Fifth Semester(CBCS)
B.E. Degree Examination

POWER ELECTRONICS
Solution

Module 1

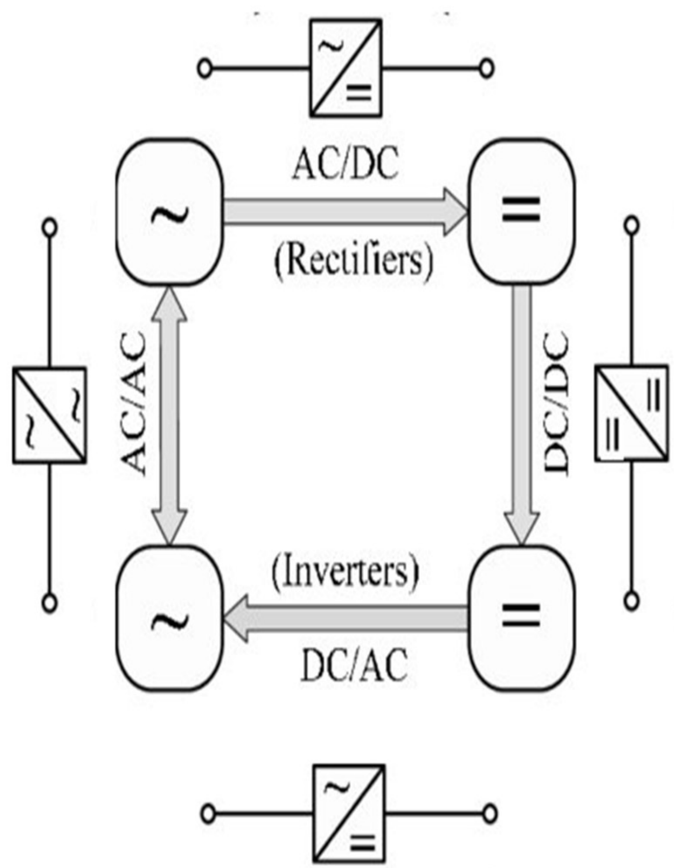
- Q1.a.

- **With the help of neat block diagram explain the power electronic converters. (10 marks)**

Types of Power Electronics

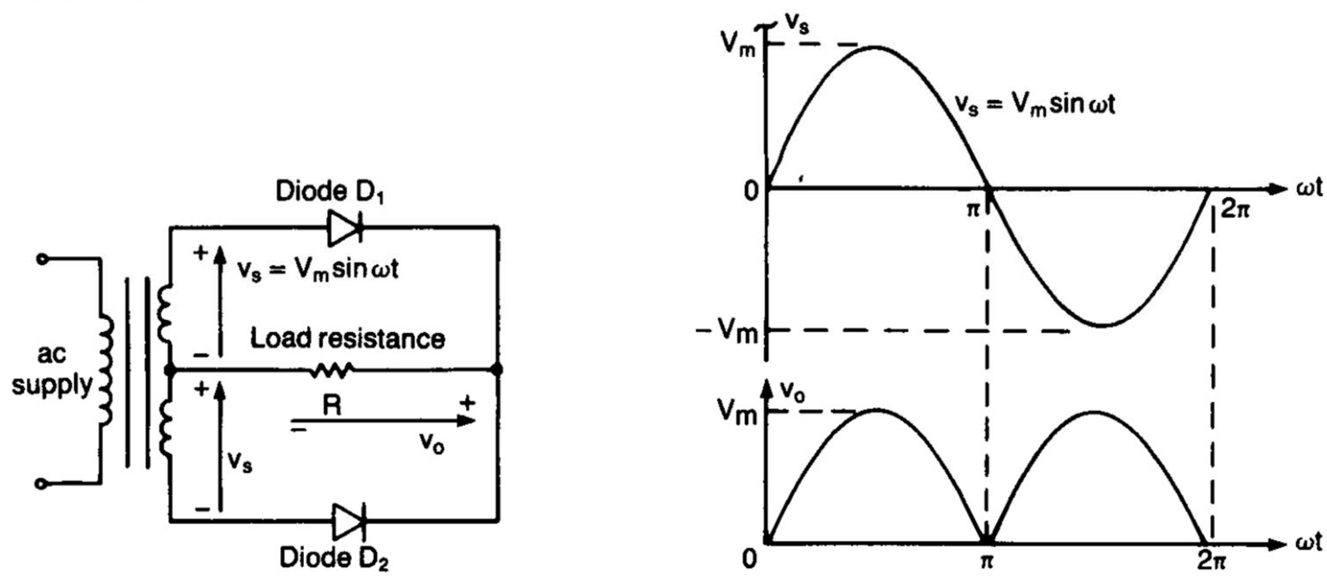
The power electronics circuits can be classified into six types:

1. Diode rectifiers
2. Ac–dc converters (controlled rectifiers)
3. Dc–dc converters (dc choppers)
4. Dc–ac converters (inverters)
5. Ac–ac converters (ac voltage controllers)
6. Static switches



1. Diode rectifiers

- **It converts AC Voltage into a FIXED DC**

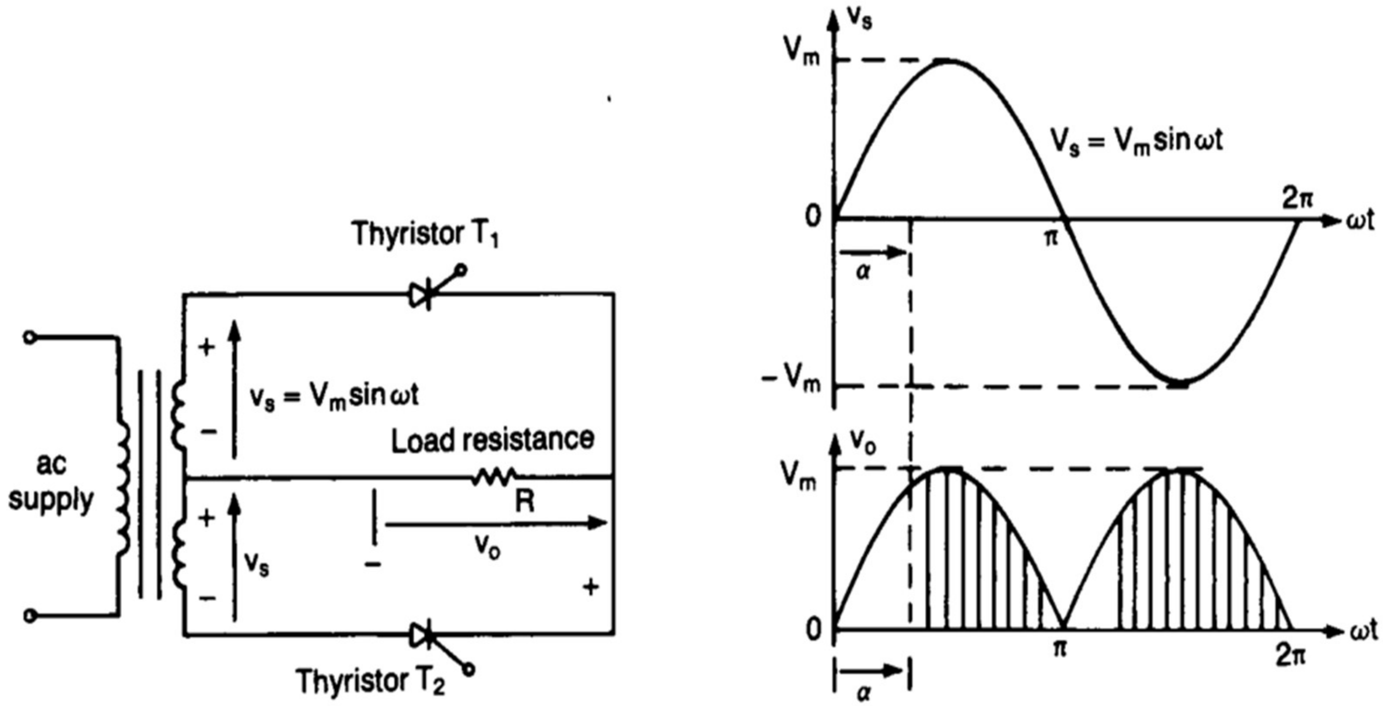


(a) Circuit diagram (b) Voltage waveforms

- Converts fixed ac voltage into fixed dc voltage
- Input could be either single or three phase
- Example circuit for single phase diode rectifier is shown

Ac–dc converters (controlled rectifiers)

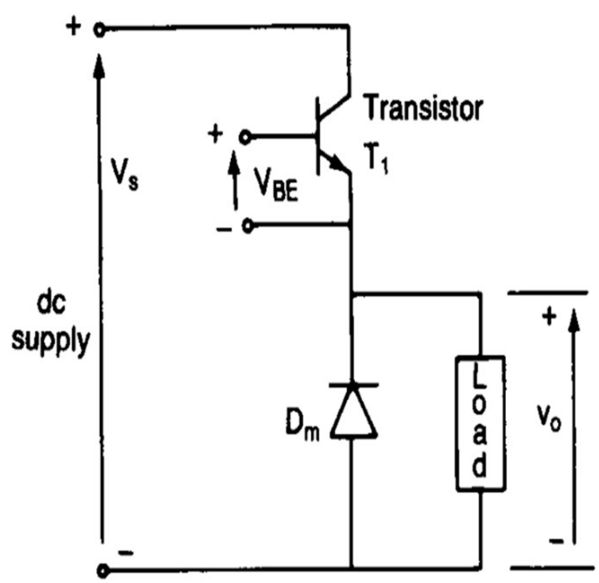
- **A single-phase** converter with two natural commutated thyristor is shown
- Average value of the output voltage can be controlled by varying the conduction time of thyristors
- This converters are also known as *controlled rectifiers*



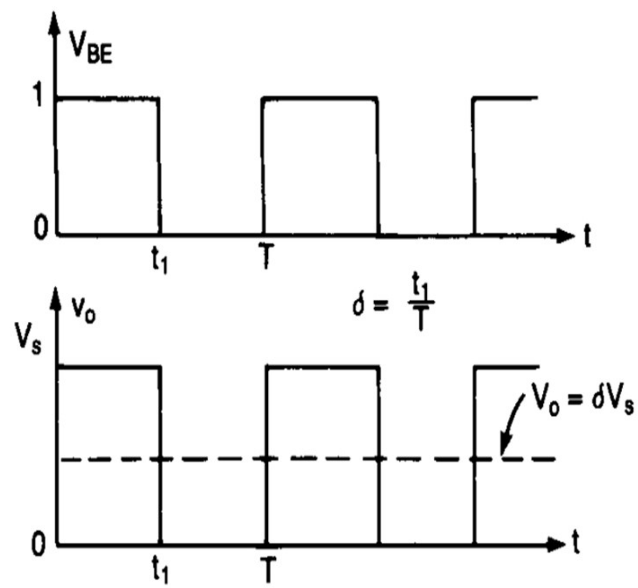
(a) Circuit diagram (b) Voltage waveforms

Dc–dc converters (dc choppers)

- Is also known as Chopper or Switching Regulator
- The average output voltage is controlled by varying the conduction of transistor, t1 .
- If T is the chopping period, then t1=δT
- δ is called as the duty cycle of chopper



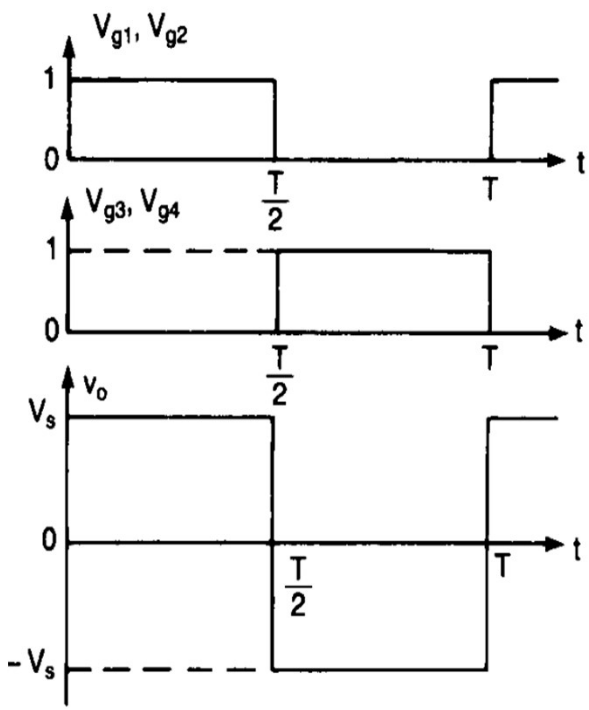
(a) Circuit diagram



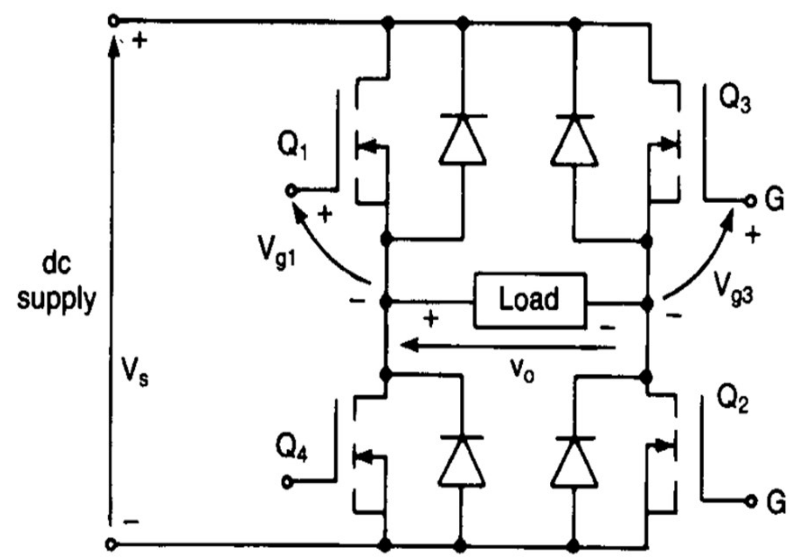
(b) Voltage waveforms

DC-AC Converters

- Is also known as Inverter
- If transistor Q1 and Q2 conduct for one-half period and Q3 and Q4 conduct the other half, the output voltage is of alternating form
- Fixed dc voltage to variable ac voltage
- Voltage control is obtained by controlling duty cycle
- Also known as inverter



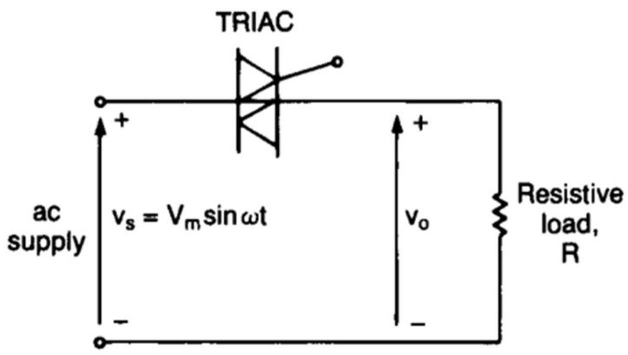
(b) Voltage waveforms



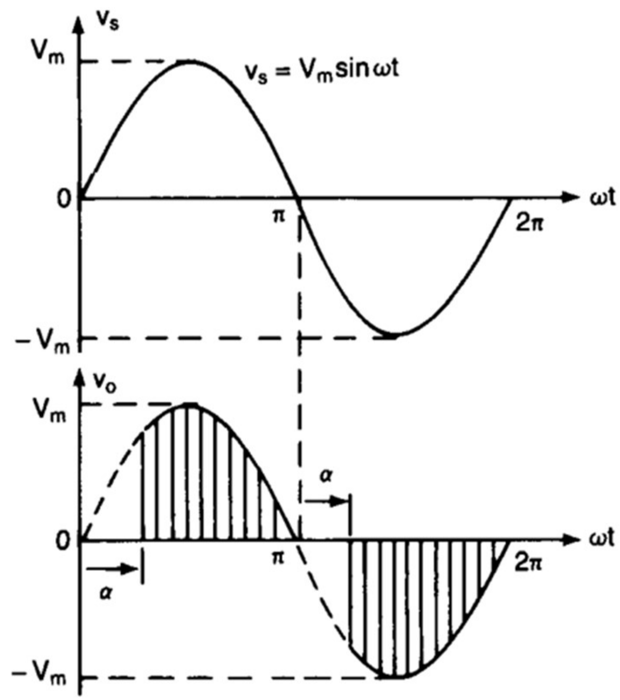
(a) Circuit diagram

AC-AC Converters

- AC Voltage Controller / Cyclo Converter
- **Fixed AC source** into **variable AC** output voltage
- a single-phase converter with a TRIAC is shown below



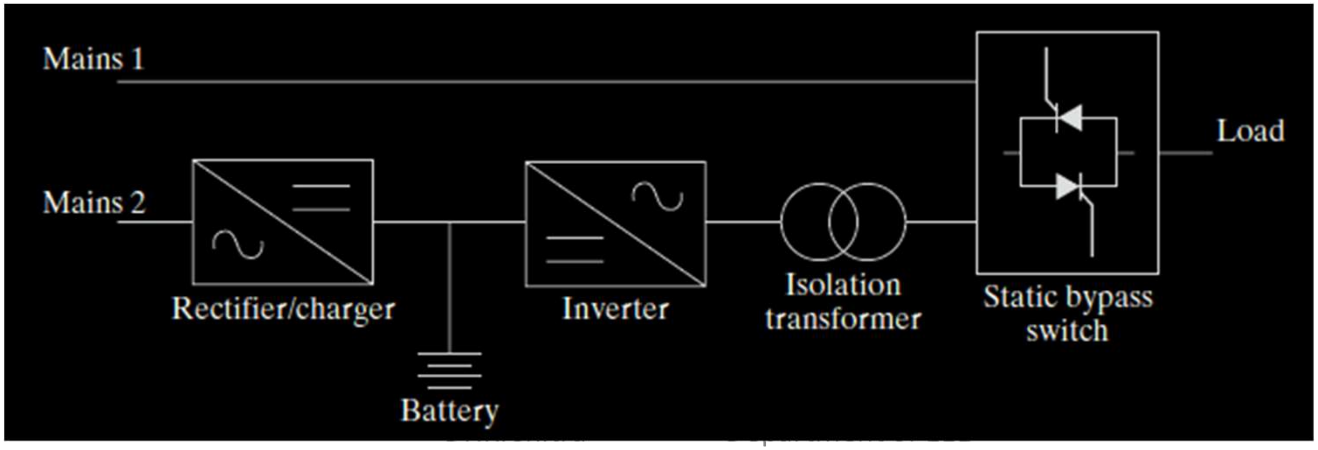
(a) Circuit diagram



(b) Voltage waveforms

Static Switches

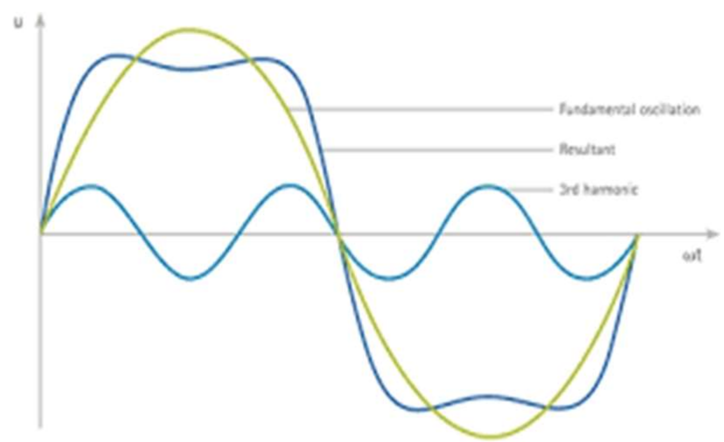
- Power devices can be operated as static switches or contactors
- Supply to these switches could **be either AC or DC**
- **The switches are called as *AC static switches or DC switches***
- Power electronic devices used as static switches in an UPS shown
- Mains 1 and 2 are connected to same supply
- Mains 1 supplies the load thro static bypass switch
- The rectifier charges the battery from Mains 2.
- The inverter supplies the emergency power to the load



Q1.b

- **Explain the peripheral effects caused by power electronic converters and remedies for them. (5 marks)**

Harmonics



Harmonics

- **Harmonics** are unwanted higher frequencies which superimposed on the fundamental waveform (50 Hz) creating a distorted wave pattern.
- **Harmonic** is a
  - voltage or current waveforms at a multiple of the fundamental frequency of the system,
  - produced by the action of non-linear loads such as rectifiers, discharge lighting, or saturated magnetic devices.
- "harmonics" are multiples of the fundamental frequency f and can therefore be expressed as: $2f, 3f, 4f$, etc.

Effects of Harmonics

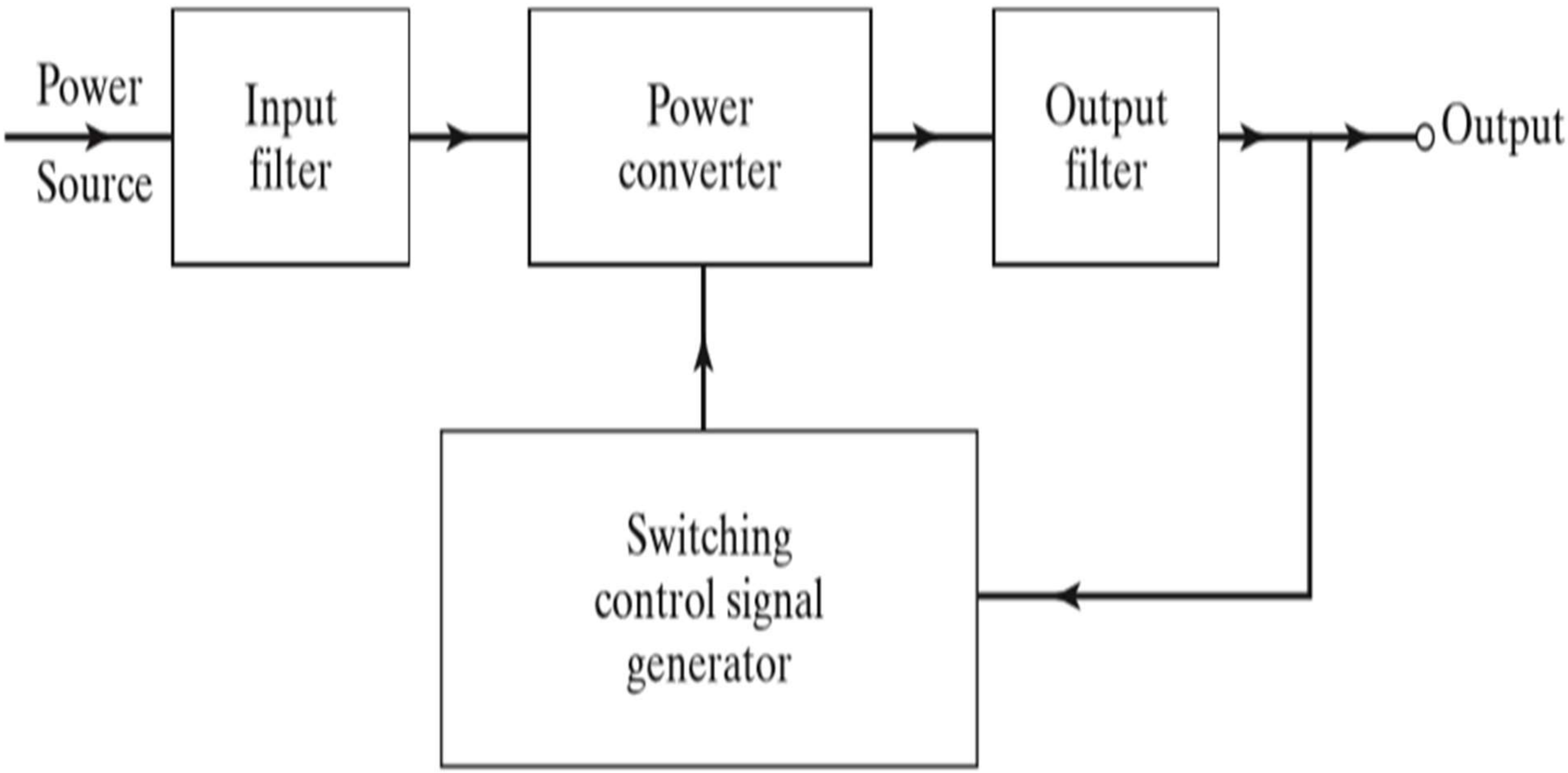
The operations of the power converters are based mainly on the switching of power semiconductor devices

- As a result the converters **introduce current and voltage harmonics into the supply system and on the output of the converters.** These can cause
  - **Problems of distortion of the output voltage and current**
  - **harmonic generation into the supply system**
  - **Interference with the communication and signalling circuits.**
  - Harmonic frequencies in the power grid are a frequent cause of power quality problems.
  - Increased heating in the equipment and conductors
  - Misfiring in variable speed drives
  - Torque pulsations in motors.

Need for Filter

- It is normally necessary to introduce filters on the input and output of a converter system to reduce the harmonic level to an acceptable magnitude.

Generalized Power Converter System

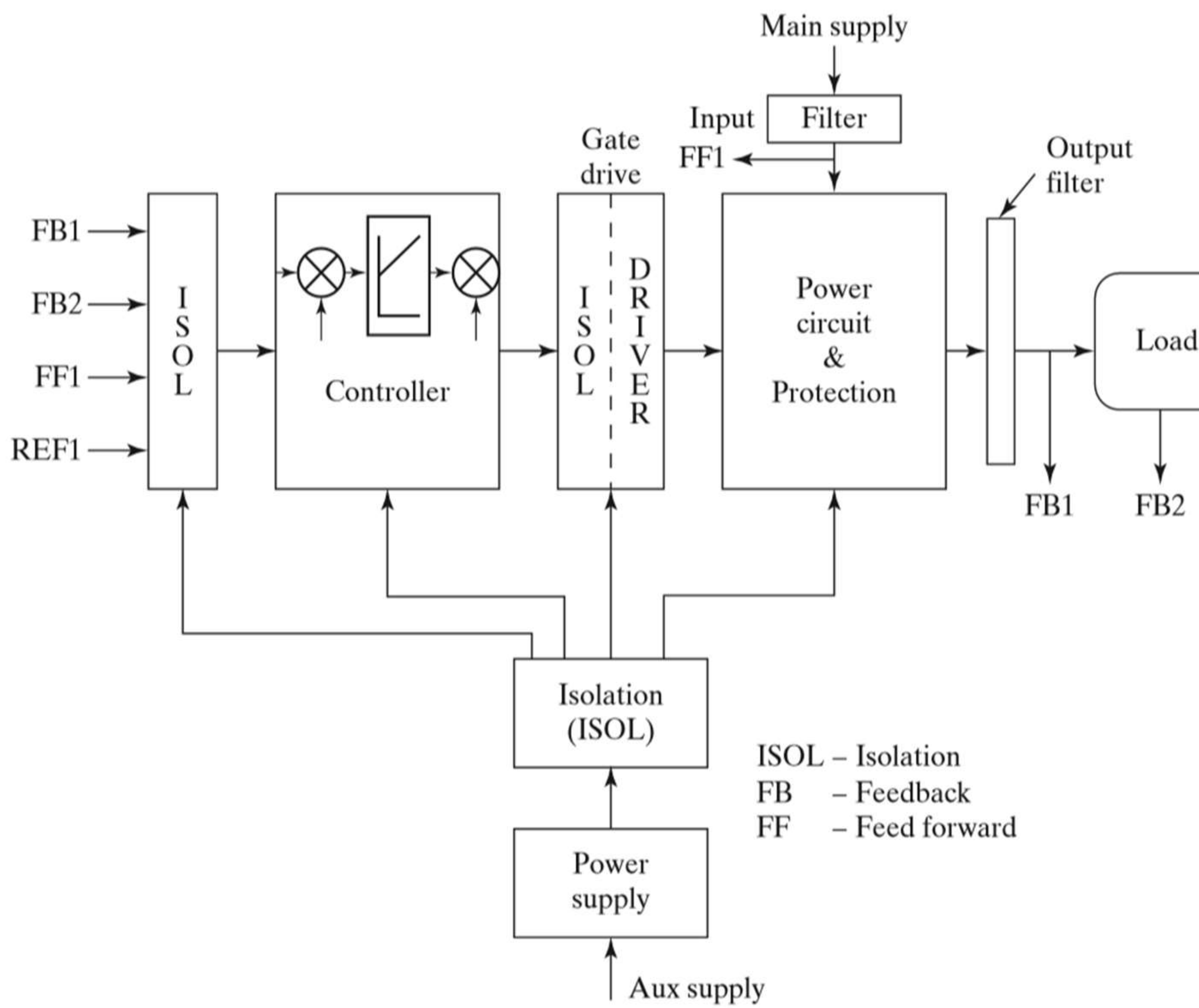


- The application of power electronics to supply the sensitive electronic loads poses a challenge on the power quality issues and raises problems and concerns to be resolved by researchers.
- The input and output quantities of converters could be either ac or dc.
- Factors such as total harmonic distortion (THD), displacement factor (DF), and input power factor (IPF) are measures of the quality of a waveform.
- To determine these factors, finding the harmonic content of the waveforms is required.
- To evaluate the performance of a converter, the input and output voltages and currents of a converter are expressed in a Fourier series.

- The quality of a power converter is judged by the quality of its voltage and current waveforms.

- The control strategy for the power converters plays an important part on the harmonic generation and output waveform distortion, and can be aimed to minimize or reduce these problems.
- The power converters can cause radio-frequency interference due to electromagnetic radiation, and the gating circuits may generate erroneous signals.
- This interference can be avoided by grounded shielding.
- AS shown in above Figure, power flows from the source side to the output side.
- The waveforms at different terminal points would be different as they go through processing at each stage.
- It should be noted that there are two types of waveforms: one at the high power level and another from the low-level signal from the switching or gate control generator.
- These two voltage levels must be isolated from each other so that they do not interfere with each other.

Block diagram of a typical power converter including isolations, feedback, and reference signals



Q1. c (5 marks)

- **List the various types of power diodes indicating the differences.**

Types of Power Diodes

- Depending on the recovery characteristics, on state drop and manufacturing techniques, the power diodes can be classified into the following categories:

1. General-purpose diodes or Standard diodes
2. Fast-recovery diodes
3. Schottky diodes

Special Diodes

4. Silicon Carbide Diodes
5. Silicon Carbide Schottky Diodes
6. Freewheeling diodes

1. General-Purpose Diodes (standard diodes)

- General-purpose diodes are available up to 5000 V, 4500 A
- The general-purpose rectifier diodes have relatively high reverse recovery time trr, typically 25 μs
- Used in low-speed applications, where recovery time is not critical
- (e.g., diode rectifiers and converters for a low-input frequency up to 1-kHz applications and line-commutated converters).
- Current ratings from less than 1 A to several thousands of amperes
- Voltage ratings from 50 V to around 5 kV.
- These diodes are generally manufactured by diffusion.

2. Fast-Recovery Diodes

- The fast-recovery diodes have low recovery time, normally less than 5μs.
- They are used in dc–dc and dc–ac converter circuits, where the speed of recovery is often of critical importance.
- Voltage rating from 50 V to around 3 kV
- Current rating less than 1 A to hundreds of amperes.
- For voltage ratings above 400 V, fast-recovery diodes are generally made by diffusion and the recovery time is controlled by platinum or gold diffusion.
- For voltage ratings below 400 V, epitaxial diodes provide faster switching speeds than those of diffused diodes.
- The epitaxial diodes have fast recovery time of as low as 50 ns.

3. Schottky Diodes

- **Schottky Diode** or **Schottky barrier diode** or **hot-carrier diode**, is a semiconductor **diode** formed by the junction of a semiconductor with a metal.
- It has a low forward voltage drop and a very fast switching action.
- *Schottky diodes* are constructed of a *metal*-to-N junction rather than a P-N semiconductor junction.
- low reverse-recovery time
- low forward voltage drop (typically 0.25 to 0.4 volts for a metal-silicon junction)
- low junction capacitance.

Schottky Diodes

- The charge storage problem of a *pn*-junction can be eliminated (or minimized) in a Schottky diode.
- It is accomplished by setting up a “barrier potential” with a contact between a metal and a semiconductor.
- A layer of metal is deposited on a thin epitaxial layer of *n*-type silicon.
- The rectifying action depends on the majority carriers only, and as a result there are no excess minority carriers to recombine.
- The recovery effect is due to the **self capacitance of the semiconductor junction.**
- The recovered charge of a Schottky diode is much less than that of an equivalent *pn* junction diode. Because it is due only to the junction capacitance, it is largely independent of the reverse *di/dt*.
- A Schottky diode has a relatively low forward voltage drop.
- The leakage current of a Schottky diode is higher than that of a *pn*-junction diode.
- A Schottky diode with relatively low-conduction voltage has relatively high leakage current, and vice versa.
- As a result, the maximum allowable voltage of this diode is generally limited to 100 V.
- The current ratings of Schottky diodes vary from 1 to 400 A.
- The Schottky diodes are ideal for high-current and low-voltage dc power supplies.
- However, these diodes are also used in low-current power supplies for increased efficiency.

Advantages of Schottky diode

- The capacitance of the diode is low as the depletion region of the diode is negligible.
- The reverse recovery time of the diode is very fast, that is the change from ON to OFF state is fast.
- The current density of the diode is high as the depletion region is negligible.
- The turn-on voltage of the diode is 0.2 to 0.3 volts, which is very low.

Types of Power Diodes - Differences

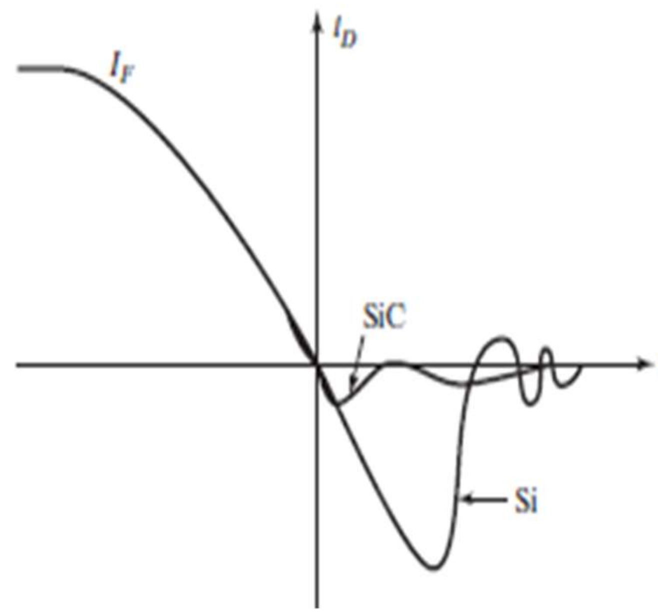
- **Line frequency** (general purpose):
  - On state voltage: very low (below 1V)
  - Large t_{rr} (about 25µs) (very slow response)
  - Very high current ratings (up to 5kA)
  - Very high voltage ratings(5kV)
  - Used in line-frequency (50/60Hz) applications such as rectifiers

- **Fast recovery**
  - Very low t_{rr} (<5µs).
  - Power levels at several hundred volts and several hundred amps
  - Normally used in high frequency circuits

- **Schottky**
  - Very low forward voltage drop (typical 0.3V)
  - Limited blocking voltage (50-100V)
  - Used in low voltage, high current application such as switched mode power supplies.

4. Silicon Carbide Diodes

- Silicon carbide (SiC) is a new material for power electronics.
- Its physical properties outperform S
  Arsenide GaAs by far.
- The typical storage charge *QRR* is
  - ✓21 nC for a 600-V, 6-A diode
  - ✓23 nC for a 600-V, 10-A device



- They have the following features:

➢ No reverse recovery time;

➢ Ultrafast switching behavior;

➢ No temperature influence on the switching behavior.

Advantages

- Low reverse recovery current.
- SiC power devices enable increased efficiency
- Reduced size
- higher switching frequency
- produce significant less electromagnetic interference (EMI) in a variety of applications.
- silicon-carbide diodes show four times better dynamic characteristics with 15% less forward voltage (V_F) than standard silicon diodes

Applications

- power supplies, solar energy conversion, transportations, and other applications such as welding equipment and air conditioners.

5. Silicon Carbide Schottky Diodes

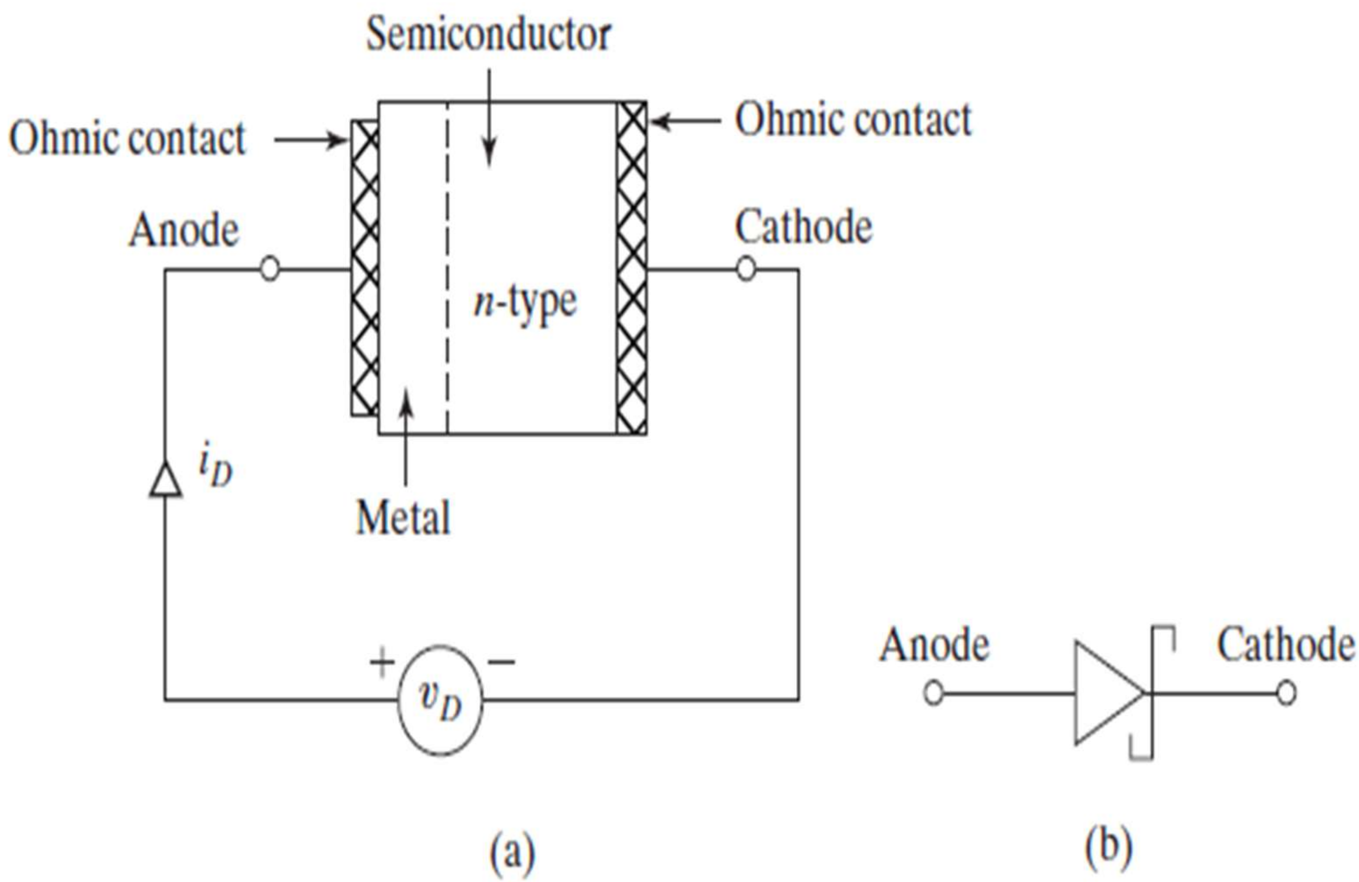
- Schottky diodes are used primarily in high frequency and fast-switching applications.
- Many metals can create a Schottky barrier on either silicon or GaAs semiconductors.
- A Schottky diode is formed by joining a doped semiconductor region, usually *n-type, with a metal such as gold, silver, or platinum.*
- *Unlike a pn-junction* diode, there is a metal to semiconductor junction.
- The Schottky diode operates only with majority carriers.
- There are no minority carriers and thus no reverse leakage current as in *pn-junction* diodes.
- The metal region is heavily occupied with conduction band electrons
- *n-type semiconductor region* is lightly doped.
- When forward biased, the higher energy electrons in the *n-region are injected into the metal region where they give* up their excess energy very rapidly.
- Since there are no minority carriers, it is a fast switching diode.

Features of SiC Schottky diodes

- Lowest switching losses due to low reverse recovery charge;
- Fully surge-current stable, high reliability, and ruggedness;
- Lower system costs due to reduced cooling requirements;
- Higher frequency designs and increased power density solutions.

- These devices also have low device capacitance that enhances overall system efficiency, especially at higher switching frequencies.

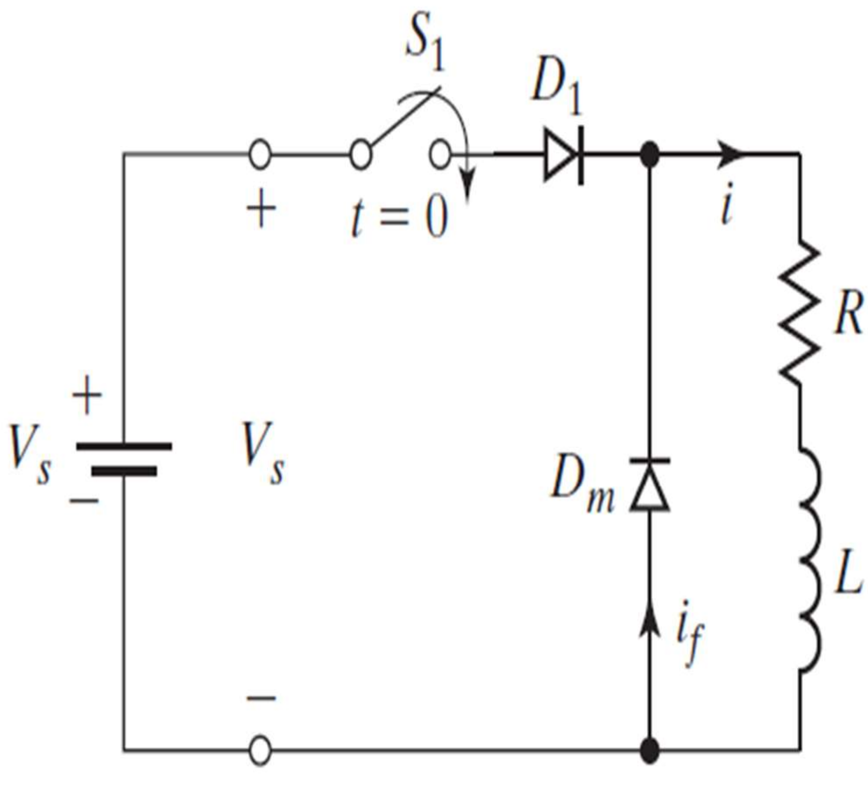
Basic Structure of Schottky Diodes



Freewheeling diodes

- A freewheeling diode is basically a diode connected across the inductive load terminals to prevent the development of high voltage across the switch.
- When the inductive circuit is switched off, this diode gives a short circuit path for the flow of inductor decay current and hence dissipation of stored energy in the inductor.
- This diode is also called Flywheel or Flyback diode.
- The main purpose of **freewheeling** or flyback **diode** is to free wheel the stored energy in inductor by providing a short **circuit** path.
- This is necessary else a sudden decay in **circuit** current will give rise to high voltage across the switch contacts and **diode**.

Freewheeling diodes with RL Load

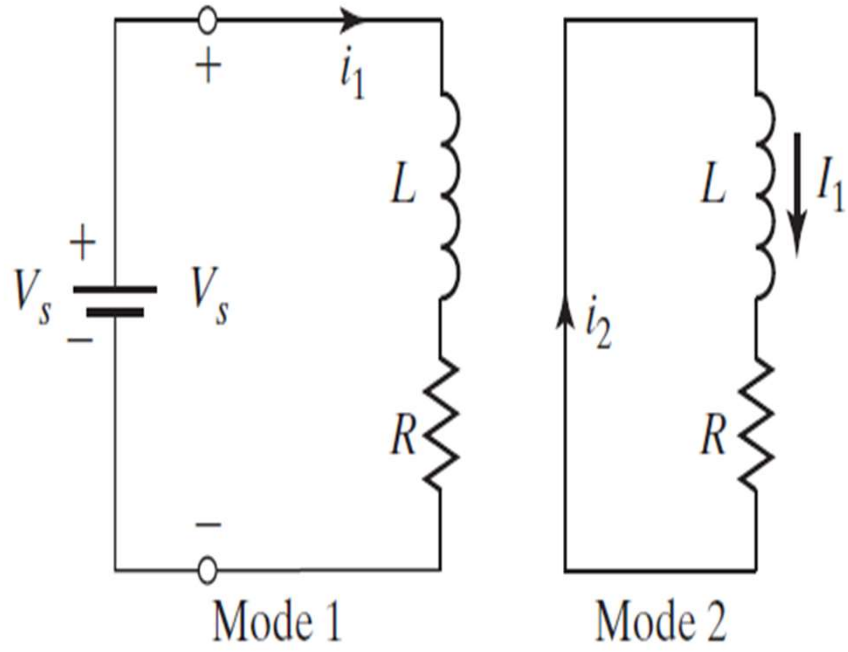


(a) Circuit diagram

- If switch $S1$ is closed for time $t1$, a current is established through the load;
- If the switch is opened, a path must be provided for the current in the inductive load.
- Otherwise, the inductive energy induces a very high voltage and this energy is dissipated as heat across the switch as sparks.
- This is normally done by connecting a diode *Dm* as shown in Figure, and this diode is usually called a *freewheeling diode*.
- Diode *Dm* is needed to prove a path for the inductive load current.
- Diode *D*1 is connected in series with the switch and it will prevent any negative current flow through the switch if there is an ac input supply voltage.
- But for dc supply, there is no need for *D*1.

D1 – Normal Diode

Dm – Freewheeling Diode



(b) Equivalent circuits

- The circuit operation can be divided into Two modes.
- Mode 1 begins when the switch is closed at $t = 0$
- Mode 2 begins when the switch is opened.
- The equivalent circuits for the modes are shown in Figure.
- Variables $i1$ and $i2$ are defined as the instantaneous currents for mode 1 and mode 2, respectively;
- $t1$ and $t2$ are the corresponding durations of these modes.

Mode 1

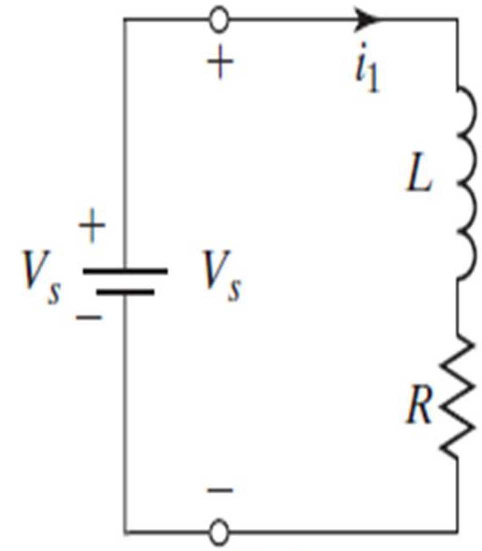
- Diode current i1

$$i_1(t) = \frac{V_s}{R}\left(1 - e^{-tR/L}\right)$$

- When the switch is opened at $t = t1$ (at the end of this mode),
- Diode current i1 at $t = t1$ becomes

$$I_1 = i_1(t = t_1) = \frac{V_s}{R}\left(1 - e^{-tR/L}\right)$$

- If the time $t1$ is sufficiently long, the current practically reaches a steady-state current of $Is = Vs/R$ flows through the load.



Mode 1

Mode 2

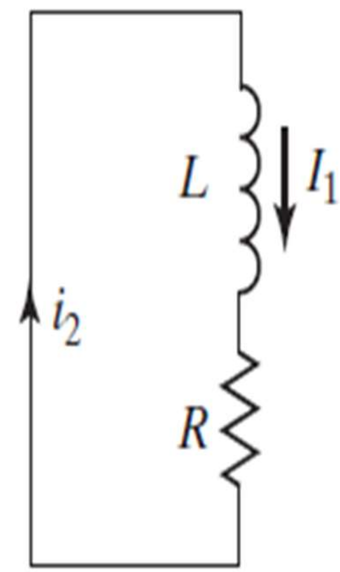
- This mode begins when the switch is opened and the load current starts to flow through the freewheeling diode *Dm*.
- Redefining the time origin at the beginning of this mode, th freewheeling diode is found f

$$0 = L\frac{di_2}{dt} + Ri_2$$

- with initial condition *i2 (t = t1) = I1.*
- *the freev i2 is given by*

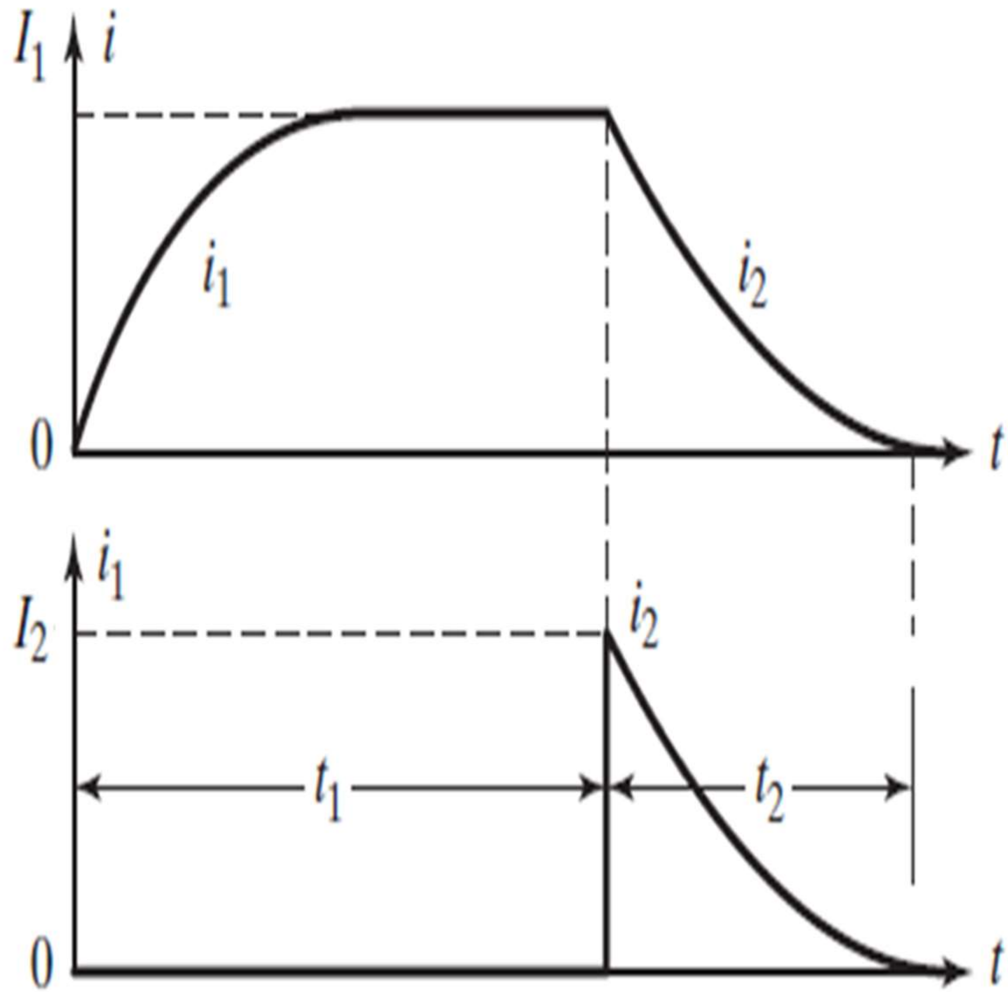
$$i_2(t) = I_1 e^{-tR/L}$$

- at *t = t2 this current decays exponentially to practically zero provided that t2 > L/R.*



Mode 2

Waveforms of Currents



(c) Waveforms

Q2. a

- **Describe reverse recovery characteristics of diode. (6 marks)**

Q2. a. Describe reverse recovery characteristics of diode. (6 marks)

Reverse Recovery Characteristics

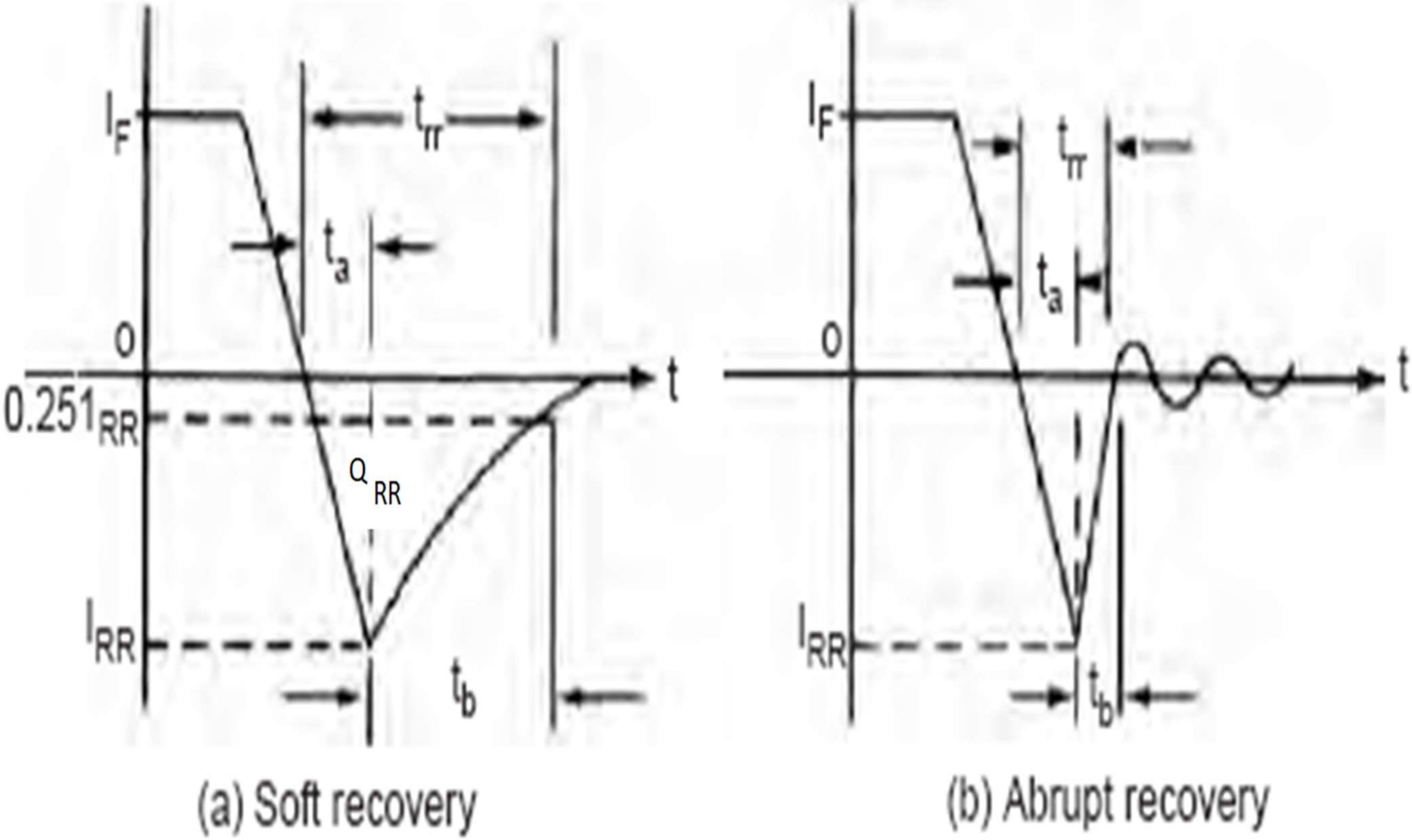
- The current in a forward-biased junction diode is due to the net effect of majority and minority carriers.
- Once a diode is in a forward conduction mode and then its forward current is reduced to zero (due to the natural behavior of the diode circuit or application of a reverse voltage), the diode continues to conduct due to minority carriers that remain stored in the pn-junction and the bulk semiconductor material.
- The minority carriers require a certain time to recombine with opposite charges and to be neutralized.
- This time is called the reverse recovery time of the diode.

There are two types of recovery:

- ✓ soft recovery
- ✓ hard (or abrupt) recovery.

The soft-recovery type is more common.

Reverse Recovery Characteristics



The Reverse recovery time t_{rr}

- The reverse recovery time trr is measured from the initial zero crossing of the diode current to 25% of maximum (or peak) reverse current IRR.

- During the changeover from forward conduction to reverse blocking condition

The trr consists of two components, ta and tb.

✓ Parameter t_a is the interval between the initial zero crossing of the diode current and peak (maximum) reverse current I_{RR}. ta is due to charge storage in the depletion region of the junction

✓ Parameter t_b is the time interval between the maximum reverse recovery current to 25% of maximum (or peak) reverse current IRR. The tb is due to charge storage in the bulk semiconductor material.

✓ The lower t_{rr} means fast diode switching.

Softness factor SF = t_b / t_a

✓ The ratio of the two parameters t_b and t_a is known as the softness factor SF.

- Reverse Recovery time t_{rr}

$t_{rr} = t_a + t_b$

- Peak Reverse Current I_{RR}

$$I_{RR} = t_a \frac{di}{dt}$$

- Reverse Recovery Charge Q_{RR}

$$Q_{RR} = Q_1 + Q_2 \cong \frac{1}{2} I_{RR} t_a + \frac{1}{2} I_{RR} t_b = \frac{1}{2} I_{RR} t_{rr} \quad \text{or} \quad I_{RR} \cong \frac{2Q_{RR}}{t_{rr}}$$

✓ Reverse Recovery Charge Q_{RR} is the amount charge carriers that flows across the diode in the reverse direction due to change over from forward conduction to reverse blocking condition.

✓ Its value is determined from the area enclosed by the curve of the reverse recovery current.

$$Q_{RR} = \frac{1}{2} I_{RR} t_a + \frac{1}{2} I_{RR} t_b = \frac{1}{2} I_{RR} t_{rr}$$

$$I_{RR} = \frac{2Q_{RR}}{t_{rr}} = t_a \frac{di}{dt}$$

$$t_{rr} t_a = \frac{2Q_{RR}}{di/dt}$$

t_b is negligible compared to t_a $\quad t_{rr}^2 = \frac{2Q_{RR}}{di/dt}$

t_a

$$t_{rr} \cong \sqrt{\frac{2Q_{RR}}{di/dt}}$$

$$I_{RR} = \sqrt{2Q_{RR} \frac{di}{dt}}$$

Q2. b The reverse recovery time of a diode is trr = 3µs and the rate of fall of the diode current is di/dt = 30 A/ µs. Determine the
(i) storage charge QRR
(ii) peak reverse current IRR. (6 marks)

Solution

$$t_{rr} = 3\,\mu\text{s and } di/dt = 30\,\text{A}/\mu\text{s.}$$

$$t_{rr}^{2} = \frac{2Q_{RR}}{di/dt}$$

$$Q_{RR} = \frac{1}{2}\frac{di}{dt}t_{rr}^{2} = 0.5 \times 30\text{A}/\mu\text{s} \times (3 \times 10^{-6})^{2} = 135\,\mu\text{C}$$

$$I_{RR} = \sqrt{2Q_{RR}\frac{di}{dt}} = \sqrt{2 \times 135 \times 10^{-6} \times 30 \times 10^{6}} = 90\,\text{A}$$

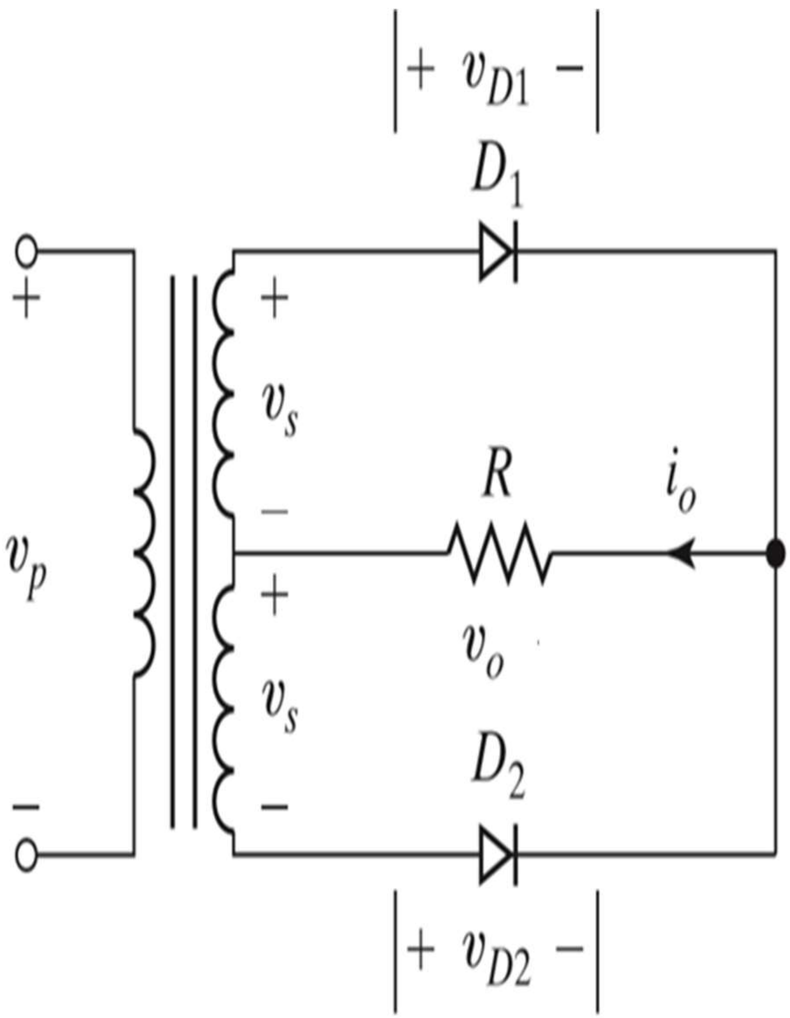
Q2. C (8 marks)

- **With circuit diagram and waveforms explain the working of single phase full wave rectifier with R load**

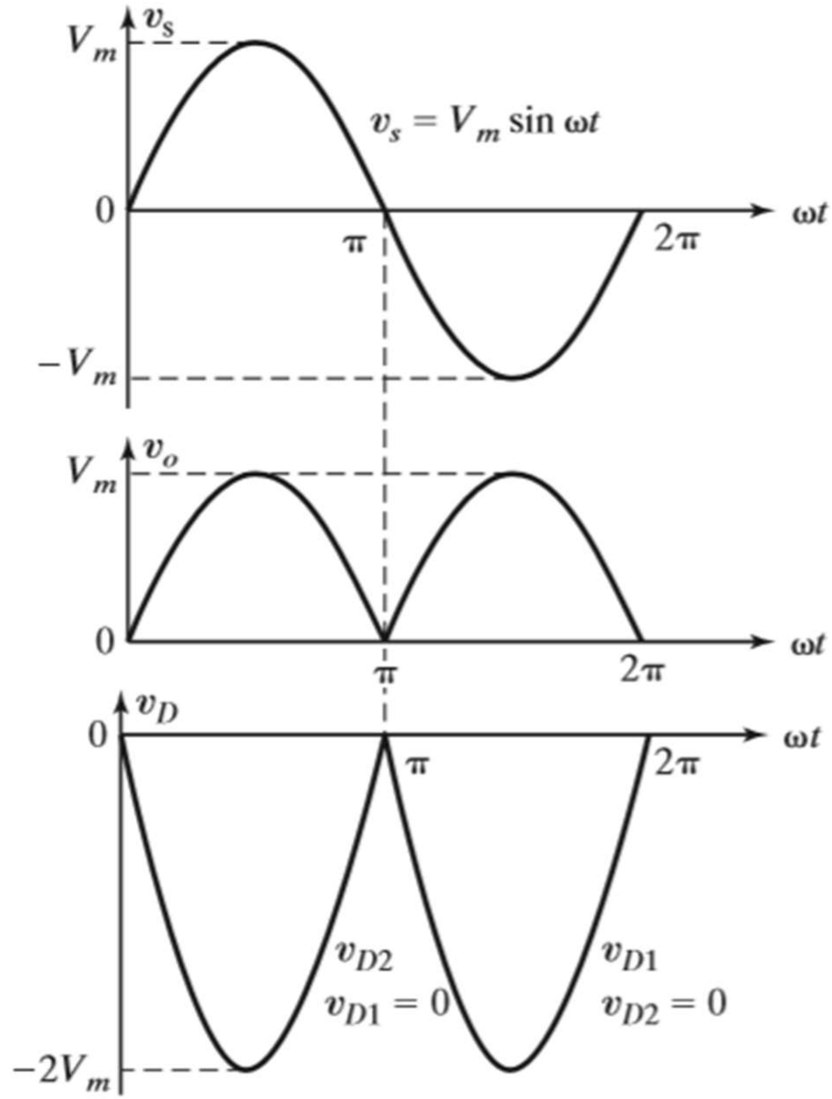
Single Phase Full wave Rectifier

1. Center-tapped Full wave Rectifier
2. Bridge type Full wave Rectifier

Center-tapped Full wave Rectifier



(a) Circuit diagram



(b) Waveforms

During the positive half-cycle of the input voltage

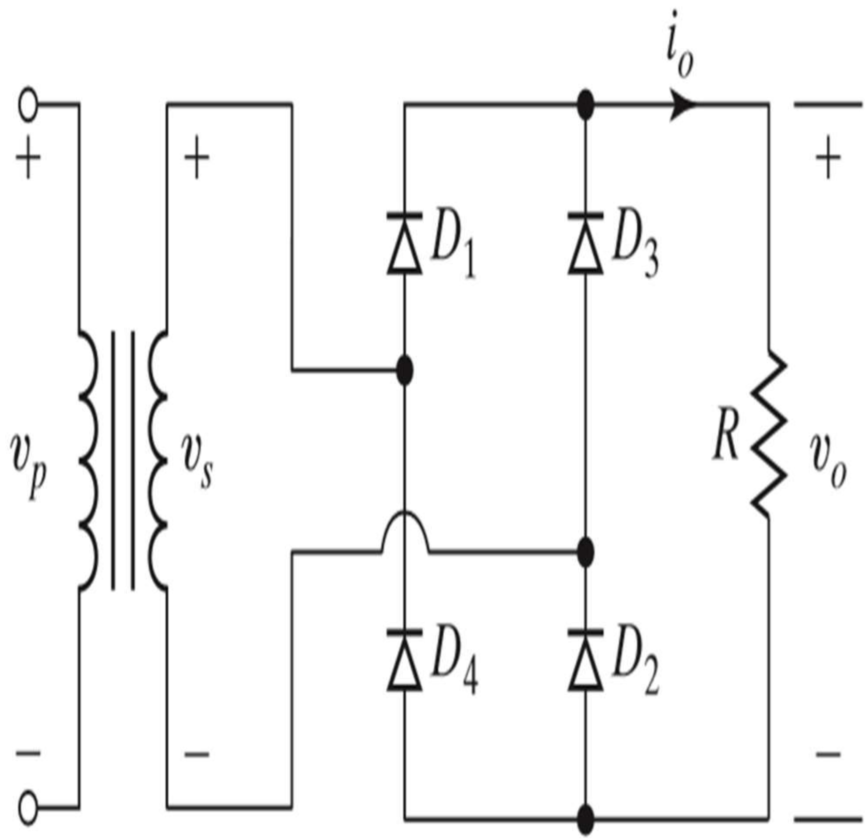
- Diode D1 conducts and diode D2 is in a blocking condition.
- The input voltage appears across the load.

During the negative half-cycle of the input voltage

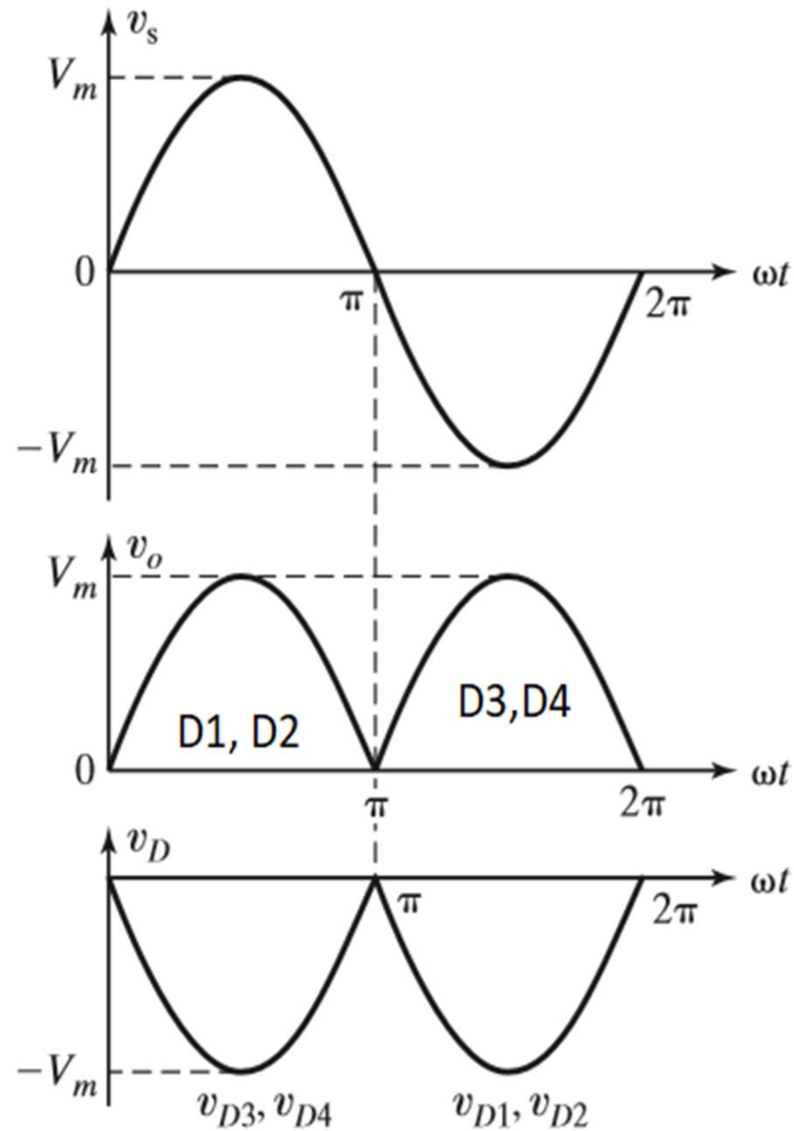
- Diode D2 conducts while diode D1 is in a blocking condition.
- The negative portion of the input voltage appears across the load as a positive voltage.

- The peak inverse voltage of a diode is 2Vm
- PIV of diode, D2 = Vm + Vm

Bridge type Full wave Rectifier



(a) Circuit diagram



(b) Waveforms

During the positive half-cycle of the input voltage

- Diodes D1 and D2 forward biased and conduct.
- Diodes D3 and D4 reverse biased
- Output current flows from Vs+, D1, R load, D2, Vs-

During the negative cycle of the input voltage

- Diodes D3 and D4 forward biased and conduct.
- Diodes D1 and D2 reverse biased.
- Output current flows from Vs+, D3, R load, D4, Vs-

- ➢ The peak inverse voltage of a diode is only Vm.
- ➢ This circuit is known as a bridge rectifier
- ➢ It is commonly used in industrial applications

Performance Parameters for Full wave Rectifier

1. Average value of the output voltage, V_{dc}

$$V_{dc} = \frac{2}{T}\int_0^{T/2} V_m \sin \omega t \, dt \qquad T = 2\pi$$

$$V_{dc} = \frac{1}{\pi}\int_0^{\pi} V_m sin\omega t \, d\omega t :$$

$$= \frac{V_m}{\pi}(-cos\,\omega t)_0^{\pi}$$

$$= \frac{V_m}{\pi}(-cos\pi + cos0^o)$$

$$V_{dc} = \frac{2V_m}{\pi} = 0.6366V_m$$

2. Average value of the output current (Load), Idc

$$I_{dc} = \frac{V_{dc}}{R} = \frac{0.6366V_m}{R}$$

3. Output dc power, P_{dc}

$$P_{dc} = V_{dc}I_{dc}$$

$$P_{dc} = (0.6366V_m)^2/R$$

4. RMS value of the output voltage, V_{rms}

$$V_{\text{rms}} = \left[\frac{2}{T}\int_0^{T/2} (V_m \sin \omega t)^2 \, dt\right]^{1/2}$$

$T = 2\pi$

The rms value of the load voltage V_{rms} can be calculated as follows:

$$V_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} v_s^2(\omega t) d\omega t}$$

$$= \sqrt{\frac{1}{\pi}\int_0^{\pi} (V_m sin\omega t)^2 \, d\omega t}$$

$$= \sqrt{\frac{(V_m)^2}{\pi}\int_0^{\pi} \frac{1}{2}(1 - cos2\omega t)d\omega t} = \frac{V_m}{\sqrt{2}}$$

$$V_{\text{rms}} = \frac{V_m}{\sqrt{2}} = 0.707 V_m$$

5. RMS value of the output Current, I_{rms}

$$I_{\mathrm{rms}} = \frac{V_{\mathrm{rms}}}{R} = \frac{0.707V_m}{R}$$

6. Output ac power, P_{ac}

$P_{ac} = V_{rms}I_{rms}$

$$P_{\mathrm{ac}} = (0.707V_m)^2/R.$$

7. Efficiency, η (Rectification Ratio)

$$\eta = P_{dc}/P_{ac}$$

$$\text{efficiency } \eta = (0.6366V_m)^2/(0.707V_m)^2 = 81\%.$$

8. AC component of Output Voltage

Output voltage consists of 1. DC component 2. AC comp

$$V_{ac} = \sqrt{V_{rms}^2 - V_{dc}^2}$$

9. Form factor, FF – Measure of the shape of the output vo..

$$FF = \frac{V_{rms}}{V_{dc}}$$

$$FF = 0.707V_m/0.6366V_m = 1.11.$$

10. Ripple factor, RF – Measure of Ripple content

$$RF = \frac{V_{ac}}{V_{dc}} \qquad V_{ac} = \sqrt{V_{rms}^2 - V_{dc}^2}$$

$$RF = \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1} = \sqrt{FF^2 - 1}$$

$$RF = \sqrt{1.11^2 - 1} = 0.482 \text{ or } 48.2\%.$$

11. Peak Inverse Voltage

Center tapped Full wave Rectifier : 2 Vm

Bridge type Full wave Rectifier : Vm

12. Transformer utilization factor, TUF

- TUF indicates how effectively the transformer capacity is used in delivering dc power to load for a given ac power.
- It is the ratio of dc power delivered to the load to ac power rating of secondary winding of the transformer.
- $TUF = P_{dc}/V_s I_s = P_{dc}/V_{rms} I_{rms\ (transformer\ secondary)}$
- V_s, I_s are rms voltage and current of the transformer secondary
- TUF for Center tapped full wave rectifier = 0.693 = 69.3%
- TUF for bridge type full wave rectifier = 0.812 = 81.2%

Transformer Utilization Factor (TUF) of bridge type Full Wave Rectifier

DC Power Output, $P_{dc} = (2I_m/\pi)(2V_m/\pi)$

$= (4I_mV_m)/\pi^2$

Since the voltage and current at transformer secondary terminal is sinusoidal, therefore their rms values will be $(V_m/\sqrt{2})$ and $(I_m/\sqrt{2})$ respectively.

VA Rating of Transformer

$= $ rms Voltage x rms Current

$= (V_m/\sqrt{2}) \times (I_m/\sqrt{2})$

$= V_mI_m/2$

$TUF = P_{dc}/V_sI_s = P_{dc}/V_{rms}I_{rms\,(transformer\ secondary)}$

$= [(4I_mV_m)/\pi^2] / [V_mI_m/2]$

$= 8/\pi^2$

$= 0.8106$

= 0.8106 = 81.06%

Displacement angle ϕ

- ✓ ϕ is the angle between fundamental components of voltage and current.
- ✓ Displacement Factor, DF

$$DF = \cos(\phi)$$

Crest factor (CF), which is a measure of the peak input current $I_{s(\text{peak})}$ as compared with its rms value I_s, is often of interest to specify the peak current ratings of devices and components. CF of the input current is defined by

$$CF = \frac{I_{s(\text{peak})}}{I_s} \qquad CF = \sqrt{2}.$$

$Is(\text{peak}) = Vm/R$

$Is = 0.707Vm/R$.

The CF of the input current is CF = $Is(\text{peak})/Is = 1/0.707 = \sqrt{2}$.

Power Factor, PF

- ✓ That is, the power factor is related by

$$PF = \frac{P_{ac}}{V_s I_s}$$

- ✓ *Vs and Is are the rms voltage and rms current of the transformer secondary*

PF for R Load.

Bridge Rectifier.

$$PF = \frac{P_{ac}}{V_s\, I_s}$$

$$= \frac{0.707^2\, V_m^2 / R}{\frac{V_m}{\sqrt{2}} \times \frac{V_m}{R\sqrt{2}}}$$

$$= 0.707^2 \times \sqrt{2} \times \sqrt{2}$$

$$= 0.9996$$

PF = 1.

Harmonic Factor, HF

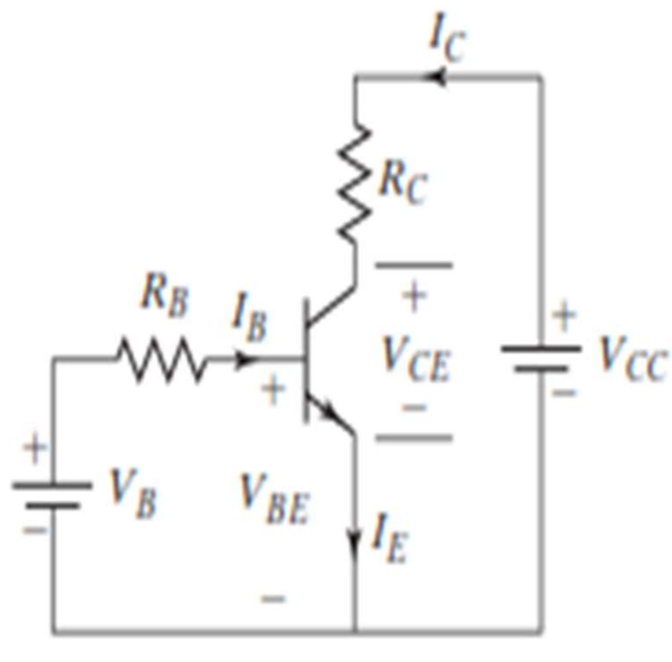
- Harmonic factor is the measure of the distortion of a waveform and is also known as total harmonic distortion.

Module 2

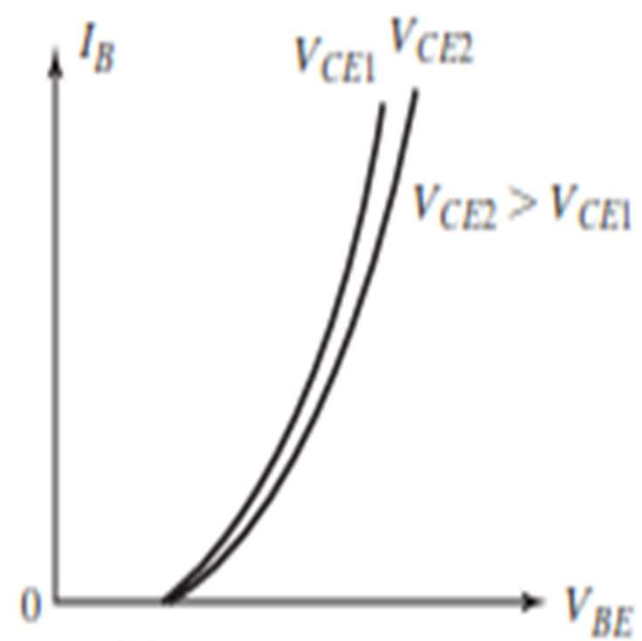
- Q3. a
- **With the aid of steady state characteristics discuss the different operating regions of a power BJT. (8 marks)**

Steady State Characteristics of Power Transistor

Input Characteristics

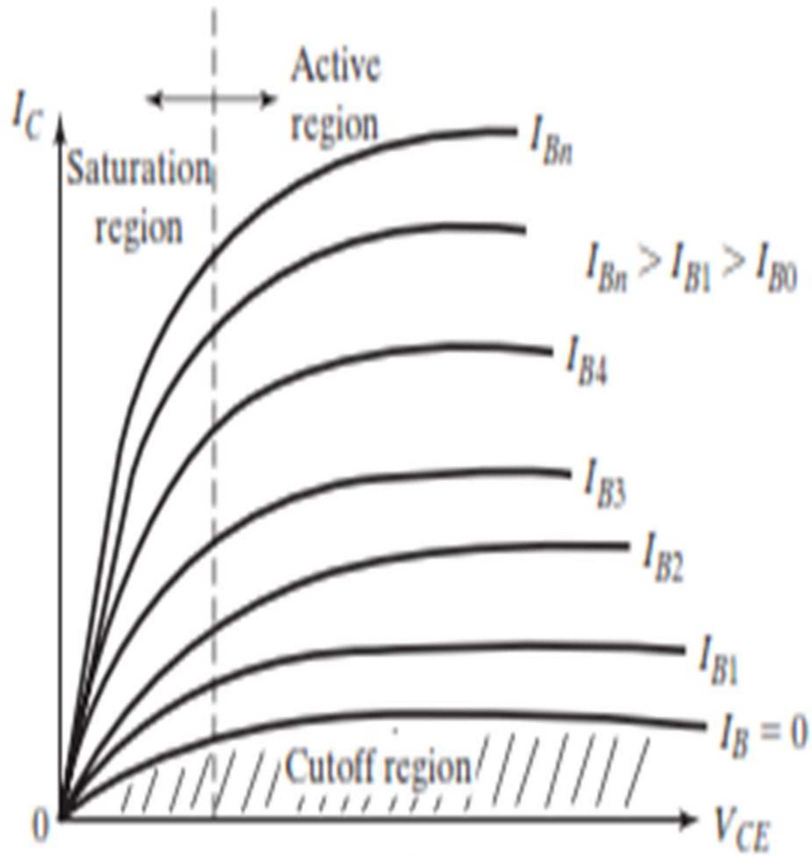


(a) Circuit diagram

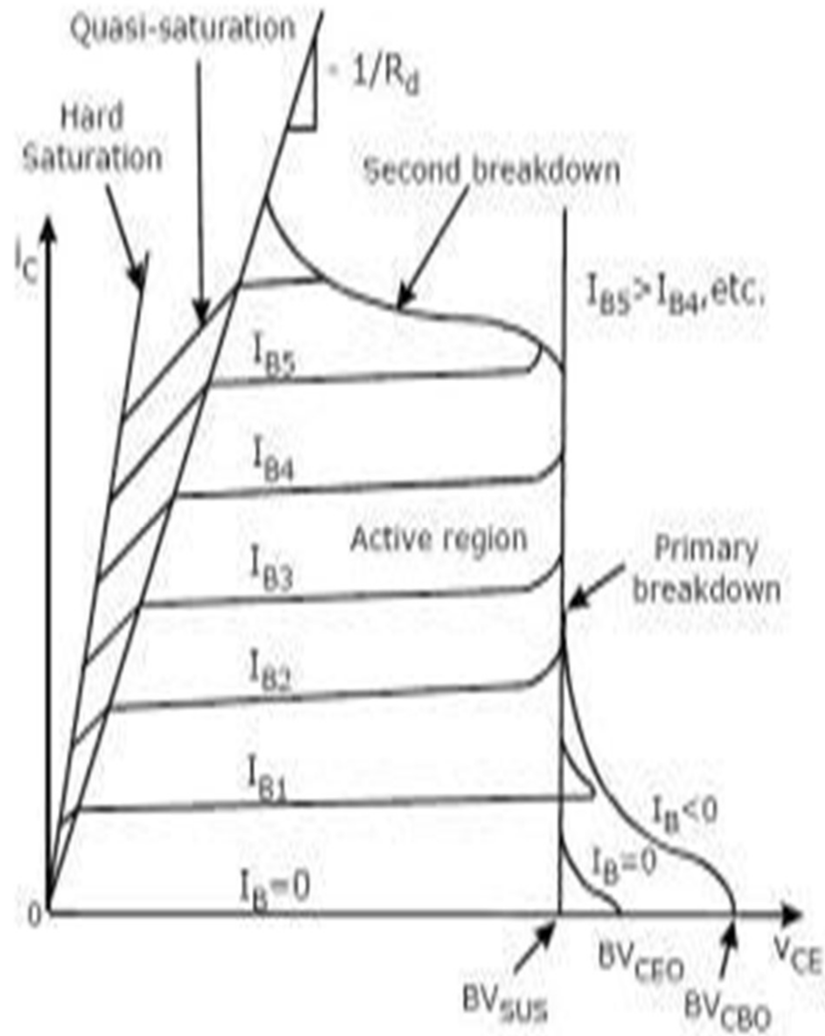


(b) Input characteristics

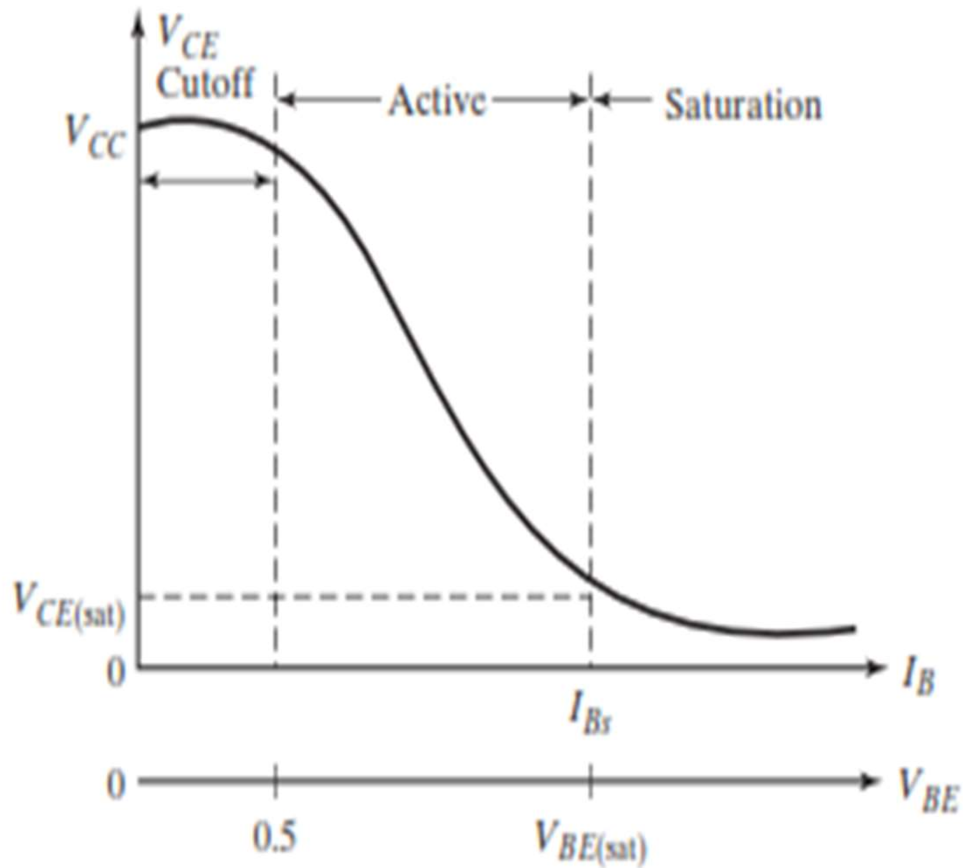
OUTPUT CHARACTERISTCS



(c) Output characteristics



Transfer Characteristics



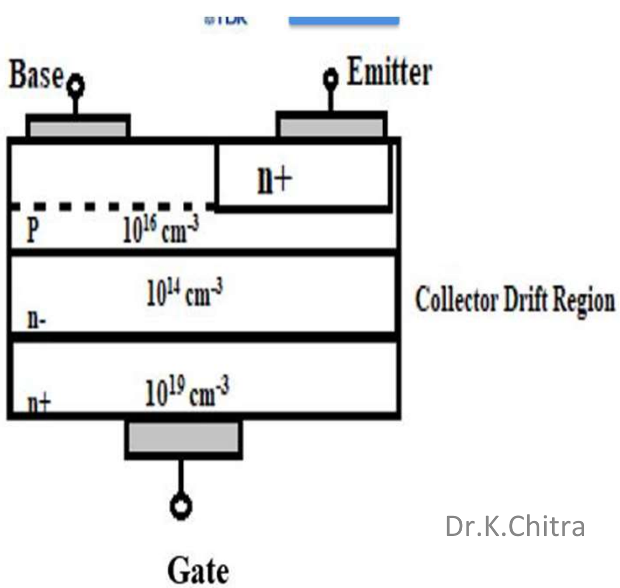
Transfer characteristics.

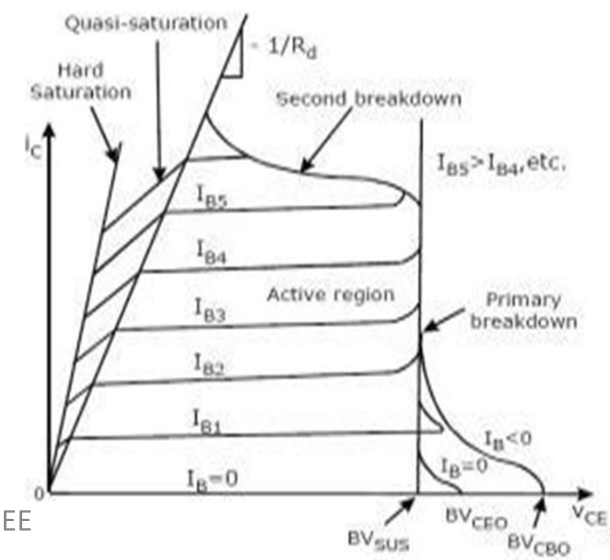
OUTPUT CHARACTERISTCS

- There are three operating regions of a transistor:
- cutoff, active, and saturation.
- In the cutoff region, the transistor is off or the base current is not enough to turn it on and both junctions are reverse biased.
- In the active region, the transistor acts as an amplifier, where the base current is amplified and the collector–emitter voltage decreases with the base current.
- The CBJ is reverse biased, and the BEJ is forward biased.
- In the saturation region, the base current is sufficiently high so that the collector–emitter voltage is low, and the transistor acts as a switch.
- Both junctions (CBJ and BEJ) are forward biased.
- The transfer characteristic, which is a plot of *VCE* against *IB*, is shown in Figure.

Quasi-saturation region:

- In the saturation region, the base current is sufficiently high so that the collector–emitter voltage is low, and the transistor acts as a switch.
- Both junctions (CBJ and BEJ) are forward biased.
- **Quasi-saturation region** is between the hard **saturation** and active **region**.
- This **region** exists due to the lightly doped drift layer.
- When the **BJT** operates at high frequency, it is operated in this **region**.
- Both junctions are forward bias.
- A transistor is said to be in a quasi saturation region if and only if the switching speed from on to off or off to on is fast. This type of saturation is observed in the medium & High -frequency application.
- Whereas in a hard saturation region the transistor requires a certain amount of time to switch from on to off or off to on state. This type of saturation is observed in the low-frequency applications.





Q3. b (6 marks)

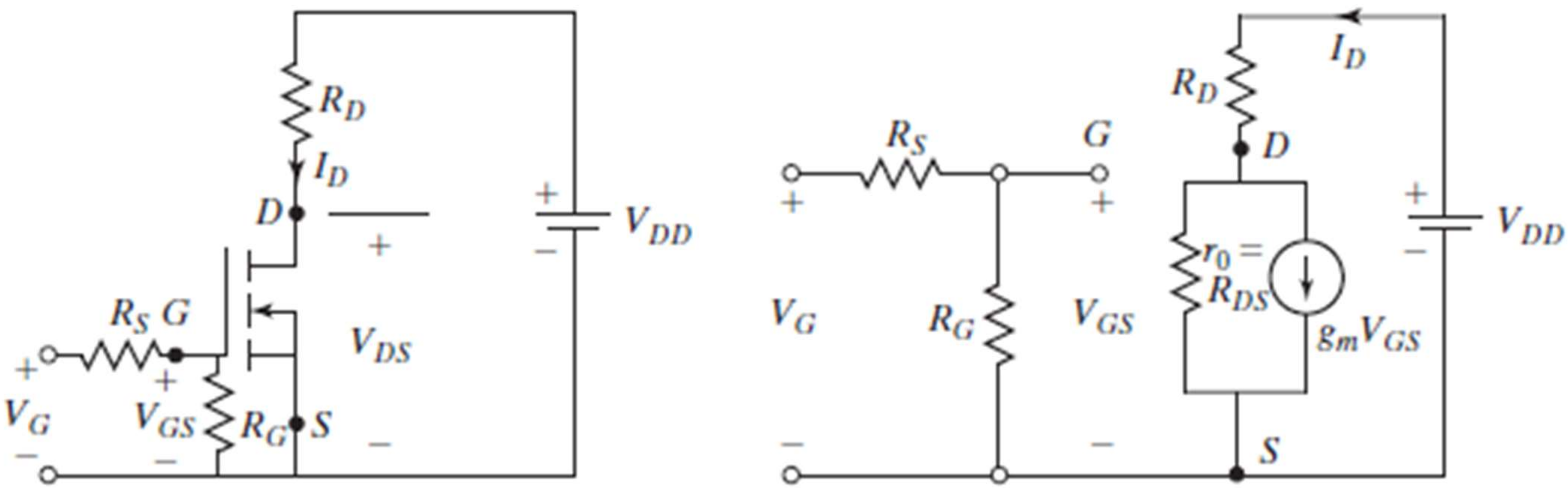
- **Draw the switching model of MOSFET and explain its switching characteristics.**

Switching Characteristics of MOSFETs

Parasitic model of enhancement of MOSFETs

- Without any gate signal, the enhancement-type MOSFET may be considered as two diodes connected back to back (*np and pn diodes) or as an NPN-transistor.*
- *The gate structure has parasitic capacitances to the source, Cgs, and* to the drain, *Cgd.*
- *The NPN-transistor has a reverse-bias junction from the drain to* the source and offers a capacitance, *Cds.*
- Hence, a MOSFET may be considered as having an internal diode and the parasitic capacitances are dependent on their respective voltages.

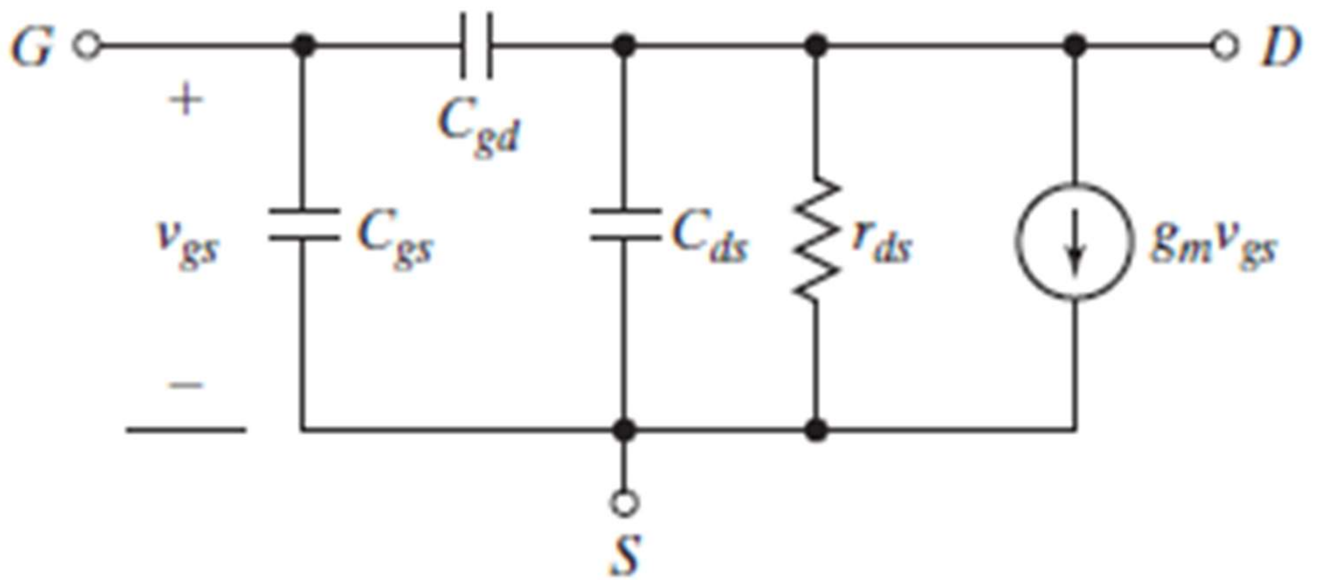
Steady-state switching model of MOSFETs



(a) Circuit diagram (b) Equivalent circuit

- *RD is the load resistance. A* large resistance *RG in the order of megohms is connected between the gate and source* to establish the gate voltage to a defined level.
- *RS (<<RG) limits the charging currents* through the internal capacitances of the MOSFET.

Switching model of MOSFETs



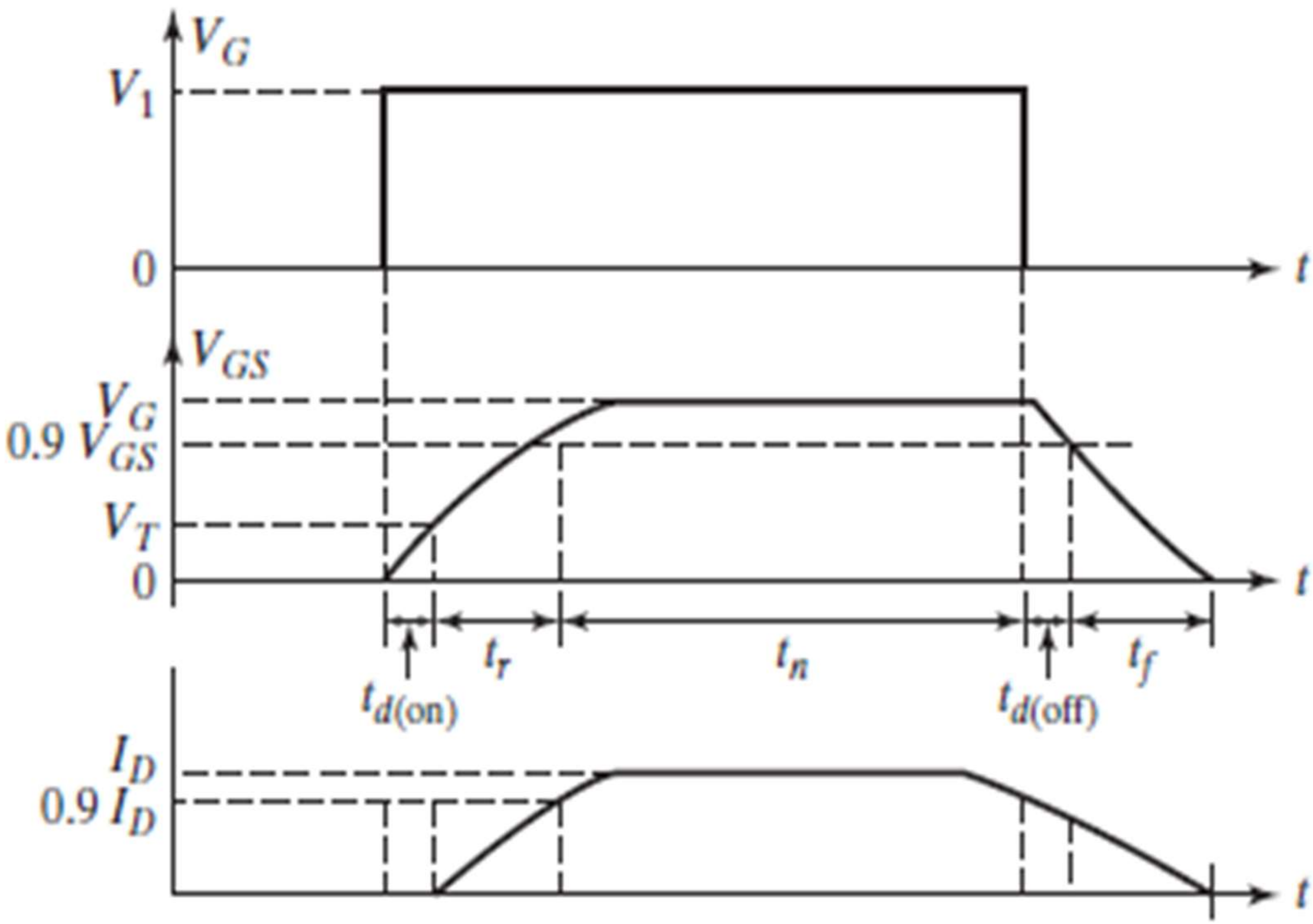
The transconductance *gm is defined as*

$$g_m = \left.\frac{\Delta I_D}{\Delta V_{GS}}\right|_{V_{DS}=\text{constant}}$$

the drain–source resistance R_{DS} as

$$R_{DS} = \frac{v_{DS}}{i_D} = \frac{1}{K_n 2\,(v_{GS} - V_T)} \quad \text{for} \quad v_{GS} > V_T$$

Switching Charcteristics



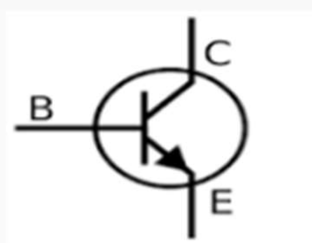
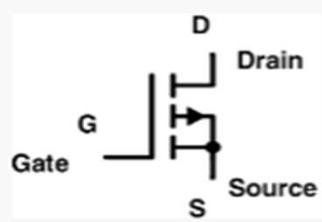
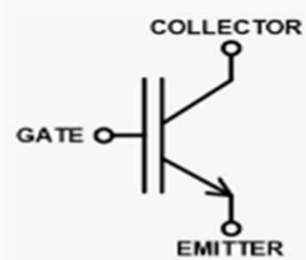
Definitions

- *Delay time $t_{d(on)}$ / Turn on Delay time is the time that is required to charge the input capacitance to threshold voltage level.*
- *It is time taken by the VGS increases from 0 to VT (Threshold voltage)*
- *Rise time t_r is the gate-charging time from the threshold level to the full-gate voltage V_{GSP}, which is required to drive the transistor into the linear region.*
- *It is time taken by ID to increase from 0 to 90% & VGS increase from VT to VGSp (Full gate voltage)*
- *Turn-off delay time $t_{d(off)}$ / storage time is the time required for the input capacitance to discharge from the overdrive* gate voltage *V1 to the pinch-off region.*
- *It is time taken by ID to decrease from 100% to 90% & VGS decrease from VGS to VGSp (Full gate voltage)*

- F*all time t_f is the time that is required for the input capacitance to discharge* from the pinch-off region to threshold voltage.
- *It is time taken by ID to decrease from 90% to 0 & VGS decrease from VGSp to 0.*
- *If VGS ≤ VT, transistor turns off.*

Q3. C. **Give a comparison between BJT, MOSFET and IGBT (6 marks)**

Sr No	Parameter	Power BJT	Power MOSFET	IGBT
1	Operating frequency	10 kHz	100 kHz	10 kHz
2	On-state voltage drop	<2 volts	4-5 volts	3 volts
3	Trigger circuit	Current controlled needs continuous base drive.	Voltage controlled needs continuous gate drive.	Voltage controlled need continuous gate drive.
4	Snubber	Necessary (polarized)	Snubber can be eliminated. If used a polarized snubber is used.	Snubber can be eliminated. If used a polarized snubber is used.
5	Applications	UPS, SMPS, Static VAR systems, AC motor control,	AC motor control, SMPS	SMPS, BLDC drives AC motor control UPS.
6	Maximum VI Rating	2 kV/ 1000 A	600 V/ 200 A	1500 V/ 400 A

7	Type of Device	Minority carrier	Majority carrier	Minority carrier
8	Voltage or Current Controlled	Current controlled	Voltage controlled	Voltage controlled
9	Communication Circuit	Not Necessary	Not Necessary	Not Necessary
10	Blocking Capacity	Asymmetrical	Asymmetrical	Asymmetrical
11	Temperature Coefficient	Negative	Positive	Flat
12	Thermal Runaway	Possible	Not Possible	Not Possible
13	Parallel Operation	Equalizing circuit required.	Easy to parallel.	Easy to parallel.
14	Symbol	 *Power BJT Symbol*	 *Power MOSFET Symbol*	 *Symbol of IGBT*

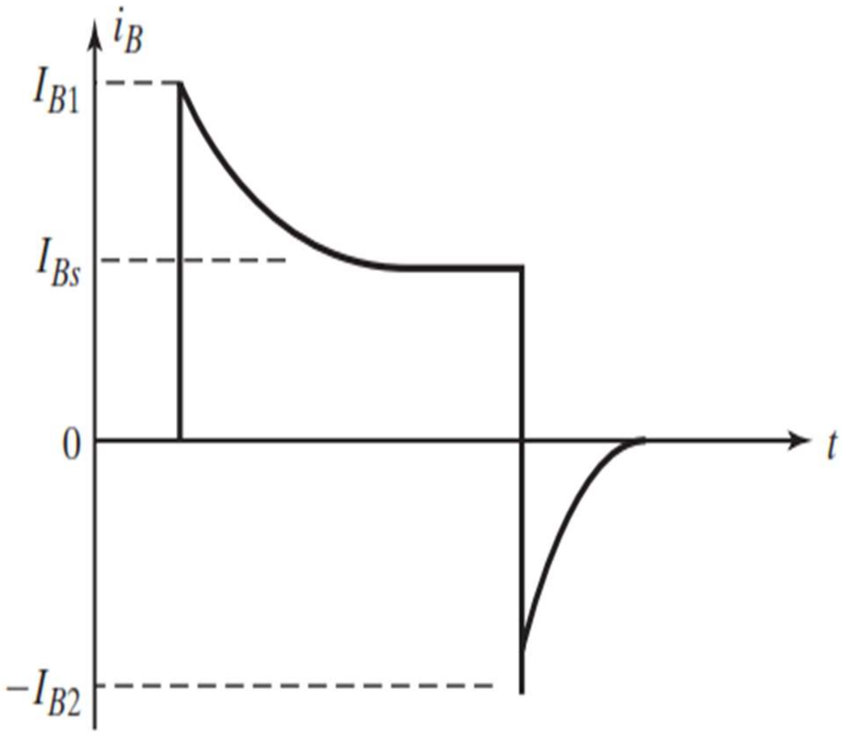
Q4. a . **Discuss the need of base drive control in a power transistor. (5 marks)**

BJT Base Drive

- Base Drive is required to optimize the base drive of transistor.
- Optimization is required to increase switching speeds.
- The switching speed can be increased by reducing turn-on time t_{on} and turn-off time t_{off}.
- The t_{on} can be reduced by allowing base current peaking during turn-on, resulting in low forced β (β_F) at the beginning.
- After turn-on, β_F can be increased to a sufficiently high value to maintain the transistor in the quasi-saturation region.

- toff can be reduced by reversing base current and allowing base current peaking during turn off.
- Increasing the value of reverse base current IB2 decreases storage time.

Base Drive Current Waveform



Base driver current waveform.

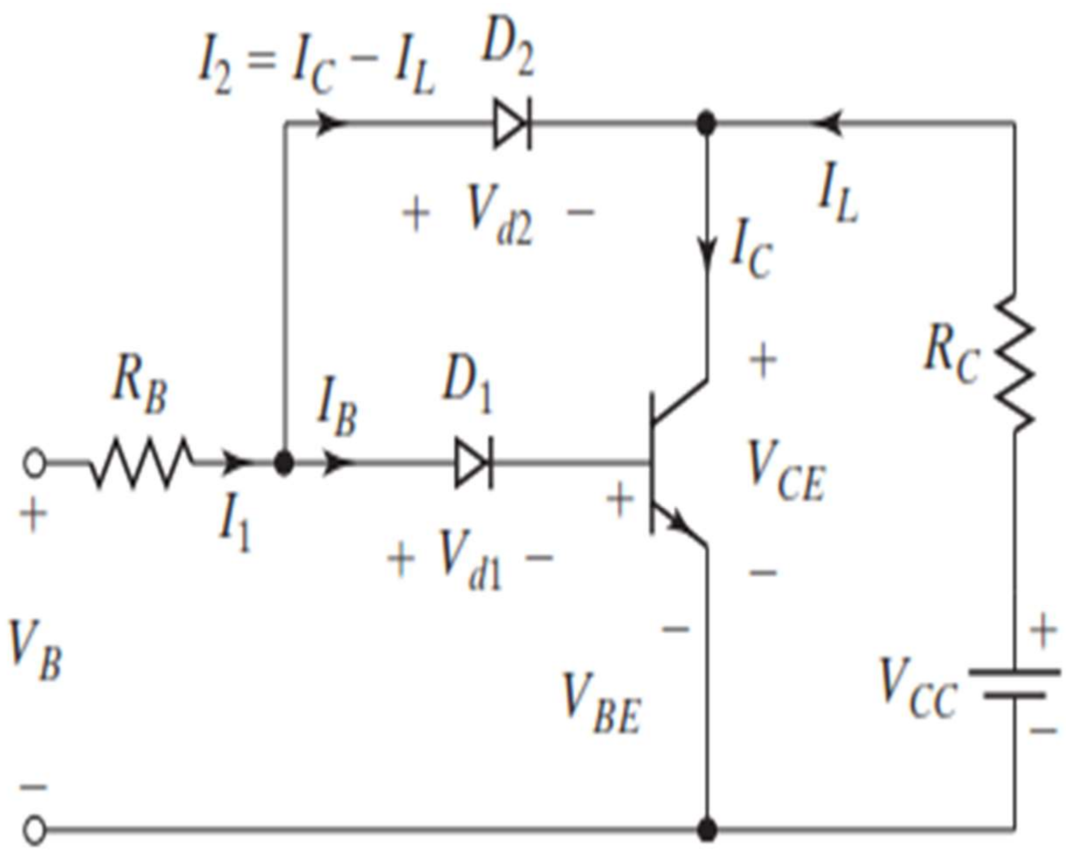
Some common types of optimizing base drive of transistor are

- Turn-on Control.
- Turn-off Control.
- Proportional Base Control.
- Anti saturation Control

Q4. b (7 marks)

- **Explain how anti saturation base control improves the switching performance of a BJT**

Anti saturation control – Collector Clamping Circuit



Collector clamping circuit.

- In the BJT, applying excess base current(I_B) increases storage time. So consequently the turn off time t_{OFF} increases (to discharge the stored charge). Such excess or heavy base drive is called as **Hard Saturation.**
- It is always recommend that the transistor must be operated in soft saturation.
- It means base must be given the carriers which are sufficient to drive the transistor in just saturation (Quasi saturation).

- **If the transistor is driven hard, the storage time, which** is proportional to the base current, increases and the switching speed is reduced.
- The storage time can be reduced by operating the transistor in soft saturation instead of hard saturation.
- This can be accomplished by clamping the collector–emitter voltage to a predetermined level
- collector current is given by $I_C = \dfrac{V_{CC} - V_{cm}}{R_C}$

where V_{cm} is the clamping voltage and $V_{cm} > V_{CE(\text{sat})}$. A circuit with clamping action (also known as Baker's clamp) is shown in Figure

The base current without clamping, which is adequate to drive the transistor hard, can be found from

$$I_B = I_1 = \frac{V_B - V_{d1} - V_{BE}}{R_B}$$

and the corresponding collector current is

$$I_C = \beta I_B$$

After the collector current rises, the transistor is turned on, and the clamping takes place (due to the fact that D_2 gets forward biased and conducts). Then

$$V_{CE} = V_{BE} + V_{d1} - V_{d2}$$

The load current is

$$I_L = \frac{V_{CC} - V_{CE}}{R_C} = \frac{V_{CC} - V_{BE} - V_{d1} + V_{d2}}{R_C}$$

and the collector current with clamping is

$$I_C = \beta I_B = \beta(I_1 - I_C + I_L)$$

$$= \frac{\beta}{1 + \beta}(I_1 + I_L)$$

For clamping, $V_{d1} > V_{d2}$ and this can be accomplished by connecting two or more diodes in place of D_1. The load resistance R_C should satisfy the condition

$$\beta I_B > I_L$$

From Eq. I_L

$$\beta I_B R_C > (V_{CC} - V_{BE} - V_{d1} + V_{d2})$$

The clamping action results in a reduced collector current and almost elimination of the storage time. At the same time, a fast turn-on is accomplished. However, due to increased V_{CE}, the on-state power dissipation in the transistor is increased, whereas the switching power loss is decreased.

Q4. c (8 marks)

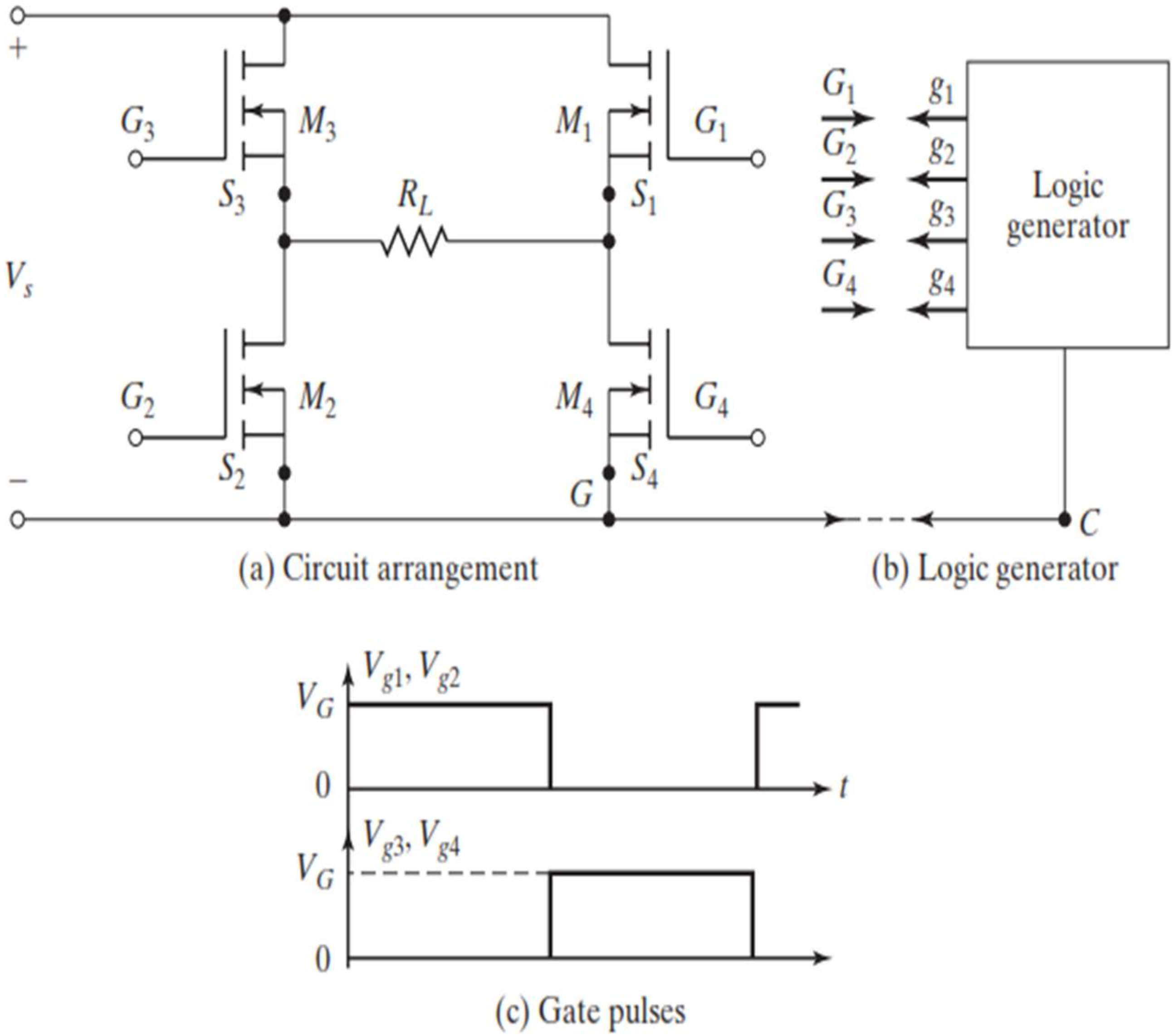
- **With circuit diagrams discuss the methods of providing isolation of gate/base circuits from power circuit.**

Isolation of GATE and Base Drives

- For operating power transistors as switches, an appropriate gate voltage or base current must be applied to drive the transistors in to the saturation mode for low on-state voltage.
- The control voltages should be applied between the gate and source terminals or between the base and emitter terminals.
- The power converters generally require multiple transistors and each transistor must be gated individually.

- Power Circuit – High voltage
- Driver Circuit – Low Voltage

Single Phase Inverter & Gating Signals



Single-phase bridge inverter and gating signals.

- Figure shows the topology of a single-phase bridge inverter.
- The main dc voltage is *Vs* with ground terminal *G.*
- The logic circuit in Figure generates four pulses. These pulses, as shown in Figure, are shifted in time to perform the required logic sequence for power conversion from dc to ac.
- However, all four logic pulses have a common terminal *C.*
- The common terminal of the logic circuit may be connected to the ground terminal *G* of the main dc supply, as shown by dashed lines.
- The terminal *g*1, which has a voltage of *Vg1* with respect to terminal *C, cannot be* connected directly to gate terminal *G*1.
- The signal *Vg1* should be applied between the gate terminal *G*1 and source terminal *S*1 of transistor *M1.*
- There is a need for isolation and interfacing circuits between the logic circuit and power transistors.
- However, transistors *M*2 and *M*4 can be gated directly without isolation or interfacing circuits if the logic signals are compatible with the gate- drive requirements of the transistors.

Necessity of Isolating Gate and Base

We know that driver circuits operate at very low power levels. Normally the signal levels are 3 to 12 volts. Sometimes digital circuits and microprocessors are also used in the triggering circuits. The gate and base drives are connected to power devices which operate at high power levels. Fig. 1. shows this situation. Observe that collector of BJT can have voltages of 200 V. But base is connected to trigger circuit that have voltages of 5 V. If BJT is damaged and collector-base gets shorted, then high voltage will get connected to trigger circuit. This will damage the trigger circuit also. This means trigger circuit is damage due to device damage. Therefore there must be some electric isolation between control and power circuit.

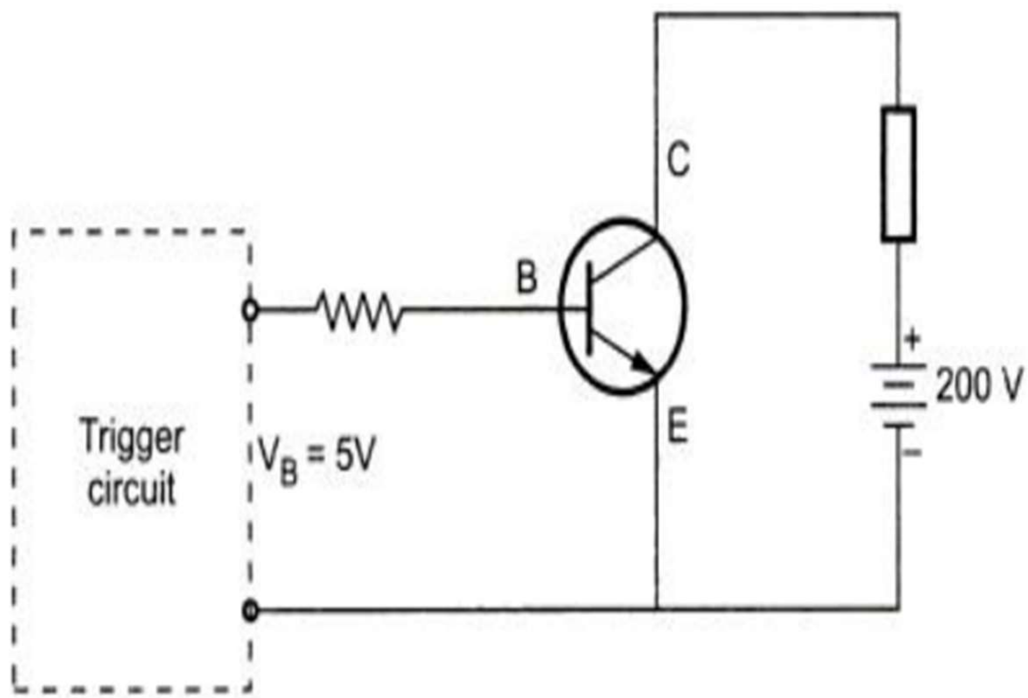


Fig. 1 Control / power levels

There is one more reason for isolation.

Consider that the trigger circuit is deriving the two devices as shown in Fig. 2.

Here observe that T_1 is given the drive between a-b. And T_2 is given the drive between c-d. The trigger circuit must isolate the two drives. If there is no electric isolation, the points 'b' and 'd' may be shorted due to common ground of the trigger circuit. Isolation can be obtained with the help of pulse transformers and optocouplers.

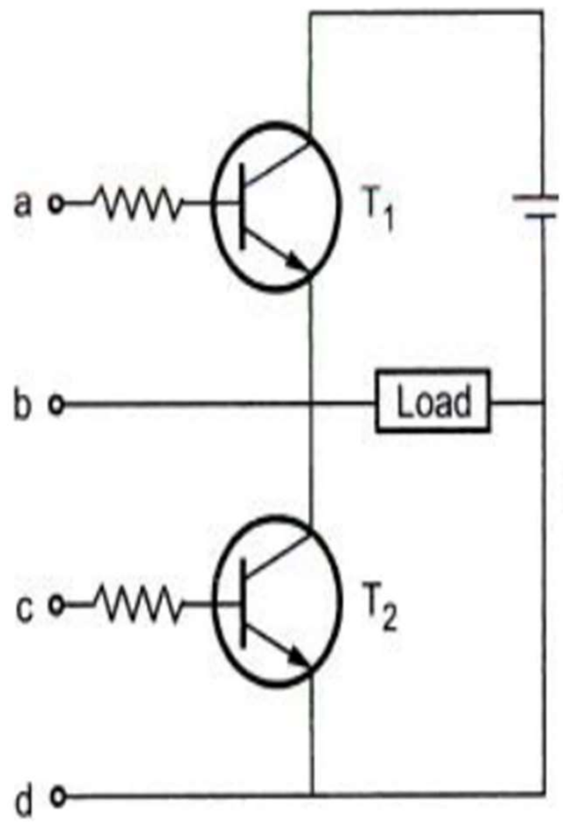


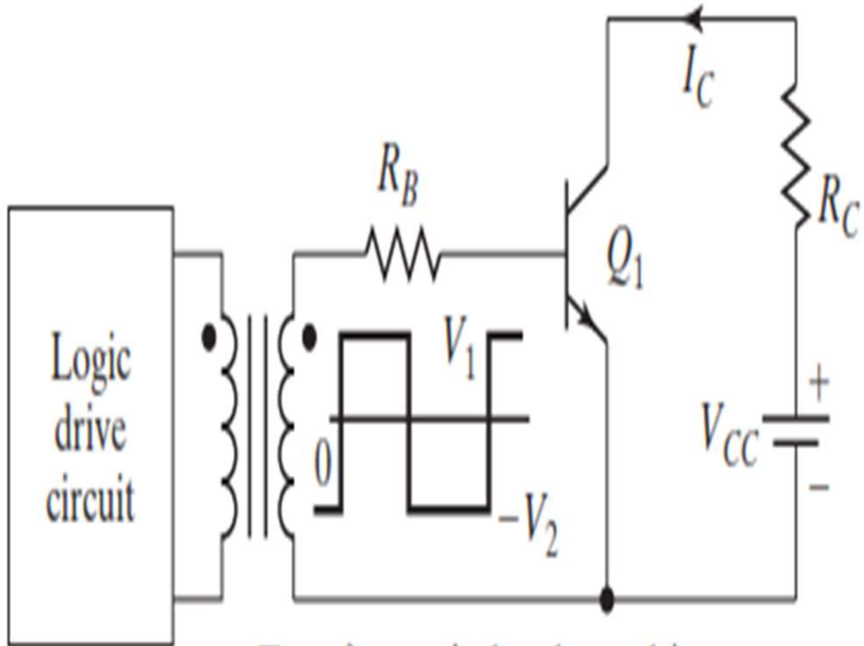
Fig. 2 Isolation of grounds

Gate Isolation

- There are basically two ways of floating or isolating the control or gate signal with respect to ground.
- **1. Pulsetransformers**
- **2. Optocouplers**

1. Gate Isolation by Pulse Transformer

- Pulse transformers have one primary winding and can have one or more secondary windings.
- Multiple secondary windings allow simultaneous gating signals to series-and parallel-connected transistors.
- Figure shows a transformer-isolated gate-drive arrangement.
- The transformer should have a very small leakage inductance and the rise time of the output pulse should be very small.
- At a relatively long pulse and low switching frequency, the transformer would saturate and its output would be distorted.



Transformer-isolated gate drive.

In the above circuit, observe that triggering circuit is electrically isolated from BJT. Hence if there is any electric damage to BJT, there will be no effect on triggering circuit.

Advantages

i) Pulse transformer does not need external power for its operation.

ii) It is very simple to use.

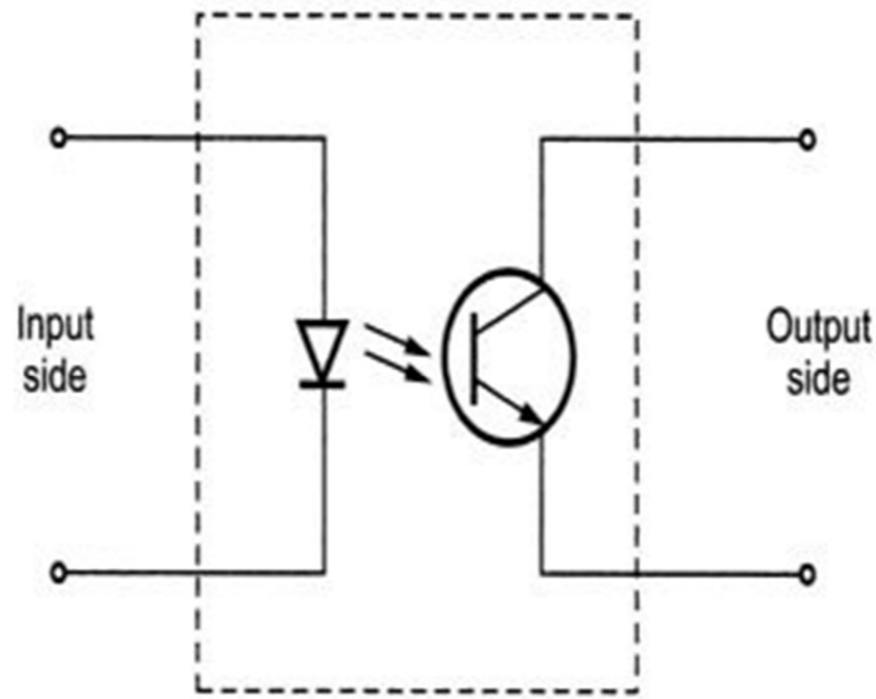
Disadvantages

i) Pulse transformer saturates at low frequencies hence it can be used only for high frequencies.

ii) Due to magnetic coupling, the signal is distorted.

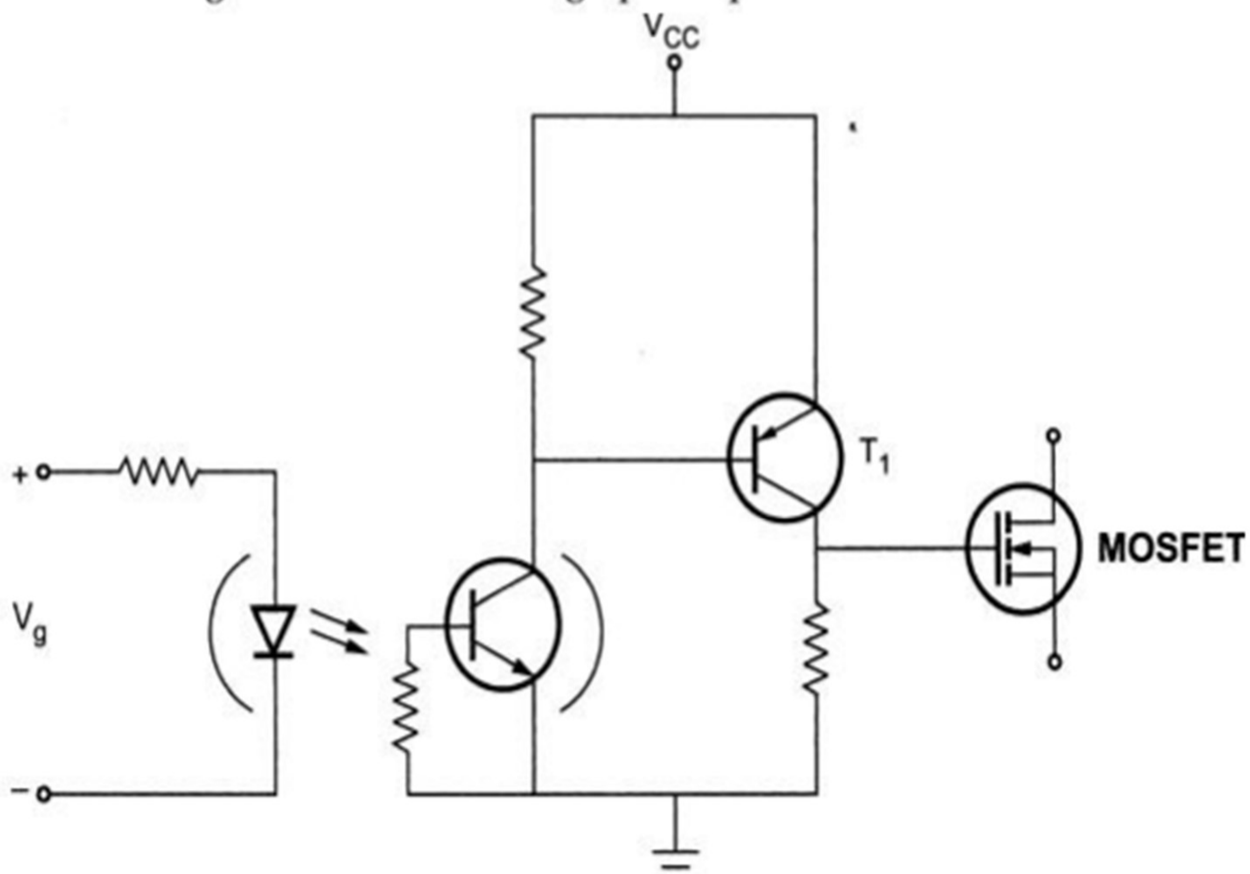
2. Gate Isolation by Optocoupler

Optocoupler consists of a pair of infrared LED and phototransistor. Fig. shows the symbol of optocoupler. When the signal is applied to the infrared LED, it turns-on. It's light falls on phototransistor. Therefore phototransistor also starts conducting. There is no electric connection between LED and phototransistor.



Optocouplers combine an infrared light-emitting diode (ILED) and a silicon photo-transistor.

Fig. shows the triggering circuit that uses optocoupler. In this circuit the triggering pulses are given to the input (LED) of optocoupler. When 'V_g' is positive, LED turns-on. It's light falls on phototransistor. Hence it turns-on. Therefore base of T_1 is connected to zero volts through phototransistor. Due to this, T_1 turns-on. Therefore the voltage V_{CC} is applied to gate of the MOSFET. Hence MOSFET turns-on. When $V_g = 0$, the LED turns-off, therefore phototransistor also turn-off. Therefore base drive of T_1 goes to V_{CC} and it turn-off. When T_1 turns-off, MOSFET gate voltage becomes zero. Therefore MOSFET turns-off. Thus gate drive circuit using optocoupler works.



MOSFET triggering circuit using optocoupler

Advantages

1) Very good response at low frequencies.
2) Compact and cheaper optocoupler devices are available.

Disadvantages

1) Optocoupler need, external biasing voltage for their operation.
2) High frequency response is poor.

Applications

Inverters, SMPS, Choppers, AC motor drives use optocouplers.

Module 3

- Q5. a. **Mention the different turn on methods employed to switch on SCR. (8 marks)**

Thyristor – Turn ON

- A thyristor is turned on by increasing the anode current.
- This can be accomplished in one of the following ways.

➢ **Thermals.**

➢ **Light.**

➢ **High voltage.**

➢ ***dv/dt.***

➢ **Gate current.**

Thyristor – Turn ON – By Thermals

- If the temperature of a thyristor is high, there is an increase in the number of electron–hole pairs, which increases the leakage currents.
- This increase in currents causes $\alpha 1$ and $\alpha 2$ to increase.
- Due to the regenerative action, $(\alpha 1 + \alpha 2)$ may tend to unity and the thyristor may be turned on.

$$I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)}$$

- This type of turn-on may cause thermal runaway and is normally avoided.

Thyristor – Turn ON – By Light

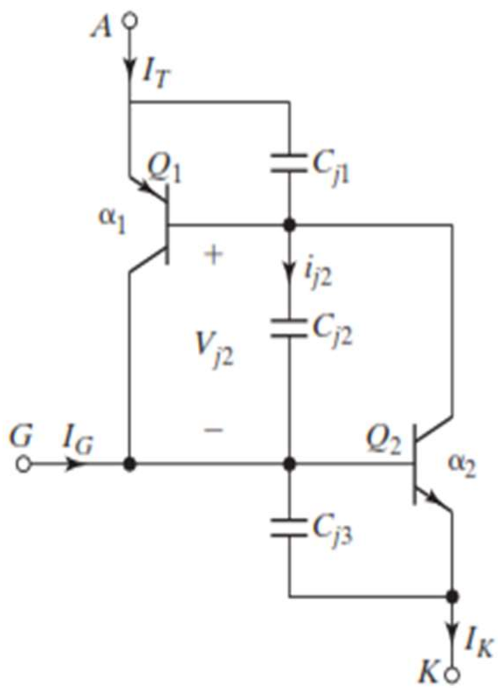
- If light is allowed to strike the junctions of a thyristor, the electron–hole pairs increase; and the thyristor may be turned on.
- The light-activated thyristors are turned on by allowing light to strike the silicon wafers.

Thyristor – Turn ON – By High Voltage

- If the forward anode-to-cathode voltage VBK is greater than the forward breakdown voltage *VBO*, sufficient leakage current flows to initiate regenerative turn-on.
- This type of turn-on may be destructive and should be avoided.

Thyristor – Turn ON – By dv/dt

Two-transistor transient model of thyristor.



If a thyristor is in a blocking state, a rapidly rising voltage applied across the device would cause high current flow through the junction capacitors.

Current through the capacitor Cj2 is given by

$$i_{j2} = \frac{d(q_{j2})}{dt} = \frac{d}{dt}(C_{j2}V_{j2}) = V_{j2}\frac{dC_{j2}}{dt} + C_{j2}\frac{dV_{j2}}{dt}$$

where C_{j2} and V_{j2} are the capacitance and voltage of junction J_2, respectively, Transistor Q_{j2} is the charge in the junction. If the rate of rise of voltage dv/dt is large, then i_{j2} would be large and this would result in increased leakage currents I_{CBO1} and I_{CBO2}. According to Eq. IA , high enough values of I_{CBO1} and I_{CBO2} may cause $(\alpha_1 + \alpha_2)$ tending to unity and result in undesirable turn-on of the thyristor. However, a large current through the junction capacitors may also damage the device.

Thyristor – Turn ON – By dv/dt

Current through the capacitor Cj2 is given by

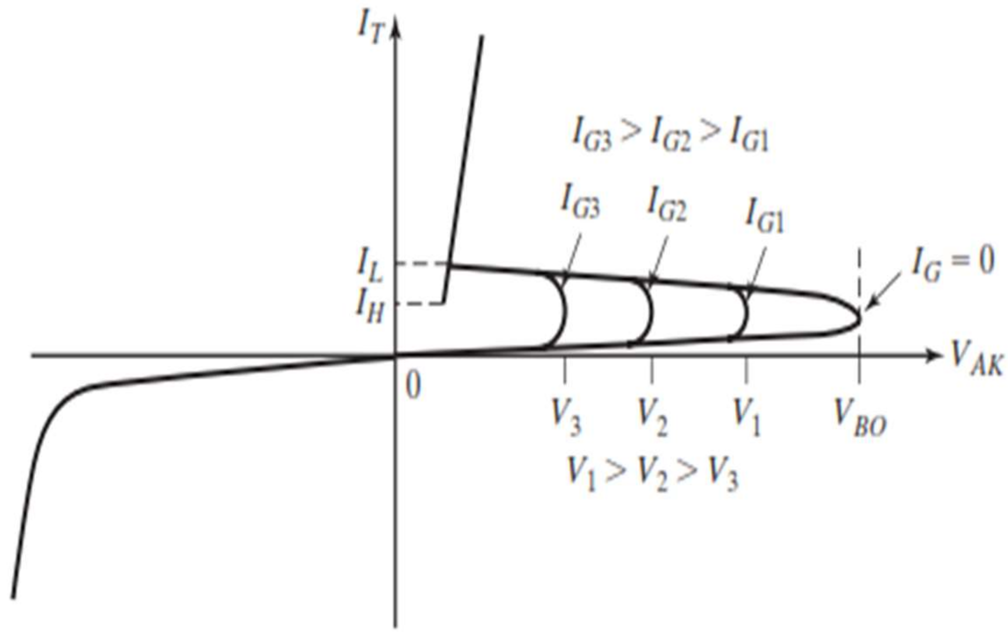
$$i_{j2} = \frac{d(q_{j2})}{dt} = \frac{d}{dt}(C_{j2}V_{j2}) = V_{j2}\frac{dC_{j2}}{dt} + C_{j2}\frac{dV_{j2}}{dt}$$

- If the rate of rise of the anode– cathode voltage is high, the charging current of the capacitive junctions may be sufficient enough to turn on the thyristor.
- A high value of charging current may damage the thyristor; and the device must be protected against high *dv/dt*.
- The manufacturers specify the maximum allowable *dv/dt* of thyristors.

Thyristor – Turn ON – By Gate Current

- If a thyristor is forward biased, the injection of gate current by applying positive gate voltage between the gate and cathode terminals turns on the thyristor.
- As the gate current is increased, the forward blocking voltage is decreased.

Effects of gate current on forward blocking voltage.



Q5 b (6 marks)

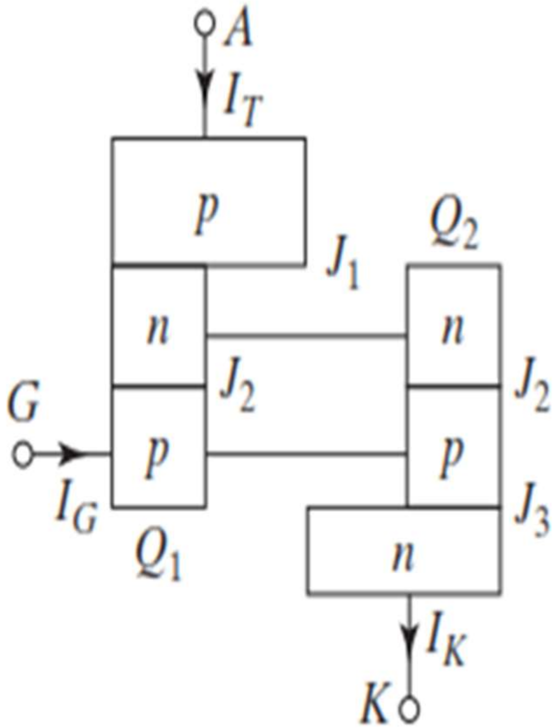
- **Derive an expression for anode current using two transistor model of thyristor.**

Two-transistor Model of Thyristor

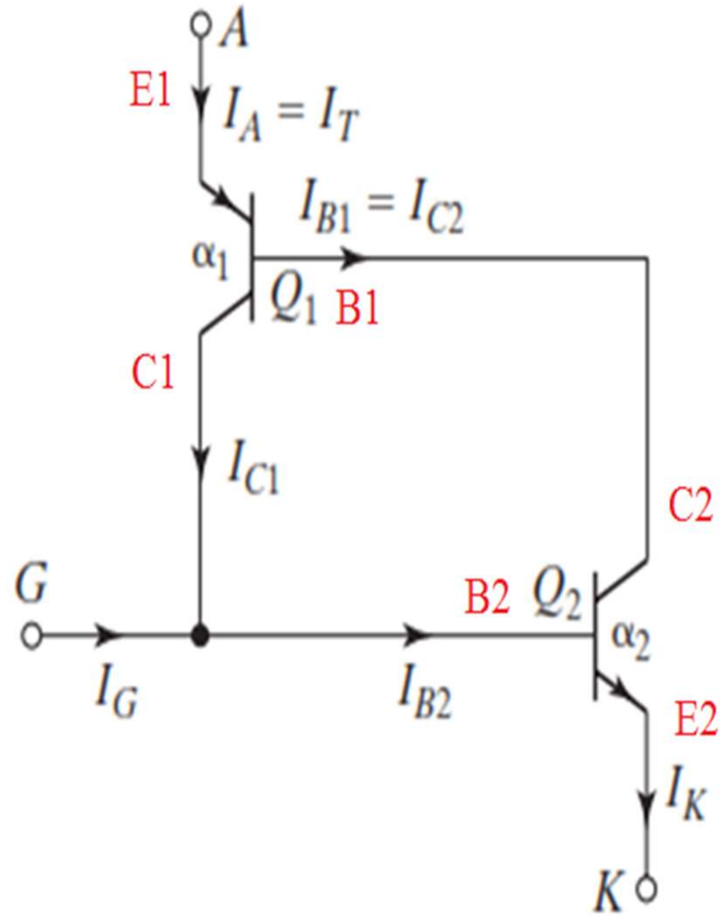
- The regenerative or latching action due to a positive feedback can be demonstrated by using a two-transistor model of thyristor.
- A thyristor can be considered as two complementary transistors
- one *PNP*-transistor,*Q*1, and other *NPN*-transistor, *Q2.*

Two-transistor Model of Thyristor

Two-transistor model of thyristor.



(a) Basic structure



(b) Equivalent circuit

Derivation of Anode Current

The collector current I_C of a thyristor is related, in general, to the emitter current I_E and the leakage current of the collector–base junction, I_{CBO}, as

$$I_C = \alpha I_E + I_{CBO} \tag{9.1}$$

and the *common-base current* gain is defined as $\alpha \simeq I_C/I_E$. For transistor Q_1, the emitter current is the anode current I_A, and the collector current I_{C1} can be found from Eq. (9.1):

$$I_{C1} = \alpha_1 I_A + I_{CBO1} \tag{9.2}$$

where α_1 is the current gain and I_{CBO1} is the leakage current for Q_1. Similarly, for transistor Q_2, the collector current I_{C2} is

$$I_{C2} = \alpha_2 I_K + I_{CBO2} \tag{9.3}$$

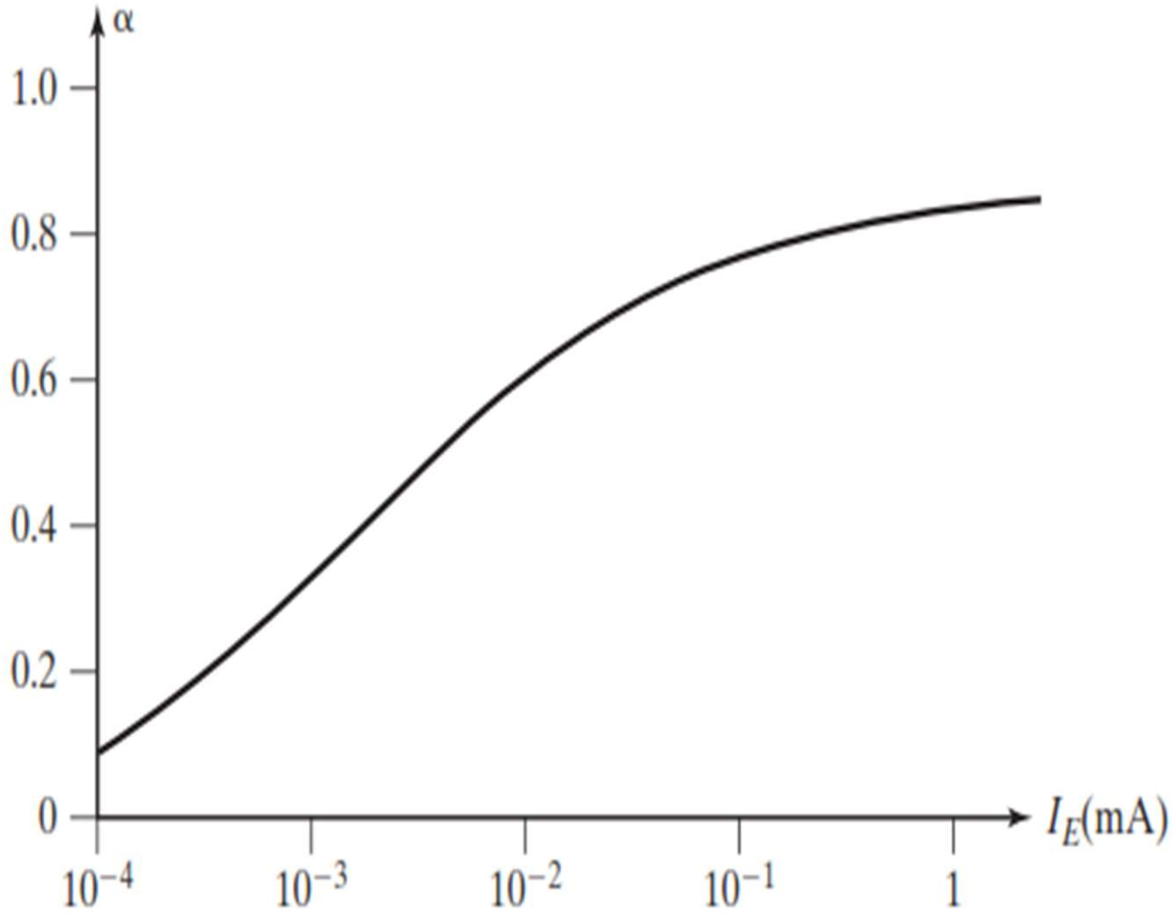
where α_2 is the current gain and I_{CBO2} is the leakage current for Q_2. By combining I_{C1} and I_{C2}, we get

$$I_A = I_{C1} + I_{C2} = \alpha_1 I_A + I_{CBO1} + \alpha_2 I_K + I_{CBO2} \tag{9.4}$$

For a gating current of $I_G, I_K = I_A + I_G$ and solving Eq. (9.4) for I_A gives

$$I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)} \tag{9.5}$$

Variation of Current Gain with Emitter Current



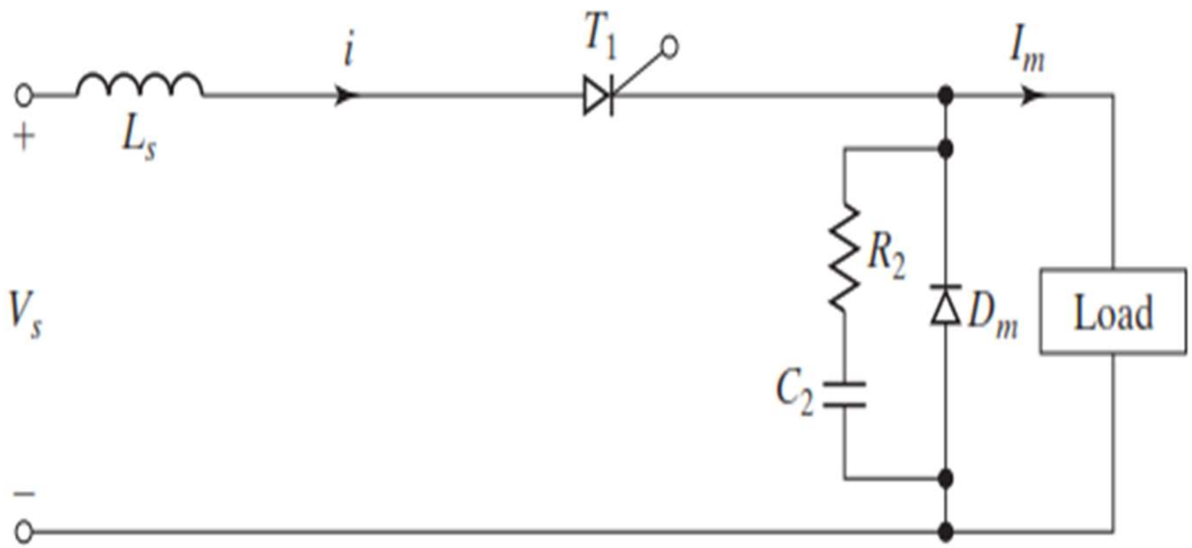
Typical variation of current gain with emitter current.

Q6. a. Describe how thyristors are protected from di/dt. (6 marks)

di/dt Protection

- A thyristor requires a minimum time to spread the current conduction uniformly throughout the junctions.
- If the rate of rise of anode current is very fast compared with the spreading velocity of a turn-on process, a localized "hot-spot" heating may occur due to high current density and the device may fail, as a result of excessive temperature.
- The practical devices must be protected against high *di/dt.*
- Under steady-state operation, *Dm* conducts when thyristor *T*1 is off.
- If *T*1 is fired when *Dm* is still conducting, *di/dt* can be very high and limited only by the stray inductance of the circuit.
- **In practice, the *di/dt* is limited by adding a series inductor *Ls***

di/dt Protection with Limiting Inductor Ls



Thyristor switching circuit with *di/dt* limiting inductors.

The forward *di/dt* is

$$\frac{di}{dt} = \frac{V_s}{L_s}$$

where L_s is the series inductance, including any stray inductance.

Q6. b Calculate the required parameters for snubber circuit to provide dv/dt protection to a SCR used in single phase bridge converter. The SCR has a maximum dv/dt capability of 60 v/ µs. The input line to line voltage has a peak value of 425 V and source inductance 0.2 mH. Take damping factor as 0.65. (6 Marks)

Q6. c (8 marks)

- **Explain UJT triggering circuit for full control of SCR with waveforms.**

Unijunction Transistor (UJT)

What is Unijunction Transistor (UJT)

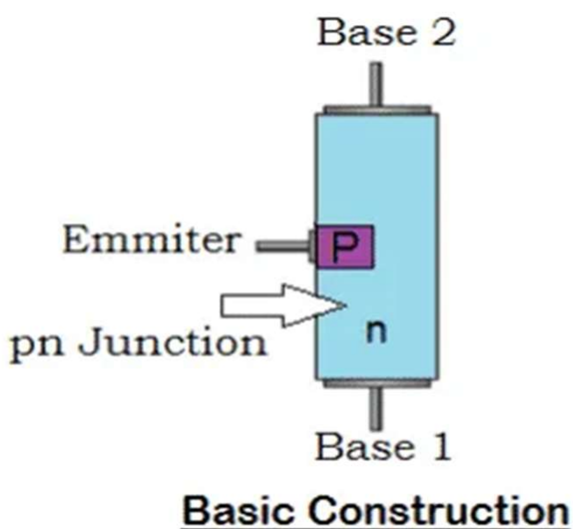
- UJT stands for **U**ni**J**unction **T**ransistor.
- It is a three terminal semiconductor switching device.
- The Unijunction Transistor is a simple device that consists of a bar of n-type silicon material with a non-rectifying contact at either end (base 1 and base 2), and with a rectifying contact (emitter) alloyed into the bar part way along its length, to form the only junction within the device (hence the name ‘Unijunction’).
- The Unijunction Transistor is also known as Double Base Diode.

Unijunction Transistor used for Trigeering SCR

- The unijunction transistor (UJT) is commonly used for generating triggering signals for SCRs .
- A UJT has three terminals, called the emitter *E, base-one B*1, and base-two *B*2.
- Between *B1 and B2* the unijunction has the characteristics of an ordinary resistance.
- This resistance is the inter base resistance *R* and has values in the range 4.7 to 9.1 k.
- The unique switching characteristics of UJT makes it different from conventional BJT's and FET's by acting as switching transistor instead of amplifying the signals.
- It exhibits negative resistance in its characteristics which employs it as relaxation oscillators in variety of applications.

Symbol and Construction of Unijunction Transistor (UJT)

In Unijunction Transistor, the PN Junction is formed by lightly doped N type silicon bar with heavily doped P type material on one side. The ohmic contact on either ends of the silicon bar is termed as Base 1 (B_1) and Base 2 (B_2) and P-type terminal is named as emitter.



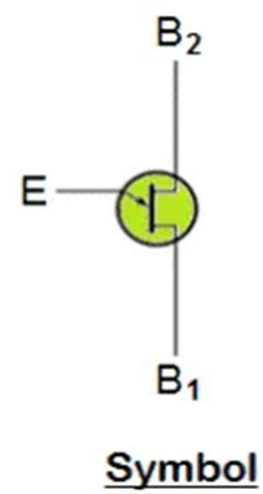
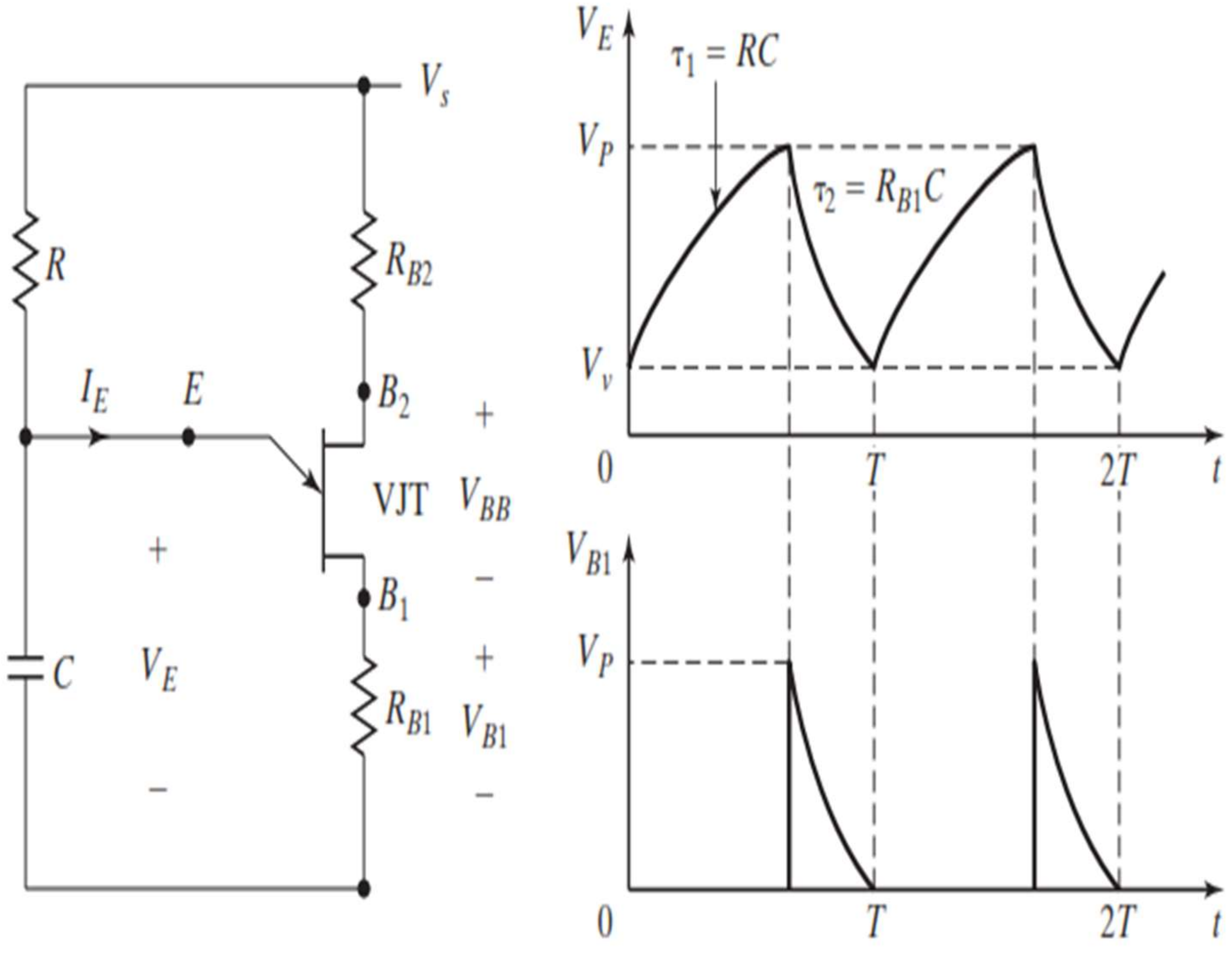


Fig. 2 – Basic Construction & Symbol of Unijunction Transistor (UJT)

The emitter junction is placed such that it is more close to terminal Base 2 than Base 1. The symbols of both UJT and JFET resemble the same except the emitter arrowhead represents the direction in which conventional current flow, but they operate differently.

UJT Circuit, Waveforms,



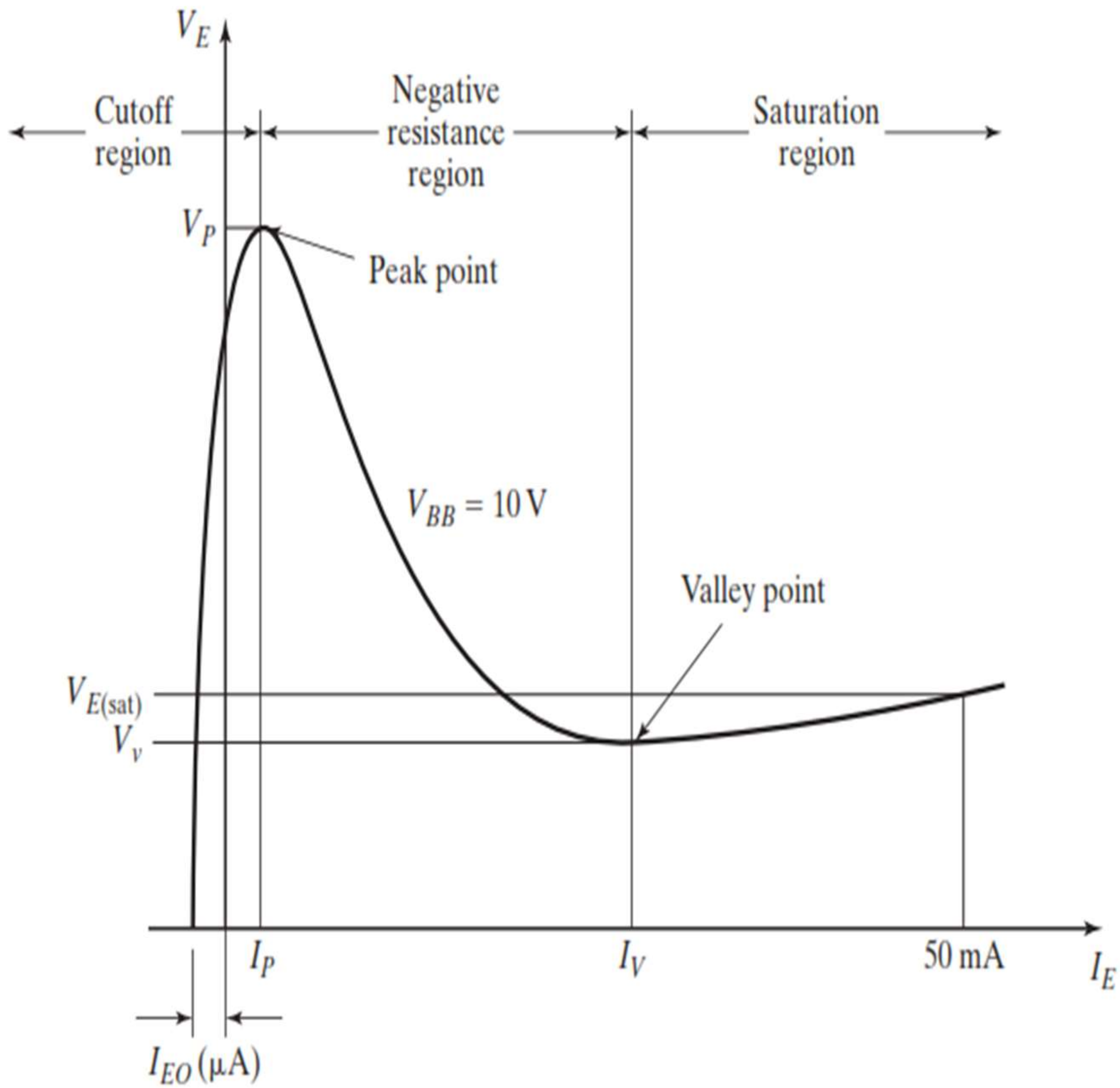
(a) Circuit (c) Waveforms

The static characteristics of a UJT

- When the dc supply voltage *Vs* is applied, the capacitor *C is charged through Resistor* because the emitter circuit of the UJT is in the open state.
- The time constant of the charging circuit is $\tau 1 = RC$.
- When the emitter voltage *VE*, which is same as capacitor voltage vc, reaches the *peak voltage Vp*, the UJT turns on and capacitor *C* discharges through *RB*1 at a rate determined by the time constant $\tau 2 = R_{B1}C$ is much smaller than $\tau 1$.
- When the emitter voltage *VE* decays to the valley point *Vv*, the UJT turns off, and the charging cycle is repeated.
- The waveform of the triggering voltage *VB1* is identical to the discharging current of capacitor *C*. The triggering voltage *VB*1 should be designed to be sufficiently large to turn on the SCR.
- The period of oscillation, *T*, is fairly independent of the dc supply voltage *Vs.*

- **Peak-Point Emitter Current. I_p**. It is the emitter current at the peak point. It represents the minimum current that is required to trigger the device (UJT). It is inversely proportional to the interbase voltage V_{BB}.
- **Valley Point Voltage V_V** The valley point voltage is the emitter voltage at the valley point. The valley voltage increases with the increase in interbase voltage V_{BB}.
- **Valley Point Current I_V** The valley point current is the emitter current at the valley point. It increases with the increase in inter-base voltage V_{BB}.
- **Special Features of UJT.** The special features of a UJT are :
- A stable triggering voltage (V_P)— a fixed fraction of applied inter base voltage V_{BB}.
- A very low value of triggering current.
- A high pulse current capability.
- A negative resistance characteristic.
- Low cost.

UJT Static Characteristics



(b) Static characteristics

- Cutoff region Cutoff region is the area where the Unijunction Transistor (UJT) doesn't get sufficient voltage to turn on. The applied voltage VE hasn't reached the triggering point, thus making transistor to remain in off state.
- Negative Resistance region When the emitter reaches the triggering voltage, VTRIG, Unijunction Transistor (UJT) will turn on. After a certain time, if the voltage applied to the emitter lead increases, it will reach out at VPEAK. The voltage drops from VPEAK to Valley Point even though the current increases (negative resistance).
- Saturation region is the part of characteristic curve in which the current and voltage both increase, if the applied voltage to emitter terminal increases.

The period of oscillation, T, $$T = \frac{1}{f} \approx RC \ln \frac{1}{1 - \eta} \qquad (9.23)$$

where the parameter η is called the *intrinsic stand-off ratio*. The value of η lies between 0.51 and 0.82.

Resistor R is limited to a value between 3 kΩ and 3 MΩ. The upper limit on R is set by the requirement that the load line formed by R and V_s intersects the device characteristics to the right of the peak point but to the left of the valley point. If the load line fails to pass to the right of the peak point, the UJT cannot turn on. This condition can be satisfied if $V_s - I_p R > V_p$. That is,

$$R < \frac{V_s - V_p}{I_p} \qquad (9.24)$$

At the valley point $I_E = I_V$ and $V_E = V_v$ so that the condition for the lower limit on R to ensure turning off is $V_s - I_v R < V_v$. That is,

$$R > \frac{V_s - V_v}{I_v} \qquad (9.25)$$

The recommended range of supply voltage V_s is from 10 to 35 V. For fixed values of η, the peak voltage V_p varies with the voltage between the two bases, V_{BB}. V_p is given by

$$V_p = \eta V_{BB} + V_D(= 0.5\text{ V}) \approx \eta V_s + V_D(= 0.5\text{ V}) \qquad (9.26)$$

where V_D is the one-diode forward voltage drop. The width t_g of triggering pulse is

$$t_g = R_{B1}C \qquad (9.27)$$

In general, R_{B1} is limited to a value below 100 Ω, although values up to 2 or 3 kΩ are possible in some applications. A resistor R_{B2} is generally connected in series with base-two to compensate for the decrease in V_p due to temperature rise and to protect

the UJT from possible thermal runaway. Resistor R_{B2} has a value of 100 Ω or greater and can be determined approximately from

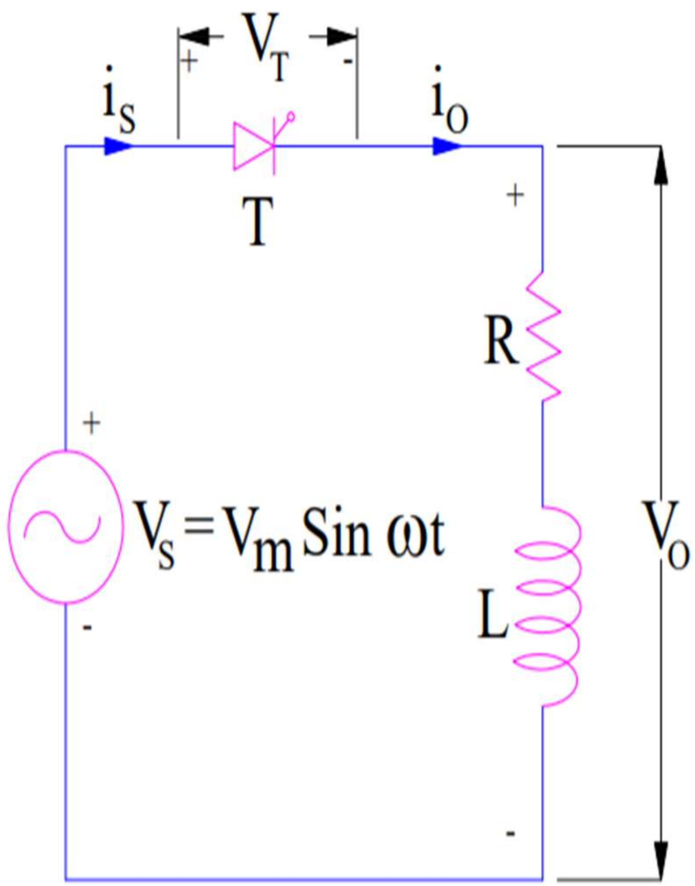
$$R_{B2} = \frac{10^4}{\eta V_s} \qquad (9.28)$$

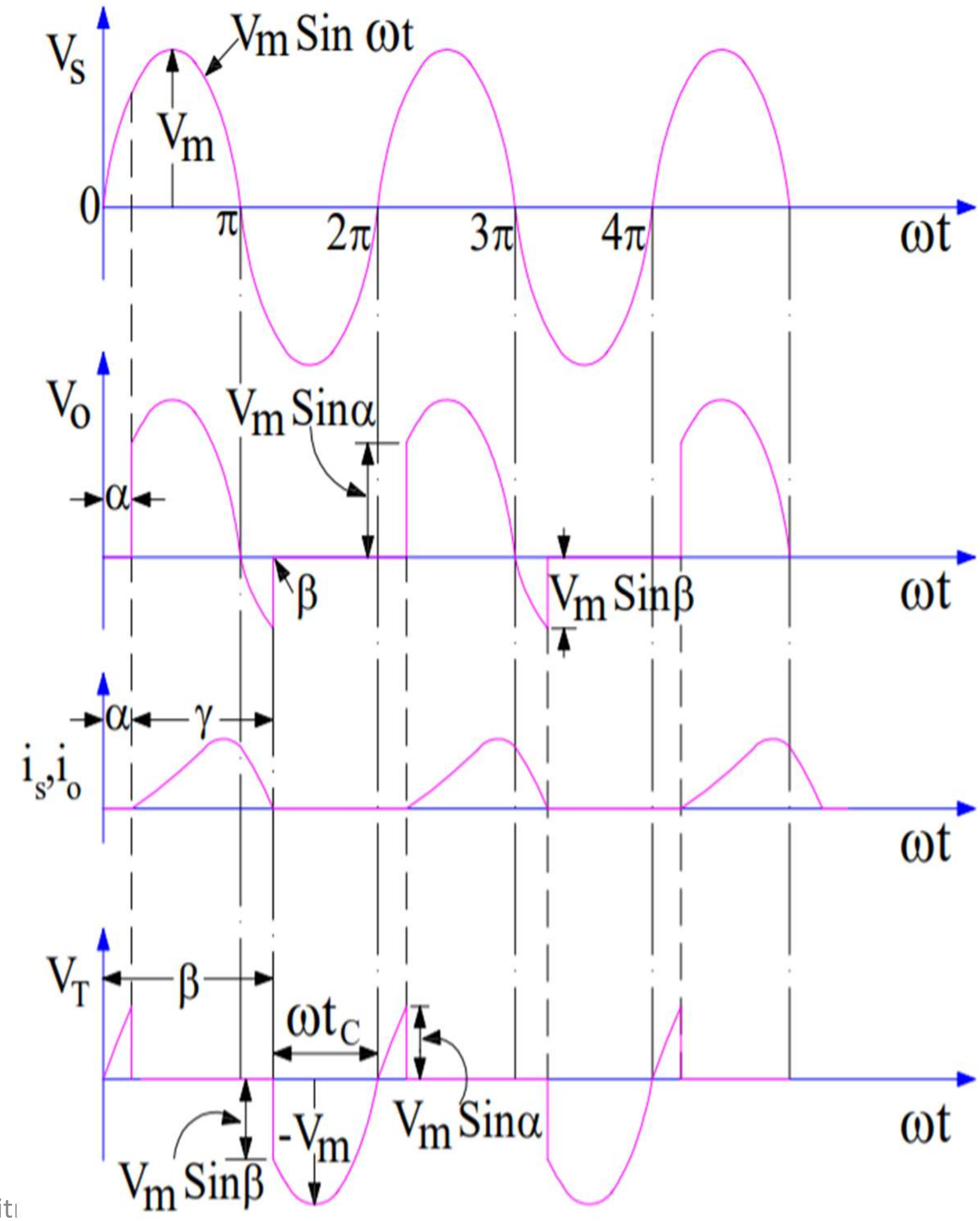
Module 4

Q.7 (a) **With neat circuit and waveforms derive an expression for the rms value of output voltage of single phase half wave controlled rectifier with RL load. (10 marks)**

Fig. circuit Diagram

Single Phase Half/Semi wave Controlled Rectifier with RL Load





- A single phase half wave controlled rectifier is a thryristor based circuit which produces output voltage for positive half of the supply voltage.
- However, the phase relationship between the initiation of load current and supply voltage can be controlled by changing firing angle.
- This is the reason; it is called phase controlled half wave rectifier.
- Single Phase half Wave Controlled Rectifier with RL load.

At ωt = α

- It is assumed that the thyristor T is fired at an angle ωt = α.
- As soon as the thyristor T is fired at ωt = α, load voltage equal to the source voltage instantaneously appears across the load terminal.
- This is because, the thyristor is forward biased in between ωt = 0 to α.
- Hence, once the thyristor is gated, it stars conducting.
- However, the current does not start at this instant of firing.
- This is just because of the nature of load.
- Since, the load is inductive, it will not allow any sudden change.
- Therefore, at ωt = α, the output current will be zero and will gradually increase.
- The output current will become maximum and then start decreasing.
- It should be noted here that, this behavior of load current i_o will not be observed for purely resistive load.

At $\omega t = \pi$

- The load voltage V_o reduces to zero.
- However, the load current will not be zero at this instant because of inductance L.
- Due to this, thyristor will not turn off, even though it is reversed biased.
- Rather it will continue to conduct till $\omega t = \beta$.

At $\omega t = \beta$

- The load current becomes zero and thyristor is reversed biased, hence it will turn off.
- This is a case of natural commutation.

After $\omega t = \beta$

- $V_o = 0$ and $i_o = 0$.

At $\omega t = (2\pi+\alpha)$

- the SCR is triggered again, v_o is applied to the load and load current develops as discussed before.

Extinction angle β

- The angle β where the load current becomes zero is called ***extinction angle***

Conduction angle γ

- The angle (β-α) for which thyristor is ON is called ***conduction angle***.

Circuit turn off time

- The SCR is reverse biased from $\omega t = \beta$ to $\omega t = 2\pi$.
- During this period, the current through thyristor is also zero.
- Therefore, circuit turn off time is $t_c = [(2\pi - \beta) / \omega]$ second.
- This time must be greater than the thyristor turn-off time otherwise thyristor may turn on at undesired instant and will lead to commutation failure.

Calculation of RMS Load Voltage:

RMS load voltage of single phase half wave controlled rectifier is given as below.

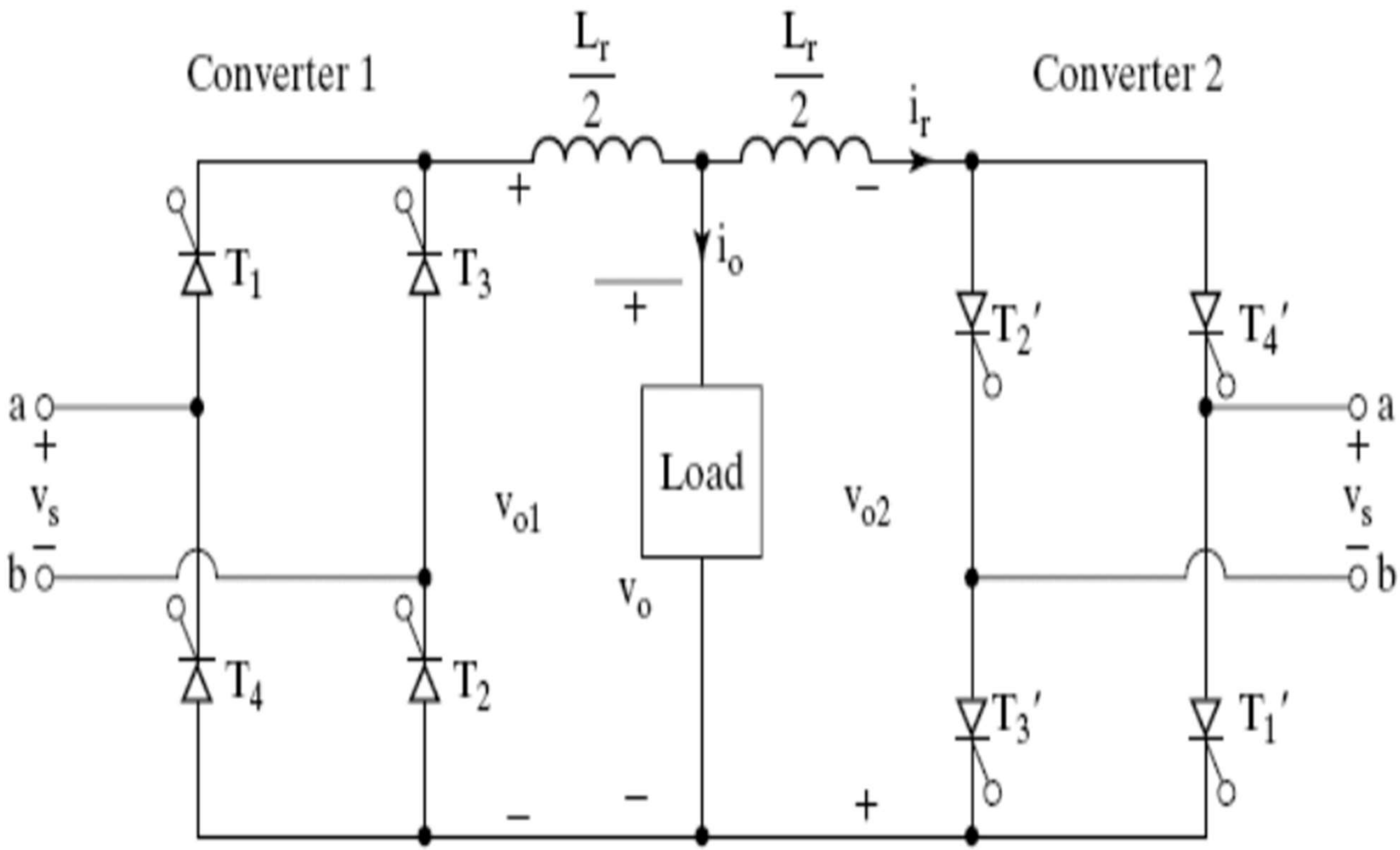
$$RMS\ Voltage, Vo = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\beta}(Vm\sin\omega t)^2\, d(\omega t)}$$

$$= \frac{Vm}{2\sqrt{\pi}}\sqrt{[(\beta-\alpha)-1/2\{\sin 2\beta-\sin 2\alpha\}]}$$

Q. 7 (b) Explain the working of single phase dual converter circuit with the help of waveforms for RL load. (10 marks)

- Dual converter- the name itself indicates that it has two converters in it.
- In the case of a single phase full converter with inductive loads, the converter can operate in two different quadrants in the *Vdc* versus *Idc* operating diagram.
- If two single phase full converters are connected in parallel and in opposite direction (connected in back to back) across a common load four quadrant operation is possible.
- Such a converter is called as a dual converter.
- The dual converter system will provide four quadrant operation
- Normally used in high power industrial variable speed drives.

Single Phase Dual Converter



- Two single phase full converters are connected in parallel and in opposite direction (connected in back to back) across a common load

Converter 1

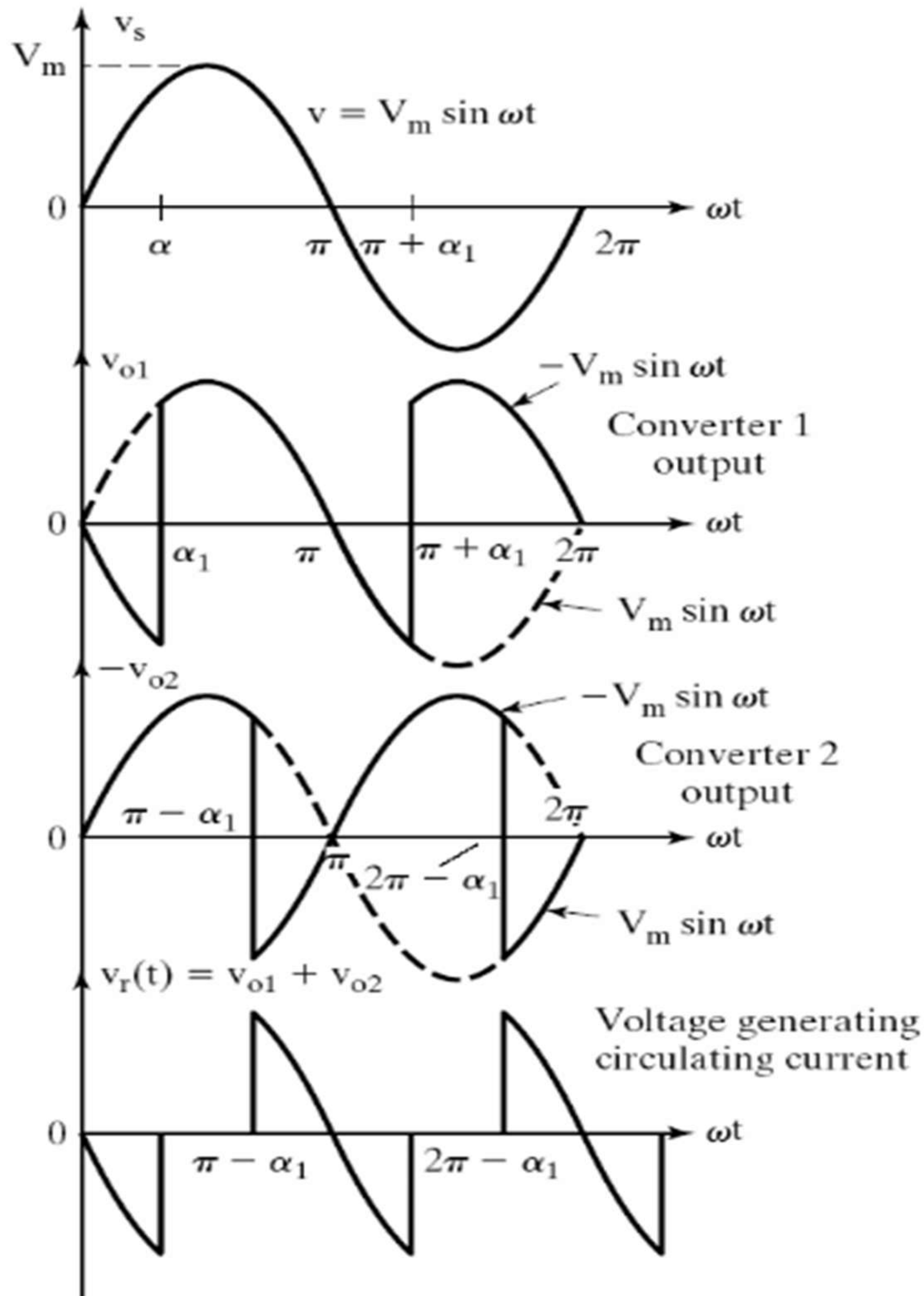
- The converter number 1 provides a positive dc output voltage and a positive dc load current, when operated in the rectification mode.
- The converter number 1 provides a negative dc output voltage and a positive dc load current, when operated in the inverter mode.

Converter 2

- The converter number 2 provides a negative dc output voltage and a negative dc load current when operated in the rectification mode.
- The converter number 2 provides a positive dc output voltage and a negative dc load current when operated in the inverter mode.

- We can have **bi- directional load current and bi-directional dc output voltage.**
- The magnitude of output dc load voltage and the dc load current can be controlled by varying the trigger angles **α** 1 & **α** 2 of the converters 1 and 2 respectively.
- **α 1 - Firing angle for converter 1**
- **α 2 - Firing angle for converter 2**

Waveforms for Dual Converter



(b) Waveforms

Vdc1 – DC output voltage of converter 1

Vdc2 – DC output voltage of converter 2

The delay angles are controlled such that one operates as rectifier and the other operates as inverter, but both produce the same average output voltage.

Average Output Voltage

The average dc output voltage of converter 1 is

$$V_{dc1} = \frac{2V_m}{\pi}\cos\alpha_1$$

The average dc output voltage of converter 2 is

$$V_{dc2} = \frac{2V_m}{\pi}\cos\alpha_2$$

Condition for α_1 and α_2

In the dual converter operation one converter is operated as a controlled rectifier with $\alpha_1 < 90^0$ and the second converter is operated as a line commutated inverter in the inversion mode with $\alpha_2 > 90^0$.

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

$$\frac{2V_m}{\pi}\cos\alpha_1 = \frac{-2V_m}{\pi}\cos\alpha_2 = \frac{2V_m}{\pi}\left(-\cos\alpha_2\right)$$

Therefore $\cos\alpha_1 = -\cos\alpha_2$ or $\cos\alpha_2 = -\cos\alpha_1 = \cos\left(\pi - \alpha_1\right)$

Therefore $\alpha_2 = \left(\pi - \alpha_1\right)$ or $\left(\alpha_1 + \alpha_2\right) = \pi$ radians

Which gives $\alpha_2 = \left(\pi - \alpha_1\right)$

When $\alpha_1 < 90^0$ (say $\alpha_1 = 30^0$) the converter 1 operates as a controlled rectifier and converts the ac supply into dc output power and the average load current I_{dc} is positive. At the same time the converter 2 is switched on and operated as a line commutated inverter, by adjusting the trigger angle α_2 such that $\alpha_2 = \left(180^0 - \alpha_1\right)$, which is equal to 150^0, when $\alpha_1 = 30^0$. The converter 2 will operate in the inversion mode and feeds the load energy back to the ac supply. When we want to reverse the load current flow we have to switch the roles of the two converters.

When converter 2 is operated as a controlled rectifier by adjusting the trigger angle α_2 such that $\alpha_2 < 90^0$, the first converter1 is operated as a line commutated inverter, by adjusting the trigger angle α_1 such that $\alpha_1 > 90^0$. The trigger angle α_1 is adjusted such that $\alpha_1 = \left(180^0 - \alpha_2\right)$ for a set value of α_2.

Four Quadrant operation of Dual Converter

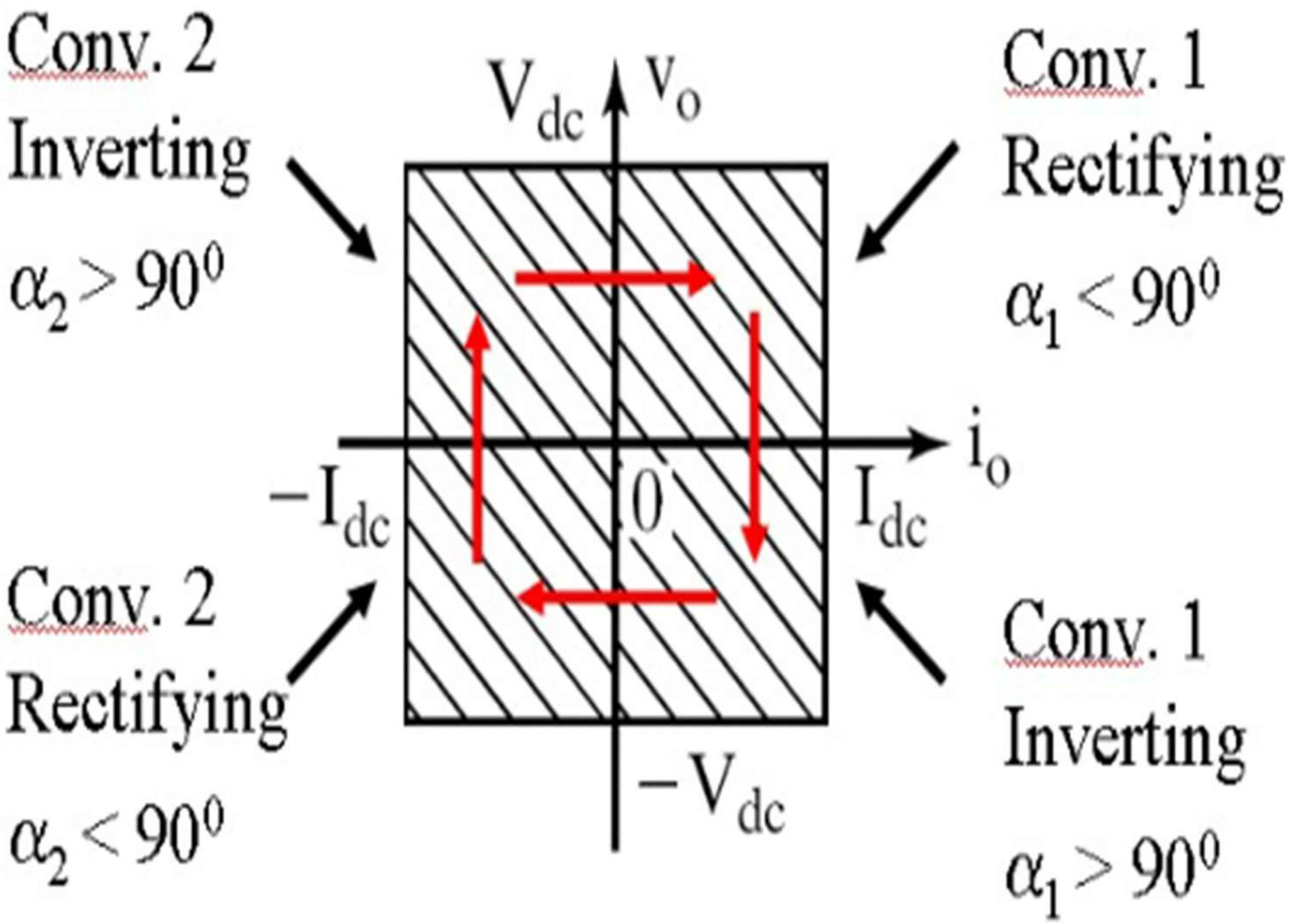


Fig.: Four quadrant operation of a dual converter

Modes of operation of Dual converter

- There are two modes of operations possible for a dual converter system.

1. Circulating current mode of operation.
2. Non circulating current mode of operation (circulating current free mode of operation).

CIRCULATING CURRENT MODE OF OPERATION

- In this mode of operation both the converters 1 and 2 are switched on and operated simultaneously and both the converters are in a state of conduction.
- If converter 1 is operated as a controlled rectifier by adjusting the trigger angle α_1 **between 0 to 90º** **($0<\alpha_1< 90^o$)**
- The second converter 2 is operated as a line commutated inverter by increasing its trigger angle α_2 **above 90** **($90^o<\alpha_2<180^o$)**.
- The trigger angles α_1 and α_2 are adjusted such that they produce the same average dc output voltage across the load terminals.
- Instantaneous output voltages of two converters are out of phase , this voltage difference causes circulating current between two converters.
- This cannot flow through the load, and it is limited by limiting reactor.

Current Limiting Reactor Lr

- In the circulating current mode a current builds up between the two converters even when the load current falls to zero.

- In order to limit the circulating current flowing between the two converters, we have to include current limiting reactors in series between the output terminals of the two converters.

Advantages of circulating current mode of operation

- We can have faster reversal of load current as the two converters are in a state of conduction simultaneously.
- This greatly improves the dynamic response of the output giving a faster dynamic response.
- The output voltage and the load current can be linearly varied by adjusting the trigger angles α_1 **and** α_2 to obtain a smooth and linear output control.
- The control circuit becomes relatively simple.
- Output response is very fast.
- The load current is free to flow in either direction at any time.
- The reversal of the load current can be done in a faster and smoother way.

Disadvantages of circulating current mode of operation

- Current flows continuously in the dual converter circuit even at times when the load current is zero.
- Hence we should connect current limiting inductors (reactors) in order to limit the peak circulating current within specified value.
- The circulating current flowing through the series inductors gives rise to increased power losses, due to dc voltage drop across the series inductors which decreases the efficiency.
- Also the power factor of operation is low.
- The current limiting series inductors are heavier and bulkier which increases the cost and weight of the dual converter system.

Non Circulating Current Mode

- Only One converter will perform at a time.
- In this mode of operation only one converter is switched on at a time while the second converter is switched off.
- So there is no circulating current between the converters.
- During the converter 1 operation, firing angle (α_1) will be $0<\alpha_1< 90^o$; V_{dc} and I_{dc} are positive.
- During the converter 2 operation, firing angle (α_2) will be $0<\alpha_2< 90^o$; V_{dc} and I_{dc} are negative.
- No need of Limiting reactor.

Advantages of non circulating current mode of operation

- No circulating current flowing between the two converters as only one converter operates and conducts at a time while the other converter is switched off.
- Hence there is no need of the series current limiting inductors between the outputs of the two converters.
- The current rating of thyristors is low in this mode.

Disadvantages of non circulating current mode of operation

- Load current tends to become discontinuous and the transfer characteristic becomes non linear.
- The control circuit becomes complex and the output response is slow as the load current reversal takes some time due to the time delay between the switching off of one converter and the switching on of the other converter.
- Hence the output dynamic response is poor.
- Whenever a fast and frequent reversal of the load current is required, the dual converter is operated in the circulating current mode.

Application of Dual Converter

- Direction and speed control of DC motors.
- Applicable wherever the reversible DC is required.
- Industrial variable speed DC drives.

Q 8 (a) Derive an expression for rms value of the output voltage for single phase full wave AC voltage controller with resistive load. (7 marks)

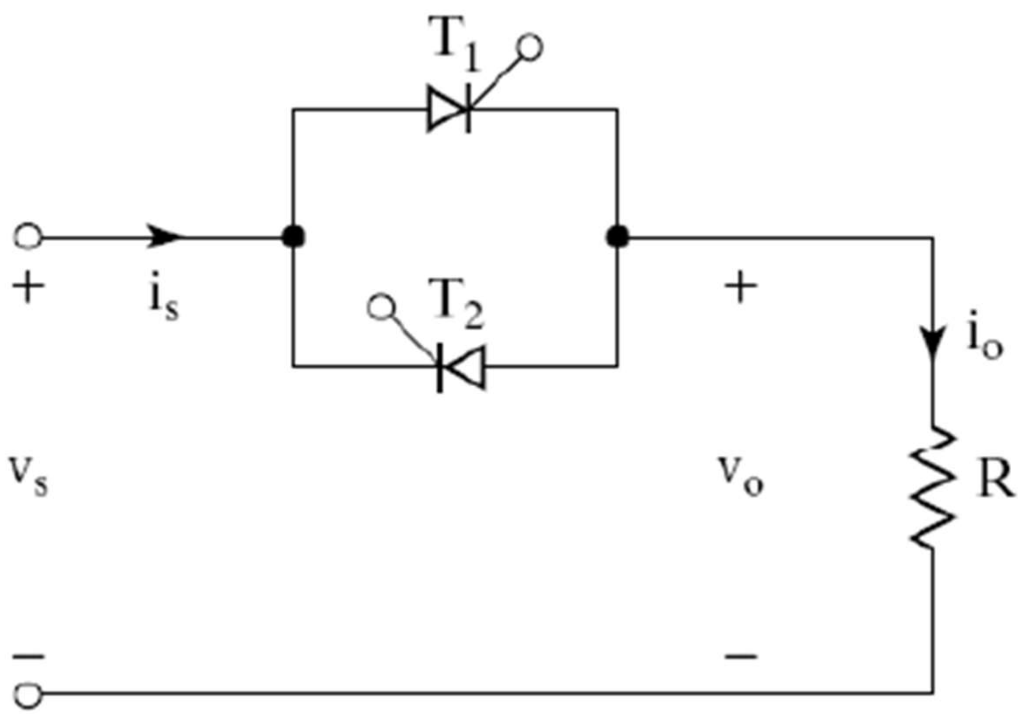
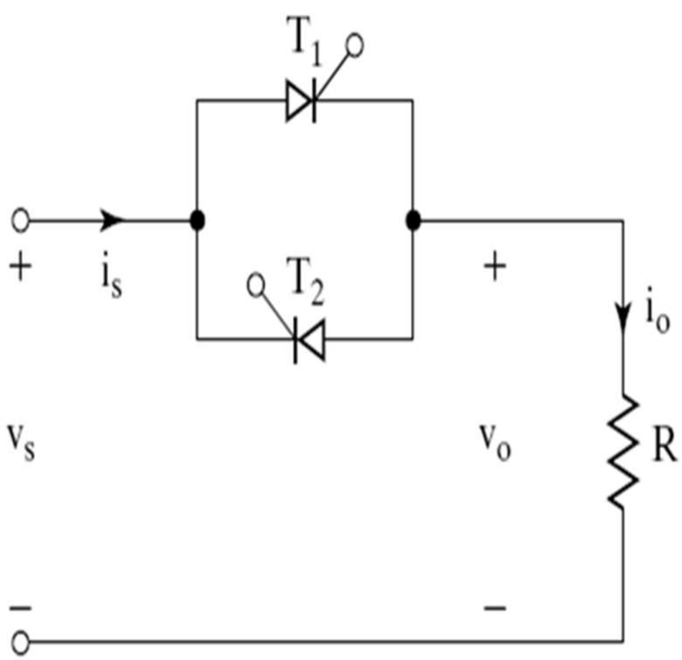


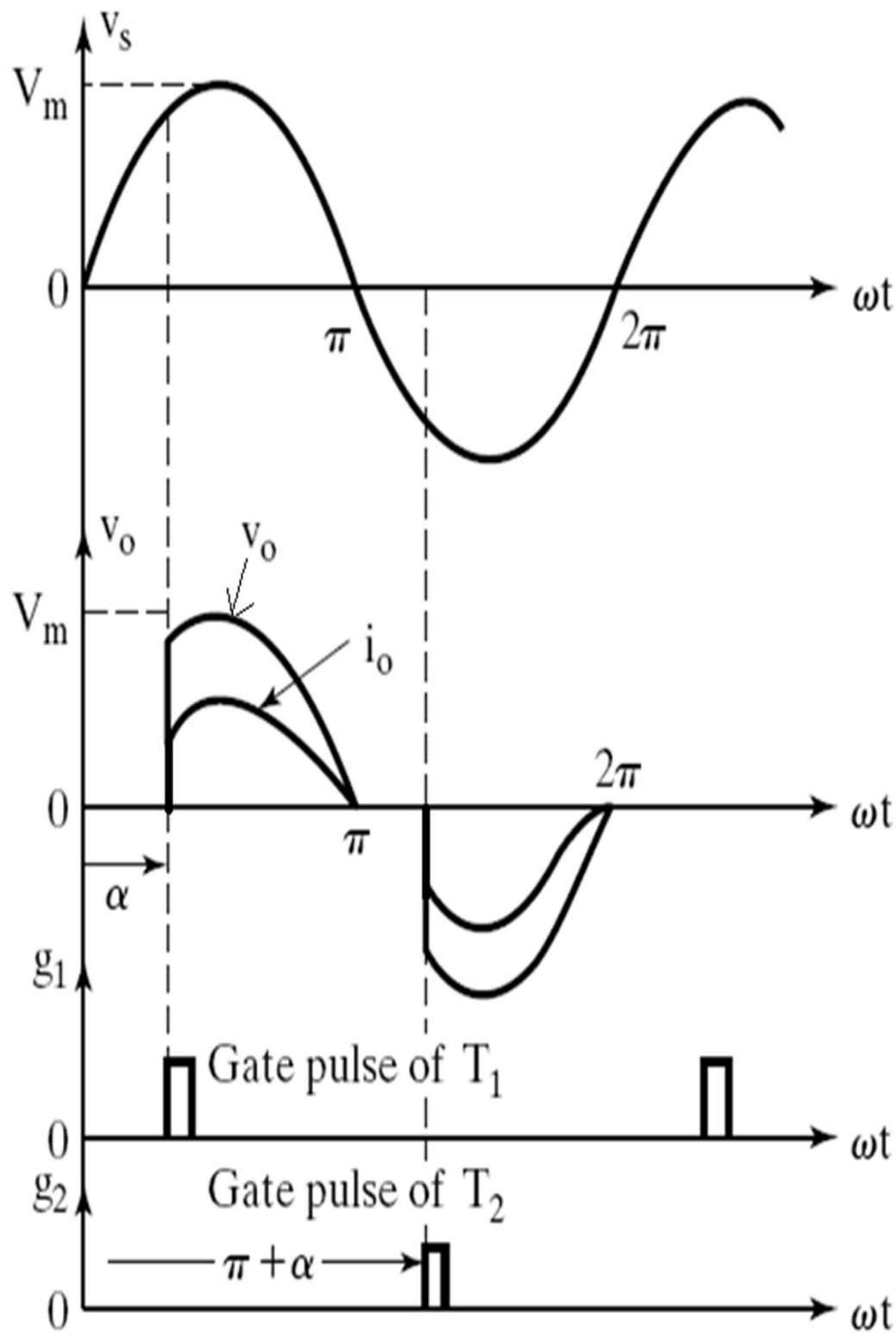
Fig. Circuit Diagram

Single phase Full wave AC voltage controller – R load

- Single phase full wave ac voltage controller is called bidirectional controller – AC Regulator.
- Single phase full wave ac voltage controller circuit using two Thyristors (T1 and T2) or a single triac is generally used in most of the ac control applications.
- The ac power flow to the load can be controlled in both the half cycles by varying the trigger angle 'α'.
- The RMS value of load voltage can be varied by varying the trigger angle 'α'.

Output Voltage and Current Waveform





During Positive Half Cycle $\omega t = 0$ to π

- The thyristor *T*1 is forward biased during the positive half cycle of input ac supply.
- It can be triggered and made to conduct by applying a suitable gate trigger pulse '**α**'. only during the positive half cycle of input supply.
- When *T*1 is triggered it conducts and the load current flows through the thyristor *T*1, the load and through the transformer secondary winding.
- By assuming *T*1 as an ideal thyristor switch it can be considered as a closed switch when it is ON during the period $\omega t = \alpha$ to π radians. Output Voltage $V_o = V_s$
- The output voltage across the load follows the input supply voltage when the thyristor *T*1 is turned-on and when it conducts from $\omega t = \alpha$ to π radians.
- When the input supply voltage decreases to zero at $\omega t = \pi$, for a resistive load the load current also falls to zero at $\omega t = \pi$
- Thyristor *T*1 turns off naturally at $\omega t = \pi$. Hence load current also zero at $\omega t = \pi$

During Negative Half Cycle $\omega t = \pi$ to 2π

- Between the time period to $\omega t = \pi$ to 2π,
- The thyristor *T*2 is forward biased during the negative cycle of input supply
- Thyristor *T*2 is triggered at a delay angle ($\pi+\alpha$)
- The output voltage follows the negative halfcycle of input from $\omega t = \pi+\alpha$ to 2π.
- When *T*2 is ON, the load current flows in the reverse direction (upward direction) through *T*2 during $\omega t = \pi+\alpha$ to 2π.
- The time interval (spacing) between the gate trigger pulses of *T*1 and *T*2 is kept at π radians or 180 degrees.
- Thyristor *T*2 turns off naturally at $\omega t = 2\pi$. Hence load current also zero at $\omega t = \pi$

EXPRESSION FOR RMS OUTPUT VOLTAGE *VO(RMS)*

$$v_S = V_m \sin \omega t = \sqrt{2} V_S \sin \omega t$$

$$V_o = \sqrt{\frac{2}{2\pi} \int_{\alpha}^{\pi} 2V_s^2 \sin^2 \omega t \, d(\omega t)}$$

$$= \sqrt{\frac{4V_s^2}{4\pi} \int_{\alpha}^{\pi} (1 - \cos 2\omega t) d(\omega t)}$$

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

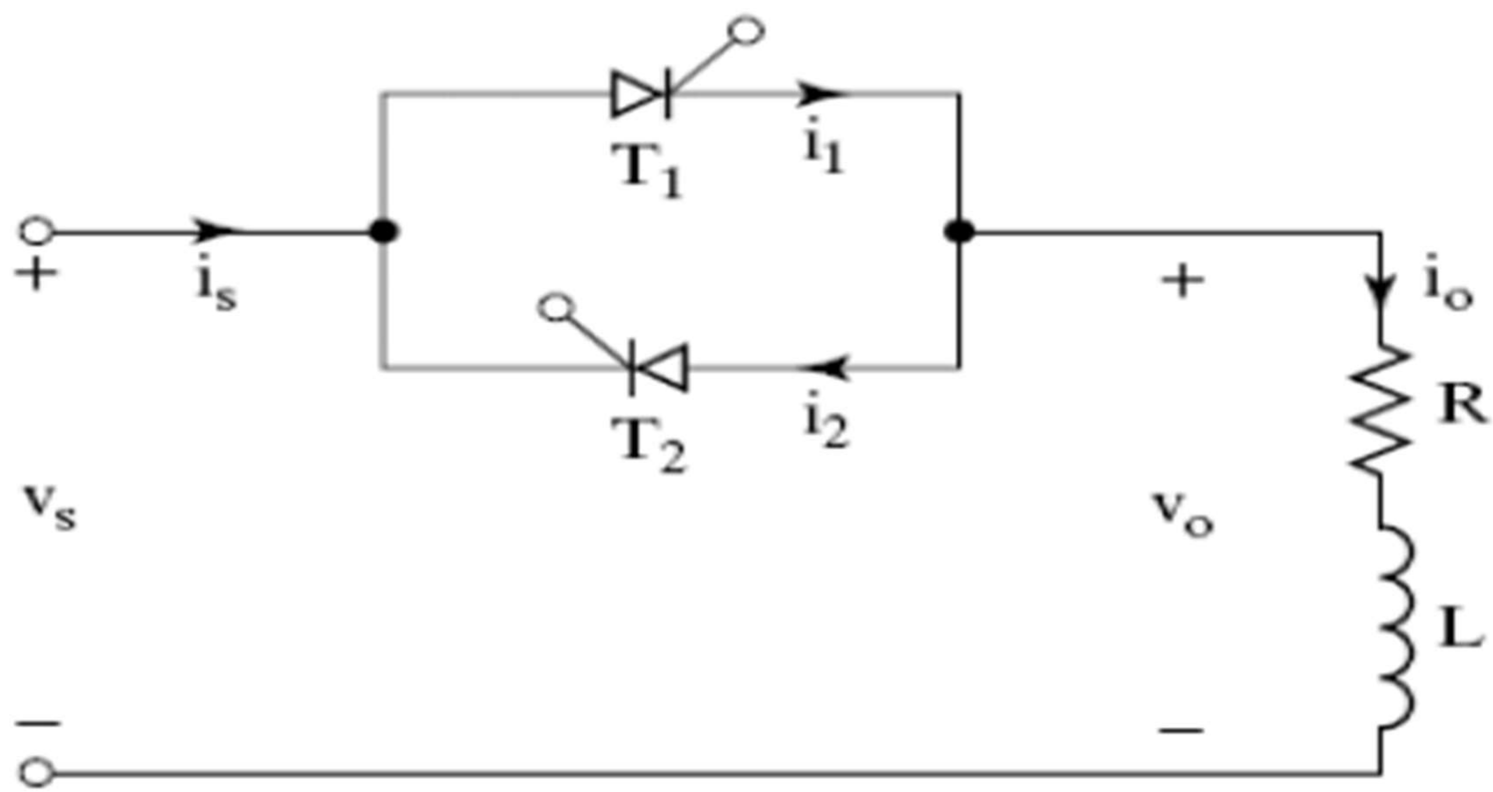
$$= V_s \sqrt{\frac{1}{\pi} \left[(\pi - \alpha) - \left\{ \frac{\sin 2\pi}{2} - \frac{\sin 2\alpha}{2} \right\} \right]}$$

$$; \sin 2\pi = 0$$

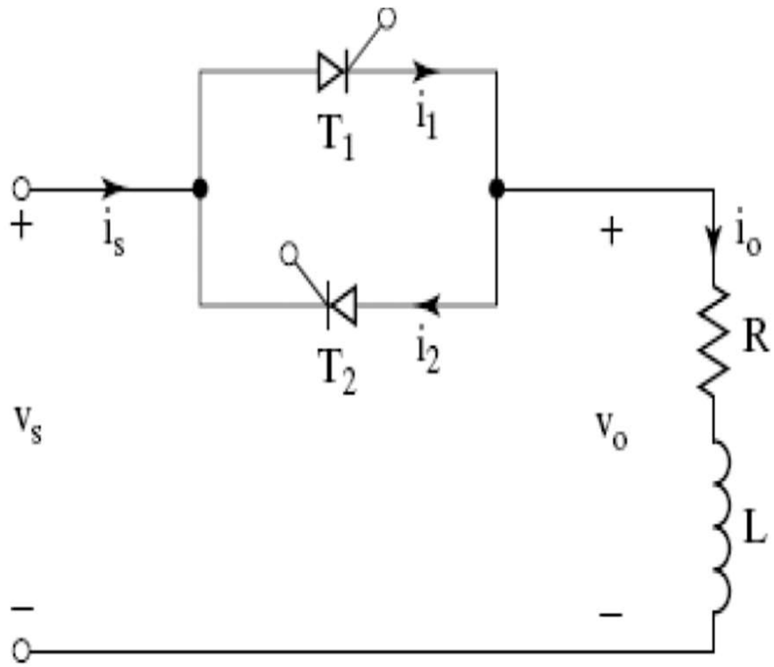
$$V_o = V_s \sqrt{\frac{1}{\pi} \left(\pi - \alpha + \frac{\sin 2\alpha}{2} \right)}$$

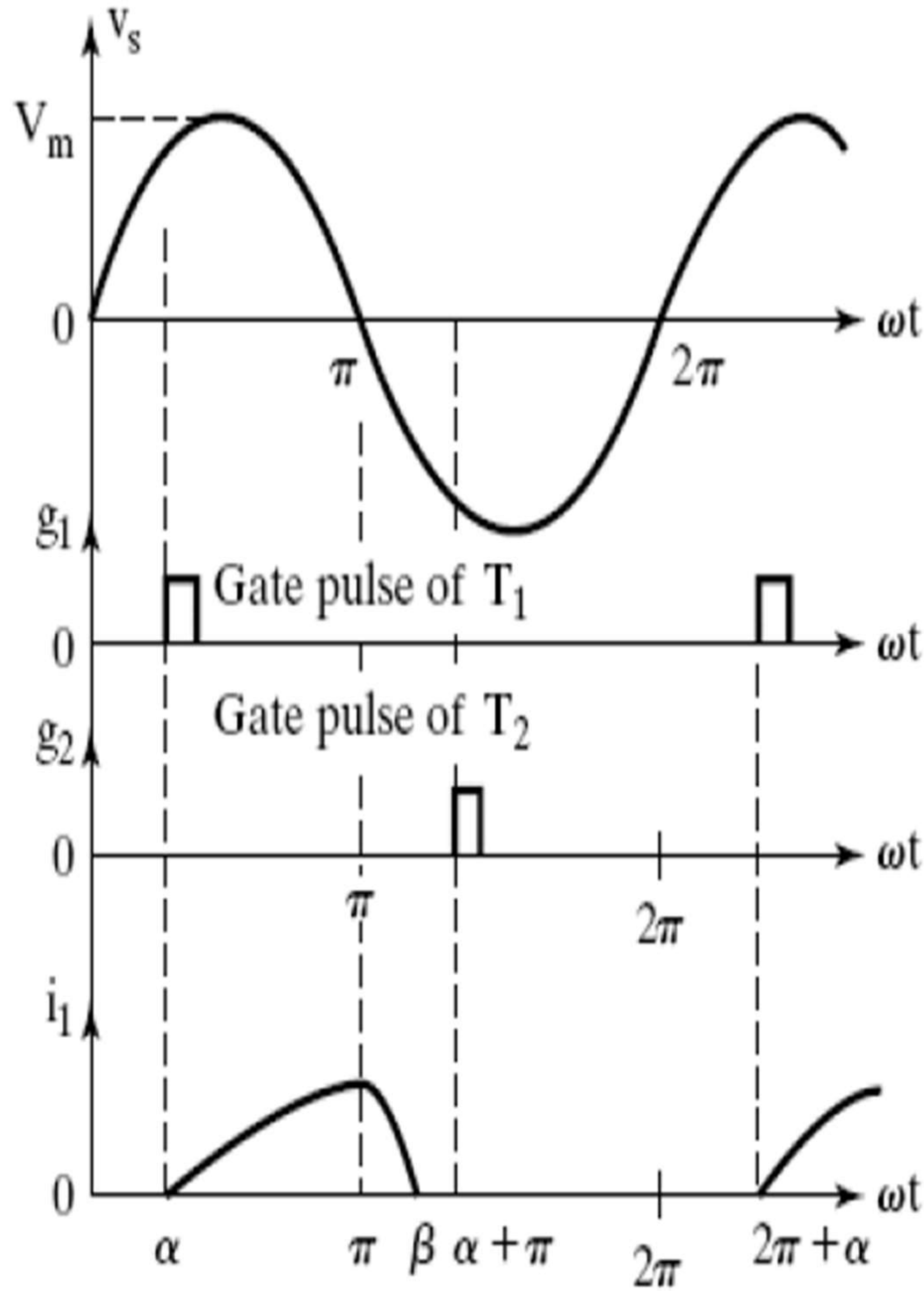
Q.08. b An on-off controller with an input of 230 V, 50 Hz is connected to a resistive load of 20Ω. The circuit is operating with the switch ON for 30 cycles and OFF for 30 cycles. Determine (i) R.M.S output current (ii0 Input power factor. (7 marks)

Q. 8 (c) Explain the operation of 1-Φ phase control type of voltage controller with RL load. (6 marks)



Input Supply Voltage and Thyristor Current Waveform





GATE PULSE TO T1 and T2

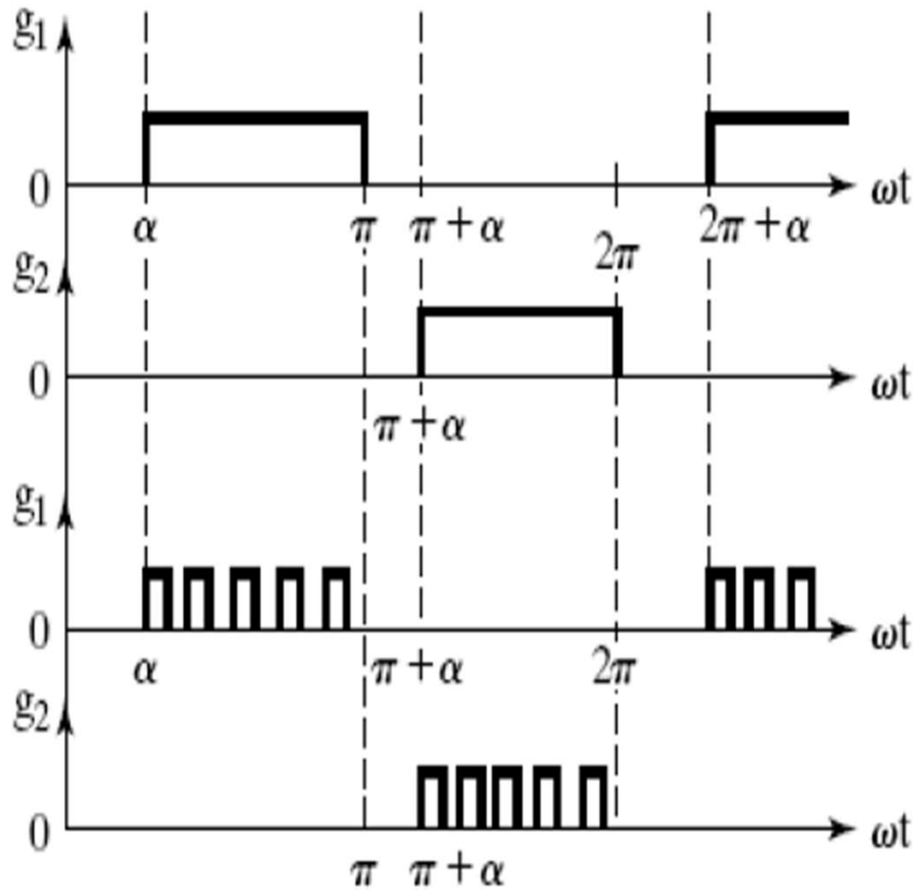


Fig.: Gating Signals

Output Voltage and Current Waveform

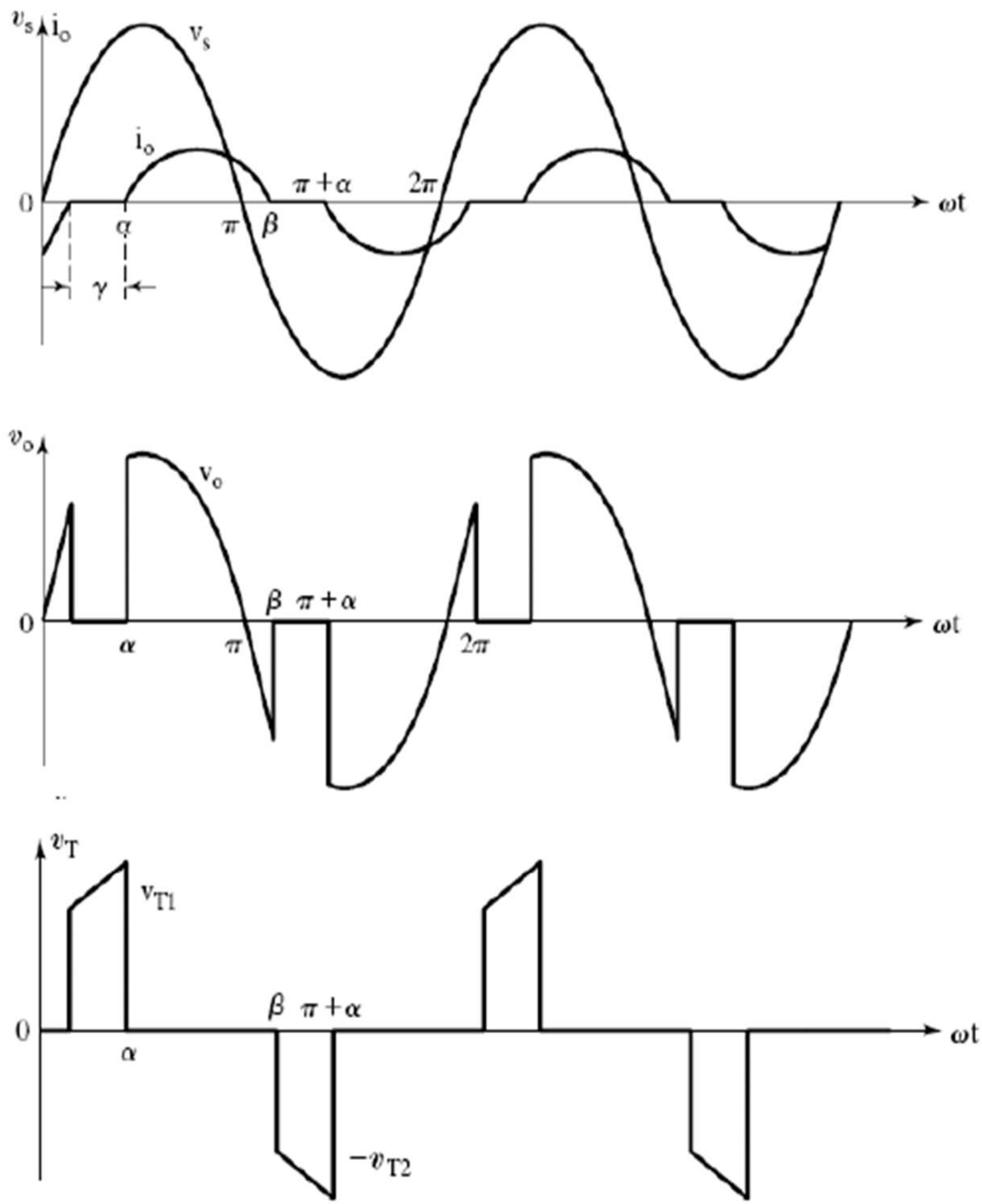


Fig.: Waveforms of Input supply voltage, Load Current, Load Voltage and Thyristor Voltage across T_1

During Positive Half Cycle $\omega t = 0$ to π

- The thyristor *T*1 is forward biased during the positive half cycle of input ac supply.
- It can be triggered and made to conduct by applying a suitable gate trigger pulse '**α**'. only during the positive half cycle of input supply.
- When *T*1 is triggered it conducts and the load current flows through the thyristor *T*1, the load and through the transformer secondary winding.
- By assuming *T*1 as an ideal thyristor switch it can be considered as a closed switch when it is ON during the period $\omega t = \alpha$ to π radians. Output Voltage $V_o = V_s$
- Due to the inductance in the load, the load current *i0* flowing through *T*1 would not fall to zero at $\omega t = \pi$, when the input supply voltage starts to become negative.
- The thyristor *T*1 will continue to conduct the load current until all the inductive energy stored in the load inductor L is completely utilized and the load current through *T*1 falls to zero at $\omega t = \beta$.
- β is referred to as the Extinction angle, (the value of ωt) at which the load current falls to zero.

Conduction Period of T1 $\omega t = \alpha$ to β

- β is referred to as the Extinction angle, (the value of ωt) at which the load current falls to zero.
- The thyristor *T*1 conducts from **$\omega t = \alpha$ to** β.
- The conduction angle of *T*1 is $\delta = (\beta - \alpha)$, which depends on the delay angle α and the load impedance angle ϕ.
- Thyristor *T*1 turns off naturally at $\omega t = \beta$.
- Hence load current flows from at $\omega t = \alpha$ **to** β.
- β is the extinction angle which depends upon the load inductance value.

During Negative Half Cycle $\omega t = \pi$ to 2π

- Between the time period to $\omega t = \pi$ to 2π,
- The thyristor $T2$ is forward biased during the negative cycle of input supply
- Thyristor $T2$ is triggered at a delay angle ($\pi+\alpha$)
- The output voltage follows the negative half cycle of input from $\omega t = \pi+\alpha$ to 2π.
- When $T2$ is ON, the load current flows in the reverse direction (upward direction) through $T2$ during $\omega t = \pi+\alpha$ to $2\pi+\beta$, because of inductive load
- The time interval (spacing) between the gate trigger pulses of $T1$ and $T2$ is kept at π radians or 180 degrees.
- Thyristor $T2$ turns off naturally at $\omega t = 2\pi+\beta$.
- Hence load current flows from $\omega t = \pi+\alpha$ to $2\pi+\beta$, due to conduction of T2

The rms output voltage

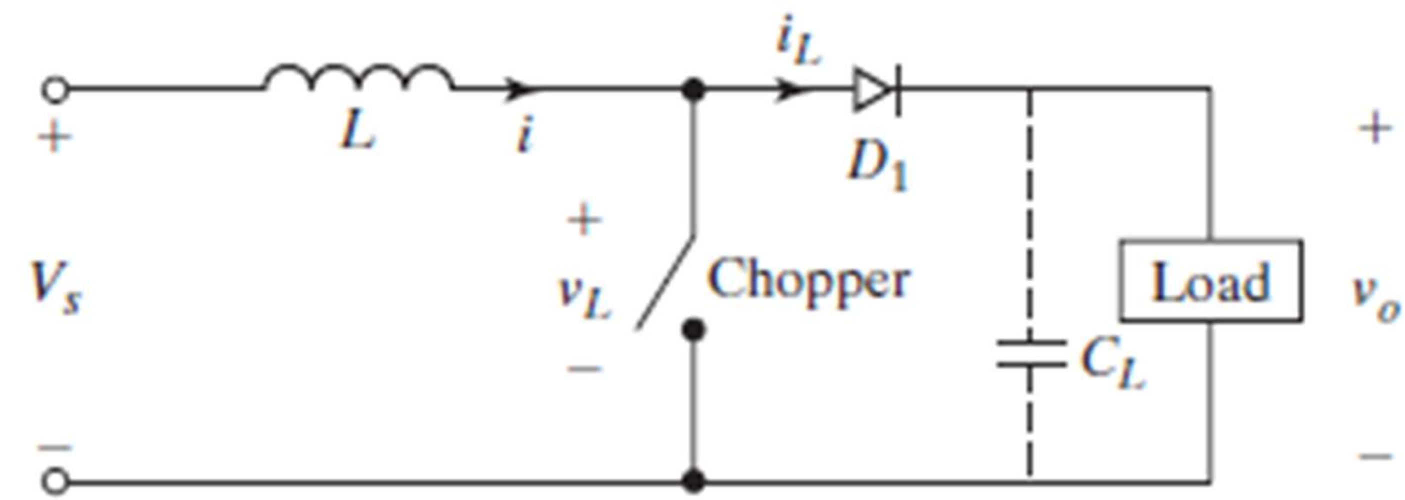
$$V_o = \left[\frac{2}{2\pi}\int_{\alpha}^{\beta} 2V_s^2 \sin^2 \omega t \, d(\omega t)\right]^{1/2}$$

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

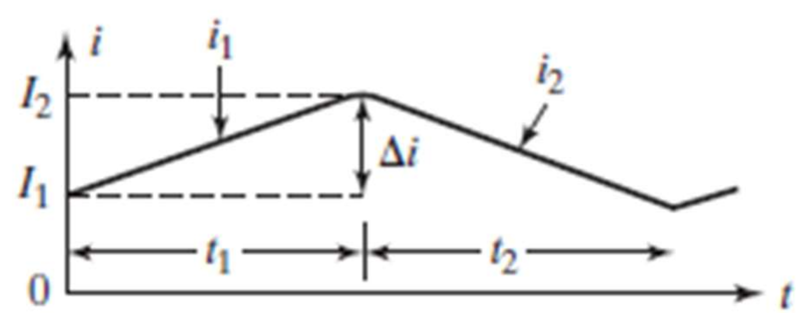
$$= V_s\left[\frac{1}{\pi}\left(\beta - \alpha + \frac{\sin 2\alpha}{2} - \frac{\sin 2\beta}{2}\right)\right]^{1/2}$$

Module 5

9 (a) Obtain an expression for the output voltage for a step-up chopper. (6 marks)



(a) Step-up arrangement



(b) Current waveform

Average Output Voltage Equation

When the converter is turned on, the voltage across the inductor is

$$v_L = L\frac{di}{dt} \Rightarrow di = \frac{v_L}{L}dt = \frac{V_s}{L}t_1$$

and this gives the peak-to-peak ripple current in the inductor as

$$\Delta I = \frac{V_s}{L}t_1$$

The average output voltage is

$$v_o = V_s + L\frac{\Delta I}{t_2}$$

$$= V_s\left(1 + \frac{t_1}{t_2}\right) = V_s\left(1 + \frac{kT}{(1-k)T}\right)$$

$$= V_s\frac{1}{1-k}$$

$$\Delta I = \frac{V_s}{L}t_1$$

$$t_1 = kT$$

$$t_2 = (1-k)T$$

$$\boxed{v_o = V_s\frac{1}{1-k}}$$

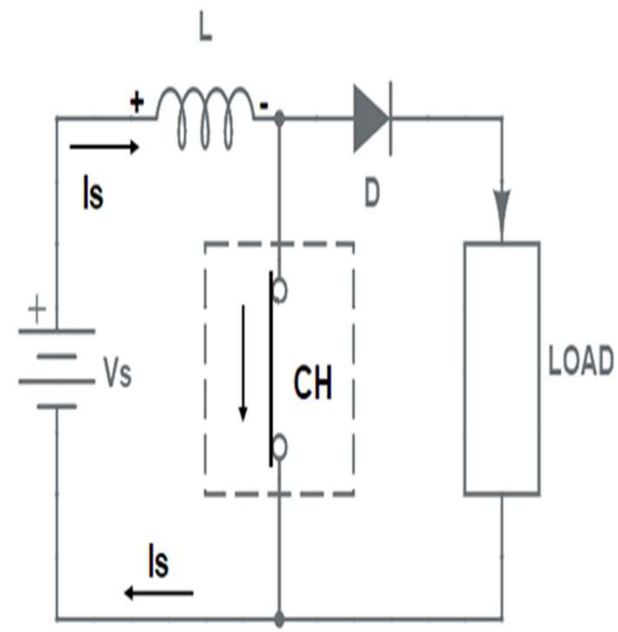
K value can be changed from 0 to 1.

Principle of Step-up Operation

- Step-up chopper is a static device whose average output DC voltage is greater than its input DC voltage.
- A converter can be used to step-up a dc voltage and an arrangement for step-up operation is shown in Figure.
- When switch SW is closed for time t, the inductor current rises and energy is stored in the inductor L.
- *If the switch is opened for time* $t1$, the energy stored in the inductor is transferred to load through diode D and the inductor current falls.

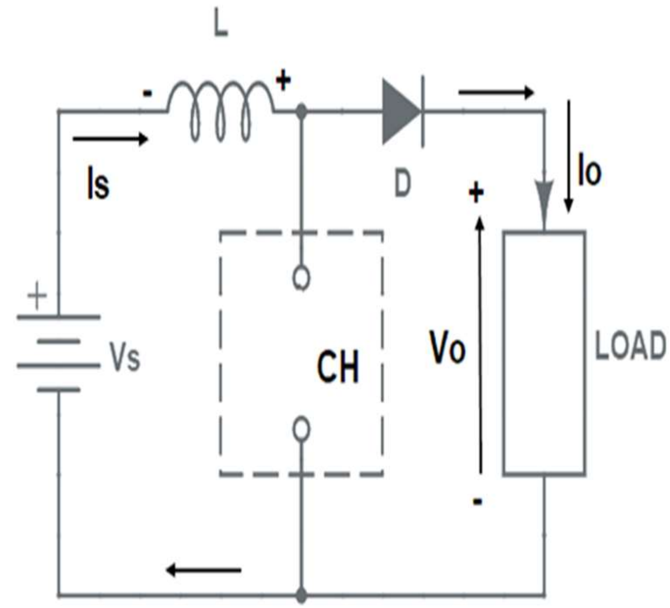
Mode 1: Switch is ON

- When chopper (CH) is switched ON, the current will flow through the closed path formed by supply source Vs, inductor L and chopper CH.
- During this period, no current will flow through the load.
- Only source current i_s will flow and the value of load current i_o will be ZERO during the ON period.
- Also, during the T_{ON} period, energy is stored in the inductor L.
- This energy storage in L is essential to boost the load output voltage above the source voltage.
- Therefore, a large value of L is essential in a step-up chopper.



Mode 2: Switch is OFF

- When the chopper CH is switched OFF, the current through the L can not reduce instantaneously rather it decays exponentially.
- Due to this behavior of L, it will force the current through the diode D and load for the entire time period T_{OFF}.
- Since, the current through the inductor L tends to decrease, the polarity of the emf induced in inductor L is reversed as shown in above figure.
- As a result, the voltage across the load becomes equal to the sum of source voltage and emf induced in inductor.
- Thus, the output voltage exceeds the source voltage V_s.
- The load / output voltage may be written as below.



$$V_0 = V_S + L(di/dt)$$

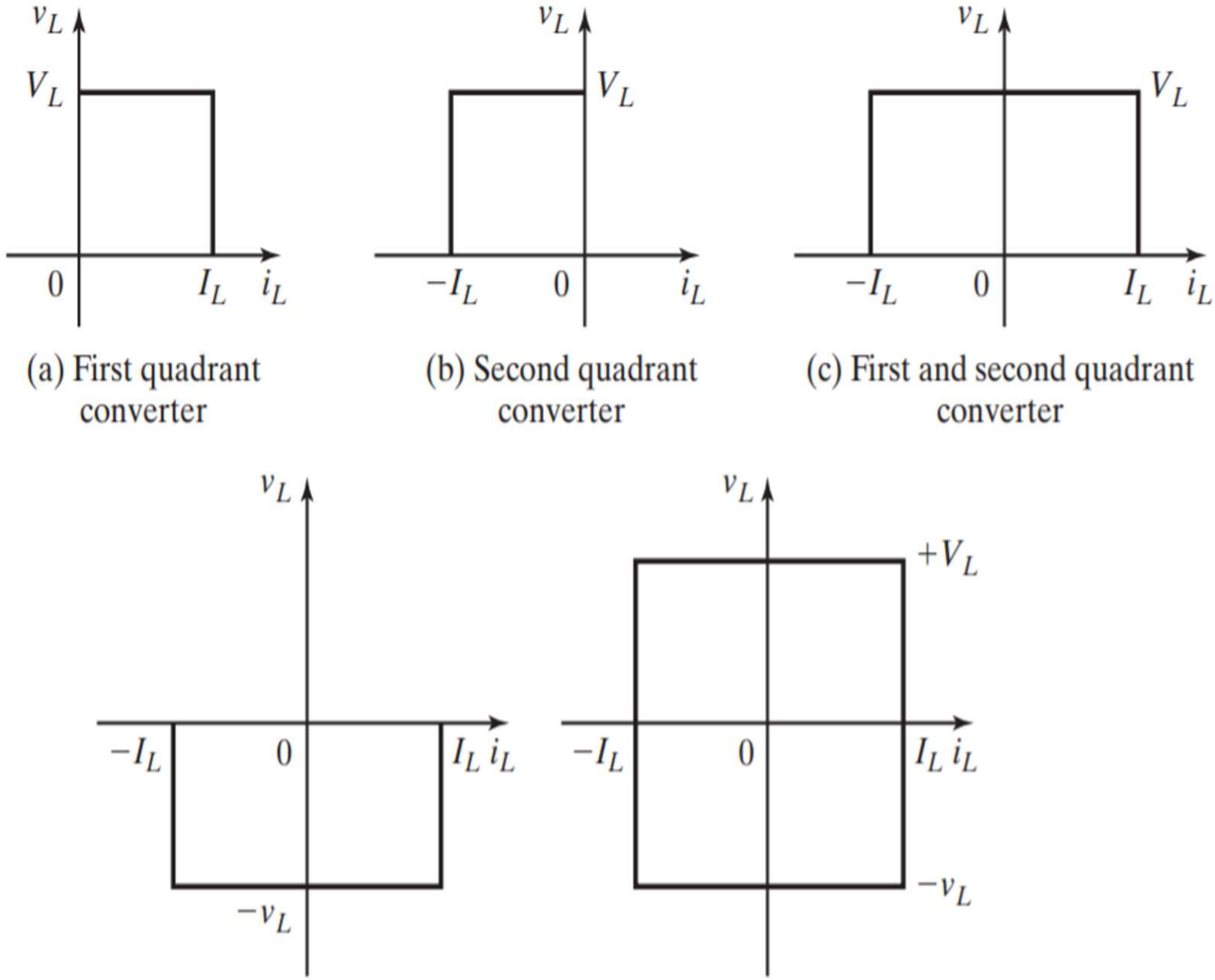
Q 9 (b) Classify choppers and their circuits (4 marks)

Classification of DC-DC Converter / Chopper

DC-DC Converter (Chopper) are classified into five types

1. First quadrant converter / Class A Chopper
2. Second quadrant converter / Class B Chopper
3. First and second quadrant converter / Class C Chopper
4. Third and fourth quadrant converter / Class D Chopper
5. Four-quadrant converter / Class E Chopper

Classification of DC-DC Converter / Chopper



(a) First quadrant converter

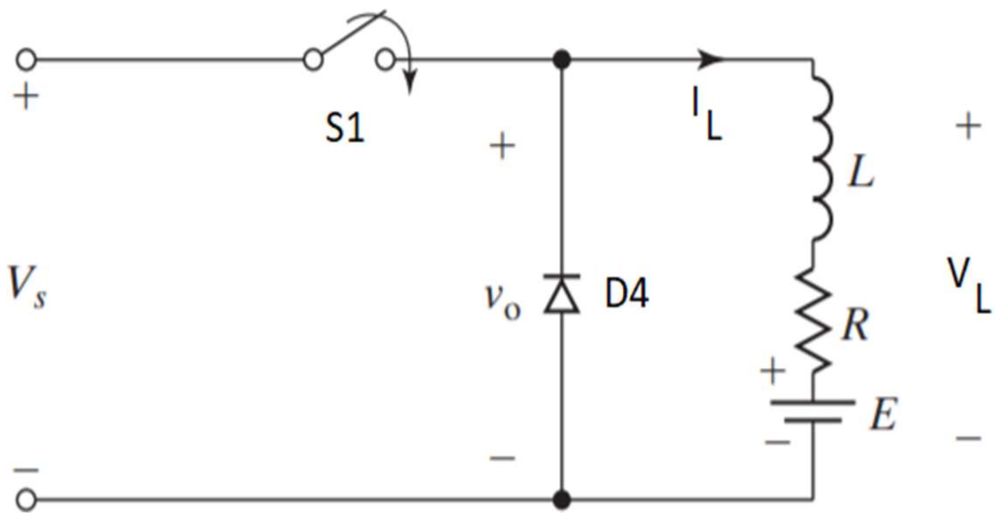
(b) Second quadrant converter

(c) First and second quadrant converter

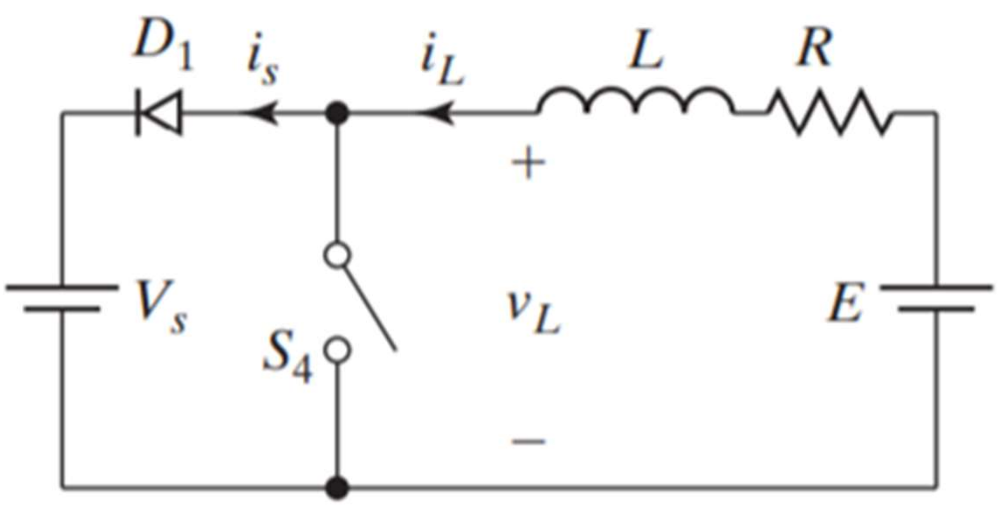
(d) Third and fourth quadrant converter

(e) Four-quadrant converter

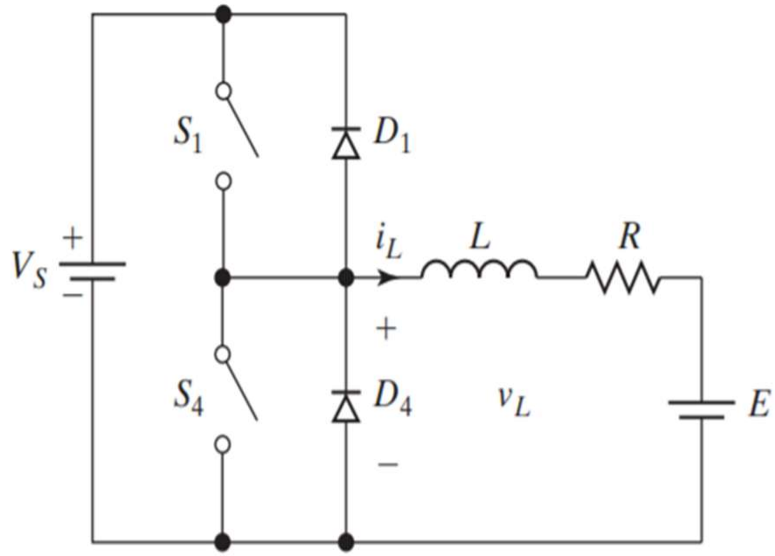
1. First quadrant converter / Class A Chopper



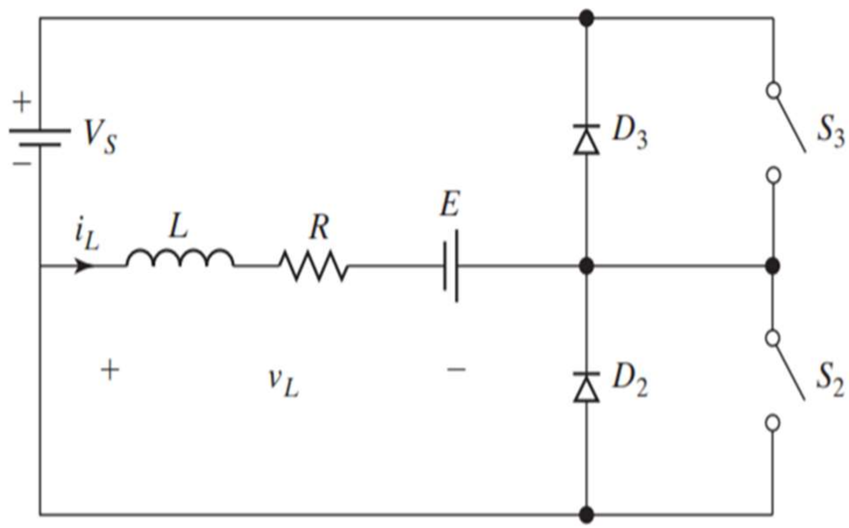
2. Second quadrant converter / Class B Chopper



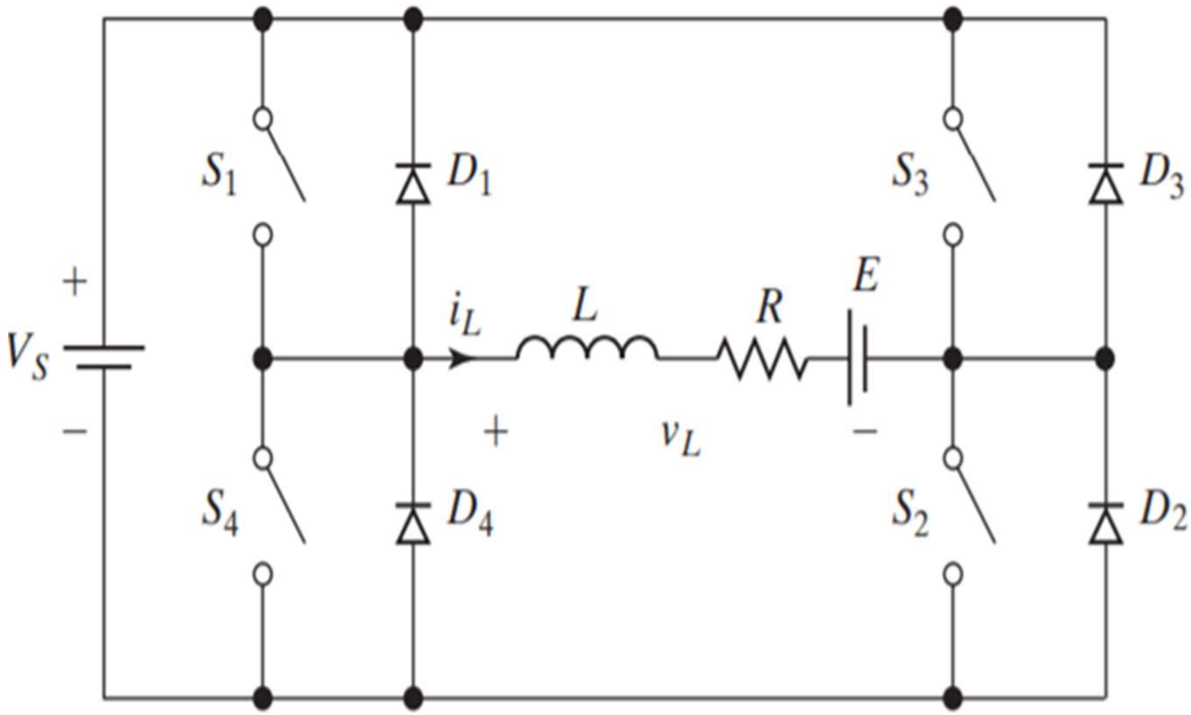
3. First and second quadrant converter / Class C



4. Third and fourth quadrant converter / Class D Chopper

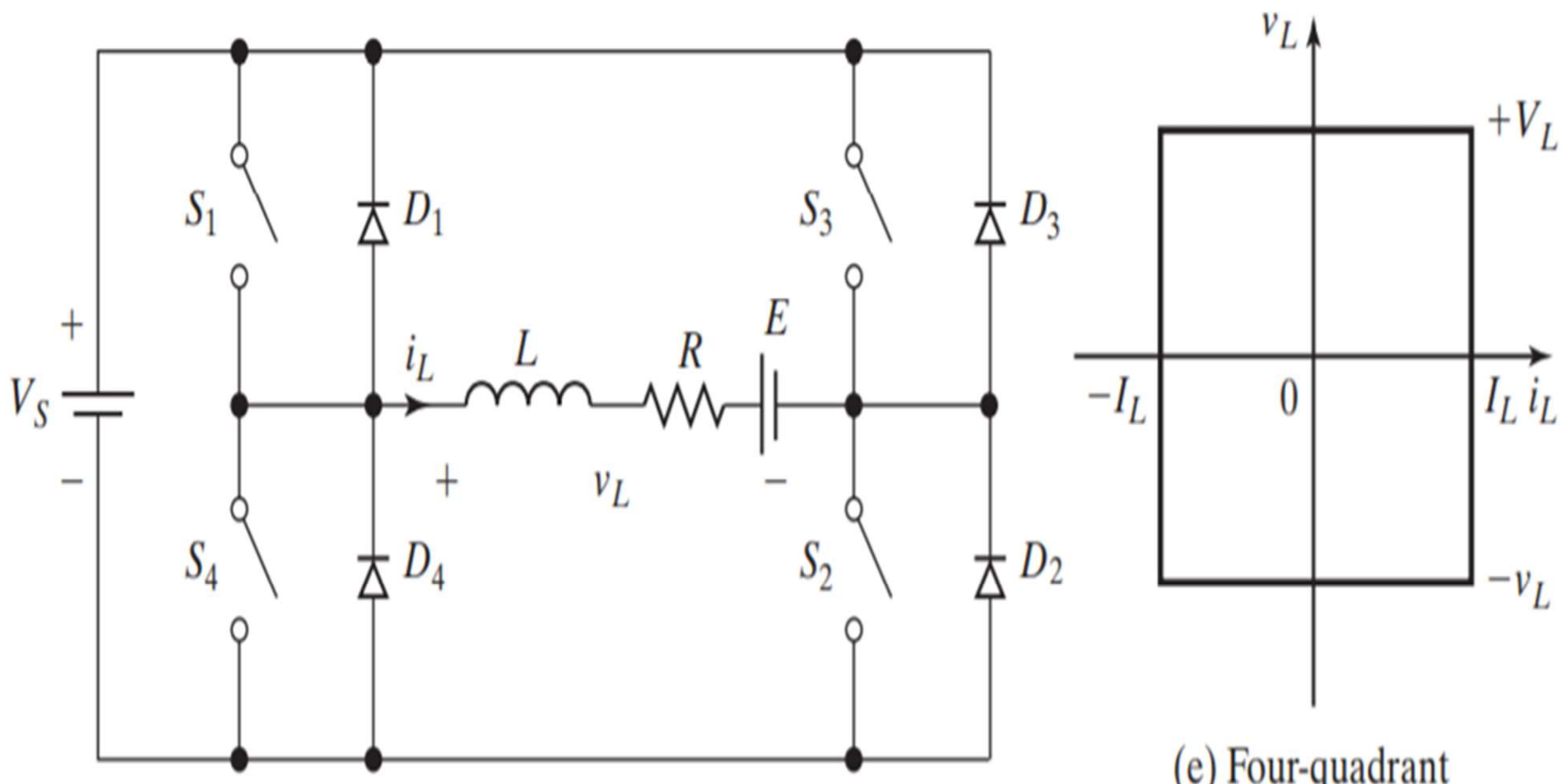


5. Four-quadrant converter / Class E Chopper



(a) Circuit

Q. 9 (c) With the help of circuit and quadrant diagrams, describe the working of a class E chopper. (10 marks)



(a) Circuit

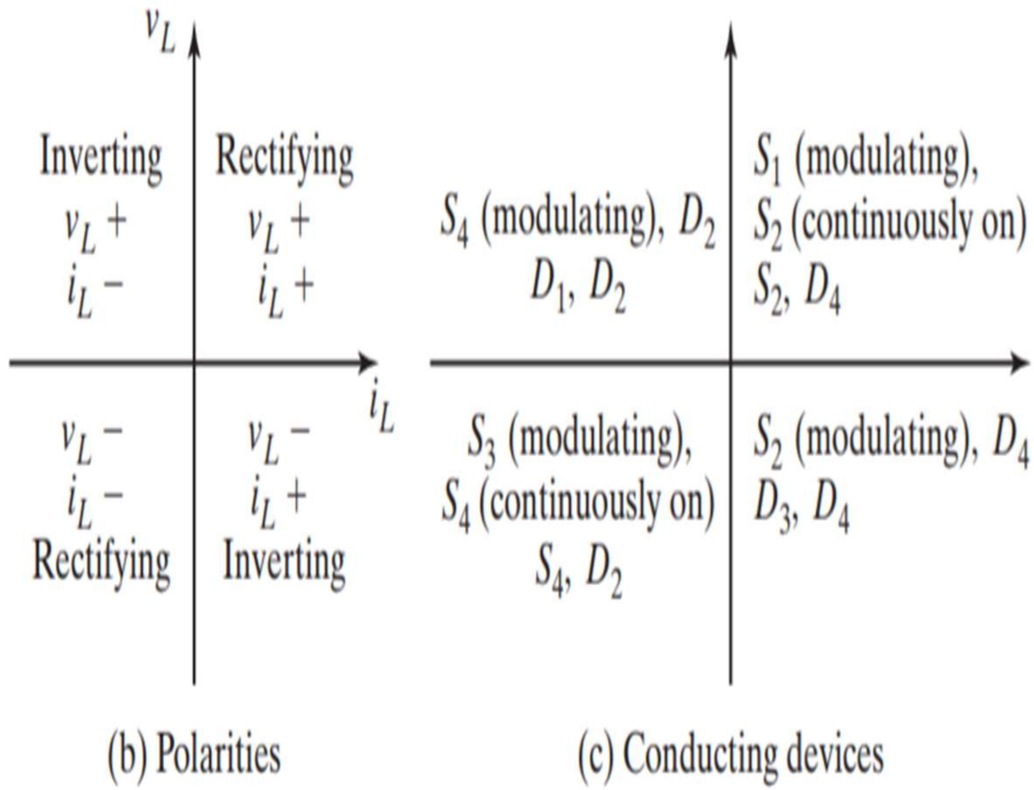
(e) Four-quadrant converter

Four-quadrant converter / Class E Chopper

- The load current is either positive or negative
- The load voltage is also either positive or negative.
- One first and second quadrant converter and one third and fourth quadrant converter can be combined to form the four-quadrant converter.
- For operation in the third and fourth quadrant, the direction of the battery E must be reversed.
- This converter forms the basis for the single-phase full-bridge inverter.

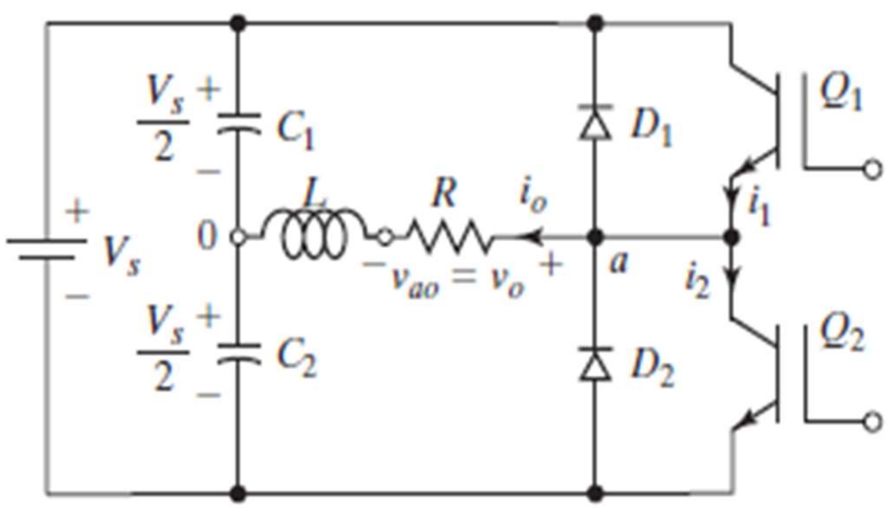
Four-quadrant Operation

- For an inductive load with an emf (E) such as a dc motor, the four-quadrant converter can control the power flow and motor speed
- Forward motoring (vL positive and iL positive),
- Forward regenerative braking (vL positive and iL negative),
- Reverse Motoring (vL negative and iL negative),
- Reverse regenerative braking (vL negative and iL positive).

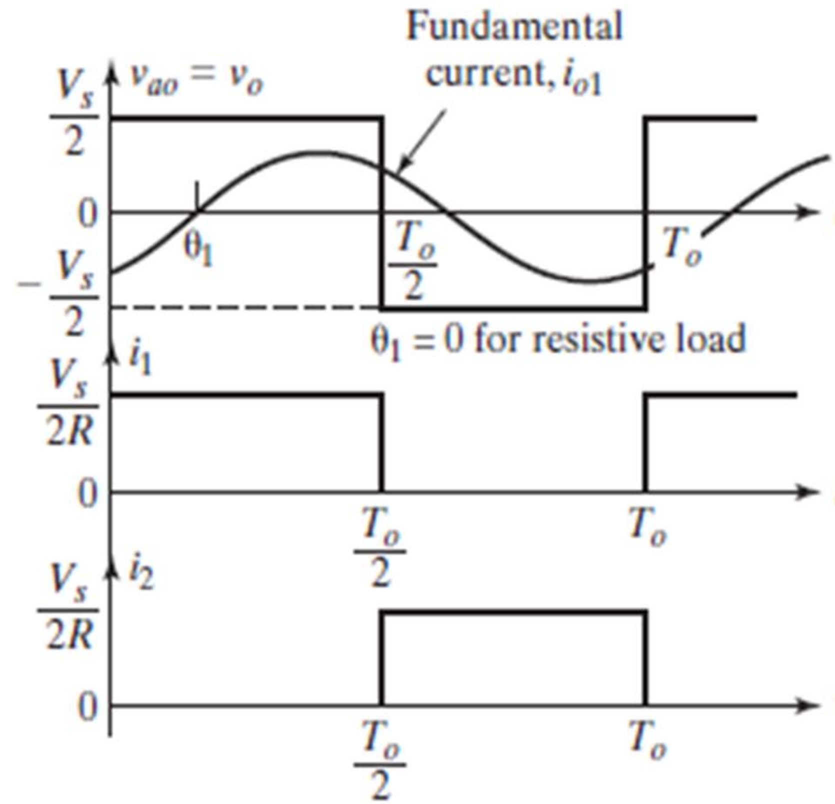


With proper switch control, the four-quadrant converter can operate and control flow in any of the four quadrants. For operation in the third and fourth quadrants, the direction of the load emf E must be reversed internally.

10 (a) Explain the working of single phase half bridge inverter with necessary waveforms. (6 marks)



(a) Circuit



(b) Waveforms with resistive load

PRINCIPLE OF OPERATION

The principle of single-phase inverters can be explained with Figure a. The inverter circuit consists of two choppers. When only transistor Q_1 is turned on for a time $T_0/2$, the instantaneous voltage across the load v_0 is $V_s/2$. If only transistor Q_2 is turned on for a time $T_0/2$, $-V_s/2$ appears across the load.

designed such that Q_1 and Q_2 are not turned on at the same time. Figure b shows the waveforms for the output voltage and transistor currents with a resistive load. It should be noted that the phase shift is $\theta_1 = 0$ for a resistive load. This inverter requires a three-wire dc source, and when a transistor is off, its reverse voltage is V_s instead of $V_s/2$. This inverter is known as a *half-bridge inverter.*

The root-mean-square (rms) output voltage can be found from

$$V_o = \left(\frac{2}{T_0} \int_0^{T_0/2} \frac{V_s^2}{4} dt \right)^{1/2} = \frac{V_s}{2}$$

The instantaneous output voltage can be expressed in Fourier series as

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

Q. 10 (b) Write a note on voltage control of single phase inverters by sinusoidal pulse width modulation technique. (6 marks)

Sinusoidal Pulse Width Modulation

- Since the desired output voltage is a sine wave, a reference sinusoidal signal is used as the reference signal.
- Instead of maintaining the width of all pulses the same as in the case of multiple-pulse modulation, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the center of the same pulse.
- The DF and LOH are reduced significantly.
- The gating signals are generated by comparing a sinusoidal reference signal with a triangular carrier wave of frequency *fc.*
- This sinusoidal pulse-width modulation (SPWM) is commonly used in industrial applications.
- The frequency of reference signal *fr* determines the inverter output frequency *fo*; and its peak amplitude *Ar,* controls the modulation index *M, then controls RMS output voltage.*

Sinusoidal Pulse Width Modulation

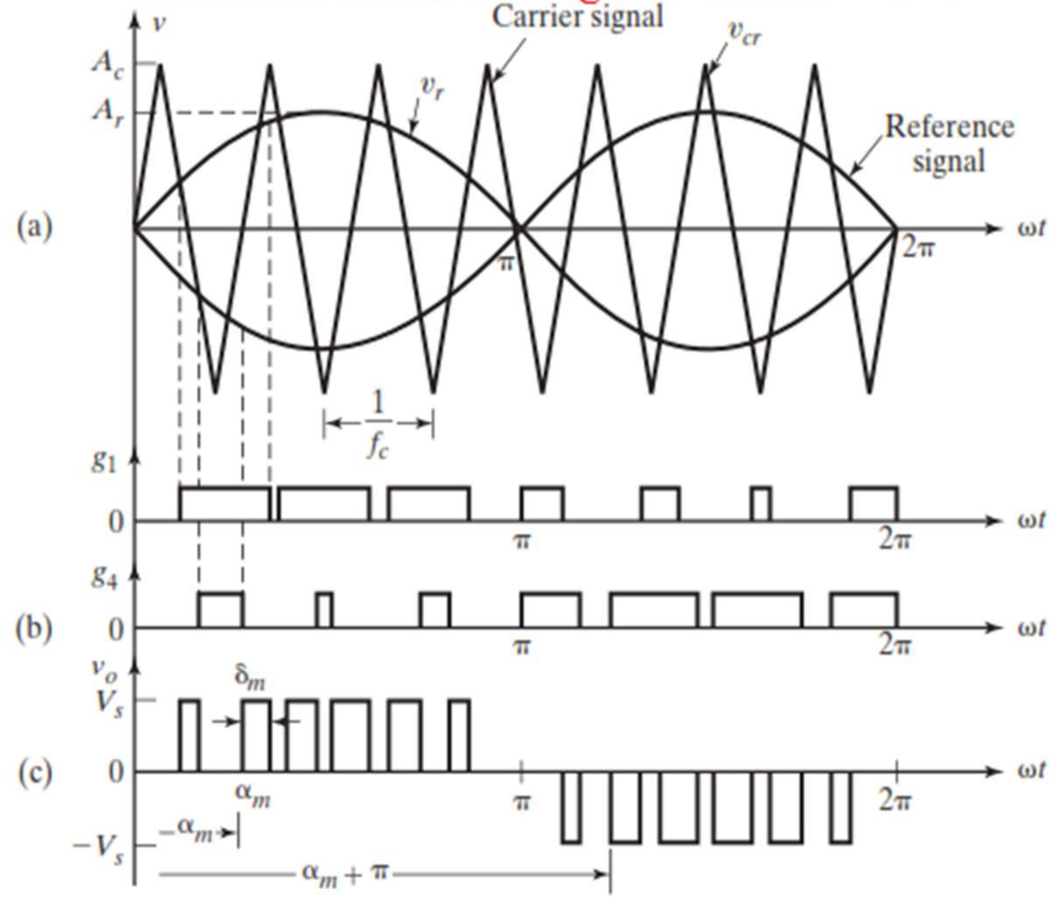
✓Comparing the bidirectional carrier signal *vcr* with two sinusoidal reference signals *vr* and -vr shown in produces gating signals *g*1 and *g*4, respectively.

✓Unidirectional triangular wave if preferred

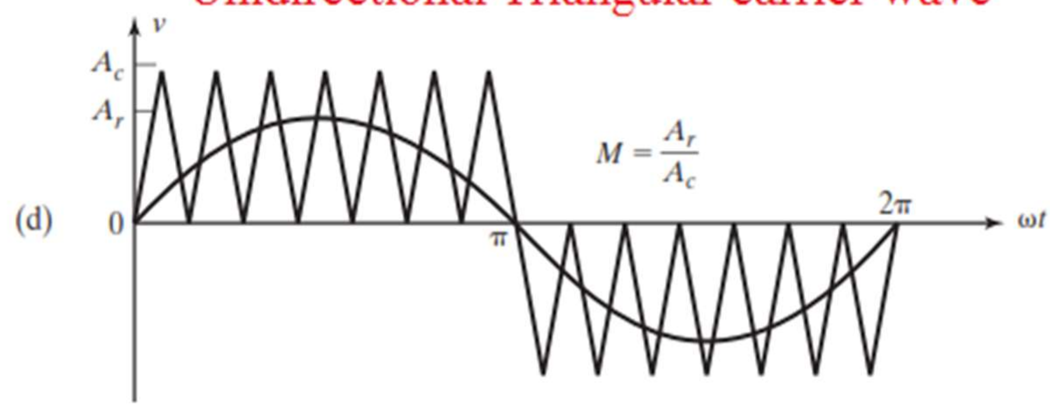
Output Voltage Vo = Vs (g1-g4)

Dr.

Bidirectional Triangular carrier wave



Unidirectional Triangular carrier wave



RMS Output Voltage

The rms output voltage can be varied by varying the modulation index M, defined by $M = A_r/A_c$.

If δ_m is the width of mth pulse

the rms output voltage by summing the average areas under each pulse as

$$V_o = V_s\left(\sum_{m=1}^{2p} \frac{\delta_m}{\pi}\right)^{1/2}$$

The peak fundamental output voltage for PWM and SPWM control can be found approximately from

$$V_{m1} = dV_s \quad \text{for } 0 \le d \le 1.0$$

d > 1, Over modulation

Fourier series of the output voltage

$$v_o(t) = \sum_{n=1,3,5,\ldots}^{\infty} B_n \sin n\omega t$$

$$B_n = \sum_{m=1}^{2p} \frac{4V_s}{n\pi} \sin \frac{n\delta_m}{2} \left[\sin n\left(\alpha_m + \frac{\delta_m}{2}\right) \right] \quad \text{for } n = 1, 3, 5, \ldots$$

✓ The DF is significantly reduced compared with that of multiple-pulse modulation.

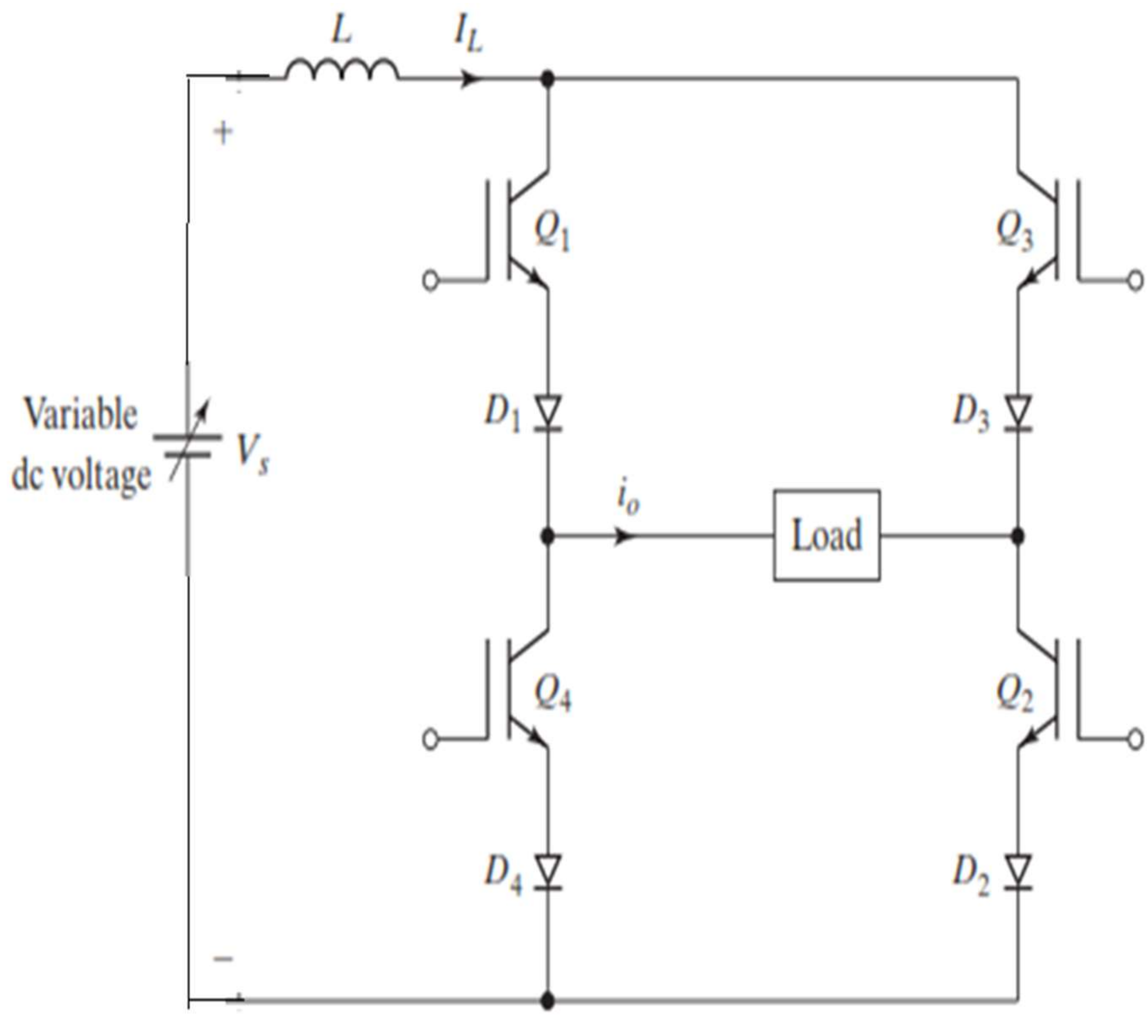
✓ This type of modulation eliminates all harmonics less than or equal to $2p - 1$. For $p = 5$, the LOH is ninth.

Q. 10 (c) Analyze the working of 1-Φ transistorized current source inverter with neat circuit diagram and waveforms. (8 marks)

Current Source Inverter

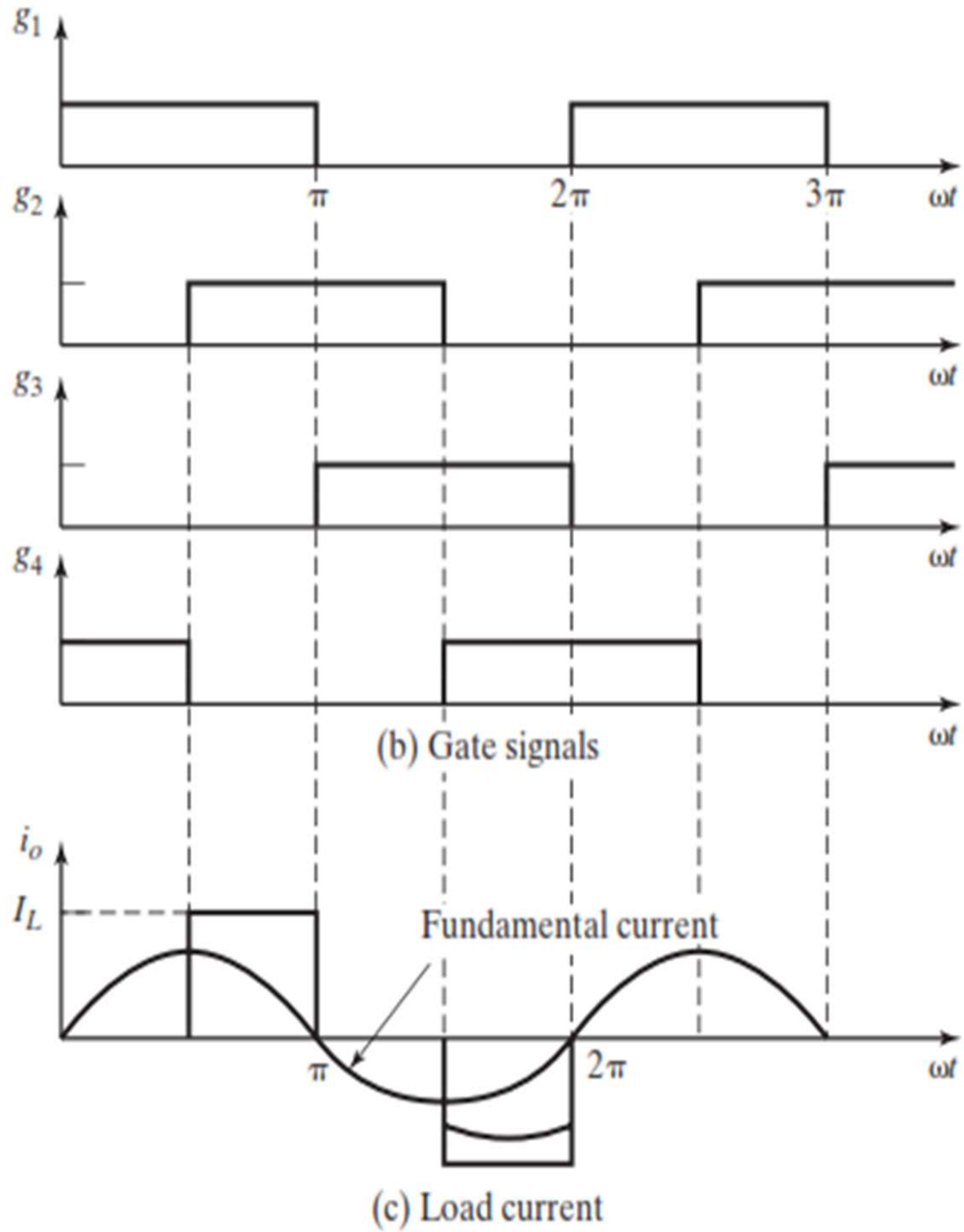
- In VSI, the inverters are fed from a voltage source and the load current is forced to fluctuate from positive to negative, and vice versa.
- To cope with inductive loads, the power switches with freewheeling diodes are required
- In a current-source inverter (CSI), the input behaves as a current source.
- The output current is maintained constant irrespective of load on the inverter and the output voltage is forced to change.

Current Source Inverter (CSI) – Single Phase



(a) Transistor CSI

Gate Pulse & Output Current Waveform



Current Source Inverter

- Because there must be a continuous current flow from the source, two switches must always conduct—one from the upper and one from the lower switches.
- The conduction sequence is 12, 23, 34, and 41.
- The switch states are shown in Table

TABLE Switch States for a Full-Bridge Single-Phase Current-Source Inverter (CSI)

State	State No.	Switch State $S_1S_2S_3S_4$	i_o	Components Conducting
S_1 and S_2 are on and S_4 and S_3 are off	1	1100	I_L	S_1 and S_2 D_1 and D_2
S_3 and S_4 are on and S_1 and S_2 are off	2	0011	$-I_L$	S_3 and S_4 D_3 and D_4
S_1 and S_4 are on and S_3 and S_2 are off	3	1001	0	S_1 and S_4 D_1 and D_4
S_3 and S_2 are on and S_1 and S_4 are off	4	0110	0	S_3 and S_2 D_3 and D_2

- Transistors *Q*1, *Q4* act as the switching devices *S*1, *S*4, respectively.
- If two switches from different arm, one upper and one lower, conduct at the same time such that the output current is +IL / -IL, the switch state is 1;
- whereas if these switches are off at the same time, the switch state is 0.
- The diodes in series with the transistors are required to block the reverse voltages on the transistors.
- When two devices in different arms conduct, the source current *IL flows through* the load.
- When two devices in the same arm conduct, the source current is bypassed from the load.

Fourier Series expression for Load Current – Single Phase CSI

The Fourier series of the load current can be expressed as

$$i_0 = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4I_L}{n\pi} \sin\frac{n\delta}{2} \sin n(\omega t)$$