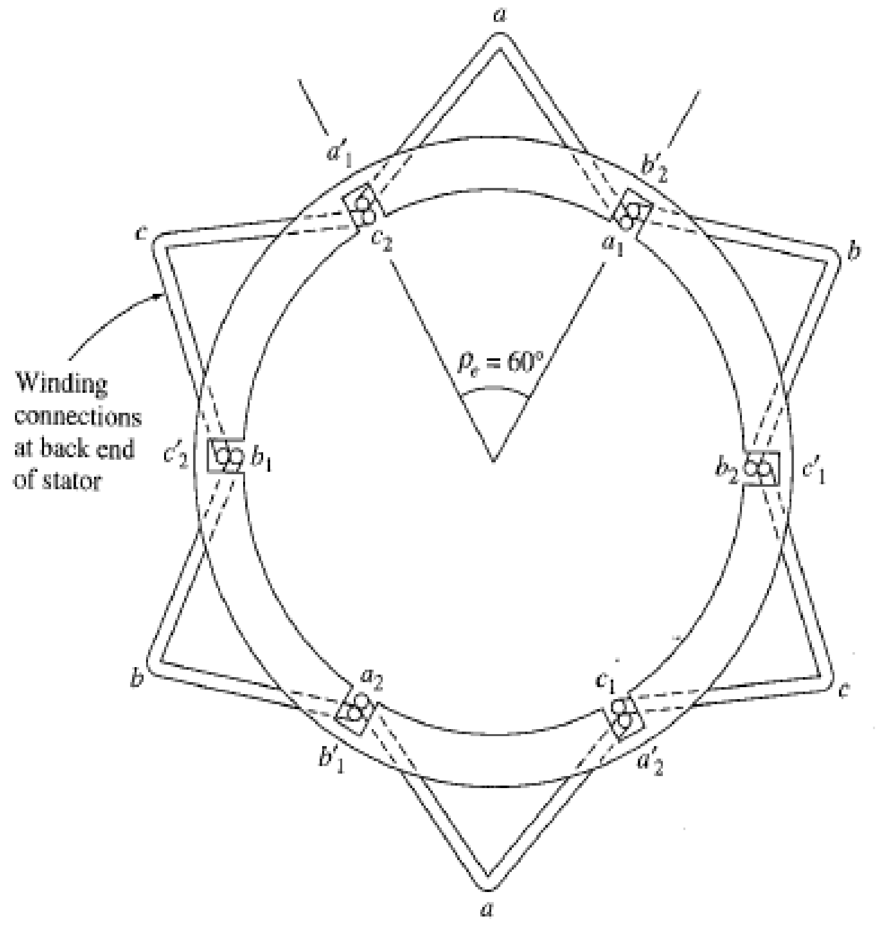
(2) Multiple stator windings

- accompanying as a consequence

INDUCTION MOTOR- Speed Control

Method of consequent poles:

- relies on the fact that number of poles in stator windings can easily changed by a factor of 2:1, with simple changes in coil connections
- A 2-pole stator winding for pole changing has very small rotor pitch
- In next figure for windings of phase "a" of a 2 pole stator, method is illustrated



INDUCTION MOTOR- Speed Control

- A view of one phase of a pole changing winding.
- In figure (a), current flow in phase **a**, causes magnetic field leave stator in upper phase group (N) & enters stator in lower phase group (S), producing 2 stator magnetic poles

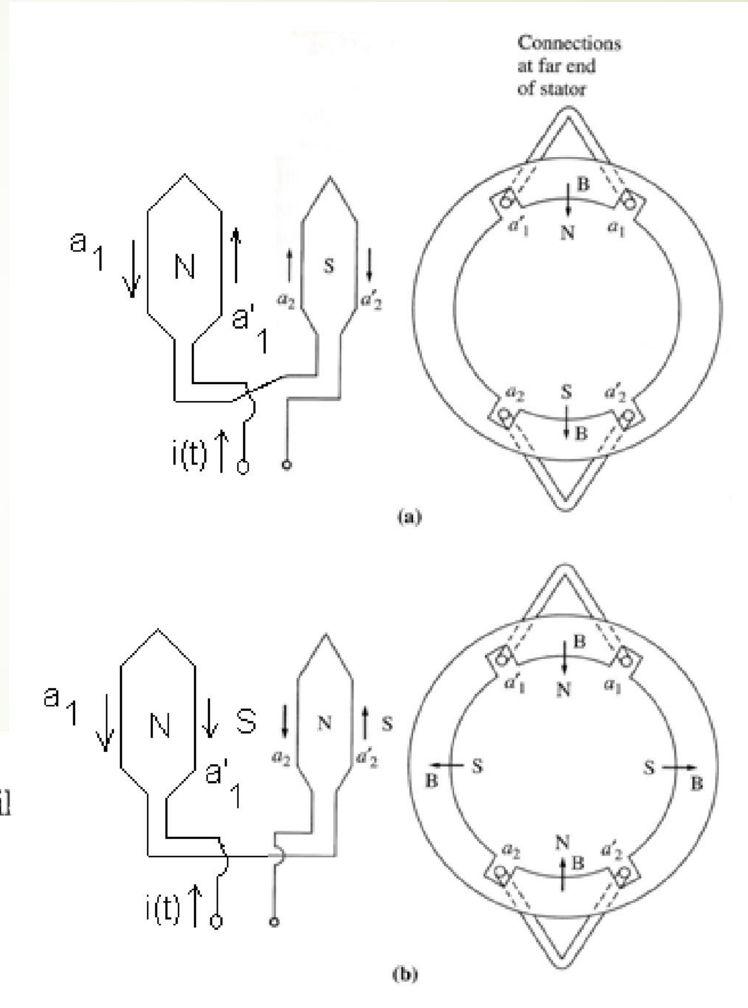


FIGURE 6–41
A close-up view of one phase of a pole-changing winding. (a) In the two-pole configuration, one coil is a north pole and the other one is a south pole. (b) When the connection on one of the two coils is reversed, they are both north poles, and the magnetic flux returns to the stator at points halfway between the two coils. The south poles are called *consequent poles*, and the winding is now a four-pole winding.

INDUCTION MOTOR- Speed Control

- Now, if direction of current flow in lower phase group reversed, magnetic field leave stator in both upper phase group, & lower phase group, each will be a North pole while flux in machine must return to stator between two phase groups, producing a pair of consequent south magnetic poles (twice as many as before)
- Rotor in such a motor is of cage design, and a cage rotor always has as many poles as there are in stator.
- When motor reconnected from 2 pole to 4 pole , resulting maximum torque is the same (for :constant-torque connection), half of its previous value (for: square-law-torque connection used for fans, etc.), or twice its previous value (for :constant-output power connection) depending on how the stator windings are rearranged
- Next figure, shows possible stator connections & their effect on torque-speed

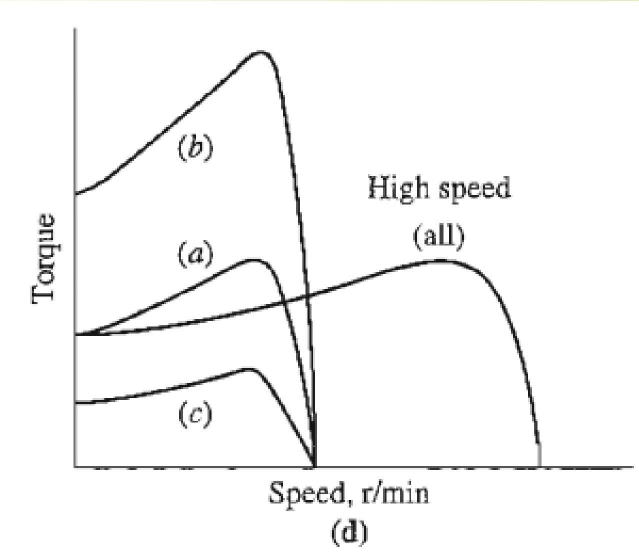
INDUCTION MOTOR- Speed Control

- Possible connections of stator coils in a pole-changing motor, together with resulting torque-speed characteristics:
- (a) constant-torque connection : power capabilities remain constant in both high & low speed connections
- (b) constant hp connection: power capabilities of motor remain approximately constant in both high-speed & low-speed connections
- (c) Fan torque connection: torque capabilities of motor change with speed in same manner as fan-type loads.

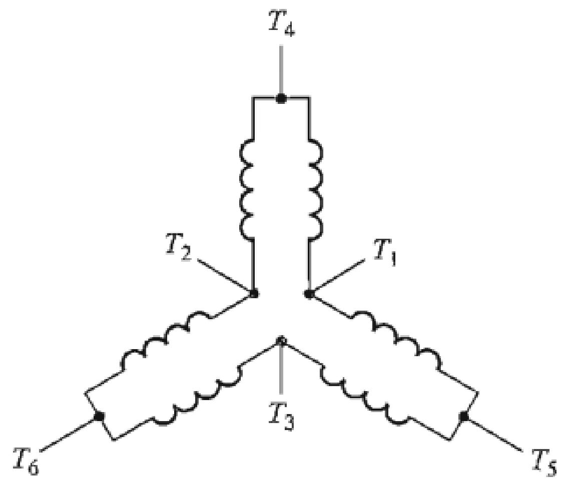
INDUCTION MOTOR- Speed Control

Figures of possible connections of stator coils in a pole changing motor

- Constant-torque Connection: torque capabilities of motor remain approximately constant in both high-speed & low-speed connection
- Constant-hp connection: power capabilities of motor remain approximately constant in both high-speed and low-speed connections.
- Fan torque connection:

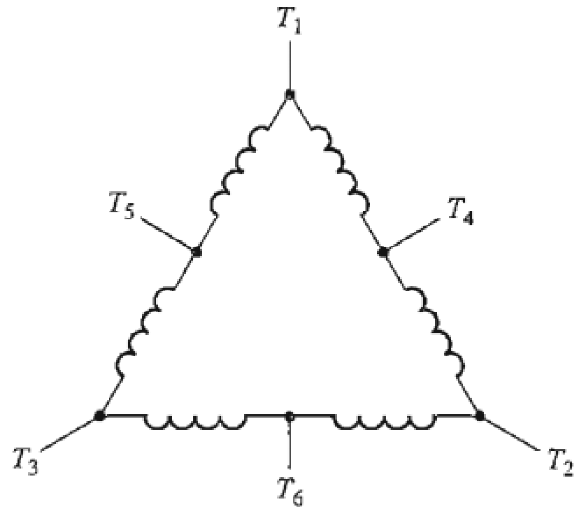


INDUCTION MOTOR- Speed Control



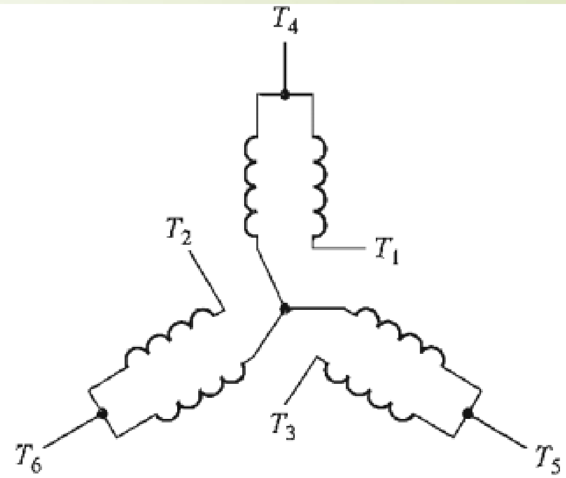
Speed	Lines			
	L_1	L_2	L_3	
Low	T_1	T_2	T_3	T_4, T_5, T_6 open
High	T_4	T_5	T_6	T_1 - T_2 - T_3 together

(a) Constant-torque Connection:



Speed	Lines			
	L_1	L_2	L_3	
Low	T_4	T_5	T_6	T_1 - T_2 - T_3 together
High	T_1	T_2	T_3	T_4, T_5, T_6 open

(b) Constant-hp connection:



Speed	Lines			
	L_1	L_2	L_3	
Low	T_1	T_2	T_3	T_4, T_5, T_6 open
High	T_4	T_5	T_6	T_1 - T_2 - T_3 together

(c) Fan torque connection:

INDUCTION MOTOR- Speed Control

- Major Disadvantage of consequent-pole method of changing speed: speeds must be in ratio of 2:1
- Traditional method to overcome the limitation: employ multiple stator windings with different numbers of poles & to energize only set at a time

Example: A motor may wound with 4 pole & a set of 6 pole stator windings, then its sync. Speed on a 60 Hz system could be switched from 1800 to 1200 r/min simply by supplying power to other set of windings.

However multiple stator windings increase expense of motor & used only it is absolutely necessary

Combining method of consequent poles with multiple stator windings a 4 – speed motor can be developed.

Example: With separate 4 & 6 pole windings, it is possible to produce a 60 Hz motor capable of running at 600, 900, 1200, and 1800 r/min.

INDUCTION MOTOR- Speed Control

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

  (a) Core saturation (non linearity effects)

  (b) Excessive magnetization current

$$\phi(t) = -\frac{V_M}{\omega N_P} \cos \omega t \qquad (6\text{–}57)$$

INDUCTION MOTOR- Speed Control

Varying frequency with or without adjustment to the terminal voltage may give 2 different effects :

(a) Vary frequency, stator voltage adjusted – generally vary speed and maintain operating torque

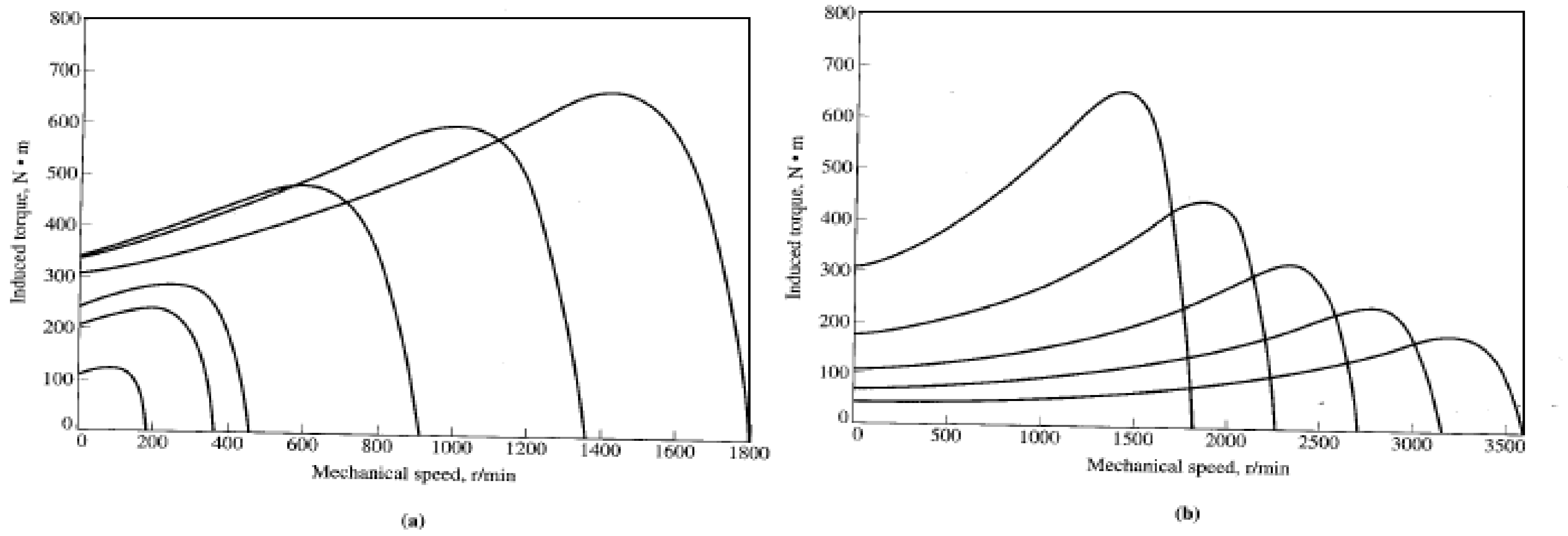
(b) Vary Frequency, stator voltage maintained – able to achieve higher speeds but a reduction of torque as speed is increased

- There may also be instances where both characteristics are needed in the motor operation; hence it may be combined to give both effects
- With the arrival of solid-state devices/power electronics, line frequency change is easy to achieved and it is more flexible for a variety of machines and application
- Can be employed for control of speed over a range from a little as 5% of base speed up to about twice base speed

INDUCTION MOTOR- Speed Control

Variable-frequency speed control

- (a) Family of torque-speed characteristic curves for speed below base speed (assuming line voltage derated linearly with frequency
- (b) Family of torque-speed characteristic curves for speeds above base speed, assuming line voltage held constant



INDUCTION MOTOR- Speed Control

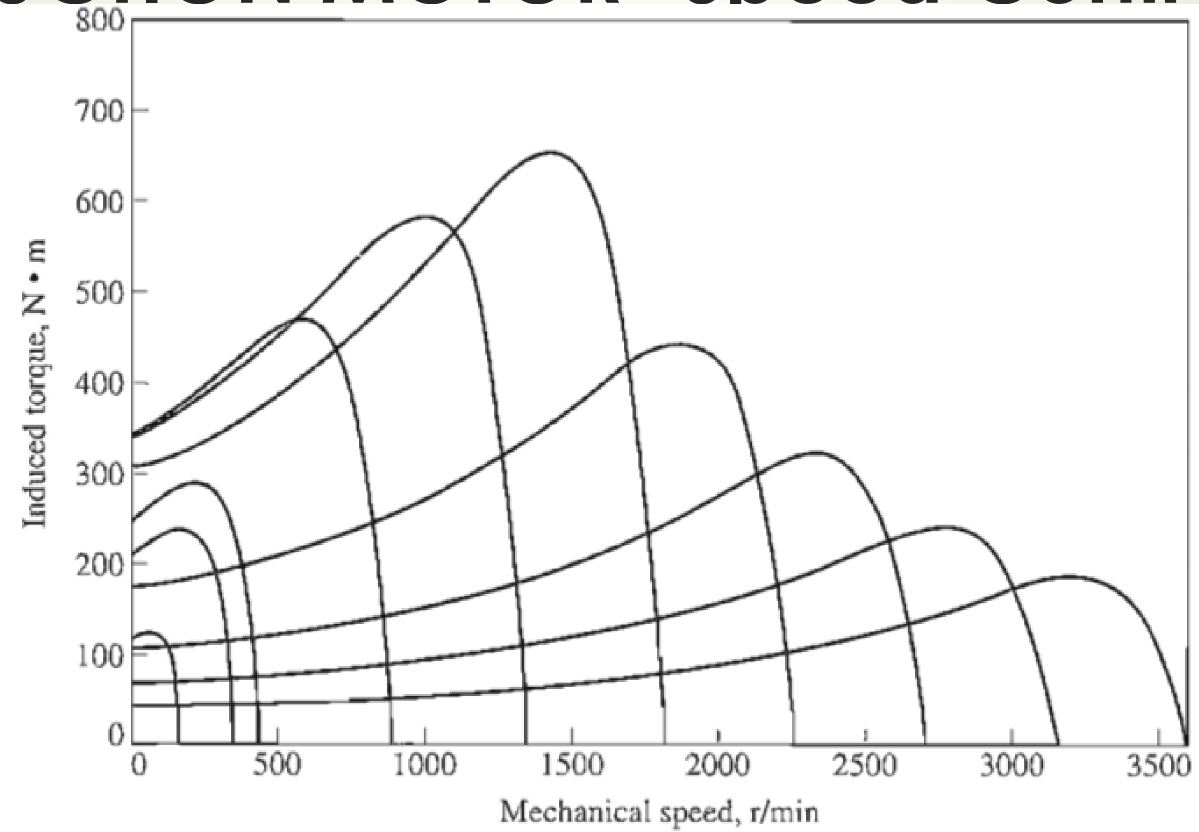
Running below base speed, the terminal voltage should be reduced linearly with decreasing stator frequency

This process called derating, failing to do that cause saturation and excessive magnetization current (if f_e decreased by 10% & voltage remain constant ➔ flux increase by 10% and cause increase in magnetization current)

When voltage applied varied linearly with frequency below base speed, flux remain approximately constant, & maximum torque remain fairly high, therefore maximum power rating of motor must be decreased linearly with frequency to protect stator from overheating.

Power supplied to : $\sqrt{3}\, V_L I_L \cos\theta$ should be decreased if terminal voltage decreased.

INDUCTION MOTOR- Speed Control



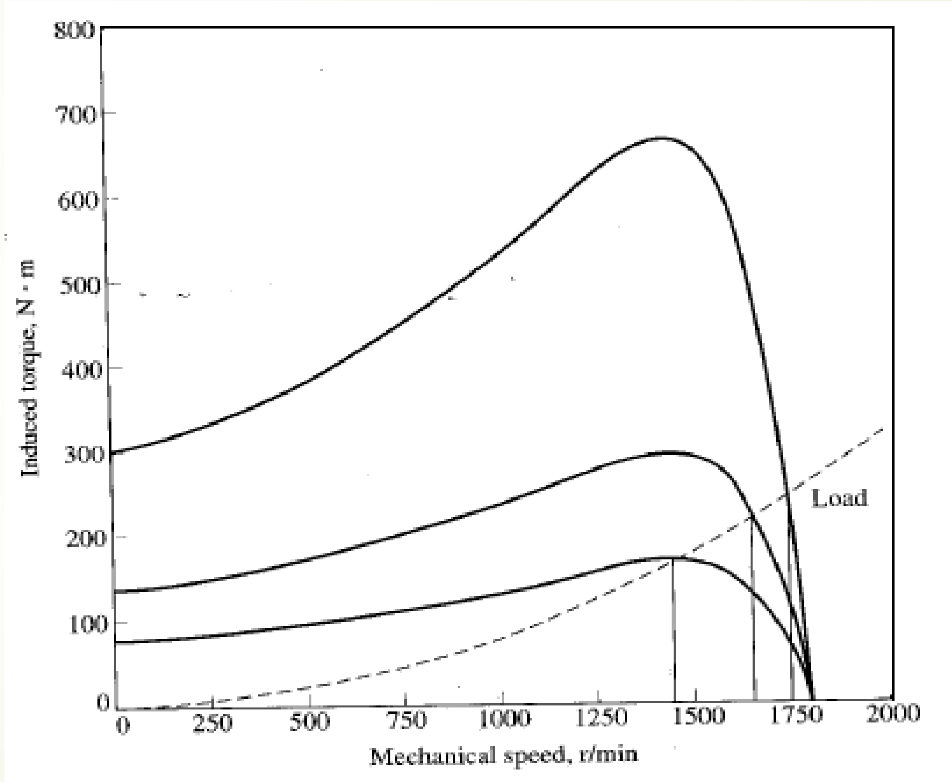
(c)

FIGURE 6–43 (concluded)
(c) The torque–speed characteristic curves for all frequencies.

INDUCTION MOTOR- Speed Control

Speed control by changing Line Voltage:

- Torque developed by induction motor is proportional to square of applied 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



INDUCTION MOTOR- Speed Control

Speed control by changing rotor resistance

- In wound rotor, it is possible to change the torque-speed curve by inserting extra resistances into rotor.
- However, inserting extra resistances into rotor seriously reduces efficiency.
- Such a method of speed control normally used for short periods, to avoid low efficiency.

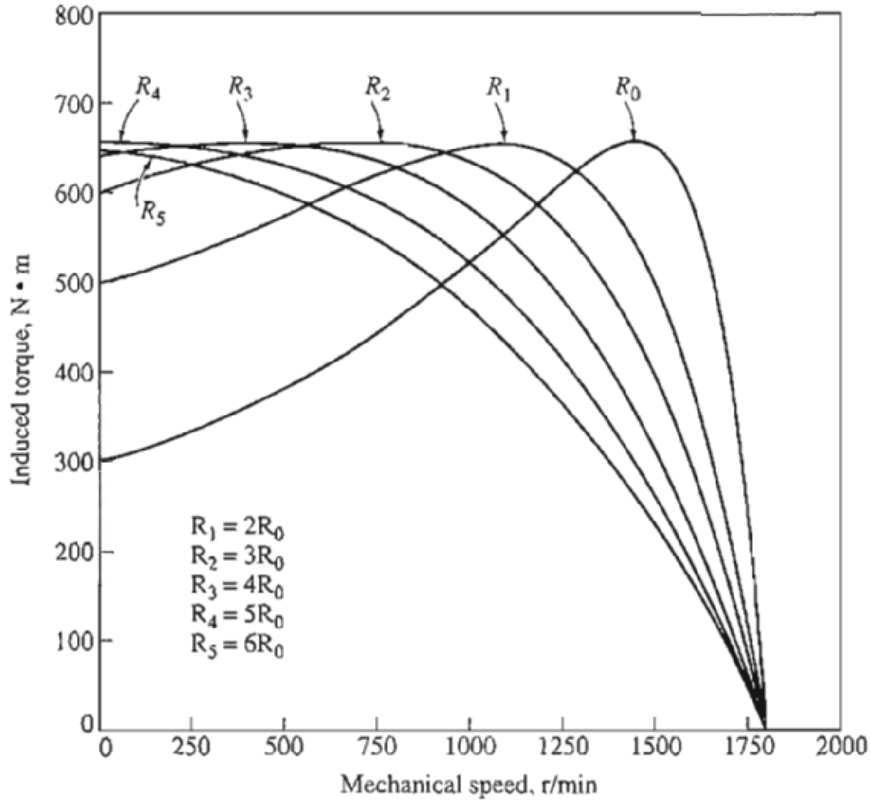


FIGURE 6–45
Speed control by varying the rotor resistance of a wound-rotor induction motor.