POWER POINT PRESENTATION

ON

STATIC DRIVES

III B. Tech II semester (JNTUH-R15)

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UNIT-I

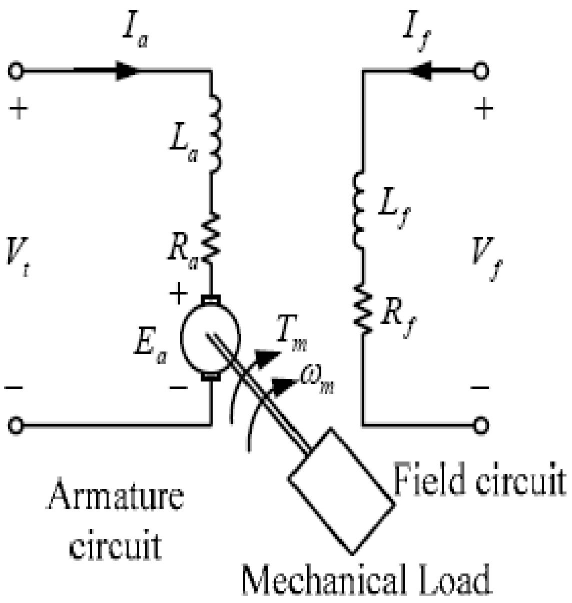
CONTROL OF DC MOTORS THROUGH PHASE CONTROLLED RECTIFIERS

Contents

- Review of dc motor equivalent circuit
- DC motor speed control
- Converters used in dc motor drives

dc motor equivalent circuit

- Equivalent circuit:



Terminology :

V_f, I_f – field voltage and current,[V]

V_t, I_a – terminal voltage and armature current,[V]

R_f, R_a – field winding resistance ,[Ω]

and armature winding resistance

L_f, L_a – field winding inductance ,[H]

and armature winding inductance

E_a – Back EMF, where $E_a = K_a \Phi \omega_m$,[V]

K_a – armature constant

Φ – flux produced by field current,[Wb]

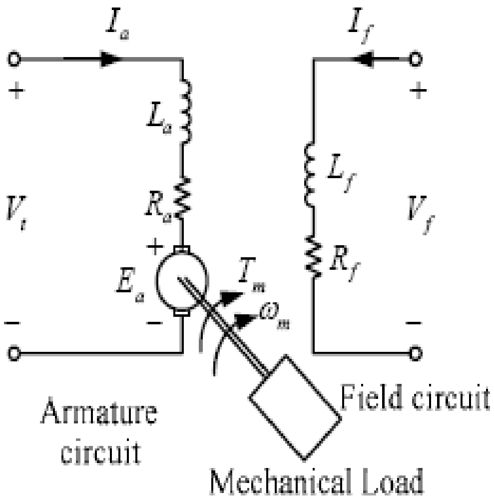
ω_m – mechanical speed,[rad/sec]

T_e – Developed mechanical torque, where $T_e = K_a \Phi I_a$,[Nm]

T_m – output mechanical torque, where $T_m = T_e - \frac{P_{rot}}{\omega_m}$,[Nm]

dc motor equivalent circuit

- Important equations:



Dynamic Equations:

(1) Armature circuit:

$$v_t = R_a i_a + L_a \frac{di_a}{dt} + E_a$$

(2) Field circuit:

$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$

(3) Motor structure:

$$E_a = K_a \Phi \omega_m$$

$$T_e = K_a \Phi i_a$$

(4) Energy conversion:

$$E_a i_a = T_e \omega_m$$

(5) Mechanical load ($P_{rot} = 0$):

$$T_e = T_m = T_L + J \frac{d\omega_m}{dt},$$

where J is the monent of inetia, $[\mathrm{kg \cdot m^2}]$

Steady state Equations:

(1) Armature circuit:

$$V_t = R_a I_a + E_a$$

(2) Field circuit:

$$V_f = R_f I_f$$

(3) Motor structure:

$$E_a = K_a \Phi \omega_m$$

$$T_e = K_a \Phi I_a$$

(4) Energy conversion:

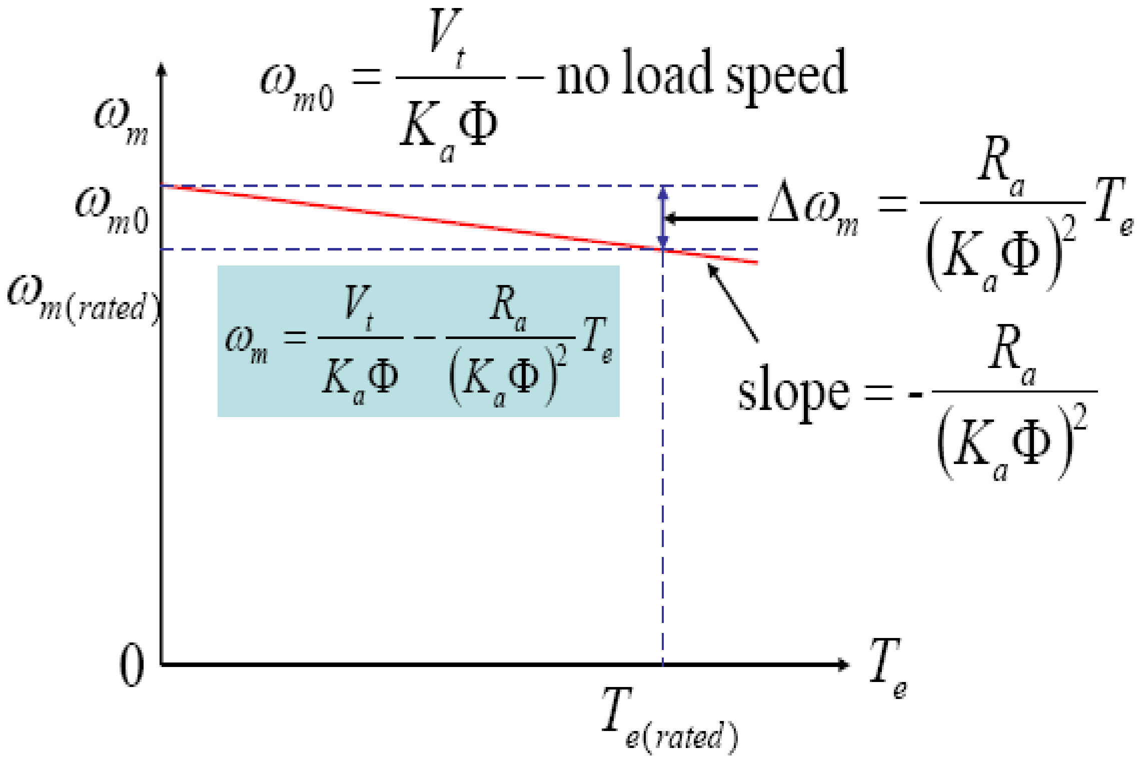
$$E_a I_a = T_e \omega_m$$

(5) Mechanical load ($P_{rot} = 0$):

$$T_e = T_m = T_L$$

Speed control

- Speed-torque characteristic:



$$\omega_{m0} = \frac{V_t}{K_a\Phi} - \text{no load speed}$$

$$\Delta\omega_m = \frac{R_a}{(K_a\Phi)^2} T_e$$

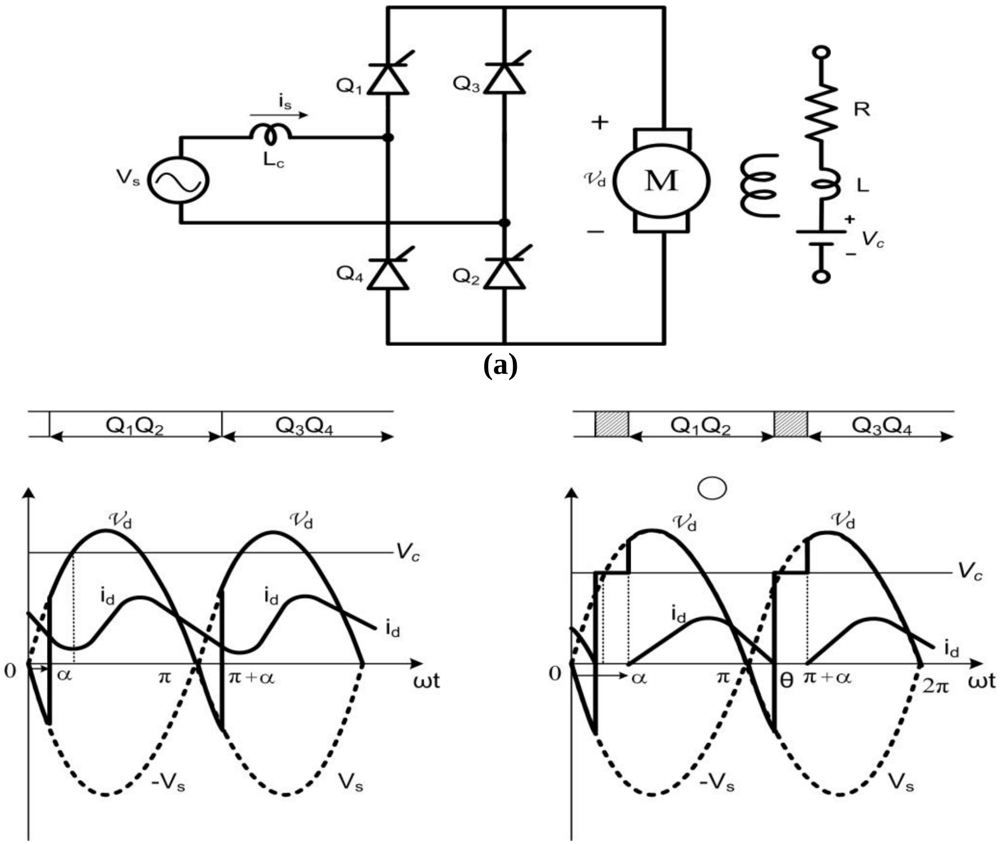
$$\omega_m = \frac{V_t}{K_a\Phi} - \frac{R_a}{(K_a\Phi)^2} T_e$$

$$\text{slope} = -\frac{R_a}{(K_a\Phi)^2}$$

SCR “phase-angle controlled” DC drives

- By changing the firing angle, variable DC output voltage can be obtained.
- Single phase (low power) and three phase (high and very high power) supply can be used
- The line current is unidirectional, but the output voltage can reverse polarity. Hence 2- quadrant operation is inherently possible.
- 4-quadrant is also possible using “two sets” of controlled rectifiers.

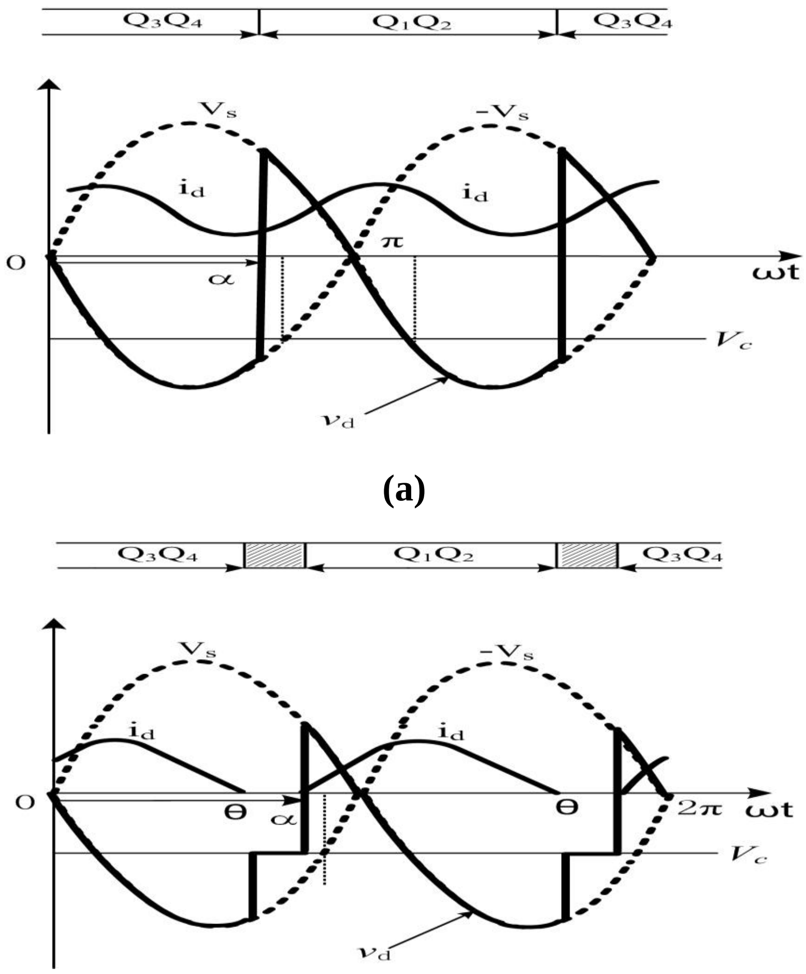
Single phase Full converter fed Dc drive



(a)

(b) **(c)**

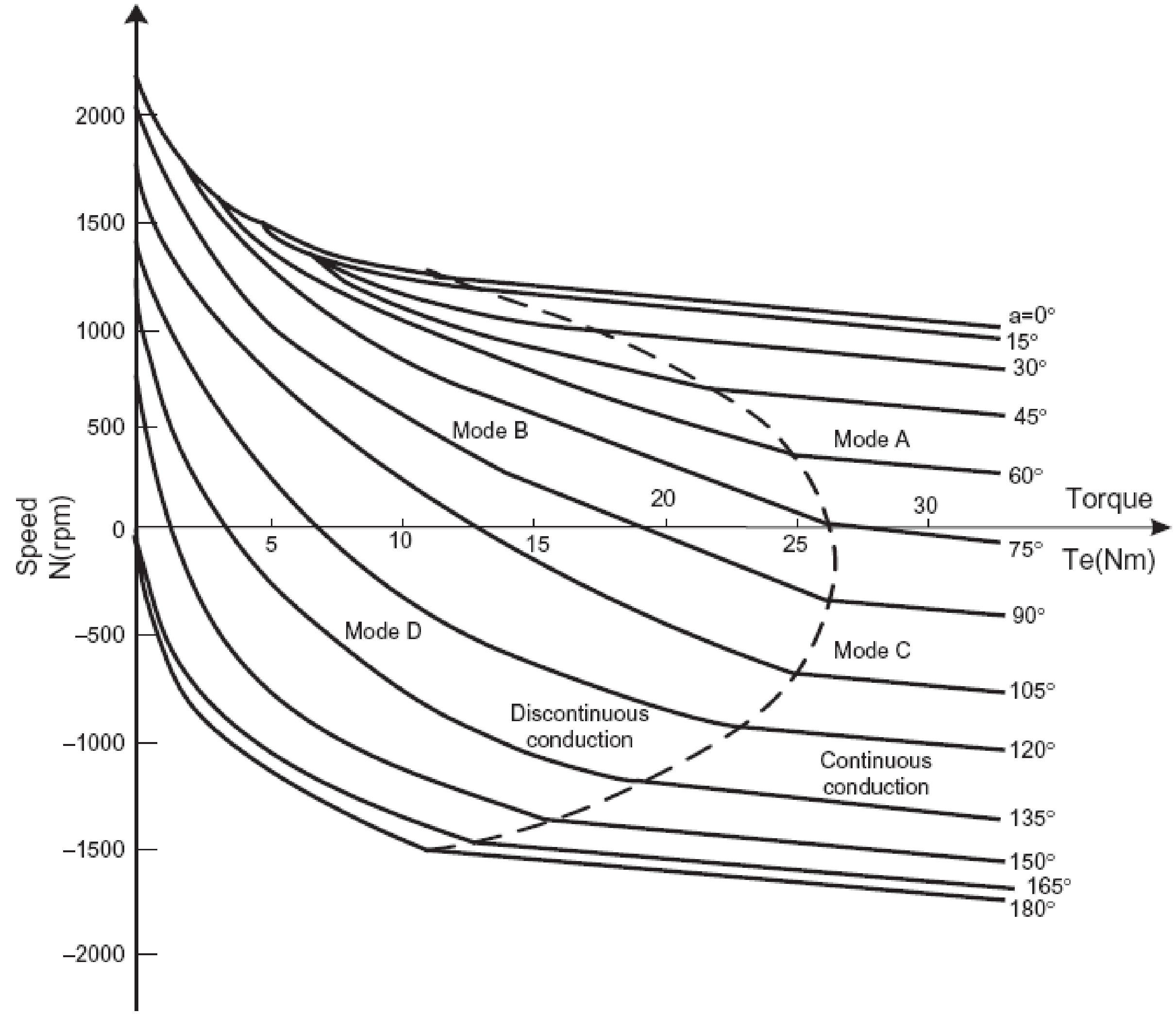
Fig. (a) 1-PHASE THYRISTOR BRIDGE WITH R-L-E LOAD
(b) CONTINUOUS CONDUCTION RECTIFICATION (Mode-A)
(c) DISCONTINUOUS CONDUCTION RECTIFICATION (Mode-B)



(a)

(b)

Fig. (a) CONTINUOUS CONDUCTION INVERSION MODE (Mode-C)
(b) DISCONTINUOUS CONDUCTION INVERSION MODE (Mode-D)



$$V_d = \frac{2}{\pi} V_m \cos\alpha = V_c + I_d R .....(1),\ V_c = K\omega_m = K'N ...(2),\ T_e = KI_d ...(3)$$

TYPICAL TORQUE-SPEED CURVES OF DC MOTOR WITH 1-PHASE BRIDGE CONVERTER

Three phase converter fed DC drive

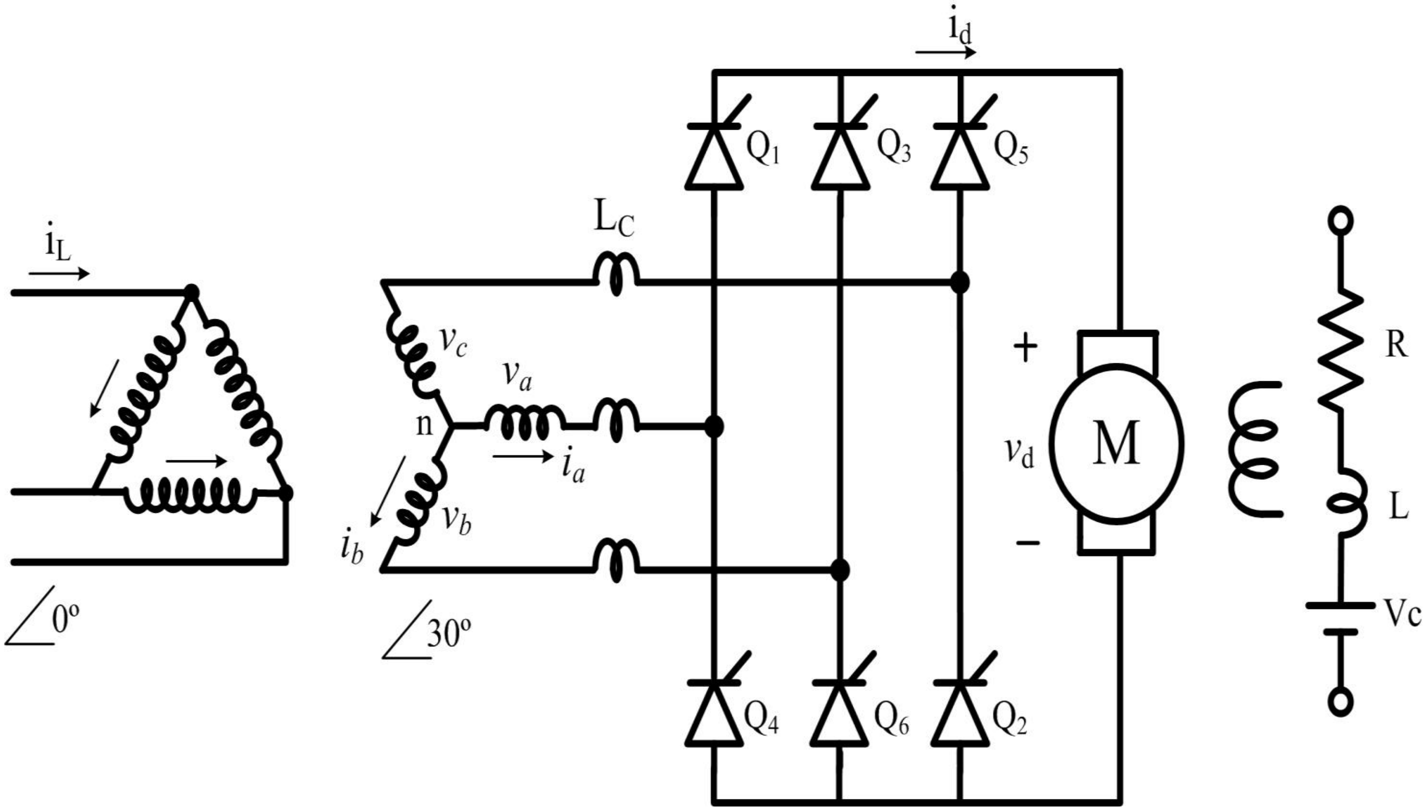


Fig. THREE-PHASE BRIDGE CONVERTER WITH DC MOTOR LOAD

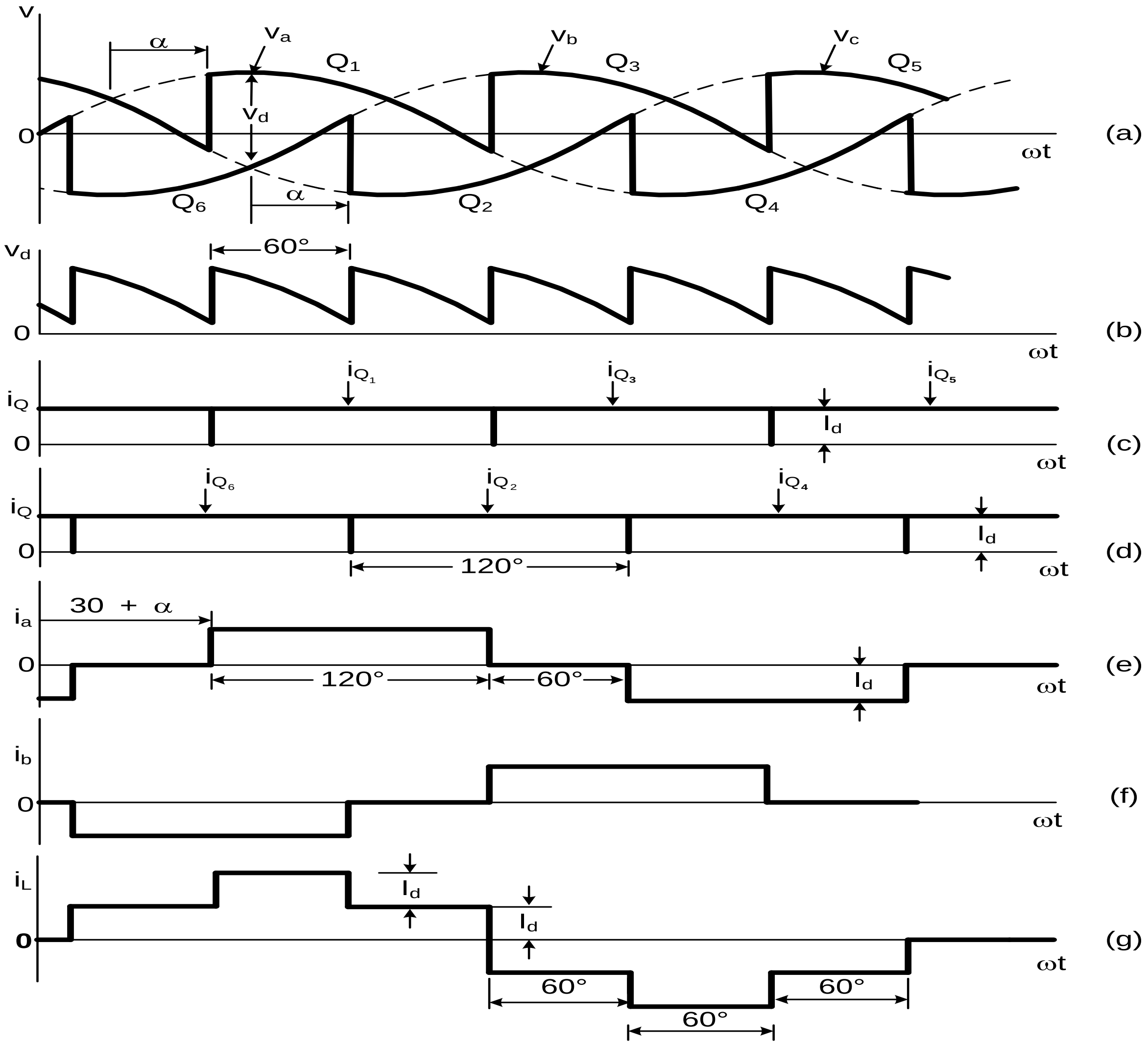


Fig. 3-PHASE THYRISTOR BRIDGE WAVEFORMS IN RECTIFICATION MODE ($\alpha = 40°$) (Mode-A)

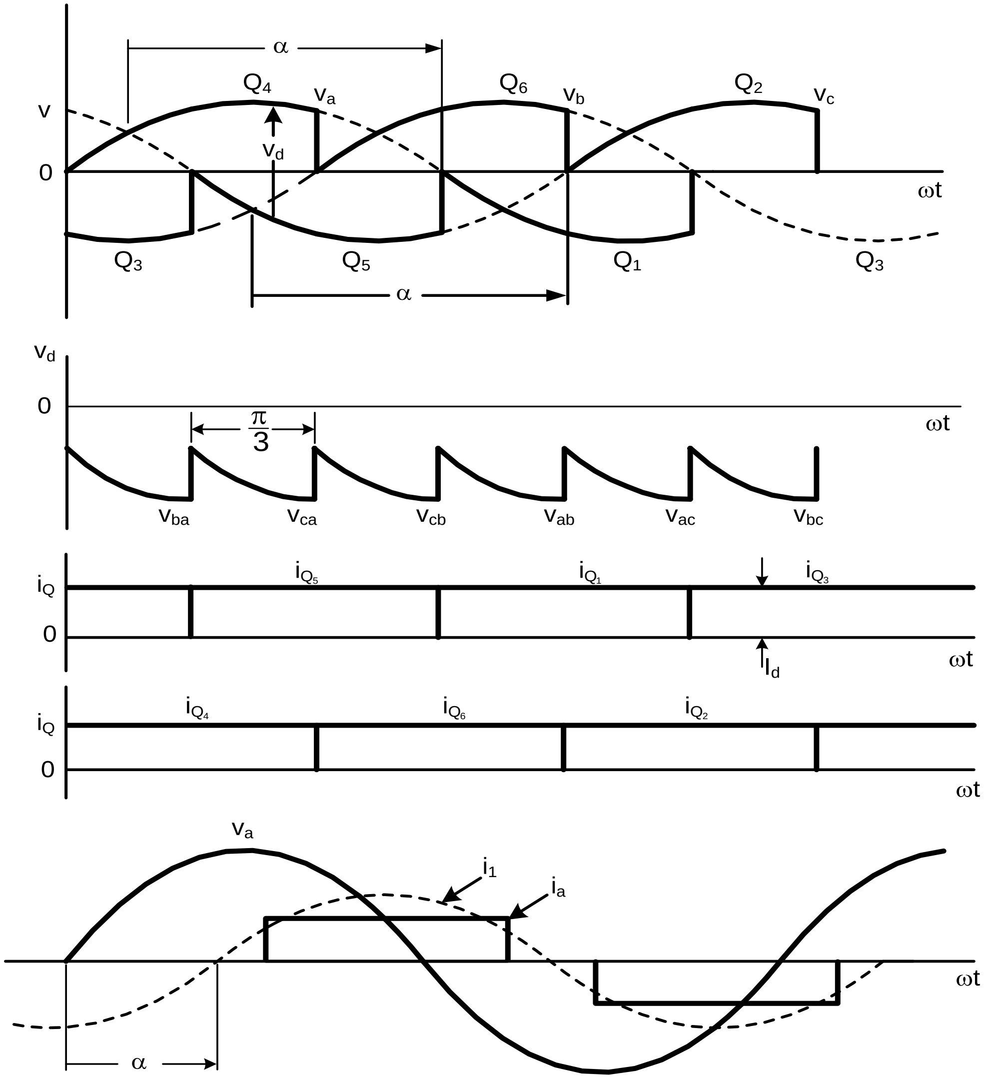


Fig. PHASE THYRISTOR BRIDGE WAVEFORMS IN INVERTING MODE ($\alpha = 150°$) (Mode – C)

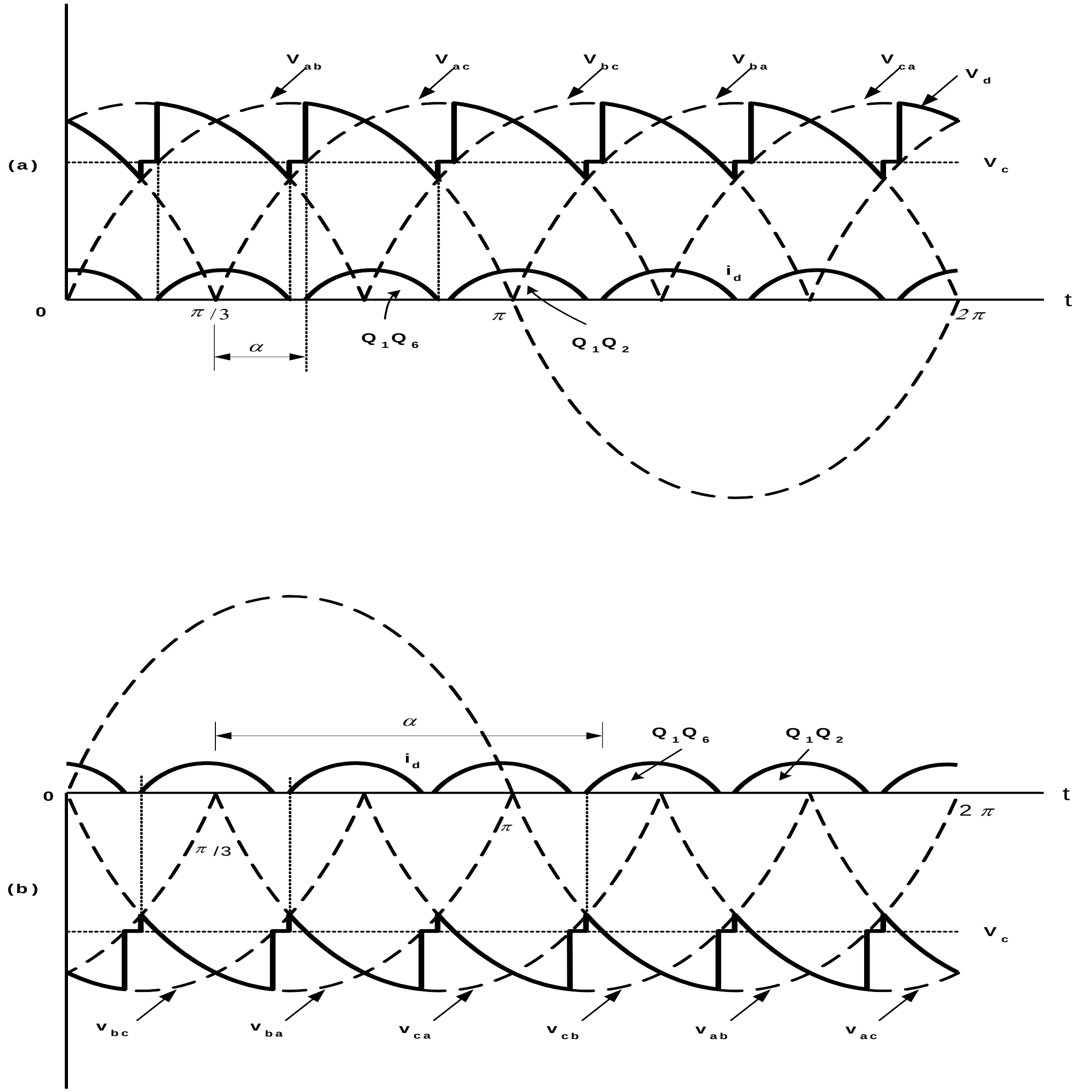


Fig. WAVEFORMS OF THREE-PHASE THYRISTOR BRIDGE CONVERTER AT DISCONTINUOUS CONDUCTION (UPPER) RECTIFICATION MODE (Mode-B), (LOWER) INVERSION MODE(Mode-D)

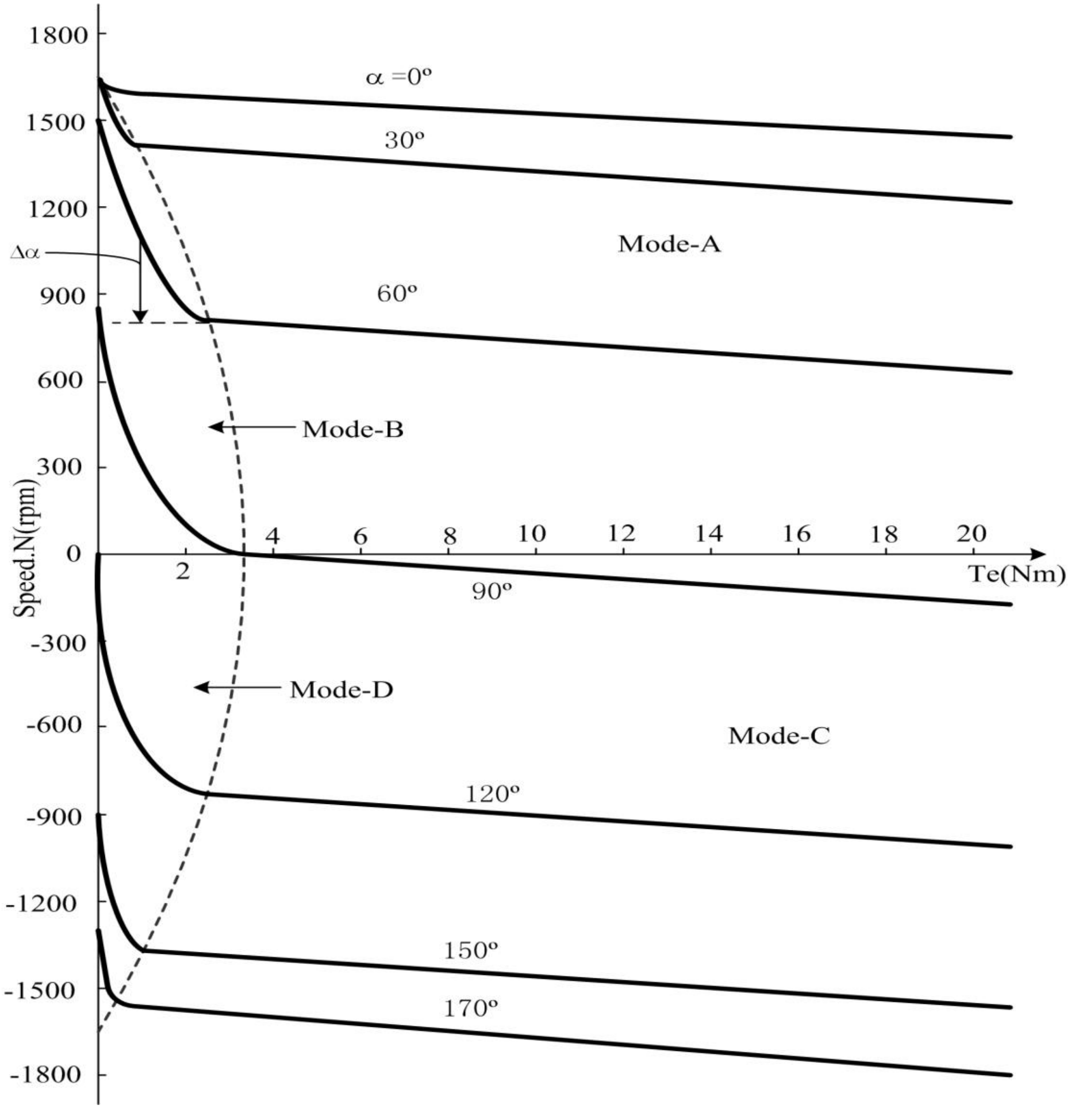


Fig. TYPICAL TORQUE-SPEED CURVES OF DC MOTOR WITH THREE-PHASE THYRISTOR BRIDGE CONVERTER

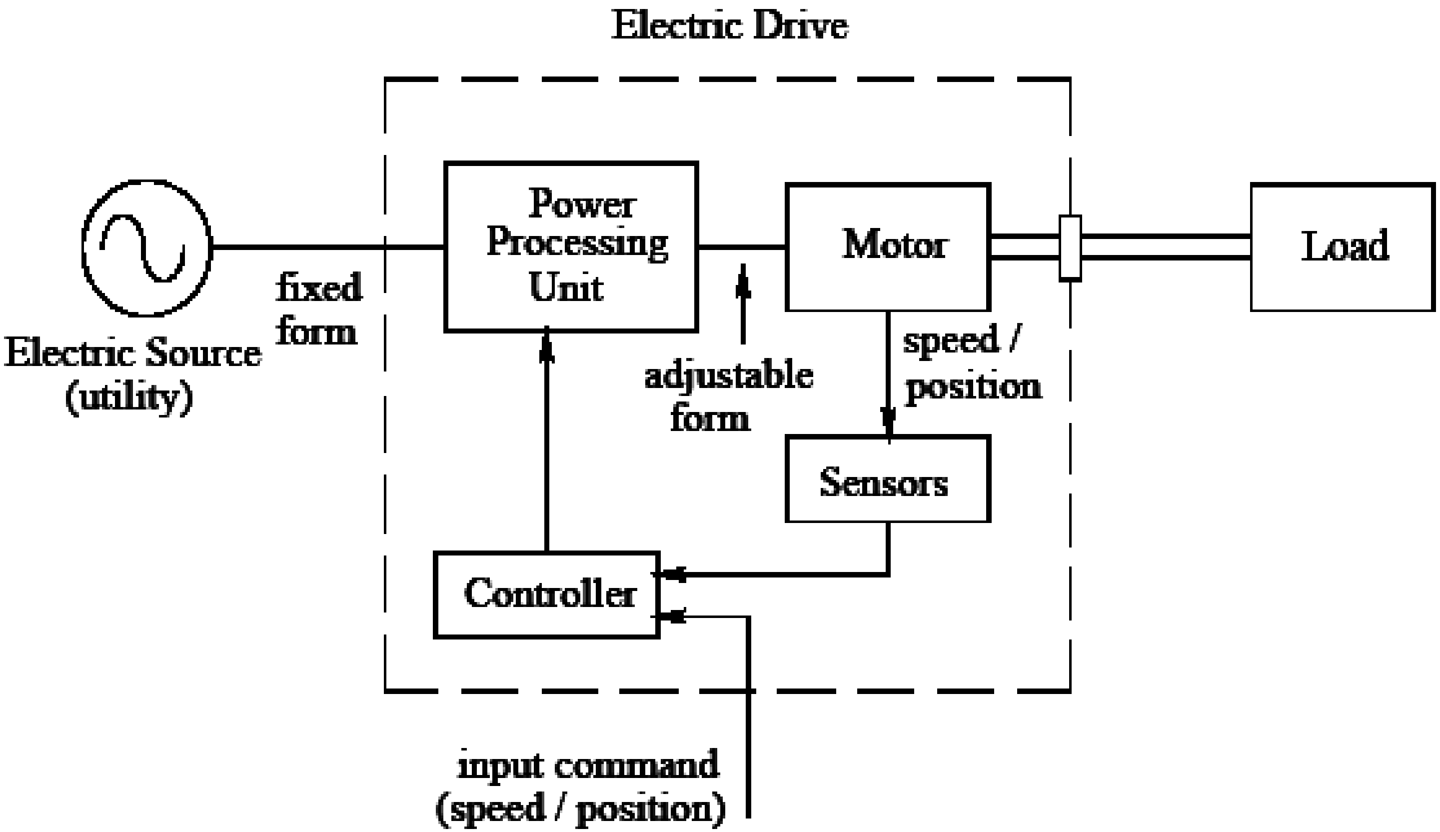
Unit -II

FOUR QUADRANT OPERATION OF DC DRIVES THROUGH DUAL CONVERTERS

Contents

- Block Diagram of a drive
- Type of loads
- Steady State Stability
- Mathematical condition for the stability of the equilibrium point
- Four quadrant operation of a drive
- Loads with rotational motion
- Loads with translational motion
- Loads with rotational and translational motion
- Regenerative braking

Block Diagram of a drive



Type of loads

- **Active load torque: -** Active torques continues to act in the same direction irrespective of the direction of the drive. e.g. gravitational force or deformation in elastic bodies.
- **Passive load torque :-** the sense of the load torque changes with the change in the direction of motion of drive. e. g. torques due to friction, due to shear and deformation of inelastic bodies

Steady State Stability

- Equilibrium speed of a motor load system is obtained when the motor torque, T_e equals the load torque T_l.

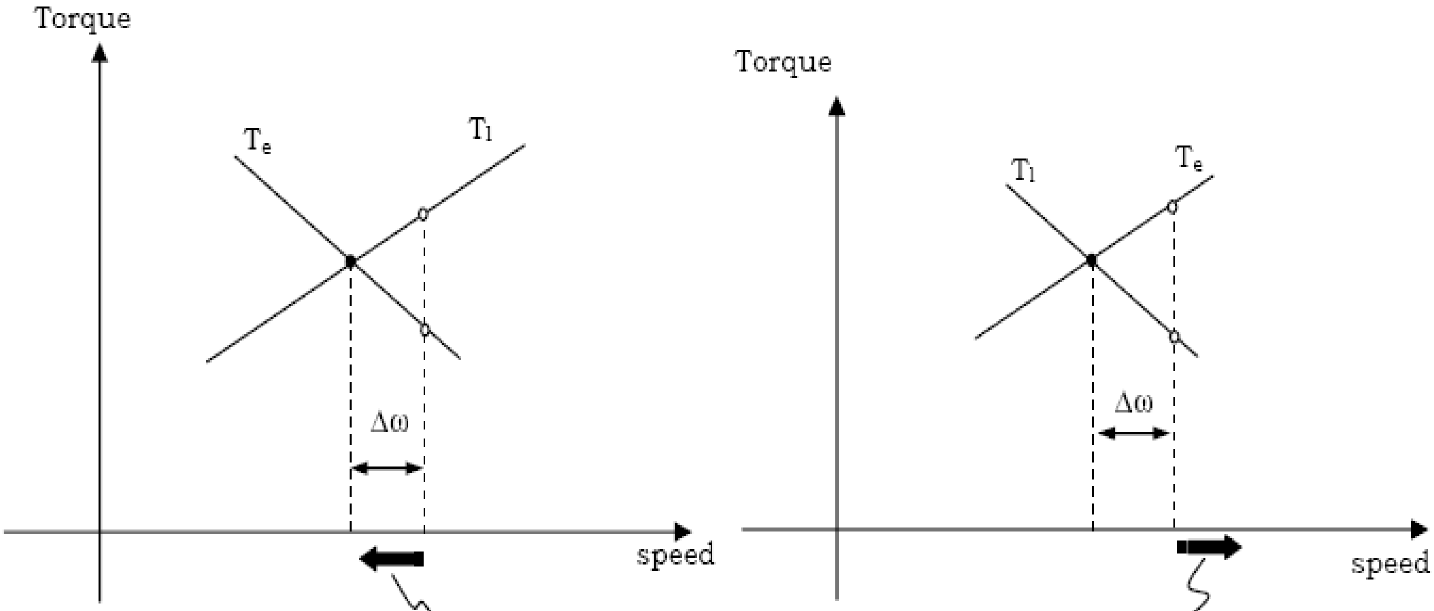
  Stable state of equilibrium point

  - The equilibrium point is termed as stable, if the operating point is restored after a small departure from it due to disturbance in the motor or load.

  Unstable state of equilibrium point

  - The equilibrium point is termed as stable, if the operating point will not be restored after a small departure from it due to disturbance in the motor or load.

Steady State Stability



Motor will decelerate back to equilibrium since $T_l > T_e$

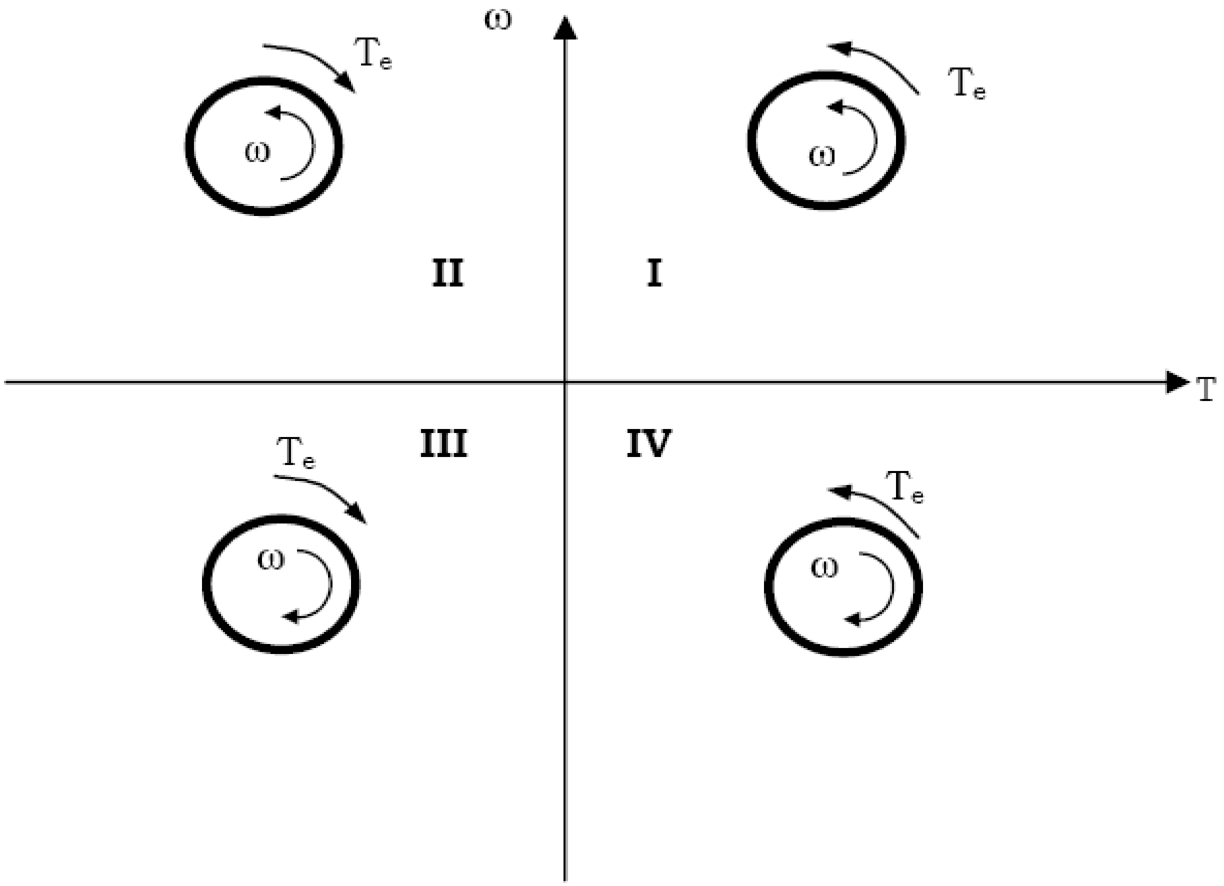
Motor will accelerate away from equilibrium since $T_e > T_l$

Steady state stability

Mathematical condition for the stability of the equilibrium point

$$\frac{dT_l}{d\omega} - \frac{dT_e}{d\omega} > 0$$

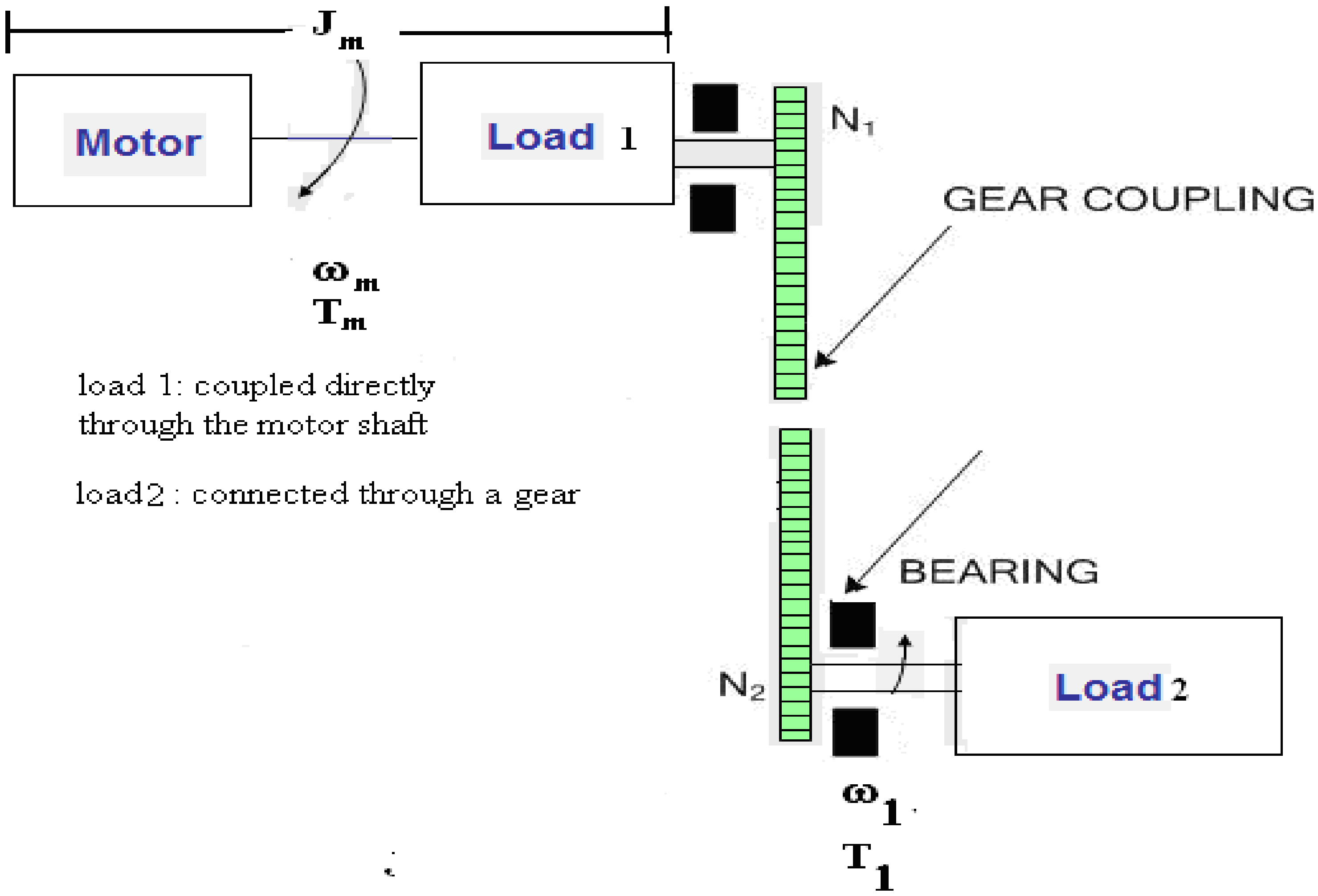
Four quadrant operation of a drive



Four quadrant operation of a drive

	I quadrant	II quadrant	III quadrant	IV quadrant
Operation of the Hoist	The hoisting up of the loaded cage	The hoisting up of the unloaded cage	The downward motion of the unloaded cage	The downward motion of the loaded cage
T_e	+VE	-VE	-VE	+VE
T_L	-VE	+VE	+VE	-VE
W_M	+VE	+VE	-VE	-VE
Power	+VE	-VE	+VE	-VE
Operation of the Drive	forward motoring	Forward Braking	Reverse motoring	Reverse Braking

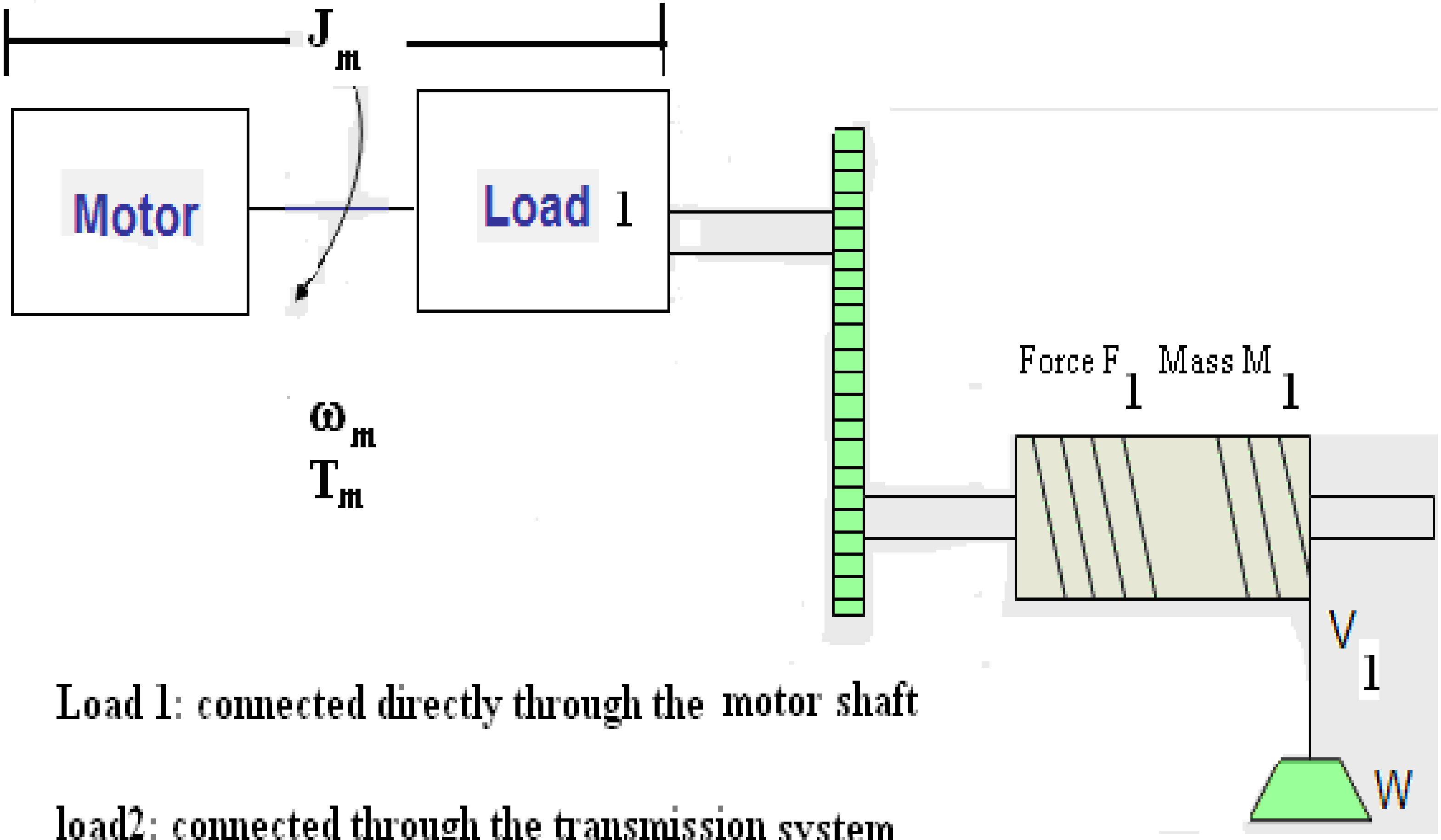
Loads with rotational motion



load 1: coupled directly through the motor shaft

load2 : connected through a gear

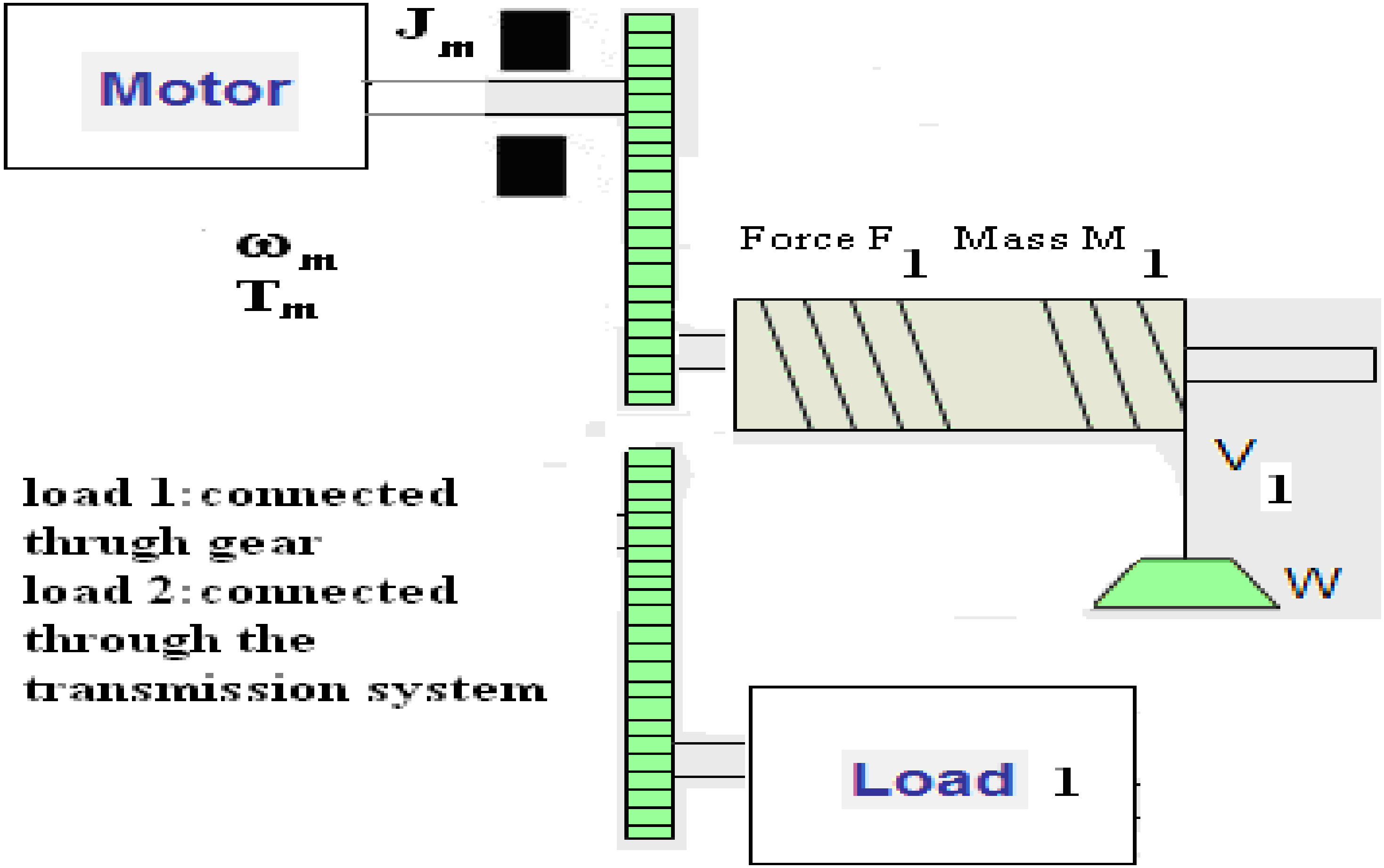
Loads with translational motion



Load 1: connected directly through the motor shaft

load2: connected through the transmission system

Loads with rotational and translational motion



load 1: connected thurgh gear
load 2: connected through the transmission system

Regenerative Braking

- Working the motor in the generator mode while it is still connected to the supply and mechanical energy is converted to electrical energy and fed back to the supply and hence the name regenerative braking.

UNIT-III
CONTROL OF DC MOTORS BY CHOPPERS

Chopper fed DC drives

- Supply is DC (maybe from rectified-filtered AC, or some other DC sources).
- DC-DC converters (coppers) are used.
- suitable for applications requiring position control or fast response, for example in servo applications, robotics, etc.
- Normally operate at high frequency

– the average output voltage response is significantly faster

– the armature current ripple is relatively less than the controlled rectifier

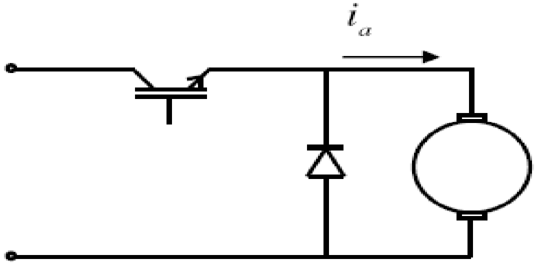
- In terms of quadrant of operations, 3 possible configurations are possible:

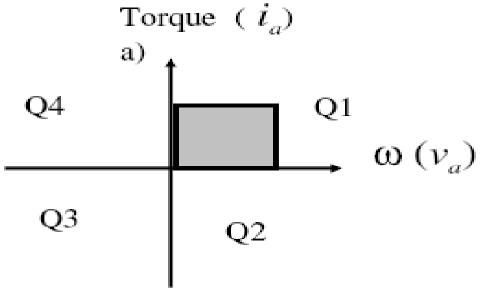
– single quadrant,

– two–quadrant and four–quadrant

Single-quadrant drive

- Unidirectional speed. Braking not required.





For $0 < t < T$,

The armature voltage at steady state :

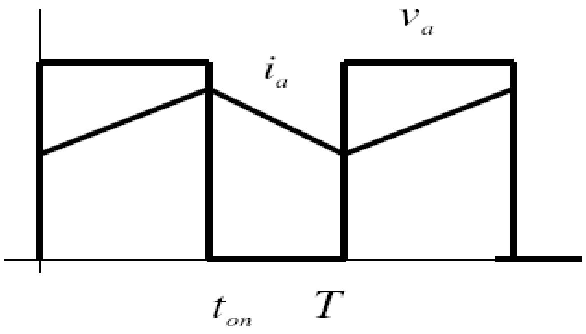
$$V_a = \frac{1}{T}\int_0^{t_{on}} V dt = \frac{t_{on}}{T} = DV$$

Armature (DC) current is :

$$I_a = \frac{V_a - E_g}{R_a};$$

and speed can be approximated as :

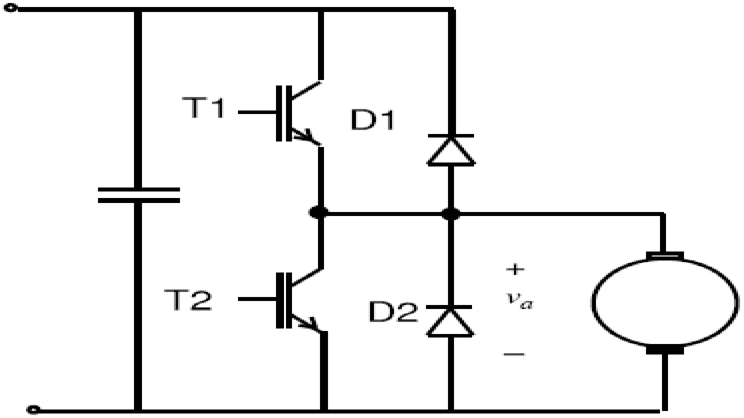
$$\omega = \frac{V_a}{K_v I_f}$$

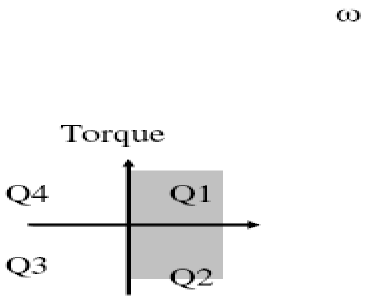


2 Quadrant DC drives

- FORWARD MOTORING (T1 and D2 operate)
  - T1 on: The supply is connected to motor terminal.
  - T1 off: The armature current freewheels through D2.
  - Va (hence speed) is determined by the duty ratio.

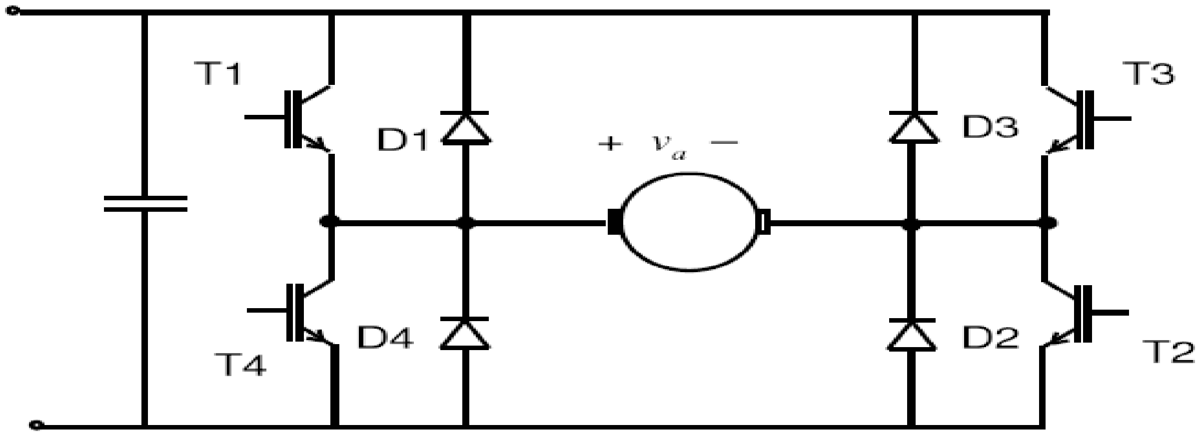
- REGENERATION (T2 and D1 operate)
  - T2 on: motor acts as a generator
  - T2 off:, the motor acting as a generator returns energy to the supply through D2.

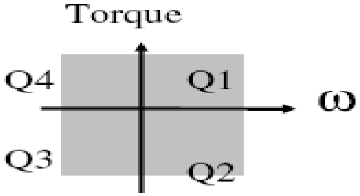




4 Quadrant DC drives

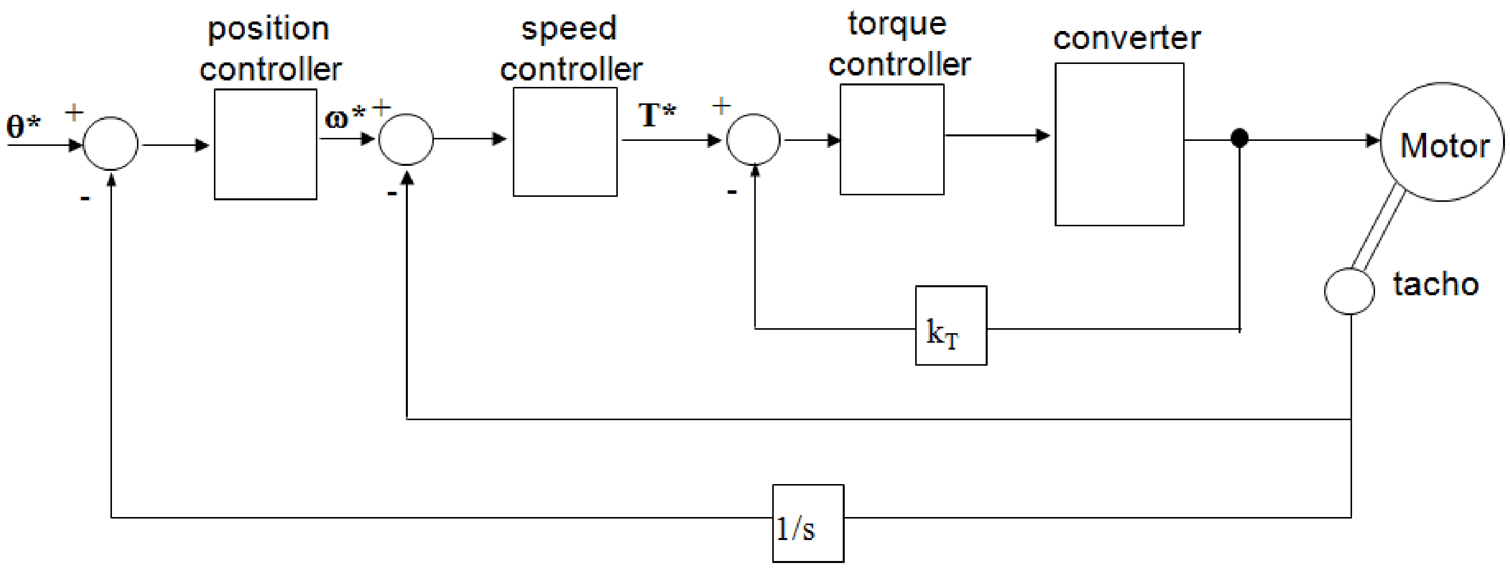
- A full-bridge DC-DC converter is used.





Closed loop speed control

Cascade control structure



- The control variable of inner loop (e.g. torque) can be limited by limiting its reference value
- It is flexible – outer loop can be readily added or removed depending on the control requirements

Controller Design

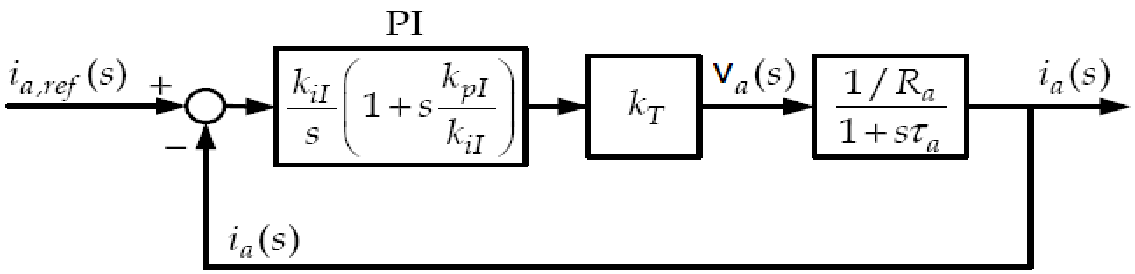
Procedure

- Design the torque loop (fastest) first.
- Design the speed loop assuming the torque loop to be ideal.
- Design the position loop (slowest) assuming the speed loop to be ideal.

Controller design

- Inner loop (current or torque loop) the fastest – largest bandwidth
- The outer most loop (position loop) the slowest – smallest bandwidth
- Design starts from torque loop proceed towards outer loops

Torque loop



$$\boxed{G_{I,OL}(s)=\frac{k_{iI}}{s}\left(1+s\frac{k_{PI}}{k_{iI}}\right)k_T\frac{1/R_a}{(1+s\tau_a)}}$$

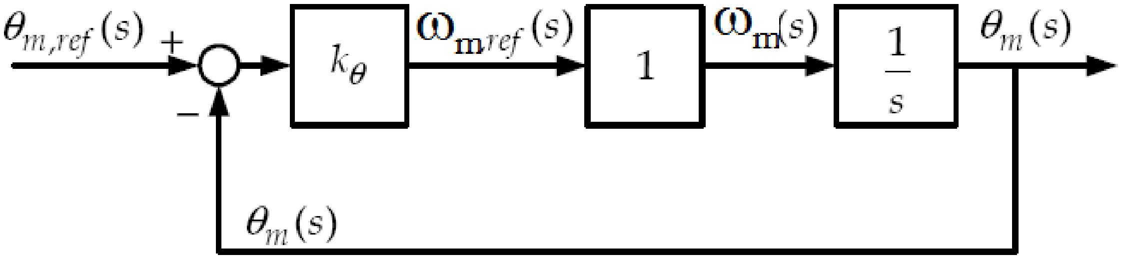
- The zero of the PI controller is selected to cancel the motor pole:

$$G_{I,OL}(s)=\frac{k_{iI}}{s}\cancel{\left(1+s\frac{k_{PI}}{k_{iI}}\right)}k_T\frac{1/R_a}{\cancel{(1+s\tau_a)}} \quad \Rightarrow \quad \frac{k_{pI}}{k_{iI}}=\tau_a$$

- *kiI is chosen to achieve the desired 0 dB crossover frequency ωcI:*

$$\left|G_{I,OL}(j\omega_{cI})\right|=\frac{k_{iI}}{\omega_{cI}}\frac{k_T}{R_a}=1 \quad \Rightarrow \quad k_{iI}=\frac{R_a\omega_{cI}}{k_T}$$

Speed loop

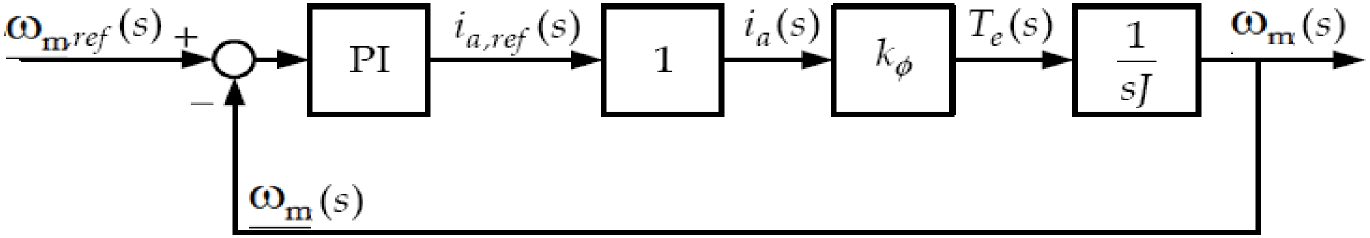


$$\boxed{G_{\theta,OL}(s) = \frac{k_\theta}{s}}$$

- The speed loop is assumed to be ideal. (corresponds to unity).
- Proportional gain *kθ alone is adequate due to the presence* of a pure integrator.
- The 0 dB crossover frequency *ωcθ is chosen*

$$\left|G_{\theta,OL}(j\omega_{c\theta})\right| = \frac{k_\theta}{\omega_{c\theta}} = 1 \quad \Rightarrow \quad k_\theta = \omega_{c\theta}$$

Position loop



- The current loop is assumed to be ideal (represented by unity).
- The open-loop transfer function is

$$G_{\Omega,OL}(s) = \frac{k_{i\Omega}}{s}\left(1 + s\frac{k_{p\Omega}}{k_{i\Omega}}\right)\cdot 1 \cdot \frac{k_\phi}{sJ}$$

or

$$G_{\Omega,OL}(s) = \frac{k_{i\Omega}k_\phi}{J}\,\frac{1 + s\dfrac{k_{p\Omega}}{k_{i\Omega}}}{s^2}$$

UNIT -IV

CONTROL OF INDUCTION MOTORS

Contents

- Advantageous features of converter Fed induction motor in comparison with line fed induction motor
- Speed control of induction
- Speed control by Variable Voltage method
- speed control by rotor resistance variation
- Slip Energy Recovery Schemes
- Speed Control of IM Using Variable Frequency
- Features of VSI Fed IM Drives
- Features of PWM Fed IM Drives
- Features of CSI Fed IM Drives
- Slip controlled Drives

Advantageous features of converter Fed induction motor in comparison with line fed induction motor

- Smooth Speed variation with VVVF(Variable Voltage Variable Frequency)
- Assured smooth Start up
- Soft Starting and acceleration at constant current and torque are possible.
- No switching surge currents with Direct Switching on even for Higher Ratings
- High Moments of Inertia can be accelerated without the need for over dimensioning the motor
- Speed control of IM by changing slip frequency.
- Speed control of IM by changing stator frequency which can change the Synchronous speed of the motor

Speed control of induction motor

Three simple means of limited speed control for an induction motor are:

1) Reduced applied voltage magnitude

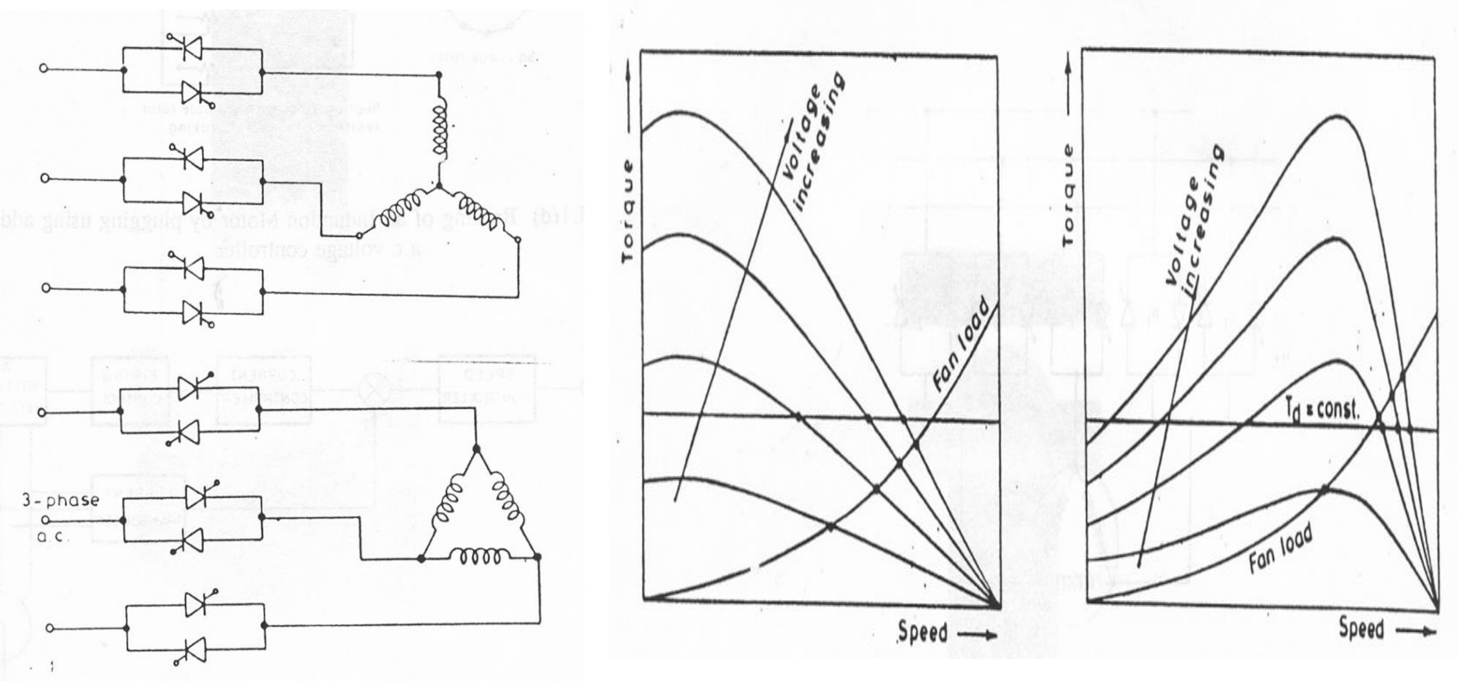
2) Adjusting rotor circuit resistance

(suitable for a wound rotor machine

and discussed earlier)

3) Adjusting stator voltage and frequency

Speed control by Variable Voltage method



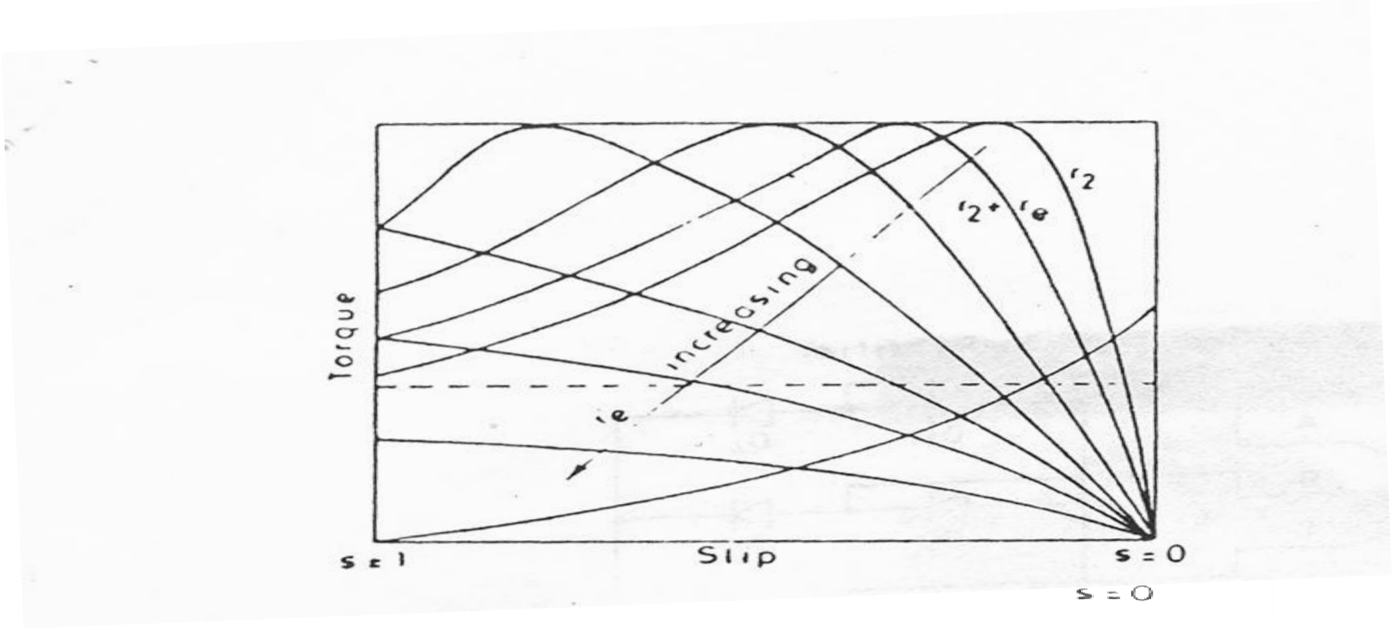
Controller Circuit and Characteristics of Induction Motor With Variable Voltage

Slip for maximum torque

$$S_m = \frac{r_2^1}{((r_1^2+(r_2^1/s)^2+(x_1+x_2^1)^2)^{1/2}}$$

- Slip at max torque does not depends on Applied Voltage and it can be changed by changing the rotor resistance.
- In slip Ring IM it is possible.

Characteristics with Rotor Resistance Control



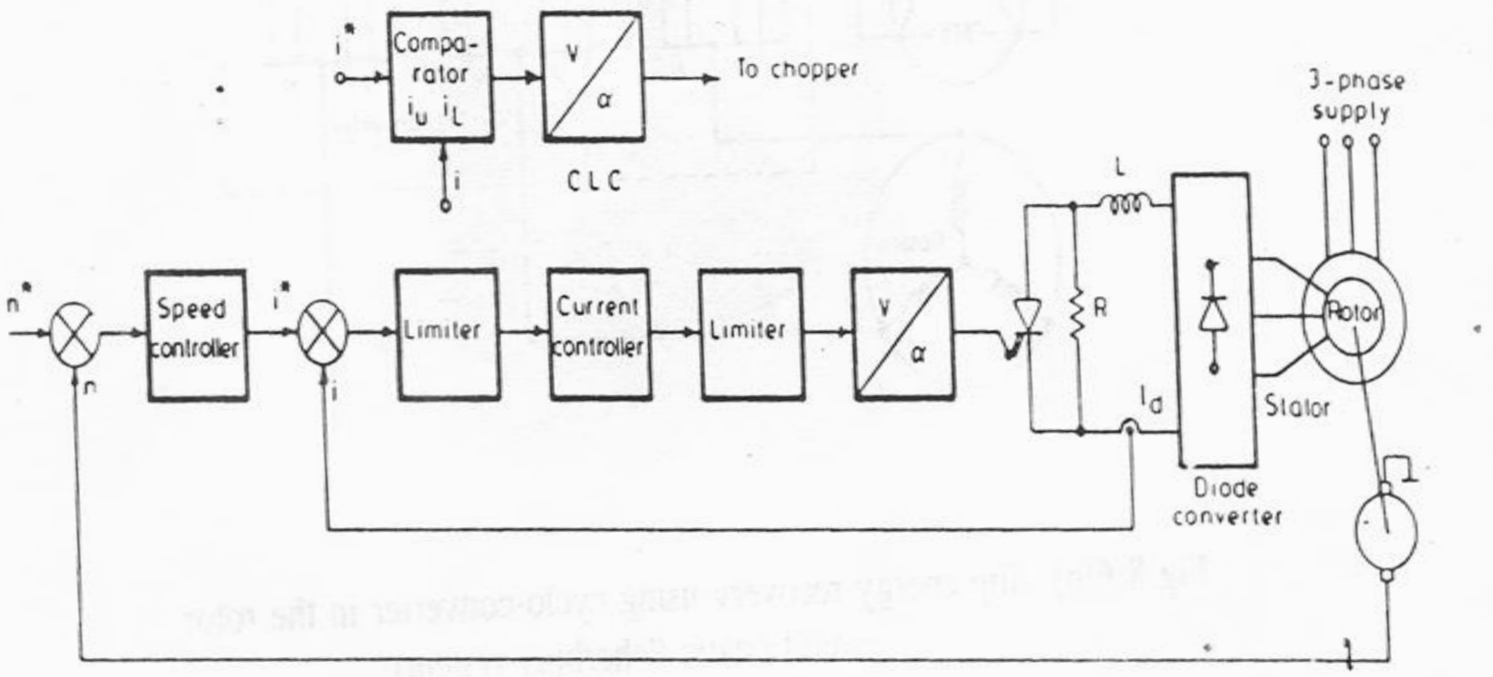
$$T_d = \frac{m_1 * x^2 * V_r^2 (r_2^1/s)}{(2*pi*ns)((r_1^2+(r_2^1/s)^2+(x_1+x_2^1)^2}$$

Torque is Proportional to Square of the Voltage

Conclusion from the above characteristics

- Linear portion of torque curve meets the locus of the breakdown torque point.
- S_m increases with increase in r_2^1
- Maximum torque is independent of r_2^1
- If Slip increases rotor copper loss increases

speed control by rotor resistance variation



Block Diagram for Rotor Resistance Control

$R^{*}=R_2(1-\alpha)$

$\alpha=1$ $R^{*}=\text{Zero}$

$\alpha=0$ $R^{*}=R_2$

$0<R^{*}<R_2$

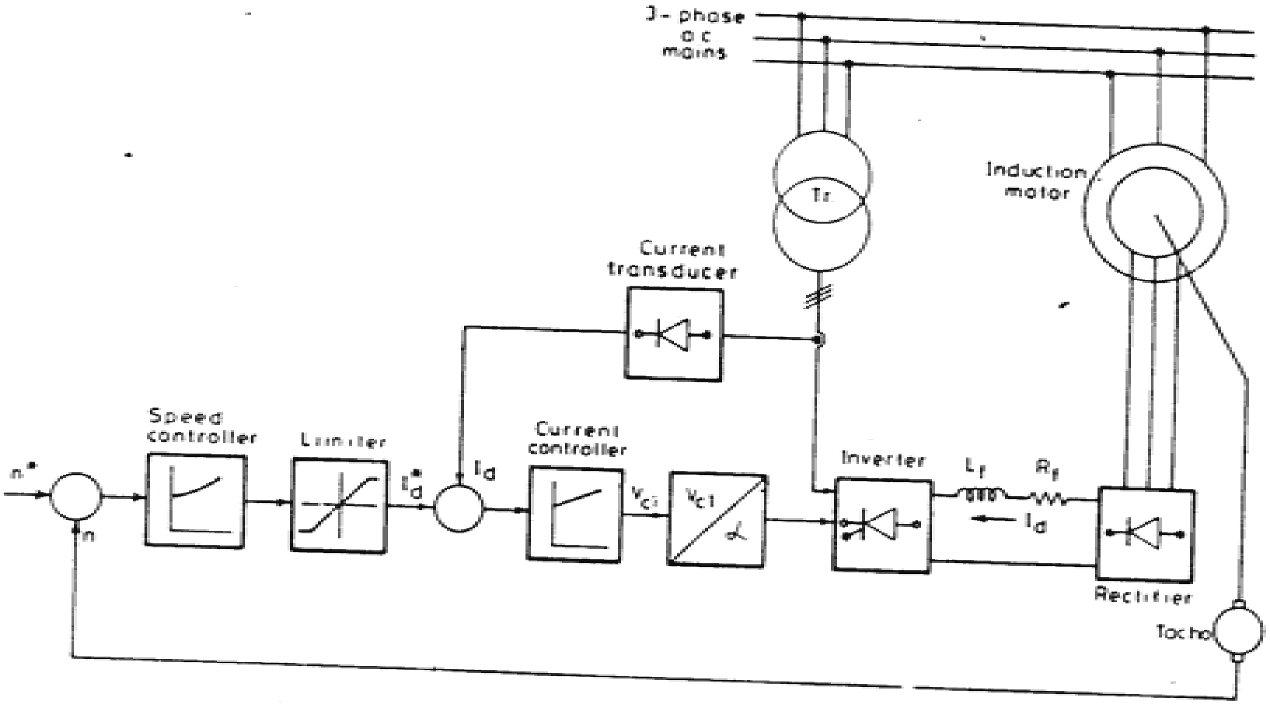
Features

- Speed Range
- Braking
- Harmonics
- Torque Pulsations
- Good pf
- Poor Efficiency
- Reasonable Cost
- General

Draw backs of Stator Voltage Control and Rotor Resistance Control

- Poor Efficiency at low speed.
- Limited range of Speed Control
- Slip power is wasted in the Motor
- Resistances in Stator Control and in Rotor Resistance in Rotor Resistance control

Slip Energy Recovery Schemes



Block Diagram for Slip Energy Recovery

Dc voltage of the diode rectifier

$V_d=1.35(sE_{20})$

Corresponding to no voltage condition

$V_{d0}=1.35(sE_{20})$

For Stator to Rotor turns Ratio ‘a’

$V_{d0}=1.35(sV_L/a)$

$V_{di} = 1.35(V_L \cos \alpha)$

$V_{d0} = -V_{di}$

$1.35(V_L \cos \alpha) = 1.35(sV_L/a)$

$s = -a \cos \alpha$

Rotor Copper loss $= sP_g$ (P_g -Air Gap Power)

$sP_g = V_d I_d$

Torque Developed=$T_d = P_g / 2*pi*n_s$

$= V_d I_d / s*2*pi*n_s$

Put $V_d = 1.35(sV_L/a)$

$T_d = 1.35*V_L I_d / a*2*pi*n_s$

$T_d = K_t I_d$

Where $K_t = 1.35*V_L / a*2*pi*n_s$

Features of Slip Power Recovery

- Power Factor is Improved
- Slip Power Can be recovered to the mains instead of wasting the same in the resistances of the motor itself.
- Converter group handles Slip power only. Therefore it's rating can be low if speed control is in a limited range.

Contd..

- For achieving Zero Speed Converter rating should be equal to the Motor rating.
- Improved efficiency
- Maximum power factor attained is 0.7.Still the pf can be improved by designing the inverter if the converter operates at 180 Degree firing angle

Contd..

For Achieving Super synchronous Speed ,Power should flow to the rotor circuit Via the converter Cascade.

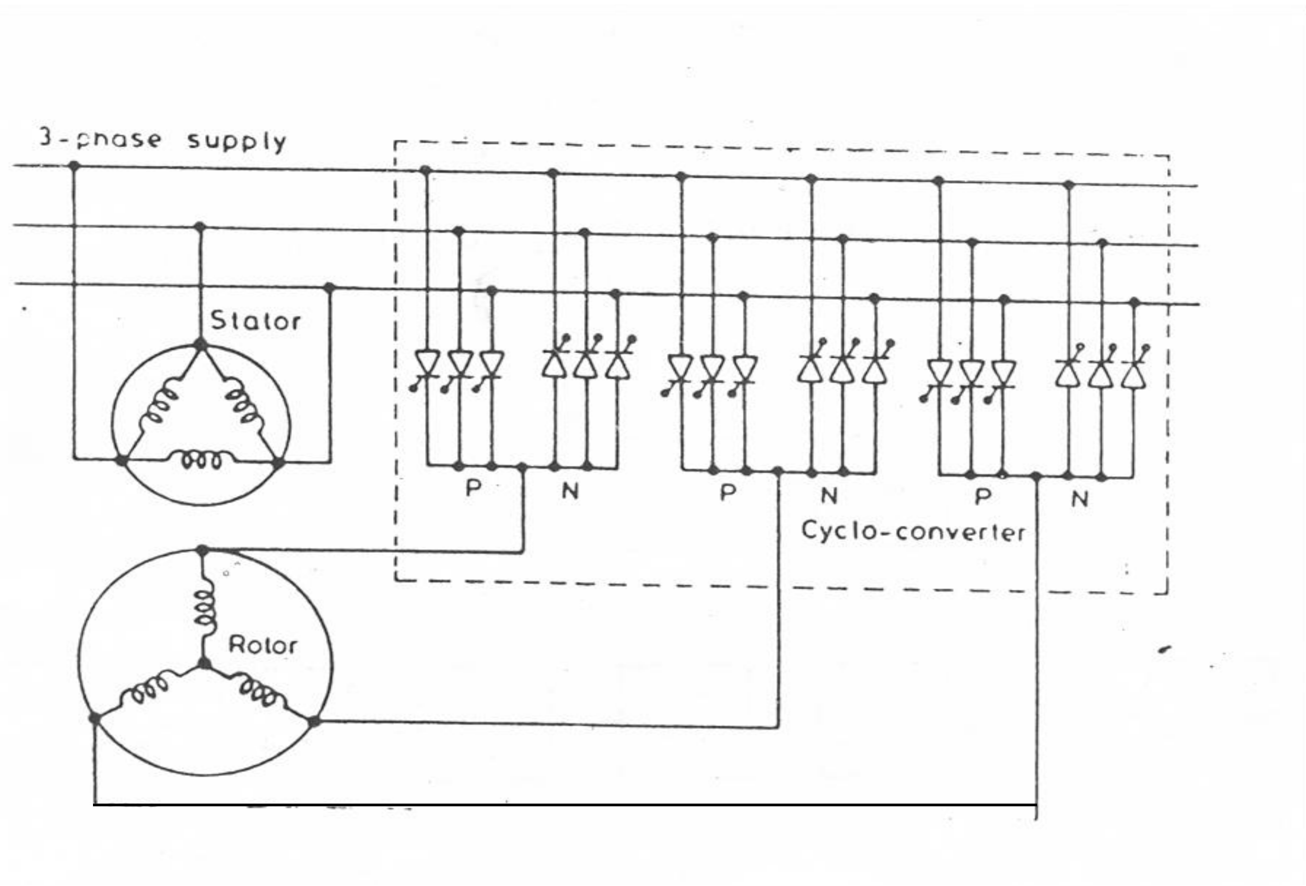
This can be achieved by

Achievement of Super Synchronous Speed

- Replacing Diode rectifier by Phase Controlled rectifier operating as rectifier.
- By replacing converter cascade by a Cycloconverter.This is known as Scherbius Drives

  Rotor Currents are non sinusoidal and it causes network reactions and torque pulsations.

Scherbius systems

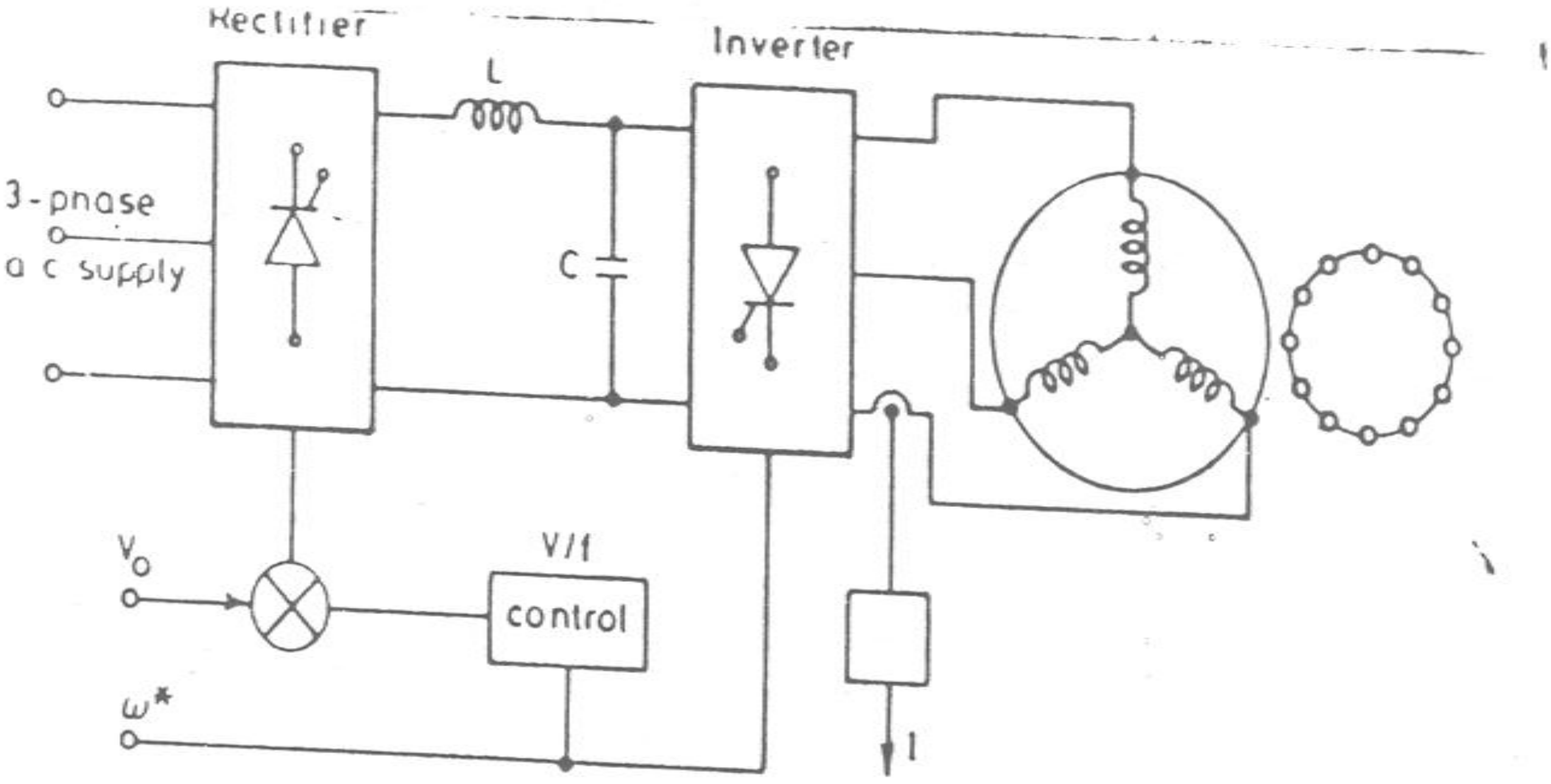


Power Circuit Diagram for Scherbius Systems

Speed Control of IM Using Variable Frequency

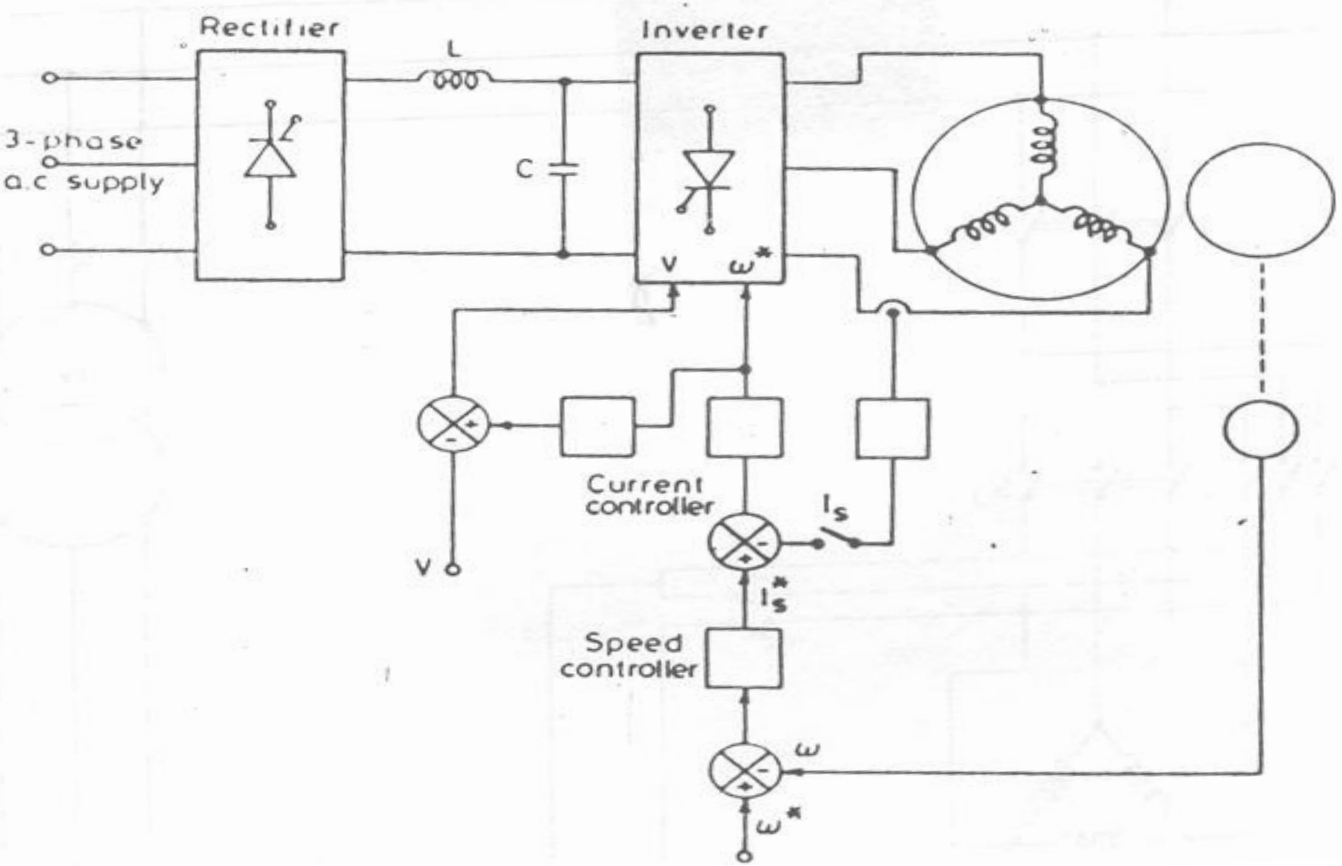
- $f = pn_s$
- If frequency varies Saturation Problems Will occur
  - To avoid this V/f has to maintained at a constant value
  - To avoid Impedance drop at low frequency compensation is necessary (i.e E/f Control)

V/f control circuit for IM (open loop control)



Open loop V/f control

V/f control circuit for IM (closed loop control)



Closed loop V/f control

Features of v/f control

- Best possible utilisation of available current capability
- Generate Highest possible Torque per Ampere of Stator Current.

Features of VSI Fed IM Drives

- Can be used for Multi motor Drives
- Load independent Commutation of the Inverter Devices.
- Inverter Frequencies can go up to 1500 Hz.
- Suitable for high speed operation
- Capacity upto 100 KVA
- At very low speed Commutation voltage is also very low. Up to 10% of the Speed is not realisable.
- Speed Range 1:20
- Not suitable for acceleration on Load and Sudden Load Changes
- Dynamic braking can be realised by an additional converter at the line side.
- Low cost with simple control circuit.
- Efficiency is very poor.

Features of PWM Based VSI Fed IM Drives

- Speed range: Up to zero speed
- Nearly Sinusoidal voltage and current.
- Minimized torque pulsations.
- Line pf is closer to Unity.
- High converter cost.
- Inverter has constant dc link voltage and employs PWM principle for both voltage control and Harmonic neutralisation.

- Improved Output voltage wave form.
- Uninterrupted operation is possible when buffer battery is used.
- Control is complicated.
- Four quadrant operation is possible.
- Smooth change over of voltage and frequency values at zero crossing for speed reversal.

Contd..

- Operating frequency is limited at 150 Hz.
- Speed Control range 1:10.
- The inverter and motor need not be matched. The converter operates as source to which the motor can be plugged.
- Size of the harmonic filter decreases.
- Good dynamic response.

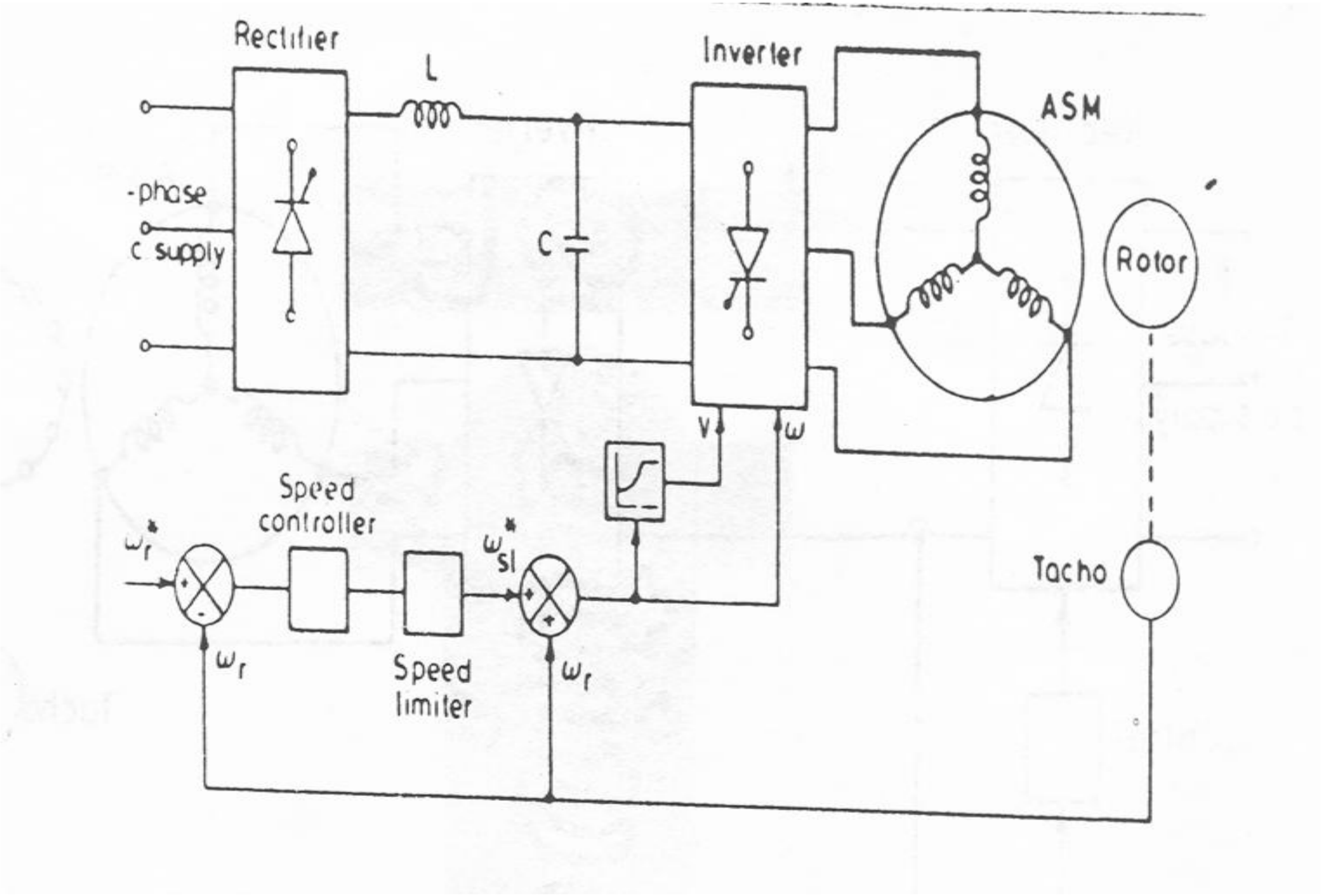
Features of CSI Fed IM Drives

- Simple Configuration.
- Feed back diodes are absent. Blocking diodes needed.
- Load dependent commutation.
- Multi motor operation is not possible.
- Four quadrant operation is straight forward.
- Inverter is force commutated to provide variable frequency.

Contd..

- Finds application in medium to high power drive.
- Torque pulsations at low speed can be eliminated by PWM operations.
- Both constant torque and constant power operations are possible.

Slip controlled drives



Features of Slip Controlled Drives

- Highly Efficient
- Precise and accurate control of torque is possible in the complete speed range.
- The slip frequency can be any value up to the value corresponding to break down torque from no load slip.
- Stable operation with good pf.
- Drive efficiency is comparable to a thyristorized dc drive.
- High power to Weight ratio, least maintenance, low inertia, no limitations on power and speed ranges.
- Selective harmonic elimination is possible.

UNIT-V

CONTROL OF SYNCHRONOUS MOTORS

Contents

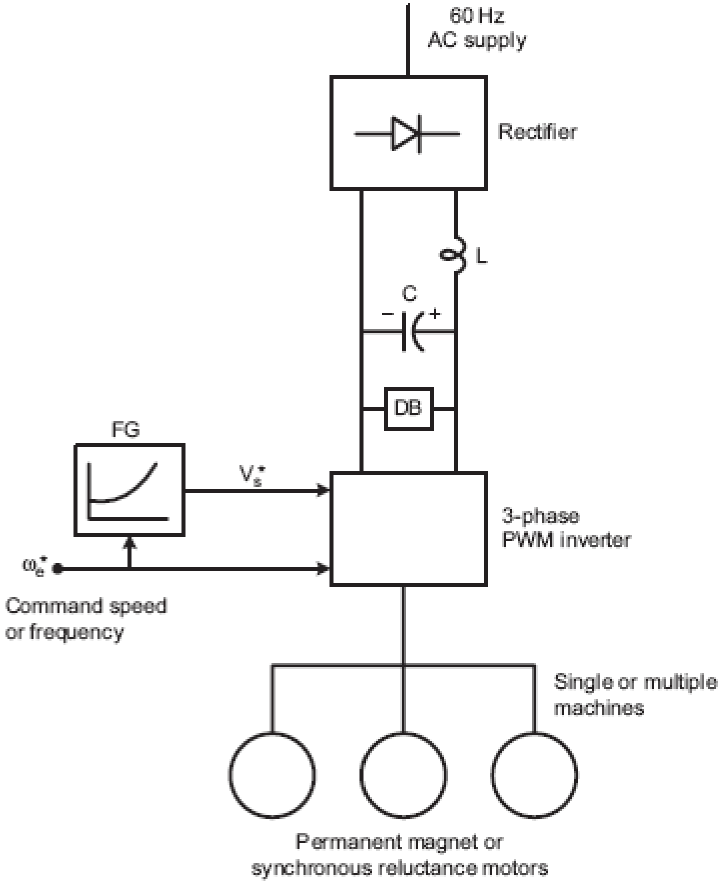
- Open loop volts/HZ speed control of synchronous motors.
- Self control.
- Separate control.
- Attractive feature of a synchronous motor.
- Synchronous motor operating with square wave inverter
- Synchronous motor operating with pwm inverter
- Brushless excitation of synchronous machine

Open loop volts/Hz speed control of synchronous motors.

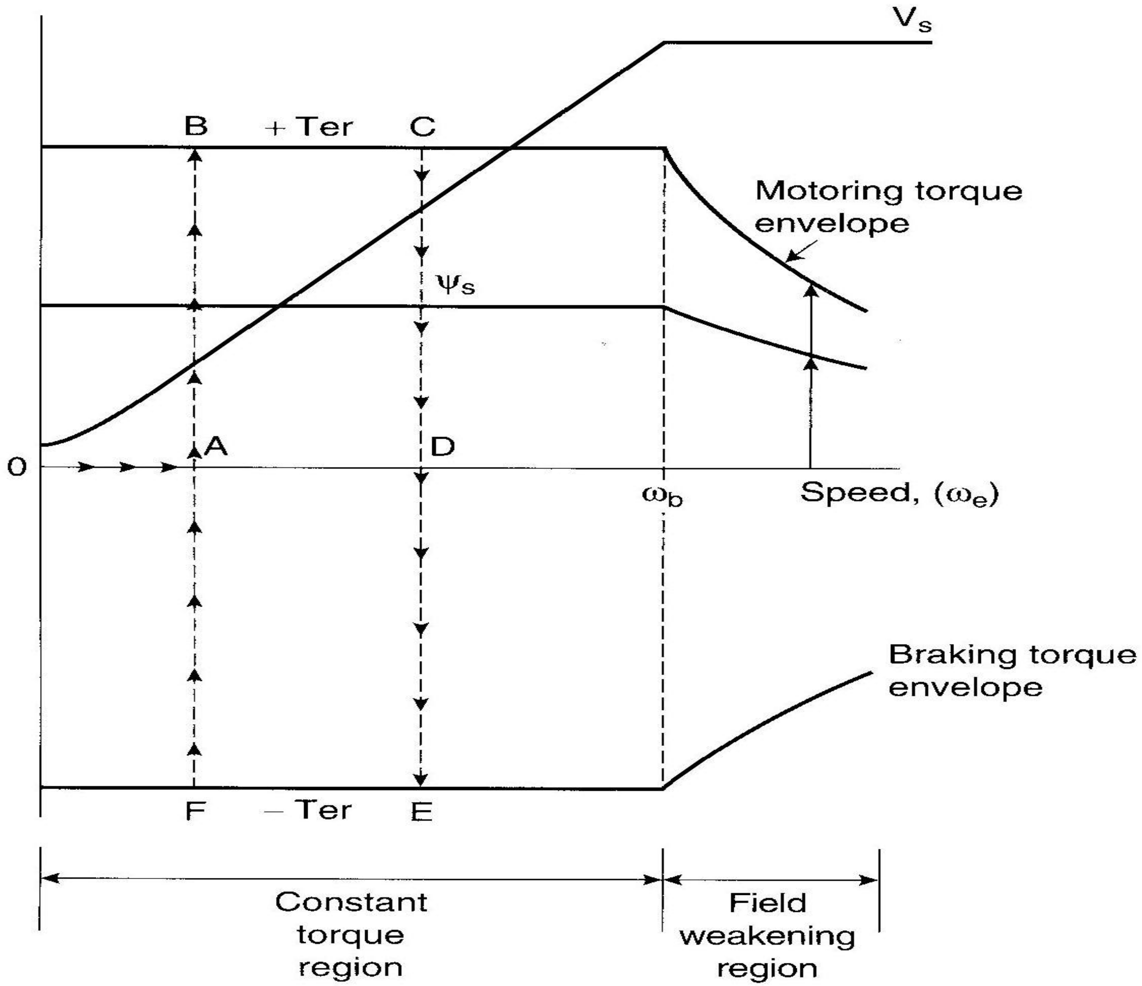
(Control of Synchronous Motors)

- Possible with variable frequency converter.
- Variable frequency synchronous motor can be controlled to possesses the characteristics of a separately excited dc motor. (E & V are controlled in proportion to frequency in order to keep air gap flux constant)

Open loop Volts/Hz speed control of synchronous motors



open loop volts/hz speed control characteristics



Self control

A Synchronous motor in self controlled mode is called “commutator less Dc motor”.

The frequency becomes the slave the speed.

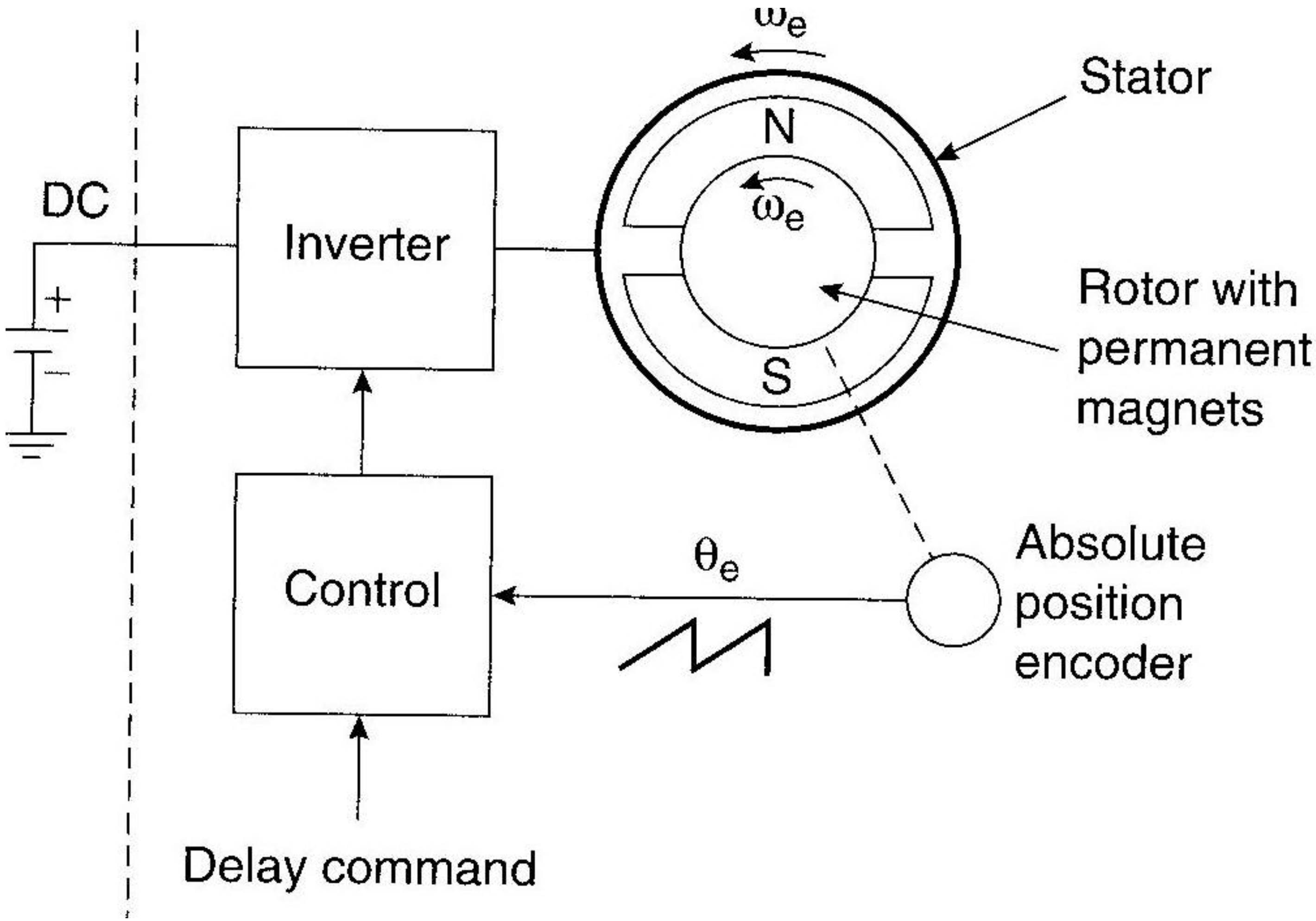
Basic features of self-controlled synchronous machine

- The inverter, controller and absolute position encoder - act as electronic commutator
- Electronic commutator replaces the mechanical commutators and brushes (mechanical inverter) of traditional dc machine
- The flux phasor diagram rotate at synchronous speed

Basic features of self-controlled synchronous machine

- Control can modify the angle between the flux phasors
- Because of self-control, machine does not show any stability or hunting problem of traditional synchronous machine
- The transient response is fast – similar to dc machine
- The rotor inertia is smaller than dc machine with high energy magnet

Self-controlled synchronous motor analogy



Self Control Principle

- Commutation of the converter feeding the motor is controlled through the rotor position information from a shaft encoder.
- Under over excitation the motor voltages can be employed to commutate the thyristors at the inverter. Now the inverter becomes simple. But at low speeds commutation assistance is required.

- Rotor position is sensed and the firing signals to the devices are synchronized to the motor position.
- For every 60^0 rotation of the rotor a new device in the sequence is fired.

Contd..

- For rotation of the rotor by 2 pole pitches all the six devices will receive firing pulses.
- Using this control the angle between the rotor and the stator mmf (Torque Angle) can be controlled. This is not possible in separately excited motor.
- Synchronous motor in self control is called as **Commutator less motor** having the steady state performance of the separately excited DC motor

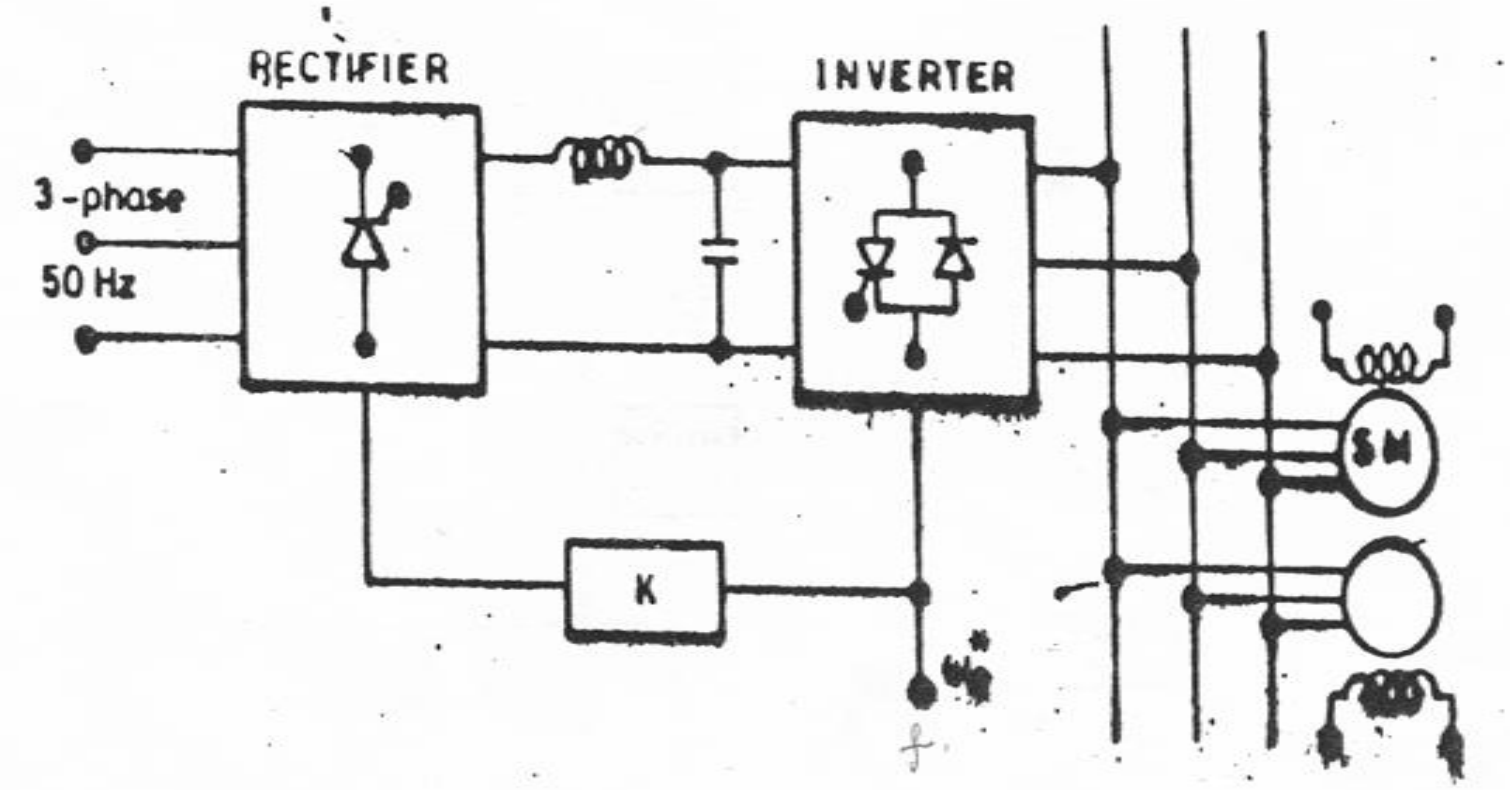
Separate control

The speed is the slave the frequency.

Separate control principle

- Supply Frequency to the synchronous motor is controlled from the inverter which receives its firing pulses from a frequency controlled oscillator.
- The machine will exhibits conventional behavior.
- Up to base speed the motor operates at constant torque and above base speed are obtained by clamping the voltage at rated voltage. Frequency can be increased and the motor operates in flux weakening region

Separate control *block* diagram

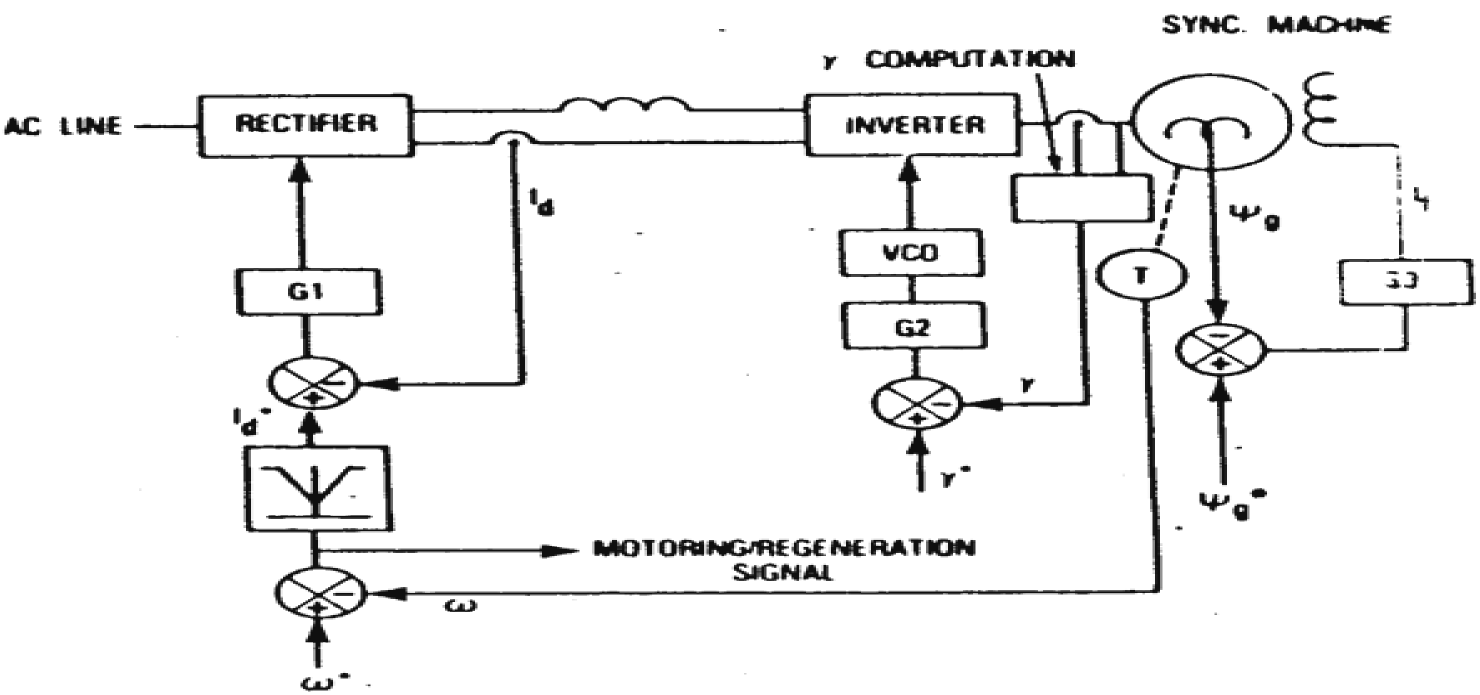


Draw backs of Separate control

- Hunting
- Poor dynamic Behavior.

Attractive feature of a synchronous machine

- Load commutation is possible only with CSI and not with VSI.



Load Commutated Inverter fed Synchronous Motor

- When forced commutation is required, the motor may be operated at UPF.
- To provide the necessary reactive power of the converter when the motor is over excited
- Load Commutation can be used when the cycloconverter is feeding the motor. When using cycloconverter, commutation difficulty is over come by utilising line commutation.

Synchronous motor operating with square wave inverter

- Speed Range
    - Medium to High
- Braking
    - Dynamic Braking Possible. Regeneration not straight forward.
- Harmonics
    - Heating effect is high at lower frequency

Contd..

- Torque Pulsations
  - Problem at Low speed
- Power Factor
  - Low Line pf
- High Cost
- Efficiency
  - Moderately good
- Open loop Control is possible.
- Staring by cage winding or by open loop method

Contd..

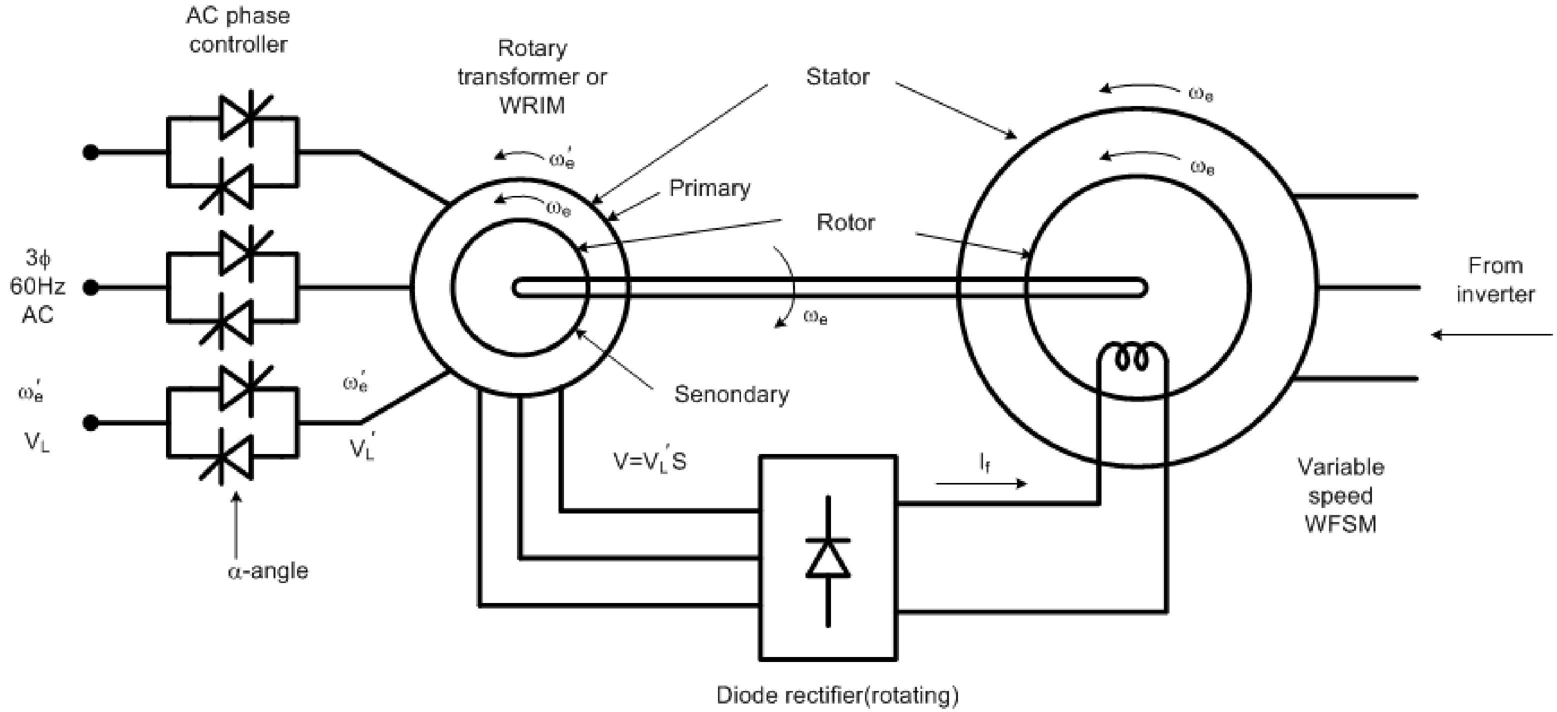
Synchronous motor operating with PWM inverter

Features

- Speed Range
  - Very wide Speed range upto zero speed is possible
- Braking
  - Dynamic Braking Possible. Regeneration possible if primary supply is dc.
- Harmonics
  - Nearly Sinusoidal

- Torque Pulsations
  - Minimal
- Power Factor
  - Line pf closer to Unity.
- High Cost
- Efficiency
  - Good
- Open loop Control is possible.

Brushless excitation of synchronous machine



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- G.K. Dubey, ‘Power semi-conductor controlled drives’, prentice hall of india.

THANK YOU