Chapter 7: Induction Motor (Part III)

7.7. Starting induction motors

An induction motor has the ability to start by simply connecting it to the power line. However, **direct starting** of an induction motor is **not advised** due to the **large starting current**.

To estimate starting current for cage rotor, we must be able to calculate the **starting apparent power** of the motor. This is represented in **all motors** by a **designated** starting ***code letter*** on their nameplates.

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		

Table of NEMA code letters, indicating the starting kilovoltampere per horsepower of rating for a motor. (from Chapman textbook, page 431)

Note: These letters must **not be confused** with the motor's ***design class*** letter.

Hence, to **determine the starting current** for an induction motor:

1. Read the rated horsepower and code letter from its nameplate. The **starting apparent power** for the motor is:

$$S_{\text{start}} = (\text{rated horse power})(\text{code letter factor})$$

2. Read the rated voltage from its nameplate. Hence, the **starting current** can be found from:

$$I_{\mathrm{L}} = \frac{S_{\mathrm{start}}}{\sqrt{3}V_{\mathrm{T}}}$$

Example: What is the starting current of a 15-hp, 208-V, code letter F, three-phase induction motor?

According to the table,
the maximum kilovoltamperes per horsepower =

Hence, the maximum starting kilovoltamperes of this motor is:

Therefore, the staring current is:

It is seen that to start an IM requires a high starting current.

How can we reduce the starting current?

Wound rotor IM – relatively low starting currents achieved **by inserting extra resistance** in the rotor circuit **during starting** and as the rotor picks up speed, the resistor banks are removed.
.

Cage rotor IM – reduced starting current achieved **by varying the starting terminal voltage** at the stator.

One way to achieve this is by using **autotransformers,** i.e. a step down transformer during the starting sequence and stepping up the transformer ratio as the machine spins faster.

When **starting induction motors** we:

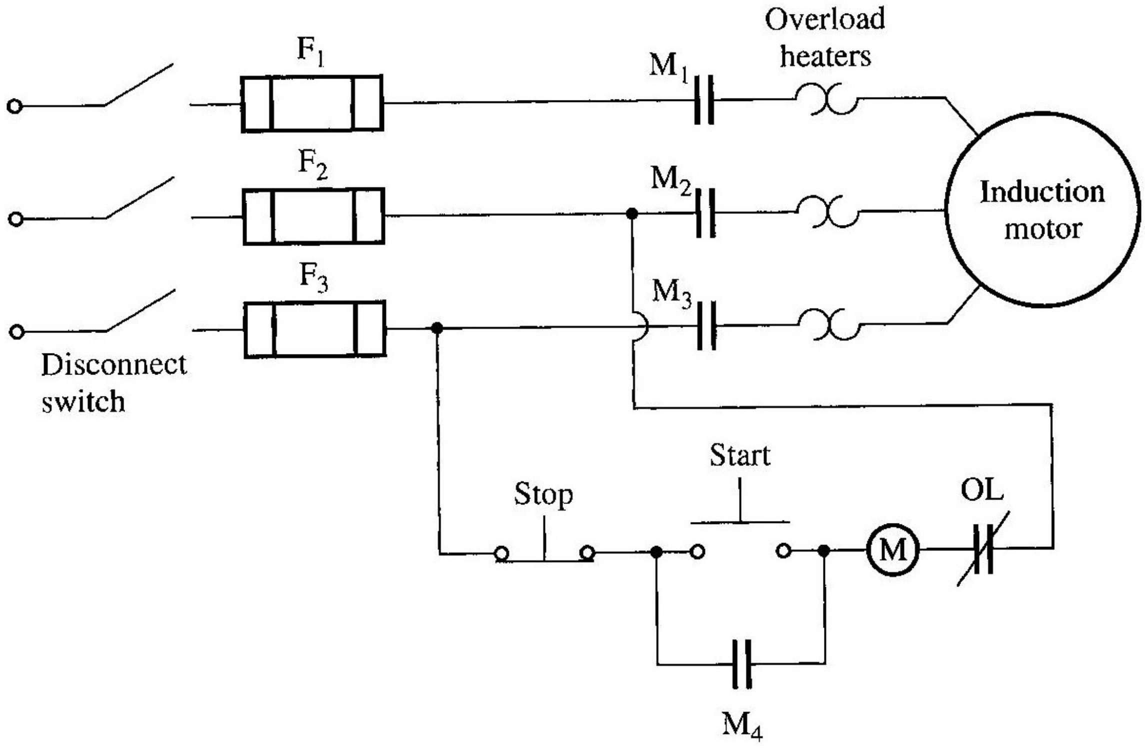
reduce terminal voltage V_{T} $\Longrightarrow$ ____________________________

BUT stating torque $\tau_{\mathrm{start}} = V_{\mathrm{T}}^2$ $\Longrightarrow$ ____________________________

Therefore, **only certain amount of current reduction can be done if motor is to start with shaft load attached.**

Induction motor starting circuits

Typical **full-voltage or across-the-line magnetic induction motor starter circuit** is shown below:



A typical across-the-line starter for an induction motor.

Circuit operation:

- when the start button is pressed, the relay or contactor coil M is energized, causing normally open contacts M1, M2 and M3 to close .
- Power is then applied to the motor, and the motor starts.
- Contact M4 also shuts, which shorts out the starting switch, allowing the operator to release it without removing power from the M relay.
- When the stop button is pressed, the M relay is deenergized, and the M contacts , stopping the motor.

A magnetic motor starter of this sort has several built-in protective features:

1. **Short circuit protection**
   ⇨ provided by fuses F_1, F_2 and F_3

2. **Overload protection**
   ⇨ provided by overload heaters & overload contacts (OL)

3. **Undervoltage protection**
   ⇨ through de-energising of M relays

7.8. 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 (design class A, B and C) is confined to less than 5% slip, and the speed variation is more or less proportional to the load on the motor shaft.

If slip is made higher, motor efficiency becomes very poor since rotor copper losses will be high as well ($P_{RCL} = sP_{AG}$).

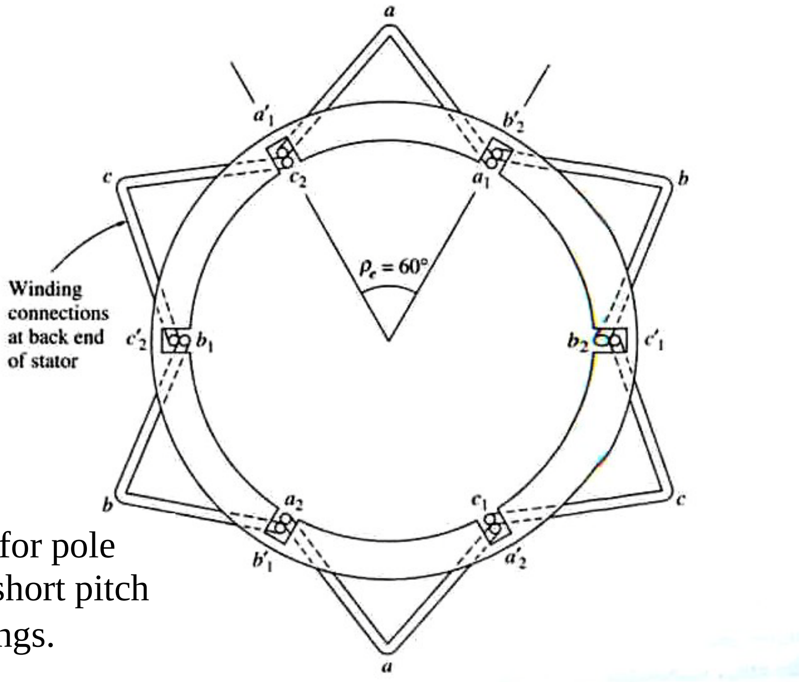
There are basically **2 techniques** to **control the speed** of an induction motor:

a) **Varying speed of the stator and rotor magnetic fields**, i.e. synchronous speed by:
   - **varying the electrical frequency** or
   - changing the ________________________

b) **Varying the slip** by:
   - varying the **rotor resistance** or
   - varying the _____________________________

Induction motor speed control by pole changing

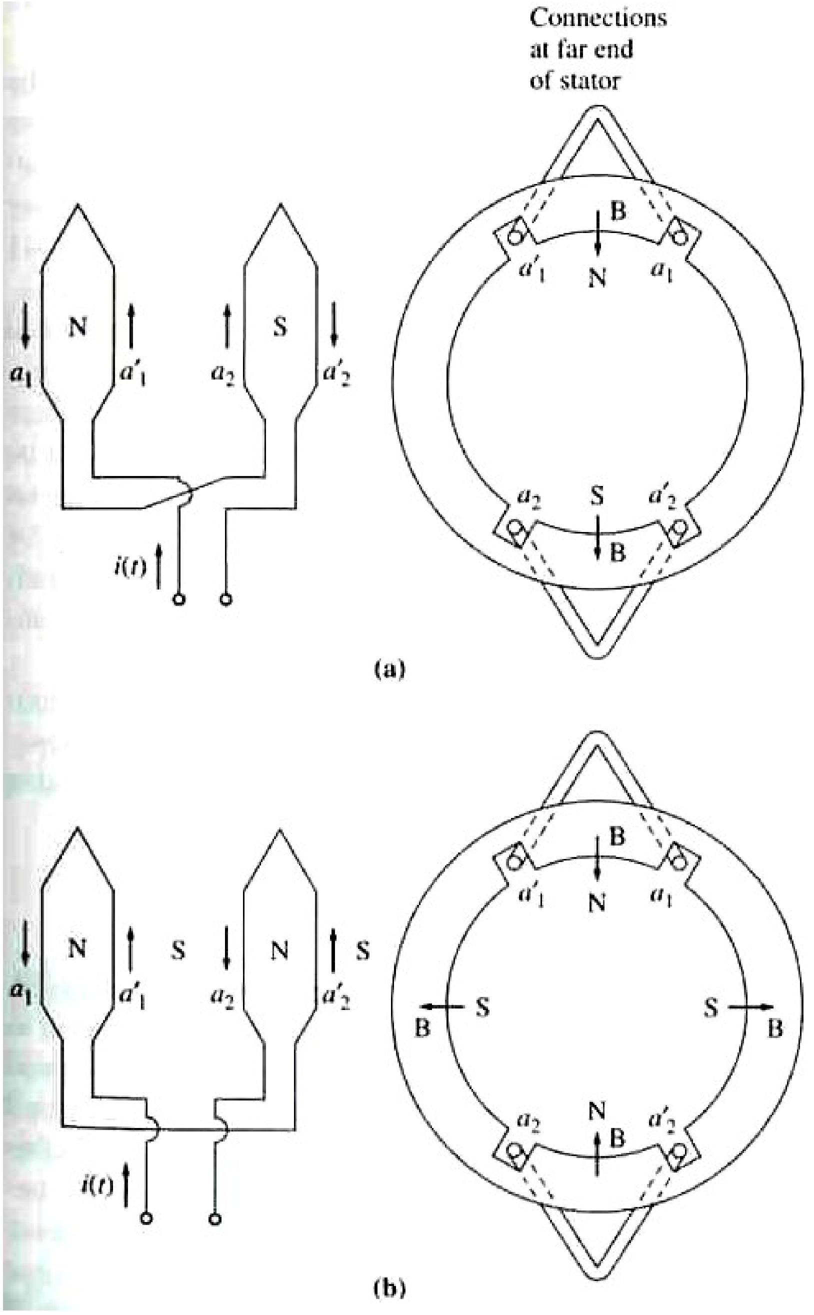
Method of consequent poles
(requires motor with special stator windings)



A two-pole stator winding for pole changing. Notice the very short pitch (60° to 90°) of these windings.

General Idea:

Consider one phase winding in a stator. By **changing** the **current flow in one portion** of the stator winding such that it is **similar to** the **current flow in the opposite portion** of the stator, an **extra pair of poles is generated**.



Close up view of one phase of a pole changing winding.

(a) In the 2-pole configuration, one coil is a north pole and the other 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 halfway between the two coils. The south poles are called consequent poles. Hence the winding is now 4-pole.

Rotor must be of cage type.

In terms of torque, the maximum torque magnitude would generally be maintained.
Disadvantage:

- **speed changes must be in a ratio of 2:1**.

Hence **to obtained variations** in speed, **multiple stator windings** have to be applied:

- **extra sets of windings with different number of poles** that may be energized one at a time as required.
  (eg: IM wound with 4-pole and 6-pole set of stator windings to give switch in n_{sync} from 1800 rpm to 1200 rpm on a 60-Hz system)

- Unfortunately this is an **expensive alternative**.

Combination of consequent poles and multiple stator windings creates a four-speed induction motor.

Speed control by changing the line frequency

This is also known as **variable frequency control.**

Changing the **electrical frequency** will **change** the **synchronous speed** of the machine.

Base speed = **synchronous speed of motor at rated conditions**

Hence, it is possible to adjust speed of motor either above or below base speed.

BUT it also **requires terminal voltage limitation** 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** will flow

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

	Below base speed	Above base speed
Terminal (stator) voltage	**decreased linearly with decrease in stator frequency**, i.e. ***derating***	**held constant at rated value**
Motor speed	varying	varying
Flux level		
Operating torque		
Notes	**maximum power rating must also be decreased to protect from overheating**	-

Note:
Flux in the core of an induction motor is given by Faraday's Law $v(t) = -N\frac{d\phi}{dt}$.

If $v(t) = V_\mathrm{M}\sin\omega t$ is applied, the resulting flux ϕ is:

$$\phi = \frac{1}{N}\int v(t)dt = \frac{1}{N}\int V_\mathrm{M}\sin\omega t dt = -\frac{V_\mathrm{M}}{\omega N_\mathrm{P}}\cos\omega t$$

There may also be instances where both characteristics are needed in the motor operation, hence it is **possible to combine both effects**.

With the arrival of solid state devices/power electronics, variable frequency control has become the method of choice for induction motor speed control.

Advantage: can be used with *any* induction motor.

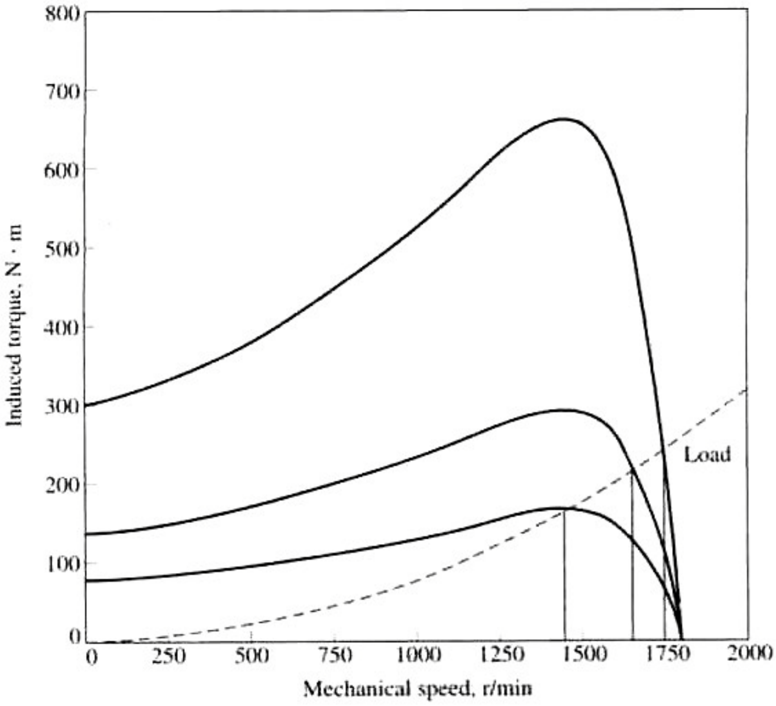
Speed control by changing the line voltage

Varying the terminal voltage will vary the operating speed.

But it **also causes variation** of **operating torque** since $\boldsymbol{\tau_{\text{start}} \propto V_T^2}$

However, it only allows for motor speed variations over **limited range**.

Hence, this method is **only suitable** for **small motors**.



Variable-line-voltage speed control in an induction motor.

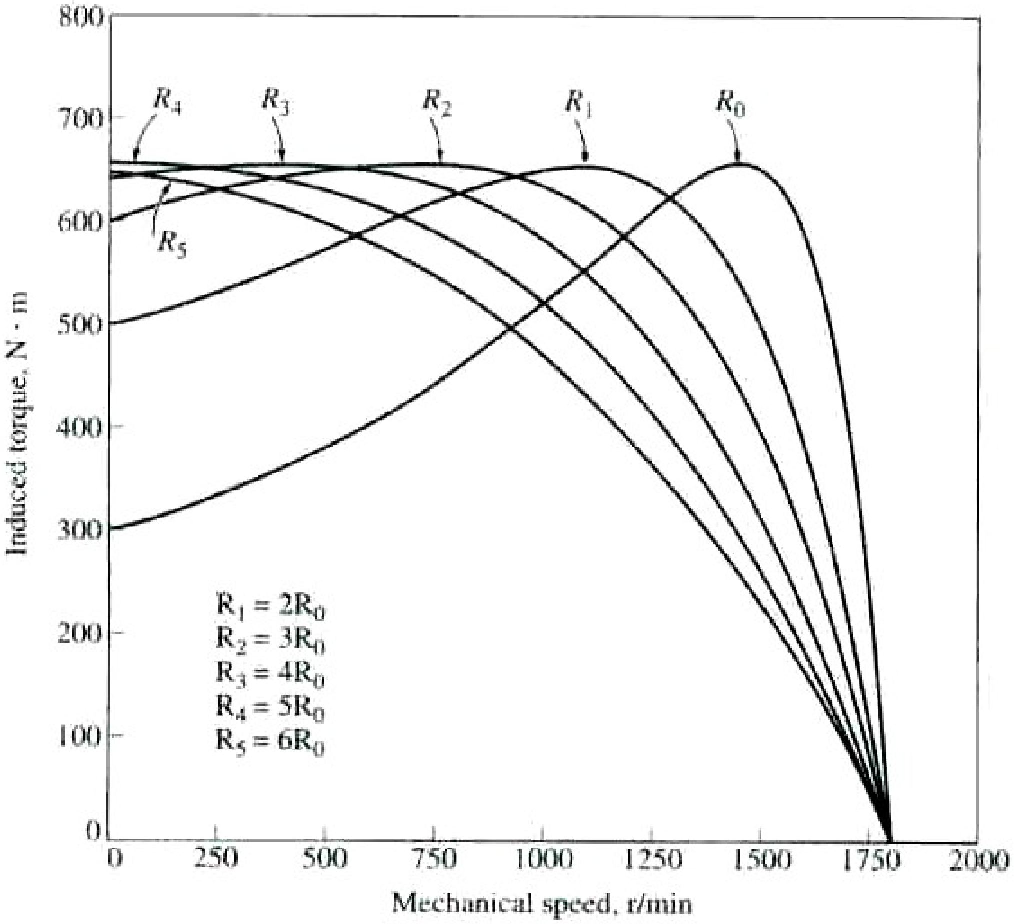
Speed control by changing the rotor resistance

This is **only possible** for **wound rotor induction motors,** i.e we can

⇨ add ________________________________ to vary the torque-speed curve.

BUT this **causes reduction in motor efficiency**.

Hence, it is used **only for short periods**.



Speed control by varying the rotor resistance of a wound-rotor induction motor.

7.9. Determining circuit model parameters

If a model of a real induction motor is required for analysis, determination of the equivalent circuit parameter values is essential, i.e. R_1, R_2, X_1, X_2 and X_M.

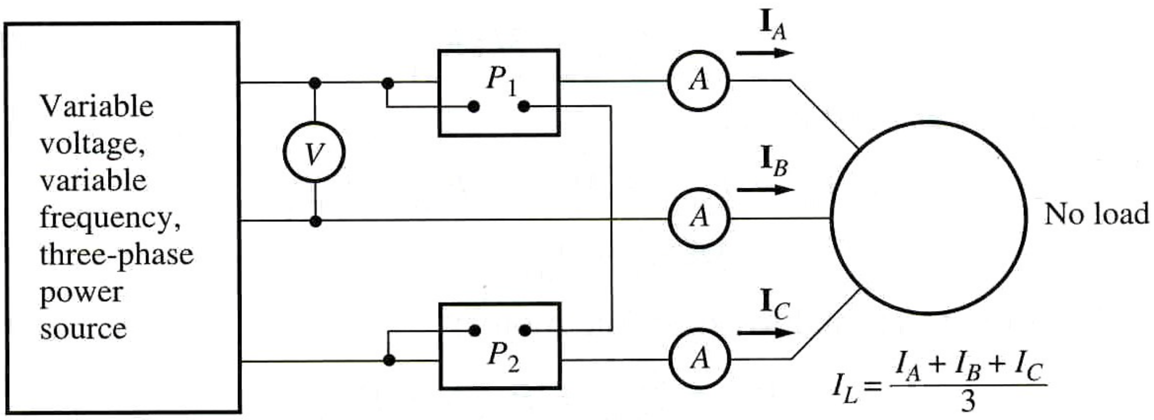
This is achieved by conducting **three types of tests**:

a) No-load test
b) DC test
c) Locked-rotor or blocked-rotor test

The no-load test

- **measures** the **rotational losses** of the motor
- provides **information** about **magnetisation current**.

Test circuit:



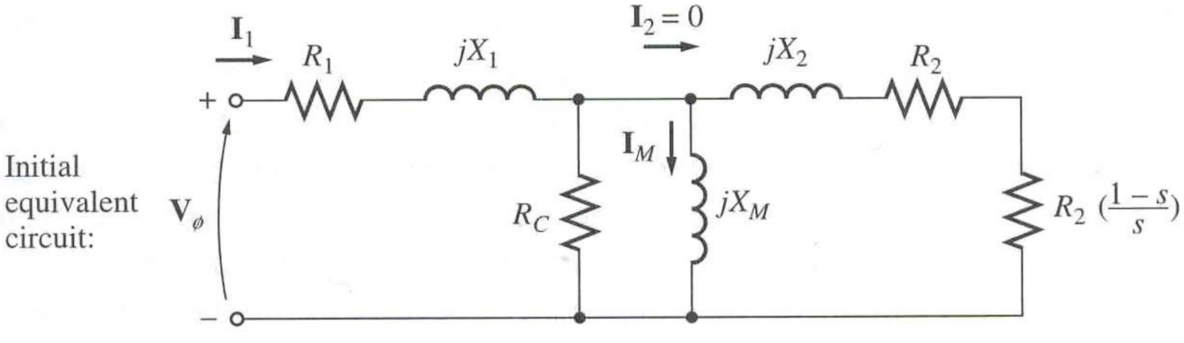
Method:

1) An ac voltage is applied to the IM with **rotor allowed to spin freely** (no load).
2) **Input voltage, V_ϕ , current $I_{1,\mathrm{nl}}$ and input power $P_{\mathrm{in,nl}}$** are **measured**.

The motor is not loaded, i.e. it **only has load due to friction and windage**.

All P_{conv} is consumed by mechanical losses and s is very small.

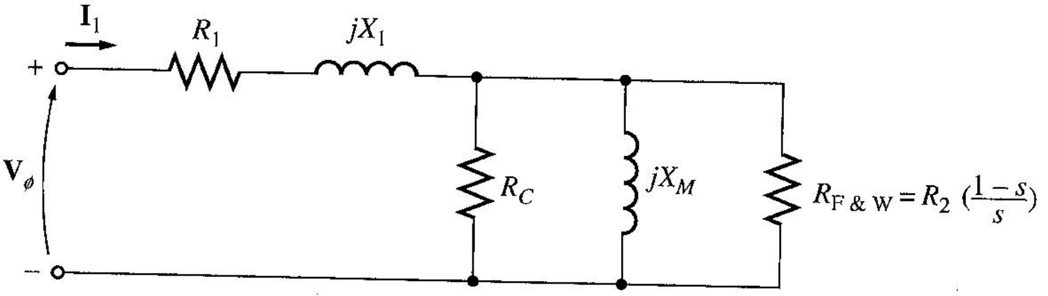
The initial equivalent circuit of this motor is:

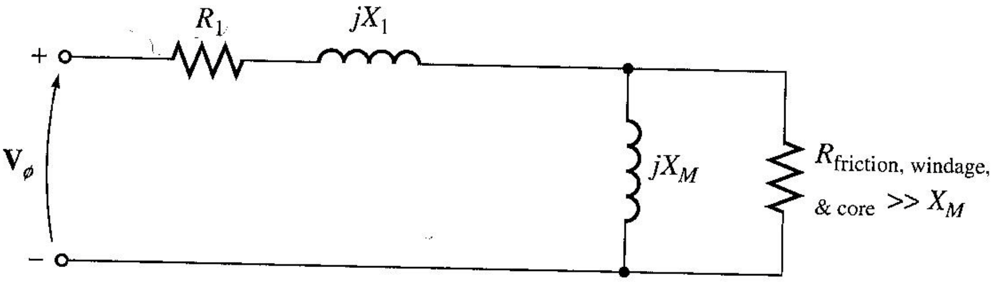


However, with **very small slip** (approx. 0.001 or less),

- $R_{\text{conv}} = R_2 \frac{(1-s)}{s} \gg R_2$
- $R_{\text{conv}} = R_2 \frac{(1-s)}{s} \gg X_2$

Hence, the **equivalent circuit reduces** to:





At **no-load** conditions,

***P_{in}* (measured by wattmeters) = losses in the motor**.

Rotor copper losses ***P_{RCL}* is negligible** because I_2 is extremely small (due to large load resistance $R_2(1-s)/s$)

The stator copper loss = ***P_{SCL}*** = $3I_1^2R_1$. Hence,

$$P_{\text{in,nl}} = P_{\text{SCL}} + P_{\text{core}} + P_{\text{F\&}W} + P_{\text{misc}}$$
$$P_{\text{in,nl}} = P_{\text{SCL}} + P_{\text{rot}}$$

$$P_{\text{rot}} = P_{\text{core}} + P_{\text{F\&}W} + P_{\text{misc}}$$

The equivalent circuit shows R_c and $R_2(1-s)/s$ in parallel with X_M.

However, induction motor **magnetising current is large** due to the high reluctance in air gap, hence the reactance $X_M$must be much smaller than the resistance in parallel with it.

This causes small overall input power factor and with large lagging current most of voltage is dropped across **inductive components** in the circuit.

Therefore, the **equivalent input impedance** is approximately given by:

If X_1 is found some other way, then X_M will be known.

The DC test

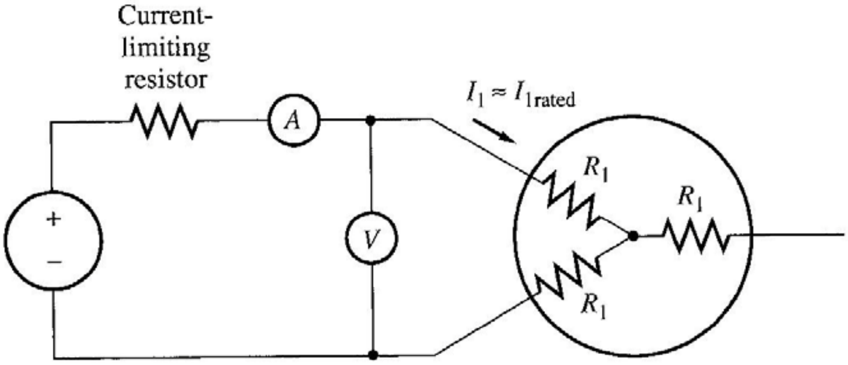
- **Determines R_1** (independent of R_2, X_1 and X_2).

DC voltage is applied to the **stator winding terminals**, thus $\boldsymbol{f = 0}$.

And no induced voltage in the rotor.

Current flows only in stator circuit and is **limited by stator resistance**, R_1 and can be determined.

Test circuit:



Method:

1) DC voltage is applied across **two of the three terminals** of the **Y-connected IM** with **stator current adjusted to rated value** (to obtain normal operating condition temperature).
2) The **voltage V_{DC} and current I_{DC}** are **noted**.

Due to the **Y-connection**,

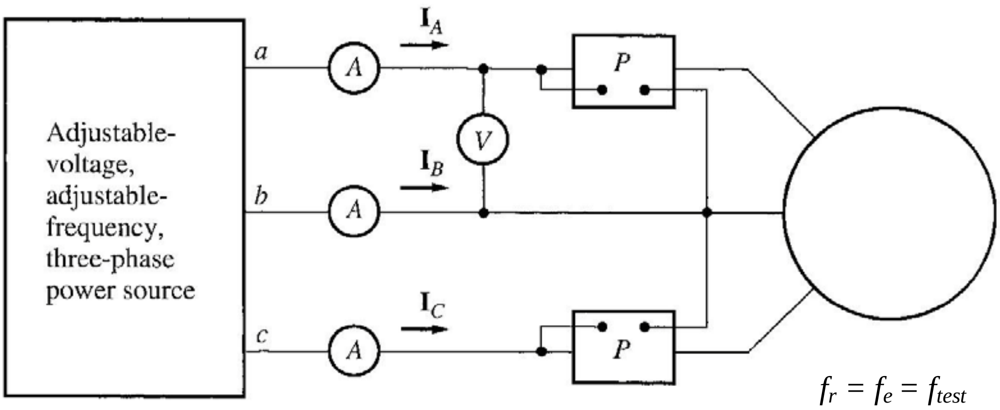
With R_1 known, $\boldsymbol{P_{\mathrm{SCL}}}$ **at no load can be determined** and finally the **rotational losses** $\boldsymbol{P_{\mathrm{rot}}}$ can be **calculated** (refer to “the no load test” above).

Unfortunately, $\boldsymbol{R_1}$ **calculated** from this method **is inaccurate** since it **neglects skin effect** which only occurs when ac voltage is applied to the windings.

The locked-rotor test (blocked-rotor test)

- **Determines R_2 and ($X_1 + X_2$)**

Test circuit:



Locked rotor

$f_r = f_e = f_{test}$

$$I_L = \frac{I_A + I_B + I_C}{3} \approx I_{L\,\mathrm{rated}}$$

The test is **generally inaccurate if the ac voltage applied is at the normal 50Hz or 60Hz frequency.** This is due to the fact that the **slip varies** from starting ($s = 1$) to normal operating speeds (s very small).

In **normal operating conditions**,

⇨ slip is only 2 - 4 % and
resulting rotor frequency is in the range of 1 – 3 Hz

Rotor frequency would **affect** the **rotor reactance**.

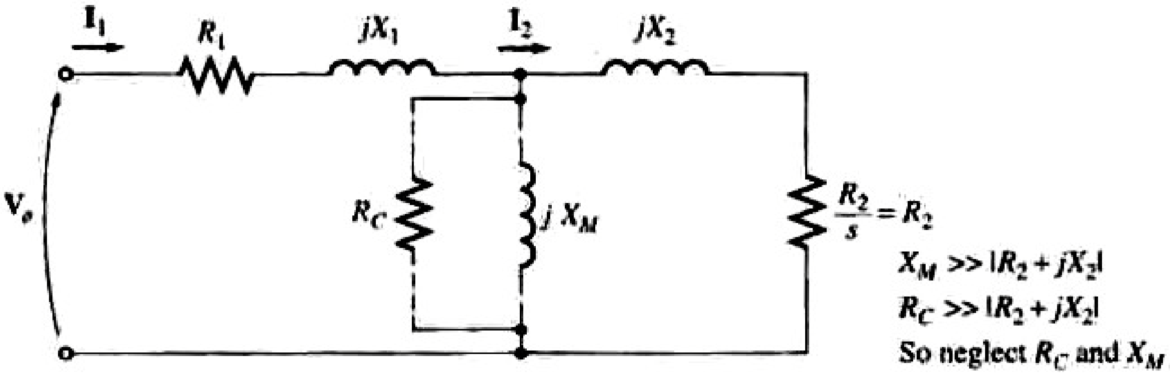
Therefore, this test is done with a ______________________________

______________________________ **to simulate small slip during operation**.

Method:

1) The **rotor is locked or blocked** (i.e. it cannot move).
2) An **ac voltage with frequency of 25% or less of the rated frequency** is applied to the stator terminals.
3) The **current flow** is quickly **adjusted** to be approximately **full-load value**.
4) The **voltage V_ϕ, current I_1 and input power P_{in}** of the motor are **measured quickly (**before the rotor heats up too much).

The equivalent circuit for this test is shown below:



Since the **rotor is blocked**, **slip = 1,** and as such

⇨ ________________________________

Hence, **almost all** of the **input current** will **flow through R_2 and X_2**, instead of through the magnetising branch.

Therefore, the overall equivalent circuit reduces to:

From this circuit, the input power is given by

$$P_{\text{in}} = \sqrt{3} V_{\text{T}} I_{\text{L}} \cos\theta$$

Hence, the **locked rotor power factor** can be found as

and the **impedance angle** $\theta = \cos^{-1}$ PF.

The magnitude of the total impedance in the motor circuit at this time is

Therefore, the **total impedance** is

$$Z_{\mathrm{LR}} = R_{\mathrm{LR}} + jX'_{\mathrm{LR}}$$

Hence the values of R_{LR} and X_{LR}' can be determined.

From the overall equivalent circuit for this test, we can define:

- **locked-rotor resistance R_{LR} =**
- **locked-rotor reactance X_{LR}' =**

where X_1' and X_2' are the stator and rotor reactances ***at the test frequency***.

Therefore, the **rotor resistance R_2** can now be found as

where R_1 was determined from the DC test.

Finally, since the reactance is proportional to the frequency, the **locked-rotor reactance at the normal operating frequency X_{LR}** can be determined from:

Unfortunately, there is no **simple way to separate the contributions of the stator reactance X_1 and rotor reactance X_2.**

However, based on experience there are certain proportions between X_1 and X_2 which apply to certain rotor design types as shown in the table below.

	X_1 *and* X_2 *as a function of* X_{LR}	
Rotor Design	**X_1**	**X_2**
Wound rotor	0.5 X_{LR}	0.5 X_{LR}
Design A	0.5 X_{LR}	0.5 X_{LR}
Design B	0.4 X_{LR}	0.6 X_{LR}
Design C	0.3 X_{LR}	0.7 X_{LR}
Design D	0.5 X_{LR}	0.5 X_{LR}

Rules of thumb for dividing rotor and stator circuit reactance.

Even so, **all torque calculations** are **based on** the **sum $X_1 + X_2$** and **not** their **individual values.**