POWER ELECTRONICS

NOTE:

MAKAUT course structure and syllabus of 5th sem has been changed from 2020. Previously **POWER ELECTRONICS** was in 6th semester. This subject has been shifted in 5th semester in present curriculum. Subject organization has been changed slightly. Taking special care of this matter we are providing chapterwise relevant MAKAUT university solutions and some model questions & answers for newly introduced topics, so that students can get an idea about university questions patterns.

INTRODUCTION TO SEMICONDUCTOR DEVICES

Multiple Choice Type Questions

1. In an SCR holding current is [WBUT 2010, 2018]
   a) equal to latching current
   b) less than IL
   c) more than IL
   d) not related to IL

Answer: (b)

2. A power electronics device with highest frequency of operation is [WBUT 2011]
   a) IGBT
   b) MOSFET
   c) GTO
   d) Thyristor

Answer: (b)

3. Presence of drift layer in a power semiconductor device [WBUT 2011, 2013, 2017]
   a) increases breakdown voltage rating
   b) increases on state current rating
   c) increase switching speed
   d) decreases on state resistance

Answer: (d)

4. An IGBT has three terminals called [WBUT 2011, 2016]
   a) collector, emitter and base
   b) drain, source and base
   c) drain, source and gate
   d) collector, emitter and gate

Answer: (d)

5. The TRIAC is equivalent to [WBUT 2011]
   a) Two SCRs in parallel
   b) Two SCRs in antiparallel
   c) One SCR & one diode connected in parallel
   d) One SCR and one diode connected in antiparallel

Answer: (b)

6. Latching current can be defined as [WBUT 2011]
   a) Minimum value of anode current to maintain continuous conduction
   b) Maximum value of anode current to maintain continuous conduction
   c) Minimum value of anode current below which SCR turns off
   d) Maximum value of anode current above which the SCR turns off

Answer: (a)

7. When a power BJT is compared to power MOSFET [WBUT 2011]
   a) BJT has lower switching losses but higher conduction loss
   b) BJT has higher switching losses but lower conduction loss
   c) BJT has lower switching losses and conduction losses
   d) BJT has higher switching losses and conduction losses

Answer: (d)

8. The switching frequency of a MOSFET will be reduced with [WBUT 2013, 2019]
a) an increase in the output impedance of the device
b) an increase in the discharge rate of the input capacitance
c) an increase in the source resistance
d) a decrease in the discharge rate of the input capacitance

Answer: (b)

9. The range of firing angle for RC firing circuit is [WBUT 2013, 2017, 2019]
a) 0° – 90° b) 90° – 180° c) 0° – 180° d) 45° – 90°

Answer: (a)

10. Which of the following is not a current triggered device? [WBUT 2014, 2018]
a) Thyristor b) GTO c) Triac d) MOSFET

Answer: (d)

11. Which of the following does not cause permanent damage of an SCR? [WBUT 2014]
a) high current b) high rate of rise of current
c) high temperature rise d) high rate of rise of voltage

Answer: (a)

12. The on state voltage drop of an SCR is [WBUT 2014]
a) 0.7V b) 1.2V c) 2.3V d) > 3V

Answer: (b)

13. If gate current of SCR is increased, then forward break over voltage will be [WBUT 2014, 2017]
a) increased b) decreased c) remain same d) reduced to zero

Answer: (b)

14. An UJT exhibits negative resistance region [WBUT 2014, 2018]
a) before the peak point b) between peak and valley point
c) after the valley point d) both (a) and (c)

Answer: (b)

15. The number of p-n junction in a thyristor is/are [WBUT 2015]
a) 1 b) 2 c) 3 d) 4

Answer: (c)

16. Presence of drift layer in a power semiconductor device [WBUT 2015]
a) increases breakdown voltage rating b) increases on state current rating
c) increases switching speed d) decreases on state resistance

Answer: (a)

17. In UJT, with V_{BB} as the voltage across two base terminals, the emitter potential at peak point is given by [WBUT 2015]
a) ηV_{BB} b) ηV_D c) $\eta V_{BB} + V_D$ d) $\eta V_D + V_{BB}$

Answer: (c)

18. SCR used [WBUT 2015]
   a) no gate
   b) one gate on p-layer next to cathode
   c) one gate on n-layer next to anode
   d) two gates

Answer: (b)

19. In SCR, the turn-off time; where T is the temperature in K [WBUT 2015]
   a) increases with T
   b) is independent of T
   c) varies as 1/T
   d) varies as $1/T^2$

Answer: (a)

20. In SCR, the turn-on time [WBUT 2015]
   a) increases with T
   b) is independent of ambient temperature T
   c) varies as 1/T
   d) varies as $1/T^2$

Answer: (b)

21. In an SCR [WBUT 2016]
   a) latching current LI is associated with turn-off process and holding current HI with turn-on process
   b) both LI and HI are associated with turn-off process
   c) HI is associated with turn-off process and LI with turn-on process
   d) both LI and HI are associated with turn-on process

Answer: (c)

22. The reverse recovery characteristics of a power diode is due to [WBUT 2016, 2017]
   a) stored charge in depletion layer
   b) stored charge in semiconductor layers
   c) stored charge in both depletion and semiconductor layers
   d) none of these

Answer: (a)

23. The metal oxide varistor (MOV) is used for protecting [WBUT 2016]
   a) gate circuit against over currents
   b) gate circuit against overvoltages
   c) both (a) and (b)
   d) none of these

Answer: (b)

24. TRIAC is a semiconductor power electronic device with contains [WBUT 2018]
   a) two SCR's connected in reverse parallel
   b) two SCR's connected in parallel
   c) two SCR's connected in series
   d) two BJT's connected in series

Answer: (a)

25. Compared BJT, MOSFET has [WBUT 2019]
   a) low switching frequency and low conduction loss
   b) high switching frequency and low conduction loss

c) high switching frequency and high conduction loss
d) low switching frequency and high conduction loss

Answer: (c)

Short Answer Type Questions

1. Explain with necessary waveforms the principle of operation of an RC triggering circuit. [WBUT 2007]

OR,

Explain with relevant waveforms, the principle of operation of an RC triggering circuit. [WBUT 2017]

Answer:

Using R-C network, a larger variation in the value of firing angle can be obtained by changing the phase and amplitude of the gate current. By varying R, the firing angle can be varied from 0° to 180°.

Working Principle:

First Step: During negative half cycle

The status of different components

C: charges through diode D1 with lower plate positive to attain peak supply voltage $-E_{max}$.

D: Reverse biased no gate current flows

T1: Remains off.

Second Step: When supply voltage goes to the positive half cycle through zero value

C: Begins to charge through R from initial value $-E_{max}$.

T1: A is positive with respect to K, i.e., reaches to forward blocking state when the capacitor charges to positive voltage and equal to gate trigger voltage, SCR is triggered.

R_L: load current (i_L) flows, voltage across the load is (e_L).

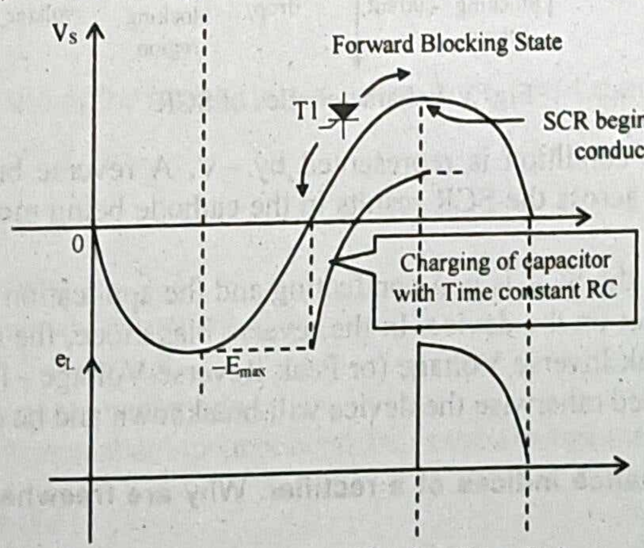


Fig: (i) Pattern of load voltage (e_L)

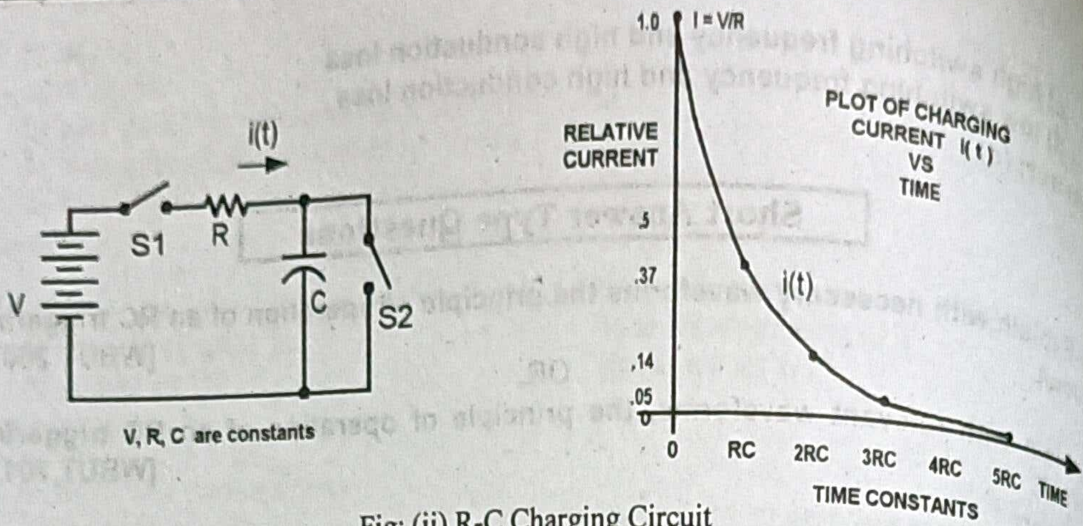


Fig: (ii) R-C Charging Circuit

2. Discuss what would happen if gate is made positive with respect to cathode during the reverse blocking of an SCR. **[WBUT 2008]**

OR,

Describe the different modes of operation using static V-I characteristics of Thyristor. What is the effect of gate current on this characteristic? **[WBUT 2014, 2016, 2019]**

Answer:

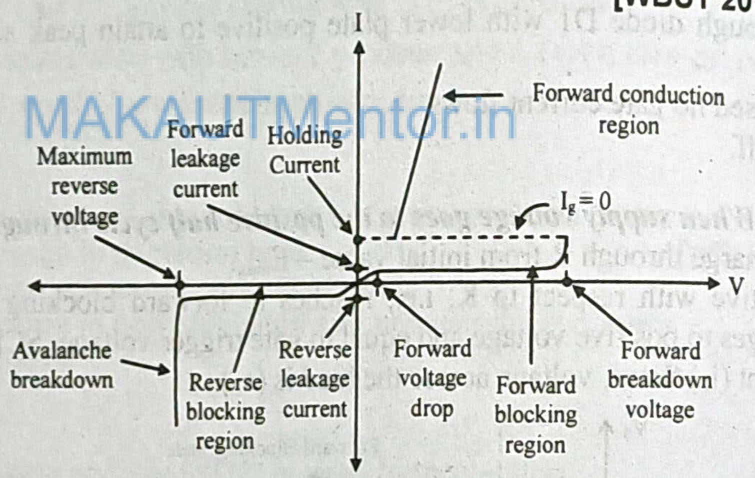


Fig: V-I characteristics of SCR

- The reverse bias condition is represented by –V. A reverse bias exists when the potential applied across the SCR results in the cathode being more positive than the anode.
- In this condition, the SCR is non-conducting and the application of a trigger voltage will have no effect on the device. In the reverse bias mode, the *knee* of the curve is known as the Peak Inverse Voltage (or Peak Reverse Voltage - PRV) and this value cannot be exceeded otherwise the device will breakdown and be destroyed.

3. Name the performance indices of a rectifier. Why are freewheeling diodes used in rectifier circuit? **[WBUT 2010]**

Answer:

1st part:

Current Ripple Factor:
It is defined as the ratio of the net harmonic content of the output current to the average output current

$$K_a = \frac{\sqrt{I^2_{dc\,rms} - I^2_{dc}}}{I_{dc}}$$

Voltage Ripple Factor:
It is defined as the ration of the net harmonic content of the output voltage to the average output voltage

$$K_v = \frac{\sqrt{E^2_{dc\,rms} - E_{dc}^{\;2}}}{E_{dc}}$$

DC Voltage Ratio:
It is defined as the ratio of average dc terminal voltage at a given firing angle to the average DC terminal voltage when the firing angle is zero.

$$\text{DC Voltage Ratio} = \frac{V_{dc}\big|_{\alpha}}{V_{dc}\big|_{\alpha=o}}$$

Input Current Distortion Factor:
It is defined as the ratio of the RMS amplitude of the fundamental component to the total RMS amplitude.

Input Harmonic Factor:
It is defined as the ratio of the total harmonic content to the fundamental component.

$$I_H = \sqrt{\frac{I^2_{rms} - I_1^2}{I_1}}$$

Input Power Factor:
It is defined as the ratio of the average input power to the input apparent power, i.e.,

$$P.F. = \frac{V_1 I_1 \cos\phi}{V_{rms} I_{rms}}$$

where,

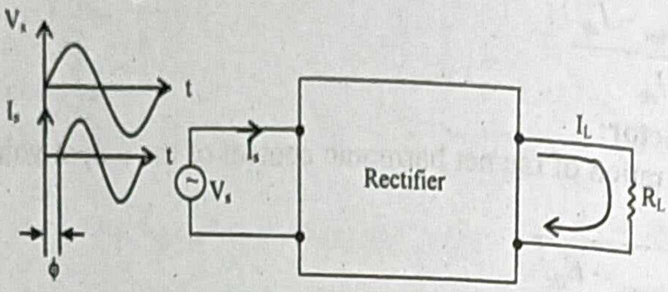
$V_1 = V_{rms}$ = Source voltage
I_1 = Fundamental component
I_{rms} = Source rms current
ϕ = Input displacement angle.

[Since, only the fundamental component contributes the average mean power]

$$\therefore \quad \text{P.F.} = \frac{I_1}{I_{rms}} \cdot \cos\phi$$

Input Displacement Factor:
It is defined as the cosine of the input displacement angle, i.e. $\cos\phi$.

Input Displacement angle (ϕ):
It is defined as the angular displacement between the fundamental component of the ac line current and ac line voltage.



Source voltage and current waveforms

2[nd] Part:
The basic property of an inductor is to oppose any change in current passing through it. So, when the electrical power is supplied to the circuit with inductive load (a combination of resistor and inductor), by the closing of a switch, say, the inductive load will accumulate energy.
When the switch (SW) is opened this energy will arc across the contacts of the switch, and could cause damage to the circuit components. An inductive device (load) produces a voltage according to the equation $v = L\frac{di}{dt}$, when the current from the source drops to zero (say, by opening the switch) $\frac{di}{dt}$ is very large, resulting 'inductive kick' voltage may cause damage to other components.
The free wheel diode puts a path for the inductive current to flow. The current through the inductor-diode at the instant of turn-off is equal to the current that was flowing just before turn-off. The current then exponentially decays to zero.
Freewheeling diodes are placed across the inductive loads to provide a path for the release of energy stored in the load when the load voltage drops to zero.

4. State the advantages of IGBT. **[WBUT 2011]**

Answer:

Advantages:

1. Insulated Gate Bipolar Transistor, as the name implies, combines the advantages of both power MOSFET (Insulated Gate) and power transistor (Bipolar transistor)
2. It has high input impedance like MOSFET and low ON-state voltage drop like BJT as ON-State resistance is low.
3. An IGBT is a voltage controlled device like MOSFET.
4. Lower switching and conduction losses.

5. An IGBT can be typically turned on by +10 V to 15 V at the gate and is turned off by zero gate voltage
6. Turn off time is high.
7. IGBTs are widely used in medium power application.

5. Compare the features of an IGBT with a power transistor. **[WBUT 2013]**

Answer:

Features	IGBT	Power Transistor
Input Impedance	High	Low
Controlling attribute	Voltage controlled	Current controlled
Switching Loss	Low	Relatively high
Conduction loss	Low	Relatively high
Power Level of application	Medium	Relatively low

6. Draw and explain circuit diagram for the synchronized UJT triggering. Also draw the associated voltage waveforms. **[WBUT 2014, 2016]**

Answer:

Synchronized UJT-Triggering (Ramp Triggering)

Synchronized UJT triggering circuit is shown in Fig. 1. The diode bridge $D_1 - D_4$ rectifies a.c. to d.c. resistor R_s lowers E_{dc} to a suitable value for the zener diode and UJT. The zener diode D_z is used to clip the rectified-voltage to a fixed voltage V_z. This voltage V_z is applied to the charging circuit RC. Capacitor C charges through R until it reaches the UJT trigger voltage V_p. The UJT then turns "on" and C discharges through the UJT emitter and primary of the pulse-transformer. The windings of the pulse-transformer have pulse voltages at their secondary terminals. Pulses at the two secondary windings feed the same inphase pulse to two SCRs of a full wave circuit. SCR with positive anode voltage would turn ON. Rate of rise of capacitor voltage can be controlled by varying R. The firing angle can be controlled up to about 150°. This method of controlling the output power by varying charging resistor R is called as ramp control, open loop control or manual control.

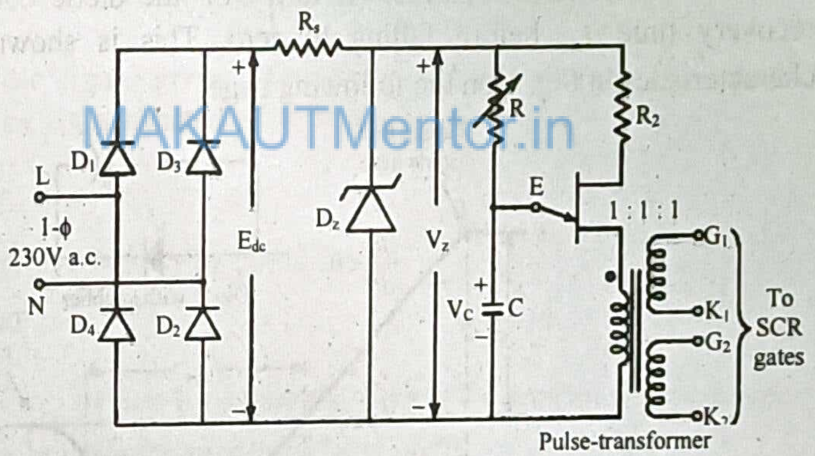


Fig. 1 Synchronized UJT trigger circuit

As the zener diode voltage V_z goes to zero at the end of each half cycle, the synchronization of the trigger circuit with the supply voltage across SCRs is achieved. Thus the time t, equal to α / ω, when the pulse is applied to SCR for the first time, will remain constant for the same value of R. The various voltage waveforms are shown in Fig. 2.

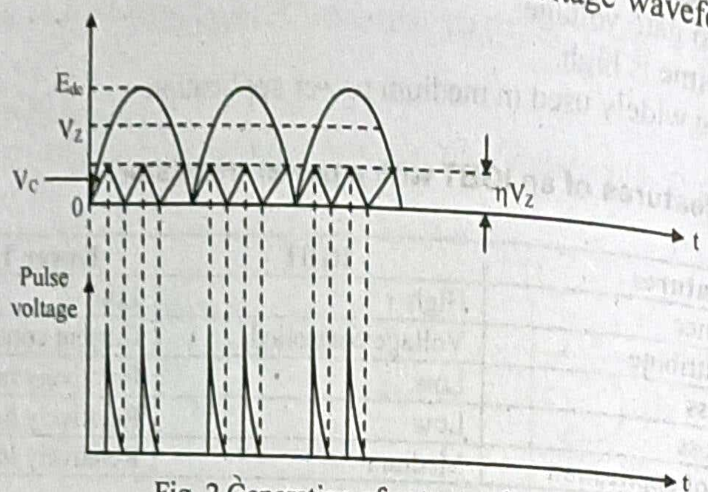


Fig. 2 Generation of output pulses

7. Discuss about softness factor PIV, reverse recovery current for power diodes. [WBUT 2015]

Answer:

The time taken by a power diode to turn OFF from ON state is relatively longer when compared to its turn-ON time. At turn-OFF the diode current reverses for a reverse recovery time t_{rr} before falling to zero. This is shown by the reverse recovery characteristics in Fig. 1 on the following page.

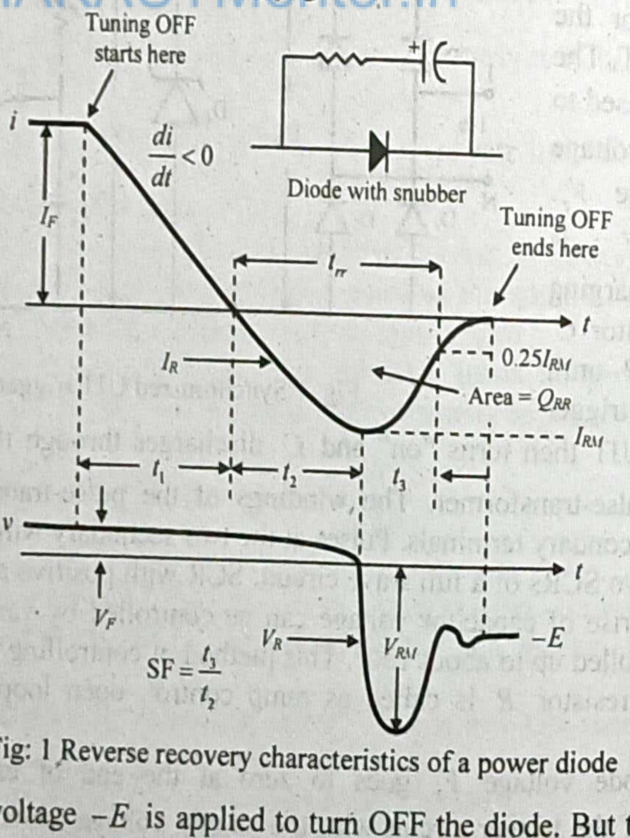


Fig: 1 Reverse recovery characteristics of a power diode

At $t = 0$ a reverse voltage $-E$ is applied to turn OFF the diode. But the diode does not stop conducting instantaneously. The forward current of the diode I_F starts decreasing at a rate $di/dt = (-E/L)$ where L is any inductance connected in series with the diode and crosses zero at $t = t_1$.

Beyond this, during t_2, the diode current becomes negative (I_R) and reaches a peak value I_{RM} at the end of t_2, the diode current becomes negative (I_R) and reaches a peak value I_{RM} at the end of t_2. At this instant, the forward voltage drops to zero. during t_3 the reverse current decays, the reverse voltage overshoots to a peak value V_{RM} and then, settles down at $-E$. This negative overshoot of voltage across the diode during turn-OFF may be destructive and can be reduced by connecting across the diode an R-C circuit called snubber as shown in Fig. 1. The reverse recovery time is defined as the time between the instant forward current crosses zero and the instant reverse recovery current decays to 25% of its reverse peak value I_{RM} as shown in Fig. 1. So, $t_{rr} = t_2 + t_3$. The hatched area in Fig. 1 gives the reverse recovery charge Q_{RR} in the diode which should be removed during the turn-OFF process. During t_1 and t_2 which are very small intervals of time of the order of micro-seconds or nano-seconds, the rate of decrease of current, di/dt may be assumed to be constant without much error. Then,

$$I_{RM} = t_2 \frac{di}{dt} \qquad \text{.... (1)}$$

The shaded area shown in the figure gives the reverse recovery charge. The reverse recovery characteristics may be approximated to be a triangle. Then,

$$Q_{RR} \approx \frac{1}{2} \cdot I_{RM} t_{rr} \quad \Rightarrow \quad I_{RM} \approx \frac{2Q_{RR}}{t_{rr}} \qquad \text{.... (2)}$$

Equating Eqns. (1) and (2) and by rearranging terms we get

$$t_{rr} t_2 = \frac{2Q_{RR}}{di/dt} \qquad \text{.... (3)}$$

If t_3 is negligible compared to t_2, which is usually the case, then, we can approximately write $t_{rr} \approx t_2$. Then, the above equation becomes

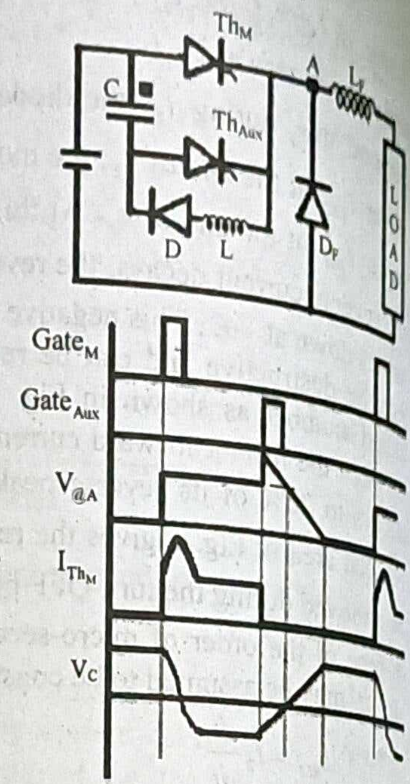
$$t_{rr} \approx \sqrt{\frac{2Q_{RR}}{di/dt}} \quad \Rightarrow \quad I_{RM} \approx \sqrt{2Q_{RR} \cdot \frac{di}{dt}} \qquad \text{.... (4)}$$

Eqn. (4) shows that t_{rr} and I_{RM} depend upon the charges stored in the device Q_{RR} and di/dt is a function of the external reverse voltage E and any inductance L connected in series with the diode. This shows that t_{rr} and I_{RM} are both functions of the forward current I_F.

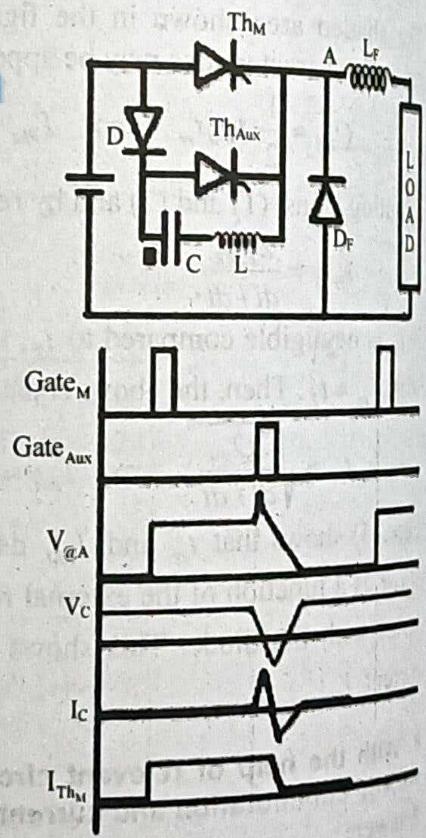
8. With the help of relevant circuit diagram and waveforms distinguish between voltage commutation and current commutation in an SCR circuit. [WBUT 2017]

Answer:

In a voltage commutated thyristor circuit a voltage source is impressed across the SCR to be turned off, mostly by an auxiliary SCR. This voltage is comparable in magnitude to the operating voltages. The current in the conducting SCR is immediately quenched, however the reverse-biasing voltage must be maintained for a period greater than that required for the device to turn-off. With a large reverse voltage turning it off, the device offers the fastest turn-off time obtainable from that particular device.



In voltage commutation Th_M is the main SCR and Th_{Aux} is the Auxiliary. As a consequence of the previous cycle, Capacitor C is charged with the dot as positive. When the Main SCR is triggered, it carries the load current, which is held practically level by the large filter inductance, LF and the Free-wheeling diode. Additionally, the charged Capacitor swings half a cycle through Th_M, L and D ending with a negative at the dot. The reverse voltage may be less than its positive value as some energy is lost in the various components in the path. The half cycle capacitor current adds to the load current and is taken by the Main SCR.



In current commutation, there is an interchange of the positions of the diode and the capacitor as shown in the figure. If Th_M is triggered first, it immediately takes the load current turning off D_F. When Th_{Aux} is triggered, it takes a half cycle of the ringing current in the L-C circuit and the polarity of the charge across the capacitor reverses. As it swings back, Th_{Aux} is turned off and the path through D-C-L shares the load current which may again be considered to be reasonably level.

The Current-share of TH_M is thus reduced in a sinusoidal (damped) manner. Turn-off process is consequently accompanied by an overlap between Th_M and the diode D in the D-C-L path. Once the main SCR is turned off, the capacitor current becomes level and the voltage decreases linearly. A voltage spike appears across the load when the voltage across the commutating inductance collapses and the capacitance voltage adds to the supply voltage.

The free-wheeling diode also turns on through a overlap with D when the capacitor voltage just exceeds the supply voltage and this extra voltage drives the commutating current through the path D-Supply-D_F-L. Thus there is soft switching of all devices during this period.

Further an additional diode may be connected across the main SCR. It ensures 'soft' turn-off by conducting the excess current in the ringing L-C circuit. The low forward voltage appearing across the SCR causes it to turn-off slowly. Consequently switching frequencies have to be low. Note that such a diode cannot be connected across the Main SCR in the voltage-commutated circuit.

Long Answer Type Questions

1. Draw a comparison between power transistor, power MOSFETS & IGBT in relation to their application in power electronics. [WBUT 2008, 2016]

Answer:

- Insulated Gate Bipolar Transistor, as the name implies, combines the advantages of both power MOSFET (Insulated Gate) and power transistor (Bipolar transistor).
- It has high input impedance like MOSFET and low ON-state voltage drop like BJT as ON-State resistance is low.
- An IGBT is a voltage controlled device like MOSFET.
- Lower switching and conduction losses.
- An IGBT can be typically turned on by +10 V to 15 V at the gate and is turned off by zero gate voltage.
- Turn off time is high.
- IGBTs are widely used in medium power application.
- Metal Oxide Semiconductor FET is a three layer, three terminal, unipolar device.
- Unlike Power BTT, a power MOSFET is a voltage-controlled device.
- Switching speed of MOSFET is very high. Switching frequencies are of the order of more seconds.
- Power MOSFETs are used in low power, high frequency applications.
- MOSFETs do not have the problems of second breakdown problem as found with power BJTs.

2. a) What are the conditions for successful turn-on and communication of an SCR? [WBUT 2015]

Answer:

A thyristor can be turned ON by applying a positive voltage of about a volt or a current of a few tens of milliamps at the gate-cathode terminals.

SCR will turn-off only after the anode current is annulled either naturally or using forced commutation techniques. These methods of turn-off do not refer to those cases where the anode current is gradually reduced below Holding Current level manually or through a slow process.

b) What are the different methods to turn-on an SCR? [WBUT 2015]

Answer:

Basic condition of Turning On

SCR is kept under forward bias i.e. anode terminal of SCR is kept at positive potential w.r.t. the cathode terminal. Then a SCR can be made to conduct by any of the following methods:

Method 1: High Voltage Turn On

With gate circuit open, when forward anode to cathode voltage increases, the depletion layer of junction J2 increases. At a specific voltage, called Forward Break Over Voltage, junction J2 undergoes an avalanche Breakdown. SCR is said now to toggle to ON-state from OFF-state.

This method has got no practical use.

Method 2: Light Turn On

When a beam of light is directed at the junction J2, sufficient energy is generated which breaks covalent bond to produce electron hole pairs. This additional minority carriers are produced to switch on the device.

These SCRs are special type SCRs called light activated SCRs (LASCRs).

Method 3: Thermal Turn On

Leakage current is highly temperature sensitive. So, as the temperature increases junction width of SCR decreases and leakage current increases.

From two transistor analogy, α_1 and α_2 increase. Due to regenerative action, when $(\alpha_1 + \alpha_2) \rightarrow 1$, SCR turns on.

Method 4: $\frac{dv}{dt}$ Turn On

It rate of forward anode to cathode voltage is very fast, then a sufficient transient gate current is generated, which in turn triggers the SCR to ON.

It is the junction capacitance that causes the Gate current to form.

In the forward blocking state, the junction J2 forms the capacitor.

The current can be calculated as follows:

$$i_C = C\frac{dv}{dt}$$

where C $\Rightarrow$ junction capacitance.

Method 5: Gate Turn On

- This is the most common, reliable and efficient method of triggering a SCR.
- Under forward biased condition, when a gate signal is injected, the SCR turns on.
- Forward break over voltage is a function of gate current. Within the safe operating region, higher the value of gate current, lesser will the forward break over voltage.
- The variation of forward break over voltage with that of gate current is shown in fig. 1.

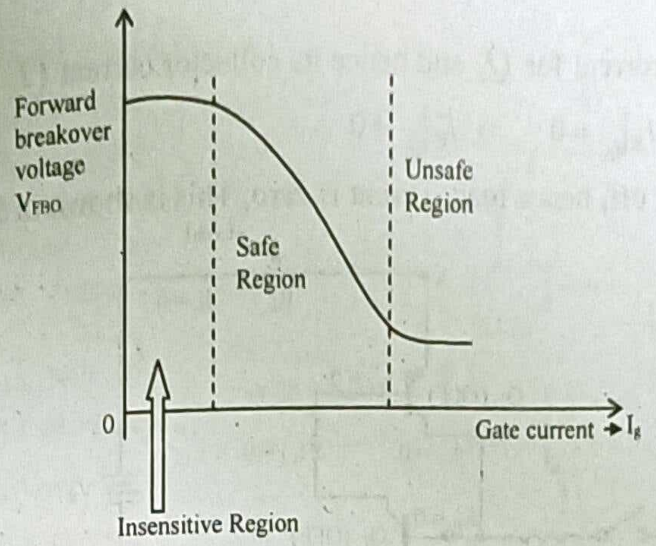


Fig: 1 Variation of V_{FBO} against that of I_g

c) With the help of two transistor model, explain how a small gate current can initiate turn-on mechanism in SCR. **[WBUT 2015]**

OR,

With two transistor analogy explain how a small gate current can turn-on a SCR. **[WBUT 2019]**

Answer:

A SCR can be visualized as two three layer transistor structures, electrically connected as shown in figures 1a and 1b.

The upper p-layer is the emitter of a pnp transistor. The upper n-layer is both the base of the same pnp transistor and collector of an npn transistor.

The lower p-region is the collector of the upper pnp transistor, but, it is also the base of lower npn transistor. Here the gate is tied out. The bottom n-layer is the emitter of the lower npn as shown in figures 1(b) and 1(c).

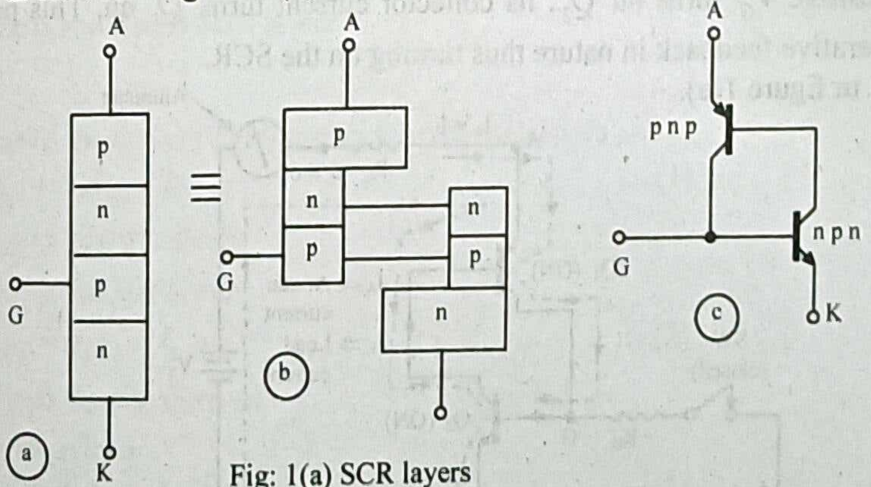


Fig: 1(a) SCR layers
(b) Two three layer BJT structure
(c) Interconnected BJTs

Physical Explanation

Let us designate pnp and npn transistors as Q_1 and Q_2 respectively.

Case 1: When the gate is open, then following events occur

- There is no base current for Q_2 and hence its collector current (I_C) is zero.
- $\because I_C|_{Q_2} = 0 \quad \therefore I_B|_{Q_1} = 0 \quad \Rightarrow I_C|_{Q_1} = 0$

$\Rightarrow$ both the transistors are off, hence load current is zero. This is shown in figure 1(d)

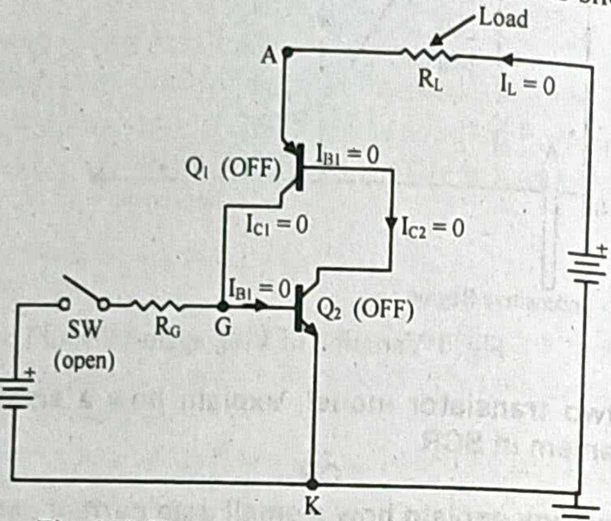


Fig: 1(d) Two transistor model with SCR

Case 2: When a small positive voltage (V_G) w.r.t. the cathode is applied at gate (i.e. switch, SW, is closed) then following events take place:

- base to emitter junction of Q_2 is forward biased.
- collector current for Q_2 is produced and as Q_2's collector current is Q_1's base current.
- Q_1 turns on. The collector current of Q_1 is the base current of Q_2.
- the positive V_G turns on Q_2. Its collector current turns Q_1 on. This process of regenerative feedback in nature thus turning on the SCR.

This is shown in figure 1(e).

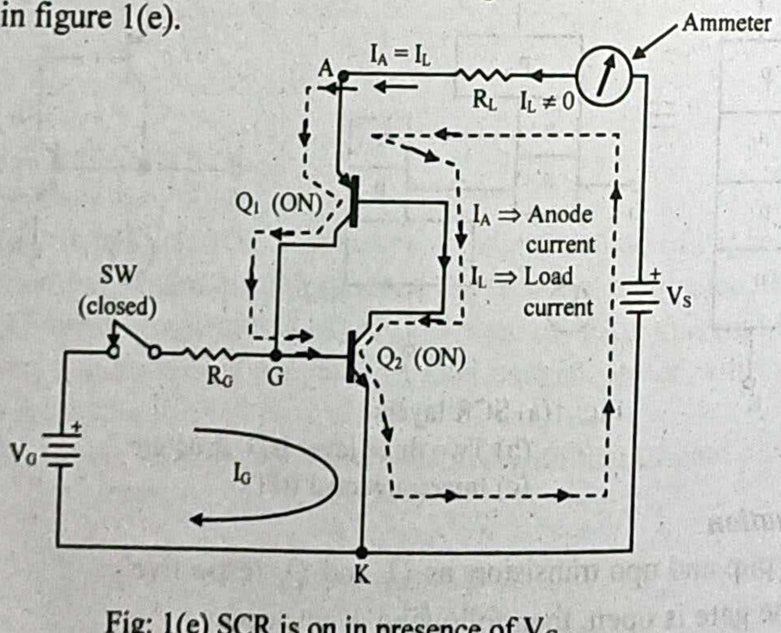


Fig: 1(e) SCR is on in presence of V_G

Case 3: Gate signal is withdrawn

Once Q_1 and Q_2 are on, the gating signal can be withdrawn as shown in figure 1(f). Though the supply of base current from the source is zero, but, collector current of Q_1 continues to provide base current to keep Q_2 on. The collector current of Q_2 is the base current of Q_1, then Q_2 keeps Q_1 on. This regeneration feedback takes very short time $\approx 100\ \mu s$ to establish.

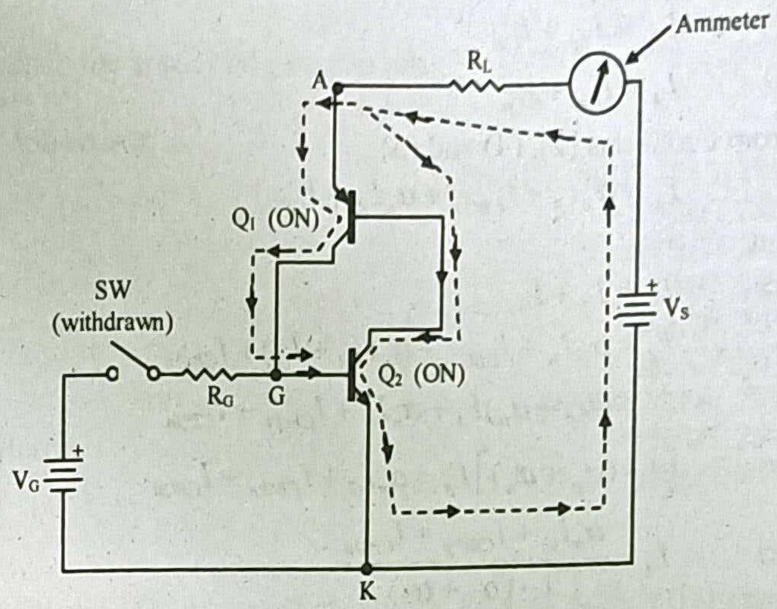


Fig: 1(f) SCR continues to stay on when gate signal is withdrawn

Case 4: Turning off the SCR

In order to turn off the SCR, the internal regenerative process must be interrupted.
For this,
Anode current is reduced below a certain level, which causes the collector current of Q_1 to weaken. This reduces the base current of Q_2, thus making Q_2 off. Q_2 now fails to supply base current to Q_1 and Q_1 becomes off. Then current through the two-transistor model is zero and hence SCR is off.

Analysis

One can write the current relationship for two transistors as

$$I_{Cp} = \alpha_p I_{Ep} + I_{CBOp} \quad \ldots (1)$$

$p \Rightarrow$ pnp transistor

$n \Rightarrow$ npn transistor

$$\Rightarrow \quad I_{Cp} = \alpha_p I_A + I_{CBOp} \quad \ldots (2)$$

where, $I_A \Rightarrow$ Anode current

For n-p-n transistor

$$I_{Cn} = \alpha_n I_{En} + I_{CBOn} \quad \ldots (3)$$

$$= \alpha_n I_K + I_{CBOn} \quad \ldots (4)$$

where,

$\alpha_p \Rightarrow$ Current gain for pnp transistor

$\alpha_n \Rightarrow$ Current gain for n-p-n transistor

For p-n-p

$$I_{Ep} = I_{Bp} + I_{Cp}$$

$$\Rightarrow \quad I_A = I_{Cn} + I_{Cp} \qquad \dots (5)$$

From equations (2), (4) and (5)

$$I_A = \alpha_p I_A + I_{CBOp} + \alpha_n I_K + I_{CBOn}$$

But.

$$\Rightarrow \quad I_K = I_A + I_G$$

$$\therefore \quad I_A = \alpha_p I_A + I_{CBOp} + \alpha_n (I_A + I_G) + I_{CBOn}$$

$$= (\alpha_p + \alpha_n) I_A + \alpha_n I_G + I_{CBOp} + I_{CBOn}$$

$$\Rightarrow \quad \left[1 - (\alpha_p + \alpha_n)\right] I_A = \alpha_n I_G + I_{CBOp} + I_{CBOn}$$

$$\Rightarrow \quad I_A = \frac{\alpha_n I_G + I_{CBOp} + I_{CBOn}}{1 - (\alpha_p + \alpha_n)} \qquad \dots (6)$$

- ***Explanation***

Case 1: When $I_G = 0,\ V_a < V_{BO}$

- I_{CBOp} and I_{CBOn} are very small
- $(\alpha_p + \alpha_n)$ is very small

$$I_A = \frac{I_{CBOp} + I_{CBOn}}{1 - \left(\alpha_p + \alpha_n\right)} \qquad \dots (7)$$

$\Rightarrow \quad I_A$ is very small.

I_A is forward blocking current and hence corresponds to the blocking state or OFF state of SCR.

Case 2: When $I_G = 0,\ V_a = V_{BO}$

Then $\alpha_p + \alpha_n \to 1 \Rightarrow I_A = \infty$ … (8)

$\therefore$ Resulting anode current is large and the device is put into conduction.

Case 3: With Gate Current

$$I_A = \frac{\alpha_n I_G + I_{CBOP} + I_{CBOn}}{\left[1 - (\alpha_p + \alpha_n)\right]} \qquad \dots (9)$$

With gate current, the leakage current through reverse biased junction J2 increases, from the above expression, I_A increases, α_p and α_n increases As α_p and α_n increases I_A increases more, thus regenerative positive feedback effect goes on.

When $\alpha_p + \alpha_n \to 1$, denominator $\to 0$, and $I_A \to \infty$.

$\therefore I_A$ becomes very large and the SCR is put into conduction state.

The collectors of the two transistors generate base currents for each other keeping them in saturation.
Now, there is no need to continue the supply of gate current.

3. Write short notes on the following:

a) GTO [WBUT 2007, 2013, 2018]
b) Power MOSFET [WBUT 2011]
c) IGBT [WBUT 2011]
d) RC triggering of SCR [WBUT 2014]
e) UJT triggering of SCR [WBUT 2014]
f) Power diodes [WBUT 2016]
g) TRIAC [WBUT 2016, 2018]
h) Turn on methods of thyristor [WBUT 2019]
i) Schottky barrier diode [WBUT 2019]

Answer:

a) GTO:
A GTO Thyristor is like an SCR with Gate turn off capability. Like an SCR, GTO can be turned on by applying a positive gate signal. However unlike SCR, it can be turned off by using negative pulse to the gate terminal.

Symbol
Figure (a) shows the symbol of a GTO

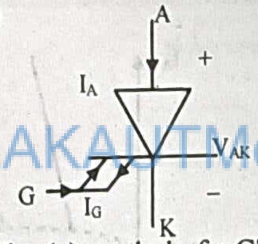


Fig. (a) symbol of a GTO

- GTO is a 3-terminal device with anode, cathode and gate terminals.
- Bi-directional arrow on gate terminal is used to show its turn off capability along with turn on capability.

Two-Transistor Analogy
Diagram

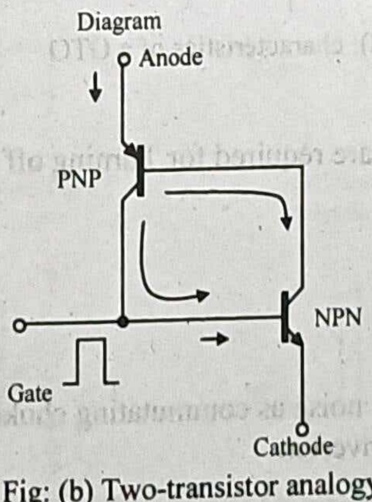


Fig: (b) Two-transistor analogy

Explanation

Step 1: A positive Gate signal is applied to the base of NPN transistor [figure (a)]. The collector current of NPN transistor drives the base of the PNP.

Step 2: The collector current of PNP then drives the base of NPN & Internal Regeneration process goes on making GTO, on.

Step 3: In order to reduce this Internal Regeneration in GTO the current gain of the PNP transistor is low and turn-off is realized by drawing sufficient current from the gate.

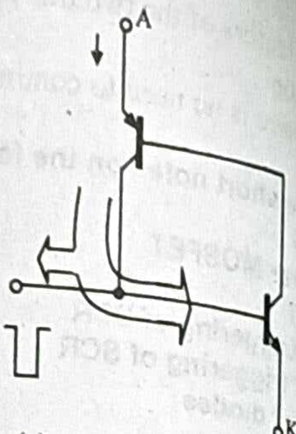


Fig: (c): negative pulse to the gate of GTO

Step 4: When a negative pulse is given at the gate (figure b), excess carriers are drawn from the base region of the NPN transistor and collector current from the PNP transistor is diverted to the external gate circuit.

Step 5: Base current of NPN transistor gets reduced, which in turn, removes the base current of PNP transistor.

Step 6: GTO now stops conducting.

GTO Characteristics

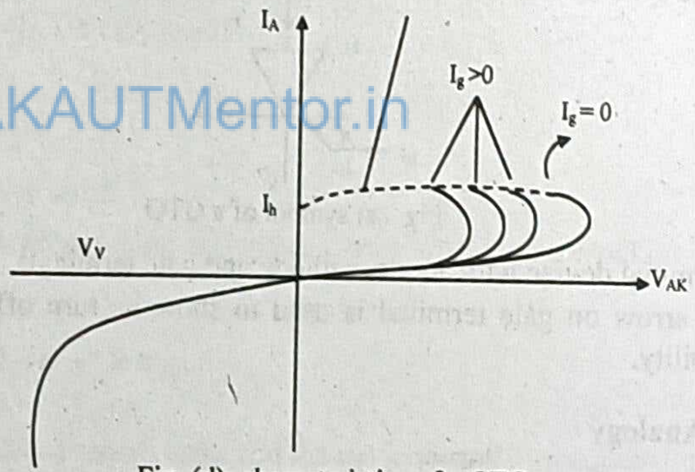


Fig. (d): characteristics of a GTO

Advantages

a) No commutating components are required for Turning off GTO, thus reducing
   - Cost
   - Weight
   - Physical space

b) Faster turn – off

c) High switching frequency

d) Reduction in electro-magnetic noise as commutating choke (Inductor) is not needed.

e) Improved efficiency of the converter.

Disadvantages

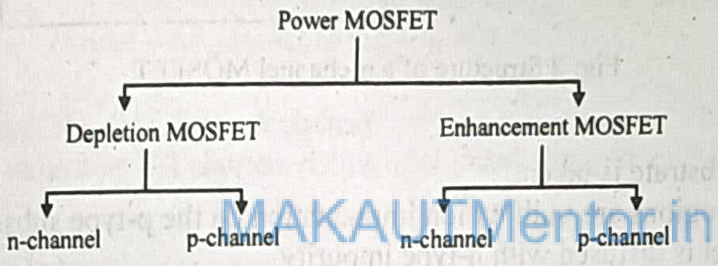
1) Forward drop of GTO during ON state is greater than SCR, thus power loss (as heat) is higher for a load current.
2) Negative current pulse to turn-off SCR is high.

b) Power MOSFETs:

Features

- Metal Oxide Semiconductor FET is a three layer, three terminal, unipolar device.
- Unlike Power BJT, a power MOSFET is a voltage-controlled device.
- Switching speed of MOSFET is very high. Switching frequencies are of the order of more seconds.
- Power MOSFETs are used in low power, high frequency applications.
- MOSFETs do not have the problems of second breakdown problem as found with power BJTs.

Classification



Symbol

Figure 1 depicts the symbols of different types of MOSFET.

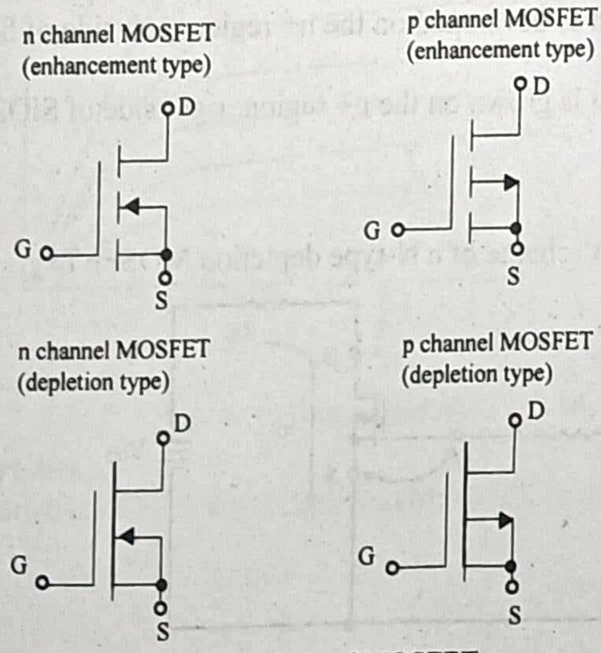


Fig: 1 Symbols of MOSFETs

Depletion MOSFET

Structure for N-Channel Depletion MOSFET

Figure 2 shows the structure of a n-channel MOSFET.

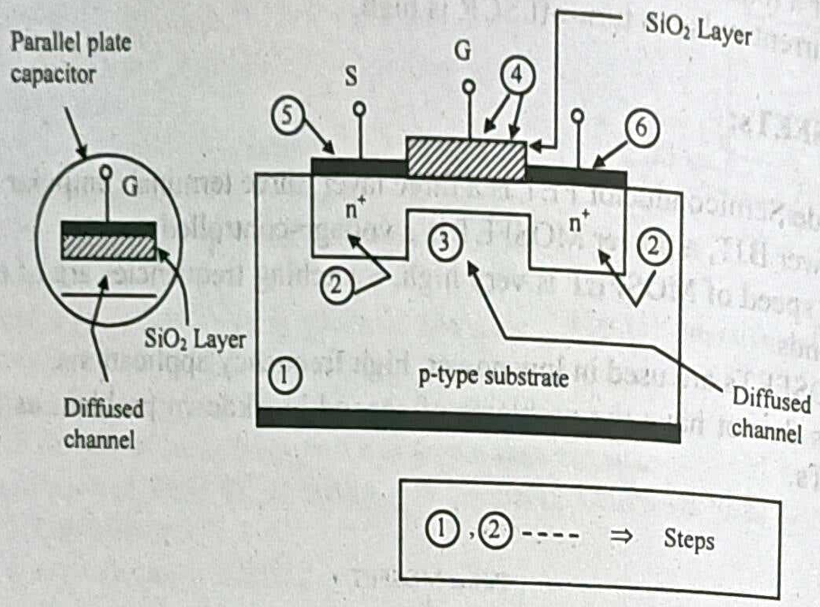


Fig: 2 Structure of a n-channel MOSFET

Description

Step 1: p-type substrate is taken.

Step 2: Two n+ regions are built by ion implantation on the p-type substrate.
Step 3: A channel is diffused with n-type impurity.
Step 4: A conductive gate electrode is formed which is kept isolated from the isolated from the diffused channel by a thin insulating SiO_2 layer. The conductive electrode of the gate in conjunction with the insulating dielectric form a parallel plate capacitor.
Step 5: A metallic contact is developed on the n+ region (left side of SiO2) forms source terminal.
Step 6: A metallic contact is grown on the n+ region, right side of SiO2 layer. This forms the drain terminal.

Circuit Scheme

Figure 3 shows the circuit scheme of a N-type depletion MOSFET.

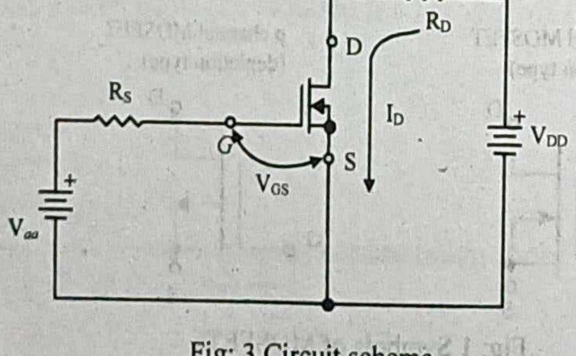


Fig: 3 Circuit scheme

Working of n-type depletion MOSFET

Step 1: If $V_{GS} = 0$, an appreciable drain current flows if V_{DS} is applied between drain to source terminals.

Step 2: If $V_{GS} < 0$

Positive charges are induced in the channel due to capacitive action (SiO_2 layer acting as di-electric material).

Induced positive charges deplete the carriers in the channel to make it less conductive.

Step 3: If V_{GS} is made more negative, width of the conducting channel reduces more causing it less conductive.

If V_{GS} is made negative enough to deplete the channel completely, then there will be no carrier flow from source to drain.

This gate voltage is called Pinch-off voltage. The device is said to be in *off-state.*

Step 4: If $V_{GS} > 0$

Negative charges are induced into the n-type channel, more charge carriers are available in the conductive channel. Consequently, conductivity of the channel increases and hence drain current increases.

So, it can be said that the application of positive gate voltage has *enhanced* the level of charge carriers in the channel with respect to the $V_{GS} = 0$.

V-I Characteristics (Output Characteristics)

Figure 4 shows the output or V-I characteristics of N-channel depletion MOSFET.

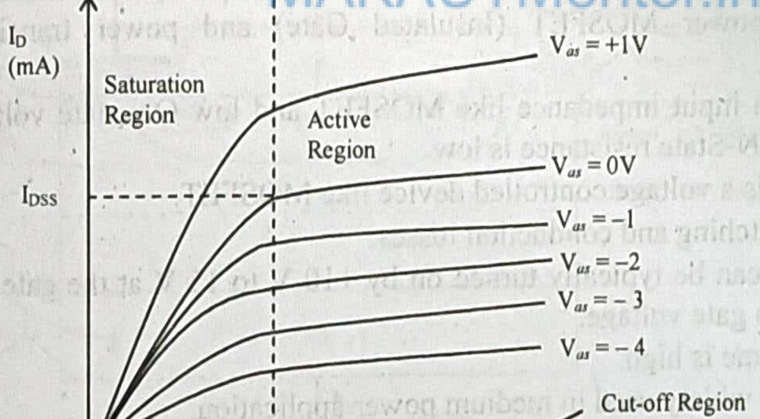


Fig. 4: V-I characteristics

Transfer Characteristics

The transfer characteristics of N-channel depletion MOSFET is shown in the fig. 5.

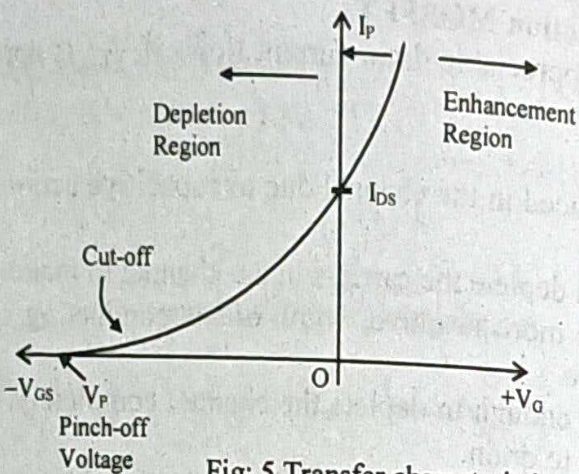


Fig: 5 Transfer characteristics

Biasing

For proper operation of MOSFET, it needs to be biased properly.

For n- channel Depletion MOSFET

- Drain is kept positive with respect to source.
- Gate is kept at negative potential with respect to source for depletion mode.
- Gate is kept at positive potential with respect to source for enhancement mode.

c) IGBT:

IGBT / Features

- Insulated Gate Bipolar Transistor, as the name implies, combines the advantages of both power MOSFET (Insulated Gate) and power transistor (Bipolar transistor).
- It has high input impedance like MOSFET and low ON-state voltage drop like BJT as ON-State resistance is low.
- An IGBT is a voltage controlled device like MOSFET.
- Lower switching and conduction losses.
- An IGBT can be typically turned on by +10 V to 15 V at the gate and is turned off by zero gate voltage.
- Turn off time is high.
- IGBTs are widely used in medium power application.

Symbol

Figure 1 shows the symbol of an IGBT.

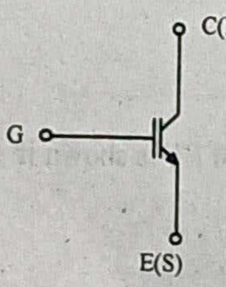


Fig: 1 Shows the symbol of the IGBT

Equivalent Circuit
The equivalent circuit of the IGBT is depicted in the Fig. 2 which is a combination of a BJT and a MOSFET.

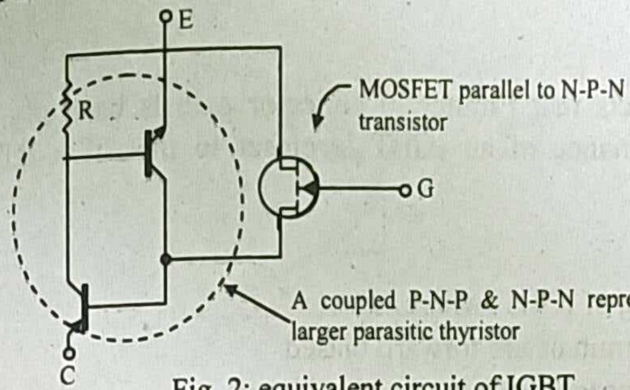


Fig. 2: equivalent circuit of IGBT

Structure
The vertical cross-sectional view of IGBT is shown in the figure 3.
It is having four alternate p-n-p-n layers with three terminals, emitter (source), collector (drain), gate.
The structure is built up through following steps.
Step 1: A heavily doped p^+ substrate is prepared.
Step 2: At the bottom of which an Ohmic contact is made. A terminal, called collector

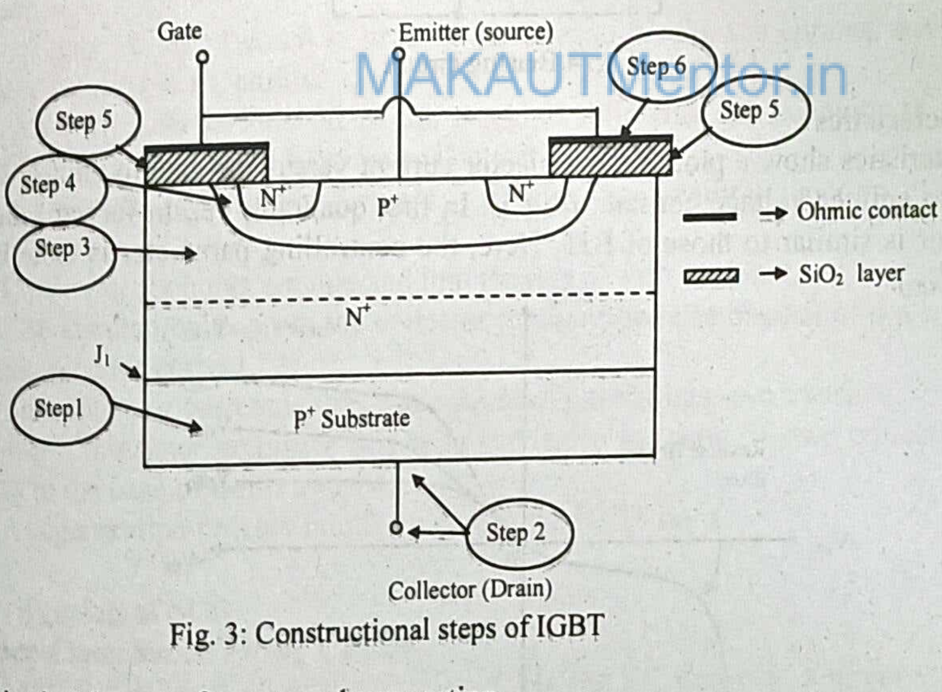


Fig. 3: Constructional steps of IGBT

or, Drain, is taken out for external connection.
Step 3: On to the substrate, a lightly doped n-type DRIFT region is grown by epitaxial process.
Step 4: Now p-type emitter is diffused with two subsequent n-type layers (heavily doped).
Step 5: Two SiO_2 layers are then deposited.

Step 6: Metallic deposition is done on the top ends of SiO_2 layer to have Ohmic contacts from where interconnected gate terminal is taken out.
Step 7: Metallic deposition is made connecting two n^+ layers. From here an Emitter terminal is formed.

The IGBT structure depicts that Emitter to collector path is basically a p-n-p bipolar structure. So, the performance of an IGBT is closer to that of a BJT rather than a MOSFET.

Biasing of IGBT

Figure 4 shows the biasing of IGBT, where
- Gate to emitter terminals are forward biased
- Collector to emitter terminals are reverse biased

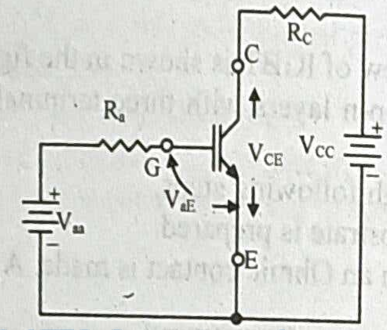


Fig: 4 Biasing circuit

V-I Characteristics

V-I characteristics show a plot of the collector current versus the gate to emitter voltage with gate to emitter voltage constant (Fig.5). In first quadrant, i.e., in forward direction the behavior is similar to those of BJT. Here, the controlling parameter is Gate-Emitter Voltage (V_{GE}).

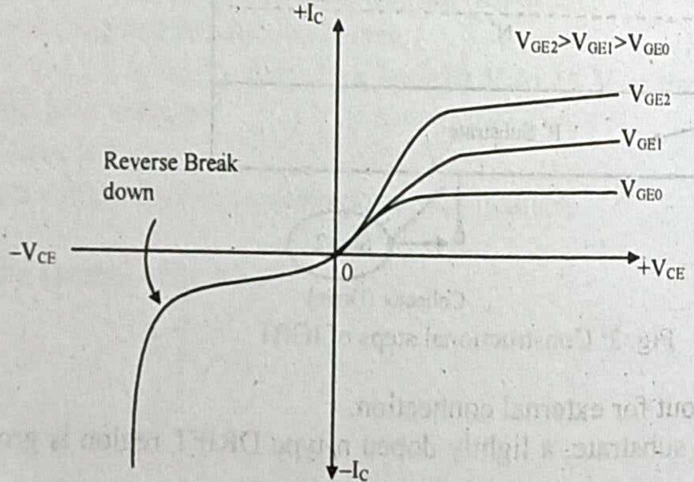


Fig. 5: characteristics of IGBT

Transfer Characteristics
Transfer characteristics is a plot of the output current (I_C) versus input gate-emitter voltage V_{GE} when V_{CE} is constant (figure 6).

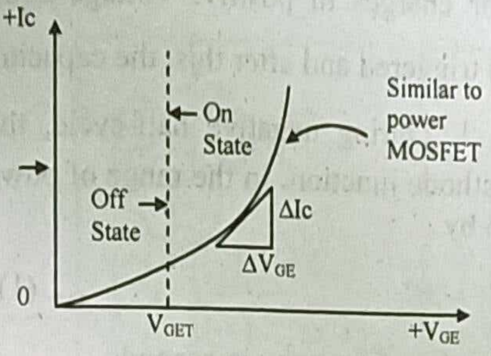


Fig. 6: transfer characteristics

When $V_{GE} < V_{GET}$ (Threshold), the device is in OFF-state.
When $V_{GE} > V_{GET}$ the device toggles to ON-State.

Transconductance of $IGBT = g_m == \left.\frac{\Delta I_C}{\Delta V_{GE}}\right|_{V_{CE}const}$

Operation
Step 1: A gate voltage (which is beyond the threshold value) is applied with collector potential is positive w.r.t. emitter.

Step 2: An n-channel is induced in the p-region following the behavior of MOSFET (capacitive action, SiO_2 layer behaves as Dielectric).
Step 3: These charge carriers forward bias the base-emitter junction of the p-n-p transistor.
Step 4: Consequently holes are injected into the n-type drift region.
Step 5: The injected holes cross the collector junction (reverse biased) of p-n-p transistor and forms collector current.
Step 6: This collector current is the base current of the biased n-p-n transistor.
Step 7: n-p-n transistor amplifies this base current to generate its own collector current and flows to the base of p-n-p transistor.
Step 8: A regeneration process builds up to turn the IGBT on.

d) RC triggering of SCR:
Resistance-Capacitance Firing Circuit
Fig. 1 shows the RC-half wave trigger circuit. By the RC network, a larger variation in the value of the firing angle can be obtained by changing the phase and amplitude of the gate current. By varying the resistor R_v, the firing angle can be controlled from 0 to 180°.
In the negative half-cycle, capacitor C charges through diode D_2 with lower plate positive to the peak supply voltage E_{max}. This capacitor voltage remains constant at $-E_{max}$ until

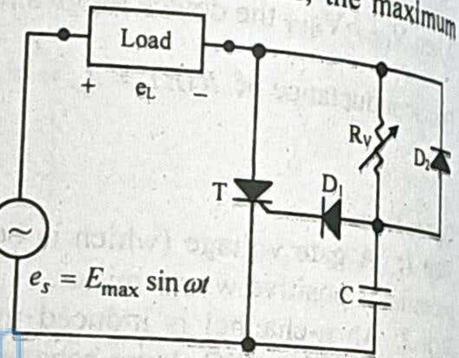
supply voltage attains zero value. Now, as the SCR anode voltage passes through zero and becomes positive, capacitor C begins to charge through R_v from the initial voltage $-E_{max}$. When the capacitor charges to positive voltage equal to gate trigger voltage $V_{gt}\left(=V_{g(min)}+V_{D1}\right)$, SCR is triggered and after this, the capacitor holds to a small positive voltage, as shown in Fig. 1. During negative half-cycle, the diode D_1 prevents the breakdown of the gate to cathode junction. In the range of power-frequencies, the RC for zero output voltage is given by

$$R_vC \geq \frac{1.3T}{2} = \frac{4}{w} \quad \text{.... (1)}$$

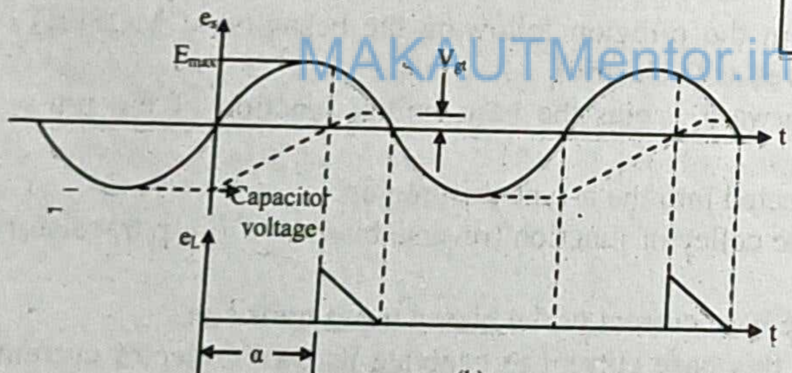
where $T = 1/f =$ period of ac line frequency in seconds.

As discussed above, the thyristors will turn ON when the capacitor voltage e_c equals $\left[V_{g(min)}+V_{D1}\right]$, provided the gage current $I_{g(min)}$ is available. Therefore, the maximum value of R_v is given by

$$e_s \geq I_{g(min)}R_v + e_c$$



(a)



(b)

Fig: 1 (a) RC firing circuit, (b) voltage-waveform

$$= I_{g(min)}R_v + V_{g(min)} + V_{D1} \quad \text{.... (2)}$$

or, $$R_v \leq \frac{e_s - V_{g(min)} - V_{D1}}{I_{g(min)}} \quad \text{.... (3)}$$

where e_s is the instantaneous supply voltage at which the thyristors will turn ON. From Eqns. (1) and (3), the suitable values of R_v and C can be obtained.

e) UJT triggering of SCR:
The circuit in Fig. 1 shows a common use for a UJT – to "fire" an SCR after a pre-determined period of time.
The basic circuit is as shown in the figure 1.

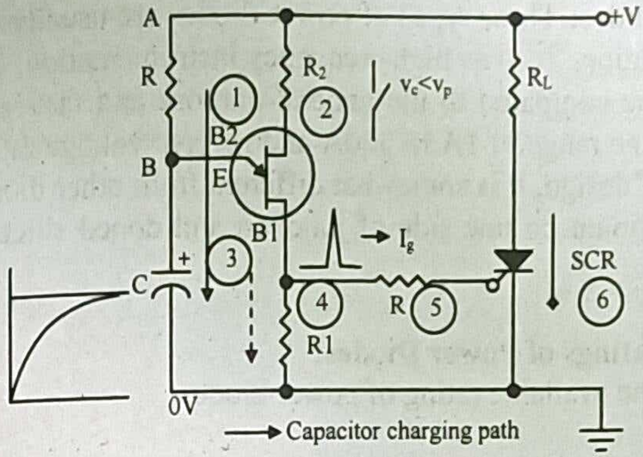


Fig.1: firing circuit for SCR using UJT

Step 1: When V is applied to the circuit capacitor starts charging following the path $+V \rightarrow A \rightarrow B \rightarrow 0V$ (shown by bold line).
Step 2: Till v_c (voltage across the capacitor) is less than V_P of UJT, UJT remains off.
Step 3: When $v_c > V_P$, UJT switches to ON state and capacitor starts discharging following the path $B \rightarrow E \rightarrow R1 \rightarrow 0V$ (shown by dotted line).
Step 4: We get a short duration pulse at B1.
Step 5: This pulse causes a Gate current to flow through R to reach at G terminal of SCR.
Step 6: This Gate current turns on the SCR.
Once SCR is ON, gate current has no effect on the switching status of SCR.

f) Power Diodes:
The diodes, ON and OFF states are controlled by power circuits on the basis of their recovery time ratings. The power diodes are classified into three types:

(a) General-purpose power diodes or conventional diodes
(b) Fast-recovery power diodes
(c) Schottky power diodes.

(a) General-Purpose Power Diodes: The name itself reveals that these types of power diodes are used for general purposes such as battery charging, UPS and electric traction systems. These power diodes have a high reverse recovery time of about 25 μs. The availability range of these diodes is current rating of 1 A to 1000 A and voltage rating of 50 V to 5 kV.

(b) Fast-Recovery Power Diodes: The fast-recovery power diodes came into existence for their use in the high frequency switching circuit system. These are having recovery time of 5 ms for diffusion type and 50ms for epitaxial type. These are used more than other diodes in power electronic types. But there are some difficulties in the manufacturing process. The design for these diodes has a voltage rating below 400V.

(c) Schotty-Power Diodes: These types of power diodes are usually used in low-voltage high-frequency applications such as high-frequency instrumentation. These diodes have a very fast recovery time compared to the general-purpose and fast-recovery diodes. The current ratings are in the range of 1A to 300A and reverse voltage rating of about 100 V. From the viewpoint of design, it is somewhat different from other diodes. It uses a metal-like golden silver platinum on one side of junction and doped silicon (Si) on the other side of junction.

Specifications and Ratings of Power Diodes:
Following table lists the available rating of power diodes,

Table 1 Ratings of available power diodes

Serial No.	Type of the diode	Voltage-current ratings	Maximum frequency	On-state drop
1.	General purpose	10 kV/5 kA	2 kHz	1-2 V
2.	High speed	3 kV/1 kA	12 kHz	1-1.5 V
3.	Schottky	50 V/50 A	20 kHz	0.5-1 V

Applications of Power Diodes:

Power diodes are required in almost all the power converters. Some of the applications are mentioned below:

1. Power diodes are used in uncontrolled rectifiers.
2. Feedback and freewheeling operations in choppers, inverters and controlled converters use power diodes.
3. Almost all the commutating circuits for SCRs use power diodes.
4. Half controlled converters and half bridge inverters use power diodes.

g) TRIAC
About TRIAC
TRIAC is a word derived by combining the words.

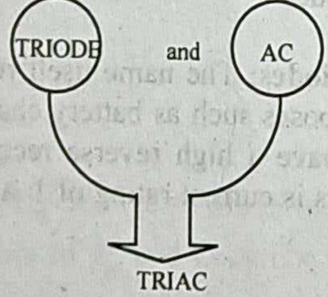


Fig: 1

The word a.c. says the TRIAC can conduct in both the directions (unlike SCR).

TRIAC is a three terminal (MT1, MT2 and Gate), bi-directional (conduction is possible from MT2 to MT1 and vice-versa) device.
The gate terminal is nearer to MT1. The terminal MT1 is the reference point for measurement of voltages.
TRIAC may be considered as two thyristors connected in anti-parallel configuration as shown in Fig: 2.

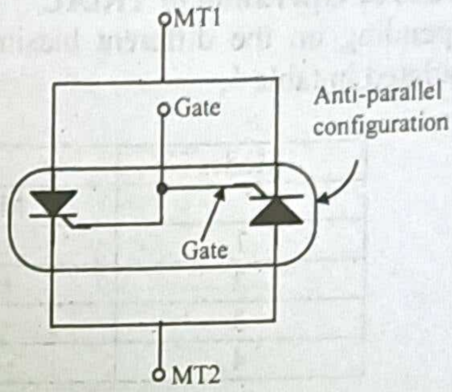


Fig: 2 TRIAC equivalent circuit

Symbol
The schematic symbol of a TRIAC is shown in Fig. 3.

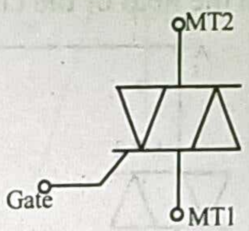


Fig: 3 TRIAC schematic symbol

TRIAC Structure
The basic TRIAC structure may be considered to be consisting of two halves. Each half comprises of PNPN layers following SCR structure (Fig: 4).

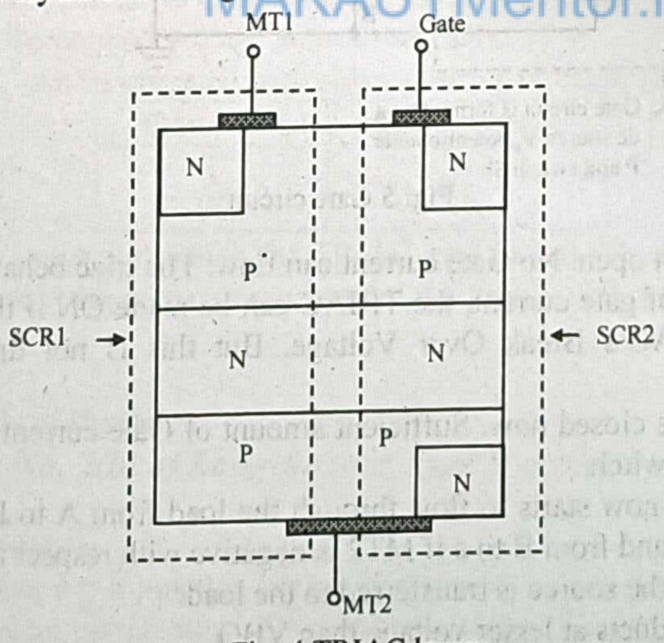


Fig: 4 TRIAC layers

Gate is the control terminal. The other two terminals are MT1 and MT2 called Main Terminals.
With proper gate current, the TRIAC may conduct when MT2 is either positive or negative with respect to MT1.

Modes of Operation of TRIAC

Depending on the different biasing conditions the operational modes of a TRIAC is tabulated in table 1.

Table 1

Modes	Biasing conditions		
	MT2	MT1	Gate current
1	+ve	–ve	+ve
2	+ve	–ve	–ve
3	–ve	+ve	+ve
4	–ve	+ve	–ve

Working Principle of TRIAC:

TRIAC operation can be explained with the help of the circuit diagram shown in Fig. 5.

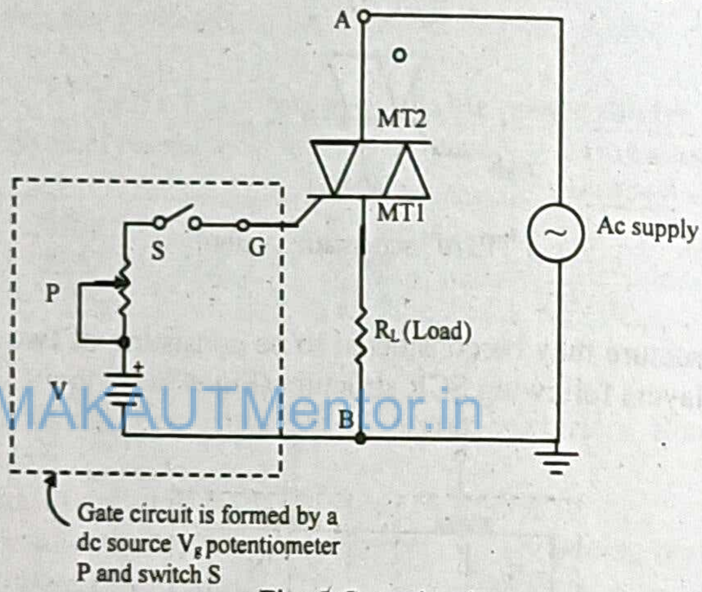


Fig: 5 Gate circuit

Step 1: Switch is kept open. No Gate current can flow. The triac behaves as open switch.

Step 2: In absence of gate current, the TRIAC can be made ON if the supply voltage is more than the TRIAC's Break Over Voltage. But this is not the practical way of operation.

Step 3: The switch is closed now. Sufficient amount of Gate current flows. TRIAC now behaves as a closed switch.

Step 4: The current now starts to flow through the load from A to B if MT2 is positive with respect to MT1 and from B to a if MT2 is negative with respect to MT1.

Then ac power from the source is transferred to the load.

Here the TRIAC conducts at lesser voltage than VBO.

Step 5: Now, by varying the gate current we can vary the transfer of ac power to the load from the source. The potentiometer P performs this task of gate current variation.

V-I Characteristics of TRIAC

Fig: 6 shows the V-I curve of a TRIAC which exhibits the characteristics of an SCR in either direction.

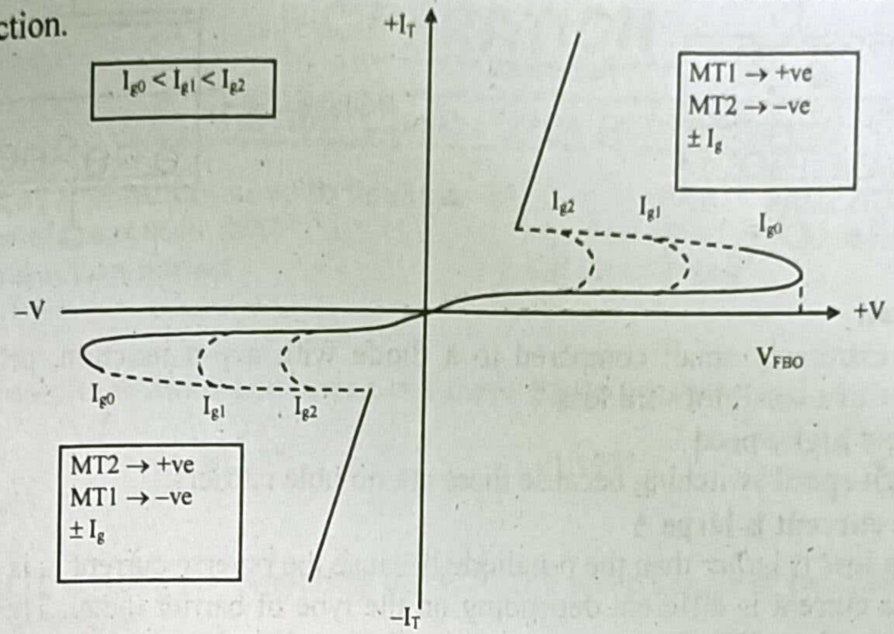


Fig: 6 TRIAC characteristics curves

- The TRIAC essentially consists of two SCRs connected in anti parallel.
- So its operating characteristics in the first quadrant is same as that of SCR and operating characteristics in the first and third quadrant are the same except for the polarity of the applied voltage and current flow.
- The TRIAC can be operated with either positive or negative gate control voltage.

Quadrant	Gate voltage
I	+ve
III	–ve

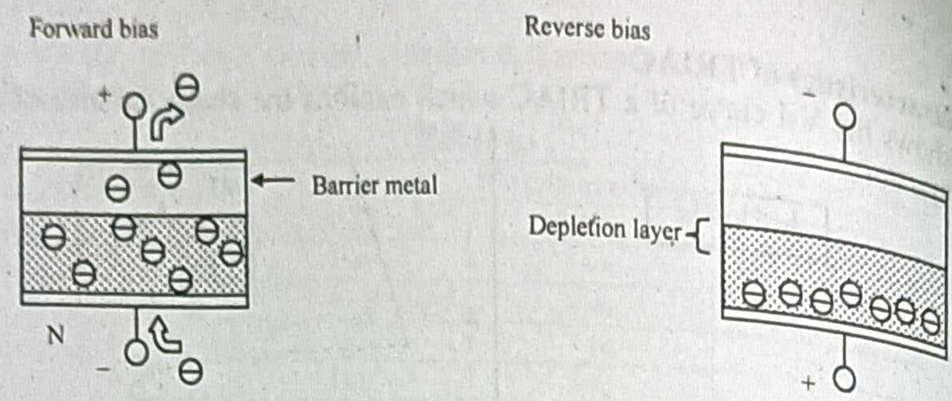
- The supply voltage at which the TRIAC gets turned ON depends upon the gate current. Higher the gate current, smaller the supply voltage at which the TRIAC is ON.

h) Turn on methods of thyristor:

Refer to Question No. 2(b) of Long Answer Type Questions.

i) Schottky barrier diode:

The diode does not use a p-n junction but a junction with a type of metal on one side and an n-type semiconductor on the other. This type of junction is called a Schottky junction. The Schottky barrier diodes has an extremely low V_F and an extremely high-speed because it does not use holes. This point could be called ideal but the reverse current I_R is large, making it inappropriate as an element to withstand high voltage.



1. V_F is small
The V_F is extremely small compared to a diode with a p-n junction, producing high efficiency with a small forward loss.
2. Extremely high-speed
There is high-speed switching because there are no hole carriers.
3. Reverse current is large Δ
The reverse loss is larger than the p-n diode because the reverse current I_R is large. The reverse current is different depending on the type of barrier metal. The SBD can be divided further into different types according to type of barrier metal that is used.

SCR PROTECTION AND SERIES-PARALLEL OPERATION

Multiple Choice Type Questions

1. RC snubber circuit is used to limit rate of [WBUT 2007, 2010, 2013, 2019]
   a) rise of current in SCR
   b) rise of voltage across SCR
   c) conduction period
   d) all of these

Answer: (b)

2. In a three-phase semi-converter, the three SCRs are triggered at an interval of [WBUT 2010, 2015, 2017]
   a) 60°
   b) 90°
   c) 120°
   d) 180°

Answer: (c)

3. When UJT is used for triggering an SCR, the wave shape of the voltage obtained from UJT circuit is [WBUT 2011]
   a) sine wave
   b) trapezoidal wave
   c) sawtooth wave
   d) square wave

Answer: (c)

4. Function of snubber circuit connected across SCR is to [WBUT 2011]
   a) increases of dv/dt
   b) decrease of di/dt
   c) suppress of dv/dt
   d) none of these

Answer: (c)

5. For an SCR, (dv/dt) protection is achieved through the use of [WBUT 2016]
   a) RL in series with SCR
   b) RC across SCR
   c) L in series with SCR
   d) RC in series with SCR

Answer: (b)

6. In SCR, the latching current is [WBUT 2017]
   a) equal to holding current
   b) greater than holding current
   c) less than holding current
   d) twice the holding current

Answer: (a)

7. In an SCR, the magnitude of anode current will [WBUT 2017]
   a) increase if gate current is increased
   b) decrease if gate current is decreased
   c) increase if gate current is decreased
   d) remain unchanged with any variation in gate current

Answer: (d)

Short Answer Type Questions

1. A thyristor is used to feed a load resistance 8 ohms from a 230 V single phase supply. The ratings of thyristors are: Repetitive peak current = 200A, $(di/dt)\max = 40\text{A}/\mu\text{s}$ and $(dv/dt)\max = 150\text{V}/\mu\text{s}$. Design a snubber circuit for protection of thyristor. **[WBUT 2010, 2019]**

Answer:

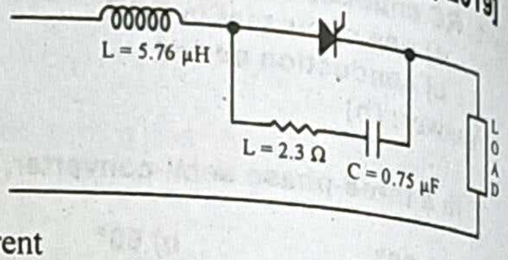
$$\frac{di}{dt} = \frac{V_s}{L_s} = \frac{230}{L_s} = 40\ \text{A}/\mu\text{s}$$

$$\therefore \quad L_s = \frac{230}{40} = 5.76\mu\text{H}$$

Again, $C\dfrac{dv}{dt} = I$ where $I \Rightarrow$ Repetitive peak current

$$\therefore \quad C = \frac{I}{dv/dt} = \frac{200\,\text{Amp}}{150\,\text{V}/\mu\text{s}} = 0.75\mu\text{F},\ R = \frac{V_s}{I} = \frac{230}{100} = 2.3\Omega$$

The designed circuit is shown in the diagram.



2. What is snubber circuit? Why snubber circuits are used in thyristor circuits? **[WBUT 2015, 2019]**

Answer: *Refer to Question No. 1(a) of Long Answer Type Questions.*

3. A thyristor is used to feed a load resistance 10Ω from a 215V single phase supply. The rating of thyristerors are: Repetitive peak current = 200A, (di/dt) max = 40A/μs and (dv/dt) max = 150V/μs. Design a snubber circuit for protection of thyristor. **[WBUT 2018]**

Answer:

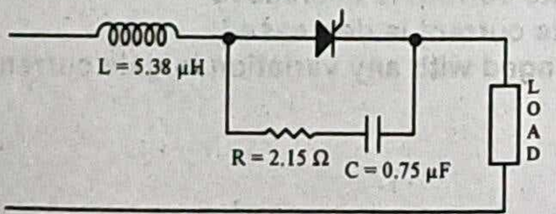
$$\frac{di}{dt} = \frac{V_s}{L_s} = \frac{215}{L_s} = 40\ \text{A}/\mu\text{s}$$

$$\therefore \quad L_s = \frac{215}{40} = 5.38\mu\text{H}$$

Again, $C\dfrac{dv}{dt} = I$ where $I \Rightarrow$ Repetitive peak current

$$\therefore \quad C = \frac{I}{dv/dt} = \frac{200\,\text{Amp}}{150\,\text{V}/\mu\text{s}} = 0.75\mu\text{F},\ R = \frac{V_s}{I} = \frac{215}{100} = 2.15\Omega$$

The designed circuit is shown in the following figure.



Long Answer Type Questions

1. How di/dt & dv/dt protections are achieved in SCR? [WBUT 2008, 2011, 2016]

Answer:

Over current protection is divided into two sections

i) $\frac{di}{dt}$ protection

ii) a) Overload protection

b) Short circuit protection

i) $\frac{di}{dt}$ Protection

It is the maximum rate of rise of anode current which will not damage SCR.

How damage takes place

We know that during turn on, only small area of junction J2 conducts immediately after the injection of suitable gate signal.

If rate of rise of anode current is more than the specified limit, then current density becomes very high $\left(\frac{i_a}{\text{small area}}\right)$ which causes localized heating.

So, junction temperature increases, creating hot spot, which leads to a permanent destruction of the device.

Protecting the SCR against $\frac{di}{dt}$

The basic objective is to restrict the fast rise in anode current. It is well known that the inductor always opposes any sudden change in currents. So,

To protect the SCR against $\left(\frac{di}{dt}\right)$ an inductor is added in series with the SCR as shown in figure.

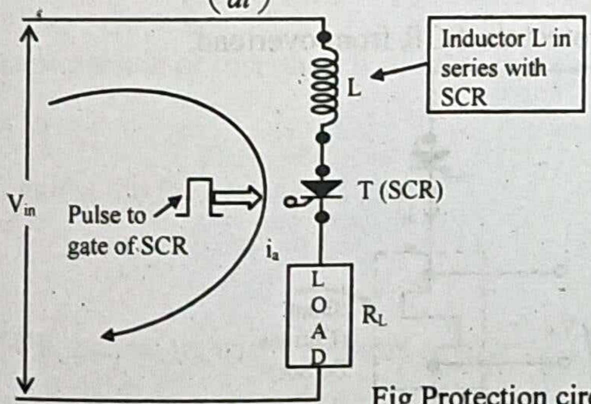


Fig Protection circuit against the $\frac{di}{dt}$

Analysis

The above figure is basically a series (R–L) circuit. When the SCR is made conducting the current grows through the R–L circuit. But the function of L is to oppose any change in current in the circuit. For a R-L series circuit, current growth is given by

$$\therefore \quad i_a(t)=\frac{V_m}{R_L}\left(1-e^{-\frac{tR_L}{L}}\right)=i \qquad \ldots(1)$$

$$\therefore \quad \frac{di_a}{dt}=\frac{V_m}{R_L}\cdot\frac{R_L}{L}e^{-\frac{tR_L}{L}} \qquad \ldots(2)$$

$$\frac{di_a}{dt}=\frac{V_m}{L}e^{-\left(\frac{R_L}{L}\right)t} \qquad \ldots(3)$$

$\frac{di}{dt}$ is maximum when t = 0

$$\therefore \quad \left(\frac{di}{dt}\right)_{max}=\frac{V_{in}}{L} \qquad \ldots(4)$$

$$\Rightarrow \quad L=\frac{V_{in}}{\left(\frac{di}{dt}\right)_{max}}$$

For $\left(\frac{di}{dt}\right)_{max}=\text{Rated}\frac{di}{dt}$

$L \rightarrow L_{min}$

Therefore, for $\frac{di}{dt}$ protection

$$L_{chosen} > L_{min} \qquad \ldots(5)$$

ii) To Protect the SCR from overload

Overload current means the current through the SCR is more than its rated or safe current.

Scheme

Figure shows the basic scheme to protect the SCR from overload.

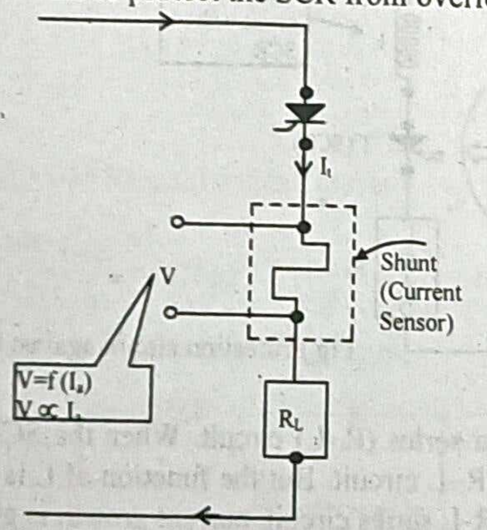


Fig: Protection against overload

- A shunt, acting as a current sensor, is used to measure the real time current drawn by the load and hence passing through SCR.
- A comparator compares the load current with the safe value of current.

Working

If $I_t = I_L > I_{Safe}$, i.e., the SCR is overloaded, then,

Step 1: Comparator toggles from V_{CC} to 0V.

Step 2: Output of the comparator then deactivates the firing circuit.

Step 3: Deactivation of the firing circuit causes load current to stop, thus protecting the SCR from overload.

For Short Circuit Protection

Types of Fuses

1. HRC (High Rupturing Capacity) fuses
2. Semiconductor fuses

Semiconductor fuses are very fast but very costly.
So, generally HRC fuses are used.
Usually, a fuse is placed in series with each device as shown in the figure.
A semiconductor device is very sensitive to overvoltages, which is supposed to be the main cause of its failure.
So, the operating voltage must not exceed the device's maximum voltage rating.

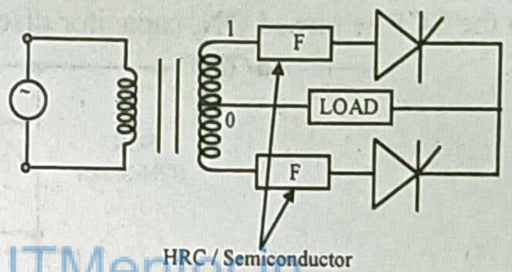


Fig: Fuses (F) for short circuit protection

Reasons for Overvoltages

The overvoltages in Power Electronic circuits occur due to
- Bad commutation
- Transients due to switching actions
- Short circuiting etc. etc.

The overvoltage protection of thyristors is divided into two sections:
1. $\frac{dv}{dt}$ protection
2. Protection against the factors as said above.

$\frac{\mathbf{dv}}{\mathbf{dt}}$ ***Protection***

To protect the SCR against transient voltages or high $\frac{dv}{dt}$, a snubber circuit is used.
Snubber circuit is a R–C network connected in shunt with SCR as shown in next figure.

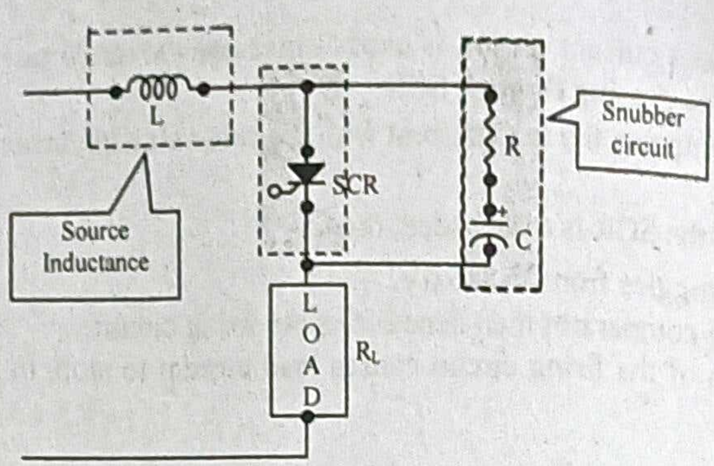


Fig: Snubber circuit for $\frac{dv}{dt}$ protection

Use of C

The function of a capacitor is to oppose any change in voltage. So, C of the snubber circuit limits the rate of rise of voltage across the SCR.

Use of R

When the SCR is turned ON, capacitor discharges through the SCR.

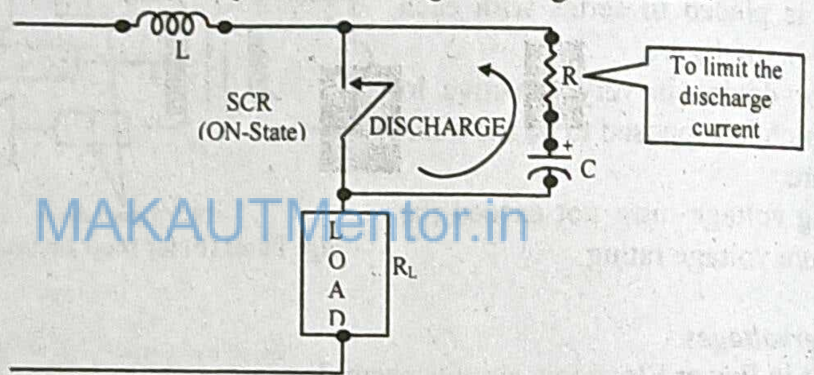


Fig: Capacitor discharge path

The discharge current may be high enough to damage the SCR.
Hence to limit this discharge current a suitable resistor R is connected in series with C.

Design of Snubber Circuit

Initially

- SCR is in forward blocking state, so it offers a very high impedance. The current finds the 'shortest' path through the snubber circuit.
- Capacitor is going to be charged, so behaves as a short circuit. The equivalent circuit looks like the next figure.

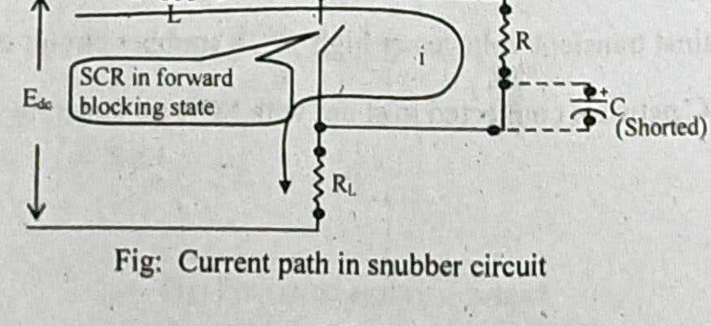


Fig: Current path in snubber circuit

For the circuit in the above figure voltage equation may be written as

$$E_{dc} = i(R+R_L) + L\frac{di}{dt} \quad \dots (1)$$

Taking Laplace transform of the above equation, we get,

$$\frac{E_{dc}}{s} = (R+R_L)I(s) + s\ L\ I(s) \quad \dots (2)$$

$$\Rightarrow \quad I(s) = \frac{E_{dc}/s}{sL+(R+R_L)} = \frac{E_{dc}}{Ls\left[s+\left(\frac{R+R_L}{L}\right)\right]} \quad \dots (3)$$

Taking inverse Laplace transform of the previous equation

$$i = \frac{E_{dc}}{\frac{(R+R_L)}{L}}\cdot\frac{1}{L}\left[1-e^{-\left(\frac{R+R_L}{L}\right)t}\right] \quad \dots (4)$$

$$\therefore \quad \frac{di}{dt} = \frac{E_{dc}}{(R+R_L)}\cdot\frac{(R+R_L)}{L}.e^{-t.\frac{(R+R_L)}{L}}$$

$$\Rightarrow \quad \frac{di}{dt} = \frac{E_{dc}}{L}.e^{\frac{-t(R+R_L)}{L}} \quad \dots (5)$$

$\frac{di}{dt}$ is maximum when $t = 0$

$$\therefore \quad \left(\frac{di}{dt}\right)_{max} = \frac{E_{dc}}{L} \quad \dots (6)$$

Now, voltage across the capacitor

$$v = Ri \quad \dots (7)$$

$$\therefore \quad \frac{dv}{dt} = R\frac{di}{dt} \Rightarrow \left(\frac{dv}{dt}\right)_{max} = R\left(\frac{di}{dt}\right)_{max} \quad \dots (8)$$

$$\Rightarrow \quad \left(\frac{dv}{dt}\right)_{max} = R.\frac{E_{dc}}{L}$$

$$\therefore \quad \boxed{R = \frac{L}{E_{dc}}\cdot\left(\frac{dv}{dt}\right)_{max}} \quad \dots (9)$$

Designing C

The values for R, L, R_L and C are so chosen that the circuit behaves as critically damped. Therefore, for a critically damped circuit

$$(R+R_L)^2 - \frac{4L}{C} = 0$$

$$\Rightarrow \quad \boxed{C = \frac{4L}{(R_L + R)^2}} \quad \cdots (10)$$

For AC Circuit

The values of R and C in equations (9) and (10) have been evaluated for DC supply for AC circuit, E_{dc} is replaced by E_{ac} in the figure below.

The maximum input voltage can be substituted for E_{dc} in the expression 14, we have

$$R < \frac{L\frac{dv}{dt}}{E_{max}} \quad \cdots (11)$$

The value of capacitance

$$C = 10.\frac{VA}{V_S^2}.\frac{60}{f} \quad \cdots (12)$$

where VA = Volt - Ampere rating of SCR
V_s = Voltage applied to the circuit (RMS value)
f = operating frequency

$\left(\frac{di}{dt}\right)$ and $\left(\frac{dv}{dt}\right)$ Failures of SCRs

High rate of rise of current $\left(\frac{di}{dt}\right)$ and voltage $\left(\frac{dv}{dt}\right)$ cause high concentration of current at the gate perimeter. This causes the development of large amount of heat. If the temperature rise is excessive and beyond the tolerance level, the silicon melts and junction is destroyed. Such a failure is destructive in nature and the device gets lost its fundamental characteristics and needs the necessary replacement.

Conditions $\left(\frac{di}{dt}\right)$ and $\left(\frac{dv}{dt}\right)$ Failures

High rate of rise of current and voltage of the device during forward blocking state causes a capacitive drive to the device. If the capacitive current is small, it increases the forward conduction loss. When the capacitive current goes beyond the limit it may take the SCR to full on state from the blocking state. Such a turn on is not destructive if $\left(\frac{di}{dt}\right)$ pressure has been taken care of properly.

2. What is the necessity of connecting SCRs in series? What are the problems associated with series connection of SCRs? How are they eliminated?

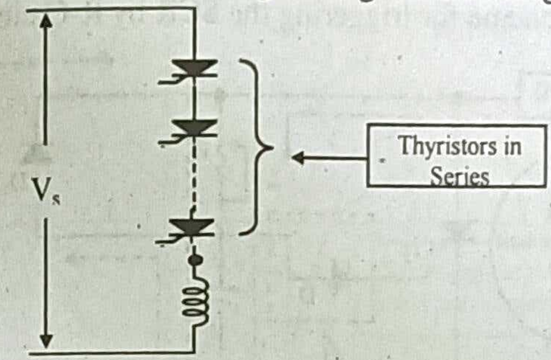
[WBUT 2009, 2014]

Answer:

Series Operation

- When we are having Thyristors of lower voltage ratings for an application, e.g. suppose supply voltage is 440V. But voltage ratings of available Thyristors are 230V.

- When it is desired to increase the voltage ratings of the string.

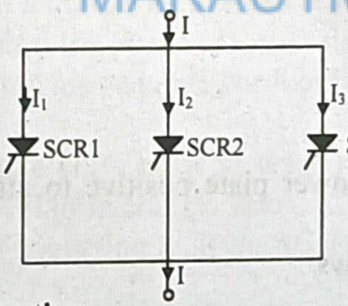


No two SCRs are having matched characteristics.
The parameters like
- Turn-ON time
- Blocking currents
- Forward & reverse blocking currents
- Reverse recovery characteristics

Differ from SCR to SCR.

Parallel operation
The current rating of the circuit for a specific application is greater than the individual SCR, then the SCRs are connected in parallel.
In other words, SCRs are connected in parallel to improve the current rating.

Scheme



Difficulties in parallel connection
Because of differences in V–I characteristics of SCRs having same rating, they do not share the current equally, i.e., in the above figure.

$$I = I_1 + I_2 + I_3$$

But, $I_1 \neq I_2 \neq I_3$

This problem leads Thermal Runaway.

Reason of this problem
The unequal sharing of current is due to unequal Dynamic resistance of the SCRs.

3. Draw the R-C firing circuit for SCR and explain with proper waveforms. Why are short pulses preferred over long pulse signals for thyristor triggering through isolation transformer? [WBUT 2010]

Answer:

1st Part: Fig. 1 shows the scheme for triggering the SCR by R-C circuit.

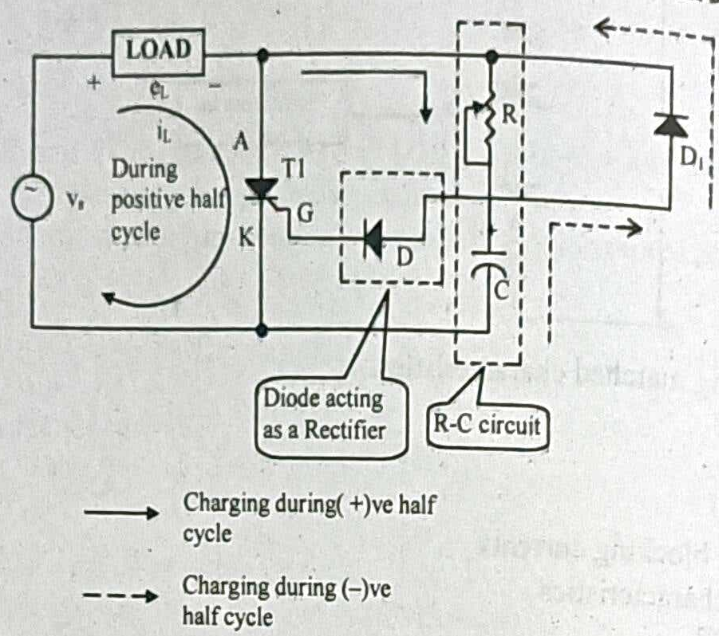


Fig: 1 R-C triggering circuit

Using R-C network

Using R-C network, a larger variation in the value of firing angle can be obtained by changing the phase and amplitude of the gate current. By varying R, the firing angle can be varied from 0° to 180°.

Working

Step 1: During negative half cycle

The status of different components

C: charges through diode D1 with lower plate positive to attain peak supply voltage–E_{max}.

D: Reverse biased no gate current flows

T1: Remains off.

Step 2: When supply voltage goes to the positive half cycle through zero value

C: Begins to charge through R from initial value – E_{max}.

T1: A is positive with respect to K, i.e., reaches to forward blocking state when the capacitor charges to positive voltage and equal to gate trigger voltage, SCR is triggered.

R_L: load current (i_L) flows, voltage across the load is (e_L).

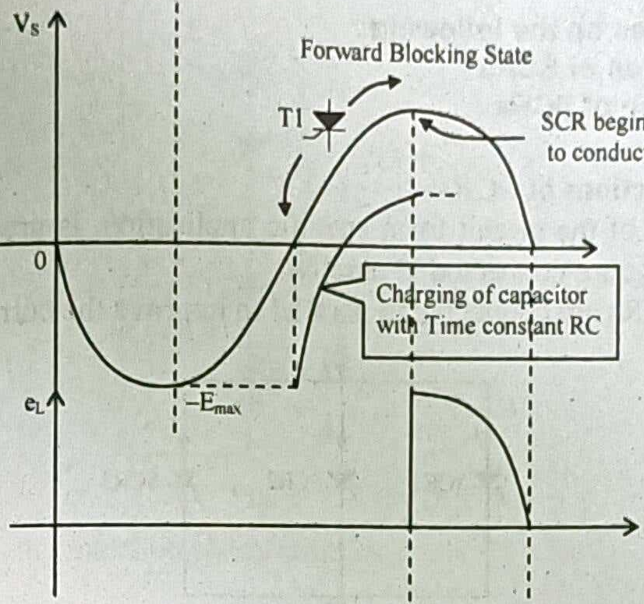


Fig: 2 Pattern of load voltage (e_L)

2nd Part:

Short pulses are preferred over the long pulses to minimize the gate losses.

In SCR. Average value of current of the short pulse through gate circuit is small. So power loss is small.

4. Draw and explain time phase triggering circuit of an SCR. **[WBUT 2011]**

Answer:

Here the gate signal is ac in nature, which is derived from the supply (ac) itself.

A R-C network is used to shift the phase of the ac signal.

Gate pulses of larger duration are required for highly inductive circuits for proper turn on of SCR.

The width of the applied gate pulse must be greater than the time required for the anode current to reach upto the level of latching current.

Fig. 1 shows the scheme of triggering SCR by AC signal.

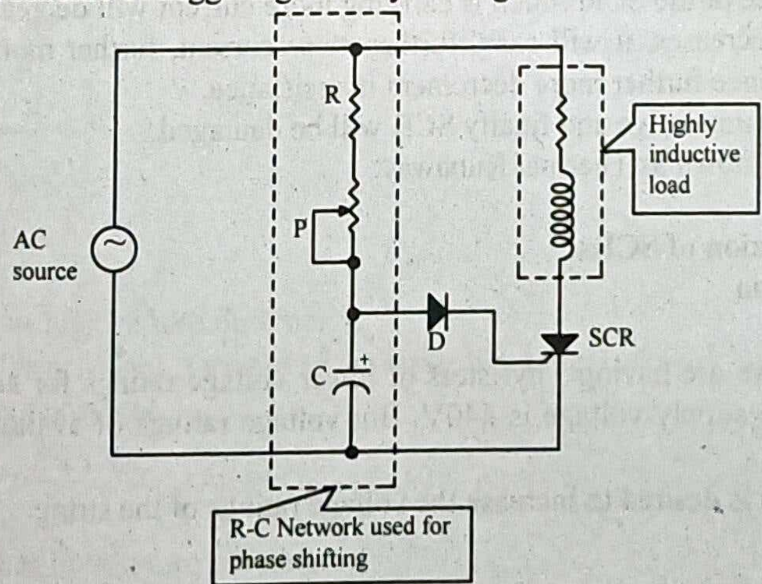


Fig: 1 SCR triggering by AC signal

5. Write short notes on the following:
a) Parallel operation of SCRs
b) Series operation of SCRs [WBUT 2013, 2015] [WBUT 2016]

Answer:

a) Parallel Connections of SCRs:

The current rating of the circuit for a specific application, is greater than the individual SCR, then the SCRs are connected in parallel.

In other words, SCRs are connected in parallel to improve the current rating.

Scheme

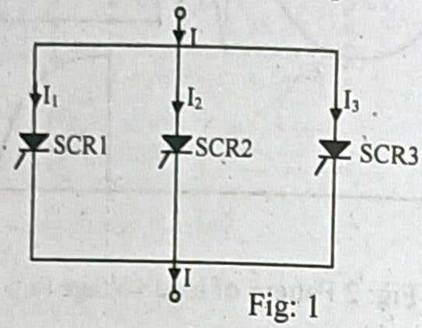


Fig: 1

Difficulties in parallel connection: Because of differences in V–I characteristics of SCRs having same rating, they do not share the current equally, i.e., in the above figure, $I = I_1 + I_2 + I_3$ But, $I_1 \neq I_2 \neq I_3$.

This problem leads Thermal Runaway.

Reason of this problem: The unequal sharing of current is due to unequal Dynamic resistance of the SCRs.

Thermal Runaway: In parallel configuration, due to inherent differences in V-I characteristics, the current sharing among SCRs is unequal.

The SCR which is carrying maximum power will dissipitate maximum power, consequently its temperature rise will be more compared to other SCRs.

SCR, being a semiconductor device, will undergo a decrement in resistance with rise in temperature.

So, the resistance of the SCR which is carrying more current will decrease.

As resistance decreases, it will carry further more current, further more heat dissipation will be there, hence further more decrement in resistance.

This process is cumulative and finally SCR will be damaged.

This process is known as Thermal Runaway.

b) Series operation of SCRs:

Series Operation

When ....

- When we are having Thyristors of lower voltage ratings for an application, e.g. suppose supply voltage is 440V. But voltage ratings of available Thyristors are 230V.
- When it is desired to increase the voltage ratings of the string.

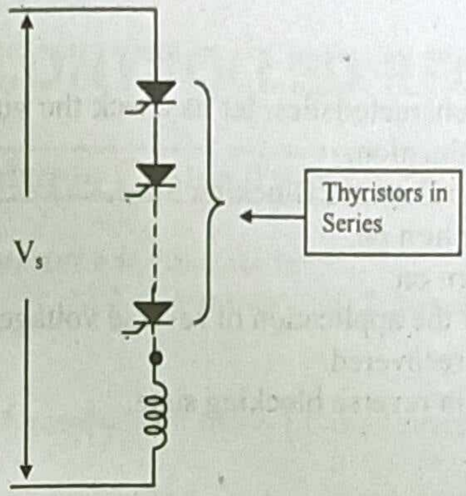


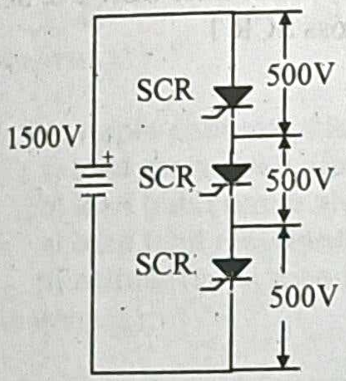
Fig: 1

No two SCRs are having matched characteristics.
The parameters like

- Turn-ON time
- Blocking currents.
- Forward & reverse blocking currents.
- Reverse recovery characteristics.
- Differ from SCR to SCR.

Ideal situation

Consider a string of 3 SCRs connected in series.



* Applied voltage across the string = 1500V

* Voltage rating of each SCR = 500V

identical characteristics of each SCR will share a voltage of 500V as shown in the figure.

Fig: 2

Practical situation

Let

- SCR1 has highest turn on time.
- SCR 2 has lowest forward & reverse blocking leakage) current, i.e. highest blocking resistance.

$$R_{Df}\Big|_2 = \frac{V_{Df2}}{I_{Df2}},\ R_{DR2} = \frac{V_{DR}}{I_{DR2}}$$

- SCR 3 has lowest turn off time

Different situations

With these differences in characteristics, let us check the voltage distribution across each SCR under the following situation:

Case 1: All the SCRs are in Forward Blocking State.
Case 2: Immediately after turn on.
Case 3: All SCRs fully turn on.
Case 4: Immediately after the application of reverse voltage
Case 5: One of the SCRs recovered.
Case 6: All the SCRs are in reverse blocking state.

Case I:

If SCR2 has highest Forward Blocking resistance, the voltage across SCR2 will be the highest.

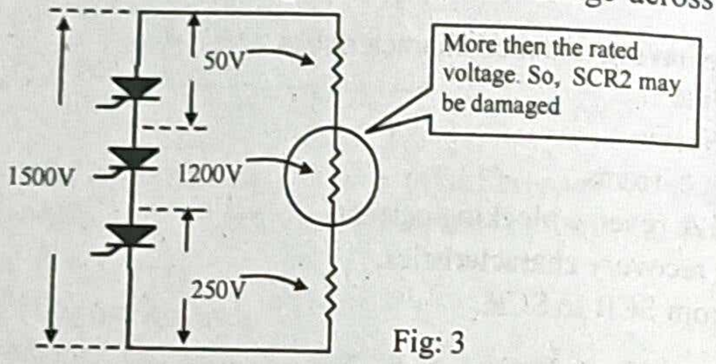


Fig: 3

Case II:

Since SCR 1 has the highest turn on time it will turn on a little later after SCR 2 & SCR 3. So for this moment, most of the applied voltage will be across SCR 1

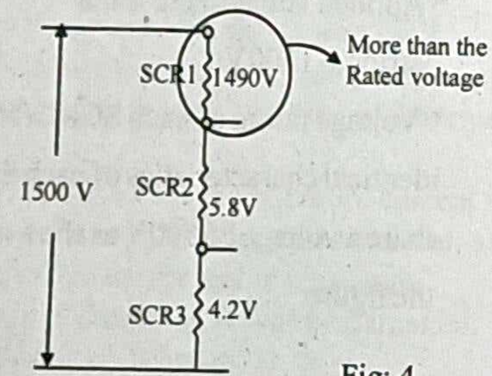


Fig: 4

To Get Rid Off

Though each SCR is identically rated, voltage distribution across the individual SCRs in the string are not same due to difference in characteristics.

This unequal distribution of voltages may cause damage to a SCR thus causing the breakdown of the entire string.

So, a compensating circuit is needed which will produce a uniform voltage distribution under all conditions of operation.

This compensating circuit is called Equalizing Network.

PHASE CONTROLLED RECTIFIERS

Multiple Choice Type Questions

1. A single-phase full converter can operate in [WBUT 2008, 2011]
a) 4 quadrants (V – I) b) 3 quadrants c) 2 quadrants d) 1 quadrant

Answer: (c)

2. The advantage of a 180° conduction three phase inverter over a 120° conduction three phase inverter is [WBUT 2010, 2013, 2019]
a) it needs less number of switches
b) there is no paralleling of switches
c) devices in series are not simultaneously switched
d) load terminals are not left open during switching

Answer: (c)

3. For continuous conduction each thyristor pair of a two pulse full converter should conduct for [WBUT 2010, 2015]
a) π b) $\pi-\alpha$ c) α d) $\pi+\alpha$.

Answer: (b)

4. The maximum firing angle that can be obtained by a pure resistive trigger circuit used in phase control circuit is [WBUT 2010, 2014]
a) 45° b) 90° c) 135° d) 180°

Answer: (b)

5. The ripple content of load current of a converter feeding RL load is decided by [WBUT 2011]
a) load resistance alone
b) load inductance alone
c) both load resistance and load inductance
d) neither resistance nor inductance

Answer: (c)

6. In a single phase half controlled rectifier with R-L load using flywheel diode, cathode of the flywheel diode is connected to [WBUT 2011]
a) anode of SCR
b) cathode of SCR
c) gate of SCR
d) across anode & cathode of SCR

Answer: (b)

7. In a single phase full converter, if output voltage has peak and average values of 325 V and 133 V respectively, then the firing angle is [WBUT 2011, 2014]
a) 40° b) 140° c) 50° d) 130°

Answer: (c)

8. A three phase controlled rectifier feeds a purely resistive load. The data are $V_s = 240$ V (RMS) and $R = 24\Omega$. If the firing angle α is 90°, then the average current delivered to load is [WBUT 2013]

a) 8.5 A
b) 9.65 A
c) 3.38 A
d) 6.75 A

Answer: (a)

9. A single phase full converter connected with a very high inductive load operates in .... of V-I plane. [WBUT 2013]

a) 4 quadrants
b) 3 quadrants
c) 2 quadrants
d) 1 quadrant

Answer: (c)

10. A free wheeling diode across inductive load of a phase controlled converter will provide [WBUT 2013, 2019]

a) quick turn-on of SCR
b) slow turn-off of SCR
c) reduced utilization factor of transformer
d) improved power factor

Answer: (b)

11. The ripple current of load current of a converter feeding RL load is decided by [WBUT 2014]

a) Load resistance alone
b) Load inductance alone
c) Both (a) & (b)
d) Neither resistance nor inductance

Answer: (b)

12. A 6-pulse bridge converter feeds a pure resistive load. The control of the converter can be varied in the range [WBUT 2014]

a) 0°≤ α ≤180°
b) 0°≤ α ≤120°
c) 0°≤ α ≤150°
d) 30°≤ α ≤150°

Answer: (a)

13. A two pulse converter supplies RLE load with R=5Ω, L=20H, E=160V from a 220V, 50 Hz supply. Load draws an average current 10 of 7.614A. If the value of E is changed to 155V, the new 10 will be – [WBUT 2014]

a) 7.914A
b) 8.614
c) 7.214A
d) 8.414A

Answer: (c)

14. In a three phase full wave rectifier, the output voltage pulsates at a frequency equal to supply frequency [WBUT 2015]

a) f
b) $2f$
c) $3f$
d) $6f$

Answer: (d)

15. A freewheeling diode is placed across the dc load [WBUT 2016]

a) to prevent reversal of load voltage
b) to permit transfer of load current away from the source
c) both (a) and (b)
d) none of these

Answer: (a)

16. A full wave rectifier with resistive load produces [WBUT 2018]
a) second harmonic
b) third harmonic
c) fifth harmonic
d) do not produce harmonics

Answer: (d)

17. In dual converters [WBUT 2018]
a) both rectifiers provides positive current to the load
b) both rectifiers provide negative current to the load
c) one rectifiers provide positive current to the load and the other negative current
d) one rectifier provide positive current to the source and the other negative current to the load

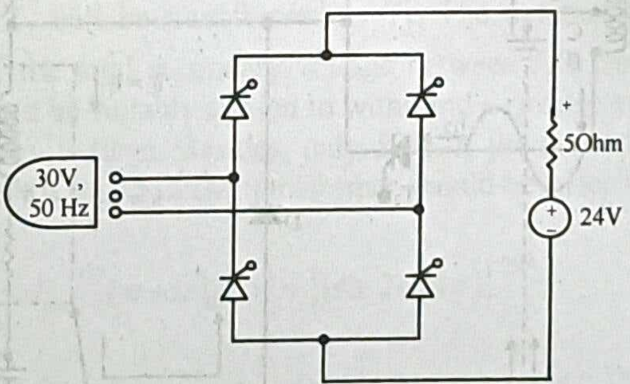
Answer: (c)

18. In continuous conduction of a single-phase semi-converter each thyristor conducts for [WBUT 2018]
a) $\Pi - \alpha$
b) $\Pi + \alpha$
c) β
d) α

Answer: (a)

Short Answer Type Questions

1. A battery is charged by a fully controlled single phase converter as shown in fig. The input supply is 30V at 50Hz. The load consists of a 24V battery and a resistance of 5Ω connected in series to limit the current. What is the minimum possible firing angle? Compute the value of average output voltage.
[WBUT 2008, 2018]



Answer:

Supply voltage $V_s = 30$ V

Average DC voltage $= V_{DC} = \frac{2V_m}{\pi}\cos\alpha$

For maximum possible firing angle $V_{DC} = 24 = \frac{2\cdot\sqrt{2}\cdot 30}{\pi}\cdot\cos\alpha$

$\left[\because V_m = \sqrt{2}V_{rms}\right]$

$$\therefore \quad \cos\alpha = \frac{24\cdot\pi}{2\cdot\sqrt{2}\cdot 30} = \frac{4\pi}{10\sqrt{2}}$$

$$\Rightarrow \quad \alpha = 26.21^\circ$$

$$\text{Average output voltage} = V_{DC} = \frac{1}{\pi}\left[\int_{26.21}^{\pi}(E_m \sin\omega t - 24)\,d\omega t\right] = 6.983\text{ V.}$$

2. a) Draw the circuit diagram of a single phase full wave controlled rectifier with centre tap transformer & explain wave shape of load voltage, load current, voltage across Th_1 & Th_2 with firing angle at 'α' **[WBUT 2011]**

Answer:

Single-phase Full-wave Controlled Rectifier using Centre-tap Transformer (M-2 Connection)

The most common type of load, i.e. *R-L* has been considered as shown in Fig. 1(a). Two SCRs T_1 and T_2 conduct alternately. The conduction of one SCR reverse biases the other and turns it off. Thus for an inductive load, there will be a period when both the SCRs may conduct. To overcome this problem of inductive loads, a freewheeling diode D is connected across the load. This circuit requires a centre-tap transformer because one point of the load is grounded.

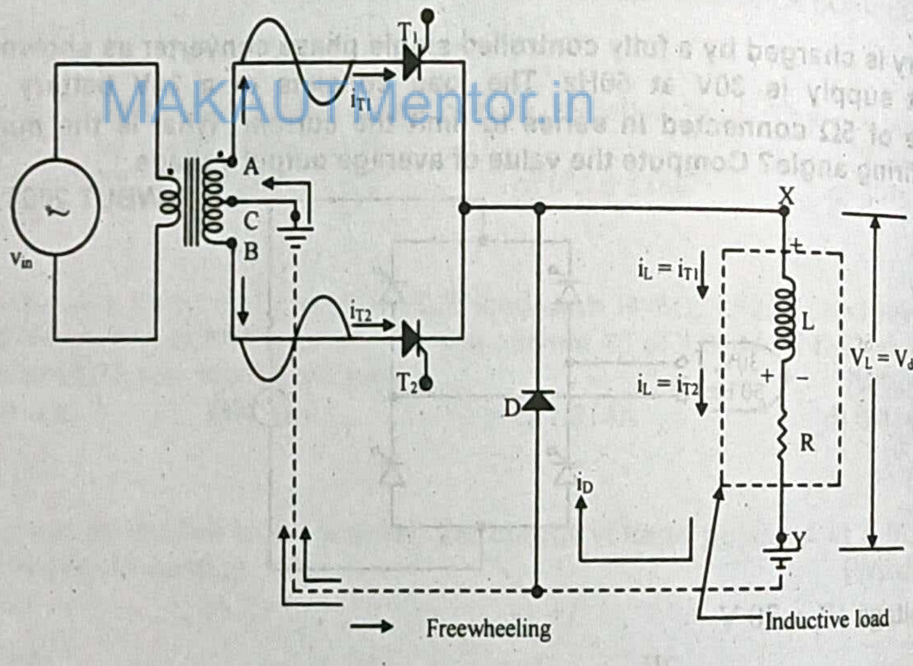


Fig: 1(a) Circuit diagram of a single-phase full-wave rectifier using centre-tap transformer (M-2 connection)

Principle of operation of the single-phase full-wave controlled rectifier using centre-tap transformer.

Assume that diode D is not connected across the load. When T_1 is triggered at $\omega t = \alpha$, its current $(i_{T1} = i_L)$ rises gradually. As the potential of the point A crosses natural zero and it tends to become negative with respect to the centre-tap point C as shown in Fig.

1(a), the potential of the point B becomes positive with respect to that of point C. It should be noted that due to the inductive load, the current through thyristor T_1 may be maintained beyond $\omega t = \pi$. Figure 1(b) represents the equivalent circuit when the conduction interval is $(\pi - \alpha)$ or $2\pi - (\pi + \alpha)$.

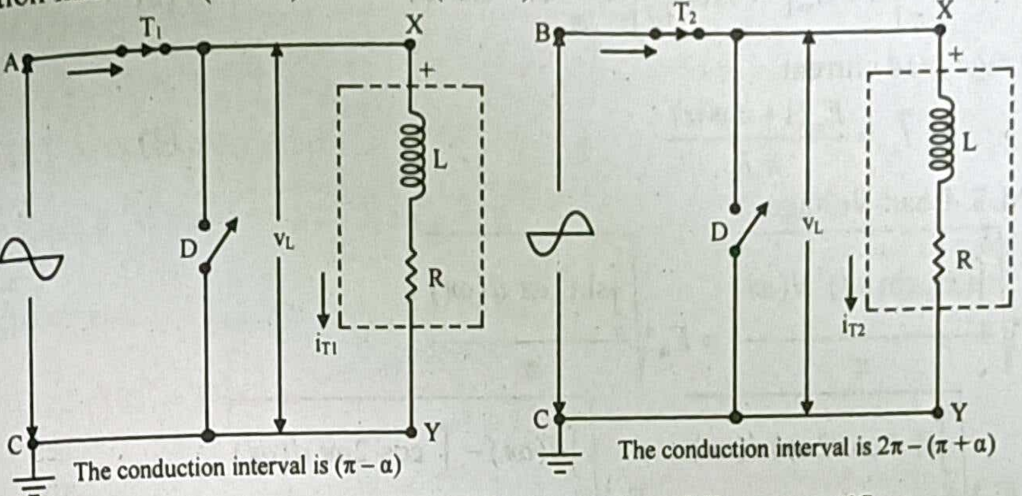


Fig: 1(b) Equivalent circuit of a single-phase full-wave rectifier when the conduction interval is $(\pi - \alpha)$ or $2\pi - (\pi + \alpha)$

At $\omega t = \pi + \alpha$, the potential of point B being positive with respect to that of point C, a triggering pulse at the gate of T_2 will cause it to turn on. As T_2 conducts, SCR T_1 is turned off by reverse biasing. During the turn-off period of T_1, the load current through T_1 will be transformed to SCR T_2. Similarly, as T_1 is turned on at $\omega t = 2\pi + \alpha$, T_2 will be turned off by reverse biasing and during the turn-off period of T_2, the load current $(i_{T2} = i_L)$ through T_2 will be transformed to T_1. The conduction of one SCR reverse biases the other by the total secondary voltage between AB [see Fig. 1(a)]. Therefore, both T_1 and T_2 should be suitably chosen to withstand a reverse voltage equal to the peak of the total secondary voltage. Besides, only 50% of the secondary coil is operative in each half-cycle, the VA rating of the transformer should be twice that of the load.

b) Prove that $E_{rms} = E_M\left[\{(\pi-\alpha)/2\pi\}+\{(\sin 2\alpha/4\pi)\}\right]^{1/2}$ **[WBUT 2011]**

Answer:

Mathematical Analysis

Here, we are interested to find out the expressions of the following parameters

i) Average dc load voltage
ii) Average dc load current
iii) RMS DC load voltage

Let ac source be mathematically expressed as

$$e = E_m \sin\omega t \quad \ldots (1)$$

i) Average d.c. load voltage

$$\overline{e}_L = \frac{1}{\pi}\int_0^{\pi} e\, d(\omega t)$$

$$=\frac{1}{\pi}\left[\int_0^{\alpha} E_m \sin\omega t\, d(\omega t)+\int_{\alpha}^{\pi} E_m \sin\omega t\, d(\omega t)\right]$$

$$=\frac{1}{\pi}\left[0+E_m\left[-\cos\omega t\right]_{\alpha}^{\pi}\right]=\frac{E_m}{\pi}(1+\cos\alpha) \qquad \ldots (2)$$

ii) Average load current

$$=\bar{I}_L=\frac{E_m(1+\cos\alpha)}{\pi.R} \qquad \ldots (3)$$

iii) R.M.S. Load Voltage

$$e_{rms}=\sqrt{\frac{\int_{\alpha}^{\pi}(E_m\sin\omega t)^2\, d(\omega t)}{\pi}}=E_m\sqrt{\frac{\int_{\alpha}^{\pi}\sin^2\omega t\, d(\omega t)}{\pi}}$$

$$=E_m\sqrt{\frac{\int_{\alpha}^{\pi}(1-\cos 2\omega t)d(\omega t)}{2\pi}}=E_m\sqrt{\frac{\int_{\alpha}^{\pi}d(\omega t)-\int_{\alpha}^{\pi}\cos 2\omega t\, d(\omega t)}{2\pi}}$$

$$=E_m\sqrt{\frac{\omega t\Big|_{\alpha}^{\pi}}{2\pi}-\frac{\sin 2\omega t\Big|_{\alpha}^{\pi}}{4\pi}}=E_m\sqrt{\frac{(\pi-\alpha)}{2\pi}-\frac{(\sin\pi-\sin 2\alpha)}{4\pi}}$$

$$e_{rms}=E_m\sqrt{\left(\frac{\pi-\alpha}{2\pi}+\frac{\sin 2\alpha}{4\pi}\right)} \qquad \ldots (4)$$

From the expression (4), we conclude

For $\alpha=0$,

$$e_{rms}=E_m\sqrt{\frac{(\pi-0)}{2\pi}+\frac{\sin 0}{4\pi}}=\frac{E_m}{\sqrt{2}} \qquad \ldots (5)$$

For $\alpha=\pi$,

$$e_{rms}=E_m\sqrt{\frac{(\pi-\pi)}{2\pi}+\frac{\sin 2\pi}{4\pi}}=0 \qquad \ldots (6)$$

3. A single phase converter feeds an R-L load having resistance of 10Ω in series with an inductance of 22 mH. The converter operates such that the dc voltage across the load is 240 V. The SCR used in the converter has holding current of 320 mA and a delay time of 4.5 μs. Determine pulse width of gate current. [WBUT 2011]

Answer:

Fig: 1 shows how the DC source is connected to the load

Let i_L be the load current.

Applying KVL in the mesh

$$E=i_L R+L\frac{di_L}{dt}----(i)$$

(Neglecting drop across SCR)
Taking Laplace transform at the both sides of equation (i)

$$L s . I_L(s) + I_L(s) R = E/s$$

$$\Rightarrow \quad I_L(s) = \frac{I}{R+Ls} = \frac{E}{sR\left(1+\frac{L}{R}s\right)} = \frac{E}{R}\cdot\frac{1}{s}\cdot\frac{1}{\left(1+\frac{L}{R}s\right)} \text{ .... (ii)}$$

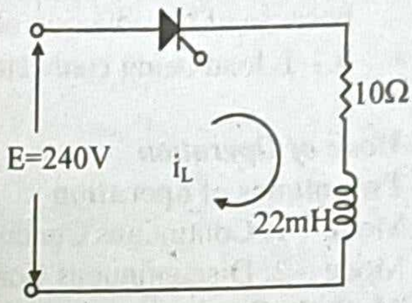


Fig. 1 Electrical connections of source and load

Taking ILT of the expression (ii)

$$i_L(t) = \frac{E}{R}\left(1-e^{-t\frac{R}{L}}\right) = \frac{240}{10}\left(1-e^{-t\frac{10\times1000}{22}}\right)$$

To reach current, $i_L = i_{latch}$, let $t = t_{on} + 4.5$ μsec

$$\Rightarrow \quad 320\times10^{-3} = 24\left(1-e^{-t_{on}+4.5\times10^{-6}\times\frac{10\times1000}{22}}\right)$$

$$\Rightarrow \quad \frac{320\times10^{-3}}{24} = \left[1-e^{-\left(t_{on}+4.5\times10^{-6}\right)\times\frac{10\times1000}{22}}\right]$$

$$\Rightarrow \quad 13.33\times10^{-3} = 1-e^{-\left(t_{on}+4.5\times10^{-6}\right)\cdot454.545}$$

$$\Rightarrow \quad e^{-\left(t_{on}+4.5\times10^{-6}\right)\cdot454.545} = 1-13.33\times10^{-3}$$

$$\Rightarrow \quad e^{-\left(t_{on}+4.5\times10^{-6}\right)\cdot454.545} = 0.987$$

$$\Rightarrow \quad -\left(t_{on}+4.5\times10^{-6}\right)454.545 = -0.013085$$

$$\Rightarrow \quad t_{on} = 28.787\times10^{-6} - 4.5\times10^{-6} = 24.287 \text{ μsec}$$

$$t = 28.787 \text{ μsec}$$

4. With a neat circuit diagram and waveform explain the operation of three phase half controlled bridge with RL load. [WBUT 2014]

Answer:

Scheme

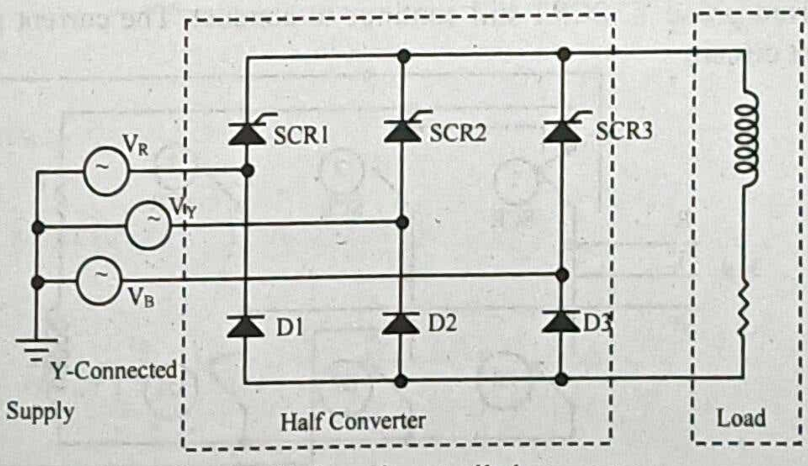


Fig: 1 Scheme of 3-ϕ semi controlled converter

- Three SCRs are placed in three arms and three diodes in the other 3 arms.
- Symmetrical configuration is chosen. Asymmetrical configuration is not used because of introduction of in balance in line current on the a.c. side.
- R – L load being connected at the output of the converter.

Mode of Operation

Two modes of operation

Mode – 1: Continuous Conduction Mode

Mode – 2: Discontinuous Conduction Mode

Mode 1: Continuous Conduction Mode Operation

Operation of the circuit is described with the help of the Phasor diagram as shown in figure 2.

Bold line ⇒ Upper arms of the Bridge

Dotted Line ⇒ Lower arms of the Bridge

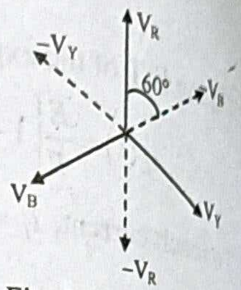


Fig: 2 Phasor diagram

Step 1: For $\alpha < 60°$ the continuous mode is possible.

Here, SCR1 is triggered at $\alpha < 60°$ (figure 2)

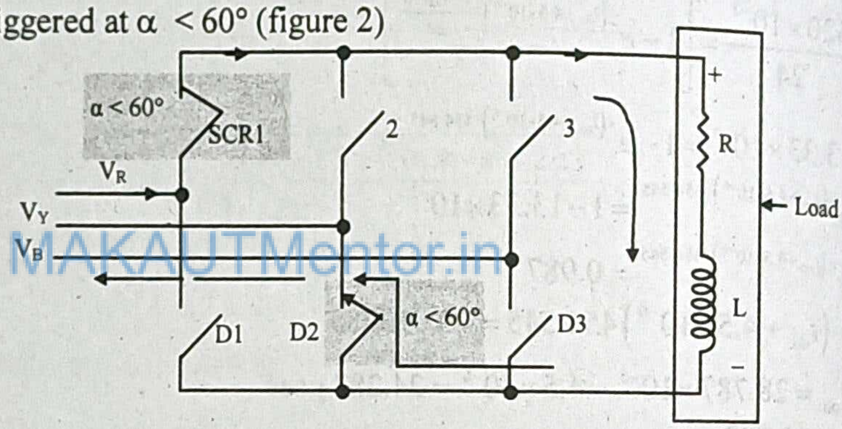


Fig: 3 Continuous mode where $\alpha < 60°$

The current path is shown by the equivalent circuit. (figure 3).

The current starting from phase R returns to phase Y. Through SCR1 →R→L→D2.

Step 2: Now, the diode D3 is more negative then diode D2. So, current return path shift to phase B from phase Y. SCR1 still continue to conduct. The current path is shown by the equivalent circuit.

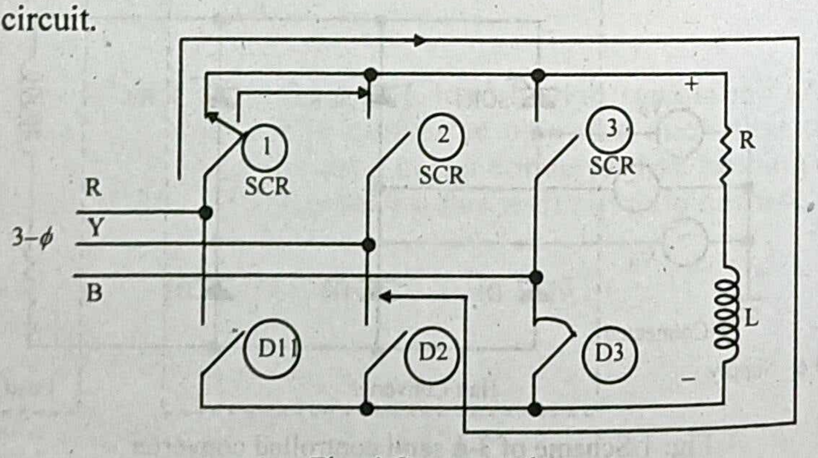


Fig: 4 Current path

The current starts from phase R and terminates at phase B through

SCR1 →R→L→D3 (figure 4)

Step 3: SCR1 conducts for 120° from α, which is maximum conduction period for all the SCRs.

Step 4: The output voltage and current will be unidirectional.

Step 5: After 120°, SCR2 and D3 will conduct as phase Y-B has the highest value compared to other combination of phases.

Step 6: Now, diode D1 is more negative (as per phasor diagram) than D3. So, the current return path shifts to phase R from phase B following as in Step 2.

Step 7: The cycle continues.

Waveforms

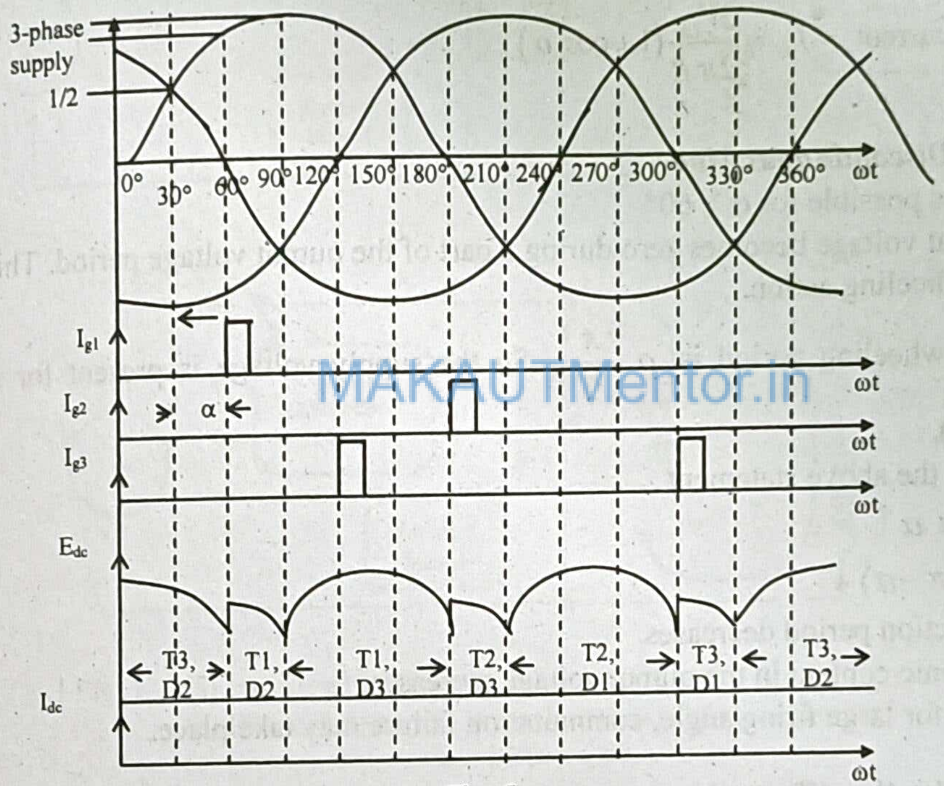


Fig: 5

Evaluating E_{dc}

From the wave form,

$$E_{dc}=\frac{\sqrt{3}\,E_{mph}}{2\pi}\left[\int_{\alpha+\frac{\pi}{3}}^{\frac{2\pi}{3}}\sin\omega t\,(d\omega t)+\int_{\pi/3}^{\frac{2\pi}{3}+\alpha}\sin\omega t\,(d\omega t)\right]$$

$$=\frac{3\sqrt{3}\,E_{mph}}{2\pi}\left[\left(-\cos\omega t\Big|_{\alpha+\frac{\pi}{3}}^{\frac{2\pi}{3}}\right)+\left(\cos\omega t\right)_{\frac{\pi}{3}}^{\frac{2\pi}{3}+\alpha}\right]$$

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

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

$$=\frac{3\sqrt{3}E_{mph}}{2\pi}\left[1+2.\sin\left(\frac{\pi}{2}+\alpha\right)-\sin\frac{\pi}{6}\right]=\frac{3\sqrt{3}E_{mph}}{2\pi}[1+\cos\alpha]$$

$\therefore$ Peak Line Voltage $=V_{Lm}=\sqrt{3}\ E_{mph}$

$$\therefore E_{dc}=\frac{3V_{Lm}}{2\pi}(1+cos\,\alpha)$$

d.c. load current $=I_{dc}=\dfrac{3V_{Lm}}{2\pi R}(1+cos\ \alpha)$

Mode 2: Discontinuous Mode

- This is possible for $\alpha > 60°$
- Output voltage becomes zero during a part of the output voltage period. This is due to freewheeling action.
- Free wheeling period is $\left(\alpha-\dfrac{\pi}{3}\right)$. So the supply voltage is present for the period $(\pi-\alpha)$.
- From the above statement

  as $\alpha\uparrow$

  $(\pi-\alpha)\downarrow$

$\therefore$ Conduction period decreases.

$\Rightarrow$ Harmonic content in the output voltage increases.

- Even for large firing angle, commutation failure may take place.

5. Describe the effect of source inductance on the DC output voltage of a single phase full controlled bridge rectifier. **[WBUT 2015, 2016]**

Answer: ***Refer to Question No. 2(a) of Short Answer Type Questions.***

6. How the power factor of a single phase half-wave converter can be improved using freewheeling diode? Explain with proper circuit diagram and waveforms. **[WBUT 2016]**

Answer:

Circuit Diagram:

Fig. 1(a) shows that a diode (FWD) is connected across the R-L load. The diode is reverse biased when R-L load is drawing current from the source and forward biased when the SCR is reversed biased.

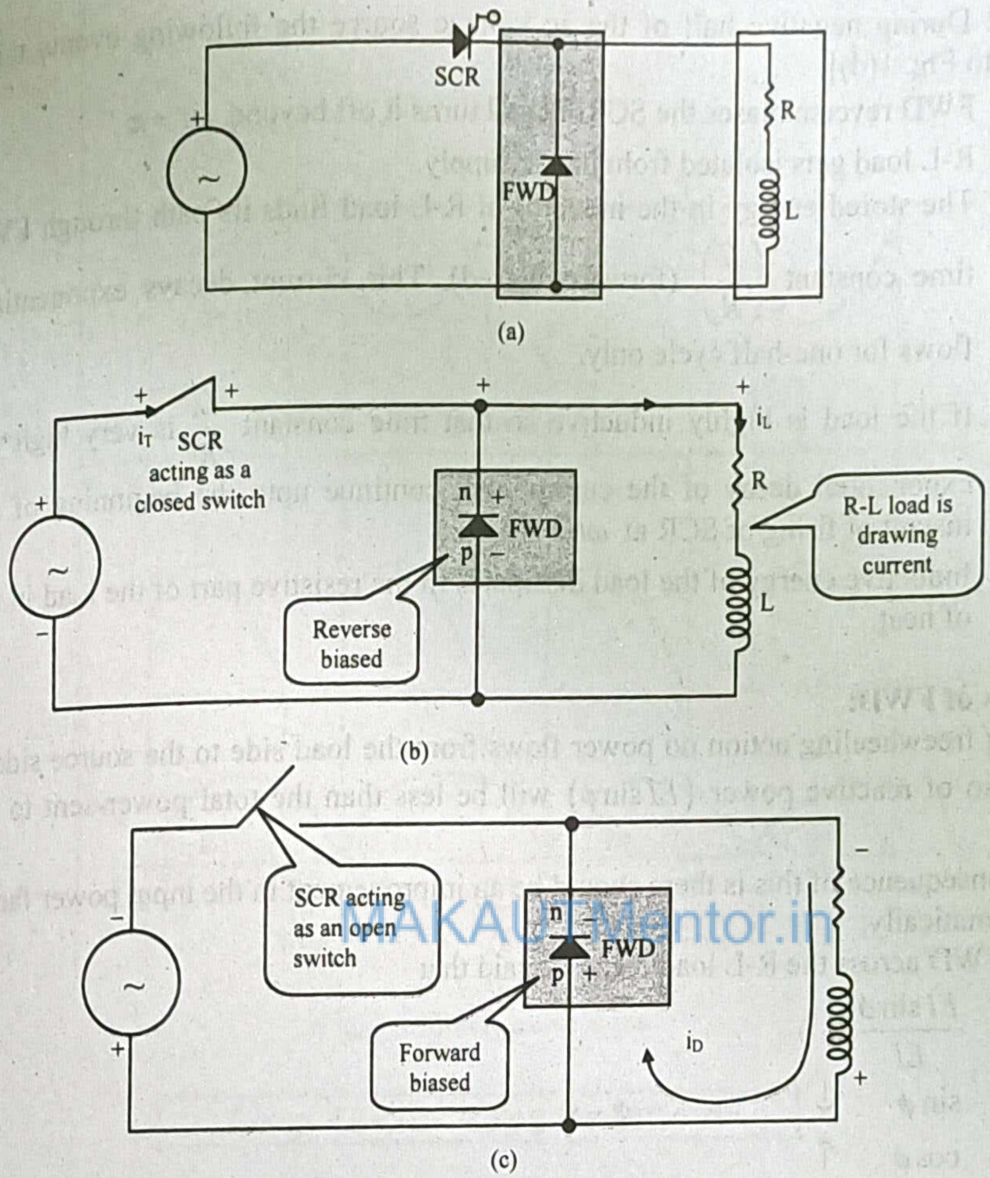


Fig: 1 (a) Inserting FWD across the R-L load
(b) Bias condition of FWD when load is drawing current
(c) Bias condition when SCR is OFF

Flywheel diode (FWD) basically acts as a commutating diode to allow the load current to flow through it and prevent it to SCR whenever the SCR goes into the reverse bias.

Circuit Operation:

Step 1: During positive half-cycle the following events occur

- Voltage is induced in the inductor (L) following Faraday's laws of induction.
- Current flows through SCR and R-L. The SCR current (i_T) will be same as the load current (i_L).
- FWD is reverse biased. [Fig. 1(c)] so it does not take any active role in the operation of the circuit during $\omega t = \alpha$ to $\omega t = \pi$

Step 2: During negative half of the ac voltage source the following events take place [Refer to Fig. 1(d)]

- FWD reverse biases the SCR(T) and turns it off beyond $\omega t = \pi$.
- R-L load gets isolated from the ac supply.
- The stored energy in the inductor of R-L load finds its path through FWD with time constant $\left(\frac{L}{R}\right)$ (forward biased). This current decays exponentially and flows for one-half cycle only.
- If the load is highly inductive so that time constant $\frac{L}{R}$ is very high then the exponential decay of the current will continue upto the beginning of the next instant of firing of SCR at $\omega t = 2\pi + \alpha$.
- Inductive energy of the load dissipates in the resistive part of the load in the form of heat.

Effects of FWD:

During freewheeling action no power flows from the load side to the source side. Hence the ratio of reactive power $(EI\sin\phi)$ will be less than the total power sent to the load (EI).

The consequence of this is there should be an improvement in the input power factor.

Mathematically,

With FWD across the R-L load it can be said that

$$\frac{EI\sin\phi}{EI}\downarrow$$

$$\Rightarrow \quad \sin\phi \downarrow \quad \Rightarrow \quad \phi \downarrow$$

$$\Rightarrow \quad \cos\phi \uparrow$$

$\therefore$ The power factor improves.

Waveforms:

Fig. 2 shows different waveforms for supply voltage, firing pulses, load voltage and load current.

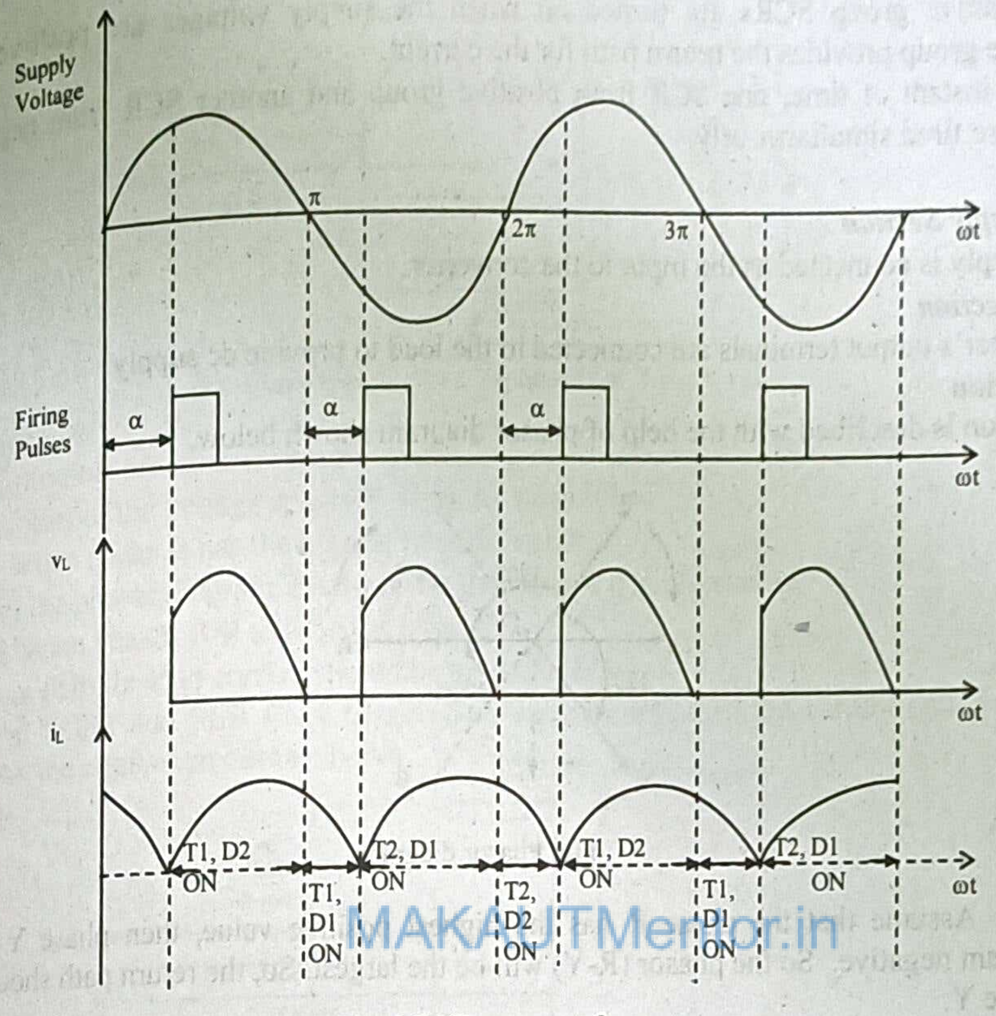


Fig: 2 Different waveforms

Long Answer Type Questions

1. A 3-phase full converter is connected to a resistive load. Show that the average output voltage is given by

$$V_o = \frac{3\sqrt{3}\,V_{mp}}{\pi}\left[1+\cos\left(\alpha+\frac{\pi}{3}\right)\right] \text{ for } \frac{\pi}{3} < \alpha < \frac{2\pi}{3}$$

where V_{mp} = maximum of phase voltage. **[WBUT 2007]**

Answer:

3-φ Fully Controlled Bridge Rectifier with Resistive Load

Circuit Description

Converter Section

Circuit comprises of six SCRs, which are divided into two groups– positive group and negative group.

Positive group is formed by SCRs 1, 2 and 3 and negative group is formed by SCRs 4, 5 and 6.

The positive group SCRs are turned on when the supply voltages are positive and negative group provides the return path for the current.
At any instant of time, one SCR from positive group and another SCR from negative group are fired simultaneously.

3-ϕ Supply Section
3-ϕ Supply is connected as the input to the converter.
Load Section
Converter's output terminals are connected to the load to provide dc supply.
Operation
Operation is described with the help of phasor diagram shown below.

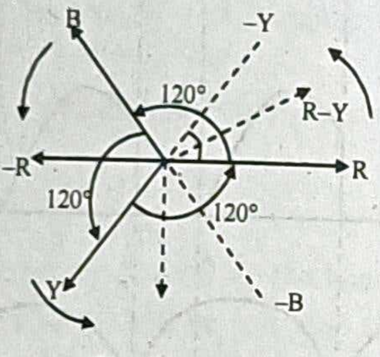


Fig: Phasor diagram

Step 1: Assume that the phase R has the highest positive value, then phase Y is at maximum negative. So the phasor (R-Y) will be the largest. So, the return path should be to Phase Y.

Step 2: If SCR1 and SCR5 are triggered simultaneously, then the current will follow the path as shown by the equivalent circuit in the figure.

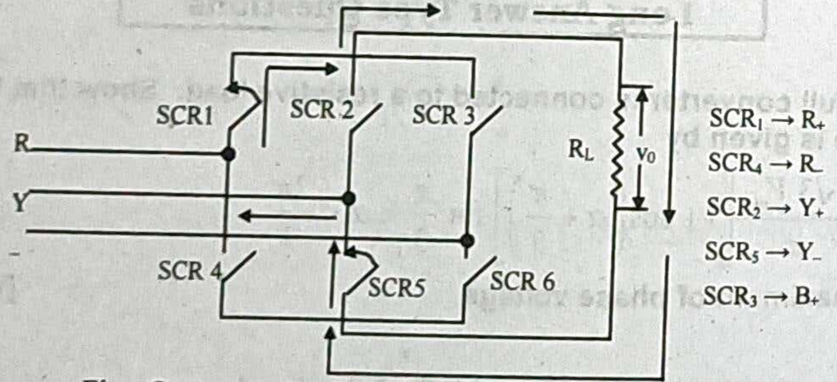


Fig: Current path when R-phase is as highest value

Step 3: So, when Phase Y has the highest value then phase B has the maximum negative value and hence phasor Y-B will be the largest. So, the return path for load current should be to phase B. in the figure.
Step 4: If SCR2 and SCR6 are triggered simultaneously. They the current path will be shown by the equivalent circuit.

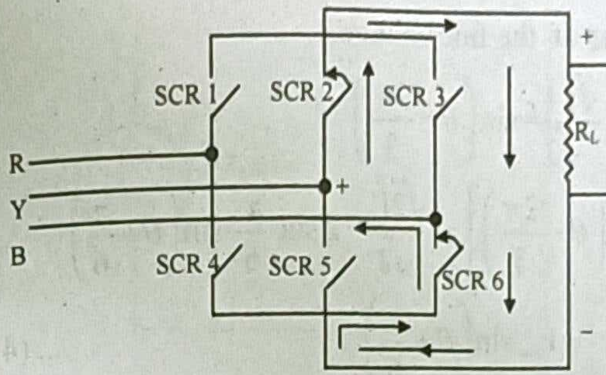


Fig: Current path when Y-phase is at highest value

It is noted that

- direction of load current remains same.
- polarities of the voltage across R_L remains same.

Step 5: When phase B has the highest positive value,

- from the phasor diagram. Phase-R has the highest negative value.
- and hence Phasor B-R will be the largest.
- return path for load current should be to phase R.

Step 6: If SCR3 and SCR 4 are triggered simultaneously, then the current path will be shown by the equivalent circuit shown.

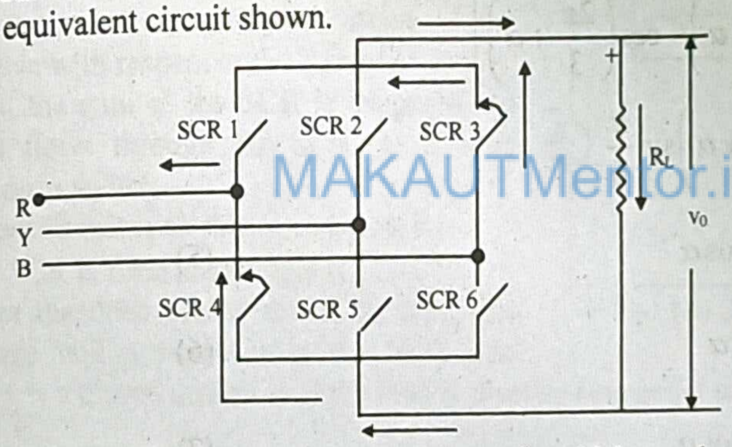


Fig: Current path when B-phase is at highest value

Step 7: The sequence continues.

Mathematical Analysis

Choosing the interval from the instant of triggering for the positive group of SCRs in R – Phase, we can say

$$v_O = v_R - v_Y \quad \text{... (1)}$$

for $\alpha+\frac{\pi}{6} < \theta < \alpha+\frac{\pi}{2}$

$$v_R = V_m \sin\theta = \frac{\sqrt{2}V_L}{\sqrt{3}} \cdot \sin\theta \quad \text{.... (2)}$$

and $v_Y = Vm\sin\left(\theta-\frac{2\pi}{3}\right) = \frac{\sqrt{2}}{\sqrt{3}}V_L \sin\left(\theta-\frac{2\pi}{3}\right)$ .... (3)

$V_L \Rightarrow$ RMS value of the line voltage.

$$\therefore v_R - v_Y = \frac{\sqrt{2}V_L}{\sqrt{3}}\sin\theta - \frac{\sqrt{2}V_L}{\sqrt{3}}\sin\left(\theta - \frac{2\pi}{3}\right)$$

$$= \frac{\sqrt{2}V_L}{\sqrt{3}}\left[\sin\theta - \sin\left(\theta - \frac{2\pi}{3}\right)\right] = \frac{\sqrt{2}V_L}{\sqrt{3}}\cdot 2\sin\frac{\pi}{6}\cdot\sin\left(\theta + \frac{\pi}{6}\right)$$

$$= \sqrt{2}V_L\sin\left(\theta + \frac{\pi}{6}\right) = V_{Lm}\sin\left(\theta + \frac{\pi}{6}\right) \quad \text{.... (4)}$$

$\therefore$ Average DC voltage

$$= \frac{1}{\frac{\pi}{3}}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_o d\theta = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha}\sqrt{2}V_L\sin\left(\theta + \frac{\pi}{6}\right)d\theta$$

$$= \frac{3\sqrt{2}V_L}{\pi}\left[-\cos\left(\theta + \frac{\pi}{6}\right)\right]_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} = \frac{3\sqrt{2}V_L}{\pi}\left[\cos\left(\frac{\pi}{6} + \alpha + \frac{\pi}{6}\right) - \cos\left(\frac{\pi}{2} + \alpha + \frac{\pi}{6}\right)\right]$$

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

$$= \frac{3\sqrt{2}V_L}{\pi}\cdot 2\cdot\sin\left(\frac{\pi}{2} + \alpha\right)\sin\frac{\pi}{6}$$

$$= \frac{3\sqrt{2}}{\pi}V_L\cdot\cos\alpha \quad \text{.... (5)}$$

$$= \frac{3}{\pi}V_{Lm}\cdot\cos\alpha \quad \text{.... (6)}$$

$$= \frac{3\sqrt{3}}{\pi}V_{mph}\cos\alpha \quad \text{.... (7)}$$

The average DC current

$$I_{dc} = \frac{3\sqrt{3}V_{mph}}{\pi R}\cos\alpha \quad \text{.... (8)}$$

2. a) Explain the operation of a single phase half controlled bridge converter connected to R-L load. Show the waveforms of the output voltage, SCR current & source current for a firing angle & considering ripple free output current.
[WBUT 2008, 2018]

Answer:

1-ϕ Half-wave Controlled Rectifier

1. Circuit Diagram

The circuit diagram in the corresponding figure (A) is for 1-ϕ half wave controlled rectifier with resistive load.

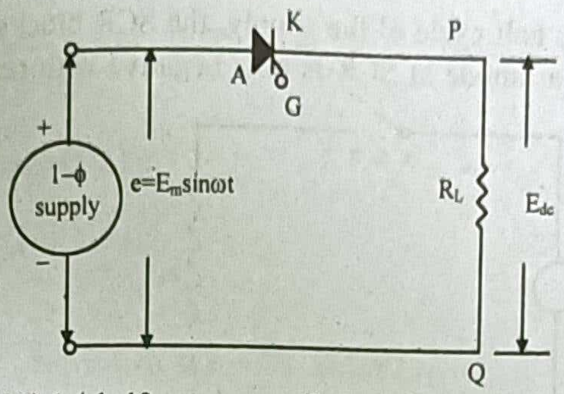


Fig: (A) 1-ϕ half-wave controlled rectifier with resistive load (R_L)

2. Circuit Description

An ac voltage $e = E_m \sin\omega t$ is fed to the rectifying circuit where, $E_m < V_{FB}$ & $< V_{RB}$ of the SCR.

[V_{FB} ⇒Forward Blocking Voltage

V_{RB} ⇒ Reverse Blocking Voltage]

The gate of the SCR is triggered with the help of a triggering circuit.

3. Circuit Operation

Step 1: During positive half-cycle, anode of the SCR is positive with respect to the cathode.

Step 2: Until the gate of the SCR is triggered, no load current flows through the SCR, as if it is acting as an open switch.

The equivalent circuit is as shown in figure B

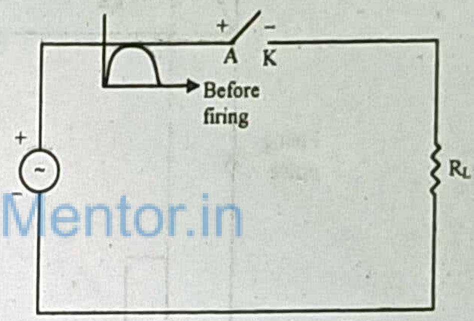


Fig: (B) SCR before firing

Step 3: The SCR is fired at an angle α.

If we neglect the drop across the SCR, then full supply voltage will appear across the load, i.e., SCR behaves as a closed switch as if the load is directly connected with the source shown figure C.

A current will flow through the load resistance.

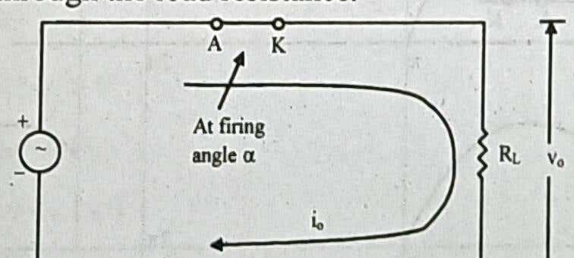


Fig: (C) SCR after firing

The *magnitude* of the current depends upon the

- amplitude of the supply voltage and
- R_L

Step 4: During the negative half cycle of the supply, the SCR blocks the flow of current (acting as an open switch) as anode of SCR is now negative with respect to the cathode shown in figure D.

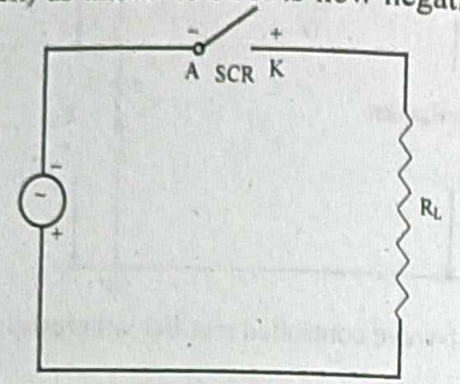


Fig: (D) SCR facing negative half cycle of the source

Waveforms

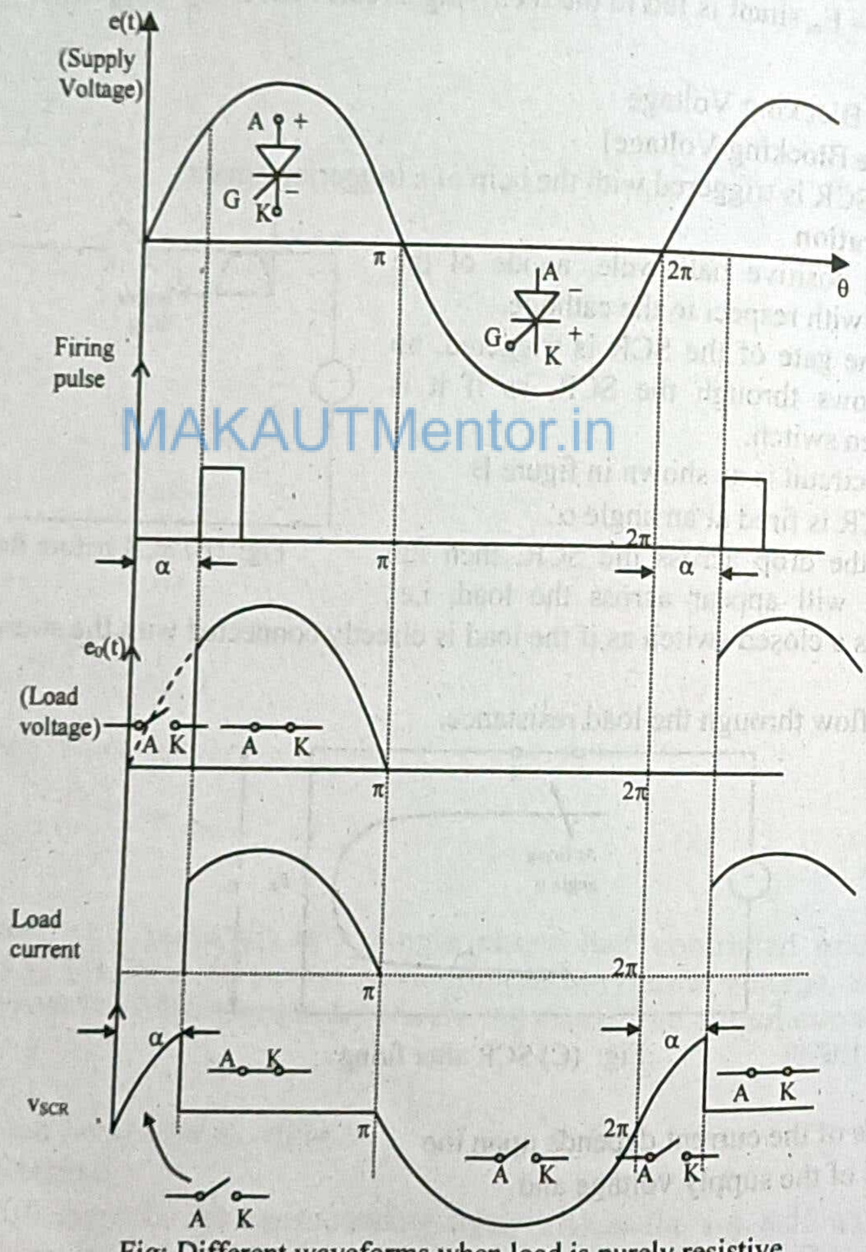


Fig: Different waveforms when load is purely resistive

b) Derive the expression for average & RMS value of output voltage for the converter mentioned in (a). **[WBUT 2008, 2018]**

Answer:

1. Average Load Voltage (V_{dc})

$$E_{dc} = \frac{1}{2\pi}\int_0^{\pi} e\, d(\omega t)$$

$$= \frac{1}{2\pi}\left[\int_0^{\alpha} E_m \sin \omega t\, d(\omega t) + \int_{\alpha}^{\pi} E_m \sin \omega t\, d(\omega t)\right]$$

$$= \frac{1}{2\pi}\left[0 + E_m \int_{\alpha}^{\pi} \sin \omega t\, d(\omega t)\right] = \frac{1}{2\pi} E_m \left[-\cos \omega t\right]_{\alpha}^{\pi}$$

$$E_{dc} = \frac{E_m}{2\pi}(1+\cos\alpha) \qquad \ldots (1)$$

From the above expression we conclude

1) As $\alpha\downarrow$, $\cos\alpha\uparrow$

$\therefore V_{dc}\uparrow$

2) When $\alpha = 0°$

$$v_{dc} = \frac{2E_m}{2\pi} = \frac{E_m}{\pi} \qquad \ldots (2)$$

$\Rightarrow$ Maximum Output Voltage

3) When $\alpha = 180°$

$$v_{dc} = \frac{E_m}{2\pi}(1-1) = 0 \qquad \ldots (3)$$

$\Rightarrow$ No output voltage (Minimum)

2. Average Load Current

$$\bar{I}_\ell = \frac{E_m(1+\cos\alpha)}{2\pi R_L} \qquad \ldots (4)$$

$$\left.\begin{aligned}\bar{I}_\ell &= \bar{I}_{\ell\,\max} \text{ for } \alpha = 0° \\ \bar{I}_\ell &= O \text{ for } \alpha = 180°\end{aligned}\right\} \qquad \ldots (5)$$

$\bar{I}_\ell = O$ for $\alpha = 180°$

3. RMS Load Voltage

$$E_{rms} = \sqrt{\frac{1}{2\pi}\int_O^{\pi} E_m \sin\omega t)^2 d(\omega t)} \qquad \ldots (6)$$

For a given firing angle α

$$E_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_0^{\alpha}(E_m \sin\omega t)^2 d\omega t + \int_{\alpha}^{\pi}(E_m \sin\omega t)^2 d\omega t\right]}$$

$$= \sqrt{\frac{E_m^2}{2\pi}\int_{\alpha}^{\pi}\sin^2 \omega t\, d(\omega t)} = \sqrt{\frac{E_m^2}{2\pi}\int_{\alpha}^{\pi}\frac{(1-\cos 2\omega t)}{2}d(\omega t)}$$

$$= \sqrt{\frac{E_m^2}{2\pi}\left[\int_{\alpha}^{\pi}\frac{d(\omega t)}{2} - \int_{\alpha}^{\pi}\frac{\cos 2\omega t\; d(\omega t)}{2}\right]} = \sqrt{\frac{E_m^2}{2\pi}\left[\frac{\omega t}{2}\Big|_{\alpha}^{\pi} - \frac{\sin 2\omega t}{4}\Big|_{\alpha}^{\pi}\right]}$$

$$= \sqrt{\frac{E_m^2}{2\pi}\left\{\frac{\pi-\alpha}{2} + \frac{\sin 2\alpha}{4}\right\}} \quad [As \sin\pi = 0]$$

$$E_{rms} = E_m\sqrt{\left[\frac{\pi-\alpha}{4\pi} + \frac{\sin 2\alpha}{8\pi}\right]} \quad \ldots (7)$$

From the expression (7) we conclude

1) For $\alpha = 0°$

$$E_{rms} = E_m\sqrt{\frac{\pi}{4\pi} + \frac{\sin 0°}{8\pi}}$$

$$= \frac{E_m}{2} = \text{half of the peak value of the source voltage} \ldots (8)$$

2) For $\alpha = \pi$

$$E_{rms} = E_m\sqrt{\frac{\pi-\pi}{4\pi} + \frac{\sin 2\pi}{8\pi}} = 0 \quad \ldots (9)$$

3) For $\alpha = \frac{\pi}{2}$

$$E_{rms} = E_m\sqrt{\frac{\left(\pi - \frac{\pi}{2}\right)}{4\pi} + \frac{\sin 2\frac{\pi}{2}}{8\pi}} = E_m\sqrt{\frac{\pi}{8\pi} + \sin\pi}$$

$$= \frac{E_m}{2\sqrt{2}} = 0.35E_m \quad \ldots (10)$$

3. For a single phase *ac* voltage regulator feeding a resistive load, draw the waveforms of source voltage, gating signals, output voltage, source and output currents and voltage across SCRs. Describe its working with reference to the waveforms drawn. **[WBUT 2009, 2016]**

Answer:

This is also known semi-controlled or 2-pulse converter. Since, there are two SCRs in the circuit, so in a cycle two pulses are needed to fire the SCRs, one at a positive half-cycle and another at a negative half-cycle.

Circuit Diagram

Figure (a) shows the circuit diagram of a half-controlled rectifier with resistive load.

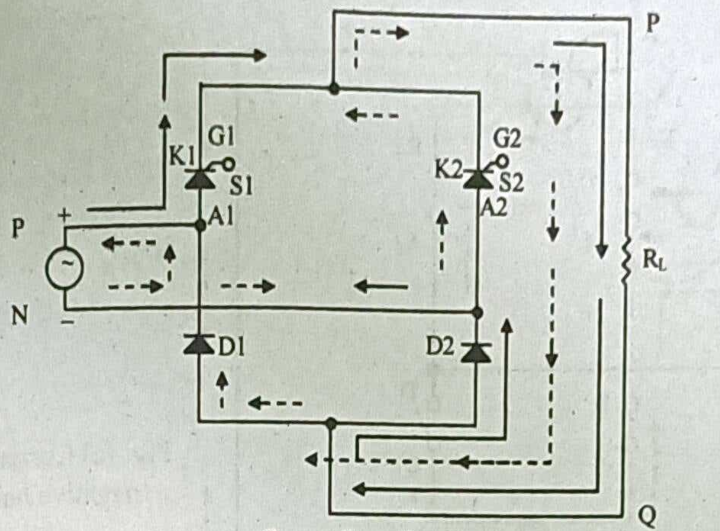


Fig: (a) Half-controlled bridge rectifier

Circuit Operation

Step 1: For positive half cycle

- S1 and D2 are forward biased and in the forward blocking state.
- S2 and D1 are Reversed biased and in the reverse blocking state.

Step 2: S1 is triggered at a firing angle α S1 and D2 conduct as shown in the equivalent circuit of figure (b).

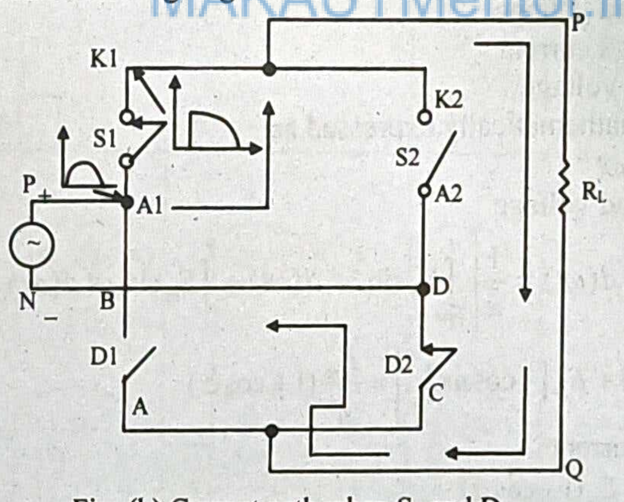


Fig: (b) Current path when S_1 and D_2 are conducting in positive half-cycle

The current flows through the path

$P_+ \rightarrow A1 \rightarrow K1 \rightarrow P \rightarrow Q \rightarrow C \rightarrow D \rightarrow N_-$ [figure (b)]

Load current flows till it is commutated by reversal of supply voltage at $\omega t = \pi$.

Step 3: During negative half cycle

- S2 and D1 are forward biased and in the forward blocking state
- S1 and D2 are in reverse blocking state.

Step 4: When S2 is triggered at an angle α with respect to π. (i.e., π+α with respect to 0°) S2 and D1 conduct. The equivalent circuit looks like in figure (c).

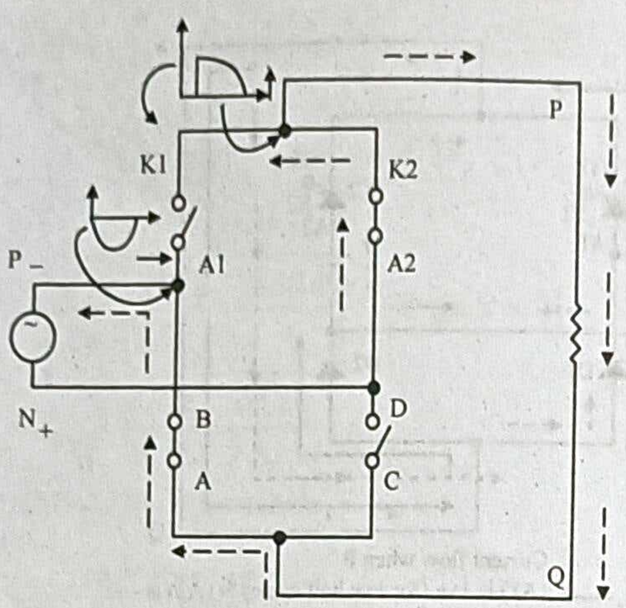


Fig: (c) Current path for negative half cycle

The current flows through the path

$N_+ \rightarrow D \rightarrow A2 \rightarrow K2 \rightarrow P \rightarrow Q \rightarrow A \rightarrow A1 \rightarrow P_-$

[as shown by the dotted arrow in figure (c)]

The current flows till $\omega t = 2\pi$, where it gets the natural zero and S2 is turned off.

Step 5: For next consecutive cycles step 1 to step 4 continue.

Mathematical Analysis

Here, we are interested to find out the expressions of the following parameters

iv) Average dc load voltage

v) Average dc load current

vi) RMS DC load voltage

Let ac source be mathematically expressed as

$$e = E_m \sin\omega t \quad \ldots (1)$$

i) Average d.c. load voltage

$$\bar{e}_L = \frac{1}{\pi}\int_0^{\pi} e\, d(\omega t) = \frac{1}{\pi}\left[\int_0^{\alpha} E_m \sin\omega t\, d(\omega t) + \int_{\alpha}^{\pi} E_m \sin\omega t\, d(\omega t)\right]$$

$$= \frac{1}{\pi}\left[0 + E_m\left[-\cos\omega t\right]_{\alpha}^{\pi}\right] = \frac{E_m}{\pi}(1+\cos\alpha) \quad \ldots (2)$$

ii) Average load current

$$= \bar{I}_L = \frac{E_m(1+\cos\alpha)}{\pi.R} \quad \ldots (3)$$

iii) R.M.S. Load Voltage

$$e_{rms} = \sqrt{\frac{\int_{\alpha}^{\pi}(E_m \sin\omega t)^2\, d(\omega t)}{\pi}} = E_m\sqrt{\frac{\int_{\alpha}^{\pi}\sin^2\omega t\, d(\omega t)}{\pi}}$$

$$= E_m\sqrt{\frac{\int_{\alpha}^{\pi}(1-\cos 2\omega t)\, d(\omega t)}{2\pi}} = E_m\sqrt{\frac{\int_{\alpha}^{\pi} d(\omega t) - \int_{\alpha}^{\pi}\cos 2\omega t\, d(\omega t)}{2\pi}}$$

$$= E_m\sqrt{\frac{\omega t\Big|_{\alpha}^{\pi}}{2\pi} - \frac{\sin 2\omega t\Big|_{\alpha}^{\pi}}{4\pi}} = E_m\sqrt{\frac{(\pi-\alpha)}{2\pi} - \frac{(\sin\pi - \sin 2\alpha)}{4\pi}}$$

$$e_{rms} = E_m\sqrt{\left(\frac{\pi-\alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right)} \quad \ldots (4)$$

From the expression (4), we conclude

For $\alpha = 0$,

$$e_{rms} = E_m\sqrt{\frac{(\pi-0)}{2\pi} + \frac{\sin 0}{4\pi}} = \frac{E_m}{\sqrt{2}} \quad \ldots (5)$$

For $\alpha = \pi$,

$$e_{rms} = E_m\sqrt{\frac{(\pi-\pi)}{2\pi} + \frac{\sin 2\pi}{4\pi}} = 0 \quad \ldots (6)$$

Waveforms

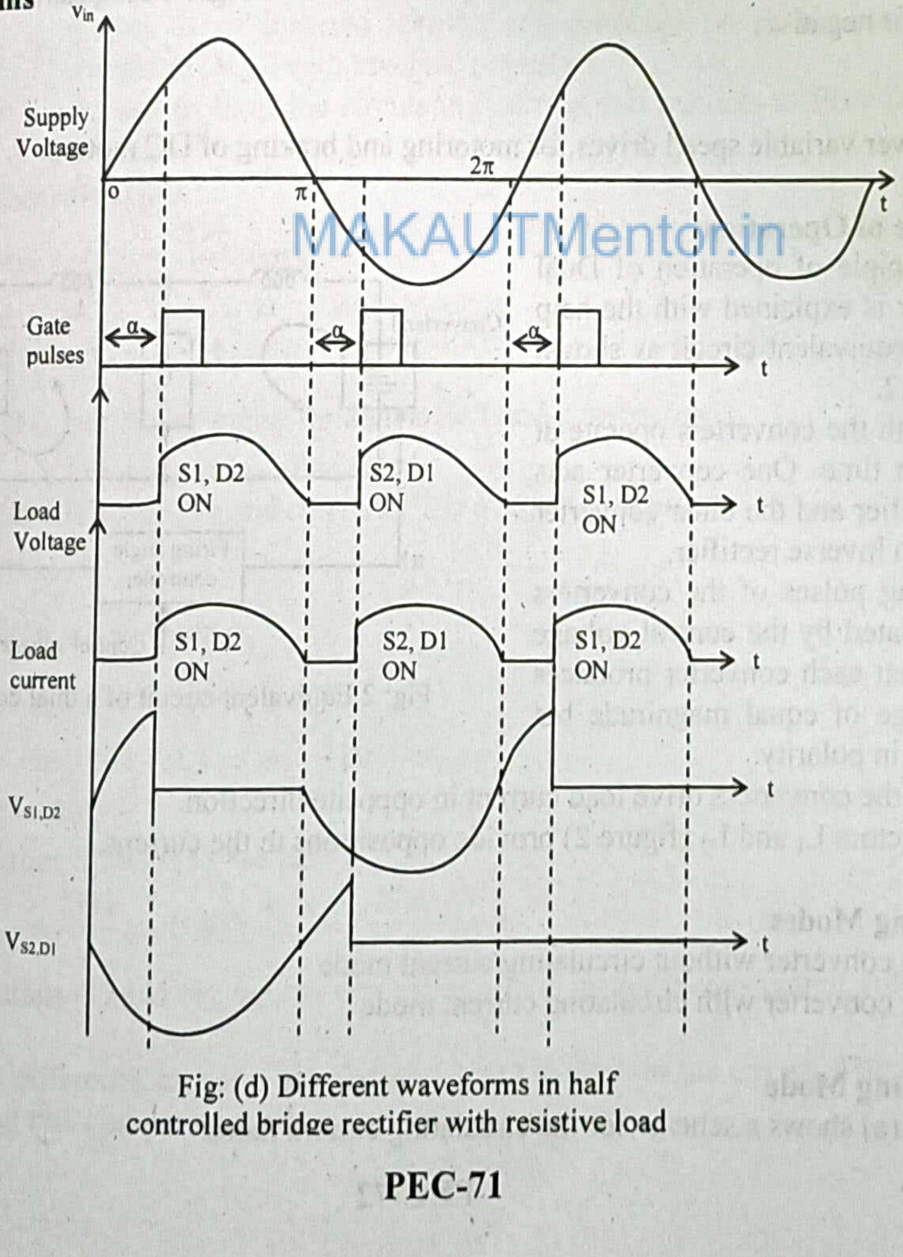


Fig: (d) Different waveforms in half controlled bridge rectifier with resistive load

4. a) Derive the expressions of average output voltage and load current for a 3φ full converter. Draw associated waveforms. **[WBUT 2010]**

Answer: *Refer to Question No. 1 of Long Answer Type Questions.*

b) Explain the operation of dual converter (circulating and non-circulating current mode). **[WBUT 2010]**

OR,

Write short note on Dual Converter. **[WBUT 2008, 2018]**

Answer:

Dual converter, as the name implies, comprises of two full converters, one is called positive converter and another is negative converter and is capable of performing all four quadrant operations as shown in figure 1.

Using this converter, by proper gating sequences, load current as well as load voltage may be made positive or negative.

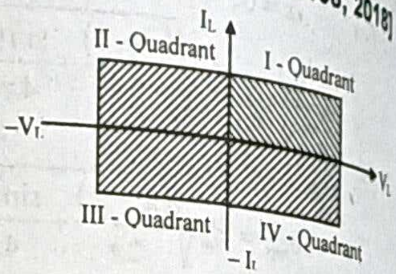


Fig: 1 Four quadrant operation

Use

High power variable speed drives for motoring and braking of DC motors.

Principle of Operation:

The principle of operation of Dual converter is explained with the help of ideal equivalent circuit as shown in figure 2.

Here, both the converters operate at the same time. One converter acts as a rectifier and the other converter acts as an inverse rectifier.

The firing pulses of the converters are regulated by the control voltage E_C, so that each converter produces dc voltage of equal magnitude but opposite in polarity.

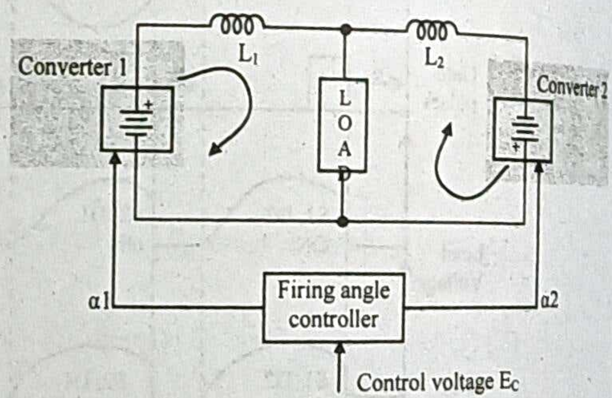


Fig: 2 Equivalent circuit of a dual converter

So, both the converters drive load current in opposite direction.

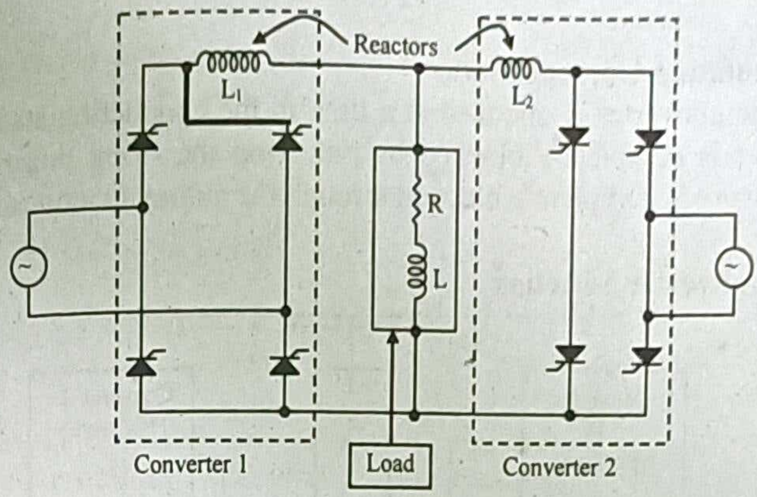
The inductors L_1 and L_2 (figure 2) provide oppositions to the current.

Operating Modes

1. Dual converter without circulating current mode
2. Dual converter with circulating current mode

Circulating Mode

Figure 2.(a) shows a scheme for the circulating current mode



Circulating Mode

Fig: 2 (a) Circulating current mode

Component Description

Converter - 1	Operates as a positive rectifier to produce an average output voltage (V_{dc1})
Converter - 2	Acts as an inverted rectifier and produces an equal average output voltage (V_{dc2}) with reversed polarity.
Reactor	Used to limit the circulating current and restricts to flow through the load.

Mathematical Analysis

For converter 1: $V_{dc1} = \frac{2V_m}{\pi}.\cos\alpha_1$ ...(1)

For converter 2: $V_{dc2} = \frac{2V_m}{\pi}\cos\alpha_2$ ...(2)

where, α_1 & $\alpha_2 \Rightarrow$ firing angles for converter 1 and 2 respectively.

$V_m \Rightarrow$ peak value of ac supply

$\because$ Converter 1 is a positive and converter 2 is a negative rectifier.

$\therefore\ V_{dc1} = -V_{dc2}$

$\Rightarrow \frac{2V_m}{\pi} cos\ \alpha_1 = \frac{-2V_m}{\pi} cos\ \alpha_2$

$\Rightarrow \cos\alpha_1 = -\cos\alpha_2 \qquad [\because V_m \neq 0]$

$\Rightarrow \cos\alpha_1 = \cos(180° - \alpha_2) \Rightarrow \alpha_1 = 180° - \alpha_2$

$\Rightarrow \alpha_1 + \alpha_2 = 180°$ ...(3)

From equations (2) and (3), we get

$$V_{dc2} = \frac{2Vm}{\pi}\cos(180° - \alpha_1) = -\frac{2Vm}{\pi}\cos\alpha_1 \quad ...(4)$$

From equations (3) and (4), we say that the rectifiers instantaneous output voltages differ by 180°.

This phase difference causes a circulating current to flow in the circuit. The reactors L1 and L2 limit this circulating current.

Without Circulating Current Mode

Principle: One converter is operated at a time in the conducting state. At this time, the other converter is completely blocked by removing the firing pulses from the flow of circulating current is completely blocked through the automatic control of firing pulses.

Scheme for Converter Selection

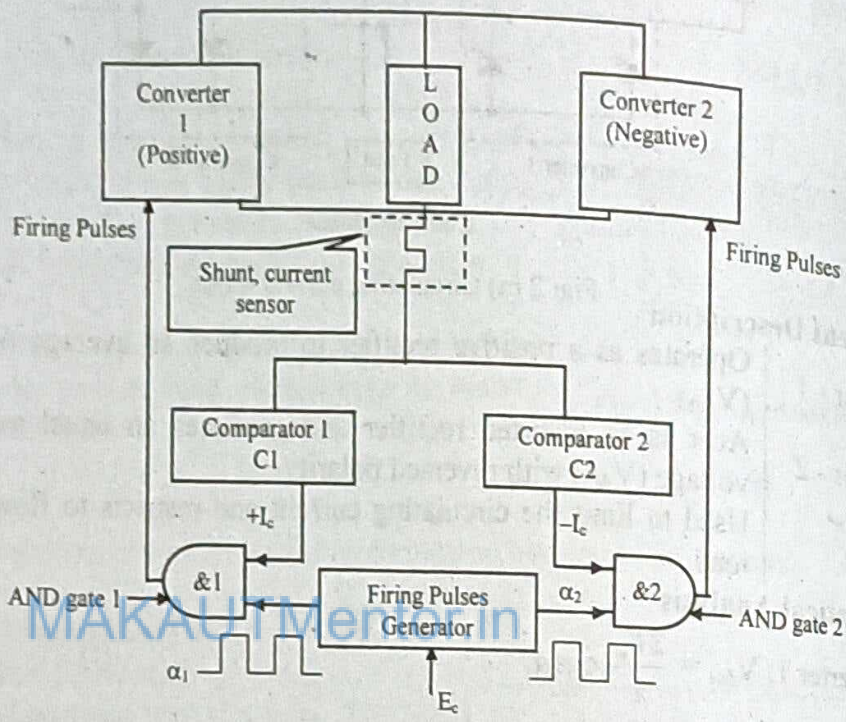


Fig: 3 Scheme for converter selection

In this scheme, firing pulse generator, comparators and current transducer act in conjunction to provide firing pulses to one converter and to block them to other converter. This blocking and de-blocking of firing pulses are done in accordance with the direction of load current. The toggling of converter conduction takes place when the current through the conducting converter reaches to zero.

At a particular instant, let converter1 is operating as a rectifier and is supplying load current, whereas pulses to converter2 are completely inhibited.

For the inversion operation, converter1 is first blocked when load current is reduced to zero and converter2 is made conducting by applying firing pulses to it.

Operation

Step 1: Assume that converter 1 is conducting (figure 3) and load current is sensed by the current sensor to give a positive voltage level.

Step 2: As long as load current gives positive voltage level

Comparator C1: produces high output

Comparator C2: produces low output

AND gate 1: Allows firing pulses to converter 1

AND gate 2 : As its one input is at logic 0, so it blocks the firing pulses (figure 4)

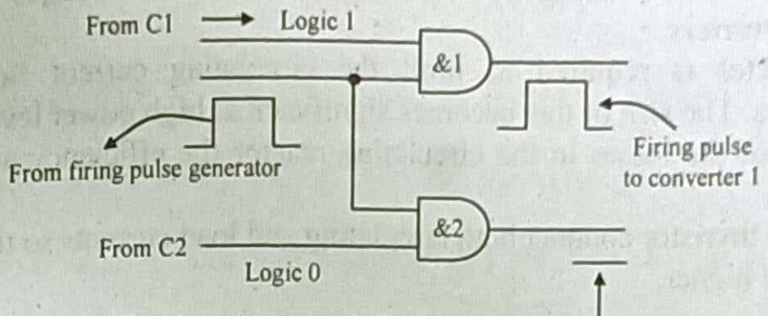


Fig: 4 Activating AND (&) gates

This process continues till the load current remains positive.

Step 3: Polarity of the control signal is reversed.

Step 4: The load current becomes negative. The moment load current becomes more negative than the reference value.

Comparator C2	:	Produces high output.
Comparator C1	:	Produces low output.
AND gate 1	:	Inhibits firing pulses to converter 1.
AND gate 2	:	Allows firing pulses to converter 2.

The scheme is shown in Fig 4.(a).

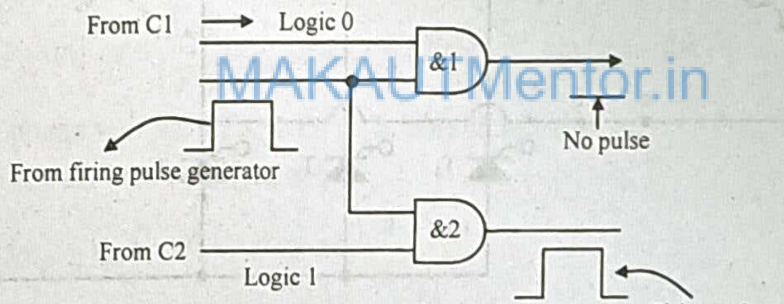


Fig: 4(a) Activating AND (&) gates

c) State the advantages and disadvantages of this scheme. **[WBUT 2010]**

Answer:

Advantages of circulating type dual converter and disadvantages advantages of non-circulating type dual converters

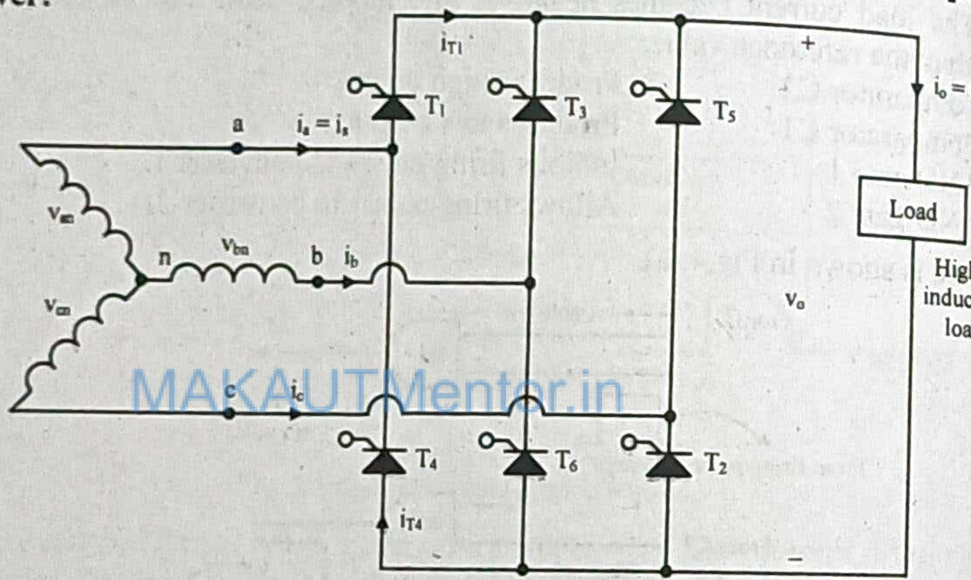
a) The circulating current maintains continuous conduction of both converters over the whole control range and independent of load.
b) Since both the converters are in continuous conduction the time response the time response of switching from one quadrant to other is faster.
c) Since one converter operates always as a rectifier and other converter operates as an inverter in either direction at any time is possible.

Disadvantages of circulating type dual converter and advantages of non- circulating type dual converters

a) An inductor is required to limit the circulating current flowing between the converters. The size of this becomes significant at high power levels.
b) Because of the losses in the circulating reactor the efficiency and power factor are low.
c) Since the thyristor conduct both circulating and load currents so the rating of thyristor should be higher.

5. a) With the help of associated waveforms & circuit diagrams, explain the principle of operation & derive the expression of average output voltage of a 3 phase full converter supplying a very high inductive load. [WBUT 2013]

Answer:



Three phase full converter is a fully controlled bridge controlled rectifier using six thyristors connected in the form of a full wave bridge configuration. All the six thyristors are controlled switches which are turned on at a appropriate times by applying suitable gate trigger signals.

The **three phase full converter** is extensively used in industrial power applications upto about 120kW output power level, where two quadrant operations is required. The figure shows a **three phase full converter** with highly inductive load. This circuit is also known as three phase full wave bridge or as a six pulse converter.

The thyristors are triggered at an interval of $\pi/3$ radians (i.e. at an interval of 30°). The frequency of output ripple voltage is $6f_s$ and the filtering requirement is less than that of **three phase semi and half wave converters.**

At $\omega t = \left(\frac{\pi}{6} + \alpha\right)$, thyristor is already conducting when the thyristor is turned on by applying the gating signal to the gate off. During the time period $\omega t = \left(\frac{\pi}{6} + \alpha\right)$ to

$\left(\frac{\pi}{2}+\alpha\right)$, thyristors and conduct together and the line to line supply voltage appears across the load.

At $\omega t=\left(\frac{\pi}{2}+\alpha\right)$, the thyristor T_2 is triggered and T_6 is reverse biased immediately and T_6 turns off due to natural commutation. During the time period $\omega t=(\pi+\alpha)$ to $\left(\frac{5\pi}{6}+\alpha\right)$, thyristor T_1 and T_2 conduct together and the line to line supply voltage appears across the load.

The thyristors are numbered in the circuit diagram corresponding to the order in which they are triggered. The trigger sequence (firing sequence) of the thyristors is 12, 23, 34, 45, 56, 61, 12, 23, and so on. The figure shows the waveforms of three phase input supply voltages, output voltage, the thyristor current through T_1 and T_4, the supply current through the line 'a'.

We define three line neutral voltages (3 phase voltages) as follows

$$v_{RN}=v_{an}=V_m\sin\omega t\,;\; V_m=\text{Max Phase Voltage}$$

$$v_{YN}=v_{bn}=V_m\sin\left(\omega t-\frac{2\pi}{3}\right)=V_m\sin(\omega t-120°)$$

$$v_{BN}=v_{at}=V_m\sin\left(\omega t+\frac{2\pi}{3}\right)=V_m\sin(\omega t+120°)=V_m\sin(\omega t-240°)$$

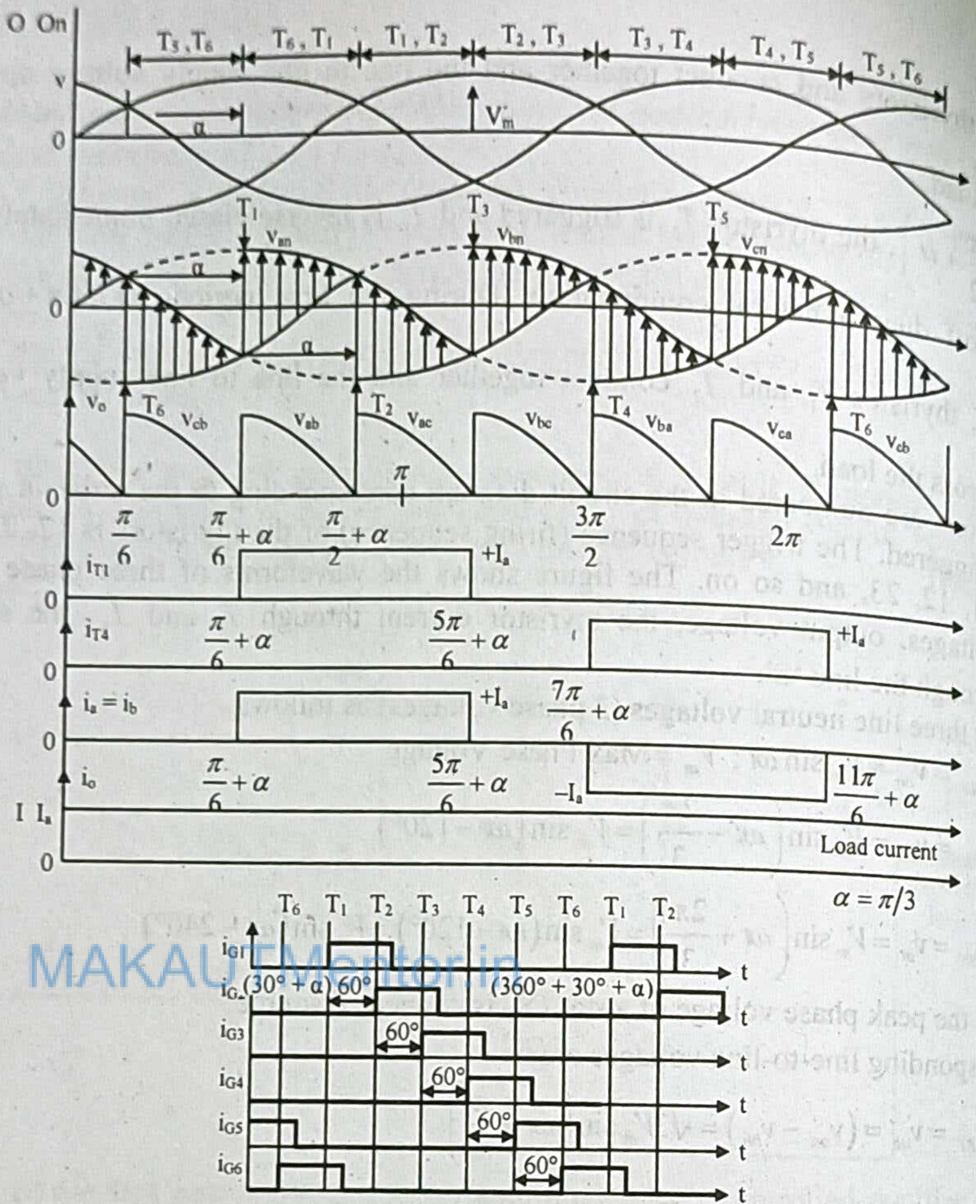
where V_m the peak phase voltage of a star (Y) is connected source.

The corresponding line-to-line voltages are

$$v_{RY}=v_{ab}=(v_{an}-v_{bn})=\sqrt{3}V_m\sin\left(\omega t+\frac{\pi}{6}\right)$$

$$v_{YB}=v_{bc}=(v_{bn}-v_{cn})=\sqrt{3}V_m\sin\left(\omega t-\frac{\pi}{2}\right)$$

$$v_{BR}=v_{ca}=(v_{cn}-v_{an})=\sqrt{3}V_m\sin\left(\omega t+\frac{\pi}{2}\right)$$



To derive an expression for the average output voltage of **three phase full converter** with highly inductive load assuming continuous and constant load current

The output load voltage consists of 6 voltage pulses over a period of 2π radians, hence the average output voltage is calculated as

$$V_{O(dc)} = V_{dc} = \frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_O\, d\,\omega t$$

$$v_O = v_{ab} = \sqrt{3}V_m \sin\left(\omega t + \frac{\pi}{6}\right)$$

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

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

where $V_{mL}=\sqrt{3}V_m=$ Max. line-to-line supply voltage

The maximum average dc output voltage is obtained for a delay angle $\alpha=0$

$$V_{dc(\max)}=V_{dm}=\frac{3\sqrt{3}V_m}{\pi}=\frac{3V_{mL}}{\pi}$$

The normalized average dc output voltage is $V_{dm}=V_n=\dfrac{V_{dc}}{V_{dm}}=\cos\alpha$

The rms value of the output voltage is found from

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

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

$$V_{O(rms)}=\left[\frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha}3V_m^2\sin^2\left(\omega t+\frac{\pi}{6}\right)d(\omega t)\right]^{\frac{1}{2}}$$

$$V_{O(rms)}=\sqrt{3}V_m\left(\frac{1}{2}+\frac{3\sqrt{3}}{4\pi}\cos 2\alpha\right)^{\frac{1}{2}}$$

b) A three phase fully controlled SCR bridge converter is supplied with 230 V (RMS) per phase. The source inductance per phase is 0.005 H. The load is highly inductive with constant load current of 20A. Compute –

i) firing angle for an output voltage of 436 V

ii) overlap angle. **[WBUT 2013]**

Answer:

Given data:

AC input r.m.s. voltage $=230\sqrt{3}$ volt

Source inductance $L_s=0.005\,\text{H}$

DC source voltage $E_b=400$ V

Load current $I_d=20$ A

Internal resistance $=1.8\ \Omega$

(i) Firing angle $\alpha=?$

$V_{dc}=436$ V

Now using the relation

$$V_{dc}=\frac{3}{\pi}V_{max}\cos\alpha-\frac{3\omega L_s}{\pi}I_d$$

$$\Rightarrow\quad 436=\frac{3}{\pi}\times\sqrt{2}\times230\sqrt{3}\cos\alpha-\frac{3\times2\pi\times50\times0.005\times20}{\pi}$$

$$\Rightarrow\quad 436=\frac{3}{\pi}\times563.38\cos\alpha-30$$

$$\Rightarrow\quad 466=\frac{3}{\pi}\times563.38\cos\alpha$$

$$\Rightarrow\quad \cos\alpha=\frac{466\times\pi}{3\times563.38}=0.865$$

$$\Rightarrow\quad \alpha=\cos^{-1}0.865=30^\circ.$$

(ii) Overlap angle $\mu=?$

Using the equation

$$V_{dc}=\frac{3}{\pi}V_{max}\cos(\alpha+\mu)+\frac{3\omega L_s}{\pi}I_d$$

$$\Rightarrow\quad 436=\frac{3}{\pi}\times\sqrt{2}\times230\sqrt{3}\cos(\alpha+\mu)+\frac{3\times2\pi\times50\times0.005\times20}{\pi}$$

$$\Rightarrow\quad 436=\frac{3}{\pi}\times563.38\cos(\alpha+\mu)+30$$

$$\Rightarrow\quad 406=\frac{3}{\pi}\times563.38\cos(\alpha+\mu)$$

$$\Rightarrow\quad \cos(\alpha+\mu)=\frac{406\times\pi}{3\times563.38}$$

$$\Rightarrow\quad \cos(\alpha+\mu)=0.7542$$

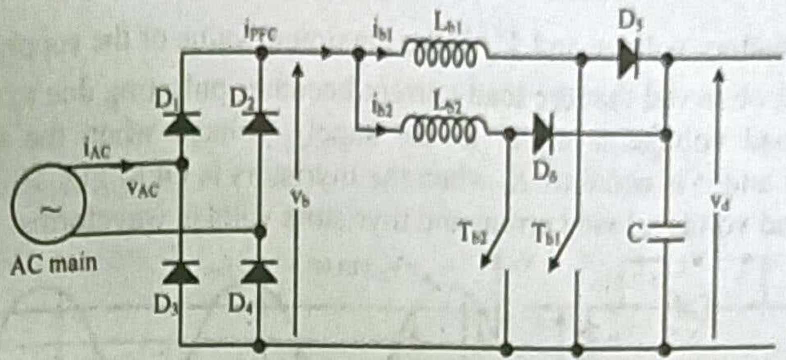
$$\Rightarrow\quad (\alpha+\mu)=\cos^{-1}0.7542=41^\circ$$

$$\Rightarrow\quad \mu=11^\circ \qquad [\text{Putting } \alpha=30^\circ].$$

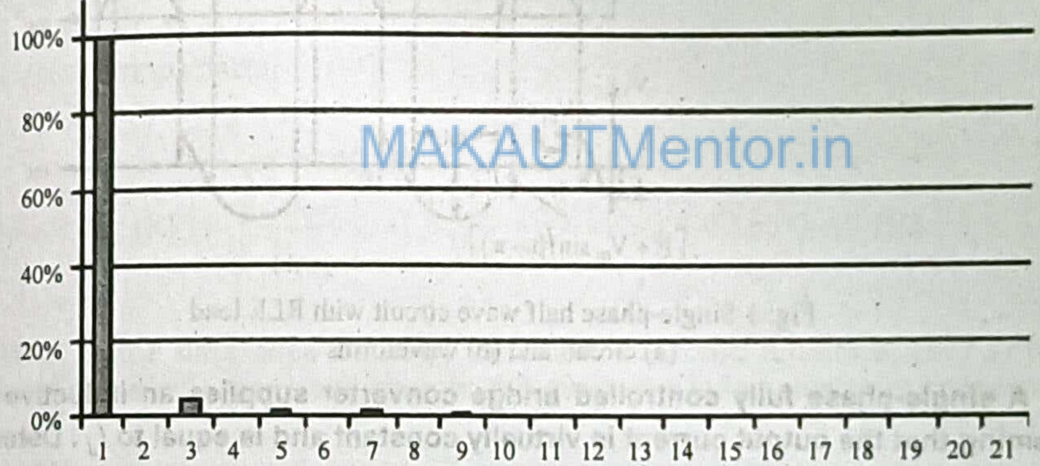
6. Explain with appropriate circuit diagram & waveforms, techniques to improve power factor of phase controlled converters. **[WBUT 2013]**

Answer:

In a linear system, the load draws purely sinusoidal current and voltage; hence the power factor is determined only by the phase difference between voltage and current. Industrial loads are mainly inductive hence power factor is less i.e. the phase difference between voltage and current is high. So improvement meant inpower factor is needed for efficient use of active power. An active approach is the most effective way to correct power factor of electronic supplies. Here, we place a dual boost converter between the bridge rectifier and the load. The converter tries to maintain a constant DC output bus voltage and draws a current that is in phase with and at the same frequency as the line voltage.



Conventionally, boost converters are used as active Power factor correctors. However, a recent novel approach for PFC is to use dual boost converter (fig. above) i.e. two boost converters connected in parallel. Where choke L_{b1} and switch T_{b1} are for main PFC while L_{b2} and T_{b2} are for active filtering the filtering circuit serves two purposes i.e. improves the quality of line current and reduces the PFC total switching loss. The reduction in switching losses occurs due to different values of switching frequency and current amplitude for the two switches. The parallel connection of switch mode converter is a well known strategy. It involves phase shifting of two or more boost converters connected in parallel and operating at the same switching frequency. Fig. below shows Harmonic content of current waveform obtained from dual boost converter



7. Explain with the necessary waveforms the principle of operation of 1-phase H.W phase controlled converter with RLE load and free wheeling diode (F.D). Discuss also the advantage. [WBUT 2014]

Answer:

Single-phase Half Wave Thyristor Rectifier with RLE Load:

A single-phase half wave controlled rectifier supplying on RLE load is shown in Fig. 1. The emf E may be the battery voltage or the back emf of a dc motor. The presence of a voltage source in the load tends to reverse bias the non-conducting SCR during the period, $\omega t = 0$ to $\omega t = \alpha_c$. Here, α_c is the critical angle, which is the minimum angle of delay for thyristors turn-on.

$$\alpha_c = \sin^{-1}\frac{E}{V_m}$$

where E is the battery voltage and V_m is the maximum value of the supply voltage. From Fig. 1, it is observed that the load current becomes pulsating due to the presence of emf E. The load voltage is equal to the supply voltage when the thyristors is in conducting state and it is equal to E when the thyristors is OFF. Fig. 1(b) also gives the trigger pulse, load voltage, load current and thyristors voltage waveforms.

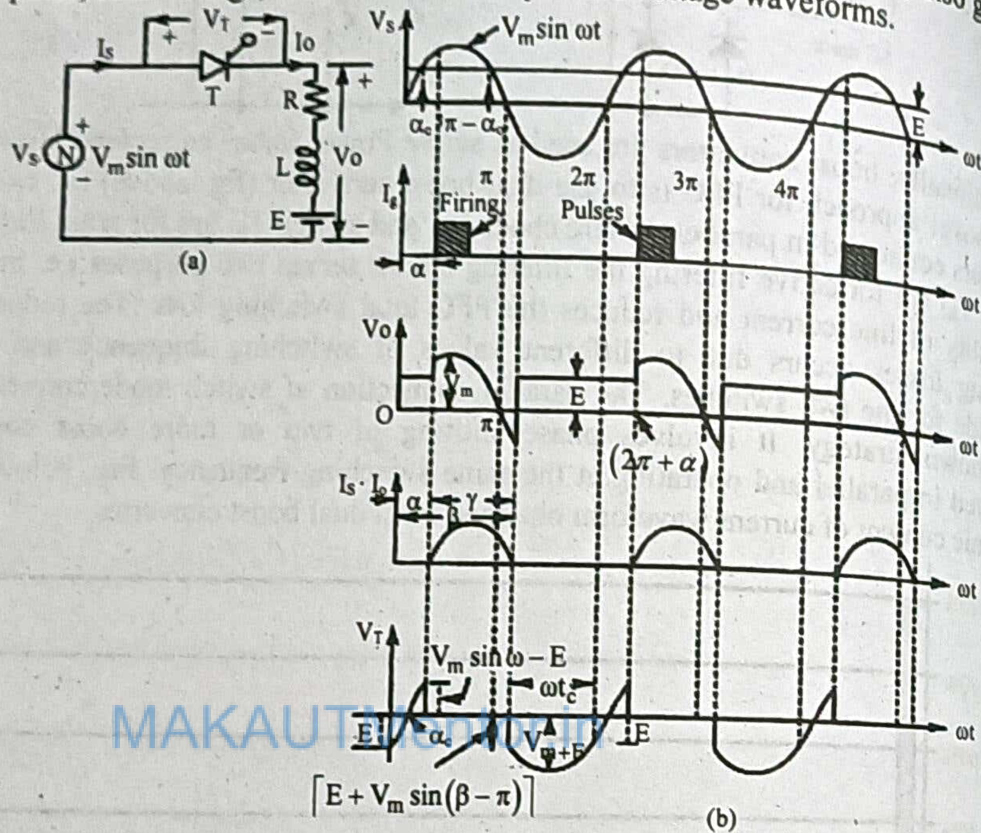


Fig: 1 Single-phase half wave circuit with RLE load
(a) circuit and (b) waveforms

8. a) A single-phase fully controlled bridge converter supplies an inductive load. Assuming that the output current is virtually constant and is equal to I_d. Determine the following performance measures if the supply voltage is 230V and if the firing angle is maintained at $\pi/6$ radians.
i) Average output voltage
ii) Supply RMS current
iii) Supply fundamental RMS current
iv) Fundamental power factor
v) Supply power factor
vi) Supply harmonic factor
vii) Voltage ripple factor. **[WBUT 2016]**

Answer:

Given data

$$I_{o(av)} = I_a$$

$$V_{s(rms)} = 230$$

$$\alpha = \frac{\pi}{6}$$

i) Average output voltage, $V_{o(av)} = \frac{2V_m}{\pi}\cos\alpha = \frac{2\times 230\times\sqrt{2}\times 0.866}{\pi} = 178.886\text{ V}$

ii) Supply RMS current, $I_{s(rms)} = I_{o(av)} = I_d$

iii) Supply fundamental RMS current, $I_{s1} = \frac{2\sqrt{2}I_{o(av)}}{\pi} = \frac{2\sqrt{2}I_d}{\pi} = 0.898I_d$

iv) Fundamental power factor

$$\text{DF} = \text{FPF} = \cos\phi_1 = \cos(-\alpha)$$

$$\phi_1 = -\alpha = \cos\alpha = \cos\frac{\pi}{6} = 0.866$$

v) Supply power factor, $\text{PF} = \frac{2\sqrt{2}}{\pi}\cos\alpha = \frac{2\sqrt{2}}{\pi}\cos\frac{\pi}{6} = \frac{2\sqrt{2}}{\pi}\times 0.866 = 0.7782$

vi) Supply harmonic factor

For 1ϕ full bridge converter with ripple free load current

$$\text{HF} = 0.4834 \text{ or } 48.34\%$$

vii) Voltage ripple factor

$$V_{o(rms)} = V_{s(rms)} = 230\text{ V}$$

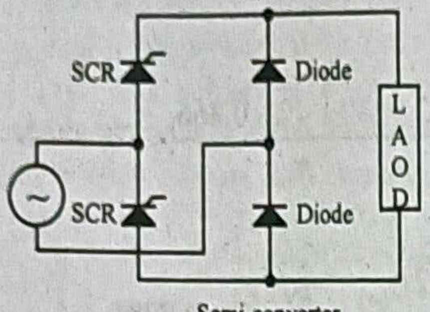
$$\text{Ripple factor (RP)} = \sqrt{\left[\frac{V_{o(rms)}}{V_{o(av)}}\right]^2 - 1} = \sqrt{\left(\frac{230}{178.886}\right)^2 - 1} = \sqrt{0.6531} = 0.808$$

b) What is the difference between semi-converter and full-converter? Why semi-converter is single quadrant whereas full-converter is two quadrant converters?
[WBUT 2016]

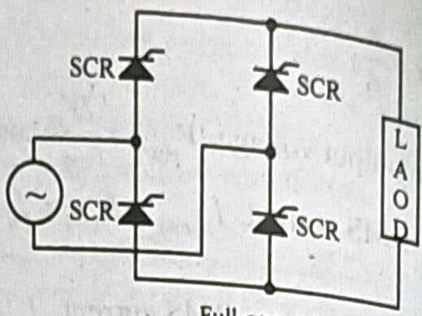
Answer:

1st Part:

Features	Semi converter	Full converter
Number of Thyristors	2	4
Number of diodes	2	Nil
Number of Conducting thyristors at any instant of time	1	2
Power Flow	Unidirectional	Bidirectional
Number of operational quadrants	1, has one polarity of output voltage and current,	2, It has either positive or negative of output voltage and which has only one polarity of output current, is called full converter.
Circuit Diagram	**Add from my book**	**Add from my book**



Semi-converter
(a)



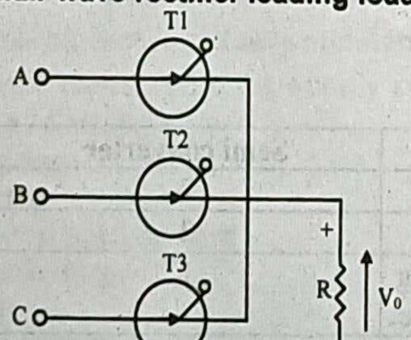
Full-converter
(b)

2nd Part:

(a) Full converter of fully controlled rectifier- $2t$ is a two-quadrant converter.

(b) Semi-converter or half-controlled rectifier- $2t$ is a single-quadrant (first quadrant) converter. It is a converter operates as a rectifier converting ac into dc, this refers to only one mode of operation called the rectifier mode. In this mode, power flow is from ac supply to the dc load. If the load contains a dc source such as batteries, this mode is also possible for the reverse flow of power, that is, from dc to ac. The converter has to operate in the inverter mode to permit this reverse power flow. Those converters using only SCRs and no diodes can operate in the inverter mode, provided the other necessary conditions are fulfilled. Such a converter is called two-quadrant converter. This is also called full-converter or fully-controlled rectifier from the above discussions it can be concluded that a full-converter permits power flow from ac to dc and from dc to ac, whereas a semi-converter permits power flow from ac to dc as a rectifier. If the output voltage pulses per cycle can be controlled for their duration of conduction, the converter producing such output voltage pulses are called full-wave controlled converters. If all the output voltage pulses are not controlled in this manner, the converter becomes an uncontrolled rectifier. If one or more than one of these voltage pulses are not controlled, the converter becomes half wave controlled converter.

9. a) For a 3-ϕ controlled half-wave rectifier leading load R as shown in the figure, **[WBUT 2017]**



Draw the waveforms for the output voltages for both conditions given below and also show that the average output voltage are given

by $V_0 = \begin{cases} \dfrac{3\sqrt{3}}{2\pi} V_{mp} \cos(\alpha); \text{ for } 0 < \alpha < \dfrac{\pi}{6} \\ \dfrac{3}{2\pi} V_{mp} \left[1 + \cos\left(\alpha + \dfrac{\pi}{6} \right) \right]; \text{ for } \dfrac{\pi}{6} < \alpha < \dfrac{5\pi}{6} \end{cases}$

where V_{mp} is the maximum value of phase voltage and α is the firing angle delay.

Answer:

This is also known as three-pulse converter.

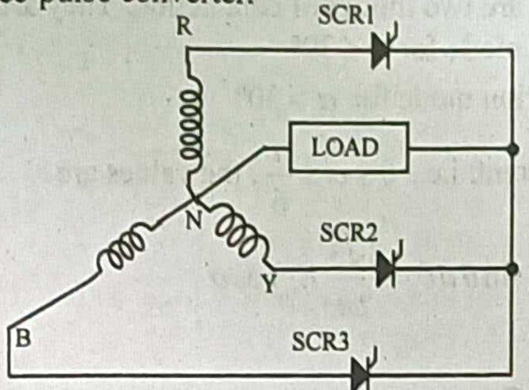


Fig: 1 Scheme of a 3-ϕ half-controlled rectifier

Here,

- At any given instant of time, only one SCR is conducting and conduction continues for 120° as the maximum conduction angle for each phase is 120°.
- No SCR can be fired below a phase angle of 30°, because SCR in one phase remains reverse biased by other phases.
- When SCR1 is fired at $\omega t = \left(\dfrac{\pi}{6} + \alpha \right)$ the phase voltage R appears across the load (R_L) till SCR2 is fired at $\omega t = \left(\dfrac{5\pi}{6} + \alpha \right)$.
- When SCR2 is fired, SCR1 and SCR3 remain reversed biased so remain off.

SCR2 continues to conduct for 120° Conduction angle till SCR3 is fired at $\omega t = \dfrac{3\pi}{2}$.

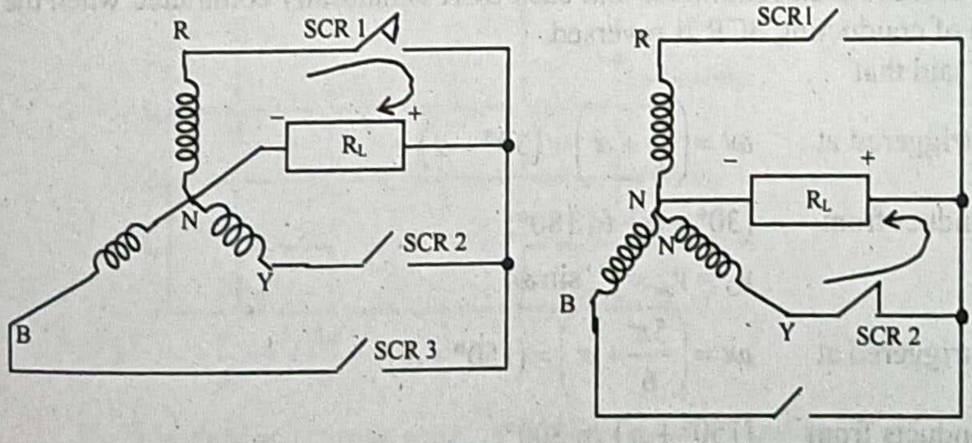


Fig: 2 Current paths (a) when SCR 1 is ON (b) SCR 2 is ON

$$\omega t = \left(\alpha + \frac{\pi}{6}\right) \text{ to } \left(\frac{5\pi}{6} + \alpha\right)$$

- At $\omega t = \frac{3\pi}{2}$, SCR3 is fired
- The output signal repeats itself three times in every cycle.

Modes of Conduction

For a resistive load, there are two modes of conduction. They are;
i) Continuous conduction mode for $\alpha \le 30°$
ii) Discontinuous conduction mode for $\alpha > 30°$

For a continuous load current, i.e., $0 \le \alpha \le \frac{\pi}{6}$, the values are

$$V_{dc} = \frac{3}{2\pi}\int_{\pi/6+\alpha}^{5\pi/6+\alpha} E_m \sin\theta\, d\theta = \frac{3\sqrt{3}}{2\pi} E_m \cos\alpha$$

$$I_{dc} = \frac{3\sqrt{3}}{2\pi R} E_m \cos\alpha$$

$$V_{rms}^2 = \frac{3}{2\pi}\int_{\pi/6+\alpha}^{5\pi/6+\alpha} E_m^2 \sin^2\theta\, d\theta$$

$$= \frac{3E_m^2}{2\pi}\left[\frac{5\pi}{6} + \alpha - \frac{\pi}{6} - \alpha - \frac{1}{2}\sin 2\left(\frac{5\pi}{6} + \alpha\right) + \frac{1}{2}\sin 2\left(\frac{\pi}{6} + \alpha\right)\right]$$

$$V_{rms} = \frac{E_m}{\sqrt{2}}\left[1 + \frac{3\sqrt{3}}{4\pi}\cos 2\alpha\right]^{1/2}$$

This rectifier is not used in practice, because of lower transformer utilization.

For $\alpha > \frac{\pi}{6}$

The load current is discontinuous and each SCR is naturally commuted when the polarity (voltage) of conducting SCR is reversed.
It can be said that

SCR1 is triggered at $\omega t = \left(\frac{\pi}{6} + \alpha\right) = (30° + \alpha)$

SCR1 conduct from $(30° + \alpha)$ to 180°;

$v_O = v_{an} = V_m \sin\omega t$

SCR2 is triggered at $\omega t = \left(\frac{5\pi}{6} + \alpha\right) = (150° + \alpha)$

SCR2 conducts from $(150° + \alpha)$ to 300°;

$$v_O = v_{bn} = V_m \sin(\omega t - 120°)$$

SCR3 is triggered at $\quad \omega t = \left(\frac{7\pi}{6} + \alpha\right) = (270° + \alpha)$

SCR3 conducts from $\quad (270° + \alpha)$ to 420°;

$$v_O = v_{cn} = V_m \sin(\omega t - 240°) = V_m \sin(\omega t + 120°)$$

∴Now from the wave forms shown, we have the average output voltage

$$E_{dc} = \frac{1}{\frac{2\pi}{3}} \int_{\frac{\pi}{6}+\alpha}^{\pi} E_m \sin\theta \, d\theta$$

$$= \frac{3E_m}{2\pi}\left[-\cos\theta\right]_{\pi/6+\alpha}^{\pi} = \frac{3E_m}{2\pi}\left[\cos\theta\right]_{\pi}^{\pi/6+\alpha}$$

$$= \frac{3E_m}{2\pi}\left[\cos\left(\frac{\pi}{6}+\alpha\right) - \cos\pi\right] = \frac{3E_m}{2\pi}\left[1+\cos\left(\frac{\pi}{6}+\alpha\right)\right]$$

The average output current is

$$I_{dc} = \frac{3E_m}{2\pi R}\left[1+\cos\left(\frac{\pi}{6}+\alpha\right)\right]$$

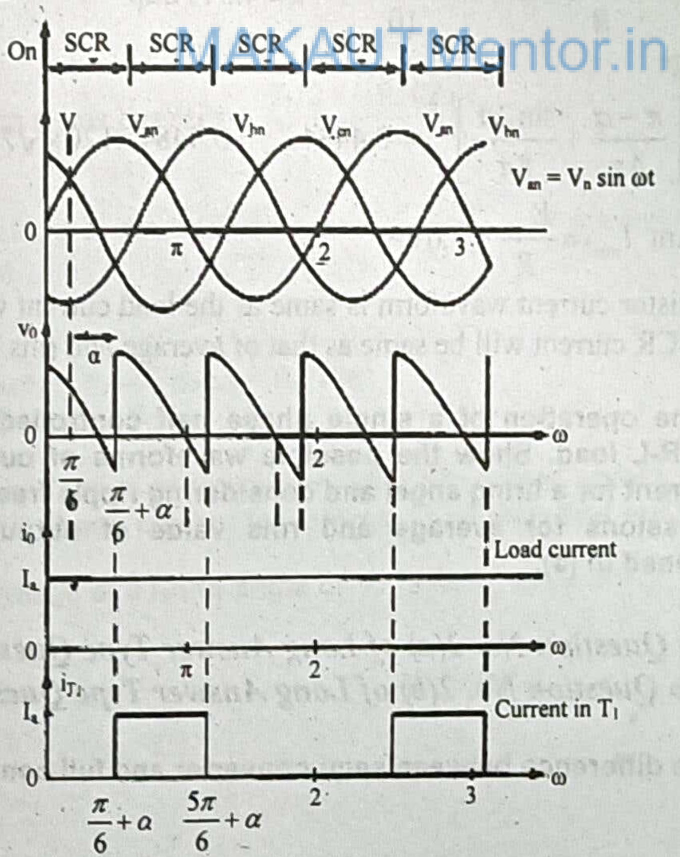


Fig: 3 Voltage and current waveforms for an inductive load in a three-phase half-wave controlled rectifier

b) A single-phase half-wave controlled converter is operated from a 120 V, 50 Hz supply. Load resistance $R = 10\Omega$. If the average output voltage is 25% of the maximum possible average output voltage, determine: (i) firing angle, (ii) r.m.s. and average output current, (iii) average and r.m.s. SCR current. **[WBUT 2017]**

Answer:

(i) We have E_{dc} (average output voltage) $= \frac{E_m}{2\pi}(1+\cos\alpha)$

The maximum output voltage is obtained when $\alpha = 0$

$$\therefore \quad E_{dc_{max}} = \frac{E_m}{\pi}$$

Given $E_{dc} = 25\%\left(\frac{E_m}{\pi}\right) = 0.25\frac{E_m}{\pi}$

$$\therefore \quad 0.25\frac{E_m}{\pi} = \frac{E_m}{2\pi}(1+\cos\alpha)$$

$\therefore$ Firing angle $\alpha = \frac{\pi}{3}$ or 60° and $E_{dc} = 0.238E_m$

(ii) Average output current

$$I_{dc} = \frac{E_{dc}}{R} = \frac{0.238E_m}{R} = \frac{0.238\times120\times\sqrt{2}}{10} = 4.04 \text{ Amp}$$

RMS output voltage

$$E_{rms} = E_m\left[\frac{\pi-\alpha}{4\pi} + \frac{\sin 2\alpha}{8\pi}\right]^{1/2} = 0.4484E_m = 0.4484\times120\times\sqrt{2} = 76.096 \text{ Volts}$$

$\therefore$ RMS load current $I_{rms} = \frac{E_{rms}}{R} = 7.61$ A

(iii) Since the thyristor current waveform is same as the load current waveform, therefore average and rms SCR current will be same as that of average and rms load current values.

10. a) Explain the operation of a single phase half controlled bridge converter connected with R-L load. Show the possible waveforms of output voltage, load current, SCR current for a firing angel and considering ripple free output current.
b) Derive expressions for average and rms value of output voltage for the converter mentioned in (a). **[WBUT 2018]**

Answer:

1st Part: *Refer to Question No. 2(a) of Long Answer Type Questions.*
2nd Part: *Refer to Question No. 2(b) of Long Answer Type Questions.*

11. a) What is the difference between semi-converter and full converter? **[WBUT 2019]**

Answer:

Refer to Question No. 8(b) (1st Part) of Long Answer Type Questions.

b) A single-phase fully controlled bridge converter is supplied from 230 V, 50 Hz ac supply and fed to a load which consists of $R = 20\Omega$ and large inductance, so that load current is constant and ripple free. If the firing angle is 30° find the

i) **average and rms of load voltage**
ii) **average and rms of thyristor current**
iii) **average and rms of source current and**
iv) **input power factor** **[WBUT 2019]**

Answer:

i) **Average load voltage** $= e_L = \frac{2E_m}{\pi}(\cos\alpha) = \frac{(2\times 230)}{\pi}(\cos 30°) = 126.80\text{V}$

rms load voltage: $e_{rms} = E_m\sqrt{\left(\frac{\pi-\alpha}{2\pi}+\frac{\sin 2\alpha}{4\pi}\right)}$

$$= E_m\sqrt{\frac{\frac{5\pi}{6}}{2\pi}+\frac{\sin\frac{\pi}{3}}{4\pi}} = 230\sqrt{\frac{5}{12}+\frac{\sqrt{3}}{2}} = 260.4\text{ V}$$

ii) **Average thyristor current** $I_T = \frac{E_m(1+\cos\alpha)}{\pi . R} = \frac{230(1+\cos 30°)}{\pi . 20} = 6.8307\text{A}$

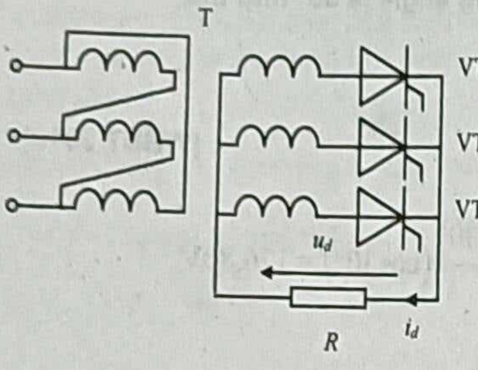
rms value of the thyristor current $= \frac{2\sqrt{2}\times 6.8307}{\Pi} = 6.149A$

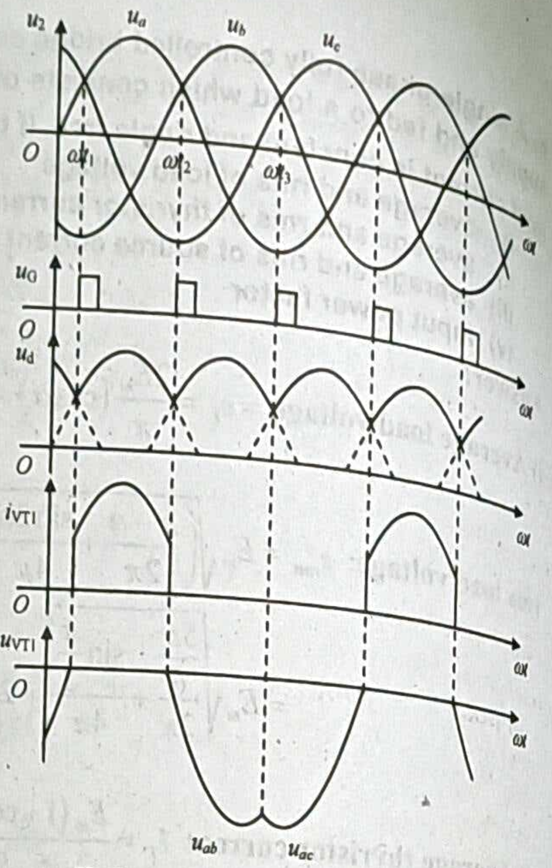
iii) Since the waveform is same so, the source average and rms current will be same as the thyristor current.

iv) **Input power factor** $= \frac{2\sqrt{2}}{\pi}\cos\alpha = 0.7796$

c) A three-phase half wave-controlled rectifier connected across R load. Draw the output voltage and phase current waveforms. And also find out the expression of average output voltage at a firing angle of ∞ [where, $0 < \infty < \frac{\pi}{6}$] **[WBUT 2019]**

Answer:
Resistive load, $\alpha = 0°$





In the case of a **three-phase half wave controlled** rectifier with resistive load, the thyristor T_1 is triggered at $\omega t = (30° + \alpha)$ and T_1 conducts up to $\omega t = 180°$ radians. When the phase supply voltage decreases to zero at, the load current falls to zero and the thyristor T_1 turns off. Thus T_1 conducts from $\omega t = (30° + \alpha)$ to $(180°)$.

Hence the average dc output voltage for a 3-pulse converter (3-phase half wave controlled rectifier) is calculated by using the equation

$$V_{dc} = \frac{3}{2\pi}\left[\int_{\alpha+30°}^{180°} v_0 d(\omega t)\right]$$

$v_0 = v_{an} = V_m \sin\omega t$, for $\omega t = (\alpha + 30°)$ to $(180°)$

$$V_{dc} = \frac{3}{2\pi}\left[\int_{\alpha+30°}^{180°} V_m \sin\omega t.\, d(\omega t)\right]$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[\int_{\alpha+30°}^{180°} \sin\omega t.\, d(\omega t)\right]$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[-\cos\omega t\right]_{\alpha+30°}^{180°}$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[-\cos 180° + \cos(\alpha + 30°)\right]$$

Since, $\cos 180° = -1$, we get $V_{dc} = \frac{3V_m}{2\pi}\left[1 + \cos(\alpha + 30°)\right]$

DC-DC CONVERTERS (CHOPPERS)

Multiple Choice Type Questions

1. Chopper control of DC motors provides variation in [WBUT 2007, 2010]
a) Input voltage b) frequency c) Current d) all of these

Answer: (a)

2. Complementary commutation is [WBUT 2010]
a) Class *C* chopper b) Class *D* chopper
c) Class *B* chopper d) Class *E* chopper

Answer: (a)

3. For a two quadrant type-A chopper, regenerative braking is [WBUT 2013, 2019]
a) possible at low speeds b) possible at high speeds
c) possible at both high & low speeds d) not possible at all

Answer: (c)

4. The features of chopper drives are [WBUT 2016]
a) smooth control but slow response
b) smooth control but fast response
c) fast response with smooth control but less efficient
d) none of these

Answer: (b)

5. In *dc* chopper, the load voltage is governed by [WBUT 2016]
a) number of thyristors used in the circuit
b) duty cycle of the circuit
c) *dc* voltage applied to circuit
d) none of these

Answer: (b)

6. A chopper, in which current remains positive but the voltage may be positive or negative, is known as [WBUT 2017]
a) Type-*A* b) Type-*B* c) Type-*C* d) Type-*D*

Answer: (b)

7. In a load commutated DC – DC chopper, the capacitor has a [WBUT 2018]
a) symmetric triangular voltage across itself
b) symmetric rectangular voltage across itself
c) symmetric trapezoidal voltage across itself
d) symmetric sinusoidal voltage across itself

Answer: (c)

8. A step up chopper has input voltage 110V and output voltage 150V. The value of duty cycle is **[WBUT 2018]**

a) 0.26 b) 0.45 c) 0.56 d) 0.78

Answer: (a)

Short Answer Type Questions

1. Draw neatly the circuit diagram of a four quadrant chopper and explain its operation. **[WBUT 2007]**

Answer:

Chopper configuration means the number of quadrants of the $V_0 - I_0$ diagram in which it can operate.

Number of quadrants are designated as–

Quadrant I ⇒ Here both output voltage and current are positive

Quadrant II ⇒ • Output voltage is positive
• Output current is reversed

Quadrant III⇒ • Output voltage polarity is reversed
• Output current is reversed

Quadrant IV ⇒• Output voltage polarity is reversed
• Output current flow is positive

This can be shown by the in fig. $V_0 - I_0$ diagram.

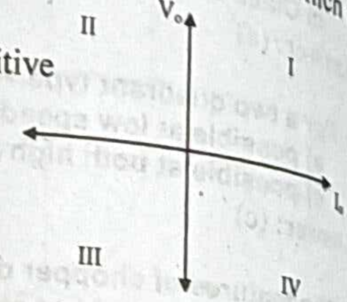


Fig: $V_o - I_o$ diagram

2. Explain the operation of buck-boost chopper with necessary calculation. **[WBUT 2011, 2018]**

Answer:

Buck - Boost Converter

A Buck-Boost converter can be realized by cascading two basic converters, the step-down and the step-up converters as shown in the fig. 1.

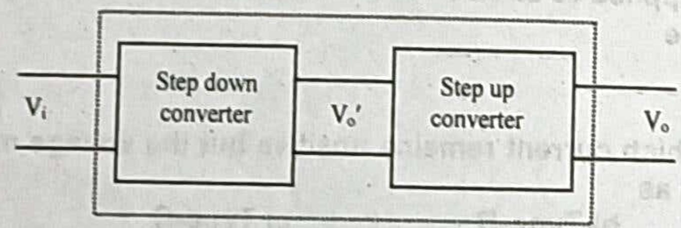


Fig: 1 Block diagram of back boost converter

$$\frac{V_o}{V_i} = \frac{V_o'}{V_i}\cdot\frac{V_o}{V_o'} = D\left(\frac{1}{1-D}\right) = \frac{D}{1-D} \quad ...(1)$$

The expression (1) says that

1) Both the converters should have same duty cycle.
2) Depending upon the duty cycle (D) the output voltage may be higher or lower than the input voltage.
3) If $V_o > V_i$, i.e., Boost effect then $\frac{D}{1-D} > 1$

$$\Rightarrow \quad D > 1 - D$$

or, $\quad 2D > 1$

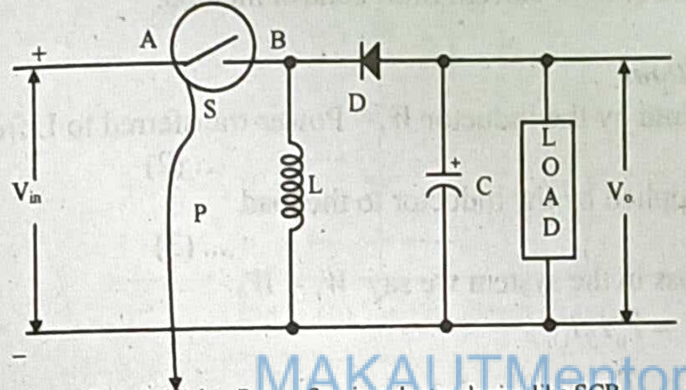
$$\Rightarrow \quad D > \frac{1}{2} \Rightarrow D > 0.5$$

4) If, $\frac{V_o}{V_i} < 1$, (i.e., Buck effect)

Then $\quad \frac{D}{1-D} < 1$

$$\Rightarrow \quad D < \frac{1}{2} \Rightarrow D < 0.5$$

Realization of the B - B Converter



Switch (S) is a Power Semiconductor device like SCR,

Fig: 2 circuit diagram of B-B converter

Circuit Operation

1. Referring to fig 1a, when the switch(S) in ON, the supply current flows following the path .

$V_{in+} \rightarrow A \rightarrow B \rightarrow L \rightarrow V_{in-}$

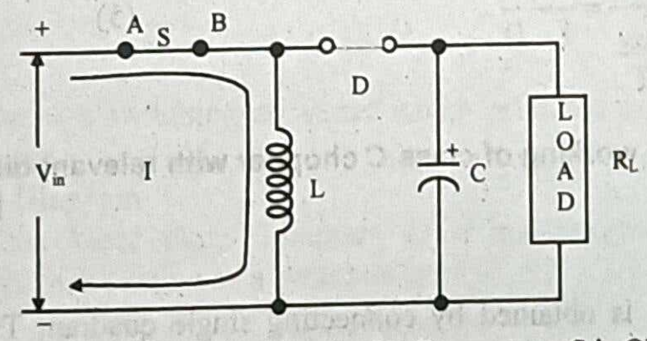


Fig: 2(a) Equivalent circuit of B-B convertor S is ON

Diode D behaves as open switch, as it is reverse biased. Hence, L stores energy during the T_{ON} period.

2.When the switch is OFF the energy stored in the inductor is transferred to the load, A current I follow the path $L_+ \rightarrow Load \rightarrow \rightarrow D \rightarrow L_-$ (figure 2 b).

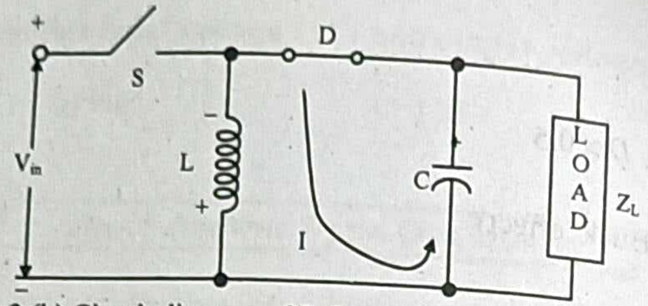


Fig: 2 (b) Circuit diagram of B-B converter when S is OFF

As the inductor current starts to decrease, the polarity of the induced e.m.f. in L is reversed which makes the diode (D) forward biased. A forward biased diode is viewed as a closed switch.

3. This sequence of T_{ON} and T_{OFF} is continued. The ON-Period and OFF-Period are controlled by PWM controller or current limit control method.

Mathematical Calculations

During T_{ON}, energy stored by the inductor W_i = Power transferred to L from the source × time = $V_{in} . I_S . T_{ON}$ ... (2)

During T_{OFF}, energy supplied by the inductor to the load

$$W_0 = V_o I_S . T_{Off} \quad \text{... (3)}$$

Assuming there is no loss in the system we say $W_i = W_0$

$$\Rightarrow \quad V_{in} I_s . T_{ON} = V_o I_S T_{OFF}$$

$$\Rightarrow \quad \frac{V_o}{V_{in}} = \frac{T_{ON}}{T_{OFF}} = \frac{T_{ON}}{T - T_{ON}}$$

$$\begin{bmatrix}\text{dividing numerator} \\ \text{\&denominator by T}\end{bmatrix} \quad \text{... (4)}$$

$$\Rightarrow \quad \frac{V_o}{V_{in}} = \frac{\frac{T_{ON}}{T}}{1 - \frac{T_{ON}}{T}} = \frac{D}{1-D} \quad \text{... (5)}$$

3. Explain briefly the working of class *C* chopper with relevant diagrams.

[WBUT 2013, 2016]

Answer:

Type C Chopper

This type of chopper is obtained by connecting single quadrant Type A and Type B choppers in parallel.Output voltage V_0 is always positive because of the presence of flywheel diode across the load.The $V_0 - I_0$ diagram of this type of chopper is as shown in the figure 1(a).

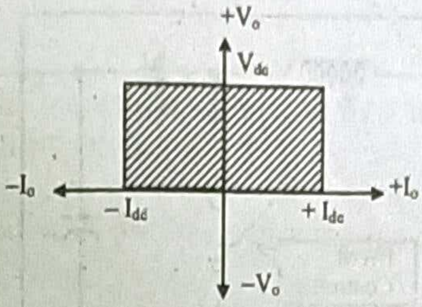


Fig: 1(a) V_o– I_o diagram of Type-C chopper

As it is a combination of Type A and Type B choppers, load current (I_0) direction may be both positive and negative.

Circuit Diagram

Fig. 1 (b) shows the circuit diagram of a two quadrant chopper.

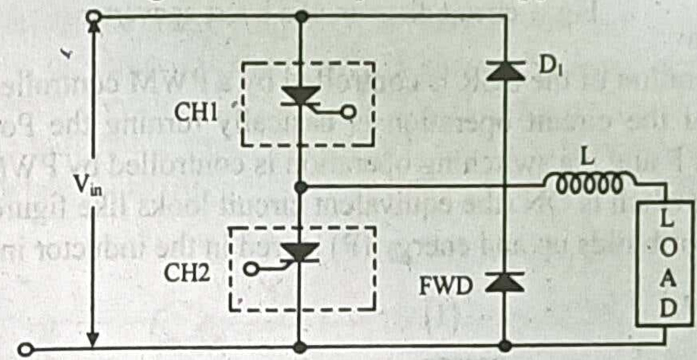


Fig: 1 (b) Two quadrant chopper

4. Explain briefly the working of class B chopper with diagram. [WBUT 2015, 2019]

Answer:

Refer to Question No. 6 of Long Answer Type Questions.

5. With the help of circuit diagrams explains the principles of operation of step-up/down chopper. [WBUT 2018]

Answer:

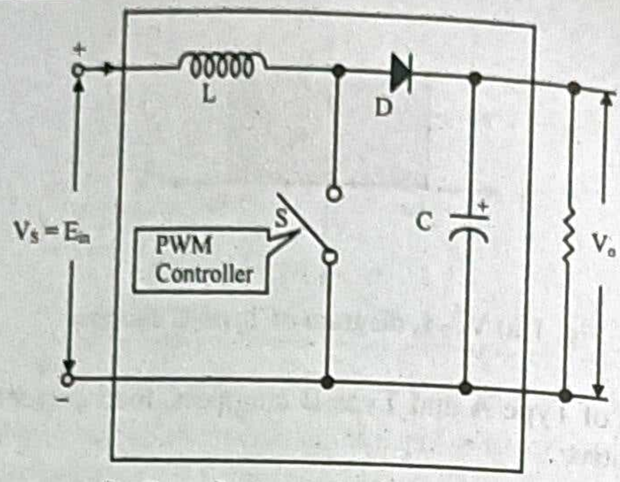
Step up:

Boost Converter

The boost converter is a switching converter which produces an output voltage greater than the input voltage.

The Basic Circuit Diagram

Figure 1 shows the basic circuit diagram of a boost converter, where a power semiconductor (e.g., SCR) acting as a switch is used.



S⇒ Power Semiconductor acting as a Switch.

Fig: 1 circuit diagram of a boost converter

Circuit Operation

The switching operation of the SCR is controlled by a PWM controller.
The mechanism of the circuit operation is basically turning the Power Semiconductor Switch ON and OFF and the switching operation is controlled by PWM controller.

Step 1: When the switch is ON (the equivalent circuit looks like figure 2.a) the current (I) through the inductor builds up and energy (P) stored in the inductor increases

$$\left(P = \frac{1}{2}LI^2\right) \quad \cdots(1)$$

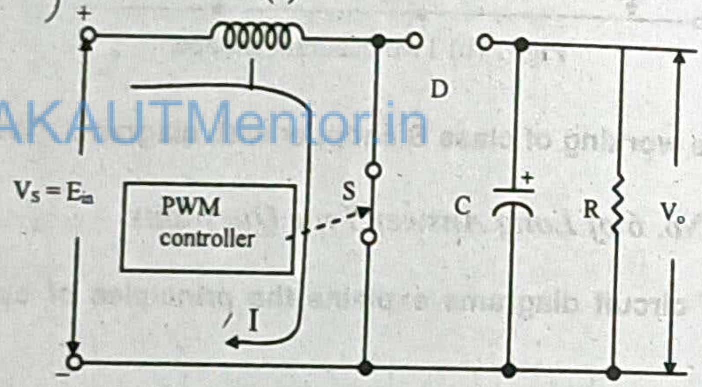


Fig: 2.a) Equivalent circuit of boost converters on S is ON.

Step 2: When the switch is OFF, the equivalent circuit may be drawn as shown in figure 2.b).

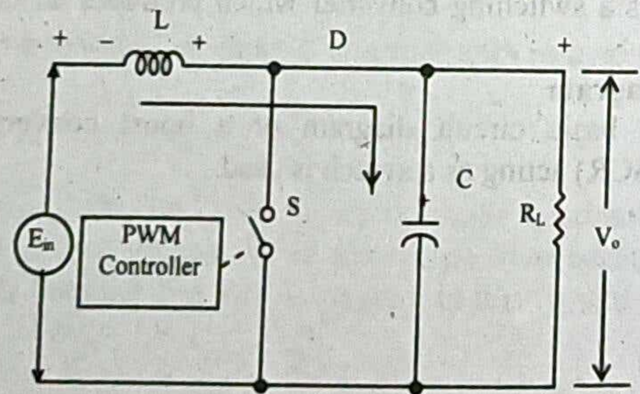


Fig: 2.b) Equivalent circuit of boost converter when S is OFF

Now the current through the inductor continues to flow through the path D (closed now), $R_L C$ Network and back to the source.

As the current tends to decrease, polarity of the induced e.m.f. in L is reversed, i.e., the inductor voltage adds to the source voltage, causing inductor current to flow through the load.

∴ Voltage across the load

$$V_o = E_{in} + L\frac{di}{dt} \qquad \ldots(2)$$

Step down:

Buck Converter / Step-Down Converter

Step down converter, as the name implies, provides an out put voltage whose average value is less then the dc input voltage. Figure 1 shows the basic circuit arrangement of such a converter which contains the power BJT (Q1) as a switching device. When the switch is closed, the inductor L stores energy and releases its energy to the load through the flywheel diode when Q1 is off.

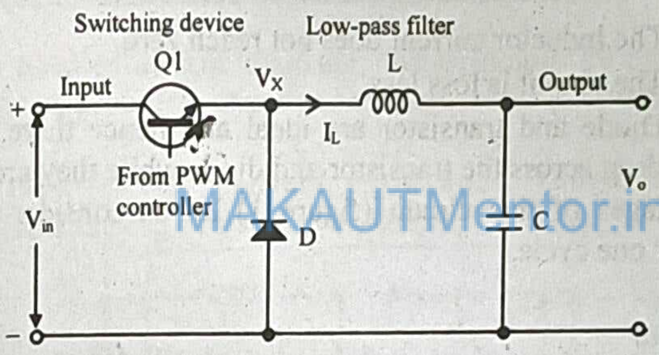


Fig: 1 Buck converter

Circuit Operation

Step 1: The transistor is turned ON. The following events occur (refer to fig. 1).

- *Input voltage Vin reaches at one end of the inductor (L).*
- This voltage will cause the inductor current (I_L) to rise. The supply current flows through path Vin+→Q1→L→C→Vin −
- The inductor stores energy during the ON period.
- The diode is reversed biased.

Step 2: The transistor is now made off. Consequently

- The current will continue flowing through the inductor but this time it will flow through the diode through freewheeling action.
- Assuming the current through the inductor does not reach zero, the voltage at Vx will now be only the voltage across the conducting diode during the full OFF time.

Step 3: The average value of voltage Vx will depend on the average ON time of the transistor provided the inductor current is continuous.

Waveforms

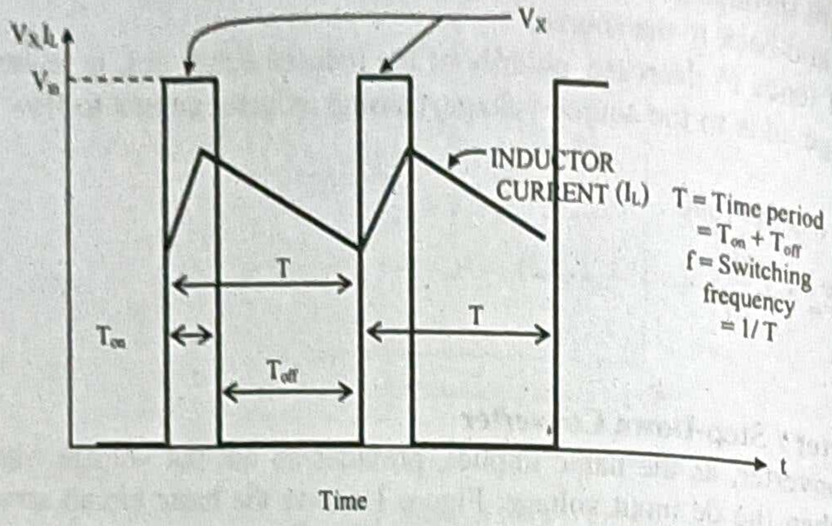


Fig: 2 Waveforms of inductor current (I_L) and V_X

Mathematical Analysis

Assumptions:

1. The inductor current does not reach zero.
2. The circuit is loss less.
3. Diode and transistor are ideal and hence there will be no voltage drop across the transistor and diode while they are on.

To analyze the voltages of this circuit (figure 1) let us consider the changes in the inductor current over one cycle.

From the relation

$$V_X - V_O = L\frac{di}{dt} \qquad \cdots(1)$$

Integrating both sides

$$di = \int_0^{t_{on}}(V_X - V_O)dt + \int_{t_{on}}^{t_{on}+t_{off}}(V_X - V_O)dt \qquad \cdots(2)$$

Now, for steady state operation the current at the start and end of a period T will not change. Again during the ON time $V_x = V_{in}$ and during the OFF, $V_X = 0$.

Thus, from equation (2)

$$0 = di = \int_0^{t_{on}}(V_{in} - V_0)dt + \int_{t_{on}}^{t_{on}+t_{off}}(-V_0)dt \qquad \ldots(3)$$

or, $$(V_{in} - V_0)t_{on} - V_0 t_{off} = 0 \qquad \ldots(4)$$

or, $$\frac{V_o}{V_{in} - V_o} = \frac{t_{on}}{t_{off}}$$

$$\Rightarrow \frac{V_o}{V_o + (V_{in} - V_o)} = \frac{t_{on}}{t_{on} + t_{off}}$$

or, $$\frac{V_O}{V_{in}} = \frac{t_{on}}{T} \qquad \cdots(5)$$

From the definition of duty cycle (D)

$$D = \frac{t_{on}}{T} \qquad \cdots(6)$$

From the equations (5) and (6) we have,

$$V_0 = D\, V_{in} \qquad \ldots(7)$$

Since the circuit is loss less. So, the input and output powers must be same.

i.e., $V_o * I_o = V_{in} * I_{in}$. ... (8)

$$\Rightarrow \frac{V_o}{V_{in}} = \frac{I_{in}}{I_o} \qquad \cdots(8a)$$

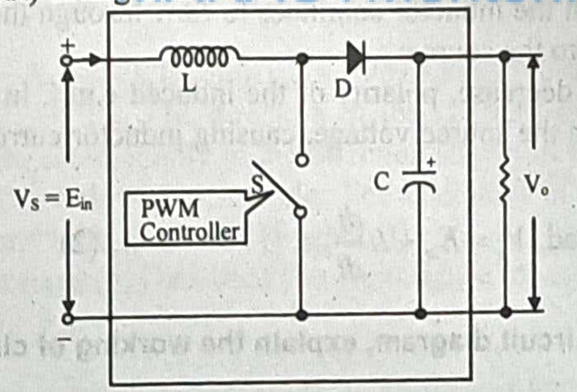
∴ from the equations (7) and [8(a)] the average input and output current must satisfy $I_{in} = DI_o$.

Long Answer Type Questions

1. Explain with the help of circuit diagram, the principle of operation of step-up chopper. Deduce the expression of output voltage of such chopper. [WBUT 2007]

Answer:

Figure shows the basic circuit diagram of a boost converter, where a power semiconductor (e.g., SCR) acting as a switch is used.



S⇒ Power Semiconductor acting as a Switch.

Fig: Circuit diagram of a boost converter

The switching operation of the SCR is controlled by a PWM controller.

The mechanism of the circuit operation is basically turning the Power Semiconductor Switch ON and OFF and the switching operation is controlled by PWM controller.

Step 1: When the switch is ON (the equivalent circuit looks like the figure (a) the current (I) through the inductor builds up and energy (P) stored in the inductor increases

$$\left(P = \frac{1}{2} LI^2\right) \qquad \cdots(1)$$

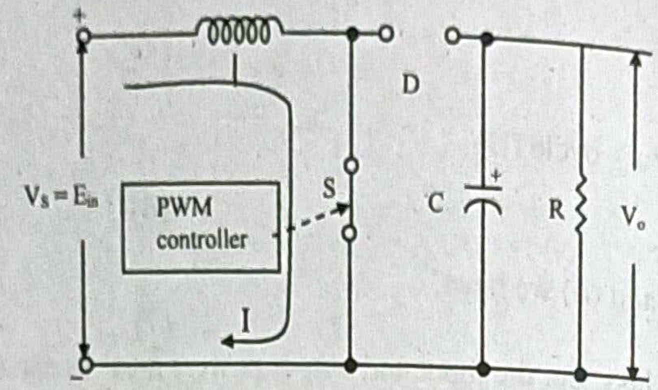


Fig: (a) Equivalent circuit of boost converters on S is ON.

Step 2: When the switch is OFF, the equivalent circuit may be drawn as shown in figure (b).

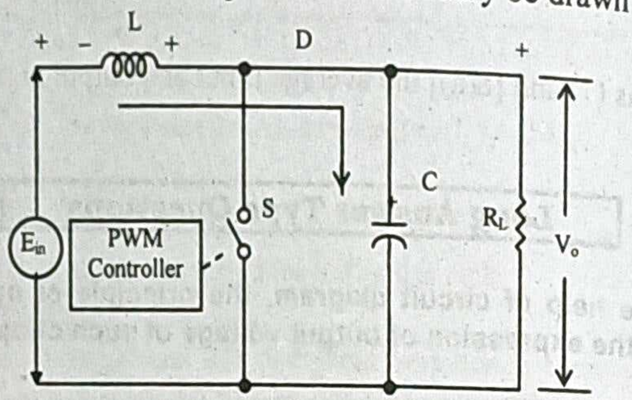


Fig: (b) Equivalent circuit of boost converter when S is OFF

Now the current through the inductor continues to flow through the path D (closed now), $R_L C$ Network and back to the source.

As the current tends to decrease, polarity of the induced e.m.f. in L is reversed, i.e., the inductor voltage adds to the source voltage, causing inductor current to flow through the load.

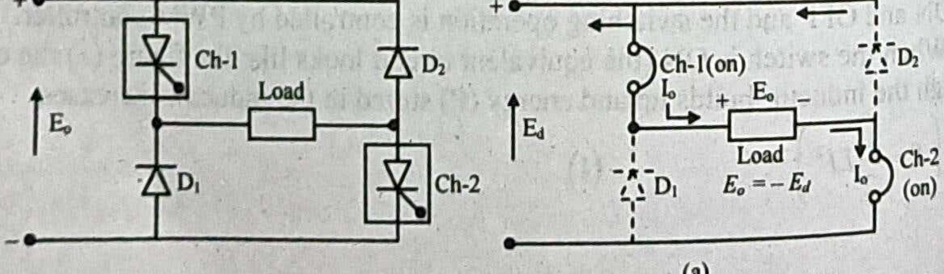
$\therefore$ Voltage across the load, $V_o = E_{in} + L\dfrac{di}{dt}$ ...(2)

2. a) With the help of circuit diagram, explain the working of class *D* chopper.

[WBUT 2009]

Answer:

The circuit diagram of Type-D chopper is shown in figure. When both Ch-1 and Ch-2 are on, the output voltage $E_o = E_d$ (figure (a)). On the other hand when both the choppers Ch-1 and ch-2 are off, the diodes D_1 and D_2 both conduct.



(a)

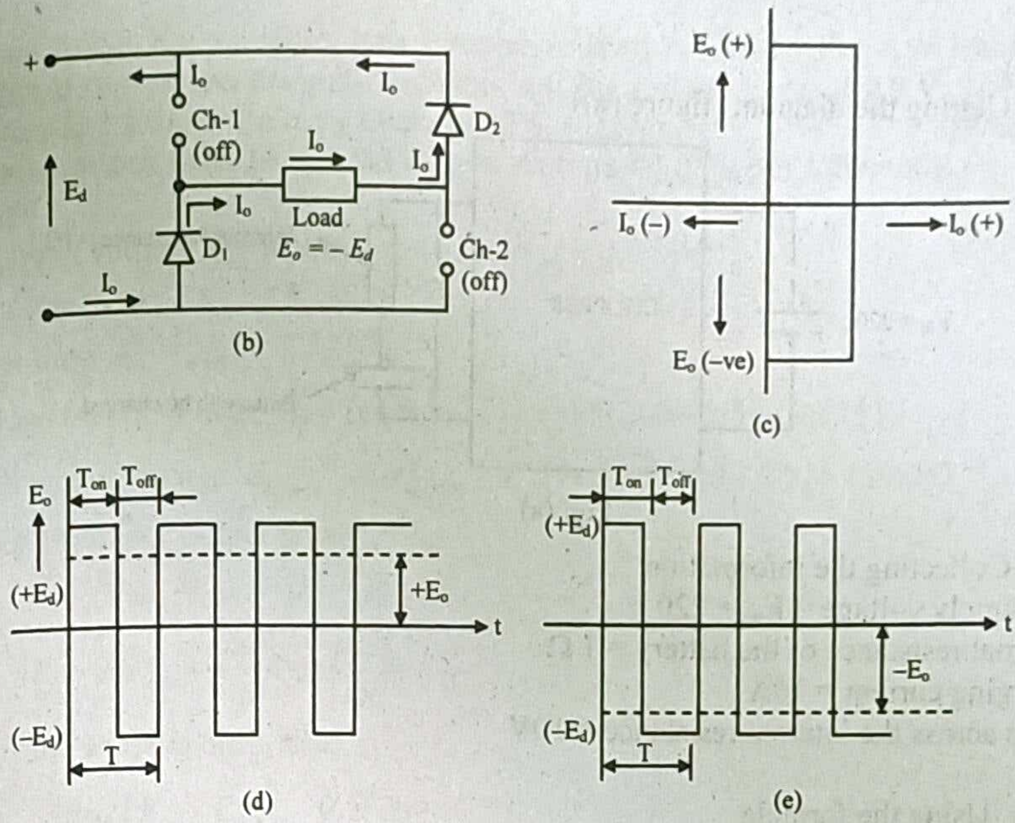


Fig: Configuration of Type-D chopper. (a) 1st quadrant operation of chopper; E_o and I_o both are positive. (b) 3rd quadrant operation of chopper E_o is virtually –ve but I_o is +ve. (c) First and Forth quadrant operation of chopper. (d) Profile of output voltage (+ve) when $T_{on} > T_{off}$ for Type-D chopper. (e) Profile of output voltage (–ve) when $T_{on} < T_{off}$ for Type-D chopper

Average output voltage E_o would be either positive or negative depending upon whether $T_{on} > T_{off}$ or whether $T_{on} < T_{off}$. The direction of load current is always positive as the choppers and diodes can conduct only in the direction shown in figure (a) and figure (b). E_0 being reversible, power flow is reversible. The operation of this type of chopper is designated in the first and third quadrants [figure (c)].
The profile of output voltage (E_o) has been shown in figure (d) and (e) for the cases when $T_{on} > T_{off}$ and when $T_{off} > T_{on}$.

b) A *dc* battery is charged from a constant *dc* source of 220 V through a chopper. The *dc* battery is to be charged from its internal *emf* of 90V to 122 V. The battery has internal resistance of 1 Ω. For a constant charging current of 10 A, calculate the range of duty cycle. [WBUT 2009, 2011, 2016]

Answer:

Step 1: Getting the diagram [figure (a)]

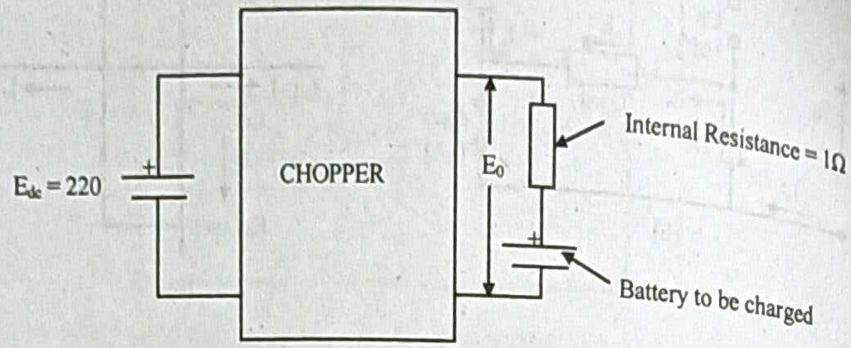


Fig: (a)

Step 2: Collecting the information

a) DC supply voltage = E_{dc} = 220 V

b) Internal resistance of the battery = 1 Ω

c) Charging current = 10A

d) Drop across the internal resistance = 10V

Step 3: Using the formula

We know that

Output voltage = $E_o = D \times E_{dc}$ .... (i)

Case 1

When the battery is to be charged to 90V the chopper should have an output of 90V + 10V = 100V

Therefore, from the relation in equation (i)

$$100\text{ V} = D \times 220\text{ V}$$

So, $D = \dfrac{100V}{220V} = 0.4545$, % Duty cycle = 45.45%

Case 2

When the battery is to be charged to 122 V the chopper should have an output of 122V + 10V = 132V

Therefore, from the relation in equation (i)

$$132\text{ V} = D \times 220\text{ V}$$

So, $D = \dfrac{132V}{220V} = 0.60$

So, % duty cycle = 60 %

Therefore, range of duty cycle = 45.45 % to 60%.

3. a) Draw the circuit of a two quadrant chopper & explain its working. **[WBUT 2010]**

Answer:

Refer to Question No. 3 of Short Answer Type Questions.

b) A step down *d.c.* chopper has a resistive load of $R = 15$ ohm and input voltage E_{dc} = 200 V. When the chopper remains on, its voltage drop is 2.5 V. The chopper frequency is 1 kHz. If the duty cycle is 50%, determine **[WBUT 2010]**
i) average output voltage ii) RMS output voltage iii) chopper efficiency.

Answer:

Given: Input voltage $E_{dc} = 200$ V duty cycle $\alpha = 0.5$

$R = 15\Omega$ $\quad f = 1\,\text{kHz}$

Chopper drop $E_d = 2.5\,\text{V}$

i) Average output voltage $E_0 = \alpha \cdot (E_{dc} - E_d) = 0.5(200 - 2.5) = 98.75\,\text{V}$

ii) RMS output voltage $E_{0(\text{rms})} = \sqrt{\alpha}\,(E_{dc} - E_d) = \sqrt{0.5}\,(200 - 2.5) = 139.653\,\text{V}$

Chopper efficiency output power

$$P_o = E_{0\,\text{rms}} \cdot I_{0\,\text{rms}}$$

$$P_o = \sqrt{\alpha}E_{dc} \cdot \frac{\sqrt{\alpha}E_{dc}}{R} = \frac{\alpha E_{dc}^2}{R}$$

If E_d is the chopper drop, then

$$P_o = \frac{\alpha(E_{dc} - E_d)^2}{R} = \frac{0.5(200 - 2.5)^2}{15} = 1300.21\,\text{W}$$

Now, the input power to the chopper is given by

$$P_i = \frac{1}{T}\int_0^T E_{dc} i_s\, dt = \frac{1}{T}\int_0^T E_{dc} \frac{(E_{dc} - E_d)}{R} dt = \frac{1}{T}\int_0^{\alpha \cdot T} \frac{E_{dc}(E_{dc} - E_d)}{R} dt$$

$$= \frac{E_{dc}(E_{dc} - E_d)}{TR}(T)_0^{\alpha} = \frac{0.5(200)(200 - 2.5)}{15} = 1316.67\,\text{W.}$$

Chopper efficiency $\eta = \dfrac{P_o}{P_i} = \dfrac{1300.21}{1316.67} = 0.9874 = 98.74\%$.

c) Derive an expression for output voltage in terms of duty cycle for a step-down chopper. **[WBUT 2010]**

OR,

With the help relevant circuit diagram and waveform, explain the principle of operation of DC-DC step down regulator. Deduce the expression of average and RMS value of output voltage **[WBUT 2017]**

Answer:

Step down converter, as the name implies, provides an out put voltage whose average value is less then the dc input voltage. Fig. (a) shows the basic circuit arrangement of such a converter, which contains the power BJT (Q1) as a switching device. When the switch is closed, the inductor L stores energy and releases its energy to the load through the flywheel diode when Q1 is off.

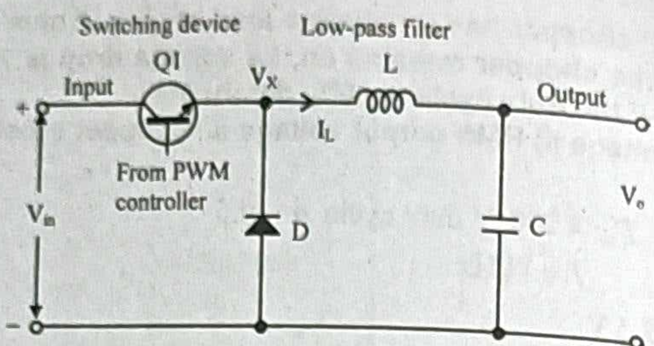


Fig: (a) Buck converter

Waveforms

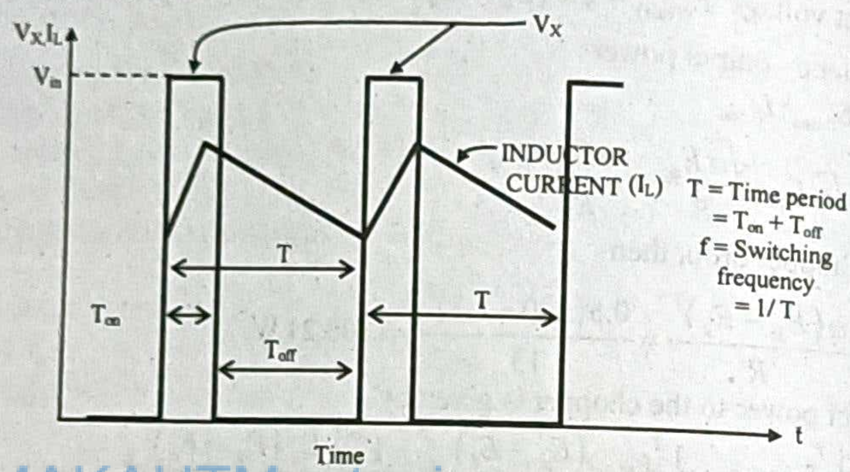


Fig: (b) Waveforms of inductor current (I_L) and V_X

Mathematical Analysis

Assumptions:

4. The inductor current does not reach zero.
5. The circuit is loss less.
6. Diode and transistor are ideal and hence there will be no voltage drop across the transistor and diode while they are on.

To analyze the voltages of this circuit [Fig. (a)] let us consider the changes in the inductor current over one cycle.

From the relation

$$V_X - V_O = L\frac{di}{dt} \quad \text{.... (1)}$$

Integrating both sides

$$di = \int_0^{t_{on}} (V_X - V_O)\,dt + \int_{t_{on}}^{t_{on}+t_{off}} (V_X - V_O)\,dt \quad \text{.... (2)}$$

Now, for steady state operation the current at the start and end of a period T will not change. Again during the ON time V_x=V_{in} and during the OFF, V_X=0.

Thus, from equation (2)

$$0 = di = \int_0^{t_{on}} (V_{in} - V_0)dt + \int_{t_{on}}^{t_{on}+t_{off}} (-V_0)dt \quad \text{.... (3)}$$

or, $$(V_{in} - V_0)t_{on} - V_0 t_{off} = 0 \quad \text{.... (4)}$$

or, $$\frac{V_o}{V_{in} - V_o} = \frac{t_{on}}{t_{off}}$$

$$\Rightarrow \quad \frac{V_o}{V_o + (V_{in} - V_o)} = \frac{t_{on}}{t_{on} + t_{off}}$$

or, $$\frac{V_O}{V_{in}} = \frac{t_{on}}{T} \quad \text{.... (5)}$$

From the definition of duty cycle (D)

$$D = \frac{t_{on}}{T} \quad \text{.... (6)}$$

From the equations (5) and (6) we have,

$$V_0 = D\, V_{in} \quad \text{.... (7)}$$

Since the circuit is loss less. So, the input and output powers must be same.

i.e., $V_o * I_o = V_{in} * I_{in}$. .... (8)

$$\Rightarrow \quad \frac{V_o}{V_{in}} = \frac{I_{in}}{I_o} \quad \text{.... (9)}$$

$\therefore$ From the equations (7) and (9) the average input and output current must satisfy $I_{in} = DI_o$.

4. a) What is the principle of operation of boost regulator? Deduce the expression of output voltage. **[WBUT 2013, 2016]**

Answer:

Refer to Question No. 1 of Long Answer Type Questions.

b) The step-down chopper has a resistive load of 10 ohm & the input voltage is 200V. When the chopper is turned on, the voltage drop across the switch is 1V, the chopping frequency is 1 kHz. If the duty cycle is 40%, determine the average output voltage, rms output voltage, efficiency of the chopper & effective input resistance of the chopper. **[WBUT 2013]**

Answer:

Given input voltage $E_{dc} = 200$ V duty cycle $\alpha = 0.4$, $R = 10\Omega$, $f = 1\text{kHz}$ copper drop $E_d = 1\text{V}$

a) Average output voltage $E_0 = \alpha(E_{dc} - E_d) = 0.4(200-1) = 0.4 \times 199 \text{ V} = 79.6 \text{ V}$

b) RMS output voltage $E_{o(rms)} = \sqrt{\alpha}(E_{dc} - E_d) = \sqrt{0.4}(200-1) = 125.8586 \text{ V}$

c) Efficiency of chopper

Output power $P_o = E_{o(rms)} \cdot I_{o(rms)}$

$$I_{o(rms)} = \frac{E_{o(rms)}}{R} = \frac{\sqrt{\alpha}\cdot E_{dc}}{R}$$

$$\therefore \quad P_o = \sqrt{\alpha}\cdot E_{dc}\cdot\frac{\sqrt{\alpha}\cdot E_{dc}}{R} = \frac{\alpha E_{dc}^2}{R}$$

If E_d is the chopper drop, then

$$P_o = \frac{\alpha(E_{dc}-E_d)^2}{R} = \frac{0.4(200-1)^2}{10} = \frac{0.4\times 199^2}{10}\,\text{W} = 1584.04\ \text{W}$$

Now, the input power to the chopper is given by

$$P_i = \frac{1}{T}\int_0^T E_{dc} i_s dt = \frac{1}{T}\int_0^{T_{on}} E_{dc}\cdot\frac{(E_{dc}-E_d)}{R}dt = \frac{1}{T}\int_0^{\alpha\cdot T}\frac{E_{dc}(E_{dc}-E_d)}{R}dt$$

$$= \frac{E_{dc}(E_{dc}-E_d)}{T\cdot R}(t)_0^{\alpha T} = \frac{\alpha E_{dc}(E_{dc}-E_d)}{R} = \frac{0.4\times 200\times 199}{10} = 1592\ \text{W}$$

$$\therefore \text{Chopper efficiency } \eta = \frac{P_o}{P_i} = \frac{1584.04}{1592} = 0.995 = 99.50\%$$

5. Discuss in detail the type-A, B choppers. **[WBUT 2014]**

Answer:

Type A or First Quadrant Chopper

This is a single quadrant type chopper, where, the output voltage V_0 and output current I_0 occur only in first quadrant of $V_0 - I_0$ diagram as shown in the Fig. 1.
The power flow in this type chopper is always from source to load.

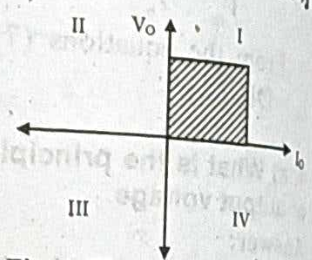


Fig: 1 First quadrant chopper

Circuit Diagram

Fig. 2 shows the circuit arrangement of type A chopper.

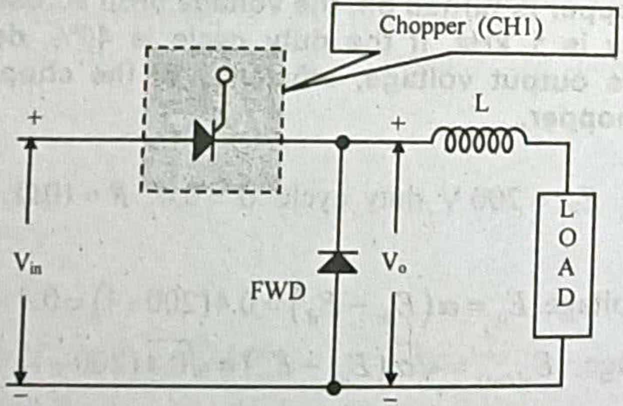


Fig: 2 Circuit diagram of type-A chopper

Circuit Operation

Step 1: When CH1 is on,

- FWD is reverse biased
- Current flows through the load from source
  $V_{in}(+) \rightarrow CH_1 \rightarrow L \rightarrow Load \rightarrow V_{in}(-)$
  $V_0 = V_{in}$ with polarity as shown in the figure 3

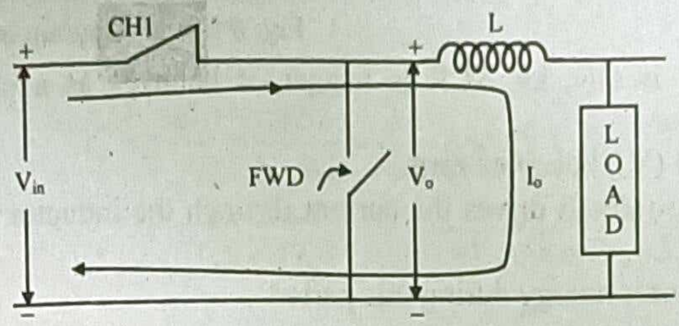


Fig: 3 Chopper circuit when SCR is closed and the current path

Step 2: When CH1 is OFF.

- FWD is forward Biased
- Current will flow through free wheeling diode (FWD), L and Load. The direction of current through the load will remain the same (Fig. 4).

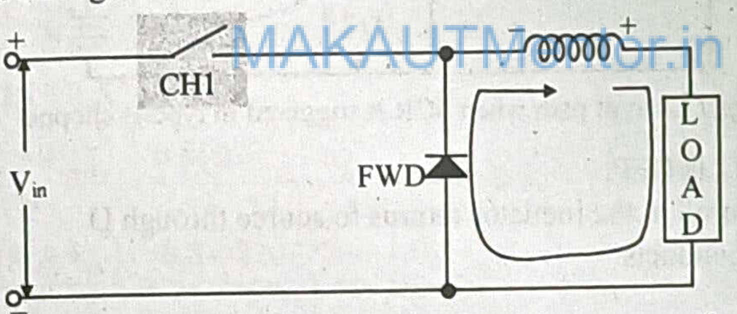


Fig: 4 Chopper circuit when SCR is off and the current path

Second Quadrant (Type-B) Chopper

Like Type-A this is another type of single quadrant chopper where the load voltage is positive while the load current flows out the load as depicted in $V_o - I_o$ diagram of figure 5.

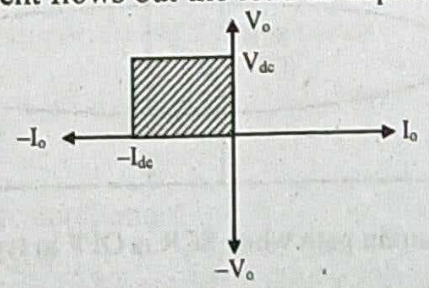


Fig: 5 $V_o - I_o$ diagram of second quadrant (type-B) chopper

Circuit Diagram:

The circuit arrangement of type-B chopper is shown in figure 6. Here the voltage source E is the part of the load that may be the, for example, back e.m.f. of the dc motor.

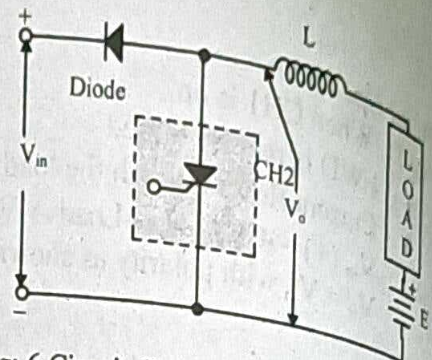


Fig: 6 Circuit diagram of Type-B chopper

Circuit Operation

Step 1: When CH2 is ON, i.e. SCR is trigger, it behaves as a closed switch. Then following events occur

- Load voltage (V_o) becomes zero.
- The voltage source E drives the current through the inductor and SCR as shown in the figure 7.
- Inductor L stores energy during this period.

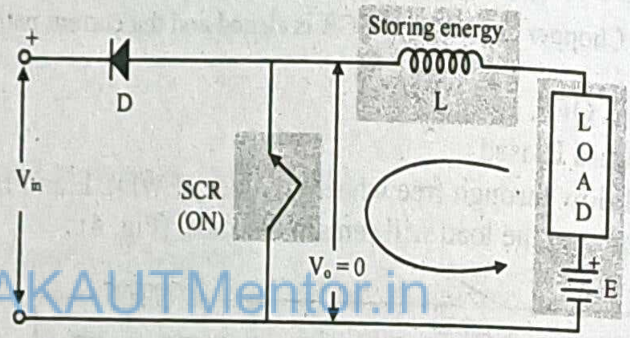


Fig: 7 Current path when SCR is triggered in type-B chopper

Step 2: When CH2 is OFF,

- Energy stored in the inductor returns to source through D
- Diode D conducts
- $V_o = V_{in}$
- Load current i0 is opposite to its flow direction, i.e., current flows from the load to the source.

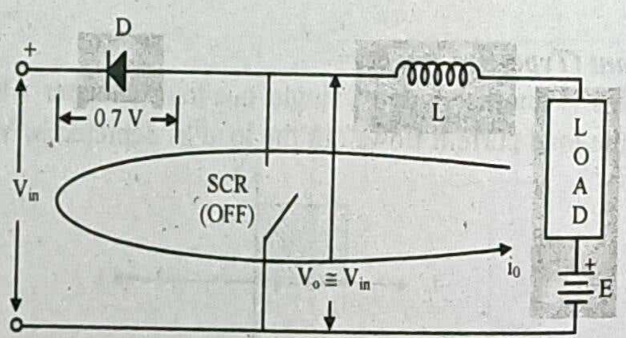


Fig: 8 Current path when SCR is OFF in type-B chopper

Thus when the SCR is OFF, the load current flows in the opposite direction w.r.t. Type-A chopper.

6. A step up chopper has R load with R=20 ohm and V_S=220V. When the converter remains on, its voltage drop is V_{ch}=1.5V and its chopping frequency is 10 KHz. If the duty cycle is 80%, determine:
i) the average output voltage.
ii) the rms output voltage
iii) the converter efficiency
iv) the effective input resistance
v) the rms value of the fundamental component of harmonics on the output voltage. **[WBUT 2014]**

Answer:

i) $\frac{V_o}{V_{in}} = \frac{1}{1-D} \Rightarrow \quad V_o = \frac{V_i}{1-D} = \frac{220}{1-0.8} = \frac{220}{0.2} = 1{,}100$ V.

ii) RMS value $= \sqrt{\left[\frac{T_{ON}}{T} \cdot V_i^2\right]} = \sqrt{(0.8)(200)^2} = \sqrt{(0.8)\cdot 40000} = \sqrt{32000} = 178.89$ Volt.

iii) $P_o = (E_{rms})_o \times (I_{rms})_o$, $o \Rightarrow$ output

$$(I_{rms})_o = \frac{(E_{rms})_o}{R} = \frac{\sqrt{\alpha}\cdot V_i}{R} \qquad \alpha = \text{duty cycle, } V_i = 220 \text{ V}$$

$$(E_{rms})_o = \sqrt{\alpha}\cdot / V_o$$

$$\therefore \quad P_o = \sqrt{\alpha} V_i \cdot \frac{\sqrt{\alpha}\cdot V_i}{R} = \frac{\alpha \cdot V_i^2}{R}$$

If chopper drop $= V_{ch} = 1.5$ V.

$$P_o = \frac{\alpha (V_i - V_{ch})^2}{R} = \frac{0.8(220-1.5)^2}{20} = 1909.68\text{W} = 1.909 \text{ kW}$$

$$P_i = \frac{\alpha V_i (V_i - V_{ch})}{R} = \frac{0.8 \times 220(220-1.5)}{20} = 1922.8\text{W} = 1.922 \text{ kW}$$

$$\therefore \quad \eta = \frac{P_o}{P_i} = \frac{(220-1.5)}{220} = \frac{218.5}{220}$$

$$\therefore \quad \%\eta = \frac{218.5}{220} \times 100 = 99.318$$

iv) i/P impedance of the chopper during commutation

$$\frac{V_{ch/rms}}{I_{rms}} + 20\Omega = \frac{15}{\frac{220}{20}} + 20 = \frac{300}{220} + 20 = \left(\frac{15}{11} + 20\right) = 21.36\ \Omega.$$

v) RMS value of n^{th} harmonic component

$$= \frac{0.9}{n} V_i \cdot \cos\left(\frac{n\pi}{6}\right) = \frac{0.9}{1} \cdot 220 \cdot \cos 30° = 0.45 \times 220 = 99 \text{ V}.$$

7. a) Draw the circuit of a two quadrant chopper & explain its working. [WBUT 2015]

Answer:

Refer to Question No. 3 of Short Answer Type Questions.

b) A step down DC chopper has a resistive load of R = 15Ω and input voltage Edc = 200V. When the chopper remains on, its voltage drop is 2.5V. The chopper frequency is 1kHz. If the duty cycle is 50%, determine

i) average output voltage
ii) RMS output voltage
iii) chopper efficiency.

[WBUT 2015]

Answer:

Given: Input voltage $E_{dc} = 200$ V, duty cycle $\alpha = 0.5$

$R = 15\Omega$, $f = 1$ kHz, Chopper drop $E_d = 2.5$ V

(i) Average output voltage

$$E_0 = \alpha \cdot (E_{dc} - E_d) = 0.5(200 - 2.5) = 98.75 \text{ V}$$

(ii) RMS output voltage

$$E_{0(\text{rms})} = \sqrt{\alpha}\,(E_{dc} - E_d) = \sqrt{0.5}\,(200 - 2.5) = 139.653 \text{ V}$$

(iii) Chopper efficiency

Output power,

$$P_0 = E_{0\text{rms}} \cdot I_{0\text{rms}}$$

Now, $I_{0\text{rms}} = \dfrac{E_{0\text{rms}}}{R} = \dfrac{\sqrt{\alpha} \cdot E_{dc}}{R}$

$$\therefore \quad P_0 = \sqrt{\alpha} \cdot E_{dc} \cdot \frac{\sqrt{\alpha} \cdot E_{dc}}{R} = \frac{\alpha E_{dc}^2}{R}$$

If E_d is the chopper drop, then

$$P_0 = \frac{\alpha (E_{dc} - E_d)^2}{R} = \frac{0.5(200 - 2.5)^2}{15} = 1300.21 \text{ W}$$

Now, the input power to the chopper is given by

$$P_i = \frac{1}{T}\int_0^T E_{dc} i_s \, dt = \frac{1}{T}\int_0^{T_{on}} E_{dc} \frac{(E_{dc} - E_d)}{R} dt = \frac{1}{T}\int_0^{\alpha \cdot T} \frac{E_{dc}(E_{dc} - E_d)}{R} dt$$

$$= \frac{E_{dc}(E_{dc} - E_d)}{T \cdot R} (t)_0^{\alpha T} = \frac{\alpha E_{dc}(E_{dc} - E_d)}{R}$$

$$= \frac{0.5(200)(200 - 2.5)}{15} = 1316.67 \text{ W}$$

$\therefore$ Chopper efficiency, $\eta = \dfrac{P_o}{P_i} = \dfrac{1300.21}{1316.67} = 0.9874 = 98.74\%$

c) Derive an expression for output voltage in terms of duty cycle for a step-up and step-down chopper. **[WBUT 2015]**

Answer: *Refer to Question No. 3(c) & 1 of Long Answer Type Questions.*

8. a) In a buck converter find a relationship to show that amplitude of ripple current depends upon duty cycle. From the relationship how can the value of duty cycle be decided for maximum ripple current amplitude? **[WBUT 2015]**

Answer: *Refer to Question No. 3(c) of Long Answer Type Questions.*

b) A buck converter has input voltage 220 V and it operates at 500 Hz. The average load current is 50 A. The load resistance is 2 Ohm. What will be the value of inductance to limit maximum peak-to-peak ripple current through inductor to 10%? Find the value of inductance for maximum ripple current. **[WBUT 2015]**

Answer:

Peak-to-peak ripple (ΔI_L) is:

$$\Delta I_L = \frac{V_{\text{in}} - V_{\text{out}}}{L} t_{\text{on}} = \frac{V_{\text{in}} - V_{\text{out}}}{L} DT \quad \text{.... (1)}$$

Here, $V_{\text{in}} = 220\text{ V},\ V_{\text{out}} = 100\text{ V},\ T = 1/500 = 0.002\text{ sec.}$

$\Delta I_L = 0.1 I_{L\max}$

$D = V_{\text{out}} / V_{\text{in}} = 100/220 = 0.45$.

The boundary is when the ripple current is the double of the load current:

$\Delta I_L / 2 = I_{\text{out}}$.

So, $I_{L\max} = 3I_{\text{out}} = 150\text{ A}$

1^st Part:

$\Delta I_L = 0.1 I_{L\max} = 0.1(150) = 15\text{ A}$

So, From (1), $L = \left[(220-100)/\Delta I_L\right] \times 45 = (110/15)\cdot(0.45) = 3.3\text{ H}$

2^nd Part:

$$L = \left[(220-100)/\Delta I_{L\max}\right] \times 0.45 = \left[(220-100)/100\right] \times 0.45 = 0.495\text{ H}$$

c) What is meant by PWM control in chopper? Explain the working principle of four-quadrant chopper. **[WBUT 2015]**

Answer:

Four-Quadrant Chopper (or Class E Chopper)

Fig. 1(a) shows the basic power circuit of Type E chopper. From Fig. 1, it is observed that the four-quadrant chopper system can be considered as the parallel combination of two Type C choppers. In this chopper configuration, with motor load, the sense of rotation can be reversed without reversing the polarity of excitation. In Fig. 1, CH_1, CH_4D_2 and D_3 constitute one Type C chopper and CH_2, CH_3, D_1 and D_4 form another Type C chopper circuit. Fig. 1(b) shows Class-E with *R-L* load.

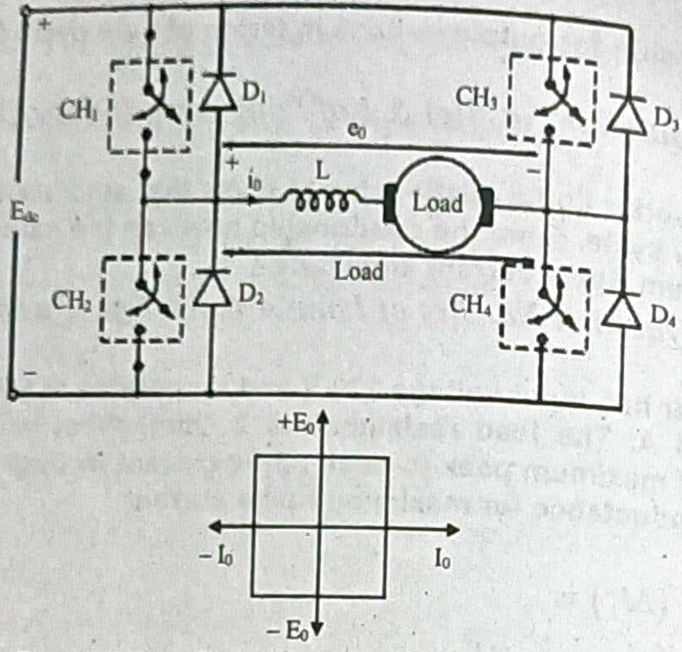


Fig: 1(a) Type E chopper circuit and characteristics

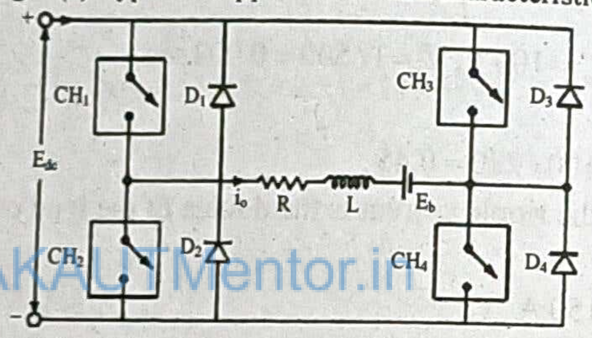


Fig: 1(b) Class E chopper with R-L load

If chopper CH_4 is turned on continuously, the antiparallel connected pair of devices CH_4 and D_4 constitute a short-circuit. Chopper CH_3 may not be turned on at the same time as CH_4 because that would short circuit source E_{dc}.

With CH_4 continuously on and CH_3 always off, operation of choppers CH_1 and CH_2 will make E_0 positive and I_0 reversible and operation in the first and second quadrants is possible. On the other hand, with CH_2 continuously on and CH_1 always off, operation of CH_3 and CH_4 will make E_0 negative and I_0 reversible and operation in the third and fourth quadrants is possible.

The operation of the four-quadrant chopper circuit is explained as:

When choppers CH_1 and CH_4 are turned-on, current flows through the path, $E_{dc+} - CH_1 -$ load $- CH_4 - E_{dc-}$. Since both E_0 and I_0 are positive, we get the first quadrant operation. When both the choppers CH_1 and CH_4 are turned-off, load dissipates its energy through the path load $- D_3 - E_{dc+} - E_{dc-} - D_2 -$ load. In this case, E_0 is negative while I_0 is positive and fourth-quadrant operation is possible.

When choppers CH_2 and CH_3 are turned-on, current flows through the path, $E_{dc+} - CH_3 - \text{load} - CH_2 - E_{dc-}$. Since both E_0 and I_0 are negative, we get the third-quadrant operation. When both choppers CH_2 and CH_3 are turned-off, load dissipates its energy through the path load $- D_1 - E_{dc+} - E_{dc-} - D_2 -$ load. In this case, E_0 is positive and I_0 is negative and second-quadrant operation is possible.

This four-quadrant chopper circuit consists of two bridges, forward bridge and reverse bridge. Chopper bridge CH_1 and CH_4 is the forward bridge which permits energy flow from source to load. Diode bridge D_1 to D_4 is the reverse bridge which permits the energy flow from load-to-source. This four-quadrant chopper configuration can be used for a reversible regenerative d.c. drive.

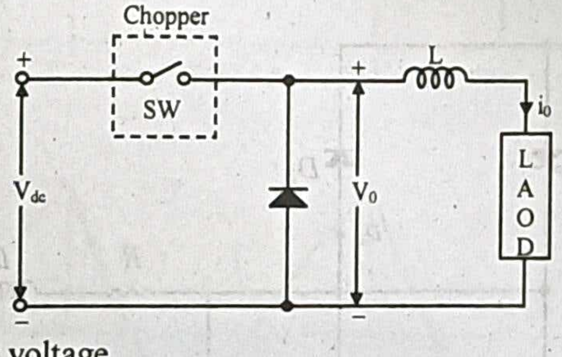
9. For type *A* chopper, d.c. source voltage =200V, load resistance = 15Ω. Assume a voltage drop of 1 V across the chopper when it is on. For a duty cycle of 0.4 and chopping frequency 1 kHz, calculate (i) average and r.m.s. values of output voltage, (ii) chopper efficiency, (iii) effective input resistance of the chopper.

[WBUT 2017]

Answer:

i) When the chopper is in the on-position the output voltage is $(V_{dc} - 1)V_o$ and during the time when the chopper is in the off-position, output voltage is zero.

$$\therefore \text{ Average output voltage} = \frac{(V_{dc} - 1)T_{on}}{T} = \alpha(V_{dc} - 1) = 0.4(200 - 1) = 0.4 \times 199 = 79.6 \text{ V}$$



The rms value of output voltage

$$V_{dc\,rms} = \left[(V_{dc} - 1)^2 \cdot \frac{T_{ON}}{T}\right]^{1/2} = \left[(199)^2 \cdot \alpha\right]^{1/2} = \sqrt{\alpha}\,(199) = \sqrt{0.4} \times 199 = 125.85 \text{ V}$$

Power output on power delivered to load

$$P_o = \frac{V_{dc\,rms}^2}{R} = \frac{(125.85)^2}{15} = 1055.8815 \text{ W}$$

Power input to chopper

$$P_i = V_{dc} \cdot T_0 = 200 \cdot \frac{79.6}{15} = 1061.33 \text{ W}$$

ii) Chopper efficiency

$$\eta = \frac{P_o}{P_i} \times 100 = \frac{1055.8815}{1061.33} \times 100 = 99.48\%$$

We know effective input resistance $R_i = \frac{V_s}{T_{S_{avg}}} = \frac{V_s \times R}{DV_s} = \frac{R}{D}$

here R = 15 Ω

duty cycle is given by 0.4

$$R_i = \frac{15}{0.4} = 37.5\Omega$$

10. a) Explain with suitable circuit diagram & waveform of load voltage & load current, the operation of a class C chopper feeding a load. Derive the expression for minimum and maximum load current considering a RLE load. [WBUT 2018]

Answer:

Following figure 1 shows class C with R-L Load. The circuit shown, modifies first-quadrant operation and converts it to second-quadrant operation. For first quadrant operation, CH_1 and D_1 perform the functions and if the average load current I_0 is high enough, CH_2 and D_2 do not conduct, even though CH_2 receives a gating signal. For second quadrant operation, CH_2 and D_2 perform the functions and if the average load current I_0 has a sufficiently large negative value, CH_1 and D_1 do not conduct, even though CH_1 receives a gating signal. Figure 2 shows the gate current, load voltage and sypply current waveforms.

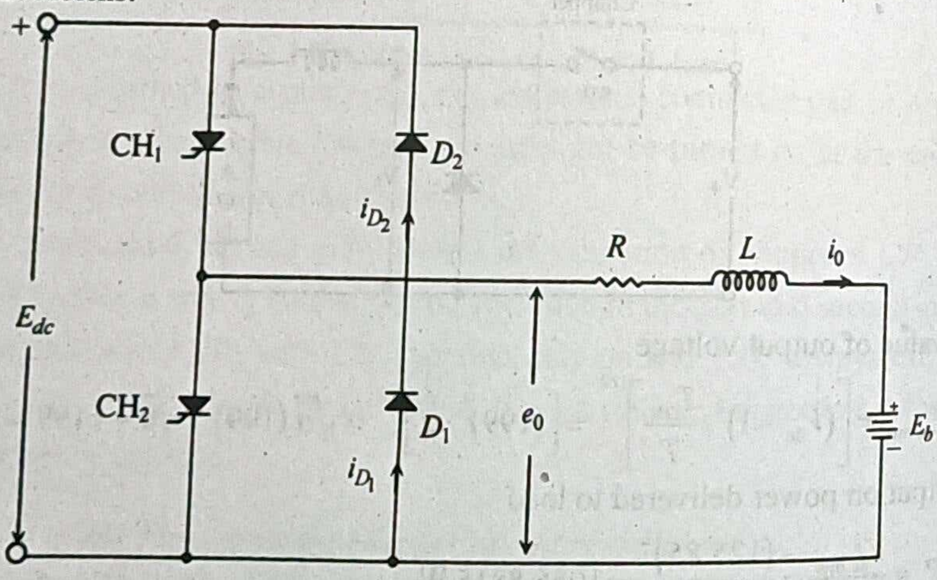


Fig: 1 Class C chopper with R-L Load

Initially, when both the choppers are OFF, both the diodes D_1 and D_2 become also OFF, and therefore, load is isolated from the supply. As shown in figure 2, at point P, chopper CH_1 is triggered and it starts to conduct. The load current i_0 is positive and the load received power from the supply. Therefore, the output voltage $e_0 = E_{dc}$ when chopper

CH_1 or diode D_2 conducts. At point Q, chopper CH_1 is turned OFF and inductance L forces the load current to flow through diode D_1 till the value of $L\frac{di_s}{dt}$ becomes equal to the back emf (E_b) of the load and the load-current i_0 becomes zero. Therefore, diode D_1 conducts from point Q to point R, as shown in figure 2. At this point R, if the gate signal to chopper CH_2 is available the back emf(E_b) of the motor forces current in the opposite direction through L and CH_2. This continues until CH_2 is turned-OFF and CH_1 is turned-ON. Now, when CH_2 is turned-OFF, the energy of the inductance forces current through diode D_2 to the supply. The input current becomes negative. During this period, CH_1 cannot conduct due to reverse bias but comes into conduction when the input current reduces to zero, provided the gate signal is available to CH_1 and both the load and input current becomes positive.

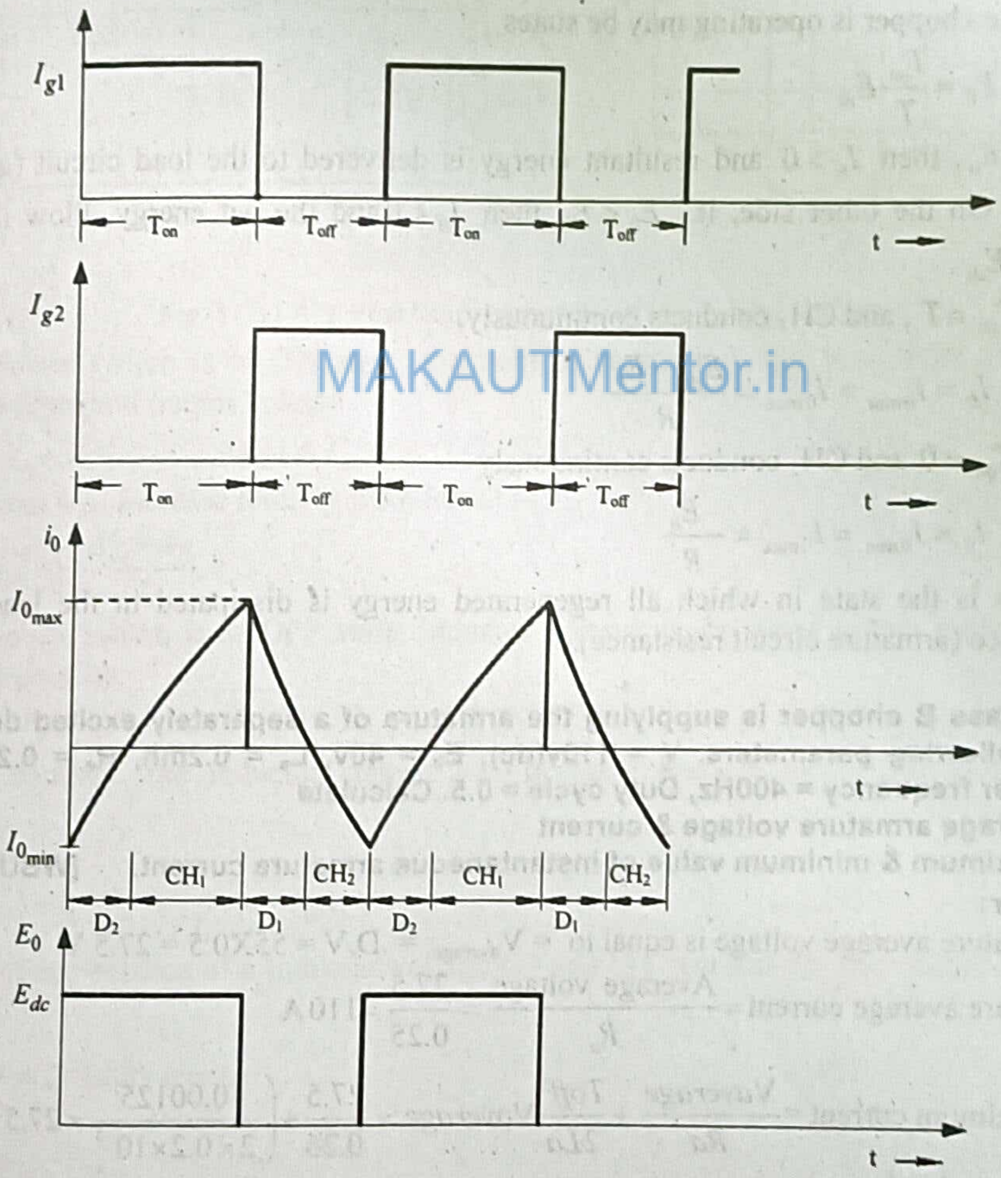


Fig: Output Voltage and Current Waveforms of the Type-C chopper

Hence, it becomes clear that load voltage $e_b = 0$ if chopper CH_2 or diode D_1 conducts, and $e_0 = E_{dc}$ if chopper CH_1 or diode D_2 conducts. Therefore, average load voltage E_0 is positive. However, load current i_0 have both positive and negative directions. It is positive if CH_1 is ON or D_1 conducts and negative if CH_2 is ON or D_2 conducts. Since average load voltage E_0 is positive and average load current I_0 is reversible, power flow is reversible. It is also clear that both thyristors may not be turned-ON simultaneously because that would short-circuit source E_{dc}. They are turned-ON alternately, as shown by the gating signal wave forms in figure 2. This chopper configuration is, therefore, used for both motoring and regenerative breaking of D.C. motor.

The Class A chopper analysis may be applied directly to this Class C chopper circuit, the only new feature being that $I_{0\min}$ and $I_{0\max}$ may be positive or negative. The quadrant in which the chopper is operating may be states

$$E_0 = \frac{T_{on}}{T} E_{dc}$$

If $E_0 > E_b$, then $I_0 > 0$ and resultant energy is delivered to the load circuit (armature circuit). On the other side, if $E_0 < E_b$ then $I_0 < 0$ and the net energy. Flow is to the source E_{dc}.

When $T_{on} = T$, and CH_1 conducts continuously,

$$I_0 = I_{0\min} = I_{0\max} = \frac{E_{dc} - E_b}{R}$$

When $T_{on} = 0$ and CH_2 conducts continuously

$$I_0 = I_{0\min} = I_{0\max} = \frac{-E_b}{R}$$

but this is the state in which all regenerated energy is dissipated in the load-circuit resistance (armature circuit resistance).

b) A class B chopper is supplying the armature of a separately excited dc motor with following parameters. V = 110v(dc), E_b = 40v, L_a = 0.2mh, R_a = 0.25Ω, f = chopper frequency = 400Hz, Duty cycle = 0.5. Calculate
(i) Average armature voltage & current
(ii) Maximum & minimum value of instantaneous armature current. **[WBUT 2018]**

Answer:

i) Armature average voltage is equal to $= V_{average} = D.V = 55X0.5 = 27.5$ V

$$\text{Armature average current} = \frac{\text{Average voltage}}{R_a} = \frac{27.5}{0.25} = 110\,\text{A}$$

$$\text{ii) Maximum current} = \frac{Vaverage}{Ra} + \frac{Toff}{2La} Vaverage = \frac{27.5}{0.25} + \left(\frac{0.00125}{2 \times 0.2 \times 10^{-3}} \times 27.5\right)$$

Therefore Maximum current = 110+ 82.5 = 192.5 A

Minimum current $=\dfrac{Vaverage}{Ra}-\dfrac{Toff}{2La}Vaverage=\dfrac{27.5}{0.25}-\left(\dfrac{0.00125}{2\times0.2\times10^{-3}}\times27.5\right)$

Therefore Minimum current = 110- 82.5 = 27.5 A

Here, T_{off} is evaluated as:

$$D=\frac{Ton}{Ton+T_{off}}=\frac{T_{on}}{T}=T_{on}\times f=0.5=T_{on}\times400\Rightarrow T_{on}=0.00125\text{sec.}=Toff$$

11. a) Derive the expression for ripple of inductor current for dc to dc buck converter. And also find out the value of duty cycle at which the ripple will be maximum. **[WBUT 2019]**

Answer:

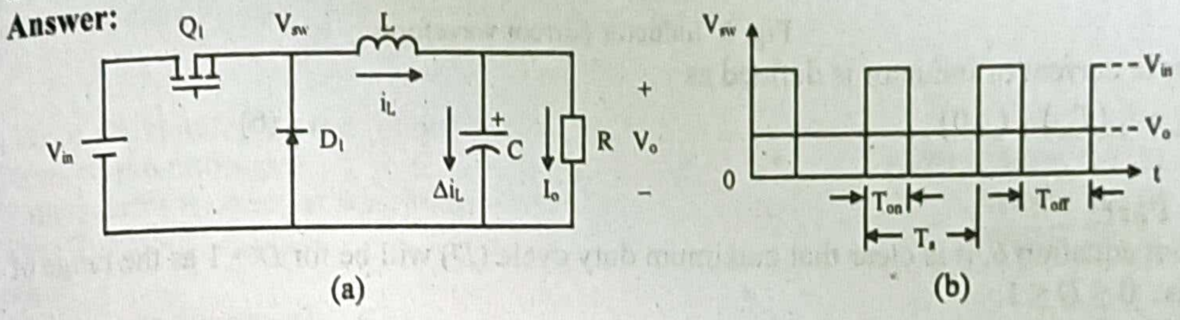


Fig. 1: (a) A typical Buck converter, (b) Switching voltage

When power switch is at ON state, the voltage across inductor is voltage difference between input and output voltage.

$V_L(t)=V_{in}-V_o$; $\quad 0\le t\le T_{on}$ $\quad$ (Q_1 "ON") .... (1)

The current will increase linearly from initial $i_L(0)$,

$i_L(t)=i_L(0)+\dfrac{V_{in}-V_0}{L}.t$ .... (2)

When power switch is at OFF state, inductor voltage is the same output voltage with negative polarity.

$V_L(t)=-V_o$; $\quad T_{on}\le t\le T_s$ $\quad$ (Q_1 "OFF") .... (3)

On the contrary, the inductor current will decrease linearly by $-V_o/L$ slope from $i_L(T_{on})$.

$i_L(t-T_{on})=i_L(T_{on})-\dfrac{V_o}{L}.(t-t_{on})$ .... (4)

Form volt-sec balance of a inductor voltage (1) and (3), one can get the voltage transfer ratio easily,

$\dfrac{V_o}{V_{in}}=\dfrac{T_{on}}{T_s}\equiv D$ (duty cycle) .... (5)

Figure 2 shows the inductor current waveform. Because voltage waveform of inductor is pulsating rectangular, the inductor current will be triangular with certain dc level

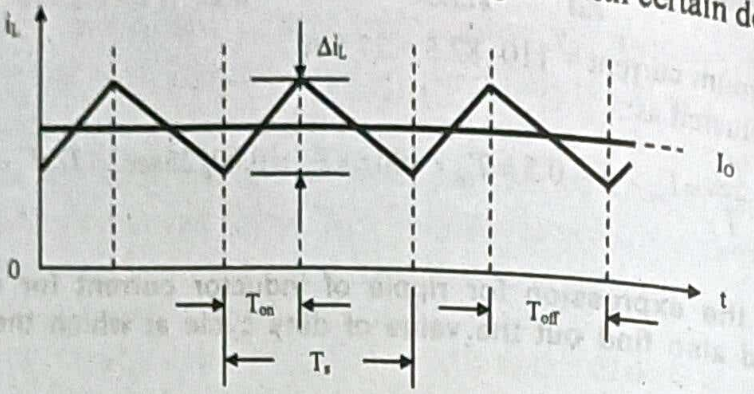


Fig. 2: Inductor current waveform

Ripple current of inductor is defined as

$$\Delta i_L = i_L(T_{on}) - i_L(0) \quad \text{.... (6)}$$

2nd Part:

From equation 6, it is clear that maximum duty cycle (D) will be for $D = 1$ as the range of D is: $0 \le D \le 1$.

$D = 1$ when $T_{on} = T$ and T_{off} is zero.

b) Draw and explain a DC-DC boost converter. Derive an expression for average output voltage. **[WBUT 2019]**

Answer: ***Refer to Question No. 1 of Long Answer Type Questions.***

c) A step-down chopper has a resistive load of $R = 10\Omega$ and input voltage of 120V, when the chopper is turned on, its voltage drop is 2V. The chopper frequency is 1 kHz. If the duty cycle is 40% determine

i) Average output voltage
ii) RMS output voltage
iii) Efficiency of chopper. **[WBUT 2019]**

Answer:

$E_{dc} = 120\text{ V}$

$\alpha = 0.4$

$R = 10\Omega$

$E_d = 2\text{ V}$

i) Average output voltage, $E_o = \alpha.(E_{dc} - E_d) = 0.5(120\text{-}2) = 59\text{V}$

ii) RMS output voltage, $E_{o\,rms} = \sqrt{\alpha}(E_{dc} - E_d) = \sqrt{0.5}(120 - 2) = 83.438\text{V}$

Chopper efficiency output power

$P_o = E_{o\,rms} . I_{o\,rms}$

$$P_o = \sqrt{\alpha} E_{dc} . \frac{\sqrt{\alpha} E_{dc}}{R} = \frac{\alpha\, E_{dc}^2}{R}$$

If E_d is the chopper drop, then

$$P_o = \frac{\alpha(E_{dc} - E_d)^2}{R} = \frac{0.4(120-2)^2}{10} = 556.96 \text{ W}$$

Now, input power to the chopper is given by

$$P_i = \frac{1}{T}\int_0^T E_{dc} \times \frac{(E_{dc} - E_d)}{R}\, dt$$

$$= \frac{1}{T}\int_0^{\alpha T} \frac{E_{dc}(E_{dc} - E_d)}{R}\, dt. = \frac{E_{dc}(E_{dc} - E_d)}{TR}(T)_0^{\alpha T} = \frac{0.4(120(120-2))}{10} = 566.4 \text{ W}$$

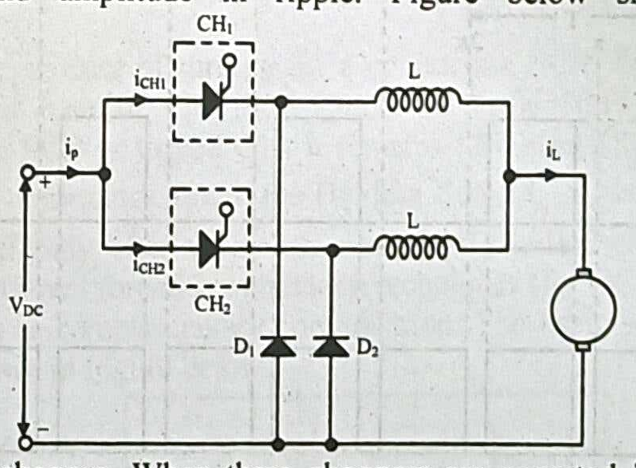
$$\text{Chopper efficiency} = \eta = \frac{P_o}{P_i} = \frac{556.96}{566.4} = 0.9833 = 98.33\%$$

12. Write short notes on the following:
a) Multi-phase choppers **[WBUT 2008, 2013]**
b) Four quadrant chopper operation **[WBUT 2018]**
c) Two-Quadrant chopper **[WBUT 2019]**

Answer:

a) Multi-phase choppers:

A multiphase chopper, as the name implies comprises of two or more choppers operating at same frequency but with desired phase shift. This type of operation causes the power supply and the load to be subjected to an effected frequency, which is a multiple of the chopping frequency of chopper. This configuration, as a result, reduces the supply harmonic current and amplitude in ripple. Figure below shows two chopper configurations



Called as two-phase chopper. When three choppers are operated in parallel called as three-phase chopper.

Operating modes:

Operating modes of the multiple chopper may be classified as

1. In-phase operating mode
2. Phase-shifted operating mode

In in-phase operating mode all the choppers configured in parallel mode are made on and off at the same instant of time as shown in the below figure:

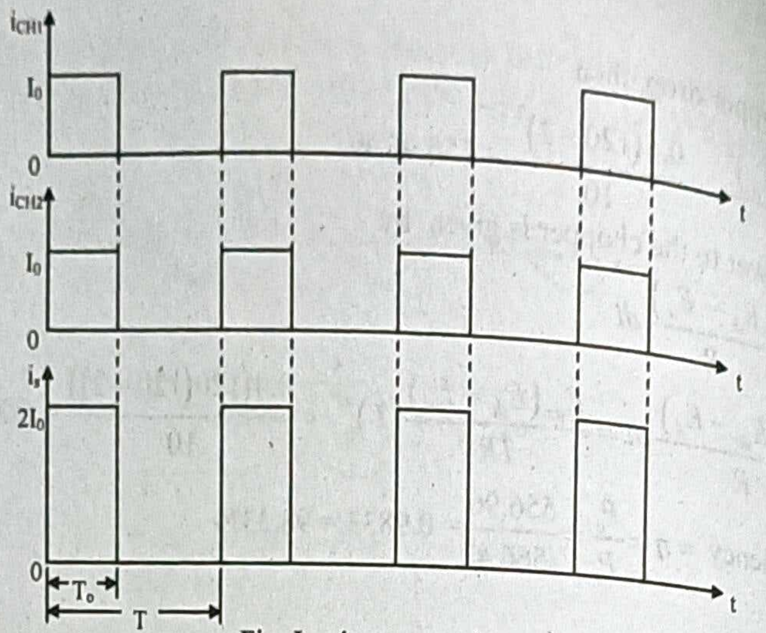


Fig: In-phase operation with α = 30%

In phase-shifted operating mode the choppers operate in parallel are made on and off at different instants of time as shown in figure. For independent operation of each chopper, configured in parallel, inductors with high valued inductance are connected in series with each chopper as shown in figure. The high valued inductance ensures almost ripple free load current.

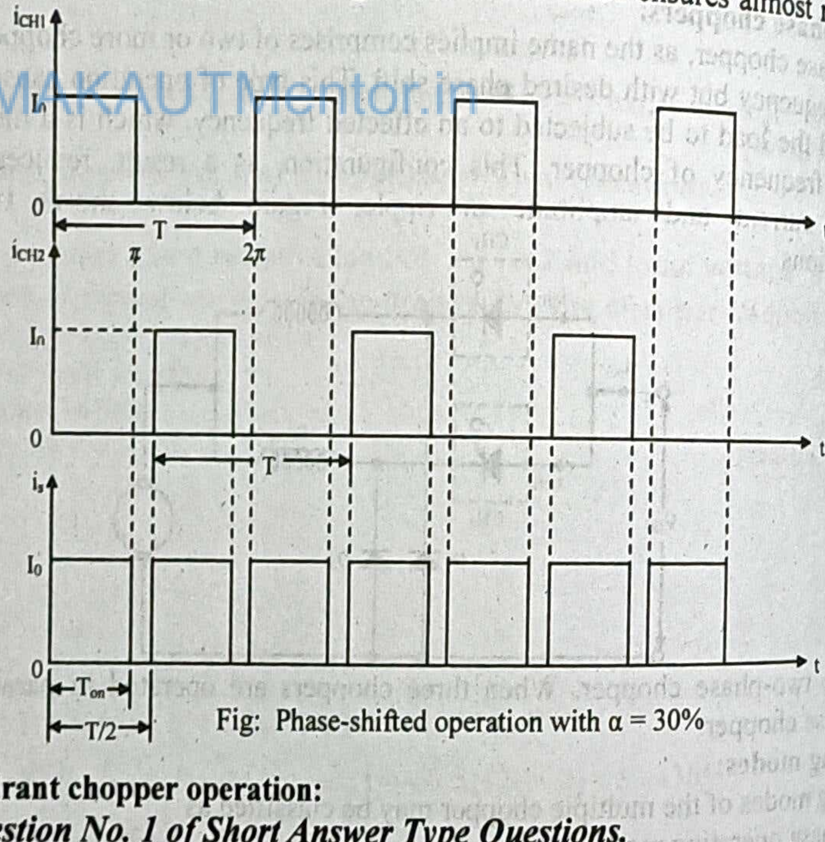


Fig: Phase-shifted operation with α = 30%

b) Four quadrant chopper operation:
Refer to Question No. 1 of Short Answer Type Questions.

c) Two-Quadrant chopper:
Refer to Question No. 3 of Short Answer Type Questions.

COMMUTATIONS

Multiple Choice Type Questions

1. In a commutation circuit employed to turn off an SCR, satisfactory turn-off is obtained when [WBUT 2007, 2017]
   a) circuit turn-off time < device turn-off time
   b) circuit turn-off time > device turn-off time
   c) circuit time constant < device turn-off time
   d) circuit time constant > device turn-off time

Answer: (b)

2. In resonant pulse commutation [WBUT 2009, 2011]
   a) the load current must be greater than peak value of peak resonant current
   b) the load current must be equal to the peak value of resonant current
   c) the peak value of resonant current must be greater than the load current
   d) is always possible whatever be the value of resonant peak current compared to load current

Answer: (c)

Short Answer Type Questions

1. What is meant by commutation? Briefly explain with relevant waveform, the complementary commutation of an SCR. [WBUT 2008]

OR,

Write short note on Complementary commutation. [WBUT 2019]

Answer:

Commutation is the process of turning off a conducting SCR. Once thyristor turns on, gate has no control over it. The SCR cannot be turned OFF via the gate-cathode terminals. Once the SCR is turned ON, it remains ON even after removal of the gate signal, as long as a minimum current, the Holding Current, I_h, is maintained through it. It will be turned-off only after the anode current is annulled either naturally (for AC circuits) or using different forced commutation techniques (for DC circuits).

This is also known as complementary commutation. The basic scheme of such type of commutation is shown in Figure below.

Scheme

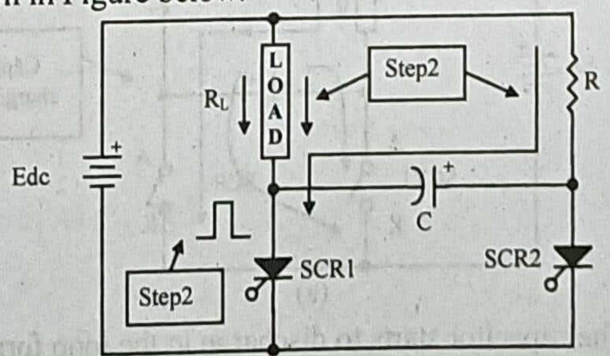


Fig: Circuit for Class C commutation

Component Description
Components used in Class C commutation are listed below:
SCR 1 → Main SCR, which carries load current (connected in series with load)
SCR 2 → Complementary SCR
C → Commutating component to commute SCR1

Operation
1: Both SCR 1 and SCR 2 are off.

$\therefore \quad I_L = 0 \quad I_C = 0$

2: SCR1 is triggered. Circuit current now flows through the two paths.
One path is $E_{dc+} \rightarrow R_L \rightarrow SCR1 \rightarrow E_{dc-}$ and the current through this path is called load current and other path is

$$E_{dc+} \rightarrow R \rightarrow C_+ \rightarrow C_- \rightarrow SCR1 \rightarrow E_{dc-}$$

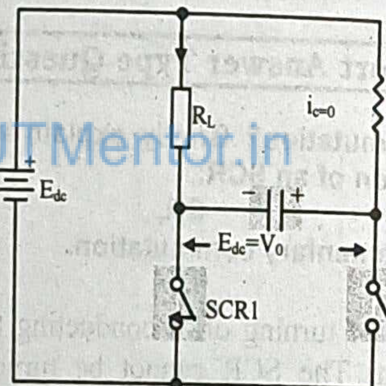
3: The capacitor C will be charged with polarities as shown in the Fig. below. Now,

$SCR1 \rightarrow ON$

$SCR2 \rightarrow OFF$(not fired till now)

$\therefore \quad i_C = 0$

$\therefore \quad v_C \approx E_{dc}$

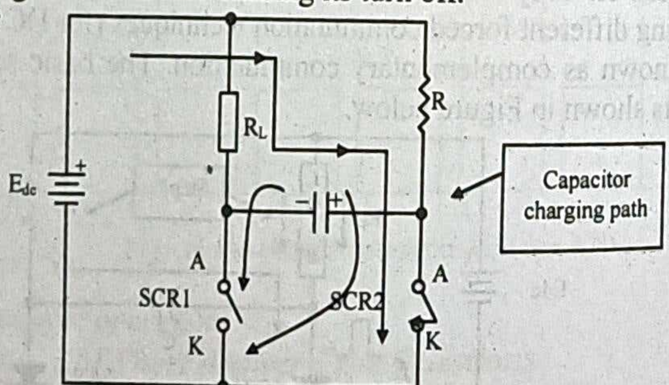


4: SCR2 is now triggered. As a result positive polarity of the capacitor C comes to cathode of SCR1 and anode of SCR1 faces negative plate of the capacitor. Thus producing reverse voltage across SCR1 causing its turn off.

Now, $SCR\ 1 \rightarrow OFF$

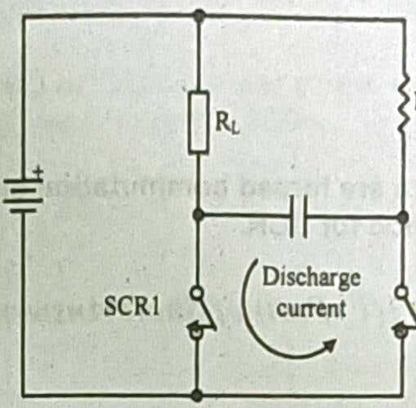
$SCR\ 2 \rightarrow ON$

$v_C \rightarrow \approx -E_{dc}$



(a)

5: SCR1 is triggered; the capacitor starts to discharge in the loop formed by SCR1, SCR2 and C.



(b)

Fig: Class C commutation (a) Charging path (b) discharging path

6: SCR 2 will be turned off now.

Circuit Analysis

When SCR 2 is triggered, current through C

$$i_C = \frac{2E_{dc}}{R_L} e^{-\frac{t}{R_L C}} \quad \dots (1)$$

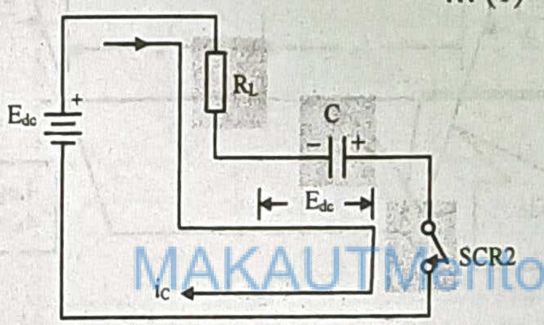


Fig: Current path when SCR2 in triggering

$$\text{Voltage Across SCR1} = V_1 = E_{dc} - i_C R_L$$

$$= E_{dc} - \left[\left(\frac{2E\ dc}{R_L}\right) e^{-\frac{t}{R_L C}}\right] \times R_L$$

$$= E_{dc}\left(1 - 2.e^{-t/R_L C}\right) = -v_C \quad \dots (2)$$

[As to make SCR1 OFF, capacitor voltage must be equal and opposite to V_1]

during $t = t_{off},\ v_C = 0$

$$\therefore \quad E_{dc}\left(1 - 2e^{-\frac{t_{OFF}}{R_L C}}\right) = 0$$

$$\Rightarrow \quad \left(1 - 2e^{-t_{OFF}/R_L C}\right) = 0 \left[\text{As } E_{dc} \neq 0\right]$$

$$\Rightarrow \quad e^{\frac{t_{OFF}}{R_L C}} = 2$$

$$\Rightarrow \quad t_{off} = R_L C . \ln 2 = 0.6931\ R_L C$$

$$\Rightarrow \quad C = \frac{1.44}{R_L} t_{off} \qquad \ldots (3)$$

2. What is commutation? Where are forced commutation circuits are implemented? Explain self-commutation method for SCR. **[WBUT 2010]**

Answer:

1st Part: *Refer to Question No 1(1st Part) of Short Answer Type Questions.*

2nd Part:

During turn-off a reverse or negative current flows through the SCR.

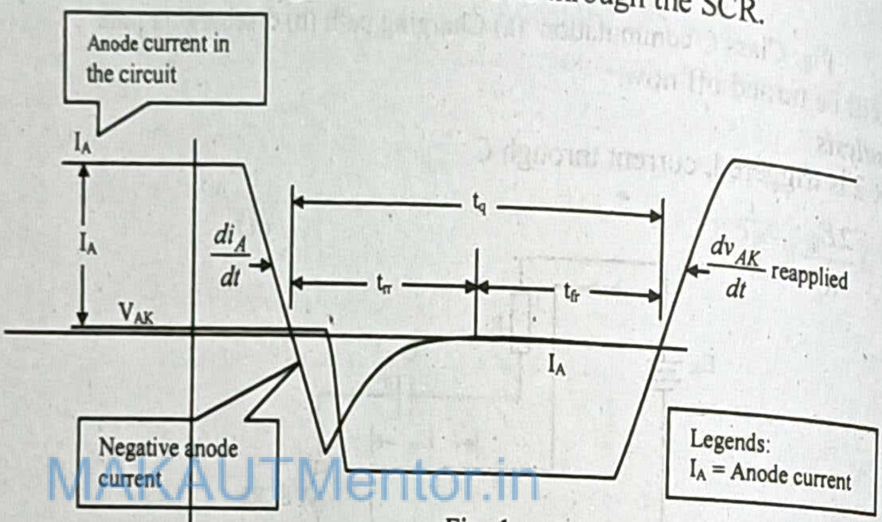


Fig: 1

3rd Part:

Natural Commutation

This method is used for AC circuits where input voltage /current is alternating. Here current through SCR naturally becomes zero and then the reverse voltage appears across it. The device turns off automatically/naturally without the aid of any external circuit. It is the line voltage or line current which turns the thyristor off. That is why this process of turning off is called Natural or line commutation.

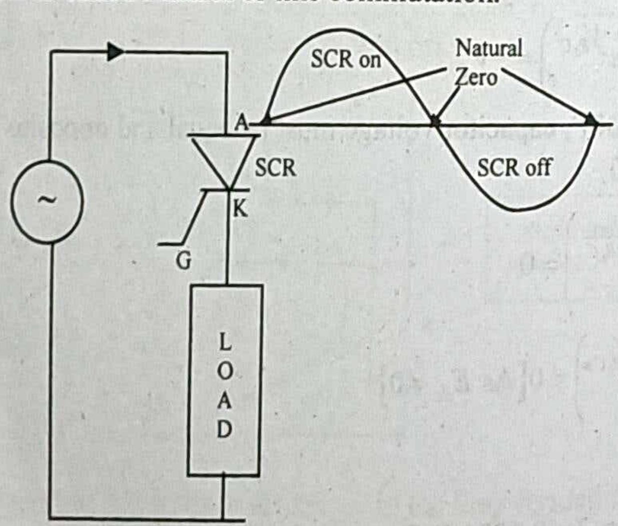


Fig: 2 Natural commutation

3. Explain the complementary commutation process with the waveform of following:
SCR gate currents, capacitor voltage, capacitor currents, SCR currents, output current (ripple free), voltages across the SCRs. **[WBUT 2011]**

Answer:

Refer to Question No. 1 of Short Answer Type Questions and rest part:

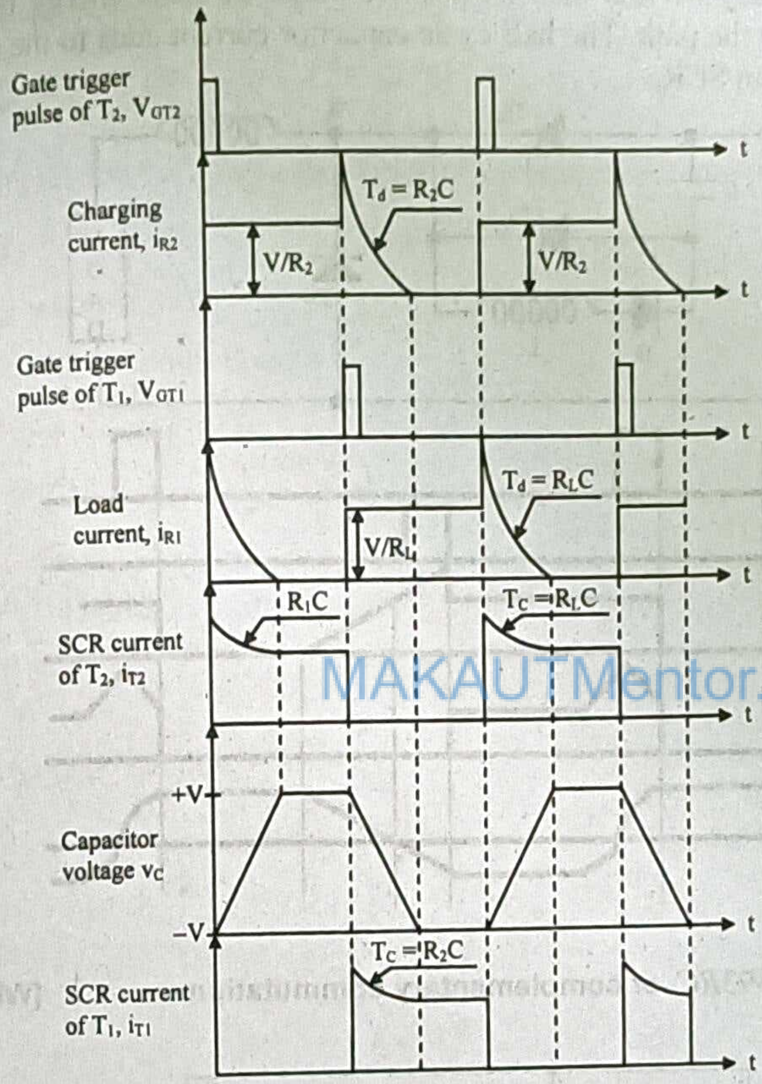


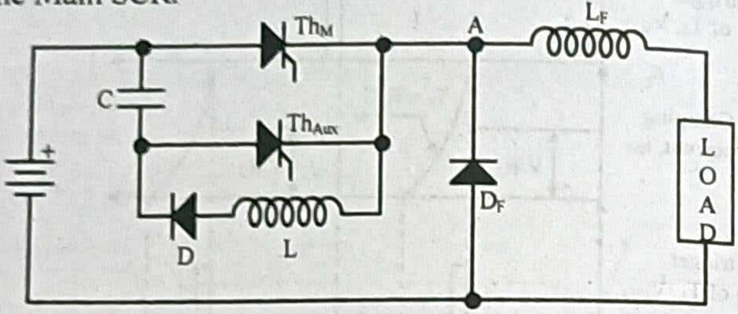
Fig: 1 Waveforms related to Class C commutation

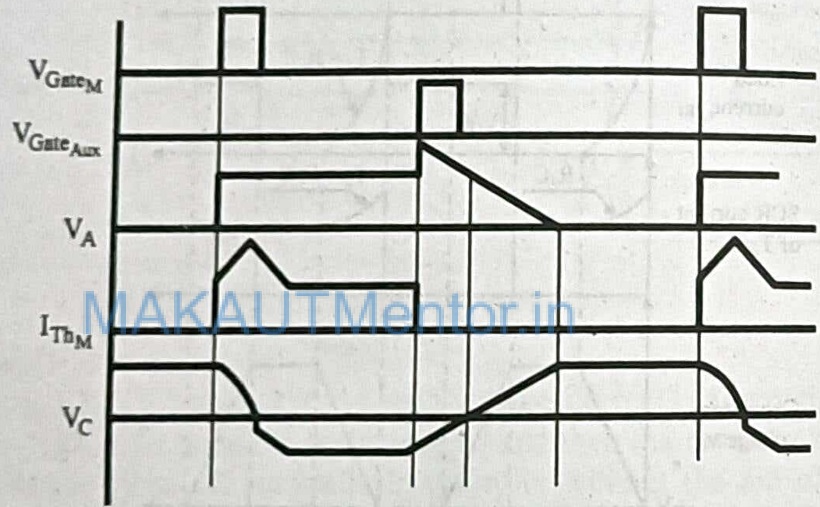
4. Discuss briefly with relevant waveforms, the voltage commutation technique used for the commutation of SCRs. **[WBUT 2013]**

Answer:

In a voltage commutated thyristor circuit a voltage source is impressed across the SCR to be turned off, mostly by an auxiliary SCR. This voltage is comparable in magnitude to the operating voltages. The current in the conducting SCR is immediately quenched, however the reverse-biasing voltage must be maintained for a period greater than that required for the device to turn-off. With a large reverse voltage turning it off, the device offers the fastest turn-off time obtainable from that particular device.

In voltage commutation Th_M is the main SCR and Th_{Aux} is the Auxiliary. As a consequence of the previous cycle, Capacitor C is charged with the dot as positive. When the Main SCR is triggered, it carries the load current, which is held practically level by the large filter inductance, L_F and the Free-wheeling diode. Additionally, the charged Capacitor swings half a cycle through Th_M, L and D ending with a negative at the dot. The reverse voltage may be less than its positive value as some energy is lost in the various components in the path. The half cycle capacitor current adds to the load current and is taken by the Main SCR.





5. Prove that $T_{off} = 0.693RC$ of complementary commutation. **[WBUT 2018]**

Answer:

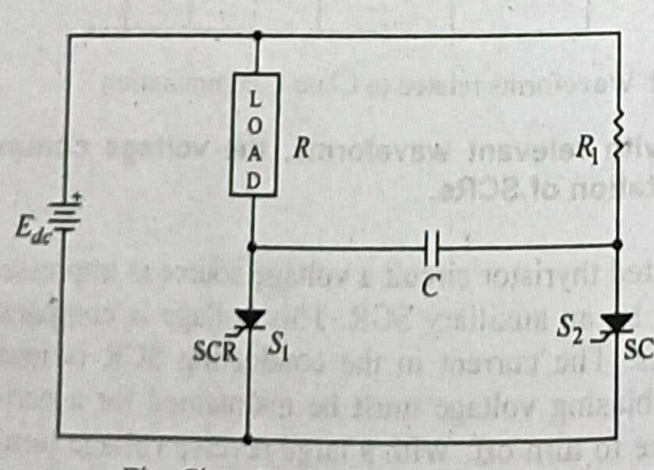


Fig: Class C–commutation circuit

When thyristor S_1 is conducting, capacitor C is charged to d.c. supply voltage E_{dc} through the resistor R_1. Now, when S_2 is triggered, a voltage twice the d.c. supply voltage E_{dc} is applied to the RC series circuit so that current through the circuit is,

$$i = \frac{2E_{dc}}{R} e^{-t/RC} \quad \ldots \text{(i)}$$

Therefore, the voltage across the thyristor S_1 is

$$E_{S_1} = E_{dc} - iR = E_{dc} - \frac{2E_{dc}}{R} e^{-t/R_L C}.R = E_{dc}\left(1 - 2e^{-t/R_L C}\right)$$

For making thyristor S_1 OFF, the capacitor voltage must be equal to the voltage E_{t_1}.

$$\therefore \quad E_C = E_{dc}\left(1 - 2e^{-t/RC}\right) \quad \ldots \text{(ii)}$$

Let $t = t_{off}$ when $E_c = 0$

$\therefore$ Equation (ii) becomes Proved

$0 = E_{dc}\left(1 - 2e^{-t_{off}/RC}\right)$ or, $0 = 1 - 2e^{-t_{off}/RC}$

$\Rightarrow 1 = 2e^{-t_{off}/RC}$

$\Rightarrow e^{t_{off}/RC} = 2$

$\Rightarrow \ln\left[e^{t_{off}/RC}\right] = \ln 2$

$\Rightarrow \frac{t_{off}}{RC} = \ln 2$

$\therefore t_{off} = 0.6931RC$ Proved.

INVERTERS

Multiple Choice Type Questions

1. A current source inverter is normally employed [WBUT 2009, 2011]
   a) if the source inductance is small
   b) if the source inductance is large
   c) on any source irrespective of its impedance
   d) if the load is pure inductive load

Answer: (b)

2. The output voltage waveform of a three phase square wave inverter contains [WBUT 2013, 2019]
   a) only odd harmonics
   b) both odd & even harmonics
   c) only even harmonics
   d) only triplex harmonics

Answer: (a)

3. A PWM switching scheme is used in 1-phase inverters to– [WBUT 2014]
   a) reduce total harmonic distortion with modest filtering
   b) minimize the load on the dc side
   c) increase the life of batteries
   d) reduce the low order harmonics and increase the higher order harmonics.

Answer: (a)

4. A single phase full bridge VSI has inductive load. For a constant source voltage, the current through the load is [WBUT 2015, 2019]
   a) square wave
   b) triangular wave
   c) sine wave
   d) pulsed wave

Answer: (b)

5. In a CSI, if frequency of output voltage is f Hz, then frequency of voltage input to CSI is [WBUT 2016]
   a) f
   b) $2f$
   c) $f/2$
   d) $3f$

Answer: (a)

6. In resonant pulse inverters [WBUT 2016]
   a) dc output voltage variation is wide
   b) the frequency is low
   c) output voltage is never sinusoidal
   d) dc saturation of transformer core is minimized

Answer: (d)

7. PWM is used in inverters [WBUT 2017]
   a) to control output voltage
   b) to reduce harmonics in output

c) to compensate the variation in d.c. input
d) all of these

Answer: (d)

8. In a 3-phase 180° mode bridge inverter, the lowest order harmonics in the line to neutral output voltage (fundamental frequency output = 50 Hz) is **[WBUT 2017]**

a) 100 Hz b) 150 Hz c) 200 Hz d) 250 Hz

Answer: (a)

9. In the SPWM, the modulating signal is **[WBUT 2018]**

a) square b) sinusoidal c) triangular d) saw-tooth

Answer: (b)

10. If the firing angle becomes negative, then the rectifier begins to work as **[WBUT 2018]**

a) a rectifier b) an inverter c) a chopper d) a regulator

Answer: (b)

Short Answer Type Questions

1. Define an inverter. What are the different types of inverters? **[WBUT 2011]**

Answer:

Inverters are nothing but d.c. to a.c. converters, i.e., an inverter converts a d.c. power into an a.c. power at desired output voltage level with desired frequency.

Figure 1 shows the different types of the inverters.

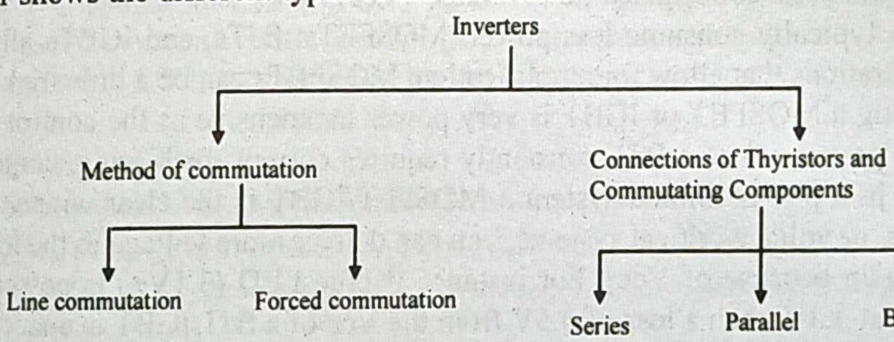


Fig: 1 Taxonomy of the inverters

2. What is the voltage source inverter? Mention its merits and demerits over the current source inverter. **[WBUT 2011]**

Answer:

1st Part:

In voltage source inverter is fed by a dc source of small internal impedance. Looking from the ac side, the terminal voltage remains almost irrespective of the load current drawn.

Depending on the circuit configurations, the voltage source inverters may be classified as half bridge and full bridge inverters.

2nd Part:

The merits of voltage source inverters includes

(i) Simple in operation and can be operated in open loops,
(ii) Reliable is reasonably good,
(iii) Successfully operated upto 500 Hz,
(iv) A single controller feeds multiple induction motor provided powers match.

The demerits include low power factor, need of additional diodes for feeding the reactive energy back to supply when operated with heavily inductive loads, possibility of motor interaction with dc link filter elements and may also lead to motor instability at very low operating frequencies.

The merits of current source inverters includes:

(i) Capability of regeneration back to the ac side,
(ii) Current limiting action is achieved due to the presence of dc link inductor,
(iii) Converter grade thyristors are sufficient for use in current source inverters.

The limitations include higher cost due to presence of large inductor, presence of voltage spikes, limitation of using only one motor, lower efficiency, motor instability at low frequency operation.

3. Compare the merits & demerits of BJT, MOSFET and IGBT as power electronics switch. **[WBUT 2017]**

Answer:

Rds(on) is the resistance when the device is in saturation. MOSFETs can switch faster and have a low on resistance (Rdson) so they make better switches than BJTs and IGBT which have a non-zero collector-emitter voltage (Vce). This also means that for high power they can typically consume less power. MOSFETs, BJTs, and IGBTs all can be setup in configurations that allow for amplification. MOSFETs can be a little trickier than BJTs. Controlling a MOSFET or IGBT is very power inexpensive as the control voltage uses almost no power, while a BJT constantly requires current for biasing, control, and amplifying. So in a power limited system a MOSFET/IGBT is the clear winner. In low voltage systems, or voltage critical systems, you can deliver more voltage to the load with a MOSFET (again because of Vce). For instance if blue LED (3.1V+) is powered in a system running at 3.3V, then a loss of 0.5V from the Vce of a BJT/IGBT is unacceptable, while the MOSFET will do it without any issues.

4. A 3-phase bridge inverter is fed from 200 V d.c. source. The inverter is operated in 180° conduction mode and it is supplying inductive, star connected load with $R = 10\Omega$ and $L = 20$ mH. The inverter frequency is $f_0 = 50$ Hz. Determine,

i) instantaneous line to line voltage and line current
ii) RMS phase voltage and RMS line voltage. **[WBUT 2017]**

Answer:

Given: $E_{dc} = 200$ V, $R = 10\Omega$, $f_0 = 50$ Hz

$\therefore \quad \omega = 2\pi \times 50 = 314$ rad/sec

(i) The instantaneous line-to-line voltage E_{AB}, can be written as

$$E_{AB} = 226.89\sin(314t+30°) - 36.01\sin 5(314t+30°)$$
$$-35.93\sin 7(314t+30°) + 10.51\sin 11(314t+30°)$$
$$+19.35\sin 13(\sin 314t+30°) - 2.34\sin 17(314t+30°) + \ldots\ldots$$

Now, $Z_L = \sqrt{R^2 + (n\omega L)^2} \angle \tan^{-1}\left(\frac{n\omega L}{R}\right) = \sqrt{(10)^2 + (6.28n)^2} \angle \tan^{-1}\left(\frac{6.28}{10}\right)$

Instantaneous line (or phase) current is given by

$$I_L = 10.62\sin(314t - 32.12) - 0.56\sin 5(5\times 314t - 72.33)$$
$$-0.402\sin(7\times 314t - 77.18) + 0.076\sin(11\times 314t - 81.76)$$
$$+0.118\sin(13\times 314t - 83) - 0.01\sin(17\times 314t - 84.69) - \ldots\ldots$$

(ii) $E_L = 0.8165 \times 200 = 163.30\text{ V}$

(iii) $E_P = 0.4714 \times 200 = 94.28\text{ V}$

Long Answer Type Questions

1. Discuss the principle of working of a 3-phase bridge inverter with an appropriate circuit diagram. Draw phase and line voltage waveforms on the assumption that each SCR conducts for 180° and the resistive load is star connected. The sequence of firing of various SCRs should also be indicated in the diagram. [WBUT 2007]

OR,

Explain the principle of working of a 3 phase bridge inverter with star connected resistive load. Assume 180° mode of conduction. Also draw the triggering sequence of each SCR, waveform of phase & line voltages. [WBUT 2018]

Answer:

180° Conduction Mode

- Each SCR conducts for a duration of 180°.
- The SCRs of same arm operate in a complementary manner i.e., with a time interval of 180°, whereas the inverter arms are operated at a 120° phase difference.

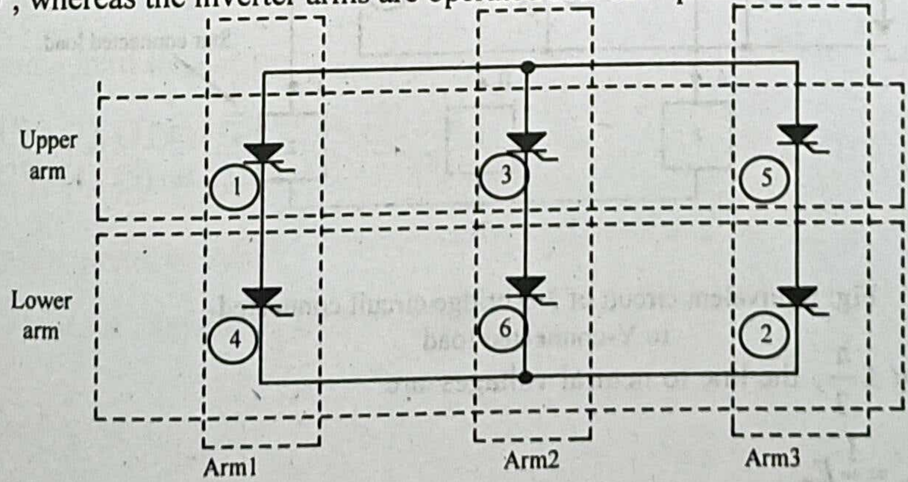


Fig: 180° conduction mode

Table 1

Arms	Related SCRs	Conduct at phase difference of
1	(1), (4)	180°
2	(3),(6)	180°
3	(5), (2)	180°

Table 1 shows the phase differences by which the related SCRs conduct in related bridge arms.

Table 2 depicts the phase differences by which the related SCRs conduct in inverter arms.

Table 2

Inverter Arms	Related SCRs	Conduct at Phase difference of
Upper arm	(1), (3), (5)	120°
Lower arm	(4), (6), (2)	120°

So, we can say

- A complete cycle (360°) comprises of six steps.
- Each step is formed by 60° $\left(=\frac{360°}{6}\right)$
- In each step three SCRs are in conducting state at any instant of time.

Analysis

The analysis is sectioned in three steps

Step 1: During first step, as per triggering sequences, which ranges as $0 \le \omega t \le \frac{\pi}{3}$,

- SCRs (1), (6) and (5) are conducting, i.e., operating as closed switches.
- SCRs (4), (3) and (2) are not conducting.

The equivalent circuit may be drawn as shown in figure below.

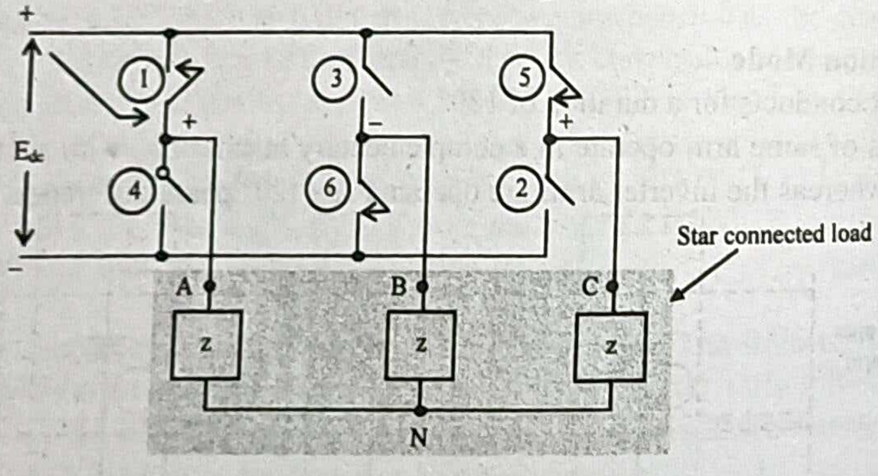


Fig: Equivalent circuit of 3-ϕ bridge circuit connected to Y-connected load

$\therefore$ For $0 \le \omega t \le \frac{\pi}{3}$, the line to neutral voltages are

$$V_{AN} = \frac{1}{3} E_{dc}$$

$$V_{BN} = -\frac{2}{3}E_{dc} = -V_{NB}$$

$$V_{CN} = \frac{1}{3}E_{dc}$$

Step 2: During second step, as per triggering sequences, which ranges as $\frac{\pi}{3} \leq \omega t \leq \frac{2\pi}{3}$

- SCRs (1), (6) and (2) are conducting
- SCRs (4), (3) and (5) are not conducting

The equivalent circuit may be drawn as shown in Figure.

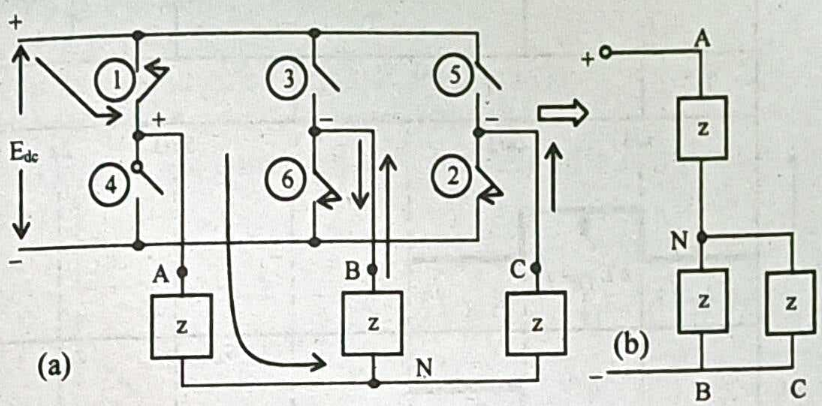


Fig: (a) Current path (b) phase wise load

$\therefore$ For $\frac{\pi}{3} \leq \omega t \leq, \frac{2\pi}{3}$, the line to neutral voltage

$$V_{AN} = \frac{2}{3}E_{dc}$$

$$V_{BN} = -V_{NB} = -\frac{1}{3}E_{dc}$$

$$V_{CN} = -V_{NC} = -\frac{1}{3}E_{dc}$$

Step 3: During third step, as per triggering sequence, which ranges from $\frac{2\pi}{3} \leq \omega t \leq \pi$

- SCRs (1), (3) and (2) are conducting.
- SCRs (4), (6) and (5) are not conducting.

The equivalent circuit becomes

$\therefore$ For $\frac{2\pi}{3} \leq \omega t \leq \pi$, the line to neutral voltages are

$$V_{AN} = \frac{1}{3}E_{dc}$$

$$V_{BN} = \frac{1}{3}E_{dc}$$

$$V_{CN} = -V_{NC} = -\frac{2}{3}E_{dc}$$

Waveforms for 180° Mode of Operation

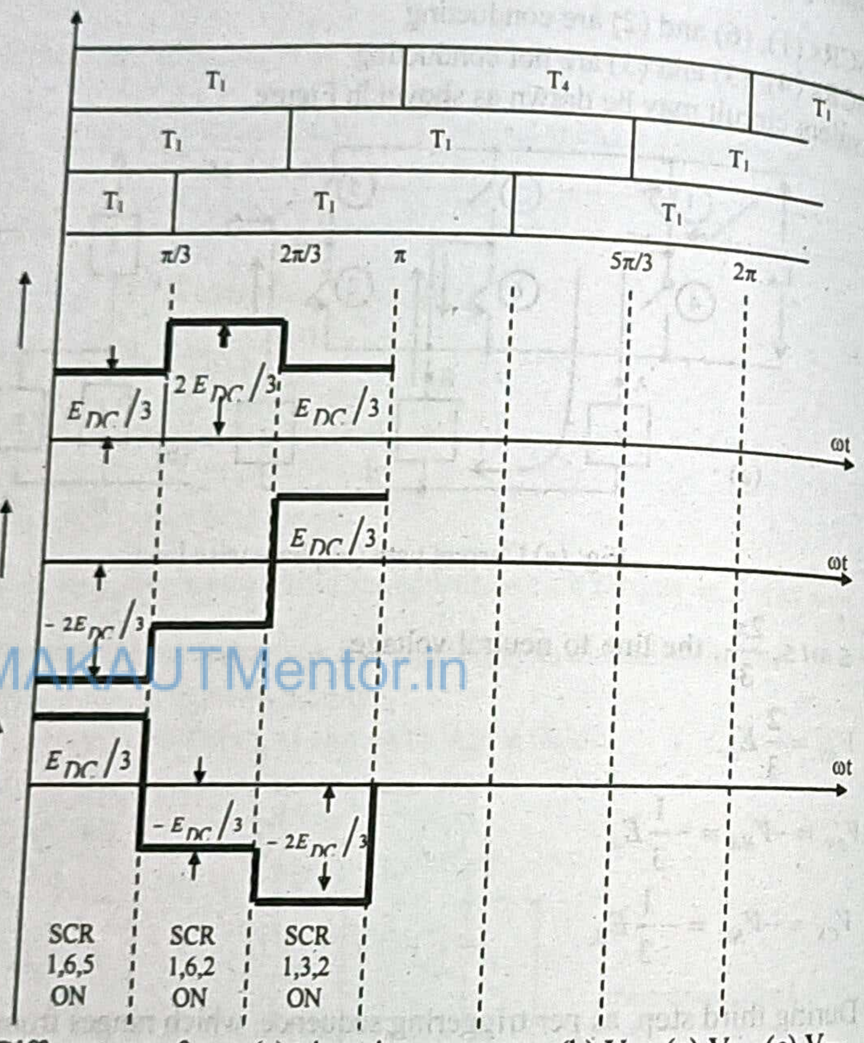


Fig: Different waveforms (a) triggering sequences (b) V_{AN} (c) V_{BN} (c) V_{CN}

2. Explain how the voltage of a single phase inverter is controlled by PWM techniques? **[WBUT 2007]**

OR,

Explain different PWM methods to control output voltage of an inverter. **[WBUT 2008, 2011, 2018]**

Answer:

1. Single-Pulse Width Modulation
2. Multiple Pulse width modulation

1. Single-Pulse Width Modulation

Features

- There is only *one pulse* in each half cycle
- The output voltage is varied by controlling the width of the pulse.

Principle

A circuit is schemed under Bridge configuration with power semi conducting devices forming the Bridge. The devices are switched ON-OFF several times or once in each half to control the output voltage.

Obtaining Gating Signals

- We should have two signals
  1. A reference rectangular signal of amplitude A_r
  2. A triangular carrier wave of amplitude A_c.
- These two signals are compared with the help of a comparator circuit as shown in Fig. 1.a.

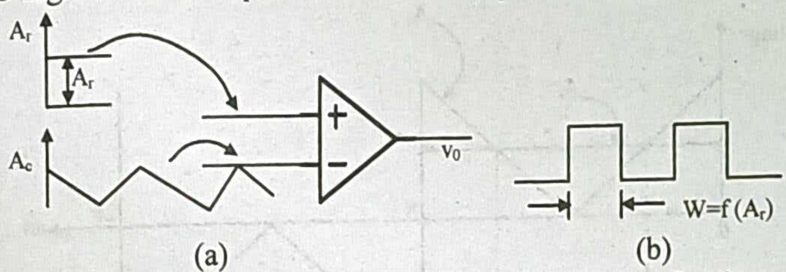


Fig: 1 (a) Generating gating signal (b) dependence of gating width

- The width of the output pulse depends upon the amplitude of reference signal which is varied from 0 to π as shown in Fig. 2.

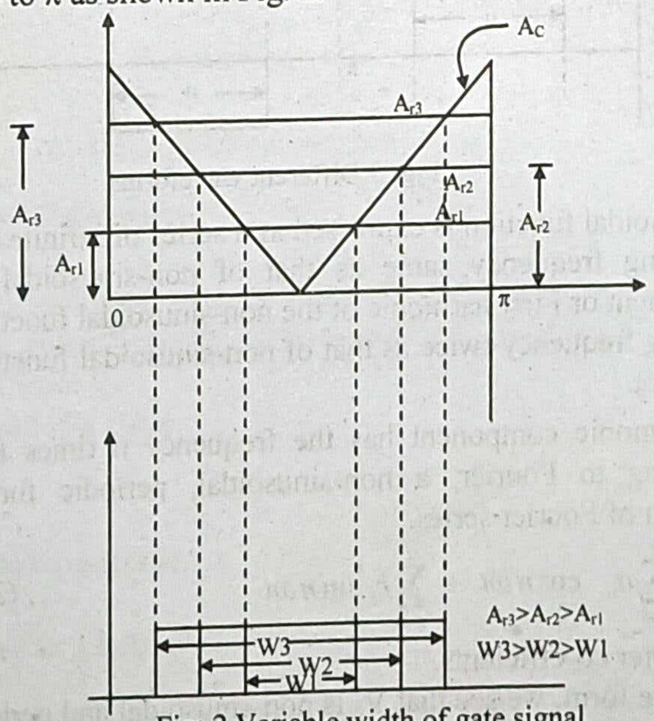


Fig: 2 Variable width of gate signal

So, by varying the ratio of A_r to A_c we can vary the width of the output pulse.

Obtaining RMS Output Voltage

$$V_{rms} = \sqrt{\frac{2}{2\pi}\int_0^{2\pi} V_0^2 d\theta} \qquad \dots (1)$$

From the waveform

$$V_{rms} = \sqrt{\frac{2}{2\pi}\left[\int_0^x V_0^2 d\theta + \int_x^{\pi+x} V_0^2 d\theta + \int_{\pi+x}^{\pi} V_0^2 d\theta\right]}$$

$$= \sqrt{\frac{2}{2\pi}\left[0 + \int_x^{W+x} v_S^2 d\theta + 0\right]}$$

$$= \sqrt{\frac{1}{\pi} V_S^2 \int_x^{W+x} d\theta} \Rightarrow V_S\sqrt{\frac{W}{\pi}} = V_{rms} \qquad \dots (2)$$

Waveforms

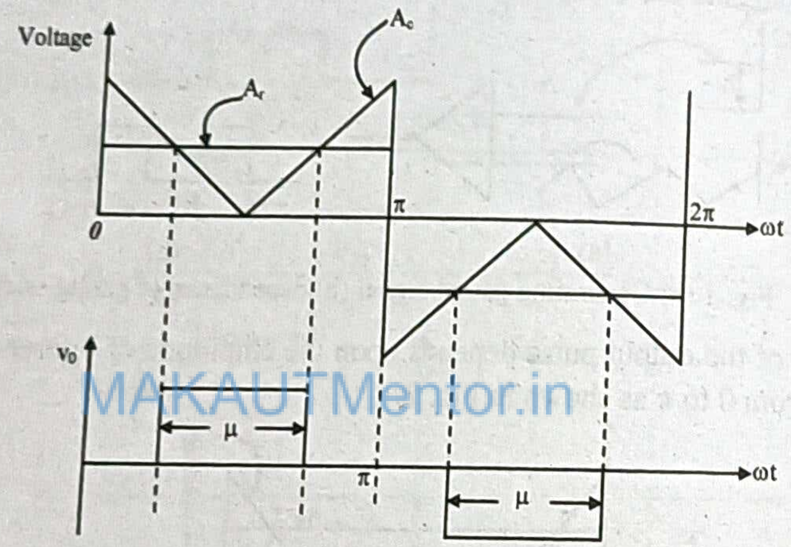


Fig: 3 Different waveforms

A periodic non-sinusoidal function is expressed as a series of infinite sinusoids.
The sinusoids having frequency same as that of non-sinusoidal function is called fundamental component or First harmonic of the non-sinusoidal function.
The sinusoids having frequency twice as that of non-sinusoidal function is called Second Harmonic Component.

In general, n^{th} harmonic component has the frequency n times that of fundamental frequency. According to Fourier, a non-sinusoidal, periodic function $f(t)$ may be expressed in the form of Fourier series.

$$f(t) = a_0 + \sum_{\eta=1}^{\alpha} a_n \cos n\omega t + \sum_{\eta=1}^{\alpha} b_n \sin n\omega t \qquad \dots (3)$$

where, a_n, $b_n \Rightarrow$ Fourier co-efficients.
From the output wave form, we see that V_0 is non-sinusoidal and periodic. So, V_0 may be expressed as Fourier series.

$$V_0(t) = a_0 + \sum_{\eta=1}^{\alpha} a_n \cos n\omega t + \sum_{\eta=1}^{\alpha} b_n \sin n\omega t \quad \dots (4)$$

The waveform for V_0 says

1) $V_0(t) = +E$

$V_0(-t) = -E$

$\therefore V_0(t) = -V_0(-t)$

So, $V_0(t)$ has odd symmetry

$\therefore a_n = 0$

2) $V_0(\pi+\omega t) = -E$

$V_0(\omega t) = E$

$\therefore V_0(\pi+\omega t) = -V_0(\omega t)$

$\therefore V_0(t)$ has rotational symmetry

$\therefore b_n = 0$ for n = 2, 4, 6,.....

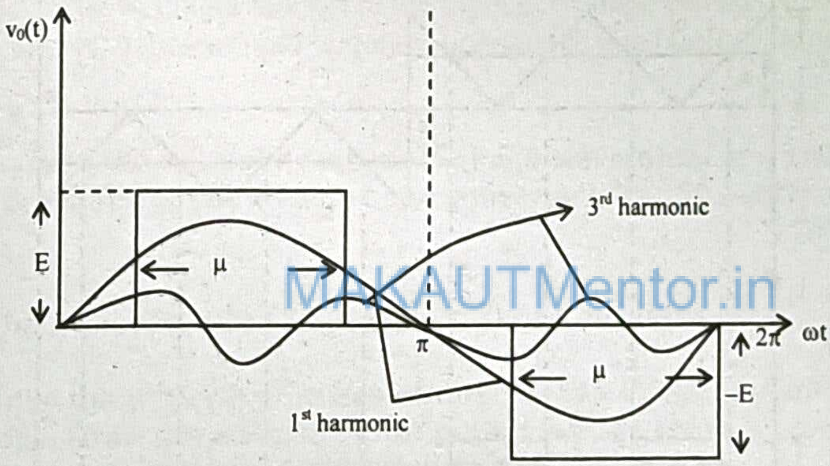


Fig: 3 Different harmonics

2. Multiple Pulse Width Modulation

Features

- Unlike single PWM, this process uses several pulses in each half-cycle.
- The *number of output pulses* depends on the ratio of the frequency of the carrier wave f_c to that of reference wave f_r.
- Number of output pulse in a cycle

$$= \frac{f_c}{f_r} = m_f \quad \dots (1)$$

where, m_f is frequency modulation ratio.

Getting number of pulses in a half cycle

$$n = \frac{1}{2} \cdot \frac{f_c}{f_r} = \frac{m_f}{2} \quad \dots (2)$$

Obtaining RMS value of output voltage

$$V_{rms} = \sqrt{\frac{2}{2\pi}\int_0^{\pi} v_0^2 d\theta} \quad \ldots (3)$$

From the waveform as shown in Fig. below we can write

$$v_{rms} = \sqrt{\frac{2}{2\pi}\cdot n \cdot \int_{\left(\frac{\pi}{n}-W\right)/2}^{\left(\frac{\pi}{n}+W\right)/2} v_0^2 d\theta} = \sqrt{\frac{n}{\pi}\cdot \int_{\left(\frac{\pi}{n}-W\right)/2}^{\left(\frac{\pi}{n}+W\right)/2} v_S^2 d\theta} = v_S\sqrt{\frac{n}{\pi}\cdot \int_{\left(\frac{\pi}{n}-W\right)/2}^{\left(\frac{\pi}{n}+W\right)/2} d\theta} = v_S\sqrt{\frac{n}{\pi}\cdot W}$$

$$\boxed{v_{rms} = v_s\sqrt{\frac{n}{\pi}}.W} \quad \ldots (4)$$

Waveforms

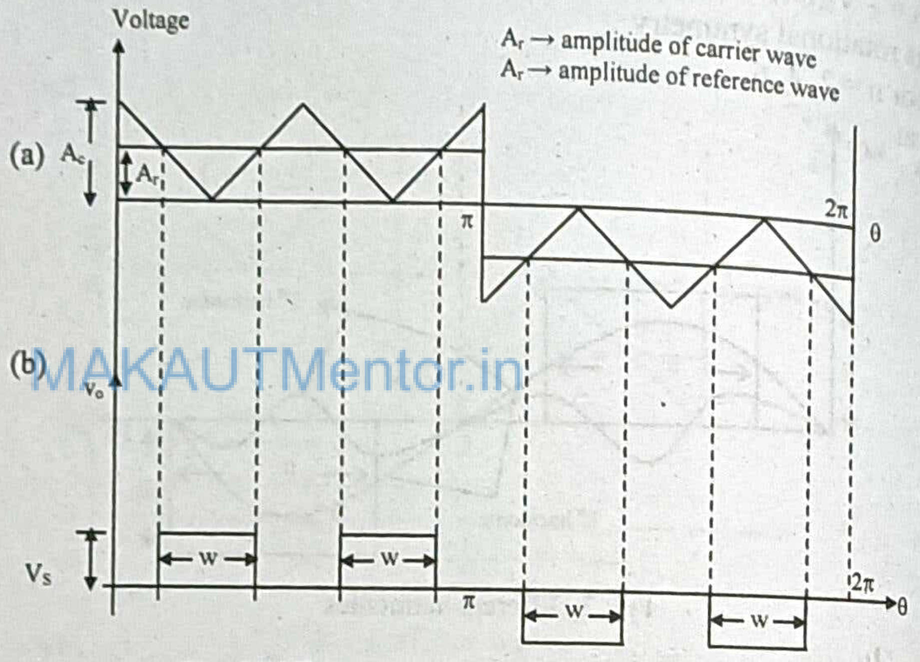


Fig: 1 Different waveforms
(a) gate signal generating signals A_c and A_r
(b) output voltage

3. a) Compare 180° and 120° condition modes of 3-phase bridge inverter. [WBUT 2009]

Answer:

It may be observed that for the case of 180° conduction, TH_1 turns on simultaneously, on the other hand, for 120° conduction, there is sufficient gap between turning off of Th_1 and turning on of Th_4. Thus there is no short circuit of the dc supply through upper and lower thyristors. Moreover, in 180° conduction mode all the three modes conduct for all the intervals but for 120° conduction, any two phases conduct during each interval. In 120° conduction scheme since each element conducts 120° instead of 180° hence the utilisation of the thyristors (or transistors) are lesser in 120° mode. Also, the potential of the open terminal, for each instant depends on the load characteristics and would be unpredictable.

b) What is a PWM inverter? What are its advantages? **[WBUT 2009, 2015]**

OR,

What is PWM inverter? What is the advantage of PWM inverter over VSI? **[WBUT 2014]**

Answer:

1st Part:

Waveform control can also be achieved by PWM (pulse width modulation). It implies that the waveform of the output voltage is changed by additional communication, and a phase potential will change signs a number of times during each half cycle.

2nd Part:

Advantages of PWM inverter are:

(i) the ratio of the ac output voltage to the input dc voltage can be increased.

(ii) PWM allows efficient and smooth operation, free from torque pulsations and cogging.

c) Describe with the help of necessary voltage waveforms and circuit diagram the operation of a three phase voltage source inverter with 180 degree conduction. **[WBUT 2009, 2010]**

Answer:

Refer to Question No. 1 of Long Answer Type Questions.

4. a) Describe the working principle of three phase bridge inverter (VSI) operating in 180° mode. Draw the waveforms for output voltage (both phase & line voltage). Assume star connected balanced resistive load. **[WBUT 2011]**

Answer:

Refer to Question No. 1 of Long Answer Type Questions.

b) A single phase bridge inverter delivers power to a series connected RLC load with $R = 2.2\Omega$ and $\omega L = 10\Omega$. The periodic time $T = 0.12$ msec. What value of C should the lad have in order to obtain load commutation for the SCRs? The thyristors turn-off time is 10 μsec. Take circuit turn-off time as 1.6 times the thyristor turn off time. Assume load current contains only fundamental component. **[WBUT 2011]**

Answer:

$$\omega L = 10\Omega$$

$$L = \frac{10}{2\pi \times 4 \times 10^3} = \frac{10}{2 \times 3.14 \times 4 \times 10^3} = \frac{1}{25.12} \times 10^{-2} = 0.39 \times 10^{-3} = 0.39\,\text{mH}$$

For faithful commutation, $\frac{R^2}{4L^2} < \frac{1}{LC}$

$$R^2 < \frac{4L}{C}$$

$$\therefore \quad C < \frac{4L}{R^2} = \frac{4 \times 0.39 \times 10^{-3}}{4.84}$$

Therefore as a limiting value C should be 322μF.

5. a) Discuss with appropriate circuit diagram the principle of operation of a three phase bridge inverter connected with star connected resistive load. The period of conduction of each SCR is 180°. Draw phase & line voltage waveforms of the load. The sequence of firing of various SCRs should also be indicated in the diagram.
[WBUT 2013, 2017]

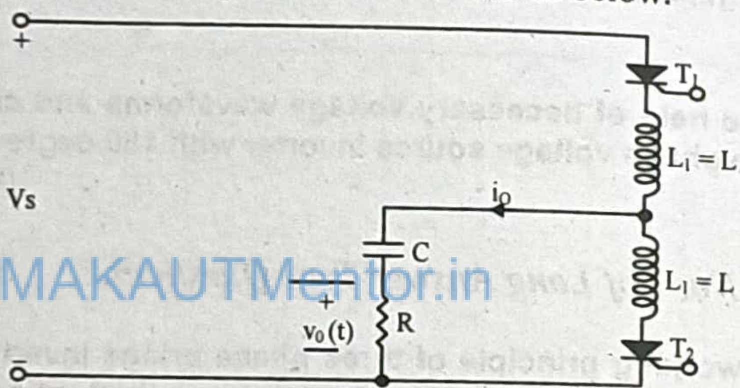
Answer:

Refer to Question No. 1 of Long Answer Type Questions.

b) Explain the working of a resonant pulse inverter. **[WBUT 2013, 2017]**

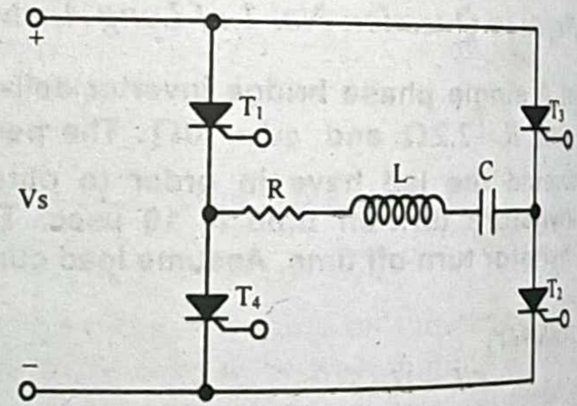
Answer:

The circuit diagram of a resonant pulse inverter is shown below.



When

T_1 fired, resonant pulse of current flows through the load. The current falls to zero at $t = t_{1m}$ and T_1 is "self-commutated".



When

T_2 fired, reverse resonant current flows through the load and T_2 is also "self-commutated". The series resonant circuit must be underdamped, $R_2 < (4L/C)$. When a full bridge configuration of a resonant pulse inverter is adopted then there is an improvement in performance.

- This configuration provides higher output power.
- Either $T_1 - T_2$ or $T_3 - T_4$ are fired.

Supply current is continuous but pulsating.

6. How are control of output voltage & harmonic reduction in the output voltage achieved in the inverter? **[WBUT 2013]**

OR,

Briefly explain any method to control the output voltage and harmonic reduction in the inverter. **[WBUT 2017]**

Answer:

Control of Inverter Output Voltage

The output voltage of a single-phase inverter is a square wave. The amplitude of this wave is nearly equal to the dc supply. For many industrial applications, output voltage needs to be controlled.

Techniques for Control

To meet the application requirements following techniques are adopted

1. Controlling the AC output voltage
2. Controlling the dc input voltage
3. The Pulse Width Modulation (PWM)

Among the three, PWM is the best technique to provide efficient control.

Modulation Techniques

3. Single-Pulse Width Modulation
4. Multiple Pulse width modulation
5. Sinusoidal pulse width Modulation.

For modulation technique:

Refer to Question No. 2 of Long Answer Type Questions.

Eliminating 3rd Harmonic

$$V_{03} = 0$$

$$\Rightarrow \quad \sin\left(\frac{3\mu}{2}\right) = 0 \Rightarrow \mu = \frac{2}{3}\sin^{-1}(0) = [0, \pi, 2\pi, \ldots\ldots]$$

This condition is not valid, as

for $\mu = 0$, pulse width $= 0 \Rightarrow v_0 = 0$

For $\quad \frac{3\mu}{2} = \pi \quad \Rightarrow \mu = \frac{2\pi}{3} = 120°$

So, 3rd harmonic will be *totally eliminated*

For $\mu = 120°$, $\qquad \frac{3\mu}{2} = 2\pi, \quad \mu = \frac{4\pi}{3} = 240°$

But $\mu \neq 240°$ as $0 < \mu < 180°$, so this is not physically possible

$\therefore$ Maximum possible width of pulse = 120° to eliminate 3rd harmonic.

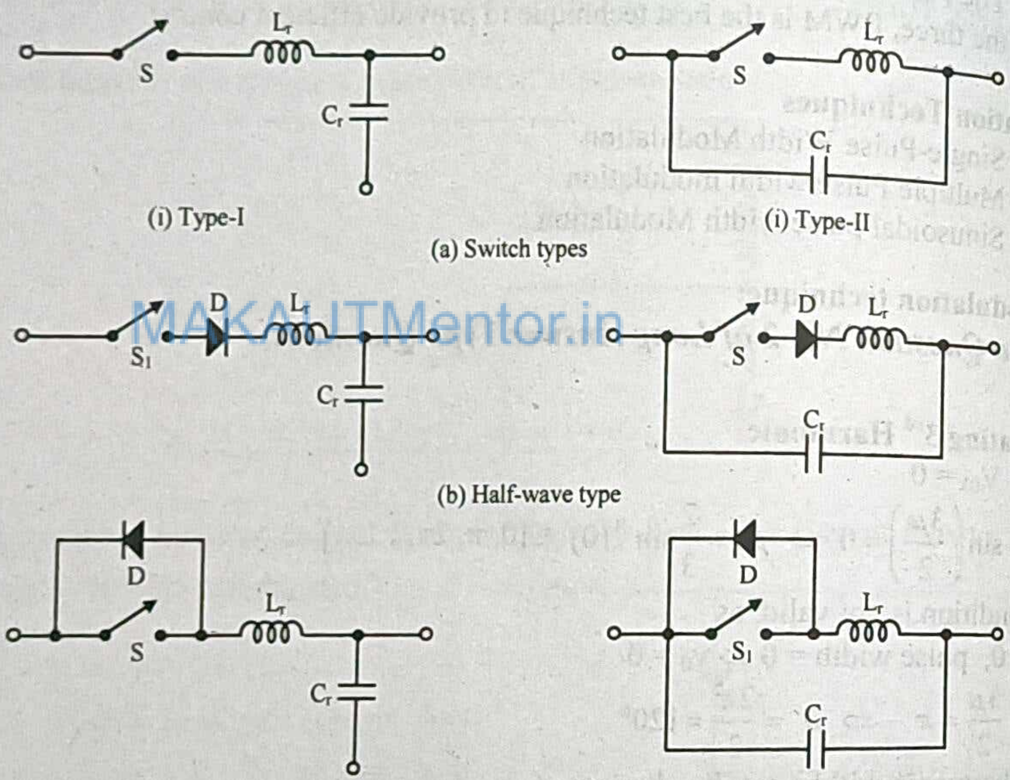
7. a) Discuss both L-type ZCS resonant converter with the help of suitable waveforms. **[WBUT 2014]**

Answer:

Zero-Current-Switching (ZCS) Topology: Here the switch turns-on and turns-off at zero current. Fig. 1(a) shows switch types. As shown, in both types the circuit consists of switch, inductor and capacitor. In both types, inductor L_r limits the di/dt of the switch current and L_r and C_r constitute a series-resonant circuit. When the switch current is zero, there will be a current $i = C_j dv_T / dt$ flowing through the internal capacitance C_j due to a finite slope of the switch voltage at turn-off. This current flow will cause power dissipation in the switch and limits the high switching frequency.

Since the devices do not turn-off at zero-current due to their recovery times, some energy will be trapped in the inductor of type-I circuit and voltage transients will appear across the switch. Hence type-I is preferred.

Fig. 1(b) shows two circuit configurations. In half-wave configuration, unidirectional current flow is maintained by diode D whereas in full-wave configuration, switch current can flow bi-directionally.



(i) Type-I (i) Type-II

(a) Switch types

(b) Half-wave type

(c) Full-wave type

Fig: 1 Zero-current switch converters

b) A 3-phase full wave bridge type inverter (180° VSI) is connected to load. Show that r.m.s value of output line voltage is given by: **[WBUT 2014]**

$$v_0 = \frac{\sqrt{2}}{\sqrt{3}} V_S$$

Answer:

1st Part: ***Refer to Question No. 1 of Long Answer Type Questions.***

Rest Part:
The line voltage $V_{AB} = V_{AN} - V_{BN}$ is obtained by reversing V_{BN} and adding it to V_{AN} as shown in Fig(refer question no 1). Similarly, line voltages $V_{BC} = V_{BN} - V_{CN}$ and $V_{CA} = V_{CN} - V_{AN}$ are plotted in Fig. 1. It can be observed from Fig. 1 that phase voltages have six steps per cycle and line voltages have one positive pulse and one negative pulse (each of 120° duration) per cycle. The phase as well as line-voltages are out of phase by 120°.
The instantaneous line-to-line voltage, V_{AB}, in Fig. 1, can be expressed in a Fourier-series, recognizing that V_{AB} is shifted by $\pi/6$ and even harmonics are zero,

$$V_{AB} = \sum_{n=1,3,5\ldots\ldots}^{\infty} \frac{4V_{dc}}{n\pi}\cos\frac{n\pi}{6}\sin n\left(\omega t + \frac{\pi}{6}\right) \quad \ldots (1)$$

V_{BC} and V_{CA} can be found from Eqn. (1) by phase shifting V_{AB} by 120° and 240°, respectively,

$$V_{BC} = \sum_{n=1,3,5\ldots\ldots}^{\infty} \frac{4V_{dc}}{n\pi}\cos\frac{n\pi}{6}\sin n\left(\omega t - \frac{\pi}{2}\right) \quad \ldots (2)$$

$$V_{CA} = \sum_{n=1,3,5\ldots\ldots}^{\infty} \frac{4V_{dc}}{n\pi}\cos\frac{n\pi}{6}\sin n\left(\omega t - \frac{7\pi}{6}\right) \quad \ldots (3)$$

For $n = 3, 9, 15, \ldots\ldots, \cos\frac{n\pi}{6} = 0$.

Hence, it is noted from Eqns. (1), (2) and (3) that the triple harmonics $(n = 3, 9, 15, \ldots\ldots)$ would be zero in the line-to-line voltages.
The line-to-line RMS voltage can be found from

$$V_L = \left[\frac{2}{\pi}\int_0^{2\pi/3} V_{dc}^2\, d(\omega t)\right]^{1/2} = \sqrt{\frac{2}{3}}V_{dc} = 0.8165V_{dc} \quad \ldots (4)$$

c) A three phase bridge inverter delivers power to a resistive load from a 450 DC source. For a star connected load of 10 ohm per phase, determine for both –
a) 180° mode and (b) 120° mode,
i) rms value of load current
ii) rms value of thyristor current
iii) load power **[WBUT 2014]**

Answer:
In case of 180° mode

$$I_{rms} = \frac{V_{dc}}{3R_L} = \frac{450}{3\times 10} = 15\text{A}$$

Load power $P_L = \frac{2}{3}\frac{V_{dc}^2}{R} = \frac{2}{3}\times\frac{450^2}{10} = \frac{2}{3}\times\frac{450.450}{10} = \frac{2}{3}\times 450.45 = 13.5\,\text{kW}$.

In case of 120°

$$I_{rms} = \frac{1}{\sqrt{3}}\left(\frac{V_{dc}}{2}\cdot\frac{1}{R_L}\right) = \frac{1}{\sqrt{3}}\times\frac{450}{2}\times\frac{1}{10} = \frac{1}{\sqrt{3}}\times\frac{45}{2} = 12.99 \text{ Amp}$$

Load power $P_O = \frac{V_{dc}^2}{2R} = \frac{450^2}{2\times10} = 10.125\,\text{kW}$

8. a) Explain the principal operation of inverter. **[WBUT 2015]**

Answer:

1) Inverters are nothing but d.c. to a.c. converters, i.e., an inverter converts a d.c. power into an a.c. power at desired output voltage level with desired frequency.

2) The process of inversion can be realized through the following approaches

  i) By controlled ON and OFF of power semiconductor switches (e.g., Power MOSFETs, BJTs, IGBTs etc.)

  ii) By forced commutation of thyristors

3) The output frequency of the inverter is governed by the rate at which the semiconductor devices (acting as switches) are switched ON and OFF.

The switching operation is controlled by the inverter control circuitry.

b) What is the reason behind using feedback diodes in anti parallel with SCRs in inverter? **[WBUT 2015]**

Answer:

Such an anti parallel connection with SCR one uses when the load is inductive. An inductive load requires lagging reactive power to be supplied in the circuit. Therefore, when the SCR is turned-off, an alternative path must be available in the circuit for the load current. It such a path is not available then the high voltage transients will damage the SCR or reduce the efficiency of the inverter. A diode connected in anti parallel mode can provide such a return path. The diode remains off when the SCR is conducting and provides a short path when SCR is in blocking state.

c) Compare 180° and 120° conduction mode's 3 phase bridge inverter. **[WBUT 2015]**

Answer: ***Refer to Question No. 3(a) of Long Answer Type Questions.***

d) What is PWM triggering? What is the difference between voltage source and current source inverter? **[WBUT 2015]**

Answer:

1st Part: ***Refer to Question No. 2 of Long Answer Type Questions.***

2nd Part: ***Refer to Question No. 2 of Short Answer Type Questions.***

9. How this inverter is used for a full bridge switched mode power supply? **[WBUT 2018]**

Answer:

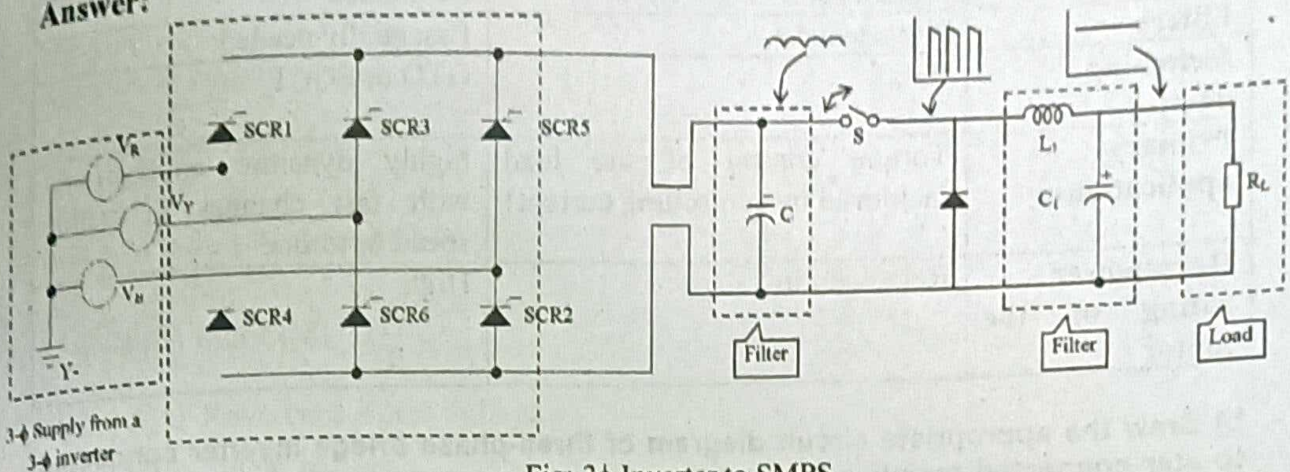


Fig: 3ϕ Inverter to SMPS

Controlling DC output

By controlling the switching time, the magnitude of the DC output may be controlled, as magnitude is a function of the ON/OFF ratio.

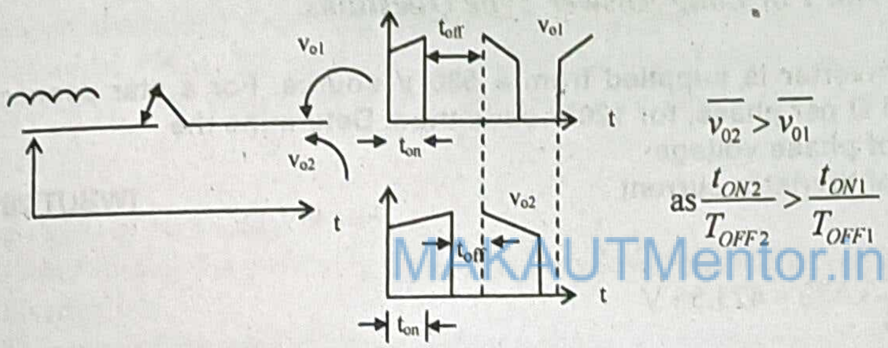


Fig: Switching time and DC output voltage

If the switching frequency is very high, then ac ripple frequency, fed to the L_1, C_1 filter is very high, hence the values of L_1 and C_1 can be taken very low.

Since we know, attenuation $\propto \dfrac{1}{\sqrt{\omega^2 L_1 C_1}}$

So, making $\omega^2 L_1 C_1 >> 1$, ac ripple attenuation may be made very high, thus almost ripple free controlled DC supply may be obtained.

10. a) State the comparison between voltage source inverter (VSI) and current source inverter (CSI). **[WBUT 2019]**

Answer:

Features	voltage source inverter (VSI)	current source inverter (CSI)
Requirements	Constant DC-link voltage	Constant DC-link current
Output nature	generates AC voltages in the form of voltage pulses	generates AC current in the form of current pulses
Output	Output Voltage with less	Output Current with high

Harmonics	harmonics	harmonics
Filters	Not needed	Essentially needed
Switching devices	IGBT	GTO or SGCT
Primary applications	Torque control of the load (achieved by controlling current)	highly dynamic applications, with fast changes in motor speed or torque
Horsepower rating of the motor	Relatively low	High

b) Draw the appropriate circuit diagram of three-phase bridge inverter connected to star connected resistive load and explain the operation with the help of phase voltage, line voltage and gate pulse waveforms for 120° conduction mode.

[WBUT 2019]

Answer:

Refer to Question No. 1 of Long Answer Type Questions.

c) A three-phase inverter is supplied from a 580 V source. For a star connected resistive load of 20 Ω per phase, for 120° conduction. Determine the

i) rms value of phase voltage

ii) rms value of thyristor current **[WBUT 2019]**

Answer:

i) $V_{rms} = \frac{\sqrt{2}}{\sqrt{3}} V_s = \frac{\sqrt{2}}{\sqrt{3}} \times 580 = 473.56$ V

ii) $I_{rms} = \frac{1}{\sqrt{3}}\left(\frac{V_{dc}}{2}.\frac{1}{R_L}\right) = \frac{1}{\sqrt{3}} \times \frac{580}{2} \times \frac{1}{20} = 8.871$ Amp.

11. Write short note on Sinusoidal PWM. **[WBUT 2019]**

Answer:

Sinusoidal PWM is a type pulse width modulation, where the modulation signal is sinusoidal and used in inverters. The carrier signal is high frequency triangular waveform.

In a source voltage inverter, the solid state switches (SCRs) can be turned ON and OFF once during each cycle. This results in a square waveform. However, in sinusoidal PWM waveform, the desired modulated waveform is compared with a high frequency triangular waveform. Regardless of whether the voltage of the signal is smaller or larger than that of the carrier waveform, the resulting output voltage of the DC source is either negative or positive.

This modulation technique provides multiple numbers of output pulse with varying widths per half cycle. The width of each pulse is varying in proportion to the amplitude of a sine wave evaluated at the centre of the same pulse. The gating signals, used to drive the power devices, are generated by comparing a sinusoidal reference with a high frequency triangular signal.

The rms ac output voltage

$$V_O = V_S\sqrt{\frac{2t_{ON}}{T}} = V_S\sqrt{2\delta}$$

where, δ = duty cycle $= \frac{t_{ON}}{T}$

Modulation Index (MI) $= \frac{V_r}{V_c}$

where, V_r = Reverence signal voltage

V_c = Carrier signal voltage

By varying the control signal amplitude V_r from 0 to V_c the pulse width ton can be modified from 0 secs to T/2 secs and the rms output voltage V_O from 0 to V_S.

For sinusoidal PWM, the modulating index (m) is given by Am/Ac, where, Am and Ac are the amplitudes of sinusoidal and triangle waveforms.

In sinusoidal PWM, the peak of the modulating signal always less than the peak of the carrier signal. For sinusoidal PWM, the amplitude modulation depth must be less than 1.0.

Advantages of sinusoidal PWM

1. Power loss in the switching devices is very low, thus increasing the efficiency of the inverter.
2. This type of inverter provides output voltage waveform which is very similar to the voltage waveform that is received from the Grid.
3. Very little harmonic distortion resulting in a very "clean" supply.
4. Ideal for trouble running of electronic systems such as computers and other sensitive equipment

Disadvantages with sinusoidal PWM:

1. A sinusoidal PWM drive cannot produce a line-line output voltage as high as the line supply.
2. Relatively more expensive.
3. Flicker is observed if the run frequency of the driver is less than 100 Hz.

CYCLOCONVERTERS

Multiple Choice Type Questions

1. A cycloconverter is effectively a [WBUT 2009]
   a) combination of a rectifier and an inverter connected antiparallal
   b) combination of two rectifiers connected antiparallel
   c) combination of two inverters connected antiparallel
   d) combination of two converters connected antiparallel

Answer: (d)

2. Cycloconverter is a [WBUT 2010, 2019]
   a) AC to AC converter
   b) AC to DC converter
   c) DC to AC converter
   d) DC to DC converter

Answer: (a)

3. Cycloconverter converts [WBUT 2016]
   a) *ac* voltage to *dc* voltage
   b) *dc* voltage to *dc* voltage
   c) *ac* voltage to *ac* voltage at same frequency
   d) *ac* voltage at supply frequency to *ac* voltage at load frequency

Answer: (d)

4. The cyclo-converters (CCs) require [WBUT 2019]
   a) Natural commutation in both step-up and step-down CCs
   b) Forced commutation in both step-up and step-down CCs
   c) Forced commutation in step-down CCs
   d) Forced commutation in step-up CCs

Answer: (d)

Short Answer Type Questions

1. What is cycloconverter? [WBUT 2007, 2008, 2010, 2017, 2019]

Answer:

The word Cycloconverter has been derived from Cycle (Time- period hence frequency) conversion. It is also known as AC–AC converter.

A Cycloconverter is a device which receives a fixed frequency power and converts this for a load with a different or variable frequency without any intermediate d.c. conversion. The Cycloconverters are most commonly used for obtaining low frequency a.c. voltage.

2. What benefit does Cycloconverter offer in comparison to inverter? [WBUT 2008, 2017]

Answer:
The cycloconverter drive has very low torque ripple from zero start-up until a relatively small frequency, while the inverter causes high torque ripple disturbing only at low frequencies.
Cycloconverters can provide very high electrical power, of the order of megawatts, to the induction and synchronous motors.

3. Explain the operation of a single phase step-up cyclo-converter.
[WBUT 2010, 2014, 2019]

OR,

Explain with relevant circuit diagrams & waveforms, the principle of operation of single phase to single phase step-up cycloconverter. **[WBUT 2013]**

Answer:
Bridge Configuration
Circuit diagram

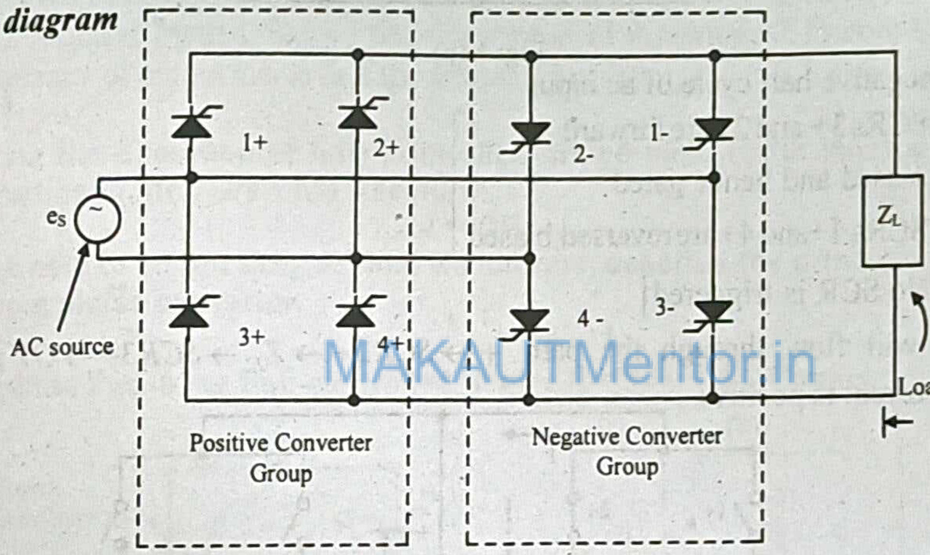


Fig: 1 Bridge configured cycloconverter

Principle
For positive load current, the firing pulses to the SCRs of Bridge 1 are given, whereas those of Bridge 2 are not allowed. For negative load current, the firing pulses to the SCRs of Bridge 2 are applied and those to Bridge 1 will be inhibited. The algorithm of firing angle control be such that one converter can conduct at any instant of time.
Change over of the firing pulses from one converter to other should be periodic and the period is governed by the desired output frequency.
The firing angles to both the converters should be such that we may get the symmetrical output.

Operation
Step 1: For positive half cycle of ac input.

$$\text{For Bridge 1}\begin{cases}\text{SCRs 1 + and 4 + are forward biased and}\\ \text{hence gated}\\ \text{SCRs 3 + and 2 + are reverse biased}\\ \text{and hence no effect of gating.}\end{cases}$$

For Bridge 2 No SCR is gated. The current will flow through the path $+ \rightarrow SCR1+ \rightarrow z_L \rightarrow SCR4+ \rightarrow 0V$.

The current through the load will be positive.

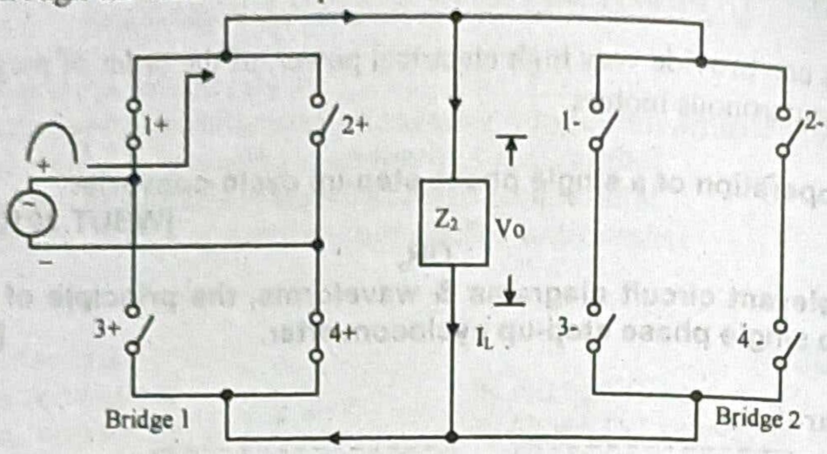


Fig: 1 (a)

Step 2: For negative half cycle of ac input

$$\text{Bridge } 1 \Rightarrow \left[\begin{array}{l}\text{SCRs } 3+ \text{ and } 2+ \text{ are forward} \\ \text{biased and hence gated} \\ \text{SCRs } 1+ \text{and } 4+ \text{ are reversed biased}\end{array}\right]$$

$$\text{Bridge } 2 \Rightarrow [\text{No SCR is triggered}]$$

The current will flow through the path $+ \rightarrow SCR2+ \rightarrow Z_L \rightarrow SCR3+ \rightarrow OV$ and the direction of current is positive.

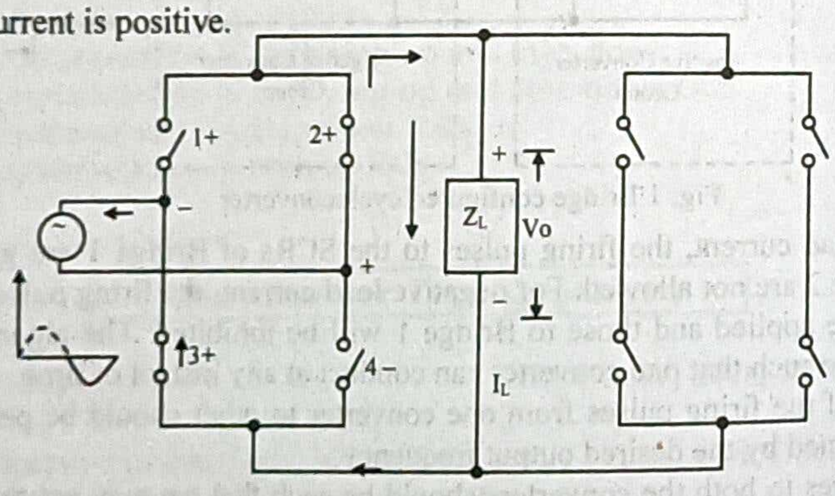


Fig: 1 (b)

Here for consecutive one positive and (-)ve cycle of ac input, we get one positive cycle of load current.

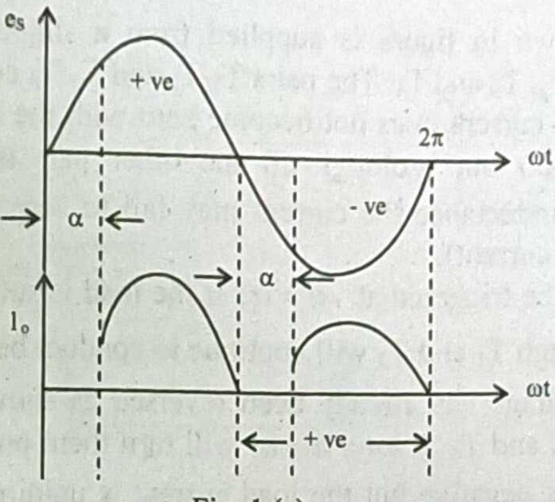


Fig: 1 (c)

Step 3: To get negative cycle of the Load Current, negative group of converter, i.e., Bridge 2 is pulsed / gated. Steps 1 and 2 are repeated for Bridge 2. Output Waveform say that frequency of output a.c. is half the frequency of input a.c.

4. Explain the operation of fully controlled bridge circuit with R-L load (rectifying and inverting mode). Draw the waveform. [WBUT 2010]

OR,

With the help of circuit diagram and waveforms, describe the principle of operation of a single phase converter. [WBUT 2018]

Answer:

Single-phase Full-wave Full-controlled Bridge Rectifier (B-2 Connection)

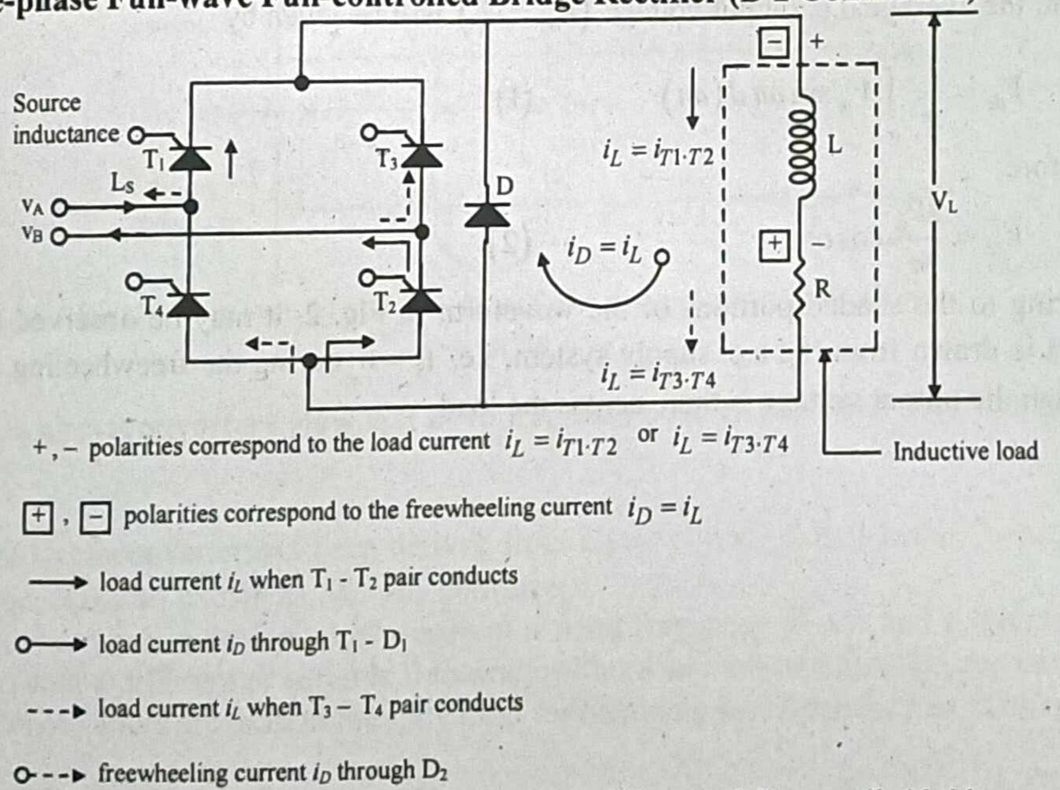


Fig: 1 Circuit diagram of a single-phase full-wave full-controlled bridge rectifier (B-2 connection)

This connection as shown in figure is supplied from a single-phase a.c. source and contains four SCRs T_1, T_2, T_3 and T_4. The pairs T_1-T_2 and T_3-T_4 conduct alternately. With inductive load, the current does not become zero with the zero input signal (i.e. at $\omega t = 0, \pi, 2\pi, 3\pi, 4\pi$ etc.) but prolongs till the other pair is triggered (continuous current), or with small inductance the current may fall to zero before the other pair is triggered (discontinuous current).

Let the SCRs T_1 and T_2 be triggered at $\omega t = \alpha$. If the load is sufficiently inductive, then the load current i_L through T_1 and T_2 will continue to conduct beyond $\omega t = \pi$. Since the polarity of the input voltage has already been reversed as shown in Fig. 1, triggering signals at the gates of T_3 and T_4 at $\omega t = \pi + \alpha$ will turn them on. The load voltage from $\omega t = \pi$ to $\omega t = \pi + \alpha$ is negative but the load current is unidirectional. Again the load voltage will be negative from $\omega t = 2\pi$ to $\omega t = 2\pi + \alpha$. The conduction of T_3 and T_4 will turn off T_1 and T_2, respectively, by reverse biasing and the load current i_L will be shifted from the pair T_1-T_2 to the pair T_3-T_4. Although the load current i_L is unidirectional, the current from the input will flow in the reverse direction, when T_3 and T_4 conduct. Thus, assuming a large value of the load inductance, the current i_L will be a rectangular a.c. wave as shown in Fig. 1. The triggering angle α can be varied from 0 to π. Within this interval, the potential of the incoming pair of SCRs will remain higher than that of the outgoing pair of SCRs. The ripple frequency of the output voltage is twice the input frequency. Assuming the load inductance to be large enough to produce continuous current, the average d.c. output voltage $(V_{dc} = V_L)$ will be given by

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

Therefore,

$$V_{dc} = \frac{2V_m}{\pi}\cos\alpha \qquad \cdots(2)$$

Referring to the shaded portions of the waveform in Fig. 2, it may be observed that no current is drawn from the a.c. supply system, i.e. $i_S = 0$ during the freewheeling period, although the output voltage is there across the load.

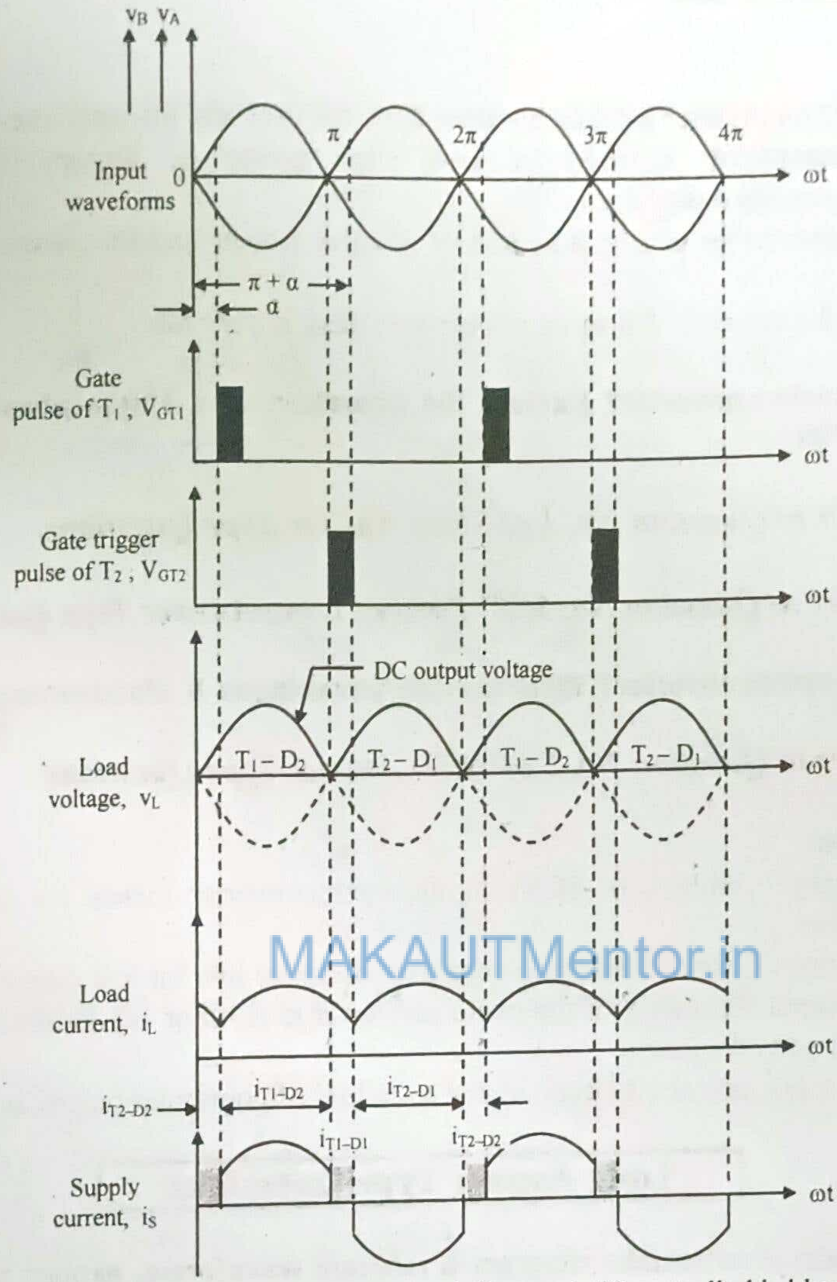


Fig: 2 Waveforms of a single-phase full-wave half-controlled bridge rectifier

5. What is cycloconverter? How is it advantageous over an inverter? [WBUT 2011]

Answer:

1st Part:

The word Cycloconverter has been derived from Cycle (Time- period hence frequency) conversion. It is also known as AC–AC converter.

A Cycloconverter is a device which receives a fixed frequency power and converts this for a load with a different or variable frequency without any intermediate d.c. conversion. The Cycloconverters are most commonly used for obtaining low frequency a.c. voltage.

2nd Part:

1. Unlike an inverter a cycloconverter does not uses any intermediate dc link.
2. Cycloconverter is used to drive high power ac motors (induction and synchronous motors).
3. Cycloconverter can be a source of reactive power and the harmonic content is low.
4. In cycloconverter distortion in output voltage is very low.

6. What is cyclo-converter? Explain the operation of a single phase step down cyclo-converter. **[WBUT 2018]**

Answer:

1st Part: ***Refer to Question No. 1 of Short Answer Type Questions.***

2nd part: ***Refer to Question No. 5(2nd Part) of Long Answer Type Questions.***

7. What is a cycloconverter? What are the advantages & disadvantages of it over an inverter? **[WBUT 2018]**

1st Part: ***Refer to Question No. 5 of Short Answer Type Questions.***

Disadvantages:

1. The large numbers of SCRs in the cycloconverter makes the control circuit complex.
2. The power factor of the cyclo converter becomes low for low output voltage
3. The output frequency of the cyclo converter is 1/3th or 1/2 for reasonable power output and efficiency.
4. The supply gets short circuited due to failure of commutation circuit.

Long Answer Type Questions

1. With the help of schematic diagram & relevant waveforms, explain the operation of three-phase to single phase cycloconverter. **[WBUT 2008]**

OR,

With the help of schematic diagram and relevant waveforms, explain the operation of 3-phase to 1-phase cycloconverter. **[WBUT 2017]**

Answer:

Here, input to the cycloconverter is 3ϕ supply having generally 50Hz frequency and output is 1ϕ having lesser frequency than that of the supply.

Circuit Diagram

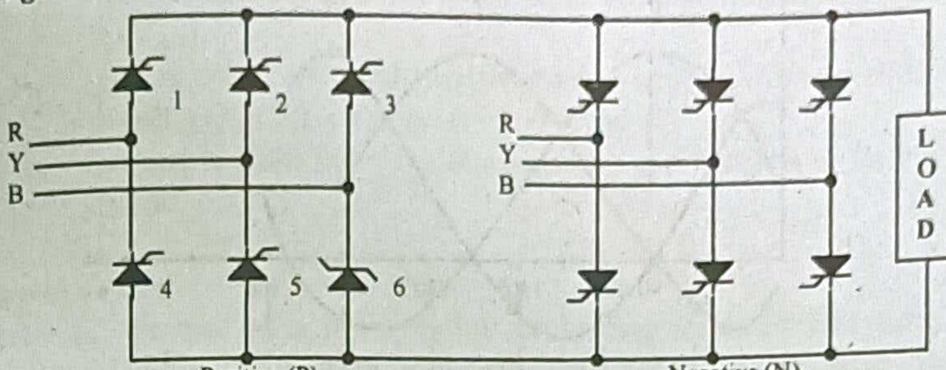


Fig: 3-ϕ to 1-ϕ Cycloconverter

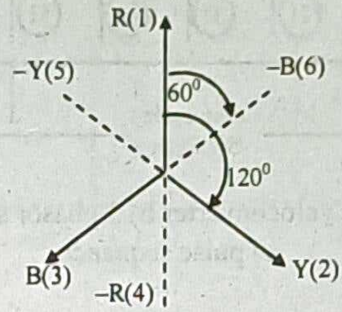


Fig: Phasor-diagram

The above configuration is nothing, but the dual converter configuration.

Circuit Operation

Step 1: During positive half cycle of the voltage at the output, the firing pulses are given to the SCRs of the P-converter as per following sequence

Pulse Number	1	2	3	4	5	6
Conducting SCRs are	1, 6	6, 2	2, 4	4, 3	3, 5	5, 1

Per cycle of the input voltage, six pulses are needed.

Step 2: During negative half cycle of the voltage at the output, firing pulses are given to the SCRs of the N-Converter.

Step 3: When N converter conducts, a negative voltage appears across the load.

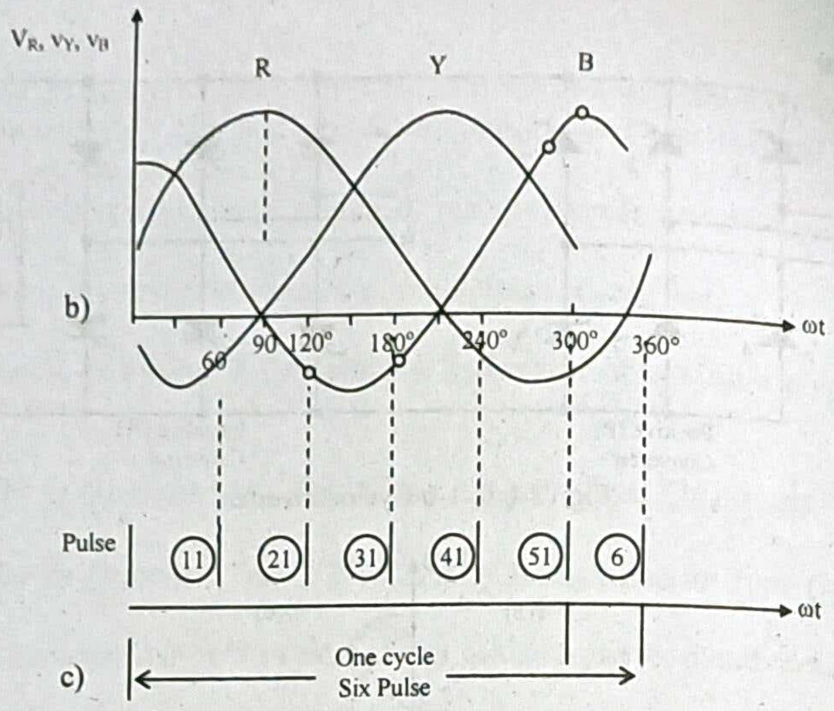


Fig: 3-ϕ to 1-ϕ Cycloconverter b) 3 phasor supply wave form
c) pulse sequence

2. a) What do you mean by blocked group operation & circulating current mode operation of a cycloconverter? **[WBUT 2008, 2011, 2017, 2018]**

Answer:

Circulating Mode

Figure (a) shows a scheme for the circulating current mode

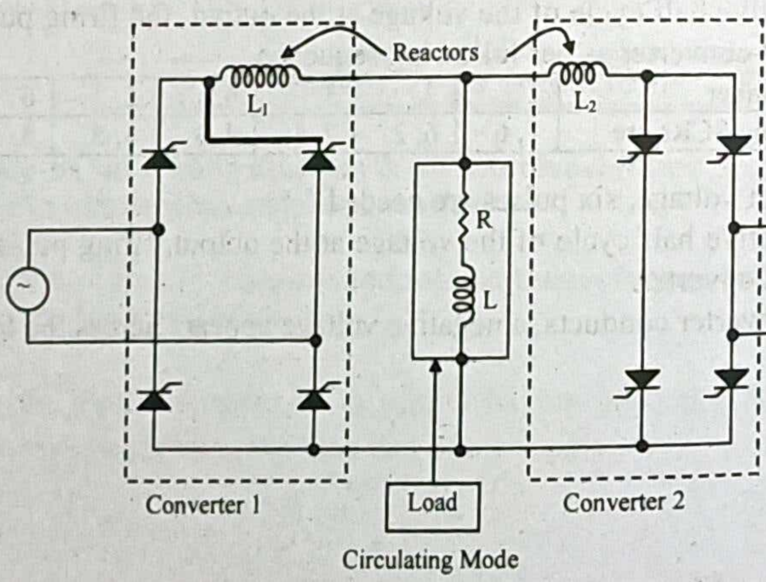


Fig: (a) Circulating current mode

Component Description

Converter - 1	Operates as a positive rectifier to produce an average output voltage (V_{dc1})
Converter - 2	Acts as an inverted rectifier and produces an equal average output voltage (V_{dc2}) with reversed polarity.
Reactor	Used to limit the circulating current and restricts to flow through the load.

Block group operation

One converter is operated at a time in the conducting state. At this time, the other converter is completely blocked by removing the firing pulses from the flow of circulating current is completely blocked through the automatic control of firing pulses as shown in figure (b) below:

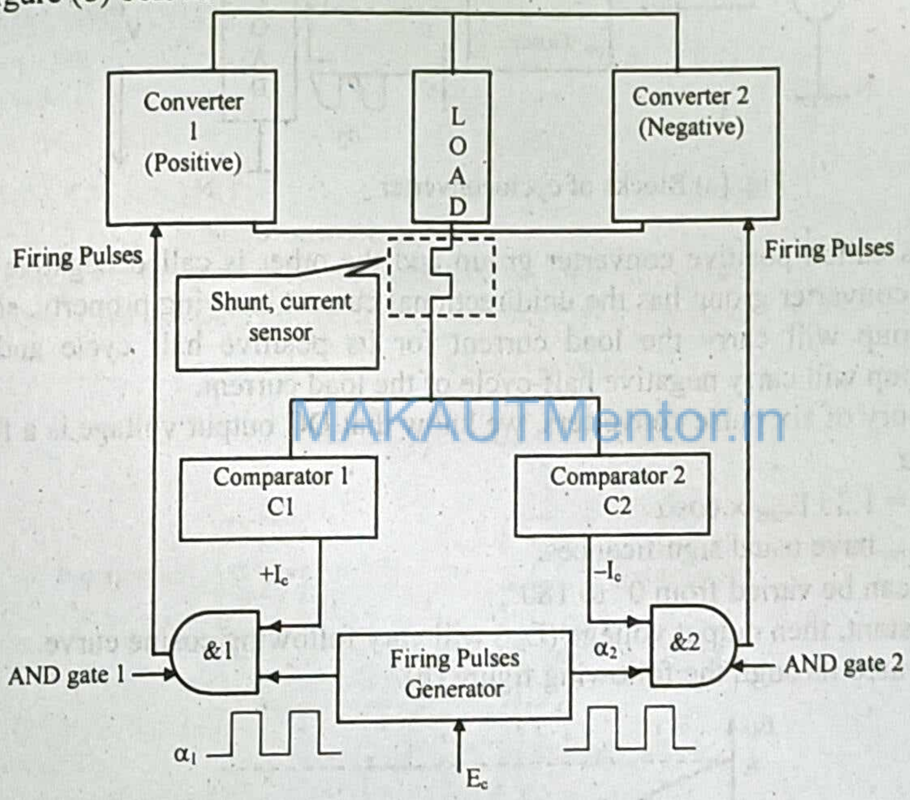


Fig: (b) Scheme for converter selection

b) Mention applications of a cycloconverter. **[WBUT 2008, 2011]**

Answer:

Typical applications are

- in controlling the speed of an AC traction motor, ac induction motors
- in controlling the starting of synchronous motor

(Most of these cycloconverters have a high power output – in the order a few megawatts and SCRs are used in these circuits)

- In controlling low power ac motor (TRIACs are used in these circuits.)

3. Explain with relevant circuit diagram and waveforms how rectification and inversion are possible in phase controlled converters with SCRs. **[WBUT 2009]**

Answer:

A Cycloconverter may be considered to be composed of two groups of converters connected back to back as shown in figure (a).

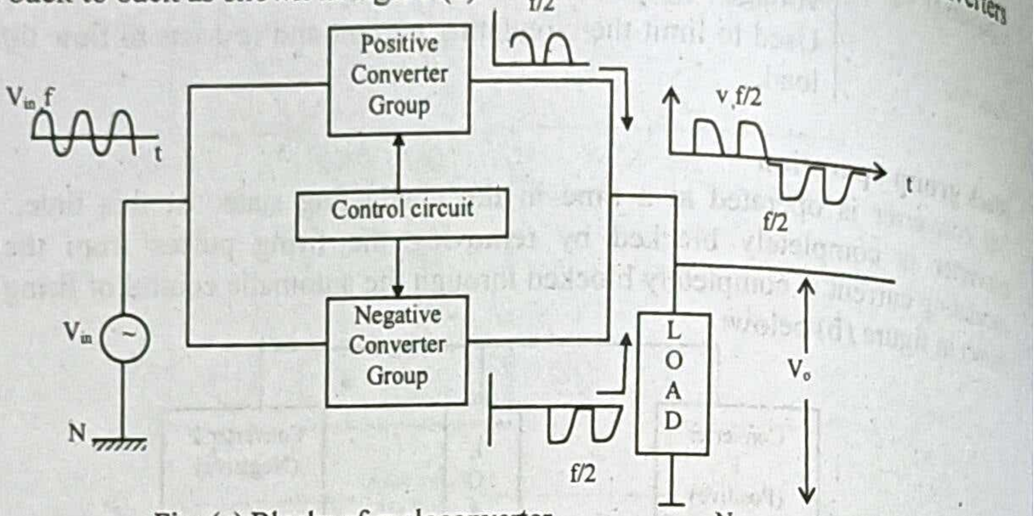


Fig: (a) Blocks of cycloconverter

One group is called positive converter group and the other is called negative converter group. Each converter group has the unidirectional current carrying property, so, positive converter group will carry the load current for its positive half cycle and negative converter group will carry negative half-cycle of the load current.

From the theory of six pulse converters, we know that DC output voltage is a function of firing angle α

$$E_{dc} = 1.35\ E_{rms} \times \cos\alpha$$

where E_{dc}, E_{rms} have usual significances.

Firing angle can be varied from 0° to 180°.

If E_{rms} is constant, then output voltage (E_{dc}) will vary following cosine curve.

This is illustrated through the following figure (b).

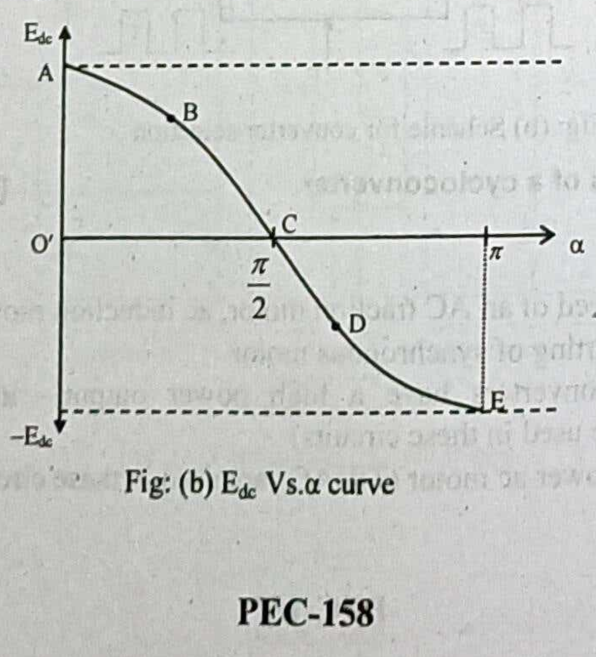


Fig: (b) E_{dc} Vs.α curve

Referring to figure above.

At point A: $\alpha = 0°$

$\therefore E_{dc} = 1.35\ E_{rms} \times \cos 0° = 1.35\ E_{rms} \Rightarrow$ Maximum value of the output voltage

At point B: $0 < \alpha < \pi/2$

The average output voltage will be less that at point A.

At point C: $\alpha = \pi/2$

$\therefore E_{dc} = 0$

During this time, device is under rectifying mode, i.e., power is transferred from main AC supply to output load.

Now, firing angle is varied from $\pi/2$ to π.

At point D: $\frac{\pi}{2} < \alpha < \pi$

$\therefore \cos\alpha \rightarrow (-)\text{ve}$

$\therefore E_{dc} \rightarrow (-)\text{ve}$

At point E: $\alpha = \pi$

$\therefore \cos\alpha = -1$

$\therefore E_{dc} = 1.35 \times E_{rms} \times (-1)$

$= -1.35\ E_{rms} \Rightarrow$ Maximum Negative

Under this condition the power flows from load to main ac supply.

The figure (c) shows the dual converter scheme for Cycloconverter:

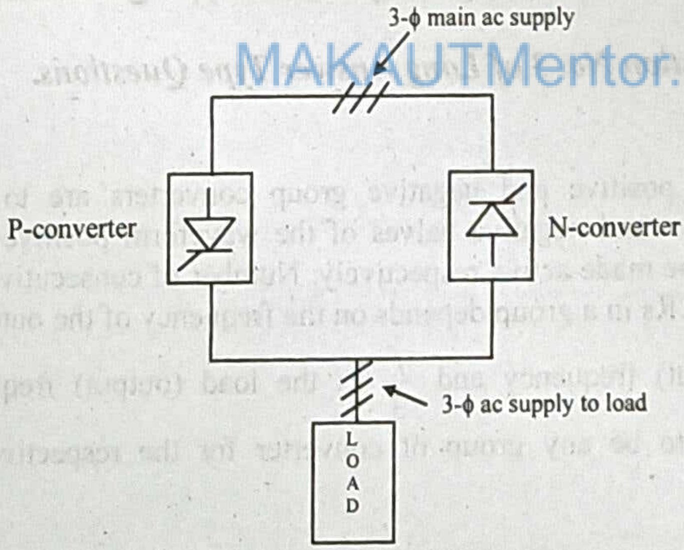


Fig: (c) Dual converter shame for cyclo converter

P-converter operates from $\alpha = 0$ to $\pi/2$, hence supplies energy to load, generating section ABC of the curve [Fig. (b)].

Whereas, N-converter operates from $\alpha = \pi/2$ to π, feeding back energy to the source from the load, generating section CDE of the curve [Fig. (b)].

If the firing angle changes from π to $\pi/2$ average value of E_{dc} will be reduced in negative side and at C, $E_{dc} = 0$.

Further reduction of firing angle from $\pi/2$ to 0, P-converter gets activated and starts supplying power from the source to load, with increasing value of E_{dc}.
So, we can say, by varying firing angle uniformly from zero to π and back to zero, we can have one complete cycle of ac.
The maximum value of ac wave at output is

$$E_{dc} = 1.35\ E_{rms}$$

and R.M.S. value of ac output is $\frac{1.35 E_{rms}}{\sqrt{2}}$

Controlling the parameters
Frequency: Frequency of the ac output can be varied by varying the rate of variation of firing angle.

Voltage: Voltage can be varied by varying input voltage to the cycloconverter.

4. Discuss why a three phase to single phase cycloconverter requires positive and negative group phase controlled converters. Under what conditions, does the group work as inverters or rectifiers? How should the firing angles of the two converters be controlled? **[WBUT 2009]**

Answer:
1st Part: ***Refer to Question No. 2(a) of Long Answer Type Questions.***

2nd Part: ***Refer to Question No. 3 of Long Answer Type Questions.***

3rd Part:
To have ac waveform positive and negative group converters are to be activated alternatively. For positive and negative halves of the waveform positive and negative group converters are to be made active respectively. Number of consecutive pulses to be fed to the gates of the SCRs in a group depends on the frequency of the output signal e.g. if f is the supply (input) frequency and $\frac{f}{3}$ is the load (output) frequency then 3 consecutive pulses are to be any group of converter for the respective half of the waveform.

5. Explain the basic principle of step up and step down cyclo-converter. **[WBUT 2016]**

Answer:
1. Step-down cycloconverter: In step-down cycloconverter, the output frequency f_o is less than the supply (input frequency f_s i.e., $f_o < f_s$. The step-down cycloconverters are naturally commutated and the output frequency is limited to a value that is a fraction of input frequency. Therefore, these types of cycloconverters are commonly used in low speed ac motor drives up to 02 MW with frequencies from 0 to 20 Hz.

2. Step-up cycloconverter: In step-up cycloconverter, the output frequency f_o is greater than the supply (input) frequency f_s i.e., $f_o > f_s$. The step-up cycloconverters are forced commutated and the output frequency is limited to a value that is a multiple of input frequency. Fast switching devices and microprocessors are used to in step-up cycloconverters to implement advanced conversion strategies. The step-up cycloconverters are also known as forced commutated direct frequency changers.

CONVERTER OPERATION

Multiple Choice Type Questions

1. Resonant converters control the output power by **[WBUT 2007]**
   a) varying the switching frequency around resonating frequency
   b) varying the on time of the switch
   c) controlling the power loss in the switch
   d) none of these

Answer: (a)

2. Resonant converters are basically used to **[WBUT 2014]**
   a) Generate large peak voltages **b) reduce switching losses**
   c) eliminate harmonics **d) convert a square wave into a sine wave**

Answer: (c)

Short Answer Type Questions

1. Describe the effect of source inductance on the *dc* output voltage of a single phase full controlled bridge converter. **[WBUT 2013, 2019]**

Answer:

Effect of Inductance

Inductance causes a delay to current change. Due to this property, current commutation is delayed, as it takes a finite time for the current to decay to zero (to commutate) in the outgoing SCR, while the current will grow at the same rate in the incoming SCR.

So, we get a period of time during which both the incoming and outgoing SCRs are conducting.

The period, during which both the incoming and outgoing SCRs are conducting is called *Overlap Period* and the angle for which both the SCRs are in simultaneous conduction is called overlap angle or commutation angle.

So, the presence of inductance in ac source creates overlap period which has following effects (refer to table 1)

Table 1

At the	Effects
Output terminals	• A decrease in average voltage and hence DC voltage ratio • An increase in harmonic distortion
Input terminals	• Reduction in Displacement factor (DSF), DSF = $\cos\alpha$ • Reduction in input power factor (PF) $PF_i = \frac{3}{\pi}.\cos\alpha$ $i \Rightarrow$ input • Reduction in active power input and hence increment in Reactive Power input.

Long Answer Type Questions

1. What is overlap. Explain in detail. **[WBUT 2014]**

Answer:

Let us consider a circuit diagram as shown below:

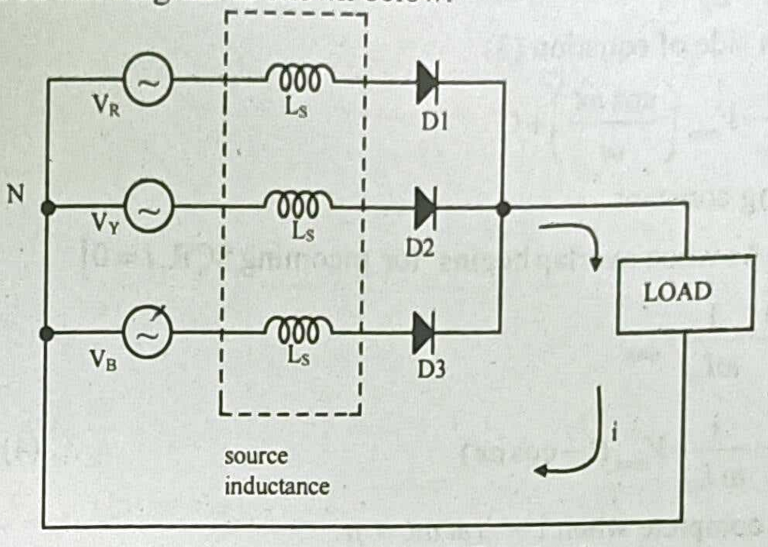


Fig: 1 (a) Uncontrolled rectifier circuit

Let us assume

1. All the three sources having identical inductances.
2. Drops across diodes are negligible.
3. D1 and D2 are under overlap period i.e. D1 and D2 are conducting simultaneously and let i be the circulating current.

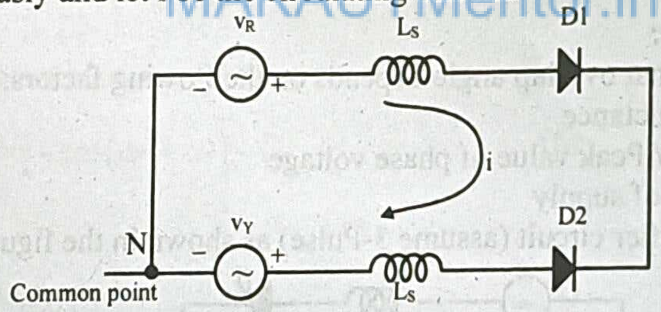


Fig: 1 (b)

Applying KVL in this mesh, we have

$$v_R - v_Y = L_S \frac{di}{dt} + L_S \frac{di}{dt} \qquad \dots (1)$$

Here, $v_R - v_Y \Rightarrow$ difference between two phase voltages

$= $ line voltage v_{RY}

$= \sqrt{3}\, v_{max} \cdot \sin \omega t$

(For Y – connection, $V_L = \sqrt{3}\, V_{ph}$)

From equation 1, we have

$$\therefore \quad v_R - v_Y = \sqrt{3}\, v_{max} \sin \omega t = 2L_S \frac{di}{dt} \qquad \dots (2)$$

$$\Rightarrow \quad \frac{di}{dt}=\frac{\sqrt{3}}{2}\times v_{max}\ ;\ \sin\omega t\cdot\frac{1}{L_S}$$

$$\Rightarrow \quad di=\frac{\sqrt{3}}{2}\cdot\frac{1}{L_S}\cdot v_{max}\sin\omega t\,dt \qquad \dots(3)$$

Integrating both side of equation (3)

$$i=\frac{\sqrt{3}}{2L_S}\cdot V_{max}\left(\frac{\cos\omega t}{\omega}\right)+C$$

$C\Rightarrow$ Integrating constant

At $t=0, i=0$ [As when overlap begins for incoming SCR, $i=0$]

$$\therefore \quad C=\frac{\sqrt{3}}{2}\cdot\frac{1}{\omega L_S}V_{max.}$$

$$\therefore \quad i=\frac{\sqrt{3}}{2}\cdot\frac{1}{\omega L_S}\cdot V_{max}(1-\cos\omega t) \qquad \dots(4)$$

The overlap is complete when $i = i_L$ at $\omega t = \mu$

$\therefore$ From the above expression,

$$i_L=\frac{\sqrt{3}}{2}\cdot\frac{1}{\omega L_S}\cdot V_{max.}(1-\cos\mu) \quad\Rightarrow\quad \cos\mu=1-\frac{2}{\sqrt{3}}\times\frac{1}{\omega L_S}\times V_{max}$$

Dependent Factors:

Equation 5 shows that overlap angle depends on the flowing factors:

1. Source Inductance
2. Maximum / Peak value of phase voltage
3. Frequency of supply

For controlled rectifier circuit (assume 3-Pulse) as shown in the figure below: 1c

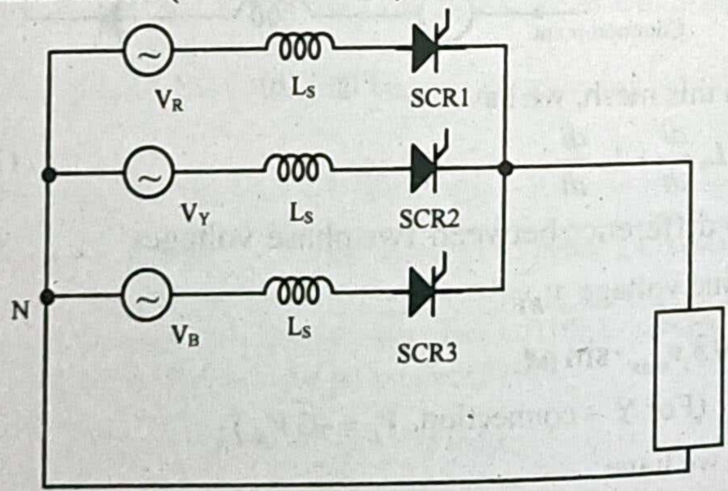
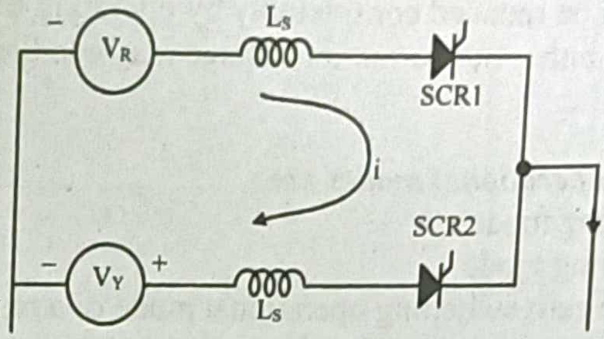


Fig: 1 (c) controlled rectifier circuit

Keeping all the assumptions same as those for previously described uncontrolled rectifiers.

Let us say, SCR1 and SCR2 are under overlap period and a circulating current is flowing in the loop formed by SCR1 and SCR2 as shown in the figure below:



$\therefore$ Applying KVL,

$$v_R - v_Y = L_S\frac{di}{dt} + L_S\frac{di}{dt} = v_{RY} \qquad \ldots (5)$$

$$= \sqrt{3}\, V_{\max/_{Ph}} \sin(\omega t + \alpha) \qquad \ldots(6)$$

Where, α = Firing angle

$$\therefore \quad \sqrt{3}\, V_{\max}\Big|_{Ph} \cdot \sin(\omega t + \alpha) = 2L_S\frac{di}{dt}$$

$$\Rightarrow \quad di = \frac{\sqrt{3}\, V_{\max} \sin(\omega t + \alpha)dt}{2 \cdot L_S} \qquad \ldots (7)$$

Integrating both sides of equation (7) we get

$$i = \frac{\sqrt{3}}{2} \cdot \frac{V_{\max}}{\omega L_S}\left[-\cos(\omega t + \alpha)\right] + C \qquad \ldots (8)$$

At $\quad t = 0,\ i = 0$

$$\therefore \quad C = \frac{\sqrt{3}}{2} \cdot \frac{V_{\max}}{\omega L_S}\cos\alpha \qquad \ldots (9)$$

$$\therefore \quad i = \frac{\sqrt{3}}{2} \cdot \frac{V_{\max}}{\omega L_S}\left[\cos\alpha - \cos(\omega t + \alpha)\right] \qquad \ldots (10)$$

At $i = i_L$, $\omega t = \mu$ i.e. commutation / overlap period is over.

$$\therefore \quad i_L = \frac{\sqrt{3}}{2}\frac{V_{\max}}{\omega L_S}\left[\cos\alpha - \cos(\alpha + \mu)\right]$$

$$\cos(\alpha + \mu) = \cos\alpha - \left(\frac{2\omega L_S}{\sqrt{3}\, V_{\max}}\right) i_L \qquad \ldots (11)$$

2. Write short notes on the following:

a) Resonant converter **[WBUT 2007, 2018]**

b) Effect of source inductance for 2-pulse converter **[WBUT 2019]**

Answer:

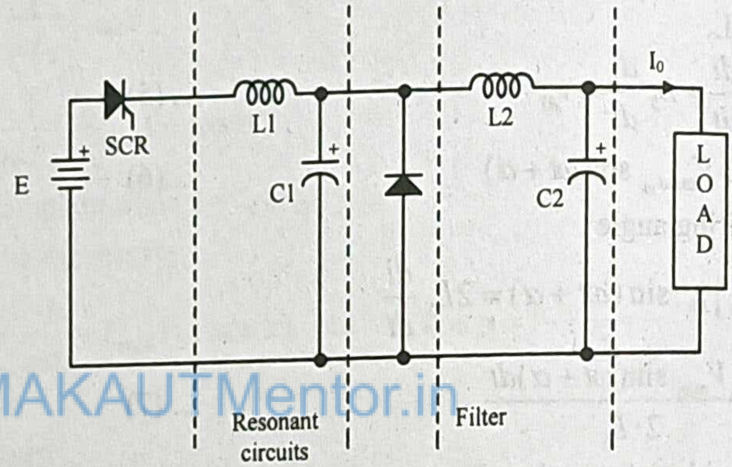
a) Resonant converter:

In SMPS, inverters etc., the power semiconductor devices (used as switches) are frequently made ON and OFF, leading to the high switching losses.
The switching losses can be reduced considerably by operating the switching devices into a resonant circuit so that either the current or voltage may oscillate to a natural zero at the instant of switching.

In resonant converters operational modes are

- Zero current switching mode
- Zero voltage switching mode

Figure below shows the zero switching operational mode of a resonant converter



A scheme for zero current switching

In order to explain the operation we have to assume first

1) The circuit is under steady state.
2) A load current I_0 is flowing.
3) Inductor current I_{L2} is constant and close to I_0.

When the SCR is fired then current through the SCR continues to grow till it has reached current level in L2. Voltage across SCR is very small and diode current begins to reduce. Capacitor then starts charging. L_1 and C_1, which form the resonating circuit, allow the thyristor (SCR) current to oscillate. The thyristor (SCR) current starts falling and when the current is lower than the holding current; SCR turns off through natural commutation. The capacitor current starts discharging. When the thyristor current becomes less than I_{L2} and continues to discharge till it becomes chargeless. Diode now comes into the field and allows the i_{L2} to flow through it. SCR is turned ON again and events repeat.
In zero voltage switching scheme voltage across the switching device in the resonant circuit oscillates to a natural zero at the instant of switching, thus preventing switching loss. Figure below shows a scheme for zero voltage switching.

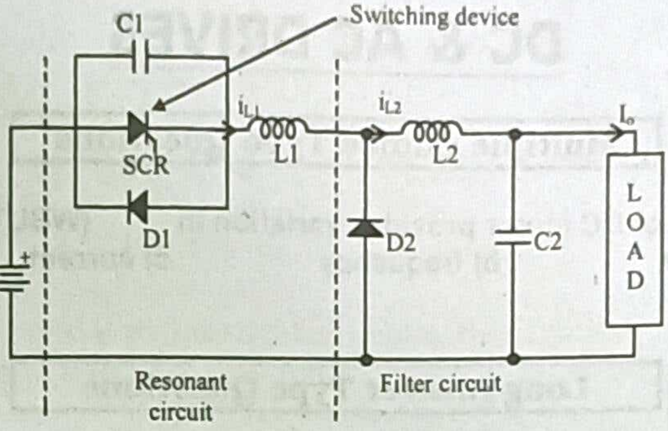
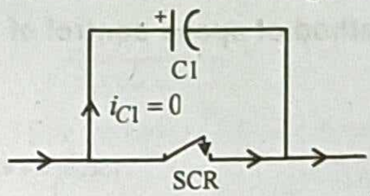


Fig: A scheme for zero voltage switching

Switching device is turned on. The events those occur are

a) Voltage across the capacitor = 0, hence current through the capacitor $C_1 = i_{C1} = 0$

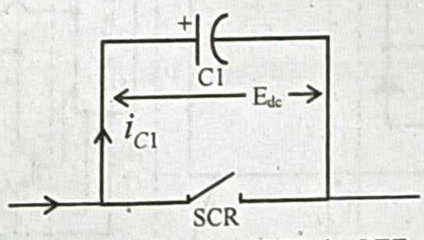


Status of C_1 when SCR is ON

b) Diodes D1 and D2 are reversed biased.

c) Current through the switching device $I_T = I_{L1} = I_{L2}$

Step 2: Switching device is turned-off. The current now flows through the capacitor C_1. Capacitor C1 charges till it reaches the supply voltage E_{dc} as shown in figure.



Status of C_1 when SCR is OFF

After this time the diode D2 becomes forward biased and conducts.

Step 3: L1 and C1 form a resonating circuit. The voltage across the capacitor is such that diode D1 now starts conducting, i.e., D1 is forward biased.

Step 4: Now a right situation is obtained (i.e., zero voltage switching condition) to turn on the switching device.

Step 5: The current i_{L1} will now rise till it reaches i_{L2} and Diode D2 is reverse biased. The cycle repeats.

b) Effect of source inductance for 2-pulse converter:

Refer to Question No. 1 Short Answer Type Questions.

DC & AC DRIVES

Multiple Choice Type Questions

1. Chopper control of DC motor provides variation in [WBUT 2010, 2015, 2017]
a) input voltage b) frequency c) current d) all of these

Answer: (a)

Long Answer Type Questions

1. Discuss constant (V/f) method of speed control of an induction machine. [WBUT 2008, 2018]

OR,

Discuss constant (V/f) method of speed control of an induction machine. [WBUT 2011]

Answer:

Basic Block Diagram

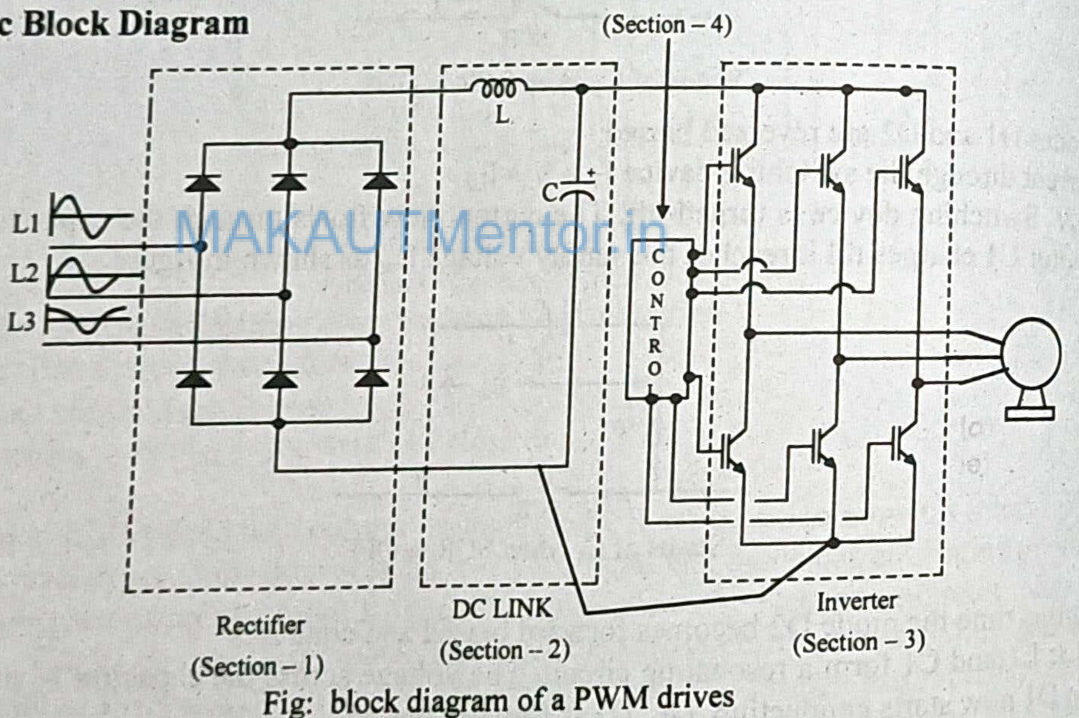


Fig: block diagram of a PWM drives

Basic Sections

An AC drive changes fixed AC voltage and frequency into variable voltage and frequency.

This transition is carried out through following blocks in stages.

Section 1

This section is a full wave diode bridge rectifier. The function of this section is to convert AC power into DC power.

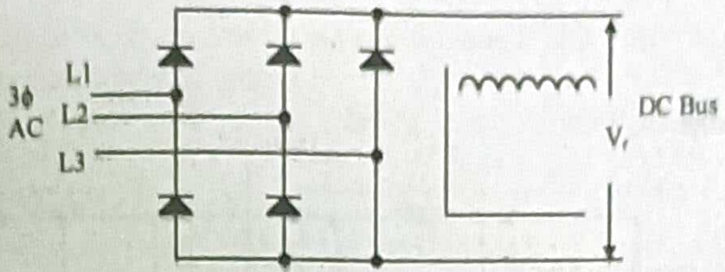


Fig: Full wave diode bridge rectifier

Section 2
Second section uses L and C to filter DC bus ripples. Rectifier section provides pulsating DC. L and C are used to smooth out the ripples present in the pulsating DC.

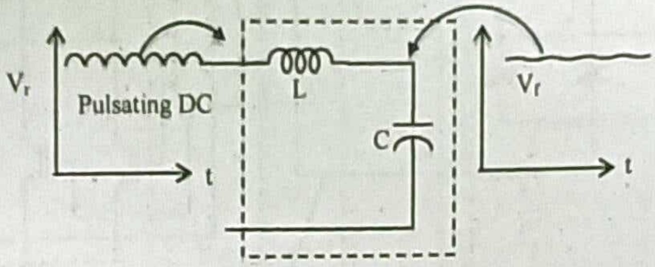


Fig: LC filter to reduce DC bus ripples

Section 3
This section uses IGBTs or BJTs to change the dc waveform back into AC. By utilizing six or more IGBTs/BJTs, the drive recreates a sine wave to the motor. For this, conventionally PWM method is adopted.

Section 4
This section is control section, which uses PWM technique to have variable voltage and variable frequency at output.

2. Write short notes on the following:
a) Speed control of AC motor with power electronic devices **[WBUT 2013]**
OR,
Speed control technique of AC motor **[WBUT 2017]**
b) Rectifier fed DC motor control **[WBUT 2015]**

Answer:

PWM Drives

Basic Block Diagram -

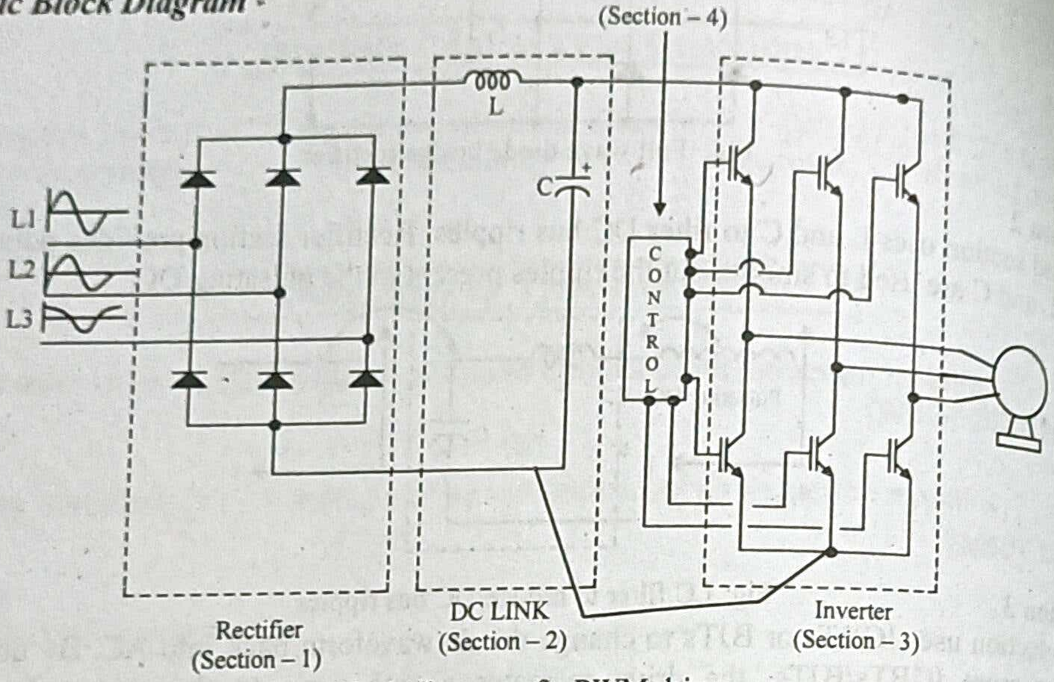


Fig: 1block diagram of a PWM drives

Basic Sections

An AC drive changes fixed AC voltage and frequency into variable voltage and frequency.

This transition is carried out through following blocks in stages.

Section 1: This section is a full wave diode bridge rectifier. The function of this section is to convert AC power into DC power.

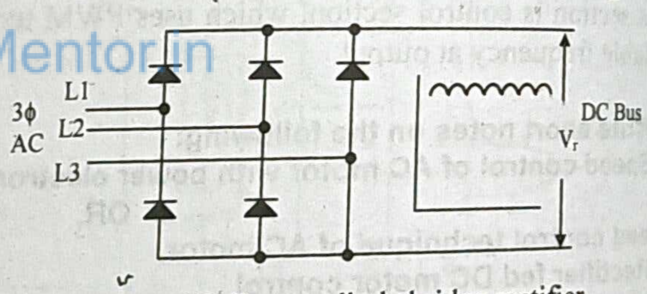


Fig: 2 Full wave diode bridge rectifier

Section 2: Second section uses L and C to filter DC bus ripples. Rectifier section provides pulsating DC. L and C are used to smooth out the ripples present in the pulsating DC.

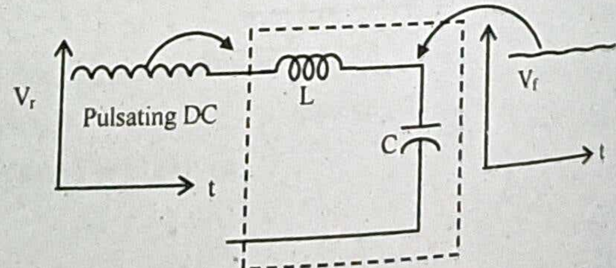
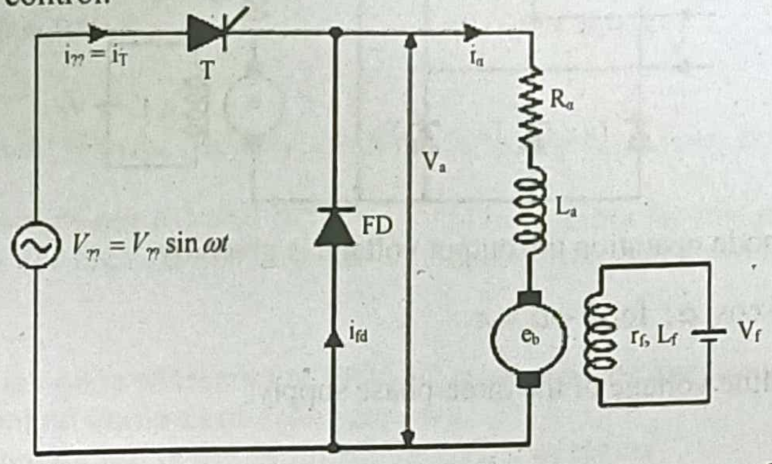


Fig: 3 LC filter to reduce DC bus ripples

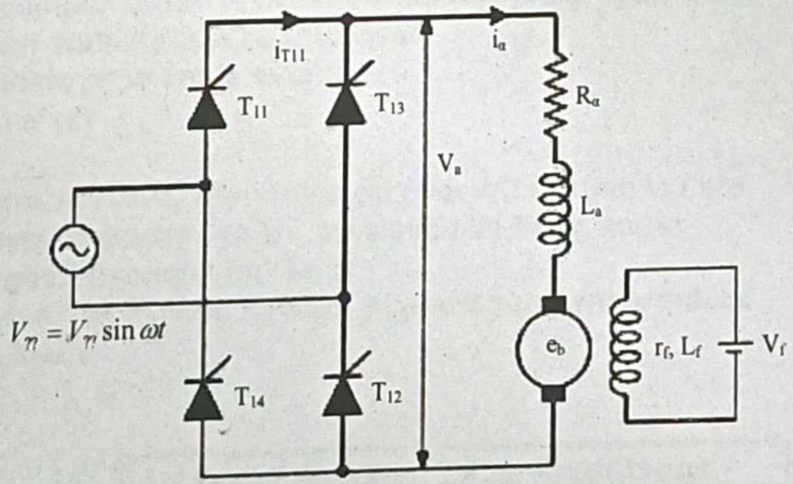
Section 3: This section uses IGBTs or BJTs to change the dc waveform back into AC. By utilizing six or more IGBTs/BJTs, the drive recreates a sine wave to the motor. For this, conventionally PWM method is adopted.

Section 4: This section is control section, which uses PWM technique to have variable voltage and variable frequency at output.
Feature: Since the load requirement is small at low speed, motor heating is not a problem.

b) Rectifier fed DC motor control:
The figure shown below is the circuit of a single-phase half wave controlled rectifier fed DC motor speed control.



The speed of a DC motor depends on the armature voltage at constant field current. The controlled rectifier regulates the armature voltage in presence of controlled gate current. Single phase or three-phase ac supply provides power up to few kilowatts of motor. Three-phase supply is provided always for larger motors (kWs). Flywheel diode (FD) connected across the load protects from motor and SCR from high voltage transients.
Figure below shows a single phase fully controlled rectifier fed DC motor speed control.

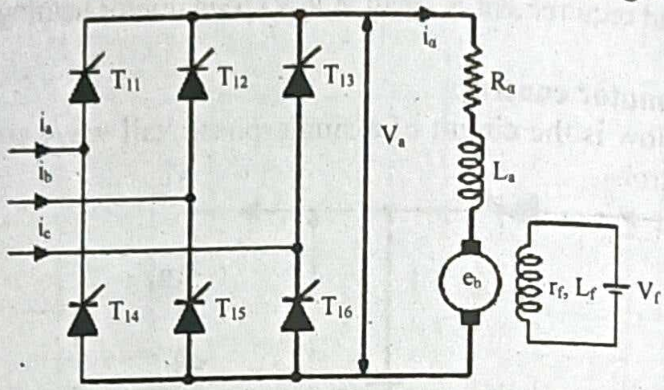


Here, single-phase full wave converter varies the armature voltage. It is a two-quadrant drive and is limited to applications up to few tens of kW. Equation below is the expression of the voltage across the armature

$$V_o = \frac{2V_m}{\pi}\cos\alpha;\ \text{for } 0 < \alpha < \pi$$

where, α is the firing angle to the gate of the SCR and V_m is the peak value of the source voltage.

Normally industrial motors may be of several tens to hundreds kilowatts. The most common configuration is three-phase fully controlled rectifier (Figure below).



For continuous mode operation the output voltage is given by

$$V_o = \frac{3V_m}{\pi}\cos\alpha;\ \text{for } 0 < \alpha < \pi$$

where, V_L is the line voltage of the three-phase supply.

POWER ELECTRONIC APPLICATIONS

Multiple Choice Type Questions

1. Switch mode power supplies are superior to linear power supplies in respect of [WBUT 2008, 2013]
   a) size & efficiency
   b) efficiency & regulation
   c) regulation & noise
   d) noise & cost

Answer: (b)

2. Switched Mode Power Supply (SMPS) is preferred over continuous types because SMPS [WBUT 2010]
   a) is suitable for both AC and DC
   b) is suitable for low power circuits
   c) is suitable for high power circuits
   d) provides low power loss

Answer: (d)

3. HVDC transmission is preferred to EHV-AC transmission because [WBUT 2013]
   a) HVDC terminal equipment are expensive
   b) VAR compensation is not required for HVDC systems
   c) system stability can be improved
   d) both (b) & (c)

Answer: (d)

4. HVDC transmission is preferred to EHV-AC transmission because [WBUT 2016]
   a) HVDC terminal equipment are expensive
   b) VAr compensation is not required for HVDC systems
   c) system stability can be improved
   d) harmonic problem is avoided

Answer: (b) & (c)

5. Advantages of HVDC transmission over AC system is / are [WBUT 2018]
   a) reversal of power can be controlled by firing angle
   b) very good dynamic behavior
   c) they can link two AC system operating unsynchronized
   d) all of these

Answer: (d)

Long Answer Type Questions

1. With the help of block diagram explain the basic principle of operation of SMPS. [WBUT 2009, 2011]

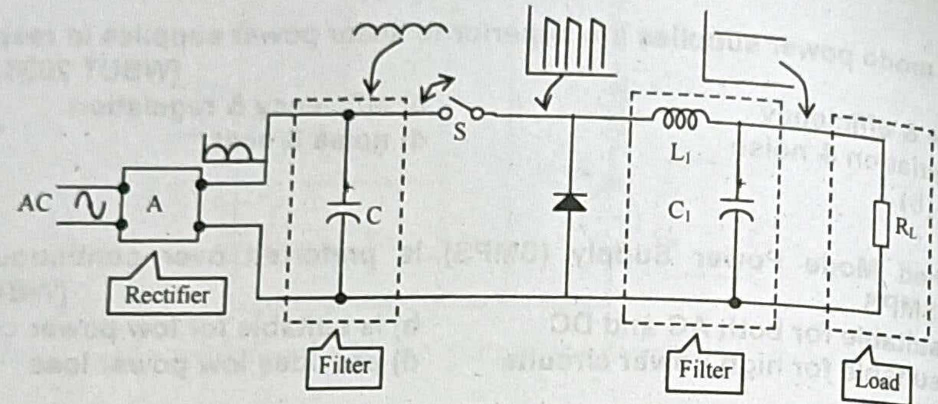
Answer:

Switched Mode Power Supply is basically a DC source of power supply which

- Contains negligible ac ripples.

- Provides controlled (Magnitude) dc output.
- Having higher efficiency.

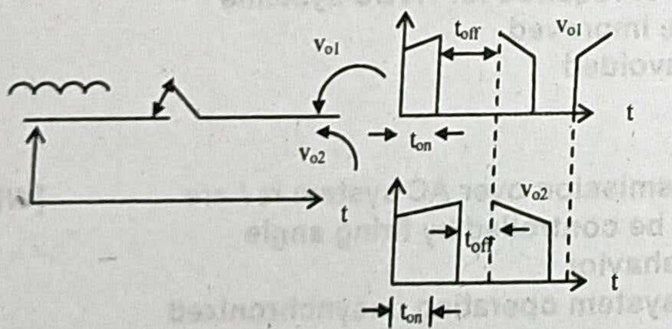
Unlike linear regulator power supply, they do not require the large transformers and filtering devices, thus reducing space and cost.



Basic scheme of a SMPS

A → A is an uncontrolled rectifier. This provides a pulsating dc output.
C → Capacitor C partially smoothes out the pulsating dc voltage.
S → S is a switch, which is a power semiconductor switching device like GTO, BJT, MOSFET, SCR etc. This switch is turned ON and OFF to give a sampled output. The chopped voltage swings between the source level and zero.
L_1, C_1 → L_1, C_1 forms a filter circuit. This smoothes the chopped waveform to give a *level* voltage to the load.

By controlling the switching time, the magnitude of the DC output may be controlled, as magnitude is a function of the ON/OFF ratio.



$\overline{v_{02}} > \overline{v_{01}}$

as $\dfrac{t_{ON2}}{T_{OFF2}} > \dfrac{t_{ON1}}{T_{OFF1}}$

Fig: Switching time and DC output voltage

If the switching frequency is very high, then ac ripple frequency, fed to the L1, C1 filter is very high, hence the values of L1 and C1 can be taken very low.

Since we know, attenuation $\propto \dfrac{1}{\sqrt{\omega^2 L_1 C_1}}$

So, making $\omega^2 L_1 C_1 >> 1$, ac ripple attenuation may be made very high, thus almost ripple free controlled DC supply may be obtained.

Types of SMPS

1. Buck
2. Boost
3. Buck - Boost Converter
4. CUK converter

Advantages of SMPS

1. High efficiency, because of less heat dissipation.
2. Compact, less space as transformer size is small.
3. Isolation from main supply without the use of large main transformer.
4. Easy generation of low and medium voltage supplies.
5. Reduced harmonics.
6. Small sizes of filtering elements.

Disadvantages

1. Complex circuit arrangement.
2. Regulation is not good.

Applications

A switch mode power supply circuit is versatile. It can be used to:

1. Step down an unregulated dc input voltage to produce a regulated dc output voltage using a circuit known as Buck Converter or Step-Down SMPS,
2. Step up an unregulated dc input voltage to produce a regulated dc output voltage using a circuit known as Boost Converter or Step-Up SMPS,
3. Step up or step down an unregulated dc input voltage to produce a regulated dc output voltage,
4. Invert the input dc voltage using usually a circuit such as the Cuk converter, and
5. Produce multiple dc outputs using a circuit such as the fly-back converter.

2. Write short notes on the following:

a) HDVC transmission **[WBUT 2007, 2017]**

OR,

Application of power semiconductor devices to HVDC system **[WBUT 2015]**

b) SMPS **[WBUT 2007, 2014]**

c) Static VAR control **[WBUT 2008, 2017]**

OR,

Static Var Compensators **[WBUT 2011]**

d) UPS **[WBUT 2011, 2016]**

e) Static Circuit Breaker **[WBUT 2011, 2017]**

f) Electronic Ballast **[WBUT 2014]**

g) Induction heating. **[WBUT 2015]**

Answer:

a) HDVC transmission:

Though AC transmission system has many advantages but in recent years, HVDC transmission over long distance has been found advantageous over multiphase AC transmission system. The *main reasons* of adoption HVDC transmission are

1. HVDC transmission is economic, i.e., savings in cable costs.

2. The two inter connected AC systems can be at different operating voltages even operating frequencies may be different, HVDC transmission systems may be used efficiently to avoid the need of synchronization.
3. Reduced line fault.
4. Problem of synchronization of 'GRID' frequency is overcome.

Overall Layout
The overall layout of HVDC transmission line is shown in following figure

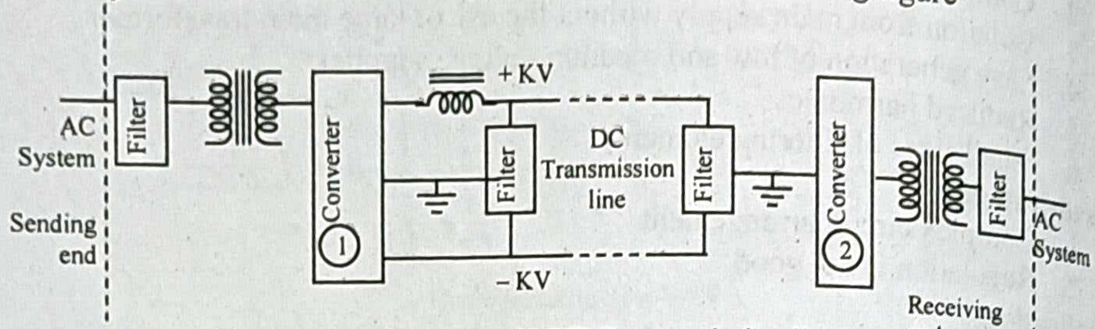


Fig: An overall layout of HVDC transmission line

Functions of Converters
Sending end converter operates in *Rectifier* Mode and Receiving end converter operates in *Inverter* mode.

Basic Working
Step 1: Sending end ac power is first rectified (with the help of a converter) to a voltage level of say ± 200KV

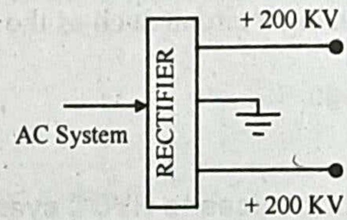


Fig: Rectification of sending of end

Step 2: Converter (Rectifier) feeds power over a two-cable (pole) line, through suitable filters to reduce harmonics.

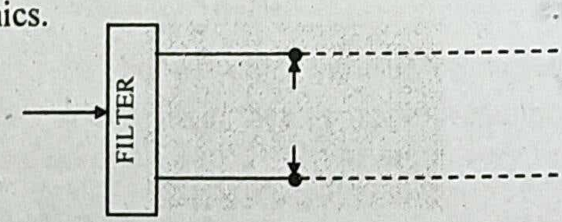


Fig: power feeing two – cable line

Step 3: At the receiving end, the pole feeds power to the converter acting as inverter mode. (refer to figure)

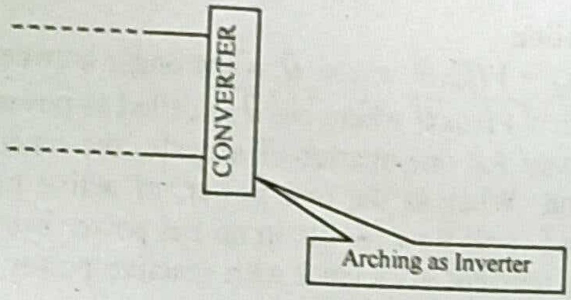


Fig: HVDC transmission lines feed power to the inverter

Step 4: Converter is controlled to provide desired voltage and frequency levels.

- Direction of Power Flow

Power flow can be in either direction as each converter can operate in either rectifying or inverting mode.

Scheme of Converter Terminal

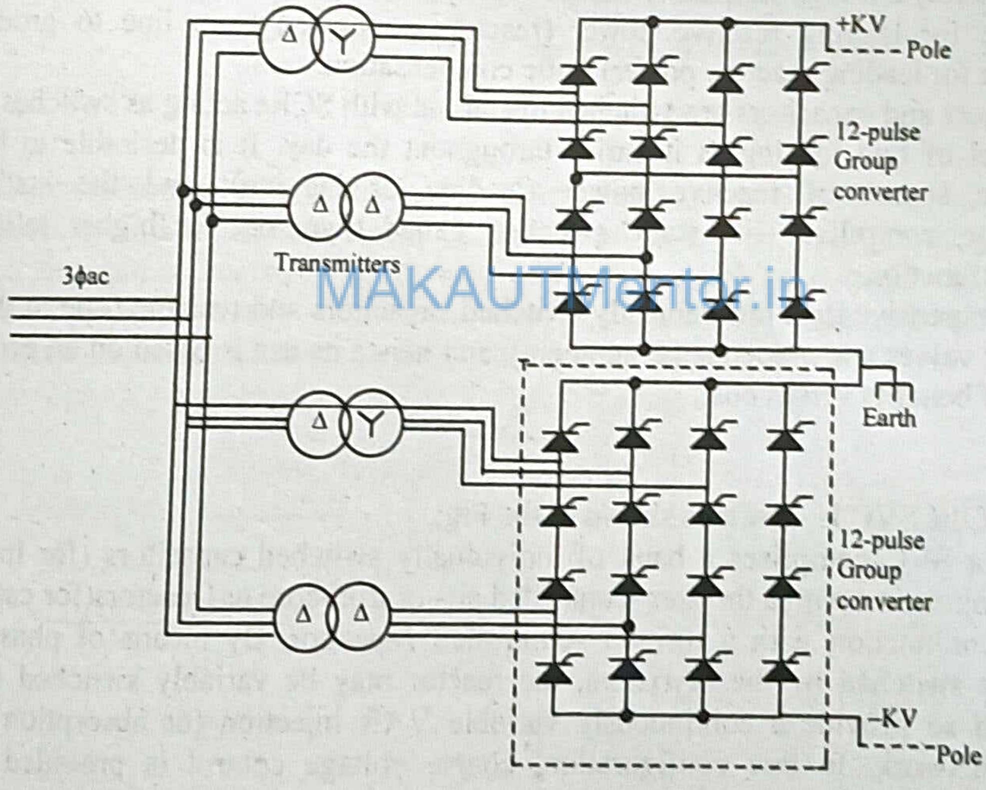


Fig: Scheme of converter terminal

b) ***Refer to Question No. 1 of Long Answer Type Questions.***

c) Static VAR control:

The word VAR stands for volt-ampere reactive, or reactive power. The device is called a reactive power controller or compensator. Since the device is Thyristor controlled hence called **static.**

Need for reactive compensation

Reactive power is given by $Q = VI\sin\theta$ where θ is the angle between V and I whereas the active power is given by $P = VI\cos\theta$ where $\cos\theta$ is called as power factor.

Reactive power flows one way for one-quarter of a cycle, the other way for the next quarter of a cycle, and so on. Whereas the real power, or active power flows in one direction only. This back- and-forth flow results in no net power being delivered by the source to the load. However, current associated with reactive power does flow through the conductor and creates extra losses.

Industrial loads are mainly inductive and draw lagging reactive power, which causes electric power system voltage to sag. On the other hand, under light loads, the capacitance of high-voltage lines can create excessive leading reactive power, causing the voltage at some locations to rise above the nominal value. Finally, it is prudent to keep reactive power flows to a minimum in order to allow the lines to carry more active power. To improve the active power the basic target is to make the $\cos\theta$ as close to 1 (i.e. θ to zero.) Utilities frequently install capacitors connected from line to ground to compensate for lagging reactive power (reactors connected from line to ground to compensate for leading reactive power) static compensation.

These reactors and capacitors are switched in and out with SCRs acting as switches based on the level of line loading as it varies throughout the day. It is desirable to have a controllable source of reactive power (leading or lagging); and the static var compensator, controlled with static switches, called thyristors for higher reliability, fulfills this function.

It is more expensive than mechanically switched capacitors and reactors (due to the cost of thyristor valves and associated equipment), and hence its use is based on an economic trade-off of benefits versus cost.

Working

Working of the SVC is shown as shown in the Fig:

Typically, a SVC comprises a bank of individually switched capacitors (for inductive load) in conjunction with a thruster -controlled air- or iron-core or [reactors(for capacitive loads) in conjunction with a thruster -controlled capacitor. By means of phase angle modulation switched by the thyristors, the reactor may be variably switched into the circuit, and so provide a continuously variable VAR injection (or absorption) to the electrical network. In this configuration, coarse voltage control is provided by the capacitors; the thruster-controlled reactor is to provide smooth control. Smoother control and more flexibility can be provided with thruster-controlled capacitor switching.

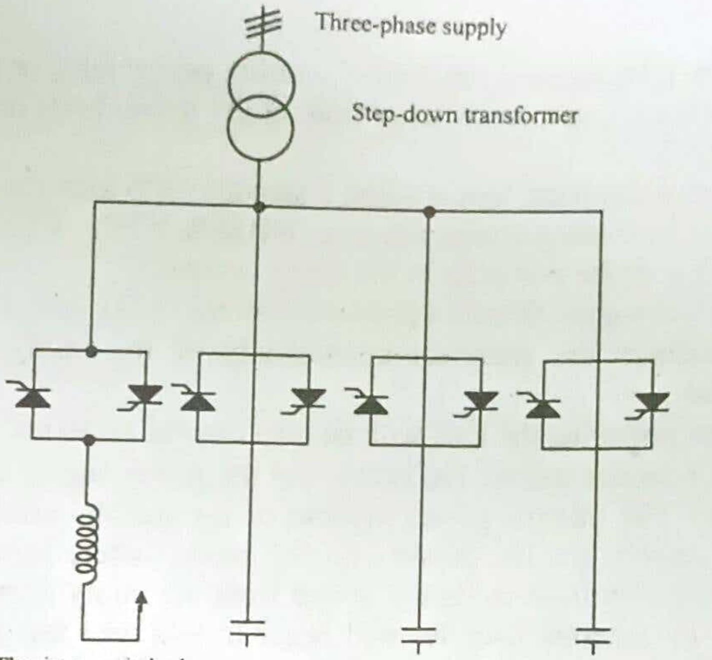


Fig: Static VAR compensator

d) UPS:

UPS is the acronym of uninterruptible power supply. It is a device which maintains a good quality and continuous supply of electric power to equipment by supplying power from a separate source when utility powerfails. UPS provides voltage regulation during power line overvoltage and undervoltage conditions. They provide excellence performance in terms of line transients, harmonic disturbances etc.

The basic block diagram of an UPS is shown in the fig. 1.

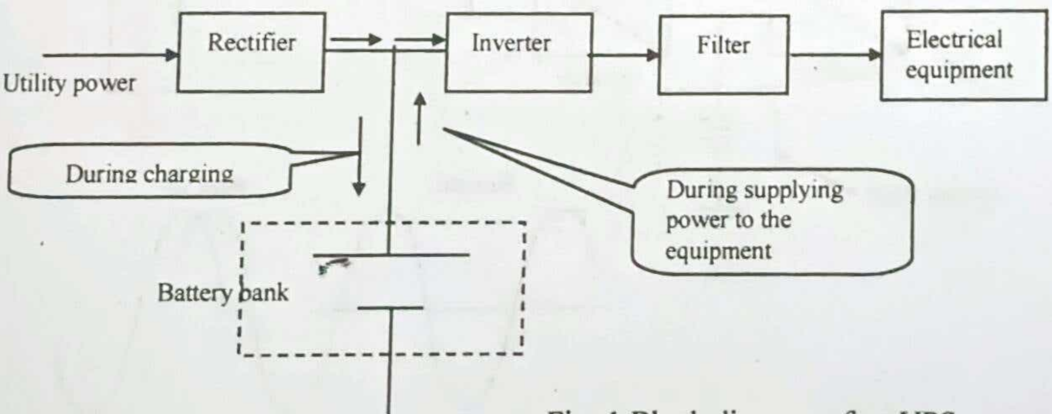


Fig: 1 Block diagram of an UPS

Types of UPS

There are two types of uninterruptible power supply.

- Standby or off- line UPS
- Continuous or on-line UPS

Standby UPS

An off-line or standby UPS remains idle until the utility power fails, or unhealthy for the equipment (electrical load) and then switches from utility power to its own power source, almost instantaneously.

An electrical load e.g. a computer that is using a standby UPS uses the regular ac mains supplied by the power generating companies (e.g. WBSEB, NTPC, CESC etc.) as long as there are no problems with the power from the utility company.

But if the standby power supply detects a problem with the utility power

- It will disconnect the electrical connectivity of the utility power with the electrical load.
- UPS will start powering the load with its own internal batteries
- The internal batteries deliver DC power but the power supply of the load should be 220V AC. The internal power inverter of the standby uninterruptible power supply will convert the DC power into AC power before using it to power the load. The transition from using the power from the utility company to using the power from the internal batteries will occur in less than few milliseconds, thus keeping the load power uninterrupted. The scheme of the standby or off-line UPS is shown in the fig. 2(a). The pattern of the supply wave to the electrical load is shown in the fig. 2(b) when the switching from the utility power to the battery bank takes place.

Scheme

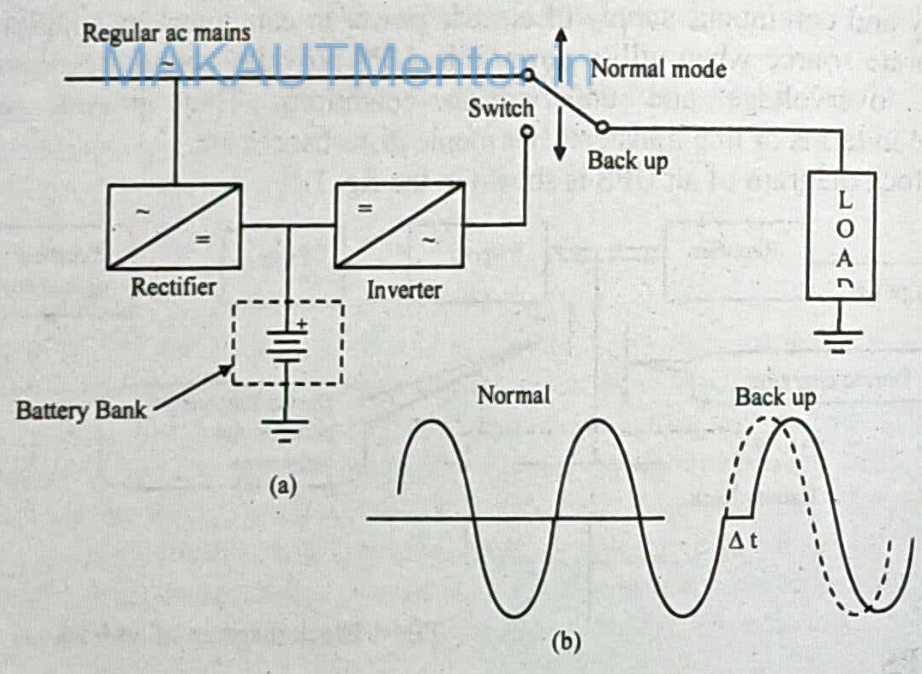


Fig: 2 Stand-by or offline UPS

Drawbacks

- In normal mode, the load sees all the disturbances (transients, EMI, HF noise) present in the utility power.
- The switchover from normal mode to back-up mode is not smooth rather takes place with generally a short interruption (5-10msec.)

Applications

For small installations, such as, shops, private offices where the equipments like computers are normally immune to power pollution, stand by UPS is used.

Continuous UPS

- The electrical load, which is connected to a continuous power supply, is constantly supplied with power from the internal batteries of the continuous UPS.
- While supplying power to the load, the internal batteries are also being recharged by the utility power.
- Like the standby UPS, the continuous power supply has a power inverter. The power inverter will continuously convert the DC power of the internal batteries into 220-volt AC power that the power supply of the load can use.
- In case of poor quality of utility power or in case of power cut the load will use whatever power is left from the internal batteries. The scheme of the standby or off-line UPS is shown in the fig. 3(a). The pattern of the supply wave to the electrical load is shown in the fig. 3(b) when the switching from the utility power to the battery bank takes place.

Scheme

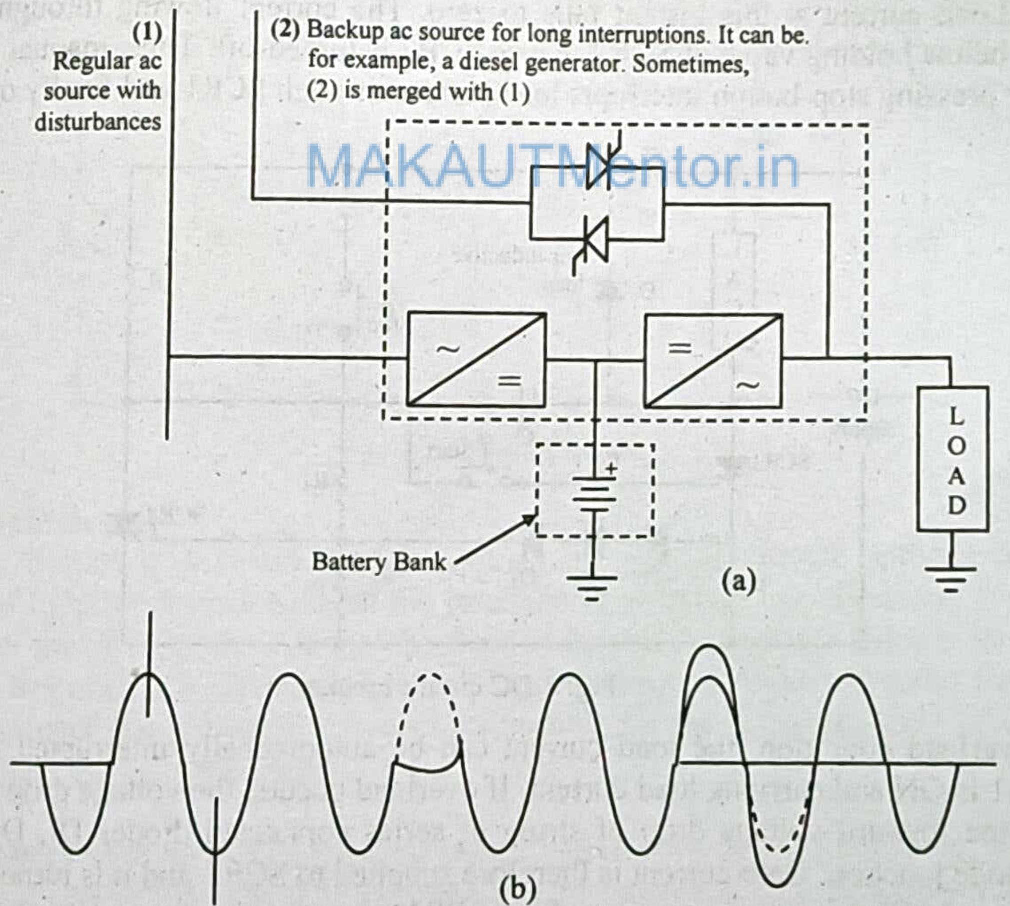


Fig: 3 Continuous or Online UPS

Drawbacks

- Switch mode inverter in the UPS generates EMI noises.
- Due to impedance mismatch power transfer is not maximum.
- The battery bank is supplying power to the equipment, thus reducing the life of the battery.

e) Static Circuit Breaker:

Fig. 1 shows circuit configuration of static circuit breaker using SCR. The circuit is basically a parallel capacitor commutated power flip-flop. SCR1 receives gate-current through R_3 when the start button is momentarily depressed and device starts conducting. Turning-on of SCR1 causes major part of supply voltage to appear across load and hence power is delivered to load. The capacitor C gets charged to load voltage with right-plate positive, as shown in Fig. 1 through R_4 and SCR1.

Stop-button is momentarily depressed to switch-off load. SCR2 receives gate-current through R_5 and it is turned-on. Turning-on of SCR2 causes charged capacitor C to place across conducting SCR1. Capacitor C applies reverse-bias for SCR1 and starts discharging. Due to this, SCR1 turns-off and load current is continued through C and SCR2. Capacitor C gets fully discharged and then charges with reverse polarity to supply voltage. Load current at this instant falls to zero. The current flowing through R_4 and SCR2 is below holding valve of SCR2, hence SCR2 is turned-off. Thus, manual firing of SCR2 by pressing stop-button interrupts load current through SCR1 and finally opens the circuit.

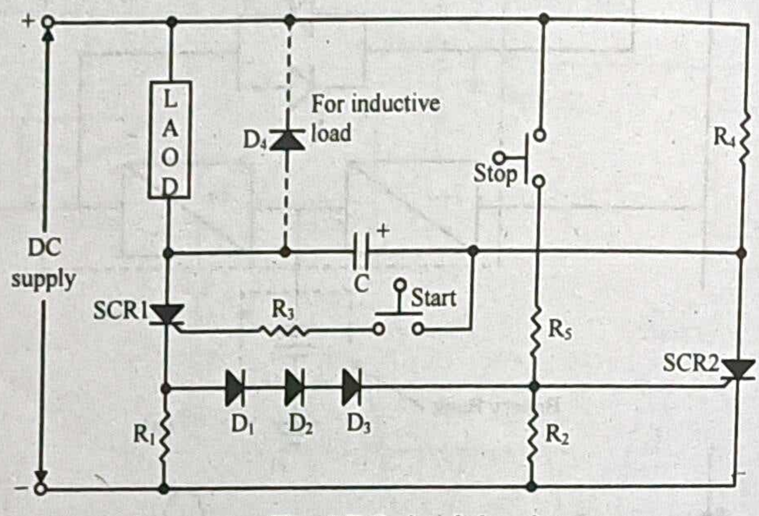


Fig: 1 DC circuit breaker

Under overload condition, the load current can be automatically interrupted. Consider that SCR1 is ON and carrying load current. If overload occurs, the voltage drop across R_1 exceeds the forward voltage drop of string of series connected diodes D_1, D_2, D_3 and gate-cathode junction. Gate-current is therefore supplied to SCR2 and it is turned-on. The turning-on of SCR2 results in turning-off of SCR1 immediately due to capacitor voltage and load is switched-off from the circuit. The circuit can be made to trip by adjustment of the value of R_1 and by selecting the proper number of series diodes D_1, D_2, D_3 ...... etc. and interrupt overload or fault current at any predetermined level.

Static AC Circuit Breaker:

Fig. 2 shows the circuit configuration of static ac circuit breaker. SCRs1 and 2 are triggered in positive and negative half-cycles respectively when switch S is closed. During positive half-cycle of the input, SCR1 receives gate current through $\left(D_2 \| R_2\right)$, switch S and R_3 and it conducts. At the end of positive half-cycle, SCR1 is turned-off due to natural current zero.

SCR2 receives gate-current through $\left(D_1 \| R_1\right), R_3$ and switch S during negative half-cycle and conducts. It is turned-off at the end of this negative half-cycle due to natural current zero value. When the load current is required to be interrupted, the switch S is opened. Opening of switch S results in blocking of gate currents of both SCRs and hence both SCRs are maintained-off. When switch S is opened at any instant in a particular half-cycle, the load current continues to flow through conducting SCR till the end of this half-cycle, however, in the next half-cycle the other SCR is not triggered due to non-availability of gate current. Thus, the maximum time delay for breaking the circuit is one half-cycle.

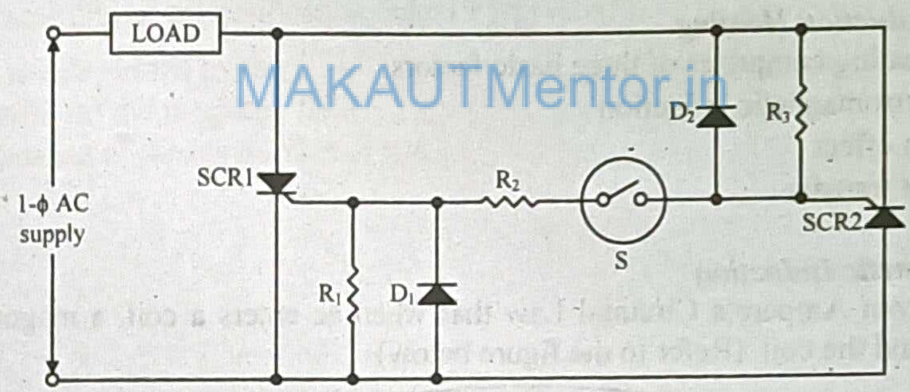


Fig: 2 AC circuit breaker

f) Electronic Ballast:

Electronic Ballast is a device, which controls the starting voltage and the operating currents of lighting devices built on the principle of electrical gas discharge. It refers to that part of the circuit, which limits the flow of current through the lighting device and may vary from being a single resistor to a bigger, complex device. In some fluorescent lighting systems like dimmers, it is also responsible for the controlled flow of electrical energy to heat the lamp electrodes.

Ballast Basics: For a lighting device based on electric gas discharge to work, the ionization of gas in the tube is necessary. This phenomenon takes place at a relatively high potential difference and/or temperature than the normal operating conditions of the lamp. After the arc is set up, the conditions can be brought down to normal. To achieve this, three types of methods are generally employed: pre-heat, instant start and rapid start.

In pre-heat, the electrodes of the lamp are heated to a high temperature before the voltage is impressed upon them through a starter. Instant start ballasts were developed to start lamps without delay or flashing and use an initial high voltage in place of raised temperatures. Rapid start ballasts make a tradeoff between pre-heat and instant start and use a separate set of windings to initially heat the electrodes for a lesser duration and then, using a relatively lower voltage to start the lamp. Another type, programmed start ballasts is a variant of rapid-start. Any of these starting principles may be used in the ballasts. Initially, when the gas is unionized, it offers a high resistance path to current. But after the ionization takes place and the arc is set up, the resistance drops to a very low value, almost acting like a short circuit. If all this current is allowed to pass through the lamp, the lamp would either burn out or cause the power supply to fail. Thus the ballast needs to perform the current limiting.

g) Induction heating:

Induction heating is a combination of electromagnetic induction and skin effect.
Induction heating refers to the generation of heat energy by high frequency Eddy current generated on the surface of a *conductive* object (according to Eddy's Law) when it is placed in the magnetic field formed around a alternating current carrying coil (Ampere's Law).

Basics of Induction Heating

Induction heating comprises of three basic factors:

- Electromagnetic induction
- Skin effect
- Heat transfer

Electromagnetic Induction

We know from Ampere's Circuital Law that when ac enters a coil, a magnetic field is formed around the coil. (Refer to the figure below)

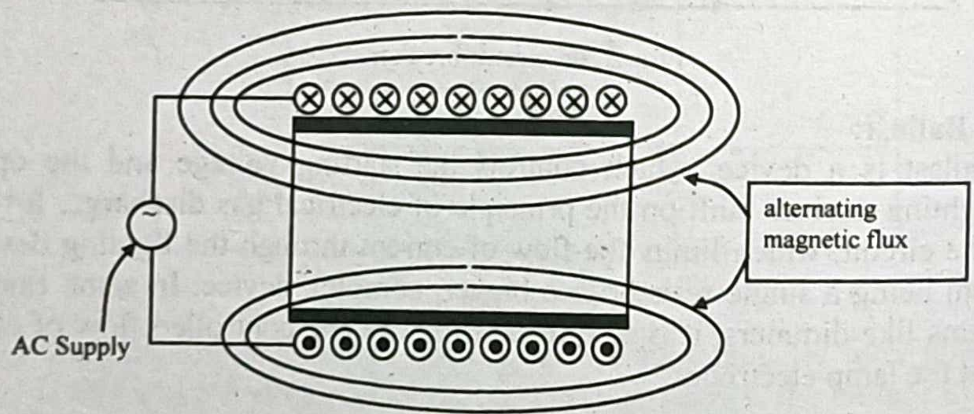


Fig: Basic scheme of induction heating

$$\boxed{\oint \vec{H}.\vec{dl} = Ni}$$

$N \Rightarrow$ No. of turns of the coil
$i \Rightarrow$ Current (ac) flowing through coil
$H \Rightarrow$ Magnetic field strength
$l \Rightarrow$ Length of the magnetic circuit.

An object when put into the magnetic field, causes a change in the velocity of the magnetic movement.
The conductive object undergoes a time varying change in the magnetic flux linkage.
According to Eddy's Law, current is generated on the surface of the conductive object, called Eddy current.
This Eddy current is responsible for the generation of heat energy (P)

$$P = i_e^{\,2} \cdot R$$

$i_e \Rightarrow$ Eddy current; A
$R \Rightarrow$ Resistance of the conductive path ; Ω

***Resistance* (*R*)** is determined by the

- Resistivity (ρ)
- Permeability of the conductive object (μ)

***Current* (i_e)** is determined by the

- Intensity of the magnetic field
- Resistance of the conductive object

MISCELLANEOUS

Multiple Choice Type Questions

1. Bipolar junction transistors have **[WBUT 2007]**
a) low input resistance compared to FET **c) zero input resistance**
b) high input resistance compared to FET **d) infinite resistance**

Answer: (a)

2. The average value of voltage of a single-phase *ac* voltage controller is given by **[WBUT 2009]**

a) $\frac{\sqrt{2}V}{\pi}(1+\cos\alpha)$ b) $\frac{\sqrt{2}V}{2\pi}(1+\cos\alpha)$ c) $\frac{\sqrt{2}V}{\pi}\cos\alpha$ d) $\frac{V}{\pi}\cos\alpha$

Answer: (a)

3. A BJT operates as a switch **[WBUT 2009]**
a) under small signal conditions
b) with no signal condition
c) in the active region of transfer characteristics
d) under large signal condition

Answer: (c)

Long Answer Type Questions

1. a) Draw and explain dynamic switching characteristics of Power BJT.
b) Explain its operation with the help of an equivalent circuit. **[WBUT 2011]**

Answer:

When the base current is applied, a transistor does not turn on instantly because of the presence of internal capacitance.

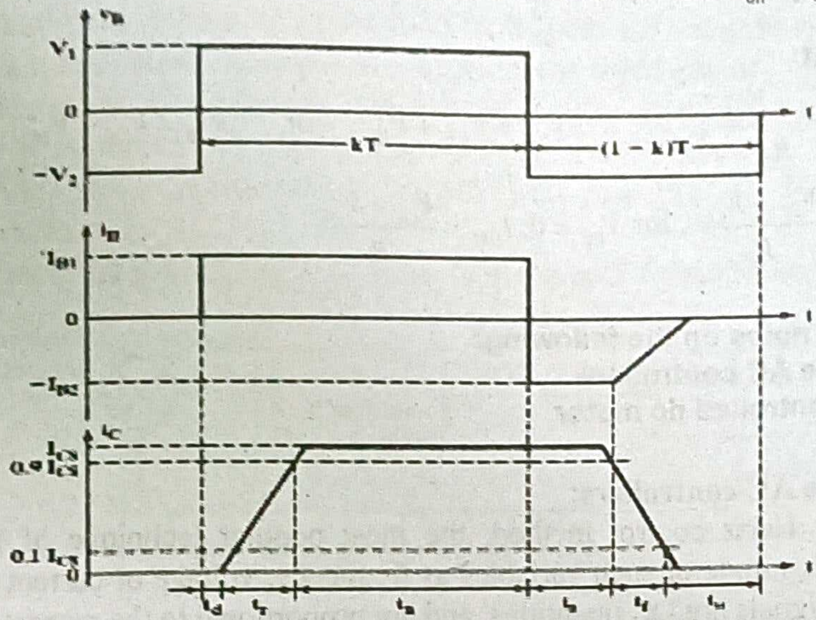
$$t_{on} = t_d + t_r$$

$$t_{off} = t_s + t_f$$

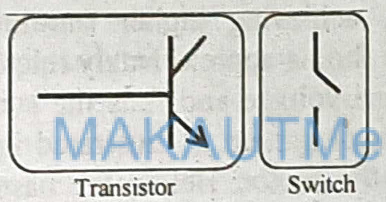
When input voltage V_B to base circuit is made $-V_2$ at t_0, junction EB is reverse biased $V_{BE} = -V_2$, a transistor is OFF i.e. $I_B = I_C = 0$ and $V_{CE} = V_{CC}$. At time t_1, input voltage V_B is made $+V_1$ and I_B rises to I_{B1}.

After time t_1, base emitter voltage V_{BE} begins to rise gradually from $-V_2$ and collector current I_C begins to rise from zero and collector-emitter voltage start falling from initial value V_{CC}. After some time td called delay time, the collector current rises to $0.1I_{CS}$ this delay time is required to change the base emitter capacitance to $V_{BES} = 0.7$ V. This delay time t_d is defined as time during which the collector current rises from 0 to 0.1Ics and collector-emitter voltage fall V_{CC} to 0.9 V_{CC}.

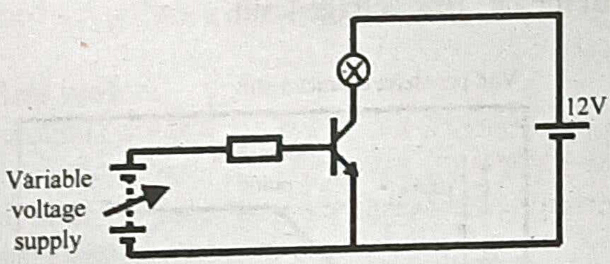
After delay time t_d, collector current rises from 0.1Ics to 0.9Ics and V_{CE} fall from 0.9V_{CC} to 0.1 V_{CC} in time t_r. This time t_r is known as rise time which depends upon transistor junction capacitance. The rise time t_r is defined as the time during which collector current rises from 0.1Ics to 0.9Ics. This shows the total turn on time $t_{on} = t_d + t_r$.



b) Power transistor acts as a switch. Transistors can either conduct or not conduct current.

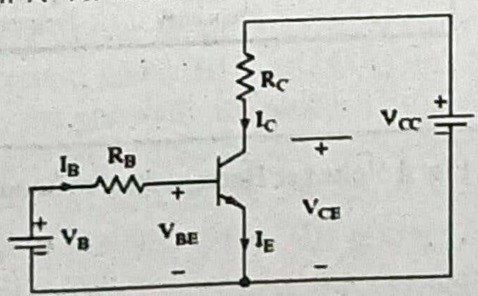


When V_{BE} is less than 0.7V the transistor is off and the lamp does not light.



When V_{BE} is greater than 0.7V the transistor is on and the lamplights. Transistor operation as switch means that transistor operates either in saturation region or in cut-off region and nowhere else on the load line.

As an ideal switch operate at A. At point B in cut-off state as an open switch.



Large base current will cause the transistor work in saturation region at point A' with small saturation voltage VCES.

KVL of circuit:

$$I_B = \frac{V_B - V_{BE}}{R_B}; \qquad V_{CE} = V_{CB} + V_{BE} \quad \text{or,} \quad V_{CB} = V_{CE} - V_{BE}$$

$$I_{CM} = \frac{V_{CC} - V_{CE}}{R_C}, \text{ for } V_{CB} = 0, I_{CM} = \frac{V_{CC} - V_{BE}}{R_C}$$

2. Write short notes on the following:
a) Three phase AC controllers
b) Chopper controlled dc motor **[WBUT 2013]** **[WBUT 2016]**

Answer:

a) Three phase AC controllers:

The Volts per Hertz control method, the most popular technique of Scalar Control, controls the magnitude of such variables as frequency, voltage or current. The command and feedback signals are DC quantities, and are proportional to the respective variables. The purpose of the Volts per Hertz control scheme is to maintain the air-gap flux of AC induction motor in constant, achieving higher run-time efficiency. In steady-state operation, the machine air-gap flux is approximately related to the ratio Vs/fs, where Vs is the amplitude of motor phase voltage and fs is the synchronous electrical frequency applied to the motor. The control system is illustrated in **Figure.** The characteristic is defined by the base point of the motor. Below the base point, the motor operates at optimum excitation due to the constant Vs/fs ratio. Above this point, the motor operates under-excited because of the DC Bus voltage limit.

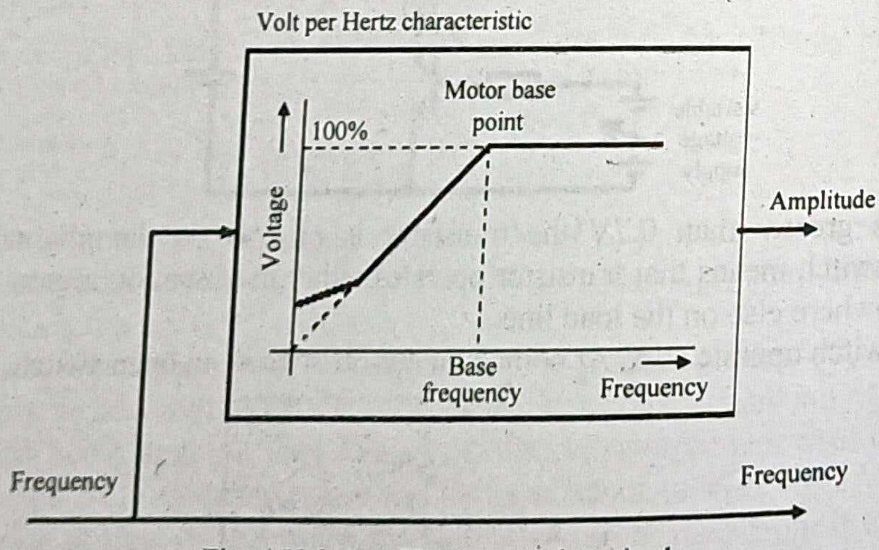


Fig: 4 Volts per Hertz control method

A simple closed-loop Volts per Hertz speed control for an induction motor is the control technique targeted for low-performance drives. This basic scheme is unsatisfactory for more demanding applications, where speed precision is required.
To improve system performance, a closed-loop Volts per Hertz control was introduced. In this method, a speed sensor measures the actual motor speed and the system takes this input into consideration. A number of applications use the closed-loop Volts per Hertz method because of its simple and relatively good speed accuracy, but it is not suitable for systems requiring servo performance or excellent response to highly dynamic torque/speed variations.
Figure below depicts the general block diagram of the speed PI control loop.

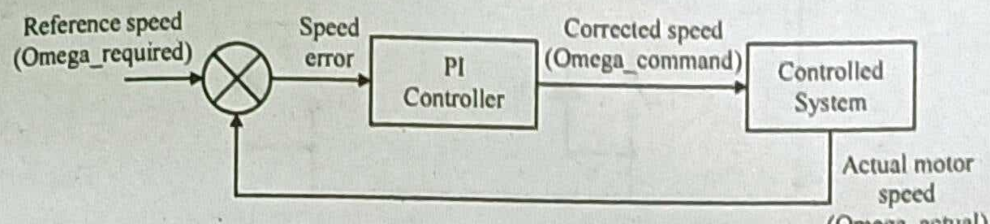


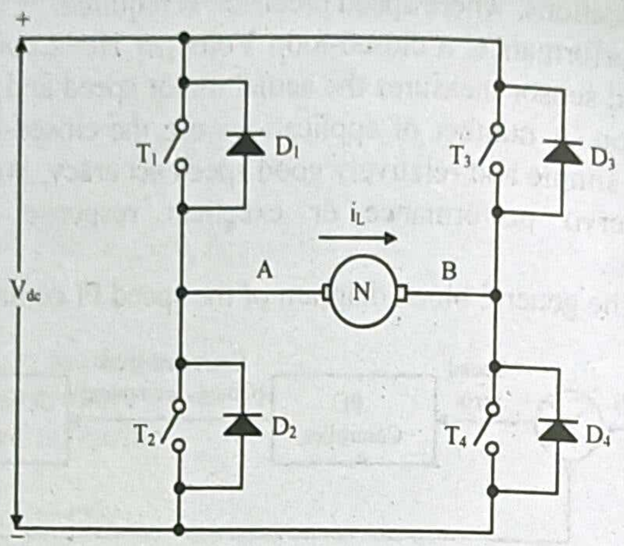
Fig: 5 Closed loop control system

The speed closed-loop control is characterized by the measurement of the actual motor speed. This information is compared with the reference speed while the error signal is generated. The magnitude and polarity of the error signal correspond to the difference between the actual and required speed. Based on the speed error, the PI controller generates the corrected motor stator frequency to compensate for the error.
In an AC V/Hz closed-loop application, the feedback speed signal is derived from the incremental encoder using the Quadrature Decoder. The speed controller constants have been experimentally tuned according to the actual load.

b) Chopper controlled *dc* motor:
DC motors provide excellent control of speed for acceleration and deceleration. The power supply of a DC motor connects directly to the field of the motor, which allows for precise voltage control, and is necessary for speed and torque control applications. Conventional speed control techniques of DC motor are

a) Varying the armature voltage for below rated speed
b) Varying the field flux for above the rated speed.

A chopper is a static power electronic device that converts fixed dc input voltage to a variable dc output voltage. The power semiconductor devices used for a chopper circuit can be force-commutated thyristor, power BJT, MOSFET and IGBT. GTO based chopper are also used. These devices are generally represented by a switch. When the switch is off, no current can flow. Current flows through the load when switch is "on". A chopper is a high speed "on" or "off" semiconductor switch. It connects source to load and disconnect the load from source at a fast speed. The average value of output voltage V_o can be controlled through duty cycle by opening and closing the semiconductor switch periodically. Among the various control strategies for varying duty cycle are as either pulse-width-modulation or frequency modulation.



Four Quadrant chopper are used extremely in adjustable speed drive and position control application. Figure below shows the circuit diagram of a four-quadrant operation. Four-quadrant operation is realized by the four switching devices with the diode connected in anti parallel with switching diode, the motor is connected between the two arms A and B. When T1 and T2 are ON, terminal A of the armature is positive with respect B and motor rotates in a direction. The speed of rotation depends on the average value of voltage across A and B terminals. Higher the ON-time more will be the average voltage and hence speed. When T3 and T4 are ON, terminal B of the armature is positive with respect a and motor rotates in opposite direction.

QUESTION 2015

Group – A
(Multiple Choice Type Questions)

1. Answer any ten questions:

i) The number of p-n junction in a thyristor is/are

a) 1 b) 2 ✓c) 3 d) 4

ii) In a three phase semi-converter the three SCRs are triggered at an interval of

a) 60° b) 90° ✓c) 120° d) 180°

iii) SCR used

a) no gate ✓b) one gate on p-layer next to cathode
c) one gate on n-layer next to anode d) two gates

iv) In SCR, the turn-off time; where T is the temperature in K

✓a) increases with T b) is independent of T
c) varies as 1/T d) varies as $1/T^2$

v) In SCR, the turn-on time

a) increases with T ✓b) is independent of ambient temperature T
c) varies as 1/T d) varies as $1/T^2$

vi) Presence of drift layer in a power semiconductor device

✓a) increases breakdown voltage rating b) increases on state current rating
c) increases switching speed d) decreases on state resistance

vii) In UJT, with V_{BB} as the voltage across two base terminals, the emitter potential at peak point is given by

a) ηV_{BB} b) ηV_D ✓c) $\eta V_{BB} + V_D$ d) $\eta V_D + V_{BB}$

viii) In a three phase full wave rectifier, the output voltage pulsates at a frequency equal to supply frequency

a) f b) $2f$ c) $3f$ ✓d) $6f$

ix) For continuous conduction each thyristor pair of a two pulse full converter should conduct for

a) π ✓b) $\pi - \alpha$ c) α d) $\pi + \alpha$

x) Chopper control of DC motor provides variation is

✓a) input voltage b) current c) frequency d) all of these

xi) A single phase full bridge VSI has inductive load. For a constant source voltage, the current through the load is

a) square wave ✓b) triangular wave c) sine wave d) pulsed wave

Group – B
(Short Answer Type Questions)

2. Discuss about softness factor PIV, reverse recovery current for power diodes.
See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Short Answer Type Question No. 7.

3. What is snubber circuit? Why snubber circuits are used in thyristor circuits?
See Topic: SCR PROTECTION AND SERIES-PARALLEL OPERATION, Short Answer Type Question No. 2.

4. Describe the effect of source inductance on the DC output voltage of a single phase full controlled bridge rectifier.
See Topic: PHASE CONTROLLED RECTIFIERS, Short Answer Type Question No. 6.

5. Explain briefly the working of class B chopper with diagram.
See Topic: DC-DC CONVERTERS (CHOPPERS), Short Answer Type Question No. 4

6. What is PWM inverter? What are its advantages?

See Topic: INVERTERS, Long Answer Type Question No. 3(b).

Group – C
(Long Answer Type Questions)

7. a) What are the conditions for successful turn-on and communication of an SCR?
b) What are the different methods to turn-on an SCR?
c) With the help of two transistor model, explain how a small gate current can initiate turn-on mechanism in SCR.
See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Long Answer Type Question No. 2(a), (b) & (c).

8. a) In a buck converter find a relationship to show that amplitude of ripple current depends upon duty cycle. From the relationship how can the value of duty cycle be decided for maximum ripple current amplitude?
b) A buck converter has input voltage 220 V and it operates at 500 Hz. The average load current is 50 A. The load resistance is 2 Ohm. What will be the value of inductance to limit maximum peak-to-peak ripple current through inductor to 10%? Find the value of inductance for maximum ripple current.
c) What is meant by PWM control in chopper? Explain the working principle of four-quadrant chopper.
See Topic: DC-DC CONVERTERS (CHOPPERS), Long Answer Type Question No. 8(a), (b) & (c).

9. a) Explain the principal operation of inverter.
b) What is the reason behind using feedback diodes in anti parallel with SCRs in inverter?
c) Compare 180° and 120° conduction mode's 3 phase bridge inverter.
d) What is PWM triggering? What is the difference between voltage source and current source inverter?
See Topic: INVERTERS, Long Answer Type Question No. 8(a), (b), (c) & (d).

10. a) Draw the circuit of a two quadrant chopper & explain its working.
b) A step down DC chopper has a resistive load of R = 15Ω and input voltage Edc = 200V. When the chopper remains on, its voltage drop is 2.5V. The chopper frequency is 1kHz. If the duty cycle is 50%, determine
   i) average output voltage
   ii) RMS output voltage
   iii) chopper efficiency.
c) Derive an expression for output voltage in terms of duty cycle for a step-up and step-down chopper.
See Topic: DC-DC CONVERTERS (CHOPPERS), Long Answer Type Question No. 7(a), (b) & (c).

11. Write short notes on any three of the following:
   a) Application of power semiconductor devices to HVDC system
   b) Induction heating
   c) Rectifier fed DC motor control
   d) GTO
   e) Parallel operation of SCRs.

a) See Topic: POWER ELECTRONIC APPLICATIONS, Long Answer Type Question No. 2(a).
b) See Topic: POWER ELECTRONIC APPLICATIONS, Long Answer Type Question No. 2(g).
c) See Topic: DC & AC DRIVES, Long Answer Type Question No. 2(b).
d) See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Long Answer Type Question No. 3(a).
e) See Topic: SCR PROTECTION AND SERIES-PARALLEL OPERATION, Long Answer Type Question No. 5.a).

QUESTION 2016

Group – A
(Multiple Choice Type Questions)

1. Choose the correct alternatives for any *ten* of the following:
i) An IGBT has three terminals called
   a) collector, emitter and base
   b) drain, source and base
   c) drain, source and gate
   ✓d) collector, emitter and gate

ii) In an SCR

a) latching current LI is associated with turn-off process and holding current HI with turn-on process

b) both LI and HI are associated with turn-off process

✓c) HI is associated with turn-off process and LI with turn-on process

d) both LI and HI are associated with turn-on process

iii) For an SCR, (dv/dt) protection is achieved through the use of

a) RL in series with SCR ✓b) RC across SCR

c) L in series with SCR d) RC in series with SCR

iv) In a CSI, if frequency of output voltage is f Hz, then frequency of voltage input to CSI is

✓a) f b) $2f$ c) $f/2$ d) $3f$

v) The reverse recovery characteristics of a power diode is due to

✓a) stored charge in depletion layer

b) stored charge in semiconductor layers

c) stored charge in both depletion and semiconductor layers

d) none of these

vi) HVDC transmission is preferred to EHV-AC transmission because

a) HVDC terminal equipment are expensive

✓b) VAr compensation is not required for HVDC systems

✓c) system stability can be improved

d) harmonic problem is avoided

vii) A freewheeling diode is placed across the dc load

✓a) to prevent reversal of load voltage

b) to permit transfer of load current away from the source

c) both (a) and (b) d) none of these

viii) The features of chopper drives are

a) smooth control but slow response ✓b) smooth control but fast response

c) fast response with smooth control but less efficient

d) none of these

ix) In dc chopper, the load voltage is governed by

a) number of thyristors used in the circuit ✓b) duty cycle of the circuit

c) dc voltage applied to circuit d) none of these

x) In resonant pulse inverters

a) dc output voltage variation is wide
b) the frequency is low
c) output voltage is never sinusoidal
✓d) dc saturation of transformer core is minimized

xi) Cycloconverter converts

a) ac voltage to dc voltage
b) dc voltage to dc voltage
c) ac voltage to ac voltage at same frequency
✓d) ac voltage at supply frequency to ac voltage at load frequency

xii) The metal oxide varistor (MOV) is used for protecting

a) gate circuit against over currents
✓b) gate circuit against overvoltages
c) both (a) and (b)
d) none of these

Group – B
(Short Answer Type Questions)

2. Describe the different modes of operation using static V-I characteristics of thyristor. What is the effect of gate current on the characteristics?

See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Short Answer Type Question No. 3.

3. Draw and explain circuit diagram for the synchronized UJT triggering. Also draw the associated voltage waveforms.

See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Short Answer Type Question No. 6.

4. Discuss a comparison between power transistors, power MOSFET & IGBT in relation to their application in power electronics.

See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Long Answer Type Question No. 1.

5. How the power factor of a single phase half-wave converter can be improved using freewheeling diode? Explain with proper circuit diagram and waveforms.

See Topic: PHASE CONTROLLED RECTIFIERS, Short Answer Type Question No. 7

6. Describe the effect of source inductance on the DC output voltage of a single phase full controlled bridge converter.

See Topic: PHASE CONTROLLED RECTIFIERS, Short Answer Type Question No. 6.

Group – C
(Long Answer Type Questions)

7. a) Describe the different modes of operation using static *V-I* characteristics of Thyristor. What is the effect of gate current on this characteristics?

b) How di/dt and dv/dt protections are achieved in SRC?

a) See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Short Answer Type Question No. 2.

b) See Topic: SCR PROTECTION AND SERIES-PARALLEL OPERATION, Long Answer Type Question No. 1.

8. a) A single-phase fully controlled bridge converter supplies an inductive load. Assuming that the output current is virtually constant and is equal to I_d. Determine the following performance measures if the supply voltage is 230V and if the firing angle is maintained at $\pi/6$ radians.

i) Average output voltage
ii) Supply RMS current
iii) Supply fundamental RMS current
iv) Fundamental power factor
v) Supply power factor
vi) Supply harmonic factor
vii) Voltage ripple factor.

b) What is the difference between semi-converter and full-converter? Why semi-converter is single quadrant whereas full-converter is two quadrant converters?

See Topic: PHASE CONTROLLED RECTIFIERS, Long Answer Type Question No. 10(a) & (b).

9. a) What is the principle of operation of boost regulator?

b) A *dc* battery is charged from a constant *dc* source 220 V through a chopper. The *dc* battery is to be charged from its internal *emf* of 90 V to 122 V. The battery has internal resistance of 1Ω. For a constant charging current of 10A, calculate the range of duty cycle.

c) Explain briefly the working of class *C* chopper with relevant diagrams.

a) See Topic: DC-DC CONVERTERS (CHOPPERS), Long Answer Type Question No. 4(a).
b) See Topic: DC-DC CONVERTERS (CHOPPERS), Long Answer Type Question No. 2(b).
c) See Topic: DC-DC CONVERTERS (CHOPPERS), Short Answer Type Question No. 3.

10. a) Explain the basic principle of step up and step down cyclo-converter.

b) For a single phase *ac* voltage regulator feeding a resistive load, draw the waveforms of source voltage, gating signals, output voltage, source and output currents and voltage across SCRs.

a) See Topic: CYCLOCONVERTERS, Long Answer Type Question No. 5.
b) See Topic: PHASE CONTROLLED RECTIFIERS, Long Answer Type Question No. 3.

11. Write short notes on any *three* of the following:
   a) Series operation of SCRs
   b) Chopper controlled *dc* motor
   c) UPS
   d) Power diodes
   e) TRIAC

a) See Topic: SCR PROTECTION AND SERIES PARALLEL OPERATION, Long Answer Type Question No. 5(b).
b) See Topic: MISCELLANEOUS, Long Answer Type Question No. 2(b).
c) See Topic: POWER ELECTRONIC APPLICATIONS, Long Answer Type Question No. 2(d).
d) See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Long Answer Type Question No. 3(f).
e) See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Long Answer Type Question No. 7(g).

QUESTION 2017

Group – A
(Multiple Choice Type Questions)

1. Choose the correct alternatives for any *ten* of the following:

i) In SCR, the latching current is
✓a) equal to holding current
b) greater than holding current
c) less than holding current
d) twice the holding current

ii) If gate current of SCR is increased, then forward break over voltage will be
a) increased ✓b) decreased c) remain same d) reduced to zero

iii) In a three-phase semi-converter, the three SCRs are triggered at an interval of
a) 60° b) 90° ✓c) 120° d) 180°

iv) Chopper control of DC motor provides variation in
✓a) input voltage b) current c) frequency d) all of these

v) The range of firing angle control for RC firing circuit is
✓a) 0° to 90° b) 0° to 180° c) 90° to 180° d) 180° to 360°

vi) In an SCR, the magnitude of anode current will
a) increase if gate current is increased
b) decrease if gate current is decreased
c) increase if gate current is decreased
✓d) remain unchanged with any variation in gate current

vii) PWM is used in inverters
a) to control output voltage
b) to reduce harmonics in output
c) to compensate the variation in d.c. input
✓d) all of these

viii) In a commutation circuit employed to turn off an SCR, satisfactory turn off is obtained when
a) circuit turn off time < device turn off time
✓b) circuit turn off time > device turn off time
c) circuit time constant > device turn off time
d) circuit time constant < device turn off time

ix) In a 3-phase 180° mode bridge inverter, the lowest order harmonics in the line to neutral output voltage (fundamental frequency output = 50 Hz) is
✓a) 100 Hz
b) 150 Hz
c) 200 Hz
d) 250 Hz

x) A chopper, in which current remains positive but the voltage may be positive or negative, is known as
a) Type-*A*
✓b) Type-*B*
c) Type-*C*
d) Type-*D*

xi) Presence of drift layer in a power semi-conductor device
a) increases breakdown voltage rating
b) increases on state current rating
c) increases switching speed
✓d) decreases on state resistance

xii) The reverse recovery characteristics of a power diode is due to
✓a) stored change is depletion layer
b) stored change in semiconductor layers
c) stored charge in both depletion and semi-conductor layers
d) forward current

Group – B
(Short Answer Type Questions)

2. Explain with relevant waveforms, the principle of operation of an RC triggering circuit.
See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Short Answer Type Question No. 1.

3. With the help of relevant circuit diagram and waveforms distinguish between voltage commutation and current commutation in an SCR circuit.
See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Short Answer Type Question No. 8.

4. Compare the merits & demerits of BJT, MOSFET and IGBT as power electronics switch.
See Topic: INVERTER, Short Answer Type Question No. 3.

5. A 3-phase bridge inverter is fed from 200 V d.c. source. The inverter is operated in 180° conduction mode and it is supplying inductive, star connected load with $R = 10\Omega$ and $L = 20$ mH. The inverter frequency is $f_0 = 50$ Hz. Determine,

i) instantaneous line to line voltage and line current
ii) RMS phase voltage and RMS line voltage.

See Topic: INVERTER, Short Answer Type Question No. 4.

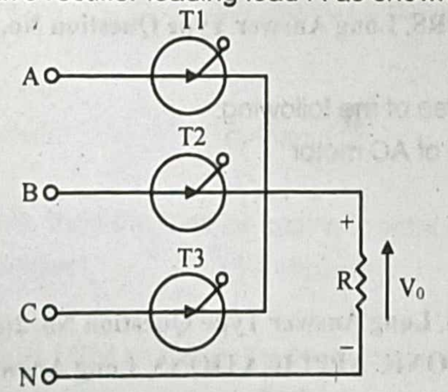
6. Briefly explain any method to control the output voltage and harmonic reduction in the inverter.
See Topic: INVERTER, Long Answer Type Question No. 7.

Group – C
(Long Answer Type Questions)

7. a) Discuss with appropriate circuit diagram, the principle of operation of a three-phase bridge inverter connected with star connected resistive load. The period of conduction of each SCR is 180°. Draw phase and line voltage waveforms of the load. The sequence of firing of various SCRs should also be indicated in the diagram.
See Topic: INVERTER, Long Answer Type Question No. 6.a).

b) Explain the working of a resonant pulse inverter.
See Topic: INVERTER, Long Answer Type Question No. 6.b).

8. a) For a 3-ϕ controlled half-wave rectifier leading load R as shown in the figure,



Draw the waveforms for the output voltages for both conditions given below and also show that the average output voltage are given by $V_0 = \begin{cases} \dfrac{3\sqrt{3}}{2\pi} V_{mp} \cos(\alpha); \text{ for } 0 < \alpha < \dfrac{\pi}{6} \\ \dfrac{3}{2\pi} V_{mp} \left[1 + \cos\left(\alpha + \dfrac{\pi}{6} \right) \right]; \text{ for } \dfrac{\pi}{6} < \alpha < \dfrac{5\pi}{6} \end{cases}$

where V_{mp} is the maximum value of phase voltage and α is the firing angle delay.

b) A single-phase half-wave controlled converter is operated from a 120 V, 50 Hz supply. Load resistance $R = 10\Omega$. If the average output voltage is 25% of the maximum possible average output voltage, determine: (i) firing angle, (ii) r.m.s. and average output current, (iii) average and r.m.s. SCR current.
See Topic: PHASE CONTROLLED RECTIFIERS, Long Answer Type Question No. 9(a) & (b).

9. a) With the help relevant circuit diagram and waveform, explain the principle of operation of DC-DC step down regulator. Deduce the expression of average and RMS value of output voltage.
See Topic: DC-DC CONVERTERS, Long Answer Type Question No. 4.c).

b) For type *A* chopper, d.c. source voltage $= 200$ V, load resistance $= 15\Omega$. Assume a voltage drop of 1 V across the chopper when it is on. For a duty cycle of 0.4 and chopping frequency 1 kHz, calculate (i) average and r.m.s. values of output voltage, (ii) chopper efficiency, (iii) effective input resistance of the chopper.
See Topic: DC-DC CONVERTERS, Long Answer Type Question No. 9.

10. a) What is a cycloconverter? What benefits does it offer in comparison to inverter?
See Topic: CYCLOCONVERTERS, Short Answer Type Question No. 1 & 2.

b) With the help of schematic diagram and relevant waveforms, explain the operation of 3-phase to 1-phase cycloconverter.
See Topic: CYCLOCONVERTERS, Long Answer Type Question No. 1.

c) What do you mean by blocked group operation and circulating current mode operation of a cycloconverter?
See Topic: CYCLOCONVERTERS, Long Answer Type Question No. 3(a).

11. Write short notes on any *three* of the following:
   a) Speed control technique of AC motor
   b) Static circuit breaker
   c) HVDC transmission
   d) Static VAR controller.

a) See Topic: DC & AC DRIVES, Long Answer Type Question No. 2(a).
b) See Topic: POWER ELECTRONIC APPLICATIONS, Long Answer Type Question No. 2(e).
c) See Topic: POWER ELECTRONIC APPLICATIONS, Long Answer Type Question No. 2(a).
d) See Topic: POWER ELECTRONIC APPLICATIONS, Long Answer Type Question No. 2(c).

QUESTION 2018

Group – A
(Multiple Choice Type Questions)

1. Answer any ten questions:

i) In an SCR holding current is
a) equal to latching current
✓b) less than latching current
c) more than latching current
d) not related to latching current

ii) Which of the following is not a current triggering device?
a) thyristor
b) GTO
c) Triac
✓d) MOSFET

iii) In a load commutated DC – DC chopper, the capacitor has a
a) symmetric triangular voltage across itself
b) symmetric rectangular voltage across itself
✓c) symmetric trapezoidal voltage across itself
d) symmetric sinusoidal voltage across itself

iv) A full wave rectifier with resistive load produces
a) second harmonic
b) third harmonic
c) fifth harmonic
✓d) do not produce harmonics

v) TRIAC is a semiconductor power electronic device with contains
✓a) two SCR's connected in reverse parallel
b) two SCR's connected in parallel
c) two SCR's connected in series
d) two BJT's connected in series

vi) In the SPWM, the modulating signal is
a) square
✓b) sinusoidal
c) triangular
d) saw-tooth

vii) If the firing angle becomes negative, then the rectifier begins to work as
a) a rectifier
✓b) an inverter
c) a chopper
d) a regulator

viii) A step up chopper has input voltage 110V and output voltage 150V. The value of duty cycle is
✓a) 0.26
b) 0.45
c) 0.56
d) 0.78

ix) In dual converters
a) both rectifiers provides positive current to the load
b) both rectifiers provide negative current to the load
✓c) one rectifiers provide positive current to the load and the other negative current
d) one rectifier provide positive current to the source and the other negative current to the load

x) Advantages of HVDC transmission over AC system is / are
- a) reversal of power can be controlled by firing angle
- b) very good dynamic behavior
- c) they can link two AC system operating unsynchronized
- ✓d) all of these

xi) In continuous conduction of a single-phase semi-converter each thyristor conducts for
✓a) $\Pi - \alpha$ b) $\Pi + \alpha$ c) β d) α

xii) UJT has negative resistance region
✓a) between peak and valley points b) before the peak point
c) after the valley point d) both (b) and (c)

Group – B
(Short Answer Type Questions)

2. Prove that $T_{off} = 0.693RC$ of complementary commutation.

See Topic: COMMUTATIONS, Short Answer Type Question No. 5.

3. What is cyclo-converter? Explain the operation of a single phase step down cyclo-converter.
See Topic: CYCLOCONVERTER, Short Answer Type Question No. 6.

4. A thyristor is used to feed a load resistance 10Ω from a 215V single phase supply. The rating of thyristerors are: Repetitive peak current = 200A, (di/dt) max = 40A/μs and (dv/dt) max = 150V/μs. Design a snubber circuit for protection of thyristor.
See Topic: SCR PROTECTION AND SERIES-PARALLEL OPERATION, Short Answer Type Question No. 3.

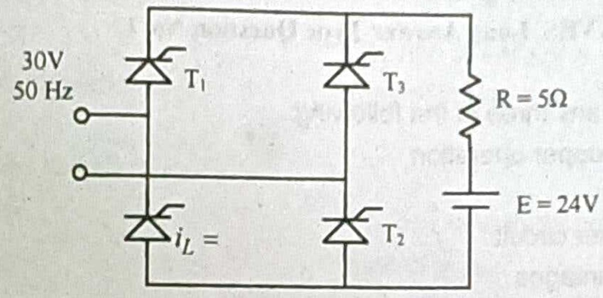
5. Explain the operation of buck-boost chopper with necessary calculation.
See Topic: DC-DC CONVERTERS (CHOPPERS), Short Answer Type Question No. 2.

6. With the help of circuit diagrams explains the principles of operation of step-up/down chopper.
See Topic: DC-DC CONVERTERS (CHOPPERS), Short Answer Type Question No. 5.

Group – C
(Long Answer Type Questions)

7. a) Explain the operation of a single phase half controlled bridge converter connected with R-L load. Show the possible waveforms of output voltage, load current, SCR current for a firing angel and considering ripple free output current.
b) Derive expressions for average and rms value of output voltage for the converter mentioned in (a).
See Topic: PHASE CONTROLLED RECTIFIERS, Long Answer Type Question No. 13(a) & (b).

c) A battery is charged by a fully controlled single phase converter as shown in fig. The input supply is 30V at 50 Hz. The load consists of a 24V battery and a resistance of 5Ω connected in series to limit the current. What is the minimum possible firing angel? Compute the value of average output voltage.



See Topic: **PHASE CONTROLLED RECTIFIERS, Short Answer Type Question No. 1.**

8. a) Explain the principle of working of a 3 phase bridge inverter with star connected resistive load. Assume 180° mode of conduction. Also draw the triggering sequence of each SCR, waveform of phase & line voltages.
See Topic: **INVERTERS, Long Answer Type Question No. 1.**

b) How this inverter is used for a full bridge switched mode power supply?
See Topic: **INVERTERS, Long Answer Type Question No. 9.**

9. a) Explain with suitable circuit diagram & waveform of load voltage & load current, the operation of a class C chopper feeding a load. Derive the expression for minimum and maximum load current considering a RLE load.
b) A class B chopper is supplying the armature of a separately excited dc motor with following parameters. V = 110v(dc), E_b = 40v, L_a = 0.2mh, R_a = 0.25Ω, f = chopper frequency = 400Hz, Duty cycle = 0.5. Calculate
(i) Average armature voltage & current
(ii) Maximum & minimum value of instantaneous armature current.
See Topic: **DC-DC CONVERTERS (CHOPPERS), Long Answer Type Question No. 10.**

10. a) What is a cycloconverter? What are the advantages & disadvantages of it over an inverter?
See Topic: **CYCLOCONVERTERS, Short Answer Type Question No. 7.**

b) With the help of circuit diagram and waveforms, describe the principle of operation of a single phase converter.
See Topic: **PHASE CONTROLLED RECTIFIERS, Short Answer Type Question No. 4.**

c) What do you mean by blocked group operation & circulating current mode operation of a cycloconverter?
See Topic: **CYCLOCONVERTERS, Long Answer Type Question No. 2(a).**

11. a) Explain different PWM methods of control output voltage of an inverter.
See Topic: INVERTERS, Long Answer Type Question No. 2.

b) Discuss constant (v/f) method of speed control of an induction machine.
See Topic: DC & AC DRIVES, Long Answer Type Question No. 1.

12. Write short notes on any three of the following:
- a) Four quadrant chopper operation
- b) Dual converter
- c) Resonant converter circuit
- d) GTO and its advantages
- e) Triac & its applications.

a) See Topic: DC-DC CONVERTERS (CHOPPERS), Short Answer Type Question No. 11(b).
b) See Topic: PHASE CONTROLLED RECTIFIERS, Long Answer Type Question No. 4(b).
c) See Topic: CONVERTER OPERATION, Long Answer type Question No. 2(a).
d) See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Long Answer Type Question No. 3(a).
e) See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Long Answer Type Question No. 3(g).

QUESTION 2019

Group – A
(Multiple Choice Type Questions)

1. Choose the correct alternatives for any *ten* of the following:

i) The advantage of an 180° conduction three phase inverter over an 120° conduction three phase inverter is
- a) it needs less number of switches
- b) there is no paralleling of switches
- ✓c) devices in series are not simultaneously switches
- d) load terminals are not left open during switches

ii) A freewheeling diode across inductive load of a phase-controlled converter will provide
- a) quick turn-on of SCR
- ✓b) slow turn-off of SCR
- c) reduced utilization factor of transformer
- d) improved power factor

iii) The switching frequency of a MOSFET will be reduced with
- a) an increase in the output impedance of the device
- ✓b) an increase in the discharge rate of the input capacitance
- c) an increase in the source resistance
- d) a decrease in the discharge rate of the input capacitance

iv) For a two-quadrant type-A chopper, regenerative braking is
a) possible at low speeds
b) possible at high speeds
✓c) possible at both high and low speeds
d) not possible at all

v) RC snubber circuit is used to limit rate of
a) rise of current in SCR
✓b) rise of voltage across SCR
c) rise of capacitance of depletion layer
d) all of these

vi) RC snubber circuit is used to limit rate of
a) rise of current in SCR
✓b) rise of voltage across SCR
c) conduction period
d) all of these

vii) Cyclo-converter is a
✓a) AC to AC converter
b) AC to DC converter
c) DC to AC converter
d) DC to DC converter

viii) The range of firing angle in case of RC firing circuit will be
✓a) 0° - 90°
b) 90° - 180°
c) 0° - 180°
d) 45° - 90°

ix) The output voltage waveform of a three phase square wave inverter contains
✓a) only odd harmonics
b) both odd and even harmonics
c) only even harmonics
d) only triplen harmonics

x) A 1-phase full bridge VSI has inductor L as load. For a constant voltage source, the current through the inductor is
a) square wave
✓b) triangular wave
c) sine wave
d) pulse wave

xi) The cyclo-converters (CCs) require
a) Natural commutation in both step-up and step-down CCs
b) Forced commutation in both step-up and step-down CCs
c) Forced commutation in step-down CCs
✓d) Forced commutation in step-up CCs

xii) Compared BJT, MOSFET has
a) low switching frequency and low conduction loss
b) high switching frequency and low conduction loss
✓c) high switching frequency and high conduction loss
d) low switching frequency and high conduction loss

Group – B
(Short Answer Type Questions)

2. Describe the effect of source inductance on the output voltage of a single phase full controlled bridge converter.
See Topic: CONVERTER OPERATION, Short Answer Type Question No. 1.

3. What is snubber circuit? Why snubber circuit are used in thyristor circuit?
See Topic: SCR PROTECTION AND SERIES-PARALLEL OPERATION, Short Answer Type Question No. 2.

4. Briefly describe the working of class B chopper with diagram.
See Topic: DC-DC CONVERTERS (CHOPPERS), Short Answer Type Question No. 4.

5. A thyristor is used to feed a load resistance 8 ohms from a 230 V single phase supply. The ratings of thyristors are repetitive peak current = 200 A, $\left(\frac{di}{dt}\right)\max = 40$ A/µs and $\left(\frac{dv}{dt}\right)\max = 150$ V/µs. Design a snubber circuit for protection of thyristor.
See Topic: SCR PROTECTION AND SERIES-PARALLEL OPERATION, Short Answer Type Question No. 1.

6. What is cycle-converter? Explain the operation of a single phase step-up cyclo-converter.
1st Part: See Topic: CYCLOCONVERTERS, Short Answer Type Question No. 1.
2nd Part: See Topic: CYCLOCONVERTERS, Short Answer Type Question No. 3.

Group – C
(Long Answer Type Questions)

7. a) Describe the different modes of operation of thyristor using static V-I characteristics. What is the effect of gate current on this characteristic?
b) With two transistor analogy explain how a small gate current can turn-on a SCR.
c) What is the necessity of connecting SCRs in series? What are the problem associated with series connection of SCRs? How are they eliminated?
a) See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Short Answer Type Question No. 2.
b) See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Long Answer Type Question No. 2(c).
c) See Topic: SCR PROTECTION AND SERIES-PARALLEL OPERATION, Long Answer Type Question No. 2.

8. a) What is the difference between semi-converter and full converter?
b) A single-phase fully controlled bridge converter is supplied from 230 V, 50 Hz ac supply and fed to a load which consists of $R = 20\Omega$ and large inductance, so that load current is constant and ripple free. If the firing angle is 30° find the
i) average and rms of load voltage
ii) average and rms of thyristor current
iii) average and rms of source current and
iv) input power factor
c) A three-phase half wave-controlled rectifier connected across R load. Draw the output voltage and phase current waveforms. And also find out the expression of average output voltage at a firing angle of ∞ [where, $0 < \infty < \frac{\pi}{6}$]
See Topic: PHASE CONTROLLED RECTIFIERS, Long Answer Type Question No. 11(a), (b) & (c).

9. a) Derive the expression for ripple of inductor current for dc to dc buck converter. And also find out the value of duty cycle at which the ripple will be maximum.
b) Draw and explain a DC-DC boost converter. Derive an expression for average output voltage.
c) A step-down chopper has a resistive load of $R = 10\Omega$ and input voltage of 120V, when the chopper is turned on, its voltage drop is 2V. The chopper frequency is 1 kHz. If the duty cycle is 40% determine
i) Average output voltage
ii) RMS output voltage
iii) Efficiency of chopper.

See Topic: DC-DC CONVERTERS (CHOPPERS), Long Answer Type Question No. 11(a), (b) & (c).

10. a) State the comparison between voltage source inverter (VSI) and current source inverter (CSI).
b) Draw the appropriate circuit diagram of three-phase bridge inverter connected to star connected resistive load and explain the operation with the help of phase voltage, line voltage and gate pulse waveforms for 120° conduction mode.
c) A three-phase inverter is supplied from a 580 V source. For a star connected resistive load of 20 Ω per phase, for 120° conduction. Determine the
i) rms value of phase voltage
ii) rms value of thyristor current
See Topic: DC-DC CONVERTERS (CHOPPERS), Long Answer Type Question No. 10(a), (b) & (c).

11. Write short notes on any *three* of the following:
a) Turn on methods of thyristor
b) Complementary commutation
c) Effect of source inductance for 2-pulse converter
d) Sinusoidal PWM

e) Schottky barrier diode
f) Two-Quadrant chopper

a) See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Long Answer Type Question No. 3(h).
b) See Topic: COMMUTATIONS, Short Answer Type Question No. 1.
c) See Topic: CONVERTER OPERATION, Long Answer Type Question No. 2(b).
d) See Topic: INVERTERS, Long Answer Type Question No. 11.
e) See Topic: INTRODUCTION TO SEMICONDUCTOR DEVICES, Long Answer Type Question No. 3(i).
f) See Topic: DC-DC CONVERTERS (CHOPPERS), Long Answer Type Question No. 12(c).