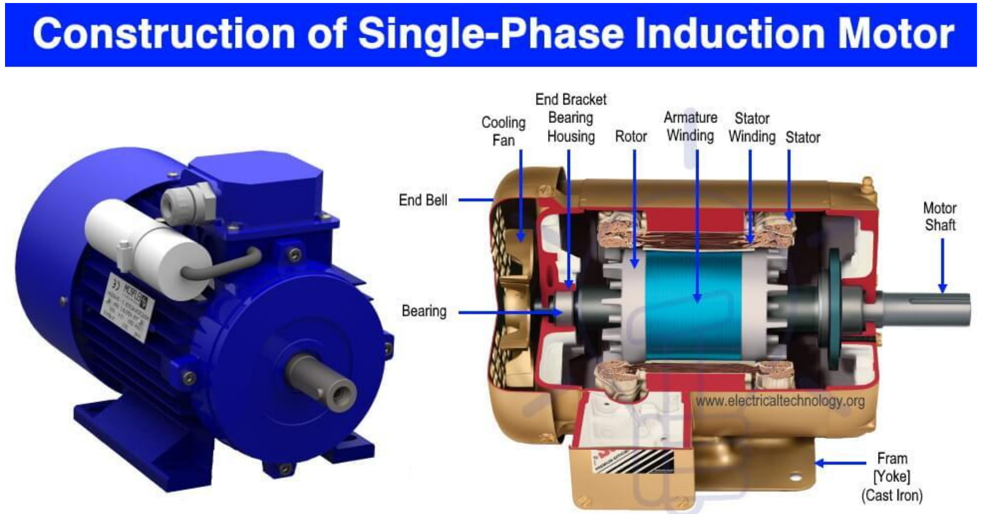
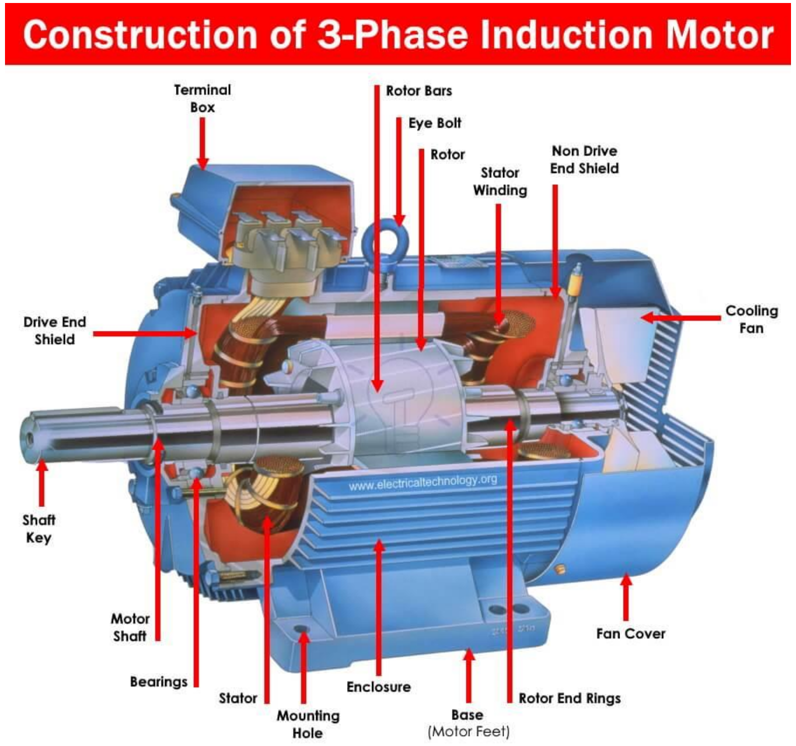
CHAPTER 3

SPEED CONTROL OF AC MOTOR


Construction of Single-Phase Induction Motor
End Bracket
Bearing
Housing
Cooling
Fan
Rotor
Armature
Winding
Stator
Winding
Stator
End Bell
Motor
Shaft
Bearing
www.electricaltechnology.org
Fram
[Yoke]
(Cast Iron)


Construction of 3-Phase Induction Motor
Terminal
Box
Rotor Bars
Eye Bolt
Rotor
Stator
Winding
Non Drive
End Shield
Drive End
Shield
Cooling
Fan
Shaft
Key
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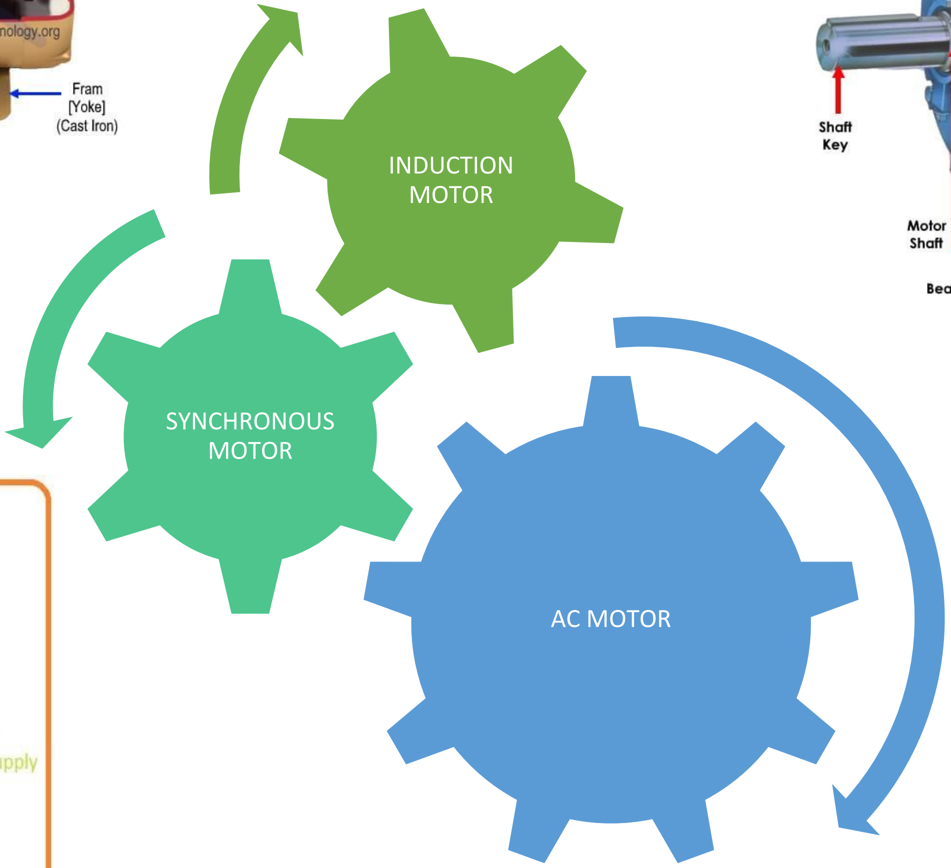
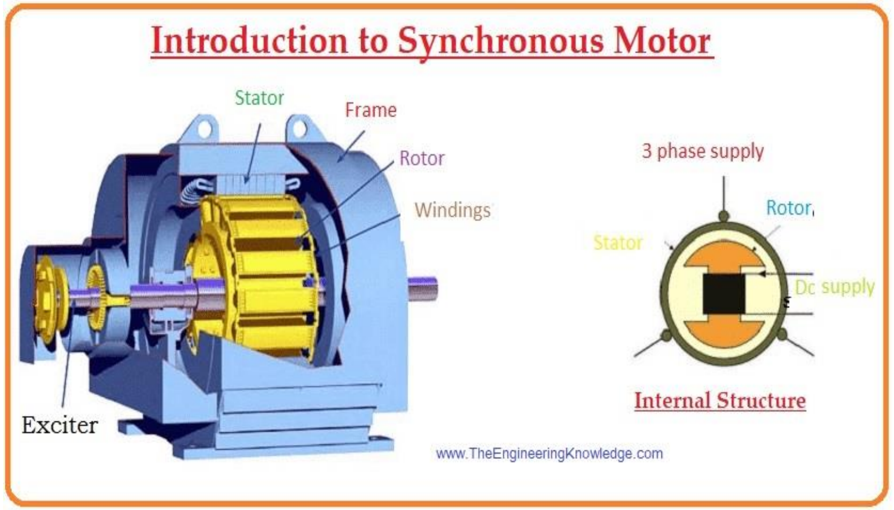
Motor
Shaft
Fan Cover
Bearings
Stator
Enclosure
Mounting
Hole
Base
(Motor Feet)
Rotor End Rings


INDUCTION
MOTOR
SYNCHRONOUS
MOTOR
AC MOTOR


Introduction to Synchronous Motor
Stator
Frame
Rotor
Windings
Exciter
3 phase supply
Rotor
Stator
Dc supply
Internal Structure
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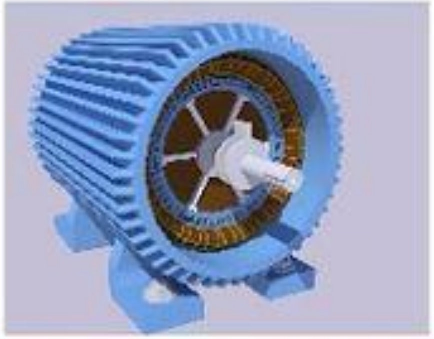


Synchronous motor	Induction motor
Construction is complicated	Construction is simpler , particularly in case of cage rotor
Not self starting	Self starting
Separate DC source is required for rotor excitation	Rotor gets excited by the induced e.m.f so separate source is not necessary
The speed is always synchronous irrespective of the load	The speed is always less than synchronous but never synchronous
Speed control is not possible	Speed control is possible though difficult
As load increases, load angle increases, keeping speed constant at synchronous	AS load increases , the speed keeps on decreasing
By changing excitation , the motor p.f can be changed from lagging and leading	It always operates at lagging p.f and p.f control is not possible
It can be used as synchronous condenser for p.f improvement	It can not be used as synchronous condenser
Motor is sensitive to sudden load changes and hunting results	Phenomenon of hunting is absent
Motor is costly and requires frequent maintenance	Motor is cheap , especially cage rotors and maintenance free

INDUCTION MOTORS (IM)

- About 65% of the electric energy in the United States is consumed by electric motors.
- In the industrial sector alone, about 75% of the total energy is consumed by motors, and over 90% of them are induction machines.
- The main reasons for the popularity of the induction machines are that they are rugged, reliable, easy to maintain, and relatively inexpensive.
- Their power densities (output power to weight) are higher than those for DC motors.

$$n_s = \frac{60f}{pp} = 120\frac{f}{p}\ \text{rpm}$$

The difference between the rotor speed *(n or w)* and the synchronous speed *(n_s or w_s)* is known as the slip *s*

$$s = \frac{\Delta n}{n_s} = \frac{\Delta\omega}{\omega_s} = \frac{n_s - n}{n_s} = \frac{\omega_s - \omega}{\omega_s}$$

INDUCTION MOTORS (IM)

- IM requires **variable-frequency power electronic drive for optimal speed control** – our topic
- IM will always run at a speed lower than synchronous speed. **N_S>N_R** → Speed fall magnetic field produces an induces voltage in rotor winding
- Three phase AC current pass into the stator produce rotating magneting field, current will be induces in the bar of squirrel cage and rotor starting rotated, electricity induced on a rotor
- Eddy current minimum: $Slip = \frac{N_S - N_R}{N_S}$
- Ns α F, when frequency (f) is increase, synchronous speed(N_S) will increase and also rotor speed(N_R).
- IM use method Pulse width modulation (PWM) and Pulse Width Controller (PWC) to control their signal that send to motor as a driver.
- PWM→ method to control output voltage without disturbance by using AC motor control. Convert digital signal to analog output voltage.
- PWC → method to change pulse width. One multivibrator and amplifier used. Control the width of a pulse signal.
- Thyristor circuit: thyristor switching circuits to control much larger loads like lamps, motor, heaters etc
- How to turn on thyristor? By inject a small trigger pulse of current (not continuous current - μs) into the gate (G) terminal when the thyristor forward direction, Anode (A) is positive respect to the Cathode (K), for regenerative latching to occur.
- When thyristor start conduct it continuous to conduct even no gate signal until the anode current decrease below the devices holding current (I_H) → auto turn off.
- Thyristor cannot be used for amplification @ controlled switching. Thyristor used for high power switching application that operate only in the switching mode.
- While, stator voltage control is method use to control speed of IM. The speed of three phase IM can be varied by varying the supply voltage
- The torque developed is proportional to the square of the supply voltage and the slip at the maximum torque is independent of the supply voltage
- The variation in the supply voltage foes not alter the synchronous speed (N_S) of the motor.

EQUIVALENT CIRCUIT OF IM

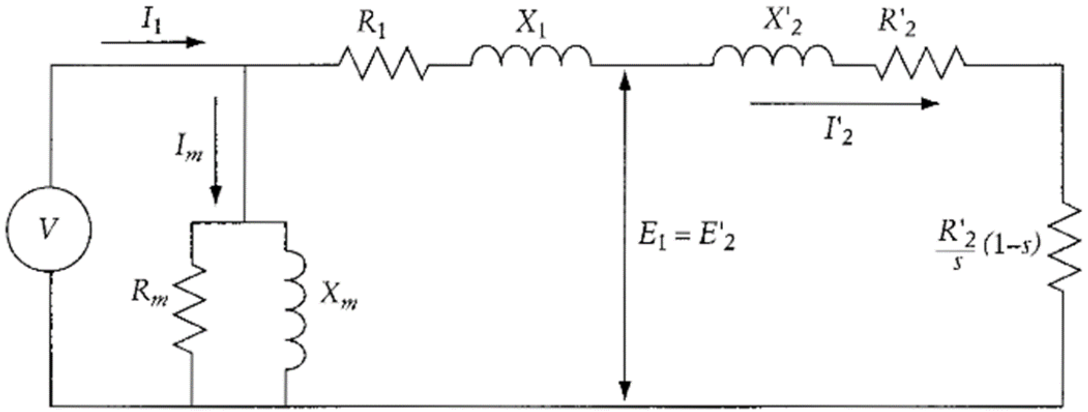
- The rotor current can be computed as;

$$I'_2 = \frac{V}{\sqrt{\left(R_1 + \frac{R'_2}{s}\right)^2 + X_{eq}^2}}$$

$$T_d = \frac{P_d}{\omega} = \frac{3V^2R'_2}{s\omega_s\left[\left(R_1 + \frac{R'_2}{s}\right)^2 + X_{eq}^2\right]}$$

$$T_d \approx \frac{V^2 s}{\omega_s R'_2}$$

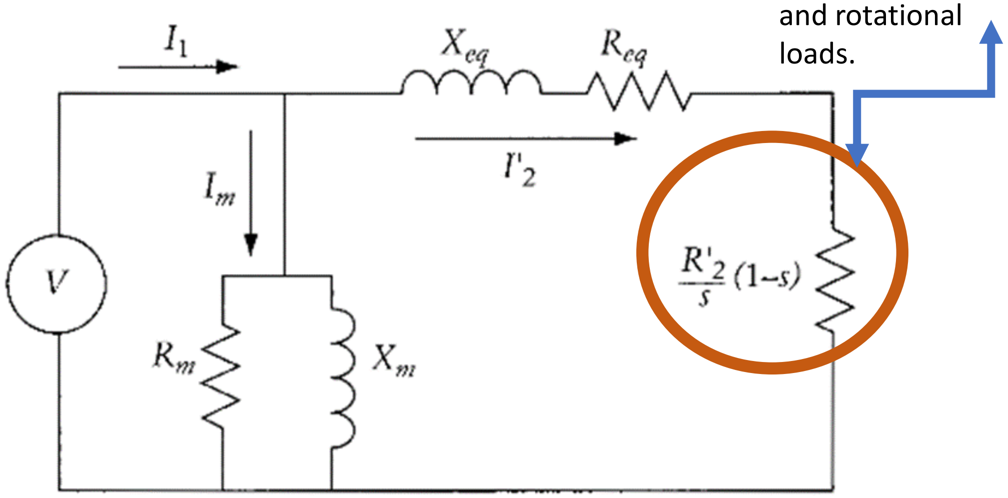
V is the phase voltage



$$R_{eq} = R_1 + R'_2$$

$$X_{eq} = X_1 + X'_2$$

Represents the load of the motor, which includes the mechanical and rotational loads.

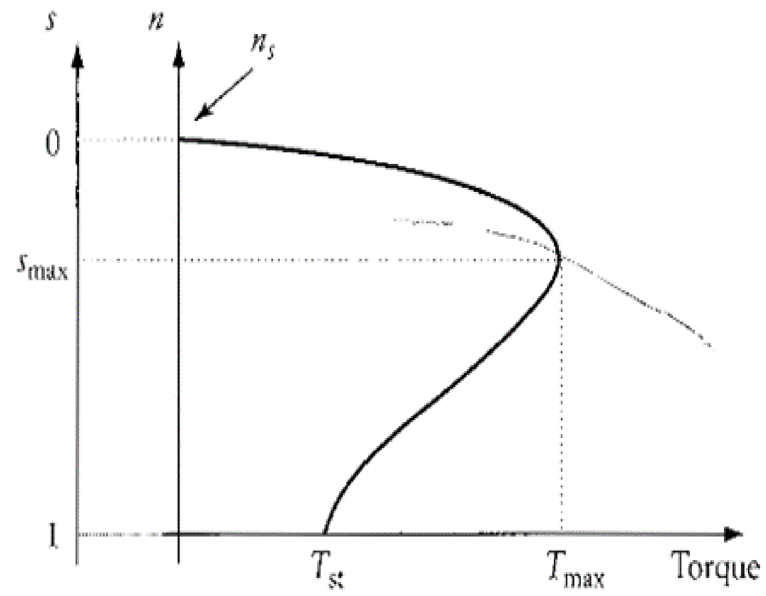


BASIC PRINCIPLES OF SPEED CONTROL OF IM

$$n_s = 120\frac{f_s}{p}$$

$$T_d \approx \frac{V^2 s}{\omega_s R'_2}$$

Speed–torque characteristics of the induction motor



BASIC PRINCIPLES OF SPEED CONTROL OF IM

- Starting torque slightly higher than its full-load torque, motor start carrying any load it can supply at full load. Torque of the motor for a given slip varies at the square of the applied voltage.
- If rotor is driven faster than Ns → run as generator (mech → elect)
- By vary supplying voltage, speed can be controlled. The voltage is varied until the torque required by the load is developed at the desired speed. The torque developed is proportional to the square of the supply voltage and the current is proportional to the voltage.

- How???
  - By connecting an external resistance in the stator circuit of the motor
  - Using auto transformer
  - Using a thyristor voltage controller
  - TRIAC controller

BASIC PRINCIPLES OF SPEED CONTROL OF IM

- Add an external resistance into rotor side circuit
- Applying cascade connection: thyristor circuit
- Injecting e.m.f into rotor side circuit of the motor
- Slip Energy Recovery (SER)

ROTOR

- By changing the supply voltage of the motor
- Changing the stator pole number of the motor
- Changing the frequency of the supply side of the motor

STATOR

BASIC PRINCIPLES OF SPEED CONTROL OF IM

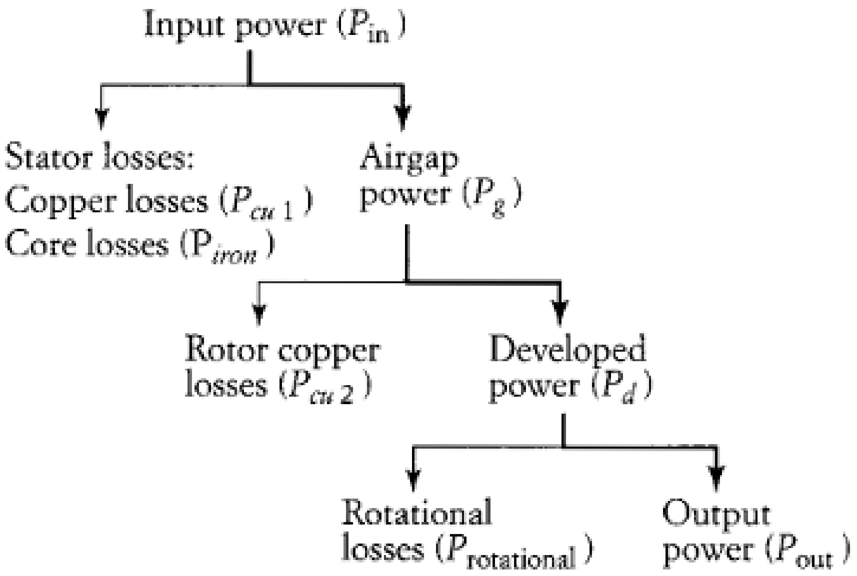
- By examining this equation, one can conclude that the speed ω(or slip *s) can be* controlled if at least one of the following variables or parameters is altered:

1. armature or rotor resistance
2. armature or rotor inductance
3. magnitude of terminal voltage
4. frequency of terminal voltage

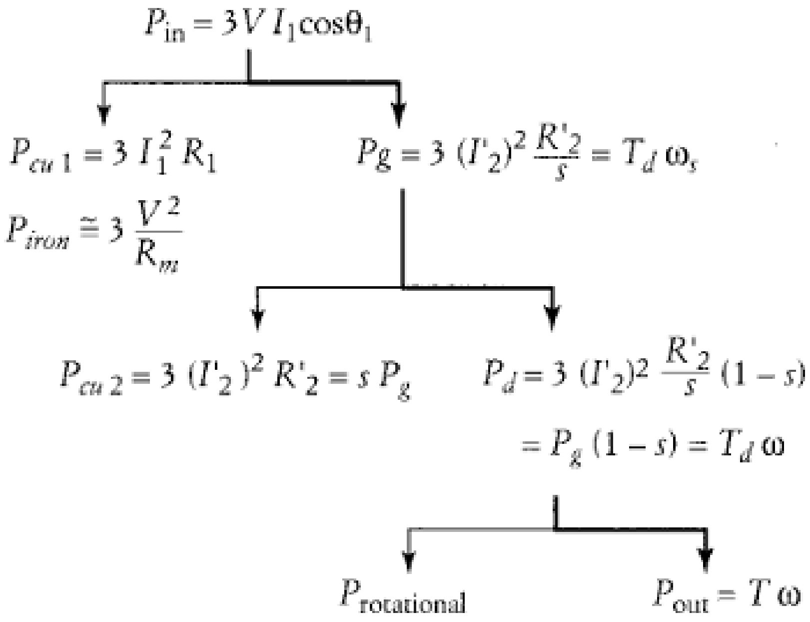
$$T_d = \frac{P_d}{\omega} = \frac{V^2 R'_2}{s\omega_s\left[\left(R_1 + \frac{R'_2}{s}\right)^2 + X_{eq}^2\right]}$$

- There are other useful and effective techniques for speed control, although it is not evident by examining as shown. Among them are:
- 5. rotor voltage injection
- 6. slip energy recovery
- 7. voltage/frequency control

POWER FLOW OF THE INDUCTION MOTOR



Detailed power flow of the induction motor



The motor efficiency η is

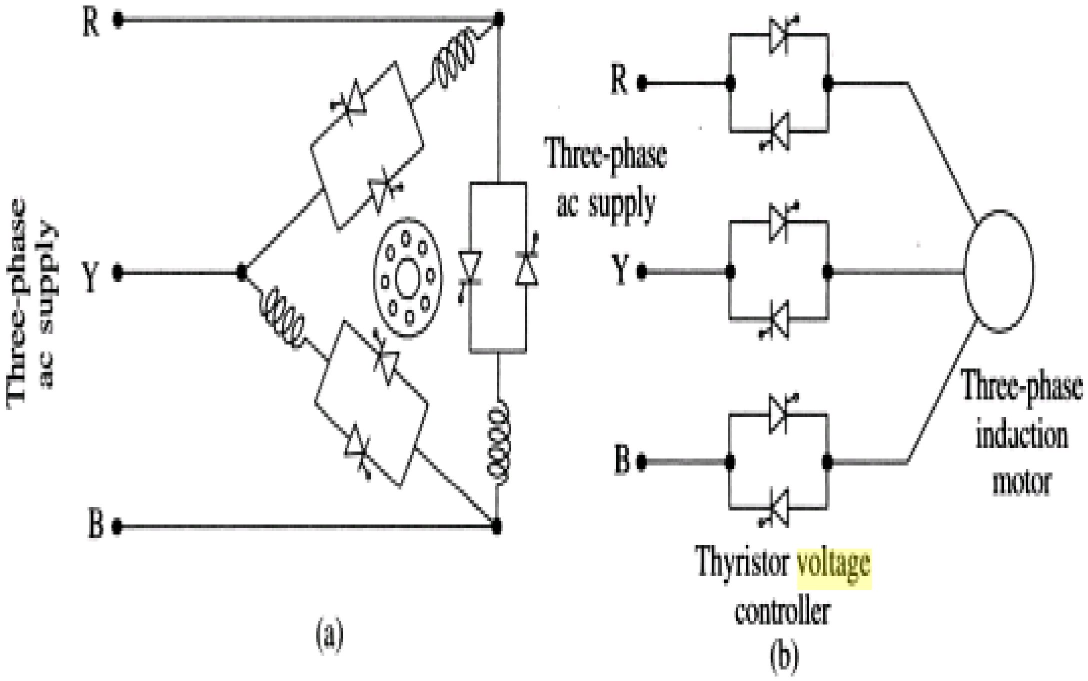
$$\eta = \frac{P_{out}}{P_{in}}$$

SPEED CONTROL OF IM

- The speed control by adjusting stator voltage
- The speed control by adjusting supply frequency
- The speed control by voltage/frequency (v/f) control

CONTROLLING SPEED BY ADJUSTING THE STATOR VOLTAGE

- Several techniques can be used to change the stator voltage of the motor.
- One of them is **using SCR connected back to back** as shown. The circuit configuration of phase control is a full wave.
- In this circuit, the induction motor is connected to a three-phase supply voltage via back-to-back SCR pairs.
- For each phase, one SCR conducts the current in one direction (from the source to the motor), and the other SCR conducts the current in the second half of the cycle (from motor to source).
- **If the triggering of these SCRs is controlled, the voltage across the stator terminals can change from zero to almost full voltage.**



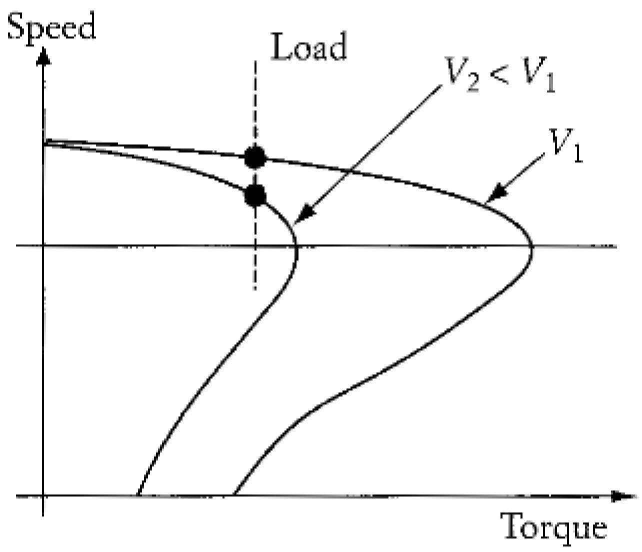
Three Phase AC Voltage Controller circuits for:
(a) Delta connection; (b) Star Connection

CONTROLLING SPEED BY ADJUSTING THE STATOR VOLTAGE

$$T_d = \frac{P_d}{\omega} = \frac{V^2 R'_2}{s\omega_s\left[\left(R_1 + \frac{R'_2}{s}\right)^2 + X_{eq}^2\right]}$$

- As seen in equation above, the torque of the motor is proportional to the square of its stator voltage.
- For the same slip and frequency, a small change in motor voltage results in a relatively large change in torque.
- A 10% reduction in voltage causes a 19% reduction in developed torque as well as the starting and maximum torques.

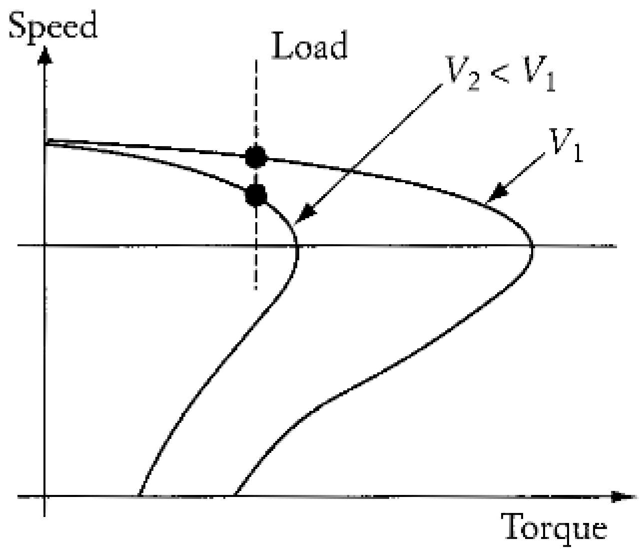
Impact of voltage on motor speed



CONTROLLING SPEED BY ADJUSTING THE STATOR VOLTAGE

- The figure shows two curves for two different values of the stator voltage. (Note that the slip at the maximum torque remains unchanged since it is not a function of voltage).
- For normal operation in the linear region, the figure shows that the motor speed can be modestly changed when the voltage is altered.
- However, a wide range of speed control cannot be accomplished by this technique.
- Nevertheless, it is an excellent method for reducing starting current and increasing efficiency during light loading conditions.
- The starting current is reduced since it is directly proportional to the stator voltage.
- The losses are reduced, particularly core losses, which are proportional to the square of the voltage.

Impact of voltage on motor speed

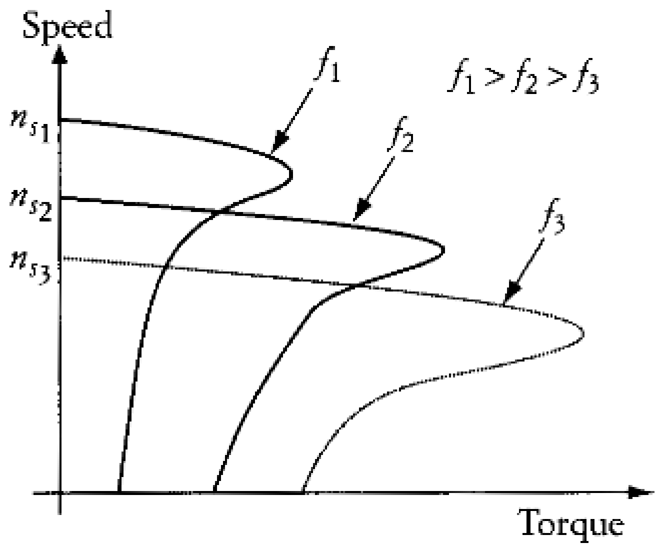


Keep in mind that the terminal voltage cannot exceed the rated value to prevent the damage of the windings' insulation. Thus, this technique is only suitable for speed reduction below the rated speed.

CONTROLLING SPEED BY ADJUSTING THE SUPPLY FREQUENCY

- In steady state, the induction motor operates in the small-slip region, where the speed of the motor is always close to the synchronous speed of the rotating flux.
- Since the synchronous speed is directly proportional to the frequency of the stator voltage, **any change in frequency results in an equivalent change in motor speed.**

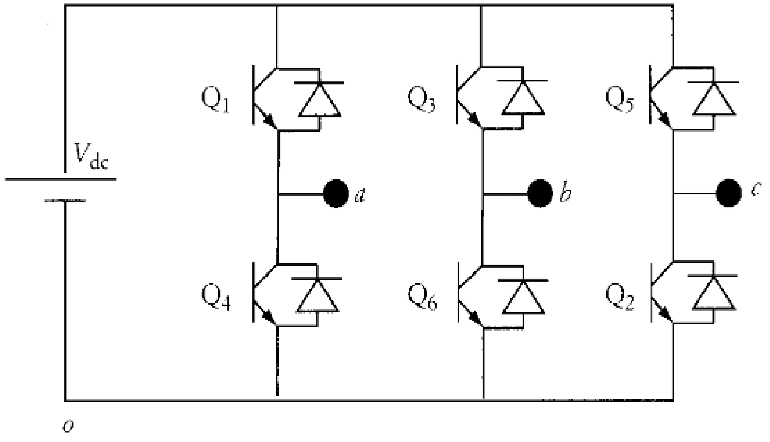
Impact of frequency on motor speed



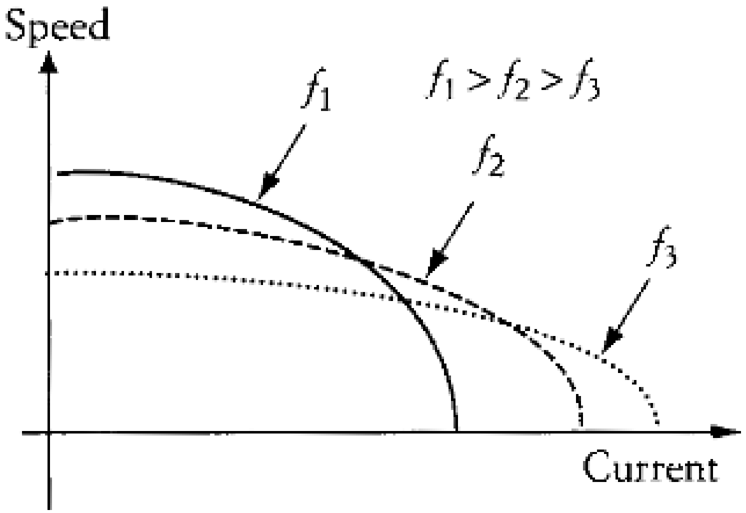
$$n_s = 120\frac{f}{p}$$

CONTROLLING SPEED BY ADJUSTING THE SUPPLY FREQUENCY

- The effect of frequency on motor current is given $I'_2 = \dfrac{V}{\sqrt{\left(R_1 + \dfrac{R'_2}{s}\right)^2 + X_{eq}^2}}$
- Frequency manipulation appears to be an effective method for speed control that requires a simple dc/ac converter with variable switching intervals.



Impact of frequency on motor current

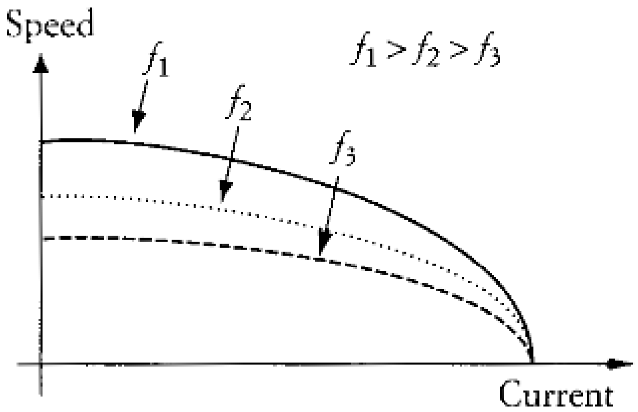


However, there are severe limitations to this method: very low frequencies may cause motor damage due to excessive currents, and large frequencies may stall the motor.

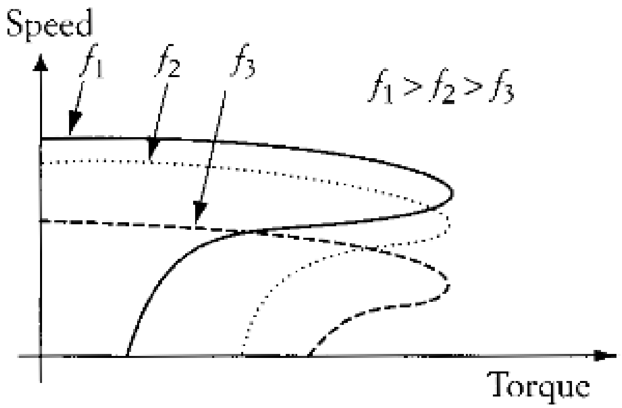
CONTROLLING SPEED BY VOLTAGE/FREQUENCY CONTROL

- The change in voltage and frequency is a powerful method for speed control.
- Note that both frequency and voltage can change simultaneously by the **pulse-width modulation technique**.
- This type of control is common for induction motors. There are several variations where the *v/f ratio is also adjusted* to provide a special operating performance.
- The most common method, though, is the fixed *v/f ratio.*
- It is clear that ***when the v/f ratio is constant, the maximum torque is unchanged.***

Speed–current characteristics for fixed v/f ratio

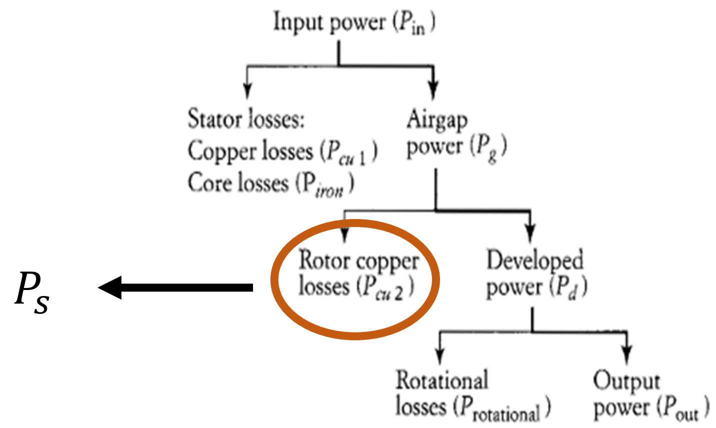


Speed–torque characteristics for fixed v/f ratio



SLIP ENERGY RECOVERY

- Most of the input electric power P_{in} is converted to mechanical power P_{out} to support the load.
- However, part of P_{in} is lost in the resistive element of the stator circuit P_{cu1}.
- *The rest is power transmitted to the rotor via the air gap* P_g.
- *At* high speeds, most of P_g *is converted to mechanical developed power* $P_d = (1 - s)P_g$
- The rest is known as the slip power $P_s = sP_g$.
- *Slip power is an electrical power dissipated* in the rotor resistance in the form of rotor copper losses P_{cu2}.
- Slip power P_s, *can be substantial at low speeds.*
- When a resistance in the rotor circuit is used to reduce the motor speed, the efficiency of the motor is substantially reduced.
- The speed reduction is due to the extra power dissipated in the rotor circuit, which results in less mechanical power for the load.
- We can still use this principle to reduce the motor speed, but instead of dissipating the extra power in the rotor resistance, we send it back to the source.
- This method is known as **Slip Energy Recovery (SER)** or **Static Scherbius Drive**.



SLIP ENERGY RECOVERY

- In the rotor resistance control method, the slip power in the rotor circuit is wasted as I^2R losses during the low-speed operation.
- The efficiency is also reduced.
- The slip power from the rotor circuit can be recovered and fed back to the AC source so as to utilize it outside the motor.
- Thus, the overall efficiency of the drive system can be increased.

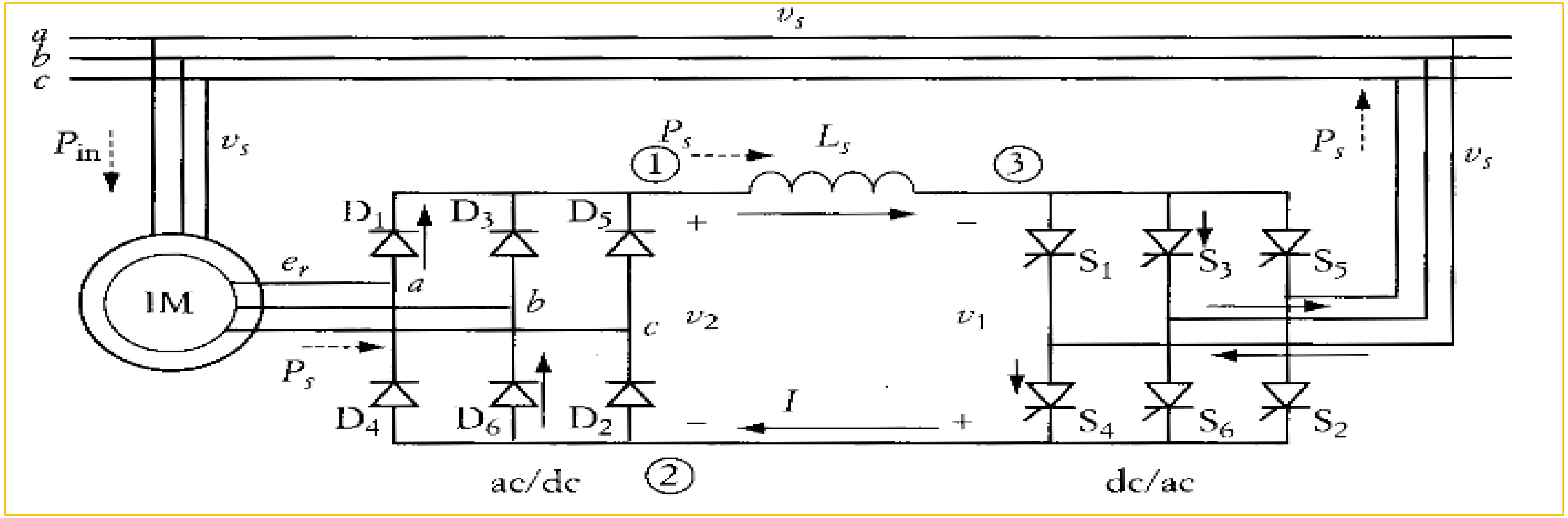
SLIP ENERGY RECOVERY (SER)

- SER is use to increase efficiency, simply utilize.
- SER recovered by adding variable voltage source in rotor of IM
- Variable source will absorb the slip power and send back to AC supply
- SER provide speed control of IM
- By varying magnitude of the variable voltage source → can control current, torque & slip of the rotor
- I^2R losses decrease by control rotor resistance
- SER consist 4 main component/block

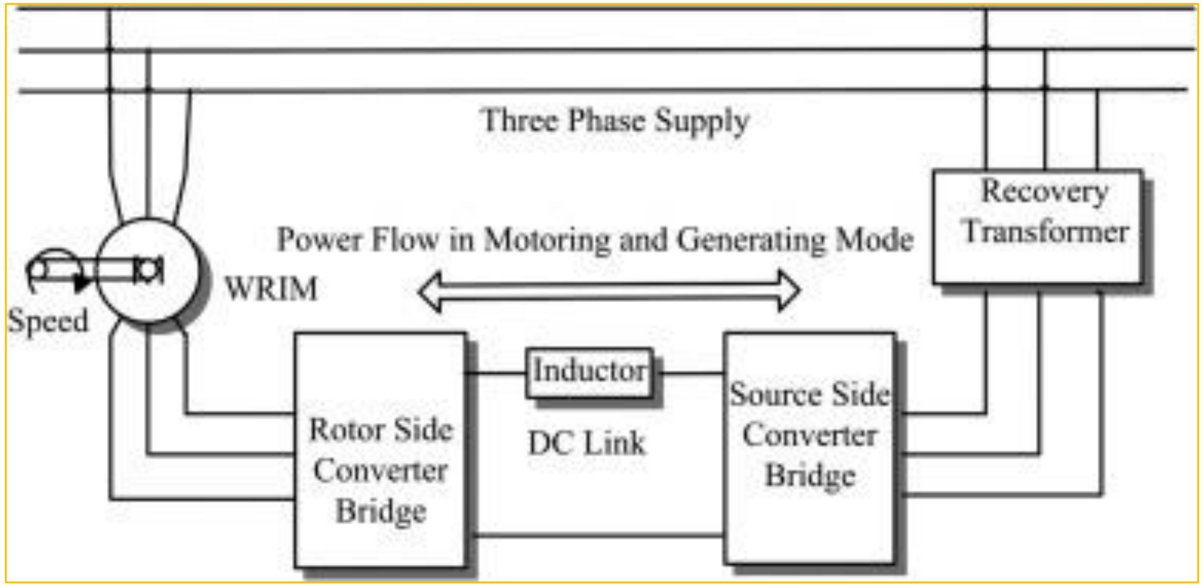
- **Rectifier**: Connect to rotor. Convert AC → DC and force power flow away from winding
- **Reactor**: Smoothen the current
- **Converter**: Phase controlled → inversion mode convert DC → AC
- **Transformer**: Improve power factor. Power absorb by the rectifier send back to supply

SLIP ENERGY RECOVERY

Circuit Diagram



Block Diagram



SLIP ENERGY RECOVERY

- And finally, the new speed for SER can be found as

$$n = n_s\left[1 + \frac{N_1}{N_2}\cos(\alpha)\right]$$

- And the current of the motor $I = \frac{T_d \omega_s}{K V_s}$

where $K = \frac{3\sqrt{2}}{\pi}\frac{N_2}{N_1}$

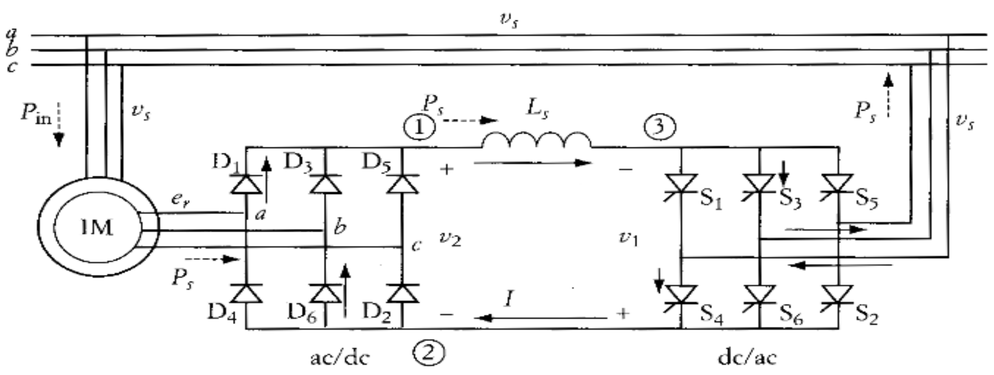
V_s rms line- to-line voltage

where N_1 and N_2 are the number of turns of the stator and rotor windings, respectively

where α is the triggering angle of the dc/ac converter, measured from the zero crossing of the line-to-line voltage

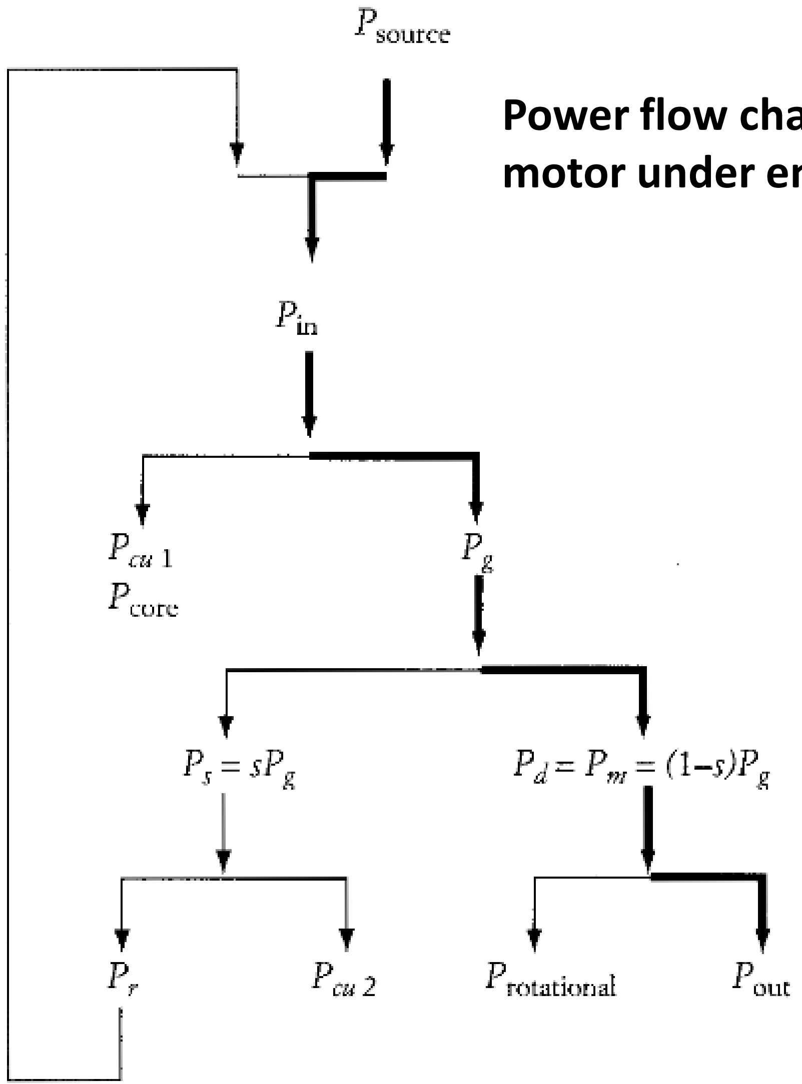
- It is shows that by adjusting the triggering angle of the dc/ac converter can control the speed of the machine.
- The range of α is from *π/2 to π* . ***In this range,*** the induction machine operates as a motor where the speed is less than the synchronous speed.

SLIP ENERGY RECOVERY



- With SER, the slip power is divided into the copper losses of the rotor and the recovery power P_r.
- The recovery power is injected back to the source.
- Thus, the actual power delivered by the source is the input power required by the motor minus P_r.

Power flow chart of induction motor under energy recovery



SUMMARY

$$Synchronous\ Speed, N_s = \frac{120f}{P}\ Where\ f = frequency\ \&\ P = No.of\ Poles$$

$$Motor\ Speed\ at\ full\ load, n = N_s(1 - S)\ where\ S\ is\ Slip\ of\ the\ motor$$

$$Torque\ Developed, T_d = \frac{P_d}{\omega} = \frac{V^2 S}{\omega_S R'_2} = \frac{V^2 R'_2}{S\omega_S\left[\left(R_1 + \frac{R'_2}{S}\right)^2 + X_{eq}{}^2\right]}$$

$$Power\ Developed, P_d = P_{out} + P_{rotational} = T_d\omega = \frac{V^2 S(1-S)}{R'_2} = 3(I'_2)^2\frac{R'_2}{S}(1-S)$$

$$P_{in} = P_d + P_{winding} + P_{core}$$

$$P_{winding} = P_{cu} + P_{cu2} = 3(I'_2)^2(R_1 + R'_2)$$

$$Motor\ efficiency, \eta = \frac{P_{out}}{P_{in}} \times 100\%$$

Where,
V = Voltage Line-to-Line
S = Slip
ω_S = Synchronous Speed in rad/s
R'_2 = Rotor Resistance
R_1 = Stator Resistance
P_d = Power Developed
X_{eq} = Reactance
P_d = Power Developed

$$Slip, S = \frac{N_S - N_R}{N_S}$$

SUMMARY

$$Maximum\ Torque, T_{max} = \frac{V}{2\omega_s(R_1 + \sqrt{R_1{}^2 + X_{eq}{}^2})} = \frac{V^2}{2(\frac{f}{60}\omega_s)(\frac{f}{60}X_{eq})}$$

$$Motor\ Starting\ Current, I'_{2st} = \frac{V}{\sqrt{(R_1 + R'_2)^2 + X_{eq}{}^2}}$$

$$Maximum\ Slip, S_{max} = \frac{R'_2}{\sqrt{R_1{}^2 + X_{eq}{}^2}}$$

$$Starting\ Torque, T_{st} = \frac{3(I'_{2st})^2 R'_2}{\omega_s}$$

$$Rotor\ Voltage\ (SER), e_r = sE_2$$

$$Motor\ Current, I'_2 = \frac{V}{\sqrt{\left(R_1 + \frac{R'_2}{S}\right)^2 + X_{eq}{}^2}}$$

$$Rotor\ voltage\ at\ standstill, E_2 = \frac{N_2}{N_1}(V_S)$$

THANK YOU