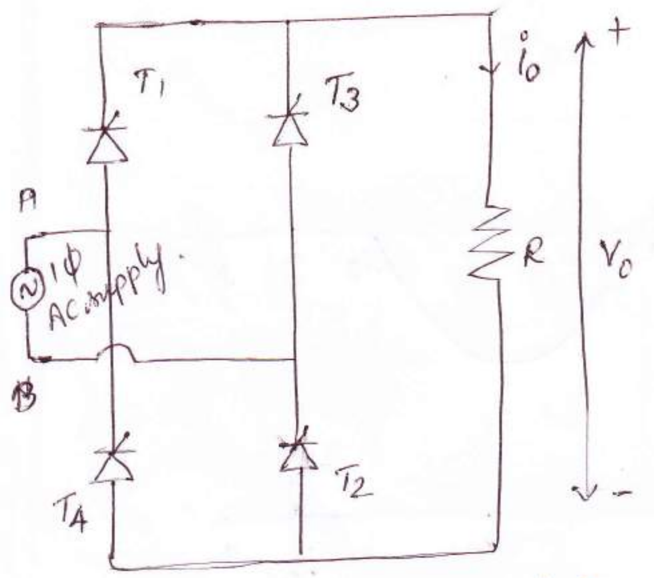
Single phase Fully controlled bridge rectifier with R Load.



1ϕ Fully controlled bridge rectifier consists of 4 SCR's.

Mode 1: +ve half cycle (α to π)

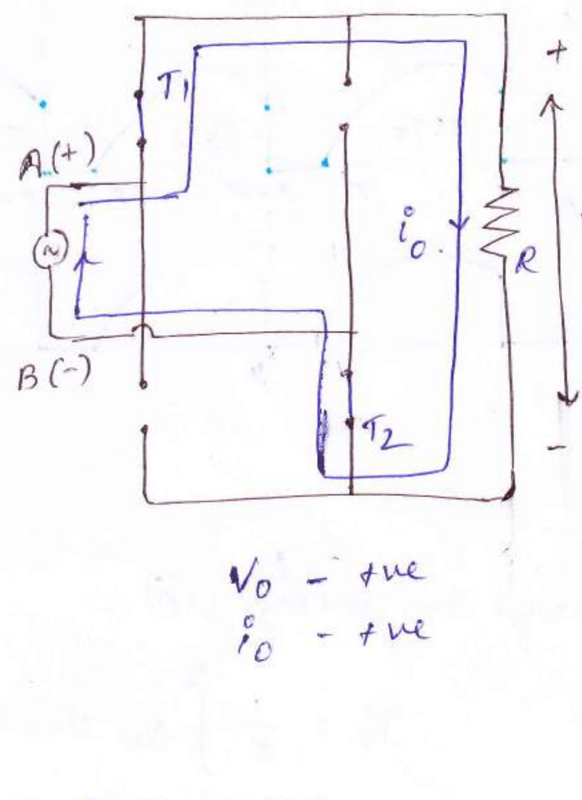
At $\omega t = \alpha$

T_1 T_2 - Forward biased.

Both triggered simultaneously.

Current flow path

$A^{(+)} \rightarrow T_1 \rightarrow R_{load} \rightarrow T_2 \rightarrow B^{(-)}$



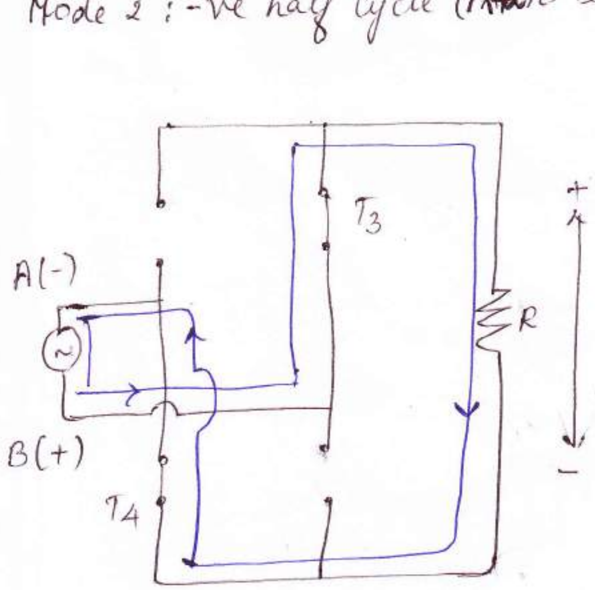
V_o - +ve

i_o - +ve

At $\omega t = \pi$

supply voltage falls to zero & the current also goes to zero.

Mode 2: -ve half cycle (π to 2π)



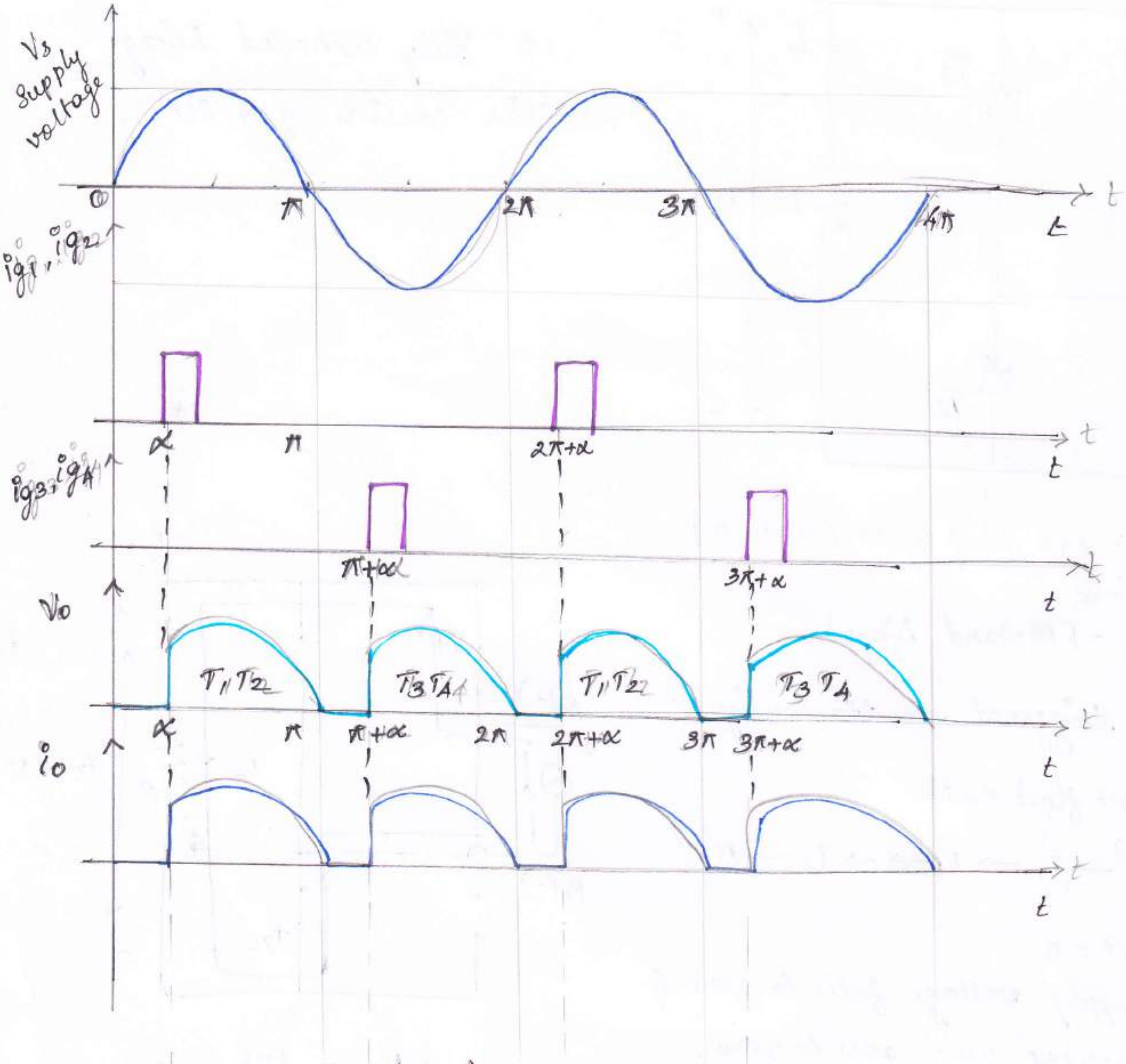
T_3 T_4 - FB.

Current flow path

$B^{(+)} \rightarrow T_3 \rightarrow R \rightarrow T_4 \rightarrow A^{(-)}$

The o/p voltage can be varied by varying the firing angle α.

As this is purely resistive load, the load current is always discontinuous.



Average o/p voltage (V_0)

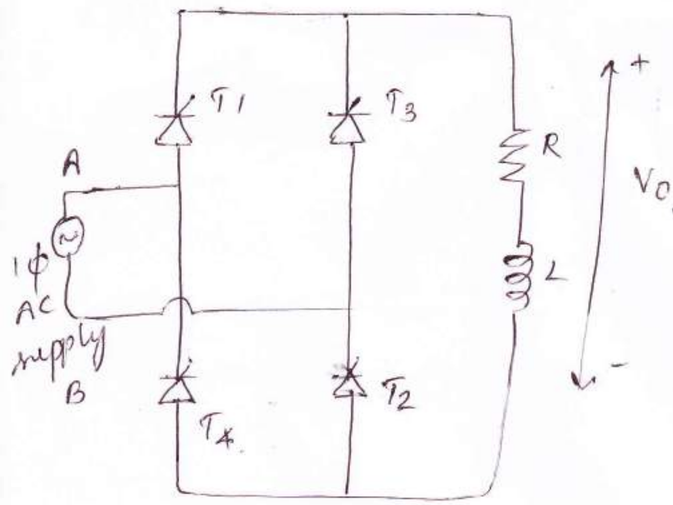
$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t$$

$$= \frac{V_m}{\pi}\left(-\cos\omega t\right)_{\alpha}^{\pi}$$

$$= \frac{-V_m}{\pi}\left[\cos\pi - \cos\alpha\right]$$

$$\boxed{V_0 = \frac{V_m}{\pi}(1+\cos\alpha)}$$

Single phase fully controlled bridge rectifier with RL Load.



Conduction doesnot takes place until the Thyristors are triggered & in order for current to flow, thyristor T_1 & T_2 must be fired together, as must T_3 & T_4 in the next half cycle from the same firing angle.

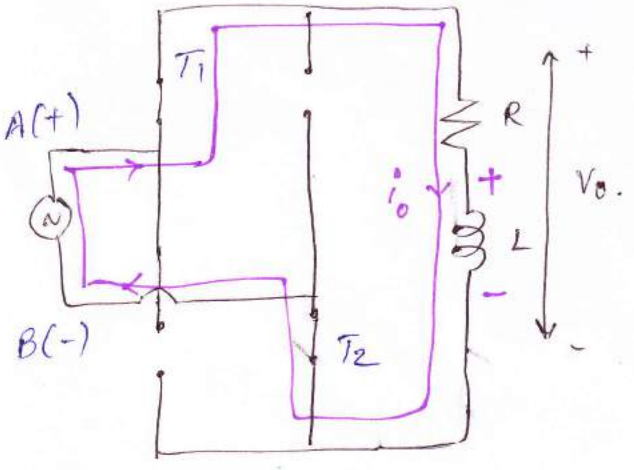
Inductance L is used to reduce the ripple

A large value of L is used for continuous steady current in the Load.

A small value of L will produce a discontinuous load current for large-firing angles.

Mode 1: α to π

T_1 T_2 - F B (Forward Biased)



Current flow path

$A^+ \rightarrow T_1 \rightarrow$ RL Load $\rightarrow T_2 \rightarrow B^-$

The Inductor (L) charges with the polarity shown in fig.

$V_0 \rightarrow +ve$

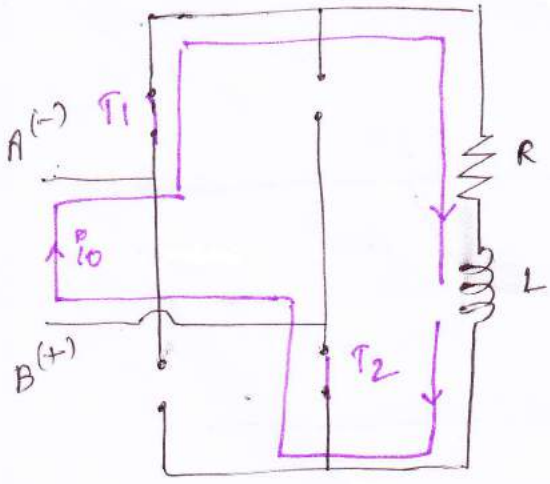
$i_0 \rightarrow +ve$

Mode 2: π to $\pi+\alpha$

Supply voltage reverses

L discharges.

Current flow path : $L \rightarrow T_2 \rightarrow B^{(+)} \rightarrow A^{(-)} \rightarrow T_1 \rightarrow RL$



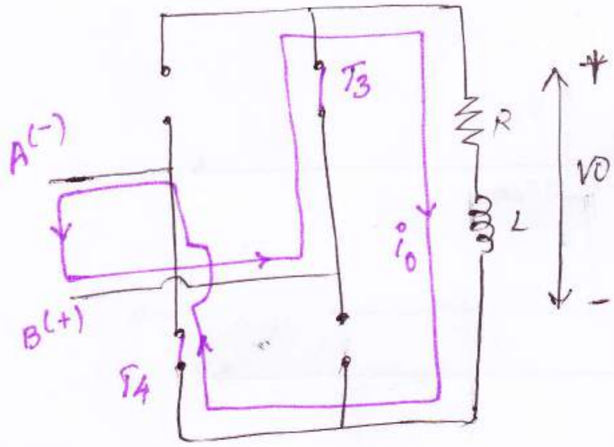
As the value of L is taken as so large, it dissipates its energy upto the time when T_3 & T_4 are triggered.

Thus $V_0 = -ve$

$i_0 = +ve$.

Mode 3 : $\pi + \alpha$ to 2π

$T_3\ T_4$ - F.B



Current flow path

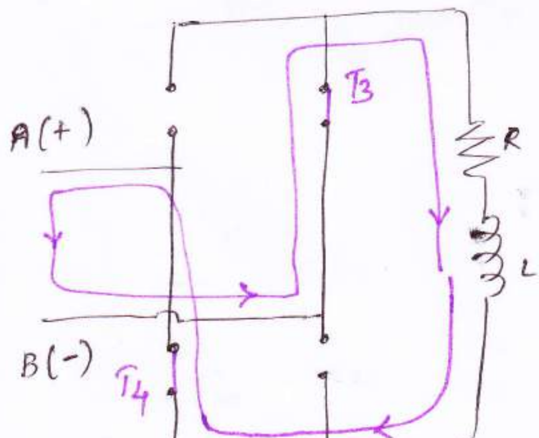
$B^{(+)} \rightarrow T_3 \rightarrow R\ L \rightarrow T_4 \rightarrow A^{(-)}$

L - Charges

$V_0 = +ve$

$i_0 = +ve$.

Mode 4 : 2π to $2\pi + \alpha$



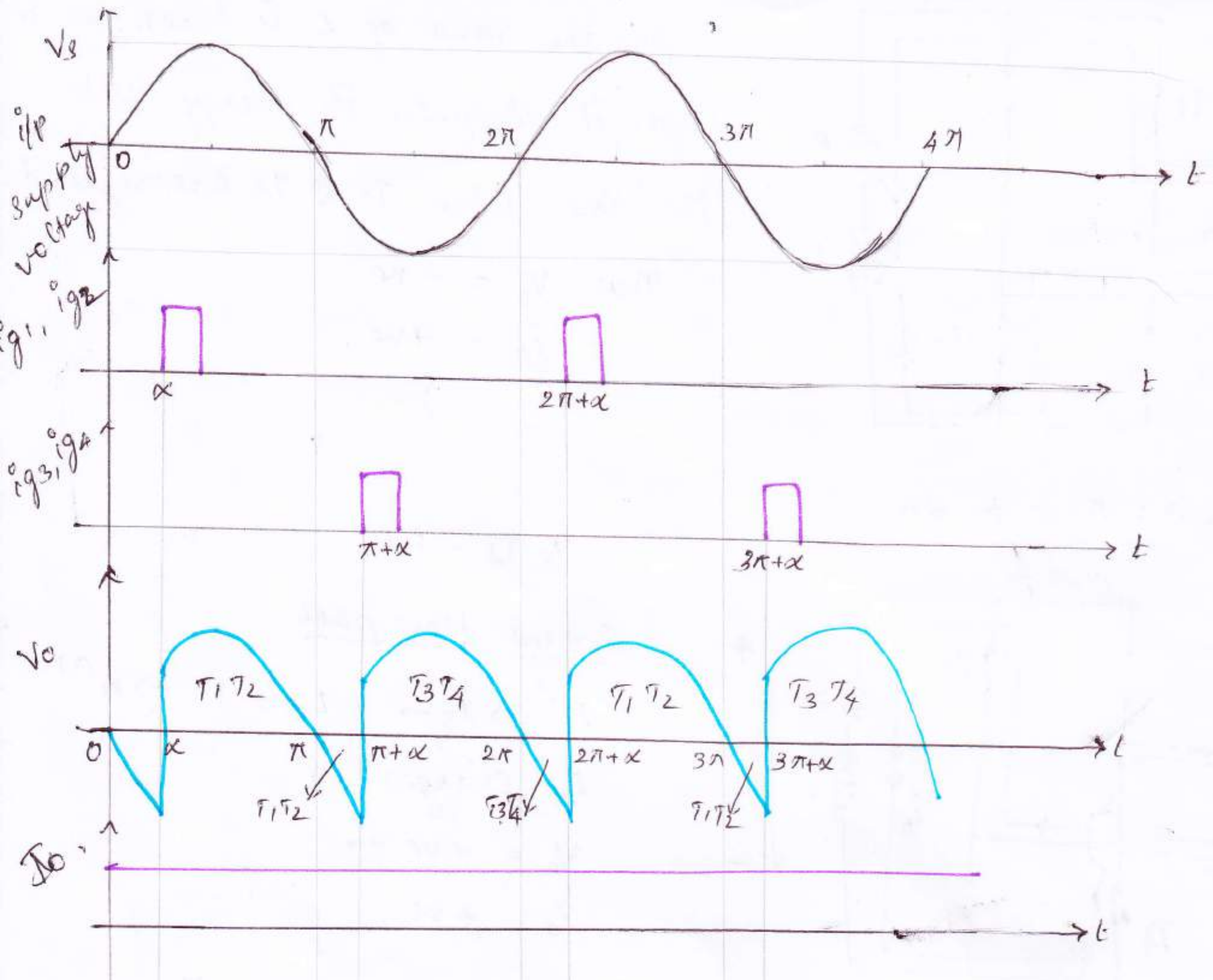
L discharges upto T_1 T_2 are fired.

Current flow path.

$RL \rightarrow T_4 \rightarrow A^{(+)} \rightarrow B^{(-)} \rightarrow T_3 \rightarrow RL$

$V_0 = -ve$

$i_0 = +ve$.



Average o/p voltage (V_0) (or) (V_{dc})

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d\omega t$$

$$= \frac{V_m}{\pi}\Big[-\cos\omega t\Big]_{\alpha}^{\pi+\alpha}$$

$$= \frac{-V_m}{\pi}\Big[\cos(\pi+\alpha) - \cos\alpha\Big]$$

$$= \frac{-V_m}{\pi}\Big[-\cos\alpha - \cos\alpha\Big]$$

$$\boxed{V_0 = \frac{2V_m}{\pi}\cos\alpha} \longrightarrow (1)$$

3

RMS load voltage (V_{rms}),

$$V_{rms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha}(V_m \sin\omega t)^2 \, d\omega t\right]^{1/2}$$

$$= \left[\frac{V_m^2}{\pi}\int_{\alpha}^{\pi+\alpha}\frac{1-\cos 2\omega t}{2} \, d\omega t\right]^{1/2}$$

$$= \left\{\frac{V_m^2}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi+\alpha}\right\}^{1/2}$$

$$= \left\{\frac{V_m^2}{2\pi}\left[(\pi+\alpha) - \frac{\sin 2(\pi+\alpha)}{2} - \alpha + \frac{\sin 2\alpha}{2}\right]\right\}^{1/2}$$

$$= \left\{\frac{V_m^2}{2\pi}\left[\pi + \cancel{\alpha} - \frac{\cancel{\sin 2\alpha}}{2} - \cancel{\alpha} + \frac{\cancel{\sin 2\alpha}}{2}\right]\right\}^{1/2}$$

$$= \left\{\frac{V_m^2}{2\cancel{\pi}}(\cancel{\pi})\right\}^{1/2}$$

$$\boxed{V_{rms} = \frac{V_m}{\sqrt{2}}}$$

As V_{dc} (or) $V_o = \frac{2V_m}{\pi}\cos\alpha$, by varying the firing angle (0° to 180°), the avg load voltage can be varied.

Here two modes of operation are possible in fully controlled bridge rectifier bcz the power flow in the converter can be in either direction.

Conversion mode.

During the interval α to π,

Both supply voltage V_s & supply current I_s are +ve.

∴ Power flows from ac source to load.

During the interval π to $\pi + \alpha$

$V_s = -ve$ but $I_s = +ve$.

The load therefore returns some of its energy to the supply system.

But the net power flows from ac source to dc load.

Thus from equation ①, for $\alpha < 90^\circ$, the voltage at the load terminals is +ve.

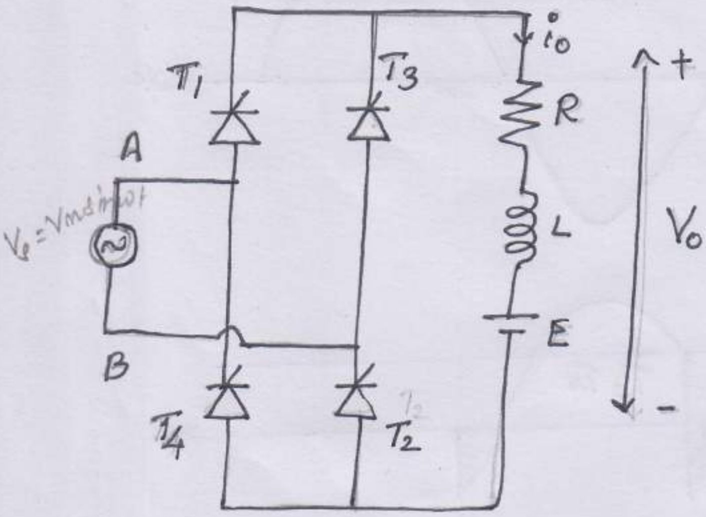
∴ Power flows from ac side to dc side & the converter operates as a rectifier.

Inversion mode.

If $\alpha > 90^\circ$, the voltage at the load terminals is -ve. Therefore, the power flows from dc side to ac side & hence the converter operates as a line commutated inverter.

In this mode power flows from load to source.

Fully Controlled Bridge Rectifier [RLE Load]



Assume load inductance is high.

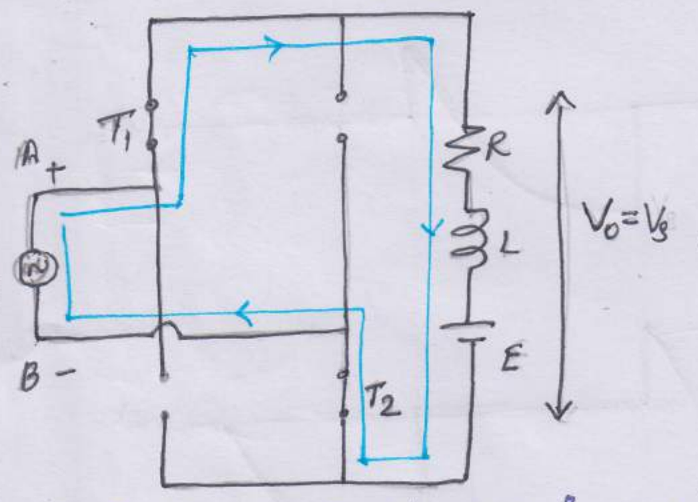
Due to this, load current is continuous and ripple free.

The load is assumed to be of RLE type, where E is the load circuit emf.

Voltage E may be due to a battery in the load circuit (or) may be generated emf of a dc motor.

Mode 1: (α to π) +ve half cycle

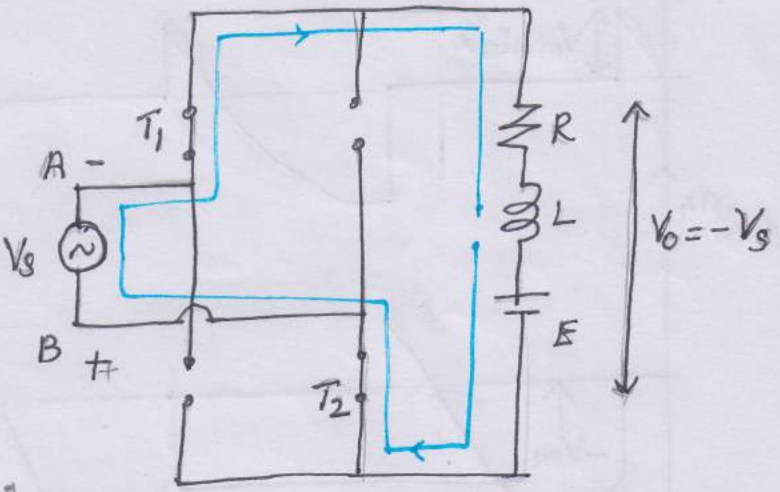
T_1 & T_2 will turn on only if $V_s > E$



$A \rightarrow T_1 \rightarrow RLE \rightarrow T_2 \rightarrow B$, V_s - +ve i_s - +ve

Power → source to load

Mode 2: (π to $\pi + \alpha$)



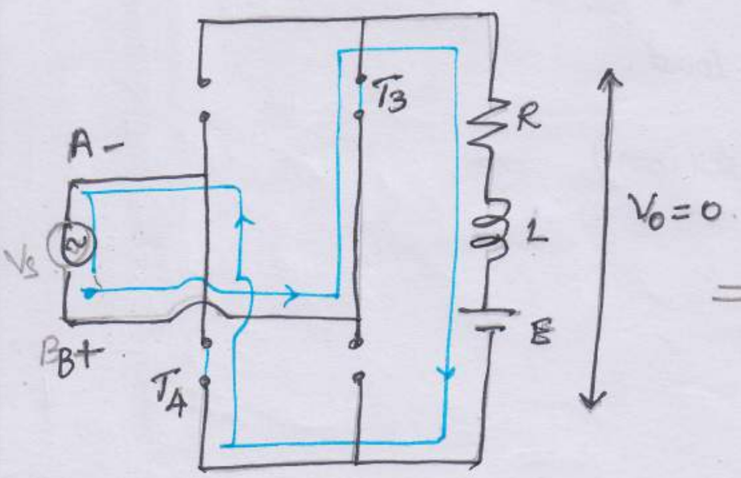
$RLE \rightarrow T_2 \rightarrow B \rightarrow A \rightarrow T_1 \rightarrow RLE$

V_s - −ve i_s - +ve

Power flows from load to source

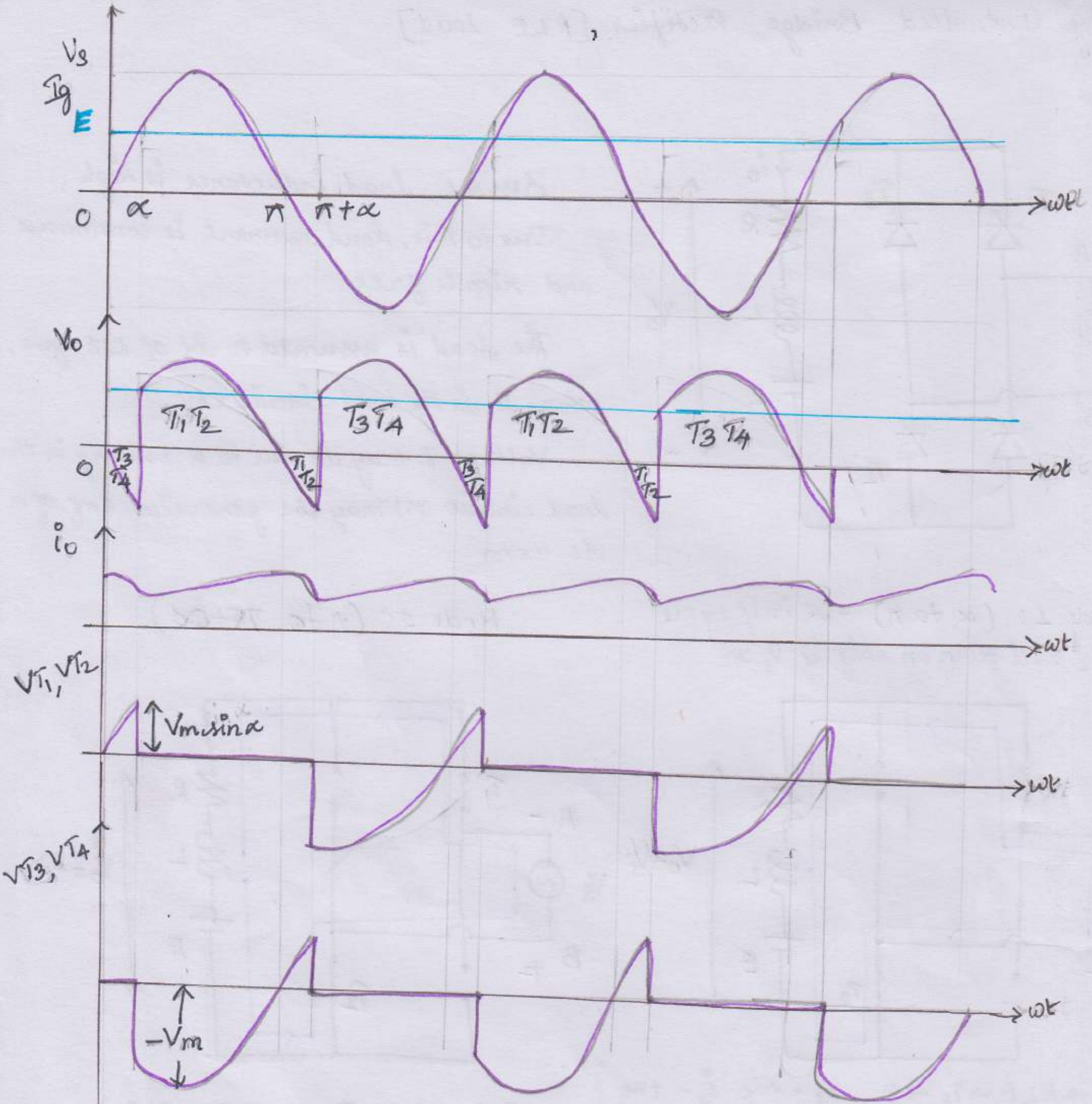
But net powerflow is from source to load bcz $(\pi - \alpha) > \alpha$.

Mode 3: $(\pi + \alpha)$ to 2π



$B \rightarrow T_3 \rightarrow RLE \rightarrow T_4 \rightarrow A$.

⇒ Power → source to load.



Waveforms for 1φ Fully controlled bridge converter with RLE load.

(converter operation)

Average dc output voltage

$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d\omega t$$

$$= \frac{V_m}{\pi}\Big[-\cos\omega t\Big]_{\alpha}^{\pi+\alpha}$$

$$= -\frac{V_m}{\pi}\Big[\cos(\pi+\alpha) - \cos\alpha\Big]$$

$$= -\frac{V_m}{\pi}\Big[-\cos\alpha - \cos\alpha\Big]$$

$$\boxed{V_{dc} = \frac{2V_m}{\pi}\cos\alpha}$$

Average load current

$$I_{dc} = \frac{V_{dc} - E}{R}$$

RMS o/p voltage V_{rms}

$$V_{rms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m^2 \sin^2\omega t \, d\omega t\right]^{1/2}$$

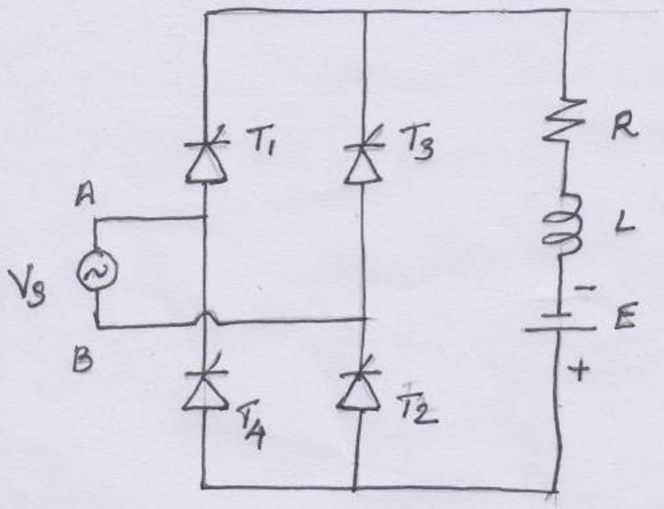
$$= \left[\frac{V_m^2}{\pi}\int_{\alpha}^{\pi+\alpha} \frac{1-\cos 2\omega t}{2}\, d\omega t\right]^{1/2}$$

$$= \left[\frac{V_m^2}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi+\alpha}\right]^{1/2}$$

$$= \left\{\frac{V_m^2}{2\pi}\left[\pi+\cancel{\alpha} - \frac{\sin 2(\pi+\alpha)}{2} - \cancel{\alpha} + \frac{\sin 2\alpha}{2}\right]\right\}^{1/2}$$

$$= \left\{\frac{V_m^2}{2\pi}\left[\pi - \cancel{\frac{\sin 2\alpha}{2}} + \cancel{\frac{\sin 2\alpha}{2}}\right]\right\}^{1/2} = \left(\frac{V_m^2}{2}\right)^{1/2} = \frac{V_m}{\sqrt{2}}$$

Inverter mode of operation of 1ϕ fully controlled bridge conv (RLE load)



For $\alpha > 90°$, o/p vol V_0 is negative.

If the load circuit emf E is reversed & with $\alpha > 90°$, then this dc source E will feed power back to ac source.

This operation of full converter with $\alpha > 90°$ is known as inverter operation.

The full conv with firing angle delay greater than $90°$ is called line-commutated inverter.

Mode 1: α to π

v_s - +ve

i_s - +ve

Power → ac source to dc source.

Mode 2: π to $\pi+\alpha$

v_s - +ve

i_s - −ve

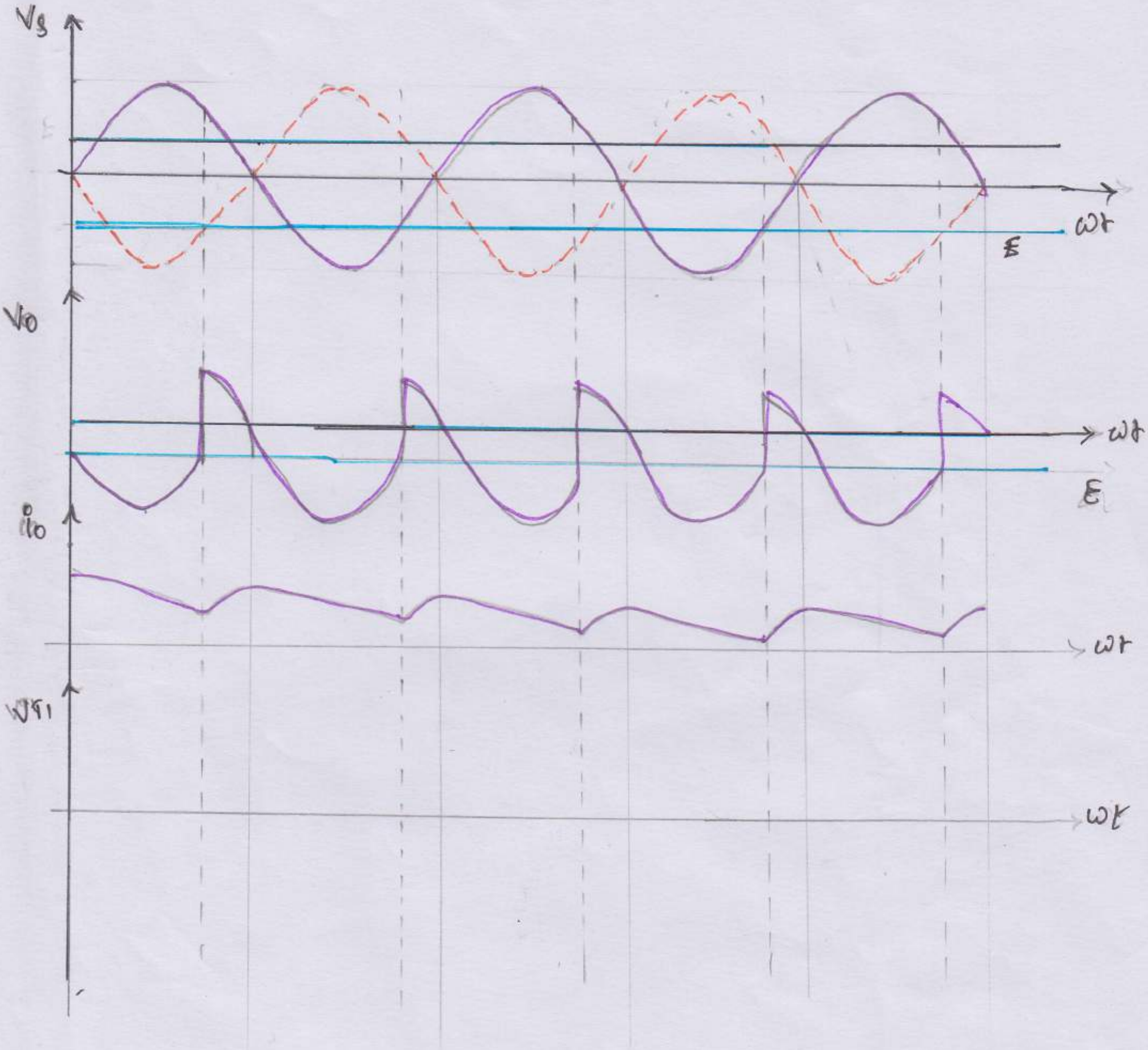
Power → dc to ac source.

* but net power flow is from dc to ac.

* In converter operation, V_0 should be greater than E.

* For inverter " $E > V_0$, then only the power would flow from dc source to ac supply system.

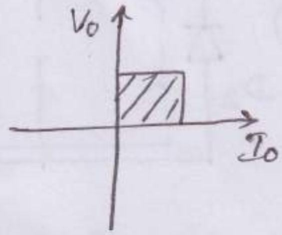
Waveform for 1ϕ fully controlled bridge converter with RLE load (Inverter operation)



Single phase semiconverter (Half controlled bridge Rectifier) / 1 Quad Converter.

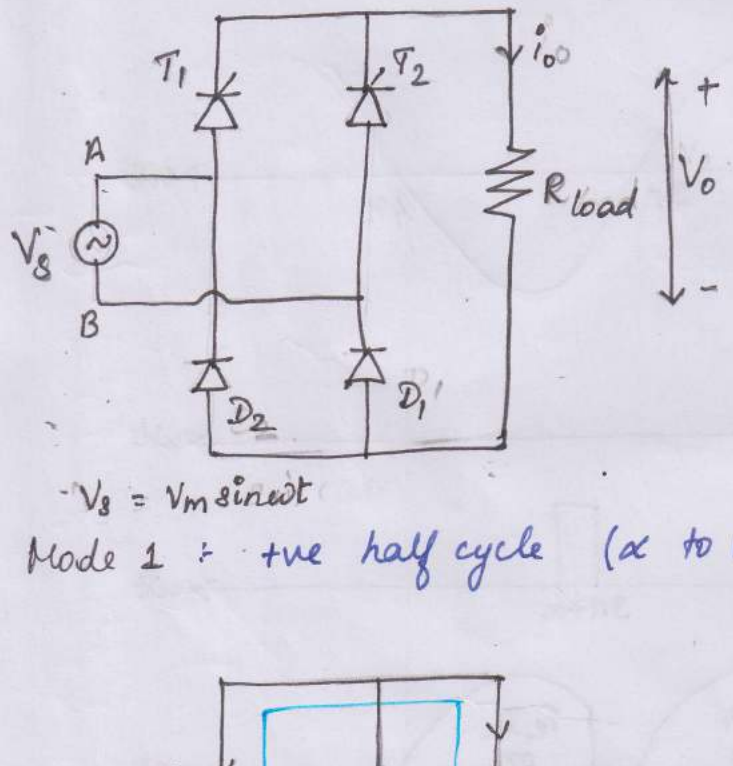
Semiconverter uses a mixture of diodes & thyristors. Hence there will be a limited control over the level of dc o/p voltage.

The o/p voltage and current is always positive. Thus it is called as 1 quadrant converter.



Semiconverter — Symmetrical configuration
— Asymmetrical "

1φ Half controlled bridge rectifier with R load
(Symmetrical Configuration)

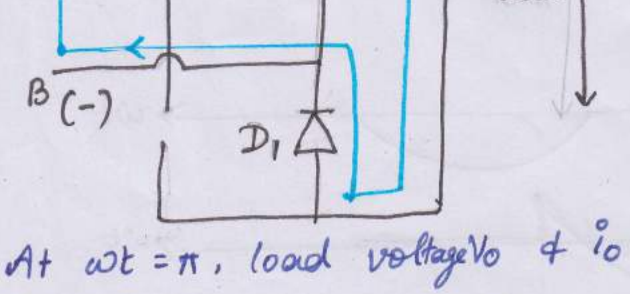


Circuit consists of the combinations of thyristors & diodes.

Single gate pulse is enough to trigger the SCR's, since the cathodes of 2 SCRs are at the same potential.

$V_s = V_m \sin \omega t$

Mode 1 : +ve half cycle (α to π)



$T_1\ D_1$ — FB

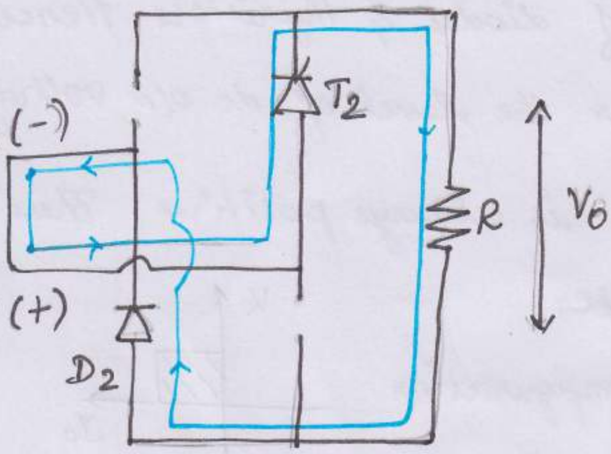
$(A^+) \rightarrow T_1 \rightarrow R \rightarrow D_1 \rightarrow (B^-)$
↓
Path of current flow.

V_0 - +ve

i_0 - +ve

At $\omega t = \pi$, load voltage V_0 & i_0 reaches to zero, then T_1 & D_1 comes to off state due to natural commutation.

Mode 2 :- $(\pi + \alpha)$ to 2π



T_2 D_2 – conducts

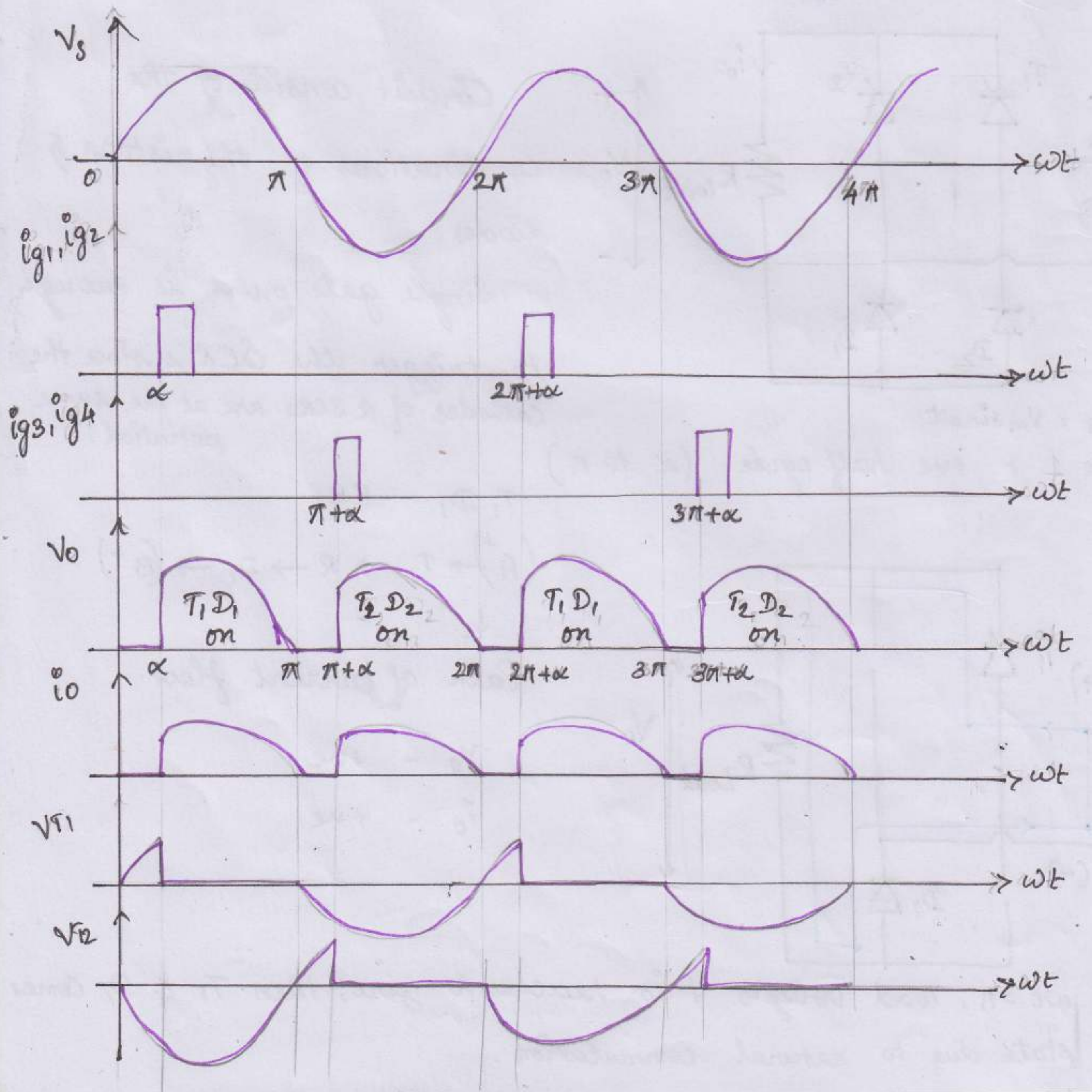
Path of load current

$B \to T_2 \to R \to D_2 \to A$

V_0 – +ve

i_0 – +ve

At 2π, T_2 & D_2 comes to off state due to natural commutation.



Average DC voltage : (V_{dc}) ; Average load current (I_{dc})

$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t$$

$$= \frac{V_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi}$$

$$= \frac{-V_m}{\pi}\left[\cos\pi - \cos\alpha\right]$$

$$= \frac{-V_m}{\pi}\left[-1 - \cos\alpha\right]$$

$$\boxed{V_{dc} = \frac{V_m}{\pi}(1+\cos\alpha)}$$

$$I_{dc} = \frac{V_{dc}}{R}$$

$$\boxed{I_{dc} = \frac{V_m}{\pi R}(1+\cos\alpha)}$$

RMS load voltage $V_{rms} = \left(\frac{1}{\pi}\int_{\alpha}^{\pi} v_s \, d\omega t\right)^{1/2}$

$$V_s = V_m \sin\omega t.$$

$$I_{rms} = \frac{V_{rms}}{R}.$$

$$V_{rms} = \left(\frac{V_m}{\pi}\int_{\alpha}^{\pi}(\sin\omega t)\, d\omega t\right)^{1/2}$$

$$= \left\{\frac{V_m^2}{\pi}\int_{\alpha}^{\pi}\sin^2\omega t \, d\omega t\right\}^{1/2}$$

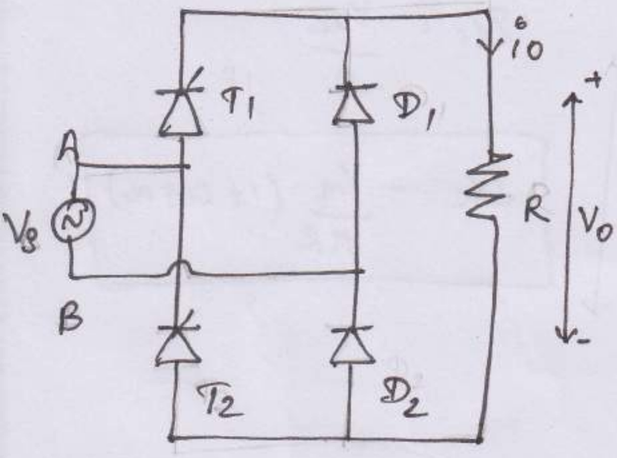
$$= \left(\frac{V_m^2}{\pi}\int_{\alpha}^{\pi}\frac{1-\cos 2\omega t}{2}\, d\omega t\right)^{1/2}$$

$$= \left\{\frac{V_m^2}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi}\right\}^{1/2}$$

$$= \left\{\frac{V_m^2}{2\pi}\left[\pi - \frac{\sin 2\pi}{2} - \alpha + \frac{\sin 2\alpha}{2}\right]\right\}^{1/2}$$

$$= \left\{\frac{V_m^2}{2\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)\right\}^{1/2} = \frac{V_m}{\sqrt{2\pi}}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]^{1/2}$$

Half controlled bridge rectifier with R load (Asymmetrical configuration)



In Asymmetrical configuration, separate - triggering circuits are to be used.

So that the conduction period of the thyristors will be different from diode conduction period.

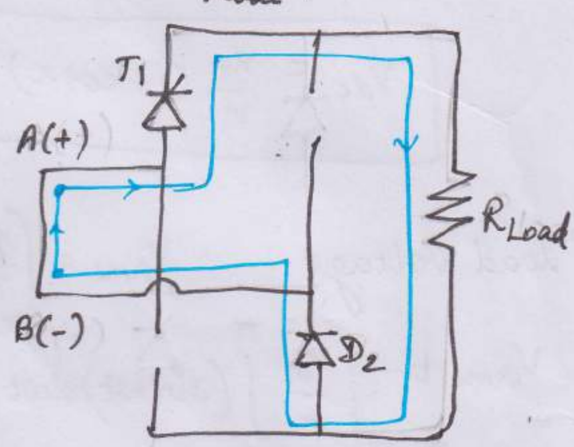
Mode 1: α to π

$T_1 D_2$ conducts

$A(+) \rightarrow T_1 \rightarrow R \rightarrow D_2 \rightarrow B(-)$

V_0 - +ve $\quad i_0$ - -ve

Mode 1



Mode 2: $\pi+\alpha$ to 2π

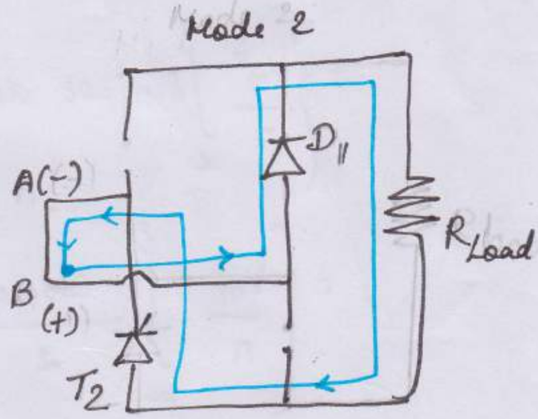
$T_2 D_1$ conducts

$B(+) \rightarrow D_1 \rightarrow R \rightarrow T_2 \rightarrow A(-)$

V_0 - +ve

i_0 - +ve

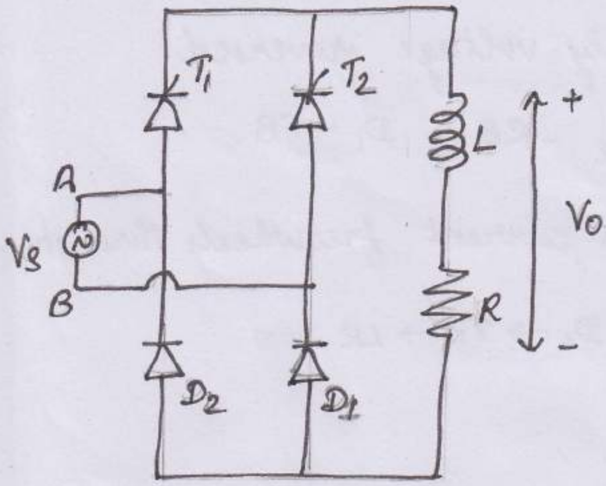
Mode 2



Average dc load voltage, Average load current, RMS voltage is similar to symmetrical configuration of semi converter.

Waveform also ||ly, but the conducting devices during mode 1 $(T_1 D_2)$ & mode 2 $(T_2 D_1)$ only changes.

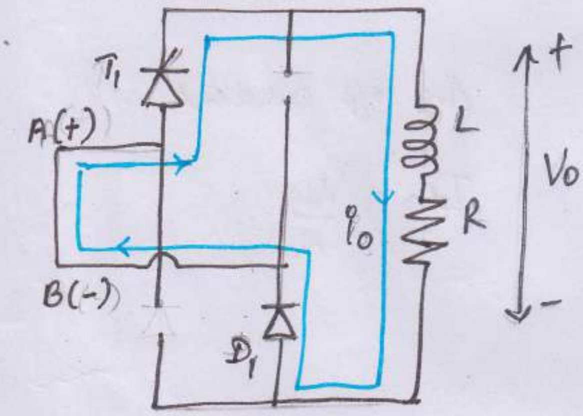
1φ Half controlled bridge converter, with RL Load (Symmetrical Configuratio



The value of inductance 'L' is assumed to be large. so that the current waveform of load will be continuous.

Hence load current I_0 is taken to be constant.

Mode 1 : α to π



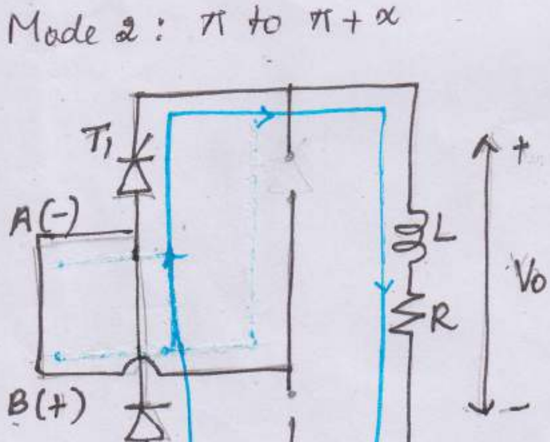
$T_1\ D_1$ − FB

$A^{(+)} \rightarrow T_1 \rightarrow LR \rightarrow D_1 \rightarrow B^{(-)}$

V_0 - +ve

i_0 - +ve

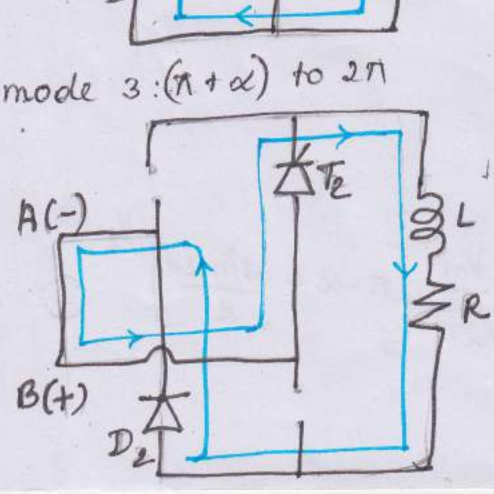
Mode 2 : π to $\pi + \alpha$



Supply voltage reverse biases D_1 & turns it off. D_2 − FB

Thus the load c/ freewheels through $LR \rightarrow D_2 \rightarrow T_1 \rightarrow LR$

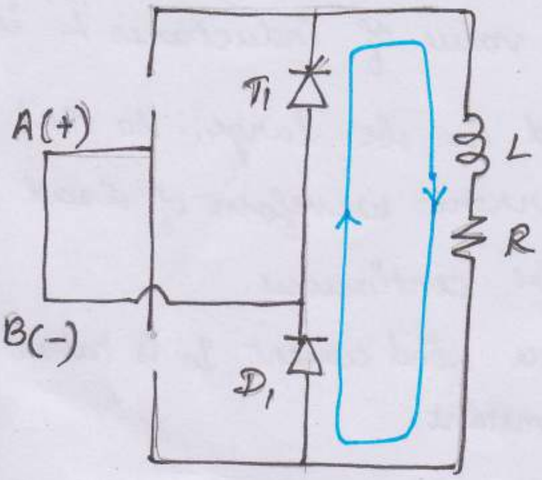
mode 3 : $(\pi + \alpha)$ to 2π



$T_2\ D_2$ − FB

$B^{(+)} \rightarrow T_2 \rightarrow LR \rightarrow D_2 \rightarrow A^{(-)}$

Mode 4 : 2π to $(2\pi+\alpha)$



Supply voltage reversed.

So D_2 - RB . D_1 - FB .

Load current freewheels through

$LR \rightarrow D_1 \rightarrow T_1 \rightarrow LR$

Advantage :- No need of additional Free Wheeling Diode .

Average dc o/p voltage

$$V_{dc} \text{ (or) } V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t$$

$$= \frac{V_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi}$$

$$= \frac{-V_m}{\pi}\left[\cos\pi - \cos\alpha\right]$$

$$\boxed{V_{dc} = \frac{V_m}{\pi}(1+\cos\alpha)}$$

Avg o/p current

$$I_{dc} = \frac{V_{dc}}{R}$$

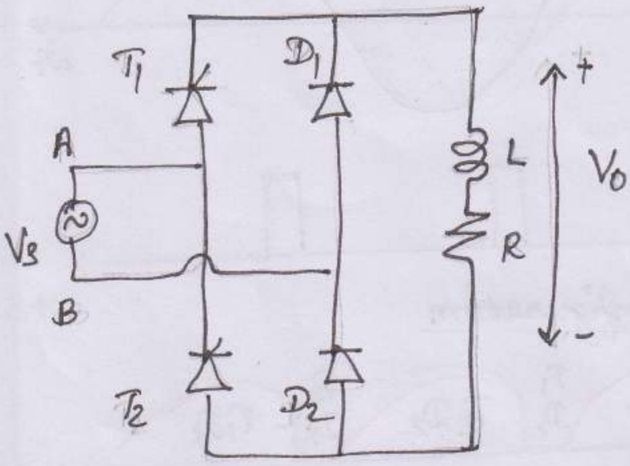
~~Average~~ RMS o/p voltage (V_{rms})

$$V_{rms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi}(V_m \sin\omega t)^2 \, d\omega t\right]^{1/2}$$

$$= \left\{\frac{V_m^2}{\pi}\int_{\alpha}^{\pi}\frac{1-\cos 2\omega t}{2} \, d\omega t\right\}^{1/2}$$

$$= \left\{\frac{V_m^2}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi}\right\}^{1/2} = \frac{V_m}{\sqrt{2\pi}}\left[\pi-\alpha+\frac{\sin 2\alpha}{2}\right]^{1/2}$$

1φ Half controlled bridge rectifier with RL Load (Asymmetrical configuration)

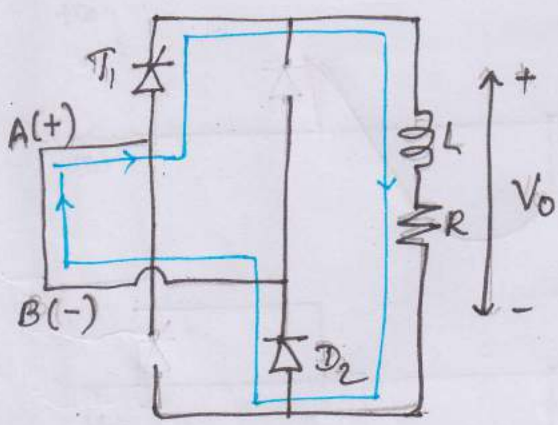


The conducting period of thyristors & diodes will be different.

L value large.

So load current continuous & so it is taken to be constant.

Mode 1 : (α to π)

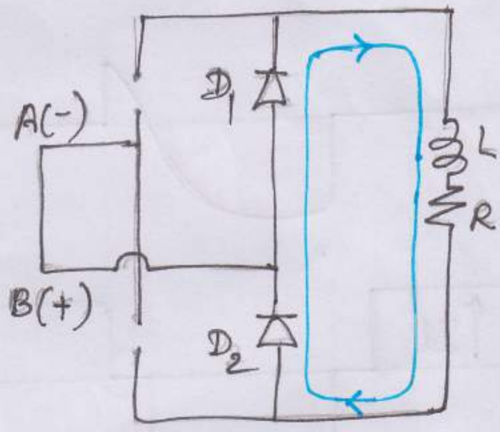


$T_1 D_2$ - FB

$A^{(+)} \rightarrow T_1 \rightarrow LR \rightarrow D_2 \rightarrow B^{(-)}$

V_0-(+)ve i_0-(+)ve

Mode 2 : π to $\pi+\alpha$

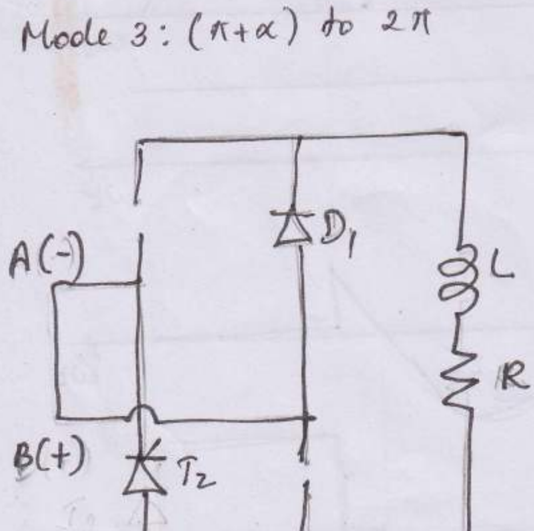


$D_1 D_2$ - FB

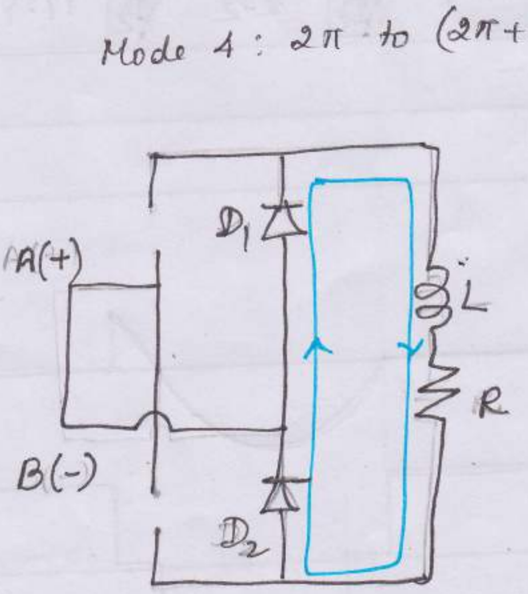
$LR \rightarrow D_2 \rightarrow D_1 \rightarrow LR$

V_0 - +ve i_0 - +ve

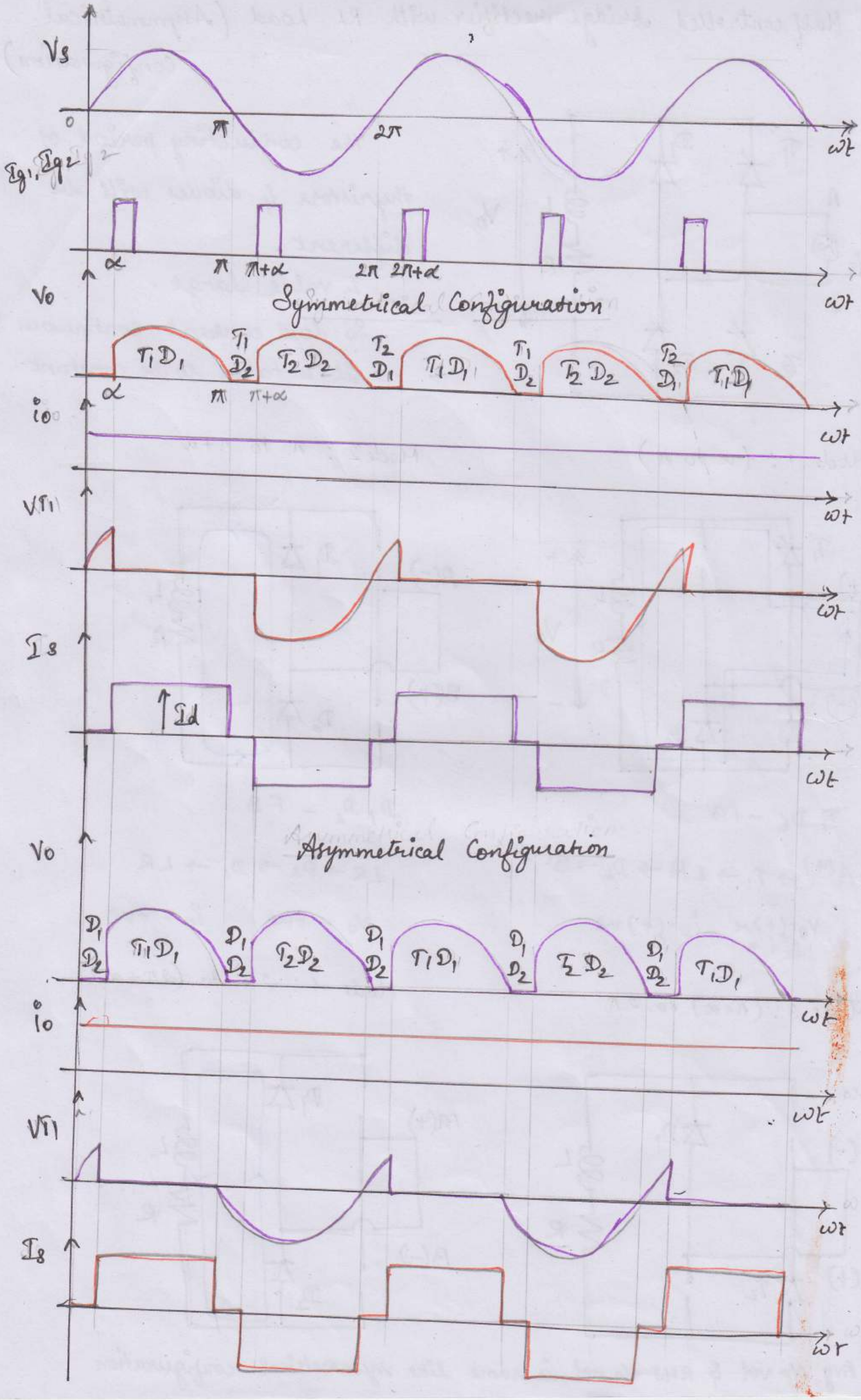
Mode 3 : $(\pi+\alpha)$ to 2π



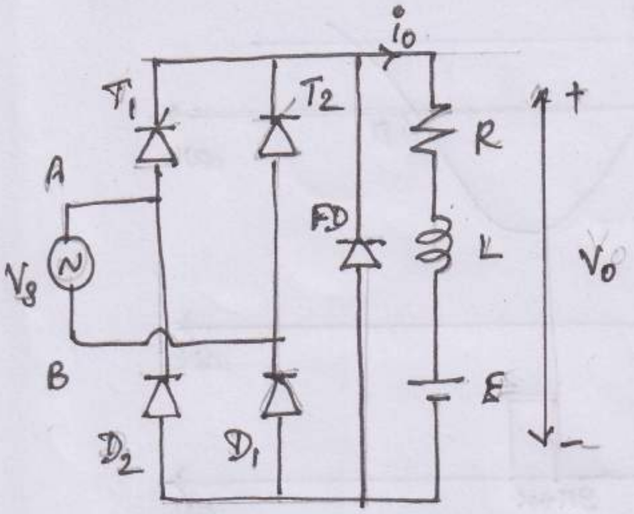
Mode 4 : 2π to $(2\pi+\alpha)$



Avg o/p vol & RMS o/p vol is same like symmetrical configuration


Vs
0
π
2π
ωt
Ig1, Ig2
α
π
π+α
2π
2π+α
Vo
Symmetrical Configuration
T1D1
T1 D2
T2D2
T2 D1
T1D1
T1 D2
T2 D2
T2 D1
T1D1
π
π+α
io
VT1
Is
Id
Vo
Asymmetrical Configuration
D1 D2
T1D1
D1 D2
T2D2
D1 D2
T1D1
D1 D2
T2 D2
D1 D2
T1D1
io
VT1
Is

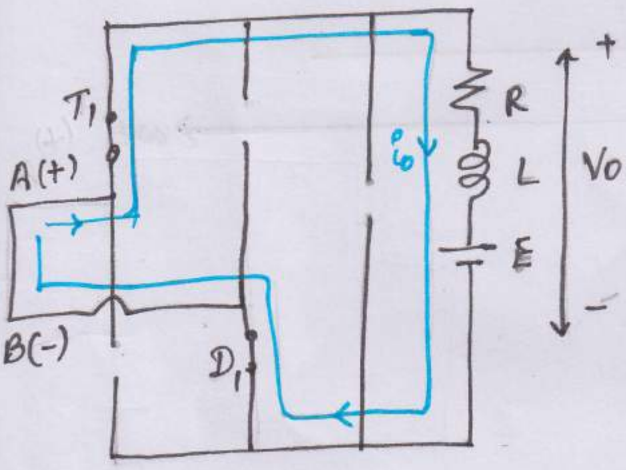
1φ Half controlled rectifier with RLE load and free wheeling Diode (Symmetrical Configuration)



Load inductance is assumed to be ~~continuous~~ large and load current is assumed continuous.

The thyristors will get forward biased only when source voltage V_s exceeds E ie, $V_s > E$

mode 1 :- α to π



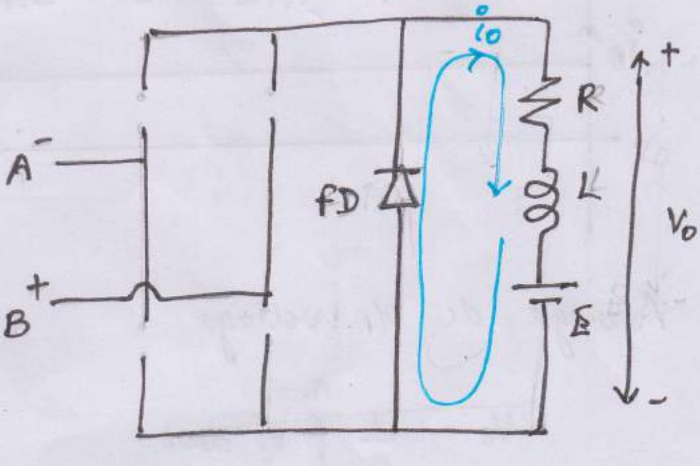
$T_1 D_1$ - FB.

$A^+ \rightarrow T_1 \rightarrow RLE \rightarrow D_1 \rightarrow B^-$

V_0 = +ve

i_0 = +ve

mode 2: π to $\pi + \alpha$



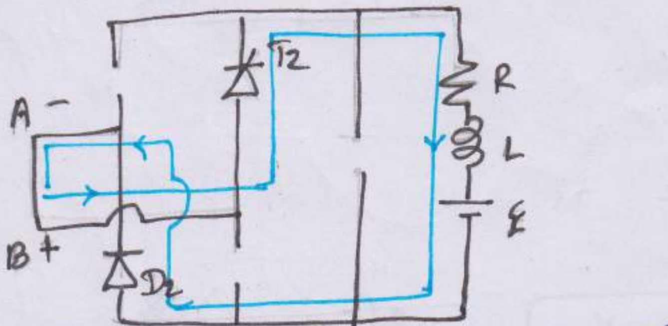
$T_1 D_1$ - off, FD - Forward biased

The freewheeling diode conducts to provide the continuity of current in the inductive load.

$V_0 = 0$ i_0 = +ve

$RLE \rightarrow FD \rightarrow RLE$

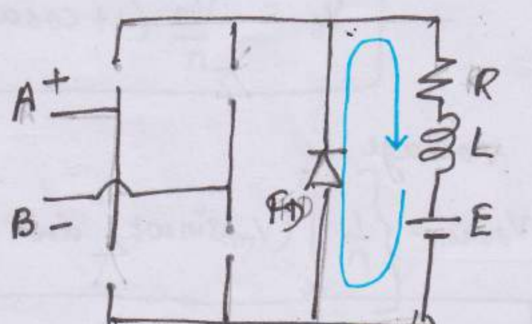
mode 3 :- $\pi + \alpha$ to 2π



$T_2 D_2$ - FB $B^+ \rightarrow T_2 \rightarrow RLE \rightarrow D_2 \rightarrow A^-$

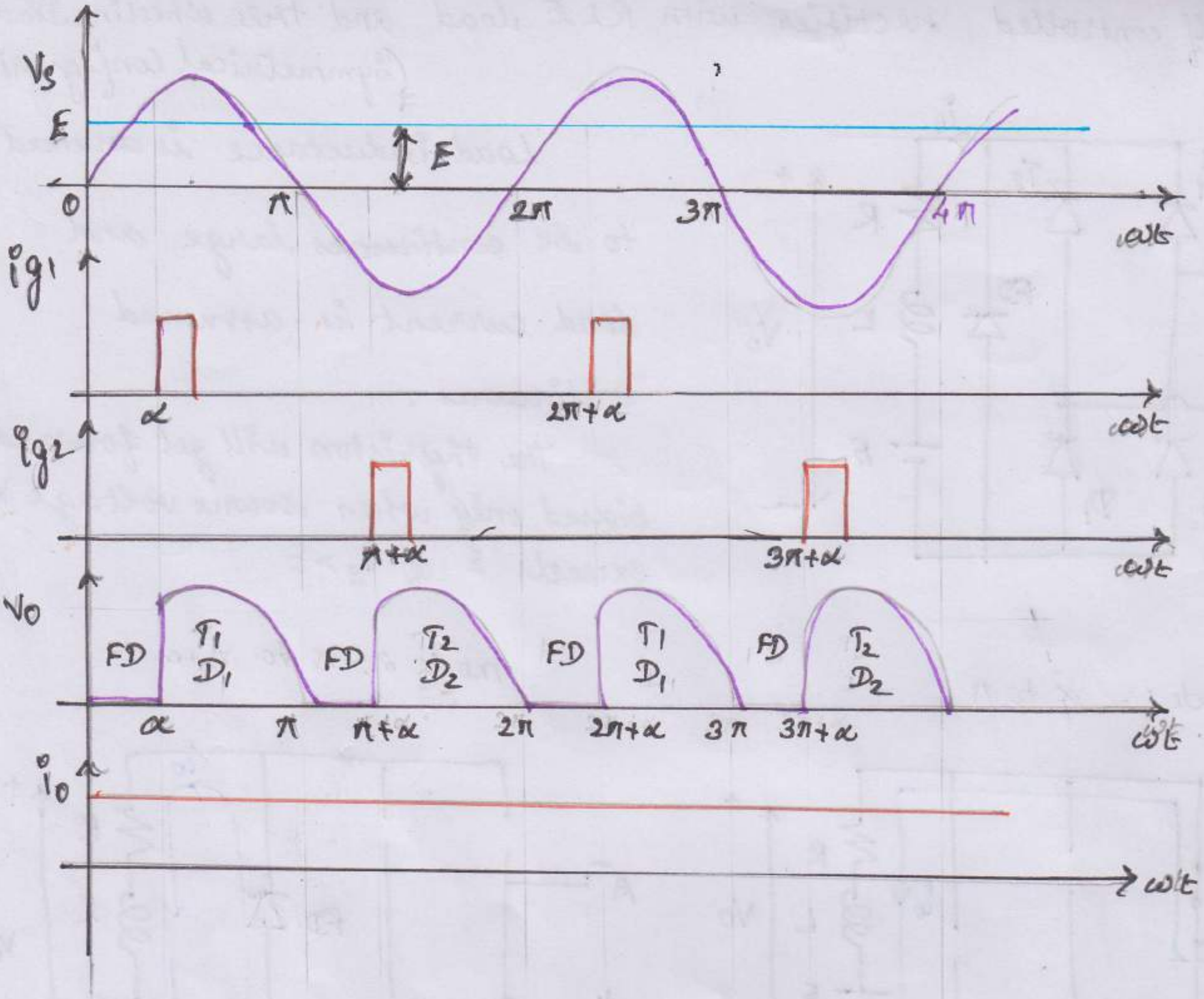
V_0 = +ve i_0 = +ve

mode 4 :- 2π to $2\pi + \alpha$



$T_2 D_2$ - off FD is FB

$RLE \rightarrow FD \rightarrow RLE$.



Average dc o/p voltage.

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_s \, d\omega t$$

$$= \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t$$

$$= \frac{V_m}{\pi}\Big[-\cos\omega t\Big]_{\alpha}^{\pi}$$

$$= -\frac{V_m}{\pi}\Big[\cos\pi - \cos\alpha\Big]$$

$$\boxed{V_0 = \frac{V_m}{\pi}(1+\cos\alpha)}$$

RMS voltage.

$$V_{rms} = \left\{\frac{1}{\pi}\int_{\alpha}^{\pi}(V_m \sin\omega t)^2 \, d\omega t\right\}^{1/2}$$

$$\boxed{V_{rms} = \left\{\frac{V_m^2}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi}\right\}^{1/2}} = \frac{V_m}{\sqrt{2\pi}}\left\{\pi - \alpha + \frac{\sin 2\alpha}{2}\right\}^{1/2}$$

3ϕ Controlled converters.

1ϕ supply → produces a relatively high proportion of a-c ripple-voltage at its d.c terminals which is an undesirable one.

Therefore, a smoothing reactor is necessary to smoothen the o/p voltage.

The need of smoothing can be minimised by increasing the number of pulses.

When the no. of pulses of the converter is ↑ed, the no. of segments that fabricate the o/p voltage also ↑s & consequently the ripple content ↓es.

3ϕ rectifier ckts are used for larger power applications.

Classification of 3ϕ controlled converters

1) 3-pulse converters
2) 6-pulse converters
3) 12-pulse converters.

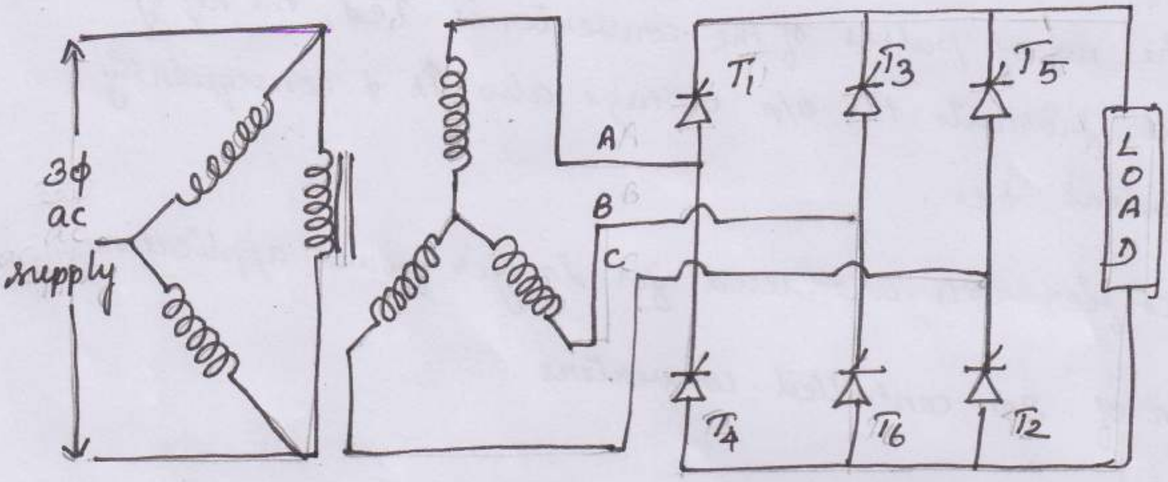
3-pulse converters are also known as 3ϕ half-wave controlled rectifier.

But the 3-pulse converters have not become very popular because of the fact that they require special types of converter transformer to prevent d.c magnetisation.

Six-pulse converters have the following advantages compared to three-pulse converters

1) Commutation is made very easier.
2) Distortion on the a.c. side is reduced due to the reduction in lower-order harmonics.
3) Inductance required in series is considerably reduced

3ϕ Fully controlled bridge converter



The load is fed via a 3ϕ half-wave connection to one of the 3 supply lines, no neutral being required.

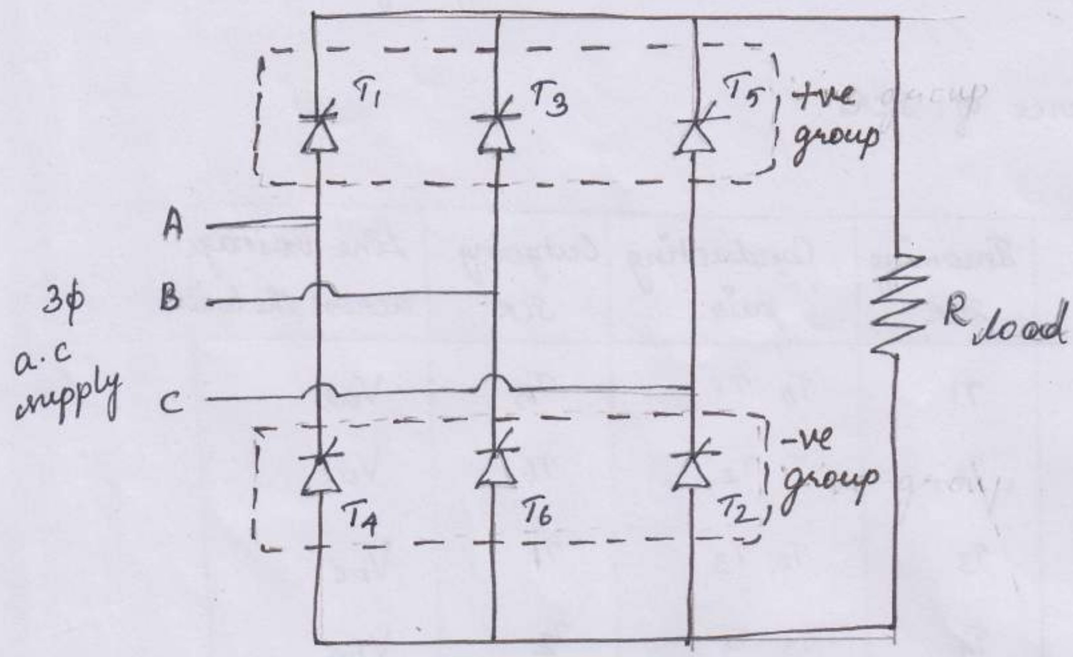
Hence transformer connection is optional.

However, for isolation of o/p from supply source, or for higher o/p requirements transformer is to be connected.

If it is used, one winding is connected in delta bcz the delta connection gives the circulating path for 3rd harmonic current.

∴ The 3rd order harmonic current does not appear in line which is an advantage.

3ϕ Fully controlled bridge rectifier with R-load.



* The ckt consists of 2 groups of SCRs, +ve group & -ve group.
* +ve group is formed by T_1, T_3 & T_5.
* -ve group is " " T_4, T_6 & T_2.

✓ The +ve group devices are turned-on when the supply voltages are +ve.

✓ The -ve group devices are turned-on when the supply voltages are -ve.

✓ To start the ckt functioning, 2 thyristors must be fired at the same time in order to commence current-flow, one of the upper arm and one of the lower arm.

* Each device should be triggered at a desired firing angle 'α'
* Each SCR can conduct for 120°.
* SCRs must be triggered in the sequence T_1, T_2, T_3, T_4, T_5 & T_6
* The phase shift between the triggering of two adjacent SCRs is 60°.
* At any instant, two SCRs can conduct and there are such 6 pairs. $(T_6\ T_1)$, (T_1, T_2), $(T_2\ T_3)$, $(T_3\ T_4)$ $(T_4\ T_5)$ & $(T_5\ T_6)$

* Each SCR conducts in 2 pairs &, each pair conducts for 60°.

* The incoming SCR commutates the outgoing SCR.

Firing sequence of SCRs.

S. No	ωt	Incoming SCR	Conducting pair	Outgoing SCR	Line voltage across the load
1.	$30° + \alpha$	T_1	T_6 T_1	T_5	V_{ab}
2	$90° + \alpha$	T_2	T_1 T_2	T_6	V_{ac}
3	$150 + \alpha$	T_3	T_2 T_3	T_1	V_{bc}
4	$210 + \alpha$	T_4	T_3 T_4	T_2	V_{ba}
5	$270 + \alpha$	T_5	T_4 T_5	T_3	V_{ca}
6	$330 + \alpha$	T_6	T_5 T_6	T_4	V_{cb}

* When two SCRs are conducting, ie, one from +ve group & one from -ve group, the corresponding line voltage is applied across the load.

For 6-pulse operation, each SCR has to be fired twice in its conduction cycle, that is firing intervals should be 60°.

The o/p voltage waveform for any value of α is a 6 pulse wave with a ripple frequency of 300 Hz.

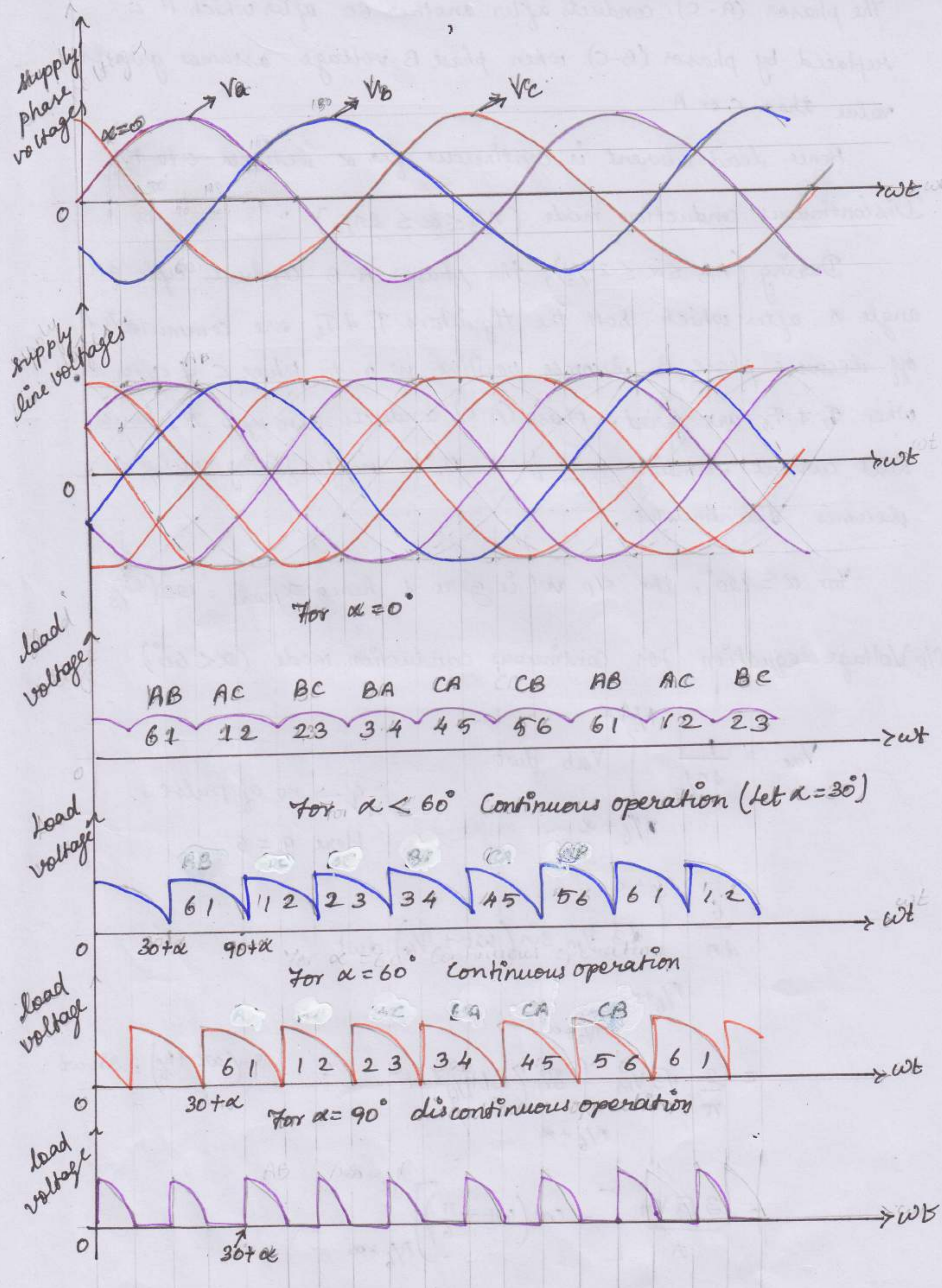
Continuous conduction mode $(0 \le \alpha \le \overset{\pi/3}{60°})$

$\alpha = 30°$

When the phasor (A-B) is allowed to conduct at α between 0 to $\pi/3$, it continues to conduct by 60° when the phasor (A-C) is fired.

The conduction is shifted from SCR T_6 to T_2.

T_6 is commutated by the reverse-voltage of phase C & B across it.



supply phase voltages
Va
Vb
Vc
α=0
0
ωt
supply line voltages
0
ωt
For α=0°
load voltage
AB AC BC BA CA CB AB AC BC
61 12 23 34 45 56 61 12 23
ωt
For α < 60° Continuous operation (let α=30°)
load voltage
AB
61 12 23 34 45 56 61 12
0
30+α
90+α
ωt
For α = 60° Continuous operation
load voltage
BA CA CB
61 12 23 34 45 56 61
0
30+α
ωt
For α = 90° discontinuous operation
load voltage
0
30+α
ωt

The phasor (A - C) conducts after another 60° after which it is replaced by phasor (B-C) when phase B voltage assumes greater value than C or A.

Hence load current is continuous for α between 0 to $\pi/3$.

Discontinuous conduction mode ($\pi/3 \le \alpha \le 2\pi/3$)

During ($\pi/3 \le \alpha \le 2\pi/3$), the phasor A-B conducts upto an angle π after which both the thyristors T_1 & T_6 are commutated off because phase B becomes positive w.r. to phase C & after 60°. when T_2 & T_1 are fired, phase (A-C) conducts also upto π, hence load current remains zero from π to next firing pulse & becomes discontinuous.

For $\alpha = 120^\circ$, the o/p vol is zero & hence $\alpha_{max} = 120^\circ \left(\text{i.e. } 2\pi/3\right)$

O/p Voltage equation for continuous conduction mode ($\alpha < 60^\circ$)

$$V_{dc} = \frac{1}{2\pi/q} \int_{\pi/6+\alpha}^{\pi/2+\alpha} V_{ab} \, d\omega t$$

$q \to$ no of pulses.

Here $q = 6$

$$= \frac{6}{2\pi} \int_{\pi/6+\alpha}^{\pi/2+\alpha} \sqrt{3}\, V_m \sin\left(\omega t + \pi/6\right) d\omega t.$$

$$= \frac{3}{\pi} \sqrt{3}\, V_m \int_{\pi/6+\alpha}^{\pi/2+\alpha} \sin\left(\omega t + \pi/6\right) d\omega t$$

$\sin\left(\omega t + \pi/6\right) = \sin \omega t$

$$= \frac{3\sqrt{3}\, V_m}{\pi} \left[-\cos\left(\omega t + \frac{\pi}{6}\right)\right]_{\pi/6+\alpha}^{\pi/2+\alpha}$$

$$= -\frac{3\sqrt{3}\, V_m}{\pi} \left[\cos\left(\frac{\pi}{2} + \alpha + \frac{\pi}{6}\right) - \cos\left(\frac{\pi}{6} + \alpha + \pi/6\right)\right]$$

$$= -\frac{3\sqrt{3}V_m}{\pi}\left[\cos\left(\frac{2\pi}{3}+\alpha\right) - \cos\left(\frac{\pi}{3}+\alpha\right)\right]$$

$$= -\frac{3\sqrt{3}V_m}{\pi}\left[\left(\cos\frac{2\pi}{3}\cos\alpha - \sin\frac{2\pi}{3}\sin\alpha\right) - \left(\frac{1}{2}\cos\alpha - \frac{\sqrt{3}}{2}\sin\alpha\right)\right]$$

$$= -\frac{3\sqrt{3}V_m}{\pi}\left[\left(-\frac{1}{2}\cos\alpha - \frac{\sqrt{3}}{2}\sin\alpha\right) - \left(\frac{1}{2}\cos\alpha - \frac{\sqrt{3}}{2}\sin\alpha\right)\right]$$

$$= -\frac{3\sqrt{3}V_m}{\pi}\left[\frac{-1}{2}\cos\alpha - \cancel{\frac{\sqrt{3}}{2}\sin\alpha} - \frac{1}{2}\cos\alpha + \cancel{\frac{\sqrt{3}}{2}\sin\alpha}\right]$$

$$= -\frac{3\sqrt{3}V_m}{\pi}\left(-\frac{\cancel{2}\cos\alpha}{\cancel{2}}\right)$$

$$\boxed{V_{dc} = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha}$$

For R & RL

Average load current (I_{dc})

$$\boxed{I_{dc} = \frac{V_{dc}}{R} = \frac{3\sqrt{3}V_m}{\pi R}\cos\alpha}$$

O/p voltage equation for discontinuous conduction mode ($\alpha > 60^\circ$)

$$V_{dc} = \frac{6}{2\pi}\int_{\pi/6+\alpha}^{5\pi/6} \sqrt{3}V_m \sin\left(\omega t + \frac{\pi}{6}\right) d\omega t$$

$$= \frac{3\sqrt{3}V_m}{\pi}\int_{\pi/6+\alpha}^{5\pi/6} \sin\left(\omega t + \pi/6\right) d\omega t$$

$$= \frac{3\sqrt{3}V_m}{\pi}\left[-\cos\left(\omega t + \frac{\pi}{6}\right)\right]_{\pi/6+\alpha}^{5\pi/6}$$

$$= -\frac{3\sqrt{3}V_m}{\pi}\left[\cos\left(\frac{5\pi}{6}+\frac{\pi}{6}\right) - \cos\left(\frac{\pi}{6}+\alpha+\frac{\pi}{6}\right)\right]$$

$$= \frac{-3\sqrt{3}\,V_m}{\pi}\left[\cos \frac{\cancel{6}\pi}{\cancel{6}} - \cos\left(\frac{\cancel{2}\pi}{\cancel{6}_3} + \alpha\right)\right]$$

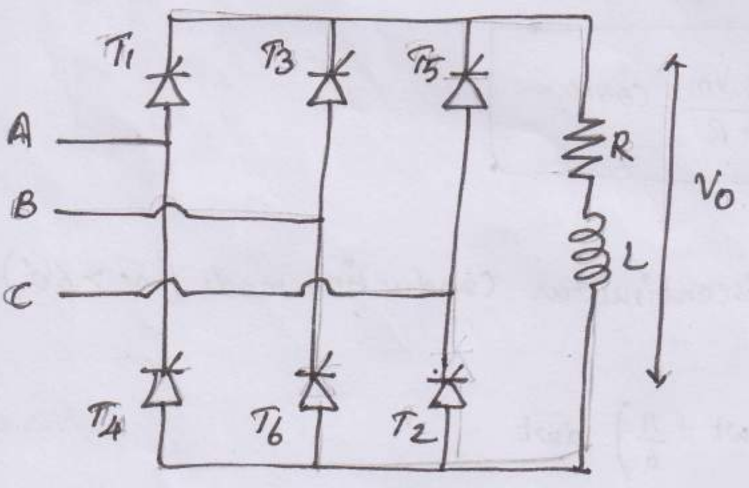
$$= \frac{-3\sqrt{3}\,V_m}{\pi}\left[-1 - \cos\left(\frac{\pi}{3}+\alpha\right)\right]$$

$$\boxed{V_{dc} = \frac{3\sqrt{3}\,V_m}{\pi}\left[1 + \cos\left(\frac{\pi}{3}+\alpha\right)\right]}$$

Avg load current

$$\boxed{I_{dc} = \frac{V_{dc}}{R} = \frac{3\sqrt{3}}{\pi R}\left[1+\cos\left(\frac{\pi}{3}+\alpha\right)\right]}$$

3ϕ Fully controlled bridge rectifier with RL Load



The load inductance is assumed to be very large so as to produce a constant load current.

Operation & Conduction sequence same like R load.

Waveforms are similar with R-load for $\alpha = 0°$, $30°$ & $60°$

✓ For $\alpha > 60^\circ$, the waveforms are different.

✓ Because of inductive nature of load, the voltage goes -ve.

✓ The previous thyristor pair continuous to conduct till the next SCR is triggered.

For eg: T_6 & T_1 continuous to conduct upto $(90+\alpha)$ till thyristor T_2 is triggered and when T_2 is triggered it commutates the SCR T_6 and so T_1 & T_2 starts conducting.

✓ For $\alpha = 90^\circ$, the area under the +ve & -ve cycle are equal & the average voltage is zero.

✓ For $\alpha < 90^\circ$, the average o/p voltage is positive

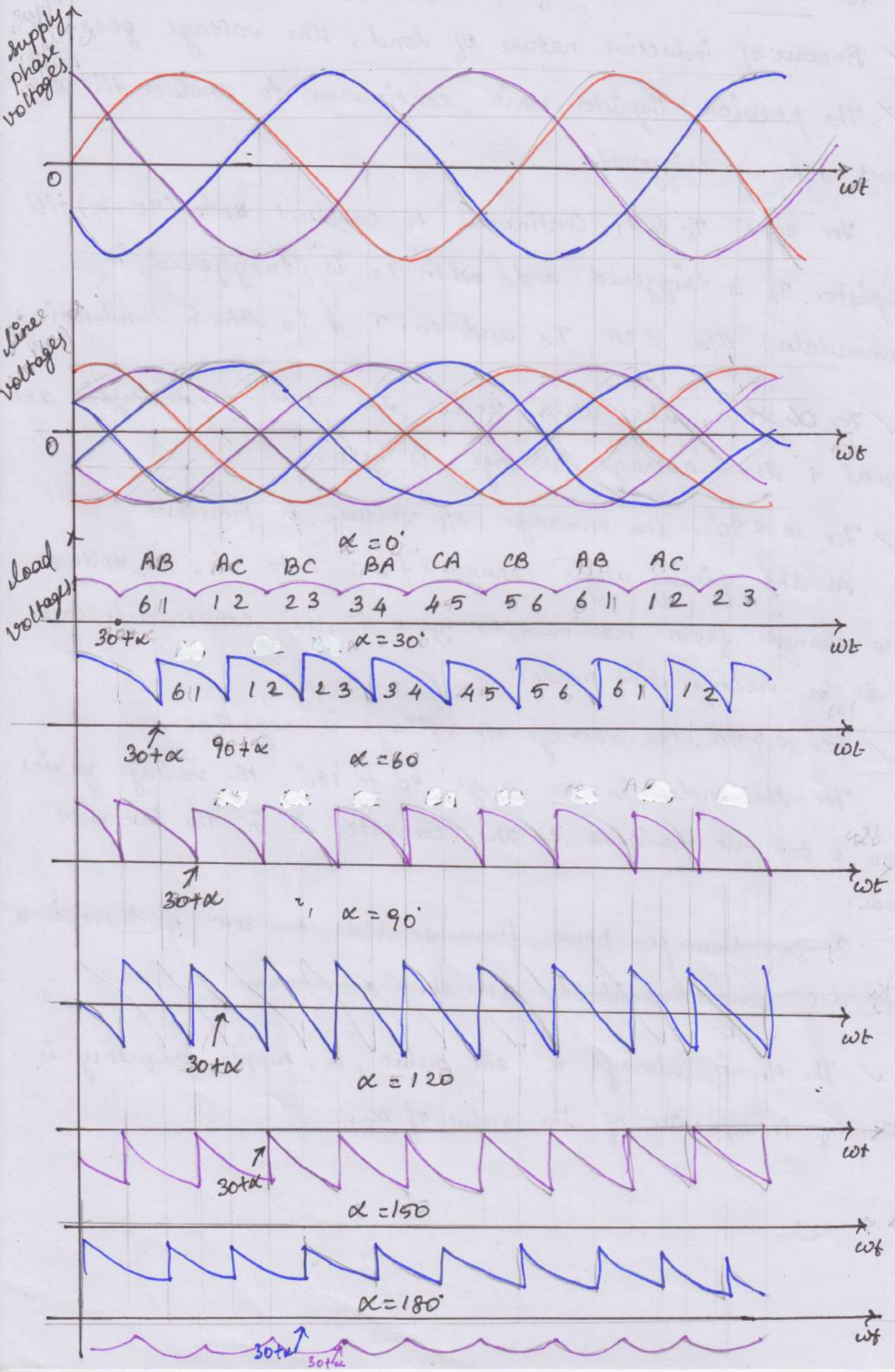
As the firing angle changes from 0 to 90°, the voltage also changes from maximum to zero & the converter is said to be in rectification mode.

✓ For $\alpha > 90^\circ$, the average o/p voltage is negative.

For the angles in the range 90° to 180°, the voltage varies from 0 to -ve maximum & the converter is in the inversion mode.

~~It can transfer power from dc side to a.c if there is a -ve d.c source available at the d.c term~~

✓ The o/p is always a six pulse, ie, ripple frequency is 300Hz irrespective of the value of α.


supply phase voltages
O
ωt
line voltages
O
ωt
load voltages
α = 0°
AB AC BC BA CA CB AB AC
6 1 1 2 2 3 3 4 4 5 5 6 6 1 1 2 2 3
30+α
ωt
α = 30°
6 1 1 2 2 3 3 4 4 5 5 6 6 1 1 2
30+α 90+α
ωt
α = 60
30+α
ωt
α = 90°
30+α
ωt
α = 120
ωt
30+α
α = 150
ωt
α = 180°
ωt
30+α 30+α

Average o/p voltage and current similar to R load of continuous conduction

$$V_{dc} = \frac{3\sqrt{3}\,V_m}{\pi}\cos\alpha \quad \text{for } (0 \le \alpha \le 180^\circ)$$

$\alpha < 90 \rightarrow$ rectification mode.

$\alpha > 90 \rightarrow$ inversion mode.

RMS o/p voltage.

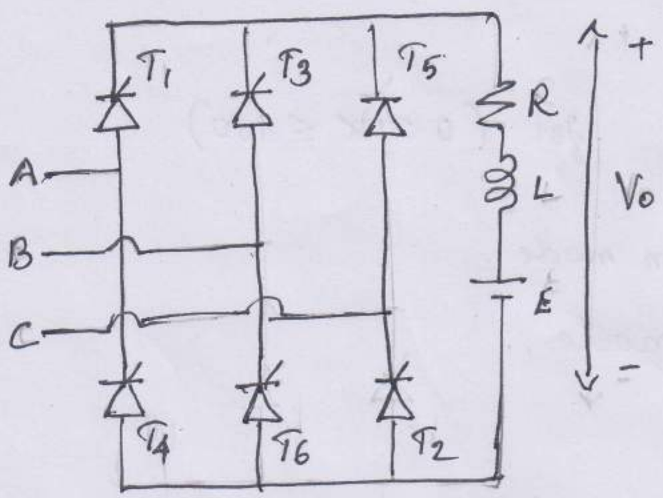
$$V_{rms} = \left[\frac{1}{2\pi}\int_0^{2\pi} V_{dc}^2(\omega t)\, d\omega t\right]^{1/2}$$

$$= \left\{\frac{6}{2\pi}\int_{\pi/6+\alpha}^{\pi/2+\alpha} \left[V_{ab}(\omega t)\right]^2 d\omega t\right\}^{1/2}$$

$$= \left\{\frac{9V_m^2}{2\pi}\left[60^\circ + \frac{1}{2}\left(\sqrt{3}\cos 2\alpha\right)\right]\right\}^{1/2}$$

$$= \frac{3V_m}{2}\left\{\frac{2}{3} + \frac{\sqrt{3}}{\pi}\cos 2\alpha\right\}^{1/2}$$

3ϕ ~~Full~~ bridge converters with RLE Load



The 3ϕ full bridge converter will works as a 3ϕ ac to dc converter for firing angle delay $0° < \alpha \leq 90°$ and as 3ϕ line-commutated inverter for $90° < \alpha < 180°$.

Thus this 3ϕ full converter is preferred where regeneration of power is required.

For $\alpha = 0°$, T_1 to T_6 behave like diodes.

For $\alpha = 60°$, T_1 is triggered at $\omega t = 30° + 60 = 90°$.

IIIly T_2 triggered at $\omega t = 90 + 60 = 150$ & so on.

Each SCR conducts for $120°$.

Conduction sequence : $T_5\ T_6$
$T_6\ T_1$
$T_1\ T_2$
$T_2\ T_3$
$T_3\ T_4$
$T_4\ T_5$
$T_5\ T_6$ & repeats.

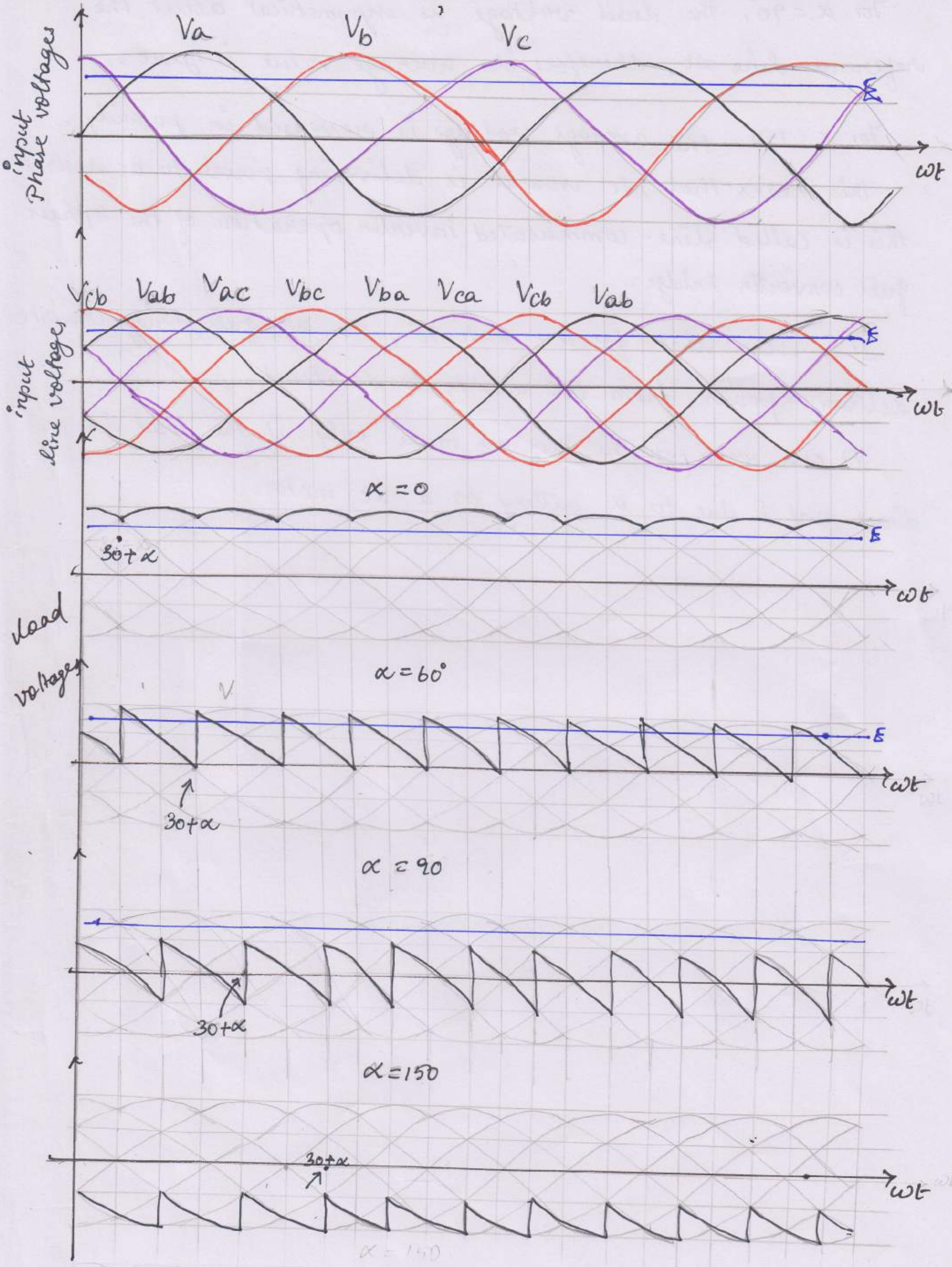
The SCRs from both the groups (positive or negative) are fired at an interval of $60°$.

This means that commutation occurs every $60°$.

When T_1 is turned on, T_5 is turned off. T_6 is already conducting.

As T_1 & T_6 are connected to A & B, load voltage must be V_{ab}.

When T_2 is turned on, T_6 is commutated.



input Phase voltages
Va
Vb
Vc
ωt
E
input line voltage
Vcb
Vab
Vac
Vbc
Vba
Vca
Vcb
Vab
ωt
E
α = 0
30+α
Load voltage
α = 60°
30+α
α = 90
30+α
α = 150
30+α

For $\alpha = 90^\circ$, the load voltage is symmetrical about the reference line ωt, therefore its average value is zero.

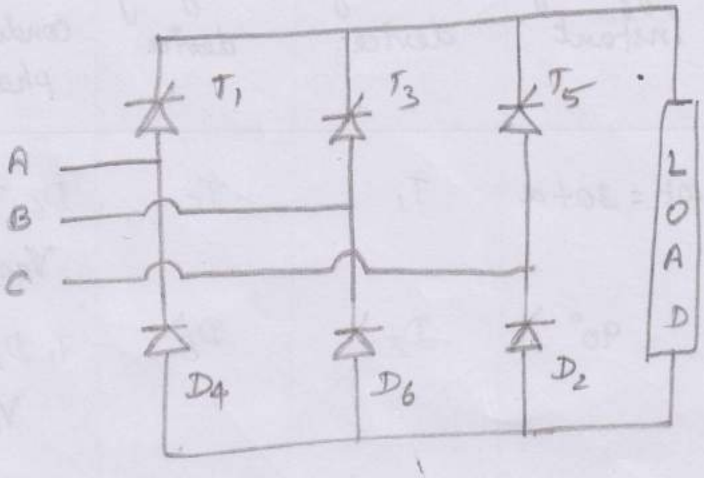
For $\alpha = 150^\circ$, the average voltage is reversed in polarity. This means that dc source is delivering power to ac source; this is called line-commutated inverter operation of the 3phase full converter bridge.

It is seen that for $\alpha = 0^\circ$ to 90°, the 3ϕ full bridge converter delivers power from ac source to dc load.

It can work in the inverter mode only if the load has a direct emf E due to a battery or a dc motor.

3ϕ Half controlled bridge converter / (3ϕ semi converter) (or) 3-pulse converter.

The circuit contains 3 SCRs & 3 diodes.

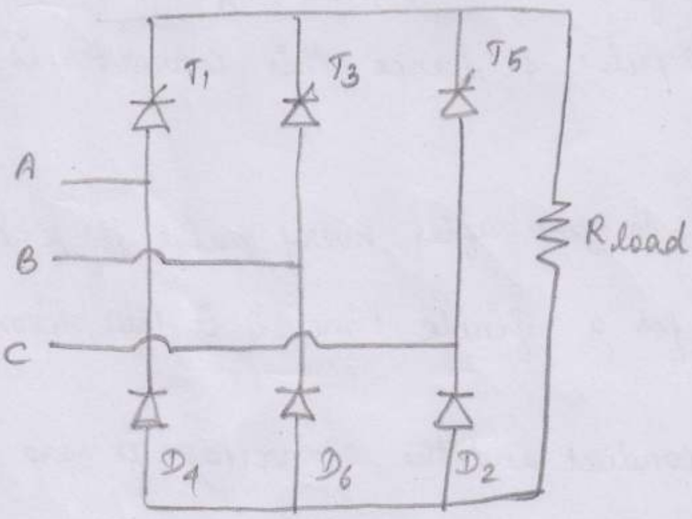


Here asymmetrical configuration is not used because it introduces imbalance in line-currents on the a.c side.

Operates in one quadrant only. Hence can be used for industrial applications upto 120 kW level.

If delay angle of this converter is ↑ed, the P.F is ↓ed.

Operation with Resistive load.



*) Diode starts conducting as soon as they are forward-biased

* Line voltages conducts in the sequence V_{AB}, V_{AC}, V_{BC}, V_{BA}, V_{CA} and V_{CB}.

* A line voltage which has the highest value compared to others will conduct, ie, when it makes an angle of 60° with neutral.

Incoming, Outgoing + conducting devices.

S. No	Triggering instant	Incoming device	Outgoing device	Pair conducting + phasor	Conducting period of each pair	conducting period of outgoing device
1.	$\omega t = 30+\alpha$	T_1	T_5	$D_6\ T_1$ V_{AB}	$60-\alpha$	120°
2.	90°	D_2	D_6	$T_1\ D_2$ V_{AC}	$60+\alpha$	120°
3.	$150+\alpha$	T_3	T_1	$D_2\ T_3$ V_{BC}	$60-\alpha$	120°
4.	210	D_4	D_2	$T_3\ D_4$ V_{BA}	$60+\alpha$	120°
5.	$270+\alpha$	T_5	T_3	$D_4\ T_5$ V_{CA}	$60-\alpha$	120°
6	330	D_6	D_4	$T_5\ D_6$ V_{CB}	$60+\alpha$	120°

✓ For $\alpha = 0^\circ$, the o/p voltage waveform is a 6 pulse o/p.

✓ For $\alpha \geq 30^\circ$, the o/p is only a 3 pulse & hence this converter is known as 3-pulse converter.

✓ The o/p voltage waveforms goes to zero after every pulse for $\alpha = 60^\circ$ & for $\alpha > 60^\circ$, it remains zero for a finite time & is thus discontinuous.

✓ For $\alpha = 180^\circ$, no phasor can conduct and the o/p voltage is zero

For $\alpha \le 60°$, Average dc o/p voltage

$$V_{dc} = 3 \times \frac{1}{2\pi}\left[\int_{30+\alpha}^{90} V_{ab}\, d\omega t + \int_{90}^{150+\alpha} V_{ac}\, d\omega t\right]$$

$$= \frac{3}{2\pi}\left[\int_{30+\alpha}^{90} \sqrt{3}\, V_m \sin(\omega t+30)\, d\omega t + \int_{90}^{150+\alpha} \sqrt{3}\, V_m \sin(\omega t-30)\, d\omega t\right]$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left[\int_{30+\alpha}^{90} \sin(\omega t+30)\, d\omega t + \int_{90}^{150+\alpha} \sin(\omega t-30)\, d\omega t\right]$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left\{\left[-\cos(\omega t+30)\right]_{30+\alpha}^{90} + \left[-\cos(\omega t-30)\right]_{90}^{150+\alpha}\right\}$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left[-\left[\cos(90+30) - \cos(60+\alpha)\right] - \left[\cos(120+\alpha) - \cos 60\right]\right]$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left[-(-\sin 30) + \cos(60+\alpha) - \cos(120+\alpha) + \cos 60\right]$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left[+\frac{1}{2} + \cos(60+\alpha) - \cos(120+\alpha) + \frac{1}{2}\right]$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left[1 + \cos(60+\alpha) - \cos(120+\alpha)\right]$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left[1 + (\cos 60 \cos\alpha - \sin 60 \sin\alpha) - (\cos 120 \cos\alpha - \sin 60 \sin\alpha)\right]$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left[1 + \frac{1}{2}\cos\alpha - \cancel{\frac{\sqrt{3}}{2}\sin\alpha} + \frac{1}{2}\cos\alpha + \cancel{\frac{\sqrt{3}}{2}\sin\alpha}\right]$$

$$\boxed{V_{dc} = \frac{3\sqrt{3}\, V_m}{2\pi}(1+\cos\alpha)}$$

For $\alpha \geq 60^\circ$,

$$V_{dc} = \frac{3}{2\pi}\left[\int_{30+\alpha}^{210} V_{ac}\, d\omega t\right]$$

$$= \frac{3}{2\pi}\int_{30+\alpha}^{210} \sqrt{3}\, V_m \sin(\omega t - 30)\, d\omega t$$

$$= \frac{3\sqrt{3}\, V_m}{2\pi}\left[-\cos(\omega t - 30)\right]_{30+\alpha}^{210}$$

$$= -\frac{3\sqrt{3}\, V_m}{2\pi}\left[\cos 180 - \cos(\cancel{30}+\alpha-\cancel{30})\right]$$

$$= \frac{-3\sqrt{3}\, V_m}{2\pi}\left[-1 - \cos\alpha\right]$$

$$\boxed{V_{dc} = \frac{3\sqrt{3}\, V_m}{2\pi}(1+\cos\alpha)}$$

RMS o/p voltage

$$V_{rms} = \left[\frac{1}{2\pi}\int_0^{2\pi} V_{dc}^2\, d\omega t\right]^{1/2}.$$

For $\alpha \leq 60^\circ$

$$= \left\{\frac{3}{2\pi}\left[\int_{30+\alpha}^{90} V_{ab}^2(\omega t)\, d\omega t + \int_{90}^{150+\alpha} V_{ac}^2(\omega t)\, d\omega t\right\}\right]^{1/2}$$

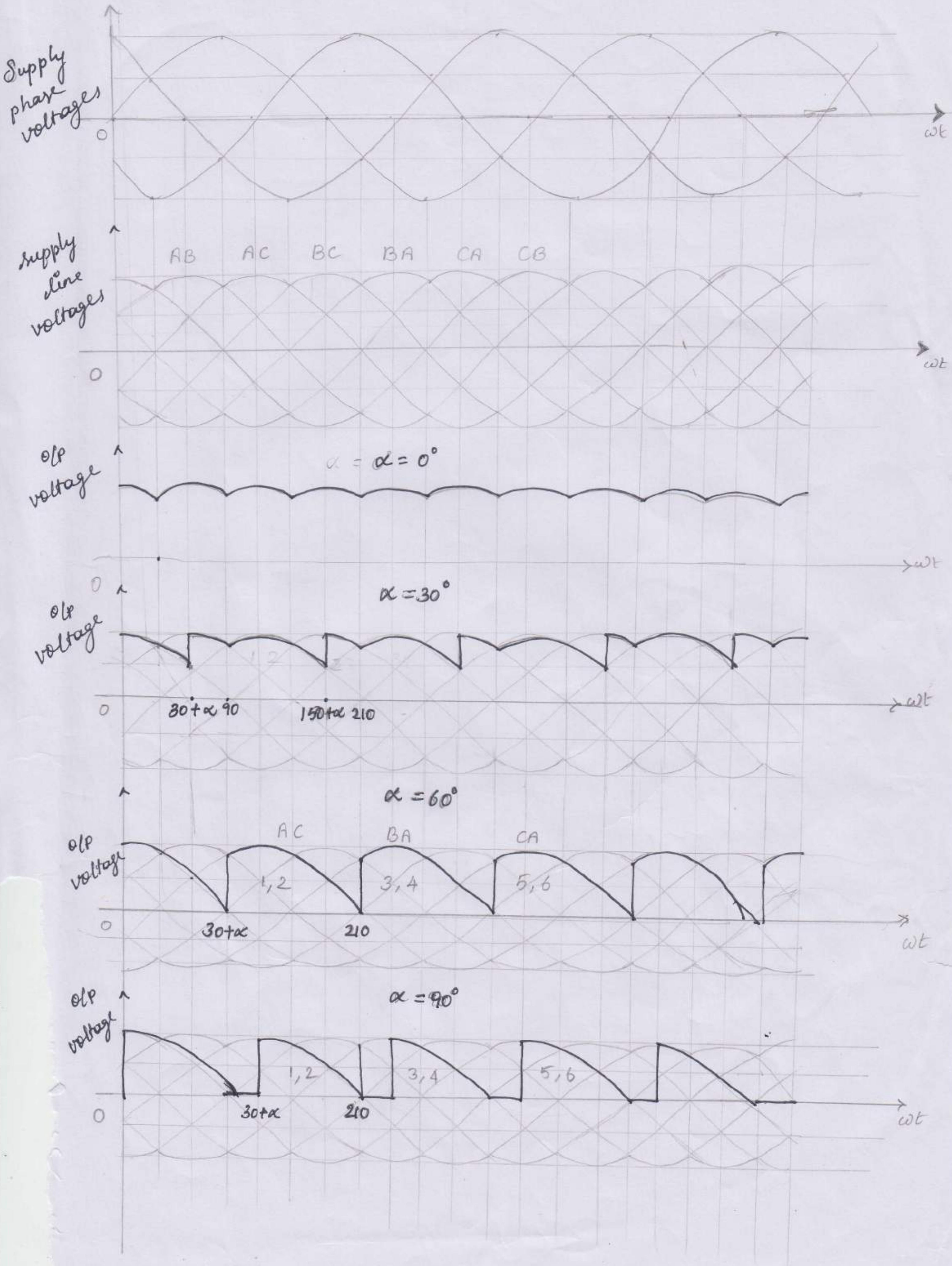
$$\boxed{V_{rms} = \frac{3}{2} V_m\left[\frac{2}{3} + \frac{\sqrt{3}}{2\pi}(1+\cos 2\alpha)\right]^{1/2}}$$

For $\alpha > 60^\circ$

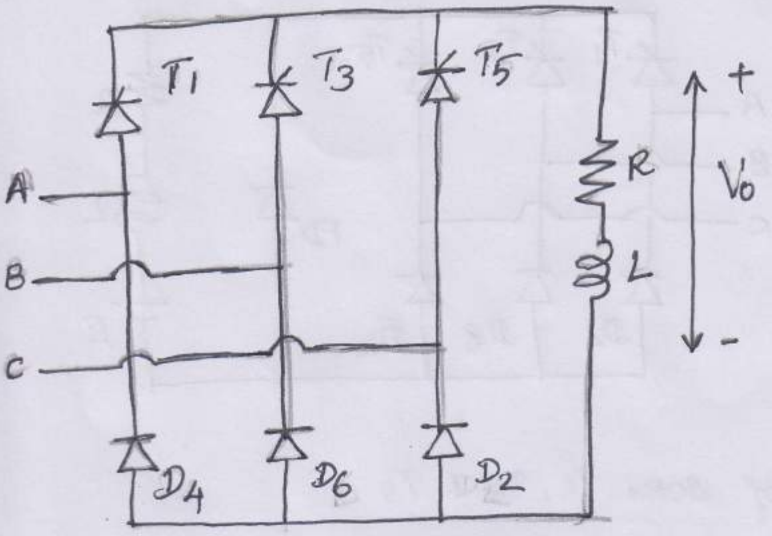
$$V_{rms} = \left\{\frac{3}{2\pi}\int_{30+\alpha}^{210} V_{ac}^2(\omega t)\, d\omega t\right\}^{1/2}$$

$$\boxed{V_{rms} = \frac{3\, V_m}{2}\left[\frac{\pi-\alpha+\frac{1}{2}\sin 2\alpha}{\pi}\right]^{1/2}}$$

3ϕ Half controlled bridge rectifier (R load) & RL Load.



3ϕ Half controlled converter with RL Load.



The value of inductance (L) is assumed to be so large. Hence the O/p current is continuous waveform.

The voltage waveform is ||lr to that of Resistive Load.

Hence, the avg & RMS values of O/p voltage waveform are same.

continuous conduction mode.

The O/p ~~ct~~ waveform is continuous for $\alpha < 60°$ & is ripple free as shown for $\alpha = 30°$.

The Form Factor of current waveform is unity & the ripple factor is zero.

Discontinuous conduction mode.

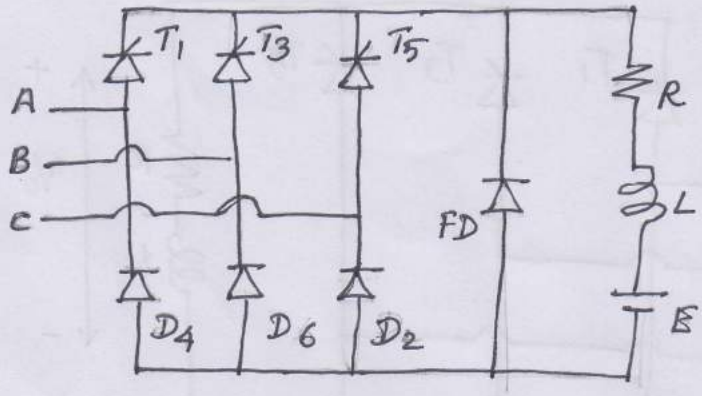
For $\alpha > 60°$, the O/p voltage becomes zero during a part of the O/p voltage period because of freewheeling action.

Waveforms & avg O/p voltages are ||lr to 3ϕ semiconverter with R load.

$$\text{ie, } V_{0(avg)} = \frac{3\sqrt{3}\,V_m}{2\pi}(1+\cos\alpha)$$

3ϕ Semiconverter with RLE load & FD

A free wheeling diode FD, is connected in parallel with RLE load, ie, across the o/p terminals of the semiconverter.



The o/p voltage V_o across the load terminals is controlled by varying the firing angles of SCRs. T_1, T_3 & T_5.

The diodes D_4, D_6 & D_2 provide merely a return path for the current to the most negative line terminal.

Each SCR & diode conduct for 120°.

For $\alpha = 0°$, the thyristors T_1, T_3 & T_5 would behave as diodes & the o/p voltage of semiconverter would be symmetrical 6-pulse per cycle.

A 3ϕ semiconverter has the unique feature of working as a 6-pulse converter for $\alpha < 60°$ and as a 3 pulse converter for $\alpha \geq 60°$.

For $\alpha = 60°$, the thyristors are fired so that current returns through one diode during each 120° conduction period.

For voltage V_{ac}, T_1 and D_2 conduct simultaneously for 120°.

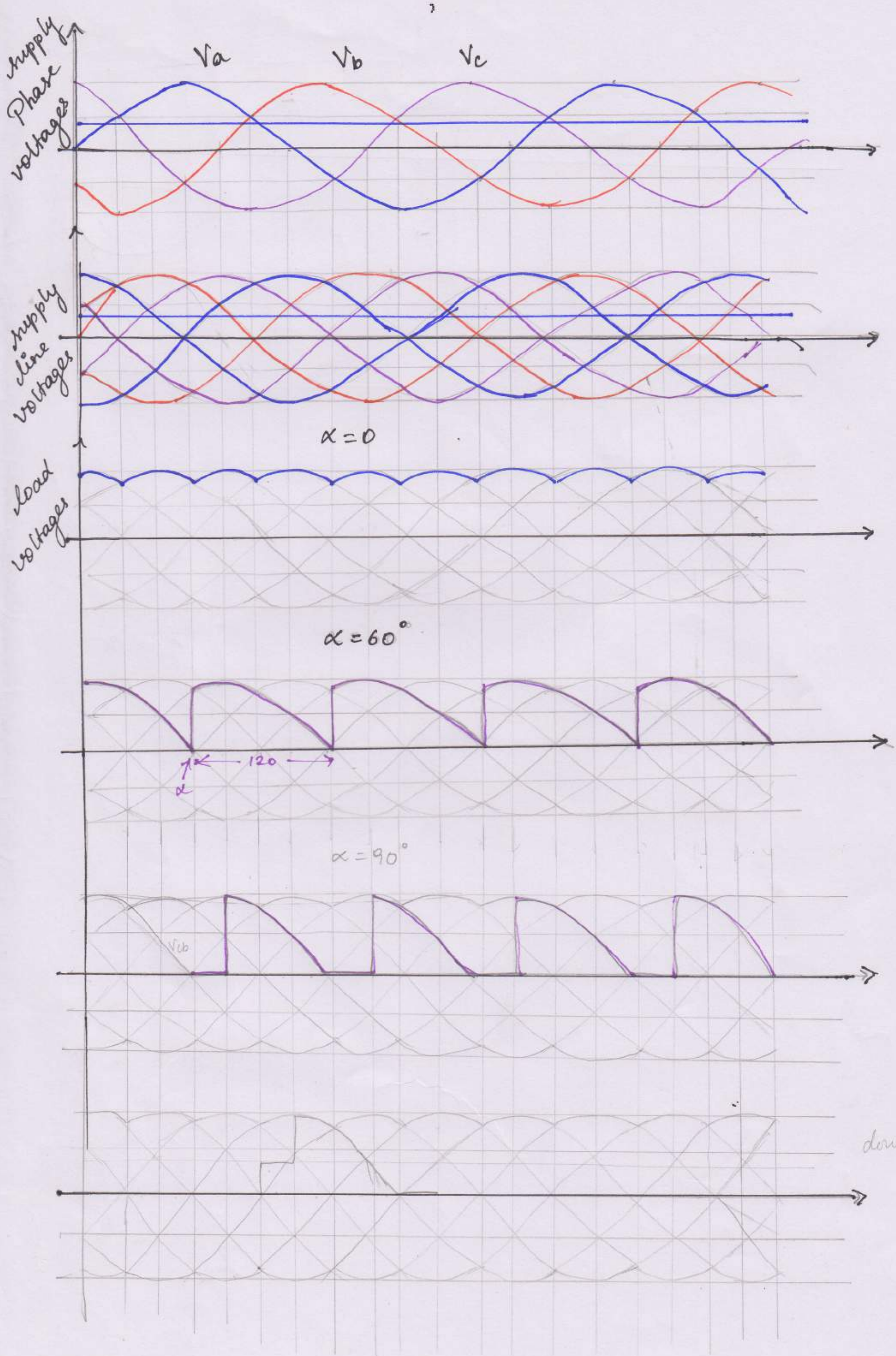
Similarly other elements conduct.

The Freewheeling diode doesnot come into play even for $\alpha = 60°$.

The voltage pulses V_{ab}, V_{bc}, V_{ca} donot appear in the o/p voltage waveform for $\alpha \geq 60°$.

For firing angle delay of 90°, the o/p voltage V_o is discontinuous.

For $\alpha = 90°$, the conduction angle of SCRs and diodes is seen to be less than 120° for every o/p pulse



supply Phase voltages
Va
Vb
Vc
supply line voltages
α=0
load voltages
α=60°
120
α
α=90°
Vcb
doubt.

Dual converters

✓ Semiconverters are single quadrant converters

✓ The avg +ve voltage and current of the semiconverter indicates rectification mode & the power flow from ac source to dc load.

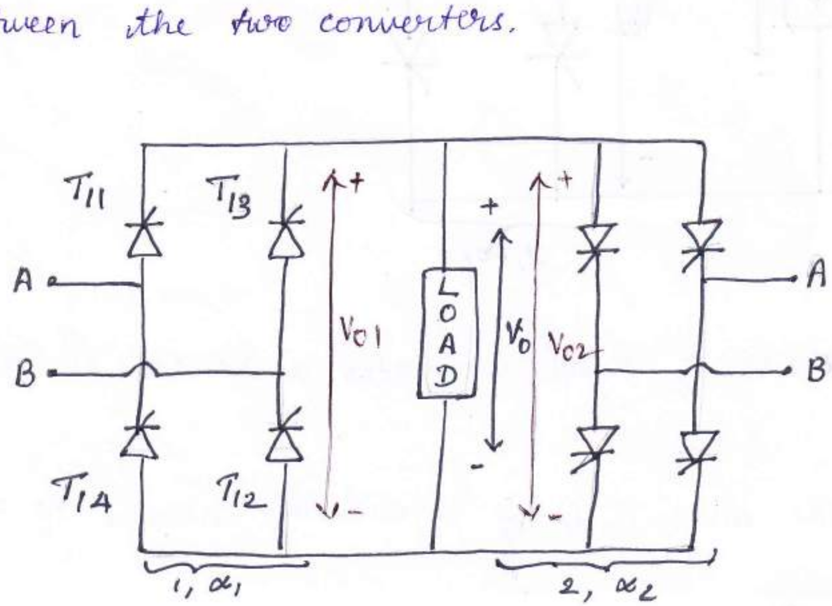
✓ The full converters operates as a rectifier in first quadrant (both V_0 I_0 +ve) from $\alpha = 0°$ to $90°$ & as an inverter (V_0 - -ve but I_0 - +ve) from $\alpha = 90°$ to $180°$ in the fourth quadrant. Thus, the full converters are two quadrant converters.

✓ Incase four quadrant operation is required without any mechanical changeover switch, two full converters can be connected back to back to the load ckt. Such an arrangement using two full converters in antiparallel & connected to the same dc load is called a dual converter.

✓ There are 2 functional modes of a dual converter. one is non-circulating current mode & the other is circulating current mode.

Dual converter without circulating current

* With non-circulating current dual converter, only one converter is in operation at a time and it alone carries the entire load current.
* Only this converter receives the firing pulses from the trigger control.
* The other converter is blocked from conduction; this is achieved by removing the firing pulses from this converter.
* Such an arrangement for the dual converters has no reactor in-between the two converters.



* Suppose converter 1 is in operation & is supplying the load current.

* For blocking converter 1 and switching on converter 2, first the firing pulses to converter 1 are immediately removed or the firing angle of converter 1 is increased to maximum value & then its firing pulses are blocked.

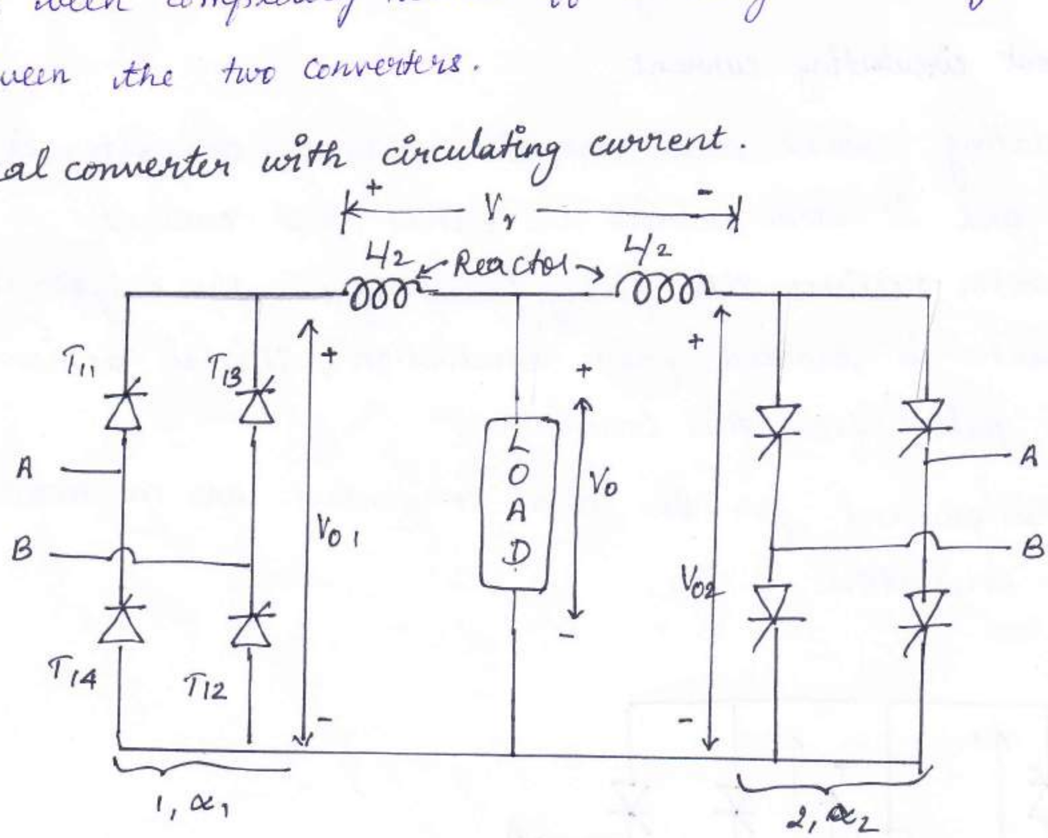
* With this, load current would decay to zero & then only converter 2 is made to conduct by applying the firing pulses to it.

* It should be ensured that during changeover from one converter to the other, the load current must decay to zero.

* After the outgoing converter has stopped conducting, a delay time of 10 to 20 msec is introduced before the firing pulses are applied to switch on the incoming converter.

* If the incoming converter is triggered before the outgoing converter has been completely turned-off a large circulating current would flow between the two converters.

Dual converter with circulating current.



- In the circulating mode of dual converter, a reactor is inserted in-between converters 1 & 2.

- This reactor limits the magnitude of circulating current to a reasonable value.

Dual converters

✓ Semi converters are single quadrant converters

✓ The avg +ve voltage and current of the semiconverter indicates rectification mode & the power flow from ac source to dc load.

✓ The full converters operates as a rectifier in first quadrant (both V_0 I_0 +ve) from $\alpha = 0°$ to $90°$ & as an inverter (V_0 - -ve but I_0 - +ve) from $\alpha = 90°$ to $180°$ in the fourth quadrant. Thus, the full converters are two quadrant converters.

✓ Incase four quadrant operation is required without any mechanical changeover switch, two full converters can be connected back to back to the load ckt. Such an arrangement using two full converters in antiparallel & connected to the same dc load is called a dual converter.

✓ There are 2 functional modes of a dual converter, one is non-circulating current mode & the other is circulating current mode.

Dual converter without circulating current

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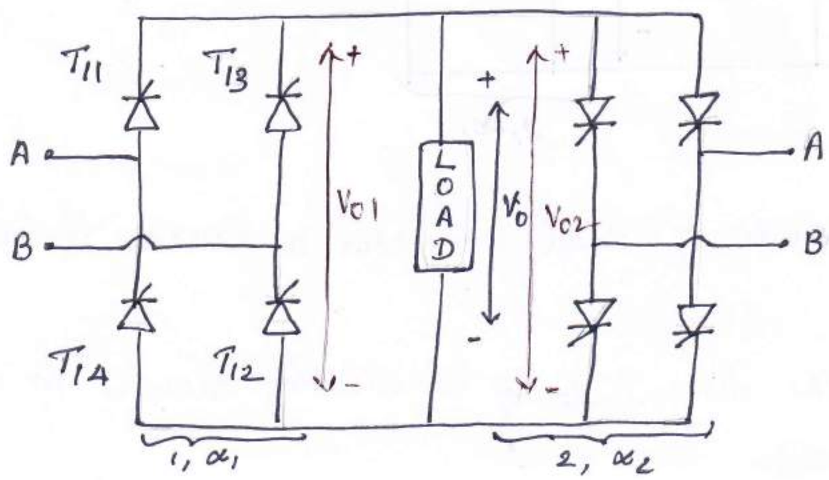
* Such an arrangement for the dual converters has no reactor in-between the two converters.



The firing pulses of the two converters are so adjusted that $\alpha_1 + \alpha_2 = 180°$.

For eg, if firing angle of conv-1 is 60°, then firing angle of conv-2 must be 120°.

Therefore for these firing angles, conv-1 is working as a rectifier and conv-2 as an inverter.

Though the o/p vol at the terminals of both conv 1 & 2 has the same avg value & also has the same polarity, their instantaneous o/p vol waveforms, however are not similar as shown by v_{01} & v_{02}.

As a consequence of it, circulating current flows between the two converters.

This circulating current is limited by the reactor.

If the load current is to be reversed, the role of two converters is interchanged.

The normal delay period of 10 to 20 msec, as required in non-circulating operation, is not needed here.

This makes the dual converter with circulating current operation faster.

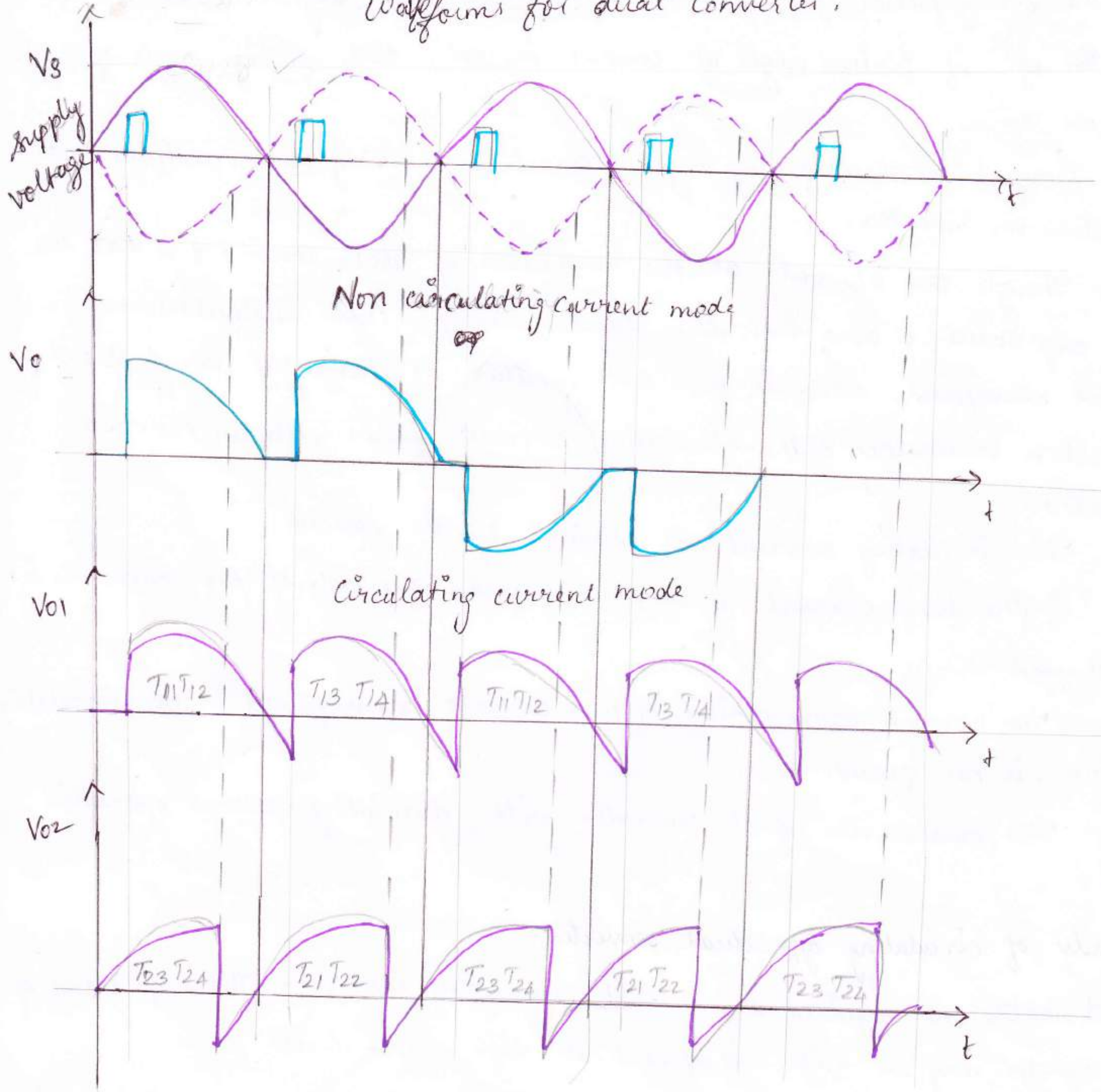
Disadv of circulating type dual converter.

i) A reactor is required to limit the circulating current. The size & cost of this reactor may be quite significant at high power levels.

ii) Circulating current gives rise to more losses in the converters, hence the efficiency & power factor are low.

iii) As the converters have to handle load aswell as circulating currents, the thyristors for the two converters are rated for higher currents.

Waveforms for dual Converter.



Average load current (I_o)

$$I_{dc} \text{ (or) } I_o = \frac{V_o}{R}$$

$$\boxed{V_o = \frac{V_m}{\pi R}(1+\cos\alpha)}$$

RMS load-Voltage (V_{rms})

$$V_{rms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \, d\omega t\right]^{1/2}$$

$$= \left[\frac{V_m^2}{\pi}\int_{\alpha}^{\pi} \frac{1-\cos 2\omega t}{2} \, d\omega t\right]^{1/2}$$

$$= \left\{\frac{V_m^2}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi}\right\}^{1/2}$$

$$= \left\{\frac{V_m^2}{2\pi}\left[\pi - \frac{\sin 2\pi}{2} - \left(\alpha \mp \frac{\sin 2\alpha}{2}\right)\right]\right\}^{1/2}$$

$$= \left[\frac{V_m^2}{2\pi}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]\right]^{1/2}$$

$$= \frac{V_m}{\sqrt{2\pi}}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]^{1/2}$$

RMS load current (I_{rms})

$$I_{rms} = \frac{V_{rms}}{R}$$

$$\boxed{I_{rms} = \frac{V_m}{R\sqrt{2\pi}}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]^{1/2}}$$