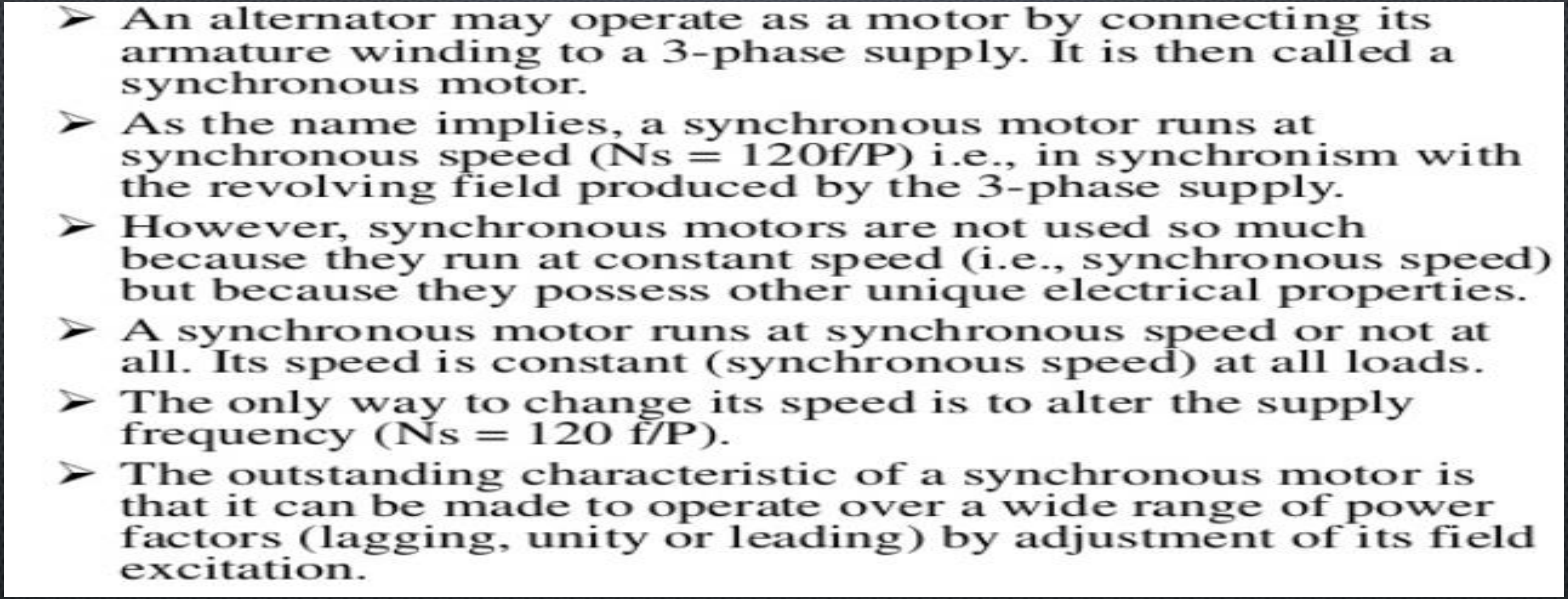
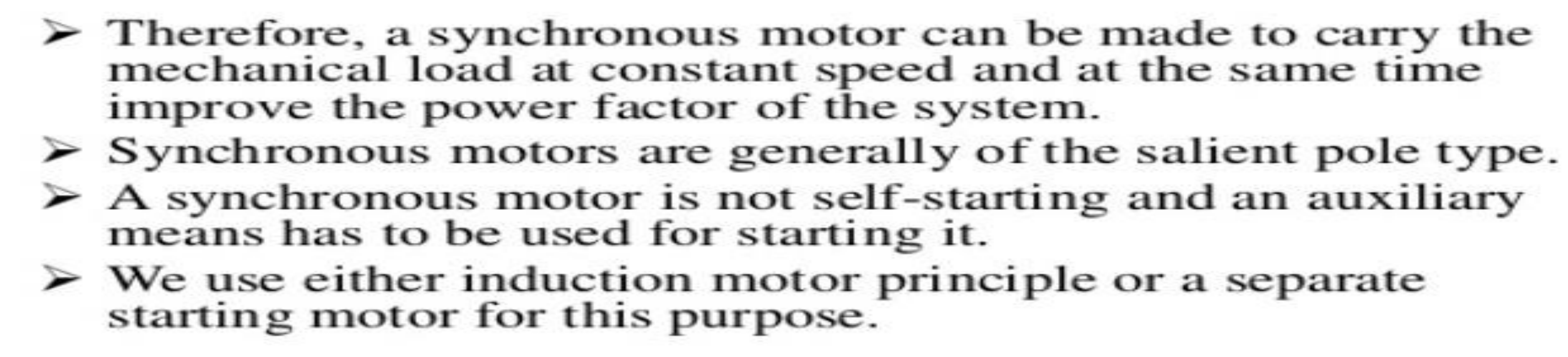
SYNCHRONOUS MOTOR

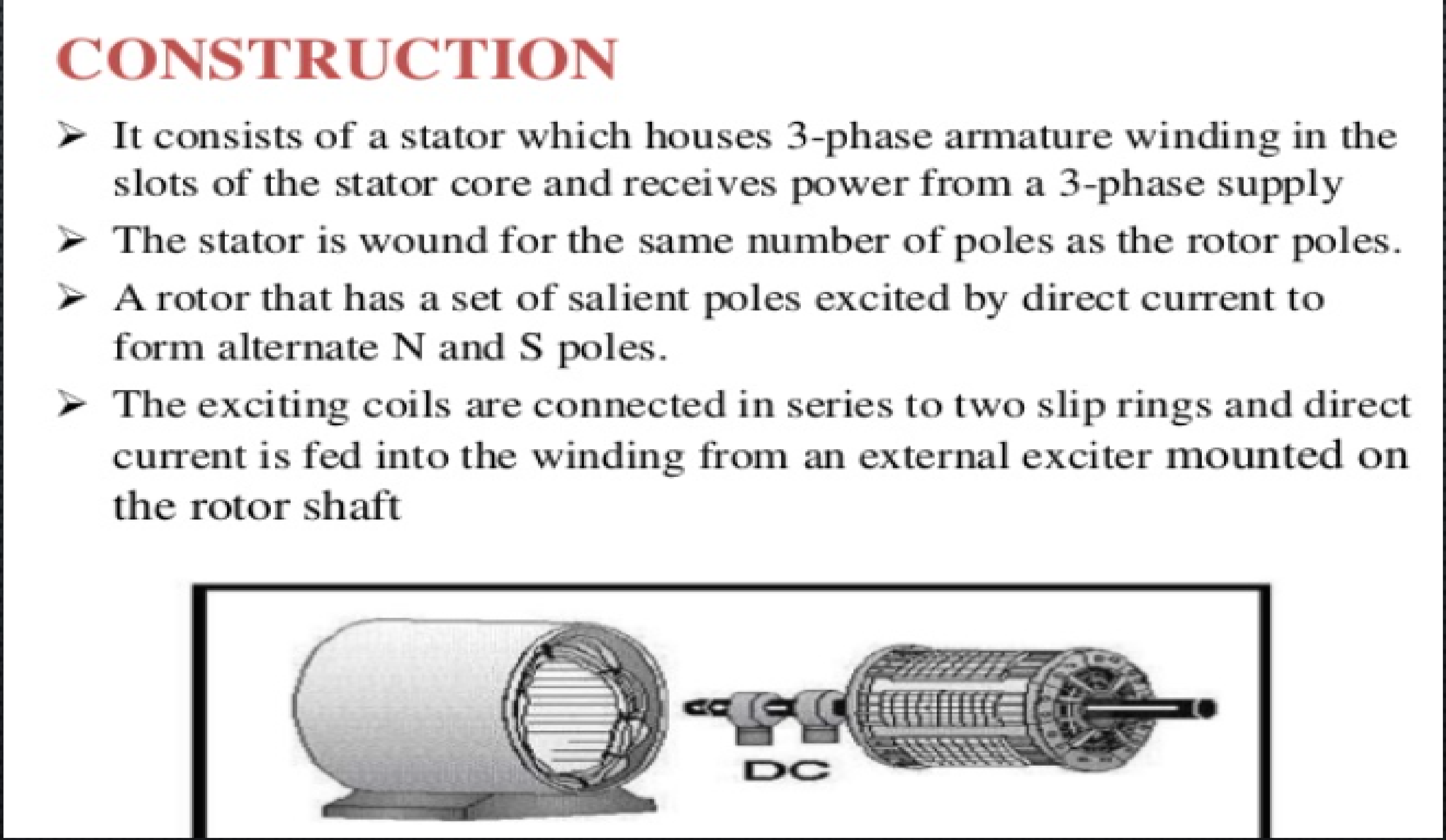


- An alternator may operate as a motor by connecting its armature winding to a 3-phase supply. It is then called a synchronous motor.
- As the name implies, a synchronous motor runs at synchronous speed (Ns = 120f/P) i.e., in synchronism with the revolving field produced by the 3-phase supply.
- However, synchronous motors are not used so much because they run at constant speed (i.e., synchronous speed) but because they possess other unique electrical properties.
- A synchronous motor runs at synchronous speed or not at all. Its speed is constant (synchronous speed) at all loads.
- The only way to change its speed is to alter the supply frequency (Ns = 120 f/P).
- The outstanding characteristic of a synchronous motor is that it can be made to operate over a wide range of power factors (lagging, unity or leading) by adjustment of its field excitation.



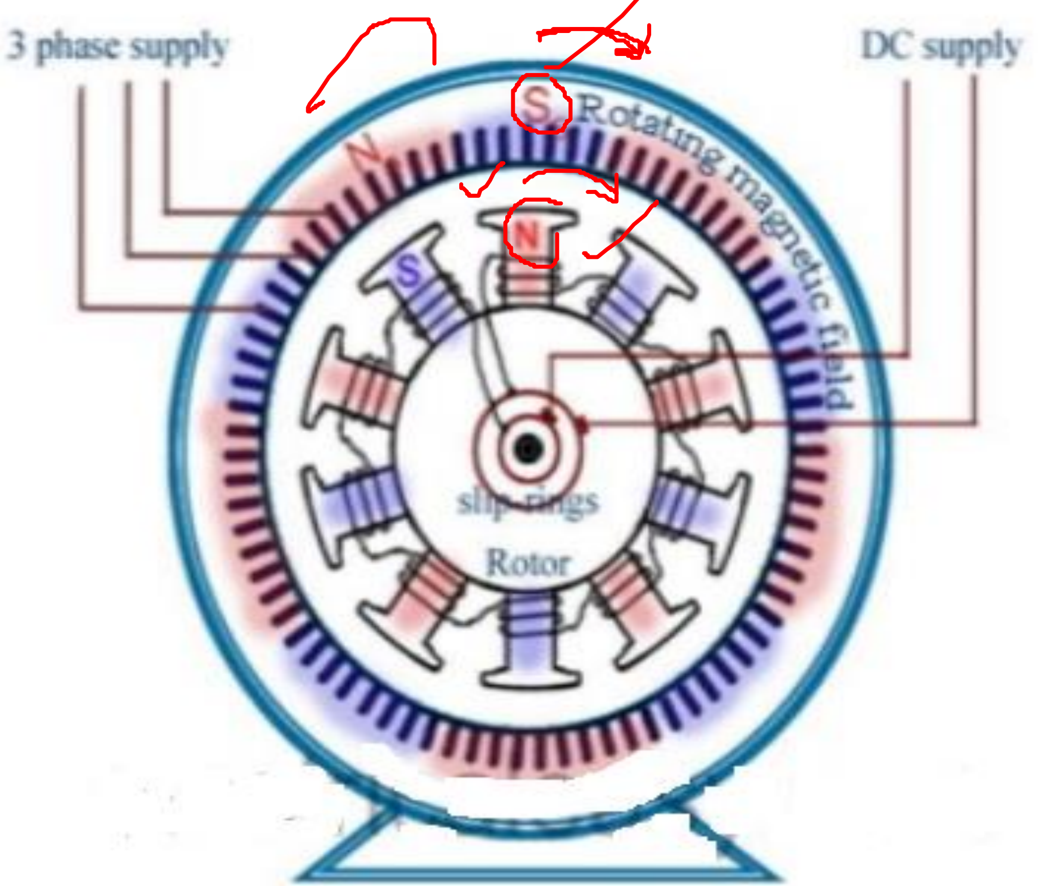
- Therefore, a synchronous motor can be made to carry the mechanical load at constant speed and at the same time improve the power factor of the system.
- Synchronous motors are generally of the salient pole type.
- A synchronous motor is not self-starting and an auxiliary means has to be used for starting it.
- We use either induction motor principle or a separate starting motor for this purpose.

CONSTRUCTION

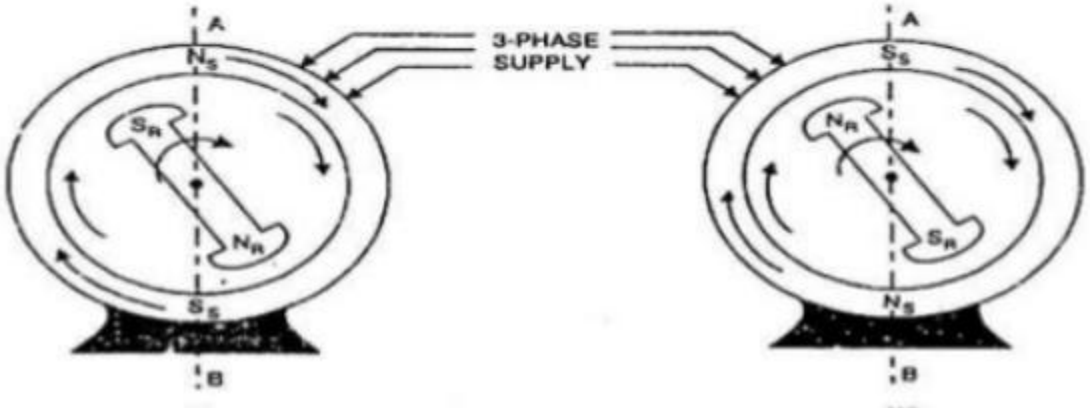


CONSTRUCTION

- It consists of a stator which houses 3-phase armature winding in the slots of the stator core and receives power from a 3-phase supply
- The stator is wound for the same number of poles as the rotor poles.
- A rotor that has a set of salient poles excited by direct current to form alternate N and S poles.
- The exciting coils are connected in series to two slip rings and direct current is fed into the winding from an external exciter mounted on the rotor shaft



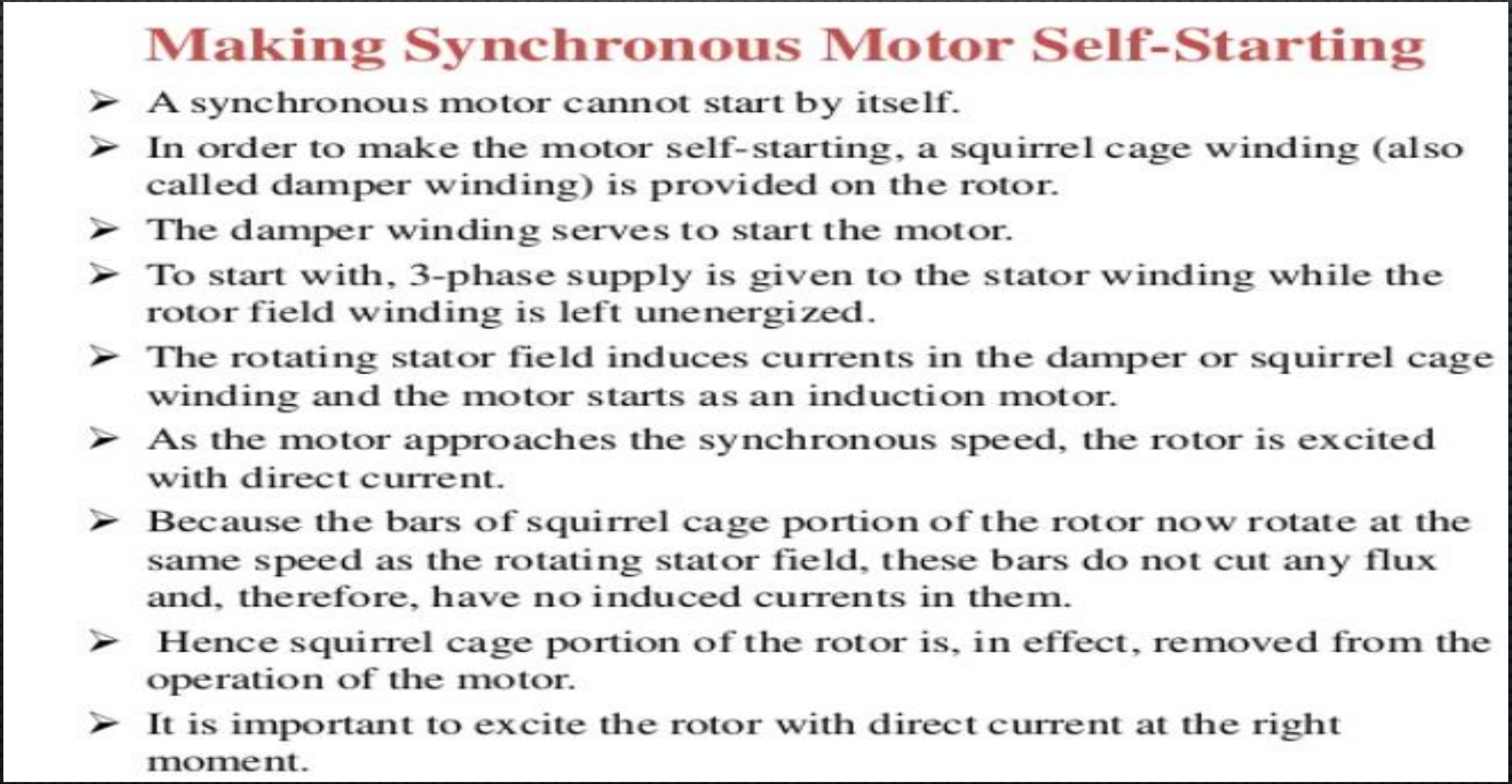
- If the rotor poles are rotated by some external means at such a speed that they interchange their positions along with the stator poles, then the rotor will experience a continuous unidirectional torque.



(i) (ii)

- If now the external prime mover driving the rotor is removed, the rotor will continue to rotate at synchronous speed in the clockwise direction because the rotor poles are magnetically locked up with the stator poles.
- This magnetic interlocking between stator and rotor poles that a synchronous motor runs at the speed of revolving flux i.e., synchronous speed.

HOW TO MAKE SYNCHRONOUS MOTOR SELF STARTING



Making Synchronous Motor Self-Starting

- A synchronous motor cannot start by itself.
- In order to make the motor self-starting, a squirrel cage winding (also called damper winding) is provided on the rotor.
- The damper winding serves to start the motor.
- To start with, 3-phase supply is given to the stator winding while the rotor field winding is left unenergized.
- The rotating stator field induces currents in the damper or squirrel cage winding and the motor starts as an induction motor.
- As the motor approaches the synchronous speed, the rotor is excited with direct current.
- Because the bars of squirrel cage portion of the rotor now rotate at the same speed as the rotating stator field, these bars do not cut any flux and, therefore, have no induced currents in them.
- Hence squirrel cage portion of the rotor is, in effect, removed from the operation of the motor.
- It is important to excite the rotor with direct current at the right moment.

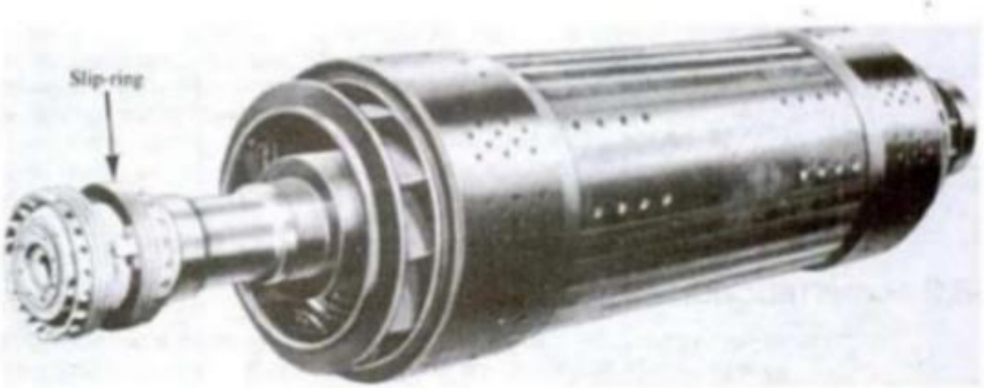
TYPES OF ROTOR

THE two types of rotor ARE:

1. CYLINDRICAL ROTOR (ROUND ROTOR)
2. SALIENT POLE ROTOR

1. CYLINDRICAL ROTOR (ROUND ROTOR)

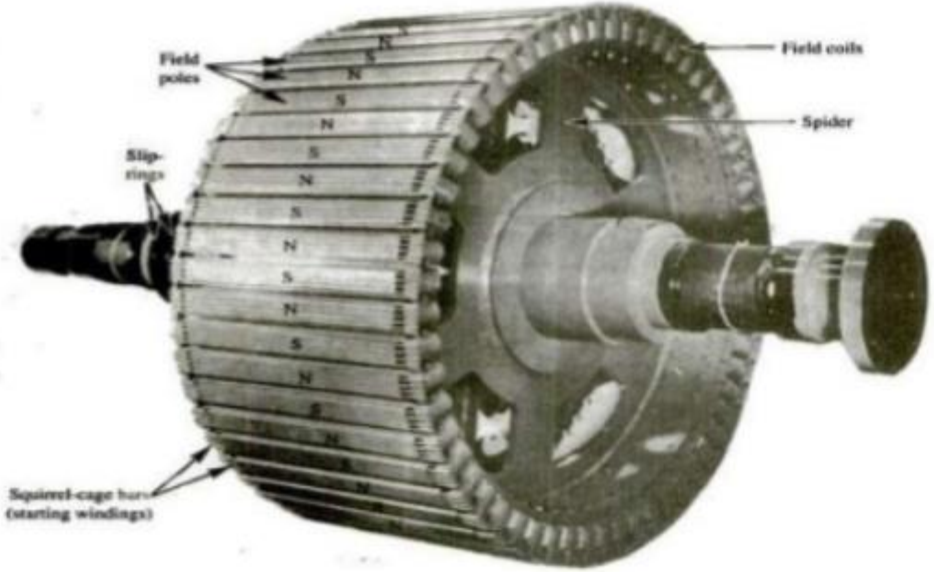
It is constructed from a solid – steel forging so as to withstand the large centrifugal stresses inherent in high – speed operation.



Cylindrical rotors cannot accelerate high – inertia loads. They are limited in application to pumps, fans, blowers, and other loads with similar low starting – torque requirements.

1. SALIENT POLE ROTOR

This type of rotor is built for use with high – inertia low – speed loads have many poles projecting radially outward from a steel spider, as shown in the figure.

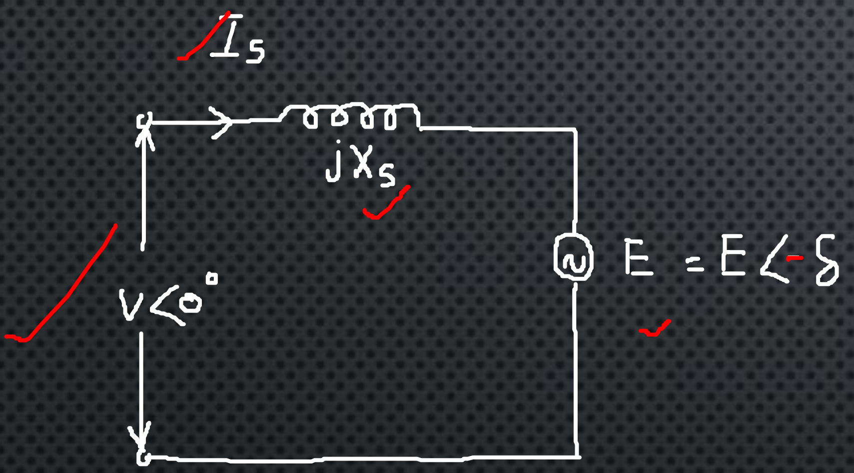


These salient poles are bolted or keyed to the spider, and the spider is keyed to the shaft.

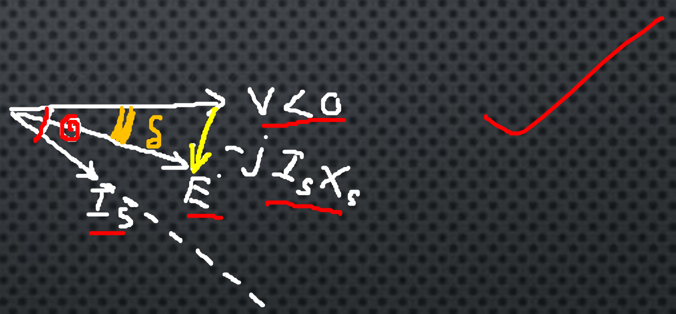
CYLINDRICAL ROTOR WOUND FIELD SYNCHRONOUS MOTOR

Equivalent Circuit

R_s



Phasor Diagram



$$\bar{V} = jI_sX_s + \bar{E} \quad - ①$$

$$\bar{E} = \bar{V} - jI_s \cdot X_s \quad - ②$$

$$\boxed{\bar{I}_s} = \frac{\bar{V} - \bar{E}}{j \cdot X_s} = \frac{V\angle 0 - E\angle -\delta}{X_s\angle 90} = \frac{V}{X_s}\angle -\pi/2 - \frac{E}{X_s}\angle -(\delta + \pi/2)$$

$$I_s\cos\theta = \mathrm{Real}(\bar{I}_s) = \underbrace{\frac{V}{X_s}\cos(\pi/2)}_{0} - \frac{E}{X_s} \cdot \cos(\delta + \pi/2) = \frac{E}{X_s} \cdot \sin\delta$$

$$\boxed{P_m = 3V_sI_s\cos\theta = \frac{3VE\sin\delta}{X_s}}$$

SPEED TORQUE CHARACTERISTIC

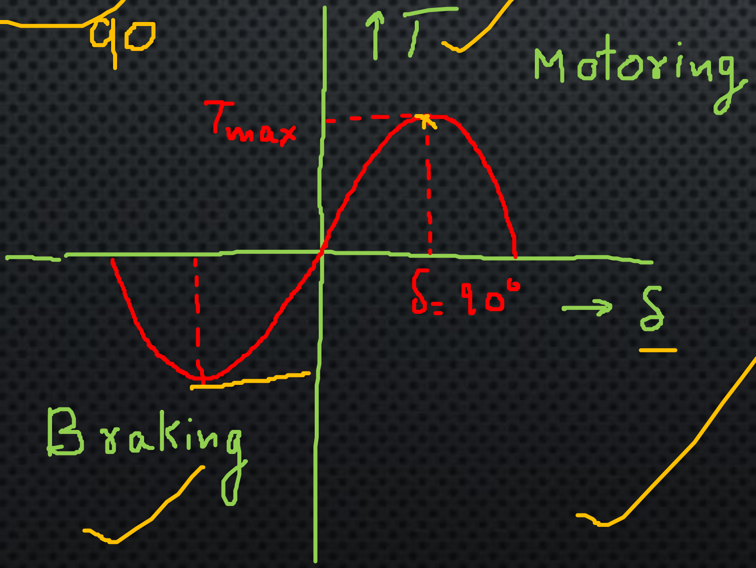
$$P_m = \frac{3 V \cdot E \sin\delta}{X_s} = \underline{T \cdot \omega_s}$$

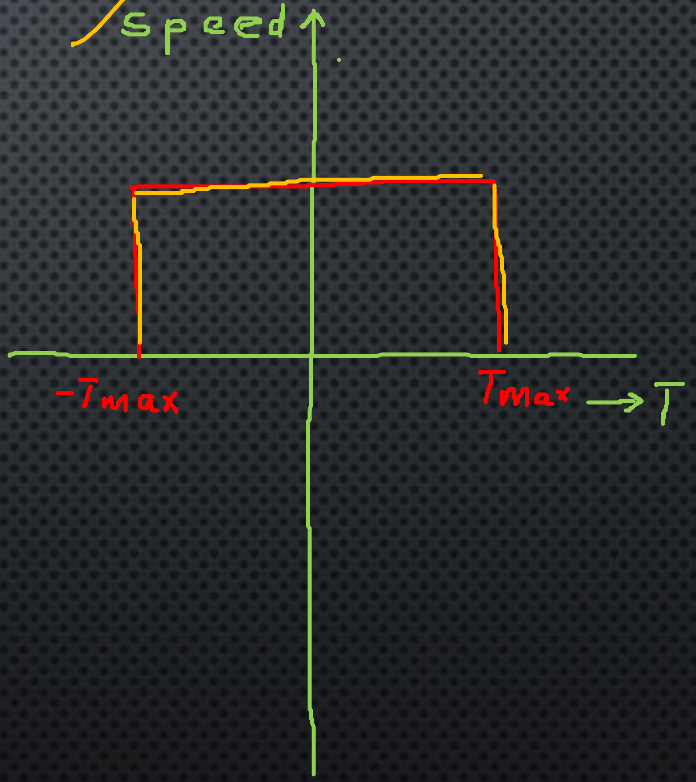
$$T = \frac{P_m}{\omega_s} = \boxed{\frac{3 \cdot V \cdot E \cdot \sin\delta}{X_s \cdot \omega_s}}$$

$$\boxed{T \propto \sin\delta}$$

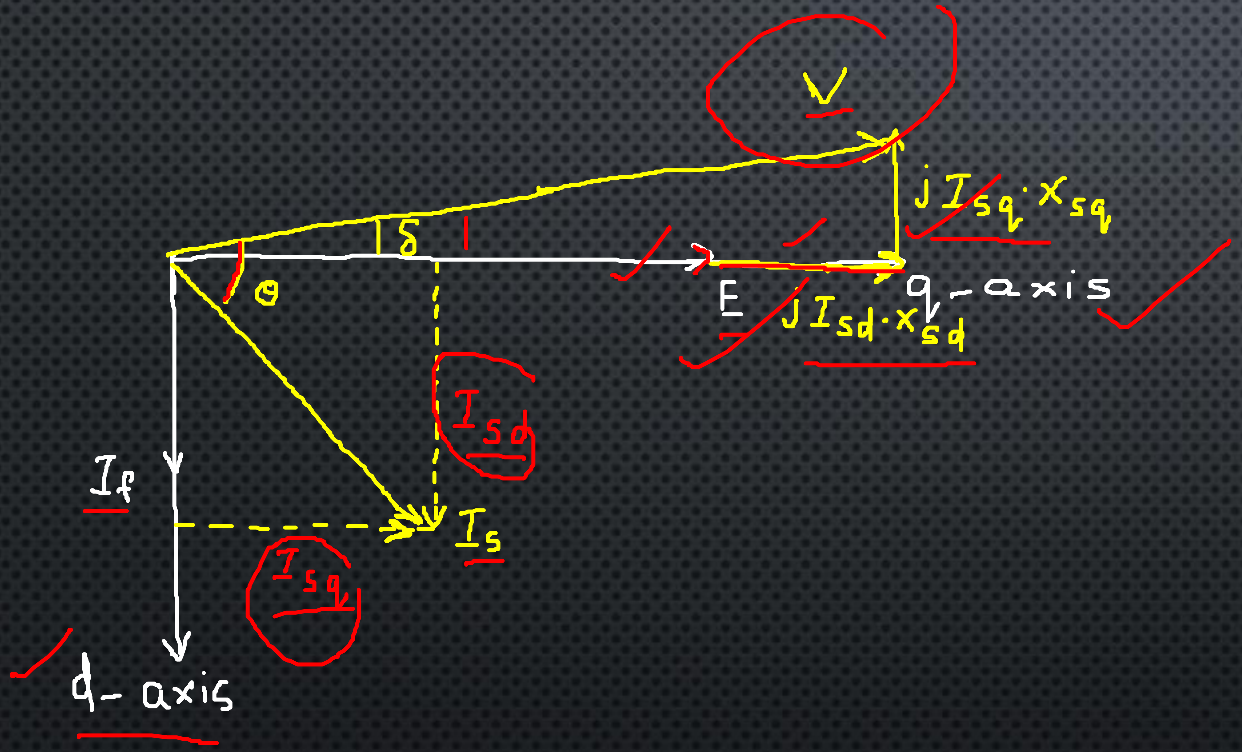
$$\downarrow$$

$$90$$





SALIENT POLE WOUND FIELD INDUCTION MOTOR



$$\bar{V} = \bar{E} + j \cdot I_{sd} X_{sd} + j I_{sq} \cdot X_{sq}$$

$$I_s \cdot \cos\theta = I_{sq} \cdot \cos\delta - I_{sd} \cdot \sin\delta \quad — ①$$

$$\cos\delta = \frac{E + I_{sd} \cdot X_{sd}}{V}$$

$$I_{sd} = \frac{V\cos\delta - E}{X_{sd}} \quad — ②$$

$$\sin\delta = \frac{I_{sq} X_{sq}}{V}$$

$$I_{sq} = \frac{V \cdot \sin\delta}{X_{sq}} \quad — ③$$

Substitute ② and ③ in ①

$$I_s \cdot \cos\theta = \frac{V \sin\delta \cos\delta}{X_{sq}} - \frac{(V\cos\delta - E) \cdot \sin\delta}{X_{sd}}$$

$$I_s \cdot \cos\phi = \frac{V \cdot \sin 2\delta}{2X_{sq}} - \frac{V \sin 2\delta}{2X_{sd}} + \frac{E \sin\delta}{X_{sd}}$$

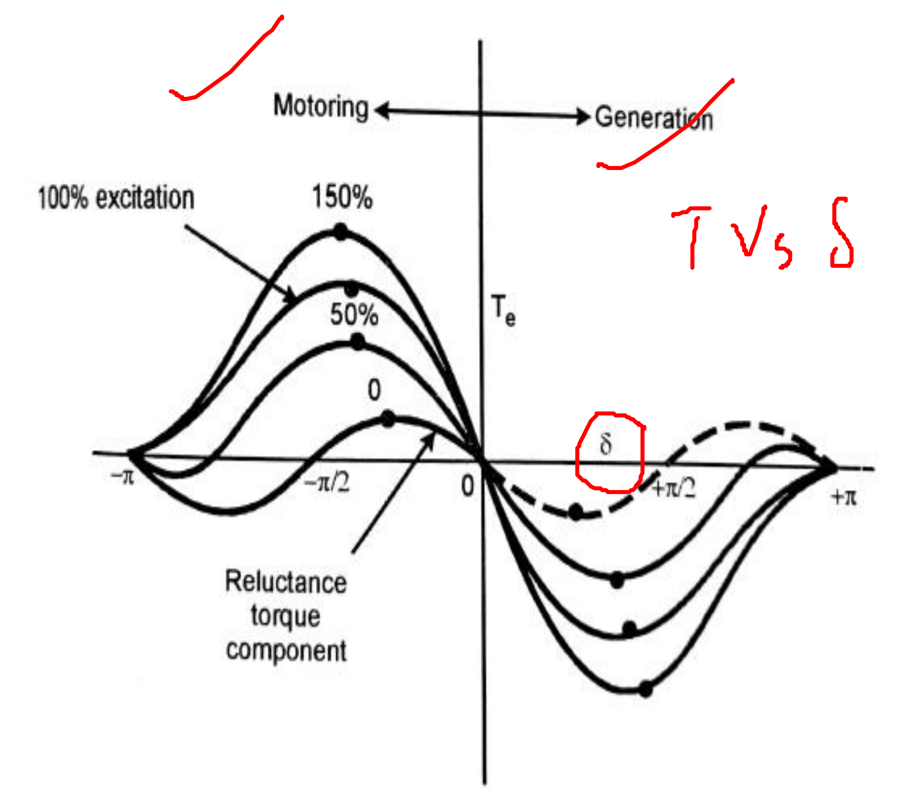
$$P = 3VI_s\cos\phi = 3\left[\frac{VE\sin\delta}{X_{sd}} + \frac{V^2 \sin 2\delta (X_{sd} - X_{sq})}{2 \cdot X_{sd} \cdot X_{sq}}\right]$$

$$P = T \cdot \omega$$

$$T = \frac{P}{\omega} = \frac{3}{\omega_s}\left[\frac{VE\sin\delta}{X_{sd}} + \underbrace{\frac{V^2 \sin 2\delta (X_{sd} - X_{sq})}{2 \cdot X_{sd} \cdot X_{sq}}}_{\text{Reluctance Torque}}\right]$$

$I_f = 0$

$E = 0$



T Vs δ

VARIABLE SPEED SYNCHRONOUS MOTOR DRIVE

- True synchronous mode
- Self controlled mode

SYNCHRONOUS MOTOR VARIABLE SPEED DRIVES

VARIABLE FREQUENCY CONTROL

$\phi = \frac{V}{f}$

- For a given frequency, a synchronous motor runs at a fixed speed equal to synchronous speed.
- Its speed can be controlled by the control of its supply frequency
- Constant flux operation below base speed is achieved by operating the motor with a constant V/f ratio. This gives a constant pull out torque for all types of synchronous motors.
- Rated voltage is reached at base speed. ✓
- For higher speeds the machine is operated at a rated terminal voltage and variable frequency and the torque decreases with increase in frequency

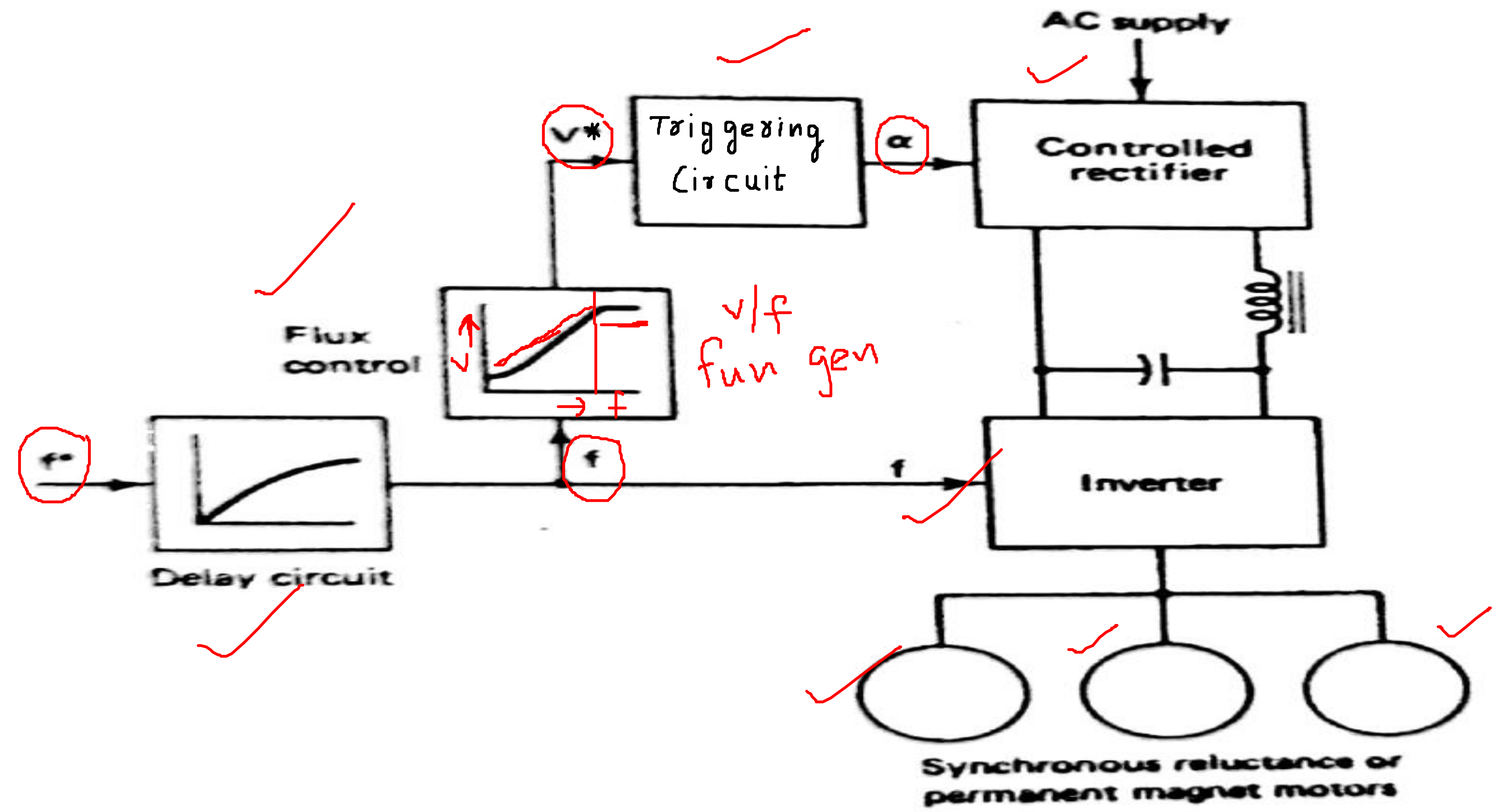
MODES OF VARIABLE FREQUENCY CONTROL

- TRUE SYNCHRONOUS MODE
- SELF CONTROL MODE

TRUE SYNCHRONOUS MODE

- THE SUPPLY FREQUENCY IS CONTROLLED FROM AN INDEPENDENT OSCILLATOR
- FOR A GIVEN FREQUENCY SETTING THE MACHINE RUNS AT A FIXED SPEED INDEPENDENT OF VARIATIONS IN LOAD, SUPPLY VOLTAGE AND FIELD CURRENT.
- THE SPEED CAN BE CONTROLLED PRECISELY IN OPEN LOOP BY PRECISELY CONTROLLING THE FREQUENCY.
- FREQUENCY FROM ITS INITIAL TO THE DESIRED VALUE IS CHANGED GRADUALLY SO THAT THE DIFFERENCE BETWEEN SYNCHRONOUS SPEED AND ROTOR SPEED IS VERY SMALL.
- THIS ALLOWS THE ROTOR SPEED TO TRACK THE CHANGES IN SYNCHRONOUS SPEED.
- WHEN THE DESIRED SYNCHRONOUS SPEED IS REACHED, THE ROTOR PULLS INTO STEP AFTER HUNTING OSCILLATIONS.
- A MOTOR WITH DAMPER WINDING IS USED FOR PULL INTO SYNCHRONISM.
- THE FREQUENCY MUST BE CHANGED GRADUALLY TO ALLOW THE ROTOR TO TRACK THE CHANGES IN THE REVOLVING FIELD SPEED OTHERWISE THE ROTOR MAY PULL OUT OF STEP.

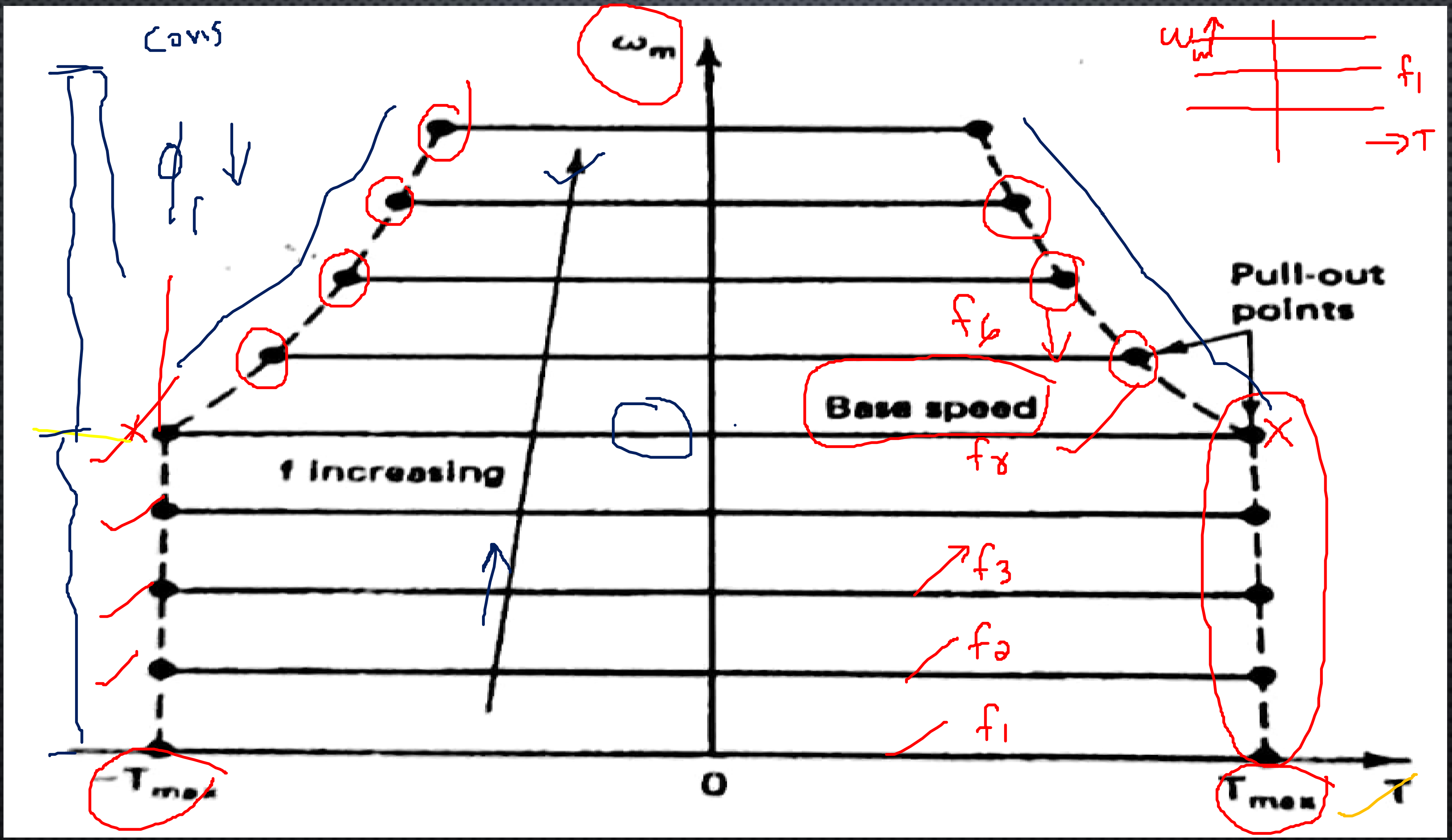
VARIABLE FREQUENCY CONTROL OF MULTIPLE SYNCHRONOUS MOTORS



EXPLANATION

- The frequency command f* is applied to the inverter through a delay circuit to ensure that the change in inverter frequency is slow enough for the motor speed to track the revolving field speed.
- A flux controller changes the machine terminal voltage with frequency to maintain a constant flux below the base speed and a constant terminal voltage above base speed for all motors.
- Since all motors are connected in parallel to a common inverter, their speeds are uniquely related to the command frequency.
- 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 tracking between the motors is required

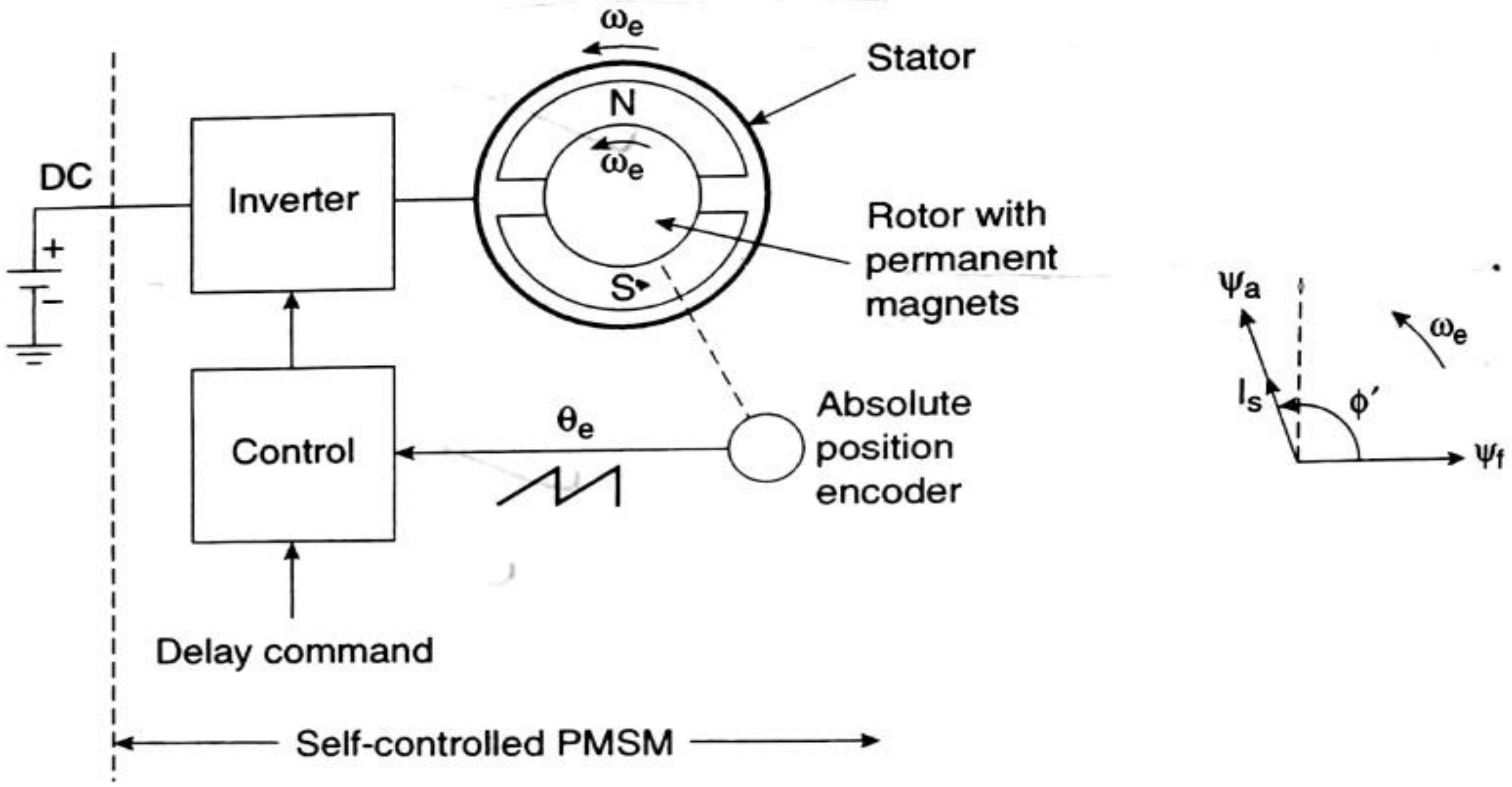
SPEED TORQUE CURVES OF A SYNCHRONOUS MOTOR WITH VARIABLE FREQUENCY CONTROL



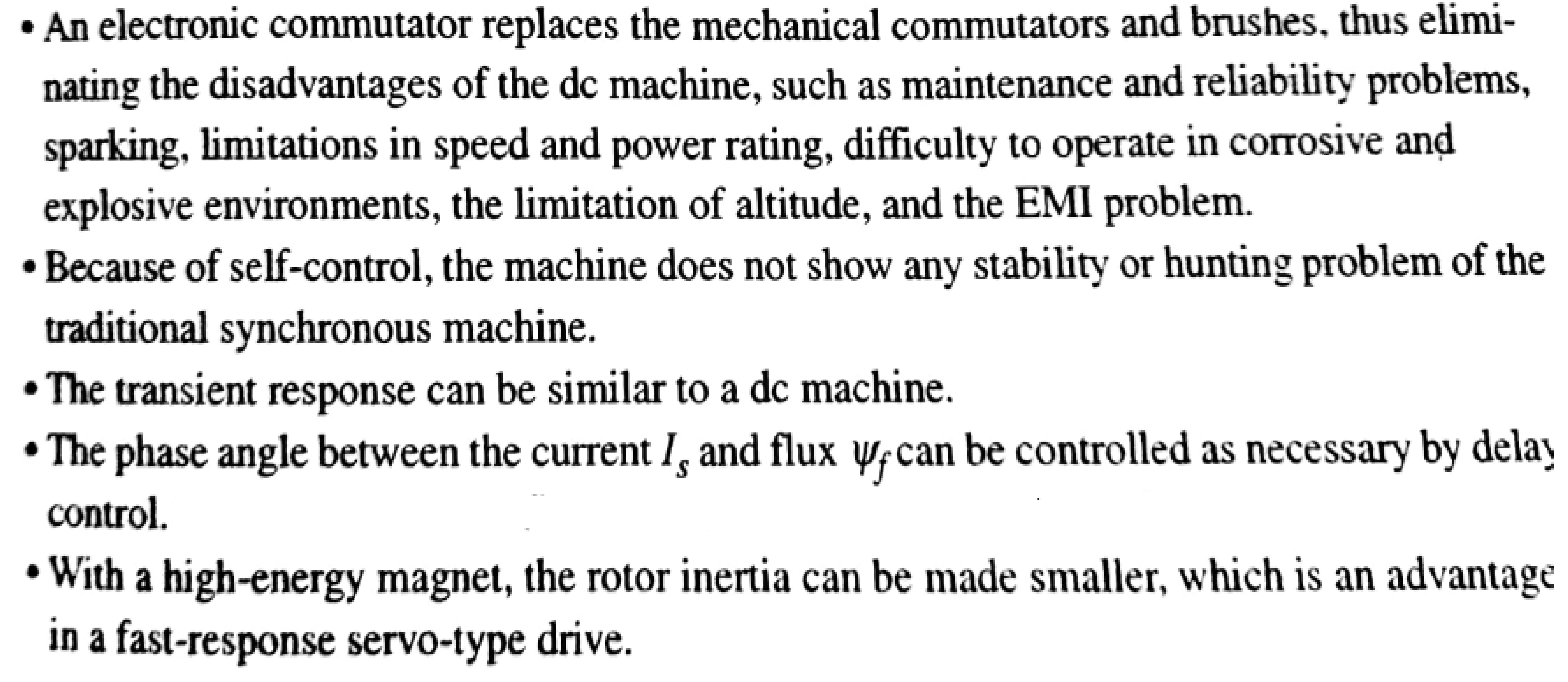
V/F curve

SYNCHRONOUS MOTOR VARIABLE SPEED DRIVES

SELF CONTROLLED SYNCHRONOUS MOTOR

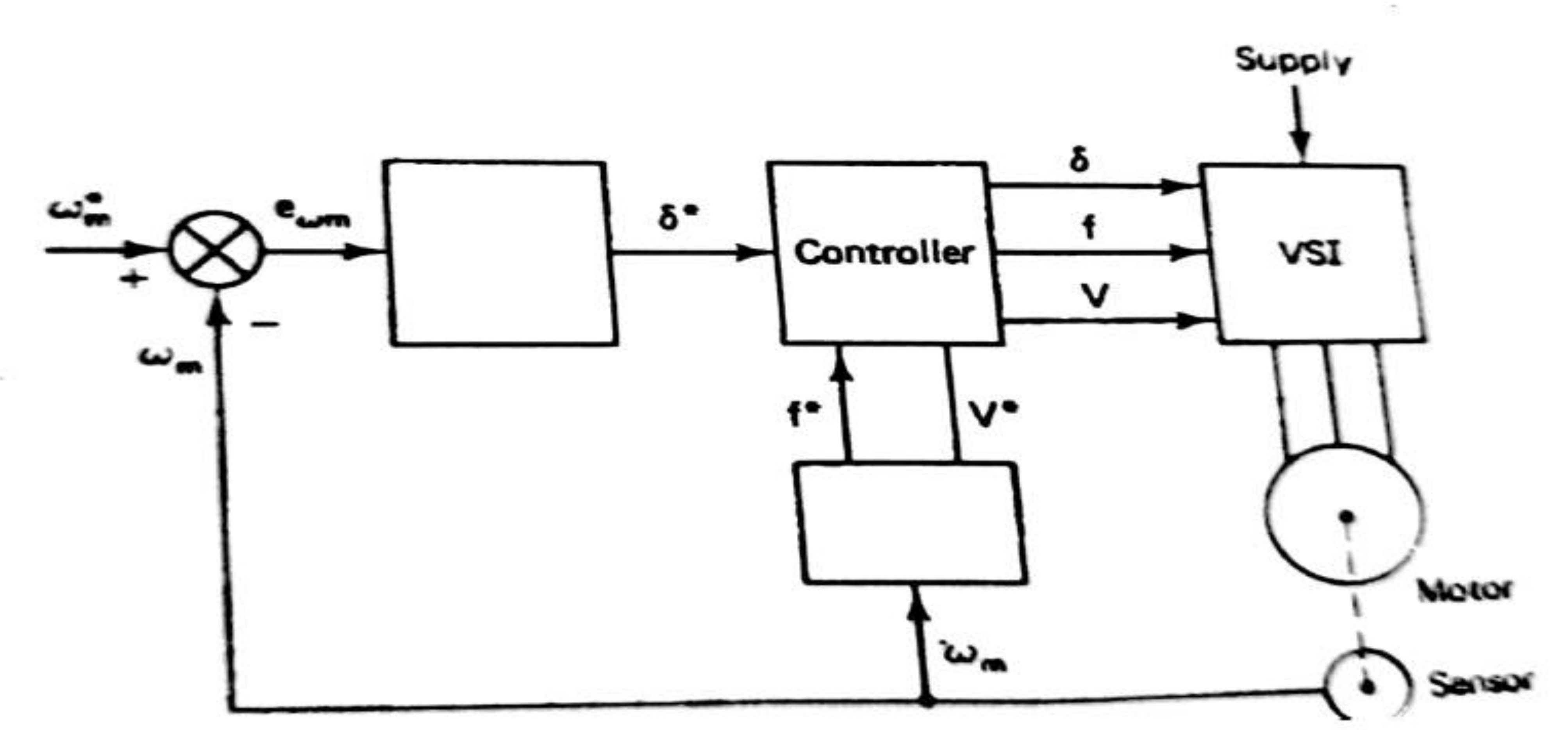


FEATURES OF SELF CONTROLLED SYNCHRONOUS MACHINES

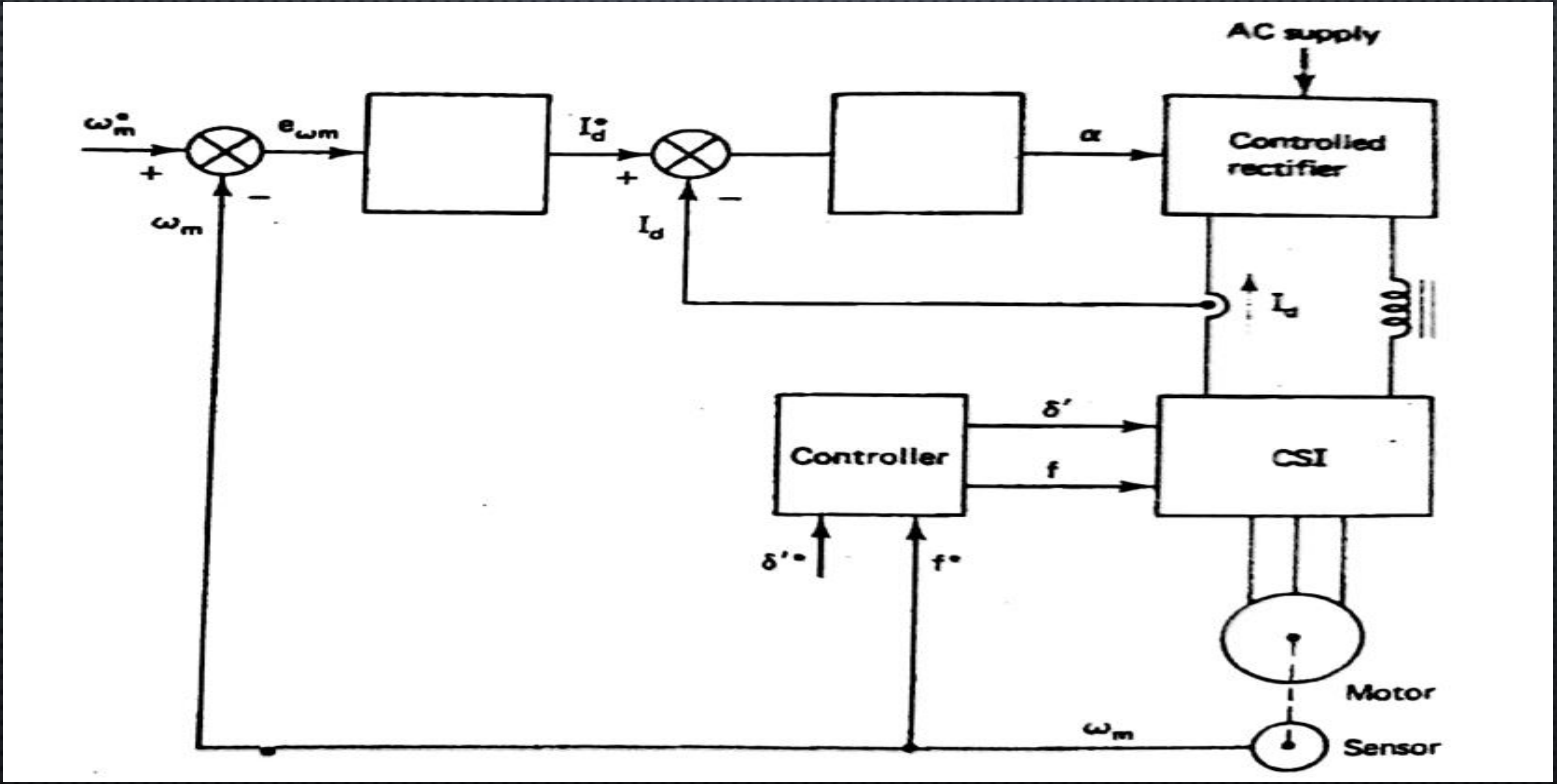


- An electronic commutator replaces the mechanical commutators and brushes, thus eliminating the disadvantages of the dc machine, such as maintenance and reliability problems, sparking, limitations in speed and power rating, difficulty to operate in corrosive and explosive environments, the limitation of altitude, and the EMI problem.
- Because of self-control, the machine does not show any stability or hunting problem of the traditional synchronous machine.
- The transient response can be similar to a dc machine.
- The phase angle between the current I_s and flux ψ_f can be controlled as necessary by delay control.
- With a high-energy magnet, the rotor inertia can be made smaller, which is an advantage in a fast-response servo-type drive.

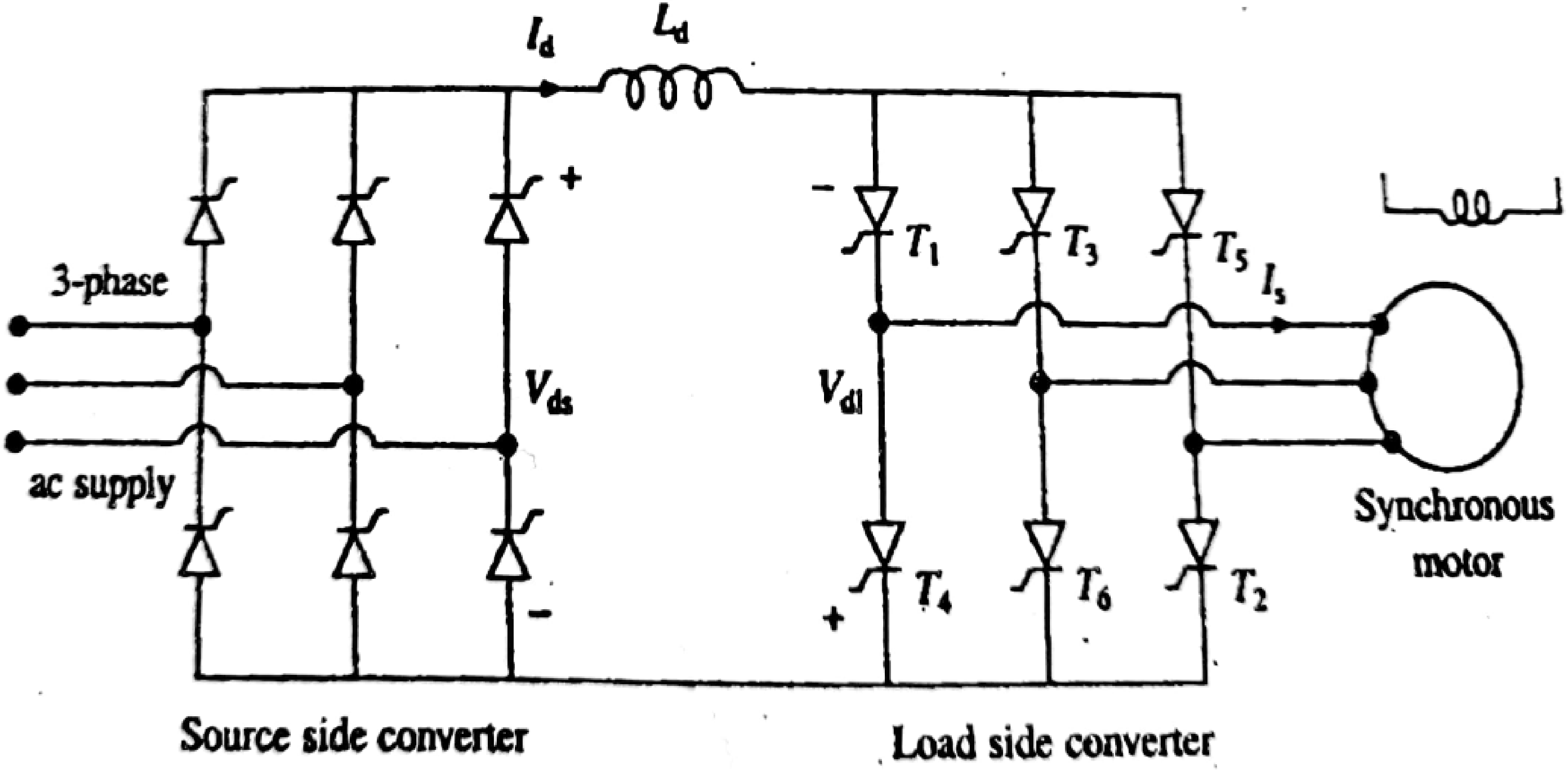
VSI DRIVEN SYNCHRONOUS MOTOR DRIVE



CSI DRIVEN SYNCHRONOUS MOTOR DRIVE

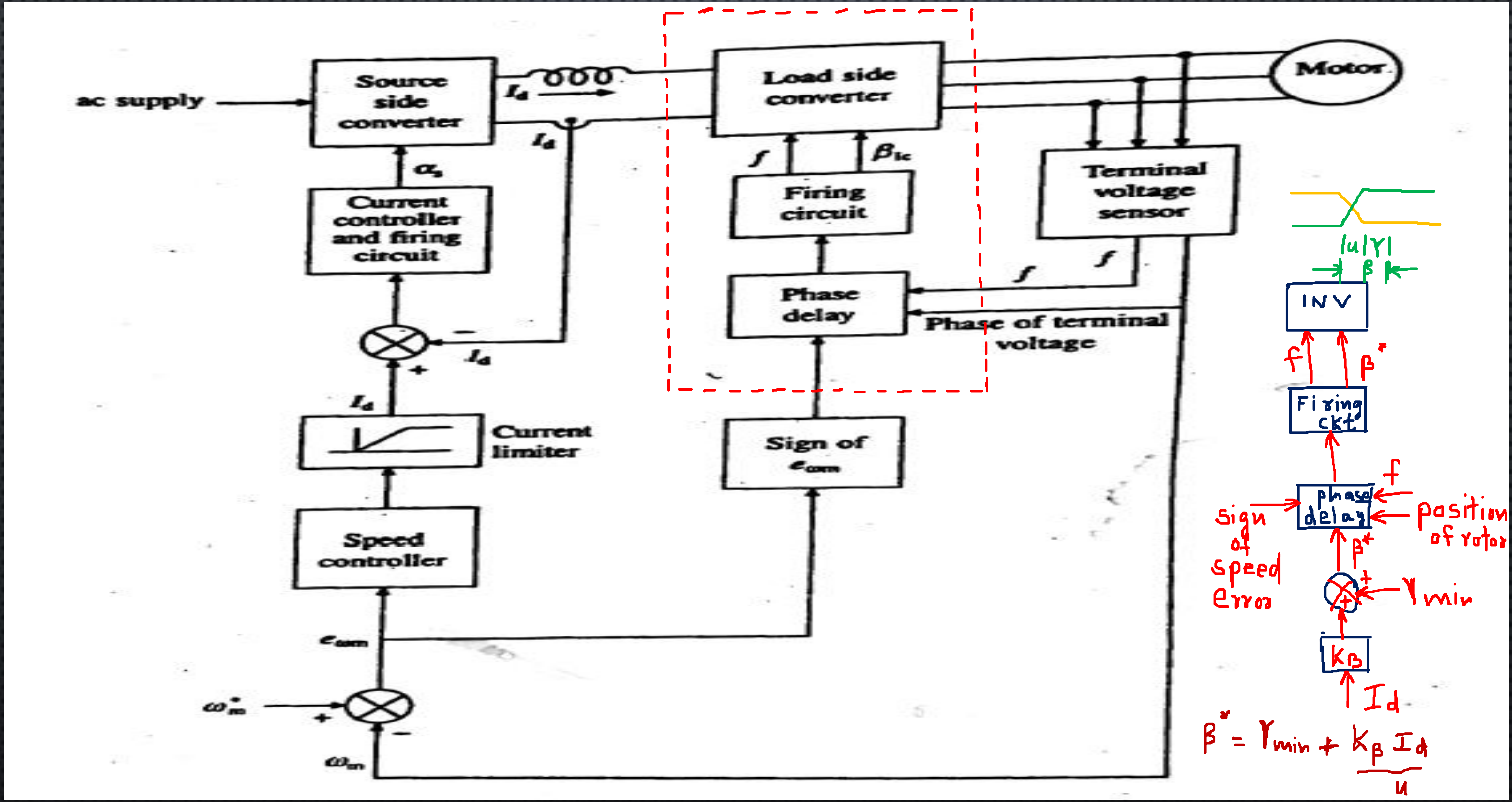


SELF CONTROLLED SYNCHRONOUS MOTOR DRIVE USING LOAD COMMUTATED INVERTER



Self-controlled synchronous motor drive employing load commutated inverter

CLOSED LOOP SPEED CONTROL OF LOAD COMMUTATED INVERTER SYNCHRONOUS MOTOR DRIVE

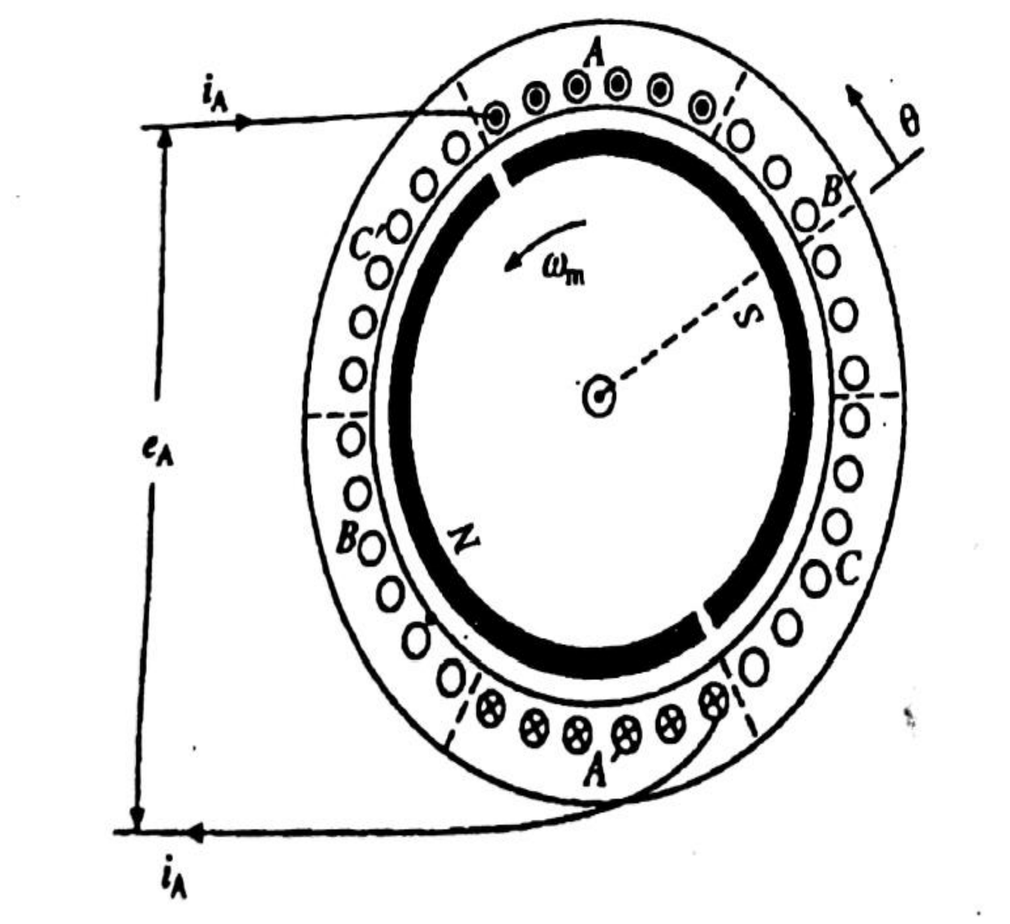


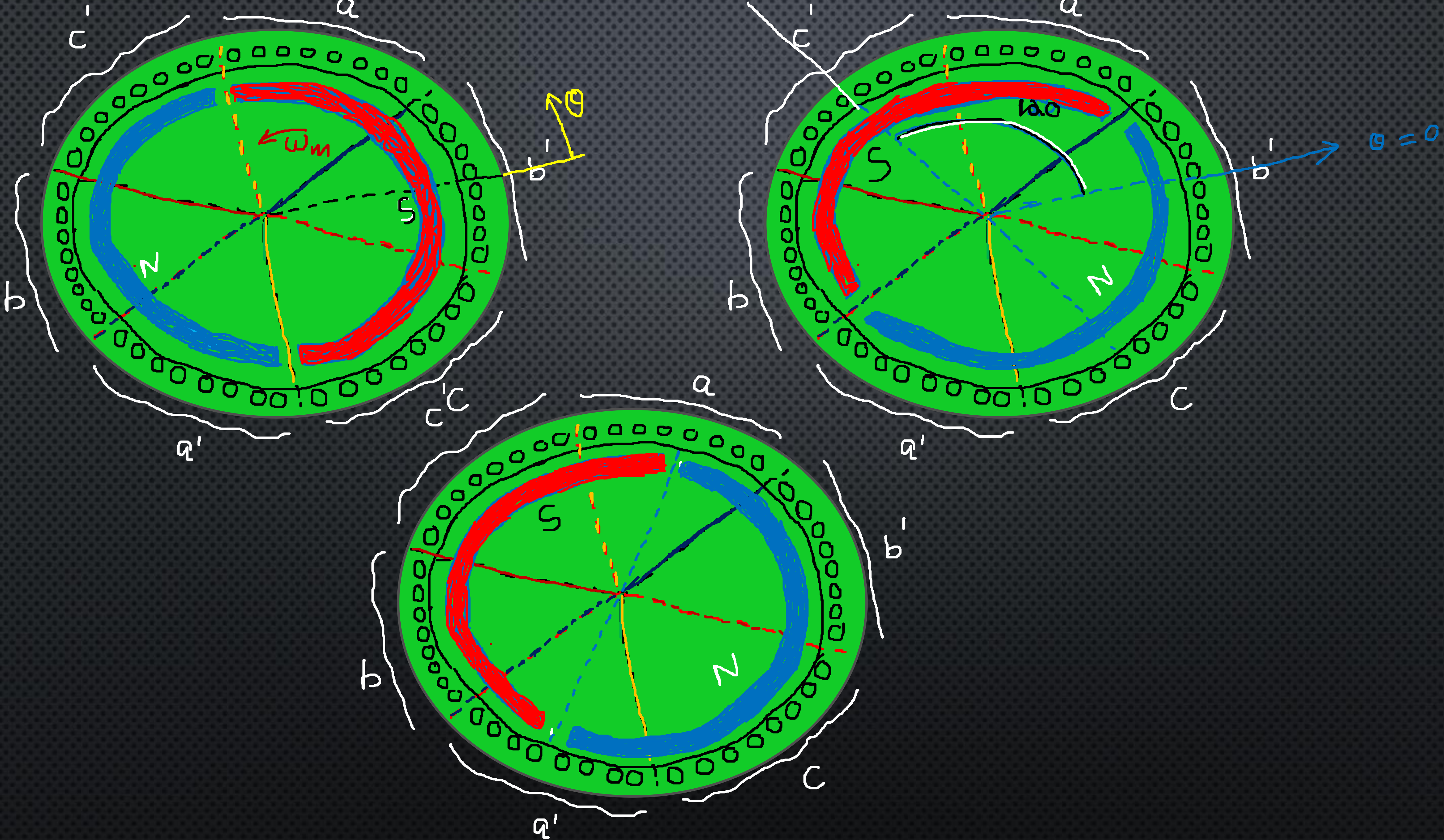
$$\beta^* = \gamma_{min} + \underbrace{K_\beta I_d}_{u}$$

TYPES OF PERMANENT MAGNET SYNCHRONOUS MOTORS

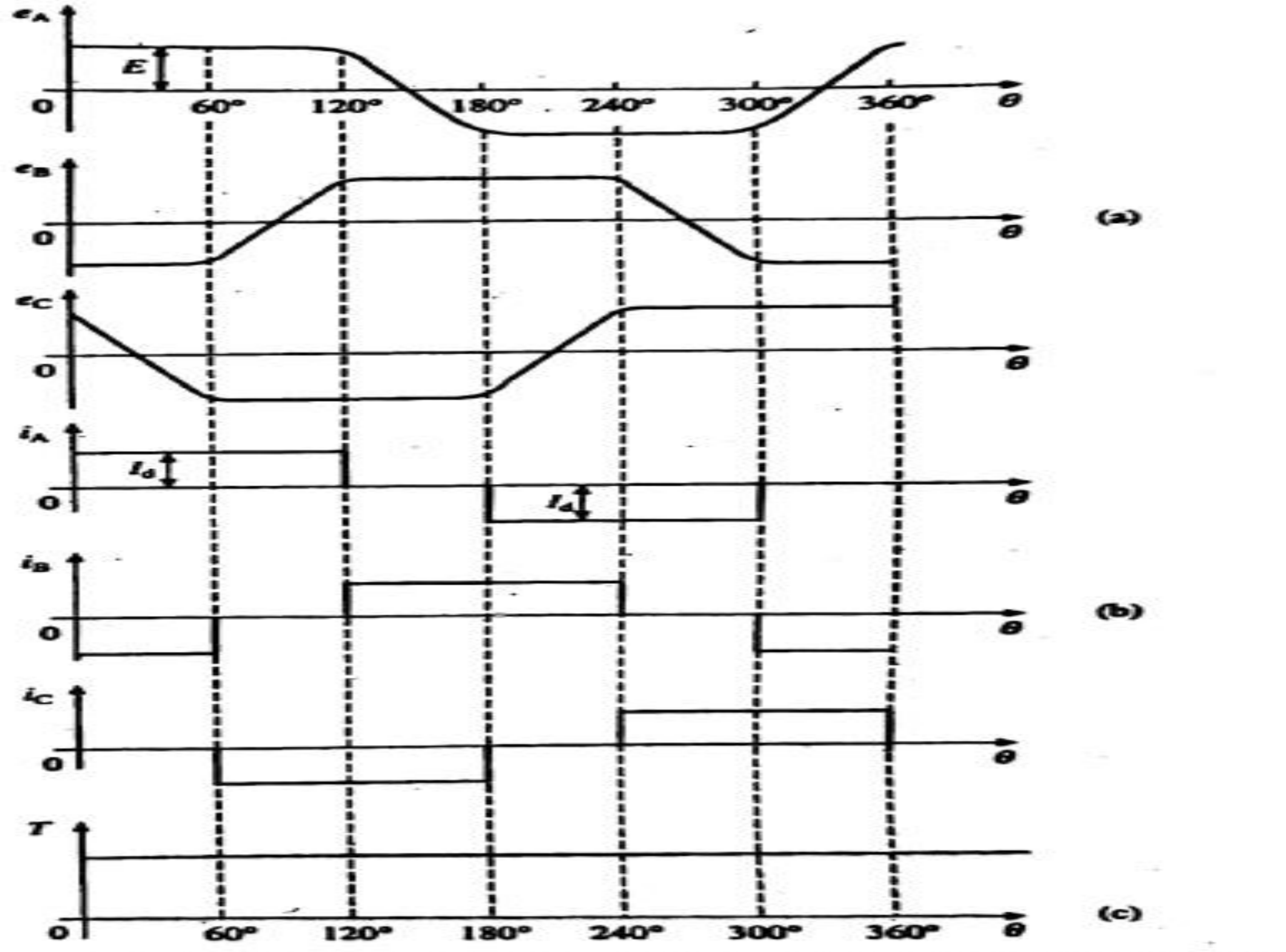
- Sinusoidal pmac motor
- Trapezodial pmac motor(brushless dc motor)

TRAPEZOIDAL PMAC MOTOR(BRUSHLESS DC MOTOR) DRIVE



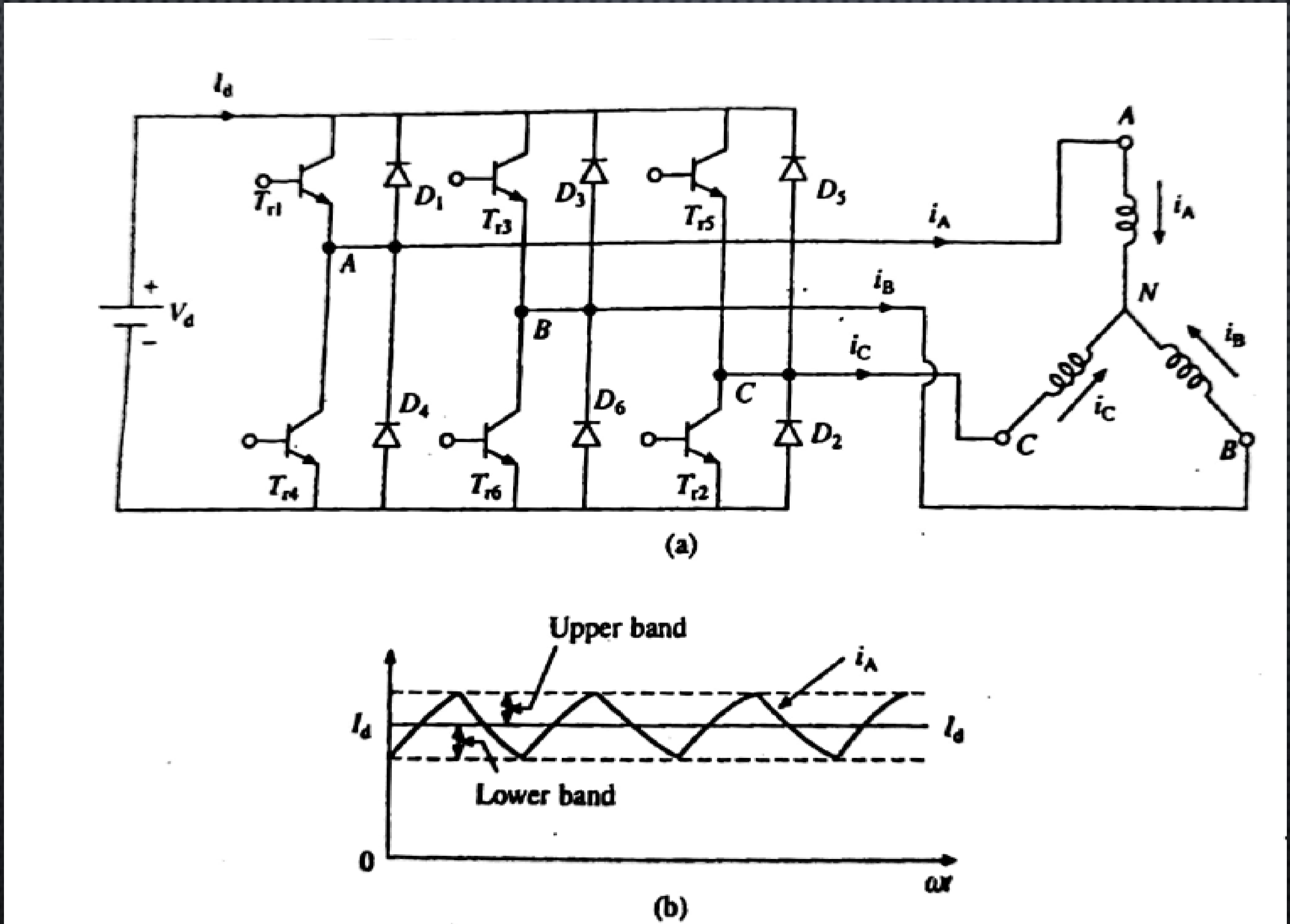

a
c'
b'
θ
ωm
S
N
b
c
a'
a
c'
120
S
b'
θ = 0
N
b
c
a'
a
S
b'
N
b
c
a'

INDUCED VOLTAGE,PHASE CURRENT AND TORQUE WAVEFORMS OF A BRUSHLESS DC MOTOR



Induced voltage, phase current and torque wavefors of a brushless dc motor

TRAPEZOIDAL PMAC MOTOR FED FROM A CURRENT REGULATED VOLTAGE SOURCE INVERTER



SPEED TORQUE CHARACTERISTIC

$$P = e_a \cdot i_a + e_b \cdot i_b + e_c \cdot i_b$$

$$0 \le \omega t \le 60$$

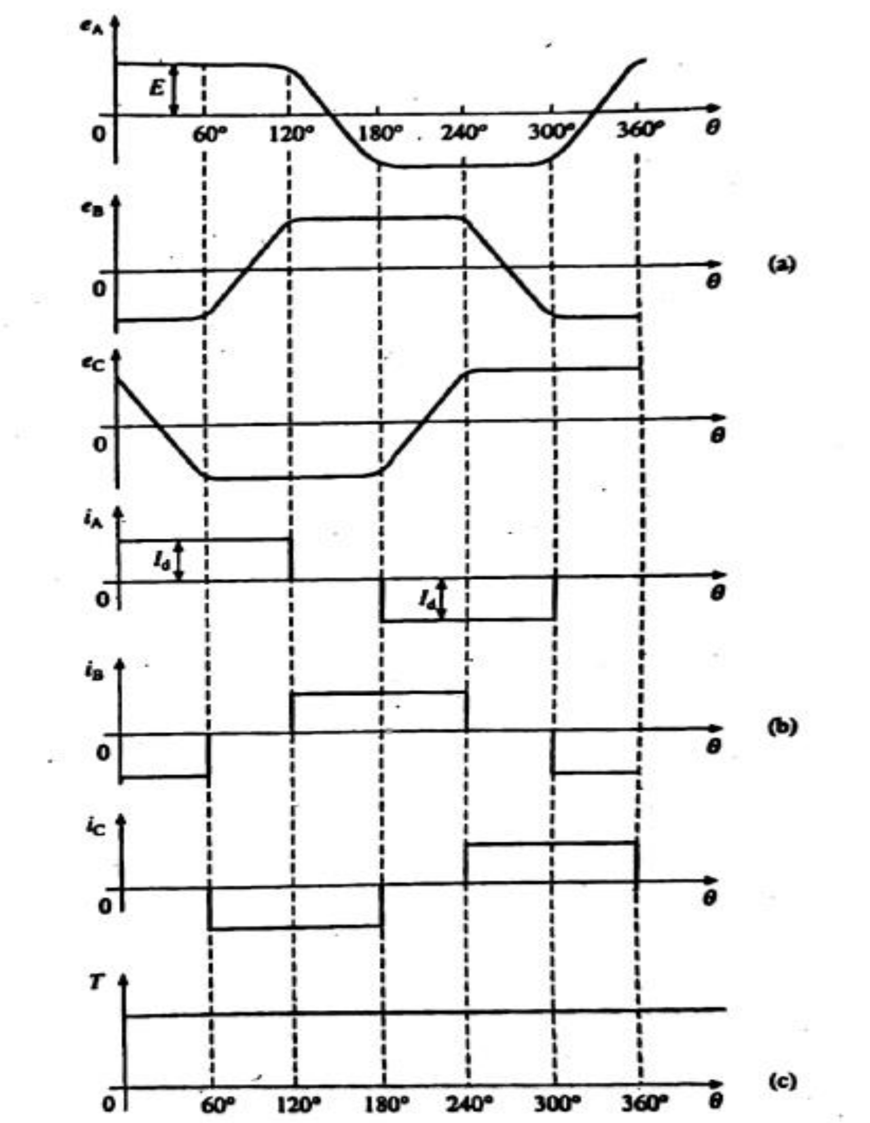
$$P = E \cdot I_d + -E \cdot -I_d + 0 = 2 E I_d$$

$$E = K \cdot \omega_m$$

$$P = T \cdot \omega_m$$

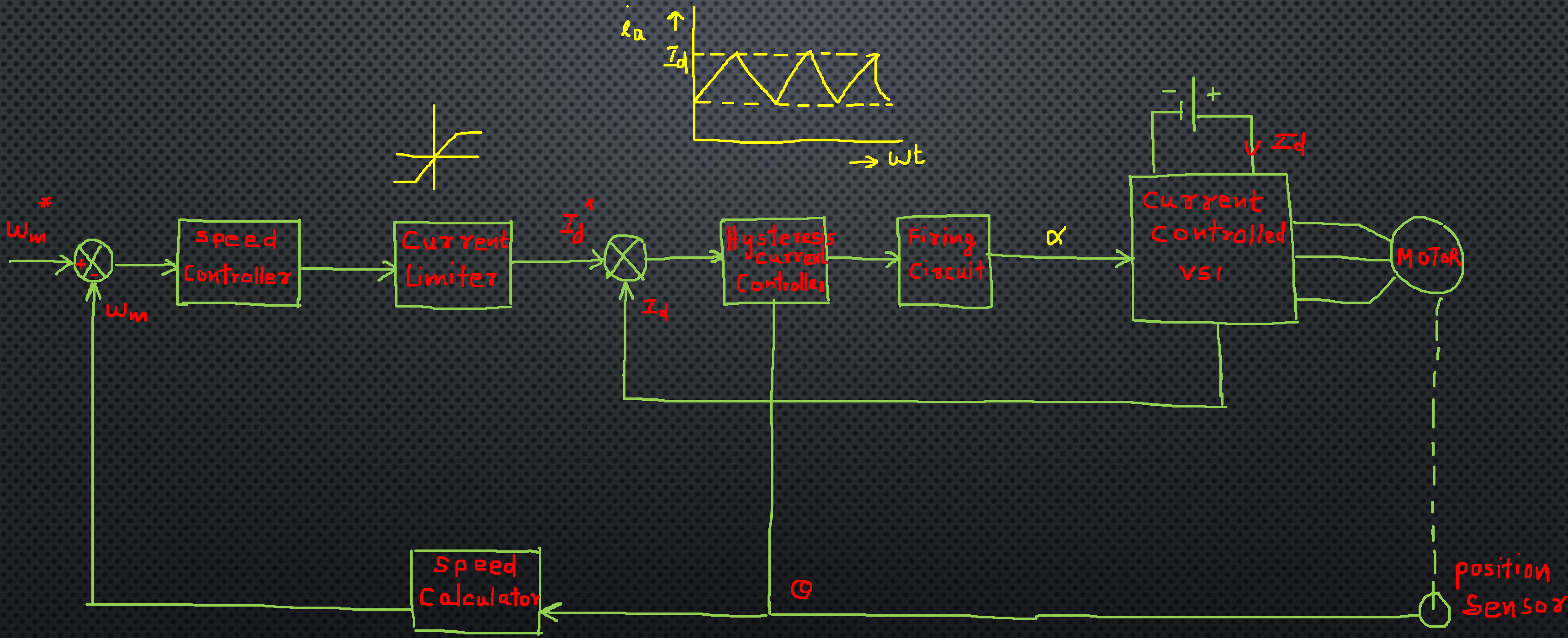
$$T = \frac{P}{\omega_m} = \frac{2 \cdot \cancel{E} \cdot I_d \cdot k}{\cancel{E}} = 2 \cdot k \cdot I_d$$

$$T \propto I_d$$



Induced voltage, phase current and torque wavefors of a brushless dc motor

CLOSED LOOP CONTROL OF TRAPEZOIDAL PMAC MOTOR DRIVE

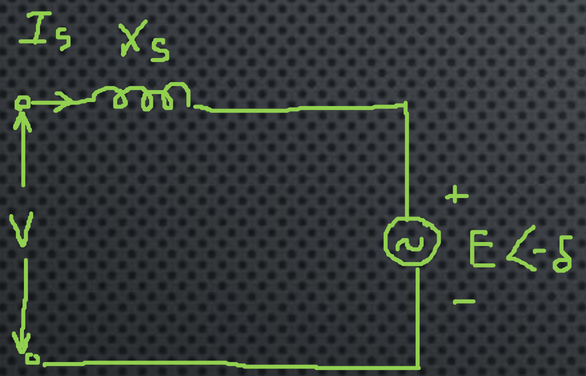


TYPES OF PERMANENT MAGNET SYNCHRONOUS MOTORS

- Sinusoidal pmac motor
- Trapezodial pmac motor(brushless dc motor)

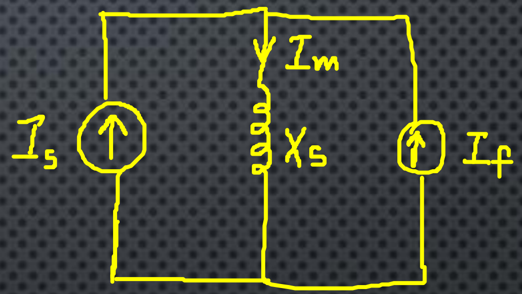
SINUSOIDAL PMAC MOTOR DRIVE

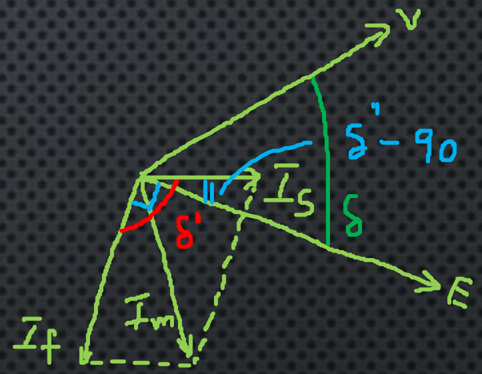
Equivalent Circuit of cylindrical rotor Motor



$\Longrightarrow$

Norton equivalent circuit





V - applied voltage

X_s - Synchronous Reactance

E - Excitation emf

I_s - Stator current

$$P_{in} = 3 V I_s \cos\phi$$

$$P_m = 3 V E \sin\delta / X_s$$

$$\bar{I}_m = \bar{I}_s + \bar{I}_f \quad - ①$$

$$\bar{I}_f = \frac{\bar{E}}{j \cdot X_s} = \frac{E\angle -\delta}{X_s \angle \pi/2} = \frac{E}{X_s} \angle -(\delta + \pi/2) \quad - ②$$

$$\boxed{P_m = 3 E I_s \cos(\delta' - \pi/2)} \quad - ③$$

From ② $E = I_f \cdot X_s$

$$\boxed{P_m = 3 I_f \cdot I_s X_s \sin\delta'}$$

PHASOR DIAGRAM

$$P_m = 3 X_s I_s I_f \cdot \sin\delta'$$

$$T = \frac{P_m}{\omega_s} = \frac{3 X_s I_s I_f \cdot \sin\delta'}{\omega_s} = K \cdot I_s \cdot I_f \cdot \sin\delta'$$

δ' ⇒ The angle between the rotating fields produced by the stator and Rotor.

$$K = \frac{3 X_s}{\omega_s}$$

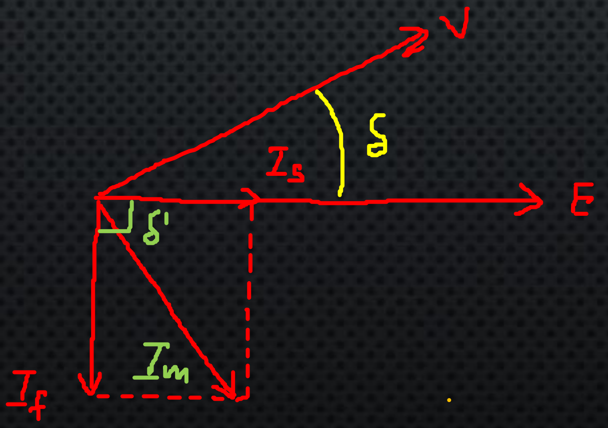
$T = \pm K \cdot I_s \cdot I_f \cong \pm k_1 I_s$ where $\delta' = \pm 90^\circ$

$$\boxed{T \propto I_s}$$

Maximum Torque is obtained when $\delta' = 90^\circ$

$T = +k_1 I_s$

for Motoring



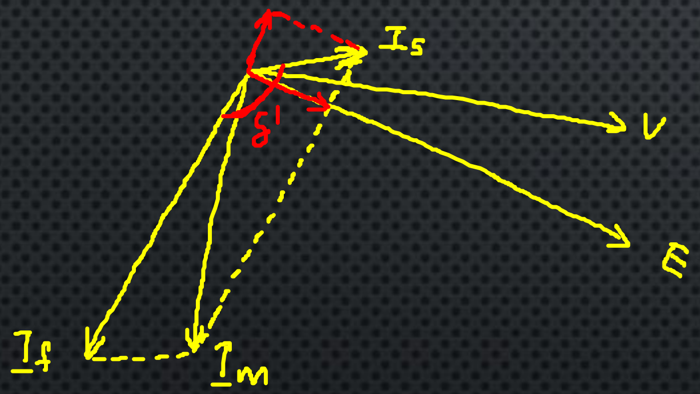
Motoring

Braking operation

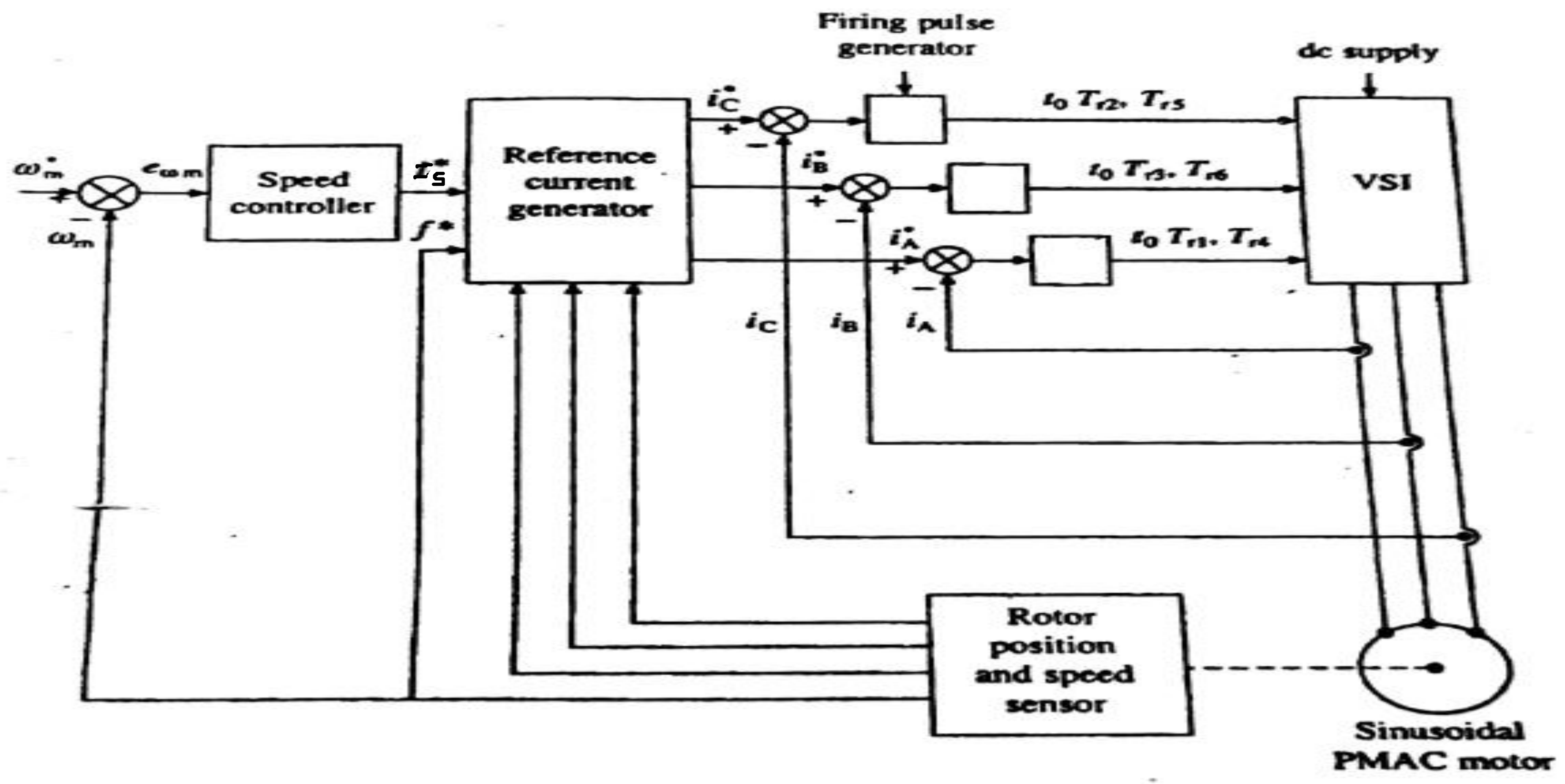
$T = -k_1 I_s$

FLUX WEAKENING IN PMSM DRIVES

Flux weakening in PMSM
by increasing δ'

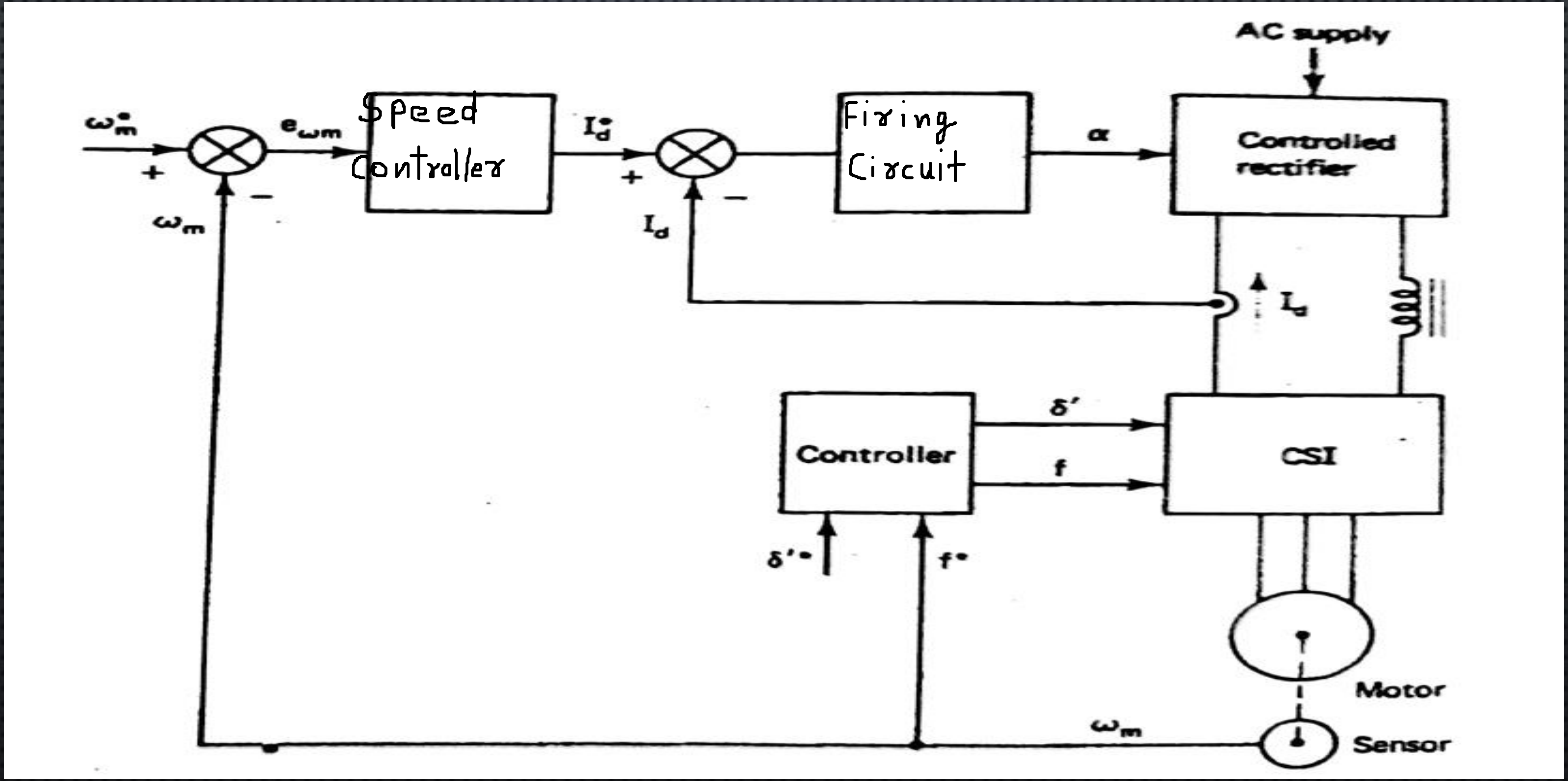


CLOSED LOOP CONTROL OF SINUSOIDAL PMSM DRIVE

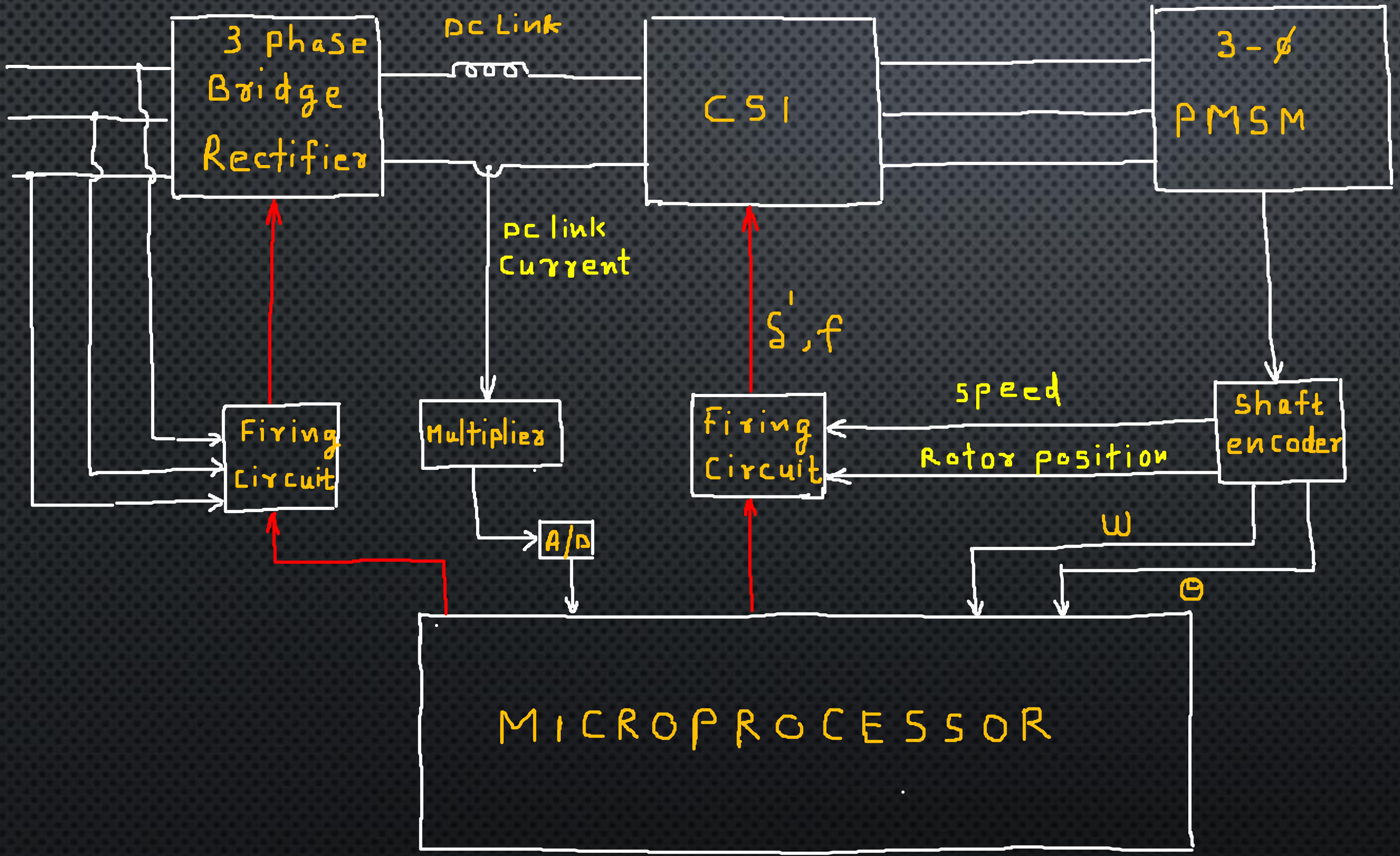


Current regulated VSI fed sinusoidal PMAC motor drive

CSI DRIVEN SYNCHRONOUS MOTOR DRIVE



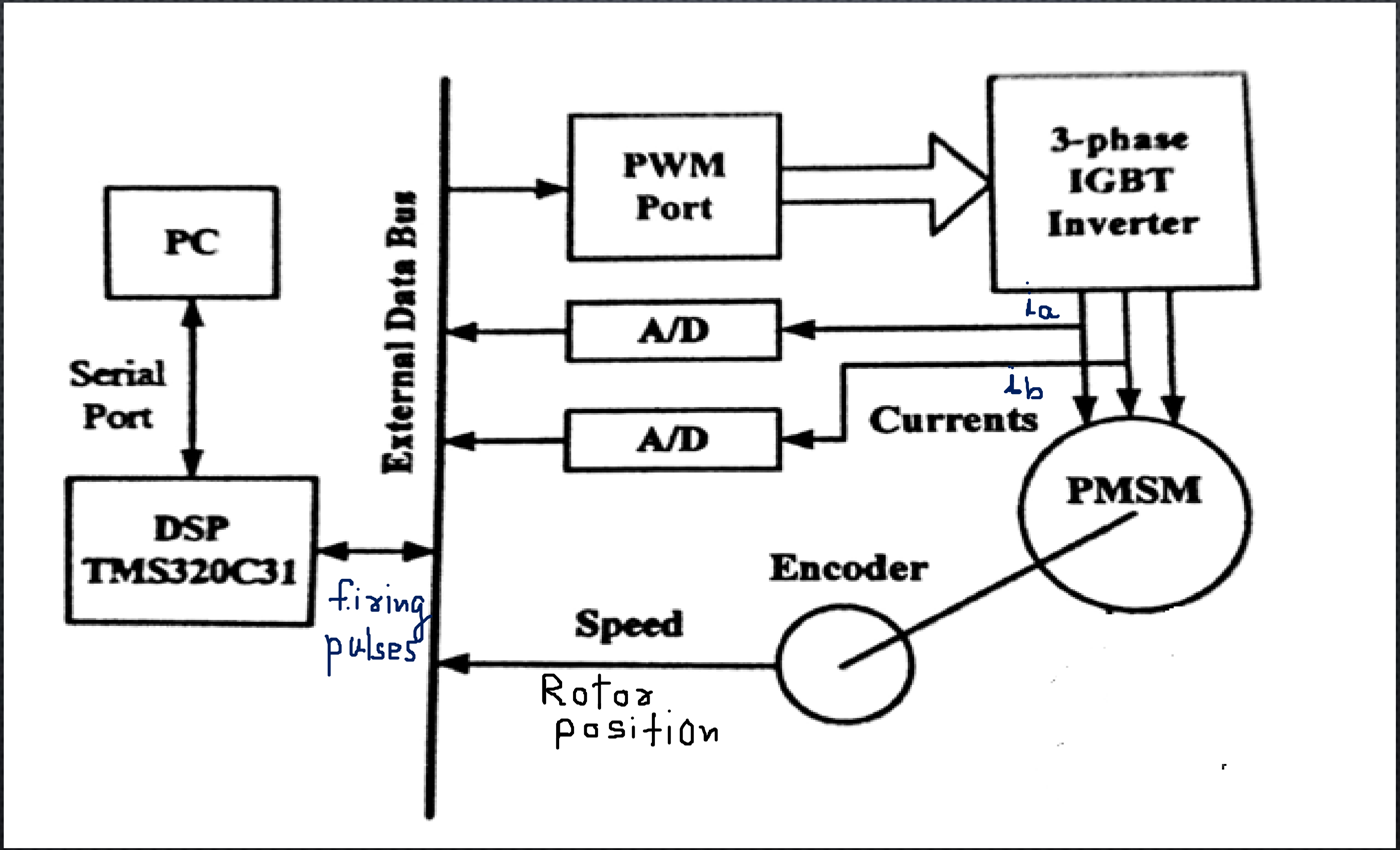
MICROPROCESSOR BASED PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVES



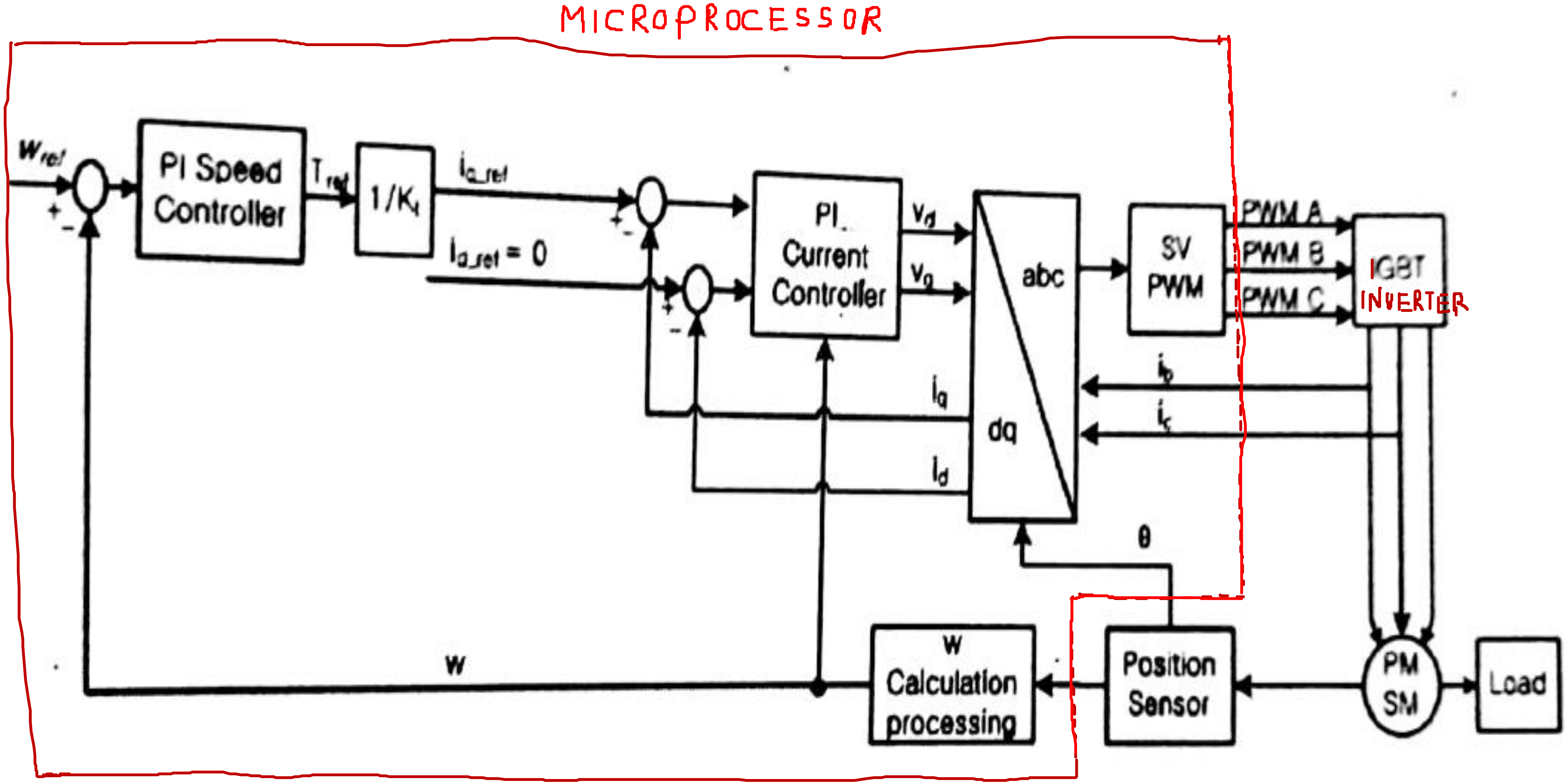
WORKING

- A self controlled current source inverter fed synchronous motor utilising machine voltage commutation is used.
- Csi fed synchronous motor has better performance because of absence of mechanical commutator.
- Inverter supplying power to the motor is supplied from a line commutated rectifier via dc link.
- The desired dc link current decides the firing of the thyristors of the bridge rectifier .
- The inverter receives its firing pulses from a rotor position sensor.
- Regeneration is possible by operating the machine side converter as a rectifier and line side converter as an inverter.
- Microprocessor has to ensure automatic changeover from forced commutation to machine commutation when the motor assumes the capability for machine commutation.
- the system variables(dc link current, rotor position and speed) and the commands from the input-output terminals are fed to the cpu.
- The various routines for current regulation and speed regulation are executed by interrupt signals generated by real time clocks.
- The actual speed measured by means of a shaft encoder is compared with the desired speed stored in the memory registers of the microprocessor.
- The current regulating routine is also initiated by an interrupt signal.

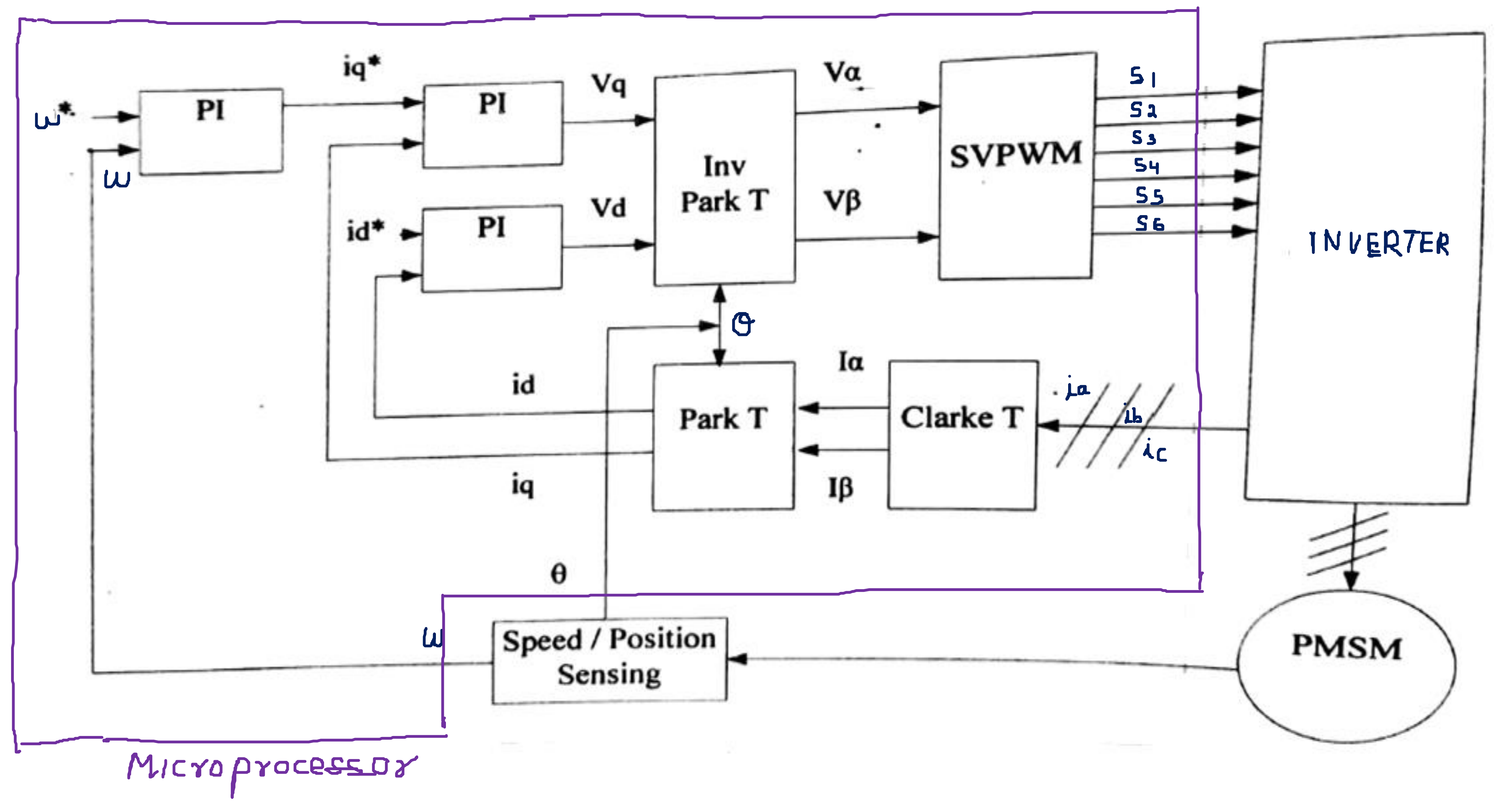
MICROPROCESSOR BASED SPEED CONTROL OF PMSM(VECTOR CONTROL)



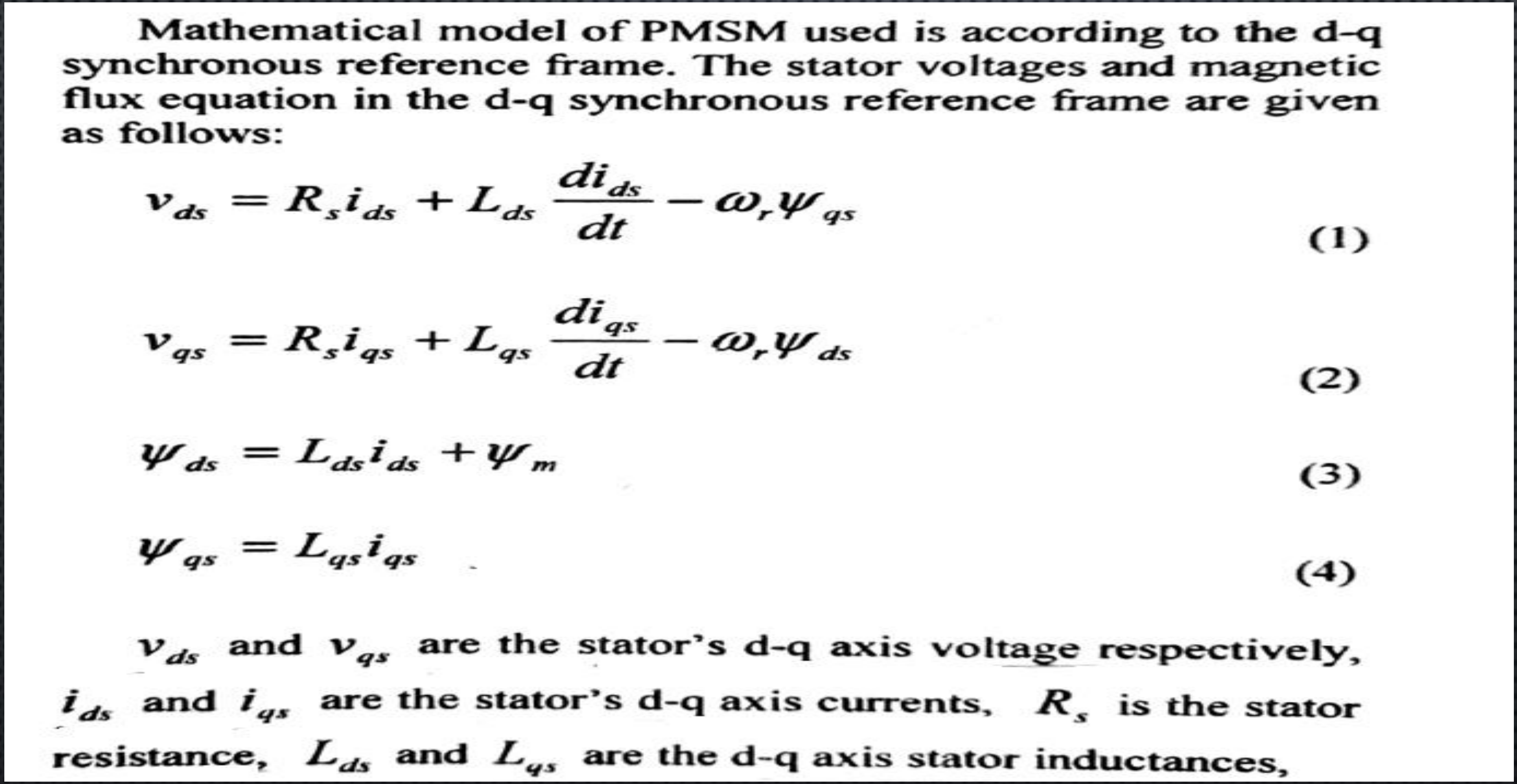
MICROPROCESSOR BASED SPEED CONTROL OF PMSM(VECTOR CONTROL)



MICROPROCESSOR BASED SPEED CONTROL OF PMSM(VECTOR CONTROL)



MODELING OF PERMANENT MAGNET SUNCHRONOUS MOTOR



Mathematical model of PMSM used is according to the d-q synchronous reference frame. The stator voltages and magnetic flux equation in the d-q synchronous reference frame are given as follows:

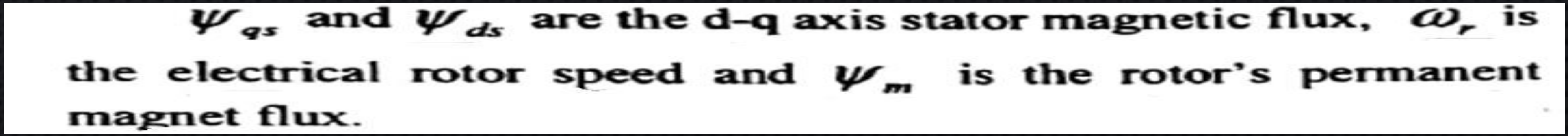
$$v_{ds} = R_s i_{ds} + L_{ds}\frac{di_{ds}}{dt} - \omega_r \psi_{qs} \tag{1}$$

$$v_{qs} = R_s i_{qs} + L_{qs}\frac{di_{qs}}{dt} - \omega_r \psi_{ds} \tag{2}$$

$$\psi_{ds} = L_{ds} i_{ds} + \psi_m \tag{3}$$

$$\psi_{qs} = L_{qs} i_{qs} \tag{4}$$

v_{ds} and v_{qs} are the stator's d-q axis voltage respectively, i_{ds} and i_{qs} are the stator's d-q axis currents, R_s is the stator resistance, L_{ds} and L_{qs} are the d-q axis stator inductances,



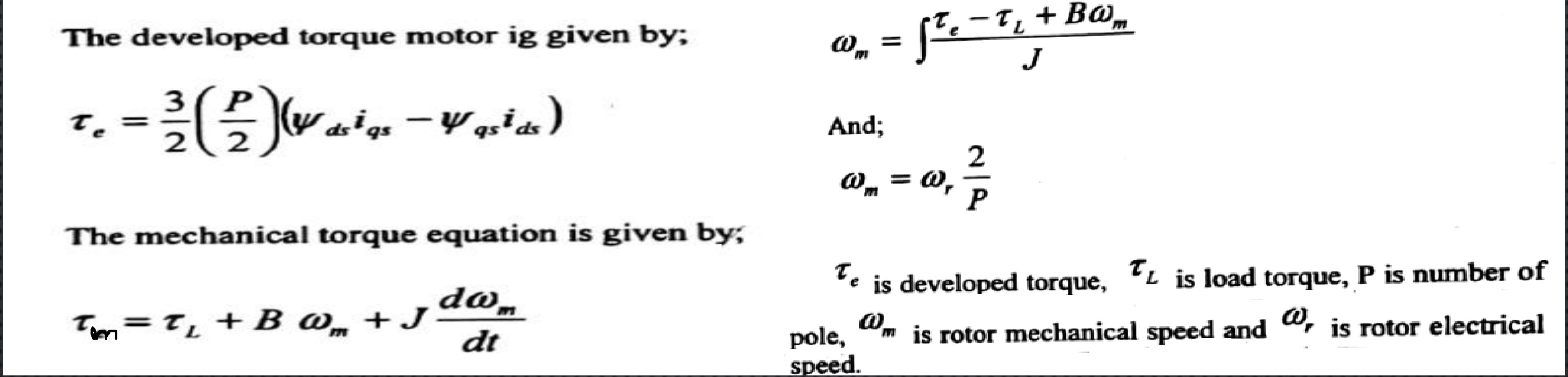
ψ_{qs} and ψ_{ds} are the d-q axis stator magnetic flux, ω_r is the electrical rotor speed and ψ_m is the rotor's permanent magnet flux.

EQUATIONS REPRESENTING CURRENT MODEL

$$\frac{di_{ds}}{dt} = -\frac{R_s}{L_{ds}} i_{ds} + \frac{\omega_r L_{qs}}{L_{ds}} i_{qs} + \frac{1}{L_{ds}} v_{ds}$$

$$\frac{di_{qs}}{dt} = -\frac{R_s}{L_{qs}} i_{qs} - \frac{\omega_r L_{ds}}{L_{qs}} i_{qs} + \frac{1}{L_{qs}} v_{qs} - \frac{\omega_r \psi_m}{L_{qs}}$$

SPEED AND TORQUE EQUATIONS



The developed torque motor ig given by;

$$\tau_e = \frac{3}{2}\left(\frac{P}{2}\right)(\psi_{ds} i_{qs} - \psi_{qs} i_{ds})$$

The mechanical torque equation is given by;

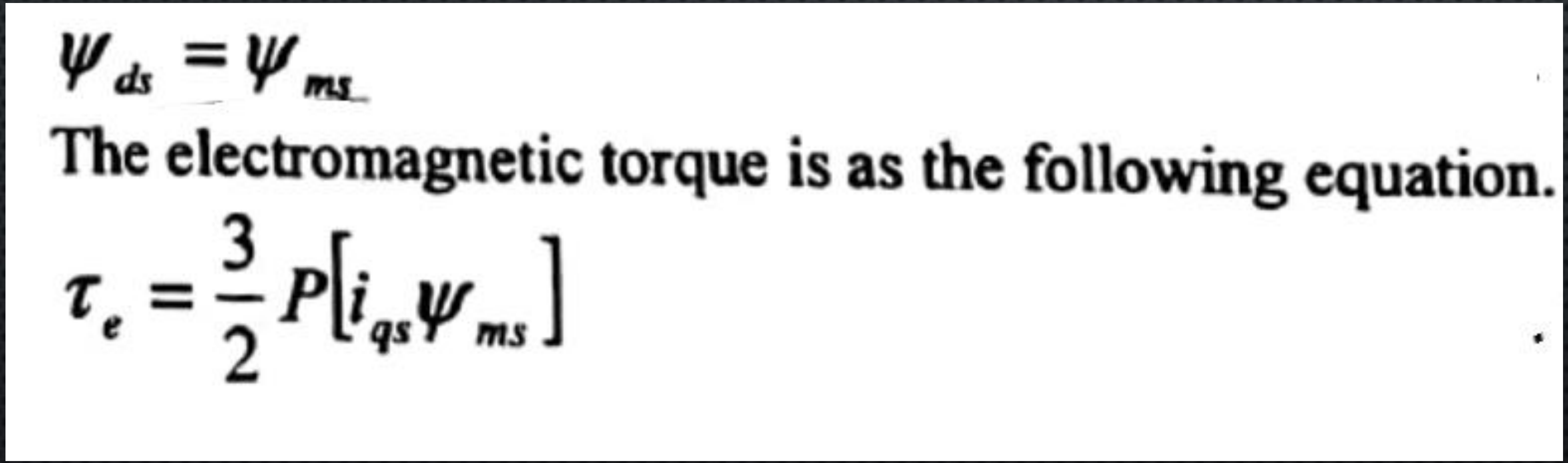
$$\tau_m = \tau_L + B\,\omega_m + J\frac{d\omega_m}{dt}$$

$$\omega_m = \int \frac{\tau_e - \tau_L + B\omega_m}{J}$$

And;

$$\omega_m = \omega_r \frac{2}{P}$$

τ_e is developed torque, τ_L is load torque, P is number of pole, ω_m is rotor mechanical speed and ω_r is rotor electrical speed.



$$\psi_{ds} = \psi_{ms}$$

The electromagnetic torque is as the following equation.

$$\tau_e = \frac{3}{2} P\left[i_{qs} \psi_{ms}\right]$$