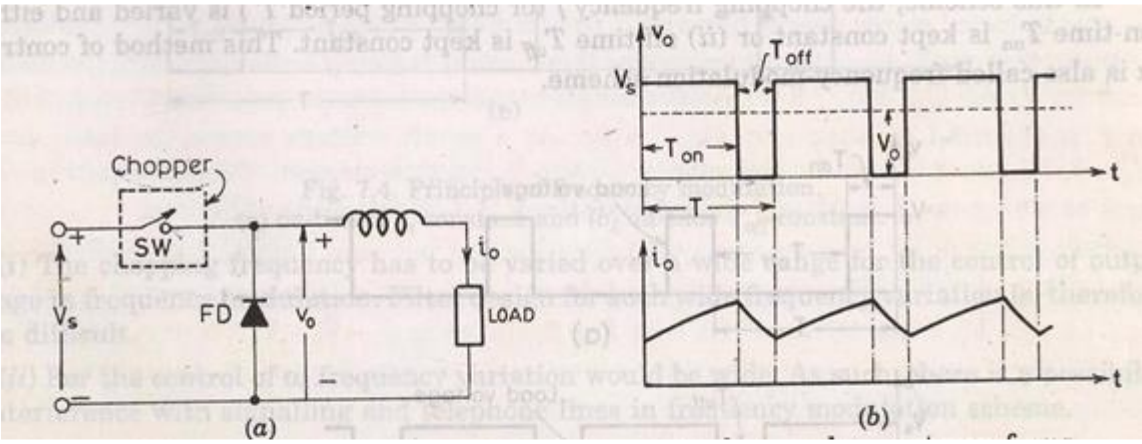
MODULE - III

CHOPPER

A chopper is a static device that converts fixed DC input voltage to variable output voltage directly. Chopper are mostly used in electric vehicle, mini haulers.

Chopper are used for speed control and braking. The systems employing chopper offer smooth control, high efficiency and have fast response.



The average output voltage is

$$V_a = \frac{1}{T}\int_0^{t1} V_0 dt = \frac{1}{T}V_s(\mathrm{t}_1) = ft_1 V_s = \alpha V_s$$

The average load current

$$I_a = \frac{V_a}{R} = \frac{\alpha V_s}{R}$$

Where, T=chopping period

Duty cycle of chopper =

$$\alpha = \frac{t_1}{T}$$

f=chopping frequency

The rms value of output voltage is

$$V_0 = (\frac{1}{T}\int_0^{\alpha} V_0^2 dt)^{\frac{1}{2}} = \sqrt{\alpha} V_s$$

If we consider the converter to be loss less then the input power is equal to the output power and is given by

$$P_i = \frac{1}{T}\int_0^{\alpha T} V_0 i dt = \frac{1}{T}\int_0^{\alpha T} \frac{V_o}{R}^2 dt$$

$$= \frac{1}{T}\frac{V_s^2}{R}(\alpha T) = \frac{\alpha V_s^2}{R}$$

The effective input resistance seen by the P source is

$$P_i = \frac{V_s}{I_a} = \frac{V_s}{\frac{\alpha V_s}{R}} = \frac{R}{\alpha}$$

The duty cycle α can be varied by varying t_1 , T of frequency.

Constant frequency operation:

1)The chopping period T is kept constant and on time is varied.

The pulse width modulation ,the width of the pulse is varied.

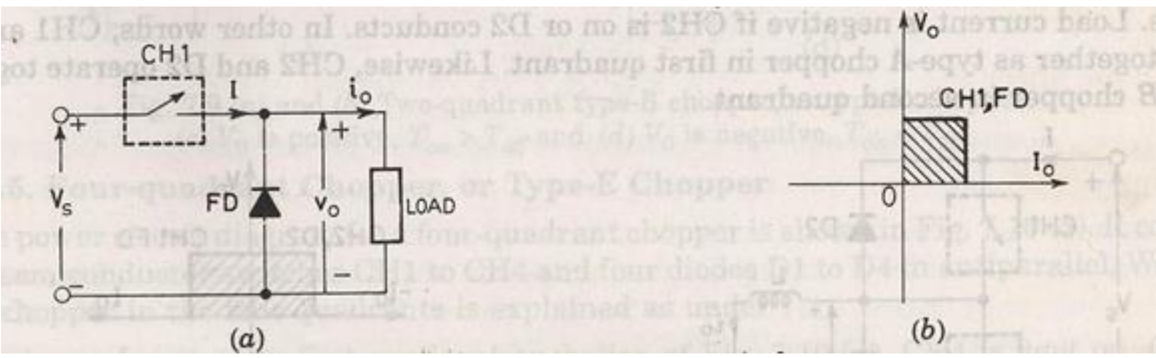
2) Variable frequency operation, the chopping frequency f is varied.

Frequency modulation, either on time or off time is kept constant.

This type of control generate harmonics at unpredictable frequency and filter design is often difficult.

TYPES OF CHOPPER:

FIRST QUADRANT OR TYPE A CHOPPER:



When switch ON

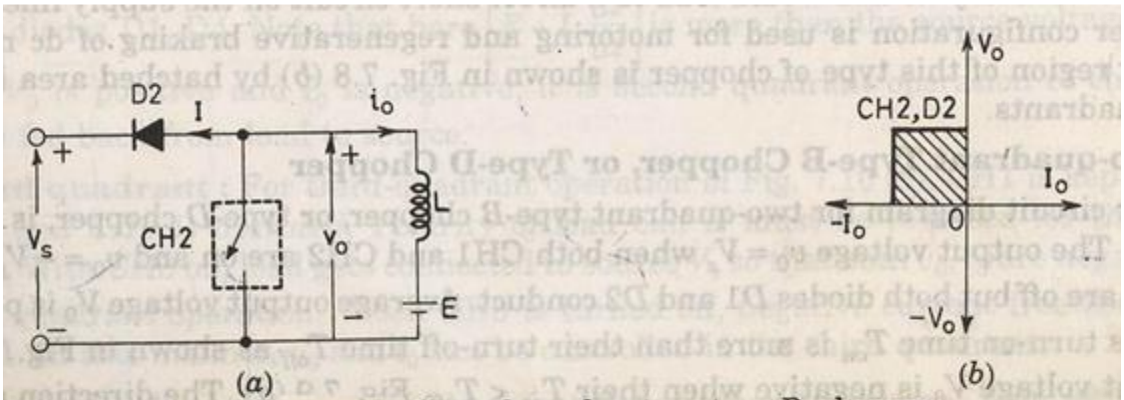
$V_0 = V_s$.

Current i_o flows in the same direction when switch off.

$V_o=0$, $i_o=0$

So, average value of both the load and the current are positive.

SECOND QUADRANT OR TYPE B CHOPPER:



Second-quadrant, or type-B, chopper.

When switch are closed the load voltage E drives current through L and switch. During T_{on}

L stores energy.

When switch off V_0 exceeds source voltage V_s.

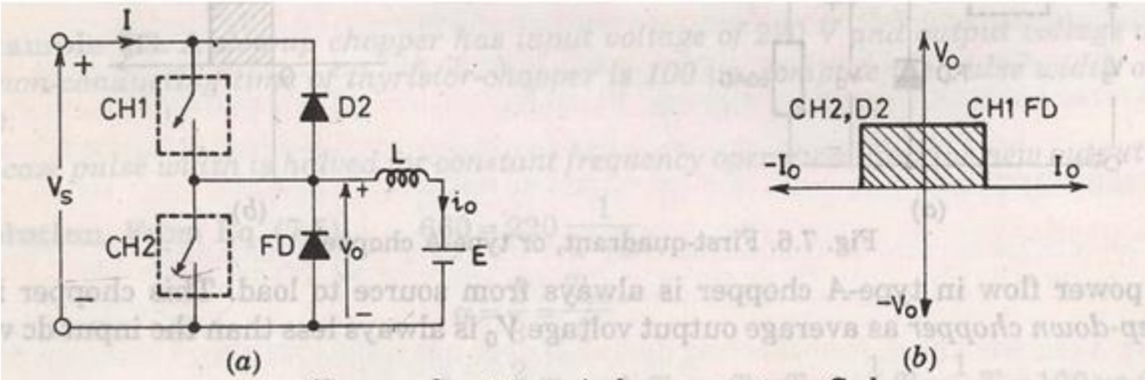
$$V_0 = E + L\frac{di}{dt}$$

Diode D_2 is forward biased.power is fed back to supply. As $V_o$is more than sourse voltage. So such chopper is called step up chopper.

$$V_0 = E + L\frac{di}{dt}$$

So current is always negative and V_o is always positive.

TWO QUADRANT TYPE A CHOPPER OR, TYPE C CHOPPER:



Two-quadrant type-A chopper, or type-C chopper.

Both the switches never switch ON simultaneously as it lead direct short circuit of the supply.

Now when sw2 is closed or FD is on the output voltage V_0 is zero.

When sw1 is ON or diode D conducts output voltage is V_0 is $+V_s$’

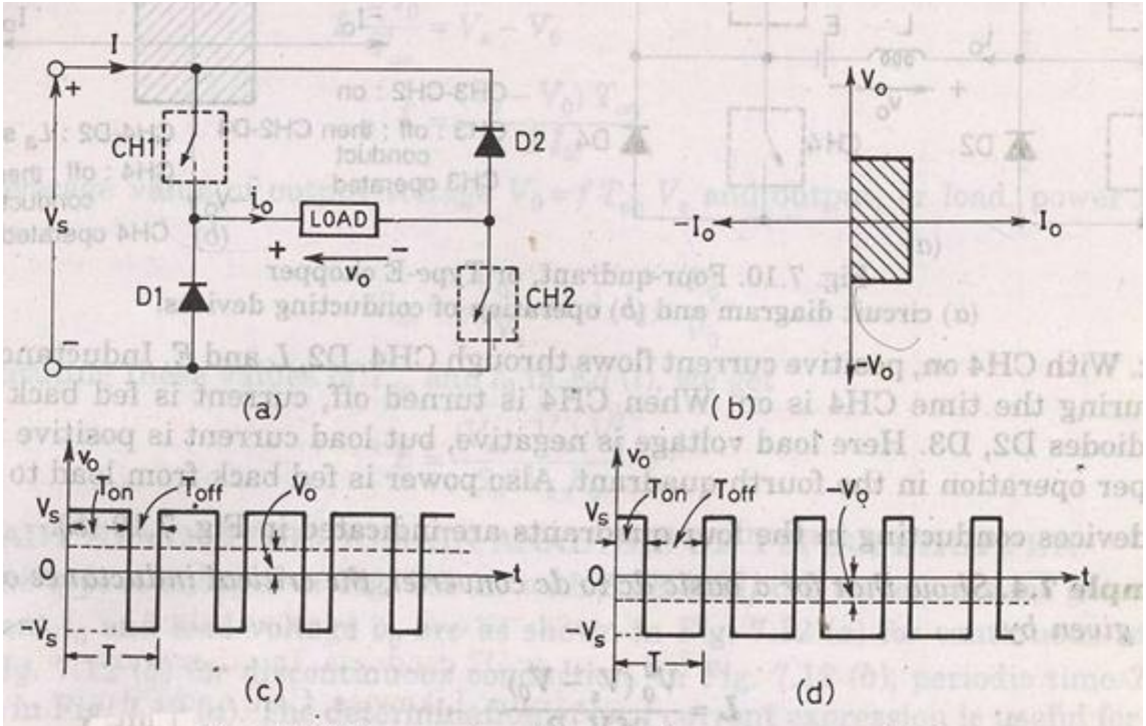
<u>CURRENT ANANLYSIS:</u>

When CH1 is ON current flows along i_0. When CH1 is off current continues to flow along i_0 as FD is forward biased. So i_0 is positive.

Now when CH2 is ON current direction will be opposite to i_0. When sw2 is off D2 turns ON.

Load current is $-i_0$. So average load voltage is always positive. Average load current may be positive or negative.

<u>TWO QUADRANT TYPE B CHOPPER, OR TYPE D CHOPPER:</u>



(*a*) and (*b*) Two-quadrant type-B chopper, or type-D chopper (*c*) V_0 is positive, $T_{on} > T_{off}$ and (*d*) V_0 is negative, $T_{on} < T_{off}$

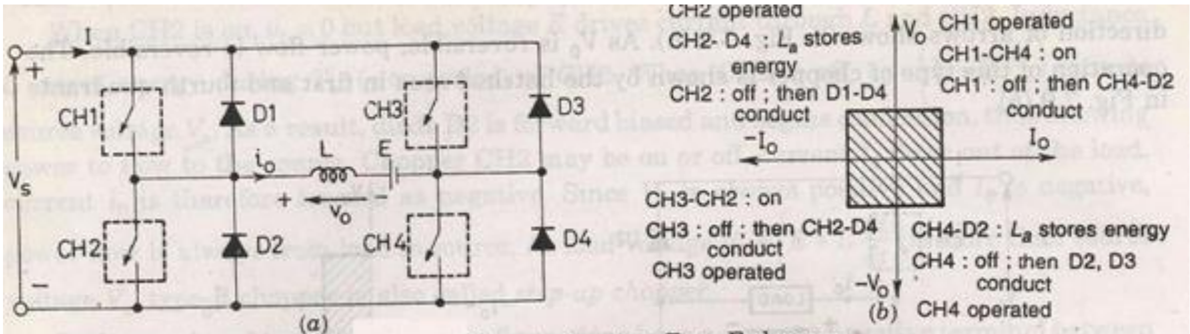
When CH1 and CH2 both are on then $V_0 = V_s$.

When CH1 and CH2 are off and D1 and D2 are on $V_0 = -V_s$.

The direction of current is always positive because chopper and diode can only conduct in the direction of arrow shown in fig.

Average voltage is positive when $T_{on} > T_{off}$

FOUR QUADRANT CHOPPER, OR TYPE E CHOPPER



Four-qudrant, or Type-E chopper
(*a*) circuit diagram and (*b*) operation of conducting devices.

<u>FIRST QUADRANT:</u>

CH4 is kept ON

CH3 is off

CH1 is operarted

$V_0=V_s$

i_0 = positive

when CH1 is off positive current free wheels through CH4,D2

so V_0 and I_2 is in first quadrant.

<u>SECOND QUADRANT:</u>

CH1,CH3,CH4 are off.

CH2 is operated.

Reverse current flows and I is negative through L CH2 D4 and E.

When CH2 off D1 and D4 is ON and current id fed back to source. So

$E + L\dfrac{di}{dt}$ is more than source voltage V_s.

As i_0 is negative and V_0 is positive, so second quadrant operation.

<u>THIRD QUADRANT:</u>

CH1 OFF, CH2 ON

CH3 operated. So both V_0 and i_0 is negative.

When CH3 turned off negative current freewheels through CH2 and D4.

<u>FOURTH QUADRANT:</u>

CH4 is operated other are off.

Positive current flows through CH4 E L D2.

Inductance L stores energy when current fed to source through D3 and D2.V_0 is negative.

STEADY STATE ANALYSIS OF PRACTICAL BUCK CHOPPER:

The voltage across the inductor L is e_i=Ldi/dt.

$$V_s - V_a = L\frac{d(i_2 - i_1)}{t_1} = L\frac{\Delta i}{t_1}$$

$$t_1 = \frac{\Delta i L}{V_s - V_a}.$$

The inductor current falls linearly from I_2 to I_1 in time t_2 as V_s =0.

So

$$-V_a = \frac{\mathrm{L}(i_1 - i_2)}{t_2}$$

If I_2-I_1=ΔI then

$$-V_a = -\frac{L\Delta I}{t_2}$$

$$t_2 = \frac{L\Delta I}{V_a}.$$

ΔI=I_2-I_1= peak to peak ripple current.

$$\Delta I = \frac{(V_s - V_a)\mathrm{t}_1}{L} = \frac{V_a t_2}{L}$$

Now t_1=αT, t_2=(1-α)T

$$V_a = V_s\frac{t_1}{T} = \alpha V_s$$

A<1 so it is a step down or buck converter.

If the circuit is lossless then $V_s I_s = V_a\, I_a = \alpha V s I_a$

$I_s = \alpha\, I_a$.

Now switching period T can be expressed as

$T=1/f= t_1+ t_2=\Delta IL/(V_s-V_a) + \Delta IL/(V_a)$

$=\Delta ILV_s/V_a(V_s-V_a)$

So peak to peak ripple current

$$\Delta I = \frac{V_a(V_s - V_a)}{fLV_s}$$

$$\Delta I = \frac{V_a\alpha(1-\alpha)}{fL}$$

The peak to peak voltage of the capacitor is

$$\Delta V_c = \frac{\Delta I}{8\,fc}$$

So from above equation

$$\Delta V_c = \frac{V_a(V_s - V_a)}{8Lcf^2V_s} \cdot \frac{V_s\alpha(1-\alpha)}{8Lcf^2}$$

Condition for continuous inductor current and capacitor voltage :

If I_L is the average inductor current

$\Delta I_L = 2I_L$ ....as

$V_a = \alpha V_s$

$$\frac{V_s\alpha(1-\alpha)}{fL} =$$

As $\frac{I_2 - I_1}{2} = I_L$

So $\Delta I = 2I_L$

$$\frac{V_s\alpha(1-\alpha)}{fL}$$ .....eq (2)

$$\frac{V_s\alpha(1-\alpha)}{fL} = 2I_L = 2I_a = \frac{2\alpha V_s}{R}$$ .....eq(4)

As $V_a = \alpha V_s$ so $I_a = \frac{\alpha V_s}{R}$

$$2I_a = \frac{2\alpha V_s}{R}$$

So equation 4 gives

$$L_c = \frac{(1-\alpha)R}{2f}$$

Which is the critical value of inductor

$$\Delta V_c = 2V_a$$

$$2V_a = \frac{V_s\alpha(1-\alpha)}{8Lcf^2} = 2\alpha V_s$$

$$c = \frac{1-\alpha}{16Lf^2}$$

Peak to peak ripple voltage of capacitor:

$$\Delta V_c = V_c - V_c(t=0)$$

$$= \frac{1}{c}\int_0^{t_1} I_c dt = \frac{1}{c}\int_0^{t_1} I_a = \frac{I_a t_1}{c}$$

So $t_1 = \frac{V_a - V_s}{V_{af}}$

$$t_1 = \frac{V_a - V_s}{V_{af}}$$

$$\Rightarrow 1-\alpha = \frac{V_s}{V_a}$$

$$\Rightarrow 1-\frac{t_1}{T} = \frac{V_s}{V_a}$$

$$\Rightarrow t_1 = \frac{V_a - V_s}{V_a f}$$

So $\Delta V_c = \frac{I_a}{c}(\frac{V_a - V_s}{V_{af}})$

$$\Rightarrow \Delta V_c = \frac{I_a \alpha}{fc}$$

Condition for continuous imductor current and capacitor voltage:

If I_L= average inductor current then

$$I_L = \frac{\Delta I}{2}$$

$$\Delta I = \frac{V_s \alpha}{fL} = 2I_L = 2I_a = \frac{2V_s}{(1-\alpha)R}$$

As $V_a = \frac{V_s}{1-\alpha}$

$$\Rightarrow 2I_a = \frac{2V_s}{(1-\alpha)\mathrm{R}}$$

So $\Delta I_L = 2I_L = 2I_a = \frac{2V_s}{(1-\alpha)R} = \frac{V_s \alpha}{fL}$

$$\Rightarrow L_c = \frac{\alpha(1-a)R}{2f}$$

$$\Delta V_c = 2V_a$$

$$\frac{I_a \alpha}{cf} = 2V_a = 2I_a R$$

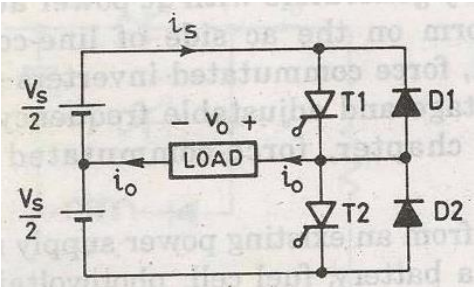
$$c = \frac{\alpha}{2fR}$$

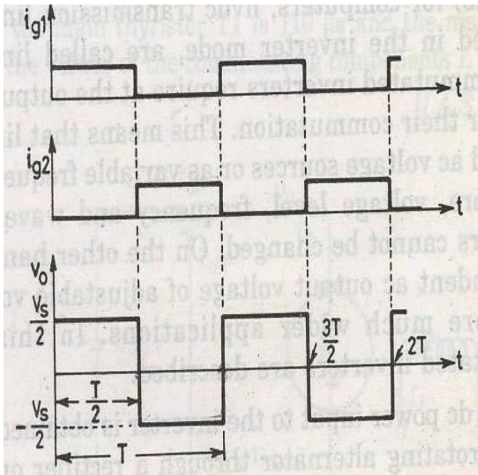
MODULE – IV

INVERTERS

The device that converts dc power into ac power at desired output voltage and frequency is called an inverter.

Single phase voltage source inverters





$V_o(rms) = \frac{1}{T_0/2}\int_0^{T_0/2} \frac{V_S^2}{4}$ dt $=\frac{V_S}{2}$

$$V_0 = \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n \cos(n\omega t) + b_n \sin(n\omega t))$$

Due to symmetry along x-axis

$a_0 = 0$, $a_n = 0$

$$b_n = \frac{4V_S}{n\pi}$$

The instantaneous output voltage

$$v_0 = \sum_{n=1,3,5\ldots}^{\infty} \frac{2V_S}{n\pi}\sin(nwt)$$

=0, n=2,4.....

The rms value of the fundamental output voltage

$V_{01} = \frac{2V_S}{\sqrt{2}\pi}$=0.45$V_S$

So if $V_0 = \sum_{n=1,3,5\ldots}^{\infty} \frac{2V_S}{n\pi}\sin(nwt)$

$$=\sum_{n=1,3,5\ldots.}^{\infty} \frac{2V_S}{n\pi\sqrt{R^2+(n\omega L)^2}}\sin(n\omega t-\theta_n)$$

$P_{01} = (I_{01})^2 R = [\frac{2V_S}{\sqrt{2}\pi\sqrt{R^2+(\omega L)^2}}]^2\text{R}$

<u>DC Supply Current</u>

Assuming a lossless inverter, the ac power absorbed by the load must be equal to the average power supplied by the dc source.

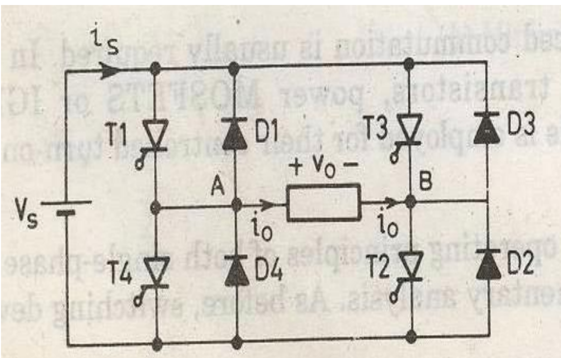
$\int_0^T i_s(t)dt = \frac{1}{V_s}\int_0^T \sqrt{2}V_{01}\sin(\omega t)\sqrt{2}I_0\sin(\omega t-\theta_1)\,dt$=$I_S$

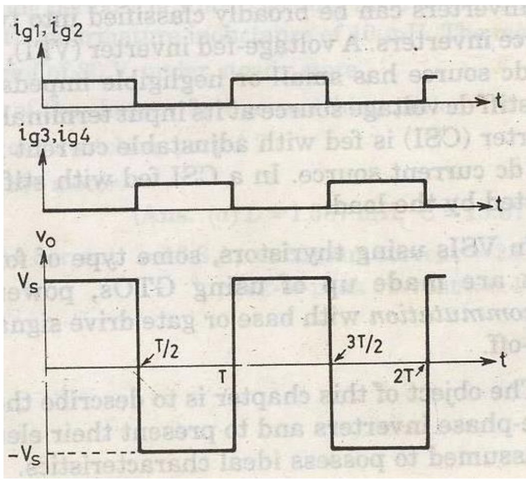
V_{01} =Fundamental rms output output voltage

I_0=rms load current

θ_1=the load angle at the fundamental frequency

<u>Single phase full bridge inverter</u>





For n=1, $V_1 = \frac{4V_S}{\sqrt{2}V_S}$=0.9$V_S$ (The rms of fundamental)

Instantaneous load current i_0 for an RL load

$i_0 = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_S}{n\pi\sqrt{R^2+(n\omega L)^2}}\sin(n\omega t-\theta_n)$

θ_n=$\tan^{-1}(\frac{n\omega L}{R})$

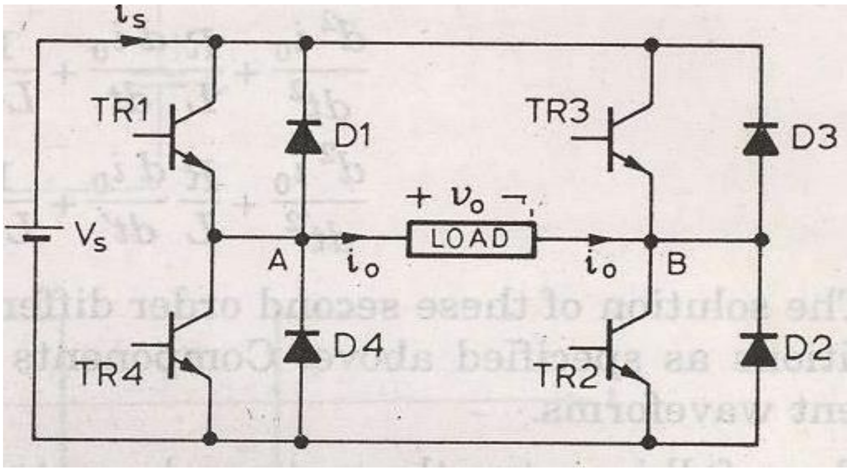
The rms output voltage is

V_0=$(\frac{2}{T_0}\int_0^{T/2} V_S^2)^{1/2}$ =V_S

The instantaneous output voltage in a fourier series

$$v_0 = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_S}{n\pi} \sin(n\omega t)$$

<u>Single phase bridge inverter</u>

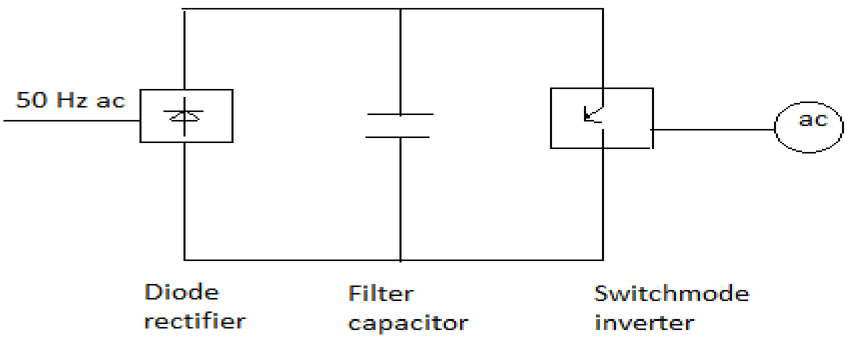


<u>INVERTER</u>

Inverters are of the two types

1) VSI
2) CSI

   Pulse width model



The VSI can be further divided into general 3 categories:

1.Pulse width modulated inverters
2.Square wave inverters
3.Single phase inverter with voltage cancellation

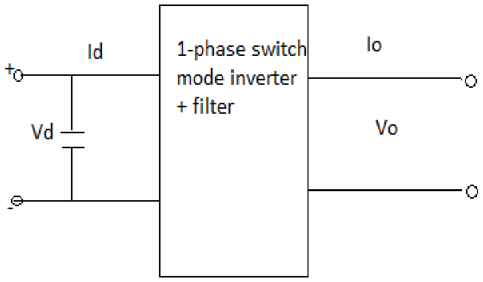
Pulse width modulated inverters

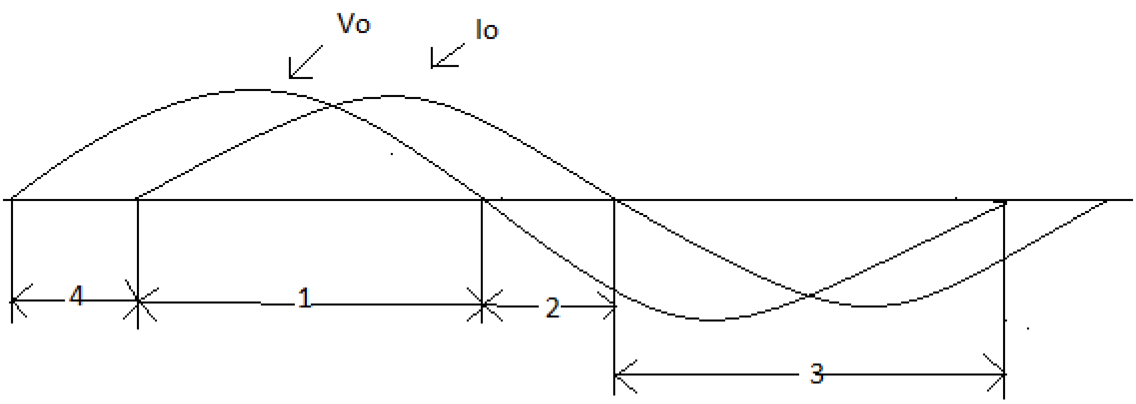
The input dc voltage is of constant magnitude . The diode rectifier is used to rectify the line voltage.The inverter control the magnitude and frequency of the ac output voltage.

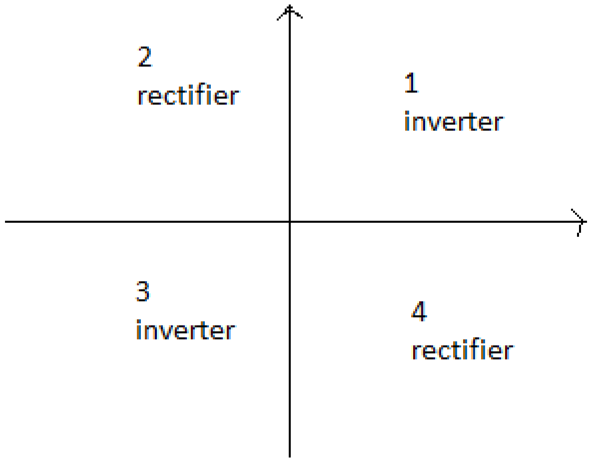
This is achieved by PWM technique of inverter switches and this is called PWM inverters.

The sinusoidal PWM technique is one of the PWM technique to shape the output voltage to as close as sinusoidal output.

Basic concepts of switch mode inverter







During interval 1 $v_0$and i_0 both are positive

During interval 3 v_0 and i_0 both are negative

Therefore during 1 and 3 the instantaneous power flow is from dc side to corresponding to inverter mode of operation.

In contrast during interval 2 and 4 v_0 and i_0 are of opposite sign i.e. power flows from ac side to dc side corresponding to rectifier mode of operation.

<u>Pulse width modulated switching scheme</u>

We require the inverter output to be sinusoidal with magnitude and frequency controllable.

In order to produce sinusoidal output voltage at desired frequency a sinusoidal control signal at desired frequency is compared with a triangular waveform as show.

The frequency of the triangular waveform established the inverter switching frequency.

The triangular waveform is called carrier waveform. The triangular waveform establishes switching frequency f_s , which establishes with which the inverter switches are applied.

The control signal has frequency f_s and is used to modulate the switch duty ratio.

f_1 is the desired fundamental frequency of the output voltage.

<u>The amplitude modulation ratio m_a is defined as</u>

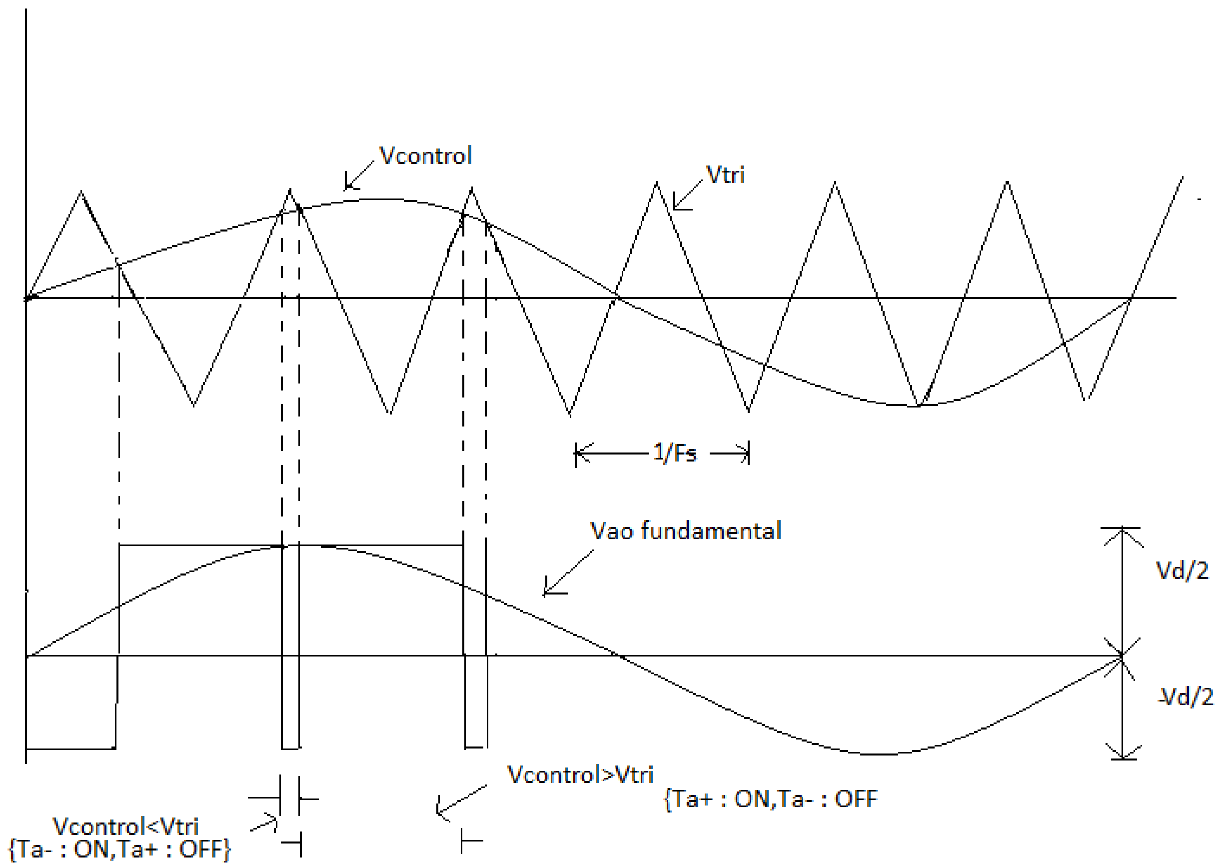
$m_a = \frac{V_{control}}{V_{tri}}$

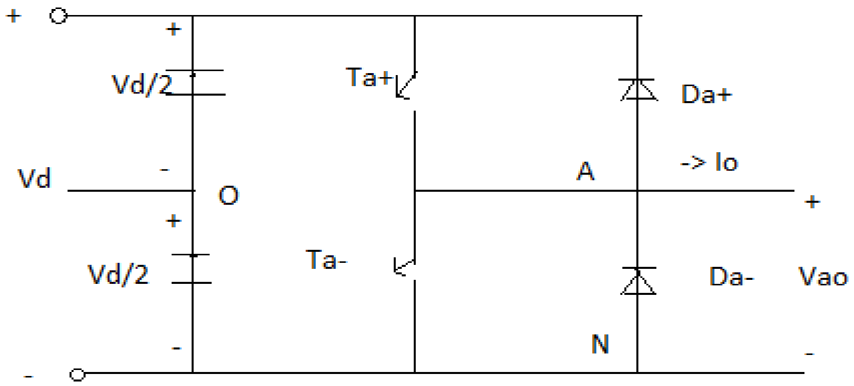
$V_{control}$ is the peak amplitude of control signal.

V_{tri} peak amplitude of triangular signal.

<u>The frequency modulation ratio m_f</u>

$m_f = \frac{f_s}{f_1}$





When $V_{control} > V_{tri}$ $\quad T_A^+$ is ON $\quad V_{AO} = \frac{1}{2}V_d$

$V_{control} < V_{tri}$ $\quad T_A^-$ is ON $\quad V_{AO} = \frac{1}{2}V_d$

So the following inferences can be drawn

The peak amplitude of fundamental frequency is m_a times $\frac{1}{2}V_d$

$V_{AO}=m_a\frac{V_d}{2}$

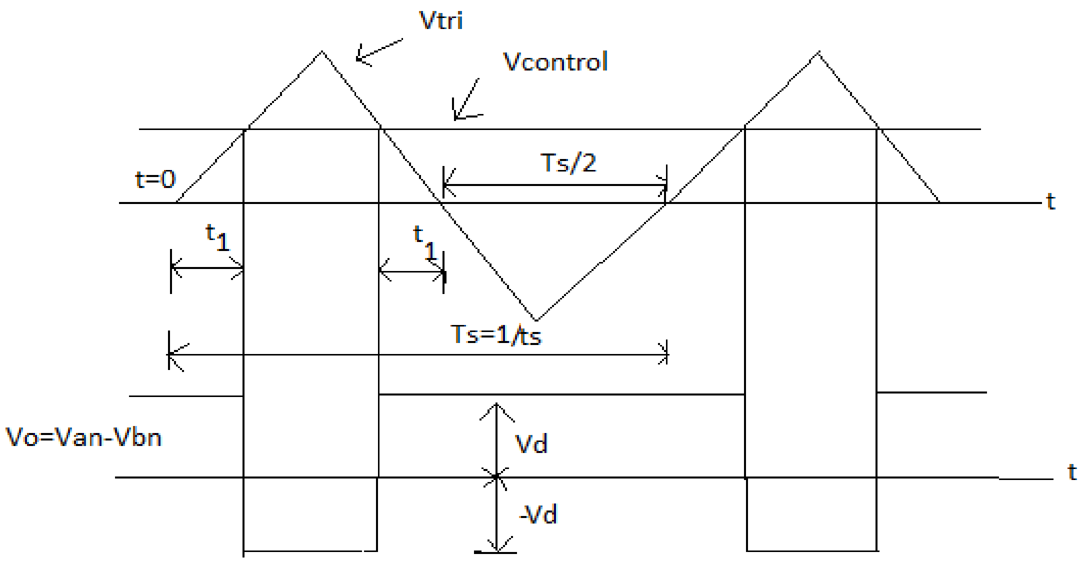
$V_{AO}=\frac{V_{control}}{\hat{V}_{tri}} * \frac{V_d}{2}$ $\qquad V_{control} \leq \hat{V}_{tri}$

<u>The foregoing arguments shown why $V_{control}$ is chosen to be sinusoidal to provide sinusoidal output voltage with fewer harmonics</u>

Let the $V_{control}$ vary sinusoidal with frequency f_1, which is the desired frequency of the inverter output voltage.

Let $V_{control}=\hat{V}_{control}\sin\omega_1 t$

$\hat{V}_{control} \leq \hat{V}_{tri}$



$\frac{\hat{v}_{tri}}{t_1}=\frac{\hat{V}_{tri}}{T_s/4}$

At t=t_1 , $v_{tri}=v_{control}$

So $\frac{v_{control}}{t_1}=\frac{\hat{V}_{tri}}{T_s/4}$

$t_1=\frac{\hat{v}_{control}}{\hat{V}_{tri}}*\frac{T_S}{4}$

$T_{on}=2t_1+\frac{T_S}{2}$

$D_1=\frac{T_{on}}{T_s}=\frac{2t_1+\frac{T_S}{2}}{2}$

$=\frac{1}{2}+\frac{2t_1}{T_S}$

$D_1=\frac{1}{2}+\frac{1}{2}(\frac{\hat{v}_{control}}{\hat{V}_{tri}})$

<u>Three phase inverter</u>

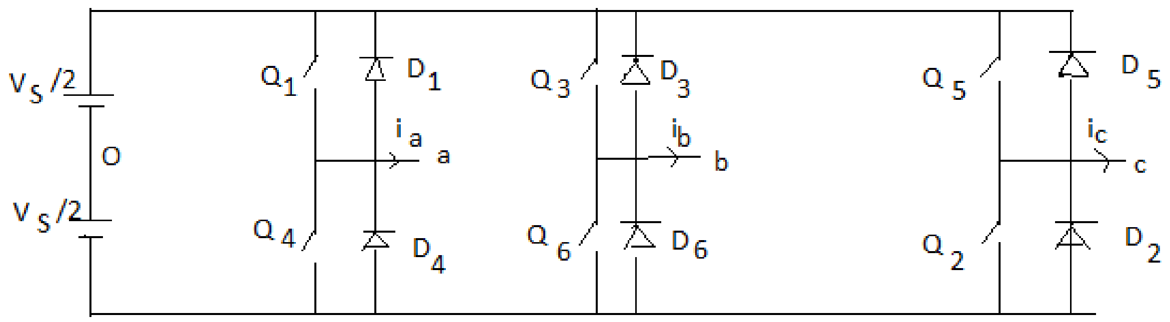
When three single-phase inverters are connected in parallel a three phase inverter is formed.

The gating signal has to be displaced by 120^0 with respect to each other so as achieve three phase balanced voltages.

A 3-phase output can be achieved from a configuration of six transistors and six diodes.

Two type of control signal can be applied to transistors, they are such as 180^0 or 120^0 conduction.

<u>180-degree conduction</u>



When Q_1 is switched on, terminal a is connected to the positive terminal of dc input voltage.

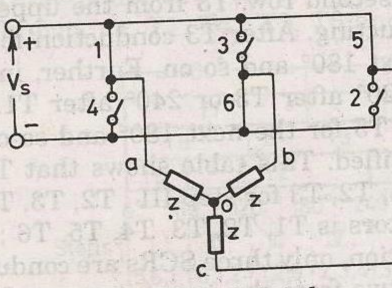
When Q_4 is switched on terminal a is brought to negative terminal of the dc source.

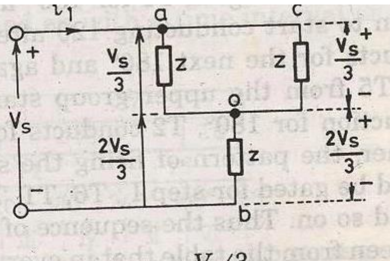
There are 6 modes of operation is a cycle and the duration of each mode is 60^0.

The conduction sequence of transistors is 123,234,345,456,561,612. The gating signals are shifted from each other by 60^0 to get 3-φ balanced voltages.

<u>Switching states for the three phase voltage inverters</u>

Step I

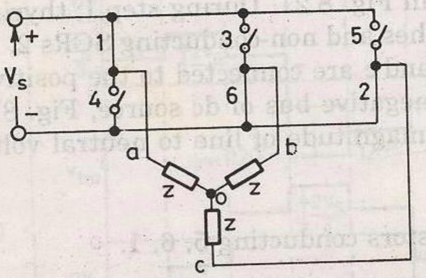


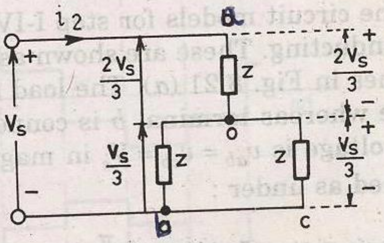


$$v_{ao} = v_{co} = V_s/3$$
$$v_{bo} = -v_{ob} = -2V_s/3$$

(*a*) 0—60° ; 5, 6, 1 closed.

Step II

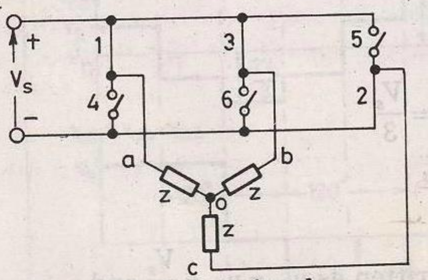


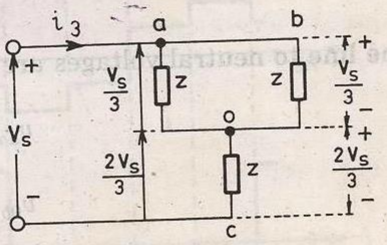


$$v_{ao} = 2V_s/3$$
$$v_{bo} = v_{co} = -V_s/3$$

(*b*) 60—120° ; 6, 1,2 closed.

Step III

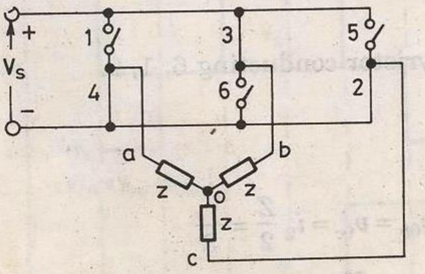


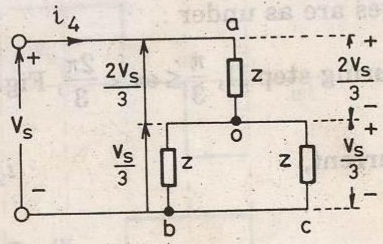


$$v_{ao} = v_{bo} = V_s/3$$
$$v_{co} = -2V_s/3$$

(*c*) 120—180° ; 1, 2, 3 closed.

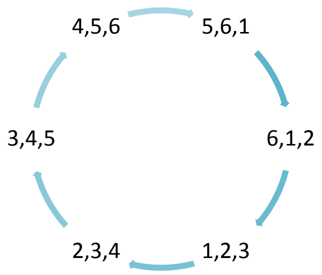
Step IV





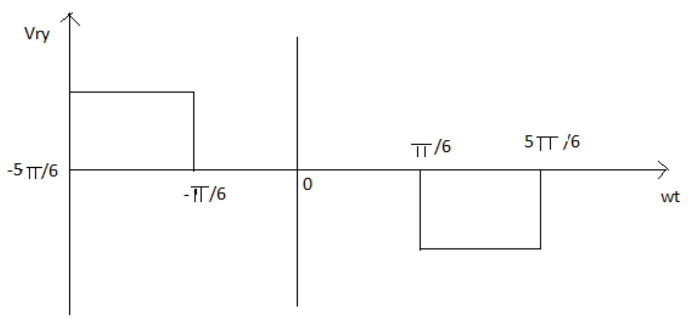
$$v_{bo} = 2\,V_s/3$$
$$v_{ao} = v_{co} = -V_s/3$$

(*d*) 180—240° ; 2, 3, 4 closed.



V_{RN}	V_{YN}	V_{BN}	V_{RY}	V_{YB}	V_{BR}	V_1
$\frac{V}{3}$	$\frac{-2V}{3}$	$\frac{V}{3}$	V_{ac}	$-V_{dc}$	0	$\frac{2}{\sqrt{3}}(330^0)$
$\frac{2V}{3}$	$\frac{-V}{3}$	$\frac{-V}{3}$	V_{dc}	0	$-V_{dc}$	$\frac{2}{\sqrt{3}}(30^0)$
$\frac{V}{3}$	$\frac{V}{3}$	$\frac{-2V}{3}$	0	V	-V	$\frac{2}{\sqrt{3}}(90^0)$
$\frac{-V}{3}$	$\frac{2V}{3}$	$\frac{-V}{3}$	-V	V	0	$\frac{2}{\sqrt{3}}(150^0)$
$\frac{-2V}{3}$	$\frac{V}{3}$	$\frac{V}{3}$	-V	0	0	$\frac{2}{\sqrt{3}}(210^0)$
$\frac{-V}{3}$	$\frac{-V}{3}$	$\frac{2V}{3}$	0	-V	0	$\frac{2}{\sqrt{3}}(270^0)$

<u>Fourier analysis</u>



If we go for harmonic analysis $V_{RY}=\sum_{n=1,3,5\ldots}^{\infty}\frac{4V}{n\pi}sin\frac{n\pi}{3}\sin n(\omega t+{}^{\pi}/_{6})$

$$V_{YB}=\sum_{n=1,3,5\ldots}^{\infty}\frac{4V_S}{n\pi}sin\frac{n\pi}{3}\sin n(\omega t-\pi/_2)$$

$$V_{BR}=\sum_{n=1,3,5\ldots}^{\infty}\frac{4V_S}{n\pi}sin\frac{n\pi}{3}\sin n(\omega t-\pi/_6)$$

All even harmonics are zero all triple n harmonics are zero.

The rms nth component of the line voltage is

$=\frac{4V}{\sqrt{2}n\pi}\sin\frac{n\pi}{3}=\frac{4V}{\sqrt{2}\pi}\sin(60)$

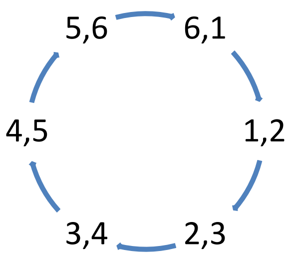
For n=1

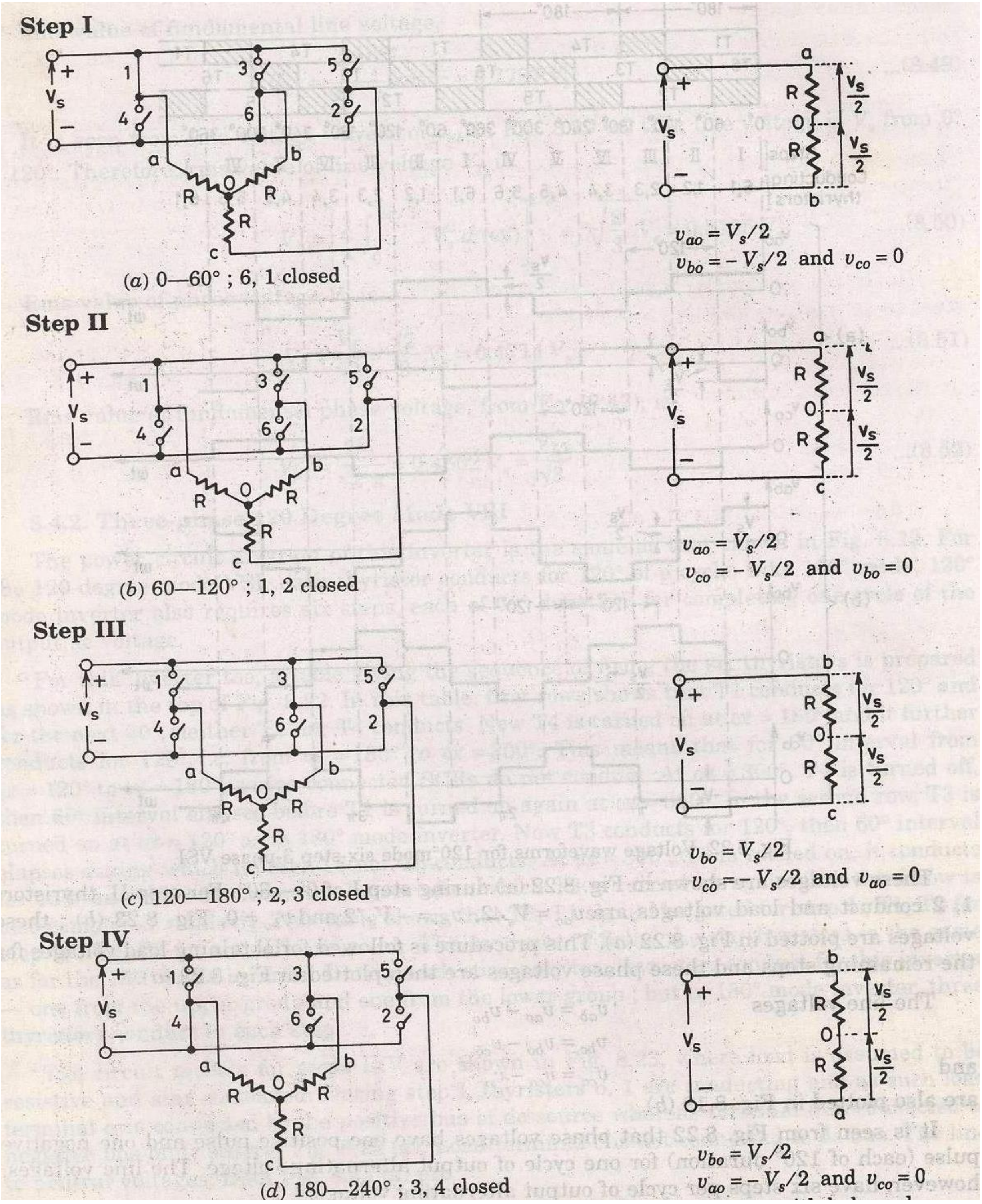
$=0.7797V_S$

<u>Three phase 120^0 mode VSI</u>

The circuit diagram is same as that for 180^0 mode of conduction.

Here each thyristor conducts for 120^0.There are 6 steps each of 60^0 duration, for completing one cycle of ac output voltage.





(a) 0—60° ; 6, 1 closed

(b) 60—120° ; 1, 2 closed

(c) 120—180° ; 2, 3 closed

(d) 180—240° ; 3, 4 closed

<u>Step 1</u>: 6,1 conducting

$V_{an} = \frac{V_S}{2}$, $V_{yn} = \frac{-V_S}{2}$, V_{cn}=0

Step 2: 1,2 conducting

$$V_{an} = \frac{V_S}{2}, V_{bn} = 0, V_{cn} = \frac{-V_S}{2}$$

Step 3: 2,3 conducting

V_{an} =0, V_{bn}=$\frac{V_S}{2}$, V_{cn}=$\frac{-V_S}{2}$

Step 4: 3,4 conducting

$V_{an} = \frac{-V_S}{2}$, V_{bn}=$\frac{V_S}{2}$, V_{cn}=0

Step 5: 4,5 conducting

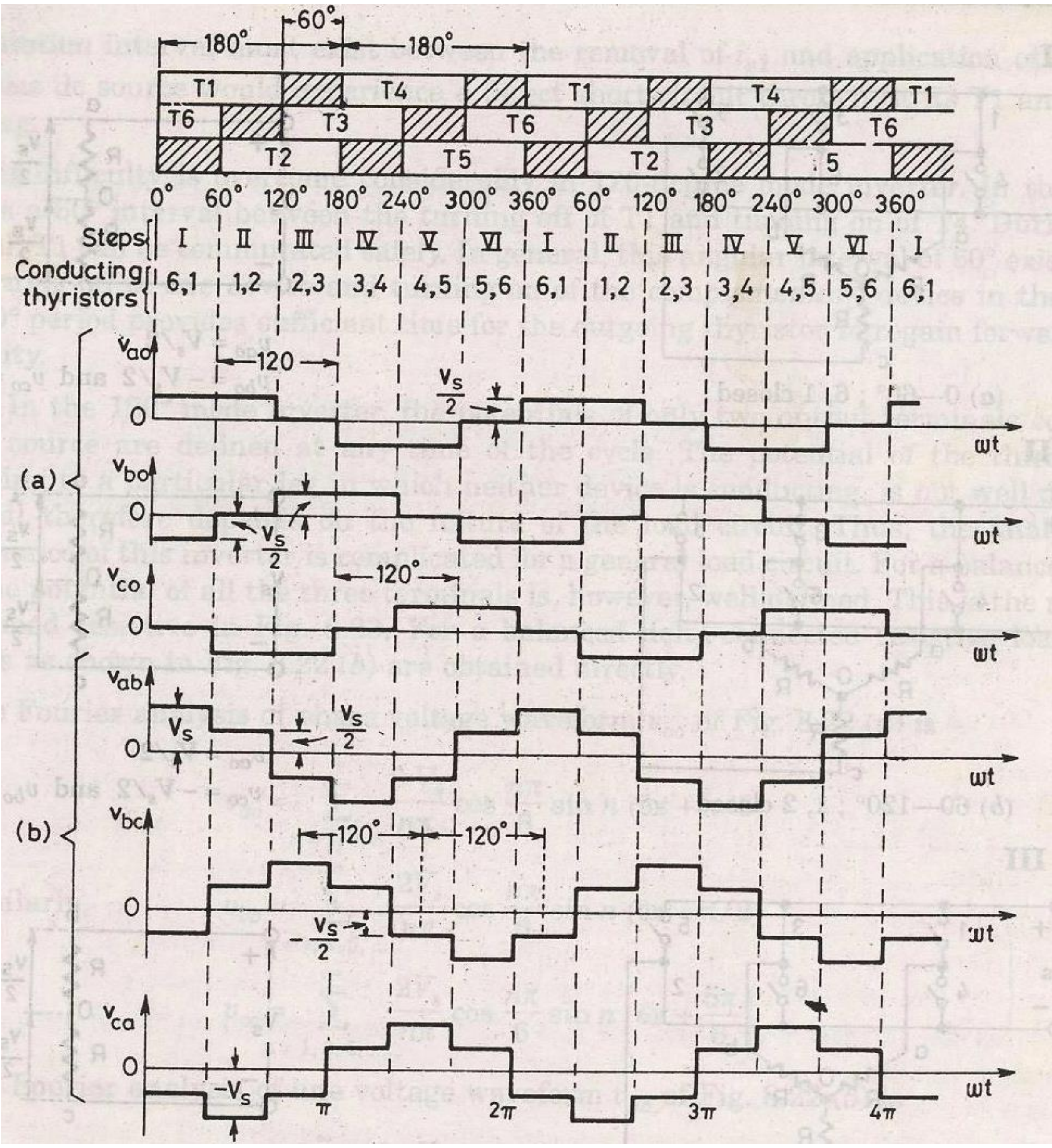
V_{an}== $\frac{-V_S}{2}$, $V_{yn} = 0$, V_{bn} =$\frac{V_S}{2}$

Step 6: 5,6 conducting

V_{an}=0, $V_{bn} = \frac{-V_S}{2}$, V_{cn}=$\frac{V_S}{2}$

120^0 conduction mode

Step	Thyristor conducting	V_{Rn}	V_{Yn}	V_{Bn}	$\vec{V}$
1	6,1	$V_s/_2$	$-V_s/_2$	0	$\frac{\sqrt{3}V_S}{2}(-30^0)$
2	1,2	$V_s/_2$	0	$-V_s/_2$	$\frac{\sqrt{3}V_S}{2}(30^0)$
3	2,3	0	$V_s/_2$	$-V_s/_2$	$\frac{\sqrt{3}V_S}{2}(90^0)$
4	3,4	$-V_s/_2$	$V_s/_2$	0	$\frac{\sqrt{3}V_S}{2}(150^0)$
5	4,5	$-V_s/_2$	0	$V_s/_2$	$\frac{\sqrt{3}V}{2}(210^0)$
6	5,6	0	$-V_s/_2$	$V_s/_2$	$\frac{\sqrt{3}V}{2}(-30^0)$



180°
60°
180°
T1
T4
T1
T4
T1
T6
T3
T6
T3
T6
T2
T5
T2
5
0°
60°
120°
180°
240°
300°
360°
60°
120°
180°
240°
300°
360°
Steps
I
II
III
IV
V
VI
I
II
III
IV
V
VI
I
Conducting thyristors
6,1
1,2
2,3
3,4
4,5
5,6
6,1
1,2
2,3
3,4
4,5
5,6
6,1
v_ao
120
V_s/2
0
ωt
(a)
v_bo
V_s/2
v_co
120°
v_ab
V_s
V_s/2
(b)
v_bc
120°
120°
V_s/2
v_ca
−V_s
π
2π
3π
4π