unit-4 Controlled Rectifiers

power semi conductor devices (or) Industrial Electronics-

A semiconductor device having high voltage and current ratings are known as power semiconductors.
They have high withstanding capability and high current conduction capability.

→ classification of power semiconductors-

⇒ Based on Turn ON and Turn OFF capability.

① un controllable power semiconductor devices.
Ex: Diode (∵ No control signal is available)

② partially controllable power semiconductor devices.
Ex: SCR (Silicon controlled Rectifier)
TRIAC (Triode for Alternating Current).
DIAC
(TURN ON - controlled, TURN OFF - NOT CONTROLLED)

③ Fully controlled power Semiconductor devices -
Ex: Power BJT
MOSFET (metal oxide Semiconductor field effect transistor)
IGBT (Insulated Gate Bipolar Transistor)
GTO (Gate TurnOFF thyristor)
(TURN-ON, TURN-OFF - controlled)

⇒ Based on Gate Signal -

① pulse Gate Requirement -
Ex: SCR, GTO

② continuous Gate Requirement
Ex: BJT, MOSFET, IGBT.

⇒ Based on current conduction capability.

① uni directional current Devices
Ex: SCR, GTO, BJT, MOSFET, IGBT

② Bi-directional current devices
Ex: TRIAC

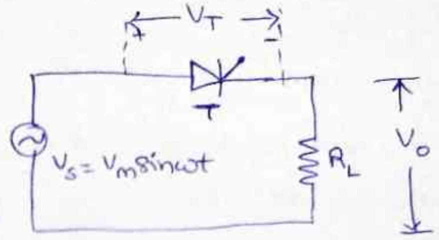
⇒ Based on voltage withstanding capability.

① uni-polar voltage withstanding devices
Ex: BJT, MOSFET, IGBT

② Bipolar voltage with standing devices
Ex: SCR, GTO

* Single phase Half-wave controlled Rectifier -

- It's an AC - DC converter.
- It uses single thyristor (SCR) only, which provides output control only in one half cycle of AC input, hence it provides low DC output.



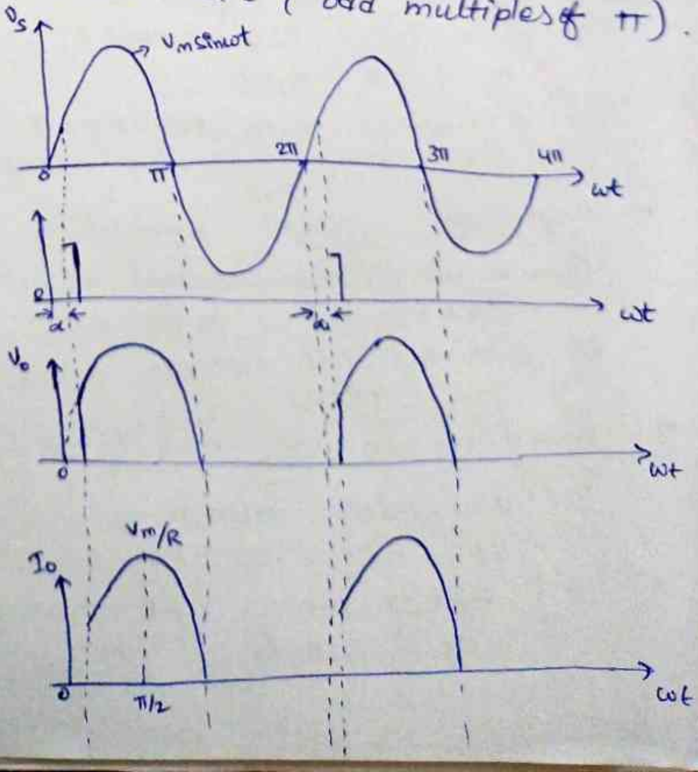
- The following circuit represents an Half wave controlled rectifier with Resistive Load.
- An AC input supply of $v_s = V_m \sin\omega t$ is applied to the anode of of the thyristor (SCR).
- During +ve Half cycle, the anode of SCR is given with +ve voltage but it conducts only when a gate signal is given.
- Assume SCR is triggered at $\omega t = \alpha$, where α is firing angle or delay angle.
- So at that time only (after firing) then $V_o = v_s$. (supply voltage) $\because$ it (SCR) conducts in forward bias.

→ That means V_o (o/p voltage) raises from '0' V to '$V_m \sin\alpha$' volts.

→ The o/p current $I_o = \frac{V_o}{R}$

→ So once the SCR is trigger ON (Turn ON), the load current flows until it's turned off by reversal of voltage (-ve half cycle) (N.H.C) at the intervals $\omega t = \pi, 3\pi, 5\pi$ etc (odd multiples of π).

* Mathematical Analysis -



Average value -

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

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

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

$$\boxed{V_{avg} = \frac{V_m}{2\pi}\left[1+\cos\alpha\right]}$$ - average voltage

The average current I_{avg} =

$$\boxed{I_{avg} = \frac{V_{avg}}{R} = \frac{V_m}{2\pi R}\left[1+\cos\alpha\right]}$$

RMS (Root mean square) value –

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

$$\therefore V_{Rms} = \left[\frac{1}{2\pi}\int_{0}^{\pi} V_m^2 \left(\frac{1-\cos 2\omega t}{2}\right) d(\omega t)\right]^{1/2}$$

$$= \left[\frac{V_m^2}{4\pi}\left\{\int_{\alpha}^{\pi} d(\omega t) - \int_{\alpha}^{\pi} \cos 2\omega t \cdot d(\omega t)\right\}\right]^{1/2}$$

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

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

$$\therefore \boxed{V_{Rms} = \frac{V_m}{2\sqrt{\pi}}\left((\pi-\alpha) + \frac{\sin 2\alpha}{2}\right)^{1/2}}$$

$$\therefore I_{Rms} = \frac{V_{Rms}}{R} = \frac{V_m}{2\sqrt{\pi}\,R}\left((\pi-\alpha) + \frac{\sin 2\alpha}{2}\right)^{1/2}$$

The power delivered to the resistive load $= P = I_{rms} \cdot V_{rms}$

$$= \text{o/p power} \Rightarrow \quad = \frac{V_{rms}^2}{R} = I_{Rms}^2 \cdot R$$

Input power $= V_s \cdot I_{Rms}$.

$$\eta = \frac{\text{o/p dc power}}{\text{i/p ac power}} = \frac{P_{dc}}{P_{ac}} = \frac{V_o I_o}{V_{rms} \cdot I_{rms}}$$

$$\text{form factor} = \frac{V_{rms}}{V_{avg}}$$

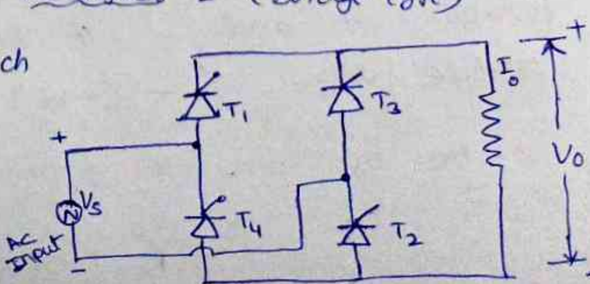
$$\text{ripple factor} = \frac{V_{ac}}{V_{dc}} = \frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}} = \frac{\sqrt{V_{rms}^2 - V_{avg}^2}}{V_{avg}}$$

$$= \sqrt{\left(\frac{V_{rms}}{V_{avg}}\right)^2 - 1} = \sqrt{(\text{Form factor})^2 - 1}$$

$$\therefore RF = \sqrt{(F.F)^2 - 1}$$

* Single phase Full wave controlled Rectifier – (Bridge type)

- It's a bridge full wave rectifier which avoids the use of a center-tapped transformer.
- It consists of 4 thyristors (SCR) connected like a bridge.



- The circuit diagram of a single-phase full wave rectifier is as follows.
- It has T_1 and T_4 on one leg (side) and T_2 and T_3 on one leg (side)

Working -

- During +ve half cycle SCR T_1 and T_2 are seems to be forward biased ∵ +ve voltage is connected to anode of T_1 and T_2 SCR's.
- But these SCR's will get the trigger pulse to get turn ON.

- Assume that the firing pulse given to SCR's T_1 and T_2 at $\omega t = \alpha$

∴ T_1 and T_2 gets start conducting and the current flows through the load resistor R.

→ The path is $L \rightarrow T_1 - R \rightarrow T_2 \rightarrow N$.

during this +ve half cycle the output voltage raises from '0' volts to $V_m \sin\alpha$ volts.

and the the current output ⇒ $I_o = \frac{V_o}{R}$.

⇒ This will continue till the -ve half cycle arrives. i.e at $\omega t = \pi$. then the SCRs T_1 and T_2 gets turned off due to -ve voltage at their anodes. This is reffered as Natural Commutation

* Commutation means turn-off process of SCR.

so now during the negative half cycle of the input SCR's T_3 and T_4 will get turn on by the firing signal and made ON because of forward bias.

- here the firing pulse is applied at $\omega t = (\pi + \alpha)$

then the conduction path is $N \rightarrow T_3 \rightarrow R \rightarrow T_4 \rightarrow N$.

→ now the o/p is same as the input.

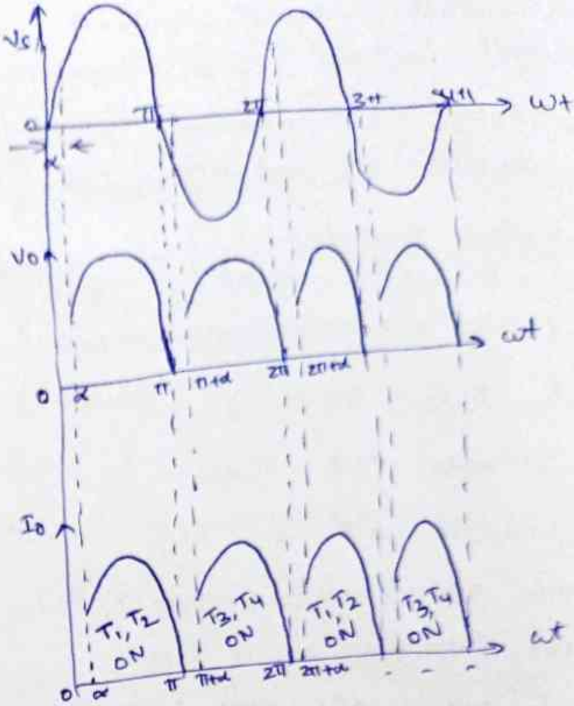
→ though the input is negative but the ouput is observed between + and - of Resistor 'R' ∴ the o/p voltage is positive only. $(-(-ve) = +ve)$.

∴ the V_o raises from '0' volts to $V_m \sin\alpha$.

I_o is $\frac{V_o}{R}$.

again T_3 and T_4 will naturally commutates and gets turn off at $\omega t = 2\pi$.

⇒ this is cyclically continues for every +ve half cycles and negative half cycles as follows



mathematical Analysis -

→ The average value of the output voltage through resistor 'R' is given as

$$V_{avg} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t).$$

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

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

$$\boxed{V_{avg} = \frac{V_m}{\pi}\left[1+\cos\alpha\right]}.$$

∴ The average output current is given as

$$\boxed{I_{avg} = \frac{V_{avg}}{R} = \frac{V_m}{\pi R}\left[1+\cos\alpha\right]}$$

→ The Root mean square value (RMS) of the voltage and current as given as following.

$$V_{Rms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2\omega t \, . d(\omega t)\right]^{1/2} \qquad \because \sin^2\omega t = \frac{1-\cos 2\omega t}{2}$$

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

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

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

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

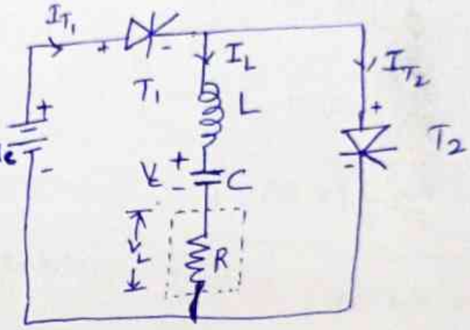
$$\therefore \boxed{V_{Rms} = \frac{V_m}{\sqrt{2\pi}}\left(\pi - \alpha + \sin\frac{2\alpha}{\alpha}\right)^{1/2}}$$

$\therefore I_{Rms} = \frac{V_{Rms}}{R} = \frac{V_m}{R\sqrt{2\pi}}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)^{1/2}$

Inverters -
Inverter circuit converts DC power to AC power at desired output voltage and frequency.

→ Input DC energy generally comes from a battery or a rectified circuit or photovoltaic cell.

Series Inverter -
A series inverter is a type of Inverter in which the commutating components are connected in series with the load.
The basic circuit of series inverter is as shown below.



- It uses two SCR's T_1 and T_2 included with an RLC circuit.
- only one thyristor either T_1 or T_2 will turn ON at a time.

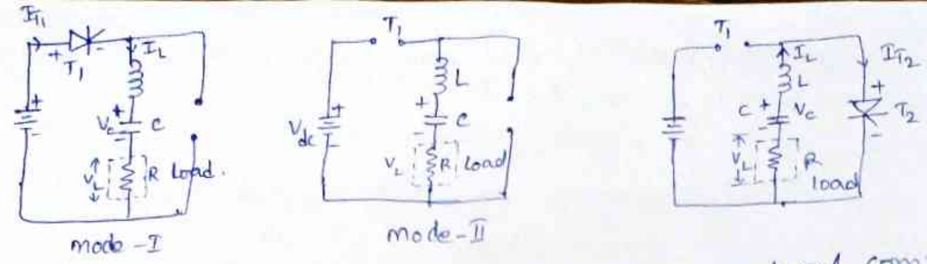
⇒ T_2 will be OFF when T_1 is ON
T_1 will be OFF when T_2 is ON.

⇒ Both T_1, T_2 must not turn ON on the same time.
→ It will damage the circuit permanently.

The working of series Inverter is explained in three modes.

mode - I : In this mode T_1 is ON and T_2 is OFF.

→ Initially both T_1, T_2 are off,
→ As T_1 is turned ON, the current starts flowing from DC source to RLC network. Here the current enters from capacitor side and leaves from Resistor side.
→ **Initially** the capacitor is charged to $-V_c$; but when once T_1 is triggered, then capacitor starts charging to positive voltage with upper plate positive and lower plate negative. as shown in fig.
- As the current increases and reaches its +ve maximum value and the voltage across the capacitor becomes equal to V_{dc}.
- Now the current starts decreasing after reaching its +ve maximum. but the voltage across the capacitor does not decrease.
- Instead of decreasing it increases further and reaches an higher value than V_{dc}.
- The capacitor retains this voltage for a while.



At $t = t_1$ SCR (T_1) is turned off due to natural commutation when current reaches '0'. but the capacitor holds the voltage ($V_c + V_{dc}$) in it.

mode-II - Here both the SCR's T_1 and T_2 are in OFF state. as shown in the above fig.

- This mode starts from $t = t_1$ and last for $t = t_2$.
- Because of open circuit the voltage across capacitor is maintained constant at ($V_c + V_{dc}$) volts as like mode-I only.

mode-III - In this mode SCR2(T_2) is turned ON and SCR1 (T_1) is turned off.

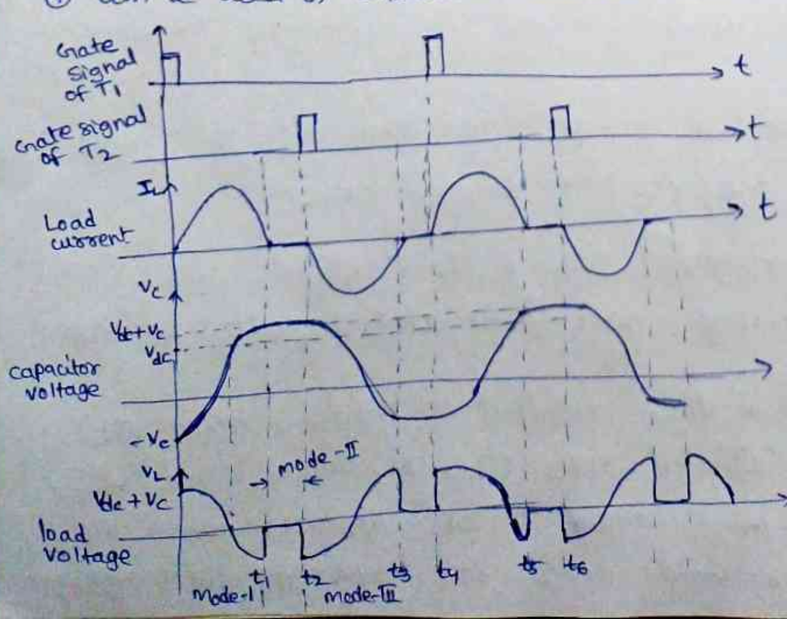
- so as T_1 is turned off it acts like open circuit and no current flows through it.
- Now the capacitor acts as voltage source and tries to discharge through SCR2 i.e T_2 (which is ON now).

∴ the capacitor voltage falls from ($V_c + V_{dc}$) to $-V_c$ (which is the initial voltage across the capacitor plates).

→ again the T_1 is triggered ON and T_2 is turned OFF which repeats the occurance of mode-I again and so on.

Advantages

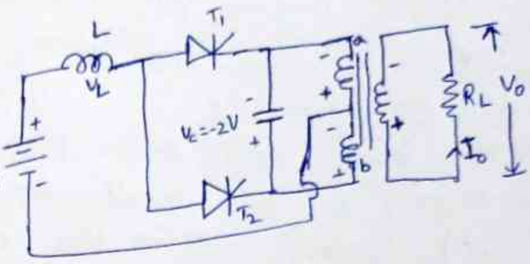
① simple to design ② the commutation circuit is simple
③ can be utilized at high frequency from 200Hz to 200kHz.
④ can be used in Induction heaters which requires extra current.



Parallel Inverter - In parallel inverters the commutating component is connected in parallel with the load.

- These are suitable for low frequency applications upto 100KHz.
- The self-commutation capacitor is connected across the load so that the overall circuit is commutated.
- This inverter produces square-wave output from DC input.

The following circuit represents a parallel inverter.



- It consists of two tyristors T_1 & T_2, a center tapped transformer, a commutating capacitor (used to turn off the SCR's). and an Inductor (L).
- The load is connected to the secondary of the transformer.
- The principle of working of parallel ~~transform~~ inverter is also explained in 3 modes, mode-I, mode-II & mode-III like the series inverter.
- The two SCR's (T_1 and T_2) are turned ON alternatively at equal time intervals, so that, the two halves of the transformer primarily will Induce an alternating voltage in the secondary winding

mode-I : T_1 (SCR_1) is triggered ON and T_2 (SCR_2) is OFF.

- By providing a gate signal to SCR_1 (T_1) it's made turn ON and hence the load current starts flowing through Inductor L and Thyristor T_1 as shown in the fig.
- A voltage equal to $2V_s$ appears across the primary winding of the transformer
- As a result of this the voltage across capacitor also becomes ($2V_s$).
- This mode-I ends when SCR_2 (T_2) is trigged ON.

mode-II : T_2 (SCR_2) is Triggered ON & T_1 (SCR_1) is OFF.

Due to this T_1 is Reverse biased gets commutated with voltage $-2V_s$ across the capacitor.

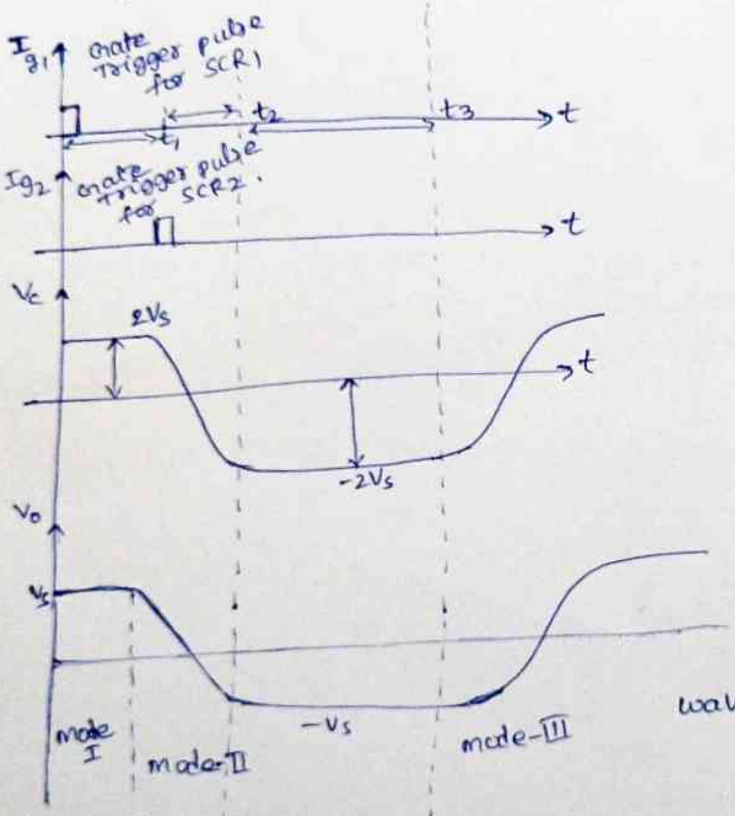
- Now SCR_2 (T_2) will alone in the conduction mode, hence the load current flows through (L) and SCR_2 (T_2) as shown in the fig.
- During this period, a voltage equal to $2V_s$ appears across the primary of the transformer and across the capacitor with reverse

polarities.

mode - III : This mode begins when SCR, (T_1) is triggered again. Now T_2 is naturally commutated (Turned off) due to the voltage across the capacitor is ($-2V_s$). appears across T_2 to commutate. and the whole process is repeated.

- when the triggering pulses applied at regular intervals to trigger T_1 and T_2 periodically to produce a square wave approximately.

Thus dc input voltage is converted to square waveform (AC) approximately. by a parallel Inverter.



wave forms of parallel Inverter.

Advantages of parallel Inverter -

① very simple to design ② small in size ③ less expensive.

② By using filter circuits at the output side, a good quality waveform can be obtained.

③ compared to series inverter, the parallel inverter donot need to carry entire load current.

④ comparitively parallel inverters have better output voltage.