ATME College of Engineering

Industrial Drives and Applications-18EE741

Module-4

Induction Motor Drives cntd.

Synchronous Motors

Presented By,

Kavyashree S

Assistant Professor

Department of EEE

ATMECE, Mysuru

Content

Induction Motor Drives (continued):

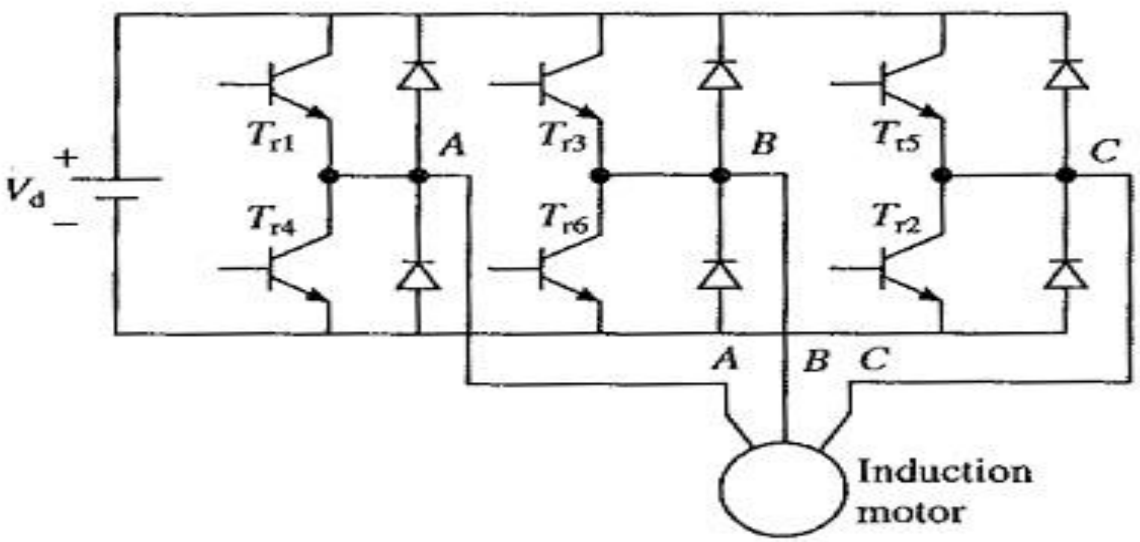
- Voltage Source Inverter (VSI) Control
- Cycloconverter Control,
- Closed Loop Speed Control Converter Rating for VSI Cycloconverter Induction Motor Drives
- Variable Frequency Control from a Current Source
- Current Source Inverter (CSI) Control
- current regulated voltage source inverter control
- speed control of single phase induction motors.

Synchronous Motor Drives:

- Operation from fixed frequency supply-starting
- synchronous motor variable speed drives
- Variable frequency control of multiple synchronous motors

Voltage Source Inverter Control (VSI)

- A VSI converts the input dc voltage into an variable frequency ac voltage.
- VSI using normal transistors is shown in below Fig.
- In voltage source inverters, the input voltage is kept constant.
- The magnitude of output voltage of VSI is independent of the load.
- But the magnitude of output current depends on the type of load.



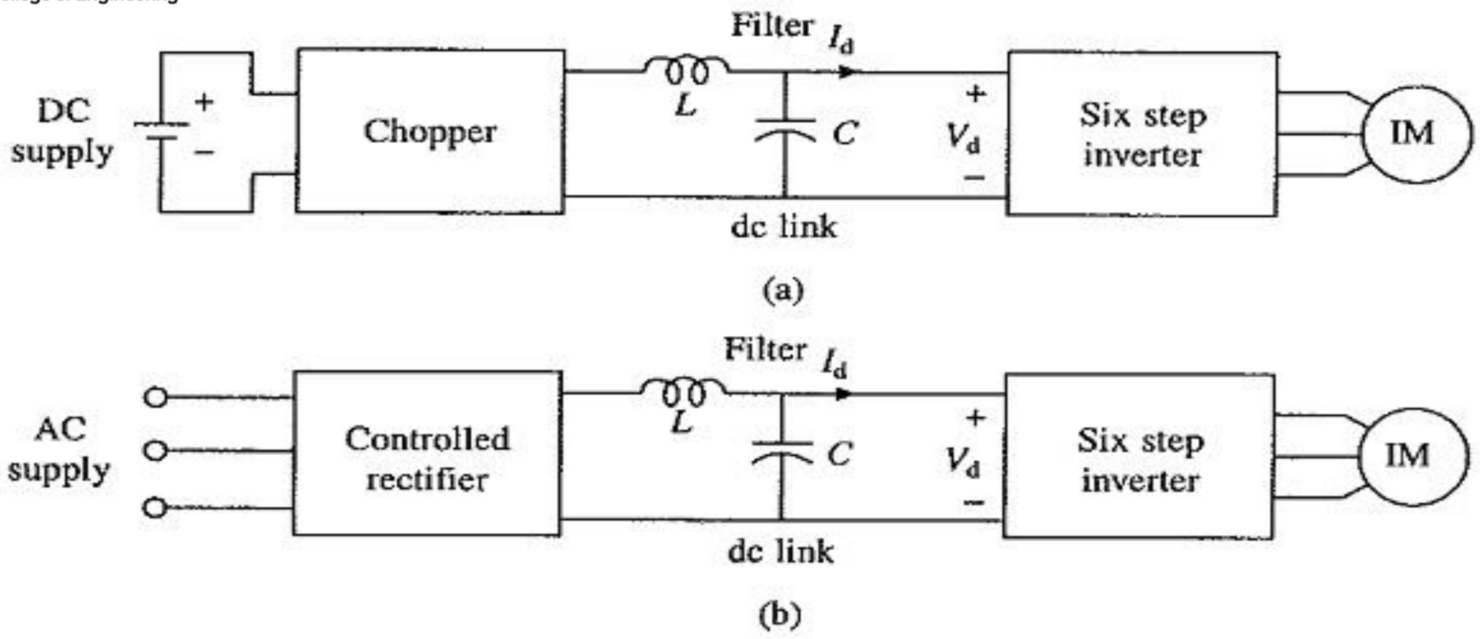
(a) Transistor inverter-fed induction motor drive

Any other self commutated device can be used in place of transistors such as

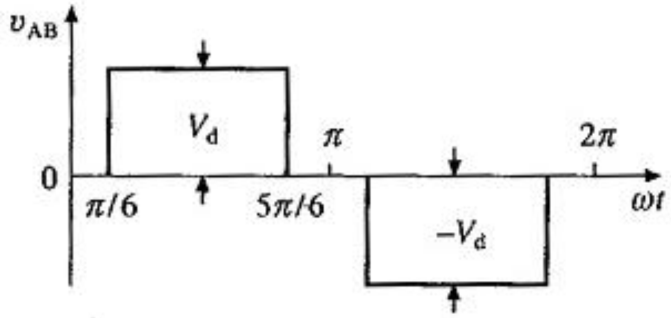
- ✓ MOSFET is used in low voltage and low power inverters.
- ✓ IGBTs and power transistors are used up to medium power levels.
- ✓ GTO and IGCT are used for high power levels.

https://www.youtube.com/watch?v=0TPjJBl3GCQ

Voltage Source Inverter Control cntd.



The output voltage waveform of a six step inverter is shown in below Fig.



(b) Stepped wave inverter line voltage waveform

- VSI can be operated as a **stepped wave inverter** or a **PWM inverter.**
- When VSI is operated as a **six step inverter**, the transistors are turned ON in the sequence of their numbers with a time interval of T/6 seconds if T is the total time period of one output cycle.
- Frequency of the inverter output is varied by varying the time period (T) of one cycle .
- If the **supply is dc**, then a variable dc voltage is obtained by connecting a **chopper** between input dc and the inverter as shown in below Fig. a
- If the input **supply is ac**, then a variable dc is obtained by connecting a controlled **rectifier** between the input ac and the inverter as shown in below Fig. b.
- A large electrotytic filter capacitor C is connected in dc link to make inverter operation independent of rectifier or chopper and to filter out harmonics in dc link voltage.

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Voltage Source Inverter Control cntd.

Inverter output line and phase voltages are given by the following Fourier series:

$$V_{AB} = \frac{2\sqrt{3}}{\pi} V_d \left[\sin \omega t - \frac{1}{5} \sin 5\omega t - \frac{1}{7} \sin 7\ \omega t + \frac{1}{11} \sin 11 \omega t + \frac{1}{13} \sin 13\ \omega t \ldots \right]$$

$$V_{AN} = \frac{2}{\pi} V_d \left[\sin \omega t + \frac{1}{5} \sin 5\omega t + \frac{1}{7} \sin 7\ \omega t \right]$$

The rms value of the fundamental phase voltage

$$V = \frac{\sqrt{2}}{\pi} V_d$$

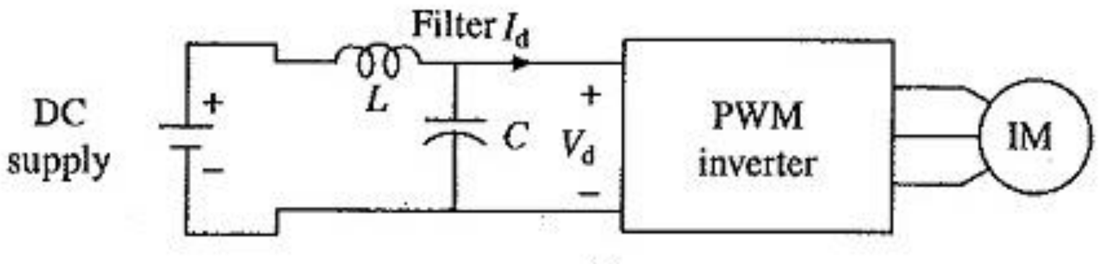
Disadvantages of six step inverter

- Low frequency harmonics are more and hence the motor losses are increased at all speeds.
- Motor develops pulsating torques due to 5th, 7th, 11th and 13th harmonics.
- Harmonic content increases at low speeds. This will overheat the machine

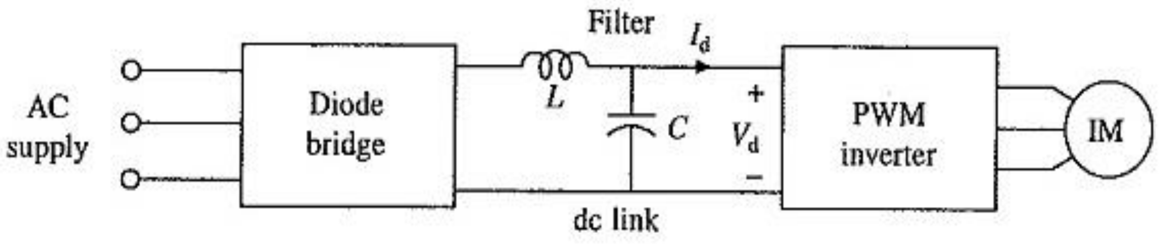
The above said problems are rectified when a PWM inverter is used.

- If a PWM inverter is used as VSI as shown in below Fig c & d, Where the harmonics are reduced, low frequency harmonics are eliminated, losses are reduced and smooth motion is obtained at low speeds
- when inverter is operated as a pulse width, then the input voltage may be a constant dc which is obtained from a simple diode rectifier.
- The output of a PWM inverter is a variable voltage and variable frequency

Voltage Source Inverter Control cntd.



(c)



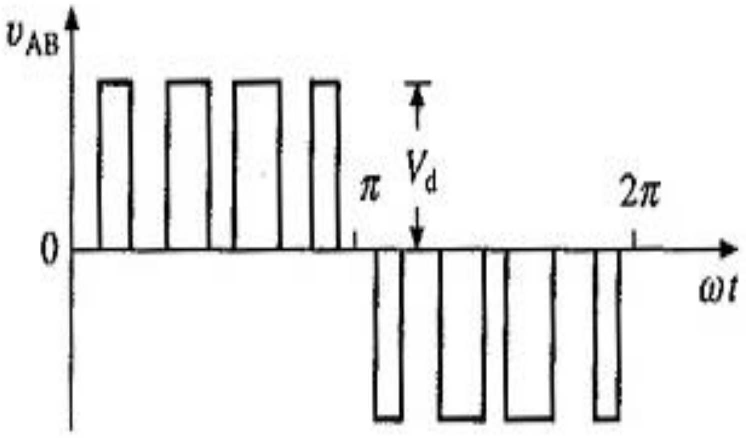
(d)

The fundamental component in the output phase voltage of a PWM inverter operating with sinusoidal PWM is given by

$$V = m\frac{V_d}{2\sqrt{2}}$$

Where m- modulation index

- When supply is dc: Inverter can be directly connected
- When supply is ac: Inverter is connected through Diode rectifier.
- The harmonics in the motor current produce torque pulsation and derate the motor.
- For a given harmonic content in motor terminal voltage, the current harmonics are reduced when the motor has higher leakage inductance, this reduces derating and torque pulsations.
- Therefore, when fed from VSI, Induction Motor with **large** (compared to when fed from sinusoidal supply) **leakage inductance are used**



(c) PWM inverter line voltage waveform

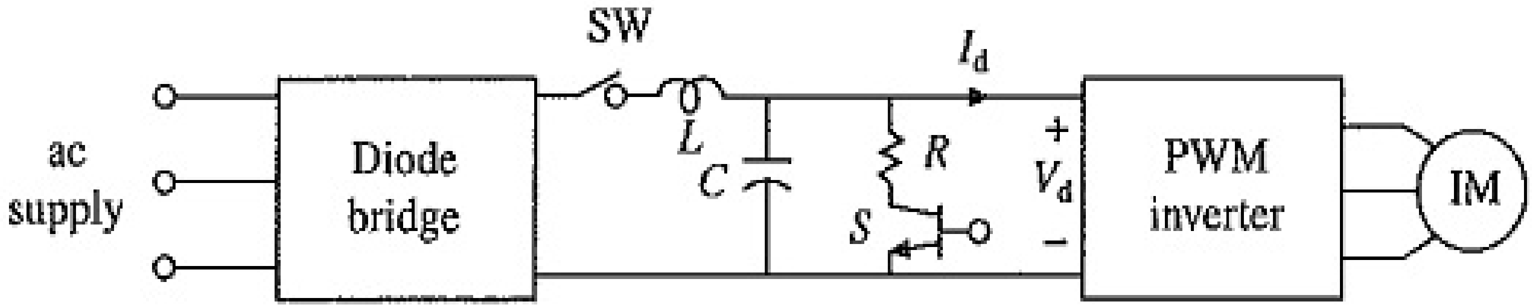
Braking and Multi-quadrant Operation of VSI Induction Motor Drives

- The power input into the motor is given by $P_{in} = 3VI_s \cos\phi$

where
V = fundamental component of the motor phase voltage
I_s = fundamental component of the motor phase current
Φ = phase angle between V and I_s.

- In **motoring operation :** $\Phi < 90°$, hence P_{in} is positive i.e. power flows from the inverter to the machine.
- A reduction in frequency makes the synchronous speed less than the rotor speed and the relative speed between the rotor conductors and air-gap rotating field reverses.
- This reverses the rotor induced emf, rotor current and component of stator current which balances the rotor ampere turns.
- Hence, $\Phi > 90°$ and power flow reverses.
- The machine works as a generator feeding power into the inverter, which in turn feeds power into dc link by reversing the dc link current I_d. Regenerative braking is obtained when the power flowing from the inverter to the dc link is usefully employed and dynamic braking is obtained when it is wasted in a resistance.

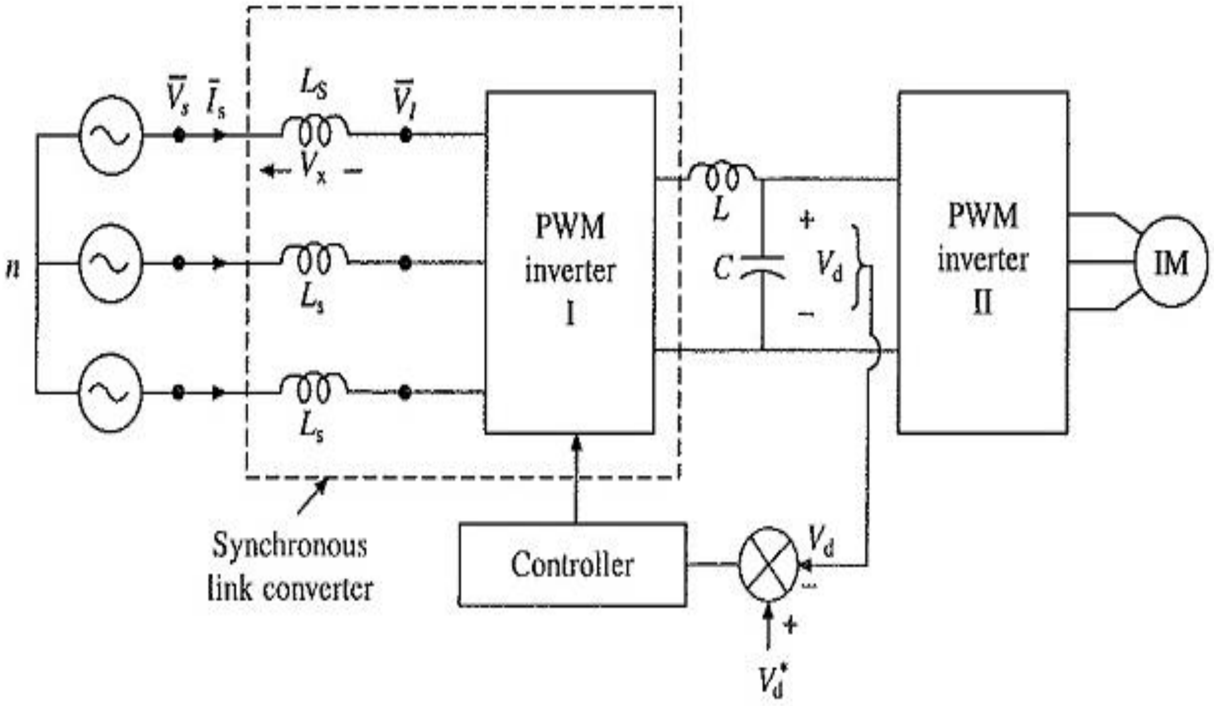
Dynamic Braking



- Generated energy flowing into the dc link charges the capacitor and its voltages rises.
- When it crosses a set value, switch S is closed, connecting the resistance across the link.
- The generated power and a part of energy stored in the capacitor flow into the resistance, and dc link voltage reduces.
- When it falls to its nominal value, S is opened.
- Thus by closing and opening switch S based on the value of dc link voltage, generated energy is dissipated in the resistance, giving dynamic braking.

Regenerative Braking

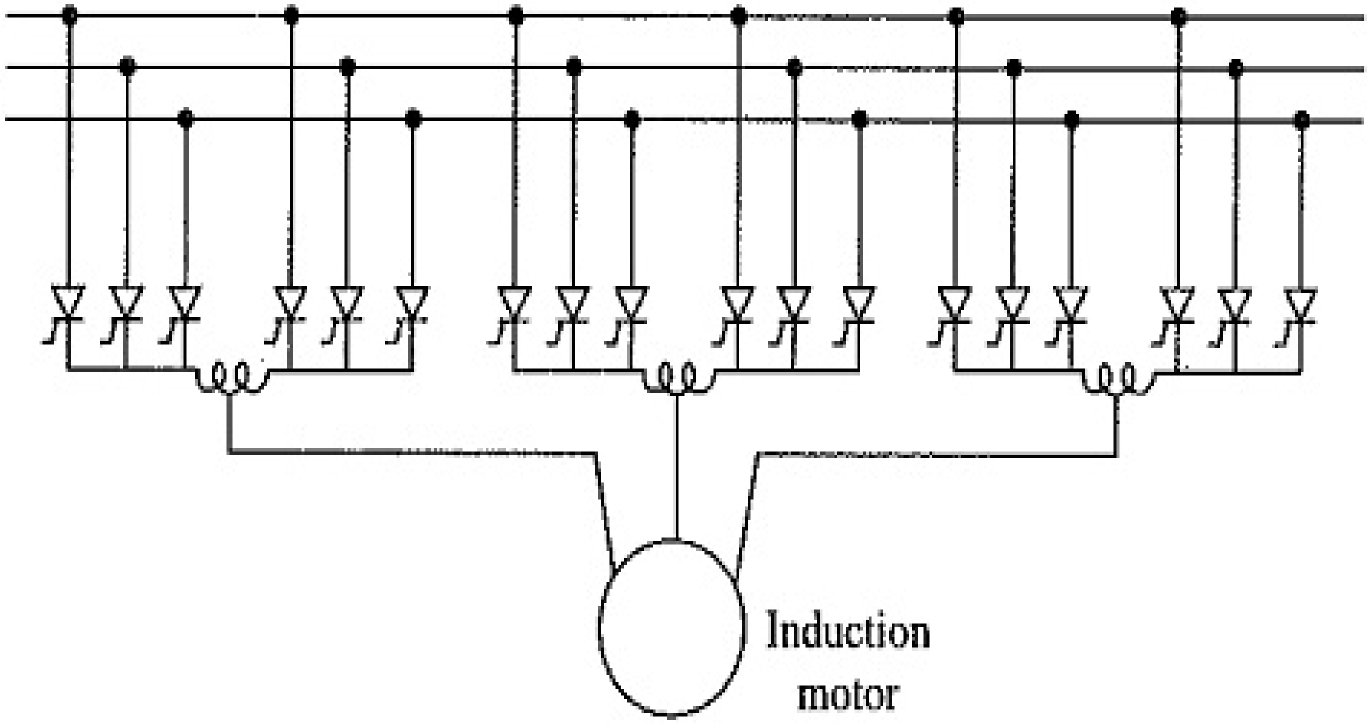
- When the operation shifts from motoring to braking I_d reverses but V_d remains in the same direction.
- For regenerative braking, a converter with dc voltage of one polarity and dc current of either direction is required.
- A dual converter with this feature is conventionally used.
- The recent drives use synchronous link converter (SLC) because it takes sinusoidal current at unity power factor from the ac source, both during motoring and braking operations.



- A regenerative drive with a SLC and PWM inverter is shown in Fig.
- The inductors Ls and PWM inverter I constitute a SLC.
- PWM inverter I is operated to produce voltage V_I of required magnitude and phase and with a low harmonic content, so that source current Is is nearly sinusoidal and in phase with Vs for motoring and 180° out of phase for braking, thus giving unity power factor.

Cycloconverter Control of Induction Motor

- Cycloconverter Control of Induction Motor allows variable frequency and variable voltage supply to be obtained from a fixed voltage and frequency ac supply.
- Half-wave Cycloconverter Control of Induction Motor and its output voltage waveform is shown in Fig.
- Because of low harmonic content when operating at low frequencies, smooth motion is obtained at low speeds.

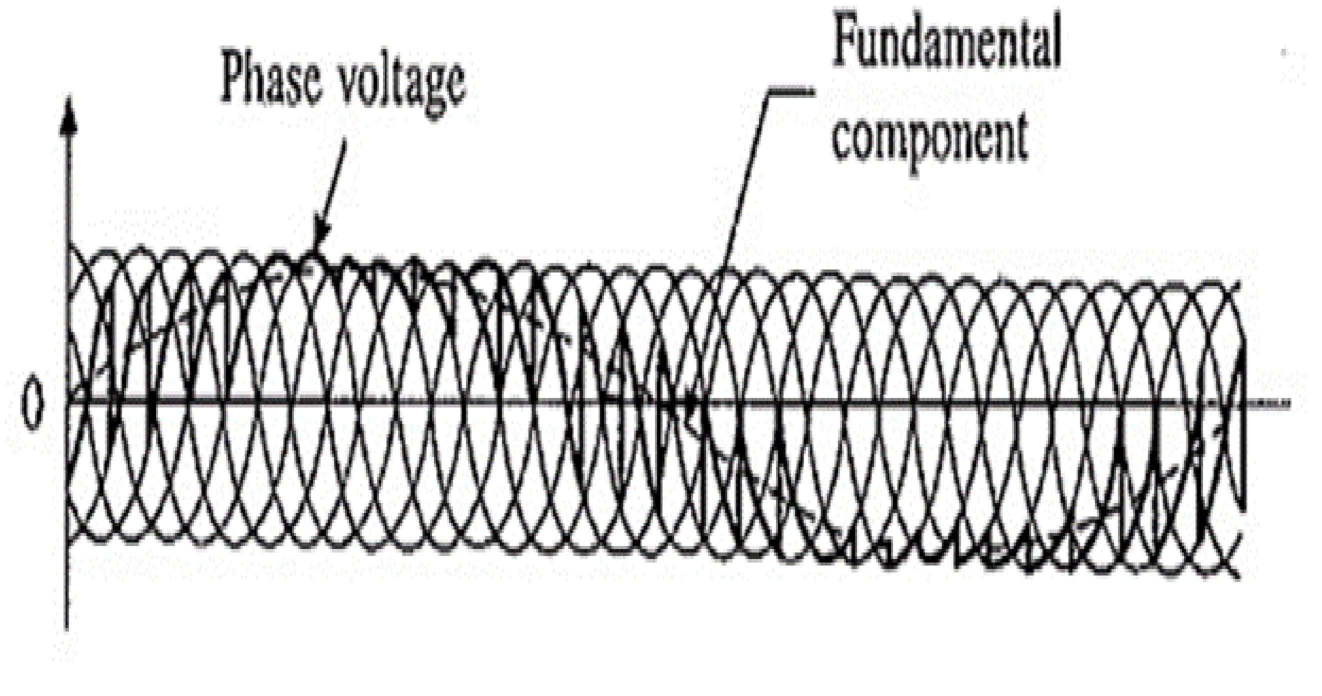


(a) Half wave cycloconverter-fed induction motor

- Harmonic content increases with frequency. Thus, maximum speed is restricted to 40% of synchronous speed at the mains frequency.
- A motor with large leakage inductance is used in order to minimize derating and torque pulsations due to harmonics in motor current.
- The drives has regenerative braking capability. Full four-quadrant operation is obtained by reversing the phase sequence of motor terminal voltage.

Cycloconverter Control of Induction Motor cntd.

- Since cycloconverter employs large number of thyristors, economically suitable only for large power drives, requiring good dynamic response but only low speed operation.
- The low speed operation is obtained by feeding a motor with large number of poles from a Cycloconverter Control of Induction Motor operating at low frequencies.
- These drives are called gearless drives because, the low speed operation of load is obtained without a reduction gear, thus eliminating the associated cost, space and maintenance.

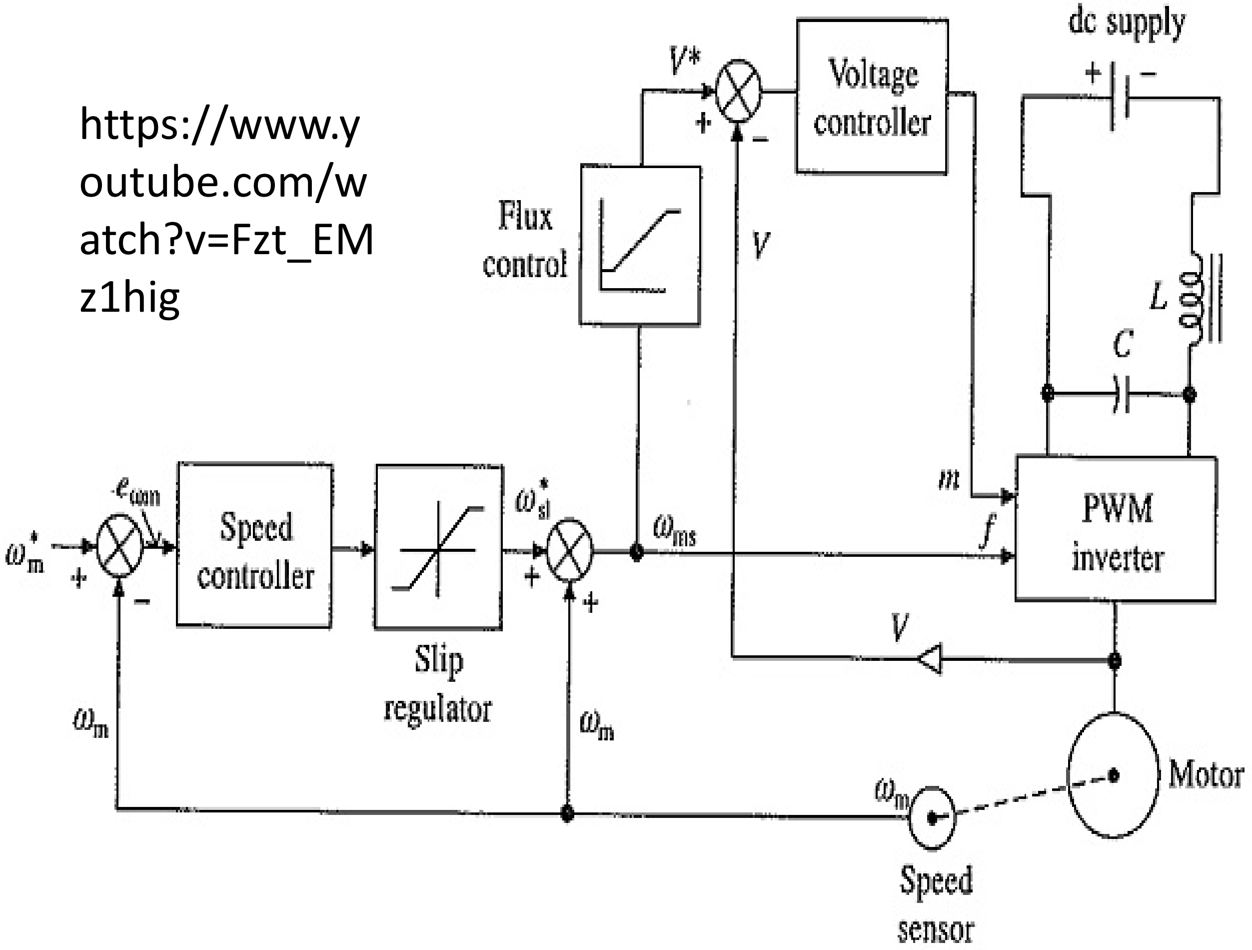


(b) Phase voltage waveform

Closed Loop Speed Control of Induction Motor Drives

- A Closed Loop Speed Control of Induction Motor Drives is shown in Fig. It employs **inner slip-speed loop** with a slip limiter and **outer speed loop.**
- Here, the Slip speed has a fixed value, the slip speed loop also functions as an inner current loop.
- Here, the motor operation always occurs on the portion of speed-torque curve between synchronous speed and the speed at the maximum torque for all frequencies, resulting in high torque to current ratio.
- The drive uses a PWM inverter fed from a dc source, which has capability for regenerative braking and four-quadrant operation.

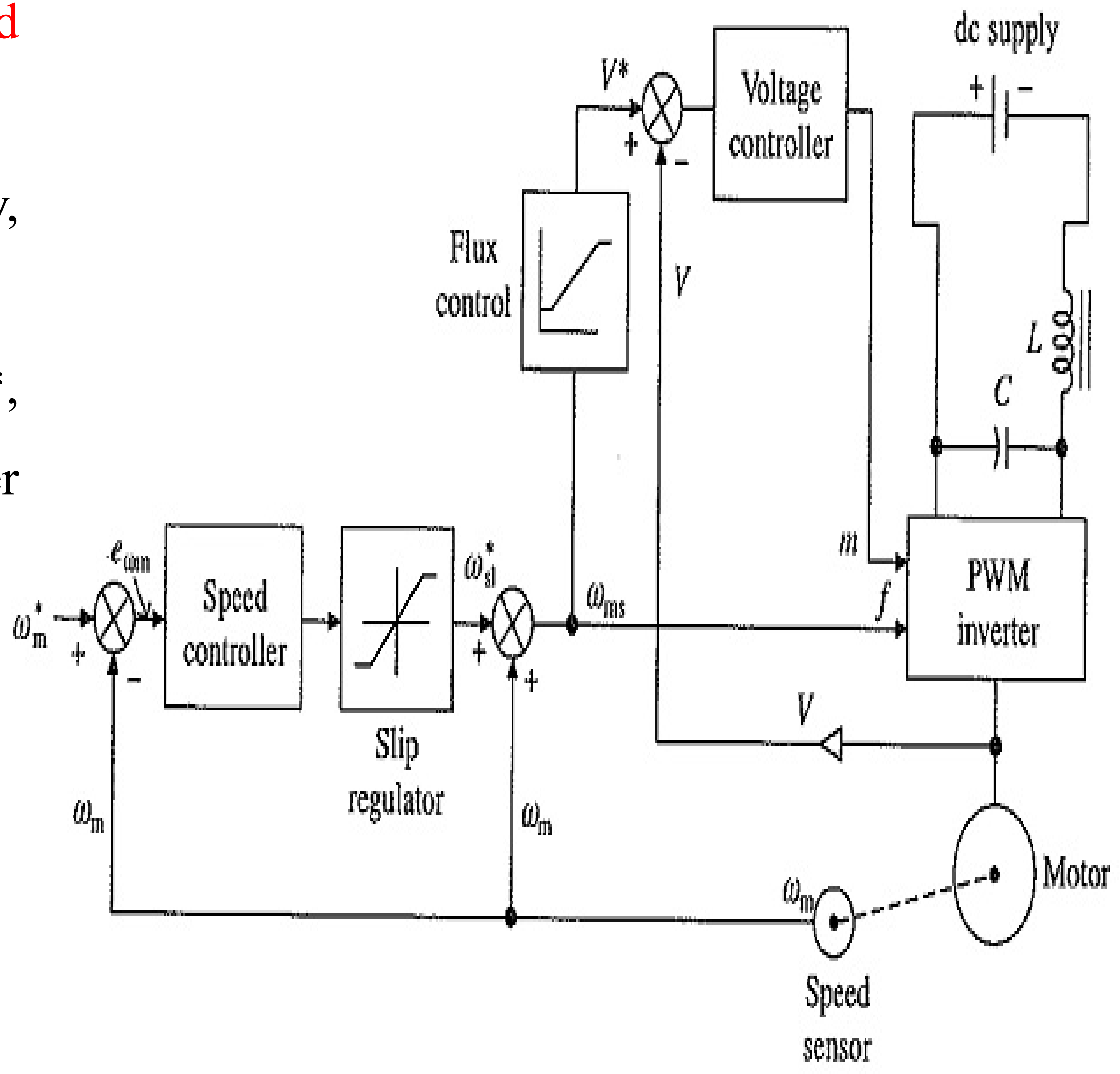
https://www.youtube.com/watch?v=Fzt_EMz1hig



- The drive scheme is applicable to any VSI or cycloconverter drive having regenerative or dynamic braking capability.

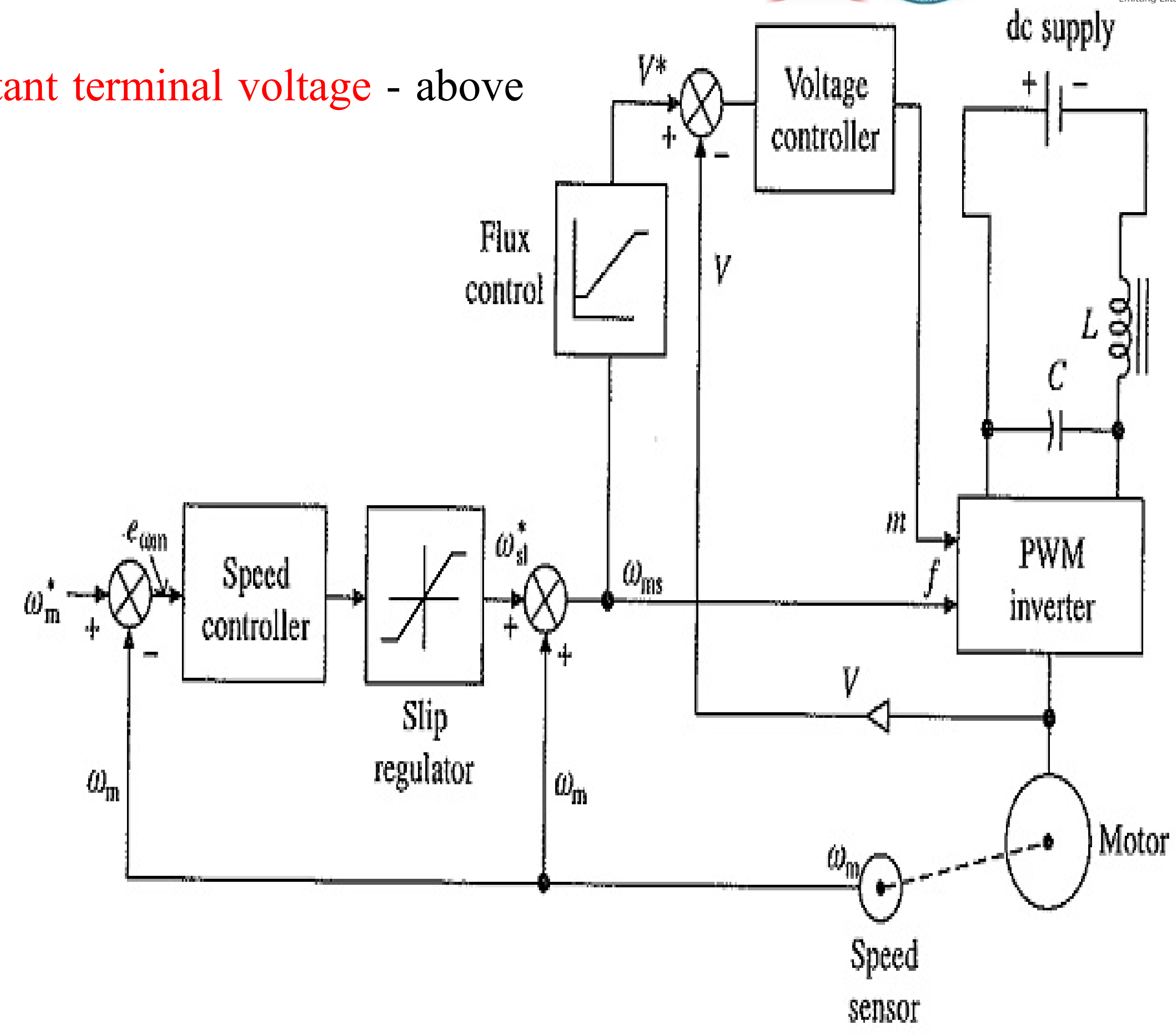
Closed Loop Speed Control of Induction Motor Drives cntd.

- The speed error is processed through a PI controller and a slip regulator.
- PI controller is used to get good steady-state accuracy, and to attenuate noise.
- The slip regulator sets the slip speed command ωs1*, whose maximum value is limited to limit the inverter current to a permissible value.
- The synchronous speed, obtained by adding actual speed ωm and slip speed ωs1*, determines the inverter frequency.
- The reference signal for the Closed Loop Speed Control of Induction Motor Drives of the machine terminal voltage V* is generated from frequency f using a function generator.



- It gives constant flux - up to base speed ; constant terminal voltage - above base speed.

- A step increase in speed command ωm* produces a positive speed error. The slip speed command ωs1* is set at the maximum value.
- The drive accelerates at the maximum inverter current, producing maximum torque, until the speed error is reduced to a small value.
- The drive finally settles at a slip speed for which the motor torque balances the load torque.
- The drive decelerates under regenerative braking, at the maximum current and the maximum braking torque, until the speed error is reduced to a small value.
- Now the operation shifts to motoring and the drive settles at the slip speed for which the motor torque equals the load torque.



Variable Frequency Control From Current Source

- Consider the motor control by **Variable Frequency Control From Current Source (VFCS).**
- An equivalent circuit for motor fed from a current source is obtained when voltage source V is replaced by a current source Is.

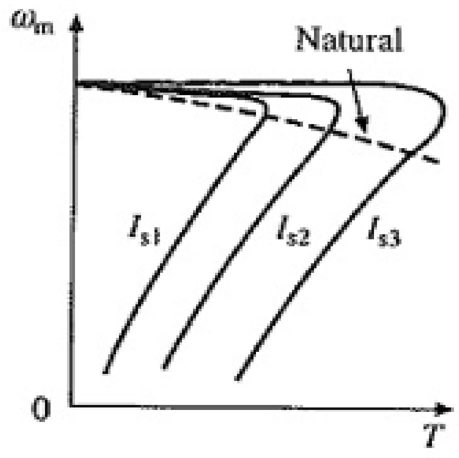
$$I_r' = \frac{X_m I_s}{\sqrt{(R_r'/s)^2 + (X_m + X_r')^2}}$$

$$T = \frac{3}{\omega_{ms}} I_r'^2 \frac{R_r'}{s} = \frac{3}{\omega_{ms}} \left[\frac{I_s^2 X_m^2 R_r'/s}{(R_r'/s)^2 + (X_m + X_r')^2} \right]$$

$$I_m^2 = \left[\frac{(R_r'/s)^2 + X_r'^2}{(R_r'/s)^2 + (X_m + X_r')^2} \right] I_s^2$$

$$= \left[\frac{(R_r'/sf)^2 + (2\pi L_r')^2}{(R_r'/sf)^2 + (2\pi L_m + 2\pi L_r')^2} \right] I_s^2$$

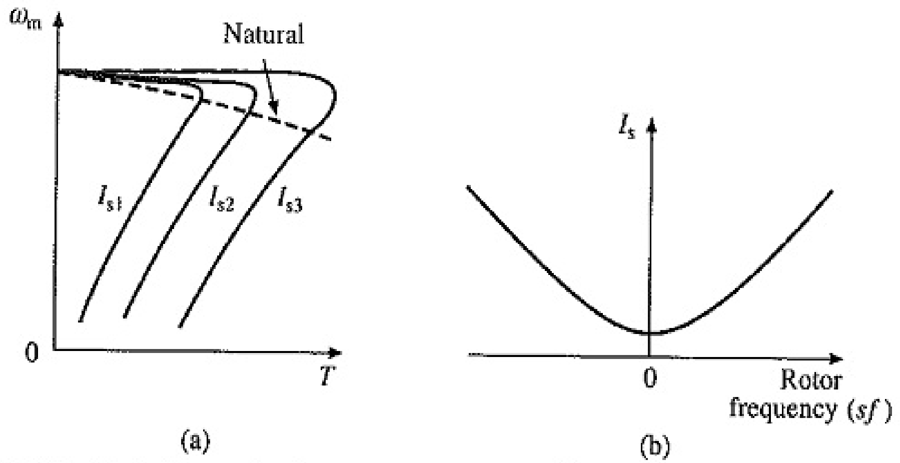
- Motor speed-torque curves for various values of Is and natural speed-torque curve, at rated constant flux is shown.
- For a given Is, motor operates above the natural characteristic- for a flux higher than rated ; motor operates below the natural characteristic – at less than rated flux.
- Since rated flux operation is preferred, the natural characteristic is locus of preferred, operating points.



(a)

Variable Frequency Control From Current Source cntd.

- Fig (b) shows stator current Is and rotor frequency (sf), when frequency is changed to control the speed.
- When operating at a constant flux, the operating points are located mostly on the part of speed torque curve, which gives unstable operation with most loads.
- Hence, closed loop control is mandatory. Since motor is constraint to operate at constant flux, its steady-state behavior is identical to that with VFVS.

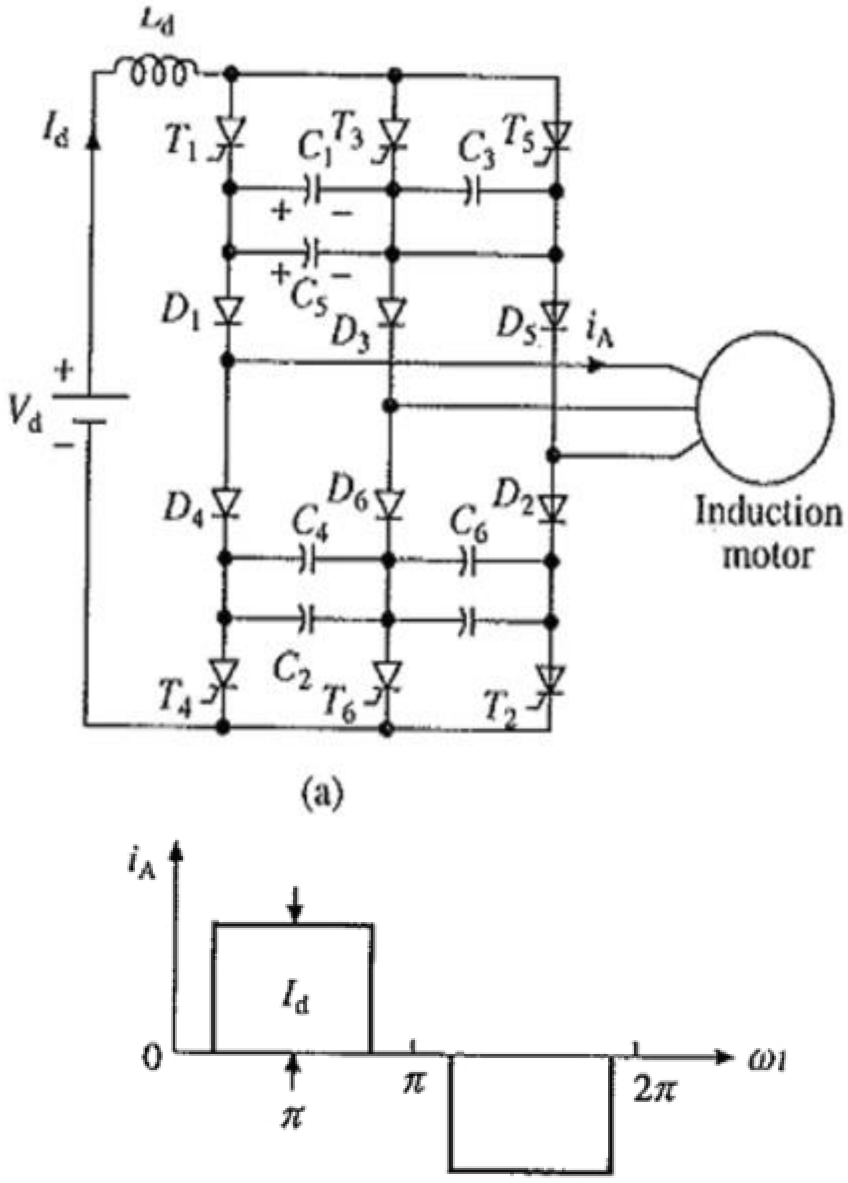


Operation of induction motor from a current source: (a) speed torque curves; (b) I_s vs sf curves

- Thus at a given slip speed (or rotor frequency), the motor draws a constant current and develops a constant torque at all frequency.
- The motor, therefore, operates in constant torque mode from zero to base speed. At base speed, either rated machine voltage is reached or VFCS voltage saturates.
- In either case machine operates at a constant terminal voltage above base speed, providing constant power mode.
- Variable frequency current supply is provided by a Variable Frequency Control From Current Source inverter.

Current Source Inverter Control of Induction Motor

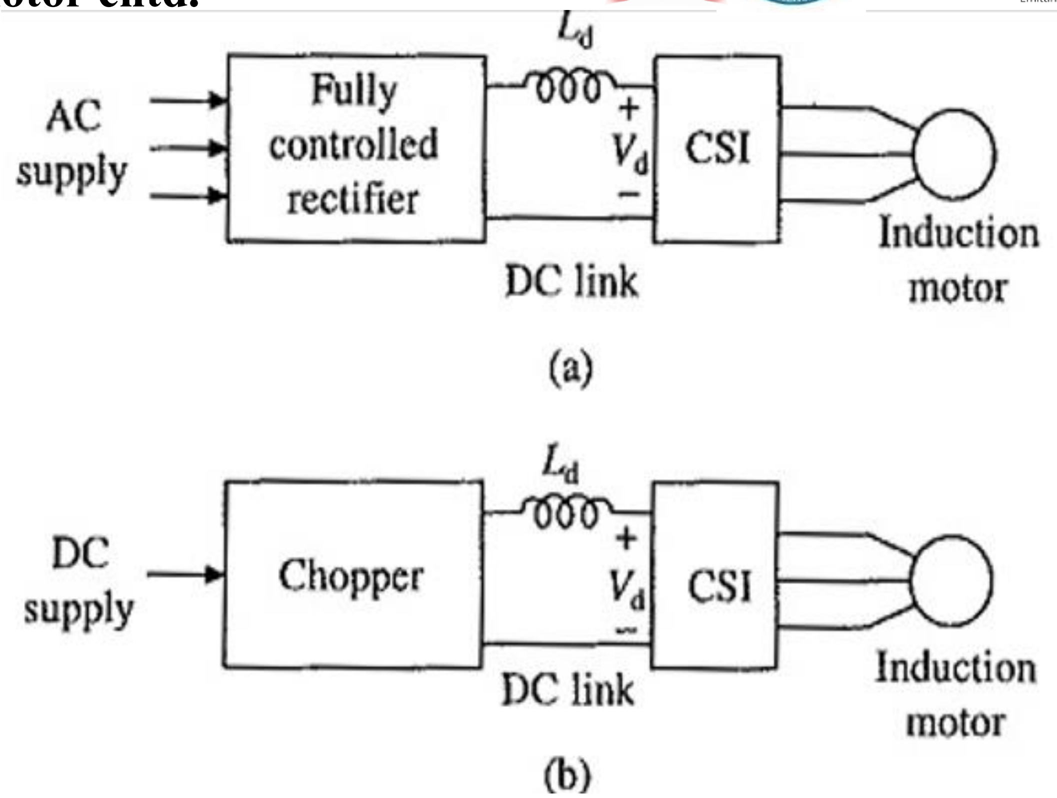
- A thyristor Current Source Inverter Control of Induction Motor (CSI) is shown in Fig.
- Diodes D1-D6 and capacitors C1-C6 provide commutation of thyristors T1-T6, which are fired with a phase difference of 60° in sequence of their numbers.
- It also shows the nature of output current waveforms.
- Inverter behaves as a current source due to the presence of large inductance Ld in dc link.
- The fundamental component of motor phase current from Fig. is $I_s = \frac{\sqrt{6}}{\pi} I_d$
- For a given speed, torque is controlled by varying dc link current I_d by changing the value of V_d.
- Therefore, when supply is ac, a controlled rectifier is connected between the supply and inverter and when supply is dc, a chopper is interposed between the supply and inverter.
- The maximum value of dc output voltage of fully-controlled rectifier and chopper are chosen so that the motor terminal voltage saturates at rated value.



(b)

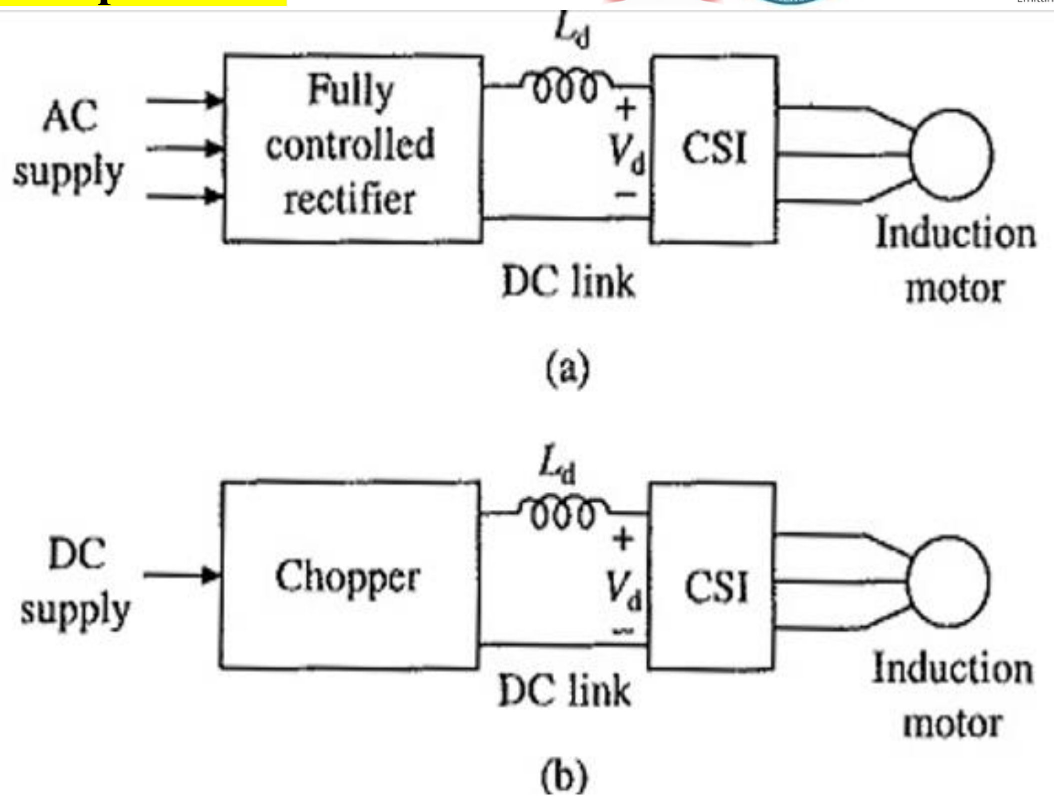
Current Source Inverter Control of Induction Motor cntd.

- The major advantage of Current Source Inverter Control of Induction Motor is its reliability.
- In **case of VSI** , a commutation failure will cause two devices in the same leg (e.g. T_{r1} and T_{r4}) to conduct. This connects conducting devices directly across the source. So, current through devices suddenly rises to dangerous values. Hence, Expensive high speed semiconductor fuses are required to protect the devices.



- In **case of CSI,** conduction of two devices in the same leg does not lead to sudden rise of current through them due to the presence of a large inductance L_d.
- This allows time for commutation to take place and normal operation to get restored in subsequent cycles. Further, less expensive HRC fuses are good enough for protection of thyristors.

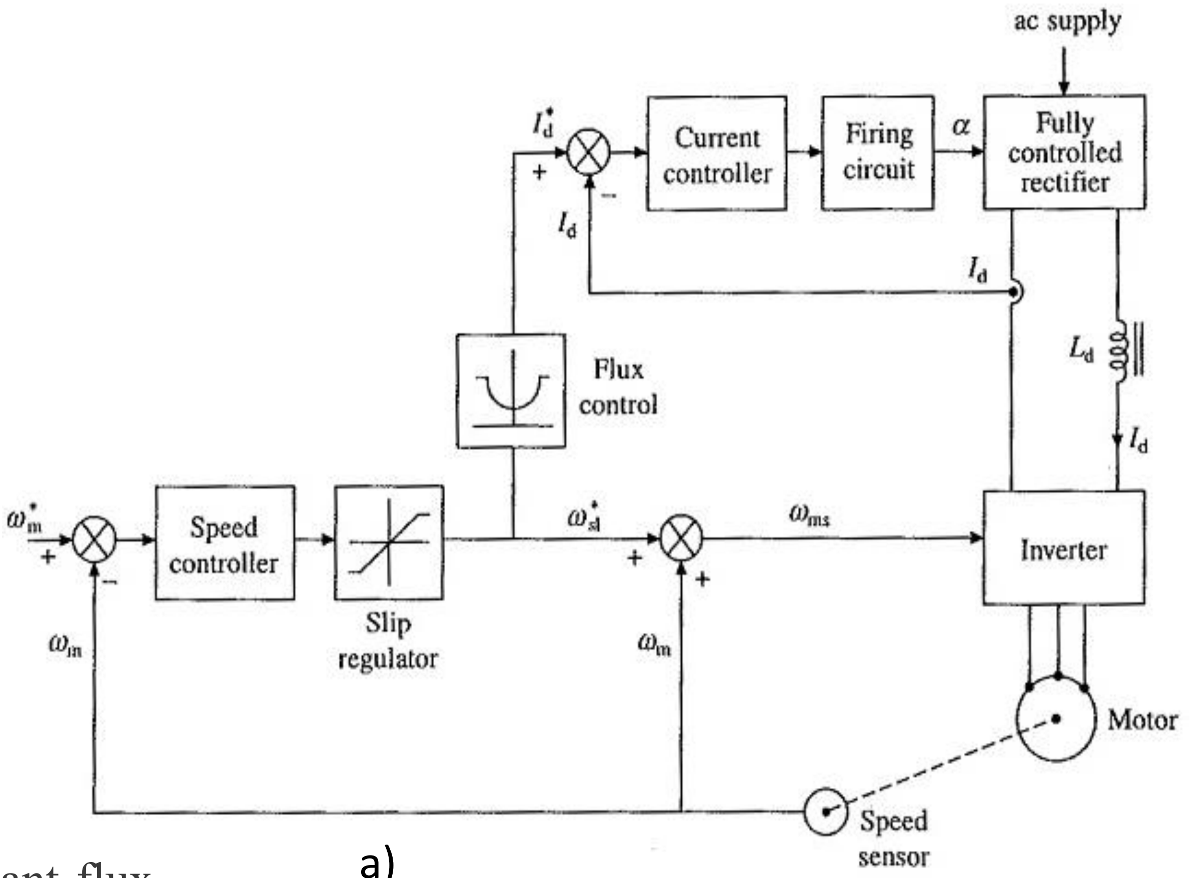
Regenerative Braking and Multiquadrant Operation:



- When inverter frequency is reduced to make synchronous speed less than motor speed, machine works as a generator.
- Power flows from machine to dc link and dc link voltage Vd (Fig.) reverses.
- If fully-controlled converter of Fig. (a) is made to work as an inverter, the power supplied to dc link will be transferred to ac supply and regenerative braking will take place.
- Thus, no additional equipment is required for regenerative braking of CSI drive of Fig. (a).
- Change of phase sequence of Current Source Inverter Control of Induction Motor will provide motoring and braking operations in the reverse direction.
- The drive of Fig.(b) can have regenerative braking capability and four-quadrant operation if a two quadrant chopper providing current in one direction but voltage in either direction is used

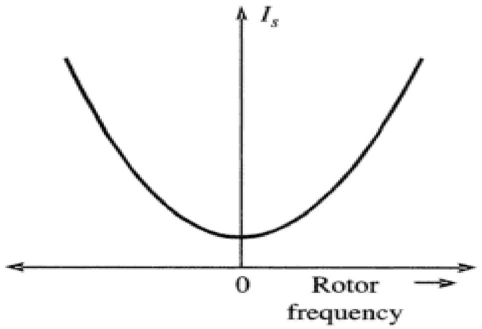
Closed Loop Speed Control of CSI Drives

- A closed loop Current Source Inverter Control of Induction Motor drive is shown in Fig a)
- Actual speed ω_m is compared with the reference speed ω^*_m.
- The speed error is processed through a PI controller and slip regulator.
- The slip regulator sets the slip speed command ω^*_{s1}.
- The synchronous speed obtained by adding ω_m to ω^*_{s1}, determines the inverter frequency. Constant flux operation is obtained when slip speed ω_{s1} (or rotor frequency) and I_s have relationship as in fig b).



a)

- Since Id is proportional to Is, as per eq. $I_s = \frac{\sqrt{6}}{\pi} I_d$
- A relation similar to Fig b) exists between ωs1 and Id for constant flux operation.
- Based on the value of ω^*_{s1}, the flux control block produces a reference current I^*_d, which through a closed-loop current control adjusts the dc link current Id to maintain a constant flux.



b)
Is Vs sf curve

Closed Loop Speed Control of CSI Drives cntd.

- The limit imposed on the output of the slip regulator, limits Id at the inverter rating.
- Therefore, any correction in speed error is carried out at the maximum permissible inverter current and maximum available torque, giving fast transient response and current protection.
- Beyond base speed, machine terminal voltage saturates .
- Flux control and closed-loop control of Id are made ineffective.
- To operate the drive up to rated inverter current, the slip speed limit of the slip regulator must increase linearly with frequency.
- This is realized by adding to the slip regulator output a signal proportional to frequency.

Comparison of CSI (current source inverter)and VSI (drives voltage source inverter)

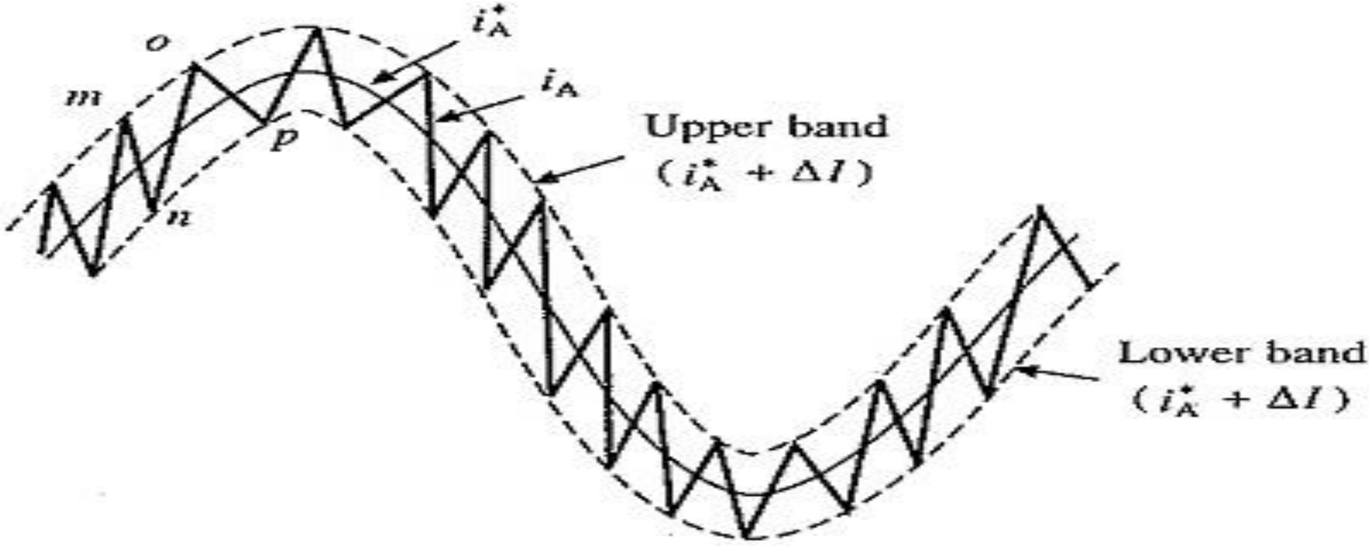
Current Source Inverter (CSI) drives	Voltage Source Inverter (VSI) drives
CSI is more reliable because conduction of two devices in the same leg does not short circuit the input supply.	Conduction of two devices in the same leg due to commutation failure causes short circuit of the input supply. This may raise the current through the devices and damage them.
Raise of current is prevented because of the presence of large inductance in the current source.	It requires expensive high speed semiconductor fuses for controlling the current due to short circuit.
Motor current rise and fall are very fast and that creates high voltage across windings.	No such problem arises here in case of VSI.
These high voltage spikes are controlled by having large values of commutating capacitors which may increase the cost and size of the inverter.	Less costly than CSI.

Comparison of CSI (current source inverter)and VSI (drives voltage source inverter)

Slow response due to large value of input inductance.	Fast dynamic response is possible if VSI uses PWM inverter. If a six step inverter is used, then response becomes slower like CSI drives.
Frequency range of CSI is lower than VSI. Hence CSI drive has lower speed range.	Frequency range is wide and hence the speed range is also wide.
CSI requires a separate rectifier and inverter combination. Hence it is not suitable for multi motor drives.	A single rectifier can be used to feed many VSIs. Hence VSI is suitable for multi motor drives.
Regenerative braking is naturally possible in CSI.	An additional full converter is required to achieve regenerative braking.
If input AC supply fails, electric braking is not possible in CSI.	But VSI can use dynamic braking in case input AC supply fails.

Current Regulated Voltage Source Inverter

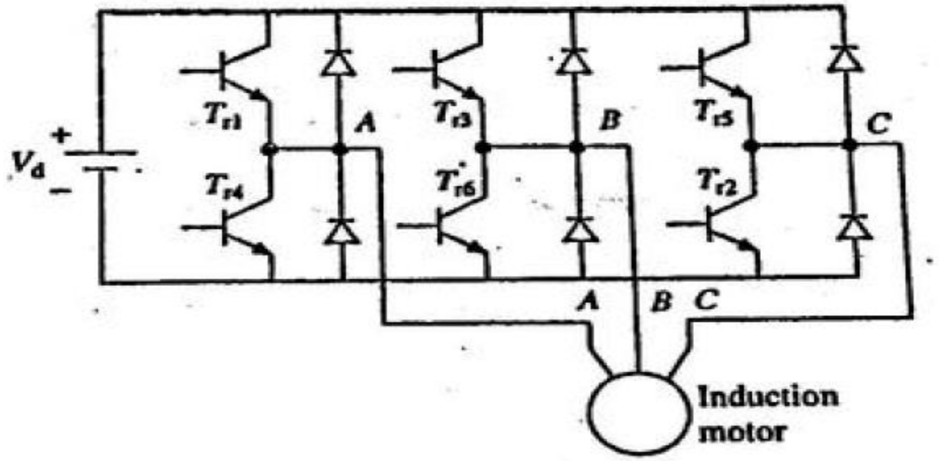
- Current Regulated Voltage Source Inverter operates with current controlled PWM.
- In current controlled pulse-width modulation, machine phase current is made to follow a sinusoidal reference current within a hysteresis band



(a)

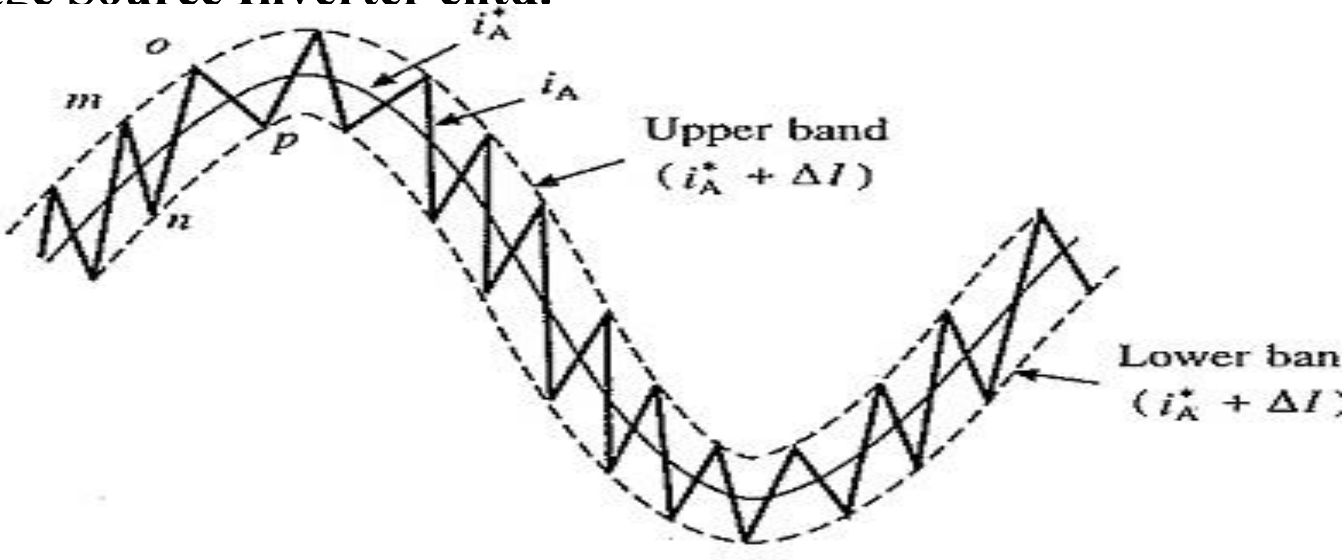
Above Fig. (a) shows a sinusoidal reference current $i^*_A = I_m \sin \omega t$.
Here, two bands, separated from i^*_A by an amount ΔI.

- Switching in the inverter is carried out such that the actual motor current iA remains within these two bands.
- For this voltage source inverter Fig. (a1) is employed. In this inverter phase A current iA is shaped by transistors Tr1 and Tr4.
- When **Tr1 is on** (Tr4 is off), phase A is connected to the positive terminal of dc source, hence the rate of change of current iA will be positive
- When **Tr4 is on** (Tr1 is Off), phase A is connected, to negative terminal of the dc source, hence rate of change of current iA will be negative.



a1) Transistor inverter-fed induction motor drive

Current Regulated Voltage Source Inverter cntd.



(a)

In Fig. (a):

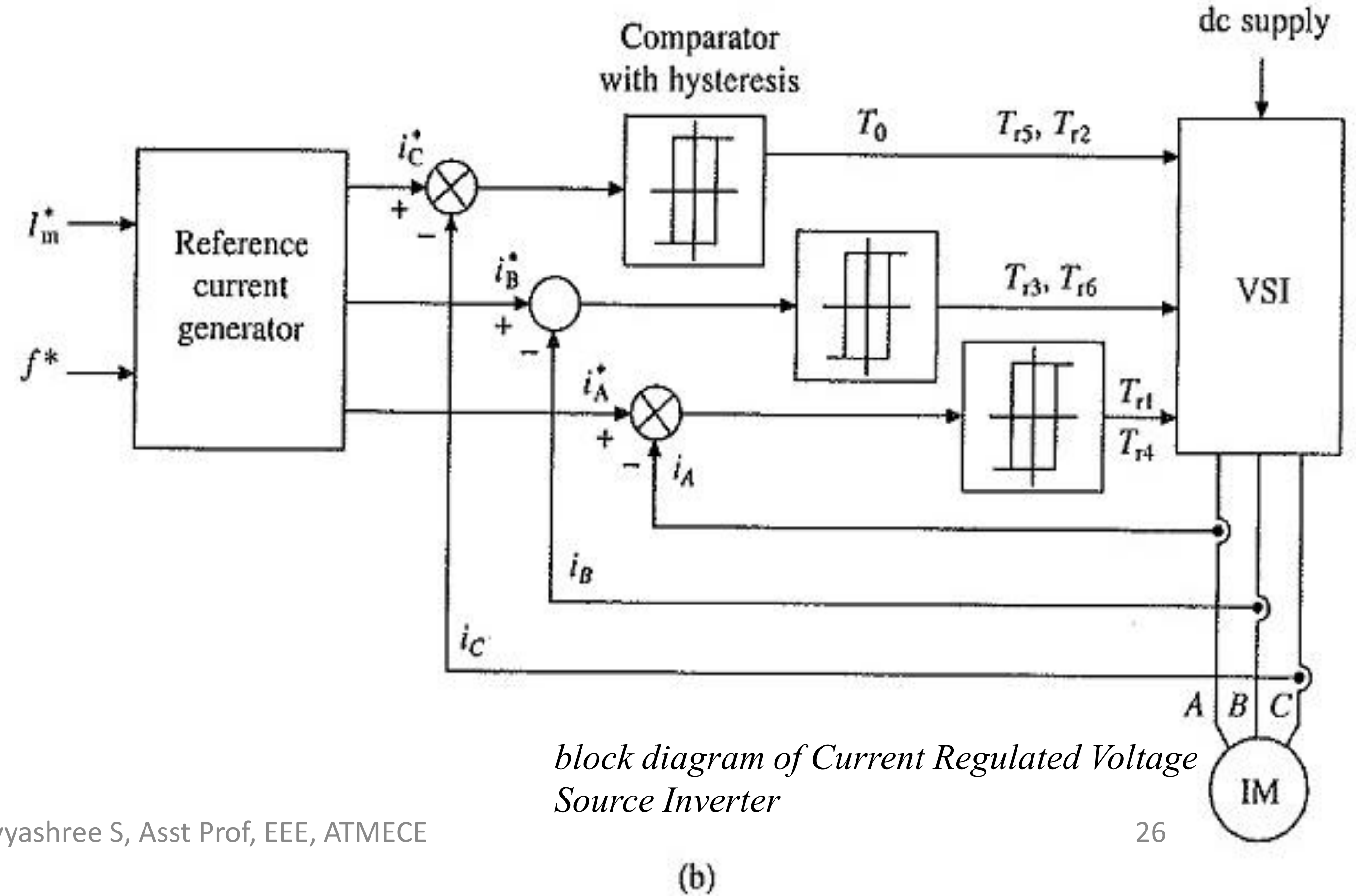
- current iA is falling along the path 'mn' when Tr4 is on.
- When iA reaches the lower band at 'n', Tr4 is turned off and Tr1 is turned on.
- This makes rate of change of IA to be **positive** and it rises along the path 'no'.

- When iA reaches the upper band at 'o' , Tr1 is turned off and Tr4 is turned on.
- This makes rate of change of iA to be **negative** and it falls along 'op'.
- This way actual current iA is constraint to remain within two hysteresis bands.

Current Regulated Voltage Source Inverter cntd.

- Reference current for phases B and C are : $i^*_B = I_m \sin(\omega t - 120°)$, $i^*_C = I_m \sin(\omega t - 240°)$ and by controlling respective transistors i_B and i_C are made to follow i^*_B and i^*_C within hysteresis bands.
- When the band is small, motor currents will be nearly sinusoidal.
- As the band reduces, harmonic content in phase currents reduces but switching frequency increases.
- Thus, inverter with fast switching devices will have lower harmonic content.

- Fig. (b) gives block diagram of Current Regulated Voltage Source Inverter.
- Based on current amplitude command I^*_m and frequency command f*, reference current generator, generates sinusoidal reference currents i^*_A, i^*_B and i^*_C.
- These reference currents are compared with respective motor currents, i_A, i_B and i_C in comparators with hysteresis to generate base drives for switches.



block diagram of Current Regulated Voltage Source Inverter

Current Regulated Voltage Source Inverter cntd.

- Since the magnitude and waveforms of motor currents are independent of changes in motor impedance and source voltage, the **inverter operates as a current source inverter.**
- The closed-loop speed control scheme of CSI drive is used for Current Regulated Voltage Source Inverter drive, is shown in Fig.c)
- A servo drive for closed-loop position control is obtained by adding a position loop around the speed loop in below Fig.

- Although Current Regulated Voltage Source Inverter operates as a CSI, it does not use large dc inductor and filter capacitors, hence it has lower weight, volume and cost and faster dynamic response.
- This drive has applications in servo control systems.

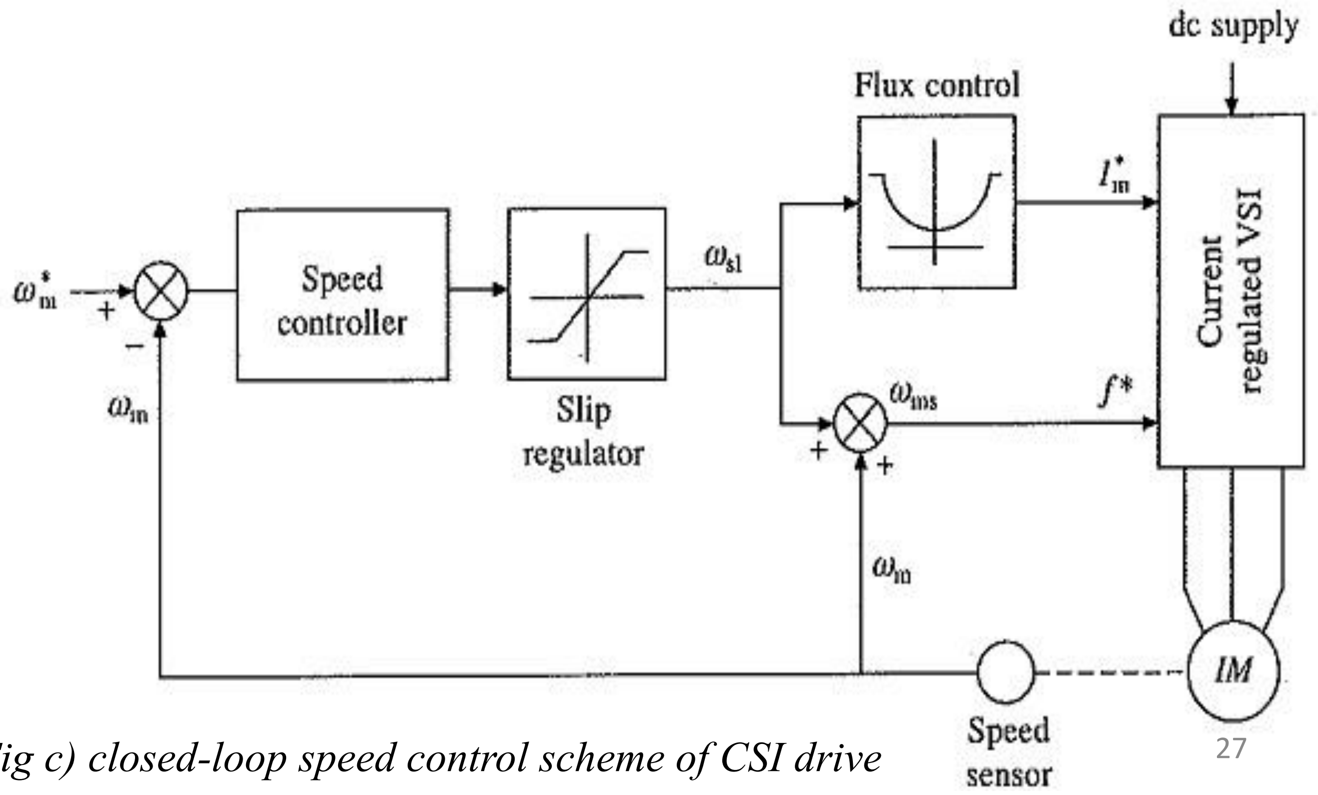
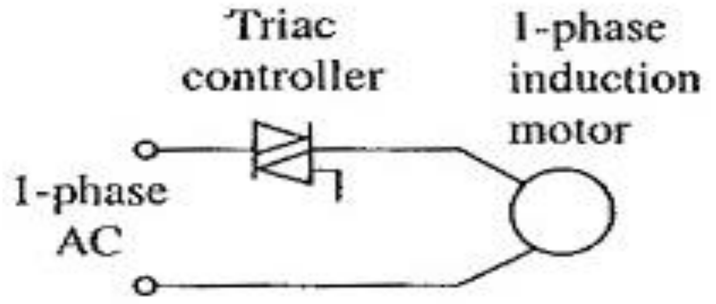


Fig c) closed-loop speed control scheme of CSI drive

ATME College of Engineering

Speed control of Single- Phase Induction Motor

- Speed of a single-phase induction motor is generally controlled by controlling its stator voltage which can be controlled by connecting a variable resistance in series with the stator. Because of poor efficiency the resistance control is now rarely used.
- Stator voltage can be controlled by the use of ac voltage controllers.

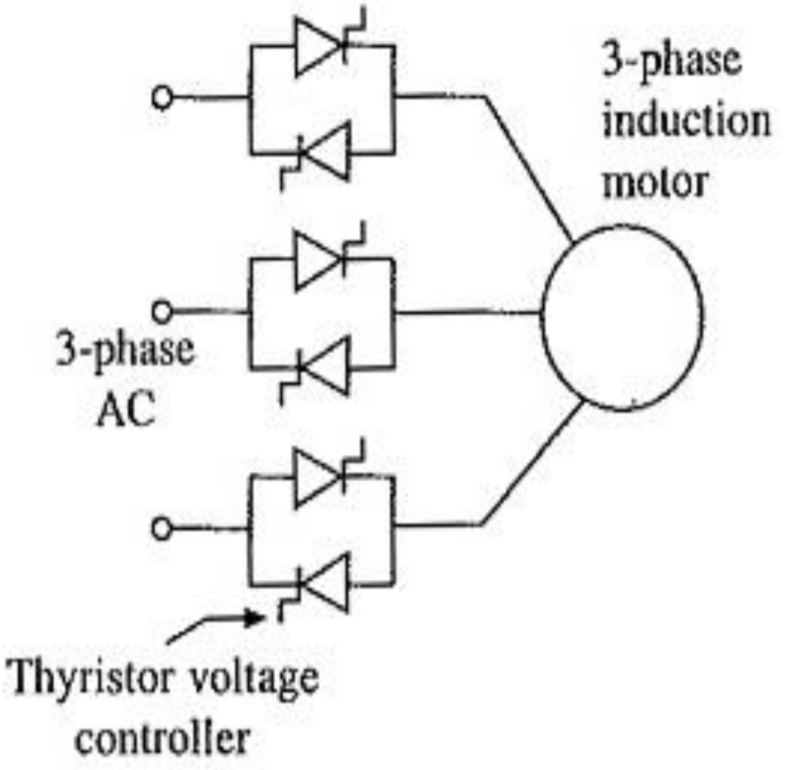


(a)

- By reducing Stator Voltage, speed of a high-slip induction motor can be reduced, suitable for the speed control of some fan and pump drives method where torque demand reduces with speed.
- Domestic fan motors, which are always single-phase, are controlled by a single-phase triac voltage controller shown in Fig. (a).
- Speed control is obtained by varying firing angle of the triac.
- These controllers, commonly known as solid state fan regulators, are now preferred over conventional variable resistance regulators because of higher efficiency.
- Industrial fans and pumps are usually driven by three-phase motors.

Speed control of Single- Phase Induction Motor cntd.

- Fig. (b) shows a commonly used thyristor voltage controller for speed control of 3-phase motors.
- Motor may be connected in star or delta.
- In delta connection, third harmonic voltage produced by motor back emf causes circulating current through the windings which increases losses and thermal loading of motor.
- Speed control is obtained by varying conduction period of thyristors.
- For low power ratings, anti-paralleled thyristor pair in each phase can be replaced by a triac.
- The speed of the motor can also be controlled by variable frequency control.
- However, it is rarely used because for most of the variable speed applications of single-phase motors, the stator voltage control is good enough.



(b)

Synchronous Motor Drives

- Operation from fixed frequency supply-starting
- Synchronous motor variable speed drives
- Variable frequency control of multiple synchronous motors

Operations from Fixed Frequency Supply

- For any speed other than synchronous speed, the relative speed between air gap flux wave and the rotor is not zero.
- δ varies from 0 to 360°, and torque fluctuates between positive and negative values, but its average value remains zero.
- Frequency of torque fluctuations depends on the relative speed between air-gap flux wave, which rotates at synchronous speed, and the rotor.
- When rotor is at stand-still, the frequency is too high for the rotor inertia to allow any change in speed. The motor is not self starting.
- If rotor is brought close to synchronous speed by some starting method and then dc field excited, the synchronous torque assisted by the damper winding torque is able to pull the rotor into step with the rotating field after a short duration of hunting, and the machine then works as a synchronous motor.
- The process of pulling rotor into step with the rotating field is called pull-in or synchronisation.

δ- angle between stator voltage and current

Starting

- The purpose of starting method is to bring rotor speed close to synchronous speed.
- One widely used method is to start the synchronous motor as an induction motor with field unexcited and damper winding serving as a squirrel-cage rotor.

Consider the following methods of starting

Method-1 : The starting torque and current can be increased and reduced respectively, by increasing the damper winding resistance. For successful pull-in, the motor speed while running as an induction motor must be close to synchronous speed. For this the damper winding resistance must be as low as possible.

Method-2 : During acceleration as an induction motor, because of large number of turns in field winding, the induced voltage in the field winding may reach several thousand volts, thus overstressing the insulation of the winding and increasing the voltage rating of the field supply converter. Here, the field circuit is closed through small discharge resistance before dc excitation is applied. So the actual potential difference between the turns is reduced to safe value.

Method-3 : DC excitation should not be applied during acceleration as an induction motor because while it produces no net motoring torque, it does produce braking torque. So, dc field should be applied only after the motor has reached close to full speed.

Starting cntd.

Method-4 : When rotor has salient pole construction, the damper winding can have conductors only over Pole arc. This leads to a dip in the speed-torque curve at half of synchronous speed.

Method-5 : When started with full supply voltage, the starting current can be 7 to 10 times of full load value. In small size motors- It leads to fluctuations in supply voltage. In case of large size motors- cause a large drop in the terminal voltage, thus reducing low starting torque further. Starting current can be reduced by employing the reduced voltage starting methods. When started at a reduced voltage, the transition to full voltage can be made before or after the pull-in. Pull-in can be achieved faster and with larger motor loads.

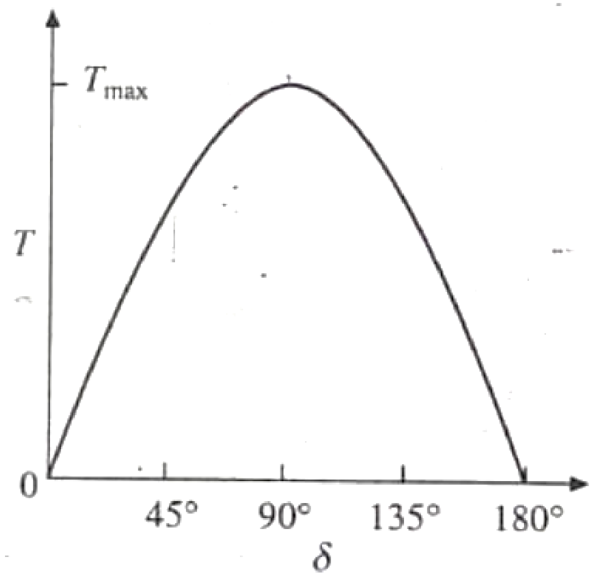
Method-6: It uses a low power auxiliary motor coupled to the synchronous motor shaft. With the help of auxiliary motor, the rotor speed is brought near, synchronous speed and then dc field is switched-in. This method has a very low starting torque.

Pull-in (Synchronism)

- Pull-in process begins when the field supply is switched-in.
- When pull-in takes place at no load or at light loads, field supply can be switched-in without regard to the value of torque angle at the instant of switching.
- This may give rise to considerable disturbance in line currents during the pull-in process, with their magnitudes going well above the rated value.
- However, this would occur without regard to polarity of the rotor poles.
- If polarity is right, the pull-in will take place with minimum disturbance.
- If wrong, the rotor may slip several poles before pull-in is completed.
- Torque is negative: for δ from 0 to 180° leading, so the synchronous torque will decelerate the rotor
- Torque is positive: for δ from 0 to 180° lagging, hence synchronous torque will accelerate the rotor.
- Rotor will be subjected to the accelerating torque of longest duration : when the field is excited at $\delta = 0$. Hence, it is the most favourable angle for exciting dc field.

Transients Due to Load Disturbance

Steady – State Stability Limit



$$T = T_{max} \sin \delta$$

$$T_{max} = \frac{3VE}{X_s \omega_{ms}}$$

Dynamic Stability

$$T = \frac{3VE'}{\omega_{ms} X'_s} \sin\delta \qquad = T'_{max} \sin\delta$$

$$T'_{max} = \frac{3VE'}{\omega_{max} X'_s}$$

Torque balance equation of the synchronous motor is [7]

$$T = T_a + T_d + T_L$$

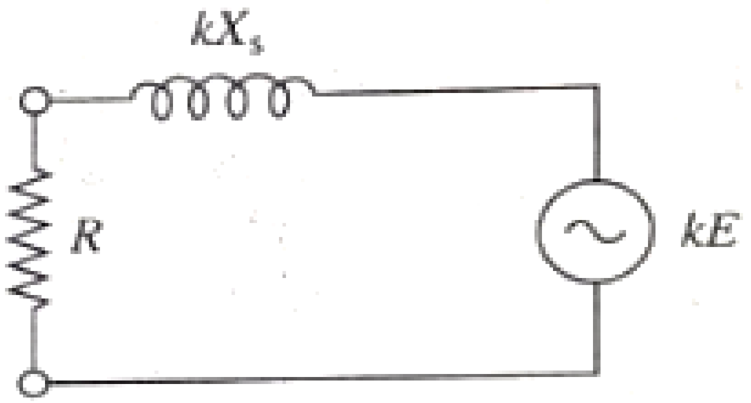
where $T_a = K_j \frac{d^2\delta}{dt^2}$ is the acceleration torque and $T_d = K_d \frac{d\delta}{dt}$ is the damping torque

$$K_j \frac{d^2\delta}{dt^2} + K_d \frac{d\delta}{dt} - T'_{max} \sin\delta + T_L = 0$$

Braking

The per unit speed k is given by

$$k = \frac{\omega_m}{\omega_{ms}}$$



Dynamic braking equivalent circuit

braking current $$I_{sb} = \frac{kE}{\sqrt{R_B^2 + (kX_s)^2}}$$

braking power $$P_B = 3I_s^2 R_B$$

braking torque $$T_B = \frac{P_B}{k\omega_{ms}}$$

$$T_B = \frac{3R_B kE^2}{\omega_{ms}(R_B^2 + k^2X_s^2)}$$

Synchronous Motor Variable Speed Drives

Variable Frequency Control

- The synchronous speed is given by, $N_s = \frac{120.f}{P}$
- From the above equation, it is clear that the speed of a synchronous motor can be controlled by varying the frequency of the supply.
- Here, the stator flux is maintained constant by keeping the (v/f) ratio constant as that of induction motors, . Constant flux operation ensures that the maximum torque at all frequencies is same.
- v/f ratio is increased at low frequencies to increase the torque producing capability of motor.
- Above rated speed, the stator voltage is kept constant and the frequency alone is increased. In this case, the torque produced by the motor may be reduced.

Modes of Variable Frequency Control

Variable frequency control may be achieved by any one of the methods listed below.

1. True synchronous mode (or) separate controlled mode.

2. Self synchronous mode (or) self controlled mode.

1) True synchronous mode (or) Separate controlled mode

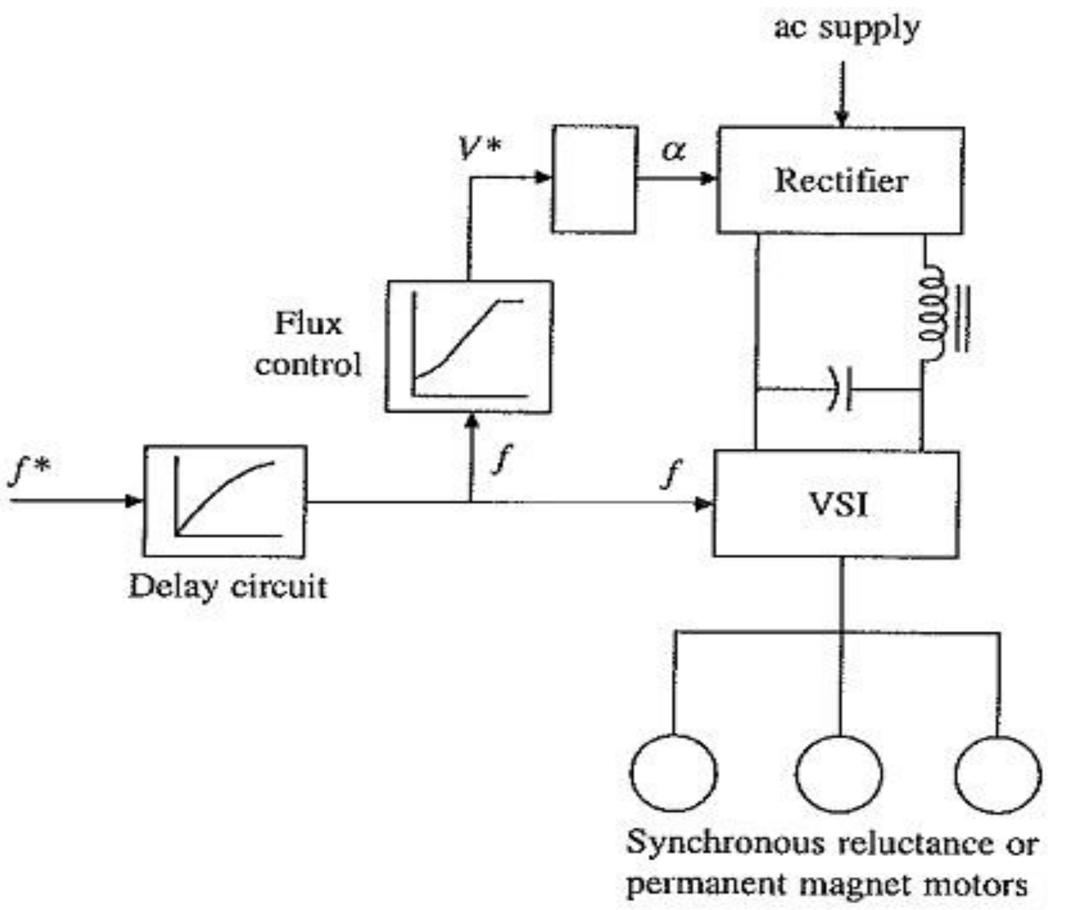
- In this mode of speed control, the stator supply frequency is controlled from outside by using a separate oscillator.
- The frequency is changed gradually so that the difference between synchronous speed and rotor speed is small during any speed change.
- This gradual change in frequency helps the rotor to follow the stator speed properly at all operating points.
- When the desired speed is reached, the rotor gets locked with the stator flux speed (rotor pulls into step) after hunting oscillations

2. Self control mode of synchronous motor drive

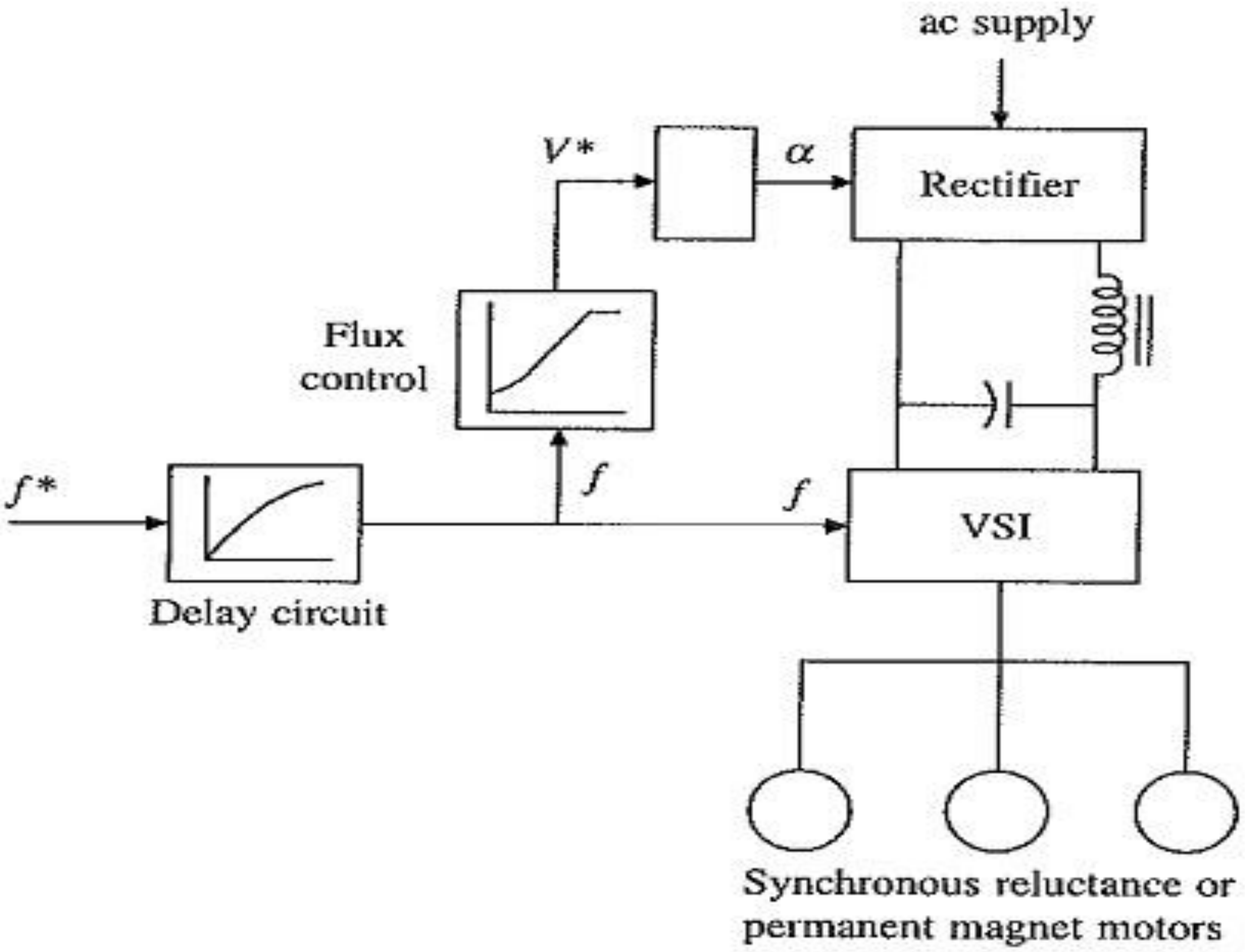
- In self control, the stator supply frequency is changed proportional to the rotor speed.
- Hence the stator rmf rotates at the same speed as the rotor speed.
- This ensures that the rotor moves in synchronism with stator at all operating points.
- Consequently a self controlled motor will never come out of synchronism or step.
- It does not suffer from hunting oscillations

Variable Frequency Control of Multiple Synchronous Motors

- A drive operating in true Variable Frequency Control of Multiple Synchronous Motors
- Frequency command f* is applied to a voltage source inverter through a delay circuit so that rotor speed is able to track the changes in frequency.
- A flux control block changes stator voltage with frequency to maintain a constant flux below rated speed and a constant terminal voltage above rated speed.
- This scheme is commonly used for the control of multiple synchronous reluctance or permanent magnet motors in fiber spinning, textile and paper mills where accurate speed.



Variable frequency control of multiple synchronous motors



Variable frequency control of multiple synchronous motors

End of Module-4

- In true synchronous mode, the stator supply frequency is controlled from an independent oscillator. Frequency from its initial to the desired value is changed gradually so that the difference between synchronous speed and rotor speed is always small.
- This allows rotor speed to track the changes in synchronous speed. When the desired synchronous speed (or frequency) is reached, the rotor pulls into step, after hunting oscillations.
- Variable Frequency Control of Multiple Synchronous Motors control not only allows the speed control, it can also be used for smooth starting and regenerative braking, as long as it is ensured that the changes in frequency are slow enough for rotor to track changes in synchronous speed.
- A motor with damper winding is used for pull-in to synchronism.
- In self-control mode, the stator supply frequency is changed so that synchronous speed is the same as rotor speed.
- This ensures that rotor runs at synchronous speed for all operating points. Consequently, rotor cannot pull-out of step and hunting oscillations are eliminated. For such applications, the motor may not require a damper winding.

- In self-control mode, the stator supply frequency is changed in proportion to the rotor speed so that the rotating field produced by the stator always moves at the same speed as the rotor (or rotor field).
- Since, the voltage induced in the stator phase has a frequency proportional to rotor speed, self-control can be realized by making the stator supply frequency to track the frequency of induced voltage.
- Alternatively sensors can be mounted on the stator to track the rotor position. These sensors are called rotor position sensors.
- The frequency of signals generated by these sensors is proportional to rotor speed. Hence, the stator supply frequency can be made to track the frequency of these signals.