POWER POINT PRESENTATION

ON

ELECTRICAL MACHINES - II

2016 - 2017

II B. Tech II semester (JNTUH-R15)

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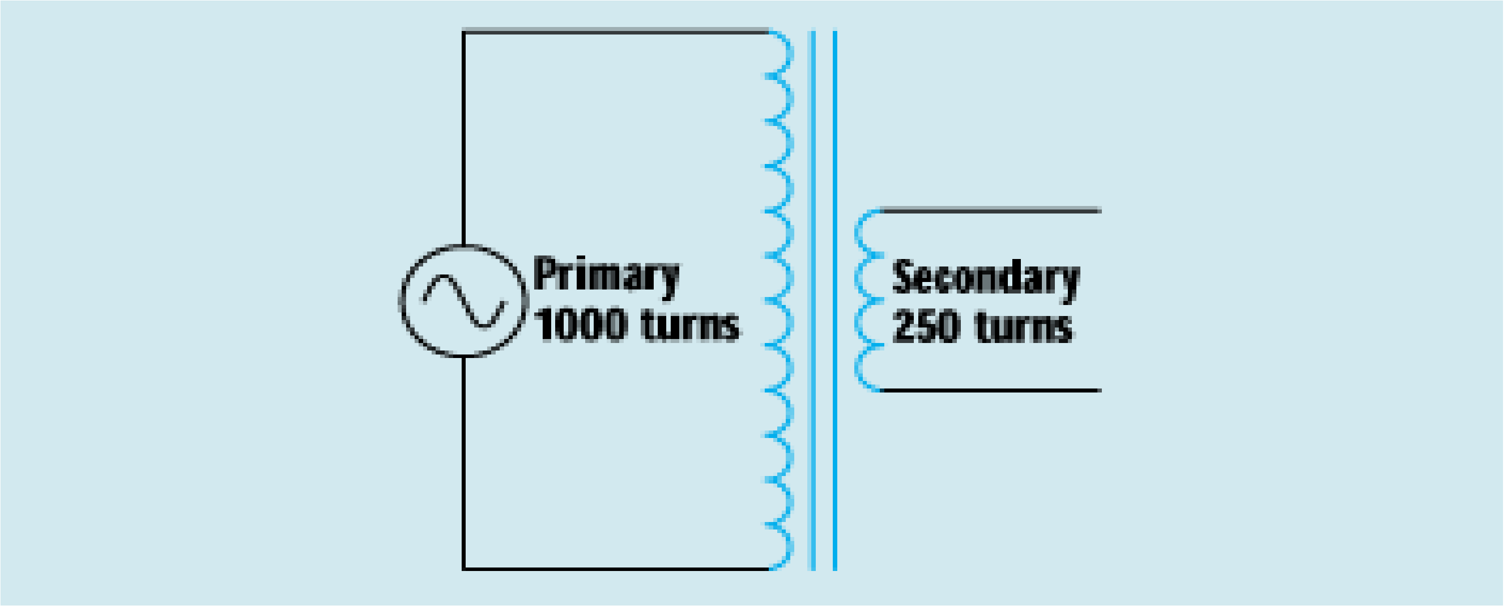
UNIT -I
Single-Phase Transformers

Single-Phase Transformers

Objectives:

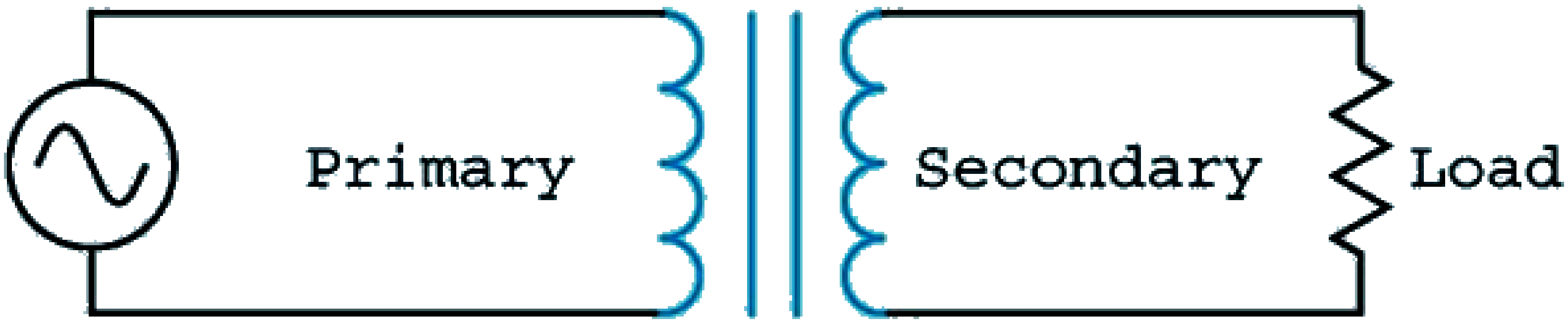
- Discuss the different types of transformers.
- List transformer symbols and formulas.
- Discuss polarity markings.

Single-Phase Transformers



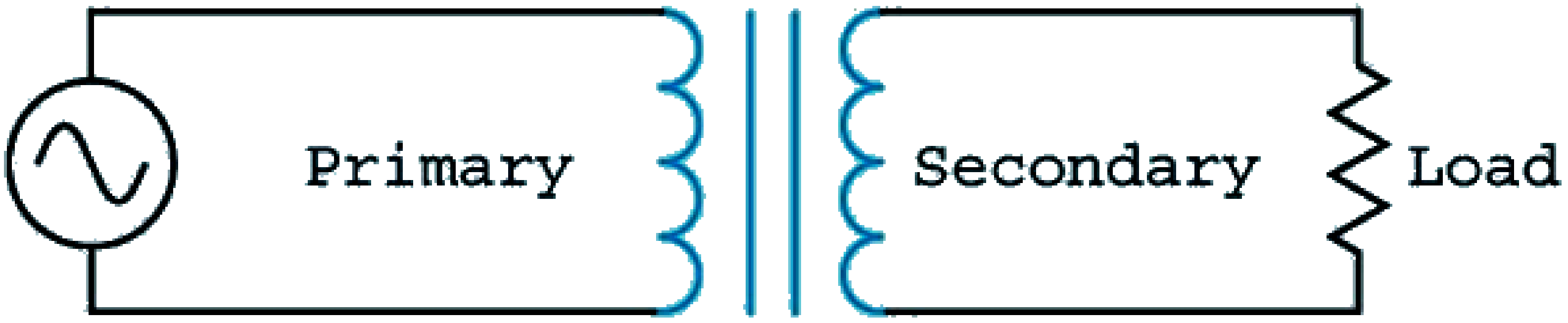
- A transformer is a magnetically operated machine.
- All values of a transformer are proportional to its turns ratio.

Single-Phase Transformers



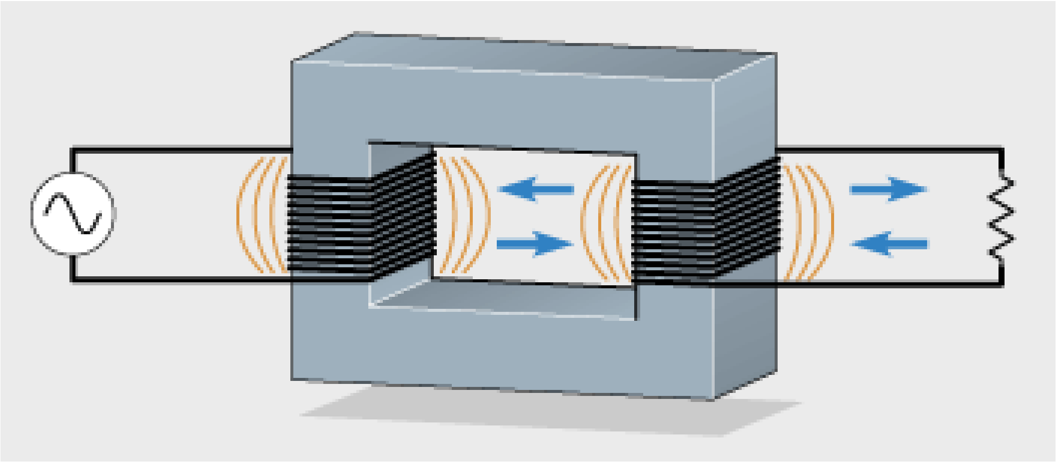
- The **primary winding** is connected to the incoming power supply.
- The **secondary winding** is connected to the driven load.

Single-Phase Transformers



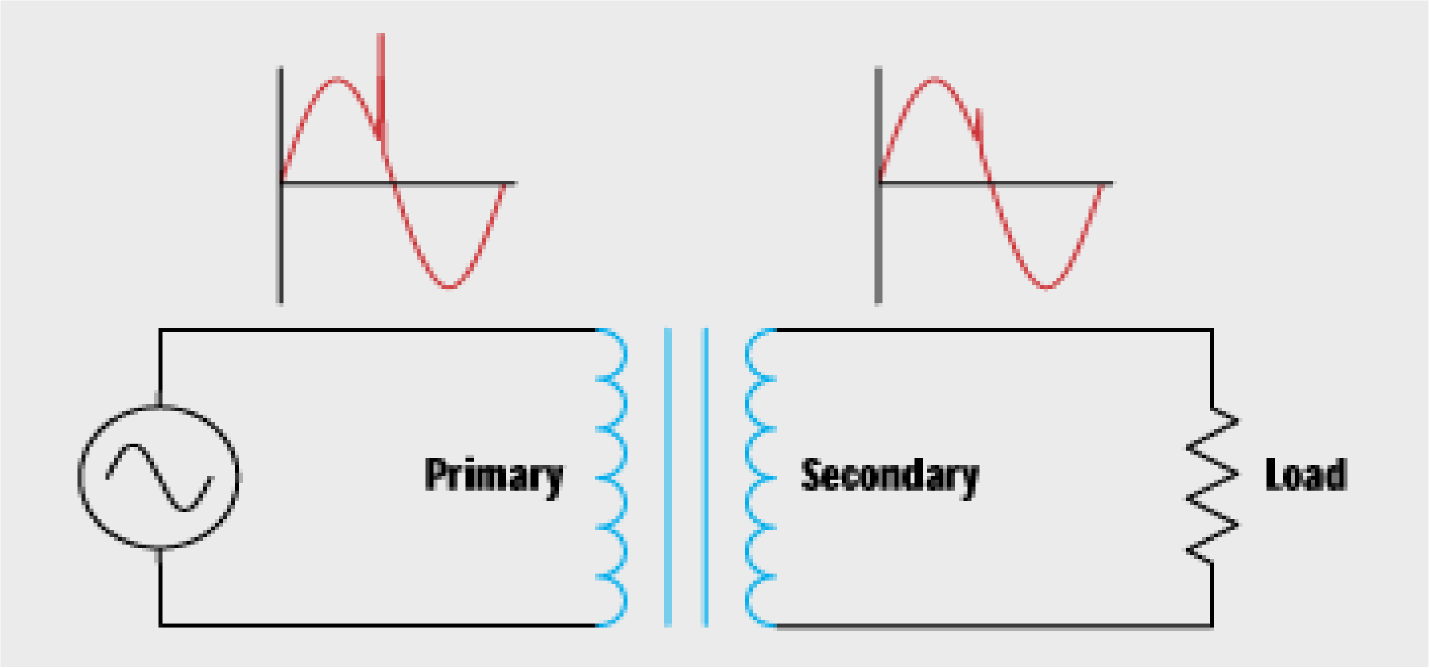
- This is an **isolation transformer**. The secondary winding is physically and electrically isolated from the primary winding.

Single-Phase Transformers



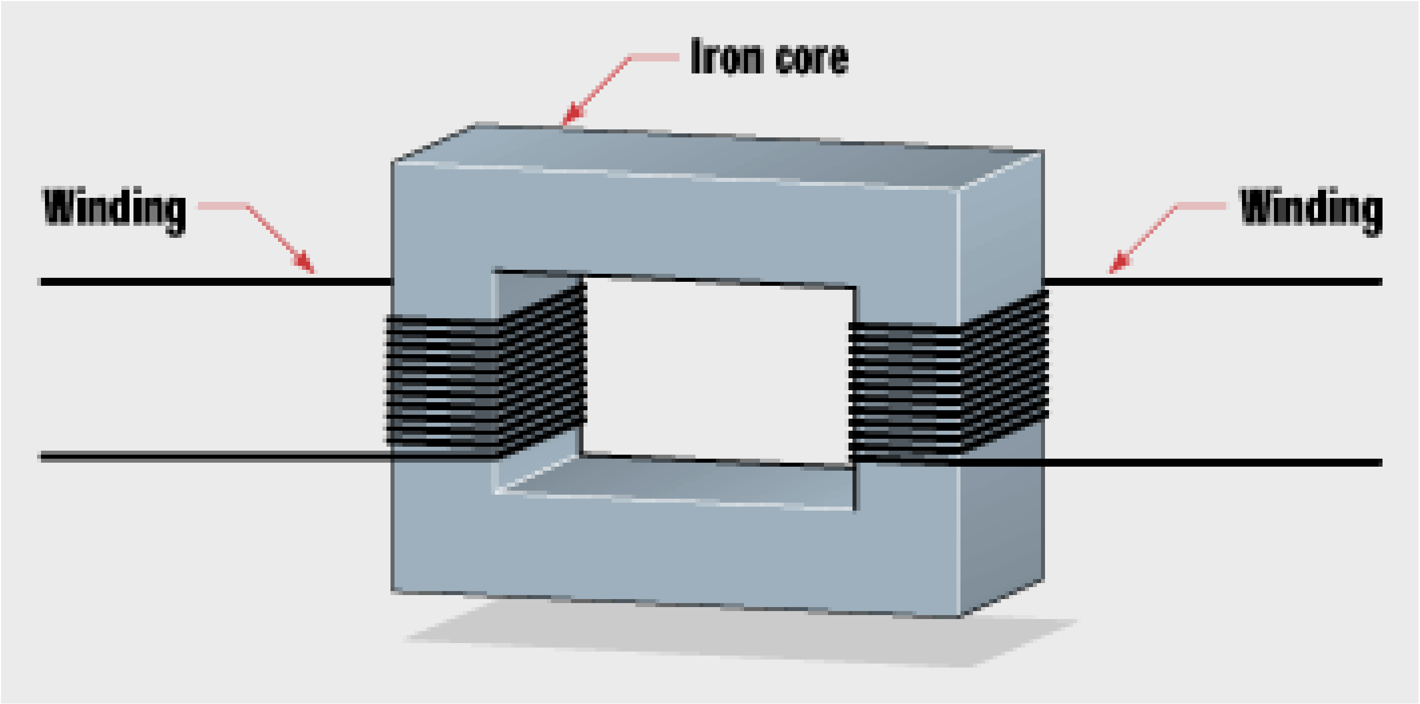
- The two windings of an isolation transformer are linked together by the magnetic field.

Single-Phase Transformers



- The isolation transformer greatly reduces voltage spikes.

Single-Phase Transformers



- Basic construction of an isolation transformer.

Single-Phase Transformers

- Each set of windings (primary and secondary) is formed from loops of wire wrapped around the core.
- Each loop of wire is called a **turn**.
- The ratio of the primary and secondary voltages is determined by the ratio of the number of turns in the primary and secondary windings.
- The volts-per-turn ratio is the same on both the primary and secondary windings.

Single-Phase Transformers

Transformer Symbols

N_P = number of turns in the primary
N_S = number of turns in the secondary
E_P = voltage of the primary
E_S = voltage of the secondary
I_P = current in the primary
I_S = current in the secondary

Single-Phase Transformers

Transformer Formulas

$$E_P / E_S = N_P / N_S$$

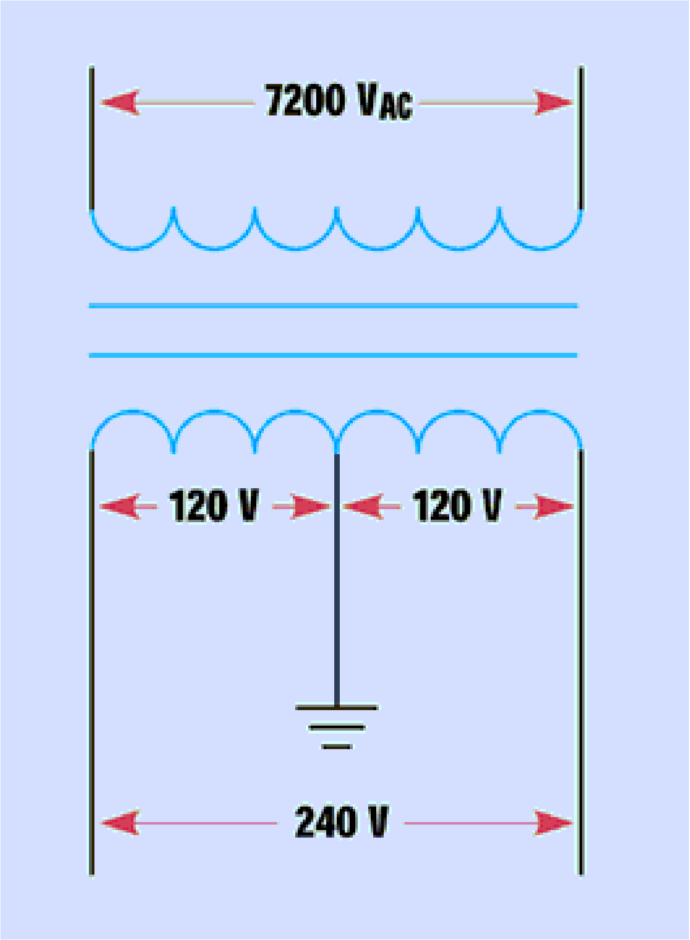
$$E_P \times N_S = E_S \times N_P$$

$$E_P \times I_P = E_S \times I_S$$

$$N_P \times I_P = N_S \times I_S$$

Single-Phase Transformers

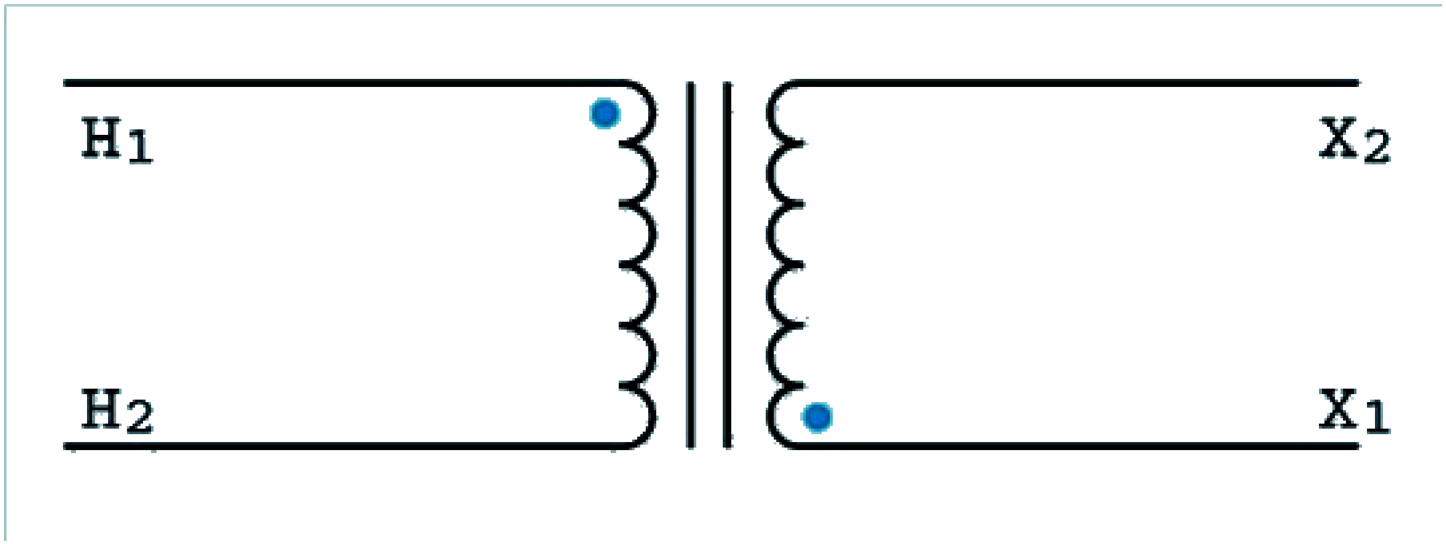
- The distribution transformer is a common type of isolation transformer. This transformer changes the high voltage from the power company to the common 240/120 V.



Single-Phase Transformers

- The control transformer is another common type of isolation transformer. This transformer reduces high voltage to the value needed by control circuits.

Single-Phase Transformers



- Polarity dots are placed on transformer schematics to indicate points that have the same polarity at the same time.

Single-Phase Transformers

Review:

1. All values of voltage, current, and impedance in a transformer are proportional to the turns ratio.
2. The primary winding of a transformer is connected to the source voltage.
3. The secondary winding is connected to the load.

Single-Phase Transformers

Review:

4. An isolation transformer has its primary and secondary voltage electrically and mechanically separated.
5. Isolation transformers help filter voltage and current spikes.
6. Polarity dots are often added to schematic diagrams to indicate transformer polarity.

Transformer Regulation

- Loading changes the output voltage of a transformer.

Definition of % Regulation

$$= \frac{|V_{no-load}| - |V_{load}|}{|V_{load}|} * 100$$

$V_{no-load}$ =RMS voltage across the load terminals without load
V_{load} = RMS voltage across the load terminals with a specified load

Maximum Transformer Regulation

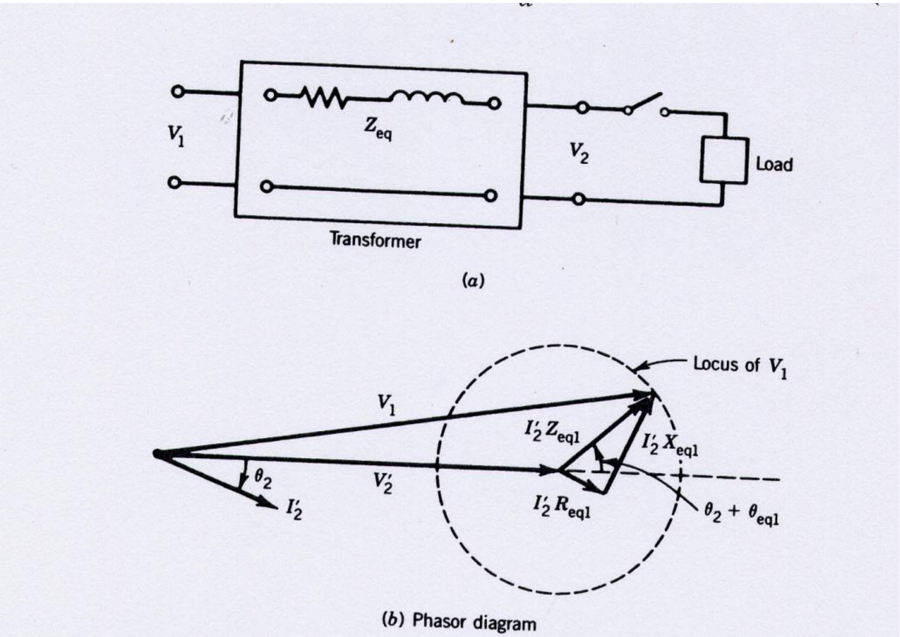


FIGURE 2.14 Voltage regulation.

$$V_1 = V_2^{'}\angle 0^0 + I_2^{'}\angle \theta_2^{0} . Z_{eq1}\angle \theta_{eq1}^{0}$$

$$Clearly\;\; V_1 \;\; is\; \max imum\; when$$

$$\theta_2 + \theta_{eq1} = 0; or\; \theta_2 = -\theta_{eq1}$$

Transformer Losses and Efficiency

- Transformer Losses
  - Core/Iron Loss $= V_1^2 / R_{c1}$
  - Copper Loss $= I_1^2 R_1 + I_2^2 R_2$

Definition of % efficiency

$$= \frac{V_2 I_2 Cos\theta_2}{Losses + V_2 I_2 Cos\theta_2} * 100$$

$$= \frac{V_2 I_2 Cos\theta_2}{V_1^2 / R_{c1} + I_1^2 R_1 + I_2^2 R_2 + V_2 I_2 Cos\theta_2} * 100$$

$$= \frac{V_2 I_2 Cos\theta_2}{V_1^2 / R_{c1} + I_2^2 R_{eq2} + V_2 I_2 Cos\theta_2} * 100$$

$Cos\theta_2$ = load power factor

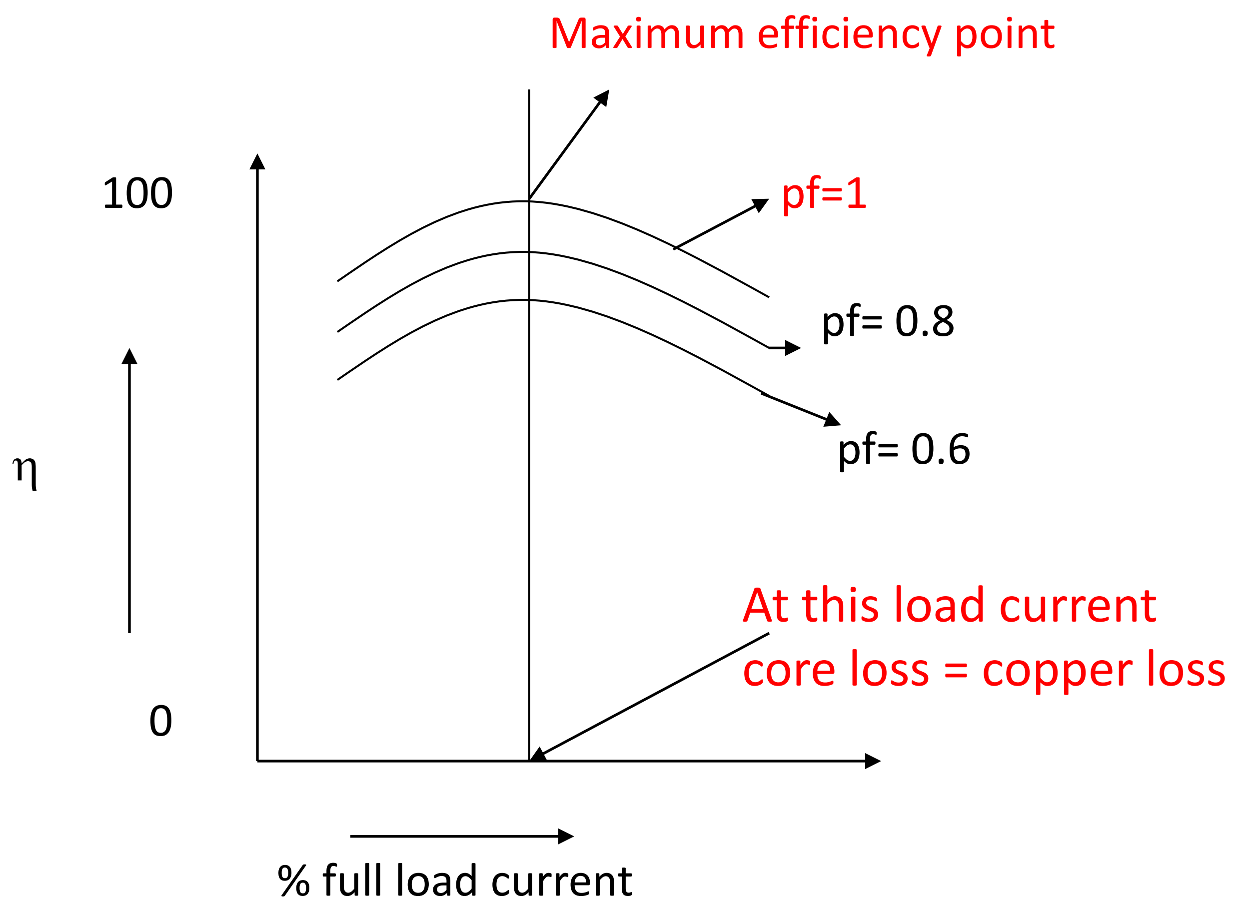
Maximum Transformer Efficiency

The efficiency varies as with respect to 2 independent quantities namely, current and power factor

- Thus at any particular power factor, the efficiency is maximum if core loss = copper loss .This can be obtained by differentiating the expression of efficiency with respect to I_2 assuming power factor, and all the voltages constant.

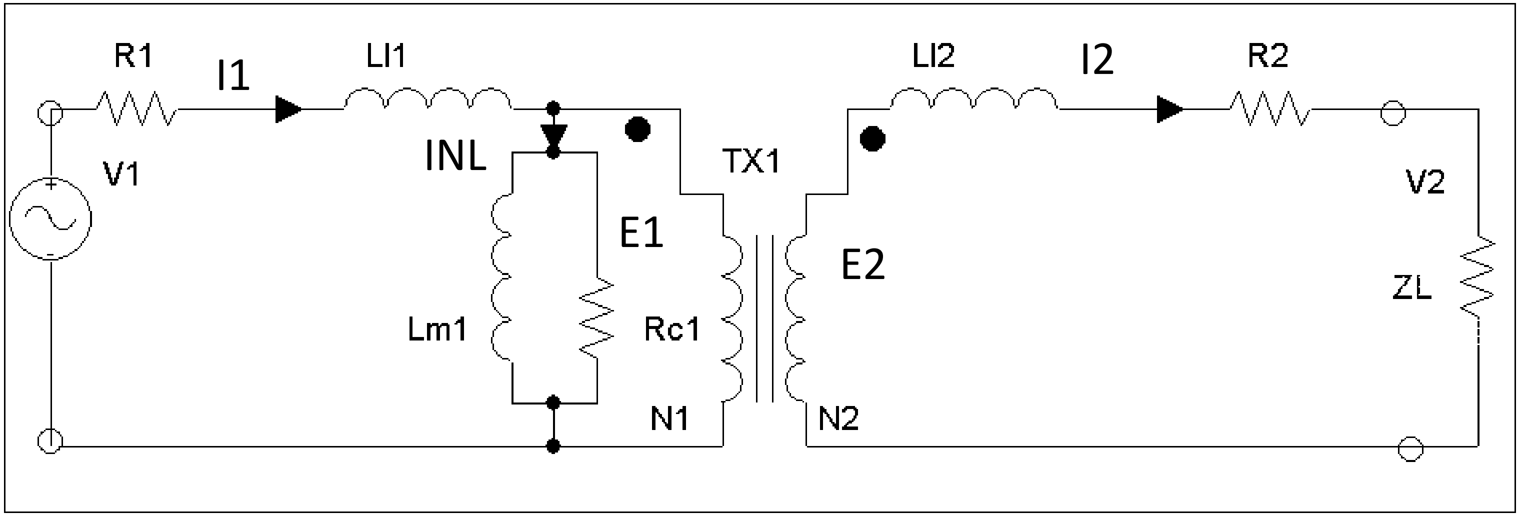
- At any particular I_2 maximum efficiency happens at unity power factor. This can be obtained by differentiating the expression of efficiency with respect to power factor, and assuming I_2 and all the voltages constant.

- Maximum efficiency happens when both these conditions are satisfied.

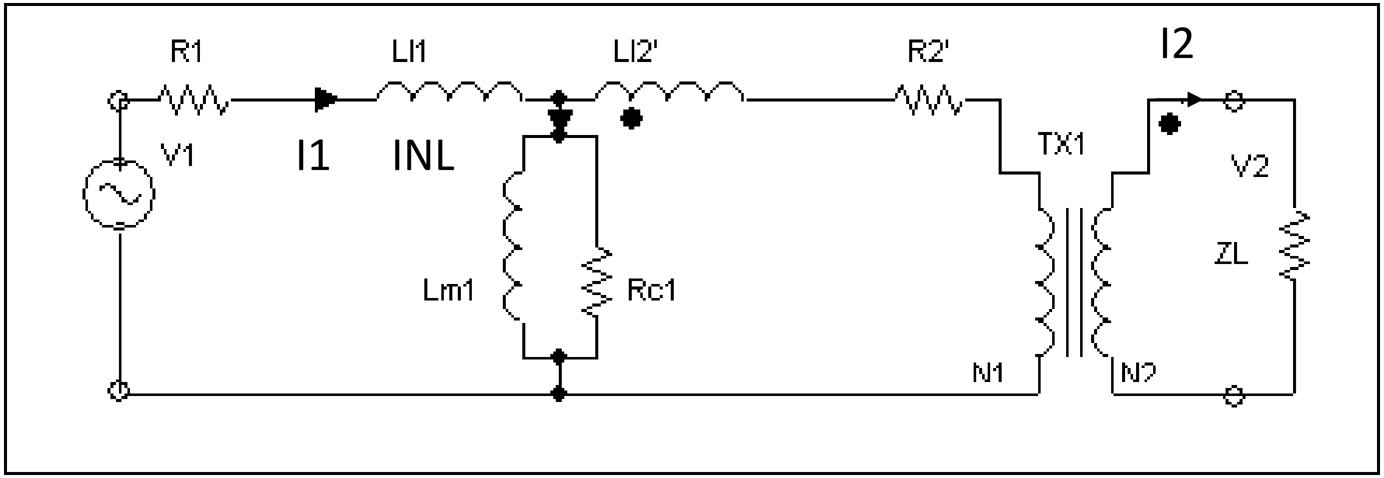


Maximum efficiency point
100
pf=1
pf= 0.8
pf= 0.6
η
At this load current
core loss = copper loss
0
% full load current

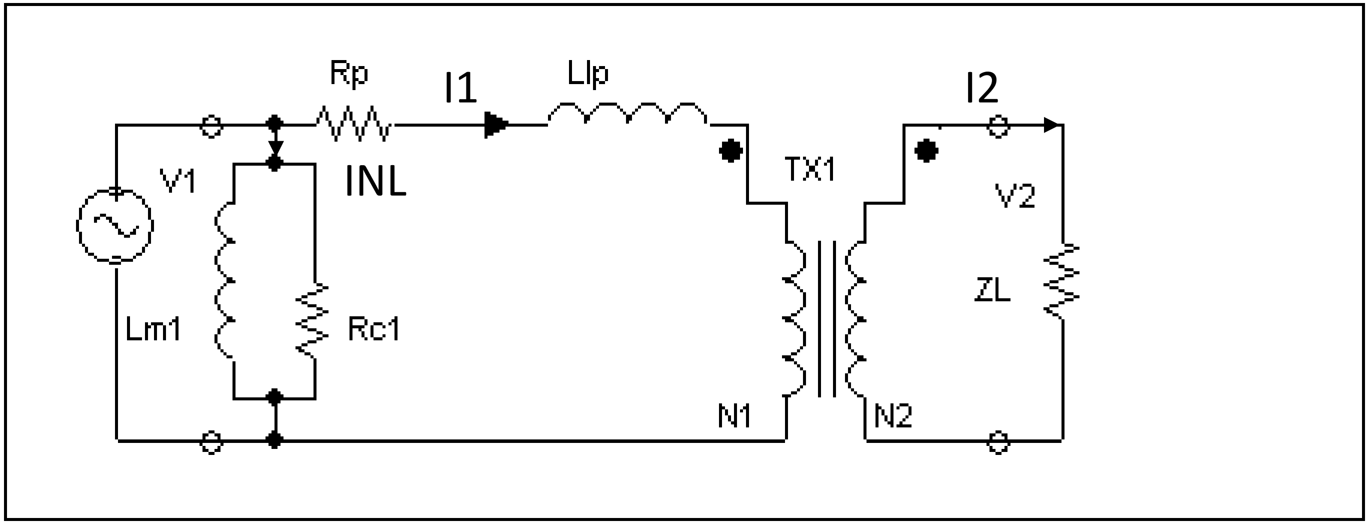
Transformer Equivalent circuit (1)



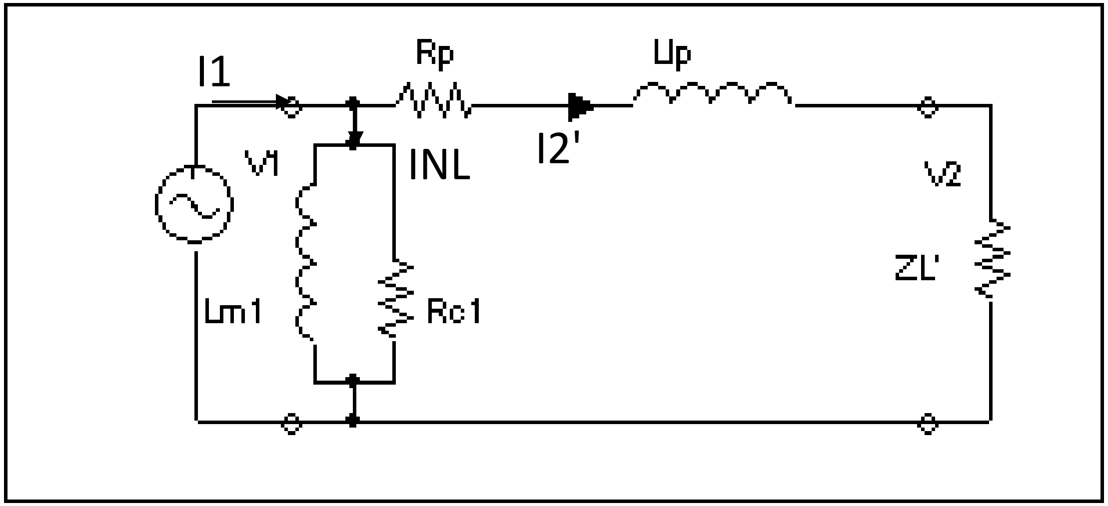
Transformer Equivalent circuit (2)



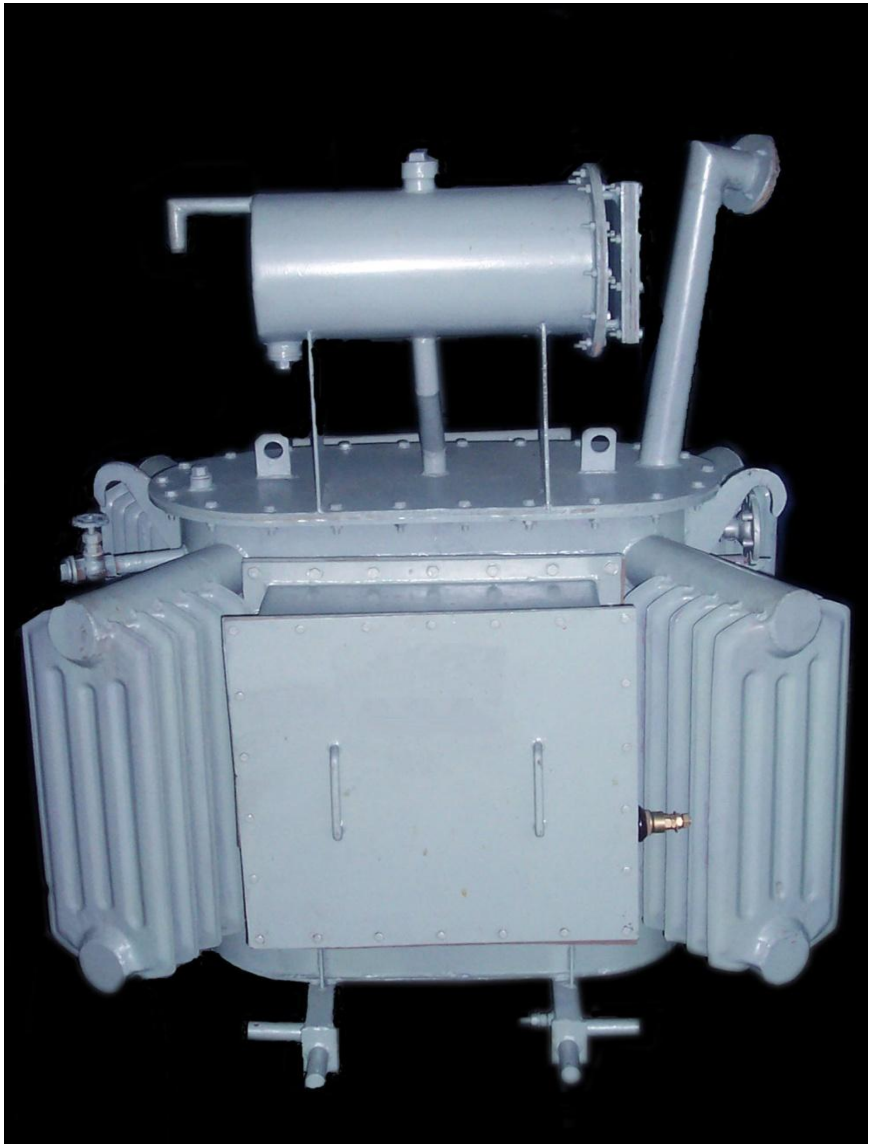
Transformer Equivalent circuit (3)



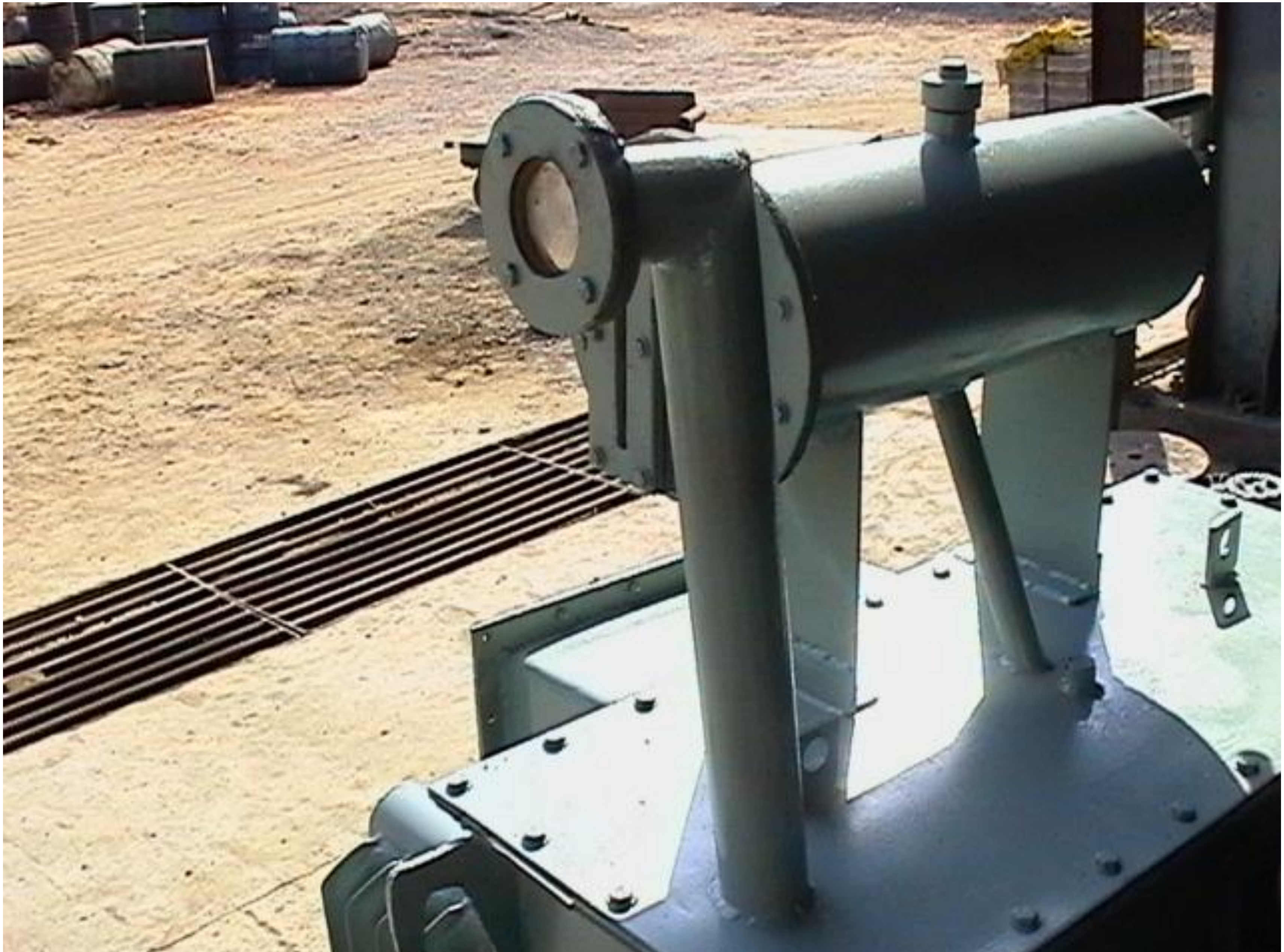
Transformer Equivalent circuit (4)



PARTS OF TRANSFORMER

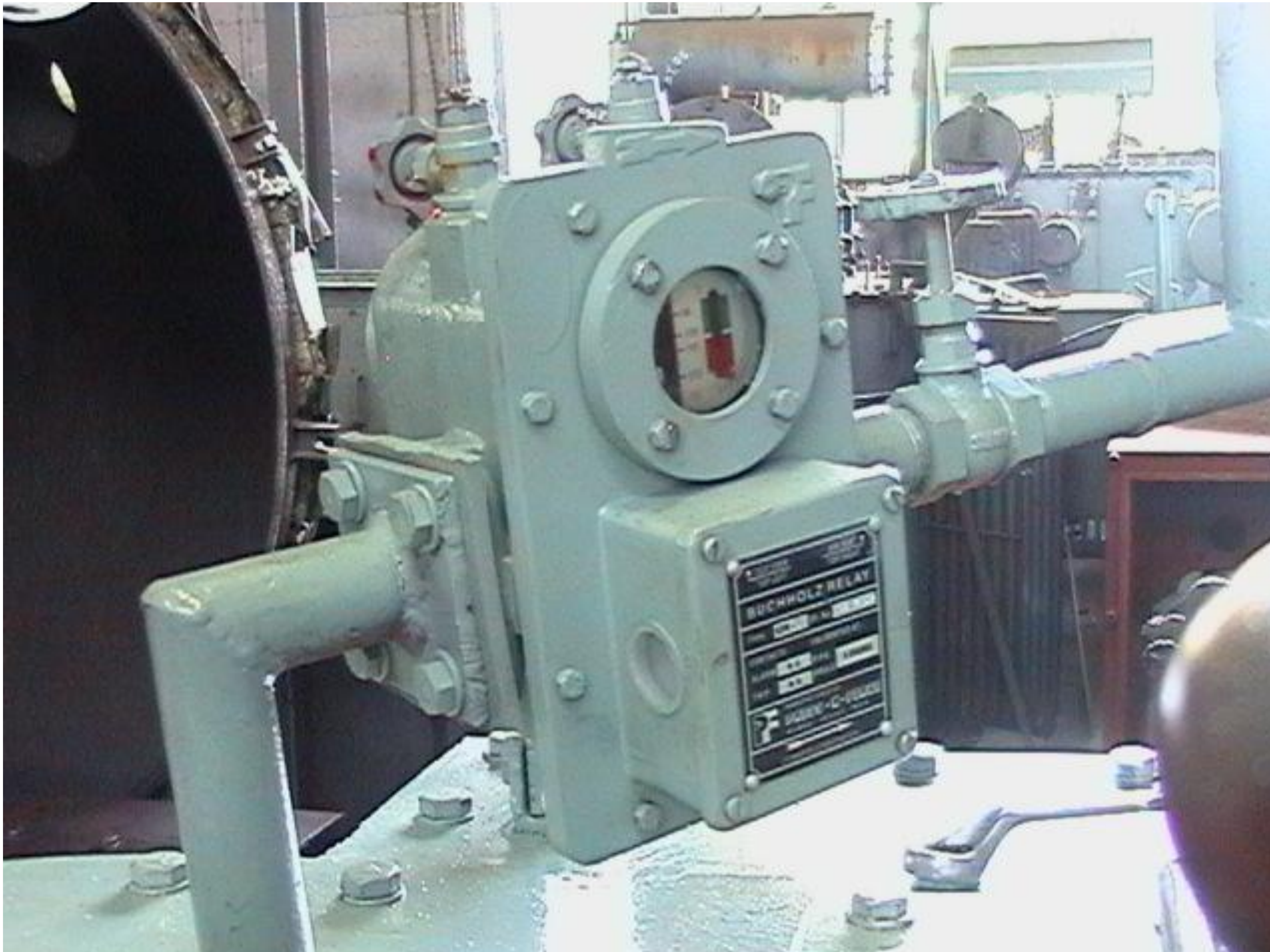


- MAIN TANK
- RADIATORS
- CONSERVATOR
- EXPLOSION VENT
- LIFTING LUGS
- AIR RELEASE PLUG
- OIL LEVEL INDICATOR
- TAP CHANGER
- WHEELS
- HV/LV BUSHINGS
- FILTER VALVES
- OIL FILLING PLUG
- DRAIN PLUG
- CABLE BOX




OPERATE OFF
CIRCUIT


2W
2V
2V


BUCHHOLZ RELAY

UNIT 2
TESTING OF TRANSFORMERS

TESTING OF TRANSFORMER

- Testing of single phase Transformers
  - OC Test
  - SC test
  - Sumpner's Test or Back to Back Test

Open circuit Test

- It is used to determine L_{m1} (X_{m1})and R_{c1}
- Usually performed on the low voltage side
- The test is performed at rated voltage and frequency under no load
- This test gives the values of core losses in a transformer

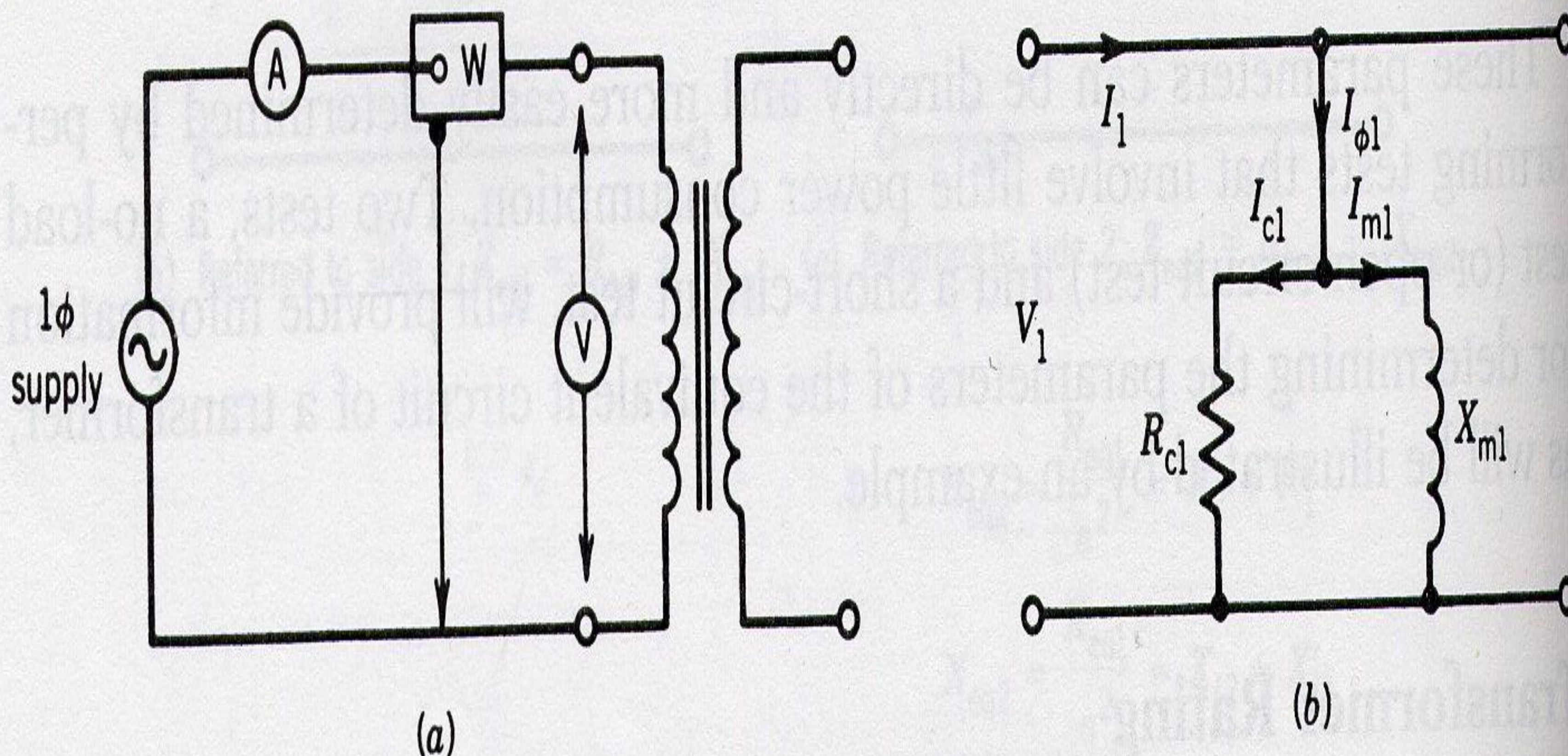


FIGURE 2.12 No-load (or open-circuit) test. (*a*) Wiring diagram for open-circuit test. (*b*) Equivalent circuit under open circuit.

W_{oc}= Core loss of the transformer

From the data

$Cos\phi = W_{oc}/(V_{oc}*I_{oc})$

$I_w = I_{oc}Cos\phi$

$I\mu = I_{oc} Sin\phi$

$R_{cl} = V_{oc}/I_w$

$X_{ml} = V_{oc}/I\mu$

Short circuit Test

- It is used to determine Ll_p (X_{eq}) and R_p(R_{eq})
- Usually performed on the high voltage side
- This test is performed at *reduced* voltage and rated frequency with the output of the low voltage winding short circuited such that rated current flows on the high voltage side.
- This test gives copper loss of the transformer.

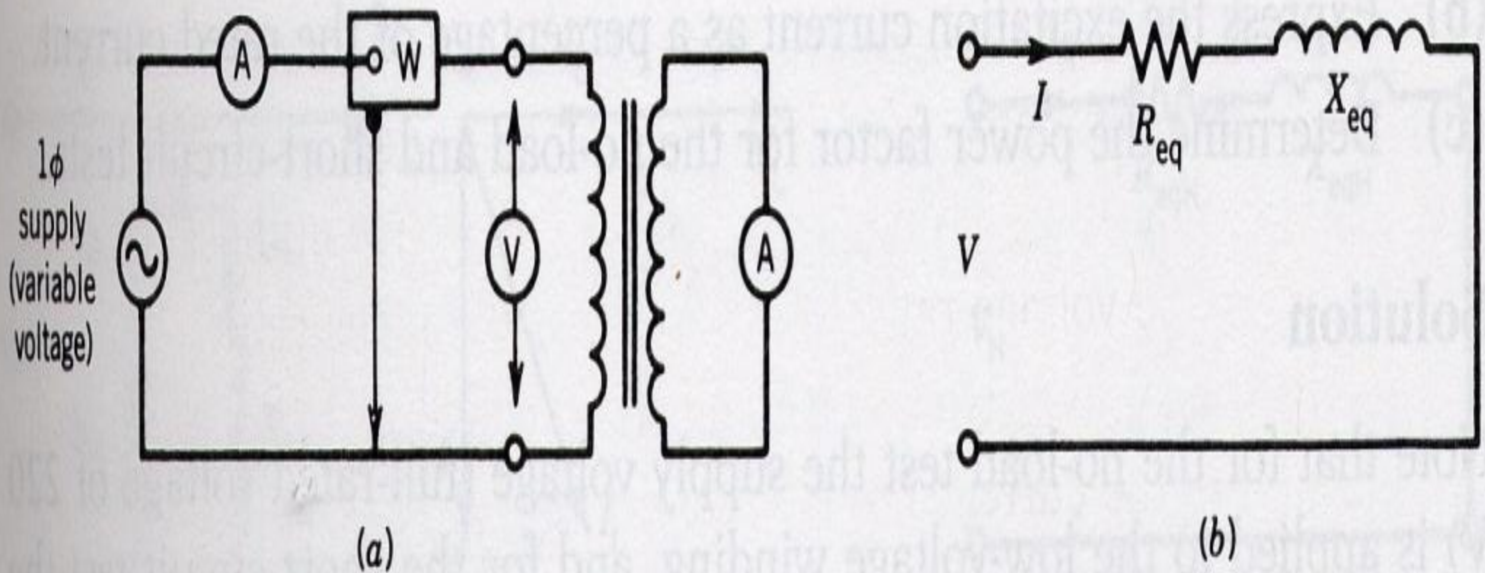


FIGURE 2.13 Short-circuit test. (*a*) Wiring diagram for short-circuit test. (*b*) Equivalent circuit at short-circuit condition.

Wsc= copper losses of the transformer.

$Zeq=Vsc/Isc$

$Req=Wsc/Isc^2$

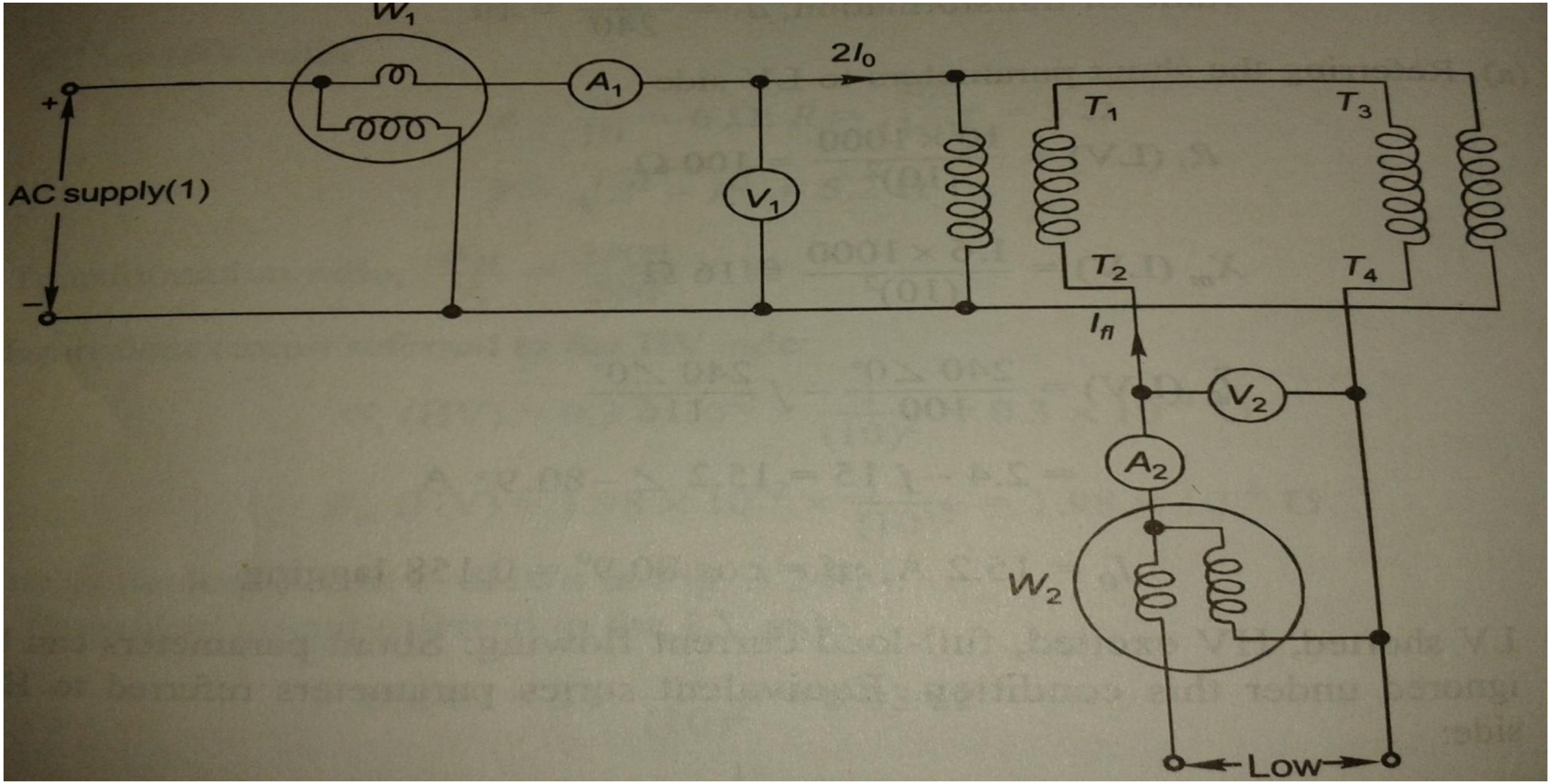
$Xeq=\sqrt{Zeq^2-Req^2}$

Efficiency of the transformer

η = output Power/ Input power

$\eta = XVICos\phi/(XVICos\phi + Pc + x^2Pcu)$

Sumpner's test or back to back test on set of transformers



From this test Losses and Efficiency of the two transformers can be determined

Parallel operation of transformers

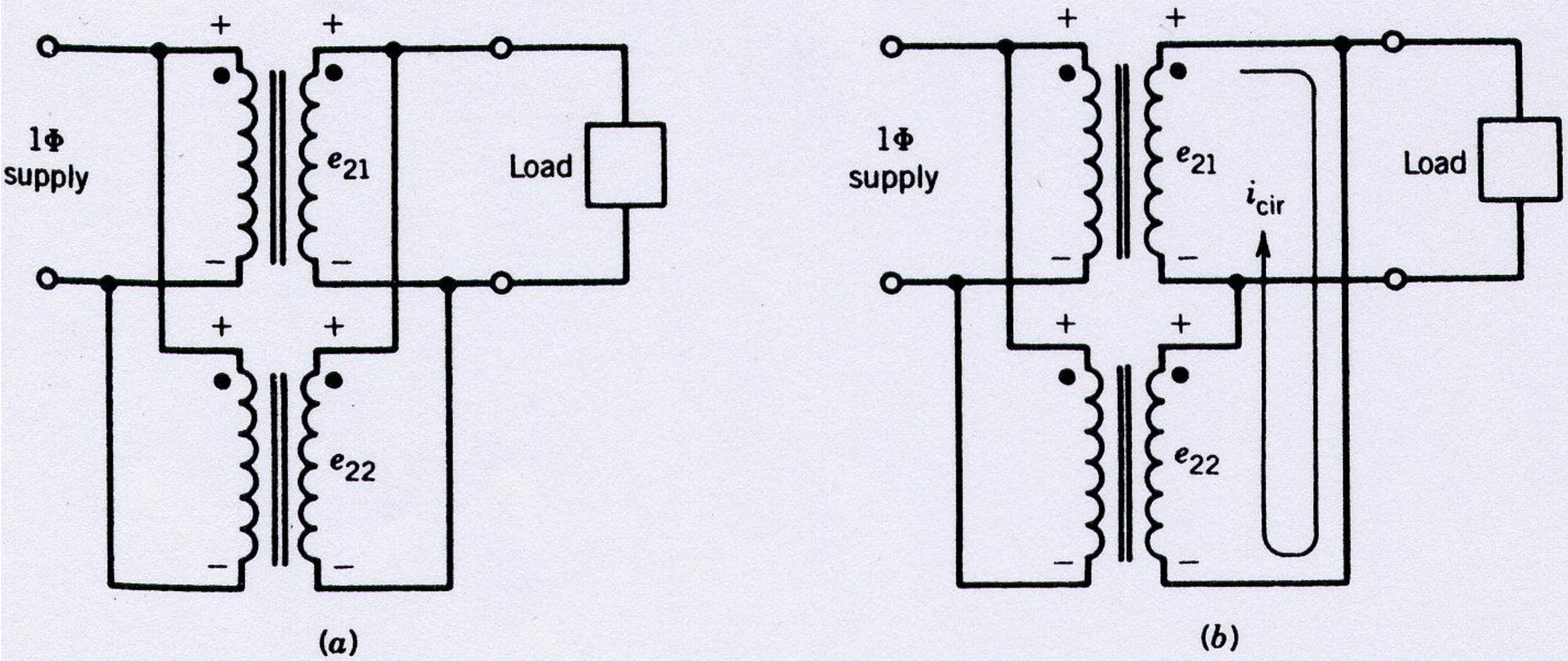


FIGURE 2.9 Parallel operation of single-phase transformers. (*a*) Correct connection. (*b*) Wrong connection.

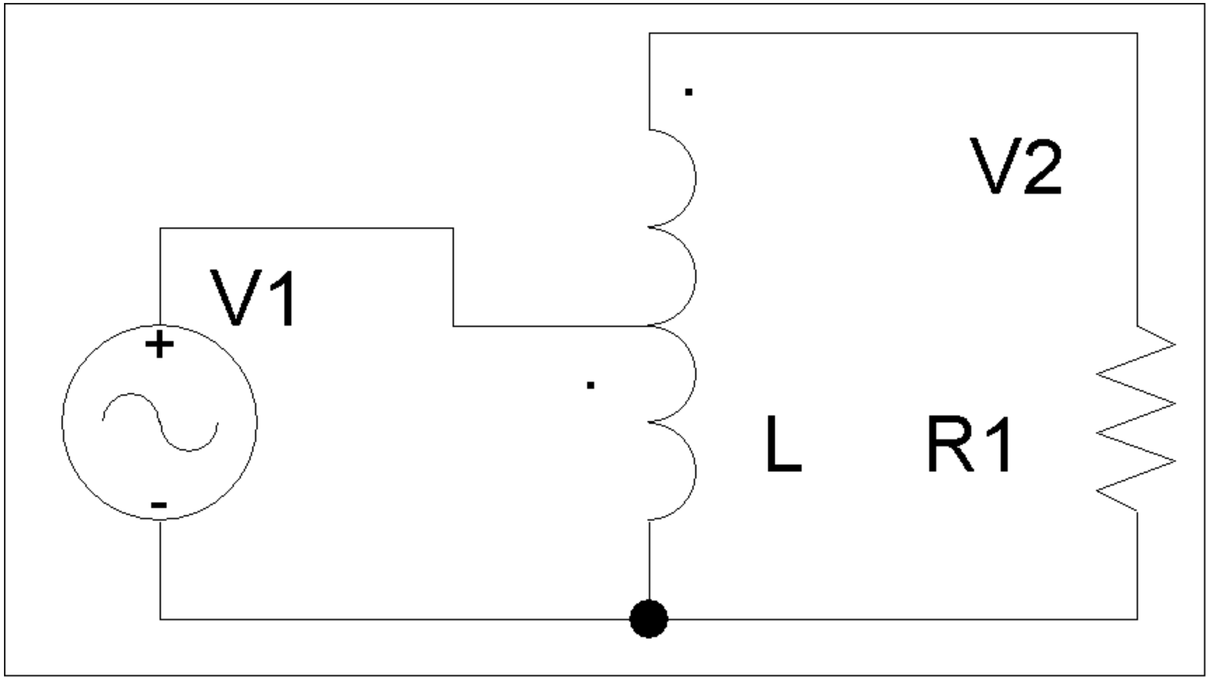
Wrong connections give circulating between the windings that can destroy transformers.

To connect the transformers in parallel the following conditions must be satisfied

i. Transformers must be of same rating.
ii. Transformers should have the same phase sequence.
iii. voltage ratio must be same.
iv. Per unit impedence of the transformers must be same.

UNIT-III
AUTO AND POLY PHASE TRANSFORMERS

Autotransformer



•Primary and secondary on the same winding. Therefore there is no galvanic isolation.

Features of Autotransformer

- ✓ Lower leakage
- ✓Lower losses
- ✓Lower magnetizing current
- ✓Increase kVA rating

× No galvanic Isolation

Review of balanced three phase circui

- Two possible configurations: Star (Y) and delta (Δ)

- Star has neutral, delta does not

Star (Y) connection

- Line current is same as phase current
- Line-Line voltage is $\sqrt{3}$ phase-neutral voltage
- Power is given by $\sqrt{3}\ V_{L-L} I_L \cos\theta$ or $3V_{ph}I_{ph}\cos\theta$

Delta (Δ) connection

- Line-Line voltage is same as phase voltage
- Line current is √3 phase current
- Power is given by $\sqrt{3}\,V_{L\text{-}L} I_{L} \cos\theta$ or $3V_{ph}I_{ph}\cos\theta$

Typical three phase transformer connections

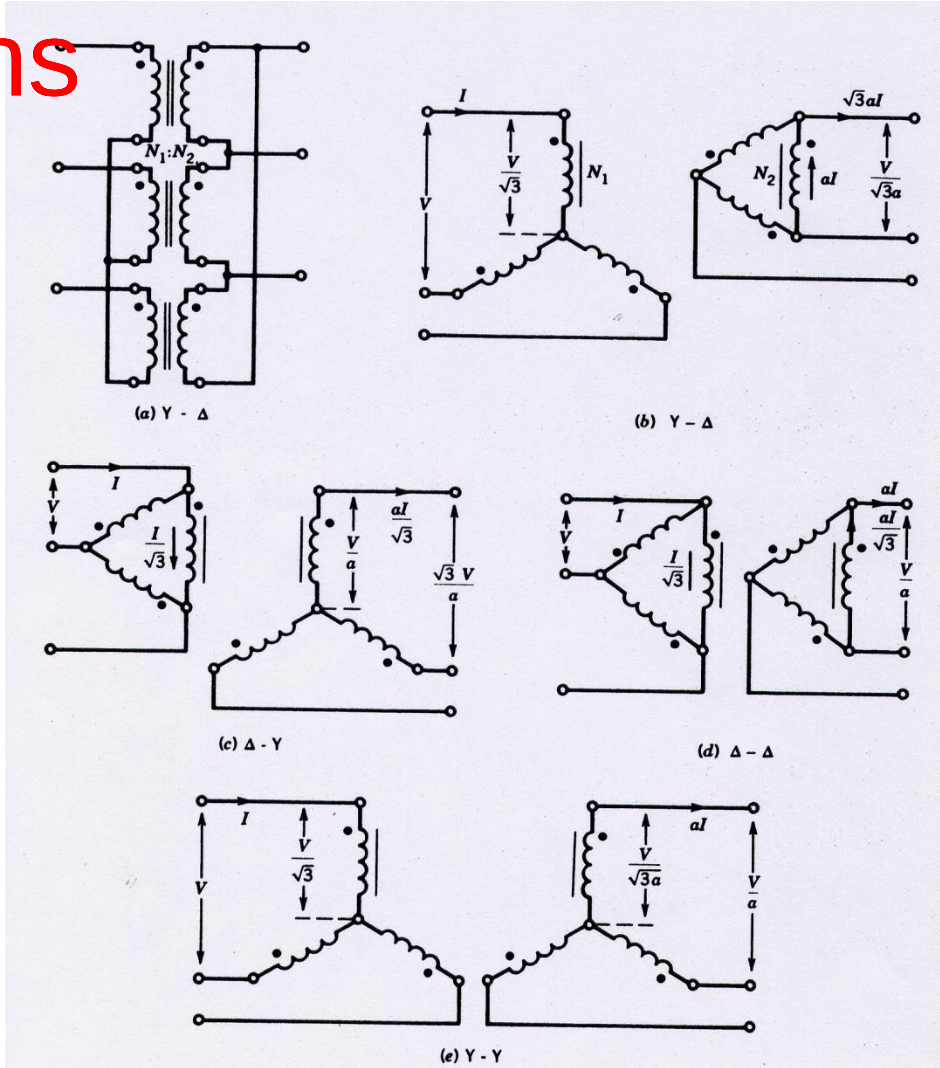


FIGURE 2.17 Three-phase transformer connections.

Other possible three phase transformer Connections

- Y- zigzag
- Δ- zigzag
- Open Delta or V
- Scott or T

How are three phase transformers made?

- Either by having three single phase transformers connected as three phase banks.

- Or by having coils mounted on a single core with multiple limbs

- The bank configuration is better from repair perspective, whereas the single three phase unit will cost less ,occupy less space, weighs less and is more efficient

Phase-shift between line-line voltages in transformers

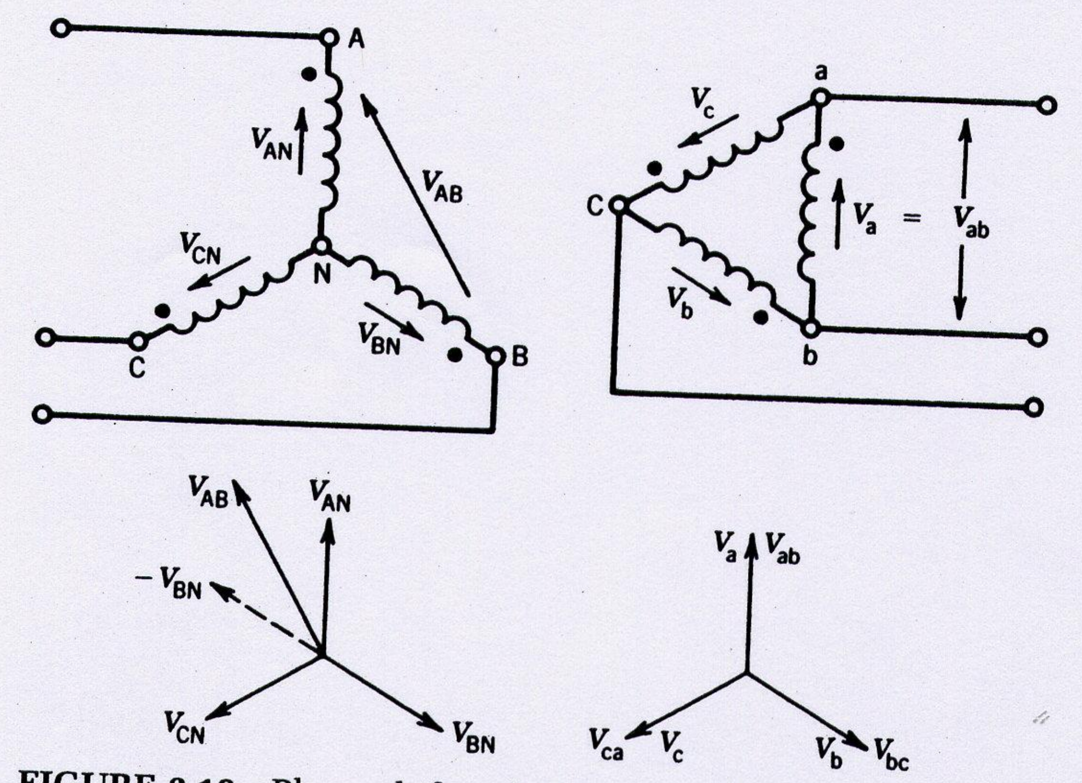


FIGURE 2.18 Phase shift in line-to-line voltages in a three-phase transformer.

Vector grouping of transformers

- Depending upon the phase shift of line-neutral voltages between primary and secondary; transformers are grouped. This is done for ease of paralleling. Usually transformers between two different groups should not be paralleled.

- Group 1 :zero phase displacement (Yy0, Dd0,Dz0)

- Group 2 :180^0 phase displacement (Yy6, Dd6,Dz6)

- Group 3 : 30^0 lag phase displacement (Dy1, Yd1,Yz1)

- Group 4 : 30^0 lead phase displacement (Dy11, Yd11,Yz11)

(Y=Y; D= Δ; z=zigzag)

Calculation involving 3-ph transformers

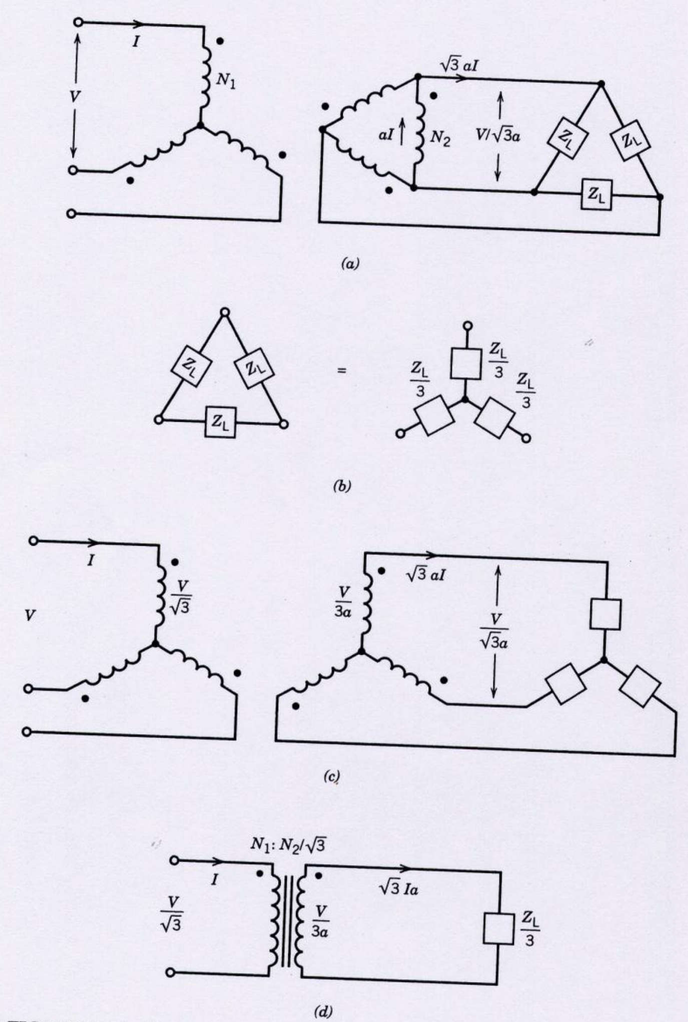
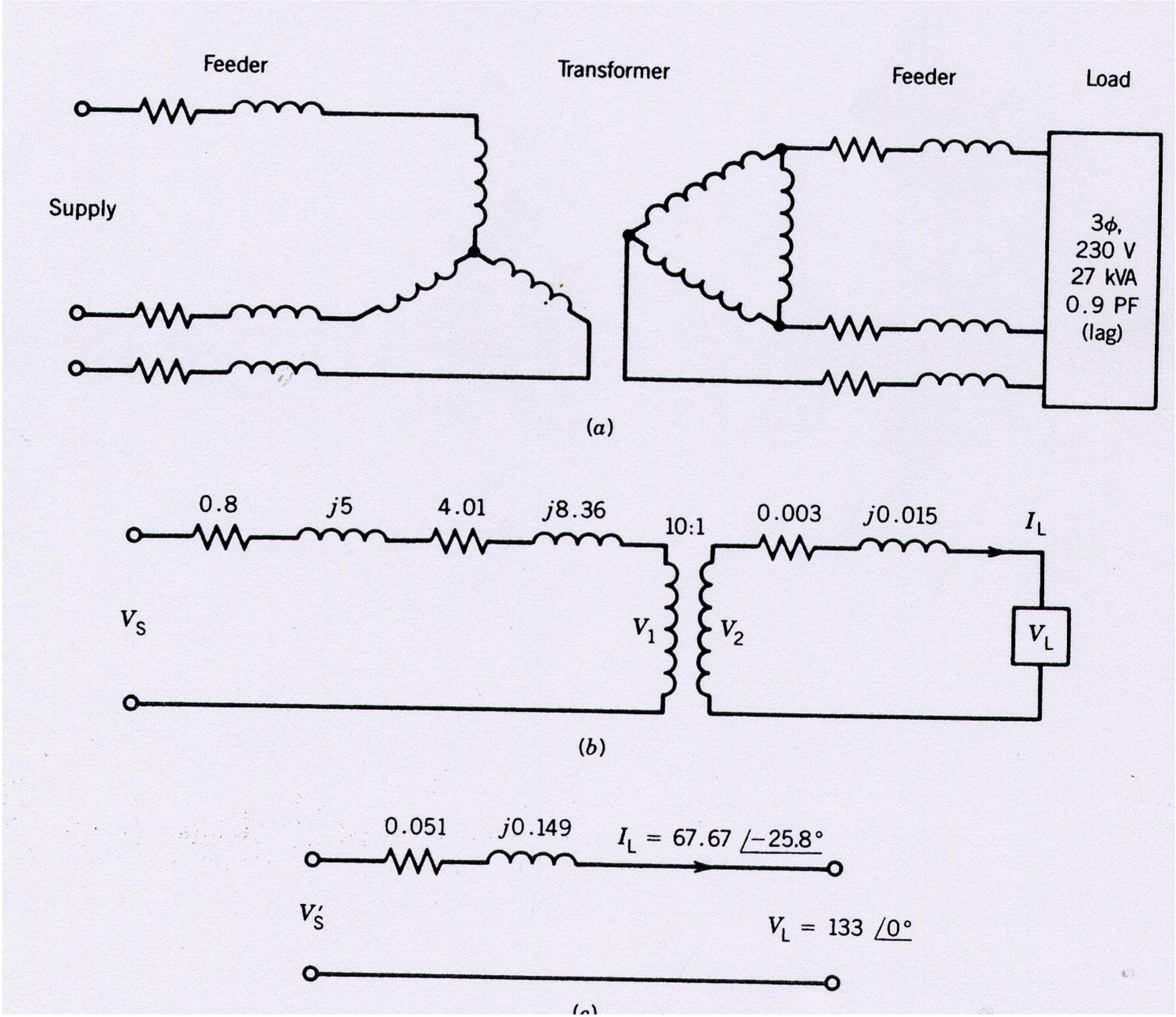


FIGURE 2.19 Three-phase transformer and equivalent circuit.

An example involving 3-ph transformers



Open –delta or V connection

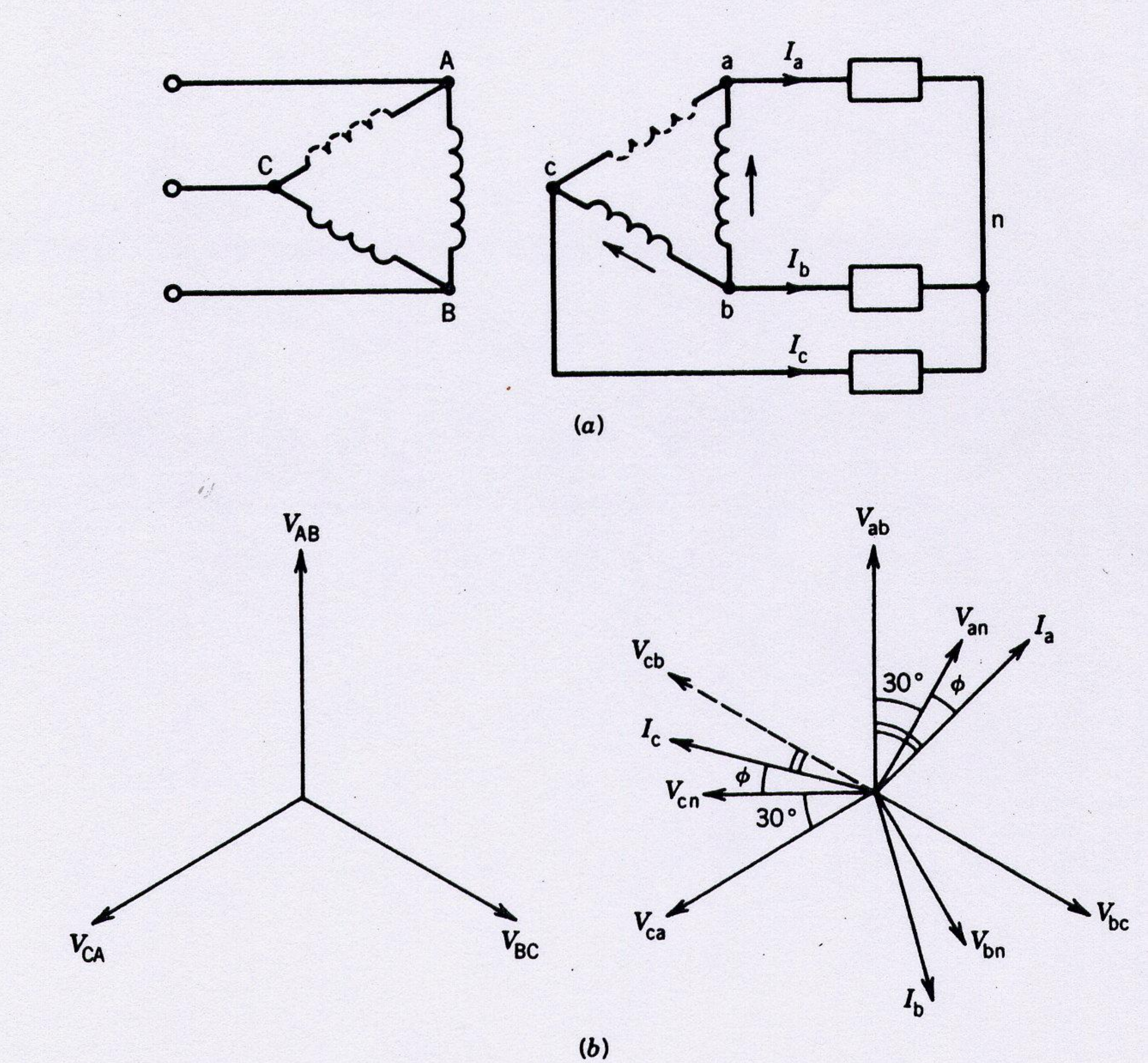


FIGURE 2.20 V connection.

Open –delta or V connection

Power from winding 'ab' is $P_{ab}=V_{ab}I_a\cos(30^0+\phi)$

Power from winding 'bc' is $P_{cb}=V_{cb}I_c\cos(30^0-\phi)$

Therefore total power is $=2V_{L-L}I_L\cos30^0\cos\phi$ or 57.7% of total power from 3 phases

Harmonics in 3-ϕ Transformer Banks

- In absence of neutral connection in a Y-Y transformers 3rd harmonic current cannot flow
- This causes 3rd harmonic distortion in the phase voltages (both primary and secondary) but not line-line voltages, as 3rd harmonic voltages get cancelled out in line-line connections
- Remedy is either of the following :
  a) Neutral connections, b) Tertiary winding c) Use zigzag secondary d) Use star-delta or delta-delta type of transformers.

a) The phenomenon is explained using a star-delta transformer.

Harmonics in 3-ϕ Transformer Banks(2)

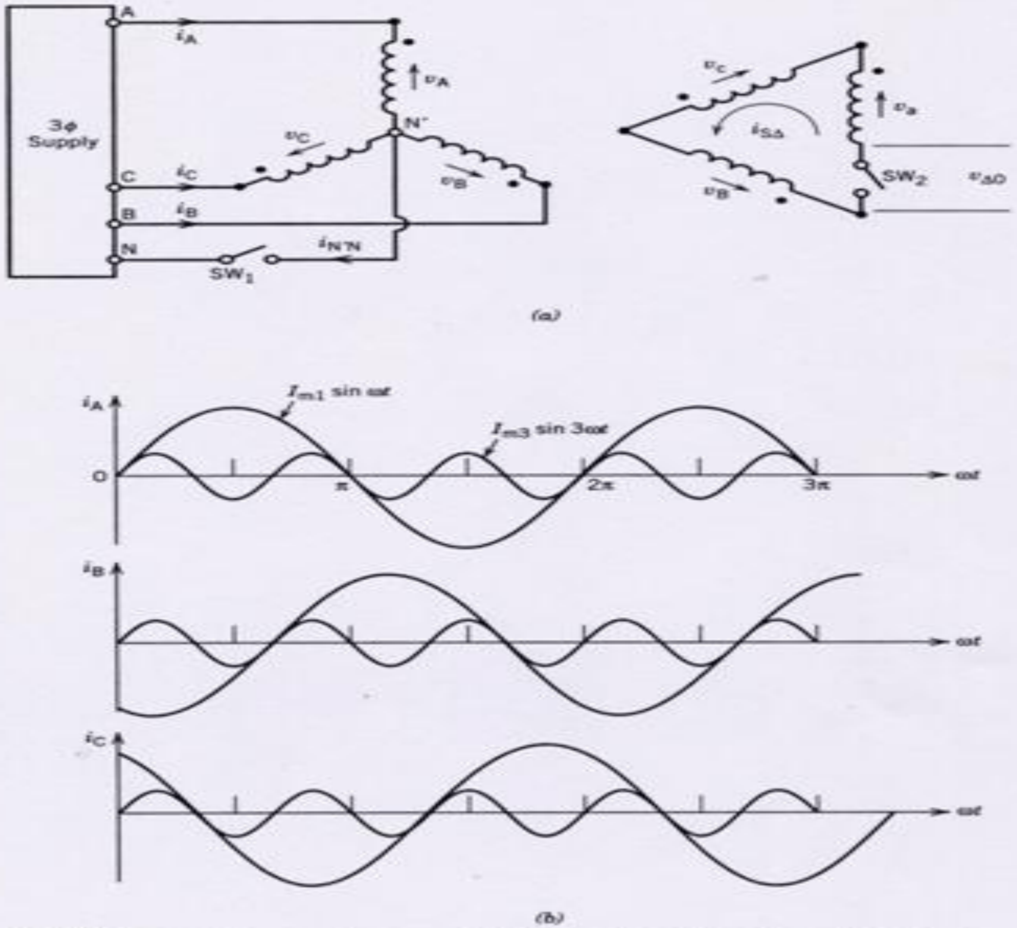


FIGURE Harmonic current in three-phase transformer connections. (*a*) Y–Δ connection. (*b*) Waveforms of exciting currents.

Harmonics in 3-ϕ Transformer Banks(3)

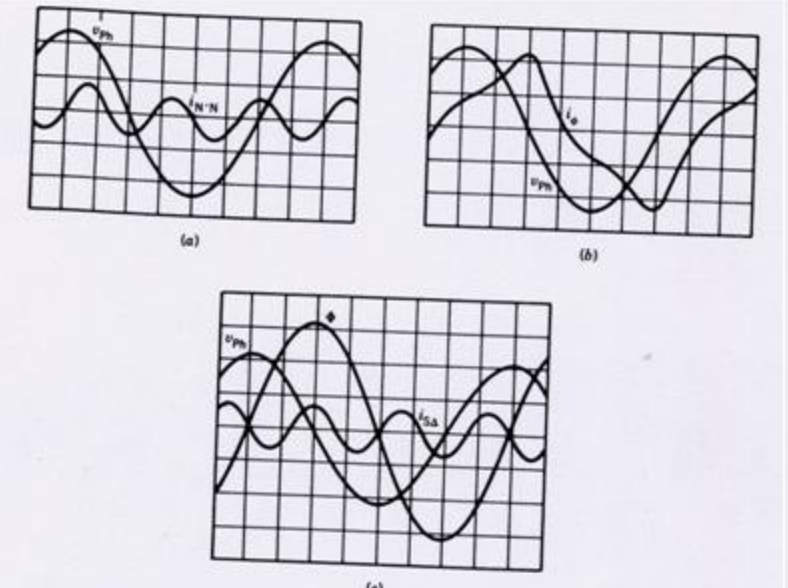


FIGURE Oscillograms of currents and voltages in a Y–Δ-connected transformer.

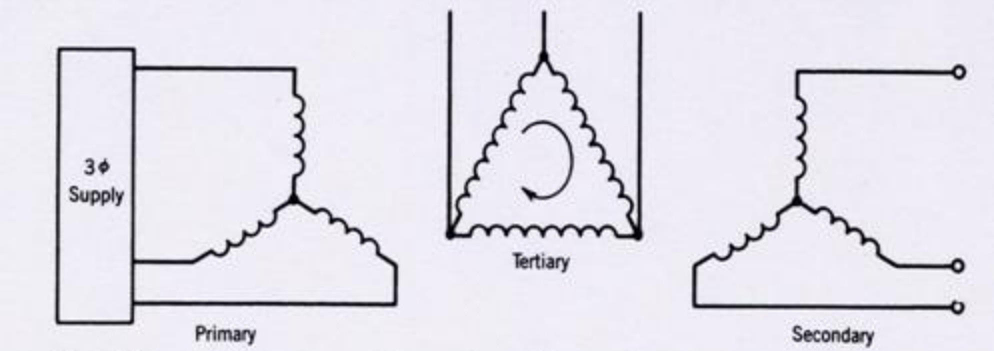
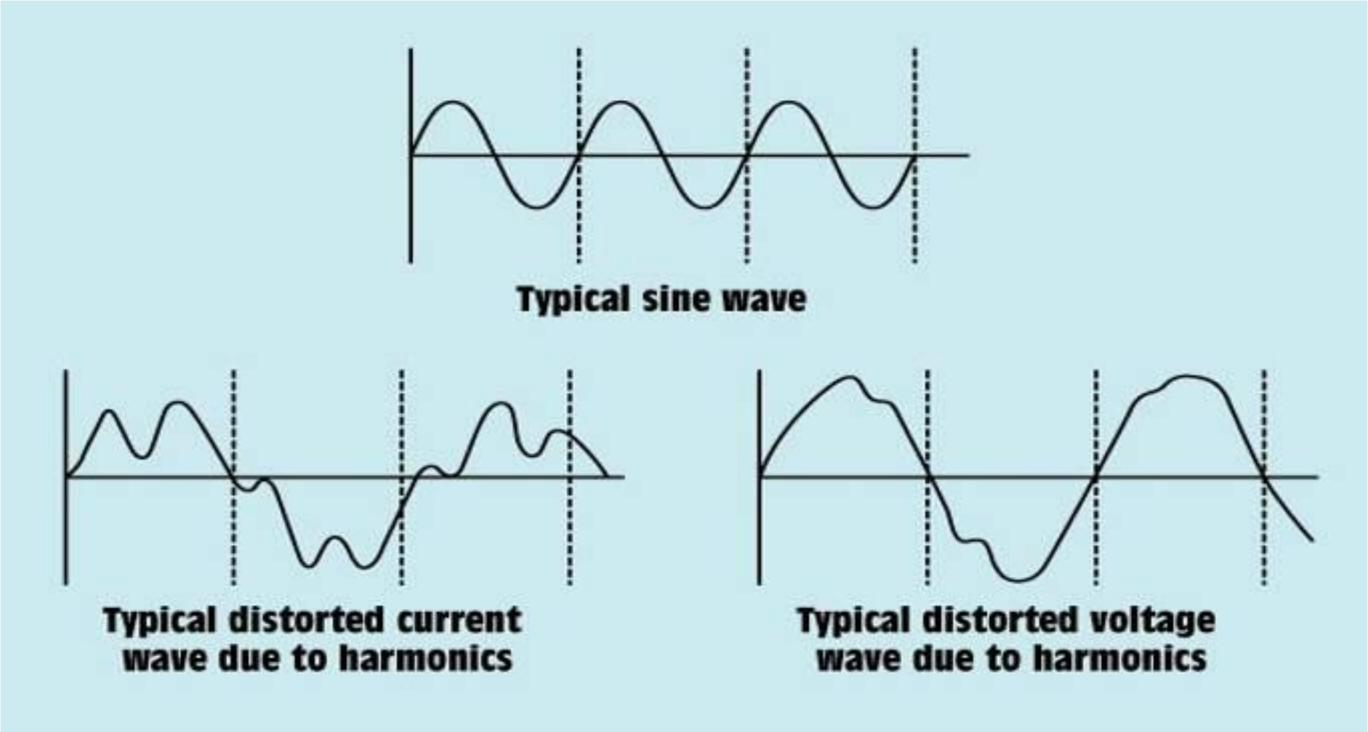


FIGURE Y–Y system with a tertiary (Δ) transformer.

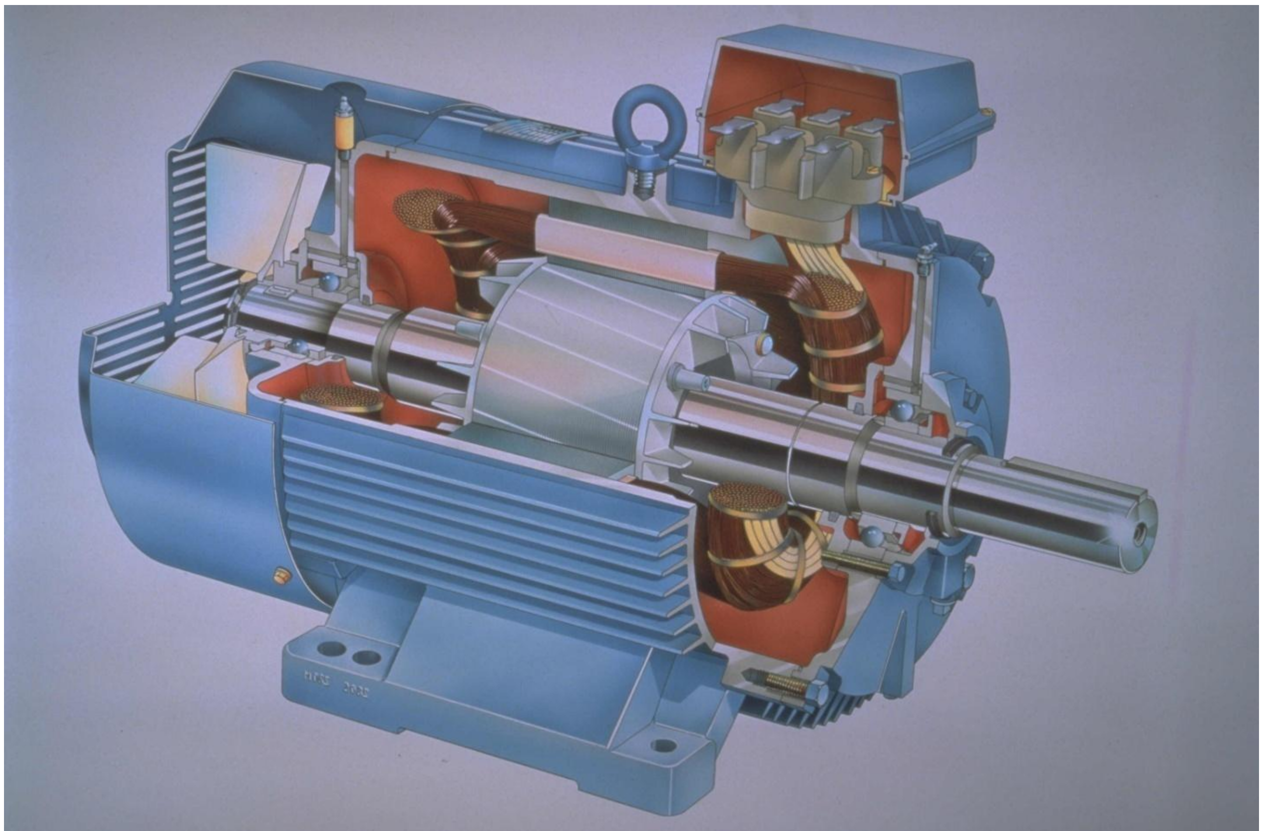
Three-Phase Transformers



Sine wave distortion caused by harmonics.

UNIT-4

POLY-PHASE INDUCTION MOTORS

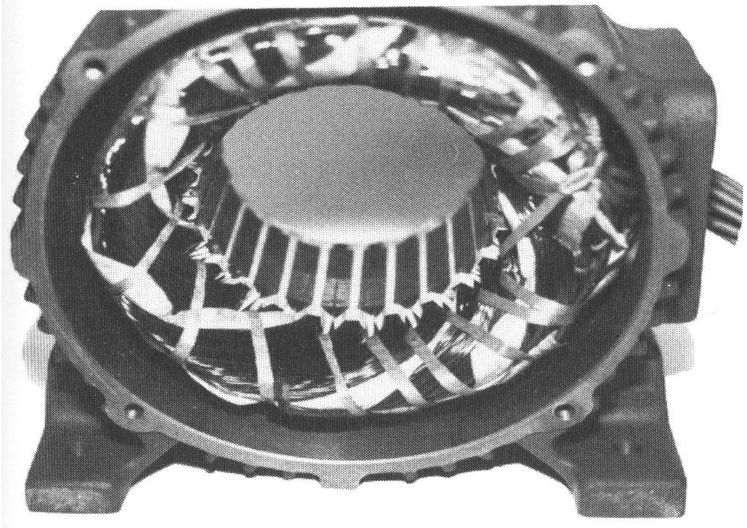


Introduction

- Three-phase induction motors are the most common and frequently encountered machines in industry
  - simple design, rugged, low-price, easy maintenance
  - wide range of power ratings: fractional horsepower to 10 MW
  - run essentially as constant speed from no-load to full load
  - Its speed depends on the frequency of the power source
    - not easy to have variable speed control
    - requires a variable-frequency power-electronic drive for optimal speed control

Construction

- An induction motor has two main parts
  - a stationary stator
    - consisting of a steel frame that supports a hollow, cylindrical core
    - core, constructed from stacked laminations (why?), having a number of evenly spaced slots, providing the space for the stator winding

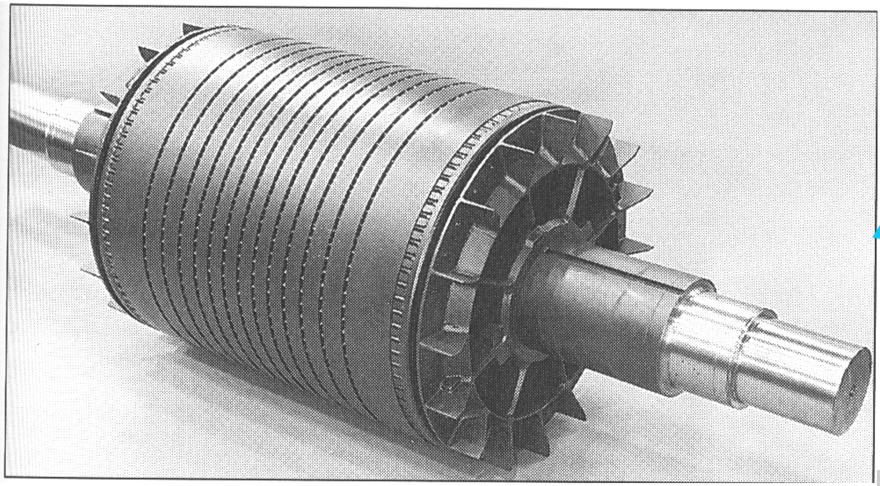


Stator of IM

Construction

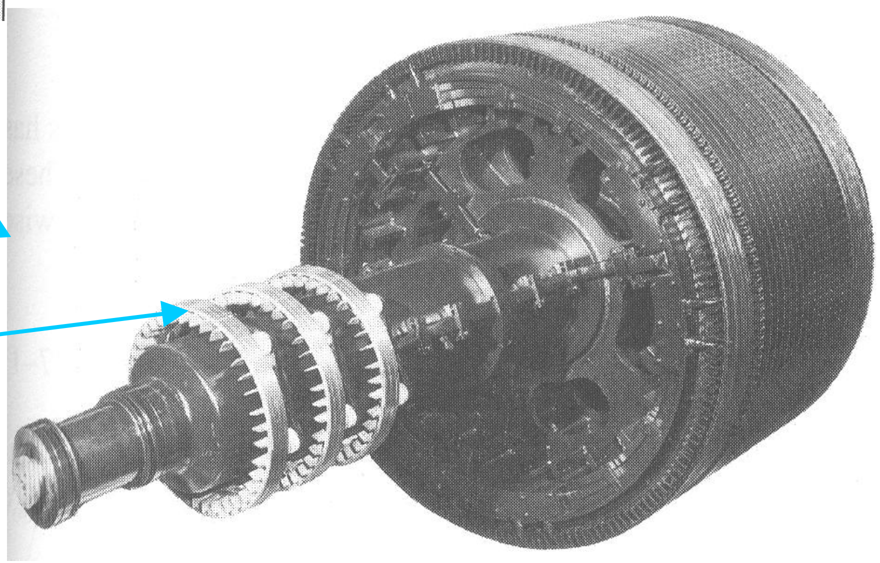
- a revolving rotor
  - composed of punched laminations, stacked to create a series of rotor slots, providing space for the rotor winding
  - one of two types of rotor windings
  - conventional 3-phase windings made of insulated wire (wound-rotor) » similar to the winding on the stator
  - aluminum bus bars shorted together at the ends by two aluminum rings, forming a squirrel-cage shaped circuit (squirrel-cage)
- Two basic design types depending on the rotor design
  - squirrel-cage: conducting bars laid into slots and shorted at both ends by shorting rings.
  - wound-rotor: complete set of three-phase windings exactly as the stator. Usually Y-connected, the ends of the three rotor wires are connected to 3 slip rings on the rotor shaft. In this way, the rotor circuit is accessible.

Construction



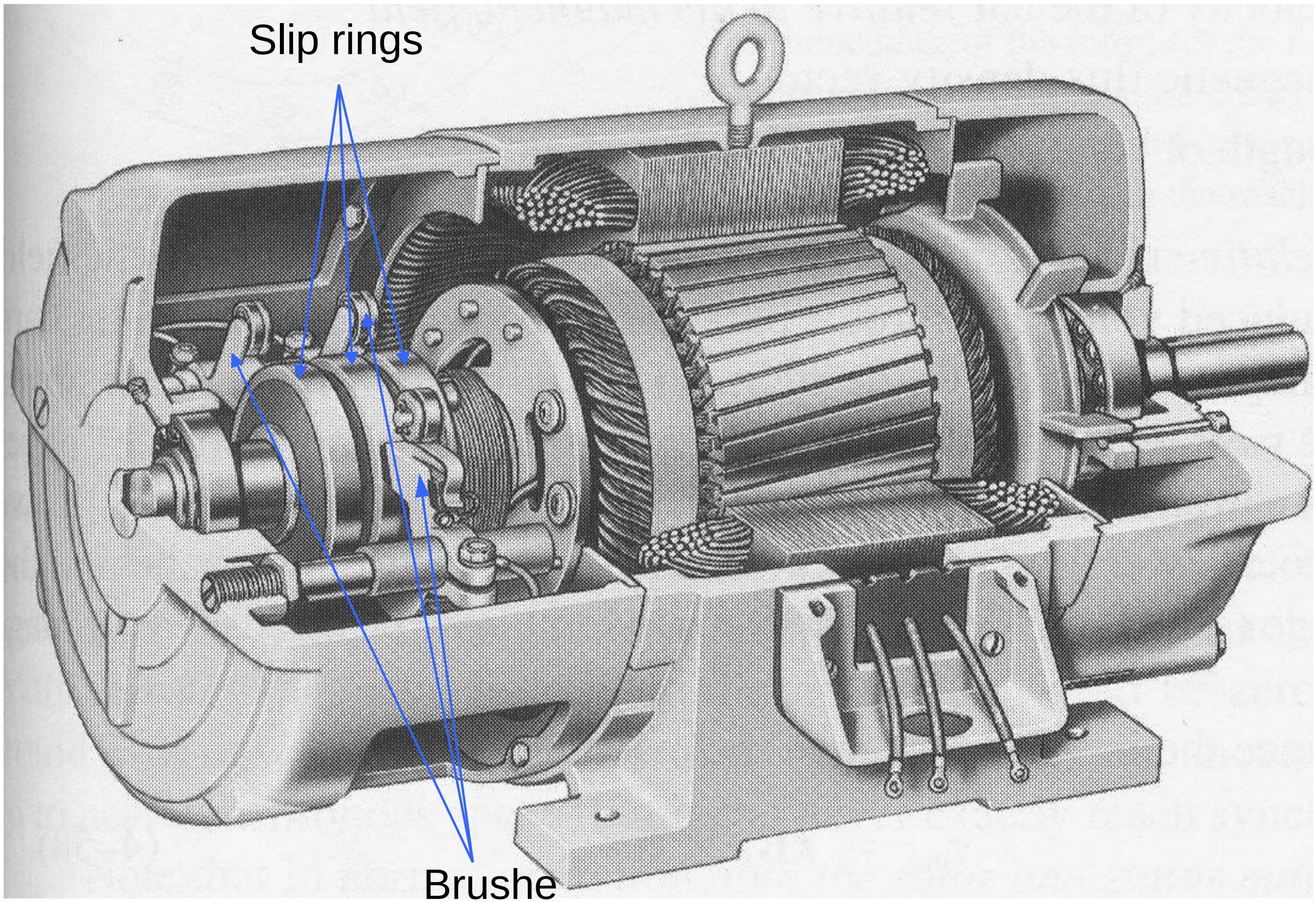
Squirrel cage rotor

Wound rotor



Notice the
slip rings

Construction

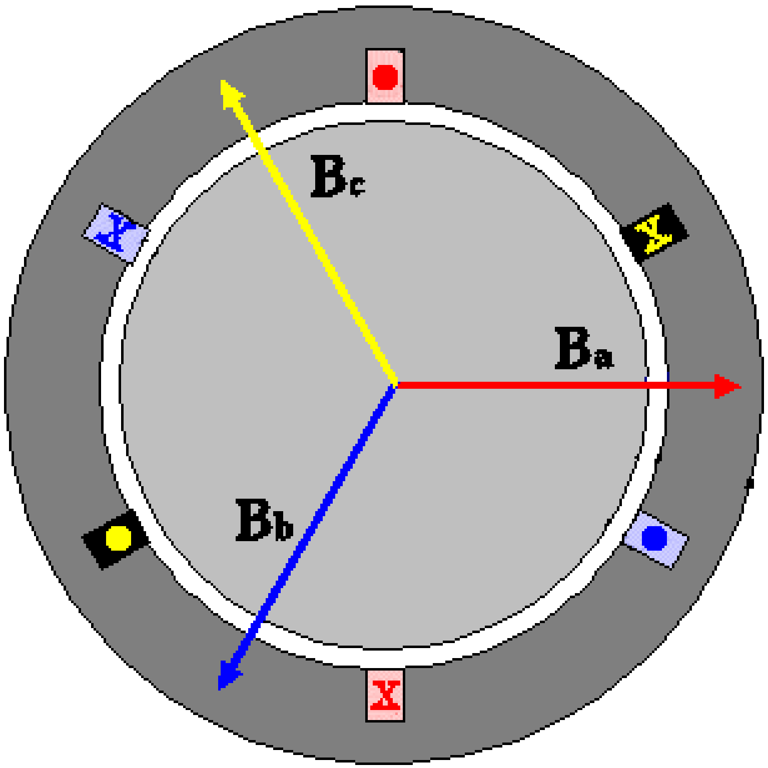


Cutaway in a typical wound-rotor IM. Notice the brushes and the slip rings

Rotating Magnetic Field

- Balanced three phase windings, i.e. mechanically displaced 120 degrees form each other, fed by balanced three phase source
- A rotating magnetic field with constant magnitude is produced, rotating with a speed

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



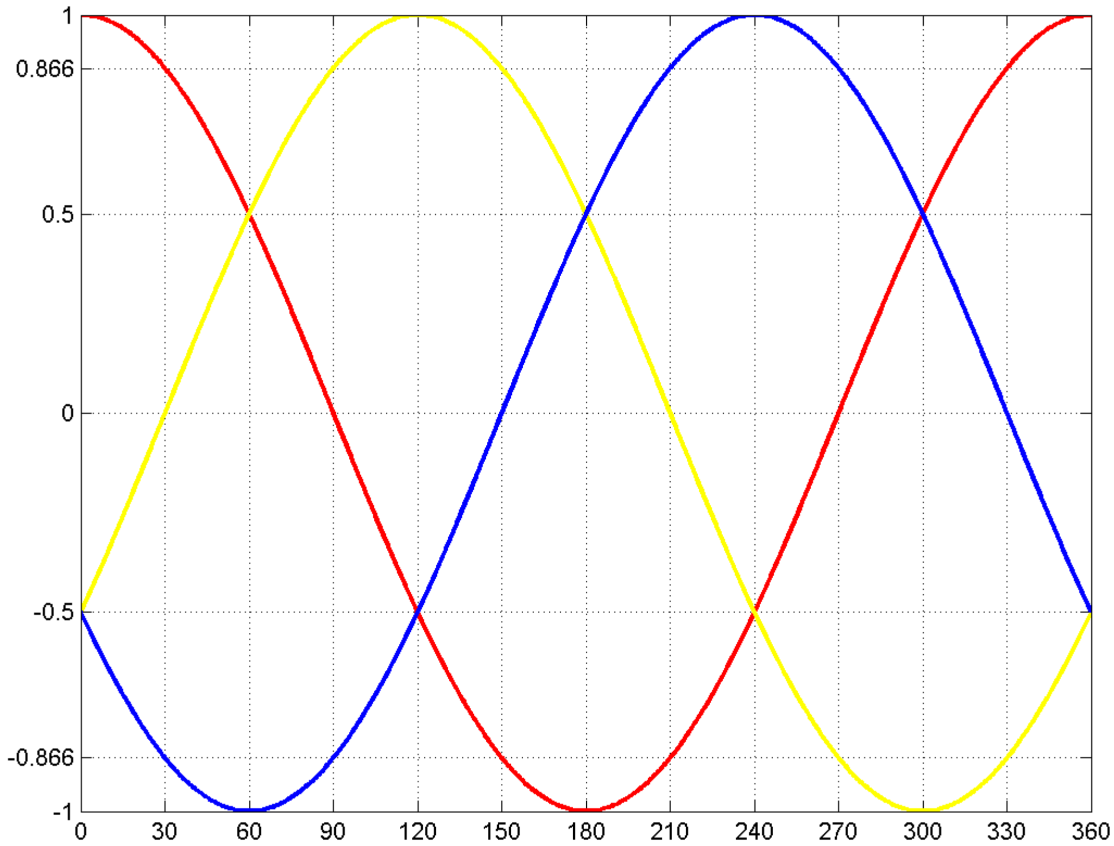
Where f_e is the supply frequency and

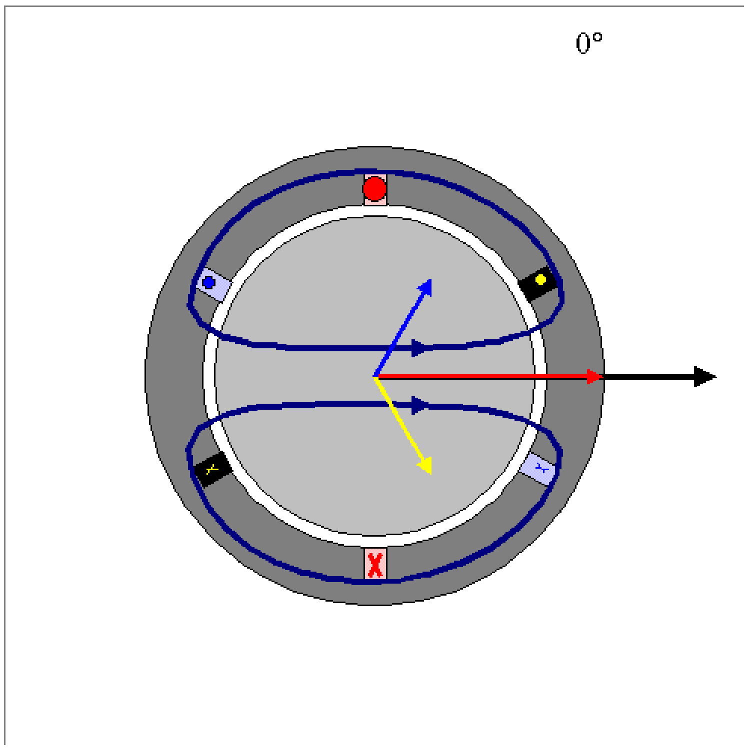
P is the no. of poles and n_{sync} is called the synchronous speed in *rpm* (revolutions per minute)

Synchronous speed

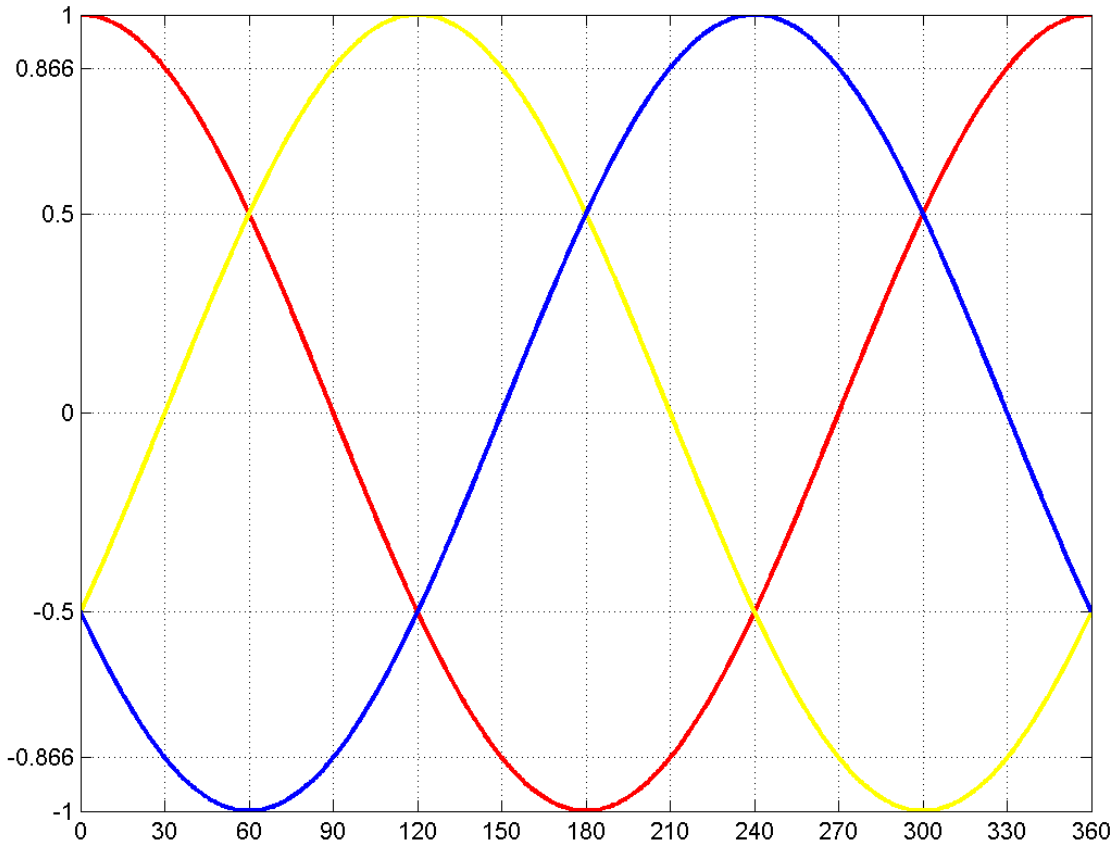
P	50 Hz	60 Hz
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600

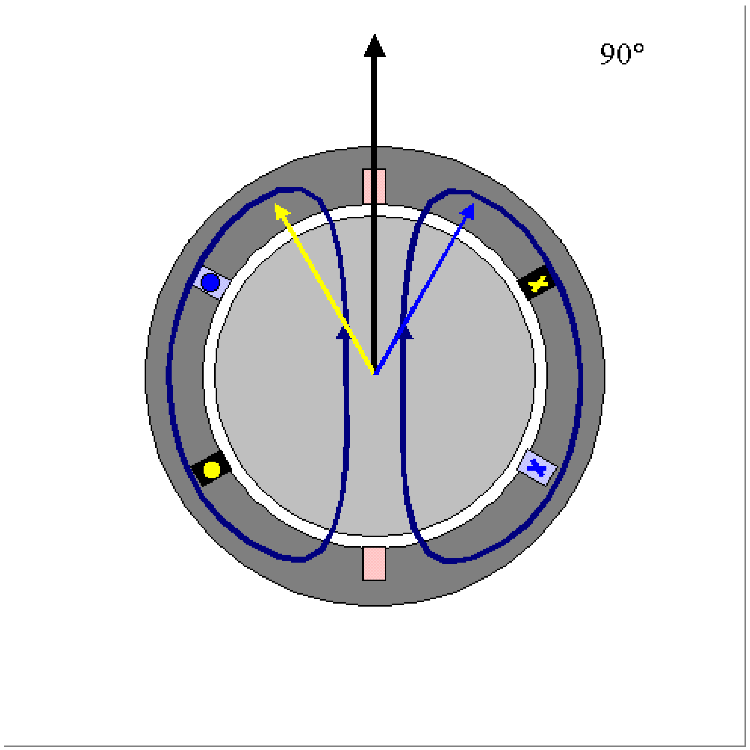
Rotating Magnetic Field





Rotating Magnetic Field





Rotating Magnetic Field

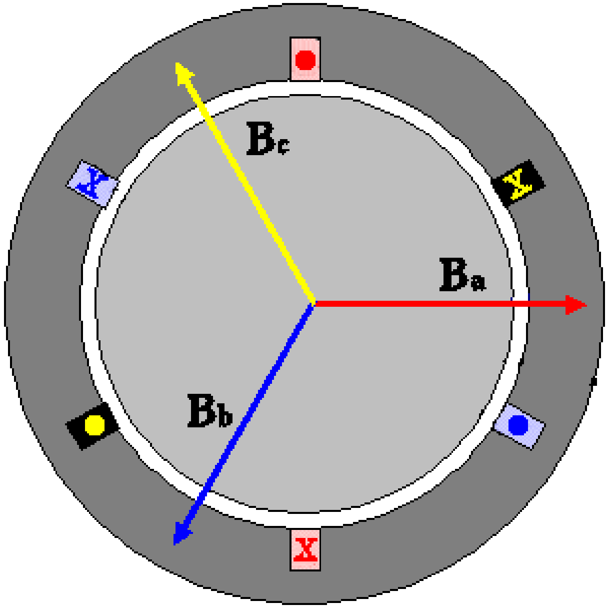
$$B_{net}(t) = B_a(t) + B_b(t) + B_c(t)$$

$$= B_M \sin(\omega t)\angle 0^\circ + B_M \sin(\omega t - 120^\circ)\angle 120^\circ + B_M \sin(\omega t - 240)\angle 240^\circ$$

$$= B_M \sin(\omega t)\hat{\mathbf{x}}$$

$$-[0.5B_M \sin(\omega t - 120^\circ)]\hat{\mathbf{x}} - [\frac{\sqrt{3}}{2} B_M \sin(\omega t - 120^\circ)]\hat{\mathbf{y}}$$

$$-[0.5B_M \sin(\omega t - 240^\circ)]\hat{\mathbf{x}} + [\frac{\sqrt{3}}{2} B_M \sin(\omega t - 240^\circ)]\hat{\mathbf{y}}$$



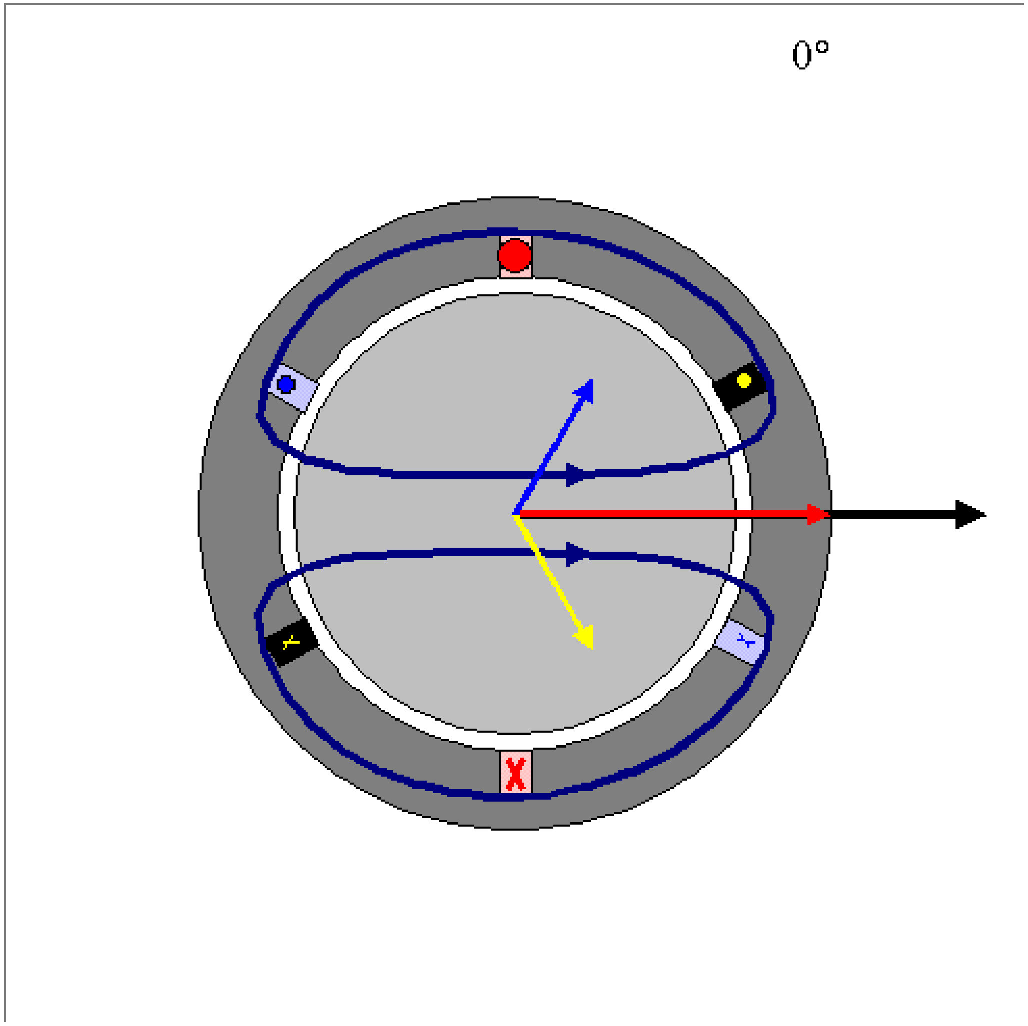
Rotating Magnetic Field

$$B_{net}(t) = [B_M \sin(\omega t) + \frac{1}{4} B_M \sin(\omega t) + \frac{\sqrt{3}}{4} B_M \cos(\omega t) + \frac{1}{4} B_M \sin(\omega t) - \frac{\sqrt{3}}{4} B_M \cos(\omega t)]\hat{\mathbf{x}}$$

$$+[-\frac{\sqrt{3}}{4} B_M \sin(\omega t) - \frac{3}{4} B_M \cos(\omega t) + \frac{\sqrt{3}}{4} B_M \sin(\omega t) - \frac{3}{4} B_M \cos(\omega t)]\hat{\mathbf{y}}$$

$$= [1.5 B_M \sin(\omega t)]\hat{\mathbf{x}} - [1.5 B_M \cos(\omega t)]\hat{\mathbf{y}}$$

Rotating Magnetic Field



Principle of operation

- This rotating magnetic field cuts the rotor windings and produces an induced voltage in the rotor windings
- Due to the fact that the rotor windings are short circuited, for both squirrel cage and wound-rotor, and induced current flows in the rotor windings
- The rotor current produces another magnetic field
- A torque is produced as a result of the interaction of those two magnetic fields

$$\tau_{ind} = kB_R \times B_s$$

Where τ_{ind} is the induced torque and B_R and B_S are the magnetic flux densities of the rotor and the stator respectively

Induction motor speed

- At what speed will the IM run?
  - Can the IM run at the synchronous speed, why?
  - If rotor runs at the synchronous speed, which is the same speed of the rotating magnetic field, then the rotor will appear stationary to the rotating magnetic field and the rotating magnetic field will not cut the rotor. So, no induced current will flow in the rotor and no rotor magnetic flux will be produced so no torque is generated and the rotor speed will fall below the synchronous speed
  - When the speed falls, the rotating magnetic field will cut the rotor windings and a torque is produced

Induction motor speed

- So, the IM will always run at a speed lower than the synchronous speed
- The difference between the motor speed and the synchronous speed is called the *Slip*

$$n_{slip} = n_{sync} - n_m$$

Where n_{slip} = slip speed

n_{sync} = speed of the magnetic field

n_m = mechanical shaft speed of the motor

The Slip

$$s = \frac{n_{sync} - n_m}{n_{sync}}$$

Where s is the *slip*

Notice that : if the rotor runs at synchronous speed

$s = 0$

if the rotor is stationary

$s = 1$

Slip may be expressed as a percentage by multiplying the above eq. by 100, notice that the slip is a ratio and doesn't have units

Frequency

- The frequency of the voltage induced in the rotor is given by

$$f_r = \frac{P \times n}{120}$$

Where f_r = the rotor frequency (Hz)

P = number of stator poles

n = slip speed (rpm)

$$f_r = \frac{P \times (n_s - n_m)}{120}$$

$$= \frac{P \times sn_s}{120} = sf_e$$

Frequency

- What would be the frequency of the rotor's induced voltage at any speed n_m?

$$f_r = s\, f_e$$

- When the rotor is blocked (s=1) , the frequency of the induced voltage is equal to the supply frequency
- On the other hand, if the rotor runs at synchronous speed (s = 0), the frequency will be zero

Torque

- While the input to the induction motor is electrical power, its output is mechanical power and for that we should know some terms and quantities related to mechanical power
- Any mechanical load applied to the motor shaft will introduce a Torque on the motor shaft. This torque is related to the motor output power and the rotor speed

$$\tau_{load} = \frac{P_{out}}{\omega_m} \quad N.m$$

and

$$\omega_m = \frac{2\pi n_m}{60} \quad rad/s$$

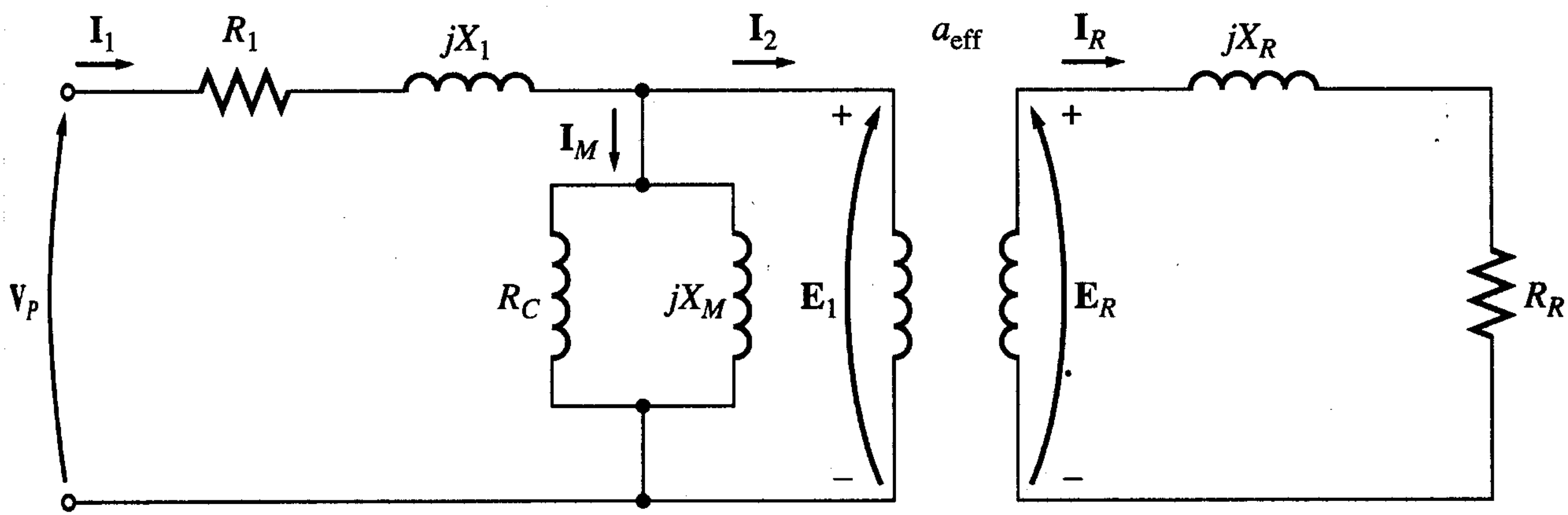
Horse power

- Another unit used to measure mechanical power is the horse power
- It is used to refer to the mechanical output power of the motor
- Since we, as an electrical engineers, deal with watts as a unit to measure electrical power, there is a relation between horse power and watts

$$hp = 746\ watts$$

Equivalent Circuit

- The induction motor is similar to the transformer with the exception that its secondary windings are free to rotate



As we noticed in the transformer, it is easier if we can combine these two circuits in one circuit but there are some difficulties

Equivalent Circuit

- When the rotor is locked (or blocked), i.e. s =1, the largest voltage and rotor frequency are induced in the rotor, Why?
- On the other side, if the rotor rotates at synchronous speed, i.e. s = 0, the induced voltage and frequency in the rotor will be equal to zero, Why?

$$E_R = sE_{R0}$$

Where E_{R0} is the largest value of the rotor's induced voltage obtained at s = 1(loacked rotor)

Equivalent Circuit

- The same is true for the frequency, i.e.

$$f_r = s\ f_e$$

- It is known that

$$X = \omega L = 2\pi f\ L$$

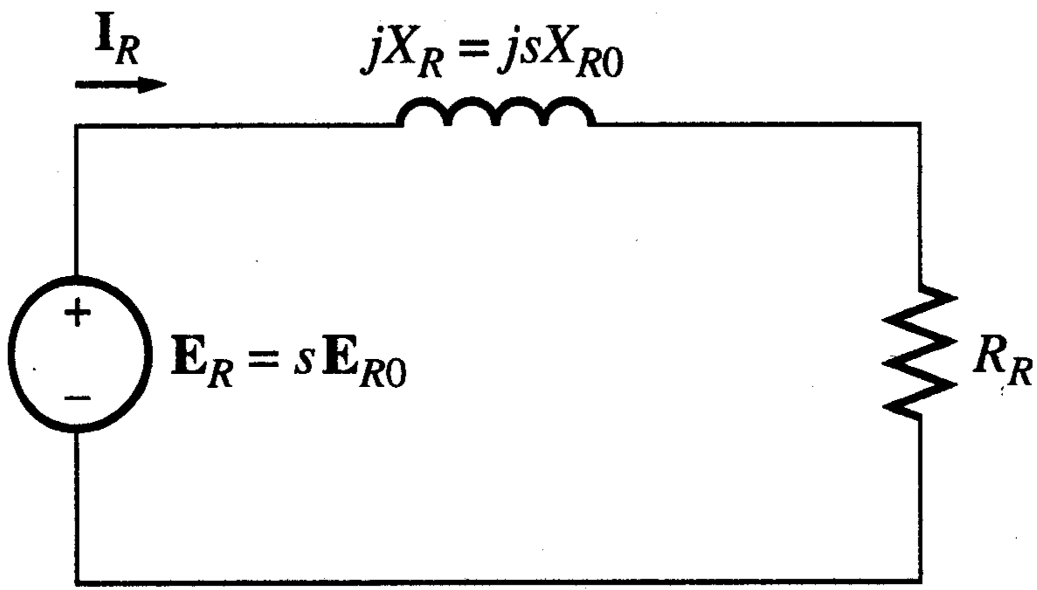
- So, as the frequency of the induced voltage in the rotor changes, the reactance of the rotor circuit also changes

$$X_r = \omega_r L_r = 2\pi f_r\ L_r$$
$$= 2\pi s f_e L_r$$
$$= s X_{r0}$$

Where X_{r0} is the rotor reactance at the supply frequency (at blocked rotor)

Equivalent Circuit

- Then, we can draw the rotor equivalent circuit as follows



Where E_R is the induced voltage in the rotor and R_R is the rotor resistance

Equivalent Circuit

- Now we can calculate the rotor current as

$$I_R = \frac{E_R}{(R_R + jX_R)}$$

$$= \frac{sE_{R0}}{(R_R + jsX_{R0})}$$

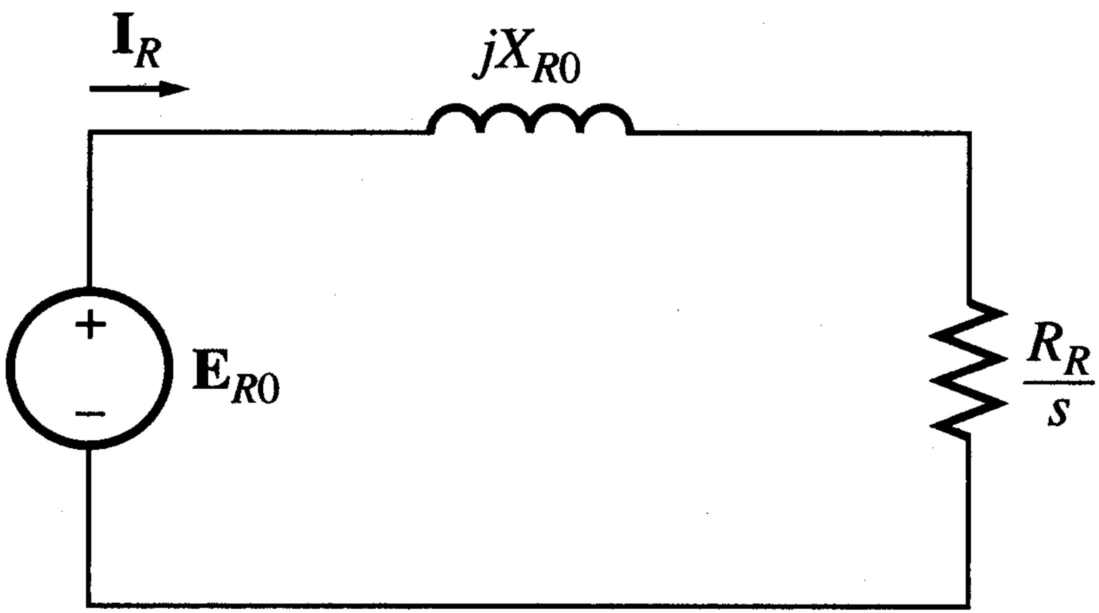
- Dividing both the numerator and denominator by *s* so nothing changes we get

$$I_R = \frac{E_{R0}}{(\frac{R_R}{s} + jX_{R0})}$$

Where E_{R0} is the induced voltage and X_{R0} is the rotor reactance at blocked rotor condition (s = 1)

Equivalent Circuit

- Now we can have the rotor equivalent circuit



Equivalent Circuit

- Now as we managed to solve the induced voltage and different frequency problems, we can combine the stator and rotor circuits in one equivalent circuit

Where

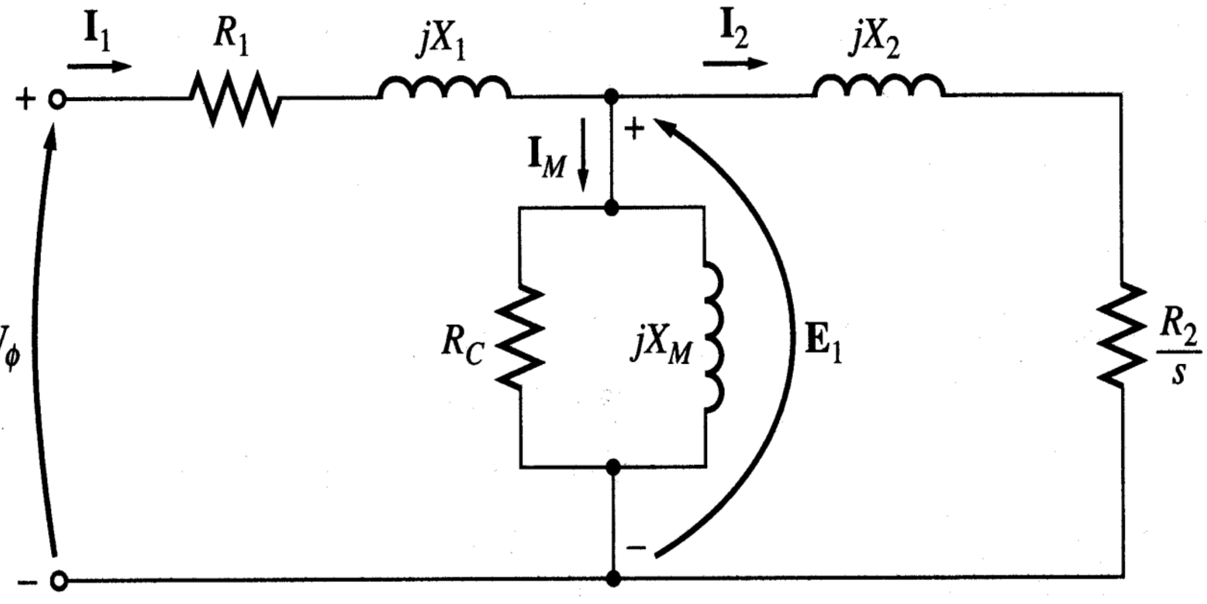
$$X_2 = a_{eff}^2 X_{R0}$$

$$R_2 = a_{eff}^2 R_R$$

$$I_2 = \frac{I_R}{a_{eff}}$$

$$E_1 = a_{eff} E_{R0}$$

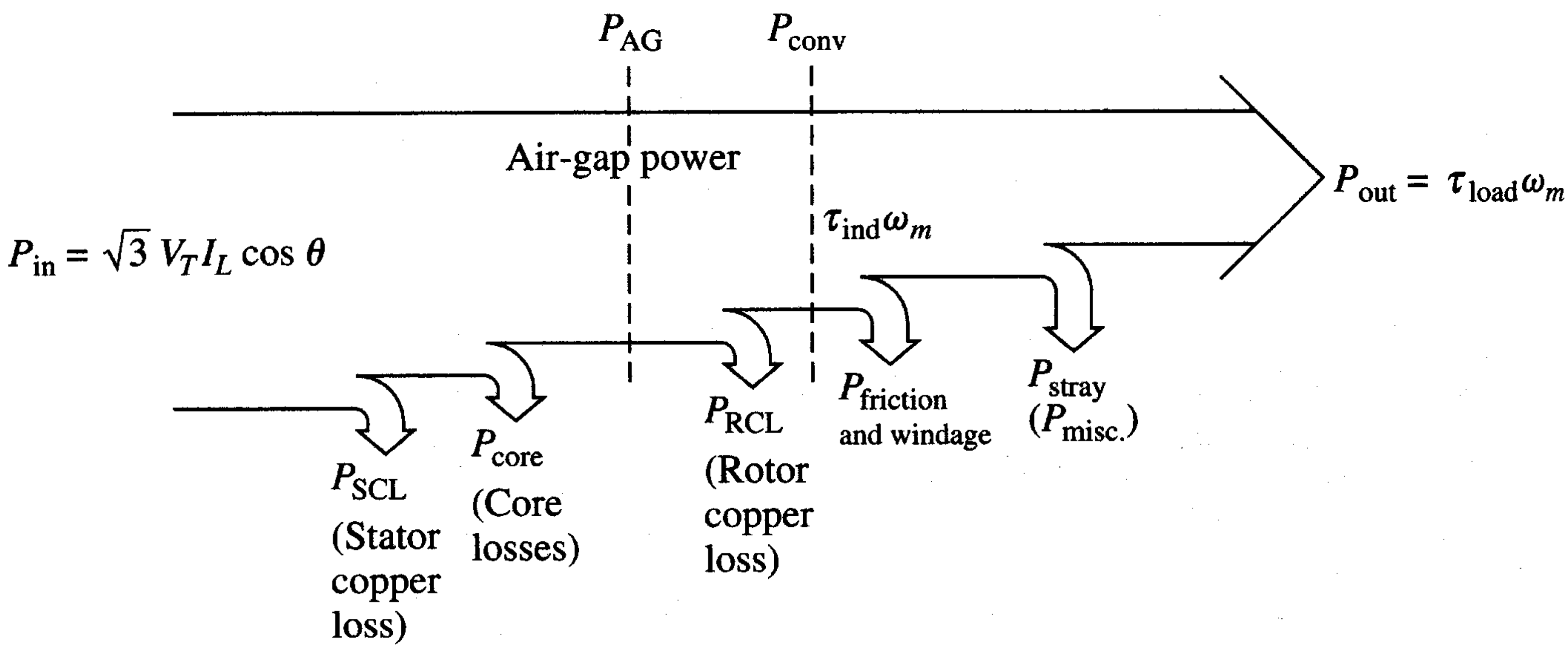
$$a_{eff} = \frac{N_S}{N_R}$$



Power losses in Induction machines

- Copper losses
  - Copper loss in the stator (P_{SCL}) = $I_1^2 R_1$
  - Copper loss in the rotor (P_{RCL}) = $I_2^2 R_2$
- Core loss (P_{core})
- Mechanical power loss due to friction and windage
- How this power flow in the motor?

Power flow in induction motor



Power relations

$$P_{in} = \sqrt{3}\,V_L I_L \cos\theta = 3V_{ph} I_{ph} \cos\theta$$

$$P_{SCL} = 3\,I_1^2 R_1$$

$$P_{AG} = P_{in} - (P_{SCL} + P_{core})$$

$$P_{RCL} = 3I_2^2 R_2$$

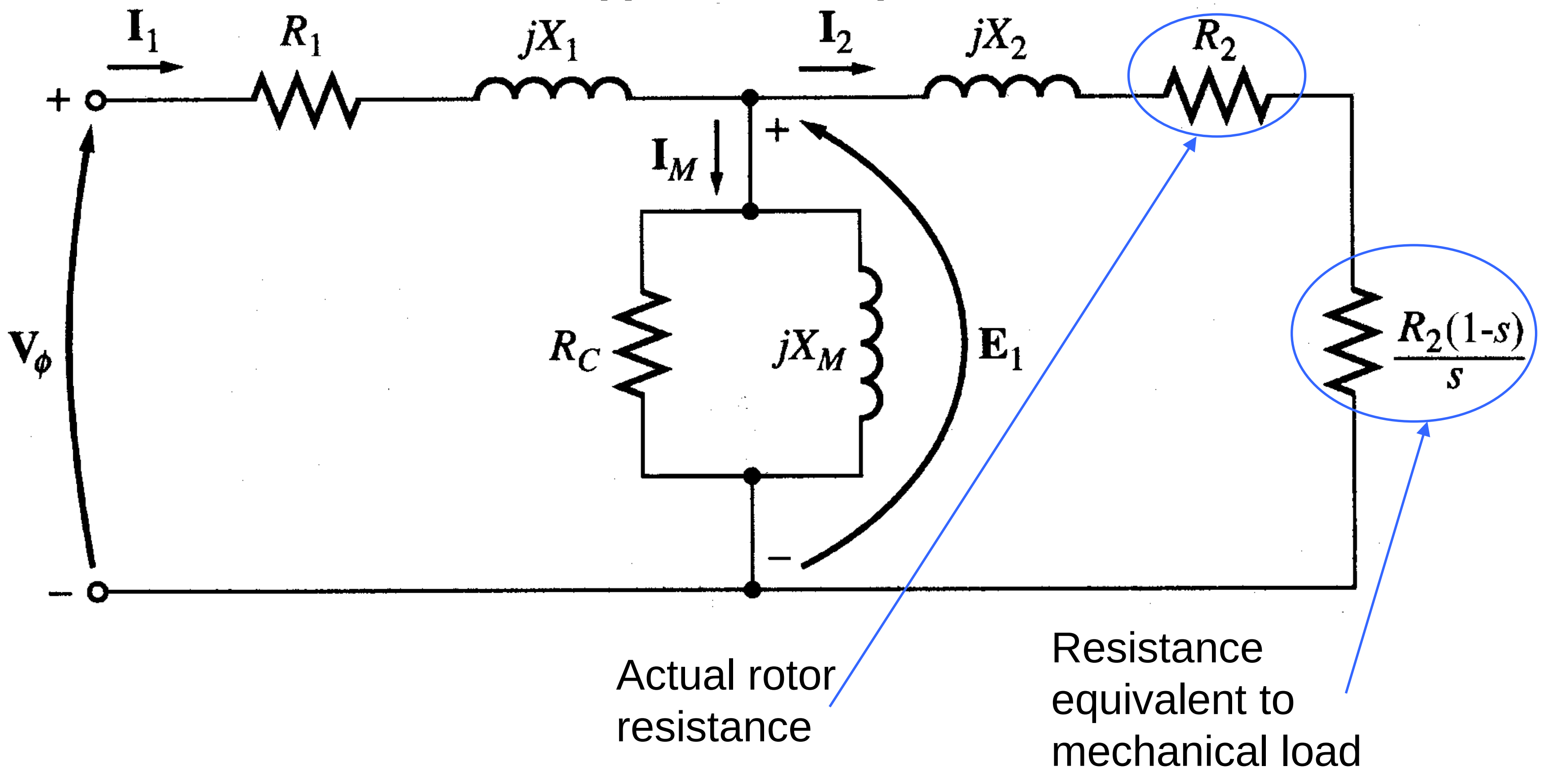
$$P_{conv} = P_{AG} - P_{RCL}$$

$$P_{out} = P_{conv} - (P_{f+w} + P_{stray})$$

$$\tau_{ind} = \frac{P_{conv}}{\omega_m}$$

Equivalent Circuit

- We can rearrange the equivalent circuit as



Power relations

$$P_{in} = \sqrt{3}\, V_L I_L \cos\theta = 3 V_{ph} I_{ph} \cos\theta$$

$$P_{SCL} = 3\, I_1^2 R_1$$

$$P_{AG} = P_{in} - (P_{SCL} + P_{core}) \quad = P_{conv} + P_{RCL} \quad = 3 I_2^2 \frac{R_2}{s} \quad = \frac{P_{RCL}}{s}$$

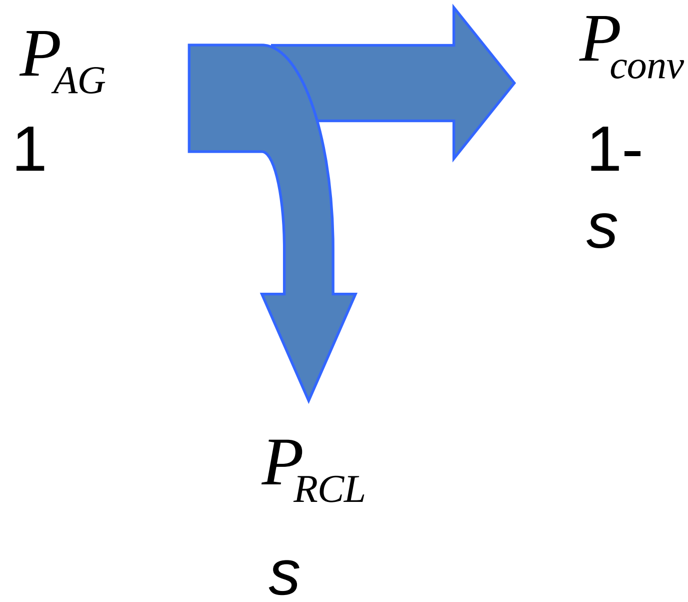
$$P_{RCL} = 3 I_2^2 R_2$$

$$P_{conv} = P_{AG} - P_{RCL} \quad = 3 I_2^2 \frac{R_2 (1 - s)}{s} \quad = \frac{P_{RCL} (1 - s)}{s}$$

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

$$P_{out} = P_{conv} - (P_{f+w} + P_{stray}) \qquad \tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{(1 - s) P_{AG}}{(1 - s)\omega_s}$$

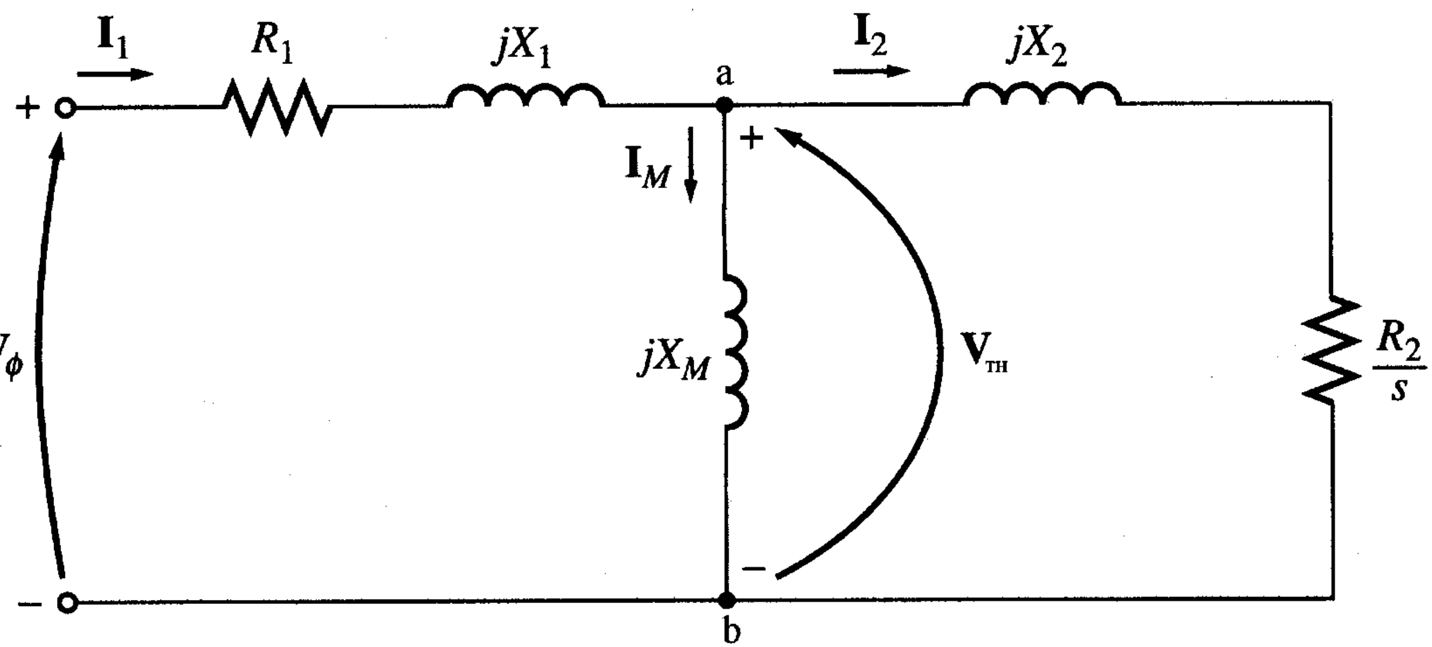
Power relations



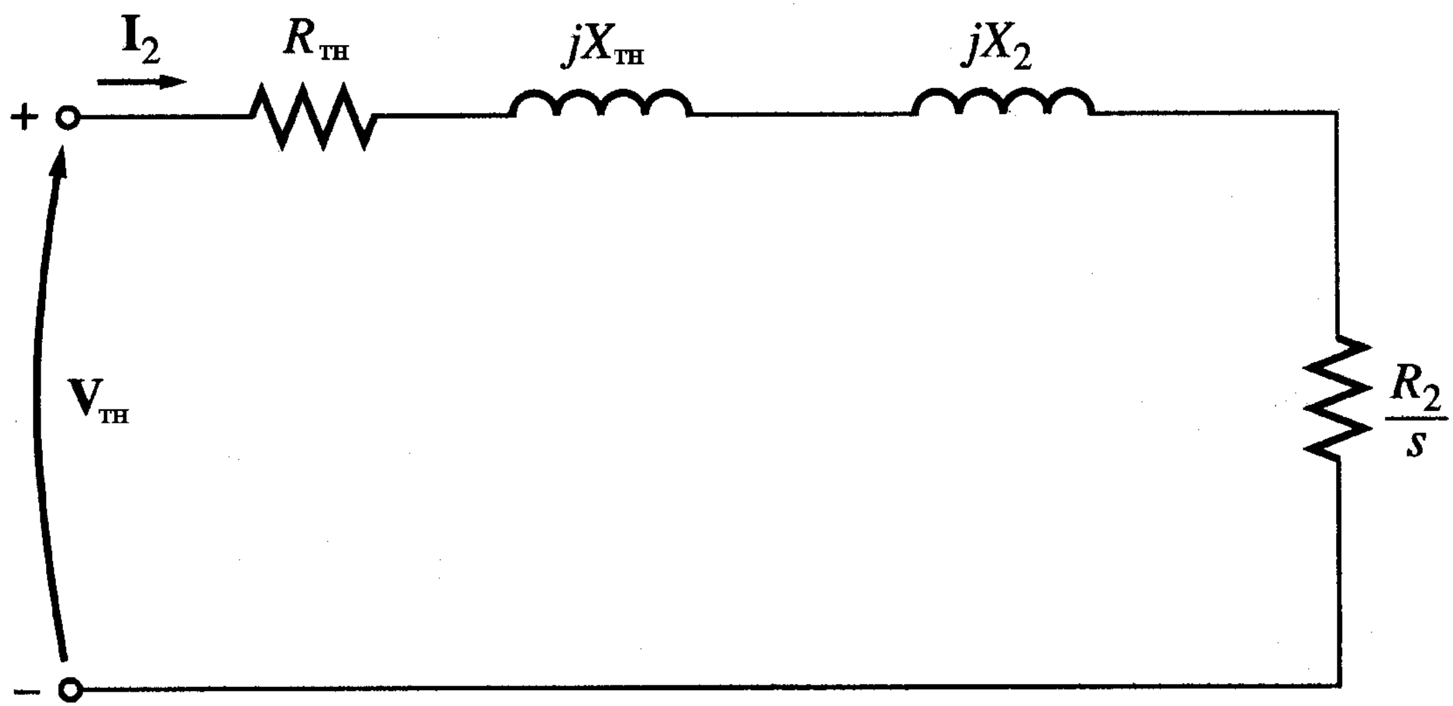
$$P_{AG} : P_{RCL} : P_{conv}$$
$$1 \; : \; s \; : \; 1\text{-}s$$

Torque, power and Thevenin's Theorem

- Thevenin's theorem can be used to transform the network to the left of points 'a' and 'b' into an equivalent voltage source V_{TH} in series w



Torque, power and Thevenin's Theorem



$$V_{TH} = V_\phi \frac{jX_M}{R_1 + j(X_1 + X_M)} \qquad |V_{TH}| = |V_\phi| \frac{X_M}{\sqrt{R_1^2 + (X_1 + X_M)^2}}$$

$$R_{TH} + jX_{TH} = (R_1 + jX_1) // jX_M$$

Torque, power and Thevenin's Theorem

- Since $X_M >> X_1$ and $X_M >> R_1$

$$V_{TH} \approx V_\phi \frac{X_M}{X_1 + X_M}$$

- Because $X_M >> X_1$ and $X_M + X_1 >> R_1$

$$R_{TH} \approx R_1 \left(\frac{X_M}{X_1 + X_M} \right)^2$$

$$X_{TH} \approx X_1$$

Torque, power and Thevenin's Theorem

$$I_2 = \frac{V_{TH}}{Z_T} = \frac{V_{TH}}{\sqrt{\left(R_{TH} + \frac{R_2}{s}\right)^2 + (X_{TH} + X_2)^2}}$$

Then the power converted to mechanical (P_{conv})

$$P_{conv} = 3I_2^2 \frac{R_2(1-s)}{s}$$

And the internal mechanical torque (T_{conv})

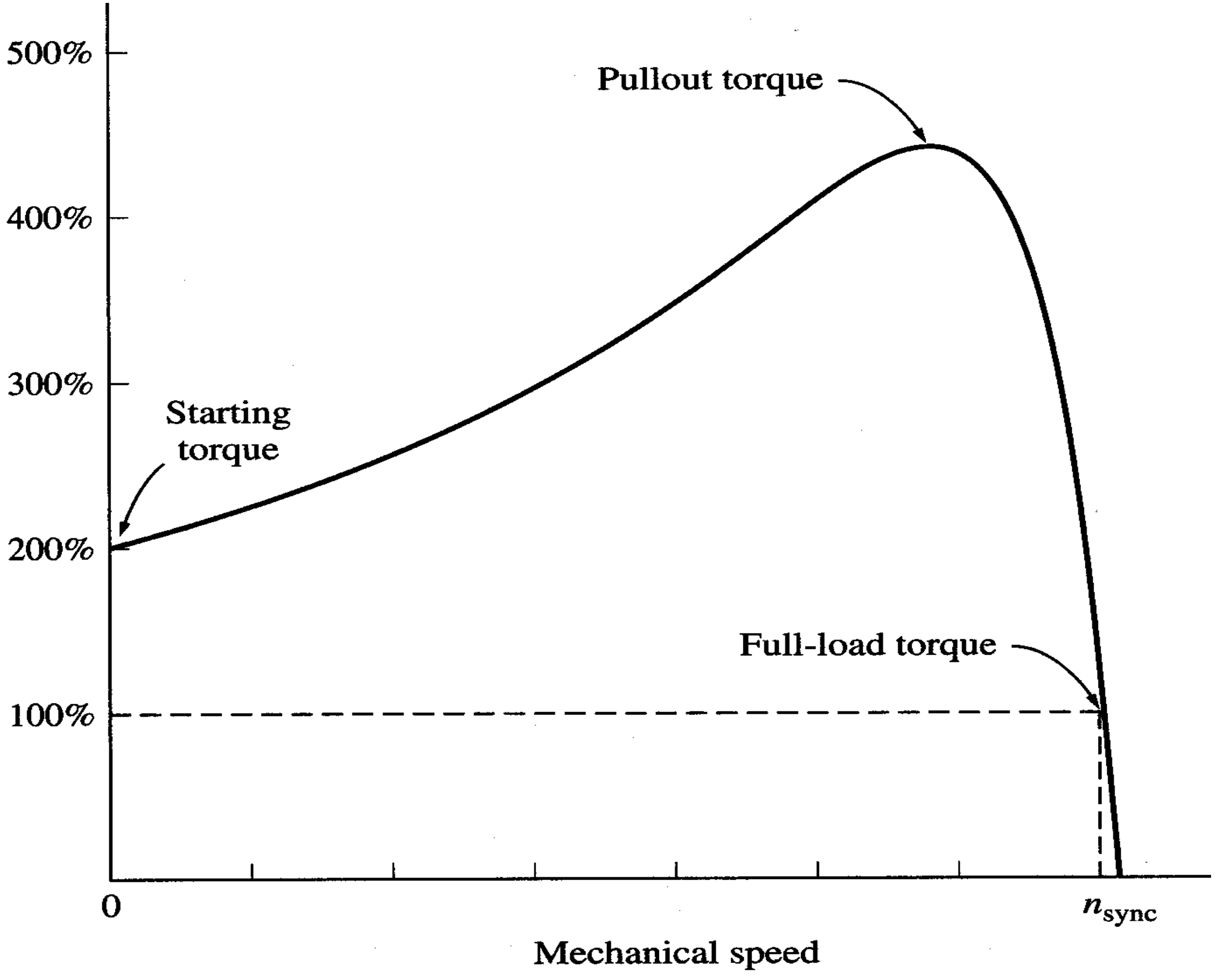
$$\tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{P_{conv}}{(1-s)\omega_s} = \frac{3I_2^2 \frac{R_2}{s}}{\omega_s} = \frac{P_{AG}}{\omega_s}$$

Torque, power and Thevenin's Theorem

$$\tau_{ind} = \frac{3}{\omega_s}\left(\frac{V_{TH}}{\sqrt{\left(R_{TH} + \frac{R_2}{s}\right)^2 + (X_{TH} + X_2)^2}}\right)^2 \left(\frac{R_2}{s}\right)$$

$$\tau_{ind} = \frac{1}{\omega_s} \frac{3V_{TH}^2 \left(\frac{R_2}{s}\right)}{\left(R_{TH} + \frac{R_2}{s}\right)^2 + (X_{TH} + X_2)^2}$$

Torque-speed characteristics



Typical torque-speed characteristics of induction motor

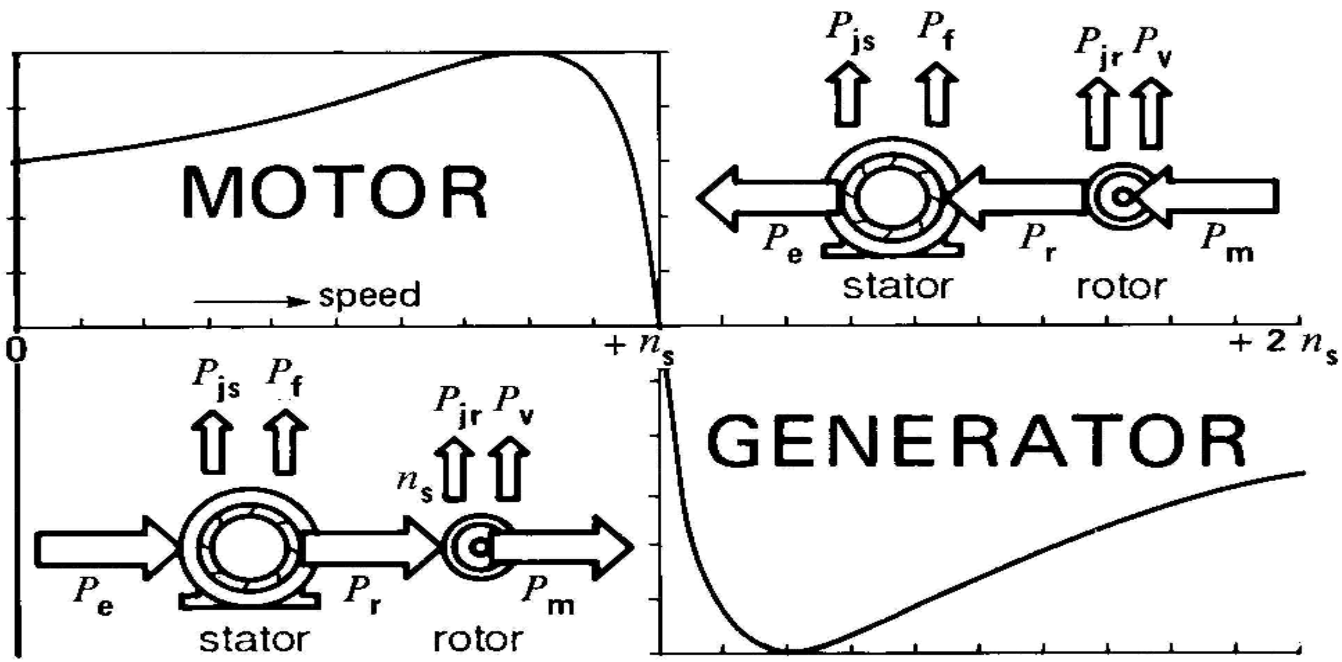
Comments

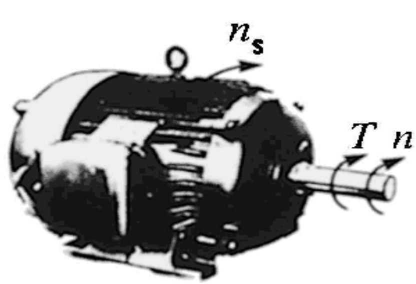
1. The induced torque is zero at synchronous speed. Discussed earlier.
2. The curve is nearly linear between no-load and full load. In this range, the rotor resistance is much greater than the reactance, so the rotor current, torque increase linearly with the slip.
3. There is a maximum possible torque that can't be exceeded. This torque is called *pullout torque* and is 2 to 3 times the rated full-load torque.

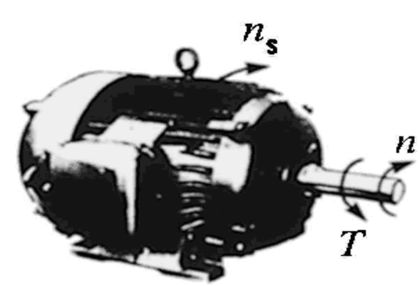
Comments

4. The starting torque of the motor is slightly higher than its full-load torque, so the motor will start carrying any load it can supply at full load.
5. The torque of the motor for a given slip varies as the square of the applied voltage.
6. If the rotor is driven faster than synchronous speed it will run as a generator, converting mechanical power to electric power.

Complete Speed-torque c/c







Maximum torque

- Maximum torque occurs when the power transferred to R_2/s is maximum.
- This condition occurs when R_2/s equals the magnitude of the impedance $R_{TH} + j\,(X_{TH} + X_2)$

$$\frac{R_2}{s_{T_{\max}}} = \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}$$

$$s_{T_{\max}} = \frac{R_2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}}$$

Maximum torque

- The corresponding maximum torque of an induction motor equals

$$\tau_{max} = \frac{1}{2\omega_s}\left(\frac{3V_{TH}^2}{R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}}\right)$$

The slip at maximum torque is directly proportional to the rotor resistance R_2

The maximum torque is independent of R_2

Maximum torque

- Rotor resistance can be increased by inserting external resistance in the rotor of a wound-rotor induction motor.

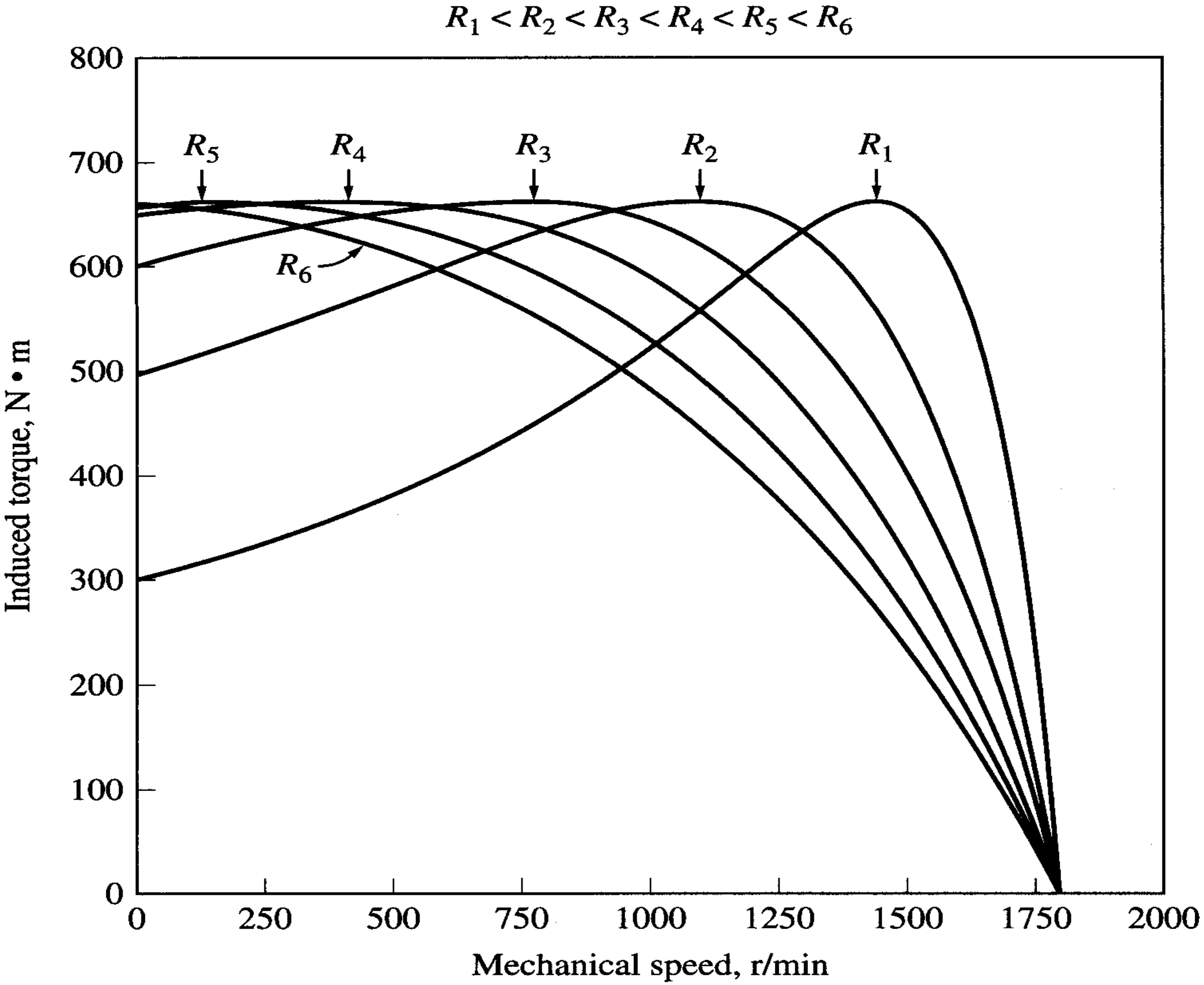
The

value of the maximum torque remains unaffected

but

the speed at which it occurs can be controlled.

Maximum torque



Effect of rotor resistance on torque-speed characteristic

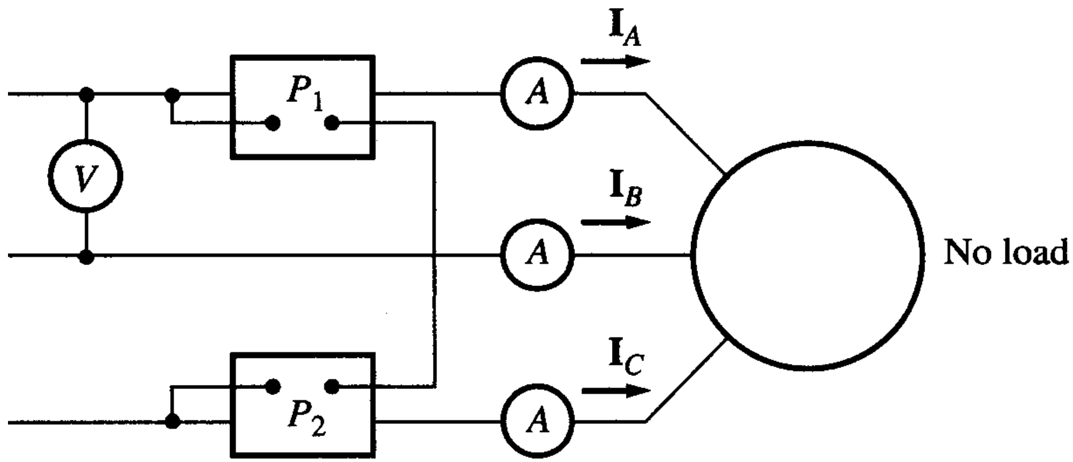
Determination of motor parameters

- Due to the similarity between the induction motor equivalent circuit and the transformer equivalent circuit, same tests are used to determine the values of the motor parameters.
  - No-load test: determine the rotational losses and magnetization current (similar to no-load test in Transformers).
  - Locked-rotor test: determine the rotor and stator impedances (similar to short-circuit test in Transformers).

UNIT-5

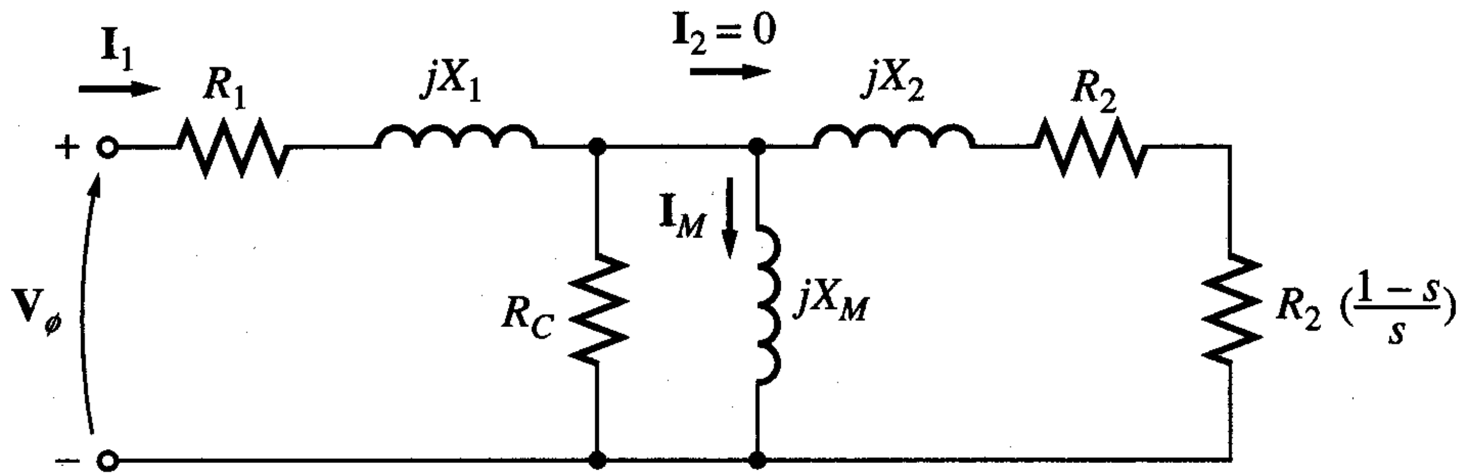
CIRCLE DIAGRAM AND SPEED CONTROL OF INDUCTION MOTORS

No-load test



1. The motor is allowed to spin freely
2. The only load on the motor is the friction and windage losses, so all P_{conv} is consumed by mechanical losses
3. The slip is very small

No-load test

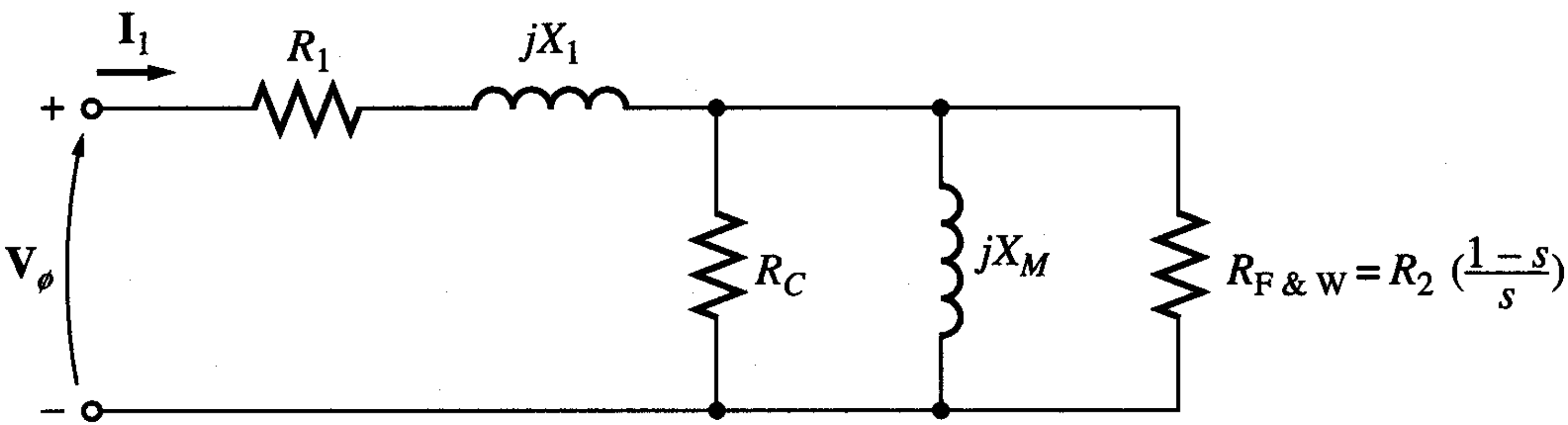


4. At this small slip

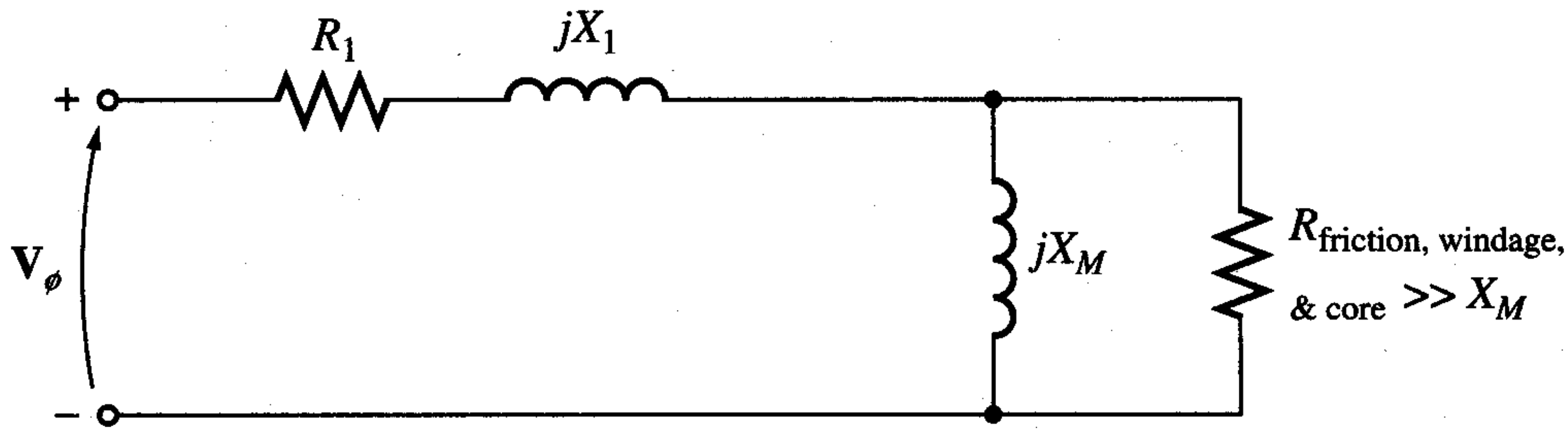
$$\frac{R_2(1-s)}{s} \gg R_2 \qquad \& \qquad \frac{\mathrm{R}_2(1-s)}{s} \gg X_2$$

The equivalent circuit reduces to…

No-load test



5. Combining R_c & R_{F+W} we get……



No-load test

6. At the no-load conditions, the input power measured by meters must equal the losses in the motor.
7. The P_{RCL} is negligible because I_2 is extremely small because $R_2(1\text{-}s)/s$ is very large.
8. The input power equals

$$
\begin{aligned}
P_{in} &= P_{SCL} + P_{core} + P_{F\&W} \\
&= 3I_1^2 R_1 + P_{rot}
\end{aligned}
$$

Where

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

No-load test

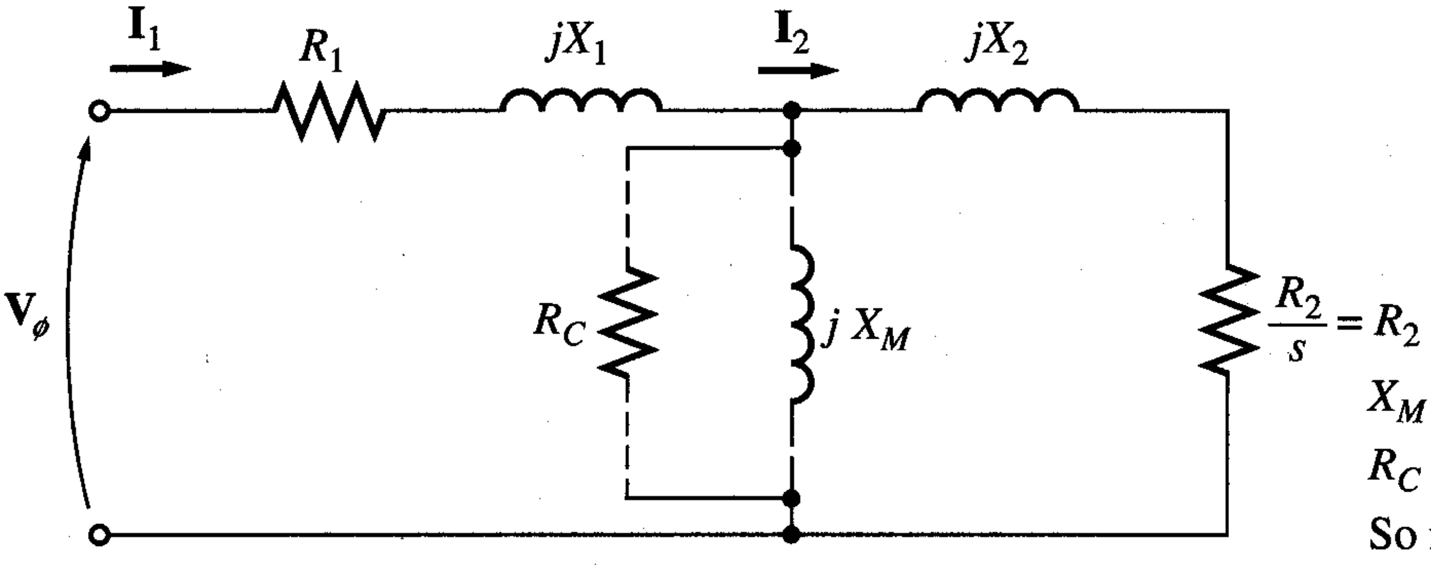
9. The equivalent input impedance is thus approximately

$$\left|Z_{eq}\right| = \frac{V_\phi}{I_{1,nl}} \approx X_1 + X_M$$

If X_1 can be found, in some other fashion, the magnetizing impedance X_M will be known

Blocked-rotor test

- In this test, the rotor is locked or blocked so that it cannot move, a voltage is applied to the motor, and the resulting voltage, current and power are measured.



$X_M >> |R_2 + jX_2|$

$R_C >> |R_2 + jX_2|$

So neglect R_C and X_M

Blocked-rotor test

- The AC voltage applied to the stator is adjusted so that the current flow is approximately full-load value.
- The locked-rotor power factor can be found as

$$PF = \cos\theta = \frac{P_{in}}{\sqrt{3}V_l I_l}$$

- The magnitude of the total impedance

$$\left|Z_{LR}\right| = \frac{V_\phi}{I}$$

Blocked-rotor test

$$\left|Z_{LR}\right| = R_{LR} + jX'_{LR}$$
$$= \left|Z_{LR}\right|\cos\theta + j\left|Z_{LR}\right|\sin\theta$$

$$R_{LR} = R_1 + R_2$$
$$X'_{LR} = X'_1 + X'_2$$

Where X'_1 and X'_2 are the stator and rotor reactances at the test frequency respectively

$$R_2 = R_{LR} - R_1$$

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

Blocked-rotor test

	X_1 and X_2 as 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	$0.5\ X_{LR}$	$0.5\ X_{LR}$

Speed Control of Induction Motor

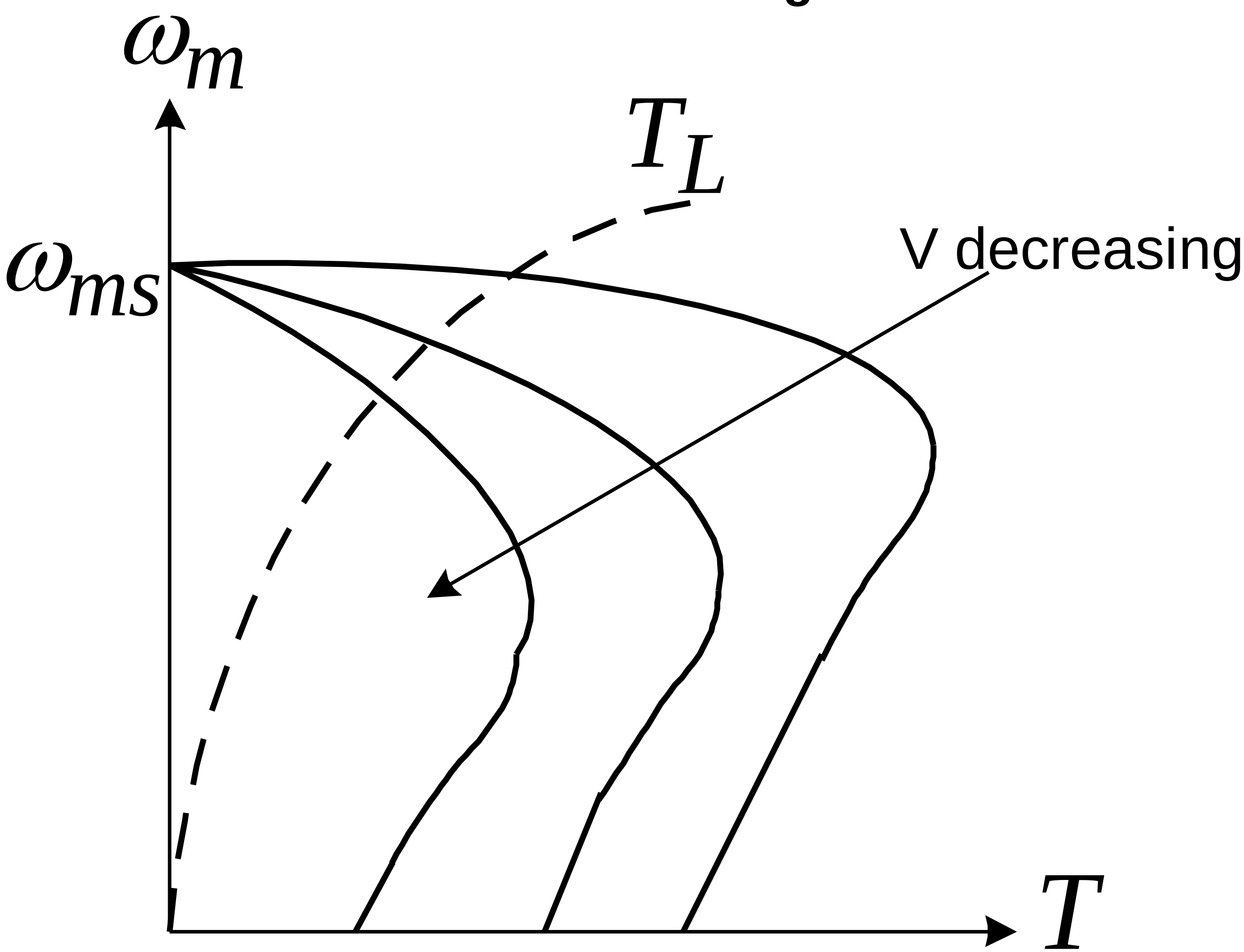
1- Variable Terminal Voltage Control

2- Variable Frequency Control

3- Rotor Resistance Control

4- Injecting Voltage in Rotor Circuit

1- Variable Terminal Voltage Control



variable terminal voltage control	variable frequency control
Low speed range	Wide speed range
Lower rated speed	Lower & higher rated speed

2- Variable Frequency Control

$$a = f \,/\, f_{rated}$$ Per-Unit Frequency

1- Operation Below the Rated Frequency $a < 1$

$$I_m = \frac{E_{rated}}{X_m} = \frac{E_{rated}}{f_{rated}} * \frac{1}{2\pi L_m} \longleftarrow$$ At rated frequency

$$I_m = \frac{E}{aX_m} = \frac{E}{a * f_{rated}} * \frac{1}{2\pi L_m} \longleftarrow$$ At any frequency, f

Comparing of the above equations, I_m will stay constant at a value equal to its rated value if

$$E = a\,E_{rated} = \frac{f}{f_{rated}} E_{rated} \longrightarrow \frac{E}{f} = \frac{E_{rated}}{f_{rated}}$$

The above equation suggests that the flux will remain constant if the back emf changes in the same ratio as the frequency, in other ward, when *E/f* ratio is maintained constant.

The rotor current at any frequency *f can be obtained from the following equation:*

$$I'_r = \frac{aE_{rated}}{\sqrt{\left(\frac{R'_r}{s}\right)^2 + (aX'_r)^2}} = \frac{E_{rated}}{\sqrt{\left(\frac{R'_r}{as}\right)^2 + (X'_r)^2}}$$

$$s = \frac{a\omega_{ms} - \omega_m}{a\omega_{ms}} = \frac{\omega_{sl}}{a\omega_{ms}}$$

ω_{ms} Synchronous Speed at rated frequency f_{rated}

ω_m Angular Speed at frequency f

$$sa = \frac{a\omega_{ms} - \omega_m}{\omega_{ms}} = \frac{\omega_{sl}}{\omega_{ms}}$$

$$\omega_{sl} = a\omega_{ms} - \omega_m$$

$$T = \frac{3}{a\omega_{ms}} I'^2_r \left(\frac{R'_r}{s}\right) = \frac{3}{\omega_{ms}} \left[\frac{E^2_{rated} * R'_r \ / as}{\left(\frac{R'_r}{as}\right)^2 + (X'_r)^2}\right]$$

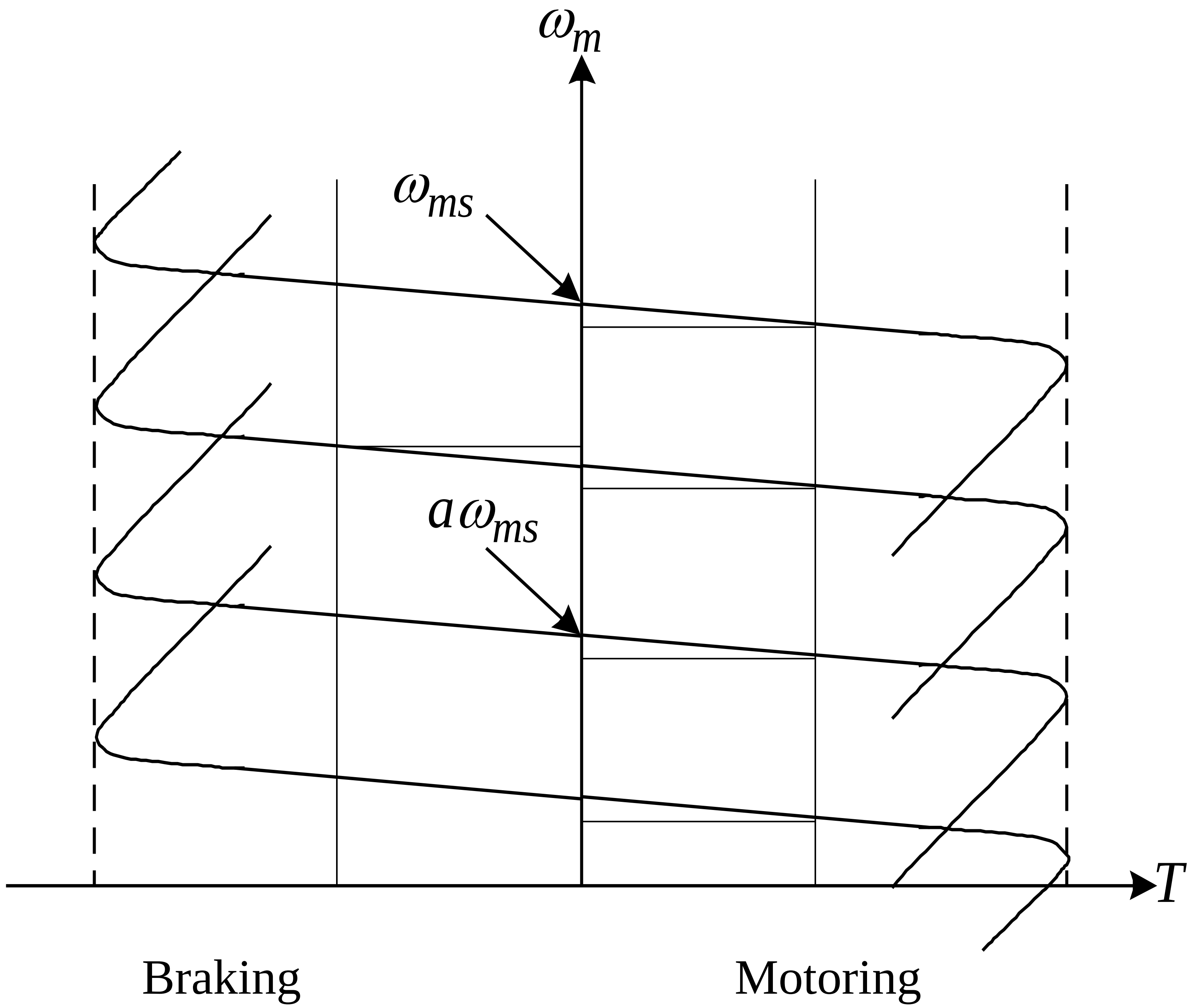
→ Torque at frequency f

At a given f and E

$$s_m \cong \pm \frac{R'_r}{aX'_r} \longrightarrow T_{\max} = \frac{3}{2\omega_{ms}} \left[\frac{E^2_{rated}}{X'_r}\right]$$

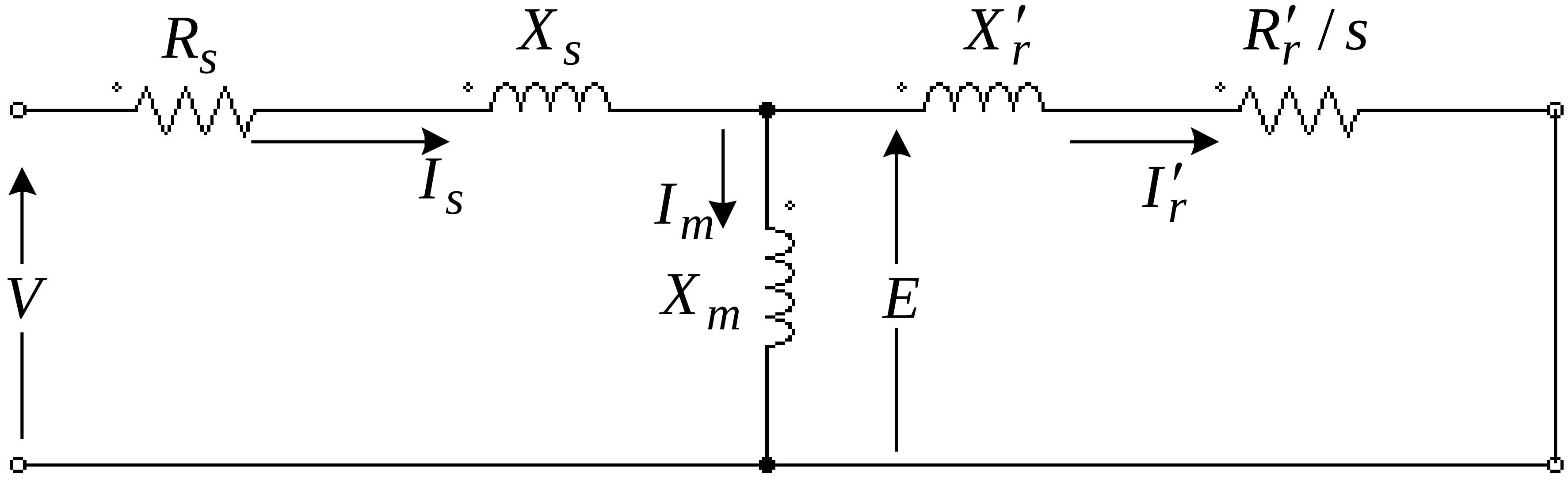
$$T = \frac{3}{a\omega_{ms}} I_r'^2 \left(\frac{R_r'}{s} \right) = \frac{3}{\omega_{ms}} \left[\frac{E_{rated}^2 * R_r' \ / as}{\left(\frac{R_r'}{as} \right)^2 + \left(X_r' \right)^2} \right] \qquad \because \frac{R_r'}{as} >> X_r'$$

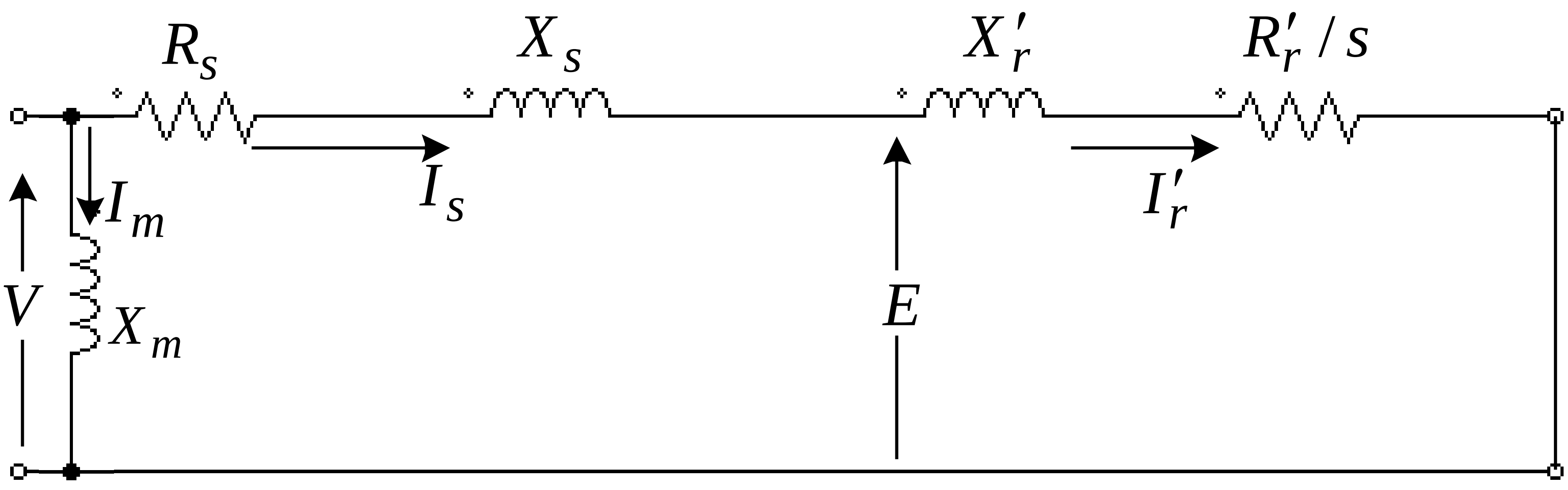
$$T = \frac{3E_{rated}^2}{\omega_{ms} R_r'} (as) = constant\left(\omega_{sl}\right) \qquad (6\text{-}51)$$



ω_m
ω_{ms}
$a\omega_{ms}$
T
Braking
Motoring

V/f Control





V/f Control

At rated frequency

$$T = \frac{3}{\omega_{ms}} I_r'^2 \left(\frac{R_r'}{s} \right) = \frac{3}{\omega_{ms}} \left[\frac{V_{rated}^2 * R_r' \ / s}{(R_s + R_r' / s)^2 + (X_s + X_r')^2} \right]$$

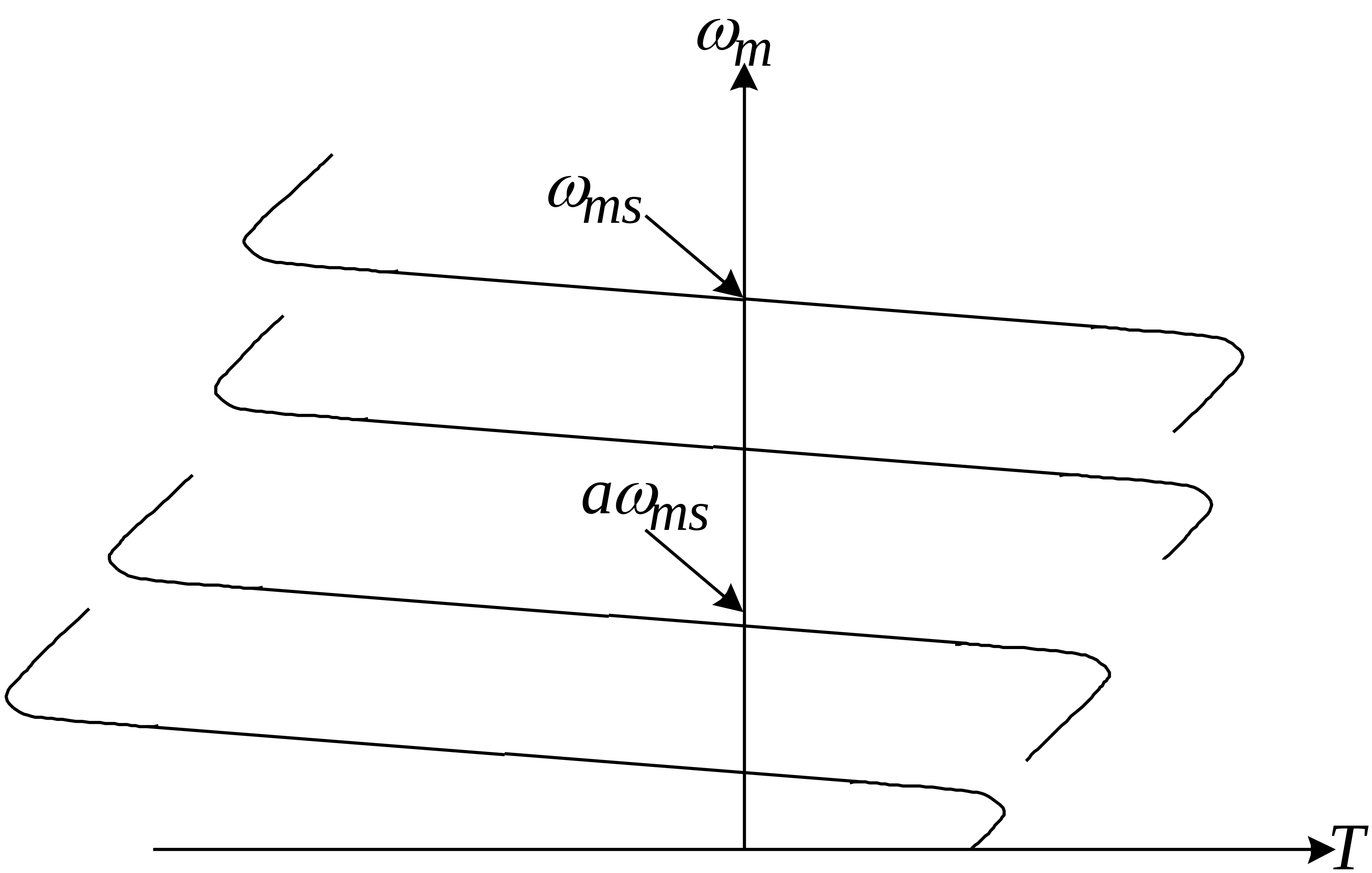
$$T_{\max} = \frac{3}{2\omega_{ms}} \left[\frac{V_{rated}^2}{R_s \pm \sqrt{R_s^2 + (X_s + X_r')^2}} \right]$$

At any frequency, *f*, $a < 1$

$$T = \frac{3}{\omega_{ms}} \left[\frac{V_{rated}^2 * R_r' \ / as}{(R_s / a + R_r' / as)^2 + (X_s + X_r')^2} \right]$$

$$T_{\max} = \frac{3}{2\omega_{ms}} \left[\frac{V_{rated}^2}{R_s / a \pm \sqrt{(R_s / a)^2 + (X_s + X_r')^2}} \right]$$

V/f Control



Operation above the rated frequency *a*>1

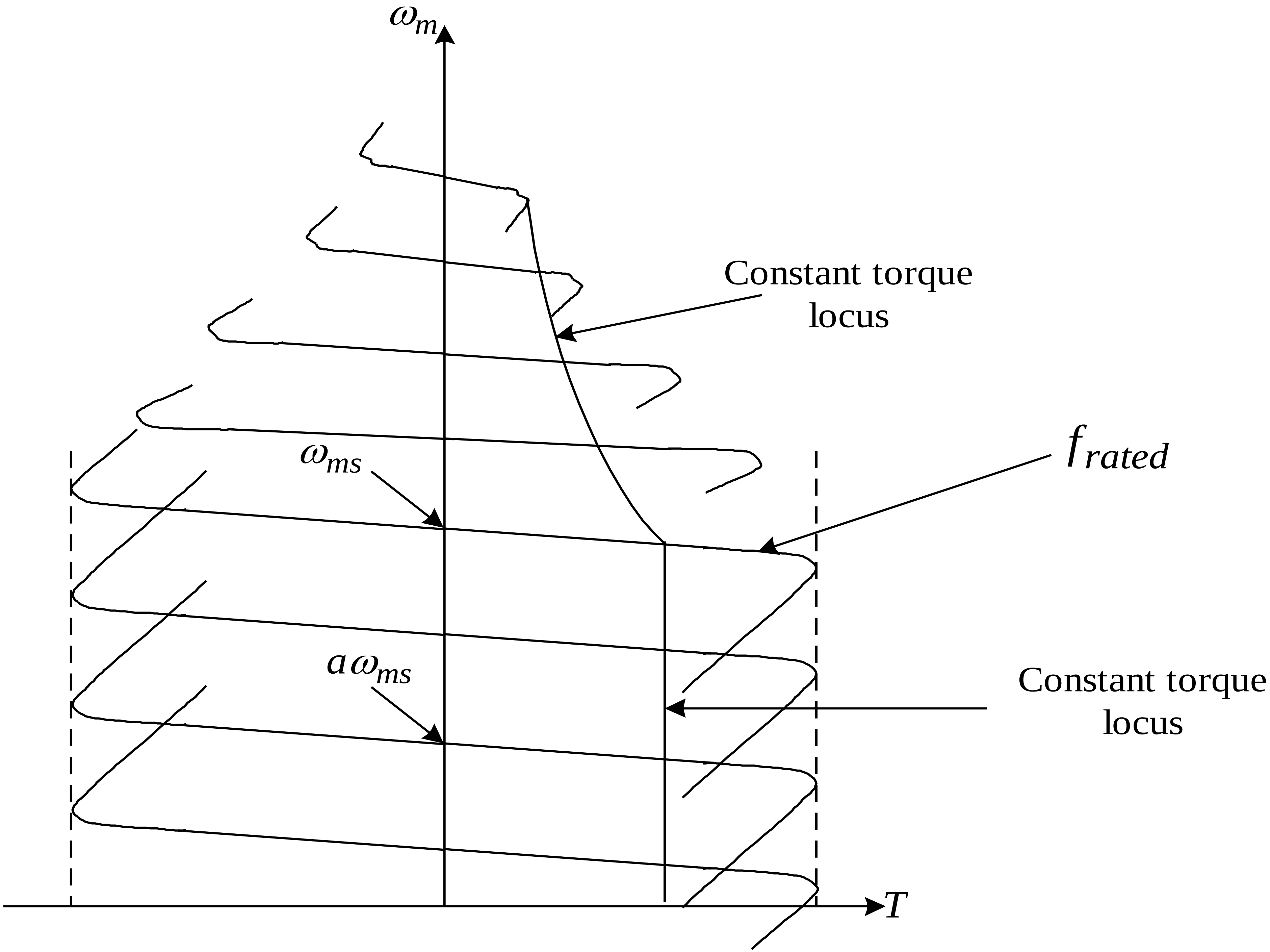
The terminal voltage has to be constant = Rated Volatge= V_{rated}

$$\because V = constant \longrightarrow \because Flux \downarrow \ \ when\ a \uparrow$$

At any frequency, *f*, $a > 1$

$$T = \frac{3}{\omega_{ms}} \left[\frac{V_{rated}^2 * R_r' \ / as}{\left(R_s + R_r' / s\right)^2 + a^2 \left(X_s + X_r'\right)^2} \right]$$

$$T_{\max} = \frac{3}{2\omega_{ms} a} \left[\frac{V_{rated}^2}{R_s \pm \sqrt{(R_s)^2 + a^2 (X_s + X_r')^2}} \right]$$



ω_m
Constant torque locus
f_{rated}
ω_{ms}
$a\omega_{ms}$
Constant torque locus
T

THANK U….