Lecture-35

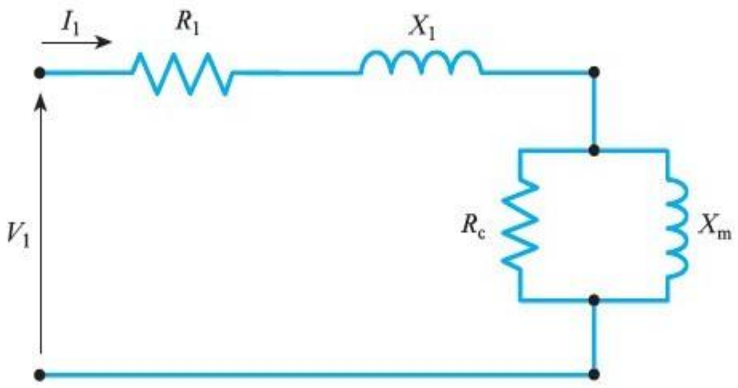
On

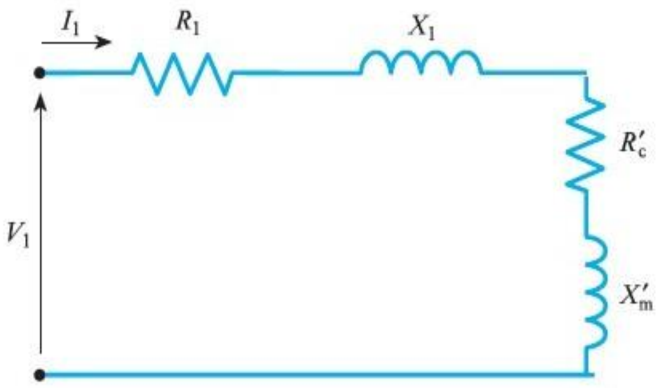
# INTRODUCTION TO ELECTRICAL ENGINEERING (ESO203)

- Induction Machine.
- Introduction to synchronous motor.

# Induction Motor Circuit Parameter (Cont...)

## ❑ No Load Test on Induction Motor:




- On no-load the induction motor runs close to synchronous speed as it supplies no torque (other than friction and rotational losses). The slip is therefore very small so $\frac{R'_2}{s}$ is very large and almost no current flows in the rotor circuit.

- The applied voltage, line current, and total three-phase power at rated voltage and, also at a range of lower applied voltages, are usually measured.

# Induction Motor Circuit Parameter (Cont...)

- The no-load test measures the rotational losses and provides information about its magnetization current.
- The induction motor is not loaded; hence any load will be based upon frictional and mechanical losses.
- The rotor will be rotating at near synchronous speed hence slip is very small.
- The no load test circuit is shown below:

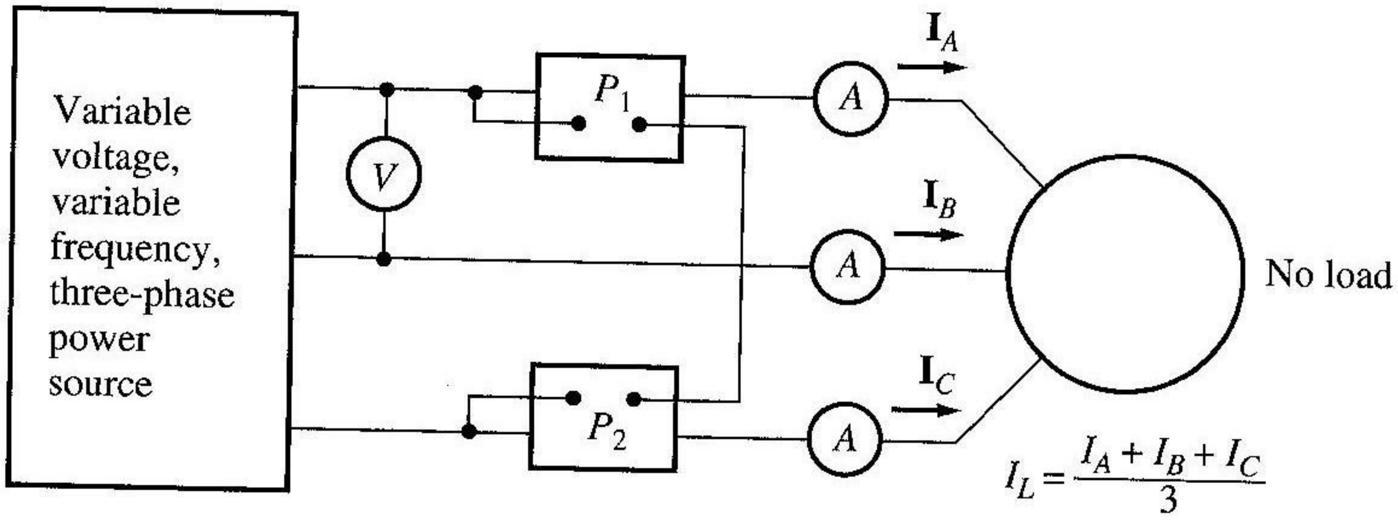
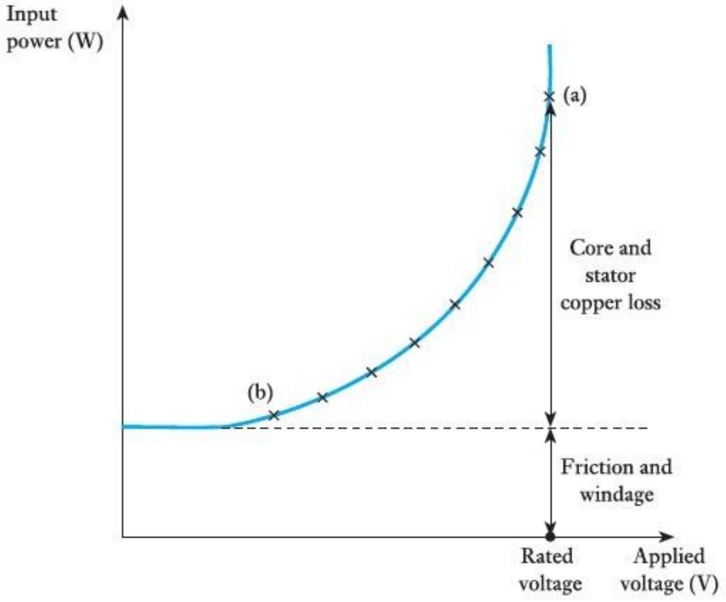



Fig: No-load test setup

# Induction Motor Circuit Parameter (Cont...)




- At no-load

$$P_{in} = 3I_1^2R_1 + 3I_1^2R_c' + P_{fw}$$

- The graph extrapolated towards the y-axis to give an estimate of the friction and windage loss. If the friction and windage loss is not measured in this way, this loss is included in the core loss, giving a different value of $R_c'$.

- The equivalent impedance per phase $Z = \frac{V_{ph}}{I_{ph}} = (R_1 + R_c') + j(X_1 + X_m')$
- For a star-connected machine, the measured voltage is a line-to-line quantity so the phase voltage is $\frac{V_{line}}{\sqrt{3}}$. The measured line current equals the phase current.
- For a delta-connected machine, the measured voltage is a line-to-line quantity – which equals $V_{phase}$. The measured current will be a line current and the phase current will be $\frac{I_{line}}{\sqrt{3}}$.

# Induction Motor Circuit Parameter (Cont...)

- From the voltmeter and ammeter readings we can find the apparent power per phase, S.
- From the Wattmeter readings, we know per phase real power, P.
- Hence, reactive power, Q can be found from :

$$Q = \sqrt{S^2 - P^2}$$

From which,

$$\frac{Q}{I_1^2} = X_1 + X_m$$

- Usually, at no-load, Q is much larger than P, since very small real power is being consumed. Hence, R1 is much smaller than the total reactance, and one can write:

$$\frac{V_{ph}}{I_{ph}} \approx X_1 + X_m$$

## ❑ Locked Rotor Test:

- The rotor is locked.
- AC voltage is applied across the stator terminals and current flow is adjusted to full load condition.
- Measure voltage, current and power flow.

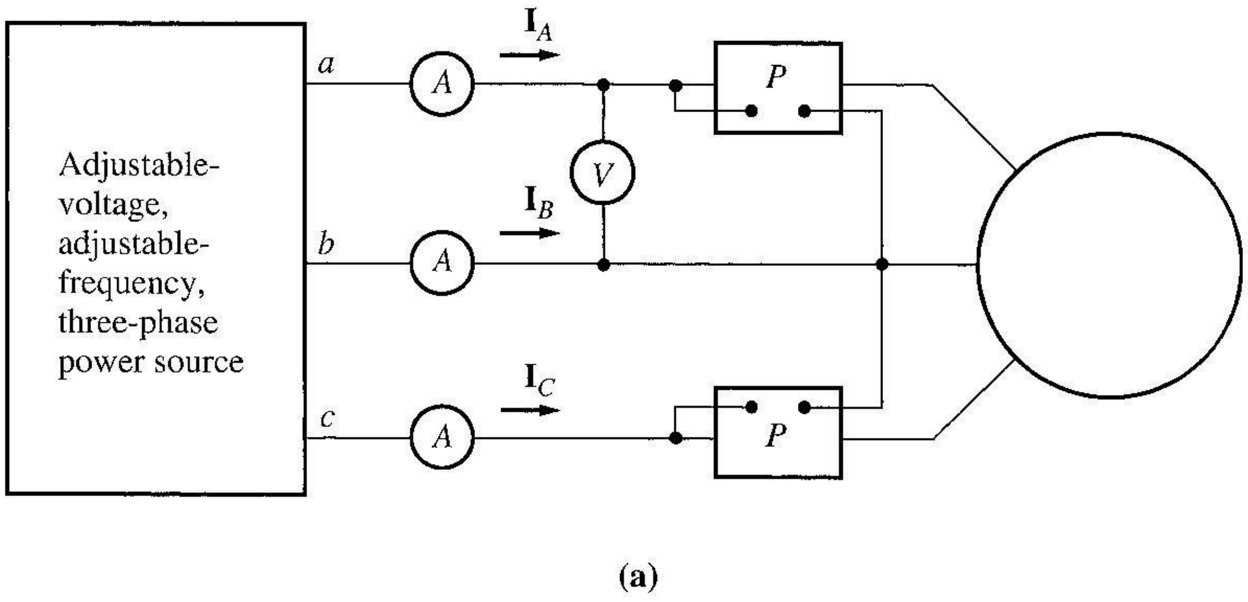
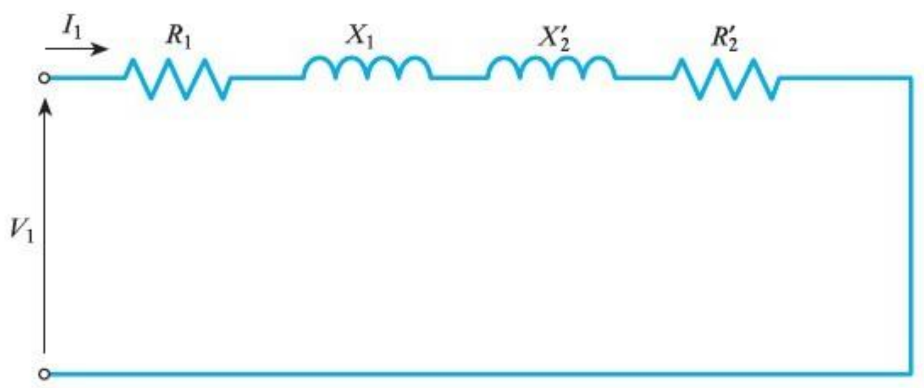



Fig: Locked Rotor Test Setup

# Induction Motor Circuit Parameter (Cont...)

- For the locked rotor test sufficient voltage is applied to the stator of the machine to circulate full-load current in the stator windings. This test corresponds to the short-circuit test on a transformer.




$$Z = \frac{V_{ph}}{I_{ph}} = (R_1 + R_2') + j(X_1 + X_2')$$

- With the rotor stationary, the slip is equal to one. For this condition the magnetizing branch impedance is very much larger than the locked rotor impedance, so the magnetizing branch canbe neglected. Same is true for Rc also.
- If no additional information is known about the design of the machine it can be assumed that $X_1 = X'_2$.

- Sometimes the locked rotor test is performed using a low-frequency three- phase supply. This has the advantage of allowing low-frequency currents to flow in the rotor. This is much closer to the normal, on-load condition (small slip) of the machine.

# Induction Motor Circuit Parameter (Cont...)

Note:

- This test is generally inaccurate due to the fact that in real operation, slip would vary from starting and as the rotor approaches operating speeds. Since slip would also correlate to rotor current and voltage frequency (at small slip, frequency is small, at high slip, frequency is high). Frequency would affect the rotor reactance. Therefore, this test is done with a lower supply frequency (25% or less) to simulate small slip during operation.

- Let the reactance quantities at the test frequency be denoted as follows:

  Total reactance at locked rotor test, $X'_{LR} = X'_1 + X'_2$

  Input power factor angle, $\theta = \cos^{-1}\left(\frac{P_{in}}{\sqrt{3}V_T I_L}\right)$

  Input Impedance $\boldsymbol{Z}_{LR} = R_{LR} + jX'_{LR} = |\boldsymbol{Z}_{LR}|\cos\theta + j|\boldsymbol{Z}_{LR}|\sin\theta$

# Induction Motor Circuit Parameter (Cont...)

- From DC test, we knew $R_1$. Hence, $R_2 = R_{LR} - R_1$

- Since reactance is directly proportional to frequency,

$$X_{LR} = \frac{f_{rated}}{f_{test}} X'_{LR} = X_1 + X_2$$

where $f_{rated}$ and $f_{test}$ are the frequency at rated condition, and during the test.

- Unfortunately, it is not easy to separate contributions of $X_1$and $X_2$ in $X_{LR}$. However, From experience, following empirical distribution has been obtained, which helps in finding $X_1$ and $X_2$ and hence $X_M$.

Empirical distribution of leakage reactances in induction motors

| | | Fraction of $X_1 + X_2$ | |
|---|---|---|---|
| Motor class | Description | $X_1$ | $X_2$ |
| A | Normal starting torque, normal starting current | 0.5 | 0.5 |
| B | Normal starting torque, low starting current | 0.4 | 0.6 |
| C | High starting torque, low starting current | 0.3 | 0.7 |
| D | High starting torque, high slip | 0.5 | 0.5 |
| Wound rotor | Performance varies with rotor resistance | 0.5 | 0.5 |

Source: IEEE Standard 112.

# Induction Motor Circuit Parameter (Cont...)

## ❑ Starting Induction Motor:

- An induction motor has the ability to start directly. However, direct starting is avoided in many cases to limit the high starting current.
- Induction motors usually come with a code letter in their name-plate, which represents the amount of starting current the motor can handle at starting.
- These limits are expressed as the starting apparent power of the motor as a fraction of its horse-power rating.
- Starting apparent power of the motor is then given by,

$$S_{rated} = (rated\ horsepower) \times (code\ letter\ factor)$$

| Nominal code letter | Locked rotor, kVA/hp | Nominal code letter | Locked rotor, kVA/hp |
|---|---|---|---|
| A | 0–3.15 | L | 9.00–10.00 |
| B | 3.15–3.55 | M | 10.00–11.00 |
| C | 3.55–4.00 | N | 11.20–12.50 |
| D | 4.00–4.50 | P | 12.50–14.00 |
| E | 4.50–5.00 | R | 14.00–16.00 |
| F | 5.00–5.60 | S | 16.00–18.00 |
| G | 5.60–6.30 | T | 18.00–20.00 |
| H | 6.30–7.10 | U | 20.00–22.40 |
| J | 7.7–8.00 | V | 22.40 and up |
| K | 8.00–9.00 | | |

Typical table of code letters

## Example:

- What  is the starting current of a 15-hp, 208 V, code-letter-F, 3 phase IM?

- Solution:

Using table, maximum kVA per horsepower is 5.6.

Hence, maximum starting kVA of the motor,

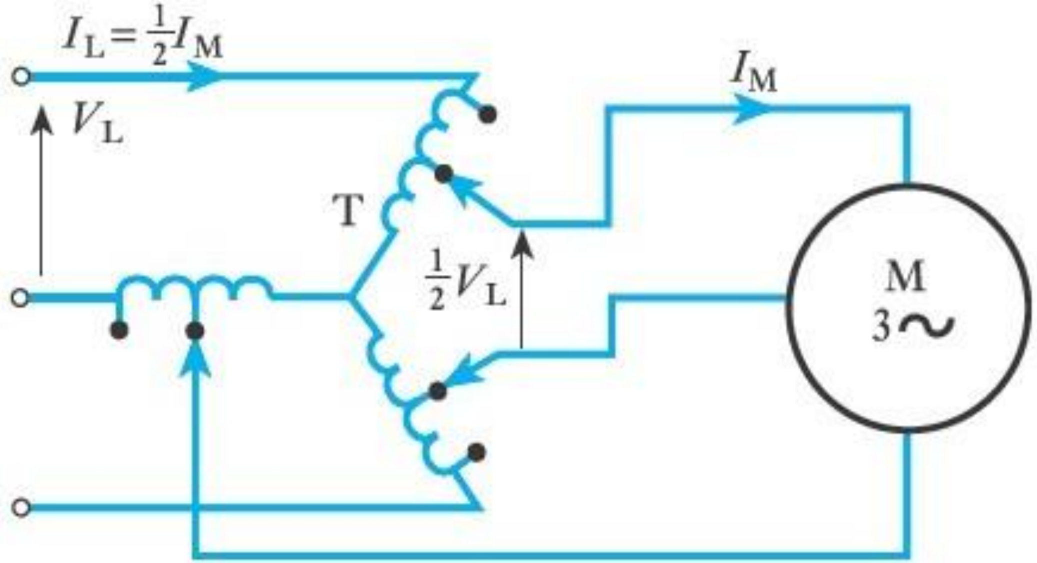
$$S_{start} = 15 \times 5.6 = 84\,kVA$$

Starting current is therefore,

$$I_{start} = \frac{S_{start}}{\sqrt{3}V_T} = \frac{84}{\sqrt{3} \times 208} = 233A$$

## ❑ Induction Motor Starters:

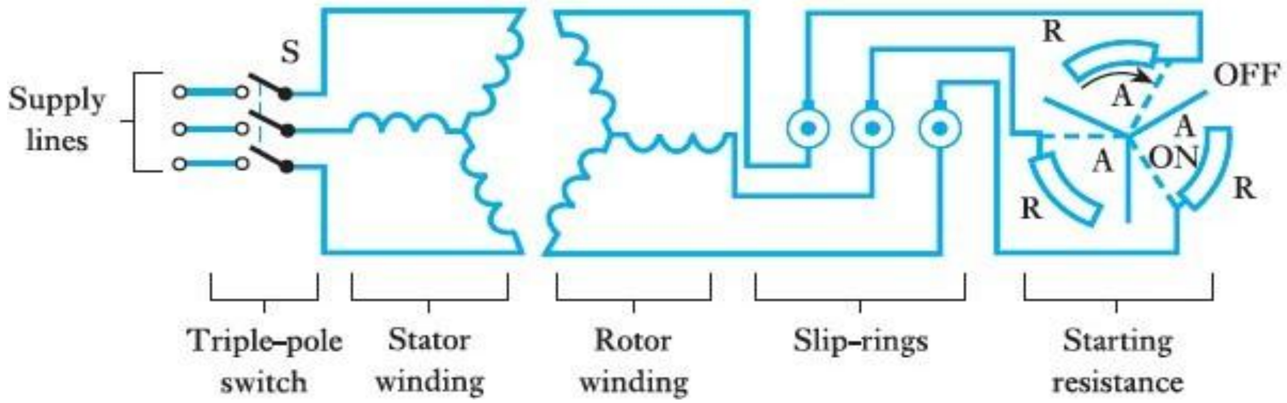
- Cage motors are usually started with one of the following type of starters:
  - ➢Star-delta starter: Initially started with ‘star’ connection, to apply of reduced voltage to IM stator phases; then switched to delta.
  - ➢Auto-transformer starter: Reduced voltage is applied initially, then gradually, rated voltage is applied.




  - ➢ Solid state starter: Uses power electronic devices to limit the starting current

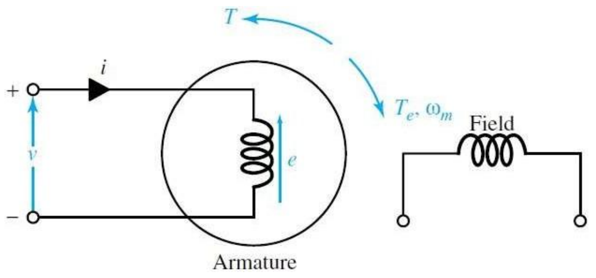
## ❑ Starting Torque:

- In usual type of cage rotor, the starting torque is small compared with the maximum torque available. If the bars of the cage rotor were made with sufficiently high resistance to give the maximum torque at standstill, efficiency would be low.
- When a motor is required to exert its maximum torque at starting, the usual practice is to insert extra resistance into the rotor circuit and to reduce the resistance as the motor accelerates. The three ends of the winding are connected via slip-rings on the shaft to external star-connected resistors R



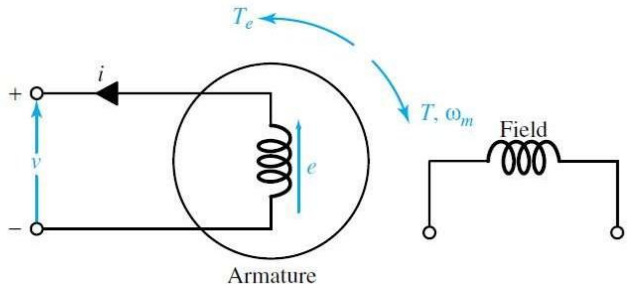

- The starting current is about four to seven times the full-load current, and can cause a relatively large voltage drop in the vicinity. It is usual to start with a reduced voltage.

## ❑ Modes Of Operation:



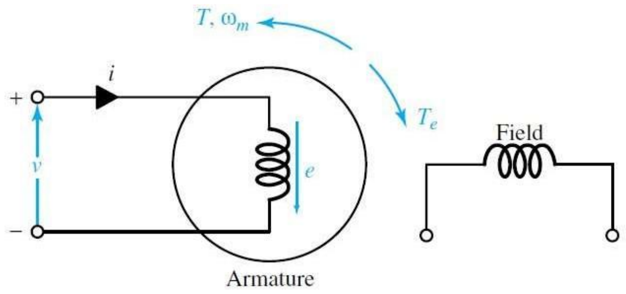

➢ **Motoring mode :**

electric power input and mechanical power output




➢ **Generating mode:**

mechanical power input and electric power output

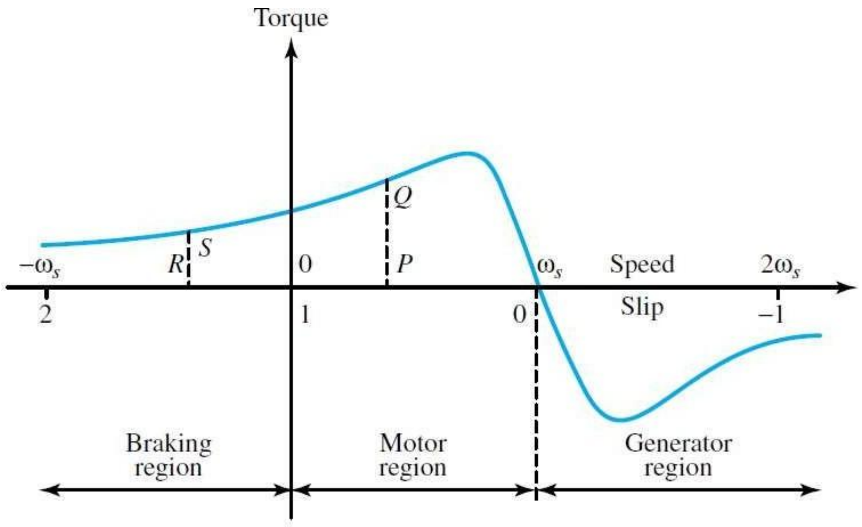



➢ **Braking mode :**

It has both mechanical and electric energy input. The total input is dissipated as heat. The machine is driven by the externally applied torque T, while the electromagnetic torque Te is opposing T, thereby braking the machine.

# Induction Motor Circuit Parameter (Cont...)

- In generating mode, Slip is negative. $\omega_m > \omega_s$




- Rotor is driven mechanically by an external means at above synchronous speed.

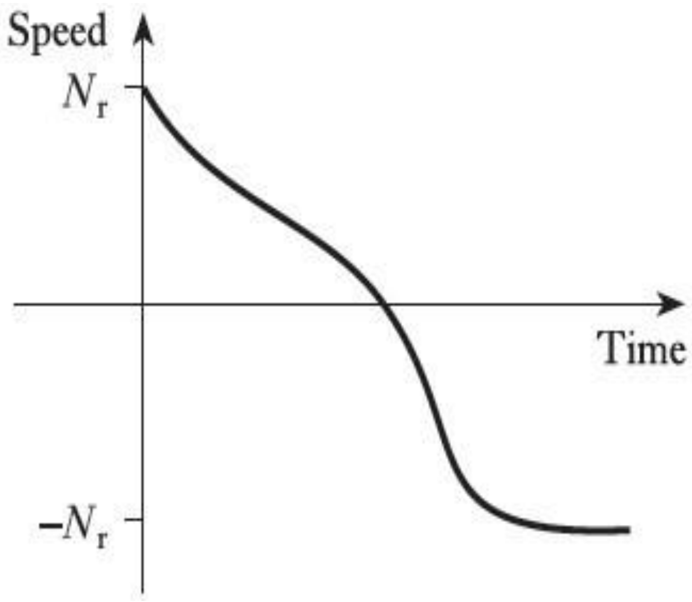
- An induction machine, can be made to generate with the powerflow reversed compared to that of a motor.

- If the machine is driven mechanically in the direction opposite to its primary rotating m.m.f, then the slip is greater than unity and the machine acts as a brake.

# Induction Motor Circuit Parameter (Cont...)

- If two of the three phase supply lines to the stator are reversed, the direction of the stator rotating m.m.f will reverse. The rotor will then be rotating in the direction opposite that of the rotating m.m.f, so the machine will act as a brake and the speed will rapidly come to zero, at which time the electric supply can be removed from the machine. This is a useful method of stopping the motor rapidly, called plugging or plug-braking.

- If the electric supply is not removed at zero speed, the machine will reverse its direction of rotation because of the change of phase sequence of the supply resulting from the interchange of the two stator leads.



# Synchronous Machine

## ❑ Introduction:

- The electric utility industry uses three-phase AC synchronous generators to produce electric power.
- These machines are also called ‘*alternators*’ since they convert mechanical energy to alternating current electric energy.
- Synchronous machines are so-named because they (essentially) rotate at a constant speed and so operate at constant frequency.
- Synchronous machine is widely used in power stations throughout the world for electrical power generation. Individual generator ratings of 500 to 600 megawatts are in vogue.

# Synchronous Machine (cont…)

## ❑ Basic Principle:

- A DC current is applied to the rotor winding, which then produces a rotor magnetic field. The rotor is then turned by a prime mover (e.g. Steam, water etc.) producing a rotating magnetic field. This rotating magnetic field induces a three-phase set of voltages within the stator windings of the generator.
- For motor, direct current supplied to the field winding (on the rotor) through two slip rings and with polyphase alternating current supplied to the armature (on the stator).
- The rotor mmf, which is obtained from a dc source, is stationary with respect to the rotor structure.
- When carrying balanced polyphase currents, the armature winding produces a magnetic field in the air gap rotating at synchronous speed.

- In a P pole machine,

$$N = \frac{120 f_s}{P} \text{ r/min}$$

# Synchronous Machine (cont…)

- The field produced by the dc rotor winding revolves with the rotor. To produce a steady unidirectional torque, the rotating fields of stator and rotor must be traveling at the same speed. Therefore, the rotor must turn precisely at the *synchronous speed*.

Generally, a synchronous machine must have at least 2 components:

a) Rotor Windings or Field Windings

   Salient Pole

   Non-Salient Pole

b) Stator Windings or Armature Windings

# Some Constructional Details

## Salient Pole

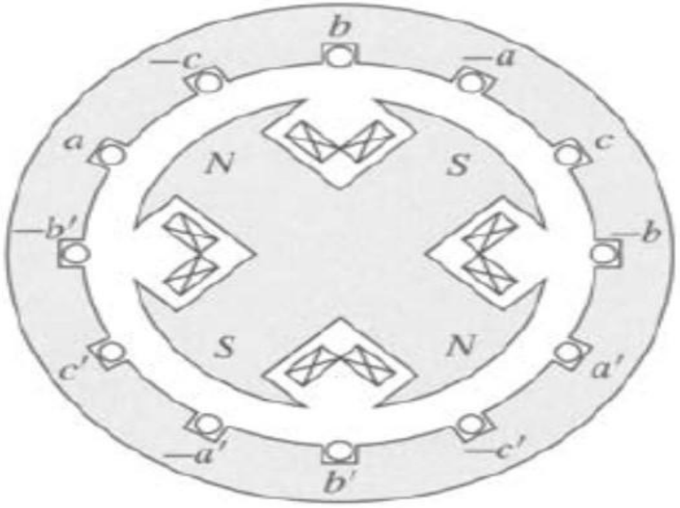



Fig. 1: 4-pole salient rotor

## Non Salient Pole

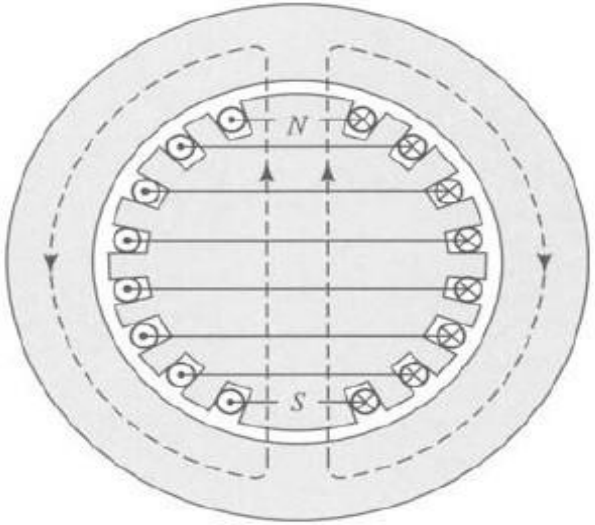



Fig.2: 2-pole cylindrical rotor

# Constructional Details (cont…)

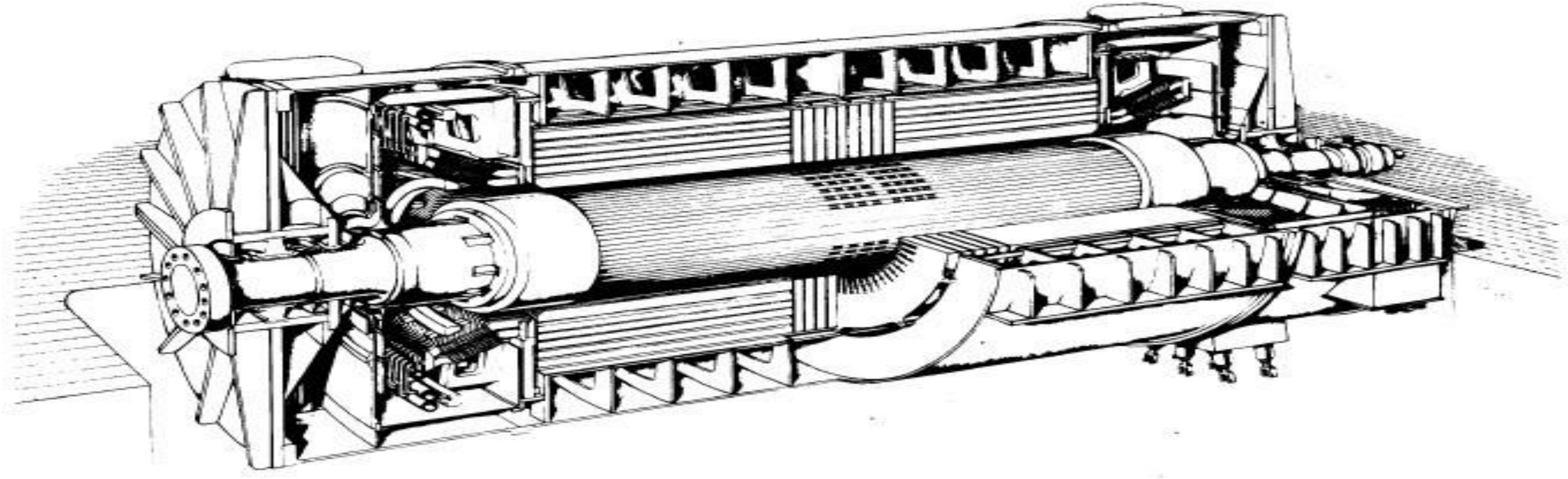


Fig.3: Cylindrical rotor generator, 1200 MVA (ABB)

Most synchronous machines are essentially high-speed machines. The centrifugal force on a high-speed rotor is enormous: To withstand such a force the rotor is usually made of a solid steel forging with longitudinal slots cut.

# Constructional Details (cont…)

- The salient-pole construction is used in comparatively small machines and machines driven at a relatively low speed.
- To accommodate the necessary number of poles, the synchronous machine must have a comparatively large diameter.
- The pole tips are well rounded so as to make the uniform flux distribution around the periphery.

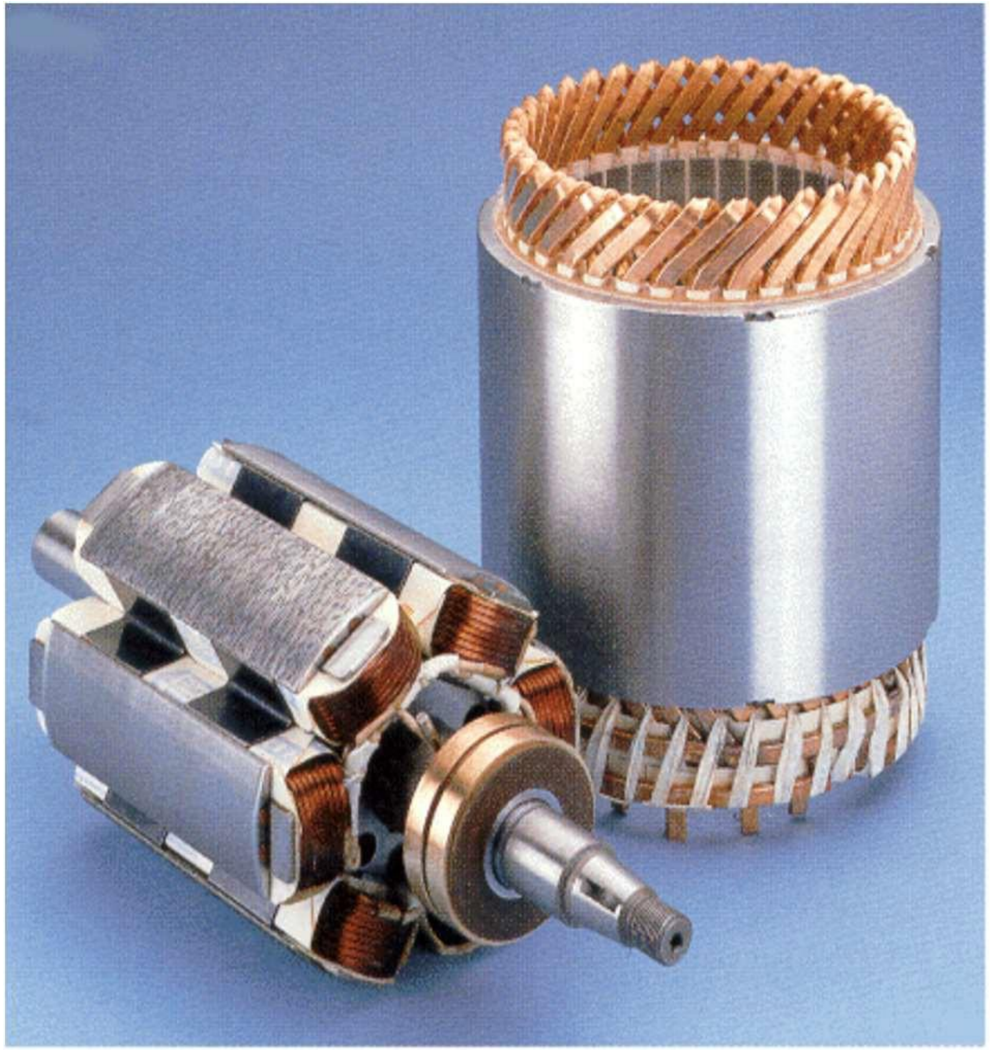


Fig.4: 6-pole salient rotor, 5 kVA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