uous gate pulse
a diode...

14/9/2011

Inverters

→ It converts Fixed DC to Variable AC. (V, f)

classification of Inverters

(1.) Voltage Source Inverters (VSI)

  (a) 1-ϕ Half bridge Inverter
  (b) 1-ϕ Full bridge Inverter
  (c) 3-ϕ VSI

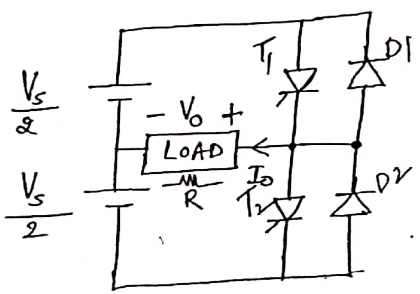
(2) Current Source Inverter (CSI)

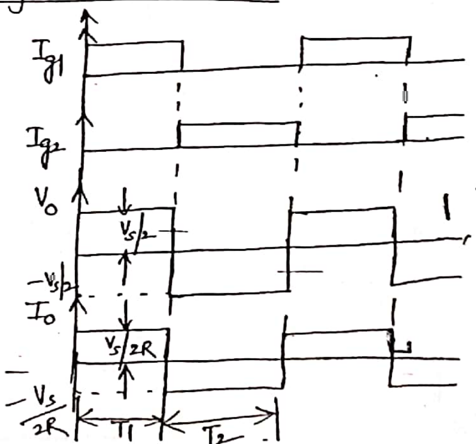
(3) Series Inverter

(4) Parallel Inverter

Voltage Source Inverters

1. 1-ϕ Half bridge Inverter





1. $T_1 \rightarrow$ ON

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

$I_o = \frac{V_s}{2R}$

2. $T_2 \rightarrow$ ON

$\therefore V_o = \frac{-V_s}{2}$; $I_o = \frac{-V_s}{2R}$

→ $V_{or} = \frac{V_s}{2}$

→ Forced commutation is required for Resistive load.

→ Feed back diodes won't conduct for resistive load.

Harmonic Analysis for o/p vg. waveform:

Finding the Fourier series for the o/p waveform, we get,

$$V_o = \sum_{n=1,3,5\ldots}^{\infty} \frac{4\left(\frac{V_s}{2}\right)}{n\pi} \sin n\omega t$$

$$\Rightarrow V_o = \sum_{n=1,3,5}^{\infty} \frac{2V_s}{n\pi} \sin n\omega t$$

$$= \frac{2V_s}{\pi}\left[\sin \omega t + \frac{\sin 3\omega t}{3} + \frac{\sin 5\omega t}{5} + \cdots\right]$$

$$V_{on} = \frac{2V_s}{n\pi} \sin n\omega t$$

$$(V_{on})_{rms} = \frac{\frac{2V_s}{n\pi}}{\sqrt{2}} = \frac{\sqrt{2}V_s}{n\pi}$$

$$(V_{o1})_{rms} = \frac{\sqrt{2}V_s}{\pi}$$

Distortion Factor, $g = \frac{(V_{o1})_{rms}}{V_{or}} = \frac{\frac{\sqrt{2}V_s}{\pi}}{\frac{V_s}{2}} = \frac{2\sqrt{2}}{\pi}$

→ g value depends only on the shape of the waveform.

→ $$THD = \left(\frac{1}{g^2} - 1\right)^{1/2}$$

$$= \sqrt{\frac{\pi^2}{8} - 1}$$

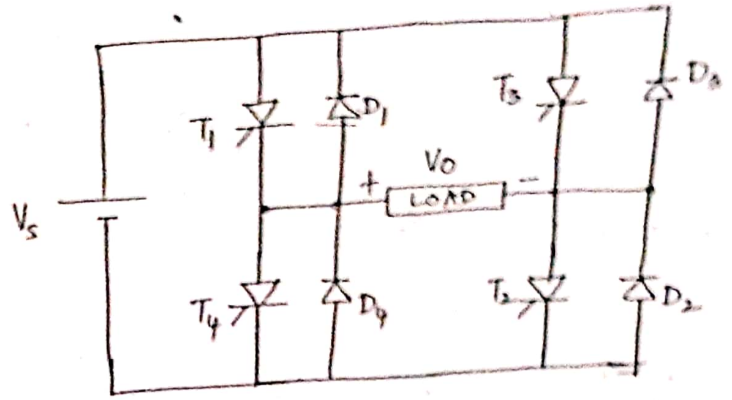
$$= 0.4834$$

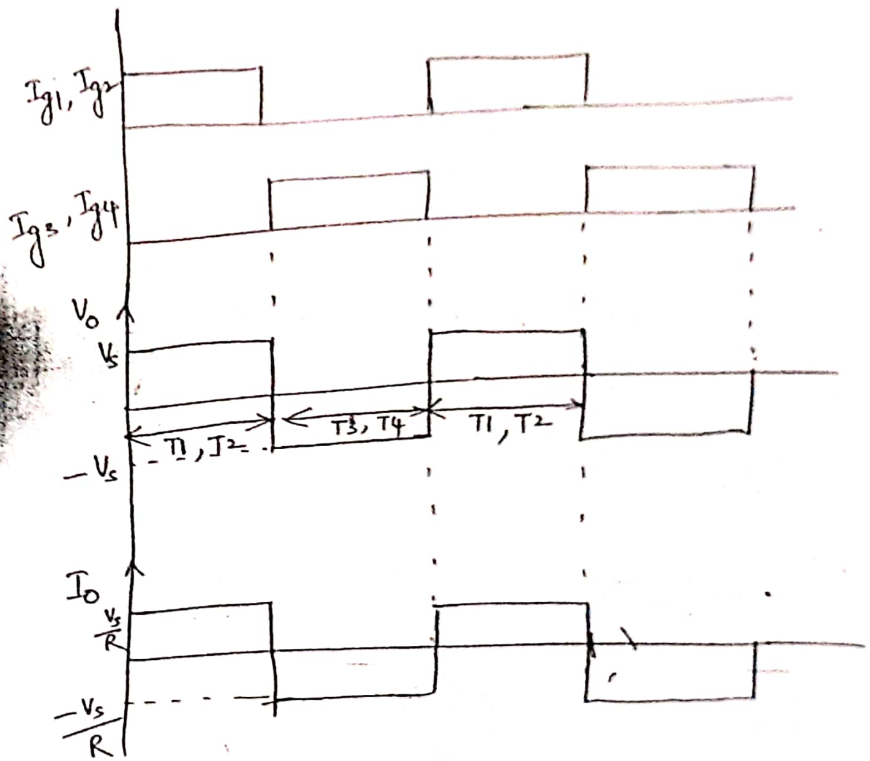
$$\boxed{T.H.D. = 48.34\,\%}$$

→ T.H.D. is a measure of harmonics in AC waveform.

*→ In a VSI, o/p vg. waveform remains same irrespective of nature of the load. The load ct. current magnitude & load waveshape changes as the ~~load~~ nature of the load changes.

$1-\phi$ Full bridge Inverter





(6)

1) $T_1, T_2 \longrightarrow$ ON

$V_o = V_s$

$I_o = \frac{V_s}{R}$

2) $T_3 T_4 \longrightarrow$ ON

$V_o = -V_s$

$I_o = \frac{-V_s}{R}$

$\rightarrow V_{or} = V_s$

$$V_o = \sum_{n=1,3,5}^{\infty} \frac{4V_s}{n\pi} \sin n\omega t$$

$$= \frac{4V_s}{\pi}\left[\sin\omega t + \frac{\sin 3\omega t}{3} + \cdots\right]$$

$$V_{on} = \frac{4V_s}{n\pi} \sin n\omega t$$

$$(V_{on})_{rms} = \frac{2\sqrt{2}V_s}{n\pi}$$

$$(V_{o1})_{rms} = \frac{2\sqrt{2}V_s}{\pi}$$

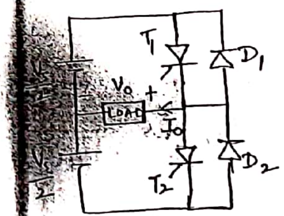
(7)

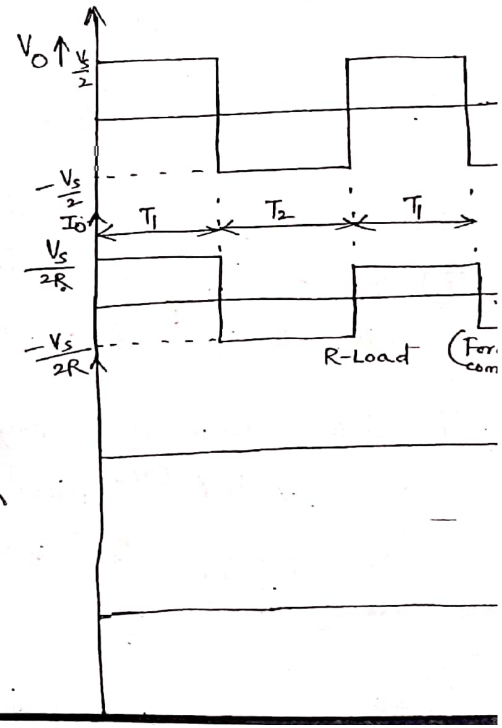
$$g = \frac{(V_{o1})_{rms}}{V_{or}}$$

$$= \frac{\left[\frac{2\sqrt{2}V_s}{\pi}\right]}{V_s} = \frac{2\sqrt{2}}{\pi}$$

$$T.H.D = \sqrt{\frac{1}{g^2} - 1} = 48.34\%$$

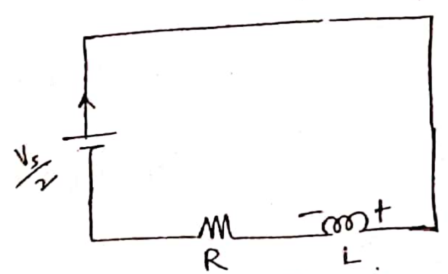
1 (a) 1-ϕ half bridge Inverter





→ For RL Load I_o lags V_o by

$\phi = \tan^{-1}\left(\frac{\omega L}{R}\right)$



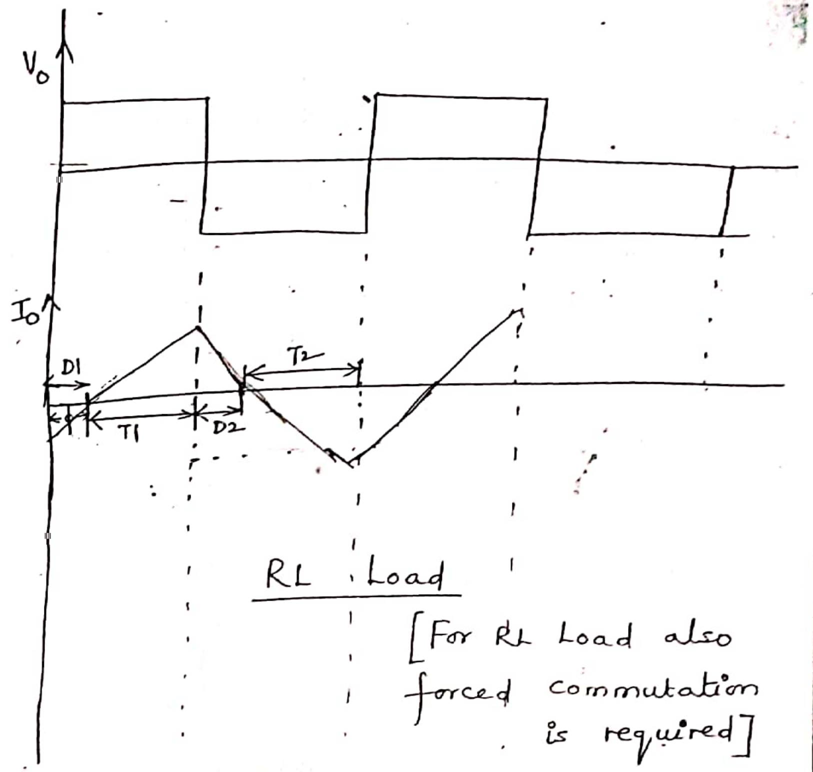
when T_1 is ON, L stores energy

⇒ Power flows from source to load.

$\left(\frac{1}{2} Li^2 + i^2 R\right)$

(i) when thyristor is ON, Power is +ve ∵ L stores energy

(ii) The moment thyristor is force commutated, inductor starts releasing its energy to source through Diode.

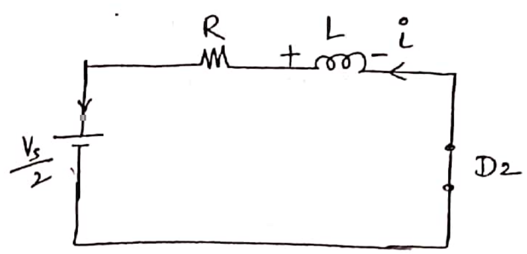


RL Load

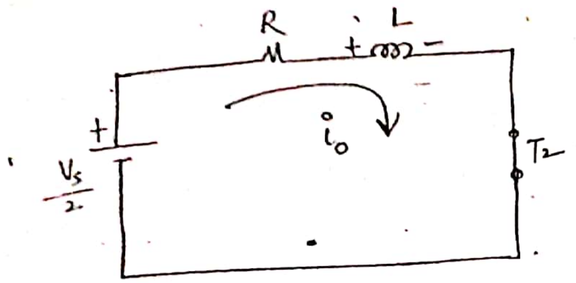
[For RL Load also forced commutation is required]

Mode 2 - D_2 is ON.

$\frac{1}{2} Li^2 \rightarrow P_{source} + i^2 R$

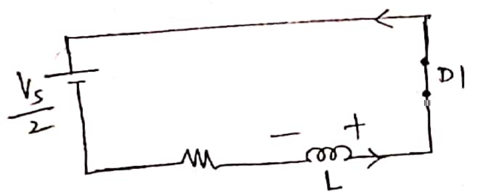


Mode 3 : T_2 is ON



$$P_{source} \rightarrow \frac{1}{2} L i^2 + i^2 R$$

Mode 4 : D1 is ON



$$\frac{1}{2} L i^2 \rightarrow P_{source} + i^2 R$$

$\left.\begin{array}{l} T_1 \rightarrow ON \\ \text{(or) } D_1 \rightarrow ON \end{array}\right\}$ $V_o = \frac{V_s}{2}$ i.e, V_o is +ve

$\left.\begin{array}{l} T_2 \rightarrow ON \\ \text{(or) } D_2 \rightarrow ON \end{array}\right\}$ $V_o = -\frac{V_s}{2}$ i.e, V_o is -ve

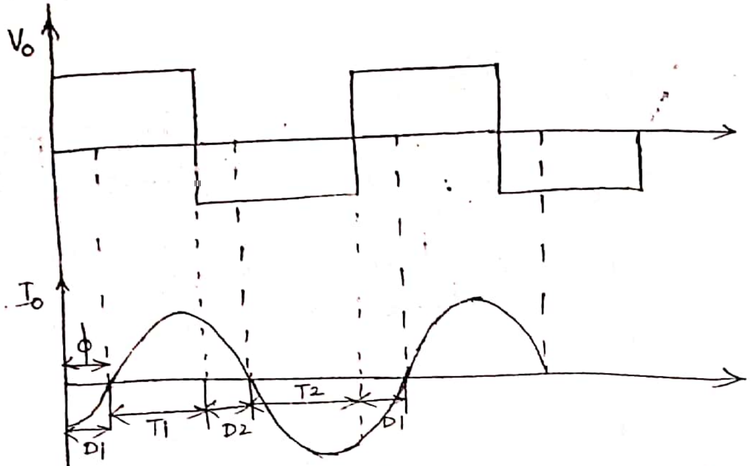
Logic Table

V_o	I_o	P	Device (ON) ½ Bridge	Device (ON) Full bridge
+ (T_1, D_1)	+	+ (T_1, T_2)	T_1	T_1, T_2
+ (T_1, D_1)	−	− (D_1, D_2)	D_1	D_1, D_2
− (T_2, D_2)	−	+ (T_1, T_2)	T_2	T_3, T_4
− (T_2, D_2)	+	− (D_1, D_2)	D_2	D_3, D_4

(iii) RLC (overdamped case) –

i.e., ($X_L > X_C$)

I_o lags V_o by $\phi = \tan^{-1}\left(\frac{X_L - X_C}{R}\right)$



Overdamped case

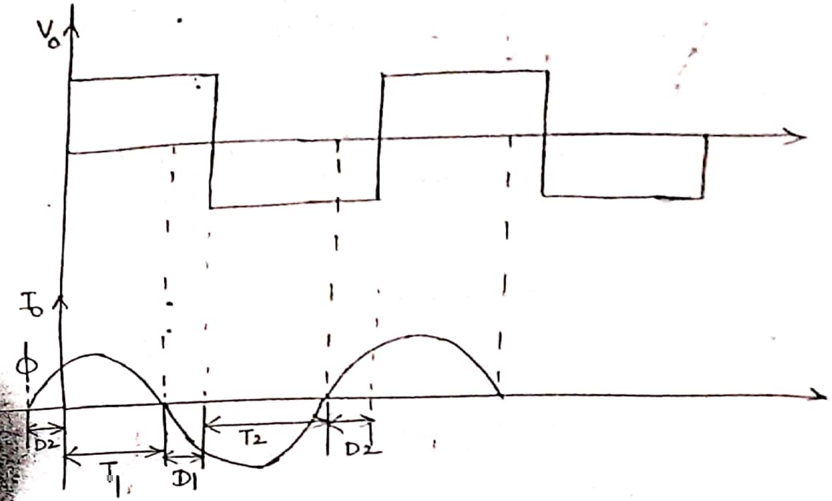
[Forced commutation is required]

RLC (Underdamped case)

i.e., $X_C > X_L$ (or $R^2 < \frac{4L}{C}$)

I_o leads V_o by $\tan^{-1}\left(\frac{X_C - X_L}{R}\right)$

(or I_o lags V_o by $\tan^{-1}\left(\frac{X_L - X_C}{R}\right)$)



Underdamped Case

[Load commutation takes place]

→ In this case t_c of T1 is same as Conduction time of D1 i.e., $\frac{\phi}{\omega}$

i.e., $t_c = \frac{\tan^{-1}\left(\frac{X_C - X_L}{R}\right)}{\omega}$

→ If $t_c > t_q$, forced commutation is not required because load commutation takes place.

→ If $t_c < t_q$, forced commutation is required.

Harmonic analysis for o/p current for a generalised load:
(Half-bridge)

→ Let RLC be the generalised load.

$$V_{on} = \frac{2V_s}{n\pi} \sin n\omega t$$

$$Z_n = R + j(X_{Ln} - X_{cn})$$

$$X_{Ln} = n\omega L$$

$$X_{cn} = \frac{1}{n\omega C}$$

$$|Z_n| = \sqrt{R^2 + (X_{Ln} - X_{cn})^2}$$

$$I_{on} = \frac{V_{on}}{|Z_n|} \angle -\phi_n$$

$$\phi_n = \tan^{-1}\left(\frac{X_{Ln} - X_{cn}}{R}\right)$$

Here ϕ_n is n^{th} harmonic displacement angle.

$$I_{on} = \frac{2V_s}{n\pi |Z_n|} \sin(n\omega t - \phi_n)$$

⇒ For pure inductive load,

$$|Z_n| = n\omega L$$

$$\phi_n = 90^\circ$$

$$I_{on} = \frac{V_{on}}{n\omega L} \angle -90^\circ$$

$$= \frac{2V_s}{n\pi(n\omega L)} \sin(n\omega t - 90^\circ)$$

$$= \frac{2V_s}{n^2(\pi\omega L)} \sin(n\omega t - 90^\circ)$$

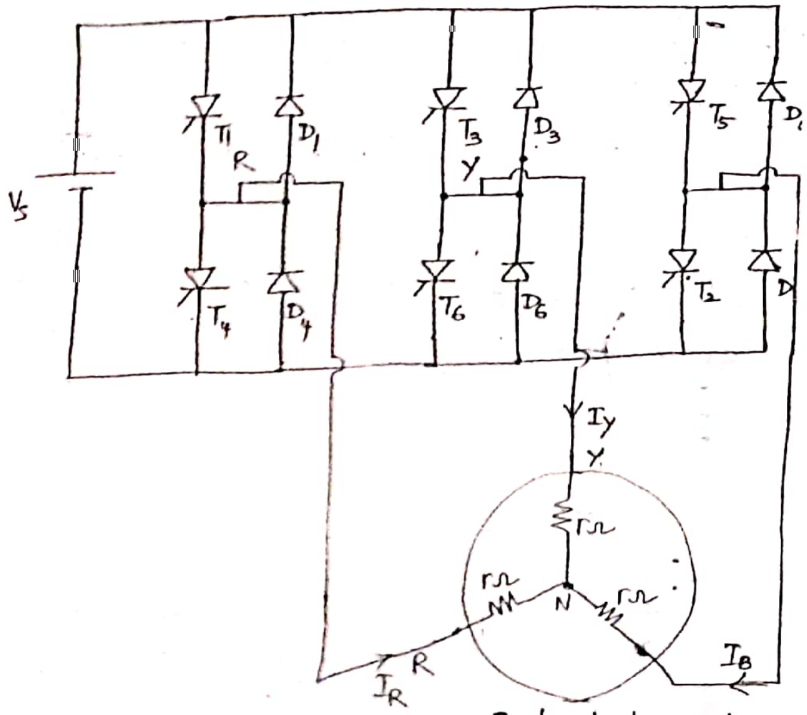
[For Square waveform, n^{th} harmonic $\propto \frac{1}{n}$
Triangular ", n^{th} harmonic $\propto \frac{1}{n^2}$]

→ In case of Full bridge inverter

$$V_{on} = \frac{4V_s}{n\pi}$$

Rest of the expressions remain same.

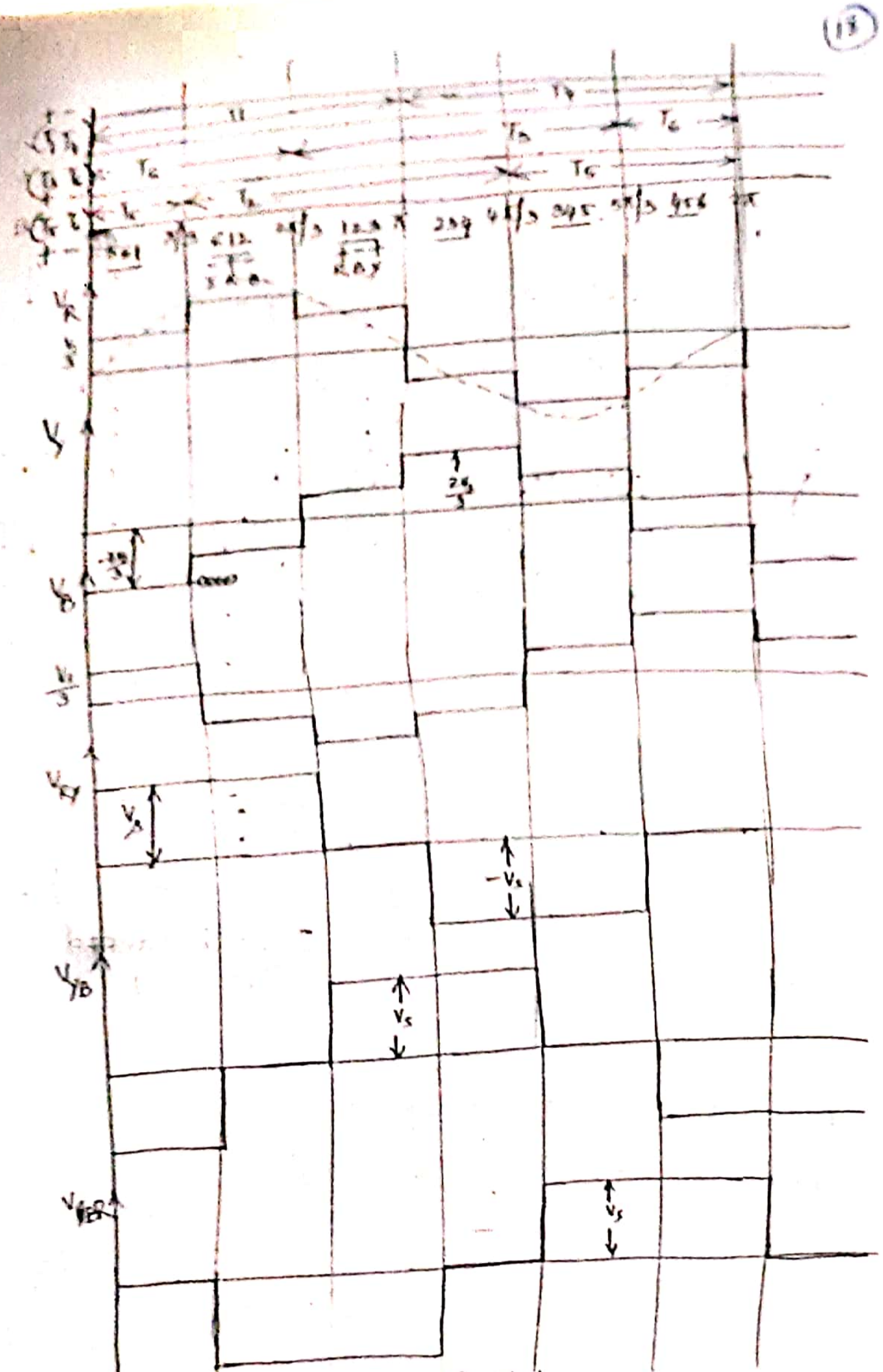
3-ϕ Voltage Source Inverter



3-ϕ balanced R Load

T_1, T_3, T_5 ⇒ +ve group SCRs

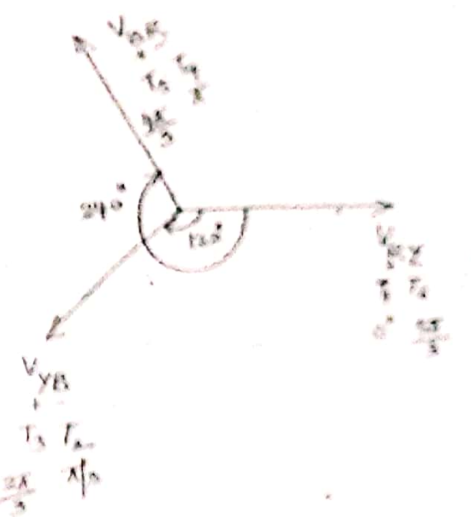
T_4, T_6, T_2 ⇒ −ve group SCRs.



150° Mode

In 150° mode, each SCR conducts for 150°

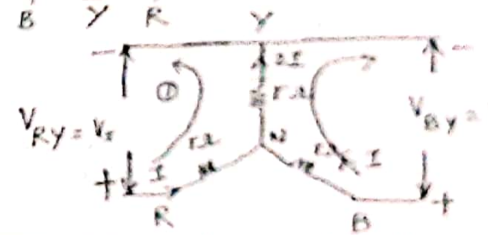
(i) 150° Mode (RYB)



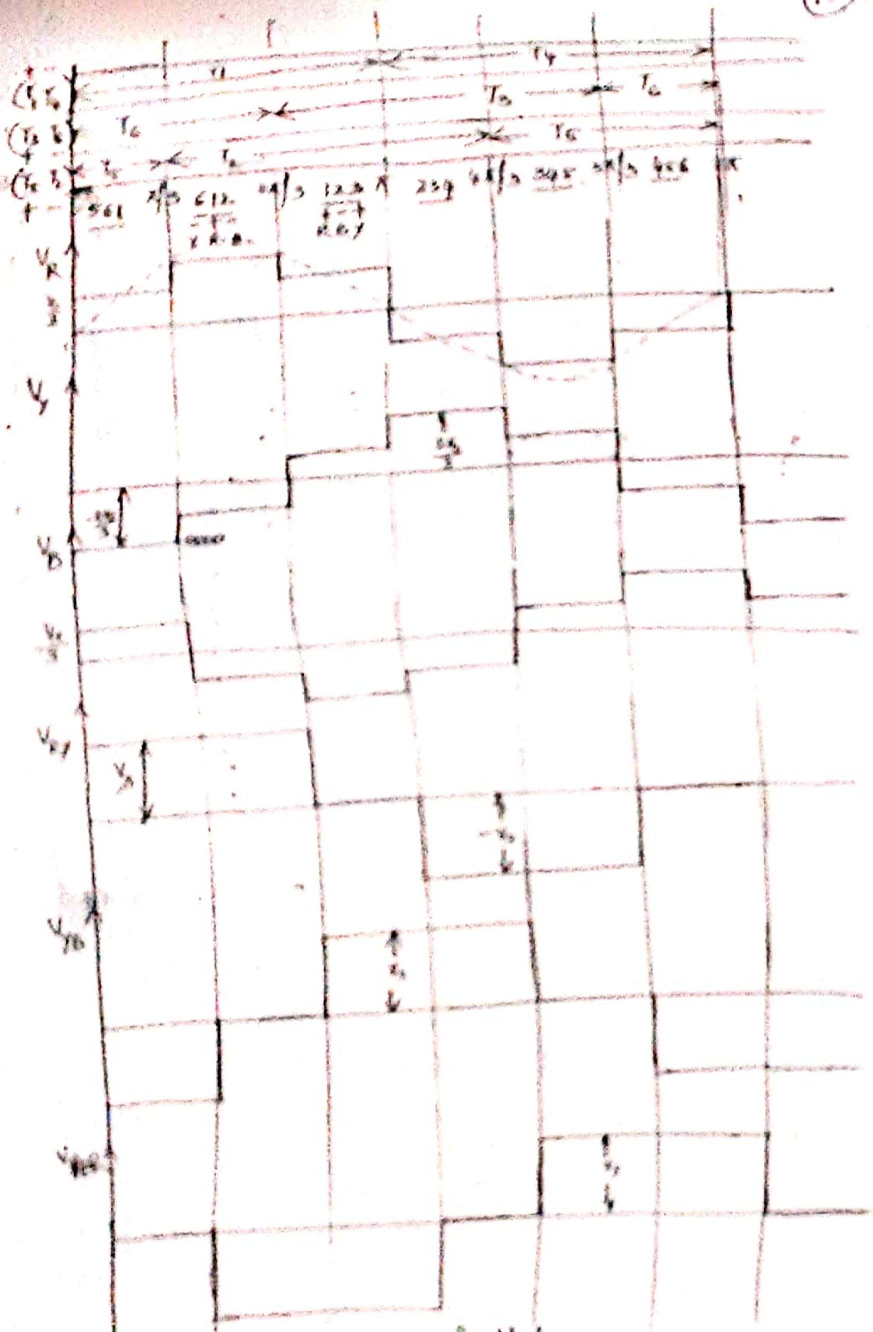
→ In 150° mode, at every instant 3 SCRs are conducting together

Mode 1 : 0 to $\pi/3$

T_5, T_6, T_1 are conducting
B+, Y−, R+



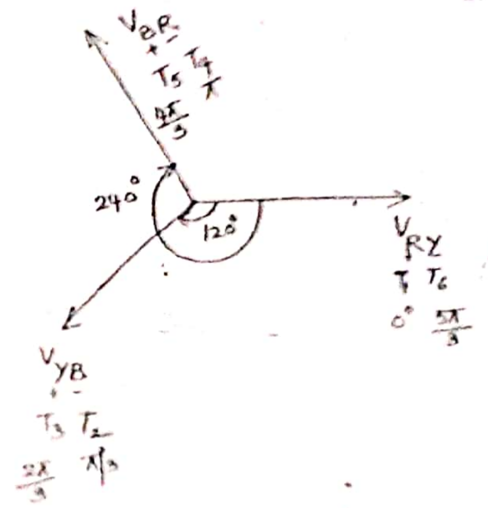
i.e, one −ve group SCR of Y-phase is sharing Ct of two +ve group SCRs



180° Mode

In 150° mode, each SCR conducts for 180°

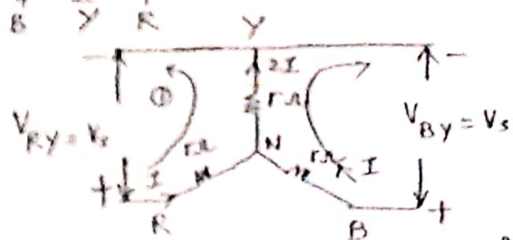
(i) 180° Mode (RYB)



→ In 150° mode, at every instant 3 SCRs are conducting together.

Mode I : 0 to $\pi/3$

T_5, T_6, T_1 are conducting.



i.e., one -ve group SCR of Y-phase is sharing ct. of two +ve group SCRs ie, current passing thro' Y-phase is double the current thro' other phases.

KVL $\Rightarrow$ $(Ir) + (2Ir) = V_s$

$\Rightarrow Ir = \frac{V_s}{3}$

$\Rightarrow V_R = r \cdot I = \frac{V_s}{3}$

Illy $V_y = -\cancel{2r \cdot I}\ 2I \cdot r$

$= \frac{-2V_s}{3}$

$V_B = r \cdot I = \frac{V_s}{3}$

$$(V_R)_{rms} = \sqrt{\frac{1}{\pi}\left\{\left(\frac{V_s}{3}\right)^2 \cdot \frac{\pi}{3} + \left(\frac{2V_s}{3}\right)^2 \cdot \frac{\pi}{3} + \left(\frac{V_s}{3}\right)^2 \cdot \frac{\pi}{3}\right\}}$$

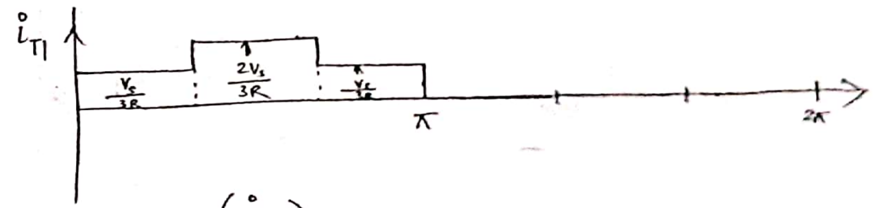
$$= \sqrt{\frac{1}{3}\left\{V_s^2\left(\frac{1}{9} + \frac{4}{9} + \frac{1}{9}\right)\right\}}$$

$$= \sqrt{\frac{V_s^2}{\cancel{3}} * \frac{\cancel{6}\,2}{9}}$$

$$= \frac{\sqrt{2}\,V_s}{3} = (V_y)_{rms} = (V_B)_{rms}$$

$$\left(I_R = I_y = I_B = I_{ph} = I_L\right)_{rms} = \frac{\sqrt{2}\,V_s}{3r}\ \text{Amp}$$

$(I_{T1})_{rms} =$



$(i_{T1})_{rms} =$

$$(i_{T1})_{rms}$$

$$= \left[\frac{1}{2\pi}\left[\left(\frac{V_s}{3R}\right)^2 \cdot \frac{\pi}{3} + \left(\frac{2V_s}{3R}\right)^2 \cdot \frac{\pi}{3} + \left(\frac{V_s}{3R}\right)^2 \cdot \frac{\pi}{3}\right]\right]^{1/2}$$

$$= \frac{V_s}{3R} \text{ Amp.}$$

$$(I_T)_{rms} = \frac{V_s}{3R} \text{ Amp.}$$

$$(V_{RY})_{rms} = V_s \sqrt{\frac{2}{3}}$$

$$\boxed{\begin{aligned} (V_{ph})_{rms} &= \frac{\sqrt{2}\, V_s}{3} \\ (V_L)_{rms} &= V_s \sqrt{\frac{2}{3}} = \sqrt{3}\,(V_{ph})_{rms} \end{aligned}}$$

Harmonic Analysis for phase v_R:

Finding the Fourier series expansion for R-phase, we get,

$$V_R = \sum_{n=6K\pm1}^{\infty} \frac{2V_s}{n\pi} \sin n\omega t$$

where $K = 0, 1, 2, 3, \ldots$

i.e., $n = 1, (5, 7), (11, 13), \ldots$

NOTE: Here even harmonics & triplen harmonics are absent.

$$\therefore (V_{Rn}) = \frac{2V_s}{n\pi} \sin n\omega t$$

$$(V_{Rn})_{rms} = \frac{\sqrt{2}\, V_s}{n\pi}$$

$$(V_{R1})_{rms} = \frac{\sqrt{2}\, V_s}{\pi}$$

$$g = \frac{(V_{R1})_{rms}}{(V_R)_{rms}} = \frac{\frac{\sqrt{2}\, V_s}{\pi}}{\frac{\sqrt{2}\, V_s}{3}} = \frac{3}{\pi}$$

$$T.H.D = \sqrt{\frac{1}{g^2} - 1}$$

$$= \sqrt{\frac{\pi^2}{9} - 1}$$

$$= \underline{31.08\%}$$

→ For a generalised load,

$$I_{Rn} = \frac{V_{Rn}}{Z_n} \angle -\phi_n$$

$$V_{Rn} = \frac{2V_s}{n\pi} \sin n\omega t$$

$$\Rightarrow I_{Rn} = \frac{2V_s}{n\pi |Z_n|} \sin(n\omega t - \phi_n)$$

$$Z_n = \sqrt{R^2 + (X_{Ln} - X_{Cn})^2}$$

$$\phi = Tan^{-1}\left(\frac{X_{Ln} - X_{Cn}}{R}\right)$$

Harmonic analysis for line vg. waveform:

Applying Fourier Series for line vg. V_{RY}, we get,

$$V_{RY} = \sum_{n=1,3,\ldots}^{\infty} \frac{4V_s}{n\pi} \cos\frac{n\pi}{6} \sin\left(n\omega t + \frac{\pi}{6}\right)$$

$n(\omega t + \pi)$

<u>NOTE:</u> Here also even harmonics & triplen harmonics are absent.

$$(V_{RY_n})_{rms} = \frac{2\sqrt{2} V_s}{n\pi} \cos\frac{n\pi}{6}$$

$$(V_{RY1})_{rms} = \frac{2\sqrt{2} V_s}{\pi} \cos\frac{\pi}{6}$$

$$= \frac{\sqrt{6}}{\pi} \cdot V_s$$

$$g = \frac{(V_{RY1})_{rms}}{(V_{RY})_{rms}} = \frac{\frac{\sqrt{6}}{\pi} \cdot V_s}{V_s \cdot \sqrt{\frac{2}{3}}}$$

$$= \frac{3}{\pi}$$

$$\therefore \text{T.H.D.} = \sqrt{\cancel{8}\frac{1}{g^2}} = 1$$

$$= \sqrt{\frac{\pi^2}{9} - 1}$$

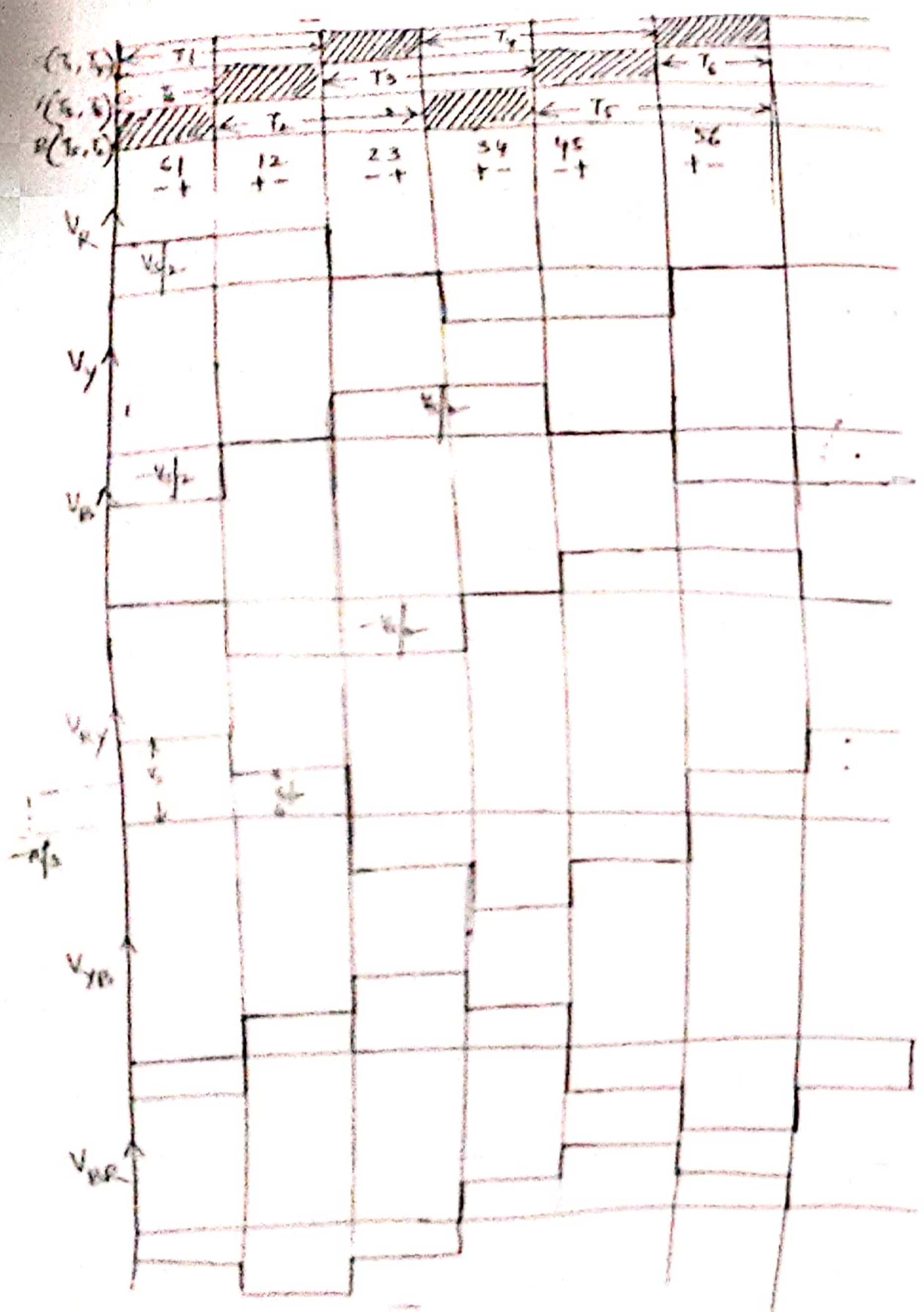
$$\simeq 31.08\%$$

Drawback of 180° mode :

There is a possibility of dead short circuit when the incoming SCR starts conducting before the outgoing SCR belonging to the same phase stops conducting.

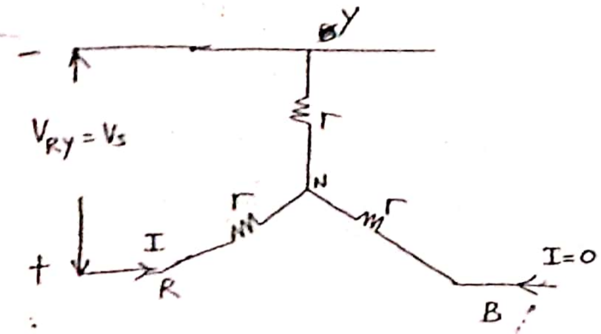
120° Mode

In 120° mode, each SCR is allotted conduction for 120° & the last 60° is allotted for commutation period.



In Mode 1 : 0 to 60°

T_1, T_6 are conducting.



$$I(r+r) = V_s$$

$$\Rightarrow Ir = \frac{V_s}{2}$$

$$\therefore V_R = \frac{V_s}{2} \; ; \; V_y = \frac{-V_s}{2}$$

$$V_B = 0$$

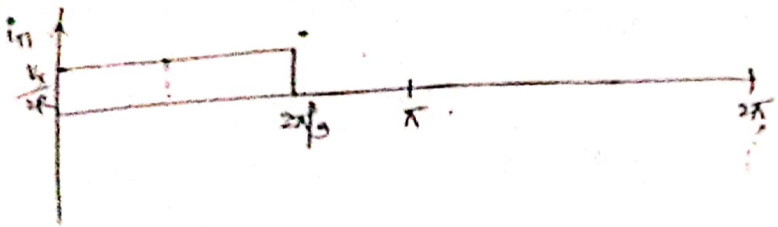
$$(V_R)_{rms} = \frac{V_s}{2} \cdot \sqrt{\frac{2}{3}} = \frac{V_s}{\sqrt{6}} = (V_y)_{rms}$$

$$= (V_B)_{rms}$$

$$= (V_{ph})_{rms}$$

$(I_R = I_Y = I_B = I_{ph} = I_L)_{rms}$

$$= \frac{V_s}{\sqrt{2}\, r} \text{ Amps}$$



$$(I_n)_{rms} = \frac{V_s}{2r} \cdot \sqrt{\frac{1}{3}}$$

$$= \frac{V_s}{2\sqrt{3}\, r} \text{ Amps}$$

$\rightarrow$ $$(V_L)_{rms} = \sqrt{3} \cdot (V_{ph})_{rms}$$

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

Harmonic Analysis of phase vg:

$$= \sum_{n=1,3,5}^{\infty} \frac{2V_s}{n\pi} \cos\frac{n\pi}{6} \sin(n(\omega t + \pi/6))$$

ie, Even & Triplen harmonics are absent

$$g = \frac{3}{\pi} \text{ \& T.H.D} \cong 31\%$$

Harmonic Analysis of line vg:

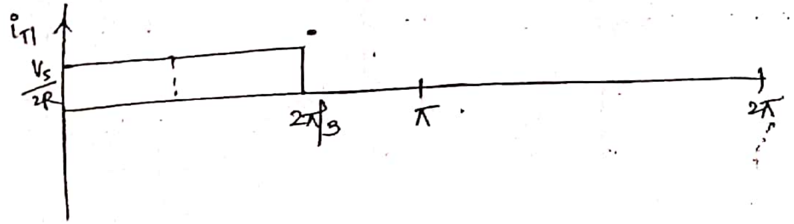
$$= \sum_{n=6k\pm1}^{\infty} \frac{3V_s}{n\pi} \sin(n(\omega t + \pi/3))$$

ie, Even & Triplen harmonics are absen

$$g = \frac{3}{\pi} \text{ \& T.H.D} \cong 31\%$$

$$\left(I_R = I_y = I_B = I_{ph} = I_L\right)_{rms}$$

$$= \frac{V_s}{\sqrt{6}\cdot r} \text{ Amps.}$$



$$(I_{T1})_{rms} = \frac{V_s}{2Rr}\cdot\sqrt{\frac{1}{3}}$$

$$= \frac{V_s}{2\sqrt{3}\,r} \text{ Amps.}$$

$\rightarrow$ $$(V_L)_{rms} = \sqrt{3}\cdot(V_{ph})_{rms}$$

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

Harmonic Analysis of phase vg:

$$= \sum_{n=1,3,5}^{\infty} \frac{2V_s}{n\pi} \cos\frac{n\pi}{6} \sin(n(\omega t + \pi/6$$

i.e, Even & Triplen harmonics are absent.

$$g = \frac{3}{\pi} \text{ \& T.H.D.} \cong 31\%$$

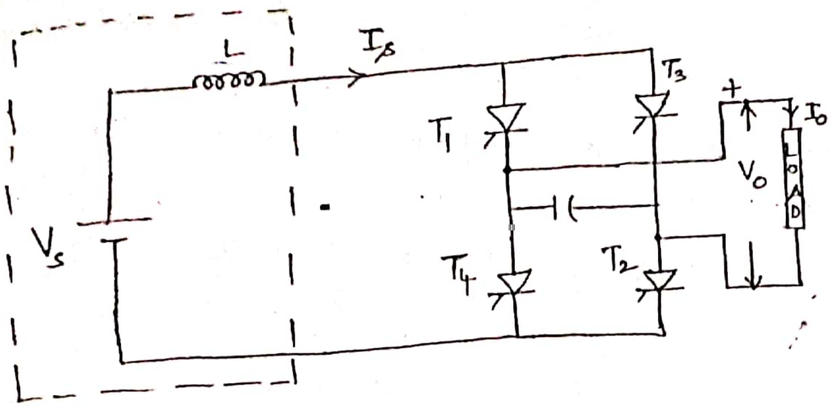
Harmonic Analysis of Line vg:

$$= \sum_{n=6K\pm1}^{\infty} \frac{3V_s}{n\pi} \sin(n(\omega t + \pi/3))$$

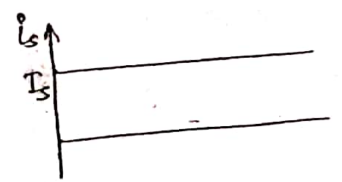
i.e, Even & Triplen harmonics are absen

$$g = \frac{3}{\pi} \text{ \& T.H.D} \cong 31\%.$$

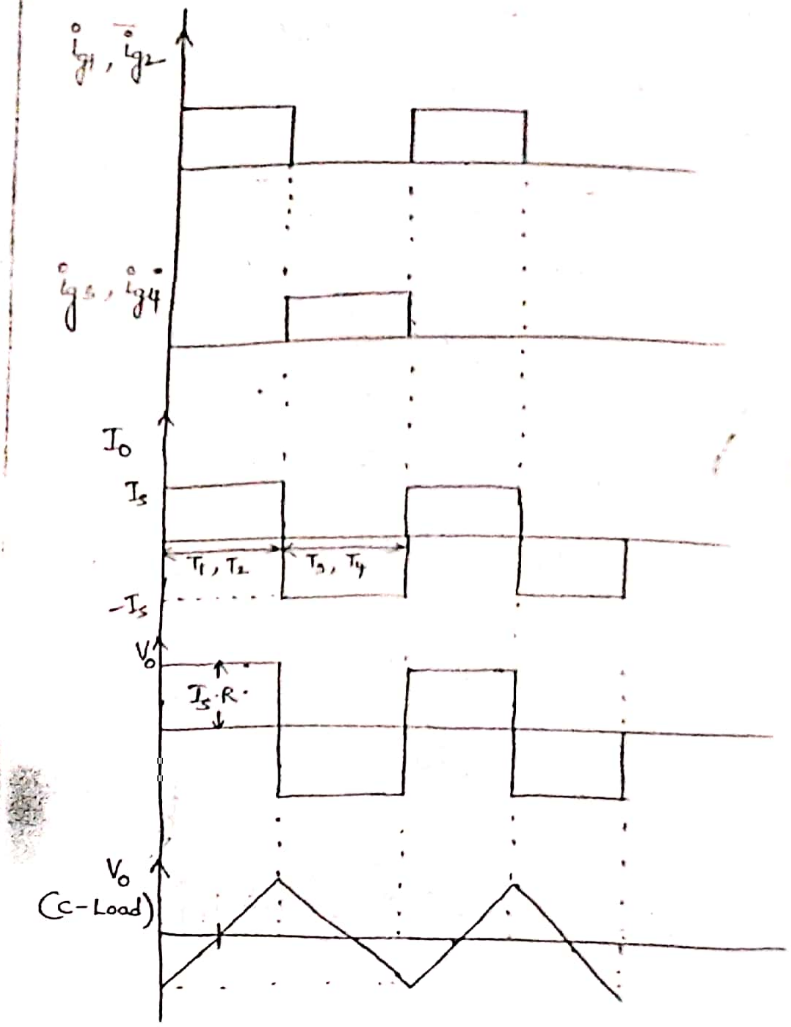
2 Current Source Inverter



Capacitor is provided for the purpose of commutation.



→ In CSI, we consider I_0 as reference where as in VSI, V_0 is the reference



$I_{or} = I_s$

For C-Load
V_0 lag I_0 by
& $\frac{1}{C}$
$v_c = \frac{I_s}{C}$

Scanned with CamScanner

Harmonic analysis for generalized load:

$$I_o = \sum_{n=1,3,5}^{\infty} \frac{4 I_s}{n\pi} \sin n\omega t$$

$$I_{on} = \frac{4 I_s}{n\pi} \sin n\omega t$$

$$\Rightarrow g = \frac{2\sqrt{2}}{\pi}$$

$$T.H.D = 48.34\%$$

For generalised load,

$$V_{on} = I_{on} \cdot Z_n$$

$$= I_{on} \angle \phi_n \; |Z_n|$$

$$= \frac{4 I_s}{n\pi} |Z_n| \sin(n\omega t + \phi_n).$$

$$\phi_n = \tan^{-1}\left(\frac{X_{Ln} - X_{Cn}}{R}\right)$$

$$|Z_n| = \sqrt{R^2 + (X_{Ln} - X_{Cn})^2}$$

→ For pure capacitive load,

$$Z_n = \frac{1}{n\omega C}$$

$$\phi_n = -90^\circ$$

$$\therefore V_{on} = \frac{4 I_s}{n\pi} \cdot \frac{1}{n\omega C} \sin(n\omega t - 90^\circ)$$

$$V_{on} \propto \frac{1}{n^2}$$ (Hence, Triangular wave)

→ The technique employed in CSI is complementary commutation technique.

* → If the load is purely capacitive then there is no need of commutating capacitor.

Advantages of CSI

1. Feedback diodes are not required in CSI.

2. Commutation is simple for CSI –
* 3. There is a possibility of load commutation if the load is capacitive.

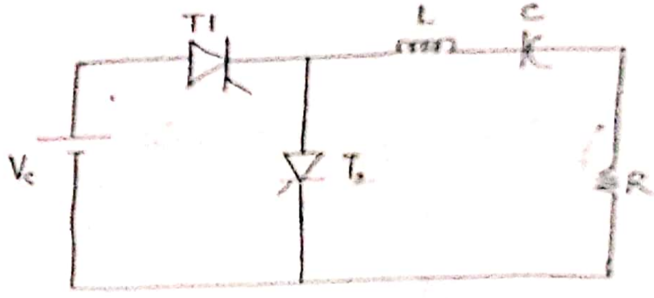
Disadvantage of CSI:

The commutating capacitor applies a very high reverse vg. across the power semiconductor device used in CSI. Therefore, the devices having low reverse blocking capability such as BJT, MOSFET, IGBT, GTO are not generally prefered in CSI. Therefore, we generally prefer SCR for CSI because of high blocking capability.

→ CSI is preferable in case of capacitive loads ∵ commutation becomes simple in that case.

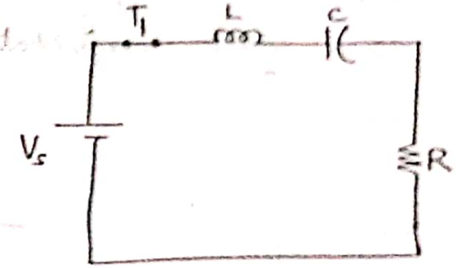
Series Inverter

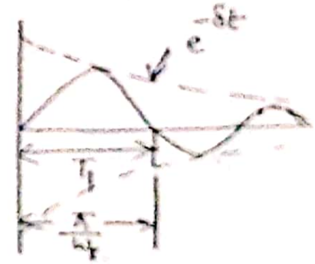
→ Here RLC should satisfy underdamped condition to make the commutation possible.



L, C : Commutating elements

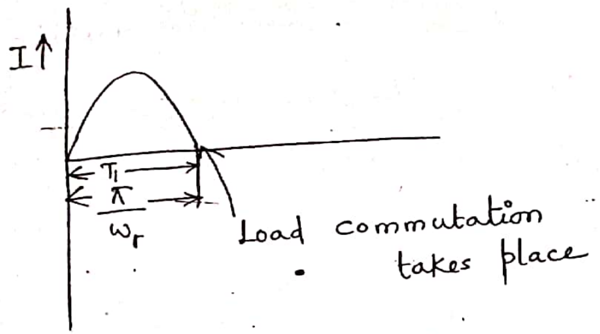
Mode I : T_1 is ON





$$I = \frac{V_s}{\omega_r L} e^{-\delta t} \sin \omega t$$

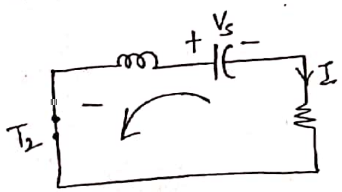
ω_r = Ringing frequency $= \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$

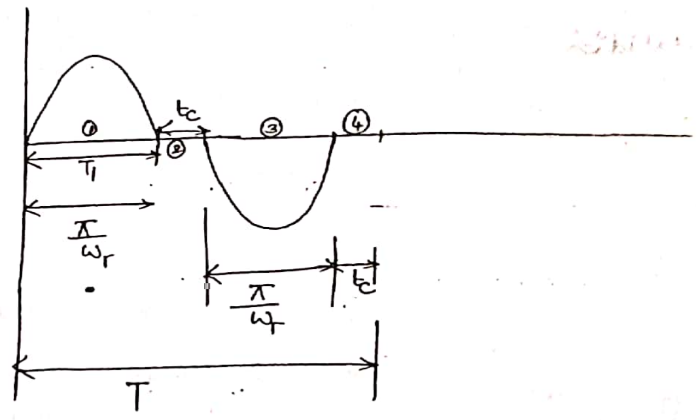


Mode 2 : ~~T_2 is switched ON~~
ALLOTMENT OF COMMUTATION TIME FOR T_1

If we switch on T_2 immediately, i.e., before T_1 stops conducting, it will short circuit the supply. ∴ we need to provide some commutation time for T_1 in Mode 2

Mode 3 : T_2 is switched ON





Mode 4 : Allotment of Commutation time for T_2

$$\frac{T}{2} = \frac{\pi}{\omega_r} + t_c$$ (Half Time period of the inverter)

$$T = 2\left(\frac{\pi}{\omega_r} + t_c\right)$$

$$f = \left\{\frac{1}{2\left(\frac{\pi}{\omega_r} + t_c\right)}\right\} \text{ Hz.}$$

→ By reducing t_c, switching frequency f is increased & simultaneously harmonics are reduced.

→ For low frequencies the current waveform is distorted with severe harmonics. [∵ of high value of t_c]. But at high frequencies, with reduced t_c, the waveform distortion is less. Hence, series inverter is preferred generally for high freq. applications i.e., near 100 KHZ.

→ Series inverters are generally preferred for fixed loads at high frequencies.

→ $$f_{max} = \frac{1}{2\left(\frac{\pi}{\omega_r} + t_q\right)}$$

(∵ t_c can't be reduced beyond t_q)

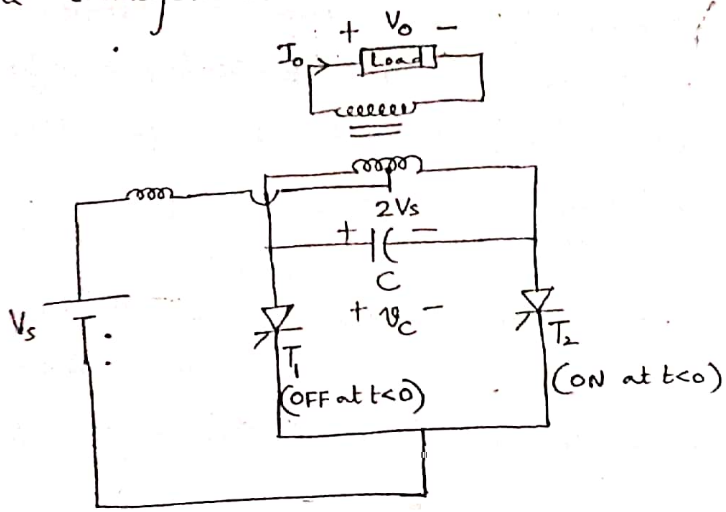
→ Series inverters can't be used for wide range of applications; It is only restricted to use for fixed load at high switching frequency.

→ Here, Commutating elements L & C are Connected in series with the resistive load. Hence, it is called Series Inverter

Parallel Inverter

In parallel inverter complementary commutation is employed.

Commutating capacitor is connected in parallel with the load through a transformer.



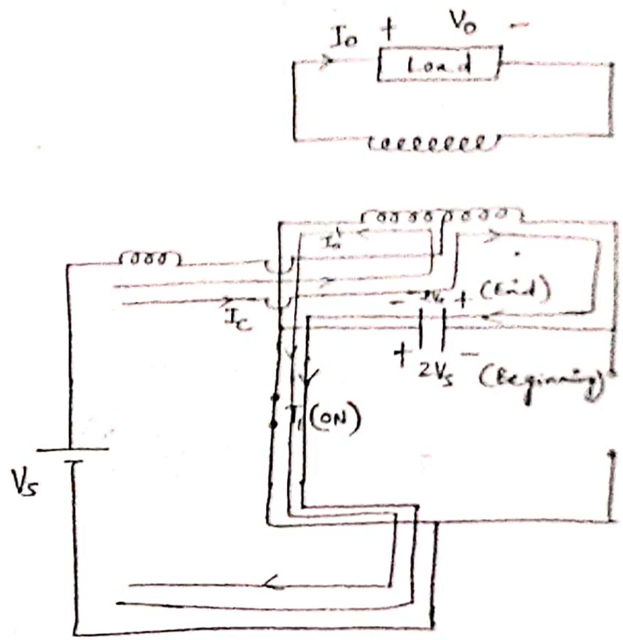
Assumption:

1. capacitor is initially charged with $2V_s$ Volts with polarities shown in the fig. $(V_C(t=0) = 2V_s)$

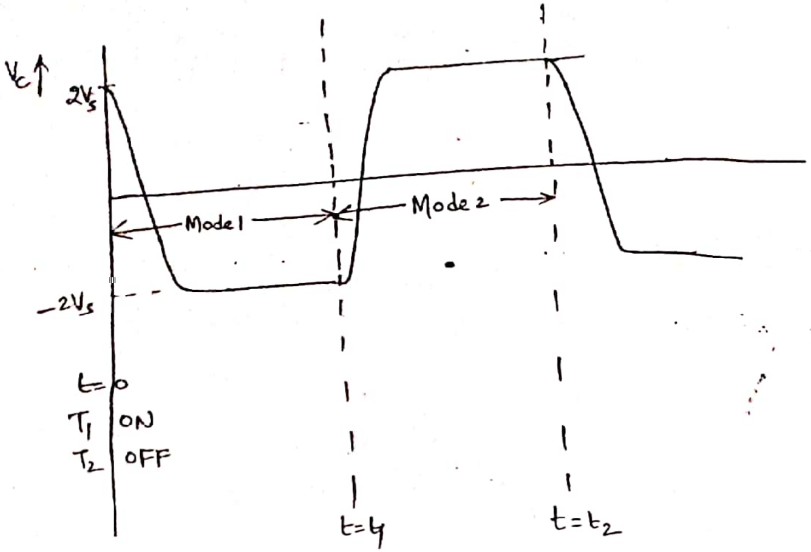
2. Before $t=0$, T_2 is in the ON state & T_1 is in the OFF state

Mode 1:

At $t=0$, T_1 is switched ON

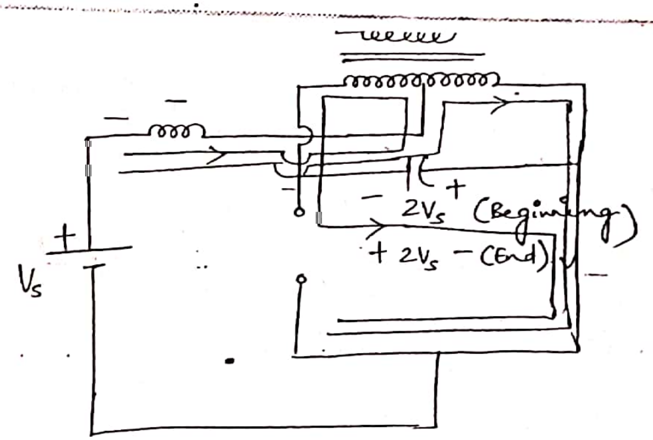


I_0' = Load ct. refered to primary side



Mode 2: T_2 is switched ON at $t=t_1$

$v_c(t=t_1) = -2V_s$ (Beginning)



$$V_o = \frac{N_2}{N_1} \cdot 2V_s$$

Shape of capacitor vg. & that of load vg. ∴ remains same.

Parallel inverters are never used for low frequencies.

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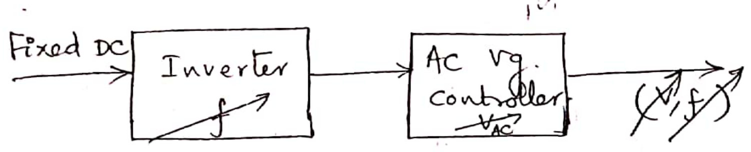
16/9/2011

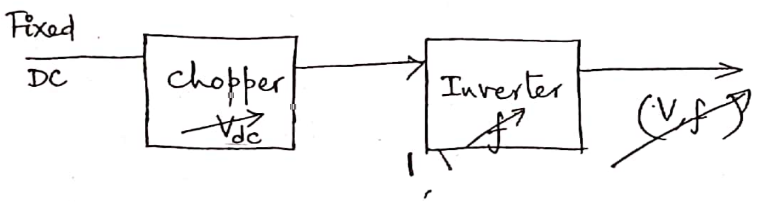
Voltage control of Inverters

→ In case of VSI, vg. control is not possible only freq. control is possible.

External control:



Ac vg. controller changes Ac vg. level with out changing the frequency



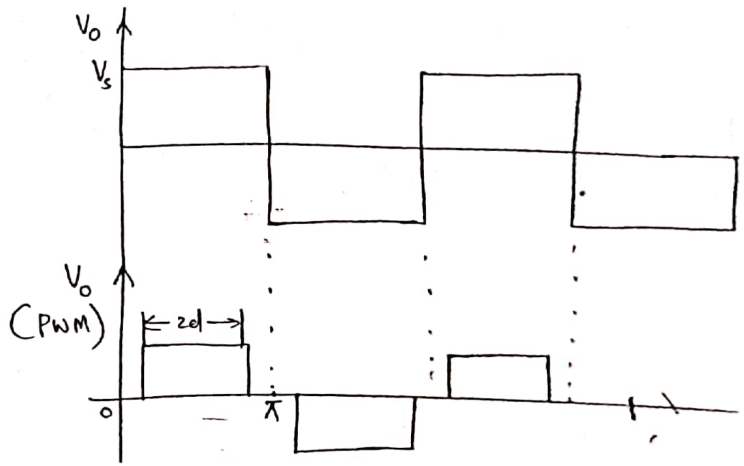
(47)

Drawback of External voltage control:

1. As the number of stages increases, there is an increase in additional cost & power loss along with the severe waveform distortion.

2. The overall setup in external control is not compact.

Internal Voltage Control using PWM Technique:



By changing the pulse width in each half cycle, we can get variable rms vg.

'2d' is Total pulse width in each half cycle.

$$V_{or} = V_s \sqrt{\frac{2d}{\pi}}$$

Advantages of PWM inverter:

1. Variable o/p vg. is possible within the inverter itself.
2. We can also eliminate some of the lower order harmonics using PWM techniques.