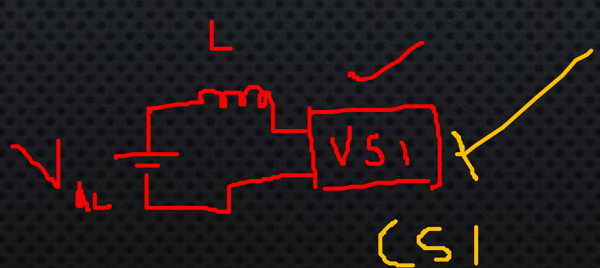
VSI Fed Induction Motor Drives

INVERTERS

- Inverters are most important power electronic equipment which is being used for various purposes such as variable speed AC drive (VSD), uninterrupted power supplies (UPS),Static frequency changer (SFC).
- A voltage fed inverter or voltage source inverter(VSI) is one in which the dc source has small or negligible impedance. In other words, a voltage source inverter has a stiff voltage source at its input terminals.
- A current fed inverter (CFI) or current source inverter (CSI) is fed with adjustable current from a dc source of high impedance, i.e. from a stiff dc current source.



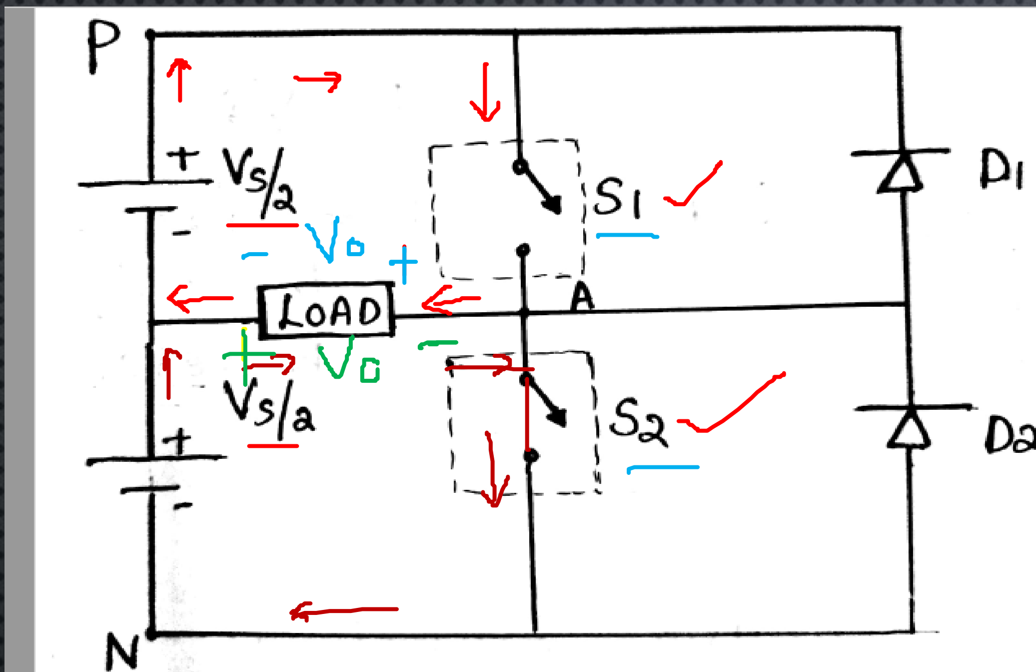
APPLICATION OF INVERTERS

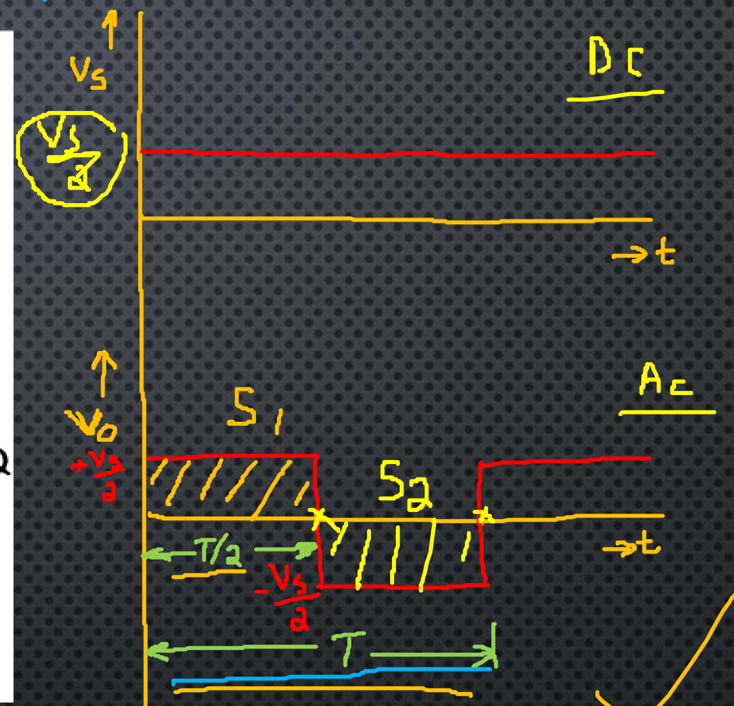
- Three phase inverters are used for high power applications such as motor drives, induction heating, UPS.
- A three phase inverter circuit changes DC input voltage to a three phase variable frequency, variable voltage output.
- The input DC voltage can be from a DC source or a rectified AC source.
- The output frequency of an inverter is determined by the rate at which the semiconductor devices are switched ON and OFF by the inverter control circuitry and an adjustable frequency AC output is obtained

VVVf
V/f
VSI, cyclo
φ → K
Kramer
Scherbius
VSI
f ~
V ~

SINGLE PHASE HALF BRIDGE VOLTAGE SOURCE INVERTER

Square pulsed Inver D = 50%





I S1 ON S2 off
T/2 T/2

II S1 off S2 ON

$V_o = \frac{V_s}{2}$

$V_o = \frac{-V_s}{2}$

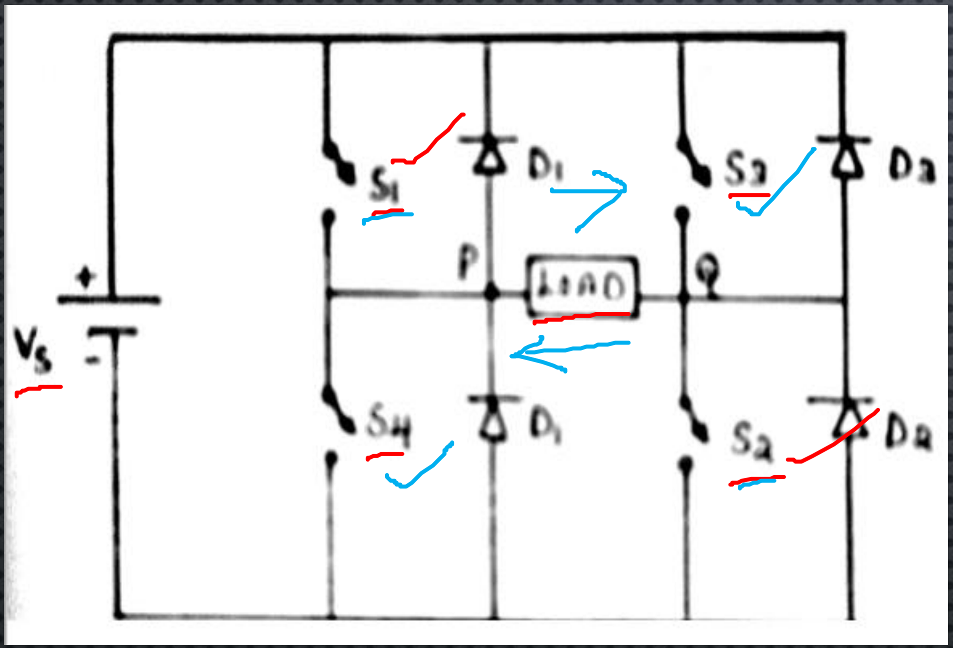
R load

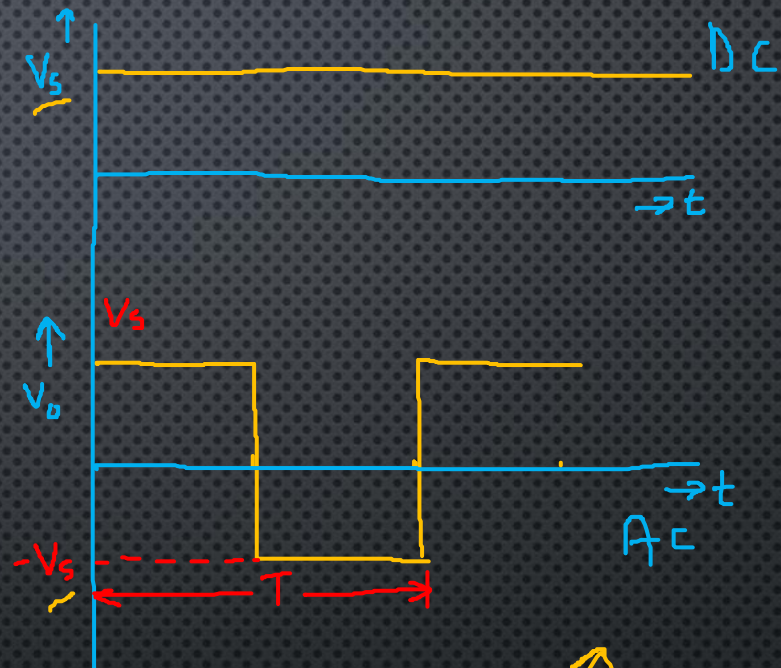
DC → AC

Con → Vari

Co

SINGLE PHASE FULL BRIDGE VOLTAGE SOURCE INVERTER





Vo Vary

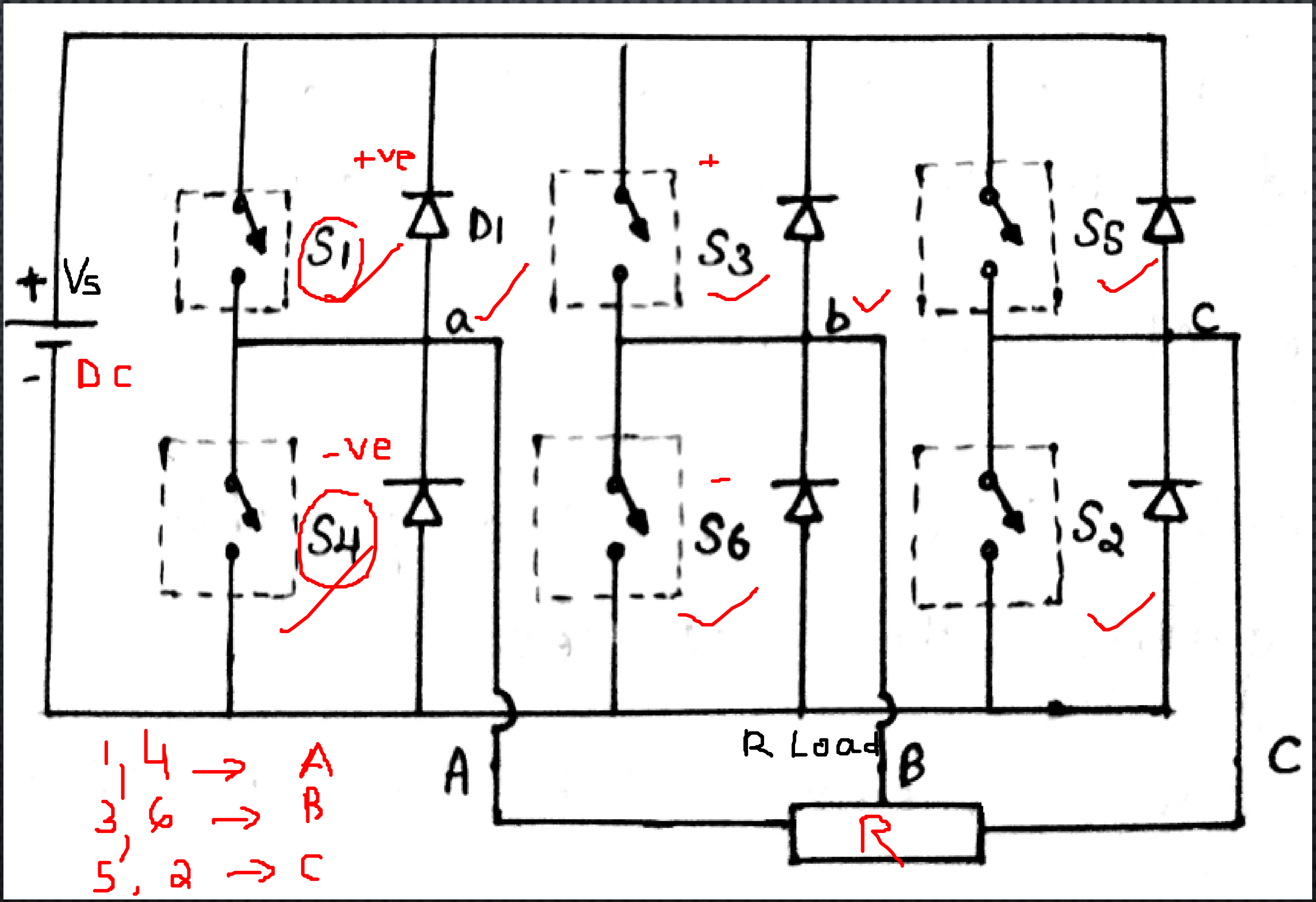
I S1 S2 $V_o = V_s$

II S3 S4 $V_o = -V_s$

THREE –PHASE INVERTER

- IT CONSISTS OF 6 POWER SWITCHES WITH SIX ASSOCIATED FREEWHEELING DIODES.
- THE SWITCHES ARE OPENED AND CLOSED PERIODICALLY IN THE PROPER SEQUENCE TO PRODUCE THE DESIRED OUTPUT WAVEFORM.
- THE RATE OF SWITCHING DETERMINES THE OUTPUT FREQUENCY OF THE INVERTER.

THREE PHASE VOLTAGE SOURCE INVERTER(VSI)



SWITCHING SCHEME USED IN 3 PHASE INVERTERS

BASICALLY THERE ARE TWO POSSIBLE SCHEMES FOR GATING THE DEVICES

- 180 DEGREES CONDUCTION MODE 3

  EACH SWITCH CONDUCTS FOR 180 DEGREES

- 120 DEGREES CONDUCTION MODE 2

  EACH SWITCH CONDUCTS FOR 120 DEGREES

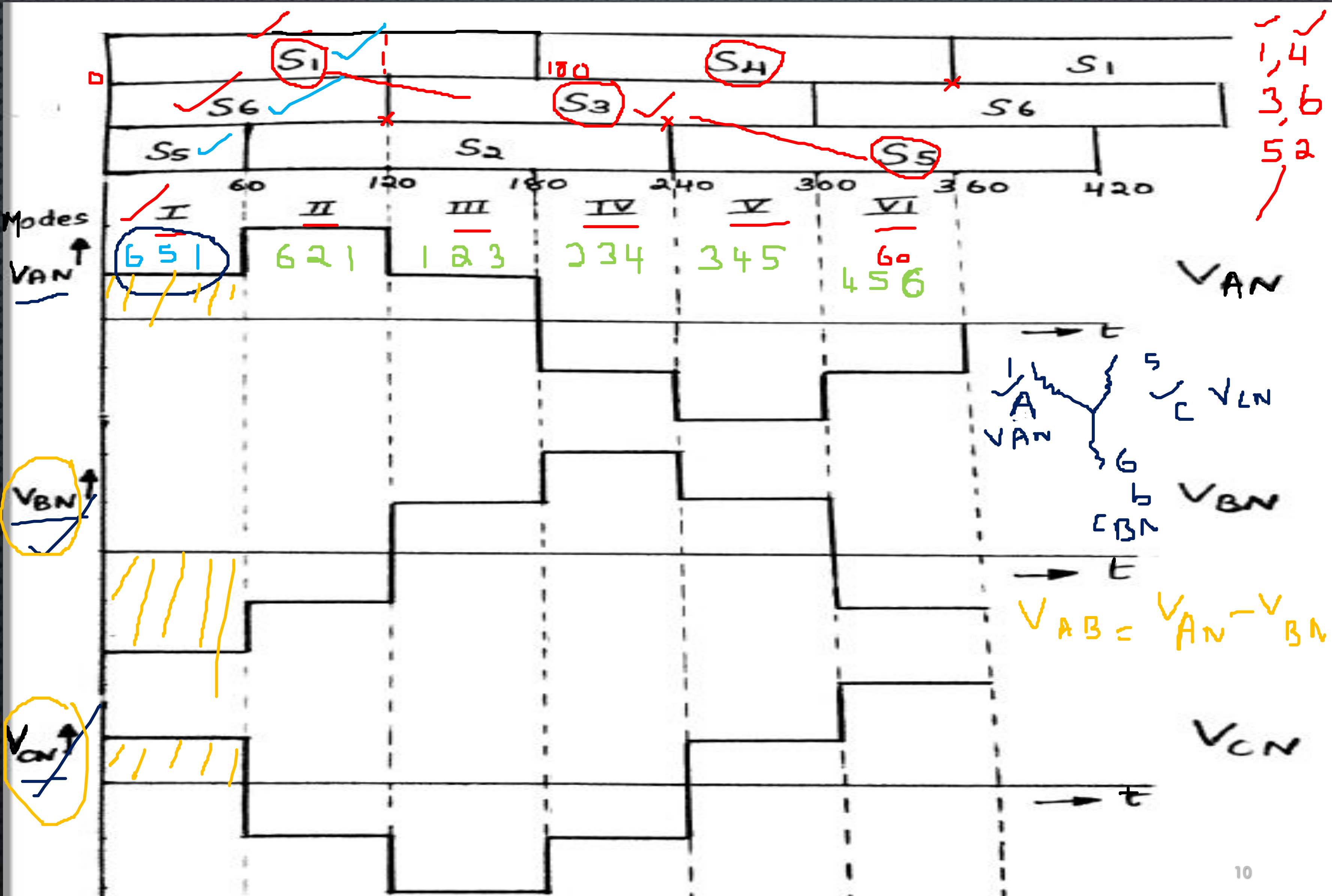
IN BOTH OF THESE SCHEMES THE GATING SIGNALS ARE APPLIED AND REMOVED AT 60 DEGREES INTERVALS

180 DEGREES CONDUCTION MODE WITH RESISTIVE LOAD

- In this control scheme , each switch conducts for a period of 180 degrees.

- Switches are numbered in the sequence of their triggering.
- At a time , 3 switches conduct.
- 2 from the upper group and 1 from the lower group or 2 from the lower group and 1 from the upper group conduct.
- Two switches of the same leg are prevented from conducting simultaneously.
- Once complete cycle is divided into 6 modes each of 60 degrees interval.

OUTPUT VOLTAGE(180 MODE)

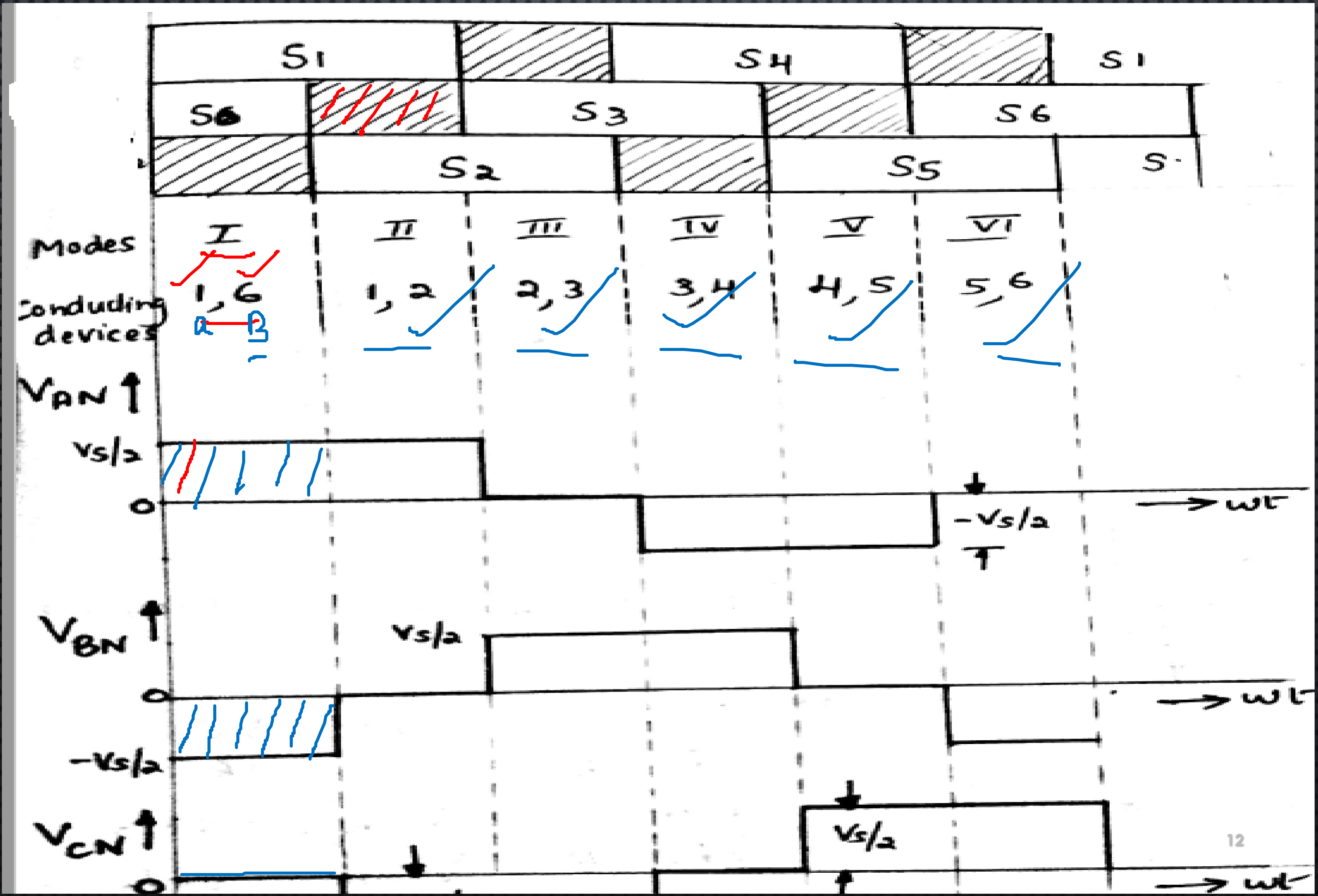


120 DEGREES CONDUCTION MODE WITH RESISTIVE LOAD

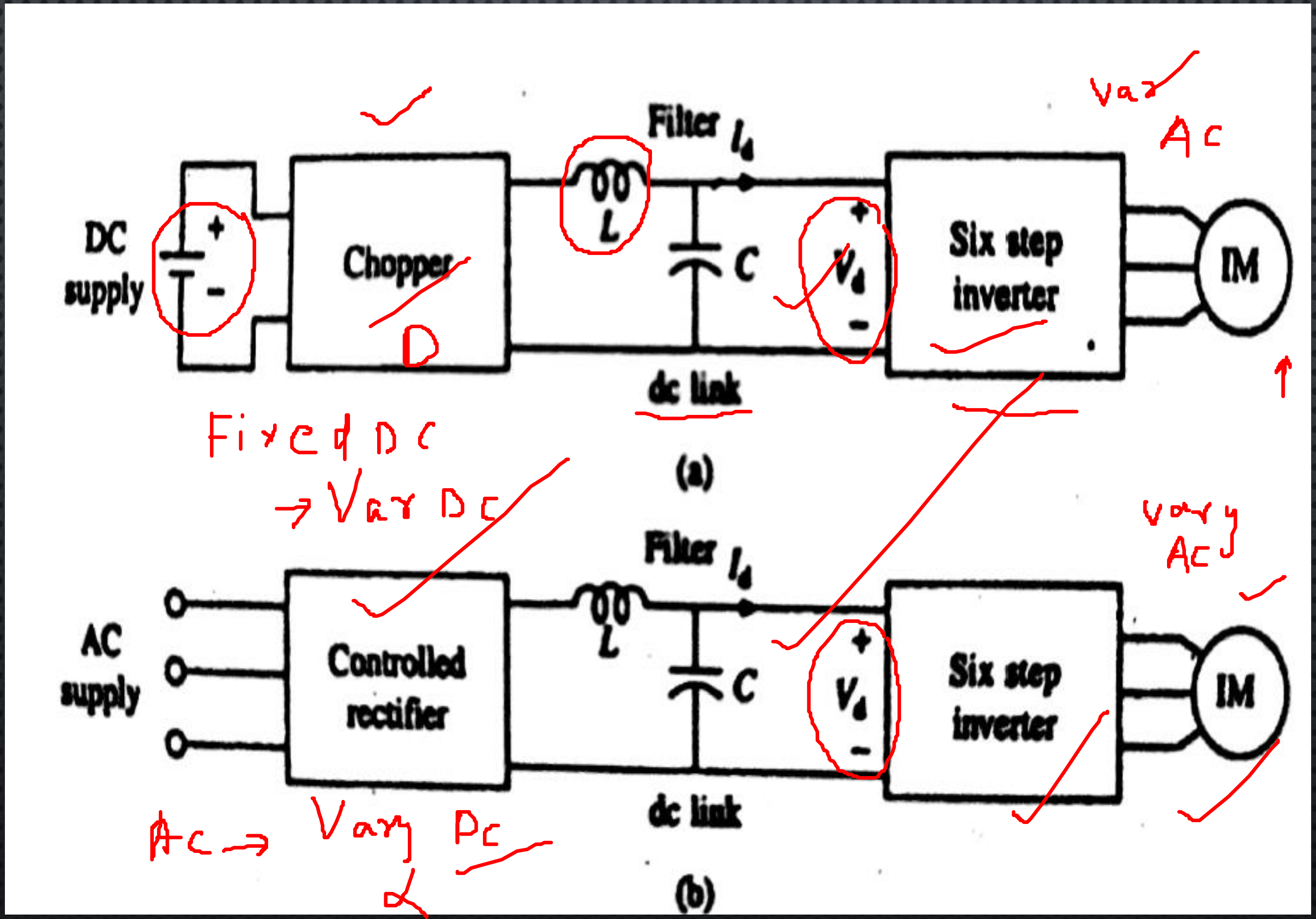
- Like 180 degrees mode , 120 degrees mode inverter also requires 6 steps each of 60 degrees duration for completing one cycle of the ouput ac voltage.
- Each thyristor conducts for a period of 120 degrees and for the next 60 degrees, neither of them conduct.
- Each pair conducts for a period of 60 degrees.

OUTPUT VOLTAGE(120 MODE)

Sorry I mentioned as 180 it is 120

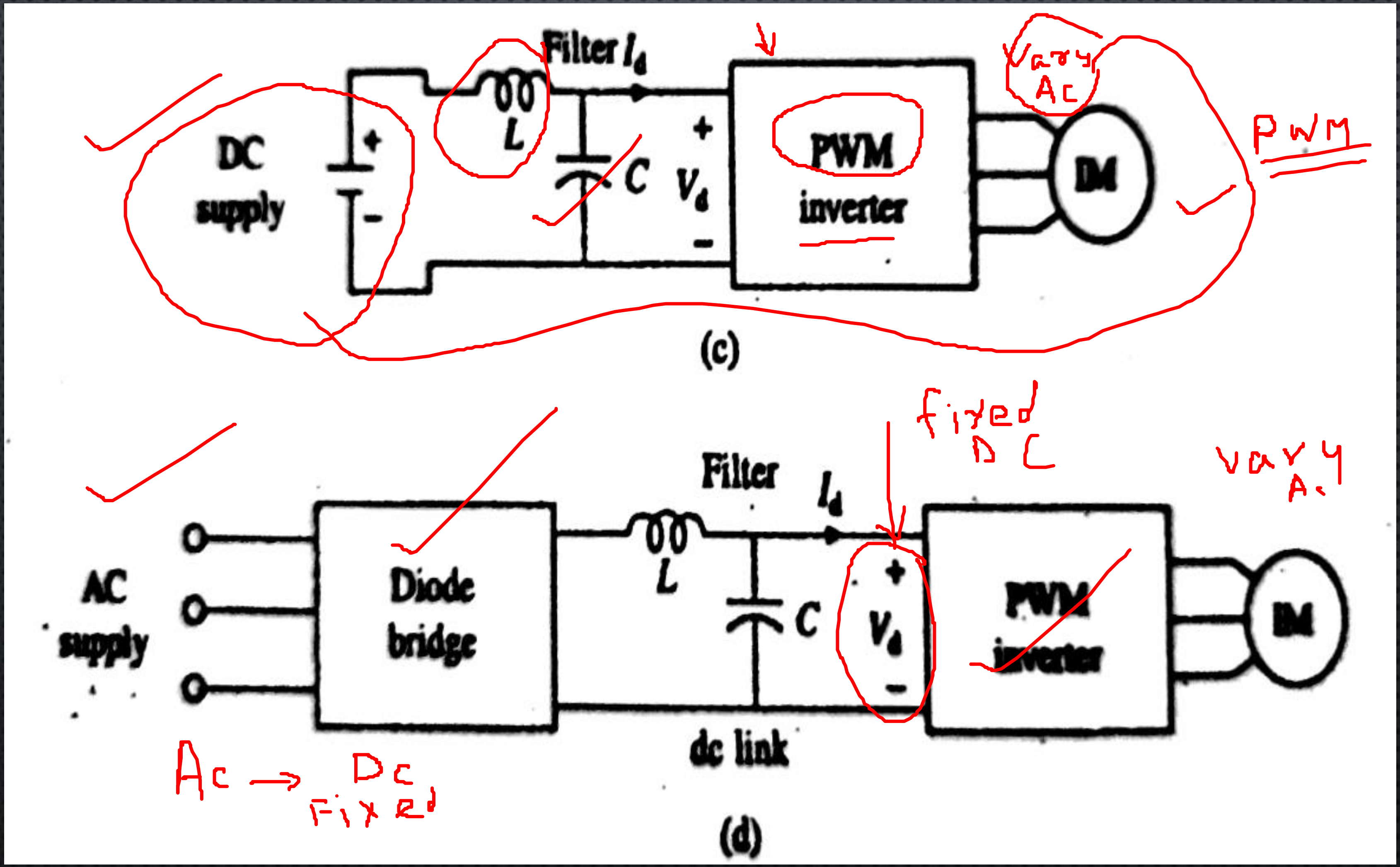


VSI FED INDUCTION MOTOR DRIVES



Square pulse Inverter

PWM INVERTERS



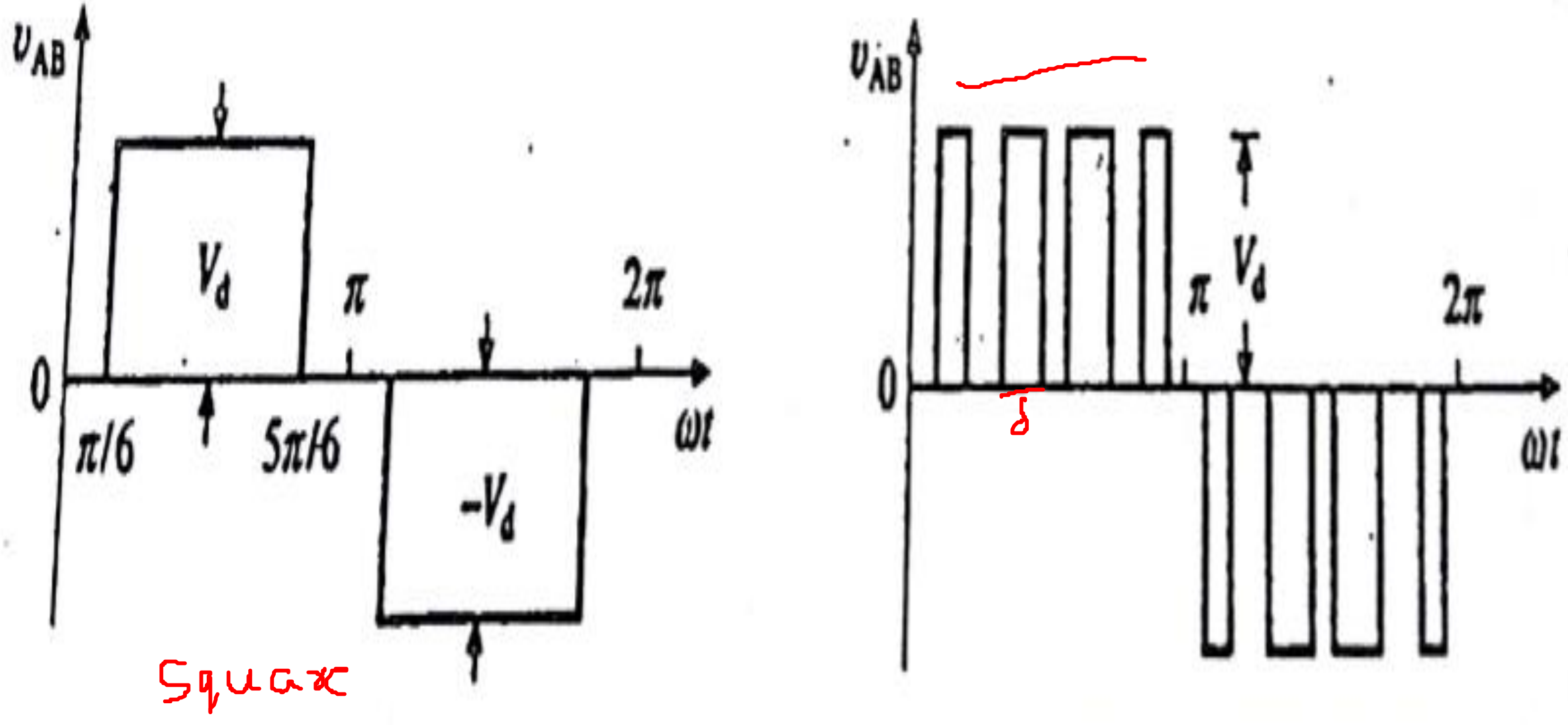
PULSE WIDTH MODULATION

TECHNIQUE USED TO VARY VOLTAGE AND FREQUENCY OF INVERTER OUTPUT.

TYPES OF PWM TECHNIQUES

- SINGLE PULSE WIDTH MODULATION
- MULTIPLE PULSE WIDTH MODULATION
- SINUSOIDAL PULSE WIDTH MODULATION
- SPACE VECTOR PULSE WIDTH MODULATION
- HYSTERESIS BAND CURRENT CONTROL PWM
- SELECTED HARMONIC ELIMINATION PWM
- SIGMA DELTA MODULATION

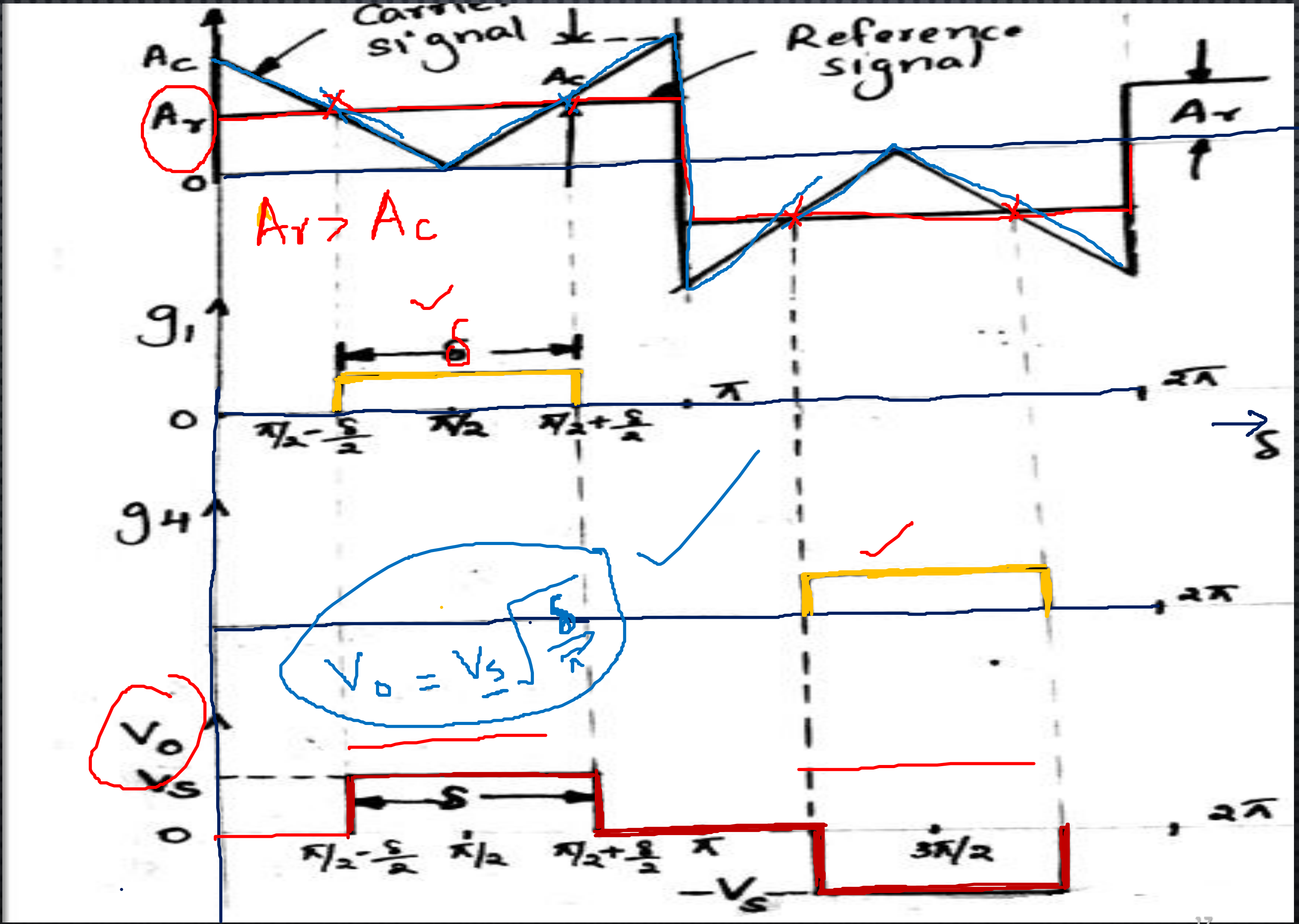
INVERTER WAVEFORMS



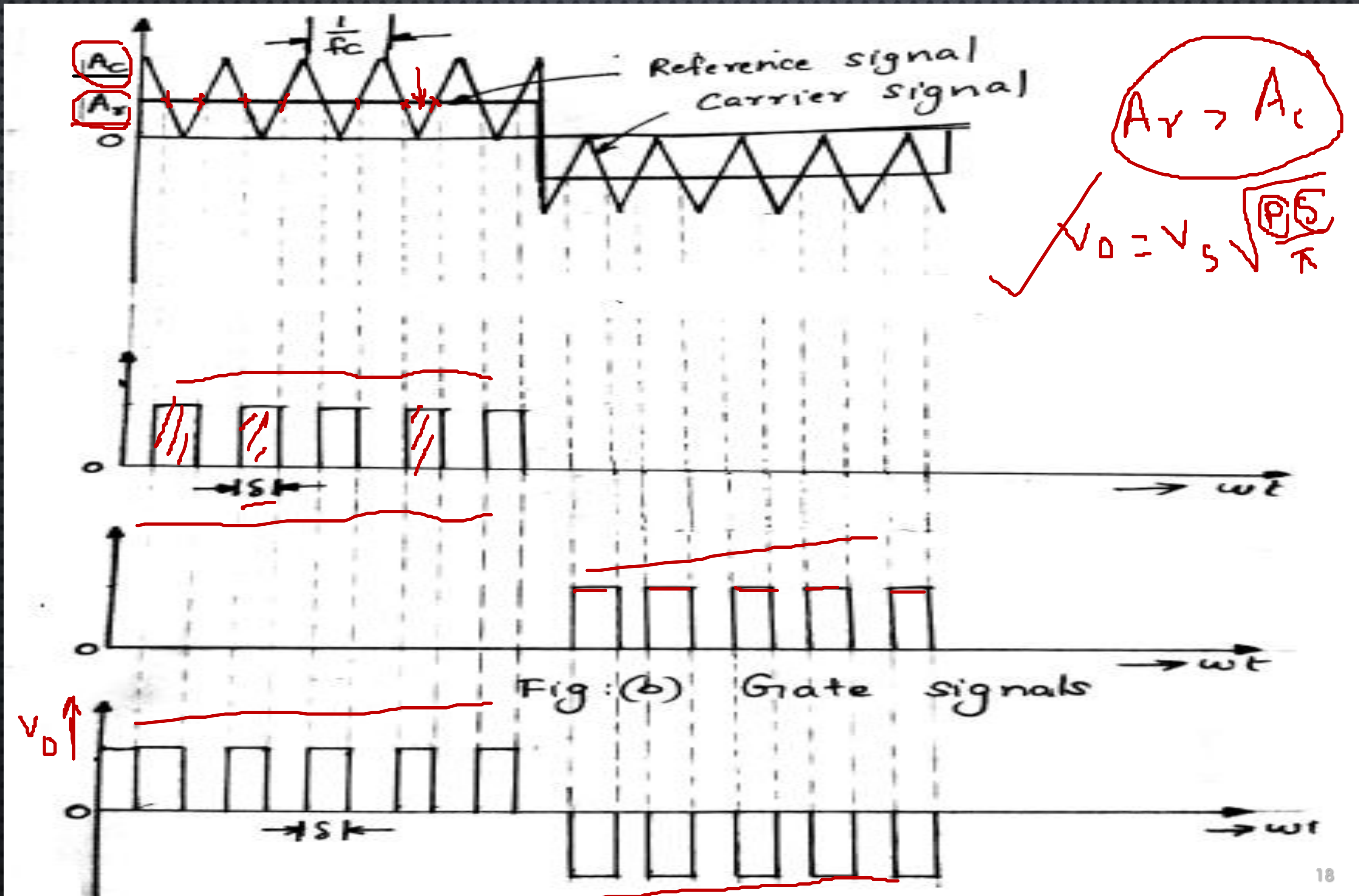
(b) Stepped wave inverter line voltage waveform

(c) PWM inverter line voltage waveform

SINGLE PULSE WIDTH MODULATION



MULTIPLE PULSE WIDTH MODULATION

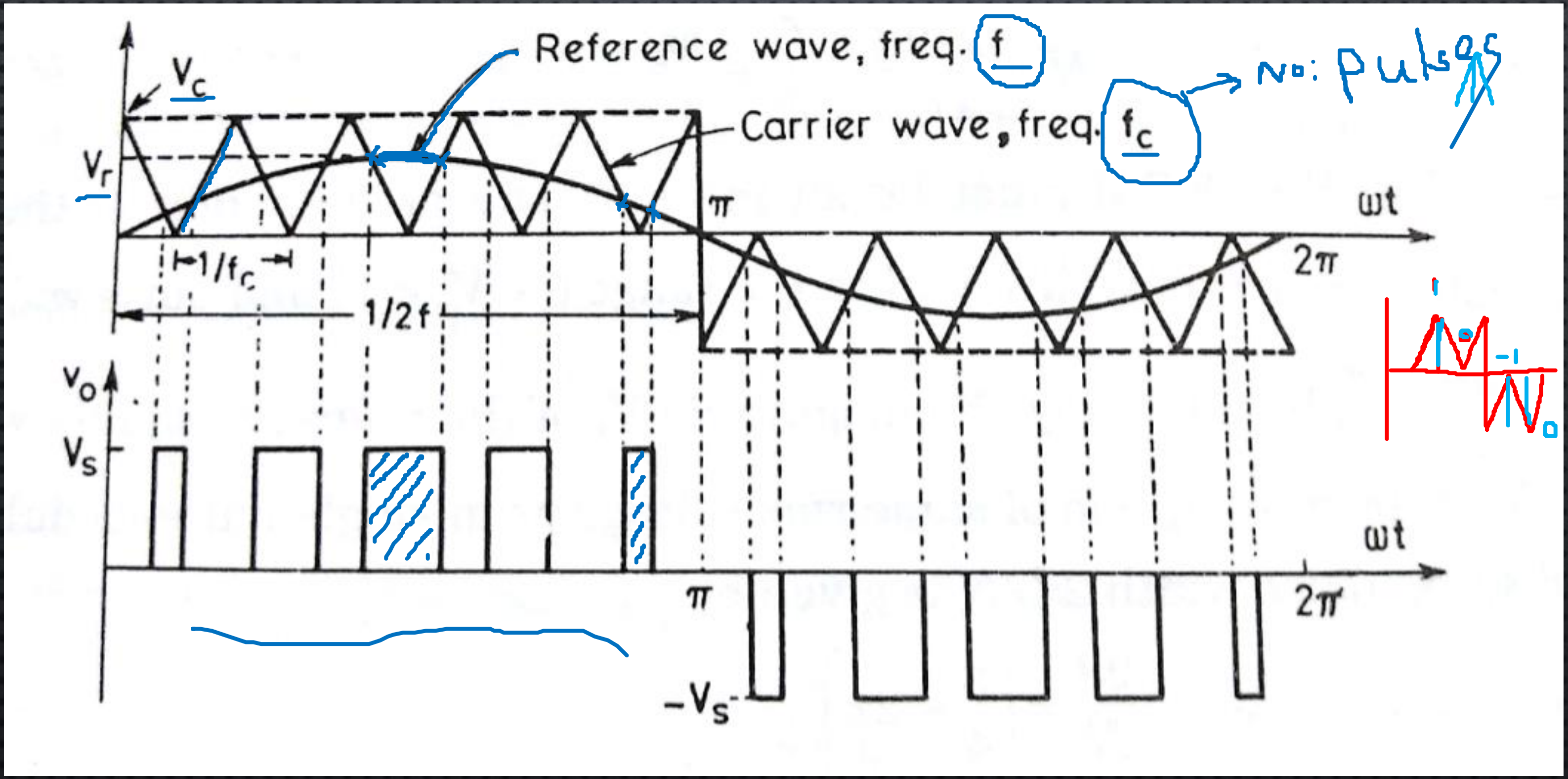


SPWM TECHNIQUE

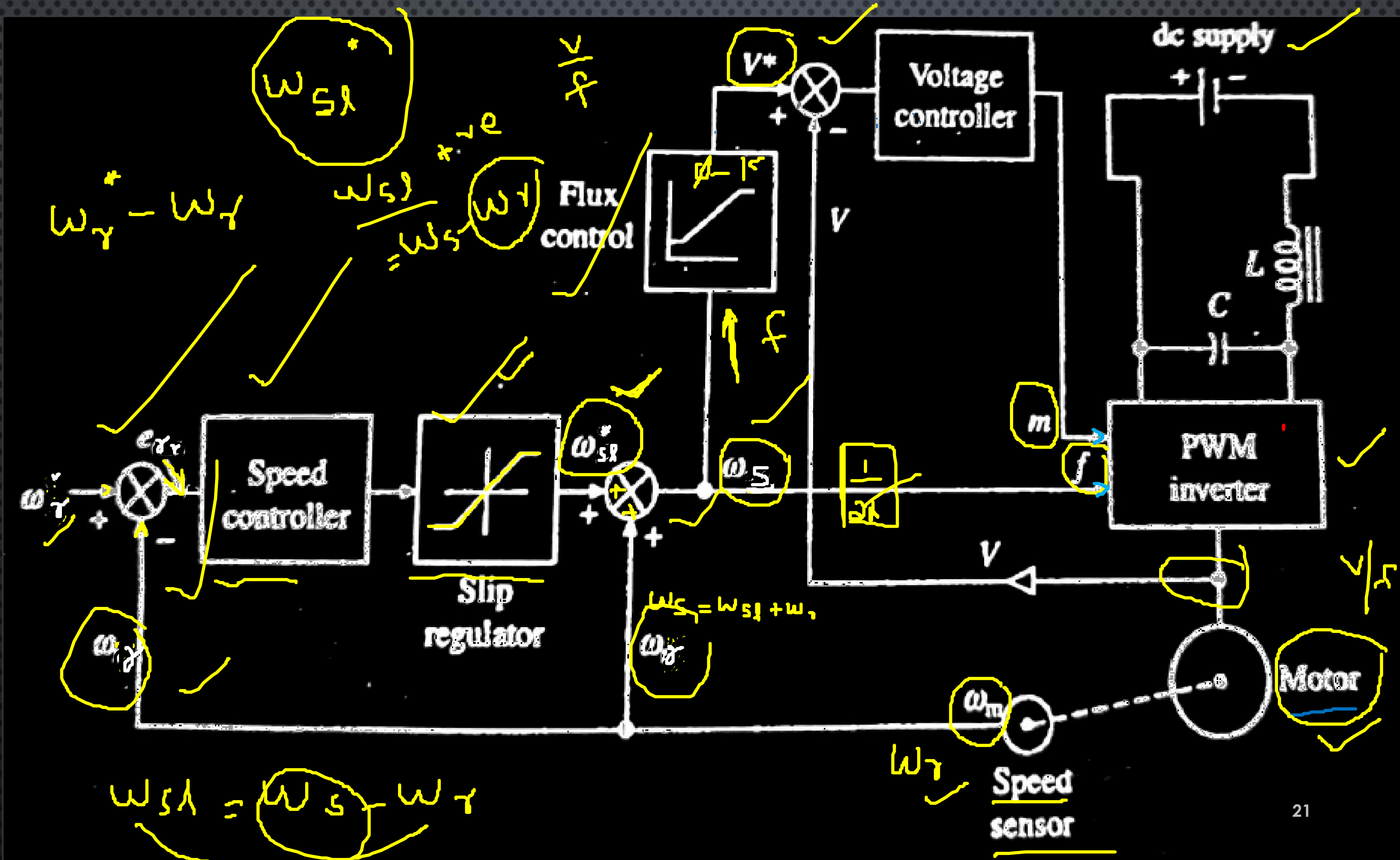
CONTROL OF THE SWITCHES FOR SINUSOIDAL PWM OUTPUT REQUIRES

- ❖ A REFERENCE SIGNAL CALLED A MODULATING OR CONTROL SIGNAL WHICH IS SINUSOIDAL
- ❖ A CARRIER SIGNAL WHICH IS A TRIANGULAR WAVE THAT CONTROLS THE SWITCHING FREQUENCY
- ❖ MODULATION INDEX (M) IS THE RATIO OF AR/AC WHERE AR IS THE PEAK AMPLITUDE OF REFERENCE SIGNAL AND AC IS THE PEAK AMPLITUDE OF CARRIER SIGNAL

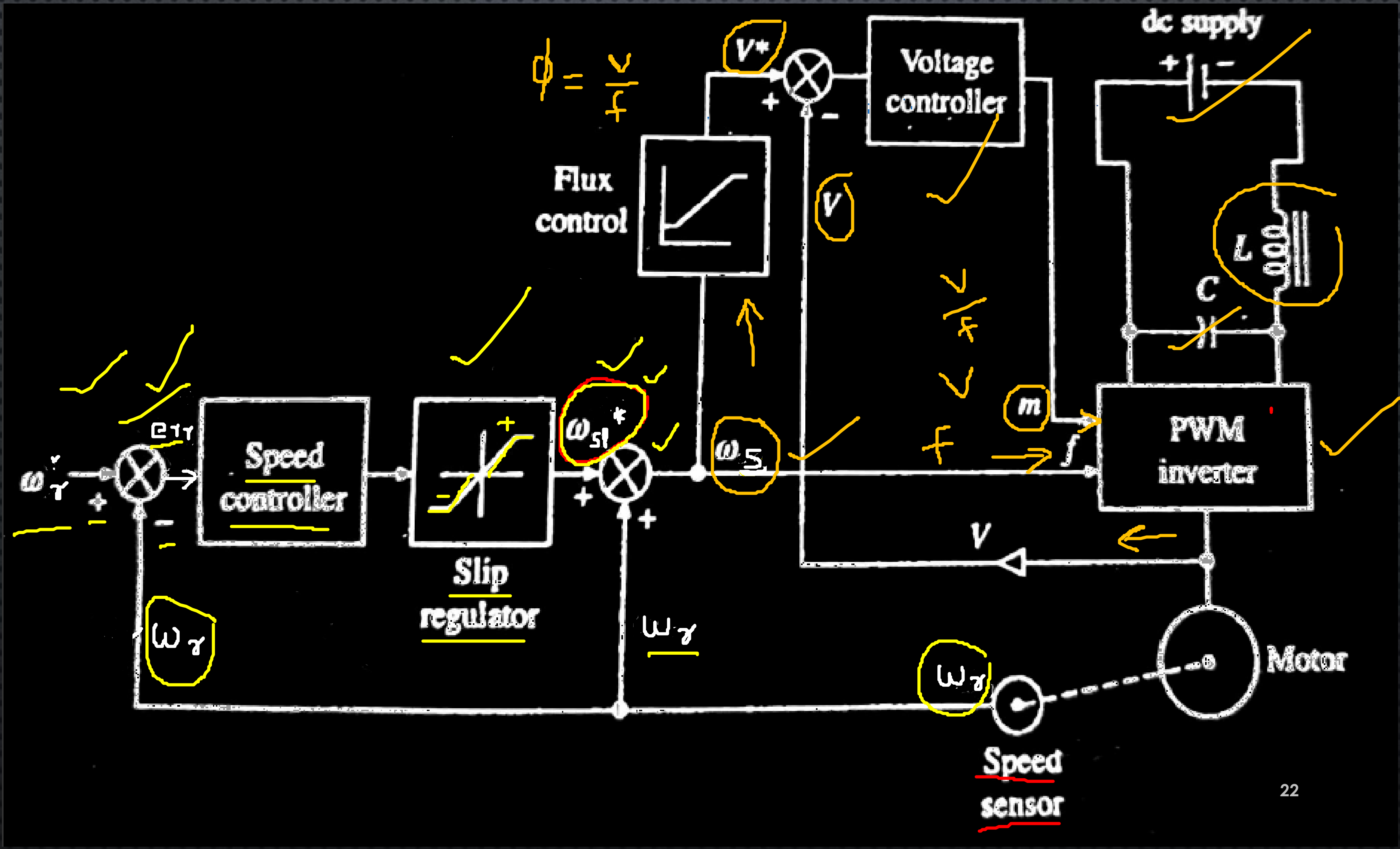
Sinusoidal pulse width modulation



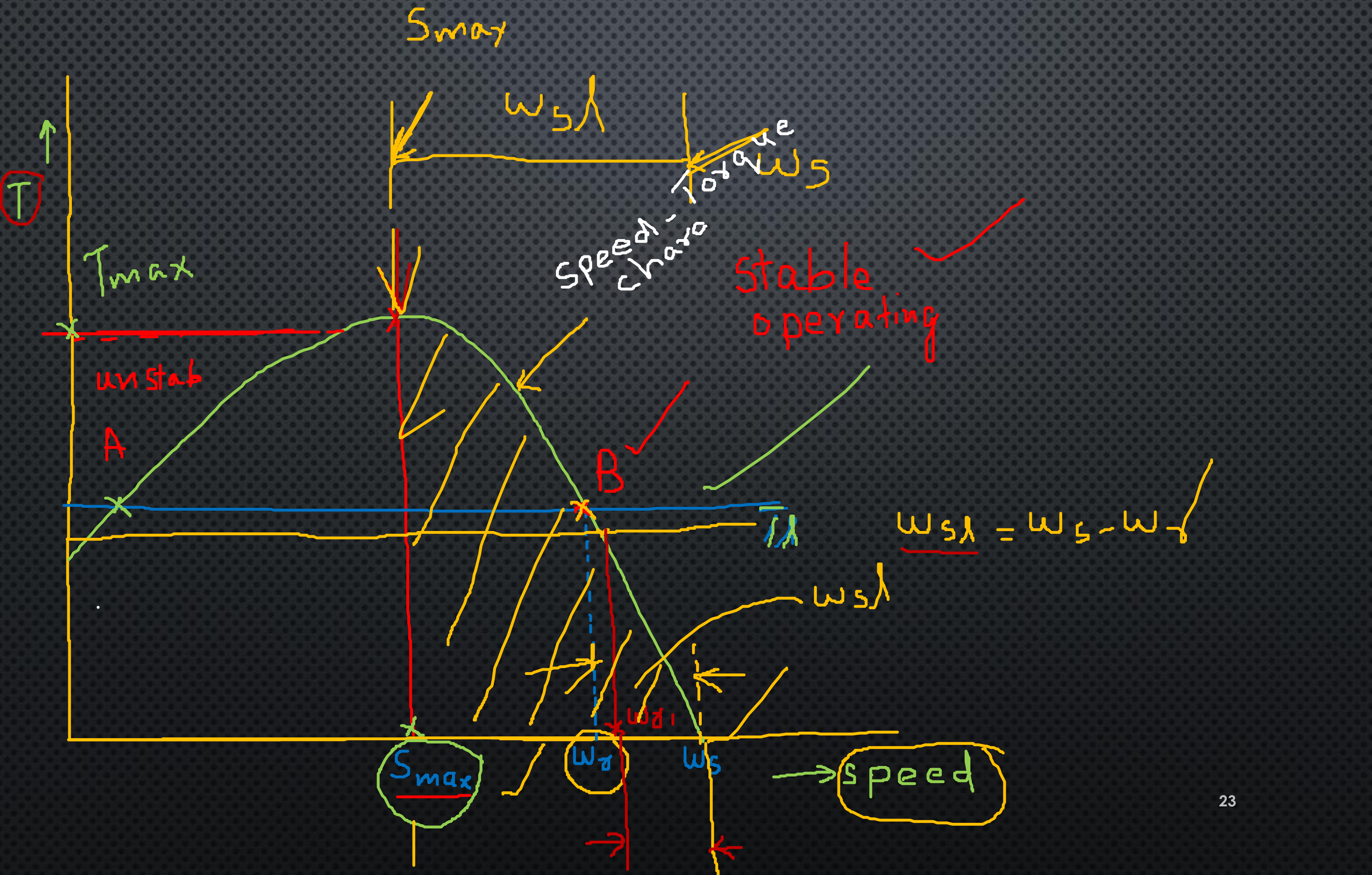
CLOSED LOOP SPEED CONTROL OF VSI DRIVEN INDUCTION MOTOR
CLOSED LOOP SLIP CONTROLLED PWM INVERTER WITH REGENERATIVE BRAKING
CLOSED LOOP SPEED CONTROL SCHEME OF INDUCTION MOTOR USING V/F METHOD



SLIP REGULATION IN CLOSED LOOP V/F SPEED CONTROL OF VSI DRIVEN INDUCTION MOTOR



Constant volts/HZ control with slip speed regulation



slip speed $= \omega_{sl} = \omega_s - \omega_r$

$$I_r' = \frac{V}{\sqrt{\left(\frac{R_r'}{s}\right)^2 + (X_s + X_r')^2}}$$

$\frac{V}{f}$ $\phi \rightarrow$ con

f^2 $K^2 f^2$

$V \rightarrow KV$

$f \rightarrow Kf$

$$I_r' = \frac{KV}{\sqrt{\left(\frac{R_r'}{s}\right)^2 + K^2(X_s + X_r')^2}} \Big/ K^2$$

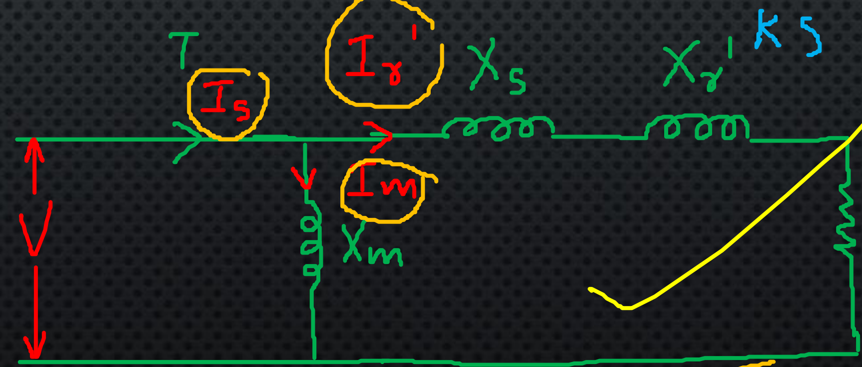
$$= \frac{\frac{V}{K}}{\sqrt{\left(\frac{R_r'}{Ks}\right)^2 + (X_s + X_r')^2}} = \frac{\left(\frac{V}{K}\right)}{\left(\frac{R_r'}{K^2 s^2}\right)}$$

$$I_r' = \frac{V}{R_r'} K \cdot S$$

$<<< \frac{R_r'}{Ks}$ $s \approx$ small

$Ks \rightarrow$ Con

$I_r' \rightarrow$ Con



resistive

$I_s = \sqrt{I_r'^2 + I_m^2}$

Torque equations

$f \rightarrow kf$

$$T = \frac{3}{k \cdot \omega_s} \left(I_r'\right)^2 \frac{R_r'}{s}$$

$$I_r' = \frac{V}{R_r'} K \cdot s$$

$$T = \frac{3}{K \omega_s} \cdot \frac{V^2 \cdot K^2 \cdot s^2}{(R_r')^2} \cdot \frac{R_r'}{s}$$

con

$$T = \frac{3}{\omega_s} \cdot \frac{V^2}{R_r'} K \cdot s = a \text{ Con} \times Ks$$

$$s = \frac{\omega_s - \omega_r}{\omega_s} \rightarrow f$$

$$I_r' = a \text{ con} \times Ks$$

$$Ks = \frac{\omega_s \lambda}{\omega_s}$$

$$s = \frac{k\omega_s - \omega_r}{k\omega_s} = \frac{\omega_s \lambda}{k\omega_s}$$

SLIP REGULATION WHEN FREQUENCY IS INCREASED AND VOLTAGE IS KEPT CONSTANT

K = 1 for Rated frequency

K > 1

$$I_r' = \frac{V}{\sqrt{\left(\frac{R_r'}{s}\right)^2 + K^2\left(X_s + X_r'\right)^2}} \cong \frac{V \cdot s}{R_r'}$$

$$s = \frac{\omega_{sl}}{K\omega_s}$$

$$I_r' = \frac{V}{R_r'} \cdot \frac{\omega_{sl}}{K \cdot \omega_s} = \frac{V}{R_r' \cdot \omega_s} \cdot \frac{\omega_{sl}}{K}$$

Con

$$I_r' \propto \frac{\omega_{sl}\uparrow}{K\uparrow}$$

If K is increased above rated frequency, then slip speed has to be increased to maintain constant Rotor current

$$T = \frac{3}{K \cdot \omega_s} \cdot (I_r')^2 \cdot \left(\frac{R_r'}{s}\right)$$

$$I_r' = \frac{V \cdot \omega_{sl}}{R_r' \cdot K \cdot \omega_s}$$ ← S

$$T = \frac{3}{K \cdot \omega_s} \cdot \frac{R_r'}{s} \cdot \frac{V^2 \omega_{sl}^2}{(R_r')^2 \cdot K^2 \cdot \omega_s^2} = \frac{3V^2}{R_r'} \cdot \frac{\omega_{sl}^2}{\omega_s^3 \cdot K^3} \cdot \frac{1}{s}$$

$$S = \frac{\omega_{sl}}{K \cdot \omega_s}$$

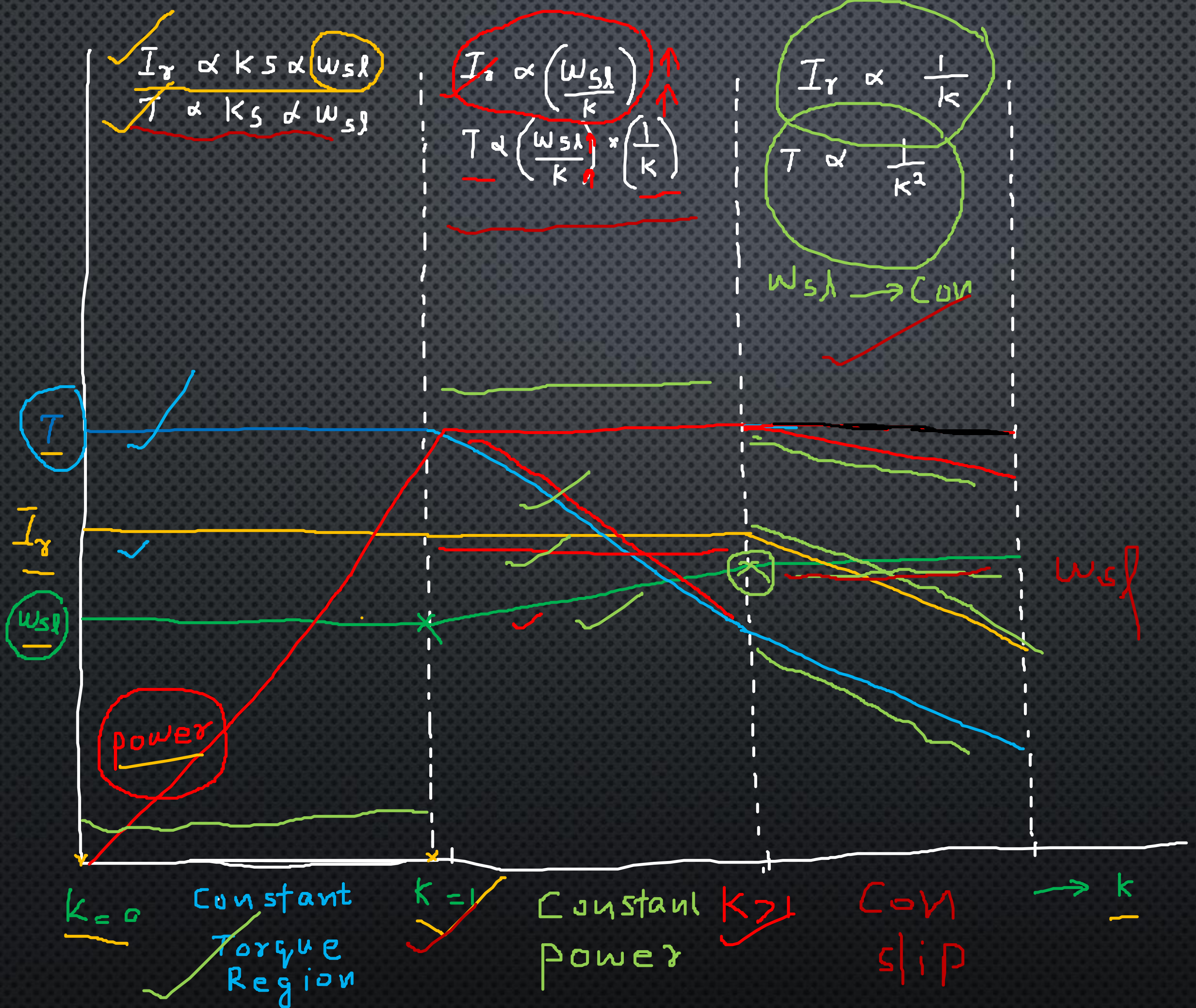
$$T = \frac{3V^2 \cdot \omega_{sl}^2 \cdot K \cdot \omega_s}{R_r' \cdot \omega_s^2 \cdot K^2 \cdot \omega_{sl}} = \frac{3V^2 \omega_{sl}}{R_r' \cdot \omega_s^2 K^2}$$ (K_1)

$$T = K_1 \left(\frac{\omega_{sl}}{K}\right) \cdot \frac{1}{K}$$

$K \uparrow \quad T \downarrow$

$$T \propto \frac{1}{K}$$

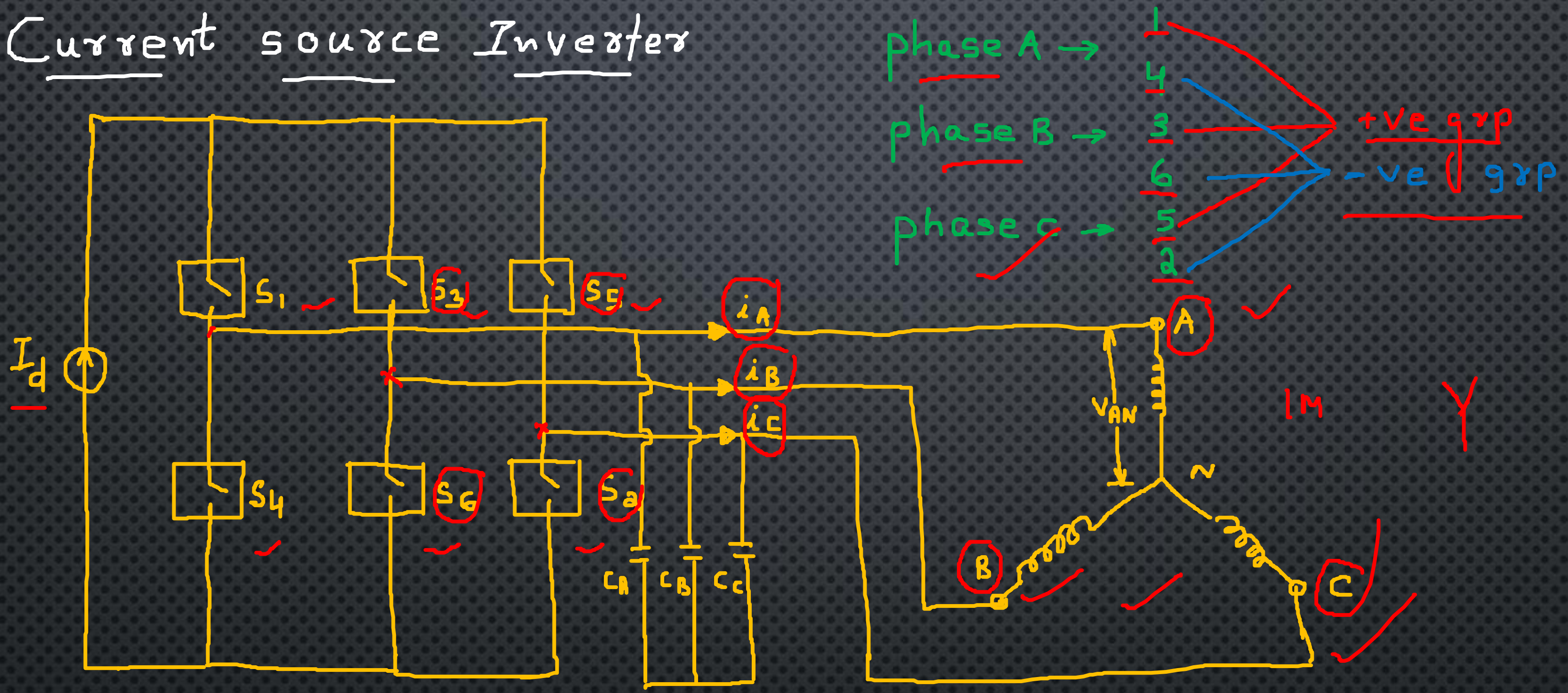
$K \uparrow \quad T \downarrow$



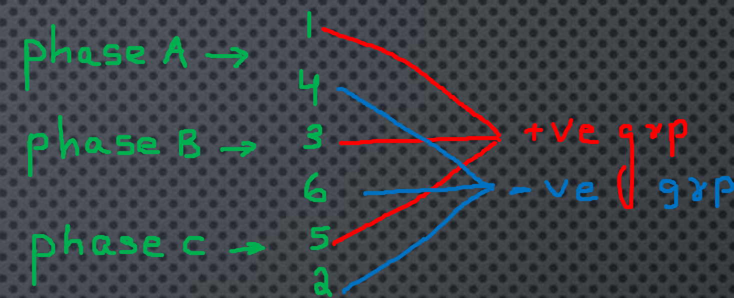
Ir ∝ Ks ∝ wsl
T ∝ Ks ∝ wsl
Ir ∝ (wsl / k)
T ∝ (wsl / k) × (1 / k)
Ir ∝ 1 / k
T ∝ 1 / k²
wsl → Con
T
Ir
wsl
power
wsl
k=0
Constant Torque Region
k=1
Constant power
k>1
Con slip
→ k

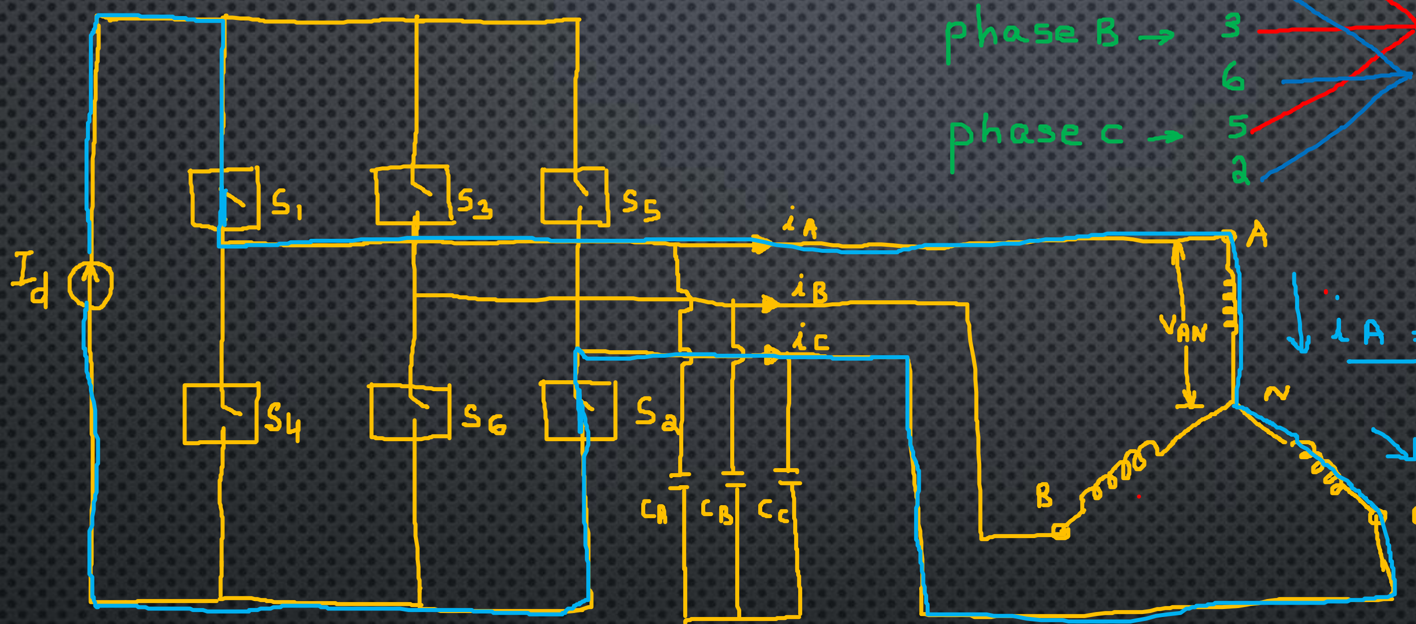
CSI FED INDUCTION MOTOR DRIVES

Current source Inverter



Current source Inverter

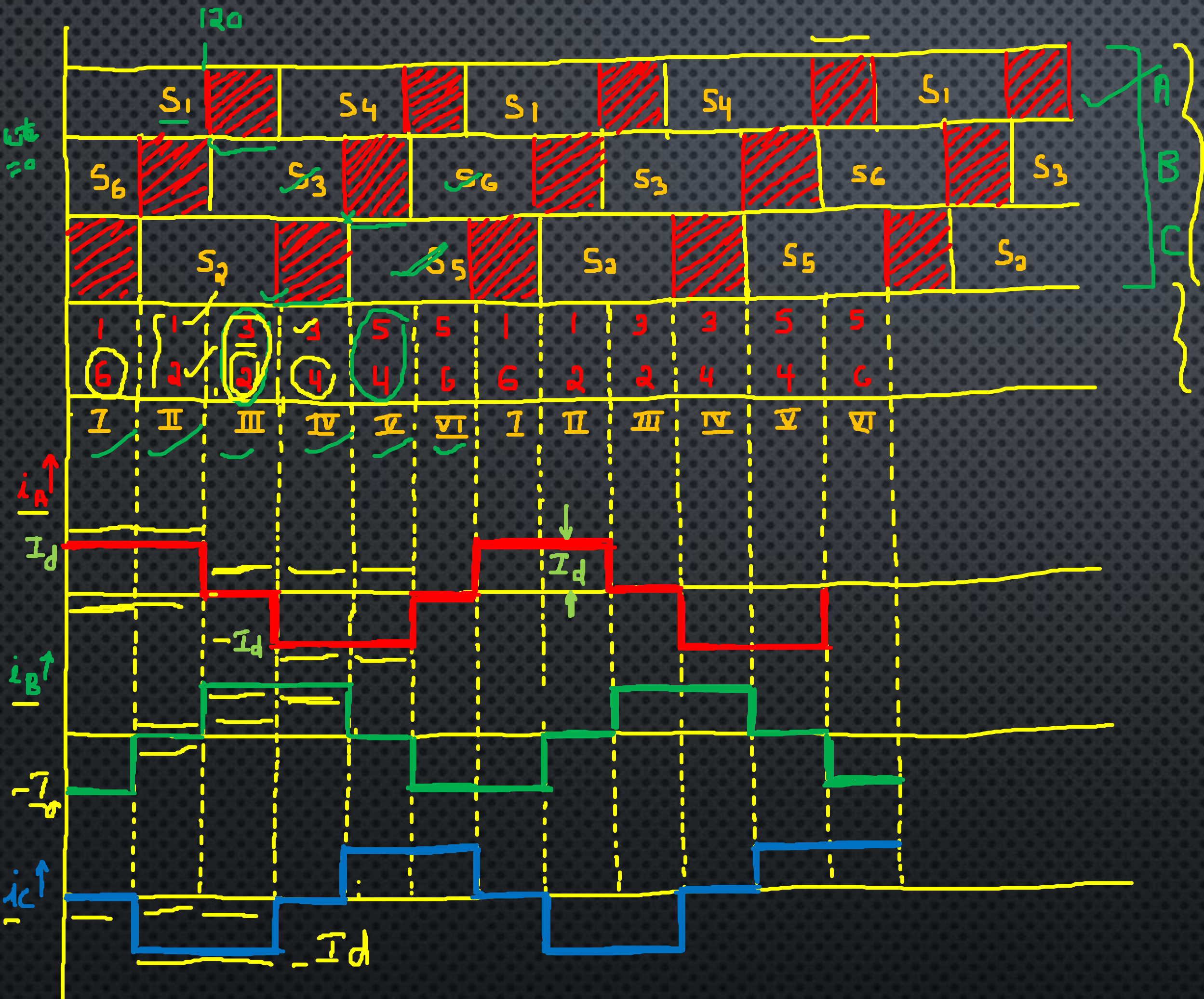




$i_A = I_d$

$i_C = -I_d$

Modes	I	II	III	IV	V	VI
	6	(A) 1 ✓	2	3	4	5
-	1	C (2)	3	4	5	6



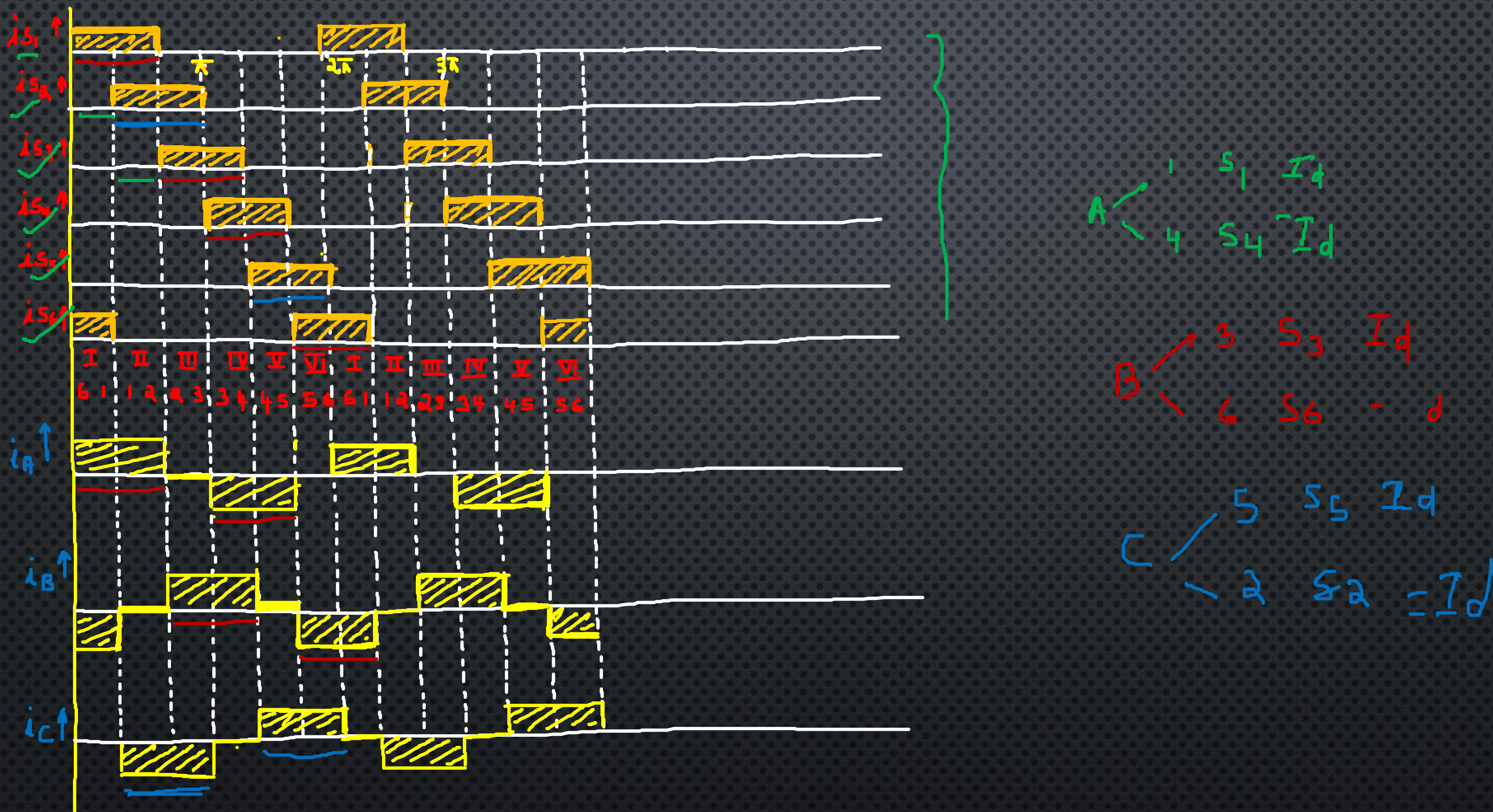
Gate Sequence

6 Modes of operation

iA → Line Current

iB → Line current

iC → Line current

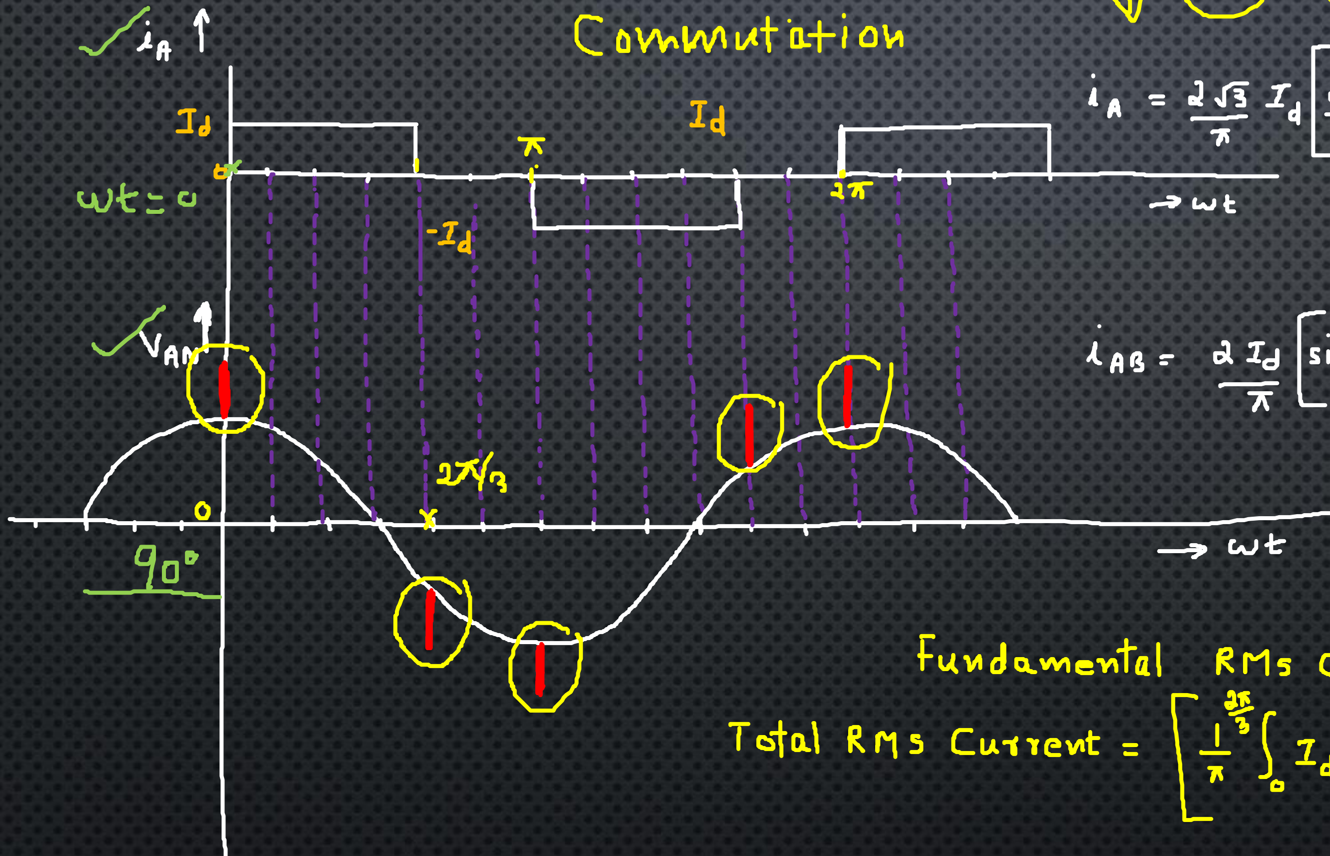


i_{S1}
i_{S2}
i_{S3}
i_{S4}
i_{S5}
i_{S6}
π
2π
3π
I II III IV V VI I II III IV V VI
61 12 23 34 45 56 61 12 23 34 45 56
i_A
i_B
i_C
A
1 S_1 I_d
4 S_4 $-I_d$
B
3 S_3 I_d
6 S_6 $-I_d$
C
5 S_5 I_d
2 S_2 $-I_d$

↓ Voltage Spikes ✓ C

$$\downarrow \uparrow V = L \downarrow \frac{di}{dt} \uparrow$$

Commutation



$$i_A = \frac{2\sqrt{3}}{\pi} I_d \left[\sin\left(\omega t + \frac{\pi}{6}\right) + \frac{1}{5}\sin\left(5\omega t - \frac{\pi}{6}\right) + \frac{1}{7}\sin\left(7\omega t + \frac{\pi}{6}\right) \ldots\right]$$

⇒ Y Load

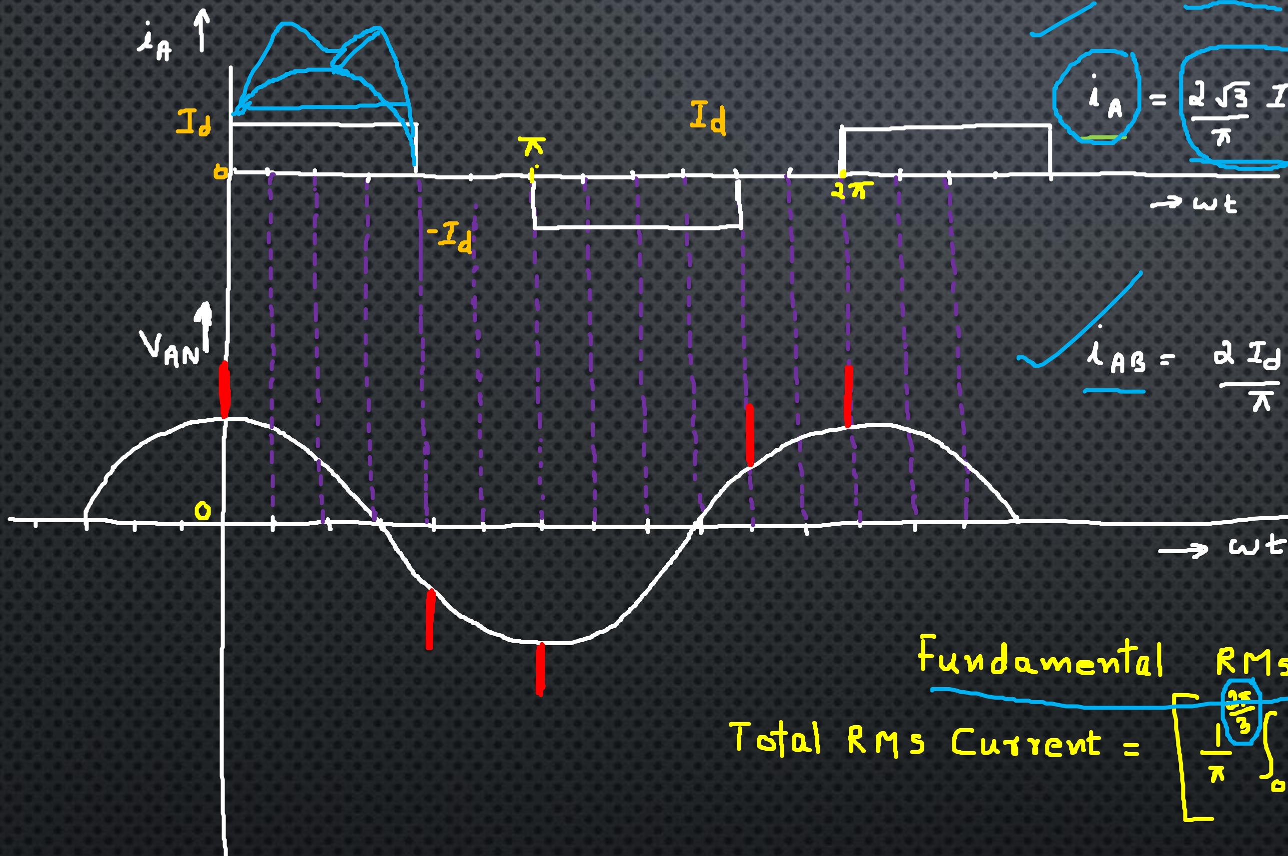
$$i_{AB} = \frac{2 I_d}{\pi} \left[\sin\left(\omega t + \frac{\pi}{3}\right) - \frac{1}{5}\sin\left(5\omega t - \pi/3\right) + \frac{1}{7}\sin\left(7\omega t + \pi/3\right) \ldots\right]$$

⇒ Δ Load

Fundamental RMS Current $= \frac{\sqrt{6}}{\pi} I_d$

Total RMS Current $= \left[\frac{1}{\pi}\int_0^{2\pi/3} I_d^2 \cdot d(\omega t)\right]^{1/2} = \sqrt{\frac{2}{3}}\, I_d$

Voltage Spikes



$$RMS = \frac{Max}{\sqrt{2}}$$

I_m

$$i_A = \frac{2\sqrt{3}\, I_d}{\pi}\left[\sin\left(\omega t + \frac{\pi}{6}\right) + \frac{1}{5}\sin\left(5\omega t - \frac{\pi}{6}\right) + \frac{1}{7}\sin\left(7\omega t + \frac{\pi}{6}\right)\ldots\right]$$

⇒ Y Load

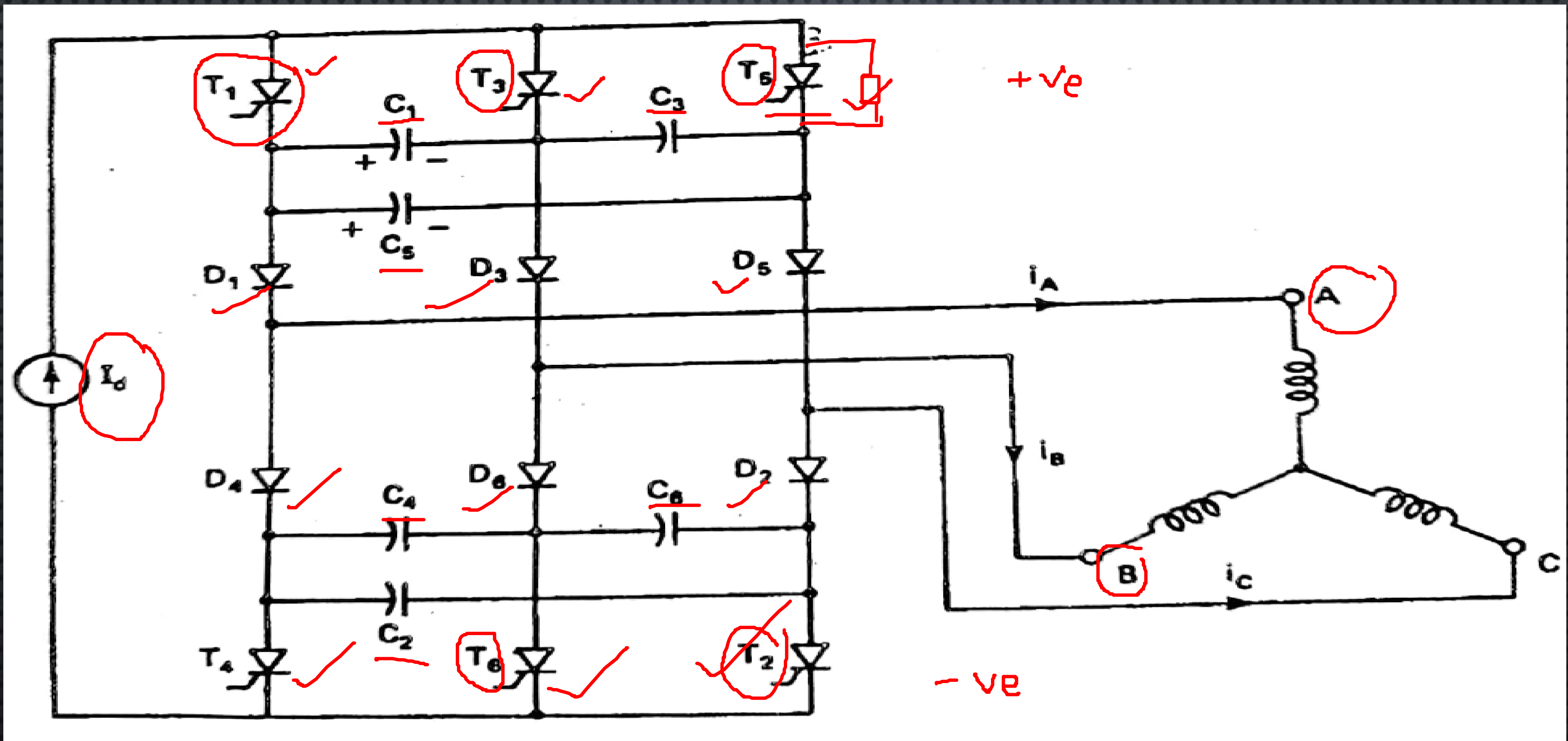
$$i_{AB} = \frac{2 I_d}{\pi}\left[\sin\left(\omega t + \frac{\pi}{3}\right) - \frac{1}{5}\sin\left(5\omega t - \pi/3\right) + \frac{1}{7}\sin\left(7\omega t + \pi/3\right)\ldots\right]$$

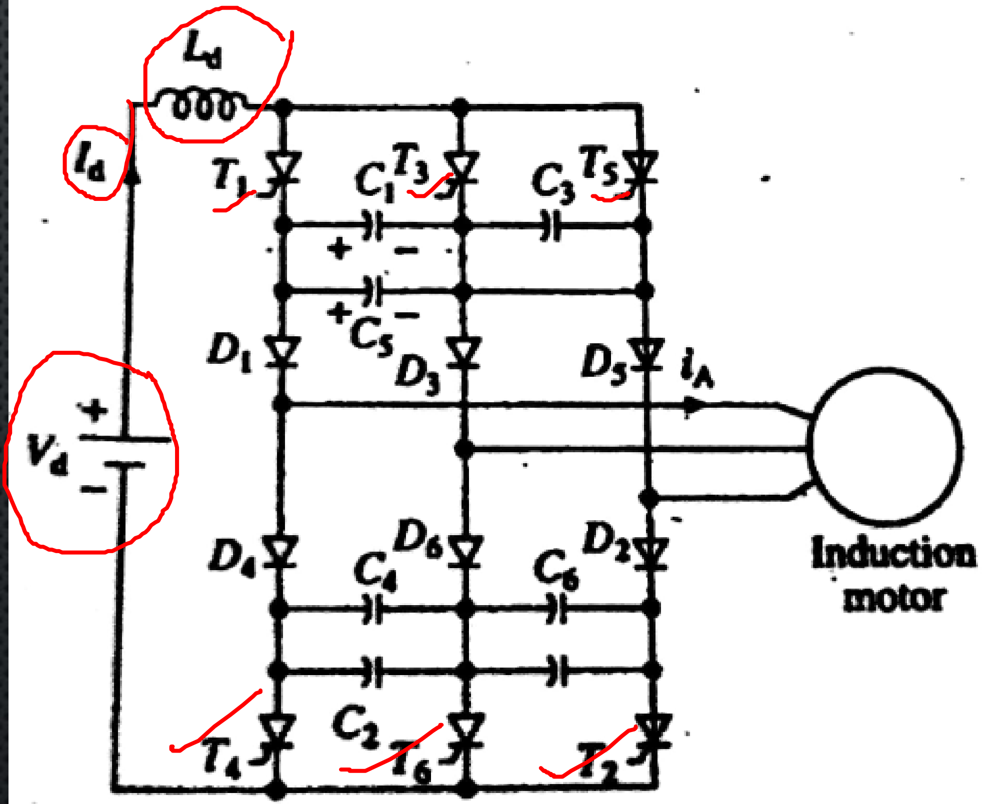
⇒ Δ Load

Fundamental RMS Current $= \frac{\sqrt{6}}{\pi} I_d$

Total RMS Current $= \left[\frac{1}{\pi}\int_0^{2\pi/3} I_d^2 \cdot d(\omega t)\right]^{1/2} = \sqrt{\frac{2}{3}}\, I_d$

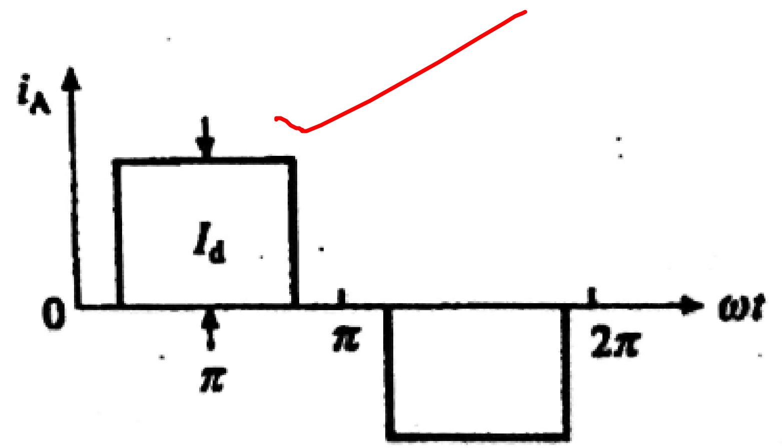
AUTO SEQUENTIALLY COMMUTATED CURRENT SOURCE INVERTER





Ld
Id
T1
C1
T3
C3
T5
+
−
C5
D1
D3
D5
iA
Vd
+
−
Induction
motor
D4
C4
D6
C6
D2
C2
T4
T6
T2

(a)



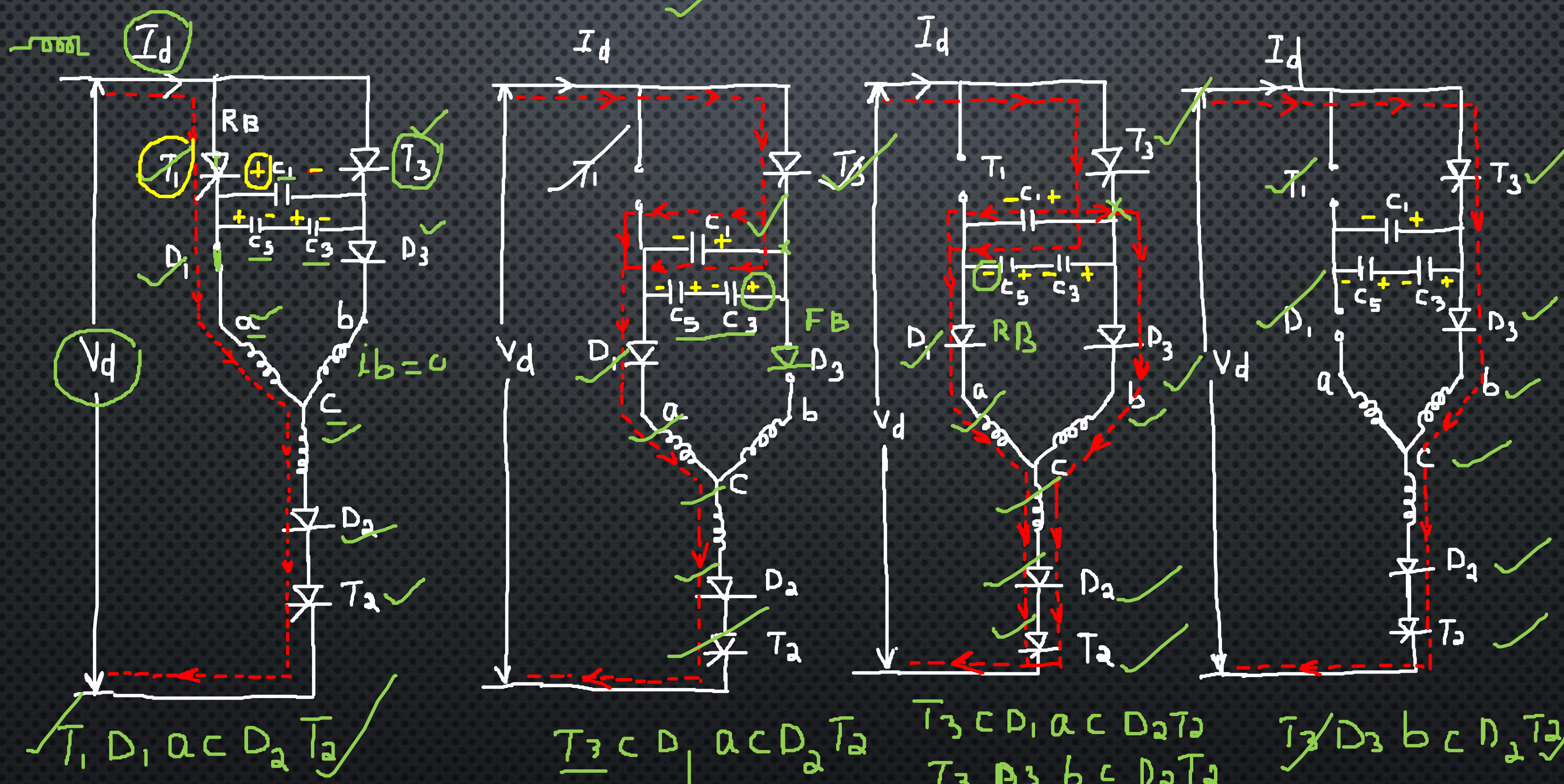
iA
Id
0
π
π
2π
ωt

(b)

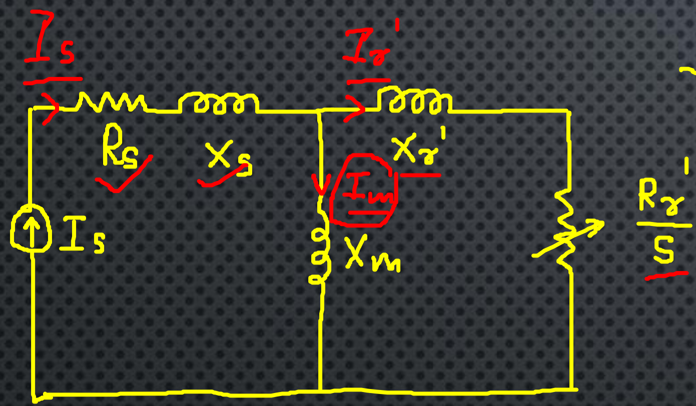

is1
is2
is3
is4
is5
is6
π
2π
3π
I II III IV V VI I II III IV V VI
61 12 23 34 45 56 61 12 23 34 45 56
iA
iB
iC

123456

Commutation process



How to implement closed loop Control using CSI



$$I_r' = \frac{I_s \cdot X_m}{\sqrt{\left(\frac{R_r'}{s}\right)^2 + (X_m + X_r')^2}} \quad — (1)$$

$$T = \frac{3}{\omega_s} (I_r')^2 \left(\frac{R_r'}{s}\right) \quad — (2)$$

$$T = \frac{3}{\omega_s} \frac{I_s^2 \cdot X_m^2 \cdot \left(\frac{R_r'}{s}\right)}{\left(\frac{R_r'}{s}\right)^2 + (X_m + X_r')^2} \quad — (3)$$

I_m produces flux

$I_m \uparrow \quad \phi \uparrow$

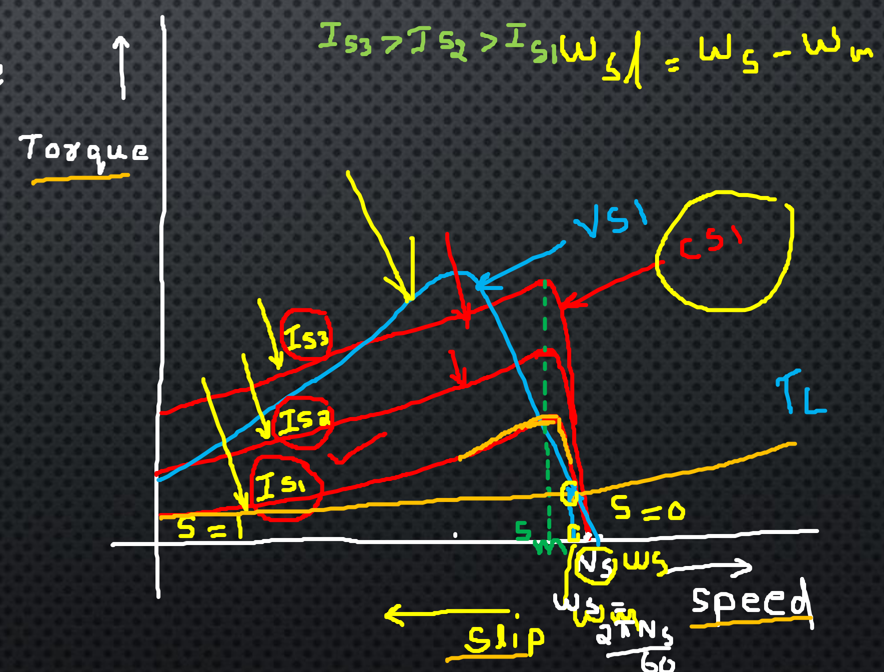
SLIP FOR MAXIMUM TORQUE

Slip for Maximum Torque, $S_m = \dfrac{R_r'}{X_m + X_r'}$

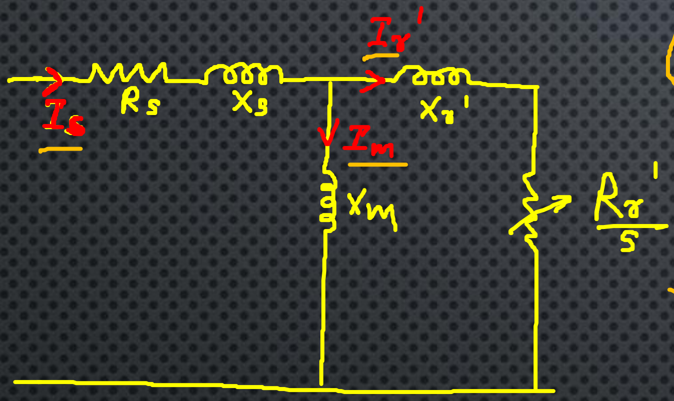
Torque is max when $S_m = \dfrac{R_r'}{X_m + X_r'}$

i.e $R_r' = X_m + X_r'$

$$\text{Torque} = \frac{3 \cdot I_s^2 \cdot X_m^2 \cdot \left(\frac{R_r'}{s}\right)}{\omega_s\left[\left(\frac{R_r'}{s}\right)^2 + \left(X_m + X_r'\right)^2\right]}$$



Stator Current (I_s) Versus slip frequency (sf)



I_s

I_m = Magnetising Current = Constant for airgap flux to be constant

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

$X_r = 2\pi f L_r'$

$$I_m^2 = \frac{I_s^2\left[\left(\frac{R_r'}{s}\right)^2 + (2\pi f L_r')^2\right]}{\left(\frac{R_r'}{s}\right)^2 + (2\pi f L_m + 2\pi f L_r')^2} = \frac{I_s^2\left[\left(\frac{R_r'}{s}\right)^2 + 4\pi^2 f^2 (L_r')^2\right]}{\left(\frac{R_r'}{s}\right)^2 + 4\pi^2 f^2 (L_m + L_r')^2}$$

div by f^2

$$I_m^2 = \frac{I_s^2\left[\left(\frac{R_r'}{sf}\right)^2 + 4\pi^2 (L_r')^2\right]}{\left(\frac{R_r'}{sf}\right)^2 + 4\pi^2 (L_m + L_r')^2}$$

Case1 : sf <<<1

$$I_m^2 = \frac{I_s^2\left[\left(\frac{R_r'}{s}\right)^2 + (2\pi f L_r')^2\right]}{\left(\frac{R_r'}{s}\right)^2 + (2\pi f L_m + 2\pi f L_r')^2} = \frac{I_s^2\left[\left(\frac{R_r'}{s}\right)^2 + 4\pi^2 f^2 (L_r')^2\right]}{\left(\frac{R_r'}{s}\right)^2 + 4\pi^2 f^2 (L_m + L_r')^2}$$

$$I_m^2 = \frac{I_s^2\left[\left(\frac{R_r'}{sf}\right)^2 + 4\pi^2 (L_r')^2\right]}{\left(\frac{R_r'}{sf}\right)^2 + 4\pi^2 (L_m + L_r')^2}$$

$$I_m^2 = I_s^2 \cdot \frac{\left(\frac{R_r'}{sf}\right)^2}{\left(\frac{R_r'}{sf}\right)^2}$$

$$I_m = I_s$$

sf → very small

CASE 2 : Sf moderately small

$$I_m^2 = \frac{I_s^2\left[\left(\frac{R_r'}{s}\right)^2 + (2\pi f L_r')^2\right]}{\left(\frac{R_r'}{s}\right)^2 + (2\pi f L_m + 2\pi f L_r')^2} = \frac{I_s^2\left[\left(\frac{R_r'}{s}\right)^2 + 4\pi^2 f^2 (L_r')^2\right]}{\left(\frac{R_r'}{s}\right)^2 + 4\pi^2 f^2 (L_m + L_r')^2}$$

$$I_m^2 = \frac{I_s^2\left[\left(\frac{R_r'}{sf}\right)^2 + 4\pi^2 (L_r')^2\right]}{\left(\frac{R_r'}{sf}\right)^2 + 4\pi^2 (L_m + L_r')^2}$$

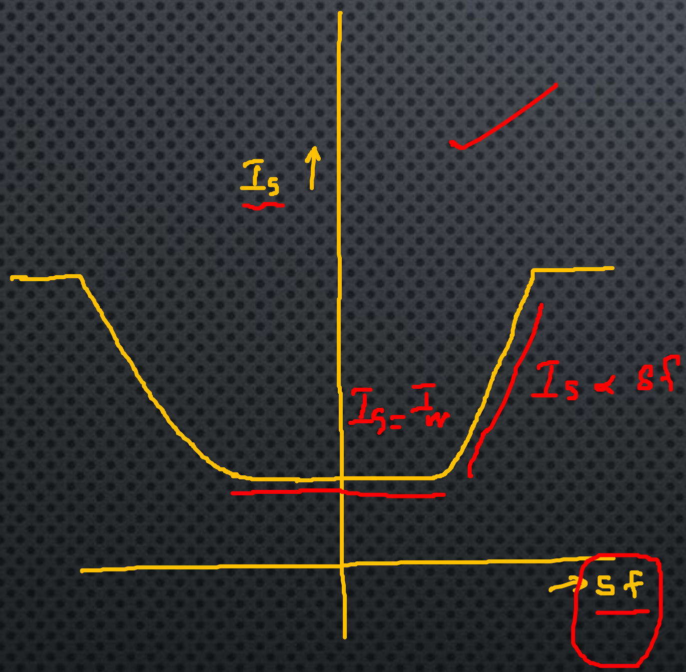
$$I_m^2 = \frac{I_s^2\left(\frac{R_r'}{sf}\right)^2}{4\pi^2 (L_m + L_r')^2}$$

$$I_s^2 = \frac{I_m^2 \cdot 4\pi^2 \cdot (L_m + L_r')^2 (sf)^2}{(R_r')^2}$$

$$I_s = \frac{I_m \cdot 2\pi (L_m + L_r) \cdot sf}{R_r'}$$

$$I_s \propto Sf$$

Stator current Vs slip frequency



$$S = \frac{\omega_{sl}}{\omega_s}$$

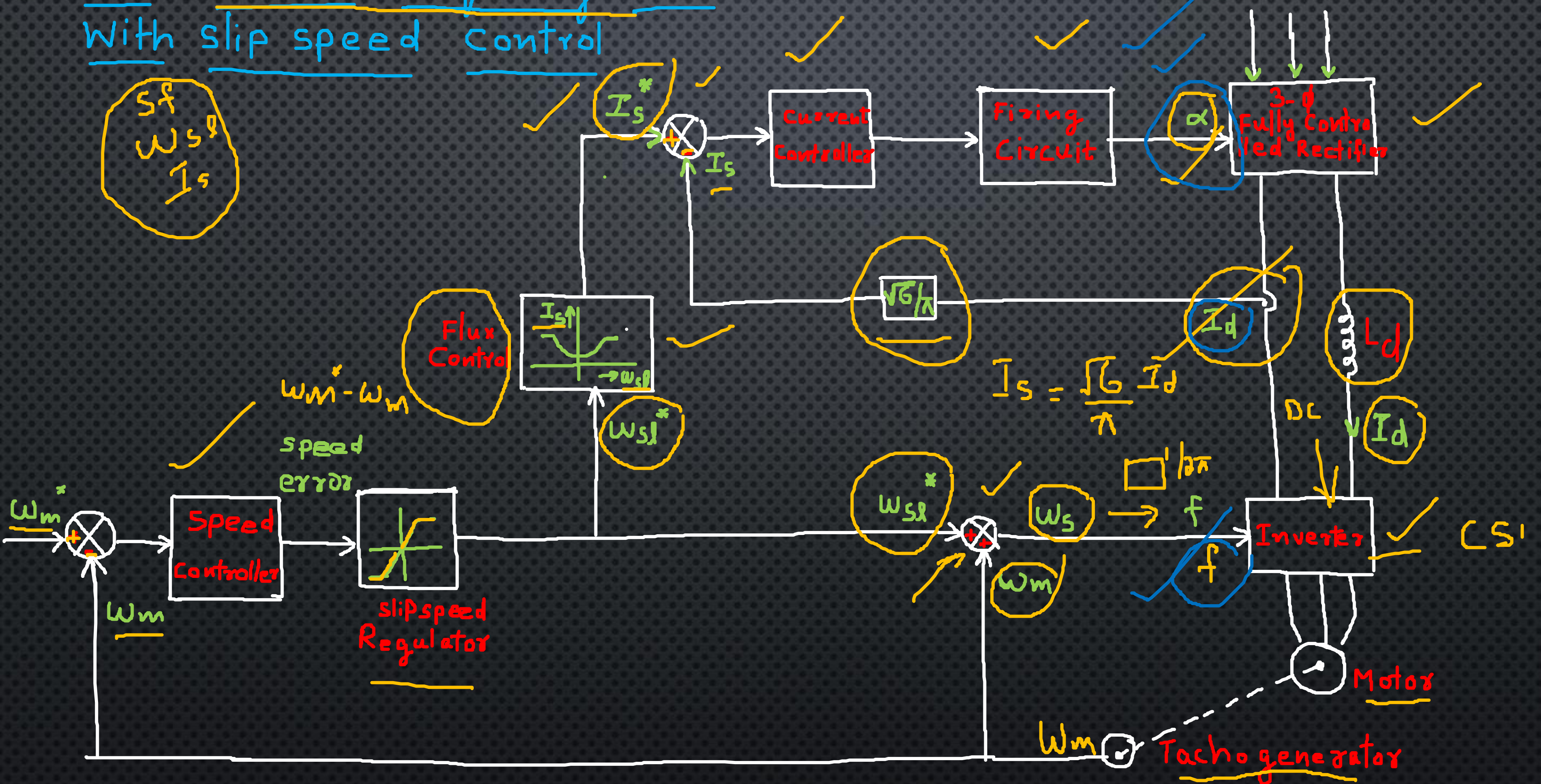
$$\omega_{sl} = S.\omega_s = S.2\pi.f$$

$$\omega_{sl} \propto Sf$$

$$I_s \propto Sf$$

$$I_s = \frac{\sqrt{6}.I_d}{\pi}$$

CSI Variable frequency Drive
With slip speed Control



MOTORING AND BRAKING MODE OPERATION OF CSI FED INDUCTION MOTOR DRIVE

method?

14 Explain the static Kramer scheme for the speed control of a slip ring IM. Explain the firing angle control of thyristor bridge with constant motor field. (10)

PART D

Answer any two full questions, each carries 10 marks.

15 a) With a neat circuit and waveform explain a thyristor based CSI fed IM drive. (5)

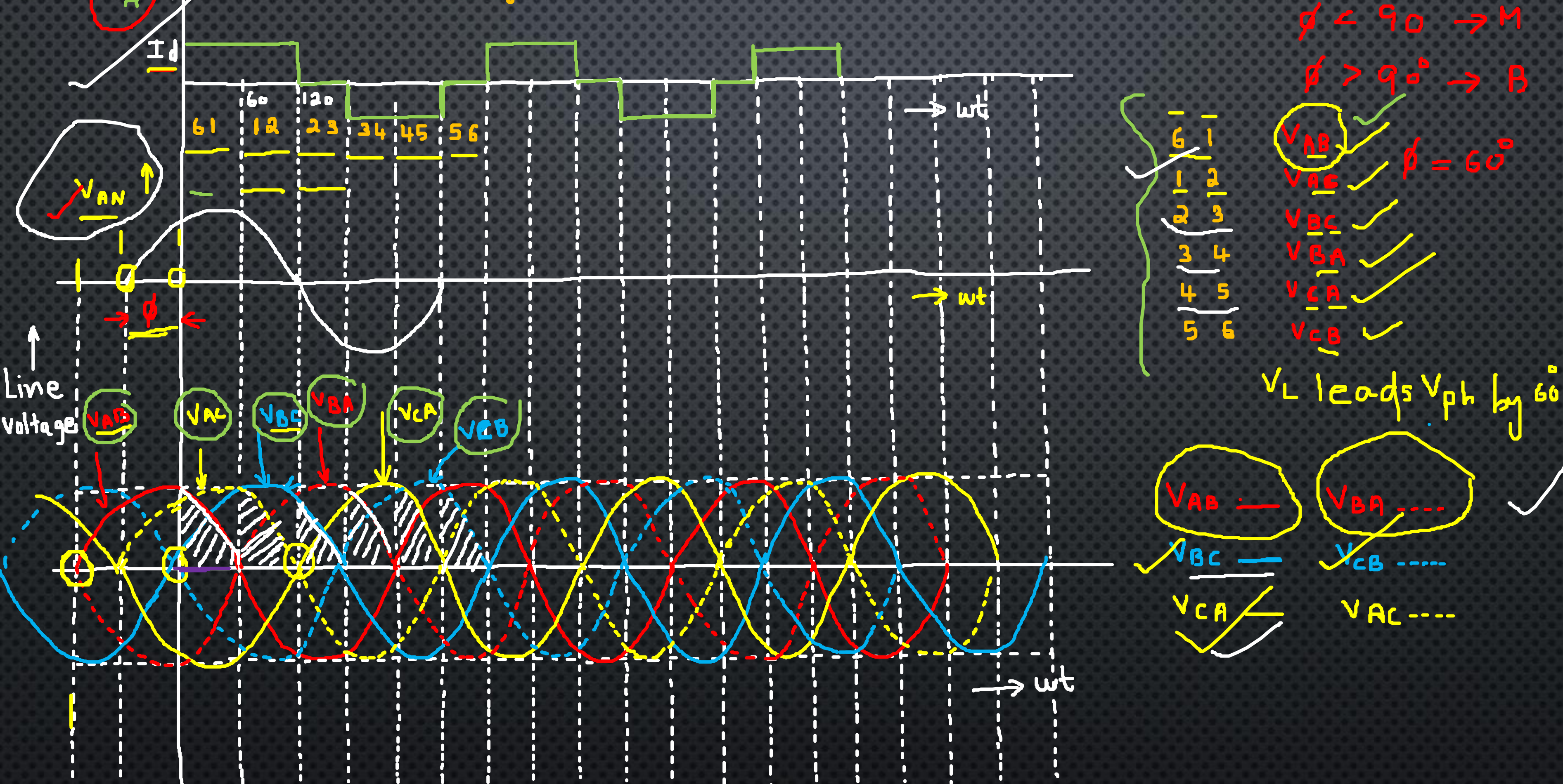
blk diag

b) Explain how CSI fed IM drive can be used for regenerative braking and multiquadrant operation. (5)

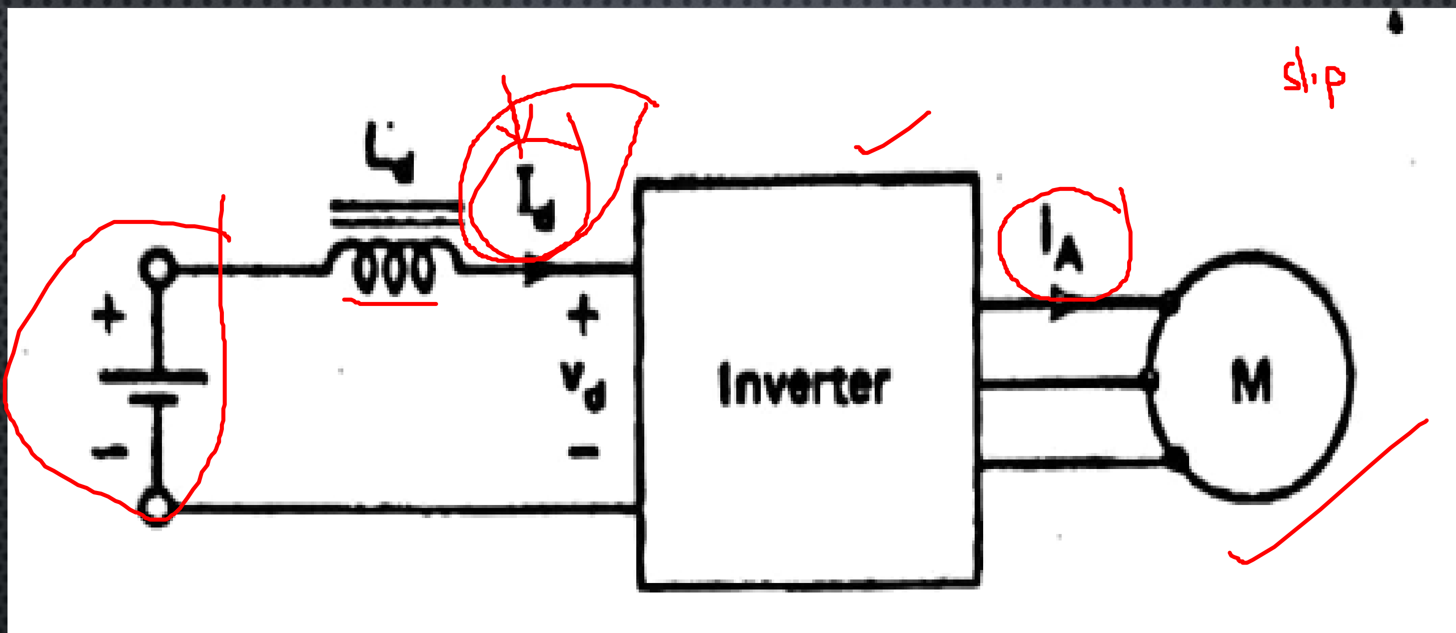
16 a) Explain in detail about the classification of PM synchronous motor? (5)

b) Explain the field oriented control (FOC) of an AC motor with a block diagram (5)

Motoring operation of CSI Fed IM Drive

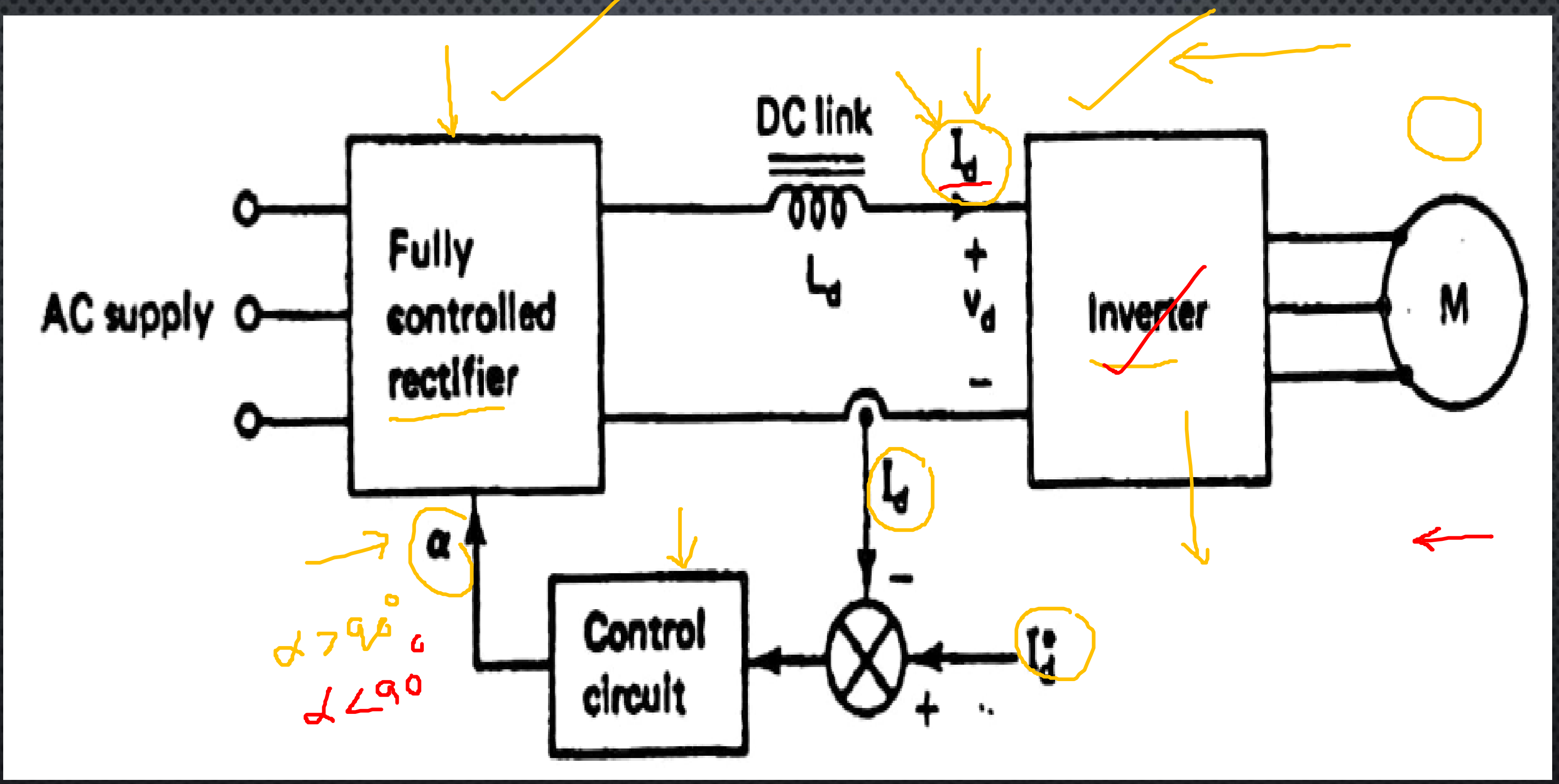


CSI DRIVEN INDUCTION MOTOR DRIVE

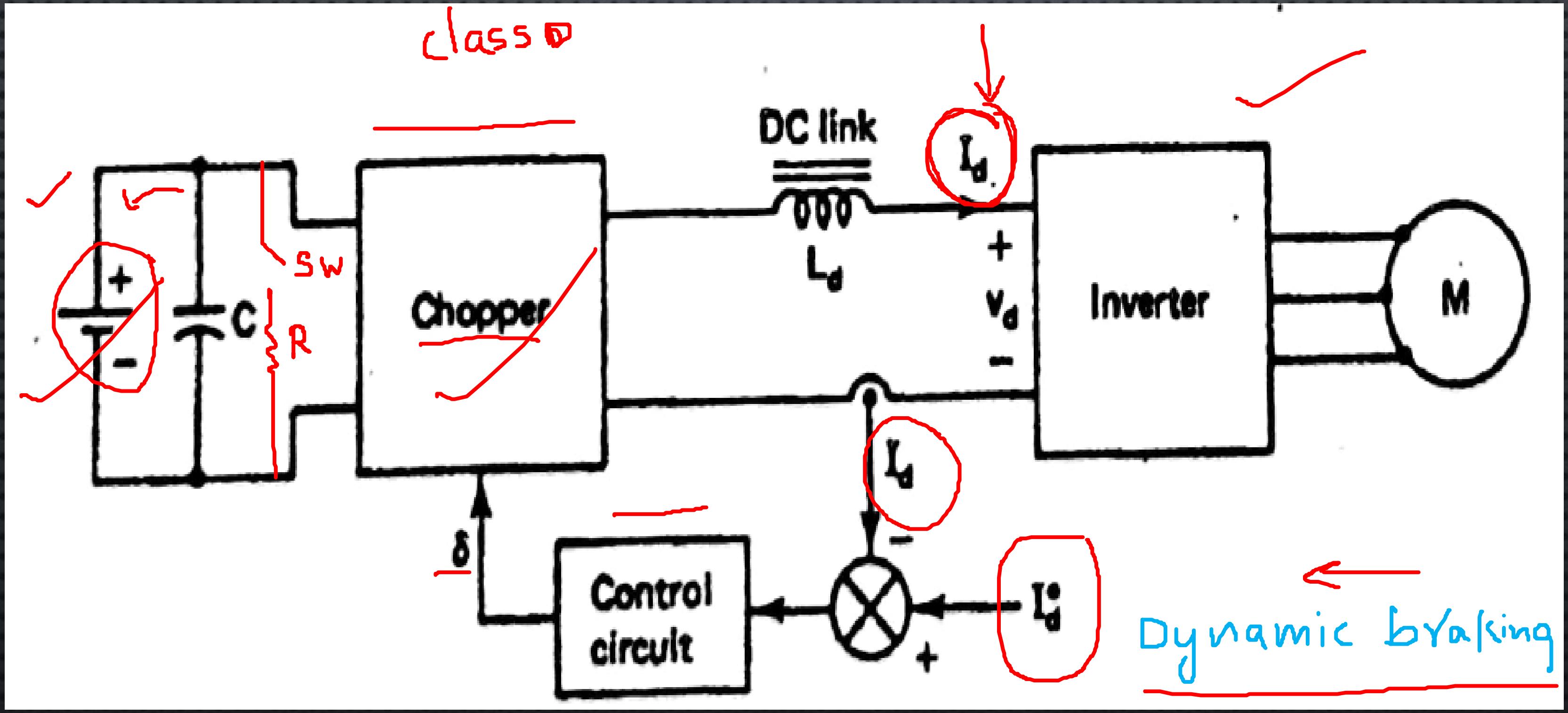


(a)

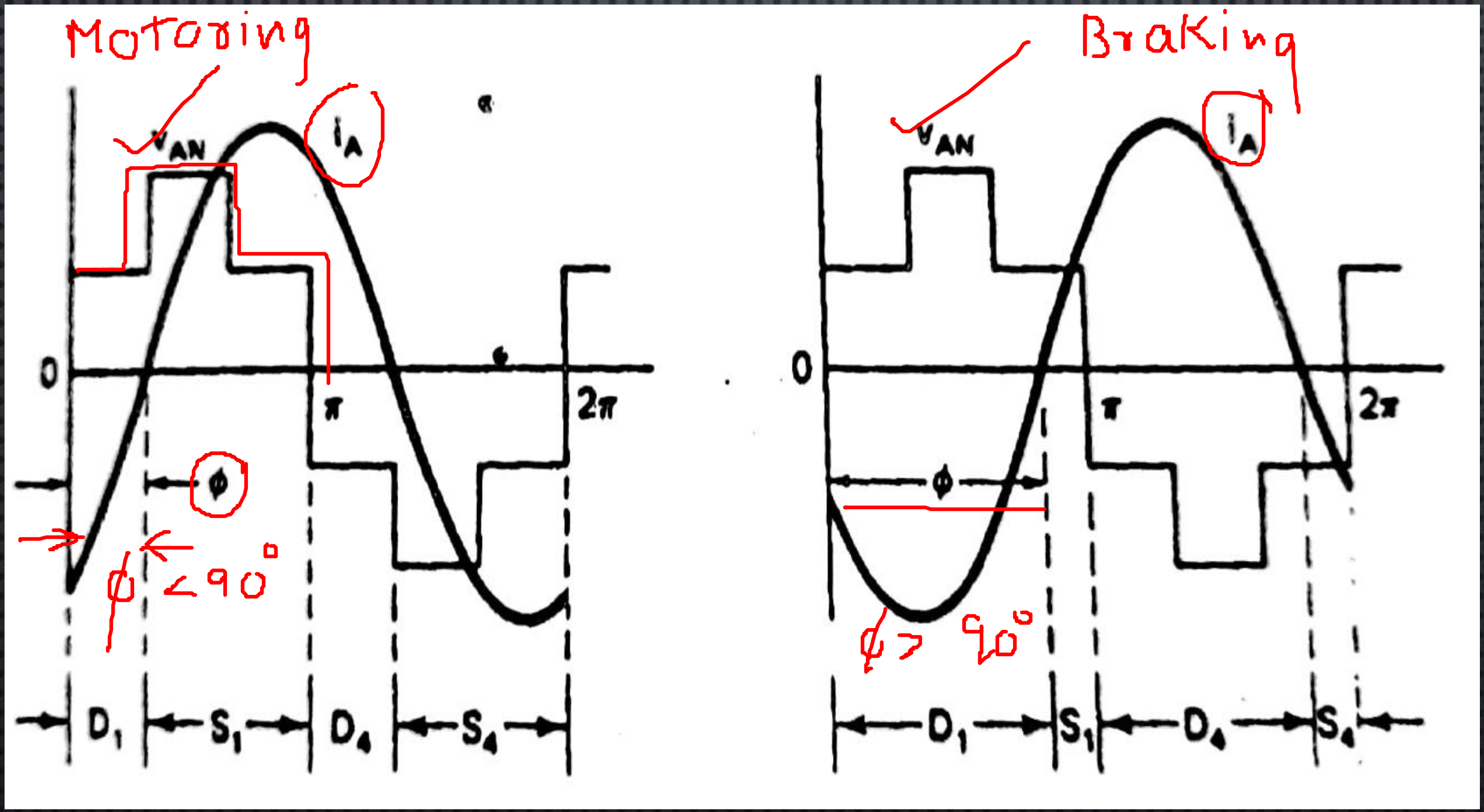
CSI DRIVEN INDUCTION MOTOR DRIVE-CLOSED LOOP



CSI DRIVEN INDUCTION MOTOR DRIVE USING CHOPPERS

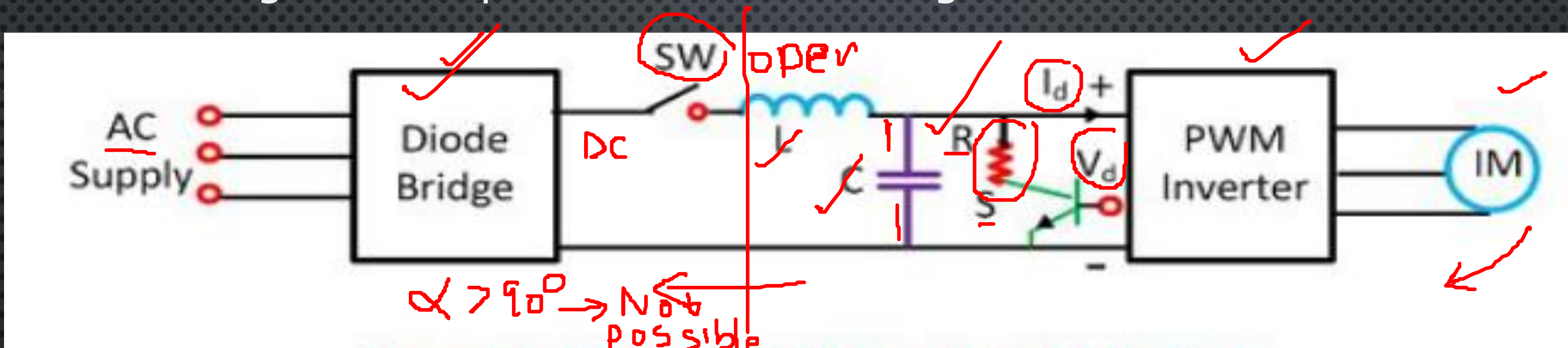


BRAKING AND MULTIQUADRANT CONTROL IN VSI FED INDUCTION MOTOR DRIVE



BRAKING OF VSI INDUCTION MOTOR DRIVES

Dynamic Braking: In dynamic braking, the switch SW and a self-commutated switch in series with the braking resistance R are connected across the DC links. When the operation of the motor is shifted from motoring to braking switch SW is opened. The energy flowing through the DC link charges the capacitors and its voltage rises.

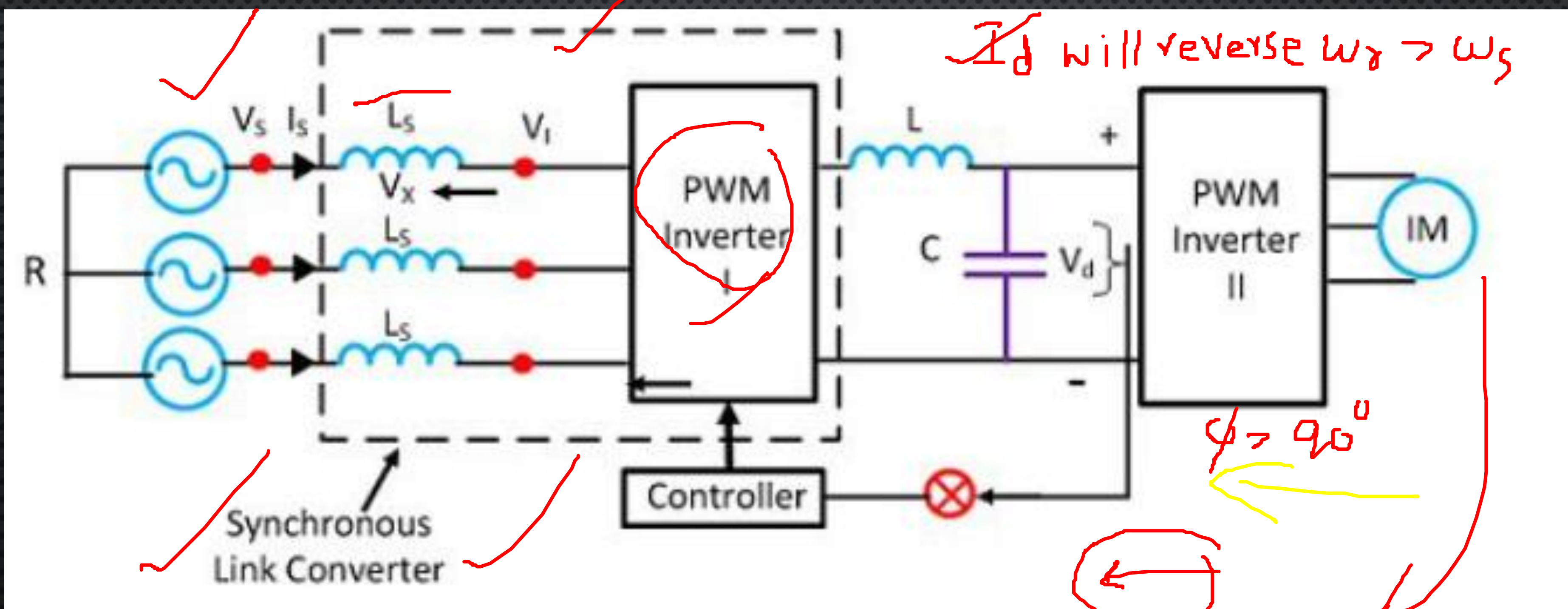


Dynamic Braking of VSI Controlled IM Drives

When the voltage crosses the set value, switch S is closed, connecting the resistance across the link. The energy which is stored in the capacitor flows into the resistance and reduces the DC link voltage. When it falls to its nominal value S is opened.Thus the closing and opening of the switch depends on the DC link voltage, and the generated energy is dissipated in the resistance gives dynamic braking.

REGENERATIVE BRAKING

When the operation shift from motoring to braking, the DC link current I_d reverse and flows into the DC supply feeding the energy to the source. Thus the drive already has the regenerative braking capability. In regenerative braking the, the power supply to the DC link must be transferred to the AC supply. When the operation shift from motoring to braking, the DC link current I_d reverse, but the V_d remain in the same direction. Thus, for regenerative braking, a converter is required for converting the DC voltage and direct current in either direction.



FOUR QUADRANT OPERATION

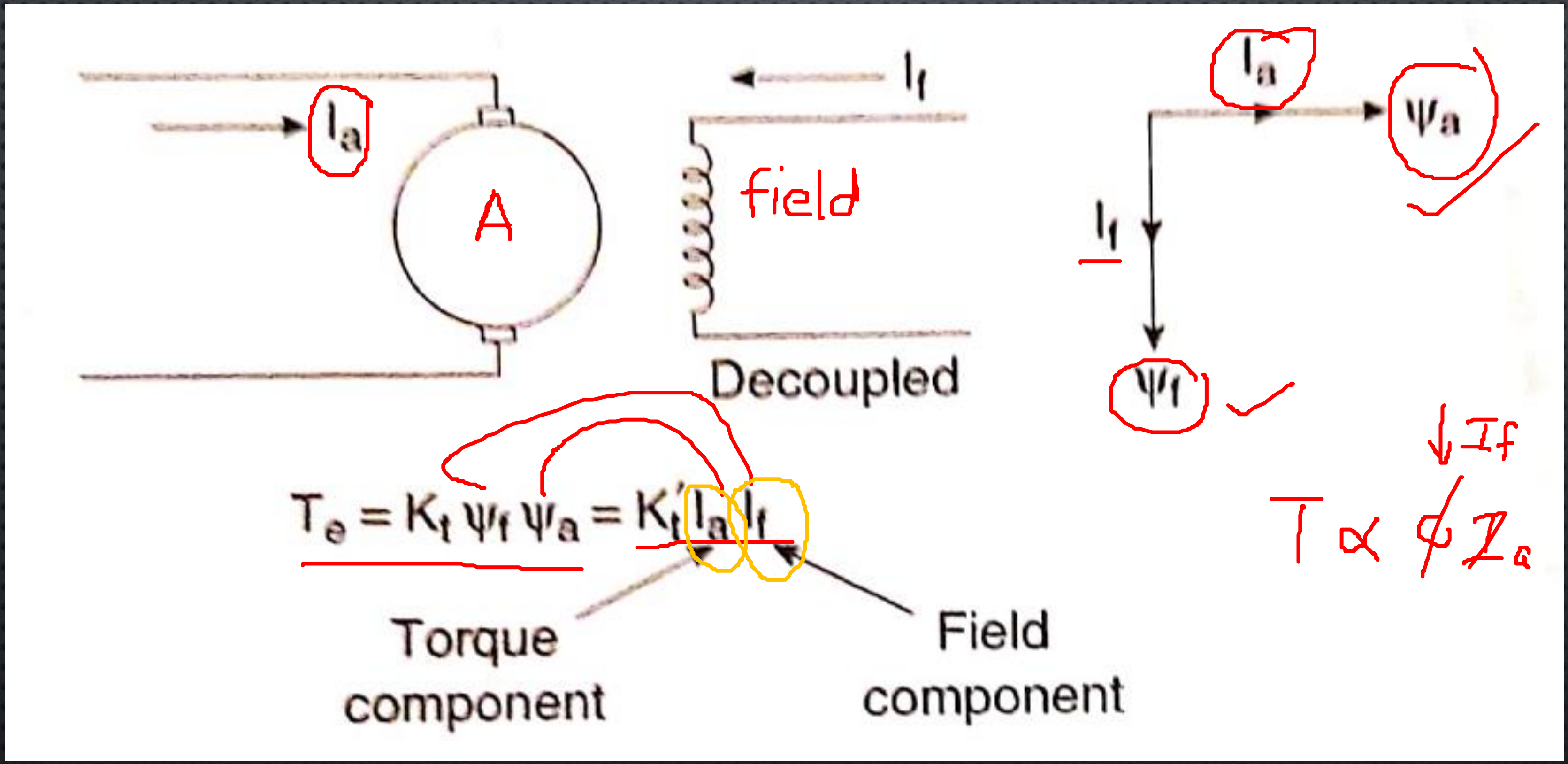
Braking capability obtains the four quadrant operation of the drive. The reduction of the inverter frequency makes the synchronous speed less than the motor speed. Thus the operation of the motors is transferred from quadrant 1 (forward motoring) to quadrant 2 (forward braking). The inverter frequency and voltage are progressively reduced as the speed falls, to brake the machine from zero speed. The phase sequence of the output voltage is reversed by interchanging the firing pulse of the thyristor. Thus, the operation of the motor is transferred from the second quadrant to the third quadrant (reverse motoring). The inverter frequency and voltage are increased to get the required speed in the reverse direction.

VECTOR CONTROL OR FIELD ORIENTED CONTROL

SCALAR CONTROL

- Scalar control techniques of voltage fed and current fed inverter drives is simple to implement but the inherent coupling effect gives sluggish response and the system is easily prone to instability.
- Inherent coupling effect means both torque and flux are functions of voltage or current and frequency

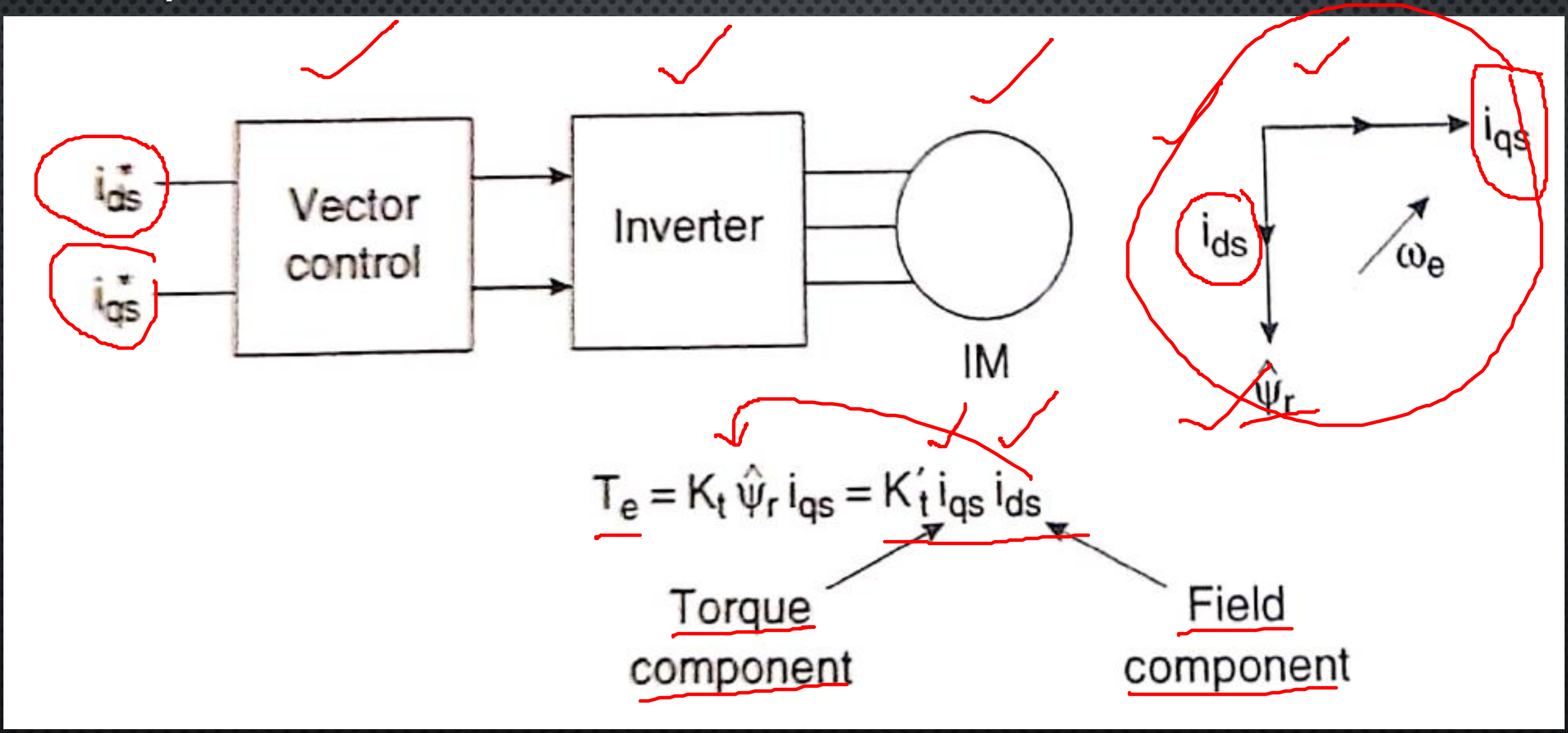
DC DRIVE ANALOGY



VECTOR CONTROL

- Vector control can be classified into two types

1) Direct Feedback control
2) Indirect feed forward control



FIELD ORIENTED CONTROL(FOC)

- VECTOR CONTROLLED AC DRIVE PROVIDES BETTER DYNAMIC RESPONSE AND LESSER TORQUE RIPPLES.
- VECTOR CONTROL IS USED TO CONTROL THE AC MOTOR IN ORDER TO ACHIEVE HIGH PERFORMANCE CONTROL CHARACTERISTICS.
- IN AC MACHINES, THE STATOR AND ROTOR FIELDS ARE NOT ORTHOGONAL TO EACH OTHER. THE ONLY CURRENT THAT CAN BE CONTROLLED IS THE STATOR CURRENT. FIELD ORIENTED CONTROL IS THE TECHNIQUE USED TO ACHIEVE THE DECOUPLED CONTROL OF TORQUE AND FLUX.
- FOC SCHEME NOT ONLY DECOUPLES THE TORQUE AND FLUX WHICH MAKES FASTER RESPONSE BUT ALSO MAKES CONTROL TASK EASY.
- FOC IS CARRIED OUT TO CONTROL THE SPACE VECTOR OF MAGNETIC FLUX, CURRENT AND VOLTAGE OF MACHINES IN ORDER TO ACHIEVE THE PRECISE SPEED TARGET.
- THE AIM OF THE FOC METHOD IS TO CONTROL THE MAGNETIC FIELD AND TORQUE BY CONTROLLING THE D AND Q COMPONENTS OF THE STATOR CURRENTS OR CONSEQUENTLY THE FLUXES.

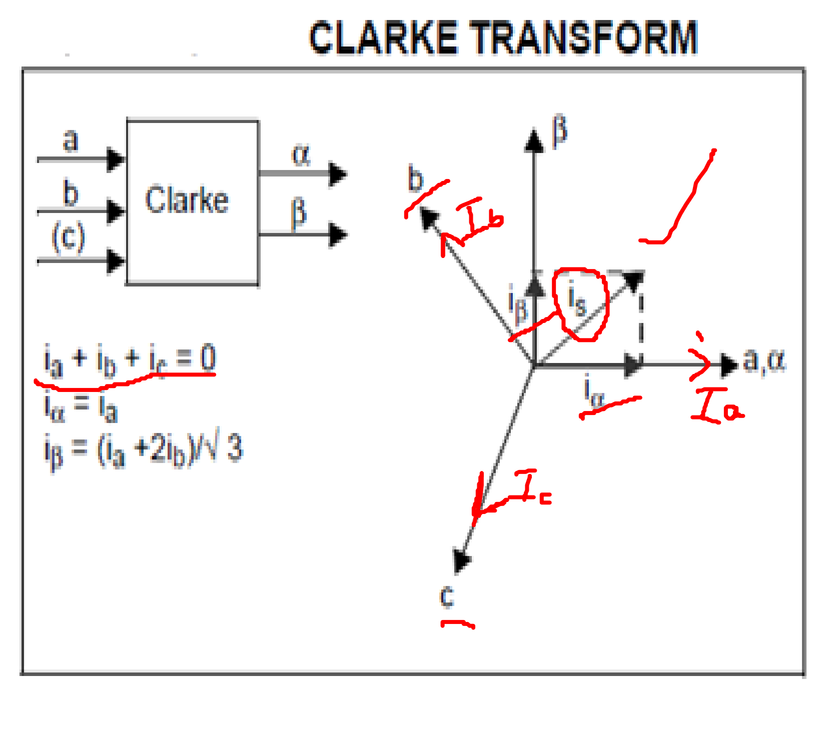
Continued...

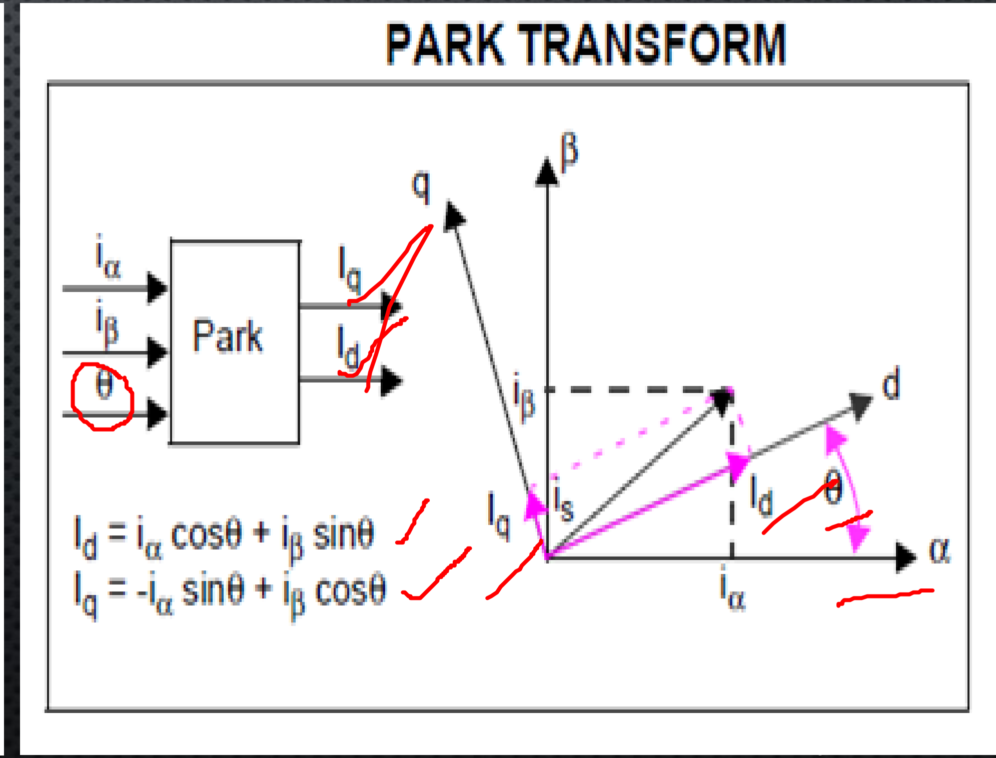
FOC TECHNIQUE

- FOC technique involves three reference frames and needs transformations from one to the other.
- Stator reference frame (A,B,C) in which the A,B,C are co-planar, at 120 degrees to each other.
- An orthogonal reference frame (α,β) in the same plane as the stator reference frame in which the angle between the two axes is 90 degrees instead of 120 degrees. The α axis is aligned with A axis in the second frame.
- Rotor reference frame (DQ), in which the D axis is along the N and S poles or along the flux vector of the rotor and the Q axis is at 90 degrees to the D axis.

Step1:Stator currents *ia* & *ib* are measured using electric current sensors, and *ic* is calculated using the formula *ic=-(ia+ib)*.

STEP2:THE ELECTRIC CURRENTS *IA*, *IB* AND *IC* ARE TRANSFORMED INTO THE DIRECT COMPONENT *IQ*, *ID* IN THE REVOLVING COORDINATE SYSTEM THROUGH THE CLARKE AND THE PARK TRANSFORMATIONS.



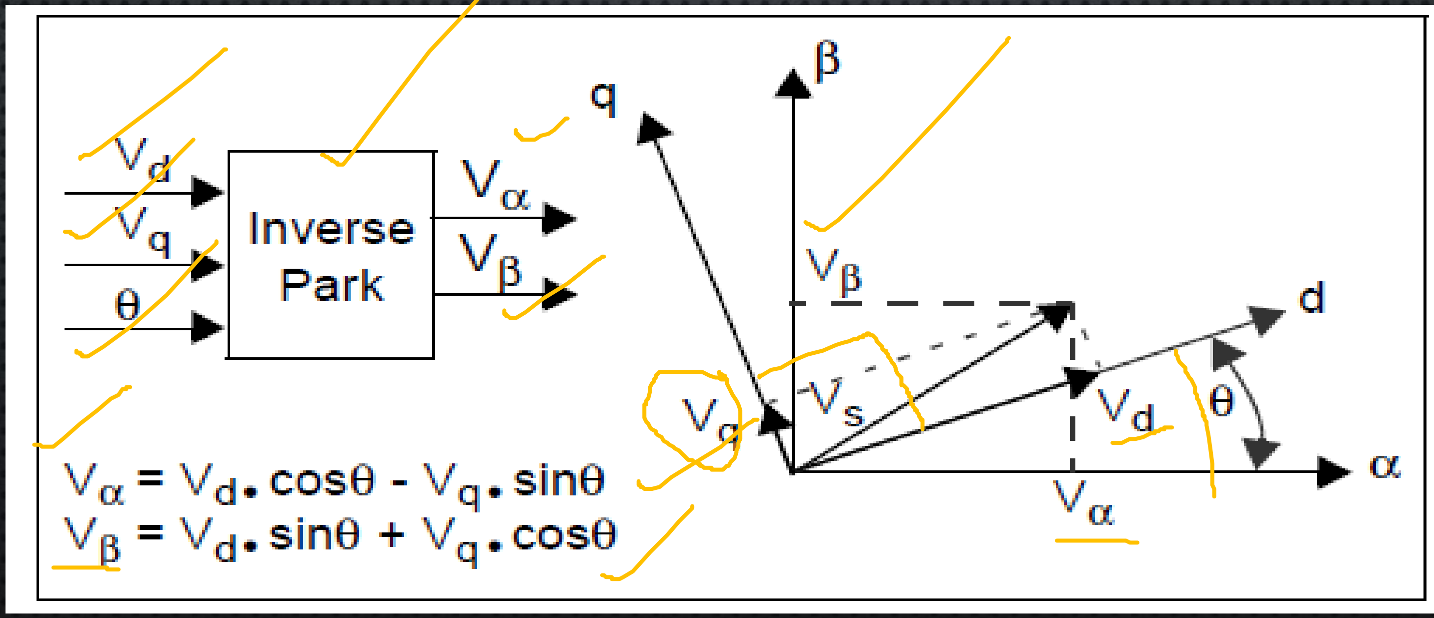


Continued....

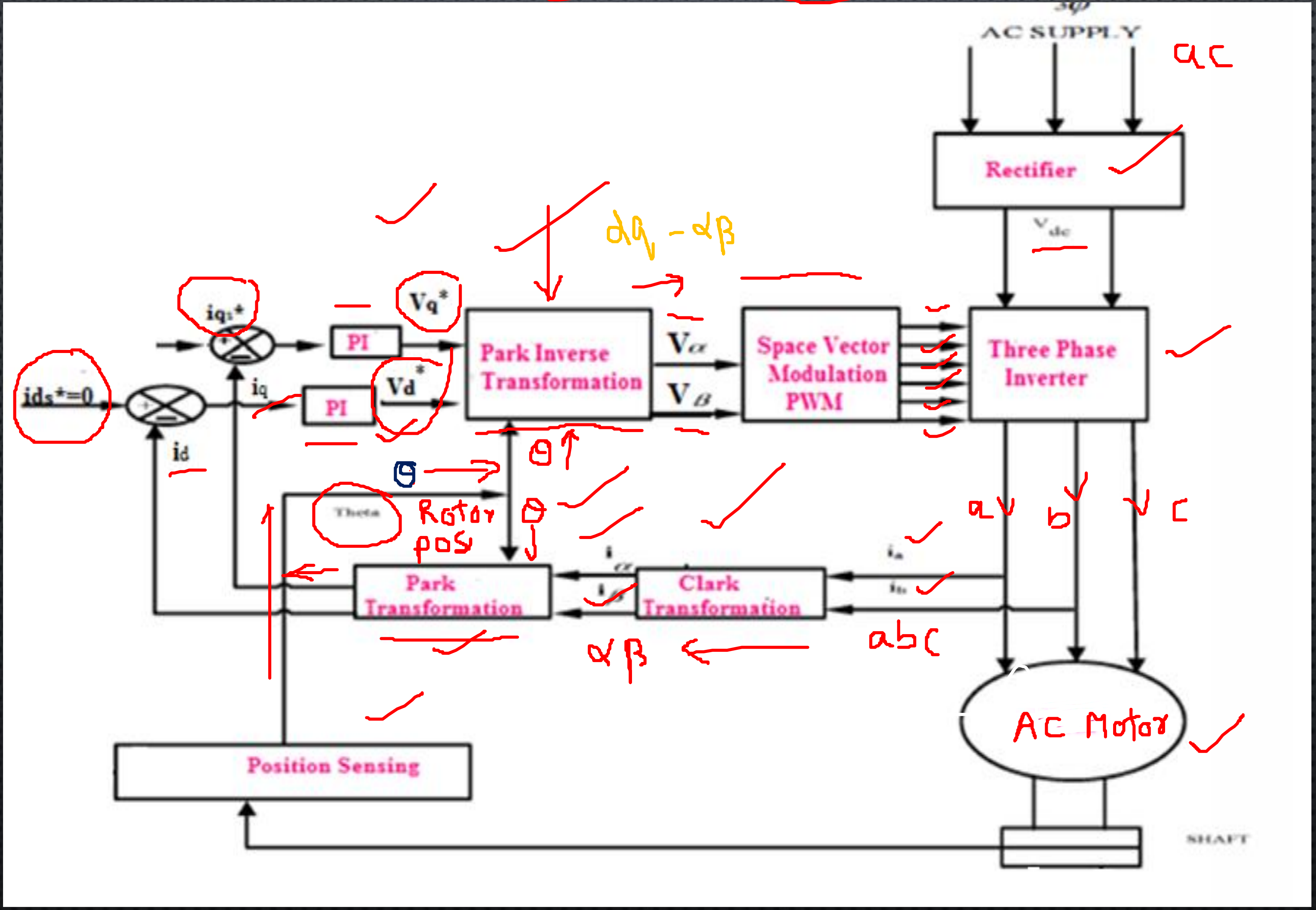
abc → αβ → dq

clark θ park

INVERSE PARK Transform



FOC WITH SVPWM IN AC DRIVE



DIRECT OR FEEDBACK VECTOR CONTROL

3-φ → 2-φ

abc → d^s - q^s → d^e - q^e

θ

ω_e

3-φ — 2φ

2-φ — 3φ

ADVANTAGES OF FIELD ORIENTED CONTROL

- Transformation of a complex and coupled AC model into a simple linear system.
- Independent control of Torque and flux
- Fast dynamic response and good transient and steady state performance.
- High torque and low current at start up.
- High Efficiency.

CLARK TRANSFORM

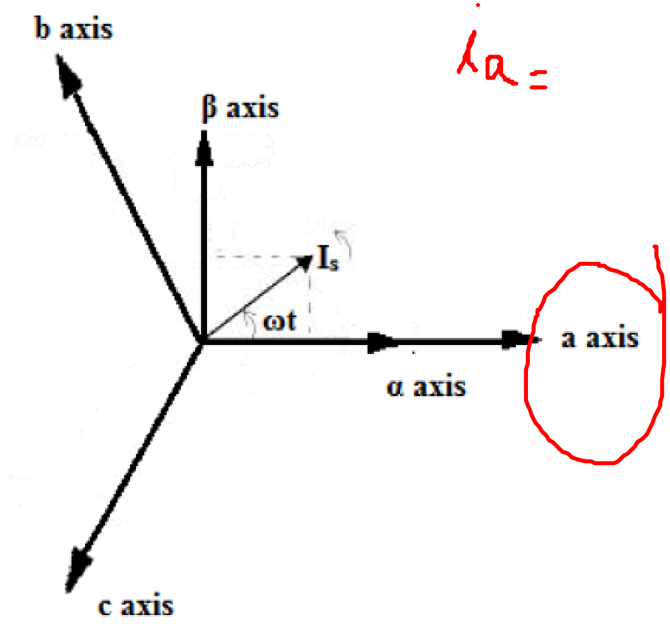
Clarke Transformation:

$$i_\alpha = i_{ds}^{s}$$

$$i_\beta = i_{qs}^{s}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$i_a =$

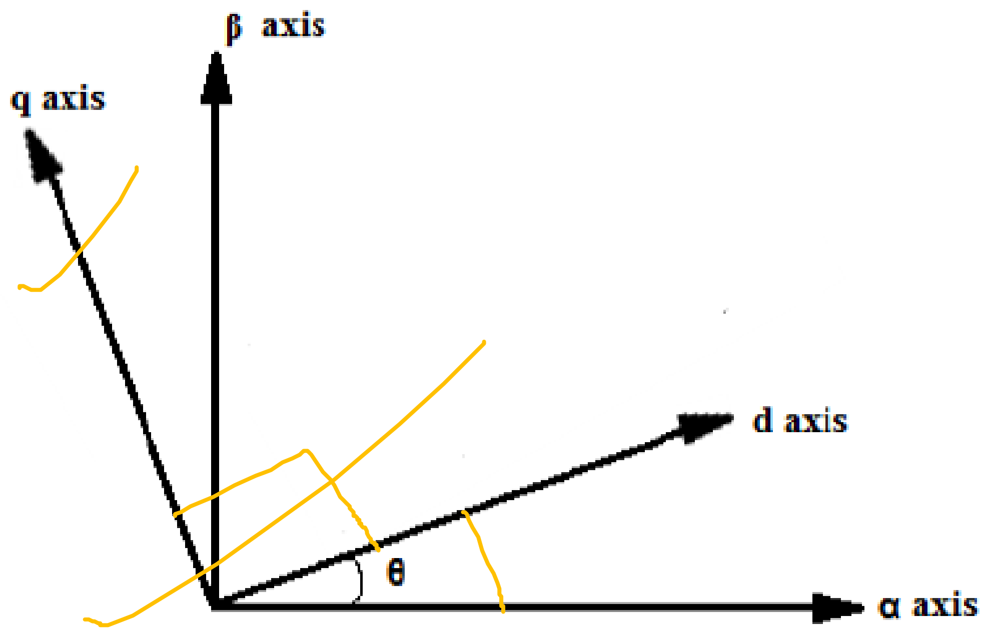


Clarke Transformation

PARK TRANSFORM

Park Transformation:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$



·Park Transformation

INVERSE PARK TRANSFORM

Inverse Park Transform

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

The Clarke transformation transforms the three phase (a, b, c) signals into α, β reference frame in the stator. In order to transform the signals to the rotor reference frame Park transformation is used so as to transform the signals into rotor reference frame (d-q). Inverse park transform converts the signals back to stator reference frame (d-q to α, β).

DIRECT OR FEEDBACK VECTOR CONTROL

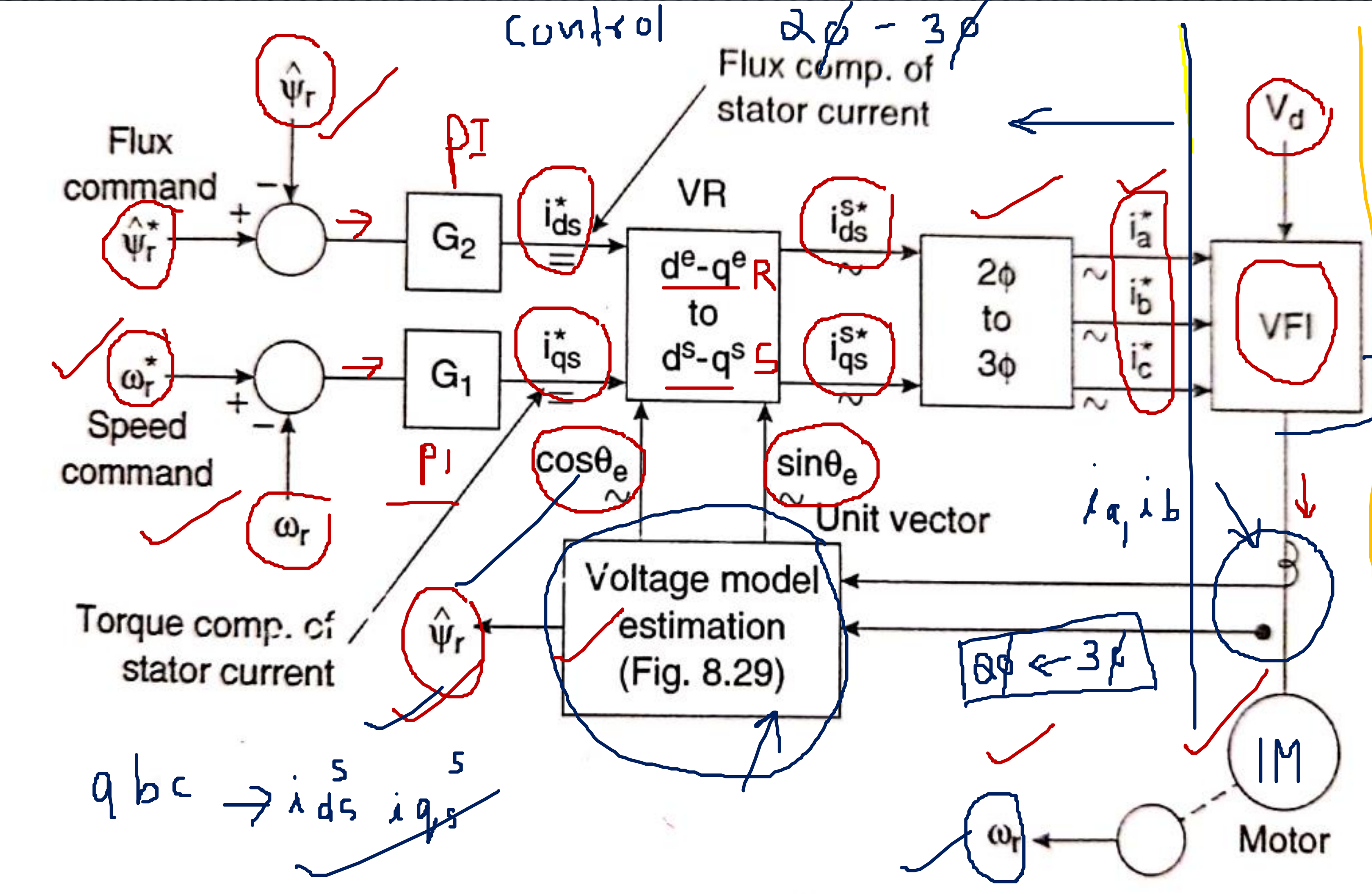
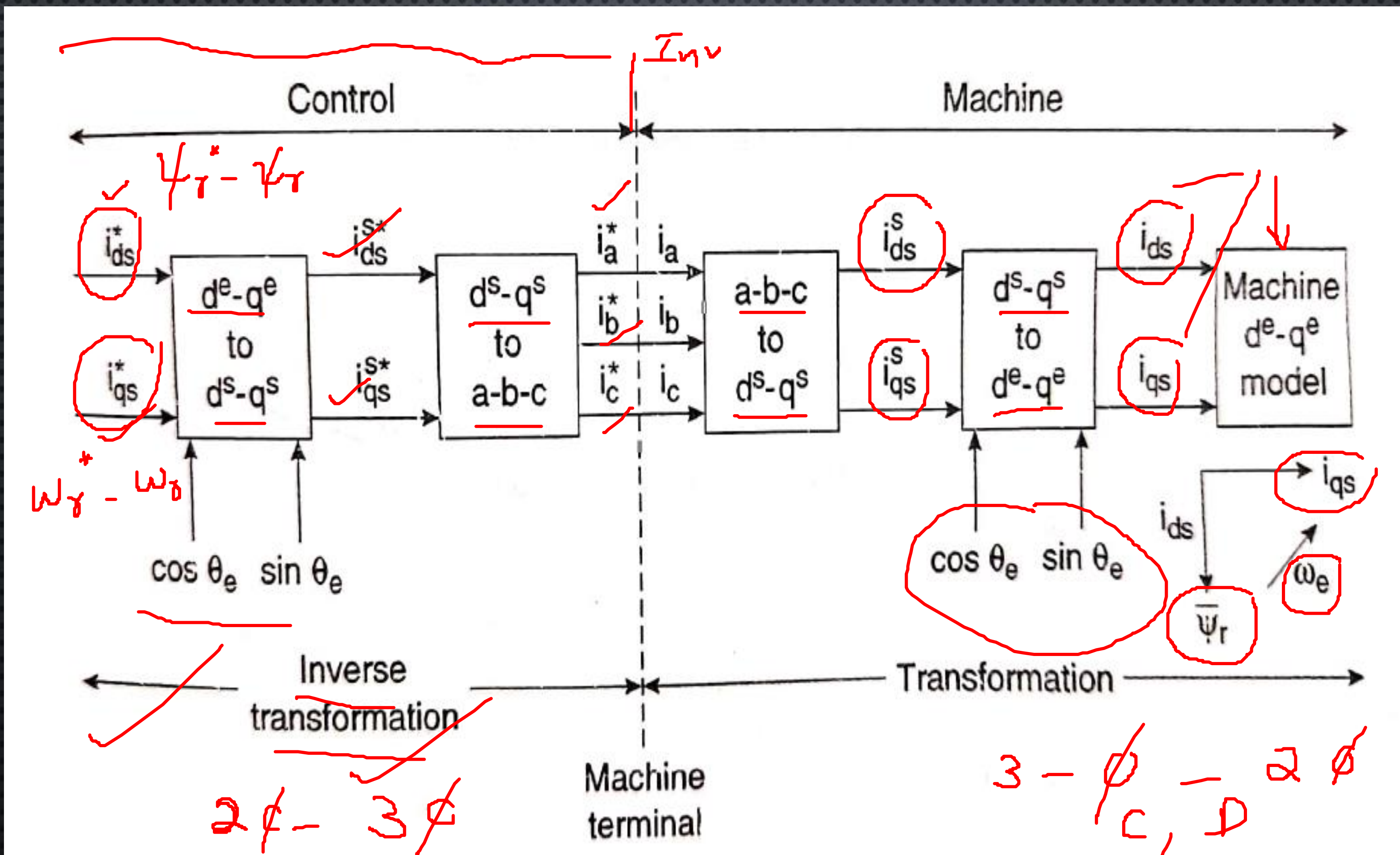
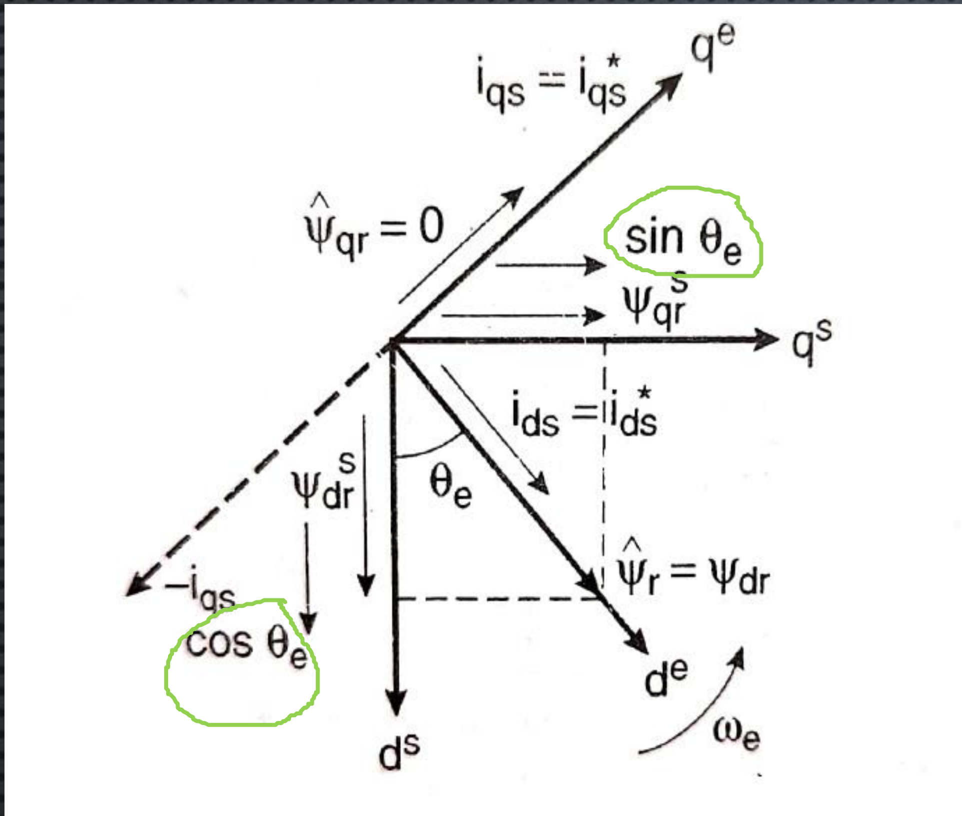
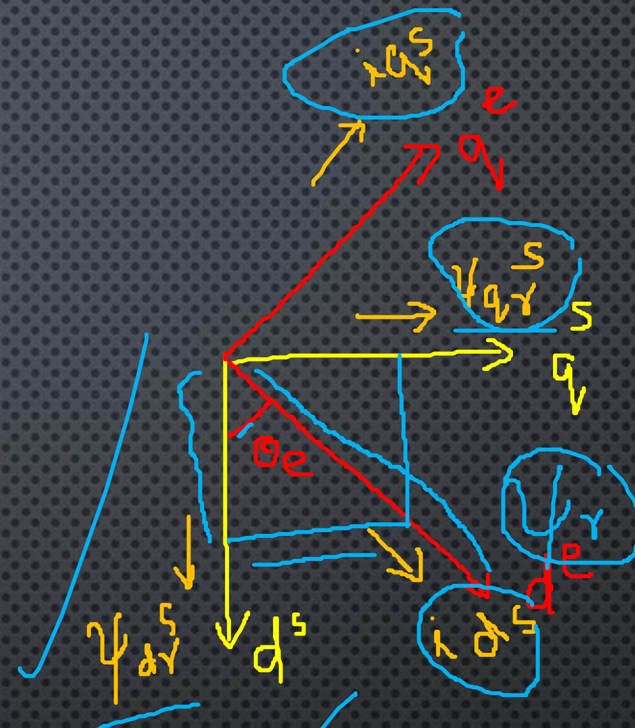


Figure 8.27 Direct vector control block diagram with rotor flux orientation

VECTOR CONTROL IMPLEMENTATION PRINCIPLE WITH MACHINE d^e-q^e Model







$$\cos\theta_e = \frac{\psi_{dr}^s}{\psi_r}$$

$$\sin\theta_e = \frac{\psi_{qr}^s}{\psi_r}$$

$$\psi_r = \sqrt{(\psi_{dr}^s)^2 + (\psi_{qr}^s)^2}$$

$$\psi_{dr}^{\;s} = \hat{\psi}_r \cos\theta_e$$

$$\psi_{qr}^{\;s} = \hat{\psi}_r \sin\theta_e$$

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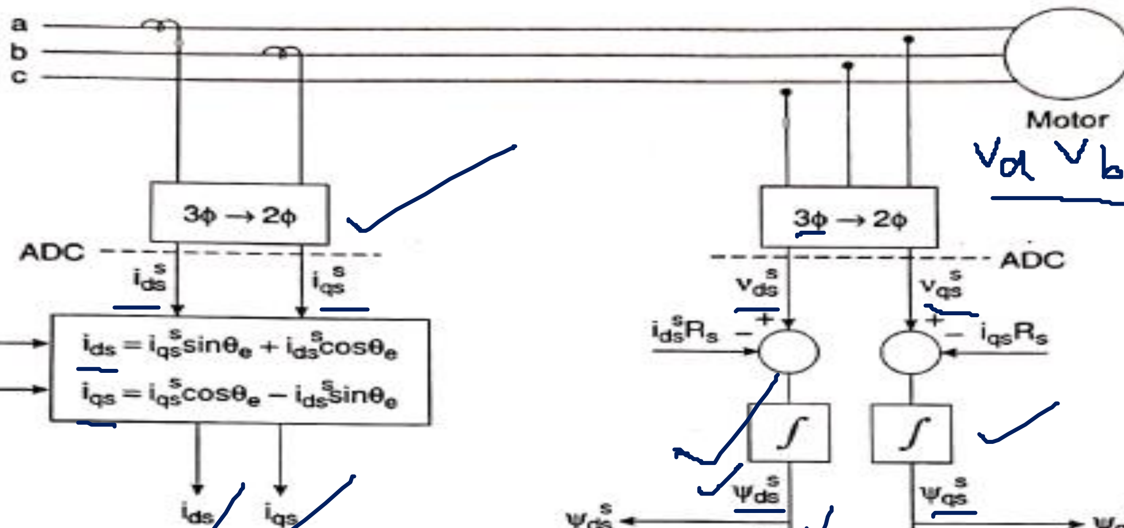
3φ − 2φ

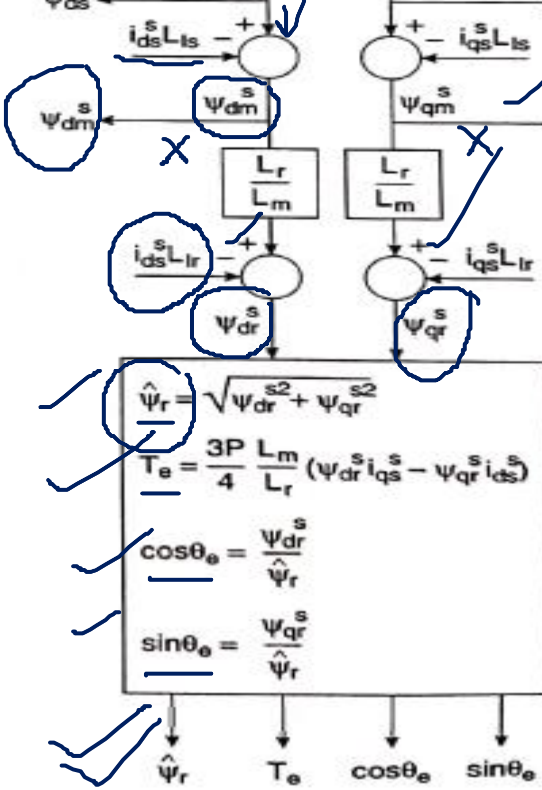
$\int E = V - IR$



$V_a \; V_b \; V_c$

↓

2 − φ



$$\psi_{ds}^s = \int (V_{ds}^s - i_{ds}^s \cdot R_s) \cdot dt$$

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$$\psi_{dm}^s = \psi_{ds}^s - L_{ls} \cdot i_{ds}^s$$

$$\psi_{qm}^s = \psi_{qs}^s - L_{ls} \cdot i_{qs}^s$$

$$\psi_{dr}^s = \psi_{dm}^s \cdot \frac{L_r}{L_m} - L_{lr} \cdot i_{ds}^s$$

$$\psi_{qr}^s = \psi_{qm}^s \cdot \frac{L_r}{L_m} - L_{lr} \cdot i_{qs}^s$$

voltage

ω_r

DIRECT OR FEEDBACK VECTOR CONTROL

3-φ → 2-φ

abc → d^s - q^s → d^e - q^e ω_e

θ

3-φ — 2φ

2-φ — 3φ

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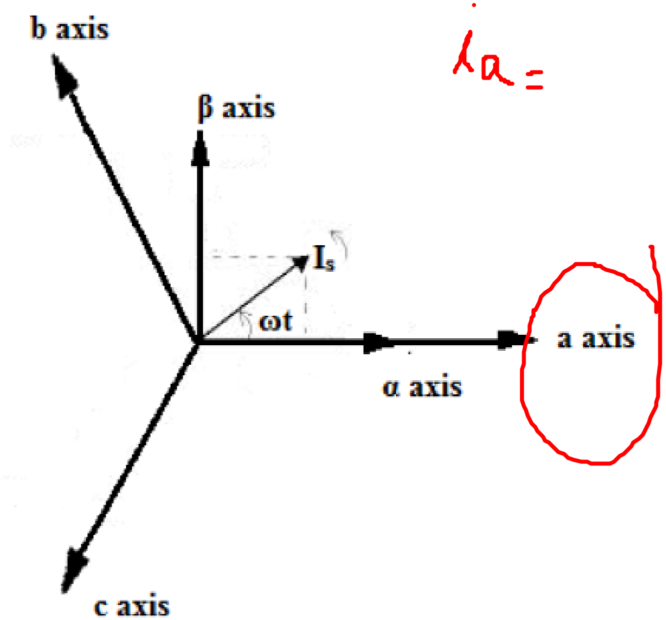

Clarke Transformation

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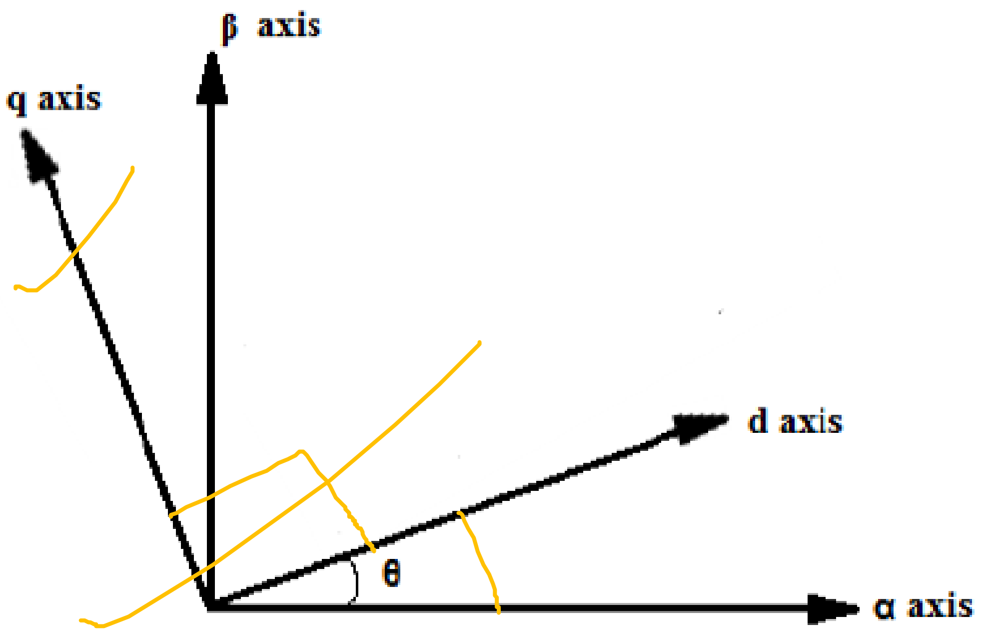

Park Transformation

INVERSE PARK TRANSFORM

Inverse Park Transform

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DIRECT OR FEEDBACK VECTOR CONTROL

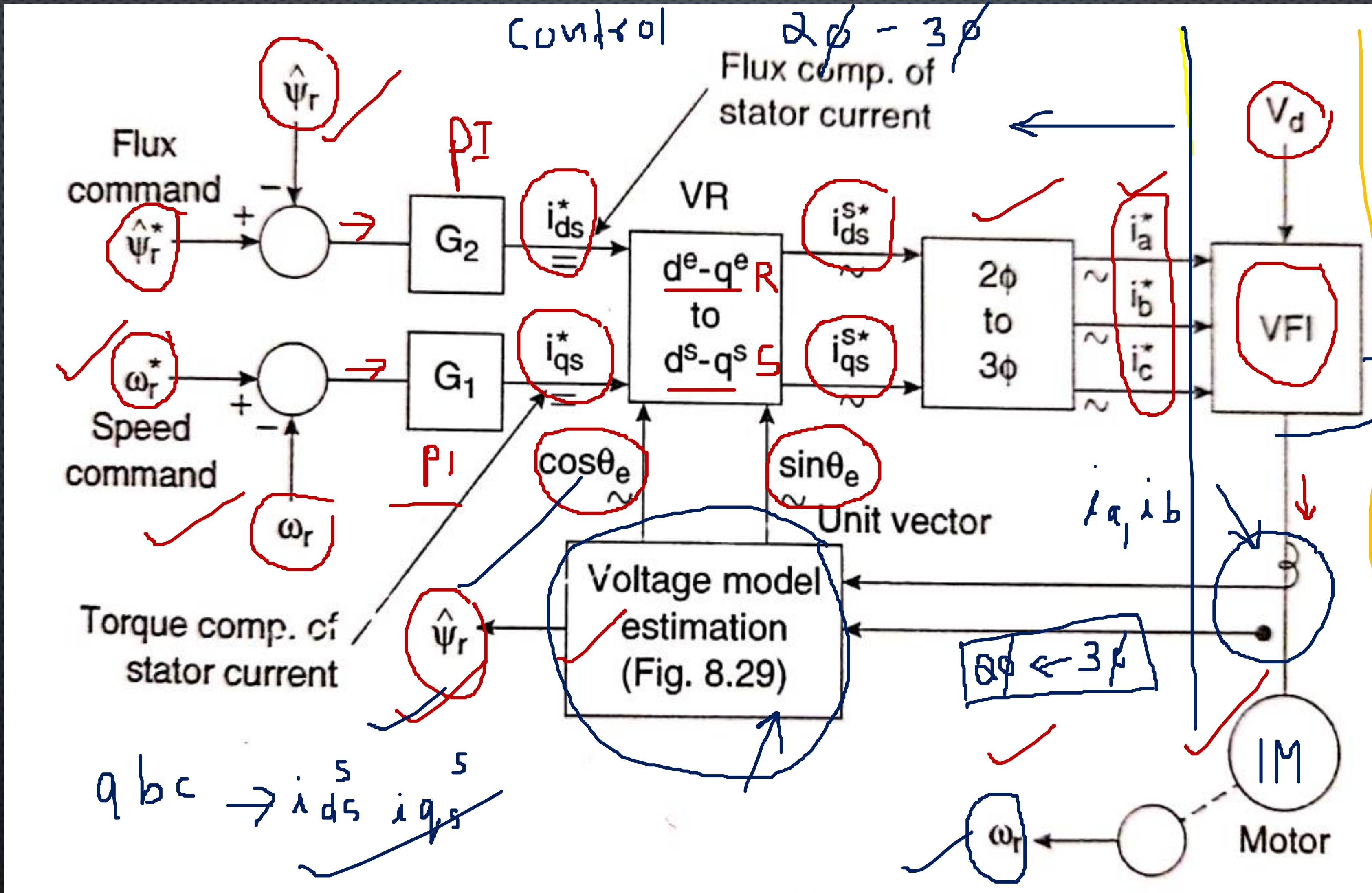
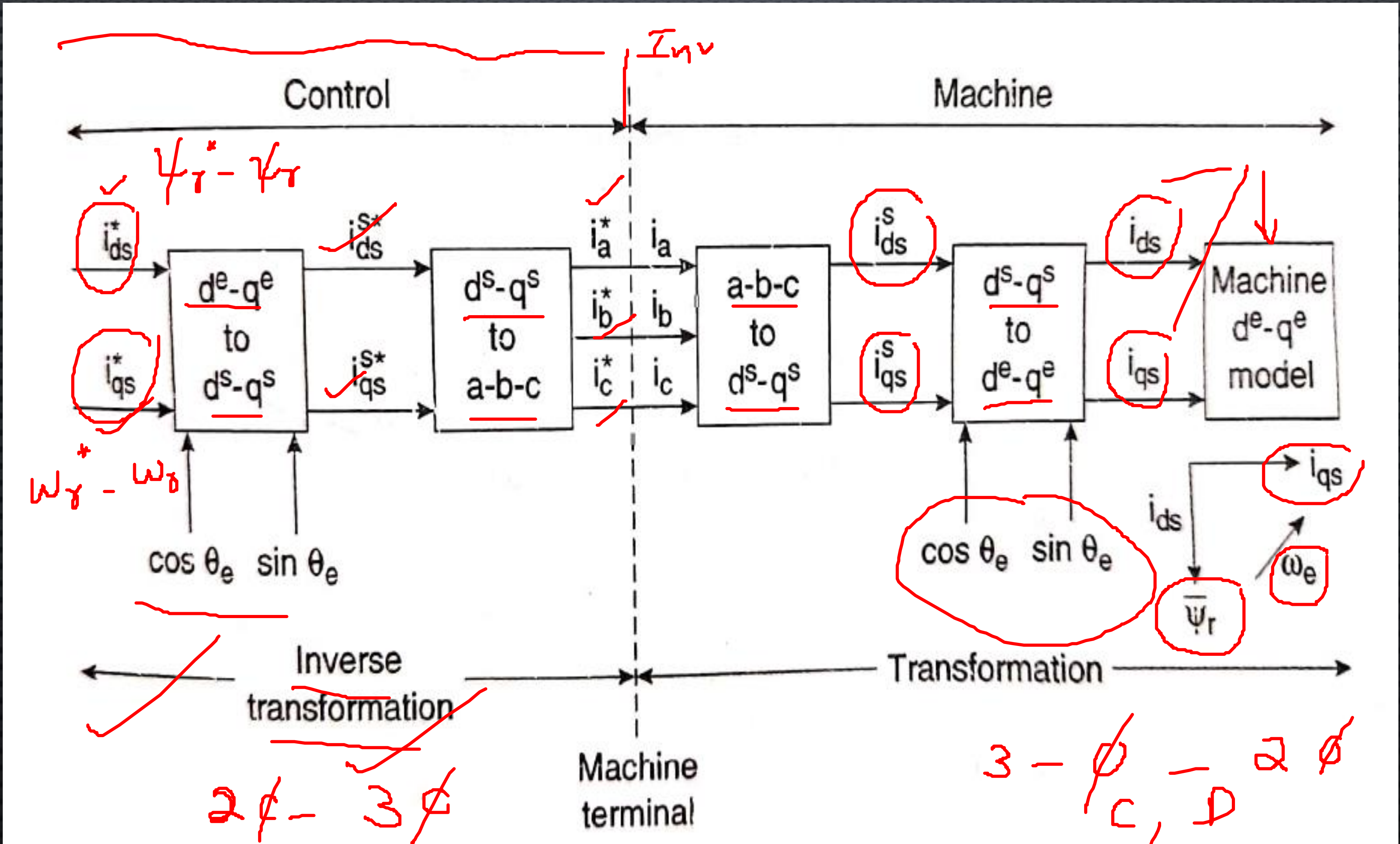
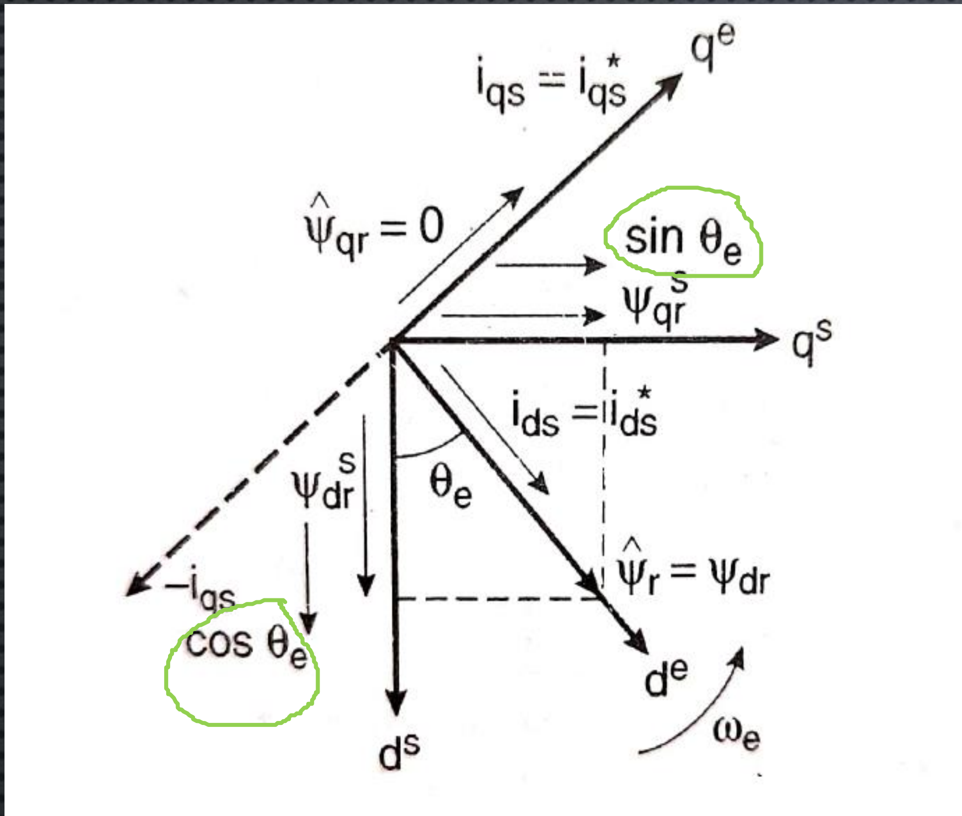
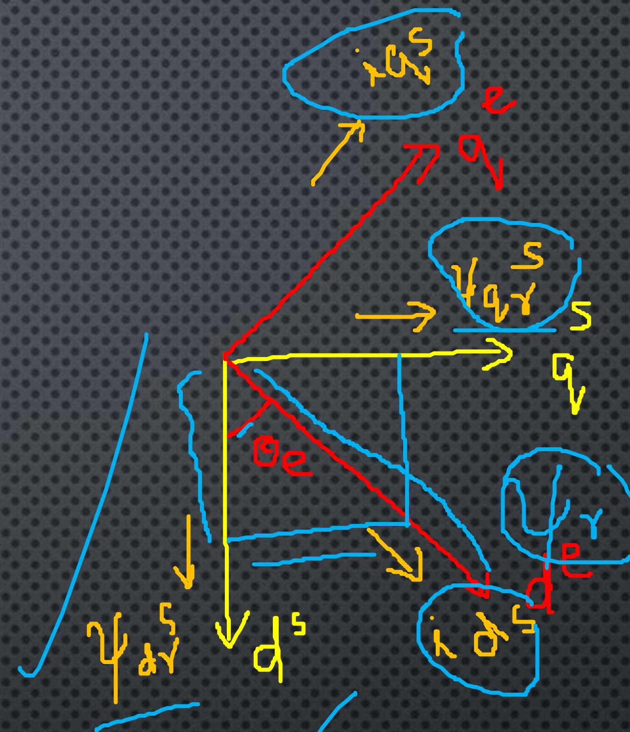


Figure 8.27 Direct vector control block diagram with rotor flux orientation

VECTOR CONTROL IMPLEMENTATION PRINCIPLE WITH MACHINE







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$$\sin\theta_e = \frac{\psi_{qr}^s}{\psi_r}$$

$$\psi_r = \sqrt{(\psi_{dr}^s)^2 + (\psi_{qr}^s)^2}$$

$$\psi_{dr}^{s} = \hat{\psi}_r \cos\theta_e$$

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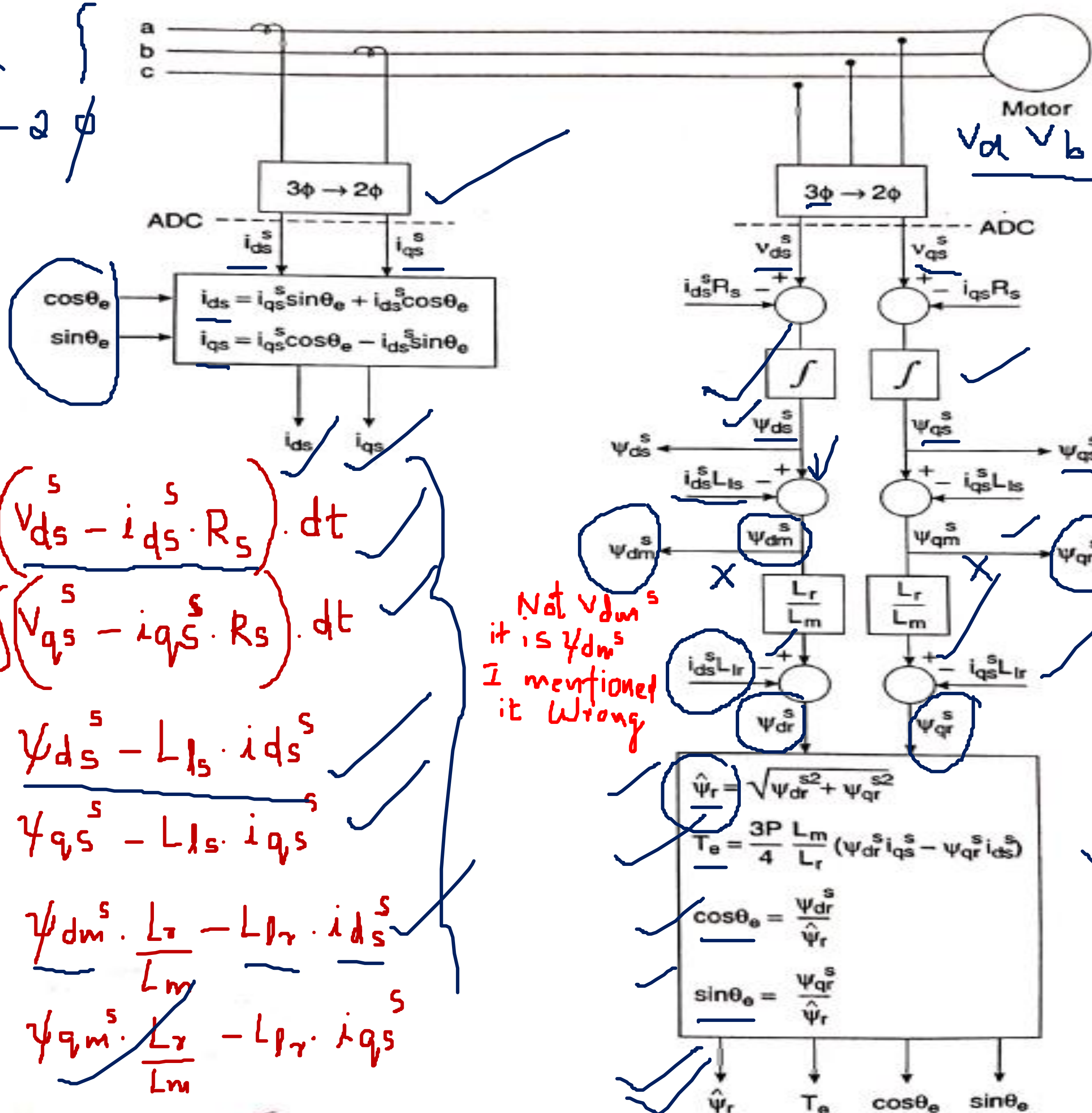
$$\sin\theta_e = \frac{\psi_{qr}^{s}}{\hat{\psi}_r}$$

$$\hat{\psi}_r = \sqrt{\psi_{dr}^{s^2} + \psi_{qr}^{s^2}}$$

3φ - 2φ

$\int E = V - IR$



$V_a \; V_b \; V_c$ ↓ 2-φ

voltage

ω_r

Not v_{dm}^s it is ψ_{dm}^s I mentioned it Wrong

$$\psi_{ds}^s = \int (v_{ds}^s - i_{ds}^s \cdot R_s) \cdot dt$$

$$\psi_{qs}^s = \int (v_{qs}^s - i_{qs}^s \cdot R_s) \cdot dt$$

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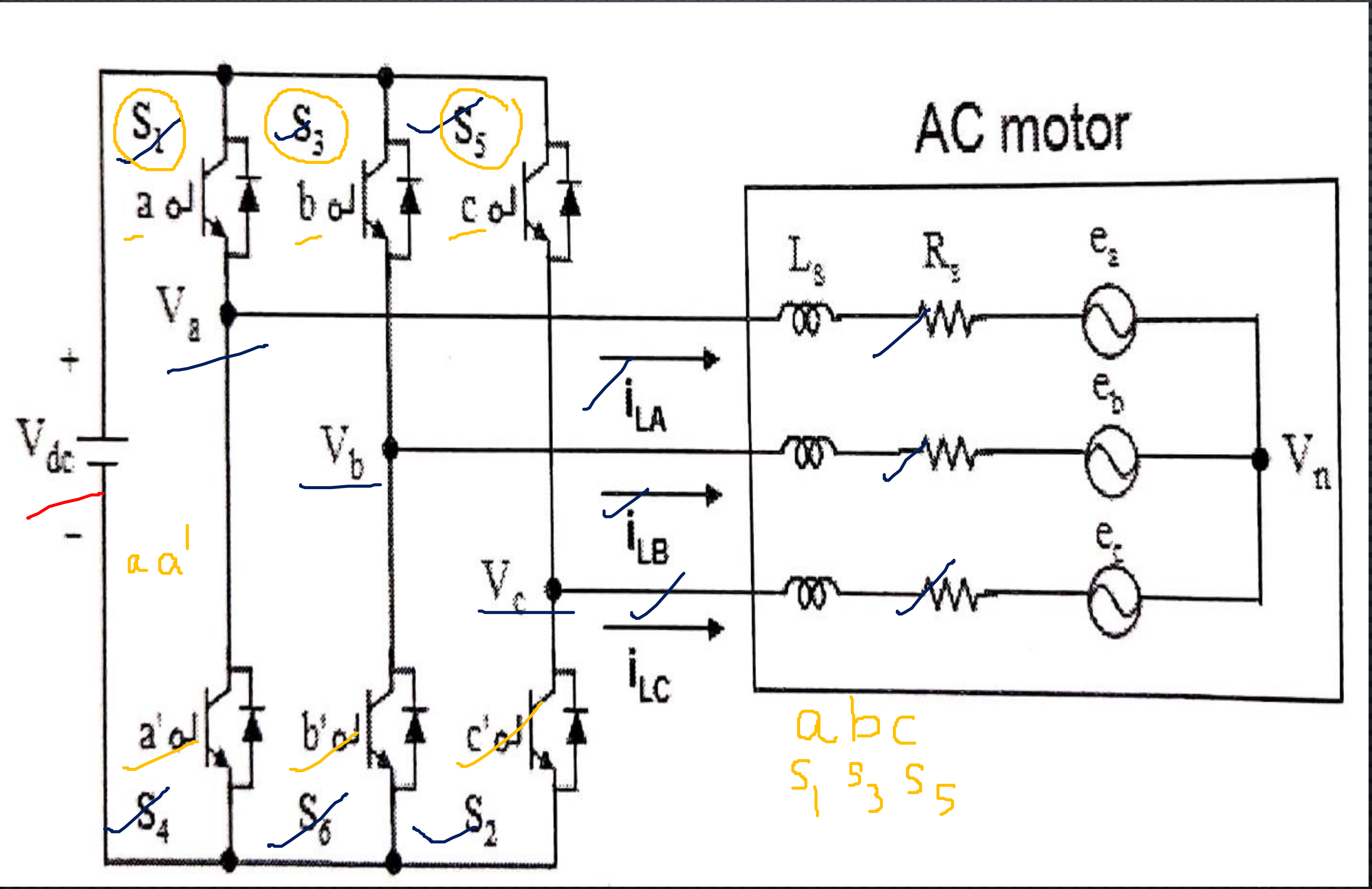
$$\psi_{qr}^s = \psi_{qm}^s \cdot \frac{L_r}{L_m} - L_{lr} \cdot i_{qs}^s$$

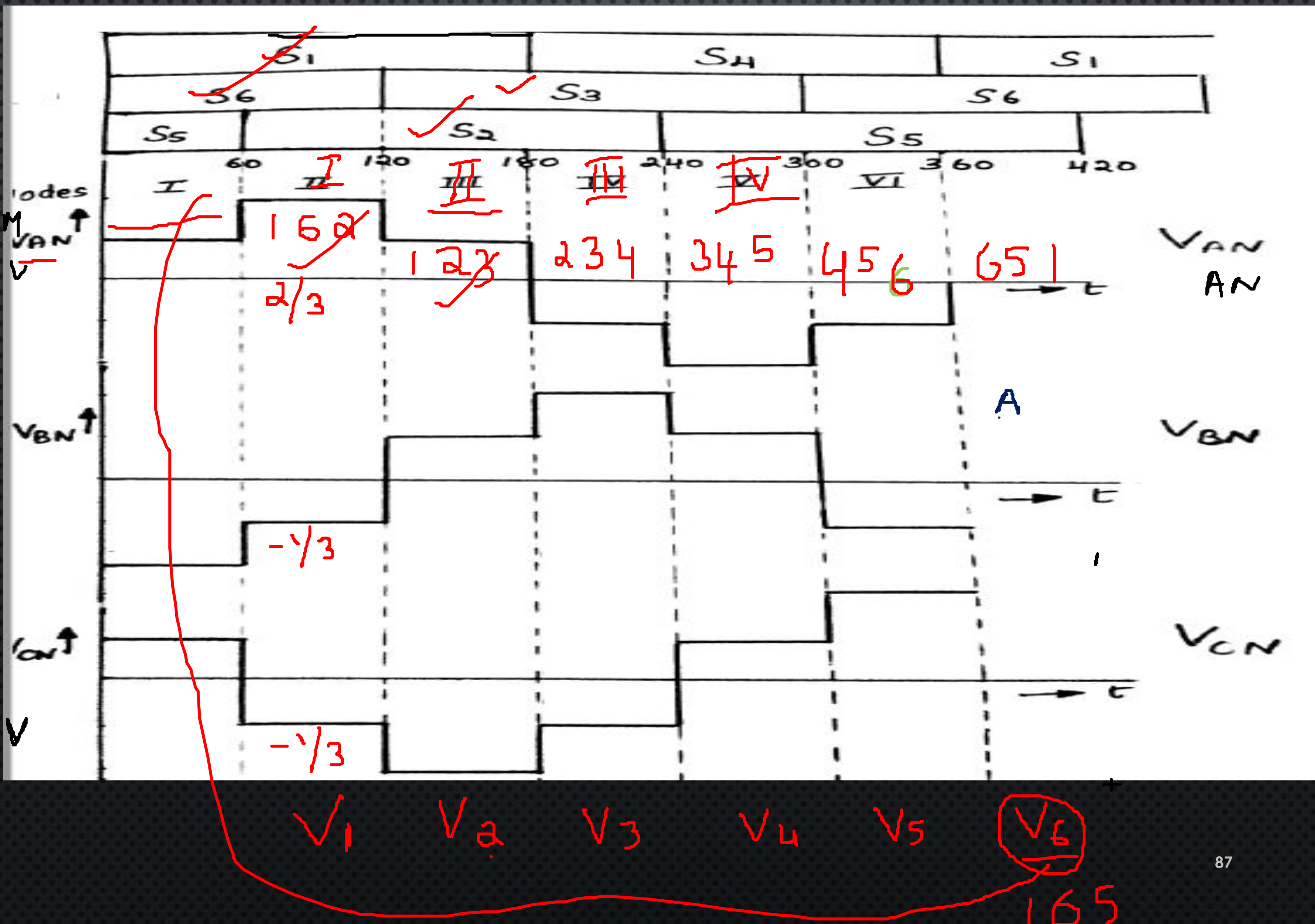
Space Vector Pulse Width modulation

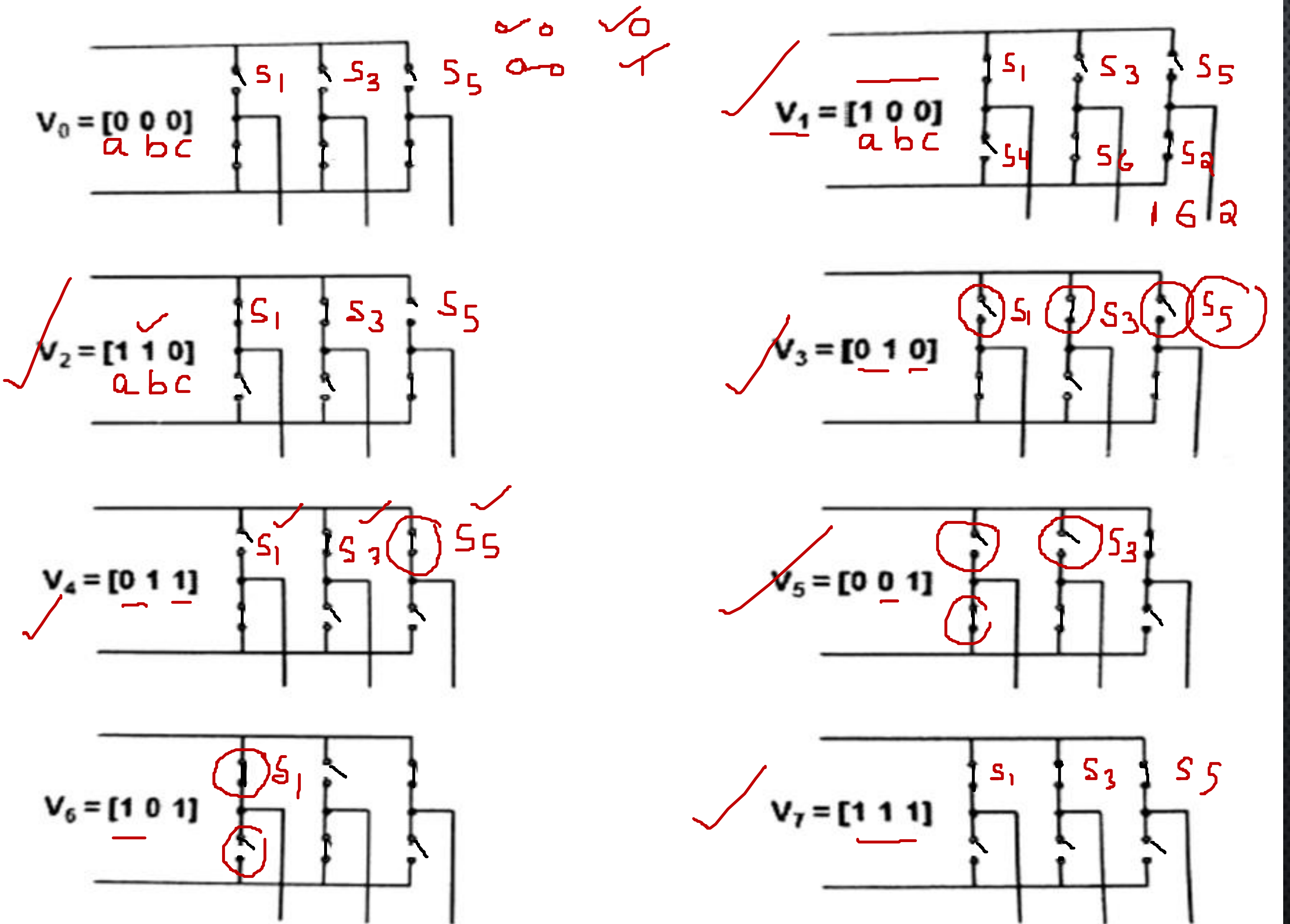
SVPWM

THREE PHASE VOLTAGE SOURCE INVERTER(VSI)



OUTPUT VOLTAGE(180 MODE)





V0 = [0 0 0]
a b c
S1 S3 S5
V1 = [1 0 0]
a b c
S1 S3 S5
S4 S6 S2
1 6 2
V2 = [1 1 0]
a b c
S1 S3 S5
V3 = [0 1 0]
S1 S3 S5
V4 = [0 1 1]
S1 S3 S5
V5 = [0 0 1]
S3
V6 = [1 0 1]
S1
V7 = [1 1 1]
S1 S3 S5

"4 6 2 are Conducting"

1 3 5
4 6 2

1 3 5
4 6 2 conducting devices

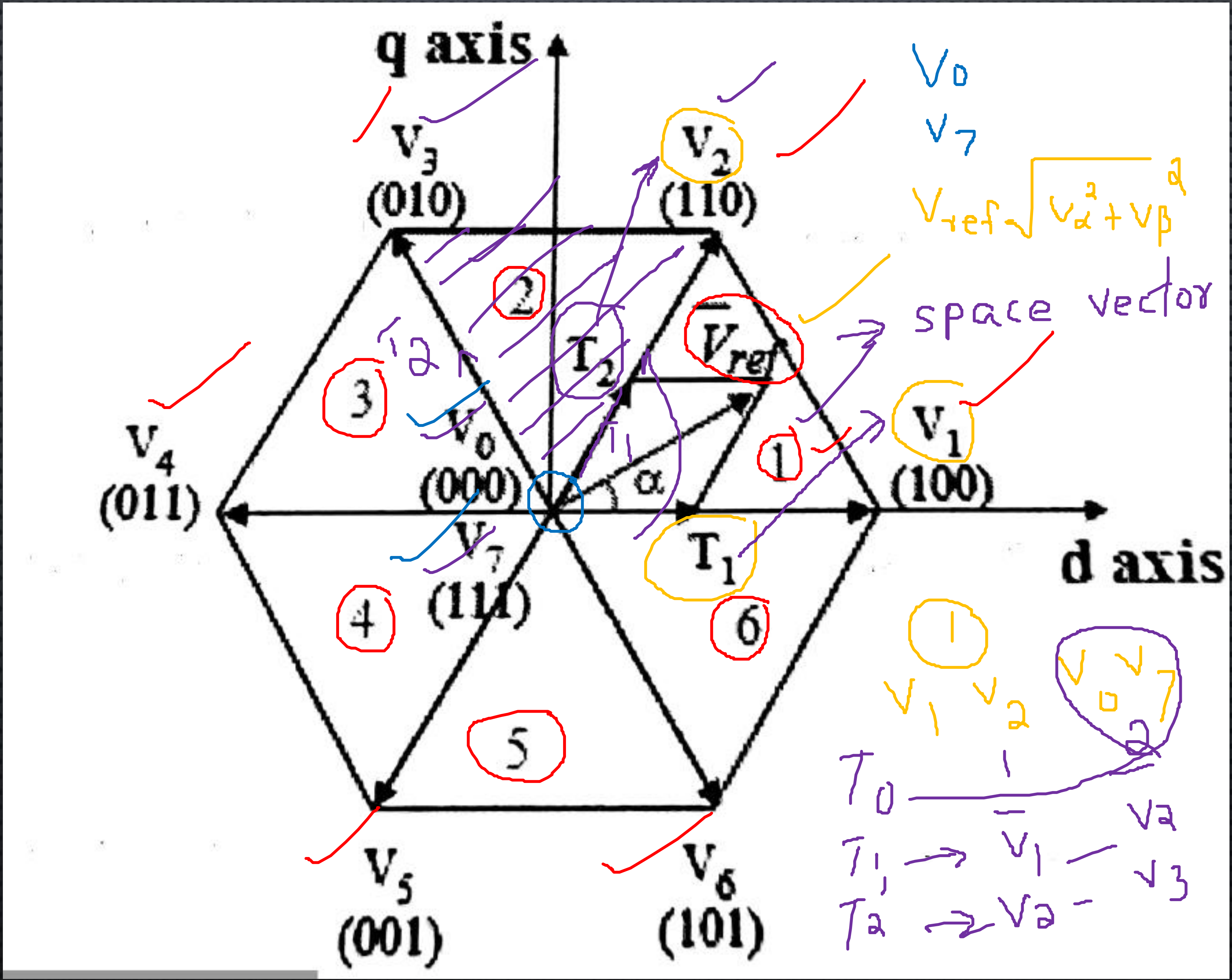
"1, 3 5 are conduct"

	V_0	V_1	V_2	V_3	V_4	V_5	V_6	V_7
switching device	1 3 5	6 1 2	1 2 3	2 3 4	3 4 5	4 5 6	5 6 1	4 6 2
switching state ($S_1 S_3 S_5$ / a b c)	0 0 0	1 0 0	1 1 0	0 1 0	0 1 1	0 0 1	1 0 1	1 1 1
V_{an}	0	$2/3$	$1/3$	$-1/3$	$-2/3$	$-1/3$	$1/3$	0
V_{bn}	0	$-1/3$	$1/3$	$2/3$	$1/3$	$-1/3$	$-2/3$	0
V_{cn}	0	$-1/3$	$-2/3$	$-1/3$	$1/3$	$2/3$	$1/3$	0

$\times V_{dc}$

Voltage Vectors	Switching Vectors			Line to neutral voltage			Line to line voltage		
	a	b	c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V_2	1	1	0	1/3	1/3	-2/3	0	1	-1
V_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V_4	0	1	1	-2/3	1/3	1/3	-1	0	1
V_5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V_6	1	0	1	1/3	-2/3	1/3	1	-1	0
V_7	1	1	1	0	0	0	0	0	0

(Note that the respective voltage should be multiplied by V_{dc})



q axis
d axis
V3
(010)
V2
(110)
V4
(011)
V1
(100)
V0
(000)
V7
(111)
V5
(001)
V6
(101)
T2
T1
Vref
α
1
2
3
4
5
6
V0
V7
space vector

SPACE VECTOR PWM CAN BE IMPLEMENTED BY THE FOLLOWING STEPS

Step 1. Determine V_{α}, V_{β}, V_{ref}, and angle (α)

Step 2. Determine time duration T_1, T_2, T_0

Step 3. Determine the switching time of each transistor (S_1 to S_6)

$$V_\alpha = V_{an} - V_{bn}\cdot\cos 60 - V_{cn}\cdot\cos 60$$
$$= V_{an} - \frac{1}{2}V_{bn} - \frac{1}{2}V_{cn}$$

$$V_\beta = 0 + V_{bn}\cdot\cos 30 - V_{cn}\cdot\cos 30$$
$$= V_{an} + \frac{\sqrt{3}}{2}V_{bn} - \frac{\sqrt{3}}{2}V_{cn}$$

abc → α_β

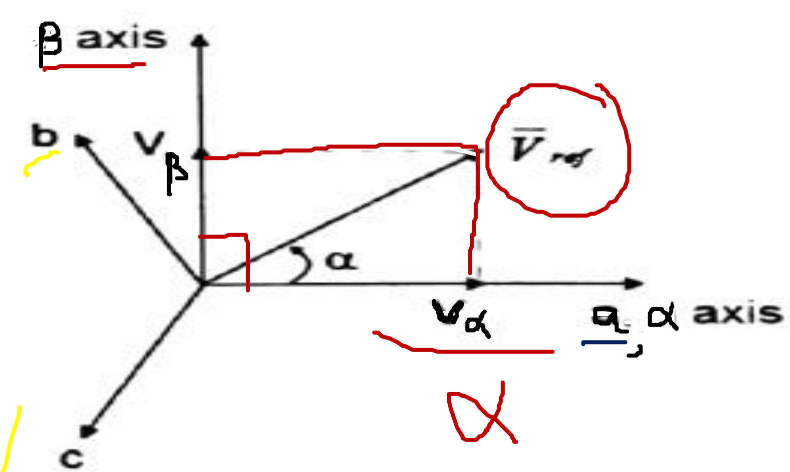
clark

$$\therefore \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

V_0

$$\therefore |\bar{V}_{ref}| = \sqrt{V_\alpha^{\,2} + V_\beta^{\,2}}$$

$$\therefore \alpha = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) = 2\pi f,$$ where f = fundamental frequency



DETERMINATION OF T1,T2 AND T0

Switching time duration at any Sector

Sector

f

$T_z = \frac{1}{f}$

$$\therefore T_1 = \frac{\sqrt{3}\cdot T_z \cdot |\overline{V}ref|}{V_{dc}}\left(\sin\left(\frac{\pi}{3} - \alpha + \frac{n-1}{3}\pi\right)\right)$$

$$= \frac{\sqrt{3}\cdot T_z \cdot |\overline{V}ref|}{V_{dc}}\left(\sin\frac{n}{3}\pi - \alpha\right)$$

$$= \frac{\sqrt{3}\cdot T_z \cdot |\overline{V}ref|}{V_{dc}}\left(\sin\frac{n}{3}\pi\cos\alpha - \cos\frac{n}{3}\pi\sin\alpha\right)$$

$$\therefore T_2 = \frac{\sqrt{3}\cdot T_z \cdot |\overline{V}ref|}{V_{dc}}\left(\sin\left(\alpha - \frac{n-1}{3}\pi\right)\right)$$

$$= \frac{\sqrt{3}\cdot T_z |\overline{V}ref|}{V_{dc}}\left(-\cos\alpha\cdot\sin\frac{n-1}{3}\pi + \sin\alpha\cdot\cos\frac{n-1}{3}\pi\right)$$

$$\therefore T_0 = T_z - T_1 - T_2, \quad \left(\begin{array}{c}\text{where, } n = 1 \text{ through } 6 \text{ (that is, Sector 1 to 6)} \\ 0 \le \alpha \le 60^\circ\end{array}\right)$$

DETERMINATION OF T1,T2 AND T0 IN SECTOR 1

Switching time duration at Sector 1

$$\int_0^{T_z} \overline{V}_{ref} = \int_0^{T_1} \overline{V}_1 dt + \int_{T_1}^{T_1+T_2} \overline{V}_2 dt + \int_{T_1+T_2}^{T_z} \overline{V}_0$$

$$\therefore T_z \cdot \overline{V}_{ref} = (T_1 \cdot \overline{V}_1 + T_2 \cdot \overline{V}_2)$$

$$\Rightarrow T_z \cdot \left|\overline{V}_{ref}\right| \cdot \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} = T_1 \cdot \frac{2}{3} \cdot V_{dc} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 \cdot \frac{2}{3} \cdot V_{dc} \cdot \begin{bmatrix} \cos(\pi/3) \\ \sin(\pi/3) \end{bmatrix}$$

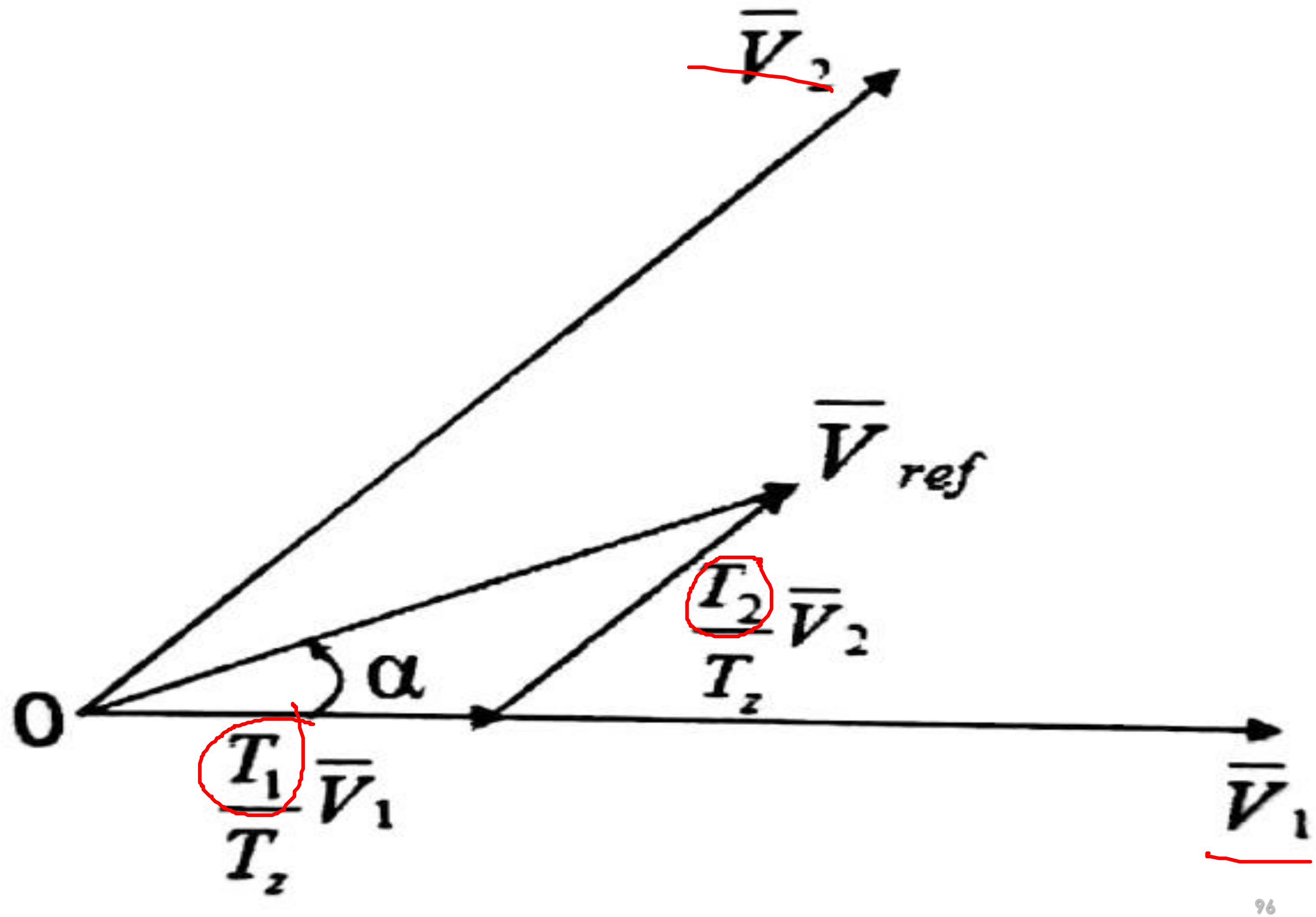
(where, $0 \le \alpha \le 60°$)

$$\therefore T_1 = T_z \cdot a \cdot \frac{\sin(\pi/3 - \alpha)}{\sin(\pi/3)}$$

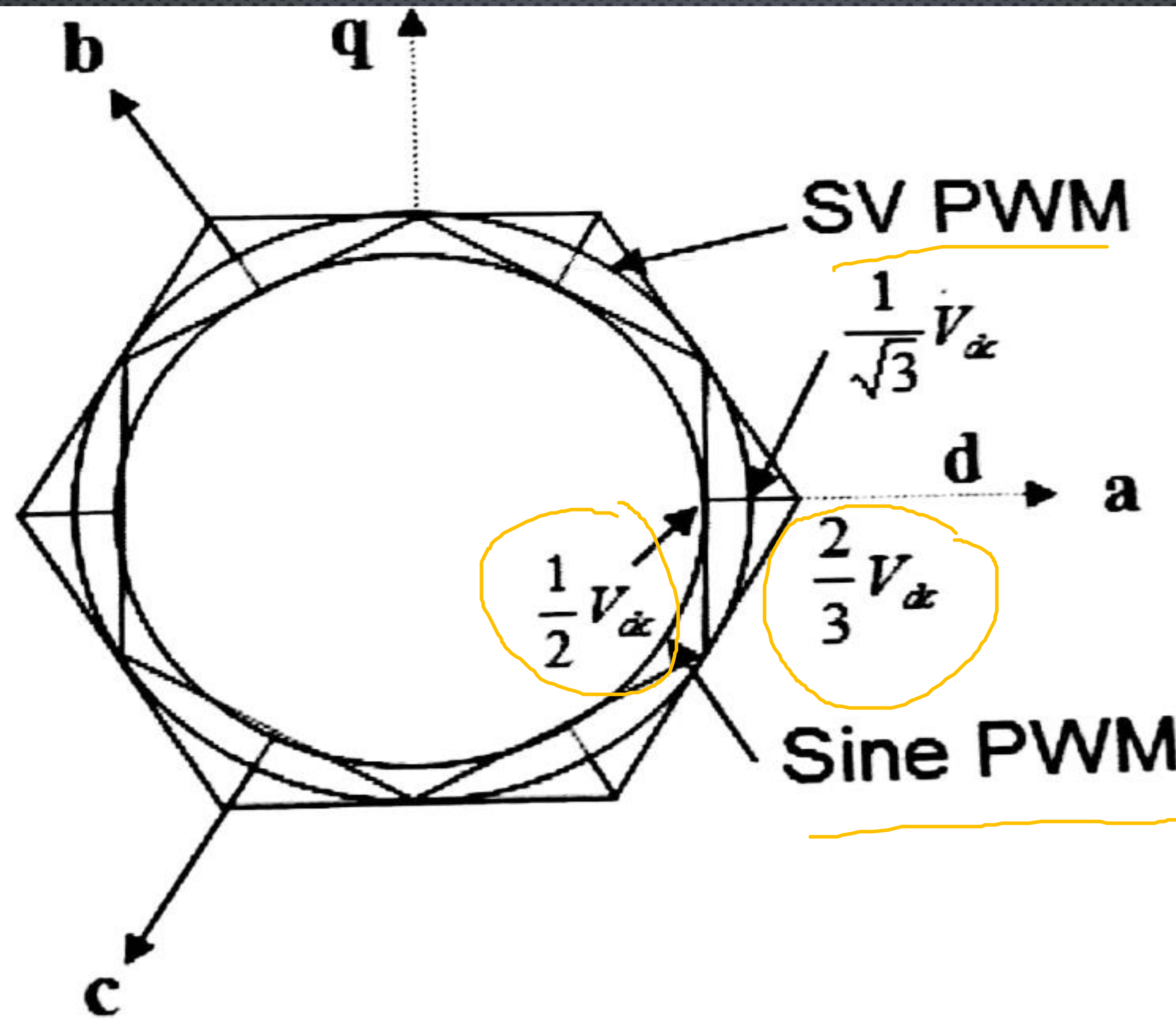
$$\therefore T_2 = T_z \cdot a \cdot \frac{\sin(\alpha)}{\sin(\pi/3)}$$

$$\therefore T_0 = T_z - (T_1 + T_2), \quad \left(\text{where, } T_z = \frac{1}{f_z} \text{ and } a = \frac{\left|\overline{V}_{ref}\right|}{\frac{2}{3} V_{dc}} \right)$$

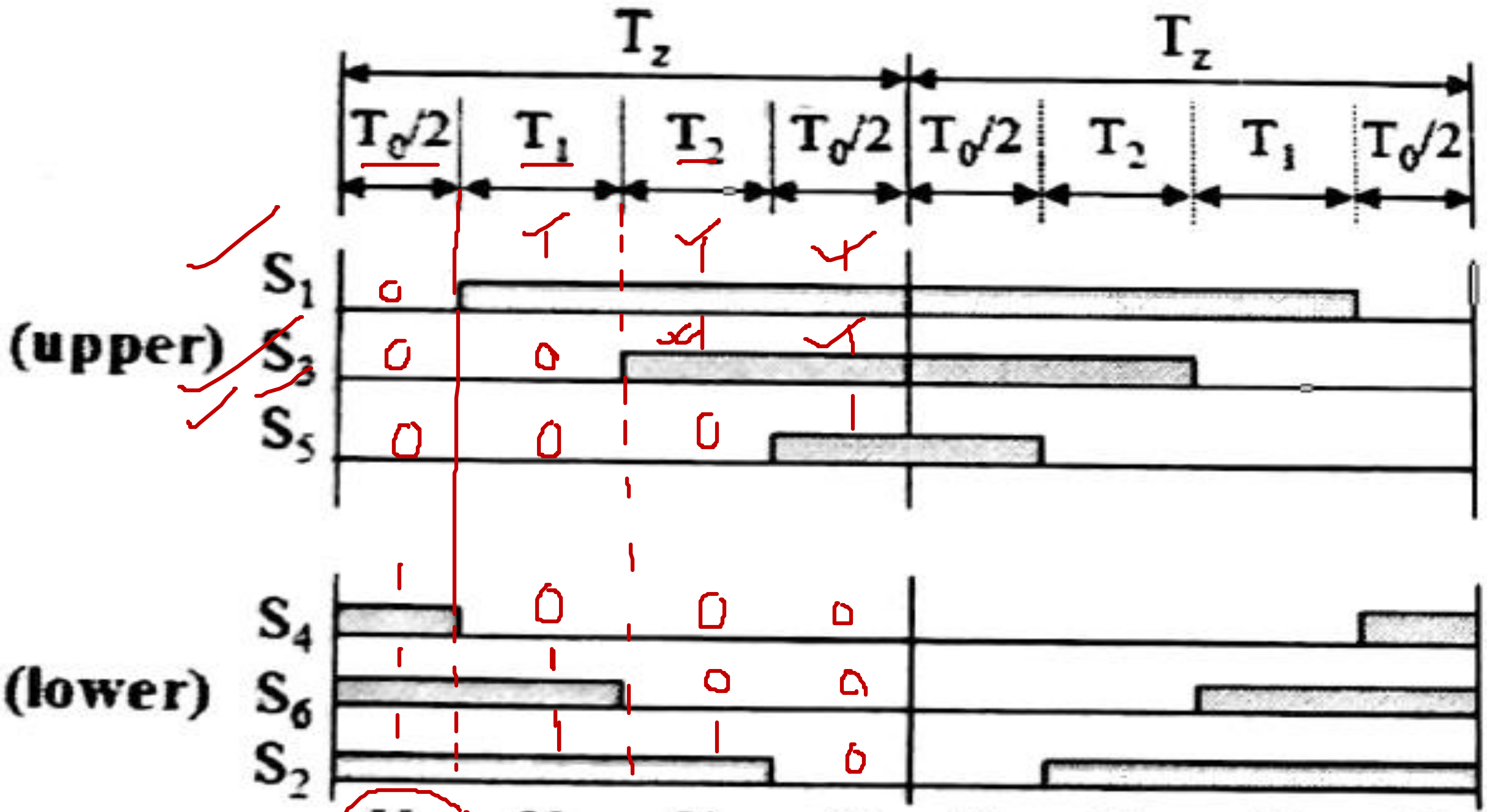
V_{REF} IN SECTOR1



COMPARE SPWM AND SVPWM



SECTOR1

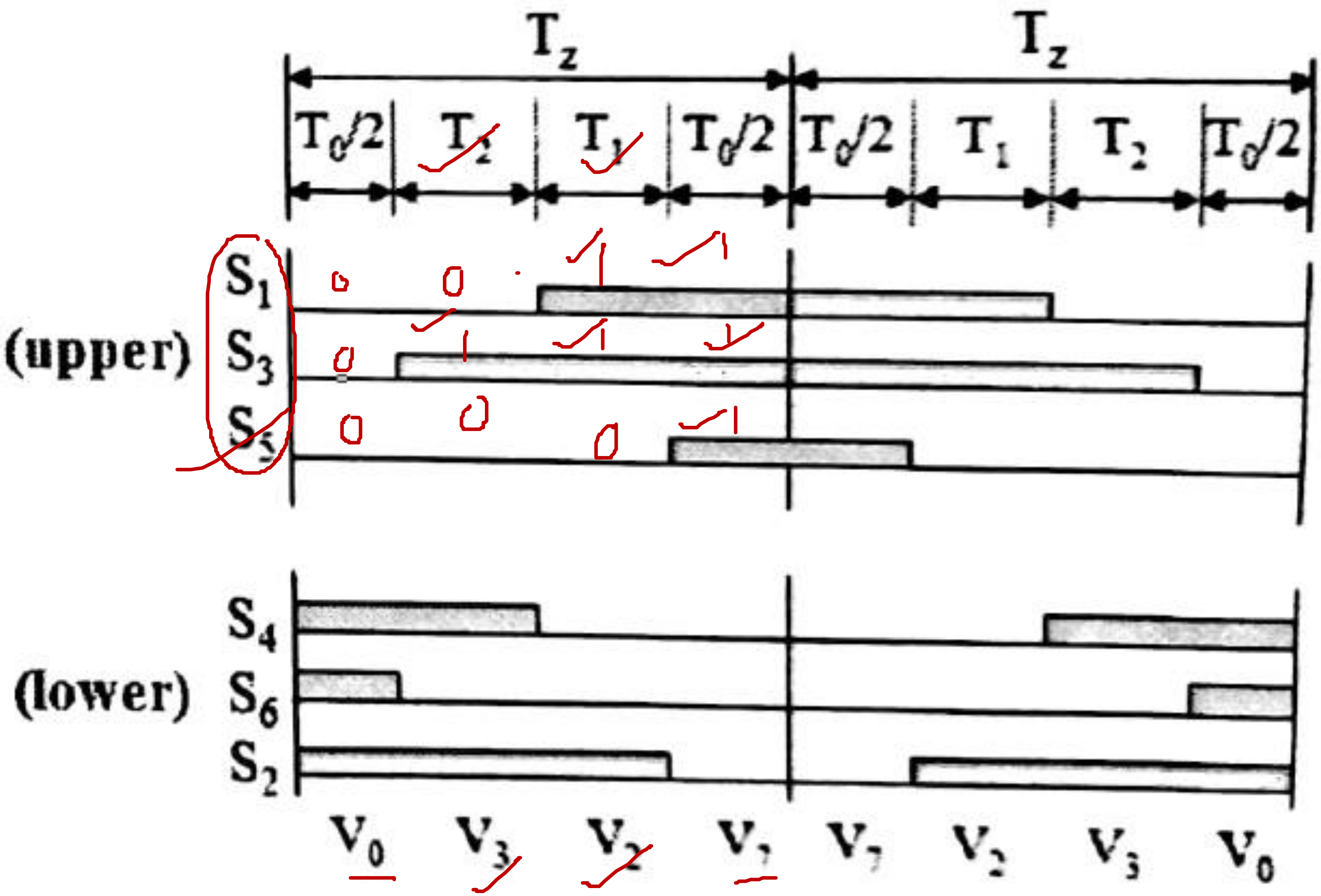


T_z
T_z
$T_0/2$
T_1
T_2
$T_0/2$
$T_0/2$
T_2
T_1
$T_0/2$
S_1
(upper)
S_3
S_5
S_4
(lower)
S_6
S_2
V_0
V_1
V_2
V_7
V_7
V_2
V_1
V_0

SWITCHING DURATION

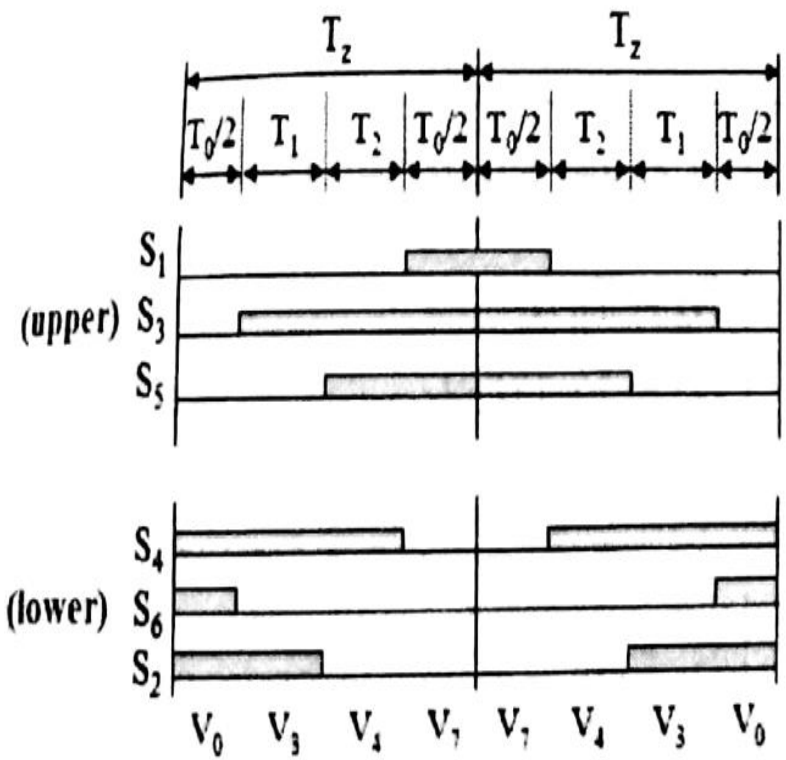
Sector	Upper Switches (S_1, S_3, S_5)	Lower Switches (S_4, S_6, S_2)
1	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_2 + T_0/2$ $S_5 = T_0/2$	$S_4 = T_0/2$ $S_6 = T_1 + T_0/2$ $S_2 = T_1 + T_2 + T_0/2$
2	$S_1 = T_1 + T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_0/2$	$S_4 = T_2 + T_0/2$ $S_6 = T_0/2$ $S_2 = T_1 + T_2 + T_0/2$
3	$S_1 = T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_2 + T_0/2$	$S_4 = T_1 + T_2 + T_0/2$ $S_6 = T_0/2$ $S_2 = T_1 + T_0/2$
4	$S_1 = T_0/2$ $S_3 = T_1 + T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	$S_4 = T_1 + T_2 + T_0/2$ $S_6 = T_2 + T_0/2$ $S_2 = T_0/2$
5	$S_1 = T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	$S_4 = T_1 + T_0/2$ $S_6 = T_1 + T_2 + T_0/2$ $S_2 = T_0/2$
6	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_0/2$	$S_4 = T_0/2$ $S_6 = T_1 + T_2 + T_0/2$ $S_2 = T_2 + T_0/2$

SECTOR2

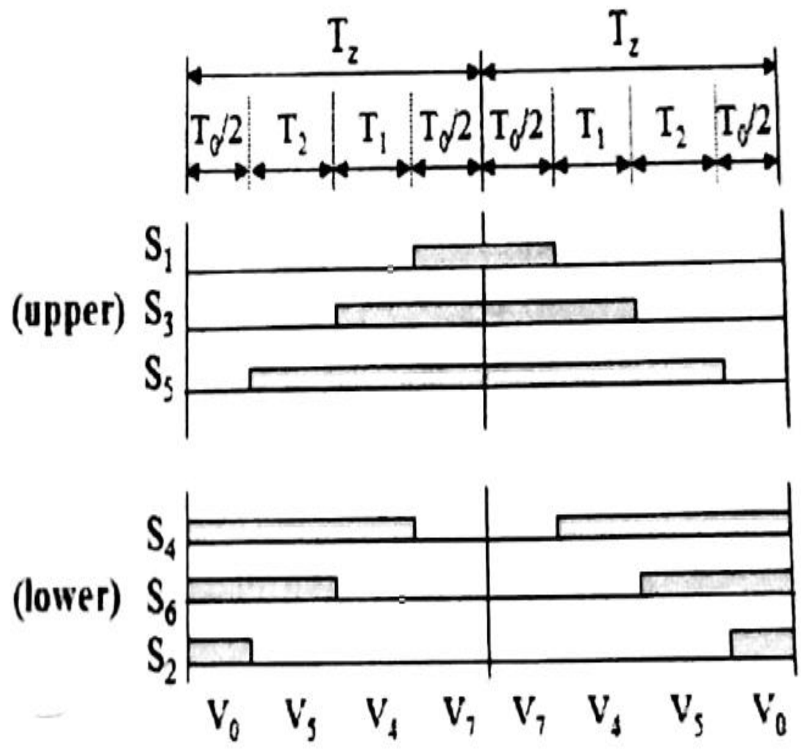


T_z
T_z
$T_0/2$
T_2
T_1
$T_0/2$
$T_0/2$
T_1
T_2
$T_0/2$
S_1
(upper)
S_3
S_5
S_4
(lower)
S_6
S_2
V_0
V_3
V_2
V_7
V_7
V_2
V_3
V_0

SECTOR3 AND SECTOR4

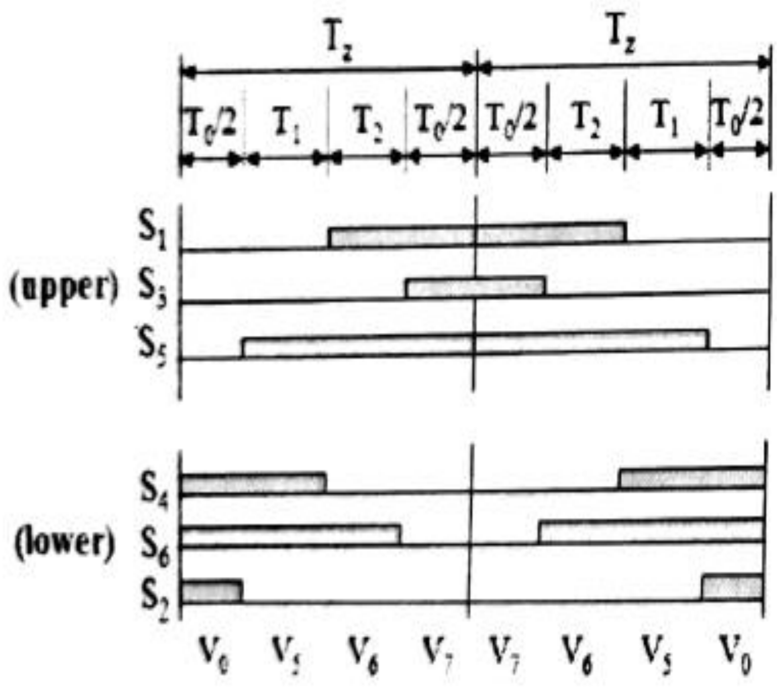


(c) Sector 3.

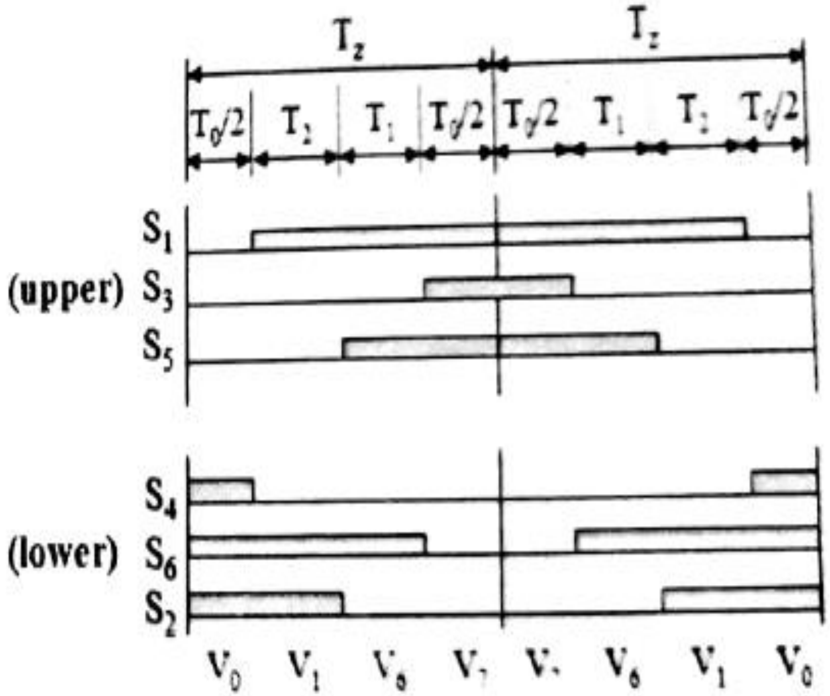


(d) Sector 4.

SECTOR5 AND SECTOR6



(e) Sector 5.



(f) Sector 6.