



**NEHRU COLLEGE OF ENGINEERING AND RESEARCH CENTRE
(NAAC Accredited)**

(Approved by AICTE, Affiliated to APJ Abdul Kalam Technological University, Kerala)



DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

COURSE MATERIAL



EE305 : POWER ELECTRONICS

VISION OF THE INSTITUTION

To mould true citizens who are millennium leaders and catalysts of change through excellence in education.

MISSION OF THE INSTITUTION

NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values.

We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- ◆ Established in: 2006
- ◆ Course offered: B.Tech Electrical and Electronics Engineering
- ◆ Approved by AICTE New Delhi and Accredited by NAAC
- ◆ Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

To excel in technical education and research in the field of Electrical & Electronics Engineering by imparting innovative engineering theories, concepts and practices to improve the production and utilization of power and energy for the betterment of the Nation.

DEPARTMENT MISSION

1. To offer quality education in Electrical and Electronics Engineering and prepare the students for professional career and higher studies.
2. To create research collaboration with industries for gaining knowledge about real-time problems.
3. To prepare students with sound technical knowledge.
4. To make students socially responsible.

PROGRAM OUTCOME (PO'S)

Engineering Graduates will be able to:

PO 1. Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

PO 2. Problem analysis: Identify, formulate, review research literature, and analyze complex

engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

PO 3. Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

PO 4. Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

PO 5. Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

PO 6. The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

PO 7. Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

PO 8. Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO 9. Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

PO 10. Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

PO 11. Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

PO 12. Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOME(PSO'S)

1. Apply Science, Engineering, Mathematics through differential and Integral Calculus, Complex Variables to solve Electrical Engineering Problems.
2. Demonstrate proficiency in the use of software and hardware to be required to practice electrical engineering profession.
3. Apply the knowledge of Ethical and Management principles required to work in a team as well as to lead a team.

COURSE OUTCOME

After the completion of the course the student will be able

CO 1	To understand the different types of power semiconductor devices and their switching characteristics
CO 2	To understand the operation and characteristics of various types of single phase rectifiers
CO 3	To understand the operation and characteristics of various types of three phase rectifiers and Dual converters
CO 4	To understand the operation and characteristics of various types of Inverters
CO 5	To understand the operation and characteristics of various types of AC Voltage converters
CO 6	To understand the operation and characteristics of various types of DC-DC converters

CO VS PO'S AND PSO'S MAPPING

CO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO 1	PSO 2	PSO 3
CO 1	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 2	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 3	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 4	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 5	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 6	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2

Note: H-Highly correlated=3, M-Medium correlated=2, L-Less correlated=1

SYLLABUS

Module	Contents	Hours	Sem. Exam Marks
I	SCR-Structure, static characteristics & switching (turn-on & turn-off) characteristics - di/dt & dv/dt protection – turn-on methods of SCR - two transistor analogy - series and parallel connection of SCRs Structure and principle of operation of power diode, TRIAC, GTO, Power MOSFET & IGBT – Comparison	6	15%
II	Gate triggering circuits – R, RC, UJT triggering circuits – natural and forced commutation (concept only). Requirements of isolation and synchronisation in gate drive circuits- Opto and pulse transformer based isolation. Controlled rectifiers – half-wave controlled rectifier with R load – 1-phase fully controlled bridge rectifier with R, RL and RLE loads (continuous & discontinuous conduction) – output voltage	8	15%
III	3-phase half-wave controlled rectifier with R load – 3-phase fully controlled & half-controlled converter with RLE load (continuous conduction, ripple free) – output voltage equation-waveforms for various triggering angles (no analysis) – 1-phase & 3-phase dual converter with & without circulating current – four-quadrant operation	7	15%
IV	Inverters – voltage source inverters– 1-phase half-bridge & full bridge inverter with R & RL loads – THD in output voltage – 3-phase bridge inverter with R load – 120° & 180° conduction mode – current source inverters.	7	15%
V	Voltage control in inverters – Pulse Width Modulation – single pulse width, multiple pulse width & sine PWM – modulation index & frequency modulation ratio. AC voltage controllers (ACVC) – 1-phase full-wave ACVC with R, & RL loads – waveforms – RMS output voltage, input power factor with R load – sequence control (two stage) with R load	7	20%
VI	DC-DC converters – step down and step up choppers – single-quadrant, two-quadrant & four quadrant chopper – pulse width modulation & current limit control in dc-dc converters. Switching regulators – buck, boost & buck-boost - continuous conduction mode only – waveforms – design of filter inductance & capacitance	7	20%

QUESTION BANK

MODULE 1

Part A

1. What is meant by light triggering?
2. Make a comparison between SCR, MOSFET and IGBT
3. Mention the turn-on methods employed in SCR.
4. Define latching and holding current in SCR with the help of its VI characteristics.
5. With neat sketch explain the structure and operation of Thyristor.
6. Compare between SCR and MOSFET
7. Illustrate the Two Transistor analogy of SCR.
8. Make a comparison between Thyristor and Power Diode.

PART B

1. Explain the structure and operation of MOSFET.
2. Derive the two transistor analogy of an SCR.
3. With necessary diagrams explain the switching characteristics of Power Diode.
4. With necessary diagrams explain the series and parallel operation of SCR.
5. With necessary diagrams explain the switching characteristics of SCR.
6. With neat sketch explain the operation of GTO.
7. Derive the two transistor analogy of GTO.
8. With neat sketch explain the operation of TRIAC.
9. Explain the structure and operation of IGBT.

MODULE 2

PART A

1. Discuss Commutation of an SCR. Classify its different methods.
2. Make a comparison between single phase midpoint and bridge rectifier.
3. Derive the output equation of single phase fully controlled rectifier with RL load.
4. Derive the output equation of single phase fully controlled rectifier with R load.
5. Give a brief note on optocoupler.
6. Derive the output equation of single phase half wave controlled rectifier with RL load.
7. Draw the circuit diagram of two types of single phase semiconverter.
8. Discuss the turn-off methods employed in SCR.
9. Derive the average and RMS output voltage of single phase half-wave controlled rectifier with RL load.
10. Explain the operation of single phase half wave controlled rectifier with RL load.
11. Derive the average and RMS output voltage of single phase half controlled rectifier with RL load.

PART B

1. Explain single phase fully controlled rectifier with R load.
2. Make an analysis of single phase half wave controlled rectifier with R load.
3. Explain single phase semiconverter with RL load.
4. Explain forced commutation technique employed in SCR.
5. With neat sketch explain the UJT triggering of SCR.
6. With neat sketch explain the R and RC triggering of SCR.
7. With neat sketch explain the resistance triggering of SCR.
8. With neat sketch explain the resistance-capacitance triggering of SCR.

9. Explain the operation of single phase fully controlled rectifier with RL load for both continuous and discontinuous modes of operation.
10. Make a comparison between single phase half controlled and fully controlled rectifier.
11. Explain the operation of single phase fully controlled rectifier with R load with a firing angle of 60 and 120 degrees.

MODULE 3

PART A

1. Draw the circuit diagram of three phase half wave rectifier with R load.
2. Derive the output equation of three phase fully controlled rectifier with RL load.
3. Derive the output equation of three phase fully controlled rectifier with R load.
4. Derive the output equation of three phase fully controlled rectifier with RL load.
5. Design a converter that works in all four quadrants.

PART B

1. Explain three phase fully controlled rectifier with R load.
2. Make an analysis of three phase half wave controlled rectifier with R load.
3. Explain three phase fully controlled rectifier with RL load for both continuous and discontinuous mode of operation.
4. Explain three phase semiconverter with RL load.
5. Explain three phase dual converter with both circulating and non-circulating mode of operation.
6. Explain four quadrant operation of single phase converter with both circulating and non-circulating mode of operation.

MODULE 4

PART A

1. Explain the operation of Half bridge inverter with R Load.
2. Explain the operation of Half bridge inverter with RL Load.
3. Explain the operation of Full bridge inverter with R Load.

4. Explain the operation of Full bridge inverter with RL Load.

PART B

1. Explain the operation of Current Source inverter
2. Illustrate the operation of a 3-phase bridge inverter operating in 180° conduction mode with output line voltage and phase voltage waveforms. Derive expressions for output line voltage and phase voltage.
3. Illustrate the operation of a 3-phase bridge inverter operating in 120° conduction mode with output line voltage and phase voltage waveforms. Derive expressions for output line voltage and phase voltage.

MODULE 5

PART A

1. Explain the control strategy employed for a AC voltage controller.
1. For a single phase ACVC with source voltage as , and load as , draw the output voltage and current waveforms if Thyristor firing angle is (i) $\alpha=30^\circ$ (ii) $\alpha=90^\circ$.
2. Derive the output equation of full wave AC voltage controller with R load.
3. Derive the output equation of full wave AC voltage controller with RL load.
4. Explain the various methods of voltage control in single phase inverters.
5. What do you mean by PWM? Discuss the advantages and disadvantages.
6. Define the terms amplitude modulation index and frequency modulation index.

PART B

7. Design the full wave AC voltage controller with R load.
8. Explain the operation of full wave AC voltage controller with RL load.
9. Explain half wave AC voltage controller with R load.
10. Explain Sequence control of AC voltage controller.
11. What is meant by Pulse Width Modulation? Describe the various PWM techniques used in Voltage control of Inverters.

MODULE 6

PART A

1. Explain the control strategy employed for a Chopper.
2. With neat sketch explain the Type A Chopper.

3. With neat sketch explain the Type B Chopper.
4. With neat sketch explain the Type C Chopper.
5. With neat sketch explain the Type D Chopper.
6. In a step down chopper the dc input voltage is of $100V$. The MOSFET switch is having a switching frequency of $2kHz$. Find the duty cycle and average dc output voltage if the turn on period of switch is $0.2ms$.
7. A step up chopper has input voltage of $220V$ and output voltage of $400V$. If the conducting time of the switch is $100\mu s$, Compute the pulse width of output voltage.

PART B

1. Design a chopper that works in all four quadrants.
2. With neat sketch explain the Step down Chopper.
3. With neat sketch explain the Step up Chopper.
4. With circuit diagram and waveforms, describe the operation of a buck-boost converter. Derive expressions for output dc voltage and the design equations for filter inductor & capacitor.
5. With circuit diagram and waveforms, describe the operation of a buck converter. Derive expressions for output dc voltage and the design equations for filter inductor & capacitor.
6. With circuit diagram and waveforms, describe the operation of a boost converter. Derive expressions for output dc voltage and the design equations for filter inductor & capacitor.

MODULE I

I	SCR-Structure, static characteristics & switching (turn-on & turn-off) characteristics - di/dt & dv/dt protection – turn-on methods of SCR - two transistor analogy - series and parallel connection of SCRs Structure and principle of operation of power diode, TRIAC, GTO, Power MOSFET & IGBT – Comparison
---	---

Power Diode:

- * Power Diodes differ in structure from Signal Diodes.
- * It is suitable for high-voltage and high-current applications.

- * It consists of heavily doped n^+ substrate and a lightly doped n^- layer.

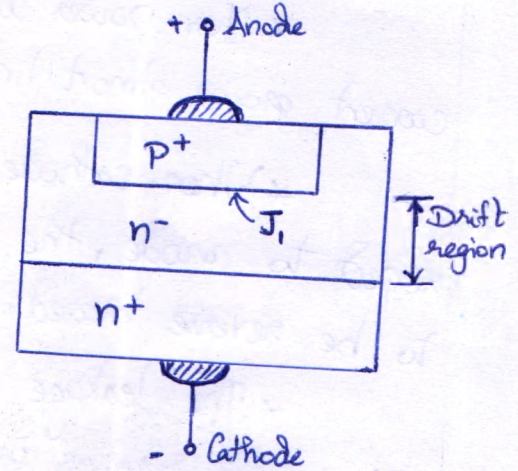
- * Now a heavily doped p^+ layer is diffused into n^- layer.

- * The function of n^- layer is to absorb the depletion layer of the reversed biased junction J_1 .

- * The break-down voltage needed in a power diode governs the thickness of n^- layer.

- * The drawback of n^- layer is to add significant ohmic resistance to the diode when it is conducting a forward current.

- * This leads to large power dissipation in the diode.



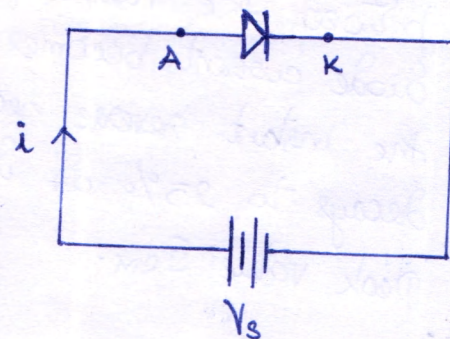
Characteristics of Power Diodes:

VI Characteristics:

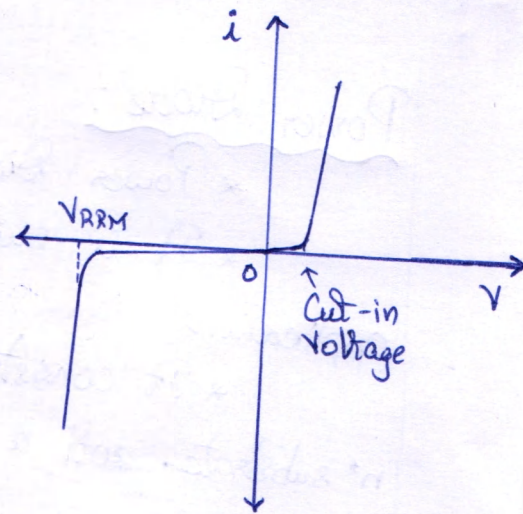
- * When anode is positive w.r.t cathode, diode is said to be forward biased.

- * From $V_s = 0$ to cut-in voltage, forward diode current is very small.

- * Beyond cut-in voltage, the diode current rises rapidly and the diode is said to conduct.



* Cut-in voltage is also known as threshold voltage or turn-on voltage and for silicon diode, it is of around 0.7V .



* For power diodes, the forward current grows almost linearly with voltage.

* When cathode is positive with respect to anode, the diode is said to be reverse biased.

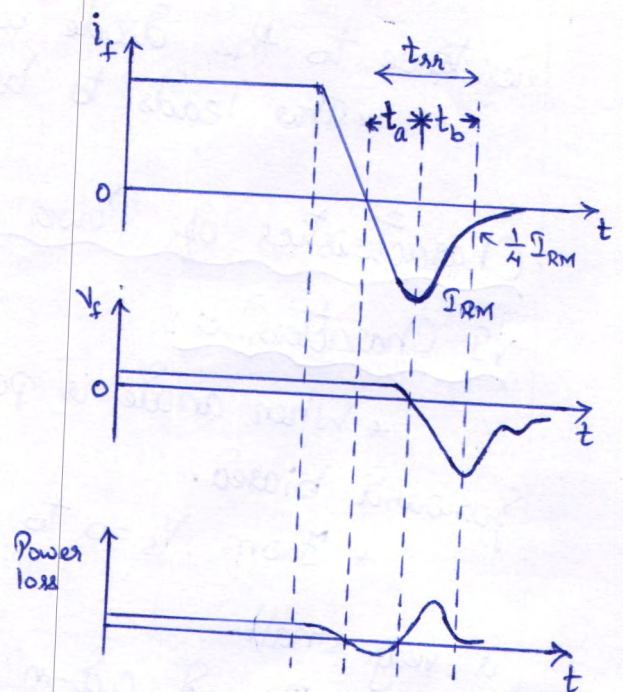
* The leakage current, of the order of microamperes or milliamperes flows in RB condition until the reverse voltage reaches breakdown voltage.

* After V_{RRM} , reverse current becomes high, leading to excessive power loss that may destroy the diode.

Diode Reverse Recovery Characteristics:

* After the forward diode current decays to zero, the diode continues to conduct in reverse direction because of stored charges in depletion region and semiconductor layers.

* The reverse current flows for a time called reverse recovery time t_{rr} and is defined as time between the instant forward diode current becomes zero and the instant reverse recovery current decays to 25% of its reverse peak value I_{RM} .



* The reverse recovery time is composed of two segments of time t_a and t_b .

* Time t_a is the time between zero crossing of forward current and peak reverse current I_{RM} .

* Time t_b is the time between instant of reverse peak value I_{RM} to the instant when $0.25 I_{RM}$ is reached.

* During the time t_a , charged stored in depletion layer is removed.

* During the time t_b , charge from the semiconductor layers is removed.

* The ratio of t_b/t_a is called softness factor or S-factor and is a measure of voltage transients that occur during the time diode recovers.

* The value of S is usually unity and this indicates low oscillatory reverse recovery process.

* If S-factor = 1, is called Soft Recovery diode
 < 1 , is called Snappy Recovery diode.

* The peak inverse current I_{RM} is expressed as,

$$I_{RM} = t_a \frac{di}{dt} \quad \text{--- (1)}$$

Stored Charge Q_R is given by,

$$Q_R = \frac{1}{2} I_{RM} \cdot t_{rr}$$

Rearranging we get,

$$I_{RM} = \frac{2 Q_R}{t_{rr}} \quad \text{--- (2)}$$

From (1) & (2),

$$I_{RM} = t_a \frac{di}{dt} = \frac{2 Q_R}{t_{rr}} \\ \therefore t_{rr} = \left[\frac{2 Q_R}{(di/dt)} \right]^{1/2} \quad \text{--- (3) where } [t_{rr} \approx t_a].$$

Sub ③ in ②, we get,

$$I_{RM} = \left[2 Q_R \left(\frac{di}{dt} \right) \right]^{1/2} \quad - (4)$$

* From above equation, we find that I_{RM} and t_{rr} are dependent on storage charge and rate of change of current.

* The storage charge depends upon the forward diode current thus shows Q_R and di/dt also depends on same (i_F).

Types of Power Diodes:

- i) General Purpose Diodes
- ii) Fast Recovery Diodes
- iii) Schottky Diodes.

Power Transistors:

* It is controlled device and is turned-on when a current signal is given to base terminal.

* It is of four types and they are

- i) Bipolar Junction Transistor
- ii) MOSFET
- iii) IGBT
- iv) Static Induction Transistor.

Power BJTs:

* It is a three layer, two junction device.

* Here the current flow is due to the movement of both holes and electrons and is called bipolar device.

* Power BJT has three terminals named Collector (C),

emitter (E) and base (B).

* It is of either npn type or pnp type. But npn type is used widely for high voltage and high current applications.

* Basically Power BJT is a current controlled device.

Steady State Characteristics:

Input Characteristics:

* It is the graph between base current, I_B and base-emitter voltage V_{BE} .

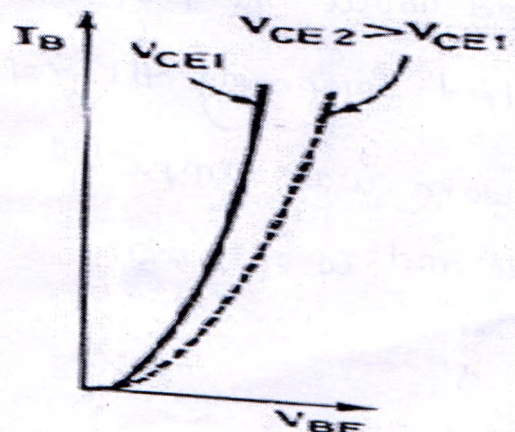
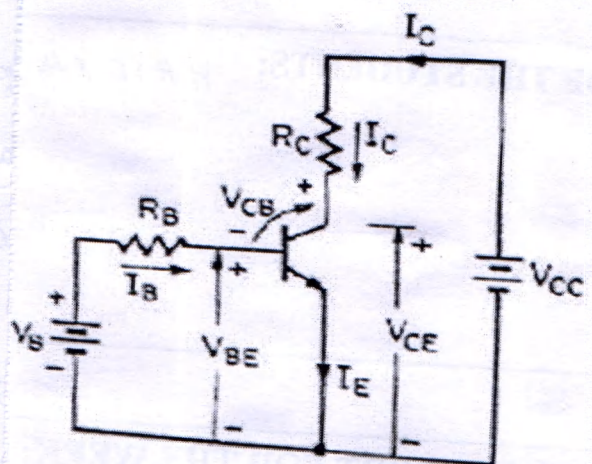
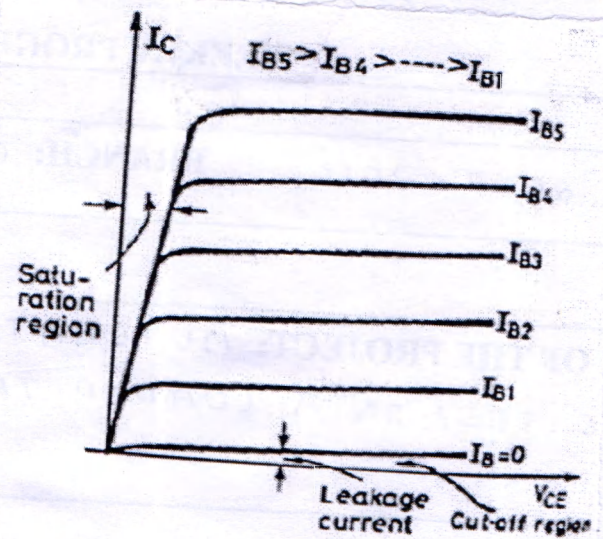
* As base-emitter junction is like a diode, I_B vs V_{BE} graph resembles a diode curve.

* For same V_{BE} , I_B starts varying according to the change in V_{CE} .

Output Characteristics:

* It is the graph between collector current and collector-emitter voltage. [I_C vs V_{CE}]

* For same V_{CE} , when I_B varies, the I_C also varies accordingly.



Switching Characteristics of BJT:

* This characteristics is classified as turn-on and turn-off characteristics.

* When input voltage V_B to base circuit is made $-V_2$ at t_0 , J_2 is reversed biased, the transistor is in turn-off condition.

* At time t_1 , V_B is made $+V_1$, and i_B rises to I_{B1} .

* After t_1 , V_{BE} begins to rise gradually from $-V_2$ and I_C begins to rise from zero.

* Also V_{CE} starts falling from its initial value V_{CC} .

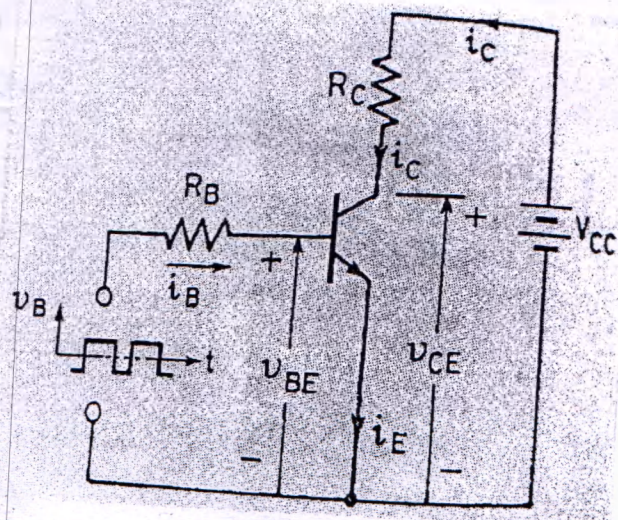
* After some time delay, I_C rises to $0.1 I_{CS}$, V_{CE} falls from V_{CC} to $0.9 V_{CC}$ and V_{BE} reaches $V_{BEs} = 0.7V$. This duration is called delay time t_d .

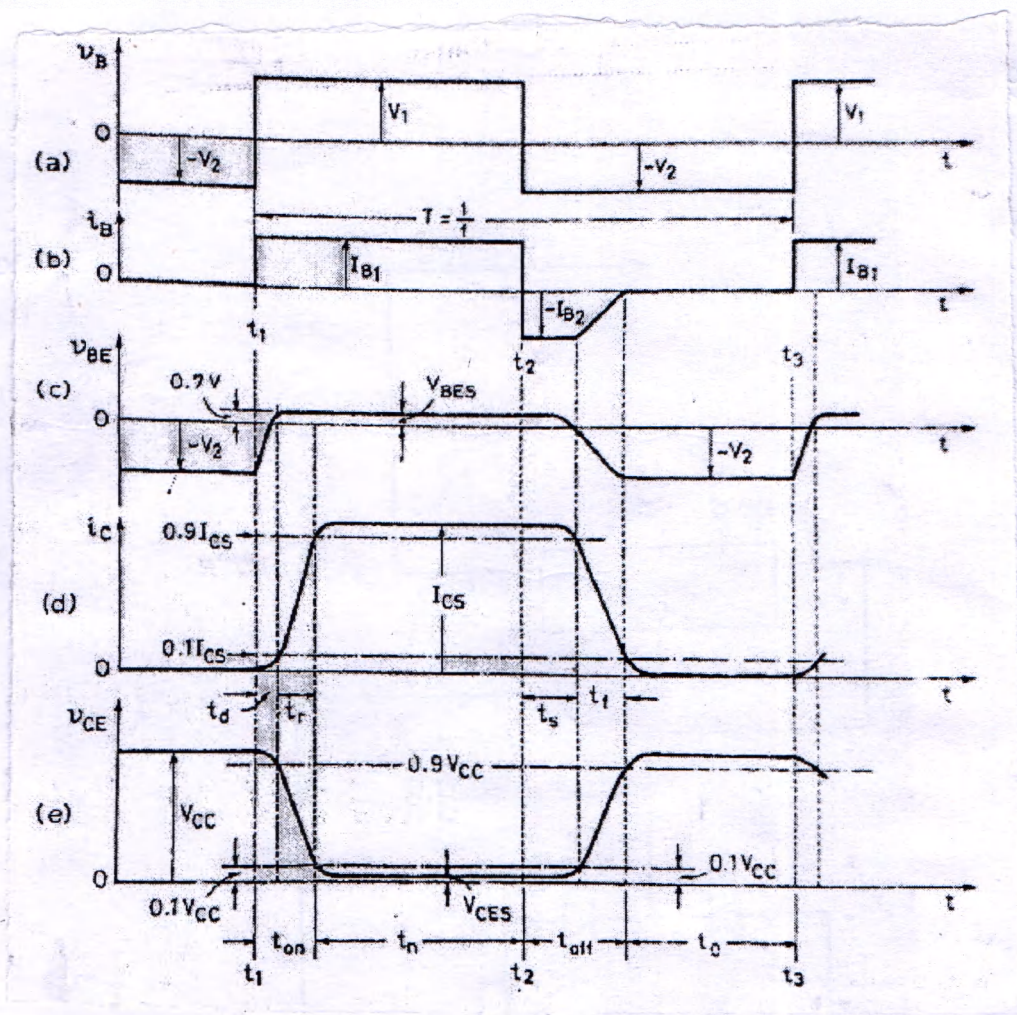
* After t_d , I_C rises from $0.1 I_{CS}$ to $0.9 I_{CS}$ and V_{CE} falls from $0.9 V_{CC}$ to $0.1 V_{CC}$ in time t_r called rise time.

* The t_d and t_r combinedly called turn-on time t_{on} .

$$t_{on} = t_d + t_r$$

* It is of the order of 30 to 300 nano seconds, and remains in the on-state or saturated state as long as input voltage stays at V_1 .





* In case transistor is to be turned off, then V_B and i_B are reversed.

* At time t_2 , V_B is reversed from V_1 to $-V_2$ and i_B changes from I_{B1} to $-I_{B2}$.

* Time t_s required to remove excess carriers from the base and is defined as time during which I_C falls from I_{CS} to $0.9I_{CS}$ (or) V_{CE} rises from V_{CES} to $0.1V_{CE}$.

* Time t_f , called fall time is defined as time during which I_C drops from $0.9I_{CS}$ to $0.1I_{CS}$ (or) V_{CE} rises from $0.1V_{CC}$ to $0.9V_{CC}$.

* Sum of t_s and t_f gives turn-off time t_{off} .

$$t_{off} = t_s + t_f$$

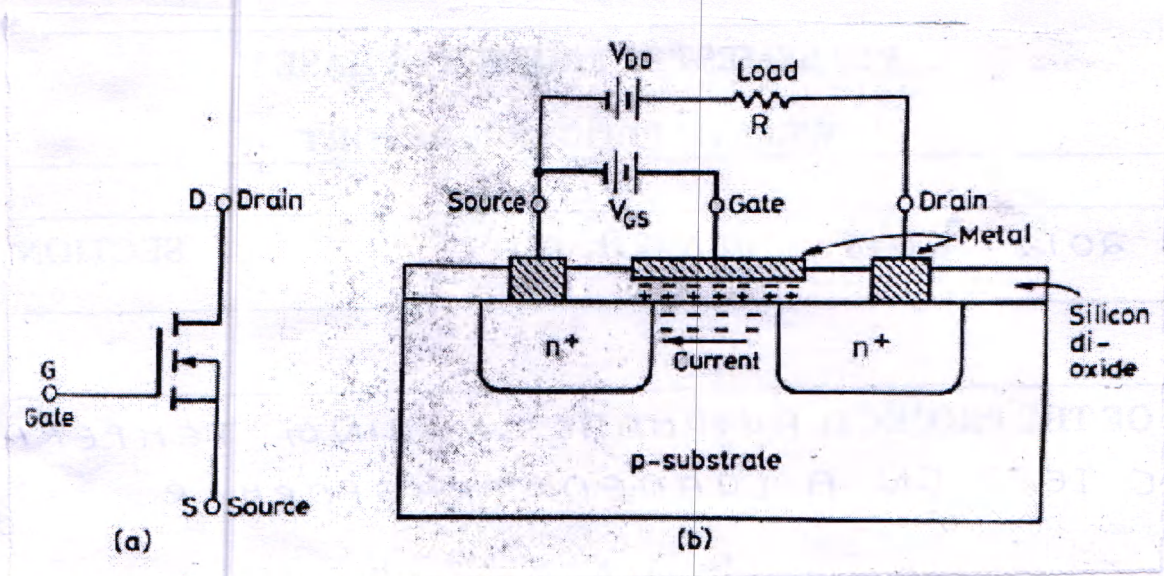
Power MOSFET:

- * It is developed by combining the area of field-effect concept and MOS technology.

- * It has 3 terminals called Drain (D), Source (S) and Gate (G).

- * MOSFET is a voltage controlled device and its operation depends upon the flow of majority carriers only. [Unipolar device]

- * It has large impedance which permits it driven directly from microelectronic circuits.



- * It is of two types namely n-channel enhancement and p-channel enhancement MOSFET.

- * A simplified structure of n-channel planar MOSFET consists of p-substrate & 2 heavily doped n⁺ regions.

- * An insulating layer of SiO₂ is grown on the surface and is etched in order to embed metallic source & drain terminals.

- * A layer of metal is also deposited on SiO₂ layer so as to form Gate in between drain and source.

* When gate circuit is open, junction between n^+ region below drain and p -substrate is reversed biased.

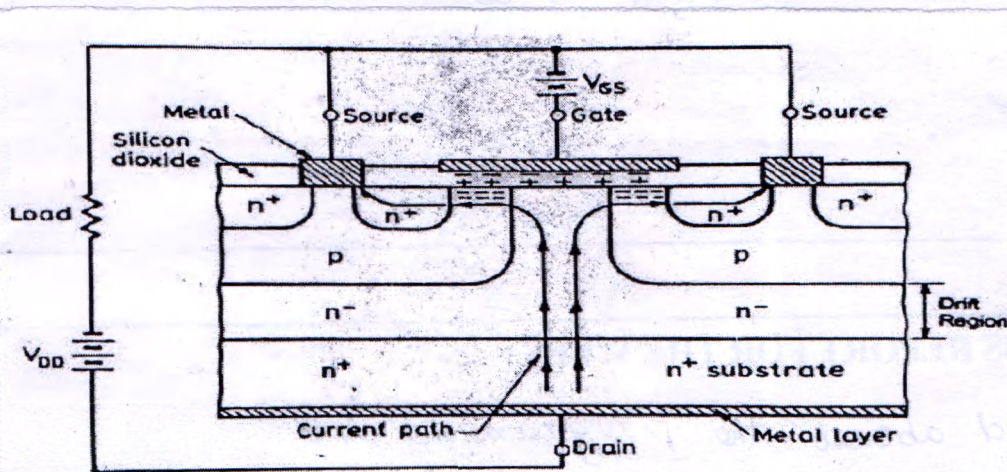
* So, no current flows from D to S and load.

* When gate is made positive w.r.t source, an electric field is established, creating negative charges in p -substrate below gate to become an induced n layer.

* Thus the current can flow from D to S and is enhanced by gradual increase of gate voltage, hence named enhancement MOSFET.

* The main disadvantage of n -channel planar MOSFET is it gives large on-state resistance leads to high power dissipation.

* To overcome this problem a planar diffused metal-oxide semiconductor (DMOS) is introduced.



* Here on n^+ substrate, high resistivity n^- layer is epitaxially grown which determines the voltage blocking capability of the device.

* On other side of n^+ substrate, a metal layer is deposited to form drain (D) terminal.

* Here p -regions are diffused in n^- layer and n^+ region on p -regions.

* Metallic source and gate terminals are fitted in SiO_2 layer through etching.

* When $V_{GS} = 0$, V_{DD} is present but n-p junctions are reversed biased and no current flows from D to S.

* When V_{GS}^{gate} is made positive w.r.t source, an electric field is established below gate.

* Thus negative charges are developed in p-region making current flow from drain to source.

* Length of n-channel can be controlled and therefore on-resistance can be made low if short length is used for the channel.

IGBT :

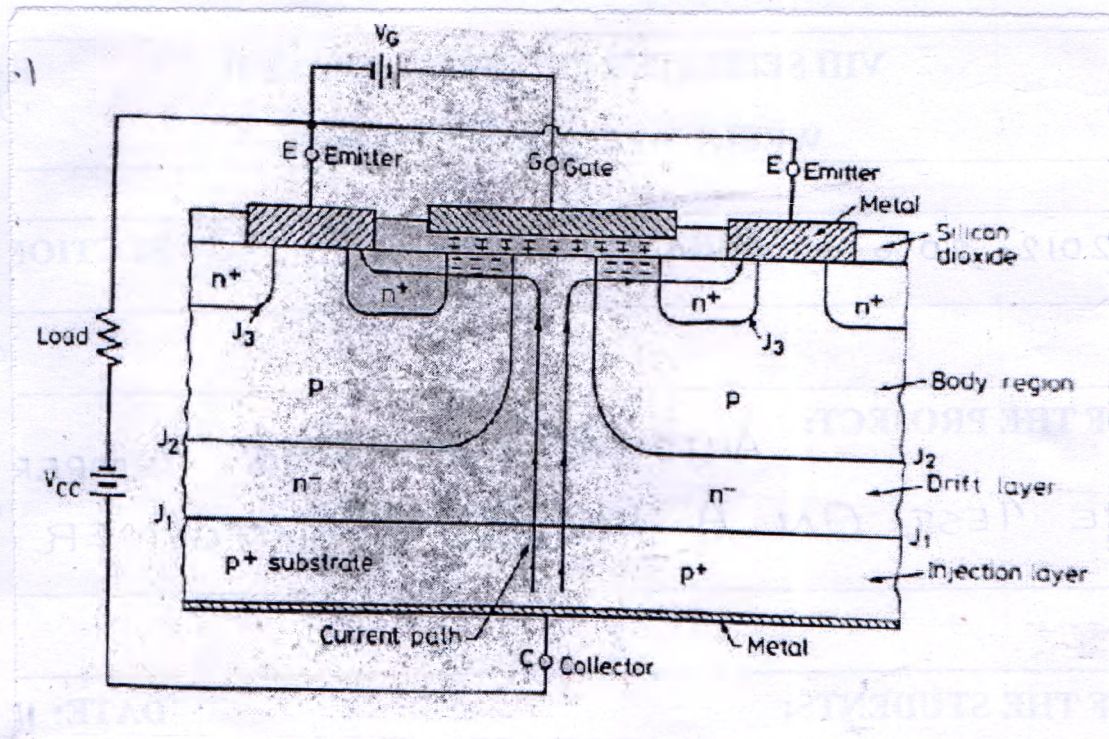
* It is developed by combining the best qualities of both BJT and MOSFET.

* Thus IGBT possesses high input impedance like MOSFET and has low on-state power loss as in BJT.

* It is constructed virtually in the same manner as a power MOSFET, however a major difference is in the substrate.

* Instead of n^+ substrate in MOSFET, IGBT has p^+ substrate called injection layer because it injects holes into n^- layer.

* The n^- layer is called drift region and is between p^+ and p regions.



Working:

* When collector is made positive w.r.t emitter, IGBT gets forward biased.

* With no voltage between gate and emitter, n - p region are reverse biased and no current flows from C to E.

* When gate is made positive w.r.t emitter by V_G , an n -channel or inversion layer is formed in the upper part of p -region just below gate, as in MOSFET.

* Thus electrons from n^+ region flows to n^- region through n -channel.

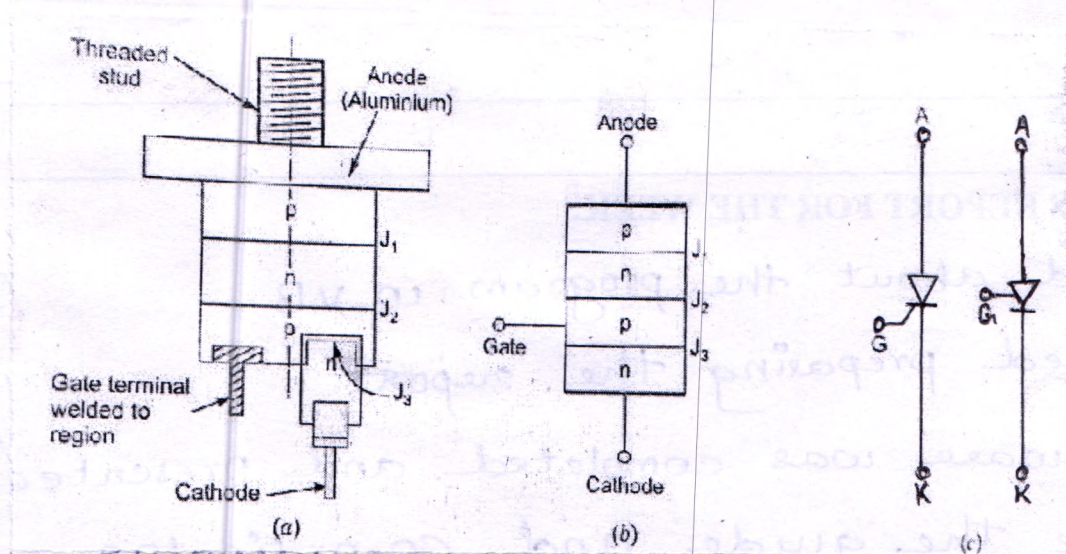
* As IGBT is FB with V_{CC} , p^+ region injects holes into n^- region.

* In short, n^- drift region is flooded with electrons from p -region and holes from p -region, resulting in conductivity of n^- region enhancing.

* Thus IGBT gets turned-on and I_C begins to flow.

Thyristor:

- * It is a four layer, three junction semiconductor device.
- * It also has 3 terminals namely anode (A), cathode (K) and gate (G).
- * SCR's are compact, possess high reliability and have low loss.
- * These have controlled turn-on by a gate signal



Static Characteristics of a Thyristor:

- * The anode and cathode are connected to main source (E) through the load.
- * The gate and cathode are fed ~~to~~ from a source (E_s).
- * Thyristor has four basic modes of operation namely
 - i) Forward Blocking Mode
 - ii) Forward Conducting Mode
 - iii) Reverse Blocking Mode
 - iv) Reverse Conducting Mode.

Forward Blocking Mode:

- * When anode is made positive w.r.t cathode, with gate circuit open, SCR is said to be forward biased [J_1 & J_3].

* But the junction J_2 is reversed biased, so there will not be flow of current from A to K.

* However a small amount of current starts flowing from A to K called forward leakage current.

* Thus SCR offers a high impedance and can be treated as an open switch in the forward blocking mode.

Forward Conduction Mode:

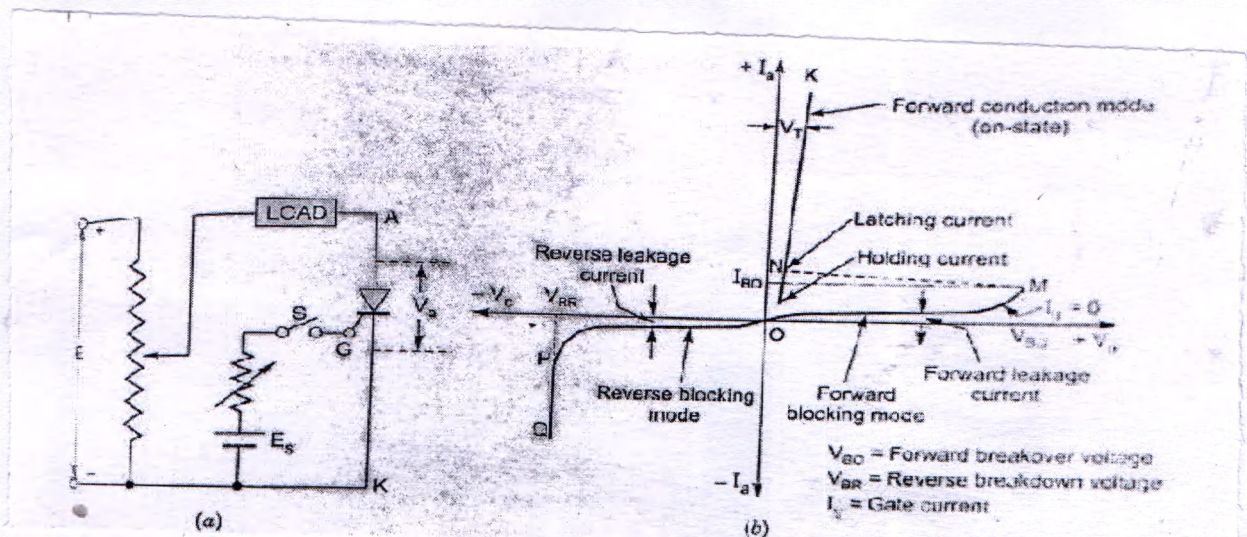
* When anode to cathode forward voltage is increased with gate circuit open, J_2 will have an avalanche breakdown at a voltage called forward breakover voltage, V_{BO} .

* After this breakdown, SCR gets turned-on with point M at once shifting to N and then to a point anywhere between N and K.

* Here NK represents the forward conduction mode.

* A SCR can be brought from FBM to FCM by turning it on by applying (i) a positive gate pulse between gate and cathode or (ii) a forward breakover voltage across anode and cathode.

* In this mode, SCR is treated as a closed switch.



Reverse Blocking Mode:

* With switch S open, if cathode is made positive w.r.t anode, J_1 and J_3 junctions are reversed biased and J_2 is forward biased.

* Since J_1 and J_3 are RB, no current flows between K to A , but a small leakage current flows in the order of few milliamperes.

* This mode is called RBM and the SCR is in off-state shown by OP.

Reverse Conducting Mode:

* When the reverse voltage is increased, then at a critical breakdown level, called Reverse Breakdown Voltage V_{BR} , an avalanche occurs and reverse current increases rapidly.

* A large current associated with V_{BR} gives rise to more losses in SCR outcoming in the form of heat, thereby leads to damage of SCR.

* This mode is called RCM and SCR should not be operated in this mode.

Switching Characteristics of SCR:

* During turn-on and turn-off process, the SCR may be subjected with various voltages and currents.

* So the time variations of voltage and currents through SCR are given by switching characteristics of SCR.

Turn-on Characteristics:

* Thyristor turn-on time is defined as the time during which it changes from forward blocking state to final on-state.

* Total turn-on time can be divided into three intervals

- i) delay time
- ii) rise time
- iii) spread time

Delay time (t_d):

* It is measured from the instant at which

i) gate current reaches $0.9 I_g$ to instant at which anode current reaches $0.1 I_a$.

ii) anode voltage falls from V_a to $0.9 V_a$

iii) anode current rises from forward leakage current to $0.1 I_a$.

* After the application of gate signal from gate to cathode, gate current has non-uniform distribution of current density over cathode surface.

* Current density is much high near gate and decreases rapidly when distance increase.

* Delay time is reduced by applying high gate current.

Rise time (t_r):

* It is defined as

i) time taken by anode current to rise from $0.1 I_a$ to $0.9 I_a$.

ii) time taken by anode voltage to drop from $0.9 V_a$ to $0.1 V_a$.

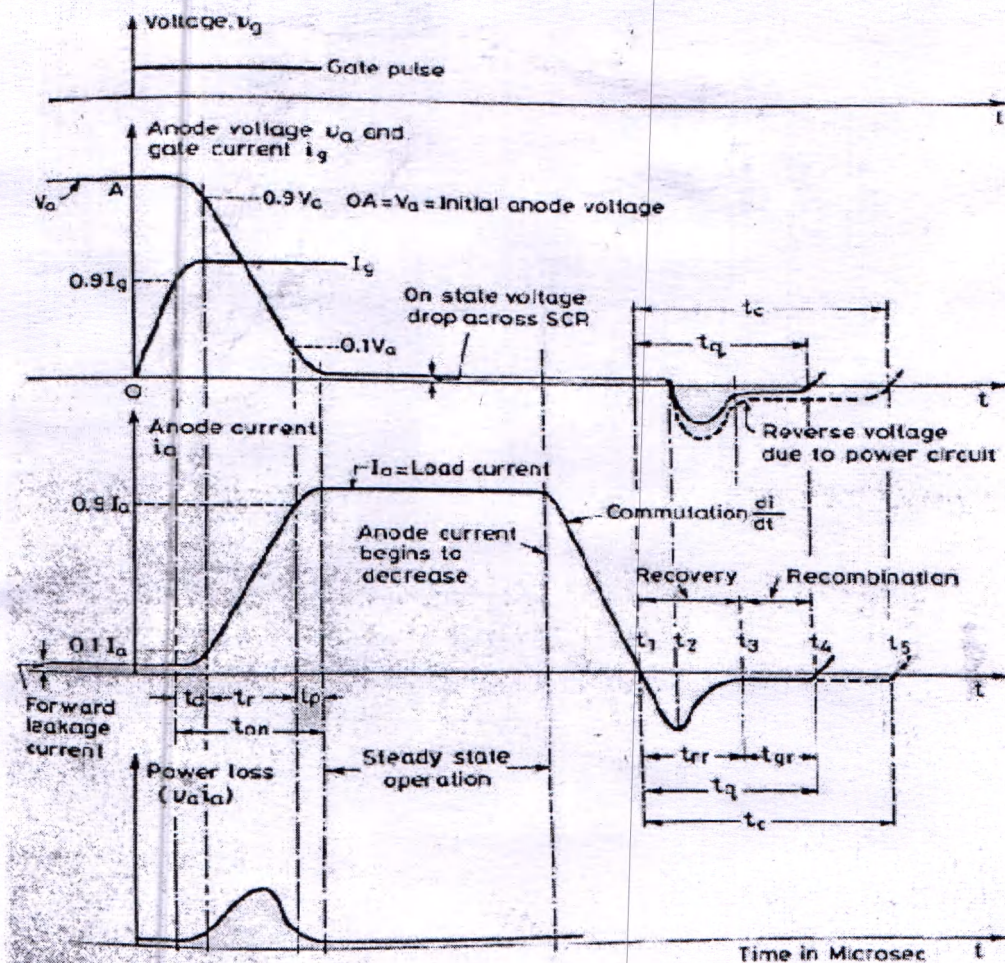
* Rise time is reduced if high and steep current pulses are applied to gate, however t_r is determined by nature of anode circuit.

* For series R-L circuit : di/dt is slow, thus t_r is more

* For series R-C circuit : di/dt is high, thus t_r is less.

* In this time period, anode current starts spreading from a small region near the gate at a velocity of $0.1 \text{ mm}/\mu\text{s}$.

* Also in this period, turn-on losses are high and it may damage the SCR.



Spread time (t_p) :

* It is defined as the

i) time taken by an anode voltage to drop from $0.1V_a$ to on-state voltage drop.

ii) time taken by anode current to rise from $0.9I_a$ to I_a .

* During this time, conduction spreads over the entire cross-section of the cathode.

* Spreading interval depends on area of cathode and gate structure of SCR.

Note:

When gate current is several times higher than minimum gate current required, SCR is said to be hard-fired (or) overdriven.

Turn-off Characteristics:

* Turn-off time (t_q) is defined as the time during which SCR changes conducting state to blocking state.

* SCR can be turned off by

- i) Reducing anode current below holding current
- ii) Application of reverse voltage.

* Even though $I_a = 0$, if we apply forward voltage to SCR, the device starts conducting because of excess charge carriers.

* So it is essential to remove this excess charge carriers from all four layers.

* Thus turn-off time can be defined as time elapsed between the instant, anode current becomes zero and the instant SCR regains its forward blocking capability.

* Turn-off time can be divided into two intervals

- i) Reverse recovery time
- ii) ~~Gate~~ recovery time

* During Reverse recovery time, excess carriers in the outer p-layer and n-layer are removed.

* During Gate recovery time, excess carriers around junction J_2 are removed only by recombination.

* Turn-off mechanism can be detailedly explained w.r.t time instants.

i) At t_1 , $I_a = 0$ and it starts build up in reverse direction.

ii) At t_2 , about 60% stored charges are removed and reverse recovery current starts decaying.

iii) At t_3 , reverse recovery current has fallen to nearly zero value. [J_1 and J_3 recovers]

iv) Still some charges are present in J_3 and this can be removed by recombination with reverse voltage maintained across SCR.

v) This process takes place at instant between t_3 & t_4 .

* Turn-off time is in the range of 3 to 100 μsec and it can be reduced by increase in magnitude of reverse voltage.

* Turn-off time provided to the SCR by the practical circuit is called circuit turn-off time (t_c).

* In order to avoid commutation failure, always $t_c > t_q$.

Note:

* SCR with slow turn-off time (50-100 μsec) - Converter grade SCR

* SCR with fast turn-off time (3-50 μsec) - Inverter grade SCR.

Turn-on methods of SCR:

* Thyristor is turned-on by increasing the anode current with anode positive with reference to cathode.

* It can be turned on by following techniques

- 1) Forward voltage triggering
- 2) Gate triggering
- 3) dv/dt triggering
- 4) Light triggering
- 5) Temperature triggering

Forward voltage triggering:

* In this mode of triggering a forward voltage is applied between anode and cathode, with gate circuit open.

* Though the SCR is forward biased, it will be in forward blocking mode because of reversed biased J_2 junction.

* If forward voltage is increased gradually, at certain stage avalanche breakdown occurs and J_2 allows free movement of carriers, making SCR to conduct.

* In practice, the transition from off-state to on-state obtained exceeding V_{BO} is never employed as it may destroy the device.

Gate triggering:

* In this mode of triggering a positive voltage is applied between gate and cathode, when it is in forward biased condition.

* Due to this, charge carriers are injected in inner p-layer, thereby reducing depletion layer thickness and SCR starts conducting.

* As the gate current is increased, forward blocking voltage decreases.

* This method of triggering is mostly used because of its reliable and efficient operation.

dV/dt triggering:

* With forward voltage across the anode and cathode of SCR, J_1 , J_3 junctions are forward biased but J_2 junction is reversed biased.

* This J_2 has the characteristics of capacitor due to charges existing across the junction.

* If forward voltage is suddenly applied, a charging current through junction capacitance may turn-on SCR.

$$i_c = C_j \frac{dV_a}{dt} = i_a$$

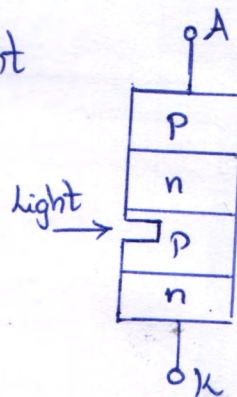
* As dV_a/dt is increased, I_a also increase and at certain stage SCR starts conducting, but it may also damage the SCR.

Light triggering:

* For light-triggered SCR's, a recess (or niche) is made in the inner p-layer instead of gate terminal.

* When this recess is irradiated by light waves, free charge carriers are generated.

* The pulse of light of appropriate wavelength is guided by optical fibers for irradiation.



* When the intensity of light thrown exceeds a certain value, SCR gets turned-on and such SCRs are called Light Activated SCR (LASCR).

Temperature triggering:

* During forward blocking, voltage across J_2 associated with leakage current, would raise the temperature of this junction.

* Due to regenerative action, $(\alpha_1 + \alpha_2)$ may tend to unity and SCR may be turned-on.

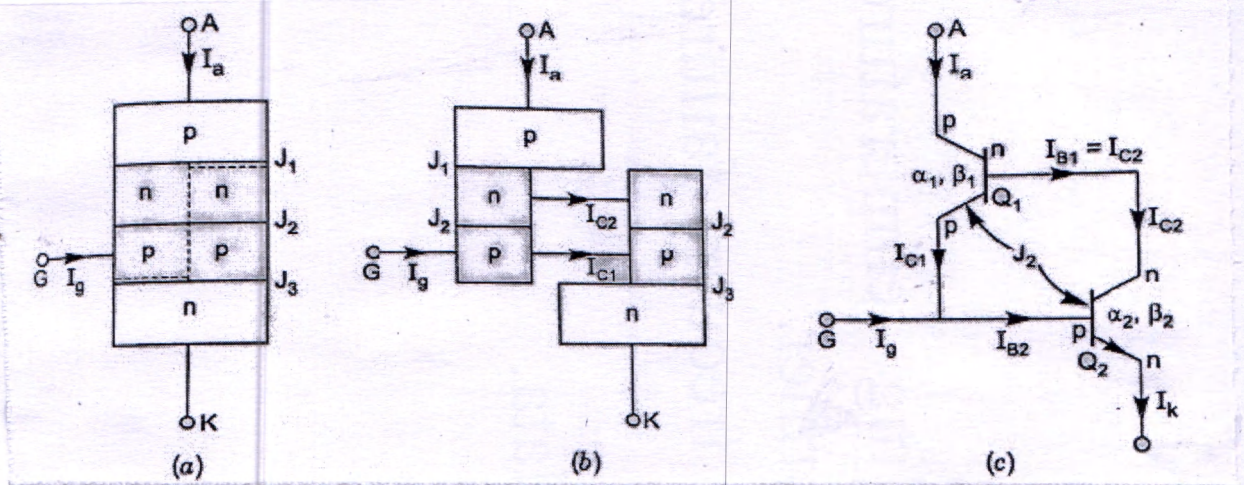
* This type of turn-on may cause thermal runaway and is normally avoided.

Two-Transistor Model of a Thyristor:

* The principle of SCR operation can be explained with the use of two-transistor analogy.

* Two Transistor model is obtained by bisecting the two middle layers.

* Junction J_1 - J_2 constitute pnp transistor and J_2 - J_3 constitute npn transistor.



Analysis:

In the off-state of a transistor, collector current I_c is related to emitter current I_E as

$$I_c = \alpha I_E + I_{CBO} \quad - (1)$$

where, α - Common-base current gain

I_{CBO} - Common-base leakage current

For transistor Q_1 and Q_2 ,

$$I_{C1} = \alpha I_{E1} + I_{CBO1} \quad \text{and} \quad I_{C2} = \alpha I_{E2} + I_{CBO2} \quad - (2)$$

wkt, $I_{E1} = I_a$

$I_{E2} = I_k$

$I_{C1} = I_{B2}$ [when $I_g = 0$]

$I_{C2} = I_{B1}$

$I_a + I_g = I_k$

$$\left. \begin{array}{l} I_{E1} = I_a \\ I_{E2} = I_k \\ I_{C1} = I_{B2} \text{ [when } I_g = 0 \text{]} \\ I_{C2} = I_{B1} \\ I_a + I_g = I_k \end{array} \right\} - (3)$$

Considering Q_1 ,

$$I_{E1} = I_{C1} + I_{B1}$$

$$I_{E1} = I_{C1} + I_{C2}$$

~~Q.1~~

Sub the eqn (2) & (3), so that

$$I_{E1} = \alpha_1 I_{E1} + I_{CBO1} + \alpha_2 I_{E2} + I_{CBO2} \quad [\text{from (2)}]$$

$$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 I_k + I_{CBO2} \quad [\text{from (3)}]$$

$$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 (I_a + I_g) + I_{CBO2} \quad [\text{from (3)}]$$

$$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 I_a + \alpha_2 I_g + I_{CBO2}$$

$$I_a - \alpha_1 I_a - \alpha_2 I_a = \alpha_2 I_g + I_{CBO1} + I_{CBO2}$$

$$I_a [1 - (\alpha_1 + \alpha_2)] = \alpha_2 I_g + I_{CBO1} + I_{CBO2}$$

$$\therefore I_a = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)} \quad \text{--- (4)}$$

* From eqn (4), we understood that when $(\alpha_1 + \alpha_2) = 0$, there is no conduction of SCR.

* But when $(\alpha_1 + \alpha_2) = 1$, I_a tends to infinity (i.e., large current) and the SCR will turn-on, even with small gate current.

* This is achieved because of regenerative action taking place in forward biased condition.

Turn-off methods of SCR:

* Turn-off of a SCR means bringing the device from forward conduction state to forward blocking state.

Series and Parallel Operation of SCR:

* Now-a-days SCRs with voltage and current ratings of 10kV and 3kA are available, however some industries demand for high voltage and current ratings that a single SCR cannot fulfil such requirements.

* In such cases, SCRs are connected in series [HV] and parallel [HC] arrangement to fulfil the demand.

* It should be ensured that for any combinations of SCR the SCR rating is fully utilized and this ~~can~~ degree of utilization is measured by term called string efficiency.

$$\text{String Efficiency} = \frac{\text{Actual Voltage/Current rating of whole string}}{\left[\frac{\text{Individual voltage/Current rating of one SCR}}{\text{Current rating of one SCR}} \right] \left[\frac{\text{Number of SCRs in the string}}{\text{the string}} \right]}$$

* In practice, this ratio is less than one. For obtaining highest value, SCR's connected in series/parallel string must have identical I-V characteristics.

* But SCRs of the same ratings and specifications, do not have identical characteristics and string efficiency can never be equal to one.

* Unequal voltage/current sharing can be minimised by using external equalizing circuits.

* Still string efficiency will not ^{be} one. This can be done with the help of adding one extra unit in the string, reliability can be improved and measured by Derating Factor.

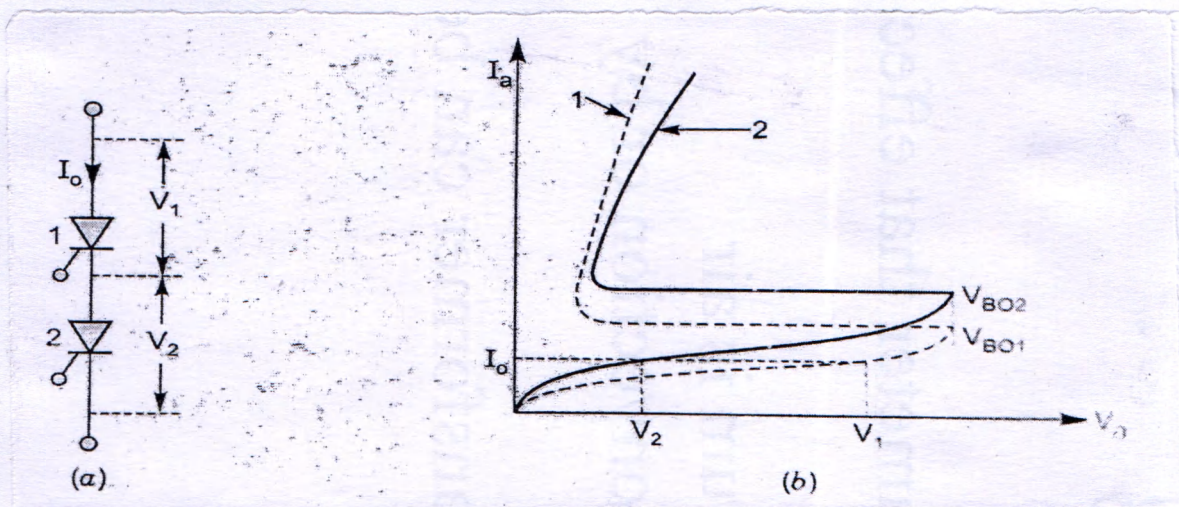
$$DRF = 1 - \text{string efficiency.}$$

Series Operation:

* SCRs are connected in series, in order to increase the voltage rating of a string.

* Two SCRs connected in series are considered and the essential requirement is that, they should possess identical VI characteristics.

* On account of inherent variations in their characteristics, voltage sharing of each SCR may not be equal.



* It is clear that, for the same leakage current I_o , SCR 1 supports the voltage V_1 and SCR 2 supports the voltage V_2 and $V_2 < V_1 < V_{BO}$.

$\therefore$ Total voltage drop across the string = $V_1 + V_2$ but,
 $\neq 2V_1$ or $2V_2$.

$$\therefore \text{String Efficiency} = \frac{V_1 + V_2}{2V_1} \text{ or } \frac{V_1 + V_2}{2V_2}$$

* This string efficiency will be less than one due to unequal voltage distribution across the SCRs in the string.

* So in order to improve the string efficiency, uniform distribution of voltages across the SCRs are essential and this can be done by connecting suitable resistance across each SCR.

* Different ratings of resistors are required for equal voltage sharing, but it is difficult task in practice.

* So a common value of resistor is designed and is approximated as,

$$R = \frac{nV_{bmn} - V_s}{(n-1)\Delta I_b}$$

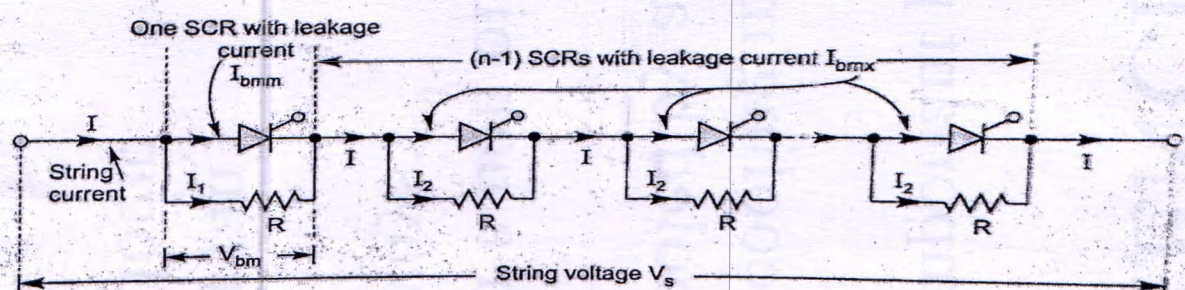
where, n - number of SCRs

V_{bmn} - Minimum blocking voltage

$$\Delta I_b = I_{bmx} - I_{bmn}$$

I_{bmx} - Maximum blocking current

I_{bmn} - Minimum blocking current



* External circuit that is used to equalize the voltage distribution across all the SCRs connected in series during forward blocking mode is called as static equalizing circuit.

* But during transient conditions, a static equalizing circuit can't equally distribute the voltage across the SCRs.

* This is due to the existence of junction capacitance and it varies based on the bias conditions.

* So this can be nullified by providing shunt capacitance (C_s).

* Before turning-on any SCR, the shunt capacitor charges to a voltage existing across the SCR and as soon as SCR starts conducting, the capacitor discharges making heavy current flows through SCR and may damage it.

* So in order to protect the SCR, the heavy currents are limited by using damping resistor (R_c) in series with the C_s .

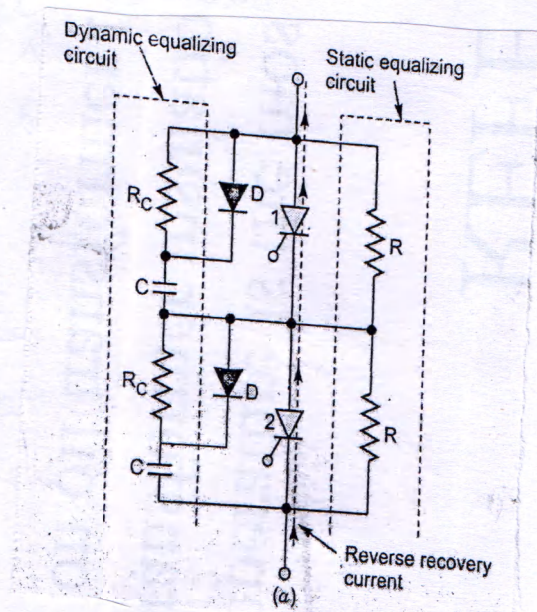
* The combination of R_c and C_s is called as dynamic equalizing circuit.

* A diode D is also placed across R_c and the function of D is

1) when forward voltage appears, diode bypasses R_c during charging time of capacitor (C_s) and when discharging R_c comes into play [diode acts as open switch].

* In series connected SCRs, voltage unbalance during turn-off time is more predominant than it is during turn-on time.

* Therefore, choice of capacitor is based on reverse recovery characteristics and it can be designed as



$$C = \frac{(n-1) \Delta Q}{nV_{bm} - V_s}$$

where $\Delta Q = Q_2 - Q_1$

ΔQ - Change in excess charge

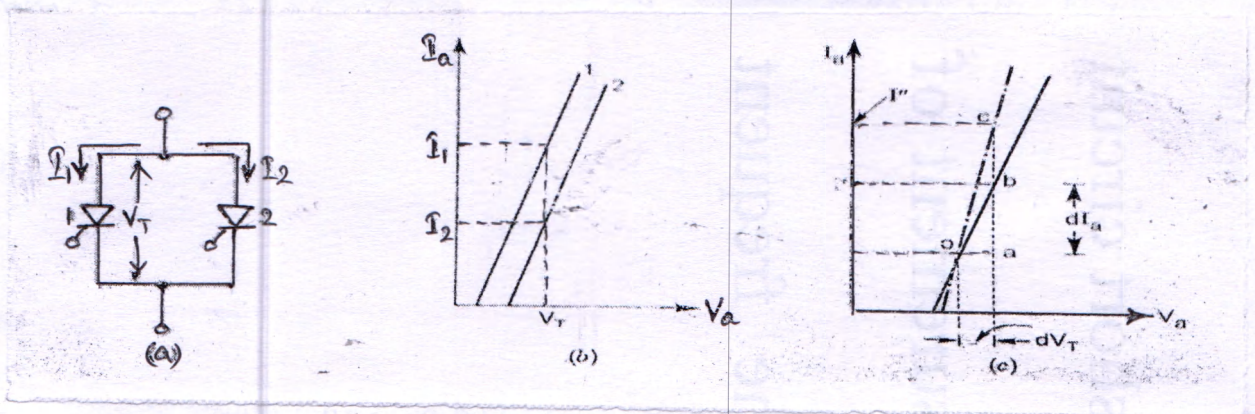
Q_1 - Stored charge in SCR₁

Q_2 - Stored charge in SCR₂

Parallel Operation:

* SCRs are connected in parallel, in order to increase the current rating of the string.

* SCR₁ and SCR₂ are connected in parallel are considered, and the essential requirement is that the SCRs should possess identical I-V characteristics, to have equal sharing of currents.



* It is clear that, for the same voltage drop V_T , SCR₁ shares a rated current I_1 and SCR₂ shares a rated current I_2 and $I_1 < I_2$.

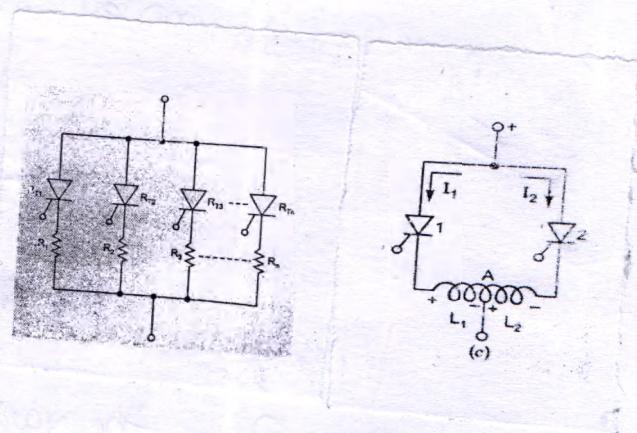
∴ Total current carried by the unit = $I_1 + I_2$ but $\neq 2I_1$ or $2I_2$.

$$\therefore \text{String Efficiency} = \frac{I_1 + I_2}{2I_1} \text{ or } \frac{I_1 + I_2}{2I_2} < 1.$$

* So in order to improve the string efficiency equal load sharing is to be provided and this can be achieved by connecting suitable resistance in series with each SCRs.

* When the resistors are connected in series with the SCRs, load current starts flowing through it, thereby causing much amount of power loss in the form of heat and can be reduced by mounting the parallel unit on one common heat sink.

* In parallel combination of SCRs, inductive effect of current carrying inductor may also cause unequal current distribution and this can be avoided by mounting the SCRs symmetrically on the heat sink.



* In addition to the series resistors, magnetically coupled inductors are to be provided for equal load distribution, and this represents dynamic sharing circuit.

Note:

* Forward blocking mode of operation is to be considered while dealing with series combination of SCRs.

* Forward conducting mode of operation is to be considered while dealing with parallel combination of SCRs.

* Valley-point current is given by V_v/R_{B1} and is also called holding current, keeps UJT on.

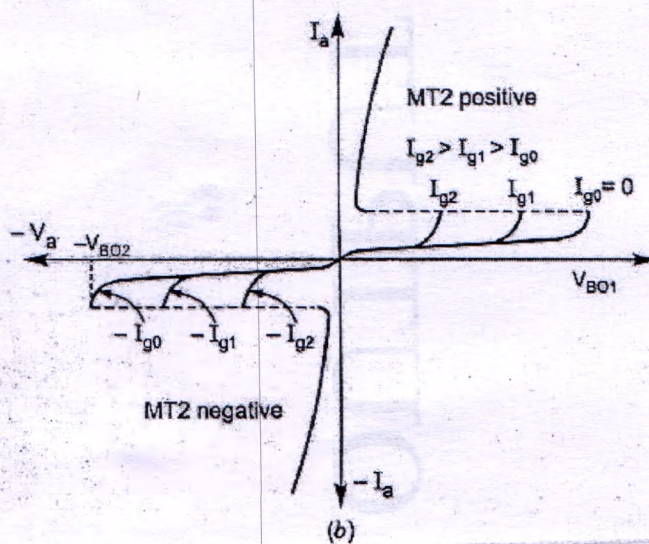
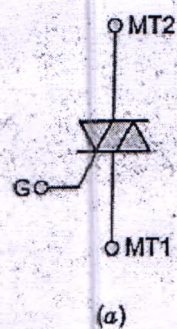
* When I_e falls below I_v , UJT turns-off.

TRIAC:

* It is a bidirectional device with three terminals, namely MT1 (main terminal), MT2 and G (gate).

* When in operation, a TRIAC is equivalent to two SCRs connected in antiparallel.

* TRIAC is the word derived by combining TRIode and AC.

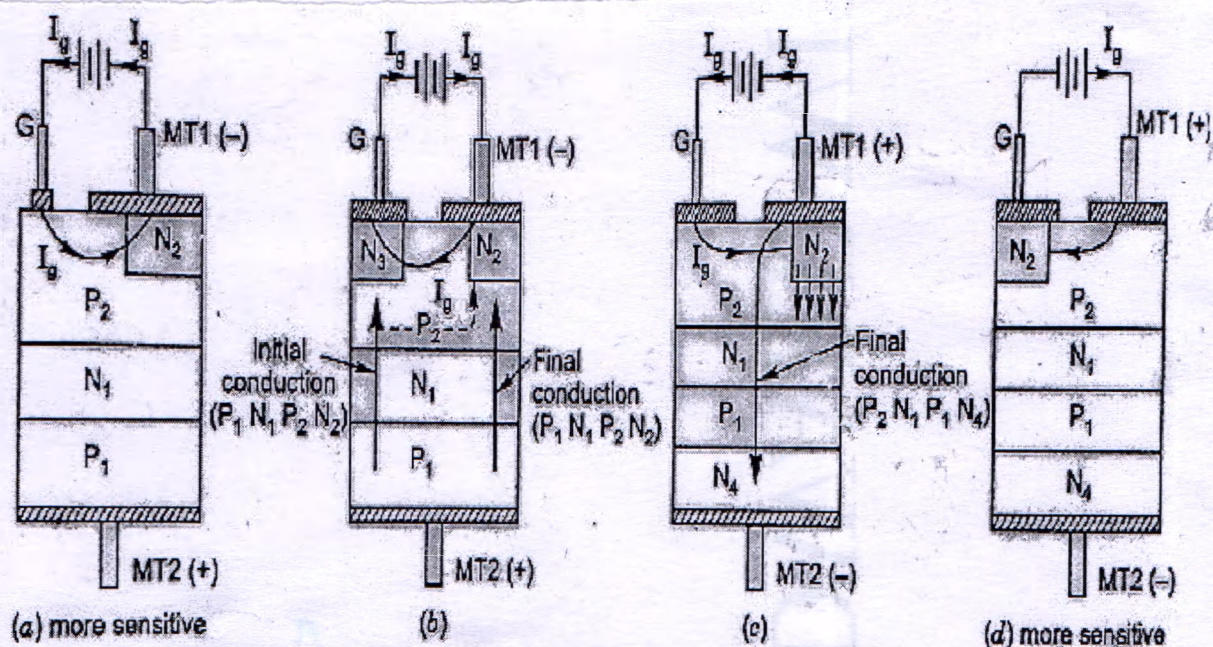


* With no signal to gate, the TRIAC will block both half-cycles of the AC applied voltage with condition peak value of this voltage is less than the breakover voltage of V_{BO1} or V_{BO2} of the TRIAC.

* The TRIAC can, however, be turned-on in each half cycle of the applied voltage by applying a positive or negative voltage to the gate w.r.t MT1.

* The turn-on process of a TRIAC can be explained as,

- i) MT2 is positive and G is positive
- ii) MT2 is positive and G is negative
- iii) MT2 is negative and G is positive
- iv) MT2 is negative and G is negative.



* Figure shows the four turn-on process of a TRIAC. In this (a) & (b) shows final conduction is through P₁N₁P₂N₂ and (c) & (d) shows the final conduction is through P₂N₁P₁N₄.

i) $M T_2$ is positive and G is also positive:

* When $M T_2$ is positive w.r.t $M T_1$, junction $P_1 N_1$ and $P_2 N_2$ are forward biased but junction $N_1 P_2$ is reverse biased.

* When G is made positive w.r.t $M T_1$, gate current flows through P_2 layer, reverse biased junction $N_1 P_2$ breaks down just as in normal SCR.

* As a result, TRIAC starts conducting through $P_1 N_1 P_2 N_2$ layers.

* Under this condition, TRIAC operates in first quadrant and the device is more sensitive.

ii) $M T_2$ is positive but G is negative:

* When G is negative with respect to $M T_1$, gate current flows through $P_2 N_3$ junction and reverse biased junction $N_1 P_2$ is forward biased as in normal SCR.

* As a result, TRIAC starts conducting through $P_1 N_1 P_2 N_2$ layers initially.

* Due to this potential gradient exists across layer P_2 , its left hand region being at higher potential than its right hand region.

* A current shown dotted is thus established in layer P_2 from left to right and is similar to conventional gate current of an SCR.

* As a consequence, TRIAC consisting of main structure $P_1N_1P_2N_2$ begins to conduct.

* The device structure $P_1N_1P_2N_3$ may be regarded as pilot SCR and $P_1N_1P_2N_2$ as main SCR.

* In this turn-on process, $M\tau_2$ positive but gate current is negative is less sensitive and therefore, more gate current is required.

iii) $M\tau_2$ is negative but G is positive:

* When $M\tau_2$ is negative w.r.t $M\tau_1$, junction N_4P_1 and P_2N_1 is forward biased but junction N_1P_1 is reverse biased.

* When G is made positive, gate current I_g , forward biases P_2N_2 junction.

* So, layer N_2 injects electrons into P_2 layer, as a result reverse biased junction N_1P_1 breaks down.

* Eventually the structure $P_2N_1P_1N_4$ is completely turned-on.

* As the TRIAC is turned-on by remote gate N_2 , the device is less sensitive in the third quadrant.

iv) $M\tau_2$ is negative and G is negative:

* When $M\tau_2$ is negative w.r.t $M\tau_1$, junction N_4P_1 and

P_2N_1 is forward biased but N_1P_1 is reversed biased.

- * As soon as G made negative w.r.t MT_1 , gate current flows through P_2 layer, then the reversed biased junction P_1N_1 breaks down.

- * As a result, TRIAC starts conducting through $P_2N_1P_1N_1$ layers.

- * Under this condition, TRIAC operates in third quadrant and the device is more sensitive.

Note:

- * Sensitivity of the TRIAC is greatest in first and third quadrant when turned-on with positive and negative gate current respectively.

- * Sensitivity of the TRIAC is low in first and third quadrant when turned-on with negative and positive gate current respectively.

- * As the two conducting paths from MT_1 to MT_2 or from MT_2 to MT_1 interact with each other in the structure of the TRIAC, their ratings are much lower than conventional SCR.

- * At present, TRIACs with ratings of 1200V and 300A are available.

- * Applications are Residential lamp dimmers, heat control and for speed control of small single phase induction motors.

Gate Turn-Off Thyristor (GTO):

* Conventional Thyristors can be easily turned-on by positive gate current but turn-off is very difficult (need of expensive & bulky commutation circuitry).

* To overcome this drawbacks, GTO are developed for use above 1 kHz applications.

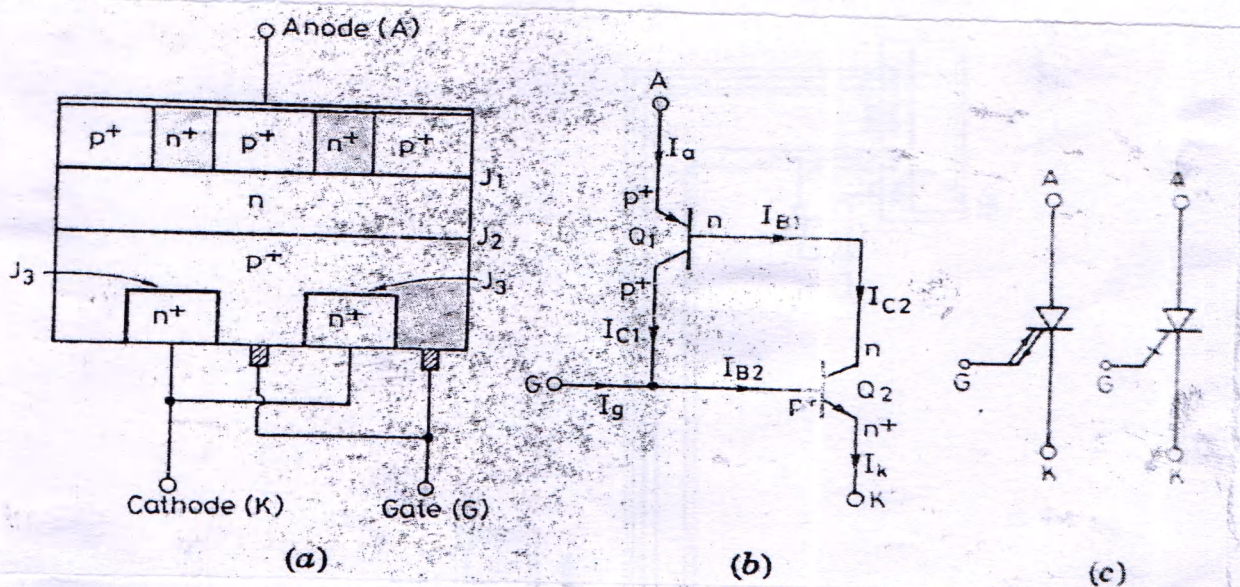
* GTO is turned-on by positive gate current as conventional thyristor and turned-off by negative gate current.

Basic Structure:

* It is a p^+np^+ , three terminal device with anode (A), cathode (K) and gate (G).

* In conventional thyristor, anode consists of p^+ layer, but in GTO, anode is made up of n^+ type fingers diffused into p^+ layer.

* Like conventional thyristor, it can also be modelled by two-transistor analogy.



Turn-on Process:

* GTO is turned on by applying a positive gate current as in conventional thyristor.

* Current gains α_1, α_2 begin to rise and when $\alpha_1 + \alpha_2 = 1$, saturation level is reached to turn-on GTO.

* I_a is limited by load impedance.

Turn-off Process:

* Two transistor model is analysed for understanding the turn-off process in GTO.

In general,

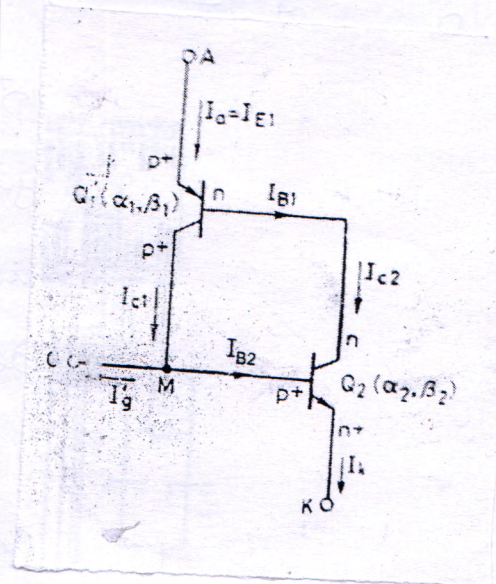
$$\alpha = \frac{I_c}{I_E} \text{ and } \beta = \frac{I_c}{I_B}$$

So, for Q_1 & Q_2

$$I_{C1} = \beta_1 I_{B1} ; I_{C2} = \beta_2 I_{B2} \quad - (1)$$

also,

$$I_{C1} = \alpha_1 I_{E1} ; I_{C2} = \alpha_2 I_{E2} \quad - (2)$$



* Turn-off process is initiated by applying negative gate current I_g' .

Applying KCL at M,

$$I_{C1} = I_g' + I_{B2}$$

$$\therefore I_{B2} = I_{C1} - I_g'$$

$$= \alpha_1 I_{E1} - I_g'$$

$$= \alpha_1 I_a - I_g'$$

$$[\text{since, } I_{E1} = I_a] \quad - (3)$$

Also, $I_{E1} = I_{B1} + I_{C1}$

$I_a = I_{C2} + I_{C1}$ [since, $I_{E1} = I_a$ & $I_{B1} = I_{C2}$]

$$\begin{aligned}\therefore I_{C2} &= I_a - I_{C1} \\ &= I_a - \alpha_1 I_{E1} \\ &= I_a - \alpha_1 I_a \\ &= (1 - \alpha_1) I_a \quad - (4)\end{aligned}$$

When saturation in Q_2 has occurred, $I_{B2} = \frac{I_{C2}}{\beta_2}$. For turn-off of GTO, Q_2 must be brought out of saturation.

So, for turning off of GTO (Q_2),

$$I_{B2} < \frac{I_{C2}}{\beta_2}$$

Substitute the value of I_{B2} & I_{C2} , we get

$$\begin{aligned}(\alpha_1 I_a - I_g') &< \frac{(1 - \alpha_1) I_a}{\beta_2} \\ - I_g' &< \frac{(1 - \alpha_1) I_a}{\beta_2} - \alpha_1 I_a \\ &< \frac{I_a}{\beta_2} - \frac{\alpha_1 I_a}{\beta_2} - \alpha_1 I_a \\ &< \frac{I_a}{\beta_2} - \left(1 + \frac{1}{\beta_2}\right) \alpha_1 I_a\end{aligned}$$

we also know that,

$$\beta_2 = \frac{\alpha_2}{1 - \alpha_2}, \text{ so}$$

$$- I_g' < \frac{I_a(1 - \alpha_2)}{\alpha_2} - \left[1 + \frac{(1 - \alpha_2)}{\alpha_2}\right] \alpha_1 I_a$$

$$-I_g' < I_a \left(\frac{1}{\alpha_2} - 1 \right) - I_a \frac{\alpha_1}{\alpha_2}$$

$$< I_a \left[\frac{1 - \alpha_1 - \alpha_2}{\alpha_2} \right]$$

$$\therefore I_g' > I_a \left[\frac{\alpha_1 + \alpha_2 - 1}{\alpha_2} \right]$$

* Gate current I_g' for turning-off GTO is low, α_2 should be made near to unity as possible and α_1 should be made small.

* Turn-off gain is defined as the ratio of anode current to gate current needed to turn-off GTO.

$$B_{off} = \frac{I_a}{I_g'} = \frac{\alpha_2}{\alpha_1 + \alpha_2 - 1}$$

Note:

To turn-off the GTO, negative gate current must be greater than anode current divided by turn-off gain.

MODULE II

II	Gate triggering circuits – R, RC, UJT triggering circuits – natural and forced commutation (concept only). Requirements of isolation and synchronisation in gate drive circuits- Opto and pulse transformer based isolation. Controlled rectifiers – half-wave controlled rectifier with R load – 1-phase fully controlled bridge rectifier with R, RL and RLE loads (continuous & discontinuous conduction) – output voltage
----	---

~~Q.1~~

Sub the eqn (2) & (3), so that

$$I_{E1} = \alpha_1 I_{E1} + I_{CBO1} + \alpha_2 I_{E2} + I_{CBO2} \quad [\text{from (2)}]$$

$$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 I_k + I_{CBO2} \quad [\text{from (3)}]$$

$$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 (I_a + I_g) + I_{CBO2} \quad [\text{from (3)}]$$

$$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 I_a + \alpha_2 I_g + I_{CBO2}$$

$$I_a - \alpha_1 I_a - \alpha_2 I_a = \alpha_2 I_g + I_{CBO1} + I_{CBO2}$$

$$I_a [1 - (\alpha_1 + \alpha_2)] = \alpha_2 I_g + I_{CBO1} + I_{CBO2}$$

$$\therefore I_a = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)} \quad \text{--- (4)}$$

* From eqn (4), we understood that when $(\alpha_1 + \alpha_2) = 0$, there is no conduction of SCR.

* But when $(\alpha_1 + \alpha_2) = 1$, I_a tends to infinity (i.e., large current) and the SCR will turn-on, even with small gate current.

* This is achieved because of regenerative action taking place in forward biased condition.

Turn-off methods of SCR:

* Turn-off of a SCR means bringing the device from forward conduction state to forward blocking state.

* This can be done by reducing anode current to a level below holding current ($I_a < I_H$).

* The various techniques for turning-off (Commutation) of a SCR are

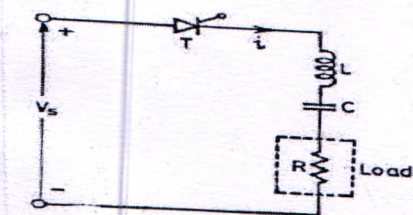
- 1) Class A Commutation - Load Commutation
- 2) Class B Commutation - Resonant Pulse Commutation
- 3) Class C Commutation - Complementary Commutation
- 4) Class D Commutation - Impulse Commutation
- 5) Class E Commutation - External Pulse Commutation
- 6) Class F Commutation - Line Commutation

* In order to turn-off SCR the conditions to be satisfied are

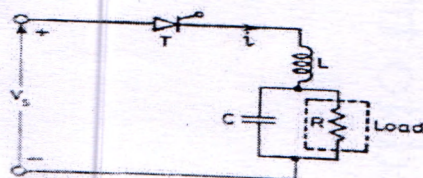
- i) $I_a < I_H$
- ii) Reverse voltage applied to SCR for sufficient time enabling it to recover its blocking state.

Class A Commutation:

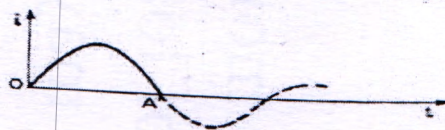
* For achieving load commutation of a SCR, the commutating components L and C are connected in either series or parallel to load.



(a)



(b)



* Here R is the load resistance and based on R value the connection varies.

* For low value of R , L and C connected in series.

* For high value of R , C and R connected in shunt.

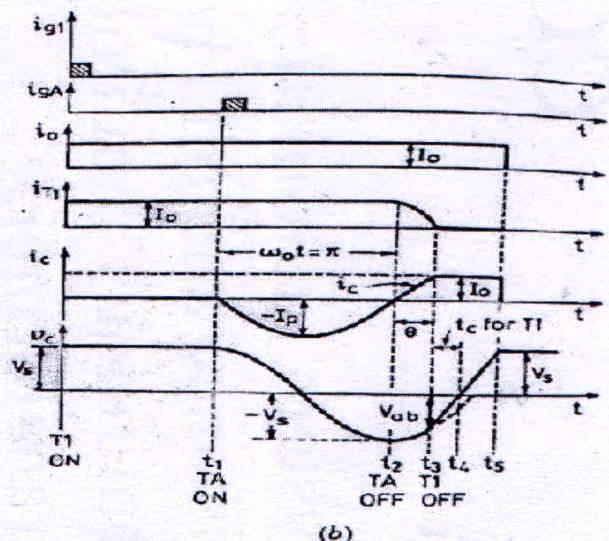
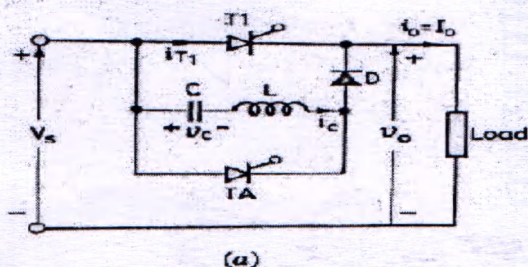
* The essential requirement for both the combination is that, overall circuit must be underdamped.

* When these circuits are energized from DC source, a current of the nature shown in above figure will be obtained across the device.

* This current, as evident from its shape, has zero value at point A where the device is automatically turned off.

Class B Commutation:

* Initially source voltage V_s charges capacitor C to voltage V_s with left hand plate positive, and main thyristor T_1 as well as auxiliary thyristor T_A are off.



* When T_1 is turned on at $t=0$, a constant current I_0 is established in the load circuit.

* Untill t_1 , $V_c = V_s$, $i_c = 0$, $i_o = I_0$.

* For initiating the commutation of T_1 , T_A is gated at $t = t_1$.

* With T_A -on, a resonant current i_c begins to flow from C through T_A , L and back to C.

$$i_c = -V_s \sqrt{\frac{C}{L}} \sin \omega_0 t = -I_p \sin \omega_0 t.$$

$$V_c = \frac{1}{C} \int i_c dt = V_s \cos \omega_0 t.$$

* After half a cycle of i_c from instant t_1 , $i_c = 0$, $V_c = -V_s$ and $i_{T_1} = I_0$.

* After π radians from instant t_1 , as i_c tends to reverse, T_A is turned off at t_2 .

* With $V_c = -V_s$, Right hand plate has positive polarity.

* Resonant current i_c now builds up through C, L, D and T_1 .

* As this current i_c grows opposite to forward thyristor current of T_1 , $i_{T_1} (= I_0 - i_c)$ begins to decrease.

* Finally, when $i_c = I_0$, $i_{T_1} = 0$ and T_1 is turned off at t_3 .

* For reliable commutation, peak resonant current I_p must be greater than I_0 .

* After T_1 is turned off at t_3 , I_o flows from V_s to load through C , L and D .

* Capacitor begins charging linearly from $-V_{ab}$ to zero at t_4 and then to V_s at t_5 , as a result at t_5 , $v_c = V_s$ and $i_o = i_c = I_o = 0$.

* Circuit turn-off time of T_1 is given by

$$t_c = t_4 - t_3 = C \frac{V_{ab}}{I_o}$$

Class C Commutation:

* In this type of commutation, a SCR carrying load current is commutated by transferring its load current to another incoming SCR.

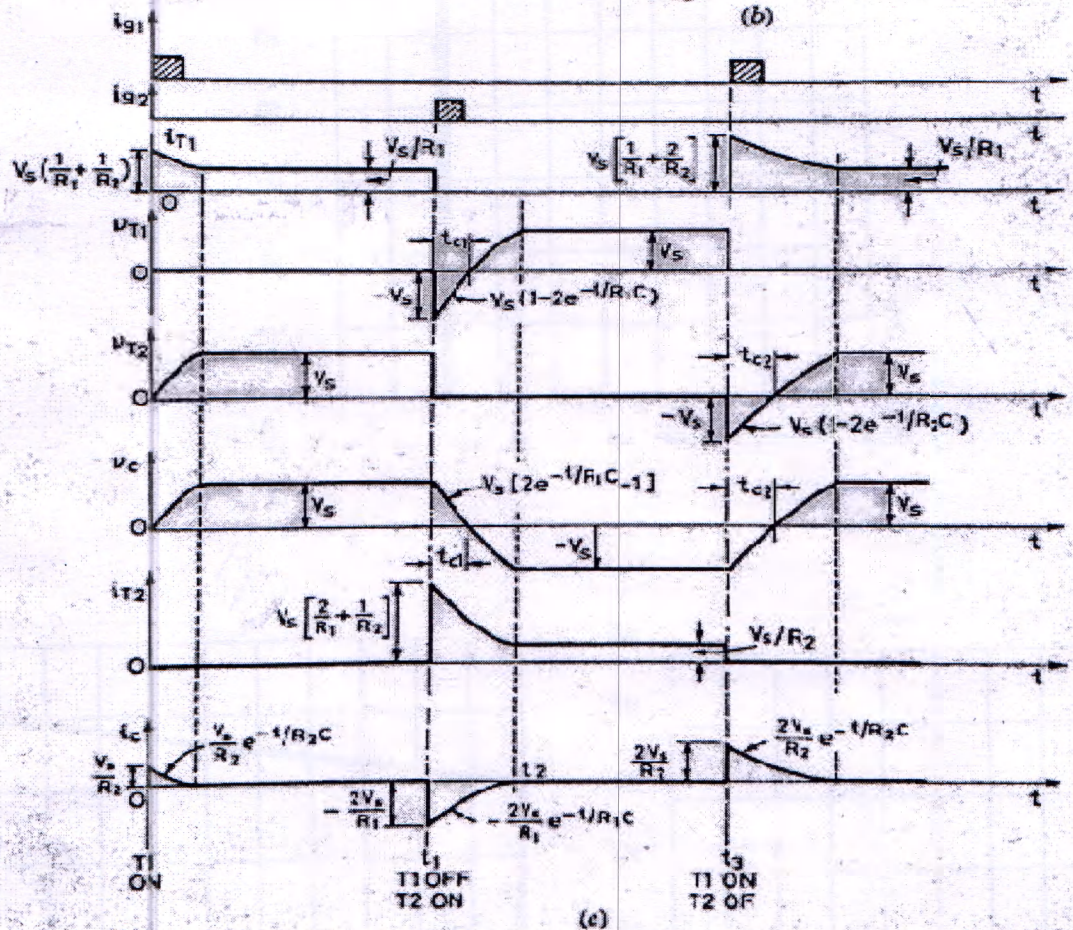
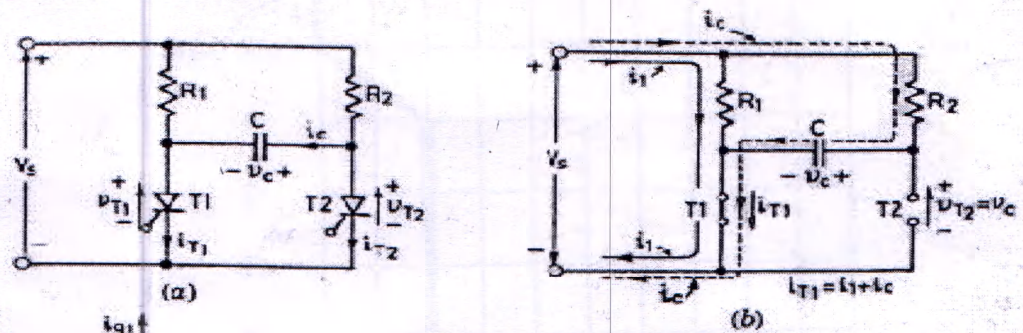
* It means, firing of T_1 commutates T_2 and subsequently firing of T_2 commutates T_1 .

* When T_1 is turned on at $t=0$, i_1 starts flowing through R_1 and R_2 .

$$i_{T1} = i_1 + i_c = V_s \left[\frac{1}{R_1} + \frac{1}{R_2} \right]$$

* Here capacitor C begins charging through R_2 from $v_c = 0$ and its current is given by

$$i_c(t) = \frac{V_s}{R_2} e^{-t/R_2 C}$$



* After sometime, when transients are over, $v_c = v_{T2} = V_s$ and i_c decays to zero.

* When T_2 is turned on, a reverse voltage across T_1 appears due to capacitor and turns off the SCR T_1 .

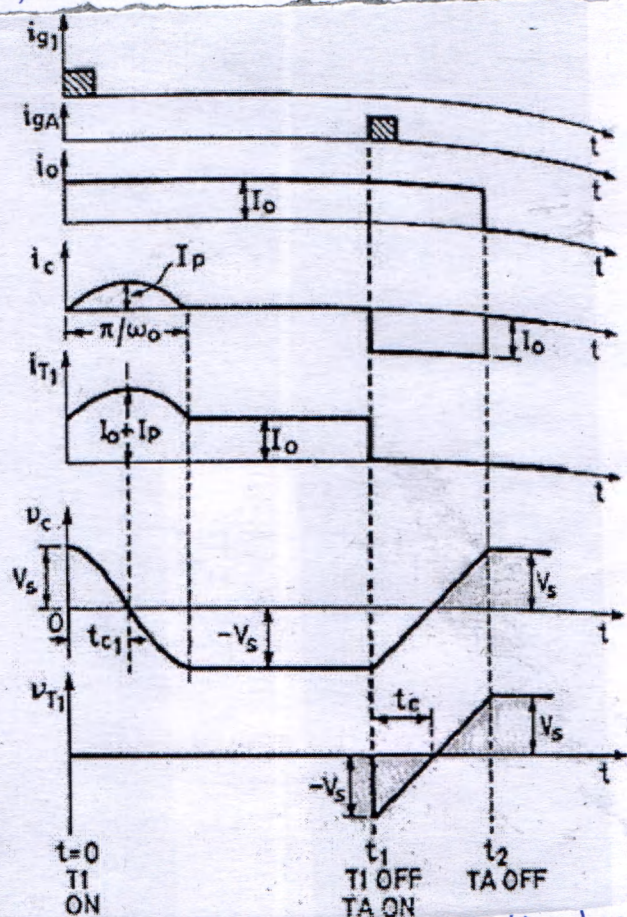
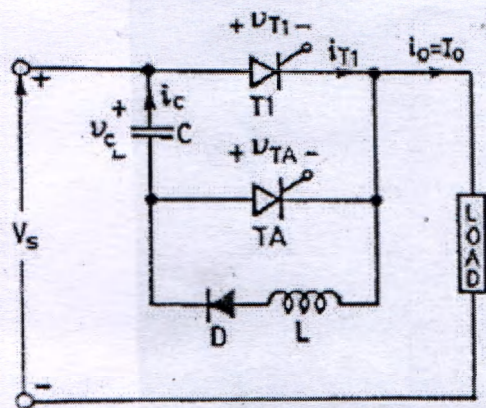
* Now charging of capacitor takes place through R_1 and load making right hand plate positive.

* When T_1 is triggered, discharging current of capacitor turns T_2 off and the process goes on.

Class D Commutation:

* In this method, an auxiliary SCR T_A is required to commutate the main SCR T_1 .

* Initially, T_1 and T_A are off, and capacitor is assumed to be charged to V_s with upper plate positive.



* Now T_1 is triggered and the current through T_1 has two paths:

- i) Load current I_o [$V_s - T_1 - \text{load} - V_s$]
- ii) Discharging capacitor current i_c [$C - T_1 - L - D - C$]

where i_c is given by

$$i_c = V_s \sqrt{\frac{C}{L}} \sin \omega_o t = I_p \sin \omega_o t.$$

* At $\omega_o t = \pi$, $i_c = 0$, $i_{T1} = I_o$ and $v_c = -V_s$, it means capacitor completely discharges and charges in opposite polarity.

* At t_1 , T_A is turned on and the capacitor starts discharging and making T_1 to be turned off.

* Now I_o flows through C and T_A .

* After completely discharging, the capacitor again charges from $-V_s$ to V_s .

* After sometime or at t_2 , T_A is turned off and circuit turn-off time is shown as t_c .

* This type of commutation is also called auxiliary commutation / voltage commutation / parallel-capacitor commutation

Class E Commutation:

* In this type of commutation, a pulse of voltage is obtained from a separate voltage source to turn off the SCR.

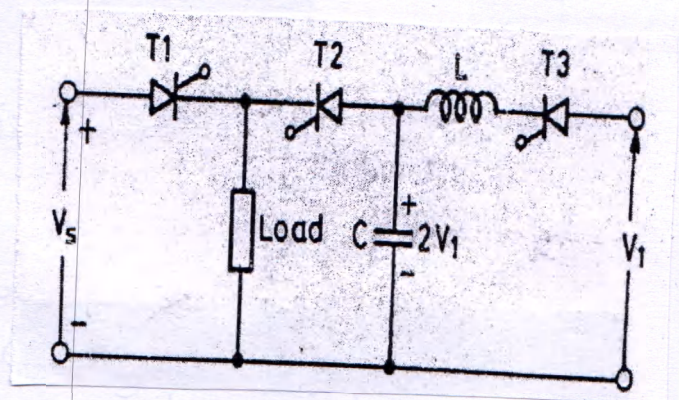
* Here V_s is the voltage of main source and V_1 is the voltage of auxiliary supply.

* SCR T_1 is conducting and load is connected to V_s .

* When T_3 is turned on, V_1 , T_3 , L and C form an oscillatory circuit.

* Capacitor C is charged to $+2V_1$, with upper plate positive.

* To turn-off T_1 , T_2 is triggered and reverse voltage appears across T_1 and turns it off.

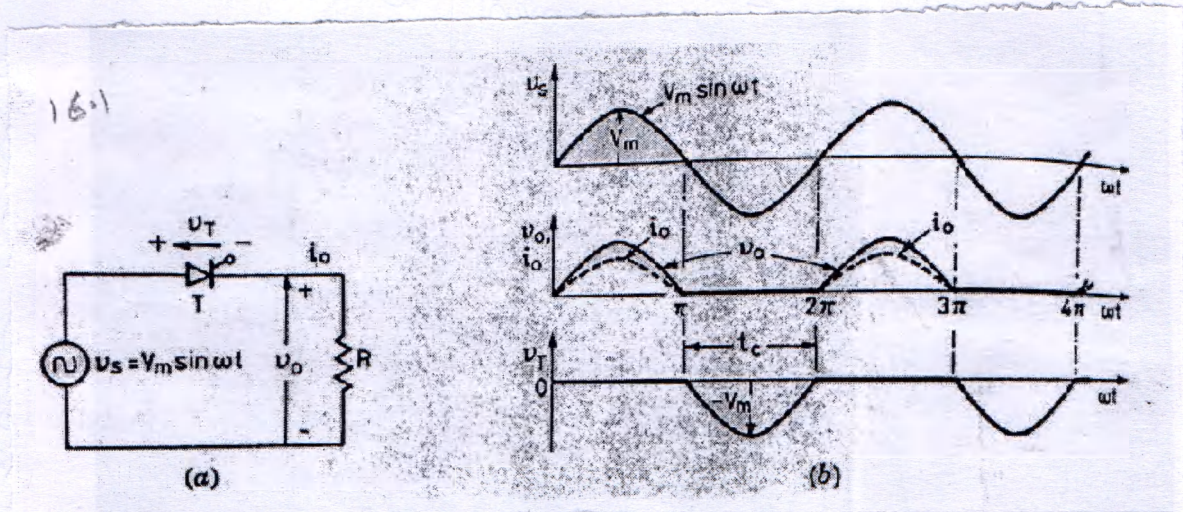


* After T_1 is off, capacitor discharges through the load.

Class F Commutation:

* This type of commutation is also known as natural commutation.

- * This can occur only when converter circuits are fed from ac source.



- * During positive half cycle of 1-phase source, SCR starts conducting when triggered.

* At $\omega t = \pi$, ac voltage becomes zero and negative half cycle begins thereafter.

* This negative voltage is applied across SCR for sometime and making it turned off.

* This resembles like the reversed biased SCR.

* This method of commutation is applied to phase controlled rectifiers, ac voltage controllers and step-down cycloconverters.

Firing Circuits for SCRs:

* The most common method of turning on the SCR is Gate triggering. The gate can be triggered with the help of following methods.

- 1) Resistance firing circuits
- 2) Resistance - Capacitance firing circuits
- 3) UJT firing circuits.

1) Resistance firing circuits:

* It is simplest and most economical type of firing circuit, but suffer from a limited range of firing angle control (0 to 90°).

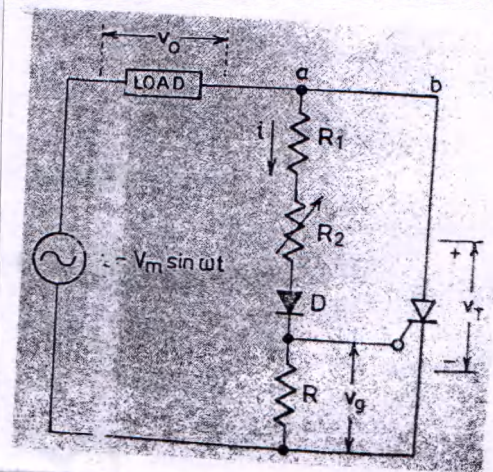
* The most basic resistance triggering circuit is depicted here.

* Here R_2 is the variable resistance, R is the stabilizing resistance and R_1 is the limiting resistance.

* The main function of R_1 is to limit gate current to a safe value.

* R should have such a value that maximum voltage drop across it does not exceed maximum possible gate voltage V_{gm} .

$$R_1 \geq \frac{V_m}{I_{gm}} \quad \text{and} \quad R = \frac{(R_1 + R_2)V_{gm}}{V_m - V_{gm}}$$



* Resistance firing circuit works on three operating conditions.

i) $V_{gp} < V_{gt}$

ii) $V_{gp} = V_{gt}$

iii) $V_{gp} > V_{gt}$.

i) * When R_2 is large, current i is small and the voltage across R is small.

* This makes $V_{gp} < V_{gt}$ and SCR will not turn-on.

* Therefore, load voltage $v_o = 0$ and $i_o = 0$.

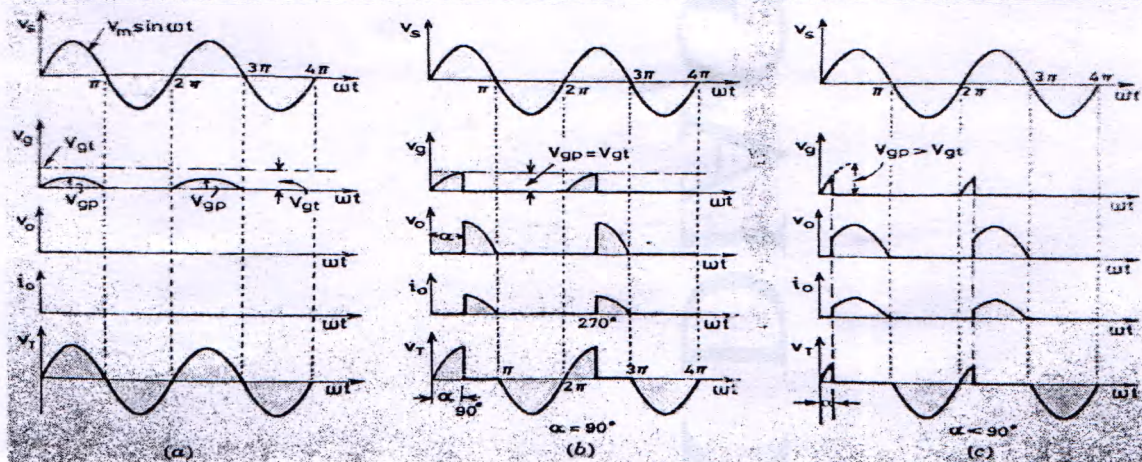
ii) * Now R_2 is adjusted such that $V_{gp} = V_{gt}$ and SCR turns-on.

* This gives the value of firing angle as 90° .

iii) * Still varying R_2 , at a particular condition $V_{gp} > V_{gt}$, the firing angle can be varied from 0 to 90° .

* The firing angle can be given as

$$\alpha = \sin^{-1} \left[\frac{V_{gt} \cdot (R_1 + R_2 + R)}{V_m \cdot R} \right]$$

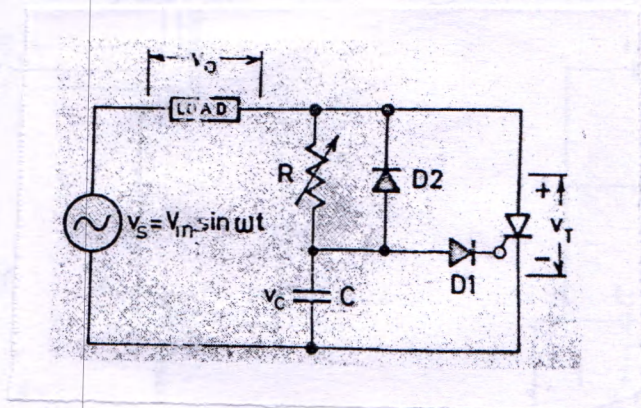


Note:

- * Firing angle can never be equal to zero degree however large V_{gp} it may be.
- * As V_{gt} , R_1 , R and V_m are fixed, $\alpha \propto R_2$.

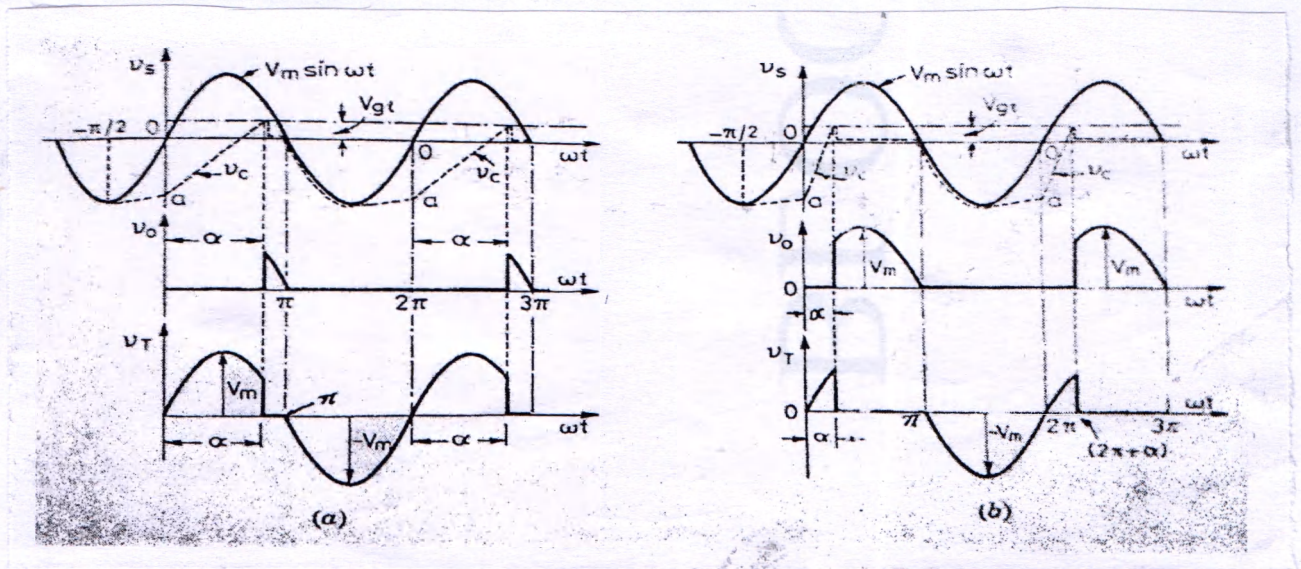
Resistance - Capacitance Firing Circuits:

- * The limited range of firing angle control by Resistance firing circuit can be overcome by RC firing circuit.
- * The figure shows the RC half-wave trigger circuit.
- * By varying the value of R , firing angle can be controlled from 0 to 180° .
- * Diode D_1 is used to prevent the breakdown of cathode to gate junction through D_2 during the negative half cycle.



- * In the negative half cycle, C charges through D_2 with lower plate positive to peak supply voltage V_m at $\omega t = -90^\circ$.
- * After $\omega t = -90^\circ$, V_s decreases from $-V_m$ to 0 , similarly V_c falls from $-V_m$ to some lower value $-0a$.
- * When V_s reaches $\omega t = 0$ and starts increasing, C begins to charge through R .

* When $V_c = V_{gt} + V_d$, SCR is fired and after this, capacitor holds a small positive voltage.



* The waveform describes the output, based on the values of R .

* If R is more, time taken for C to charge from -0.6 to $V_{gt} + V_d$ is more, firing angle is more and therefore average output voltage is low.

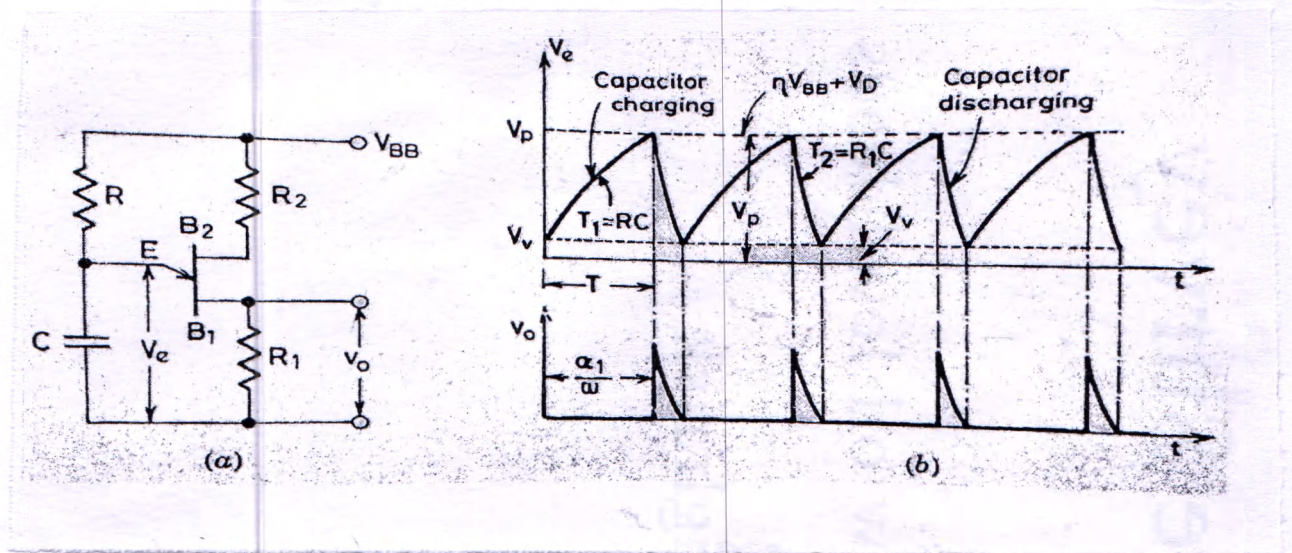
* If R is less, firing angle is less and therefore average output voltage is more.

UJT Oscillator Triggering:

* UJT is a highly efficient switch and its switching time is in the range of nanoseconds.

* Since UJT exhibits negative resistance characteristics, it can be used as relaxation oscillator.

* Figure shows a circuit diagram with UJT working in the oscillator mode.



* External resistances R_1, R_2 are small in comparison with the internal resistances R_{B1}, R_{B2} of UJT bases.

* Charging resistance R should be such that its load line intersects the device characteristics only in the negative resistance region.

* When V_{BB} is applied, capacitor C begins to charge through R exponentially.

* During this charging, emitter circuit of UJT is an open circuit and V_e is given as

$$V_e = V_c = V_{BB} (1 - e^{-t/RC}).$$

* When V_e reaches peak-point voltage $V_p = \eta V_{BB} + V_D$, unijunction between $E-B_1$ breakdown.

* As a result, UJT turns-on and C rapidly discharges through low resistance R_1 .

* The voltage drop across R_1 , equal to V_0 is applied to gate-cathode circuit of an SCR to turn it on.

* When V_c decays to valley-point voltage V_2 , emitter current falls below I_r and UJT turns off.

* Time constants are given by

$$\tau_1 = RC \text{ and } \tau_2 = R_1 C \quad [\tau_2 < \tau_1]$$

* Resistance R is given by

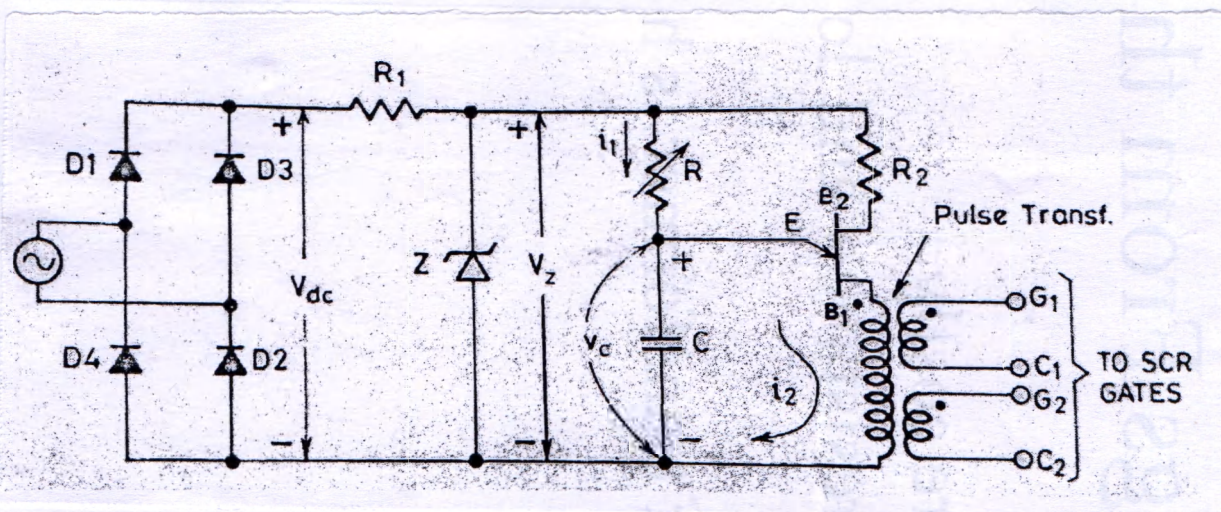
$$R_{\max} = \frac{V_{BB} - V_p}{I_p} \text{ and } R_{\min} = \frac{V_{BB} - V_v}{I_r}$$

Synchronized UJT Triggering:

* Diodes $D_1 - D_4$ rectify AC to DC and provides V_{dc} .

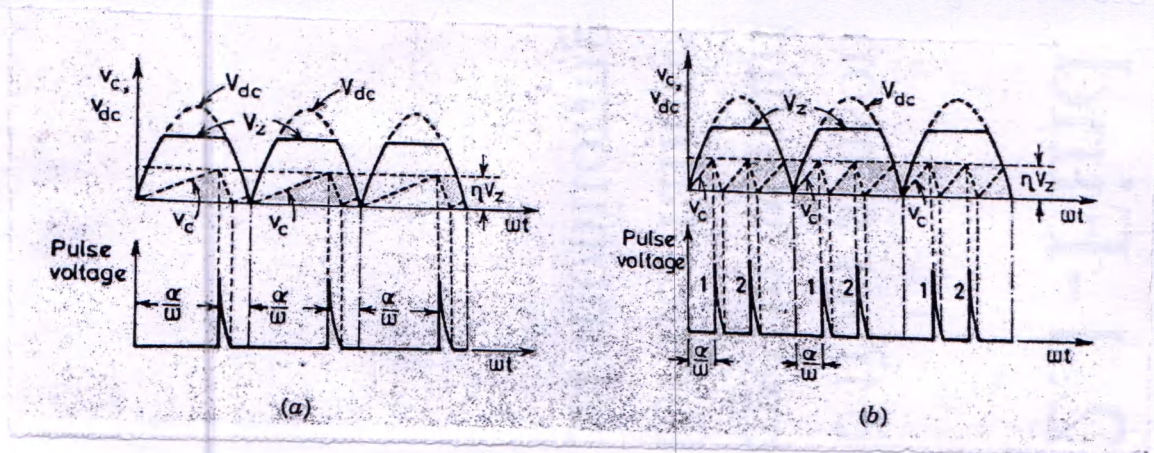
* Resistor R_1 lowers V_{dc} to a suitable value for Zener diode and UJT.

* Zener diode is used to clip the rectified voltage to a standard level V_z .



* V_z is applied to charging circuit RC. Capacitor C charges through R until it reaches UJT trigger voltage V_p .

* The UJT then turns-on and C discharges through the UJT emitter and primary of pulse transformer.



* The windings of the pulse transformer have pulse voltages at their secondary terminals which feeds two SCRs.

* SCR with positive anode voltage would turn-on.

* Rate of rise of V_c can be controlled by varying R and firing angle can be controlled upto 150° .

* This method of controlling is also called Ramp control.

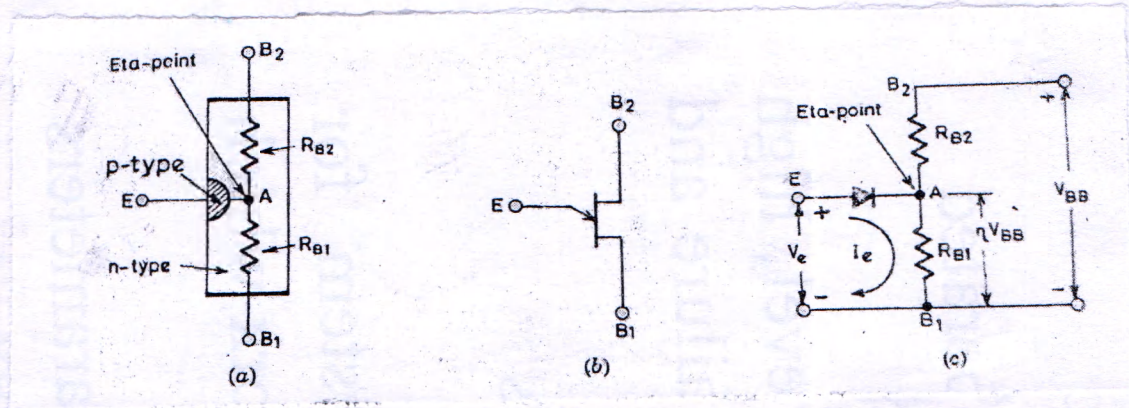
Unijunction Transistor (UJT):

* An UJT is made up of an n-type silicon base to which p-type emitter is embedded.

* The n-type base is lightly doped whereas p-type is heavily doped.

* The two ohmic contacts provided at each end are called base-one B_1 and base-two B_2 .

- * So, UJT has three terminals, namely E, B₁ and B₂.
- * R_{B1} and R_{B2} are the internal resistances from B₁ and B₂ to eta point A.



- * When a voltage V_{BB} is applied across B₁ & B₂, the potential of point A wst B₁ is given by

$$V_{AB1} = \frac{V_{BB}}{R_{B1} + R_{B2}} \cdot R_{B1} = \eta V_{BB}$$

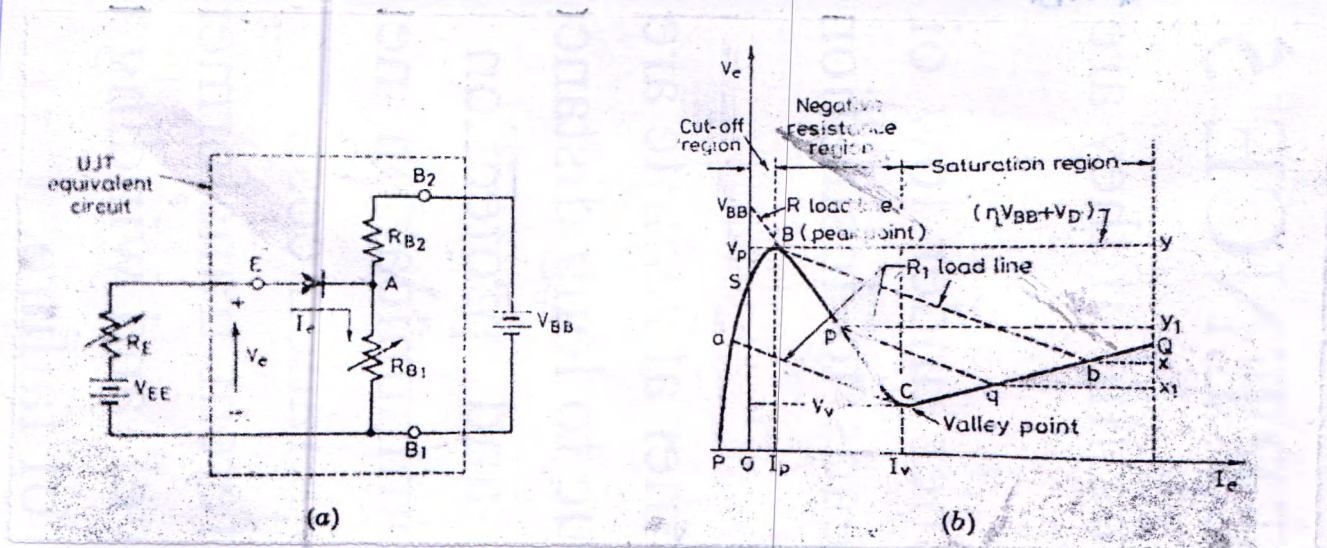
where, $\eta = \frac{R_{B1}}{R_{B1} + R_{B2}}$ is called Intrinsic Stand-off ratio and its typical values are in 0.51 to 0.82.

- * R_{BB} is the interbase resistance and can be measured by a multimeter with emitter open. [$R_{BB} = R_{B1} + R_{B2}$, 5-10k Ω]
- * Since Emitter is nearer to B₂, $R_{B2} < R_{B1}$.

Operation of UJT:

- * UJT is usually operated with both E and B₂ biased positive wst reference base terminal B₁.

* DC voltage source V_{BB} is constant and DC source V_{EE} in series with resistance R_E is considered as input to the UJT.



* The magnitude of voltage V_e can be varied by regulating R_E
 * As long as $V_e < \eta V_{BB}$, the E-B₁ junction is reverse biased and emitter current I_e is negative. [curve PS]

* The region PS of very low current is treated as "off state" of UJT and resistance between E-B₁ junction is very high.

* Actually, off-state of UJT extends to a point where V_e exceeds ηV_{BB} , by diode voltage V_D in E-B₁ junction.

* When $V_e = \eta V_{BB} + V_D$, point B is reached and E-B₁ junction gets forward biased to allow forward current and this point B is called Peak-Point.

* This $V_e = \eta V_{BB} + V_D = V_P$, is achieved by varying R_E and V_P is the peak-point voltage.

* At this point, p-emitter begins to inject holes from the E into lower base region B₁.

* As n-type base is lightly doped, the holes rarely get any chance to recombine, so B_1 is filled up with additional carriers (holes).

* As a result, R_{B1} decreases and this fall in R_{B1} causes potential of eta point A to drop, making V_e also to fall.

* As V_{EE} is constant, fall in V_e gives rise to more I_e , injecting more holes and R_{B1} still reduces and this process continues till R_{B1} drops to small value [from $4k\Omega$ to around 2 to 25Ω].

* I_e is given by

$$I_e = \frac{V_{EE} - V_D}{R_{B1} + R_E}$$

* When R_{B1} has dropped to a very small value, indicated by point C, the UJT has reached "on-state".

* Point C is called Valley-Point and entire base region B_1 is saturated and R_{B1} cannot decrease any more.

* After UJT is on (or) after Valley point, an increase in V_e is accompanied by an increase in I_e and is indicated by curve CQ.

* Between points B and C, V_e falls as I_e increases and UJT therefore exhibits negative resistance.

* This region give UJT the switching characteristics for use in SCR triggering circuits.

* Valley-point current is given by V_v/R_{B1} and is also called holding current, keeps UJT on.

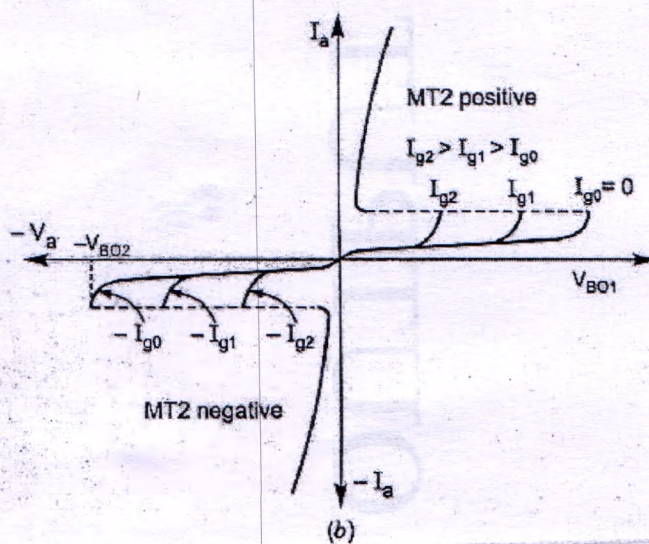
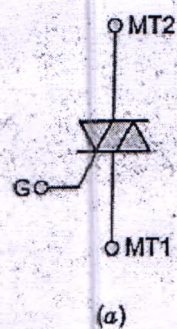
* When I_e falls below I_v , UJT turns-off.

TRIAC:

* It is a bidirectional device with three terminals, namely MT1 (main terminal), MT2 and G (gate).

* When in operation, a TRIAC is equivalent to two SCRs connected in antiparallel.

* TRIAC is the word derived by combining TRIode and AC.



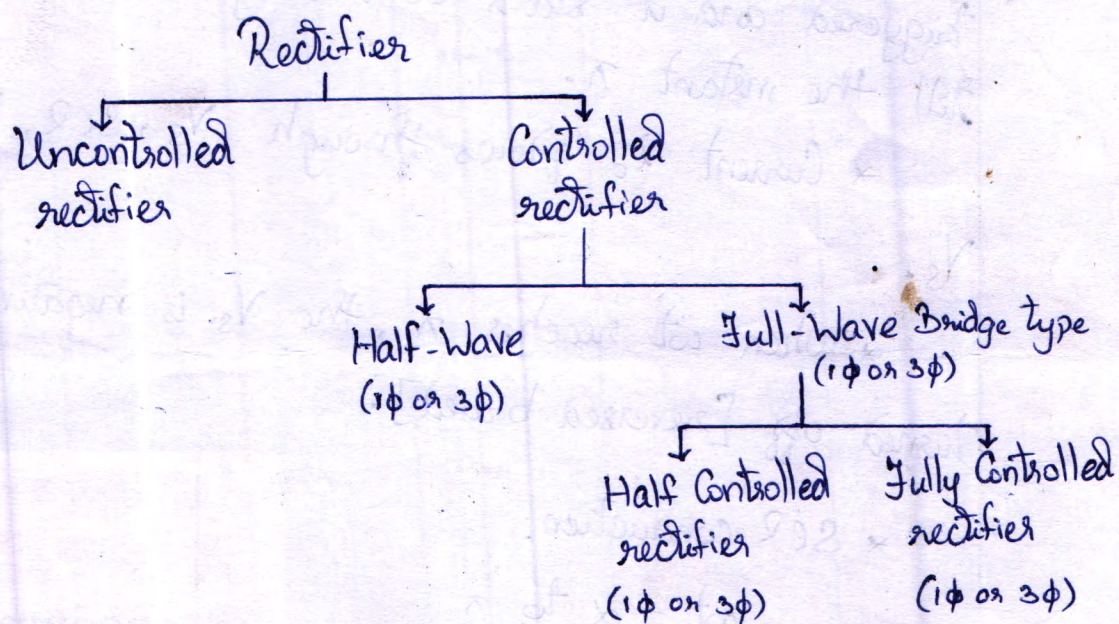
* With no signal to gate, the TRIAC will block both half-cycles of the AC applied voltage with condition peak value of this voltage is less than the breakover voltage of V_{BO1} or V_{BO2} of the TRIAC.

Rectifier:

* A rectifier is a circuit, which converts AC power to DC power.

* Rectifiers are classified as

- 1) Uncontrolled rectifier
- 2) Controlled rectifier.



Controlled Rectifiers:

* In this there is a possibility to change the conduction as well as the magnitude of output voltage.

Applications:

1. Aerospace applications
2. Electric Traction System
3. Textile mills
4. Rolling mills
5. Paper industry and etc.

25 COPY

1 ϕ Half-wave controlled rectifier with R-load:

25

* It consists of single SCR feeding dc power to a resistive load R.

* An SCR can conduct only when anode voltage is positive and a gating signal is applied.

* At some delay ^{or firing} angle α , SCR is triggered and it starts conducting till the instant π .

* Current i_o flows through V_s , SCR, load R and back to V_s .

* When ωt reaches π , the V_s is negative and SCR is turned off [reversed biased].

* SCR conduction:

$$\omega t = \alpha \text{ to } \pi$$

$$V_o = \text{present}$$

$$I_o = \text{present}$$

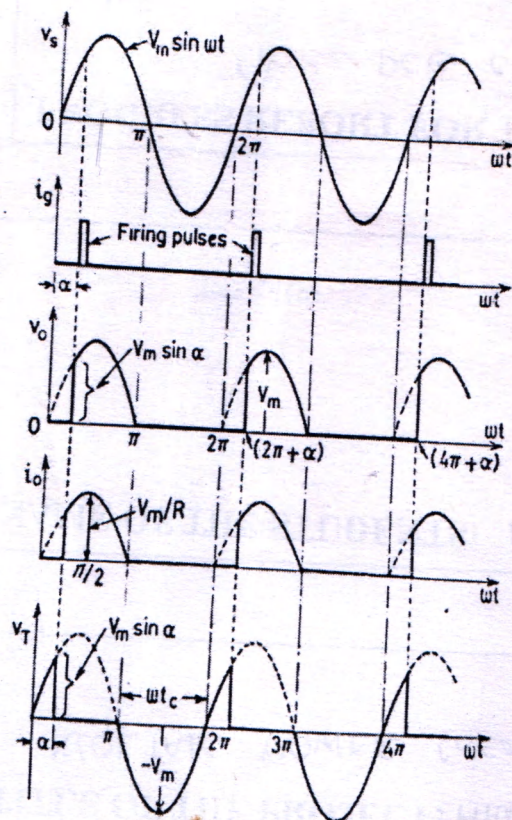
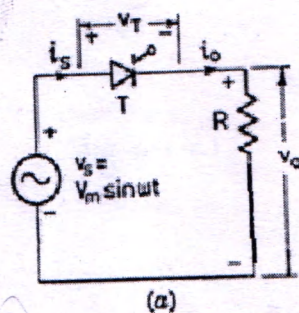
* SCR non-conduction:

$$\omega t = \pi \text{ to } 2\pi$$

$$V_o = 0$$

$$I_o = 0$$

$$\begin{aligned} * V_o &= \frac{1}{2\pi} \int_0^\alpha V_s d\omega t \\ &= \frac{1}{2\pi} \int_0^\alpha V_m \sin \omega t d\omega t \\ &= \frac{V_m}{2\pi} (1 + \cos \alpha) \quad \text{--- (1)} \end{aligned}$$



$$I_o = \frac{V_o}{R} = \frac{V_m}{2\pi R} (1 + \cos \alpha) \quad - (2)$$

$$\begin{aligned} V_{rms} &= \left[\frac{1 \times 1}{2\pi} \int_0^\alpha V_s^2 d\omega t \right]^{1/2} \\ &= \left[\frac{1}{2\pi} \int_0^\alpha V_m^2 \sin^2 \omega t d\omega t \right]^{1/2} \\ &= \left[\frac{V_m^2}{4\pi} \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right] \right]^{1/2} \quad - (3) \end{aligned}$$

$$I_{rms} = \frac{V_{rms}}{R} = \frac{1}{R} \left[\frac{V_m^2}{4\pi} \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right] \right]^{1/2} \quad - (4)$$

1 ϕ Half-wave controlled rectifier with RL-load:

* It consists of single SCR feeding DC power to a RL load.

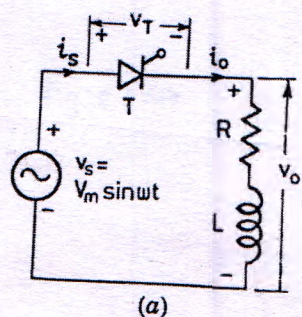
* At an firing angle α , SCR starts conducting.

* Here, current i_o rises gradually from $\omega t = \alpha$ and reaches maximum at $\omega t = \pi$.

$I_o = \text{maximum}$ and $V_o = 0$ at $\omega t = \pi$.

* After $\omega t = \pi$, i_o starts decaying and becomes zero at $\omega t = \beta$ called extinction angle.

* The SCR turns-on at $\omega t = \alpha$ and gets turned off only at $\omega t = \beta$ not at $\omega t = \pi$, because of load inductance.



* SCR conduction :

$$\omega t = \alpha \text{ to } \beta$$

$$V_o = \text{present}$$

$$I_o = \text{present}$$

* SCR non-conduction

$$\omega t = \beta \text{ to } 2\pi$$

$$V_o = 0$$

$$I_o = 0$$

$$* V_o = \frac{1}{2\pi} \int_{\alpha}^{\beta} V_m \sin \omega t \, d\omega t$$

$$= \frac{V_m}{2\pi} (\cos \alpha - \cos \beta) \quad - (1)$$

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

$$= \left[\frac{V_m^2}{4\pi} \left[(\beta - \alpha) - \frac{1}{2} (\sin 2\beta - \sin 2\alpha) \right] \right]^{1/2} \quad - (2)$$

* I_o is derived by,

$$V_s = i_o R + L \frac{di_o}{dt}$$

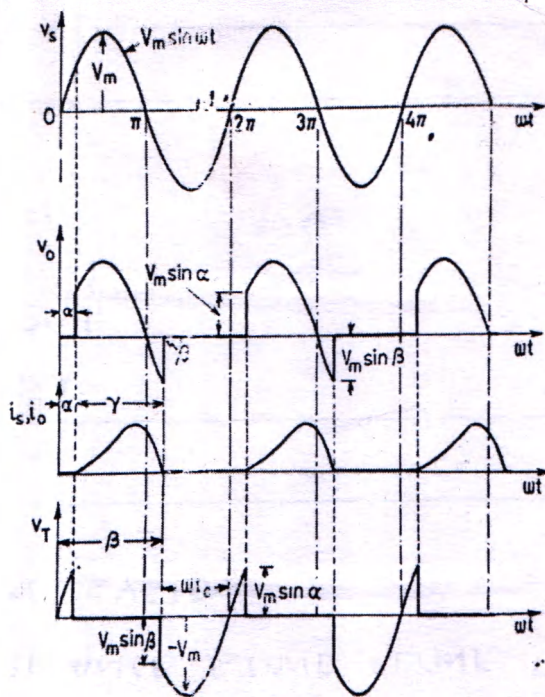
$$L \frac{di_o}{dt} + i_o R = V_m \sin \omega t$$

$$\frac{di_o}{dt} + \frac{R}{L} i_o = \frac{V_m}{L} \sin \omega t \Rightarrow i_o \left[\frac{d}{dt} + \frac{R}{L} \right] = \frac{V_m \sin \omega t}{L}$$

$$\therefore i_o = CF + PI$$

$$CF \Rightarrow \left(1 + \frac{R}{L} \right) = 0$$

$$\therefore CF = Ae^{-R/L t}$$



$$PI \Rightarrow \frac{1}{D+R/L} \frac{V_m}{L} \sin \omega t$$

$$= \frac{V_m}{L} \frac{\sin \omega t}{(D+R/L)}$$

$$= \frac{V_m}{L} \frac{\sin \omega t (D-R/L)}{(D+R/L)(D-R/L)}$$

$$= \frac{V_m}{L} \frac{D \cdot \sin \omega t - R/L \sin \omega t}{D^2 - R^2/L^2}$$

$$= \frac{V_m}{L} \frac{\omega \cos \omega t - R/L \sin \omega t}{-\omega^2 - R^2/L^2}$$

$$[D^2 = -\omega^2]$$

$$= -\frac{V_m}{L} \frac{[\omega \cos \omega t - R/L \sin \omega t] / L}{\omega^2 + R^2/L^2}$$

$$= -\frac{V_m}{L^2} \frac{(\omega L \cos \omega t - R \sin \omega t)}{(L^2 \omega^2 + R^2) / L^2}$$

$$= -\frac{V_m}{L^2} \frac{(\omega L \cos \omega t - R \sin \omega t)}{[R^2 + (\omega L)^2]}$$

$$= \frac{V_m}{L^2} \frac{(R \sin \omega t - \omega L \cos \omega t)}{R^2 + (\omega L)^2}$$

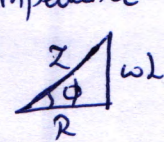
$$= \frac{V_m}{L^2} \frac{(\sin \omega t \cdot Z \cos \phi - \cos \omega t \cdot Z \sin \phi)}{Z^2}$$

$$= \frac{V_m Z}{L^2} \frac{(\sin \omega t \cos \phi - \cos \omega t \sin \phi)}{Z^2}$$

$$= \frac{V_m}{Z} (\sin \omega t \cos \phi - \cos \omega t \sin \phi)$$

$$= \frac{V_m}{Z} \sin(\omega t - \phi) \quad \text{--- (B)}$$

From Impedance Triangle,



$$Z^2 = R^2 + (\omega L)^2$$

$$\cos \phi = R/Z$$

$$\sin \phi = \frac{\omega L}{Z}$$

$$\tan \phi = \frac{\omega L}{R}$$

$$[\sin(A-B) = \sin A \cos B - \cos A \sin B]$$

$$\therefore i_o = PI + CF$$

$$i_o = \frac{V_m}{Z} \sin(\omega t - \phi) + A e^{-R/Lt} \quad - (3)$$

To find constant A:

$$\omega t = \alpha \text{ \& \; } i_o = 0.$$

$$\therefore \frac{V_m}{Z} \sin(\alpha - \phi) + A e^{-\alpha R/L} = 0$$

$$-\frac{V_m}{Z} \sin(\alpha - \phi) = A e^{-\alpha R/L}$$

$$\therefore A = -\frac{V_m}{Z} \sin(\alpha - \phi) e^{R\alpha/L}$$

Sub, A in eqn (3),

$$i_o = \frac{V_m}{Z} \sin(\omega t - \phi) - \frac{V_m}{Z} \sin(\alpha - \phi) e^{R\alpha/L} e^{-R/Lt}$$

$$i_o = \frac{V_m}{Z} \sin(\omega t - \phi) - \frac{V_m}{Z} \sin(\alpha - \phi) \exp\left\{-\frac{R}{\omega L}(\omega t - \alpha)\right\} \quad - (4)$$

β can be also find by,

$$i_o = 0 \text{ and } \omega t = \beta.$$

$$\therefore \frac{V_m}{Z} \sin(\beta - \phi) - \frac{V_m}{Z} \sin(\alpha - \phi) \exp\left\{-\frac{R}{\omega L}(\beta - \alpha)\right\} = 0$$

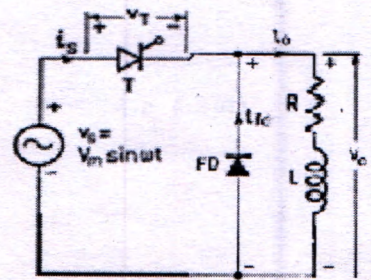
$$\frac{V_m}{Z} \sin(\beta - \phi) = \frac{V_m}{Z} \sin(\alpha - \phi) \exp\left\{-\frac{R}{\omega L}(\beta - \alpha)\right\}$$

$$\sin(\beta - \phi) = \sin(\alpha - \phi) \exp\left\{-\frac{R}{\omega L}(\beta - \alpha)\right\} \quad - (5)$$

1φ Half-wave controlled rectifier with RL load & Freewheeling Diode:

* It consists of single SCR feeding DC power to a RL load.

* The waveform of load current i_o can be improved by connecting a freewheeling diode across load.



* An SCR is triggered at $\omega t = \alpha$ and conducts till $\omega t = \pi$.

* At this instant, SCR gets reversed biased and gets turned off, so $V_o = 0$ at $\omega t = \pi$, but i_o will not become zero immediately because of load inductance [stored energy].

* So, i_o gets decay through freewheeling diode till $\omega t = \pi$ to $2\pi + \alpha$.

* SCR conduction:

$\omega t = \alpha$ to π

V_o - present

i_o - present

* Freewheeling mode:

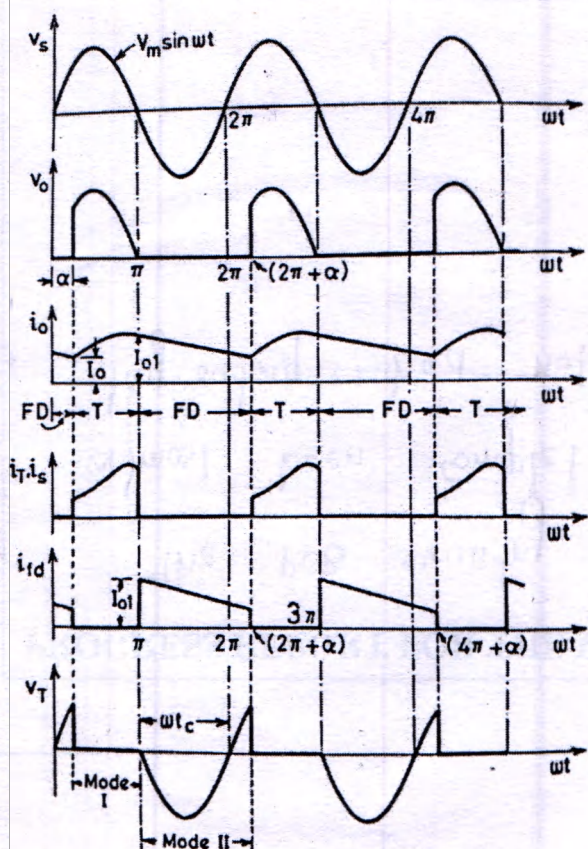
$\omega t = \pi$ to $2\pi + \alpha$

$V_o = 0$

i_o - present

$$* V_o = \frac{1 \times 1}{2\pi} \int_{\alpha}^{\pi} V_m \sin \omega t d\omega t$$

$$= \frac{V_m}{2\pi} (1 + \cos \alpha)$$



For conduction mode:

$$V_m \sin \omega t = i_o R + L \frac{di_o}{dt}$$

$$\therefore i_o = \frac{V_m}{Z} \sin(\omega t - \phi) + \left[I_o - \frac{V_m}{Z} \sin(\alpha - \phi) \right] \exp \left\{ -\frac{R}{\omega L} (\omega t - \alpha) \right\}$$

[Refer pg. 4 to 6]

$$\omega t = \alpha, i_o = I_o$$

For freewheeling mode:

$$0 = i_o R + L \frac{di_o}{dt}$$

$$\therefore i_o = I_{o1} \exp \left\{ -\frac{R}{\omega L} (\omega t - \pi) \right\} \quad [\because \omega t = \pi, i_o = I_{o1}]$$

Advantages of Freewheeling Diode:

- * input power factor is improved
- * load current waveform is improved
- * as energy stored in L is transferred to R during the freewheeling period, overall converter efficiency improves.

1 ϕ Full-wave controlled rectifier:

* In this type of rectifier, the output obtained is due to both the half cycles.

* Based on SCR arrangement, it is classified as

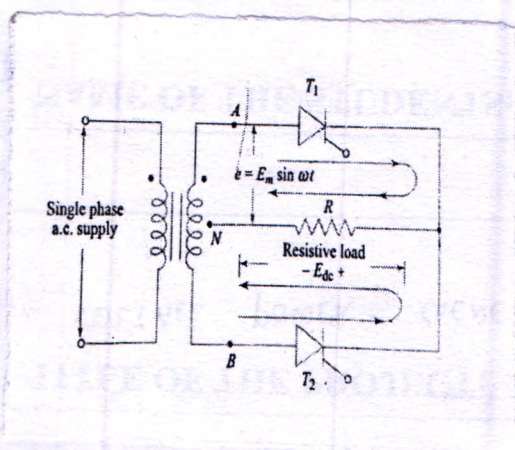
- 1) Mid-point type
- 2) Bridge type

1 ϕ Full-wave Mid-point rectifier with R-load:

* It consists of two SCR connected to load using a centre-tapped transformer.

* When terminal 'a' is positive w.r.t 'n' & terminal 'n' is positive w.r.t 'b', therefore $V_{an} = V_{nb}$.

* So, SCR T_1 and T_2 are forward biased during positive and negative half cycles respectively.



* SCR T_1 conducts for an period of $\omega t = \alpha$ to π and SCR T_2 conducts for an period of $\omega t = \pi + \alpha$ to 2π .

* It means when T_1 conducts, flow of current i_o is through 'a' - T_1 - R load - 'n'.

V_o - present

i_o - present

* Also T_2 conducts, i_o flows through 'b' - T_2 - R load - 'n'.

V_o - present

i_o - present

* Conduction period of T_1

$$\omega t = \alpha \text{ to } \pi$$

* Non-conduction period of T_1

$$\omega t = \pi \text{ to } 2\pi + \alpha$$

* Conduction period of T_2

$$\omega t = \pi + \alpha \text{ to } 2\pi$$

* Non-conduction period of T_2

$$\omega t = 2\pi \text{ to } 3\pi + \alpha$$

$$V_o = \frac{1 \times 2}{2\pi} \int_{\alpha}^{\pi} V_m \sin \omega t \, d\omega t$$

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

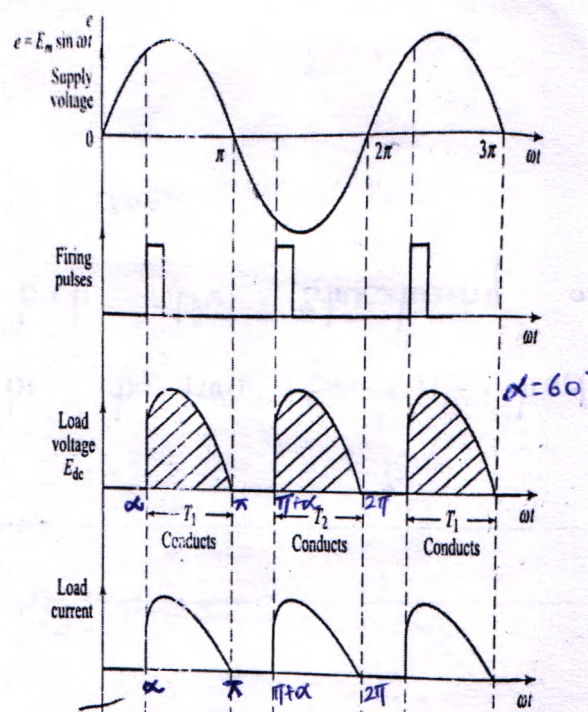
$$V_{rms} = \left[\frac{1 \times 2}{2\pi} \int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \, d\omega t \right]^{1/2}$$

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

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

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

$$PIV = -2V_m \quad \left[\text{voltage across non-conducting SCR} \right]$$



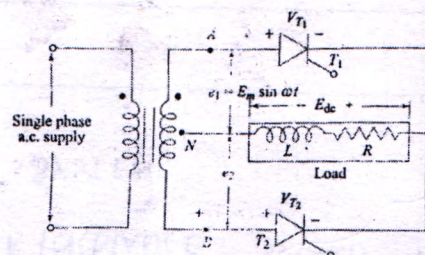
1) Full-wave Mid-point rectifier with RL load:

* In this, during positive half-cycle SCR T_1 conducts when triggered at firing angle α .

* During negative half-cycle SCR T_2 conducts when triggered.

* The difference from above rectifier operation is at $\omega t = \pi$ the SCR will not get turned off because of load inductance.

* T_1 gets turned off only at $\omega t = \beta$ or $\pi + \alpha$ based on the value of load inductance L .



- * If L - low value, T_1 turned off at $\omega t = \beta$
 L - high value, T_1 turned off at $\omega t = \pi + \alpha$

* Conduction period of T_1

$\omega t = \alpha$ to β [Discontinuous current mode]

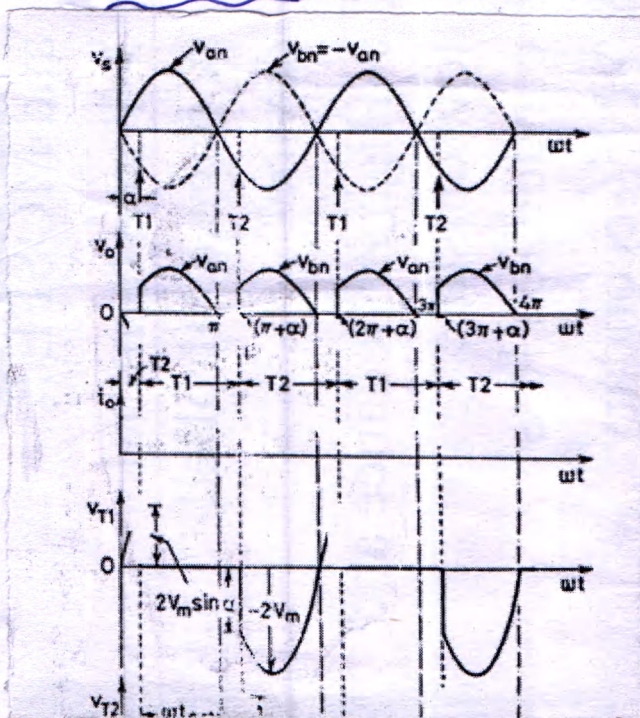
$= \alpha$ to $\pi + \alpha$ [Continuous current mode]

* Conduction period of T_2

$\omega t = \pi + \alpha$ to $\pi + \beta$ [Discontinuous current mode]

$= \pi + \alpha$ to $2\pi + \alpha$ [Continuous current mode]

(a) Discontinuous Mode



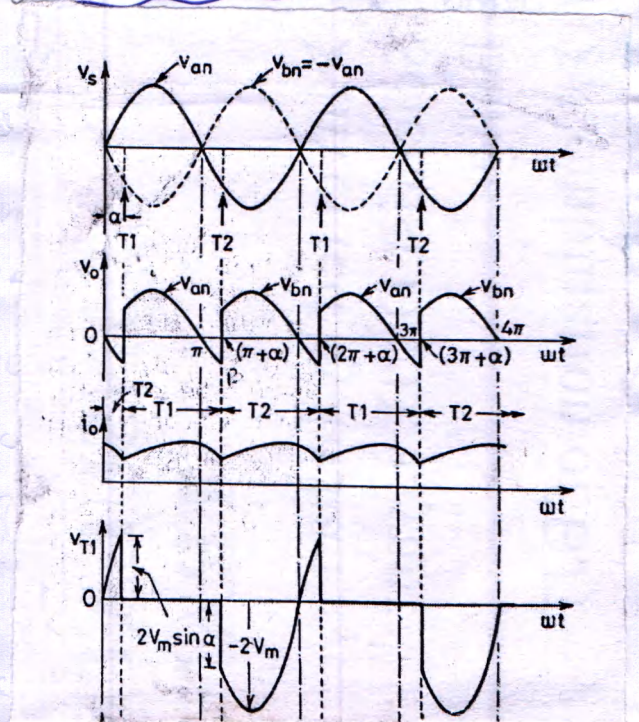
$$V_o = \frac{1 \times 2}{2\pi} \int_{\alpha}^{\beta} V_m \sin \omega t \, d\omega t$$

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

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

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

(b) Continuous Mode



$$V_o = \frac{1 \times 2}{2\pi} \int_{\alpha}^{\pi + \alpha} V_m \sin \omega t \, d\omega t$$

$$= \frac{2V_m}{\pi} \cos \alpha$$

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

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

1 ϕ Full-wave Bridge type rectifier:

* This type of rectifier is further classified into

- 1) Half Controlled
- 2) Fully Controlled

1 ϕ Fully Controlled Rectifier with R-load:

* It consists of four SCR connected in bridge configuration.

* In positive half cycle, SCR T_1 and T_2 conducts and gives output voltage. (a' +ve w.r.t 'b')

* In negative half cycle, SCR T_3 and T_4 conducts and gives output voltage across load. (b' +ve w.r.t 'a').

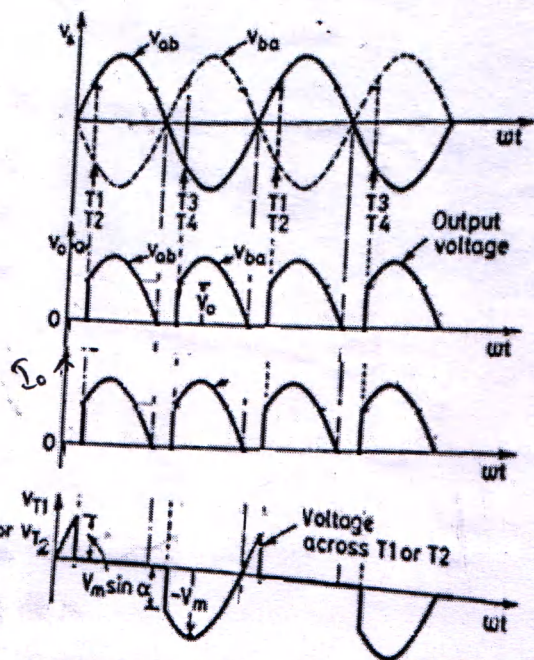
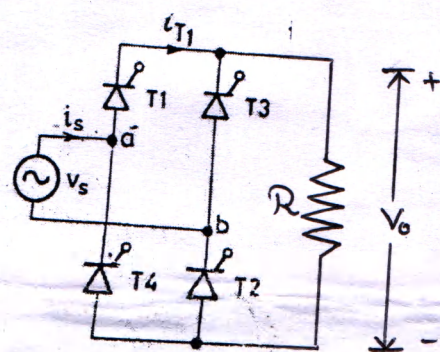
* In this T_1, T_2 conducts for an period of $\omega t = \alpha$ to π and T_3, T_4 conducts for an period of $\omega t = \pi + \alpha$ to 2π .

* It means when T_1, T_2 conducts, flow of current i_o is through 'a' - T_1 - R load - T_2 - 'b'.

v_o - present
 i_o - present

* Also when T_3, T_4 conducts flow of current i_o is through 'b' - T_3 - R load - T_4 - 'a'.

v_o - present
 i_o - present



* Conduction period of T_1, T_2

$$\omega t = \alpha \text{ to } \pi$$

* Non-conduction period of T_1, T_2

$$\omega t = \pi \text{ to } \pi + \alpha$$

$$V_o = \frac{1 \times 2}{2\pi} \int_{\alpha}^{\pi} V_m \sin \omega t \, d\omega t$$

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

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

* Conduction period of T_3, T_4

$$\omega t = \pi + \alpha \text{ to } 2\pi$$

* Non-conduction period of T_3, T_4

$$\omega t = 2\pi \text{ to } 3\pi + \alpha$$

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

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

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

$$P_{2V} = -V_m [\text{voltage across non-conducting SCR}]$$

Note:

Advantages of 1ϕ converter (Bridge) over 1ϕ midpoint converter is

* SCRs are subjected to P_{2V} of $2V_m$ in midpoint converter and V_m in fully controlled rectifiers.

* In midpoint converter, each secondary should be able to supply the load power. [Transformer rating is double the load rating].

1ϕ Fully controlled rectifier with RL load:

* The working of this rectifier is similar to that of previous one, and the difference is at $\omega t = \pi$, the SCRs T_1, T_2 will not get turned-off because of load inductance.

* This T_1, T_2 gets turned-off only at $\omega t = \beta$ or $\pi + \alpha$ based on the value of load inductance L .

- * If L - low value, T_1, T_2 turned-off at $\omega t = \beta$
- L - high value, T_1, T_2 turned-off at $\omega t = \pi + \alpha$

* Conduction period of T_1, T_2

$\omega t = \alpha$ to β [Discontinuous current mode]

$= \alpha$ to $\pi + \alpha$ [Continuous current mode]

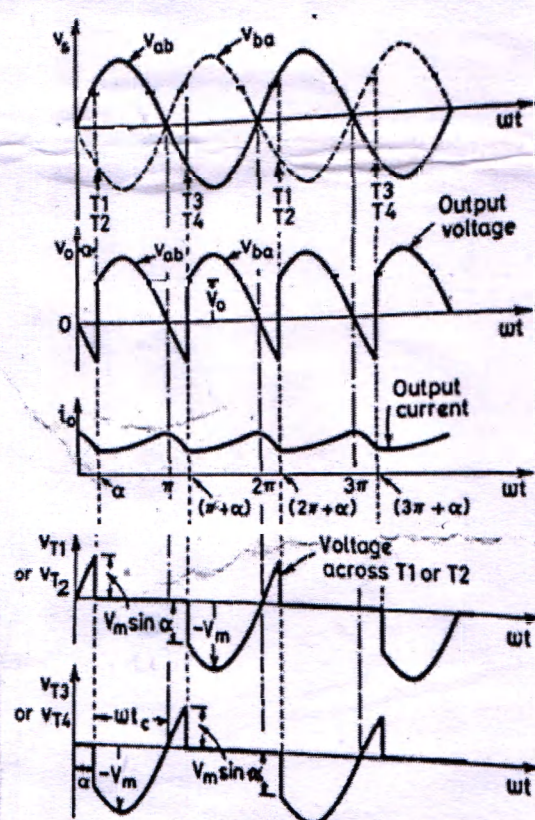
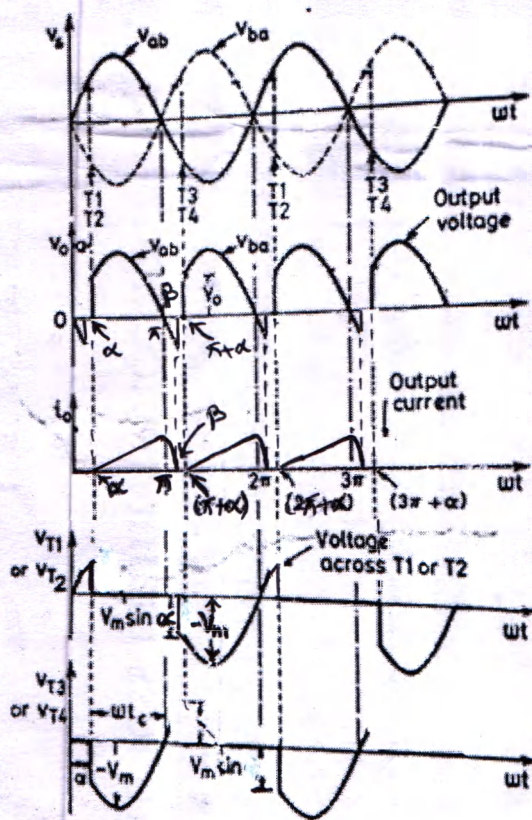
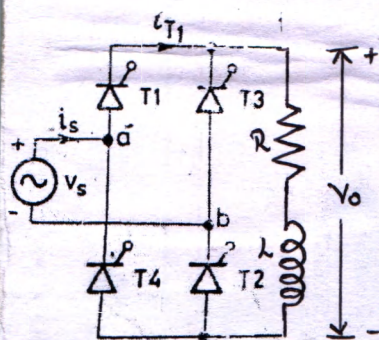
* Conduction period of T_3, T_4

$\omega t = \pi + \alpha$ to $\pi + \beta$ [Discontinuous current mode]

$= \pi + \alpha$ to $2\pi + \alpha$ [Continuous current mode].

a) Discontinuous Mode

b) Continuous Mode



* Based on the value of firing pulse, the net power flow is classified as

- 1) $\alpha < 90^\circ$ - Power flow - AC source to DC load
- Rectifying mode
- V_o is positive and i_o is positive

- 2) $\alpha > 90^\circ$ - Power flow - DC load to AC source
 - Inverting mode
 - V_o is negative and i_o is positive

a) Discontinuous Mode

$$V_o = \frac{1 \times 2}{2\pi} \int_{\alpha}^{\beta} V_m \sin \omega t \, d\omega t$$

$$= \frac{V_m}{\pi} (\cos \alpha - \cos \beta)$$

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

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

b) Continuous Mode

$$V_o = \frac{1 \times 2}{2\pi} \int_{\alpha}^{\pi + \alpha} V_m \sin \omega t \, d\omega t$$

$$= \frac{2V_m}{\pi} \cos \alpha$$

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

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

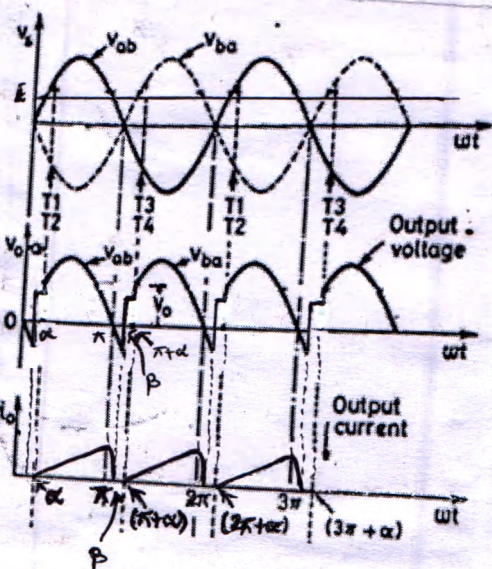
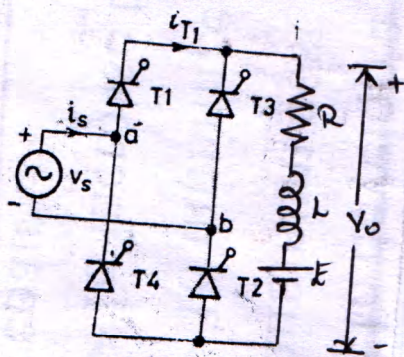
1 ϕ Fully Controlled rectifier with RLE load:

* In this the working is similar to previous rectifier (RL load) but the difference is due to E load, the i_o is discontinuous.

* Here from $\omega t = \alpha$ to β , SCR T_1, T_2 conducts and SCR T_3, T_4 conducts from $\omega t = \pi + \alpha$ to $\pi + \beta$.

* So when $\omega t = \beta$ to $\pi + \alpha$, the V_o is there but it is due to E.

* Here V_o is present but i_o is absent or zero. (β to $\pi + \alpha$).



$$* V_o = \frac{1 \times 2}{2\pi} \left[\int_{\alpha}^{\beta} V_m \sin \omega t \, d\omega t + \int_{\beta}^{\pi+\alpha} E \, d\omega t \right]$$

$$= \frac{1}{\pi} \left[V_m (\cos \alpha - \cos \beta) + E (\pi + \alpha - \beta) \right]$$

$$= \frac{V_m}{\pi} (\cos \alpha - \cos \beta) + \frac{E}{\pi} (\pi + \alpha - \beta)$$

$$= \frac{V_m}{\pi} (\cos \alpha - \cos \beta) + E \left(1 - \frac{\gamma}{\pi}\right)$$

[where $\gamma = \beta - \alpha$
 $\gamma \Rightarrow$ conduction angle]

* I_o is derived by

$$V_s = i_o R + L \frac{di_o}{dt} + E$$

$$V_m \sin \omega t = i_o R + L \frac{di_o}{dt} + E$$

$$i_o R + L \frac{di_o}{dt} = V_m \sin \omega t - E$$

$$\therefore i_o = C F + P I_1 + P I_2$$

$$= \left[\frac{V_m}{Z} \sin(\omega t - \phi) - \frac{E}{R_a} \right] + \left[\frac{E}{R_a} - \frac{V_m}{Z} \sin(\alpha - \phi) \right] e^{-(\omega t - \alpha) \cot \phi}$$

[Procedure similar to pg. no. 4 to 6]

1 ϕ Half Controlled rectifier:

* Many applications actually require operation only with positive voltage, that is only in rectifying mode.

* In such cases, Half controlled bridge rectifier or also called semiconverter is preferred.

* It consists of two SCRs and two diodes. Based on its arrangement, it is further classified as

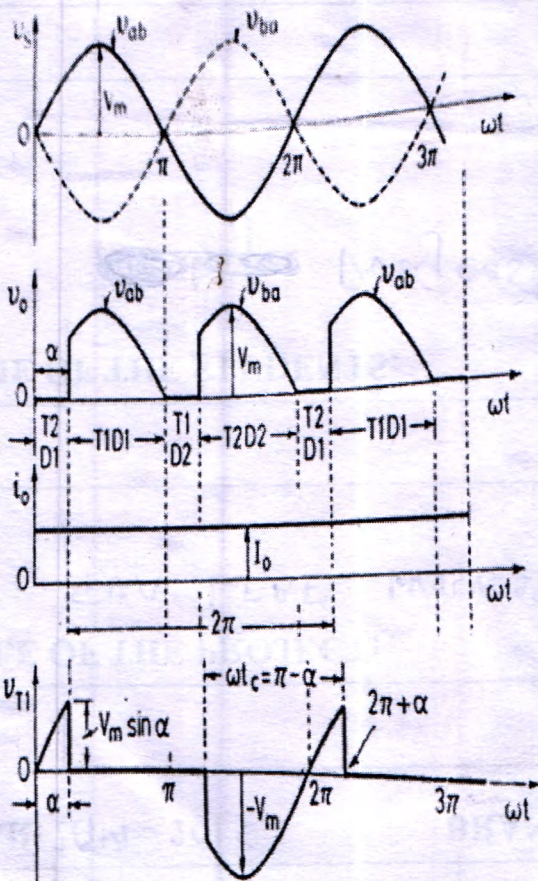
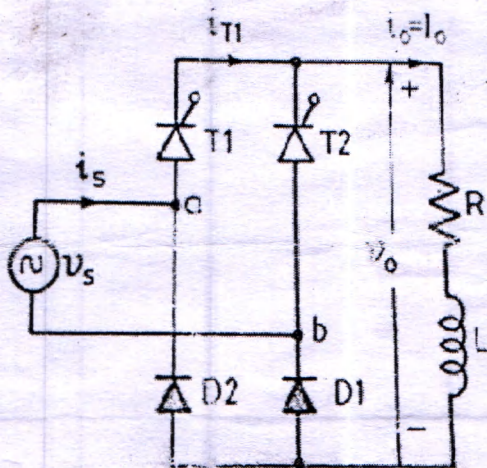
1) Symmetrical configuration

- One SCR and one Diode in each leg

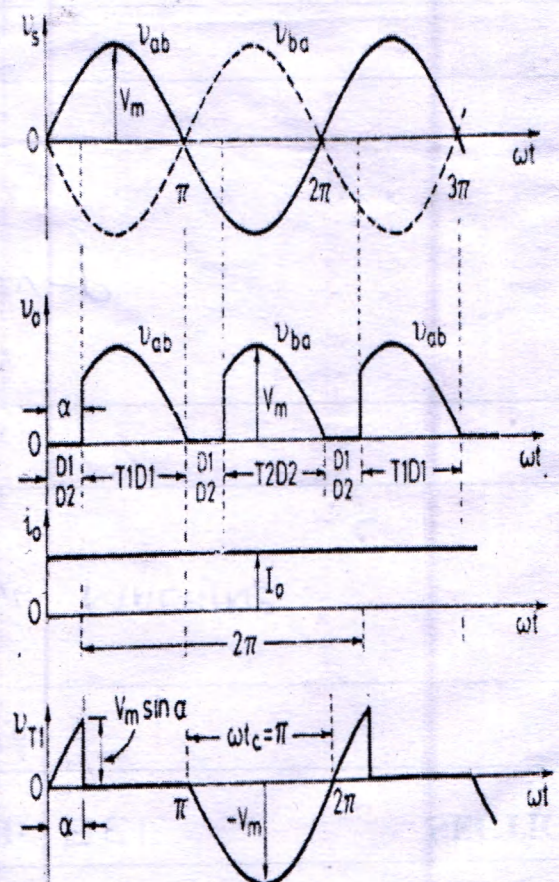
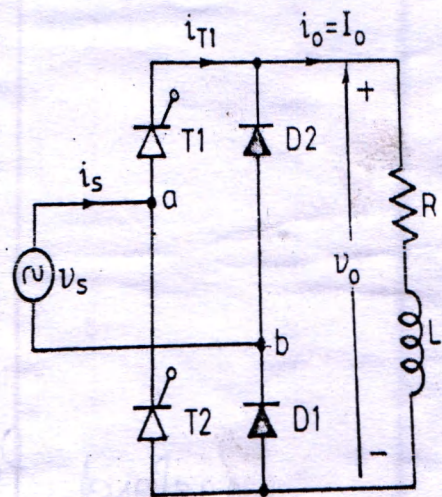
2) Asymmetrical configuration

- Two SCR in one leg and two diode in other leg.

a) Symmetrical configuration



b) Asymmetrical configuration



(3)

* In this Semiconverter based on output requirement the arrangements can be varied as,

- 1) Discontinuous current (i_o) - R load
- 2) Continuous current (i_o) - RL load

* In both the configurations, the semiconverter gives only the positive voltage.

1) 1ϕ Symmetrical semiconverter:

* From $\omega t = \alpha$ to π , T_1, D_1 conducts and provides output voltage & current. [$a' - T_1 - \text{load} - D_1 - b'$]

* When $\omega t = \pi$, D_1 gets reverse biased and load current (i_o), freewheels through $T_1 - \text{load} - D_2$ till $\omega t = \pi + \alpha$.

* At $\omega t = \pi + \alpha$, T_2 is triggered, so T_2, D_2 conducts till $\omega t = 2\pi$. [conduction of T_2, D_2 is $\pi + \alpha$ to 2π]

* When $\omega t = 2\pi$, D_2 gets reverse biased and i_o freewheels through $T_2 - \text{load} - D_1$ till $\omega t = 2\pi + \alpha$.

2) 1ϕ Asymmetrical semiconverter:

* From $\omega t = \alpha$ to π , T_1, D_1 conducts and current path is $a' - T_1 - \text{load} - D_1 - b'$. (T_1 triggered)

* Freewheeling is due to D_1, D_2 from $\omega t = \pi$ to $\pi + \alpha$.

* Then from $\omega t = \pi + \alpha$ to 2π , T_2, D_1 conducts and current path $b' - D_2 - \text{load} - T_2 - a'$. (T_2 triggered).

* Next freewheeling is also due to D_1, D_2 from $\omega t = 2\pi$ to $2\pi + \alpha$.

Note:

* In symmetrical configuration, the cathodes of two SCRs are at same potential so their gates can be connected and single gate-pulse can be used for triggering either SCR.

* In asymmetrical configuration, separate triggering circuits are to be used.

* Outputs are same for both the configuration and are given by

$$V_o = \frac{1 \times 2}{2\pi} \int_{\alpha}^{\pi} V_m \sin \omega t \, d\omega t$$

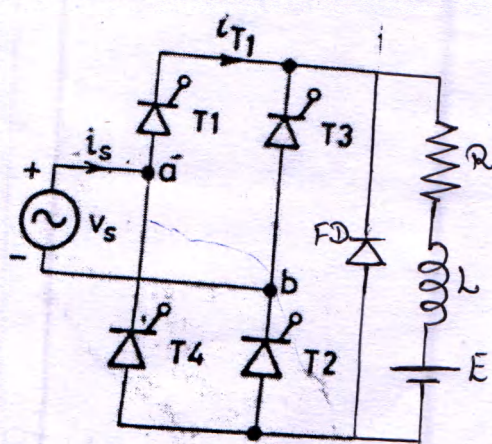
$$= \frac{V_m}{\pi} (1 + \cos \alpha).$$

* [Both R and RL load]
 V_o is same but i_o varies.

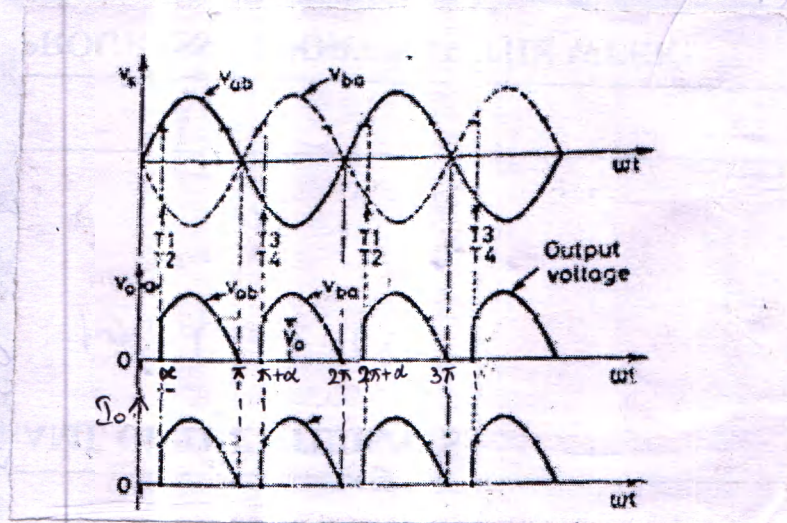
1 ϕ Fully controlled rectifier with RLE load and freewheeling diode:

* In order to avoid negative output voltage of RLE loaded rectifier, an extra arrangement called freewheeling diode can be used.

* The operation is similar to RLE load but at $\omega t = \pi$ to β freewheeling diodes comes to action.



* So during this period, i_o freewheels through load and Diode, whereas v_o is zero.



* So with the help of ID, the rectifier works only in first quadrant or else it can be said as power flow is always from source to load.

Comparison:

1 ϕ Semiconverter	1 ϕ Fully controlled rectifier
* Costs less because of less number of SCRs. * Reduction of ripple voltage at dc terminals [no negative output voltage]. * One quadrant operation. * Better power factor	* Comparatively high cost * Comparatively high because of negative voltage at dc side. * Two quadrant operation. * Comparatively low power factor.

MODULE III

III	3-phase half-wave controlled rectifier with R load – 3-phase fully controlled & half-controlled converter with RLE load (continuous conduction, ripple free) – output voltage equation-waveforms for various triggering angles (no analysis) – 1-phase & 3-phase dual converter with & without circulating current – four-quadrant operation
------------	--

Three Phase Thyristor Converters:

* Three phase rectifiers are used for high power demands.

* It has following advantages than 1 ϕ rectifiers are

- i) Higher DC voltage
- ii) Better TUF
- iii) Better input power factor
- iv) less ripple content
- v) lower size of filter circuit parameters.

* Like 1 ϕ controlled rectifiers, 3 ϕ controlled rectifiers are also classified as

- i) Half-wave controlled rectifiers
- ii) Full-wave controlled rectifiers
 - a) Fully controlled
 - b) Half controlled

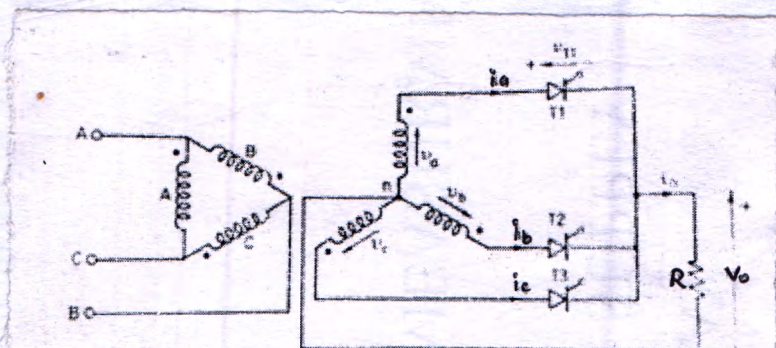
3 ϕ Half-wave controlled rectifiers with R-load:

* It consists of three SCR feeding DC power to a resistive load R.

* Here each SCR can conduct for an duration of 120° [maximum conduction period].

* SCR T_1 can conduct only at $\omega t = 30^\circ$ when the firing angle $\alpha = 0^\circ$ because only at this instant it is more positive.

* Similarly $T_2 = 150^\circ$ and $T_3 = 270^\circ$ [default] when its firing angle is $\alpha = 0^\circ$.



(2)

* This rectifier has two operating modes.

i) $\alpha < 30^\circ$

ii) $\alpha > 30^\circ$

$\alpha < 30^\circ$:

* In this mode, each SCR can conduct for an ~~maximum~~ conduction period of 120° .

* I_o flows through V_a, T_1, R load and back to V_a .

* Similarly V_b, T_2, R and V_b
 V_c, T_3, R and V_c .

* SCR conduction:

$$\omega t = 30 + \alpha \text{ to } 150 + \alpha \quad [T_1 \text{ conducts}]$$

$$= 150 + \alpha \text{ to } 270 + \alpha \quad [T_2 \text{ conducts}]$$

$$= 270 + \alpha \text{ to } 390 + \alpha \quad [T_3 \text{ conducts}]$$

* V_o and I_o will be present and it has continuous mode of operation.

$$* V_o = \frac{1 \times 3}{2\pi} \int_{\frac{\pi}{6} + \alpha}^{\frac{5\pi}{6} + \alpha} V_{mp} \sin \omega t \, d\omega t$$

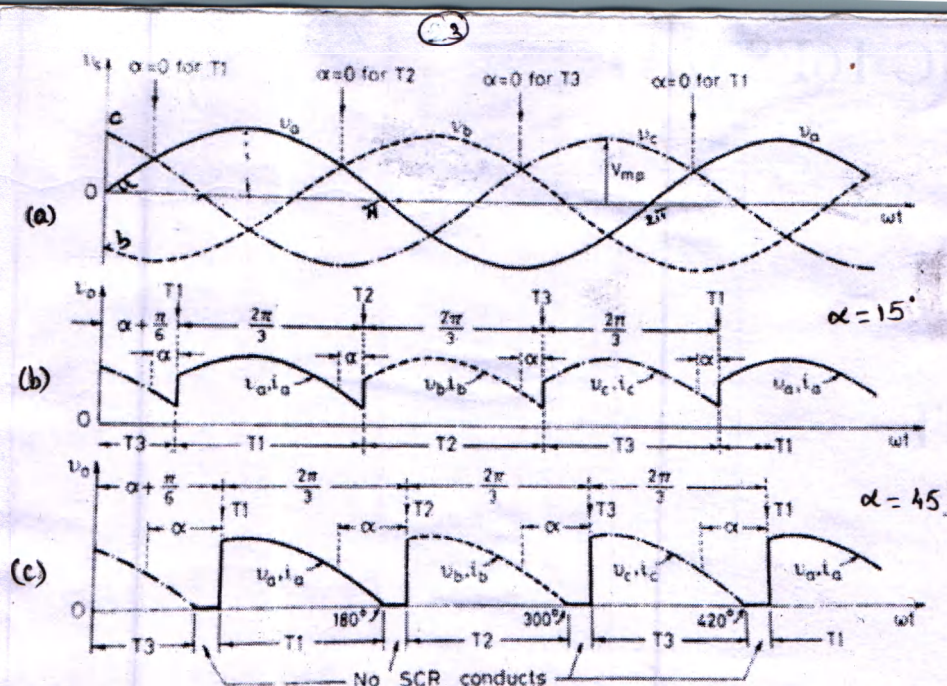
$$= \frac{3\sqrt{3}}{2\pi} V_{mp} \cos \alpha$$

$$= \frac{3V_{ml}}{2\pi} \cos \alpha$$

$$* V_{rms} = \left[\frac{1 \times 3}{2\pi} \int_{\frac{\pi}{6} + \alpha}^{\frac{5\pi}{6} + \alpha} V_{mp}^2 \sin^2 \omega t \, d\omega t \right]^{1/2}$$

$$= V_{ml} \left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi} \cos 2\alpha \right]^{1/2}$$

$$* I_o = \frac{V_o}{R} \quad \text{and} \quad I_{rms} = \frac{V_{rms}}{R}$$



Three-phase 3-pulse converter with R load (a) line to neutral source voltage Load voltage waveforms for (b) $0 < \alpha < 30^\circ$ and (c) $\alpha > 30^\circ$

$\alpha > 30^\circ$

for
 $\alpha < 30^\circ$

* In this mode, each SCR can conduct for an maximum conduction period of 120° or less than it based on α value.

* Because of R-load, when the supply voltage (v_a or v_b or v_c) reaches negative voltage [at $\omega t = 180$ or 300 or 420], the SCRs gets turned off naturally.

* SCR conduction:

$$\omega t = 30 + \alpha \text{ to } 180 \quad [T_1 \text{ conducts}]$$

$$= 150 + \alpha \text{ to } 300 \quad [T_2 \text{ conducts}]$$

$$= 270 + \alpha \text{ to } 420 \quad [T_3 \text{ conducts}]$$

* V_o and I_o will be present and it has discontinuous mode of operation.

$$* V_o = \frac{1 \times 3}{2\pi} \int_{\frac{\pi}{6} + \alpha}^{\pi} V_{mp} \sin \omega t \, d\omega t$$

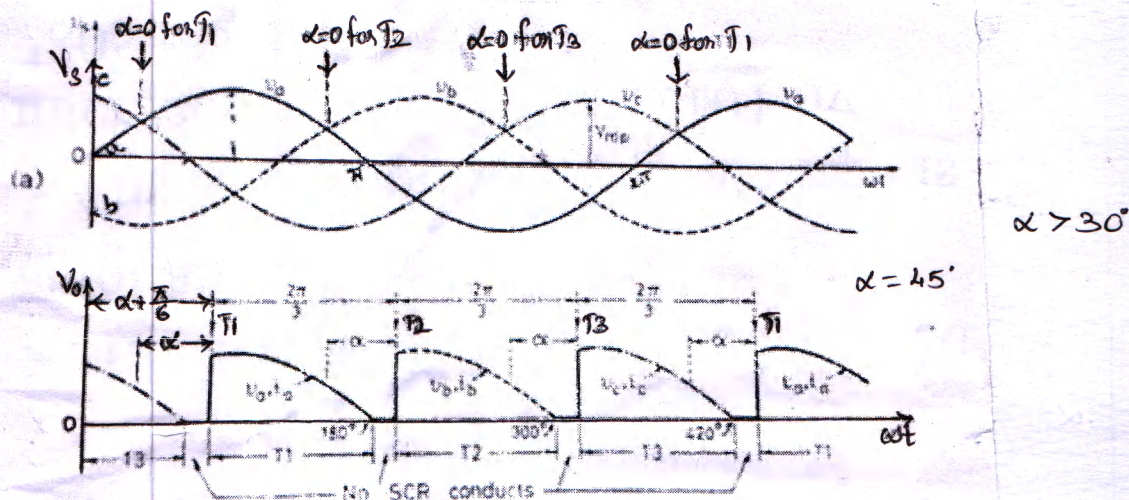
$$= \frac{3V_{mp}}{2\pi} [1 + \cos(\alpha + \frac{\pi}{6})]$$

$$* V_{rms} = \left[\frac{1 \times 3}{2\pi} \int_{\frac{\pi}{6} + \alpha}^{\pi} V_{mp}^2 \sin^2 \omega t \, d\omega t \right]^{1/2}$$

$$= \frac{V_{m1}}{2\sqrt{\pi}} \left[\left(\frac{5\pi}{6} - \alpha \right) + \frac{1}{2} \sin(2\alpha + \frac{\pi}{3}) \right]^{1/2}$$

(4)

$$* I_o = \frac{V_o}{R} \text{ and } I_{rms} = \frac{V_{rms}}{R}$$



3 ϕ Half-wave controlled rectifier with RL load:

* Its circuit is similar to previous rectifier, the difference is load is RL.

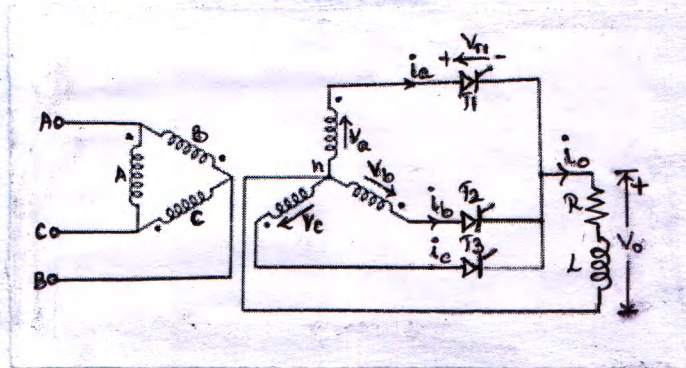
* Here each SCR can conduct for an duration of 120° .

* Here rectifier has three operating modes.

- i) $\alpha < 30^\circ$
- ii) $30^\circ < \alpha < 90^\circ$
- iii) $90^\circ < \alpha < 180^\circ$

} - Rectification process

- Inversion process.



$\alpha < 30^\circ$

* In ^{this} mode of operation, the working of SCR is same as 3 ϕ half-wave controlled rectifier with R-load.

$30^\circ < \alpha < 90^\circ$

* In this mode, considering T_1 , SCR starts conducting at

(5)

$\omega t = \frac{\pi}{6} + \alpha$ and does not get turned off at 180° because of inductance.

* So V_o will be there but gives some negative voltage.

* I_o will be charging from $\omega t = 30 + \alpha$ to π and starts discharging from $\omega t = \pi$ to $150 + \alpha$.

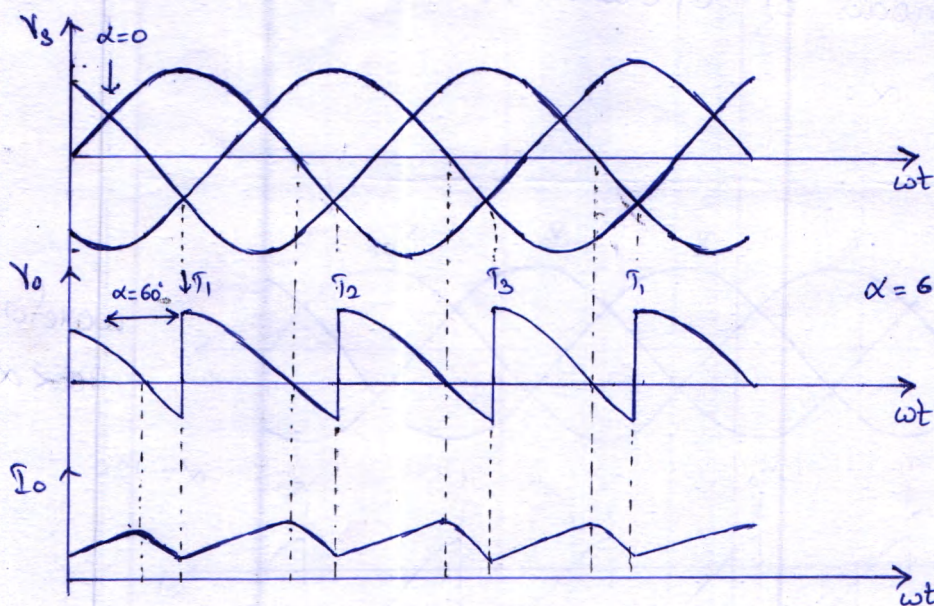
* SCR conduction:

$$\alpha = 45^\circ$$

$$\omega t = 30 + \alpha \text{ to } 150 + \alpha \quad [T_1 \text{ conducts}]$$

$$= 150 + \alpha \text{ to } 270 + \alpha \quad [T_2 \text{ conducts}]$$

$$= 270 + \alpha \text{ to } 390 + \alpha \quad [T_3 \text{ conducts}]$$



waveforms for
 $30^\circ < \alpha < 90^\circ$

* In this mode, the average output voltage V_o is positive and it can be called as rectification process.

$90^\circ < \alpha < 180^\circ$:

* In this mode of operation, the working is similar to above mode, but the difference is here the average output voltage V_o is negative and is called inversion process.

(6)

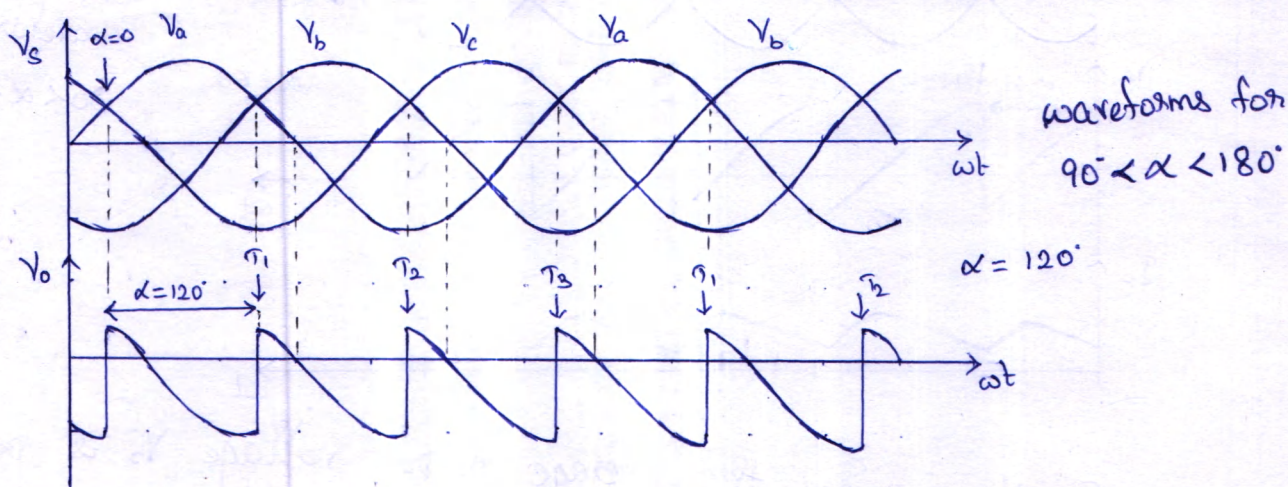
$$* V_o = \frac{1 \times 3}{2\pi} \int_{\frac{\pi}{6} + \alpha}^{\frac{5\pi}{6} + \alpha} V_{mp} \sin \omega t \, d\omega t$$

$$= \frac{3V_{m1}}{2\pi} \cos \alpha$$

$$* V_{rms} = \left[\frac{1 \times 3}{2\pi} \int_{\frac{\pi}{6} + \alpha}^{\frac{5\pi}{6} + \alpha} V_{mp}^2 \sin^2 \omega t \, d\omega t \right]^{1/2}$$

$$= V_{m1} \left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi} \cos 2\alpha \right]^{1/2}$$

* In this rectifier, V_o and V_{rms} will be same for all the three modes of operation, and its values vary only with firing angle α . [equation]



3φ Fully controlled rectifier with R load:

* In this rectifier, we will discuss the operation with line voltage [supply voltage].

* It consists of six SCRs, connected in bridge connection.

* The upper thyristors are called positive group and lower

(7)

thyristors are called negative group thyristors.

* The numbering of SCRs is 1, 3, 5 for positive group and 4, 6, 2 for negative group.

* In this each thyristor conducts for 120° but with the split of 60° and 60° .

* It means, SCR combinations or SCR pairs are 61, 12, 23, 34, 45, 56, 61.

* Considering SCR T_1 , it conducts for 120° but 60° with T_6 and 60° with T_2 .

* Since the supply voltage is 3ϕ line voltage, the SCR can start conducting only at $\omega t = 60^\circ$ when $\alpha = 0^\circ$.

* This rectifier has two modes of operation.

- i) $\alpha < 60^\circ$
- ii) $\alpha > 60^\circ$

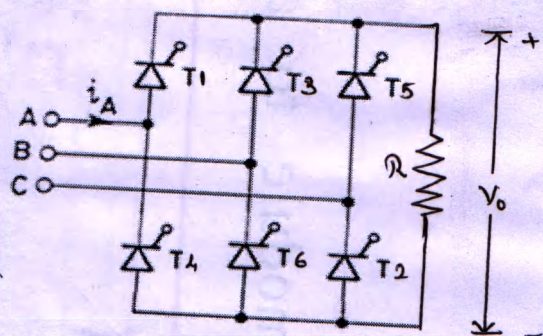
i) $\alpha < 60^\circ$:

* In this mode of operation, the conduction period of thyristor pairs are 60° .

* Here considering $T_6 T_1$, SCR starts conducting at $\omega t = \frac{\pi}{3} + \alpha$ to $\frac{2\pi}{3} + \alpha$.

* I_o flows through A- T_1 -R-load- T_6 -B.

* SCR conduction:



(8)

SCR supply

$$\begin{aligned}
 \omega t &= 60 + \alpha \text{ to } 120 + \alpha & [T_6 T_1 - ab] \\
 &= 120 + \alpha \text{ to } 180 + \alpha & [T_1 T_2 - ac] \\
 &= 180 + \alpha \text{ to } 240 + \alpha & [T_2 T_3 - bc] \\
 &= 240 + \alpha \text{ to } 300 + \alpha & [T_3 T_4 - ba] \\
 &= 300 + \alpha \text{ to } 360 + \alpha & [T_4 T_5 - ca] \\
 &= 360 + \alpha \text{ to } 420 + \alpha & [T_5 T_6 - cb]
 \end{aligned}$$

* V_o will be there and it is due to above combination of SCRs.

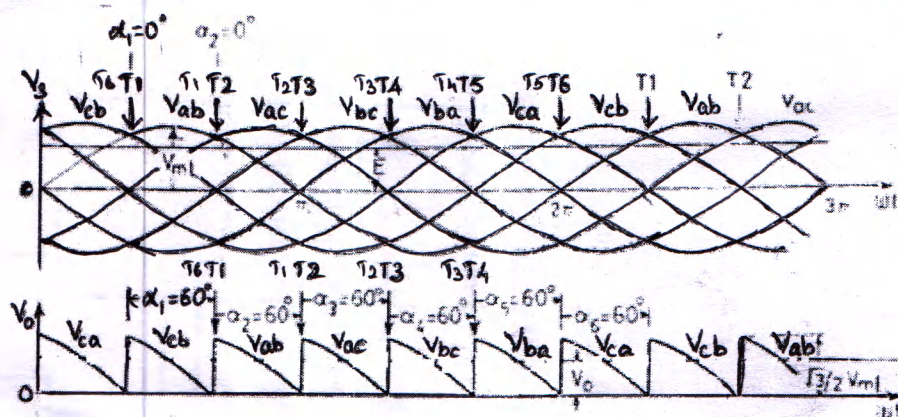
$$* V_o = \frac{1 \times 6}{2\pi} \int_{\frac{\pi}{3} + \alpha}^{\frac{2\pi}{3} + \alpha} V_m \sin \omega t \, d\omega t$$

$$= \frac{3V_m}{\pi} \cos \alpha$$

$$* V_{rms} = \left[\frac{1 \times 6}{2\pi} \int_{\frac{\pi}{3} + \alpha}^{\frac{2\pi}{3} + \alpha} V_m^2 \sin^2 \omega t \, d\omega t \right]^{1/2}$$

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

$$* I_o = \frac{V_o}{R} \quad \text{and} \quad I_{rms} = \frac{V_{rms}}{R}$$



(9)

 $\alpha > 60^\circ$:

* In this mode of operation, the conduction period of thyristor pairs will get reduced from 60° .

* For example, $\alpha = 90^\circ$

- SCR pairs T_6T_1 , starts conducting from $\frac{\pi}{3} + \alpha (=150^\circ)$ and conducts till $\omega t = 180^\circ$.
- Because at $\omega t = 180^\circ$, V_{ab} will be negative so, the SCR pairs get turned off.
- Then the next pairs T_1T_2 , starts conducting from $\omega t = \frac{2\pi}{3} + \alpha (=210^\circ)$ and conducts till $\omega t = 240^\circ$.
- Because at $\omega t = 240^\circ$, V_{ac} is negative so T_1T_2 gets turned off and this process continues.

* Here there will be some non-conduction periods.

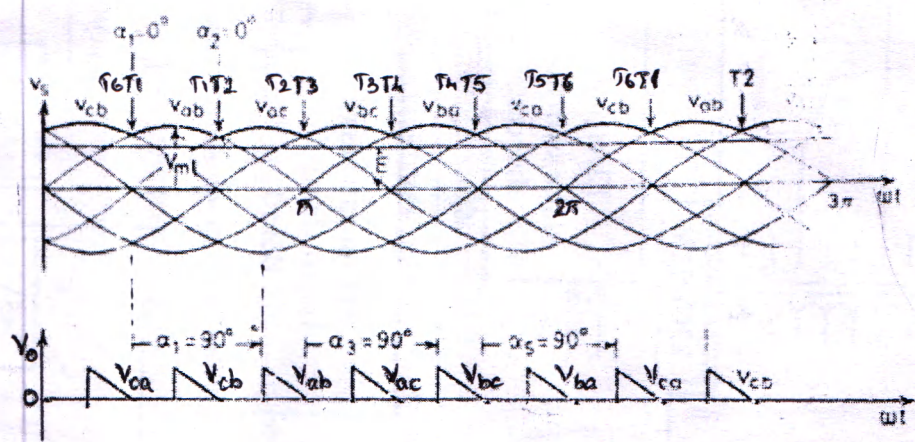
* SCR conduction:

$\omega t = 60 + \alpha$ to 180°	$[T_6T_1 - ab]$
$= 120 + \alpha$ to 240°	$[T_1T_2 - ac]$
$= 180 + \alpha$ to 300°	$[T_2T_3 - bc]$
$= 240 + \alpha$ to 360°	$[T_3T_4 - ba]$
$= 300 + \alpha$ to 420°	$[T_4T_5 - ca]$
$= 360 + \alpha$ to 480°	$[T_5T_6 - cb]$

* Non-Conduction period: for $\alpha = 90^\circ$

$\omega t = 180$ to $120 + \alpha (=210^\circ)$
$= 240$ to $180 + \alpha (=270^\circ)$
$= 300$ to $240 + \alpha (=330^\circ)$
$= 360$ to $300 + \alpha (=390^\circ)$
$= 420$ to $360 + \alpha (=450^\circ)$
$= 480$ to $420 + \alpha (=510^\circ)$

(10)



$$* V_o = \frac{1 \times 6}{2\pi} \int_{\frac{\pi}{3} + \alpha}^{\pi} V_m \sin \omega t \, d\omega t$$

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

$$* V_{rms} = \left[\frac{1 \times 6}{2\pi} \int_{\frac{\pi}{3} + \alpha}^{\pi} V_m^2 \sin^2 \omega t \, d\omega t \right]^{1/2}$$

$$* I_o = \frac{V_o}{R} \quad \text{and} \quad I_{rms} = \frac{V_{rms}}{R}$$

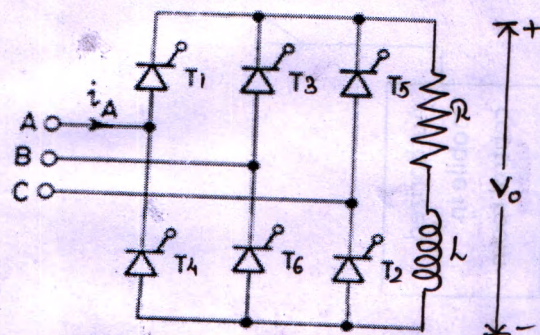
3 ϕ Fully Controlled rectifier with RL load:

* The circuit of this rectifier is similar to previous rectifier, the difference is RL load.

* Here each SCR can conduct for an duration of 120° and thyristor pair for 60° , which does not reduce because of inductance.

* This rectifier has three operating modes

- | | |
|--------------------------------------|-------------------------|
| i) $\alpha < 60^\circ$ | } Rectification process |
| ii) $60^\circ < \alpha < 90^\circ$ | |
| iii) $90^\circ < \alpha < 180^\circ$ | - Inversion process. |



(13)

i) $\alpha < 60^\circ$:

* In this mode of operation, the working is same as 3 ϕ fully controlled rectifier with R-load.

ii) $60^\circ < \alpha < 90^\circ$:

* In this mode of operation, considering $T_6 T_1$, starts conducting at $\omega t = 60^\circ + \alpha$ and does not get turned off at 180° because of inductance.

* So, V_o will be there but gives some negative voltage.

* Here SCR conduction will be for 120° always.

* In this mode, the average output voltage V_o is positive and it can be called as rectification process.

iii) $90^\circ < \alpha < 180^\circ$:

* In this mode of operation, the working is same but V_o is negative and it can be called as inversion process.

* In all the three modes, the V_o and V_{rms} are derived in same manner. as follows,

$$\begin{aligned} * V_o &= \frac{1 \times 6}{2\pi} \int_{\frac{\pi}{3} + \alpha}^{\frac{2\pi}{3} + \alpha} V_m \sin \omega t \, d\omega t \\ &= \frac{3V_m}{\pi} \cos \alpha \end{aligned}$$

$$* V_{rms} = \left[\frac{1 \times 6}{2\pi} \int_{\frac{\pi}{3} + \alpha}^{\frac{2\pi}{3} + \alpha} V_m^2 \sin^2 \omega t \, d\omega t \right]^{1/2}$$

*SCR conduction is also common for all the three mode

$$\omega t = 60 + \alpha \text{ to } 120 + \alpha \quad (T_6 T_1 - ab)$$

$$= 120 + \alpha \text{ to } 180 + \alpha \quad (T_1 T_2 - ac)$$

$$= 180 + \alpha \text{ to } 240 + \alpha \quad (T_2 T_3 - bc)$$

$$= 240 + \alpha \text{ to } 300 + \alpha \quad (T_3 T_4 - ba)$$

$$= 300 + \alpha \text{ to } 360 + \alpha \quad (T_4 T_5 - ca)$$

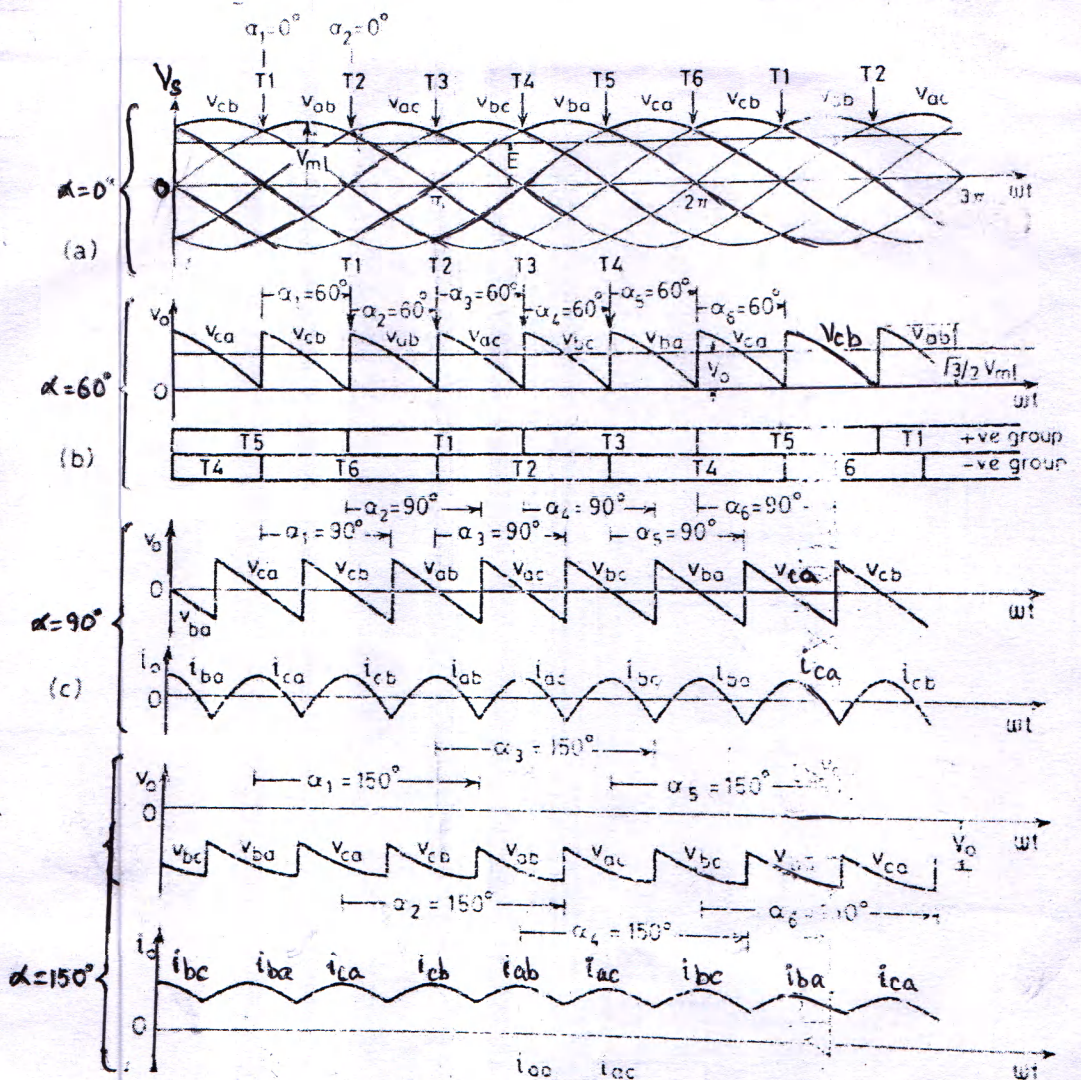
$$= 360 + \alpha \text{ to } 420 + \alpha \quad (T_5 T_6 - cb)$$

a) Supply voltage also can be made as $\alpha = 0^\circ$

b) $\alpha = 60^\circ$, V_o and operating block

c) $\alpha = 90^\circ$, V_o and I_o

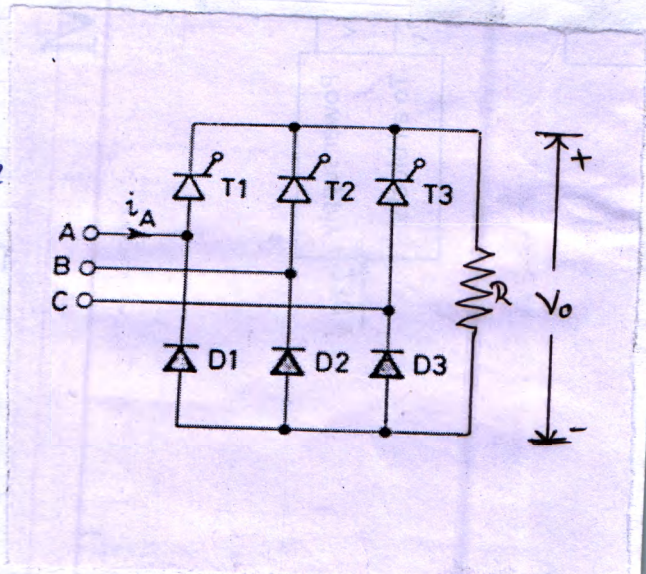
d) $\alpha = 150^\circ$, V_o and I_o .



(13)

3 ϕ Half controlled rectifier with R load:

- * It is also called 3 ϕ semiconverter.
- * It consists of three SCRs and three diodes.
- * It means replacing the negative group of SCRs by diodes in fully controlled rectifiers.
- * The output voltage V_o is controlled by varying the firing angles of SCR T_1, T_2 and T_3 .



* Here the thyristors start conducting based on its firing pulse but the diodes start conducting when the supply is switched-on.

* So the varying element is SCR and it can be explained with the conducting blocks.

* T_1 starts conducting from $\omega t = 60^\circ$ when $\alpha = 0$ and its varies with α .

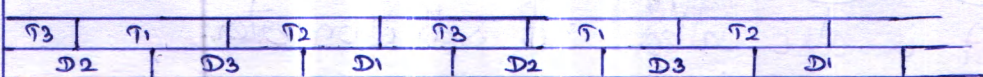
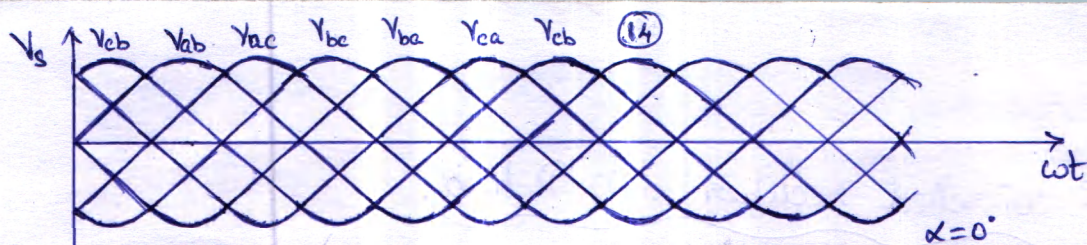
* Output V_o is due to T_1, D_2 for 60° and T_1, D_3 for next 60° , so totally T_1 conducts for 120° but when α value is increased the conduction period gets reduced.

* SCR conduction (T_1 conduction)

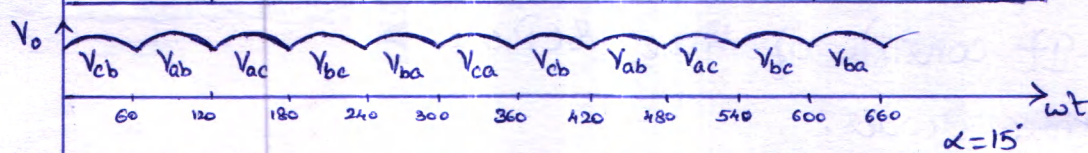
$$\begin{aligned} \omega t &= 60 + \alpha \text{ to } 120^\circ \quad (T_1, D_2 \text{ due to } ab) \\ &= 120 \text{ to } 180^\circ \quad (T_1, D_3 \text{ due to } ac) \end{aligned}$$

this applicable only upto $\alpha = 60^\circ$ and similarly for other SCRs.

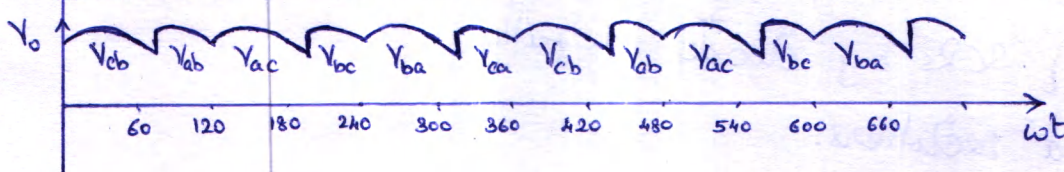
$$\begin{aligned} * V_o &= \frac{3}{2\pi} \left[\int_{\pi/3 + \alpha}^{2\pi/3} V_m \sin \omega t \, d\omega t + \int_{\pi/3}^{\frac{2\pi}{3} + \alpha} V_m \sin \omega t \, d\omega t \right] \\ &= \frac{3V_m}{2\pi} (1 + \cos \alpha) \end{aligned}$$



for $\alpha < 60^\circ$



Conduction blocks



* When α is made $\alpha > 60^\circ$, then the conduction of SCR

is

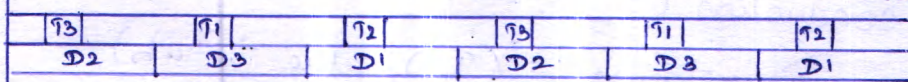
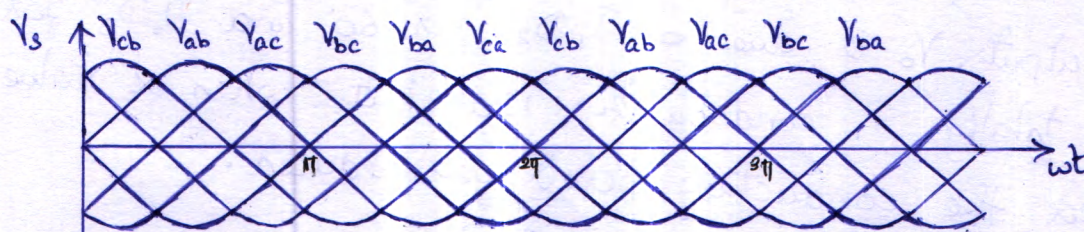
$wt = 60 + \alpha$ to 180° ($T_1 D_3$ due to ac)

$= 180 + \alpha$ to 300° ($T_2 D_1$ due to ba)

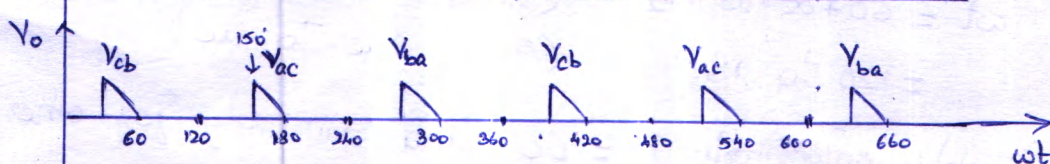
$= 300 + \alpha$ to 420° ($T_3 D_2$ due to cb)

$$* V_o = \frac{3}{2\pi} \int_{\alpha}^{\pi} V_m \sin \omega t \, d\omega t \quad [\text{for } \alpha > 60^\circ]$$

$$= \frac{3V_m}{2\pi} (1 + \cos \alpha)$$



for $\alpha > 60^\circ$



Dual Converter:

* Semiconductor are single quadrant converters. For entire firing angle range, V_o and I_o have only one polarity.

* In fully controlled converters for RL load, upto $\alpha < 90^\circ$ it operates in 1st quadrant and $\alpha > 90^\circ$ it operates in 4th quadrant.

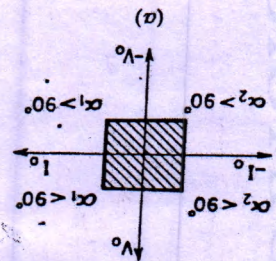
* In order to have all the quadrant operation, two fully controlled rectifiers are connected back to back to the load circuit.

* Such an arrangement is called Dual converter.

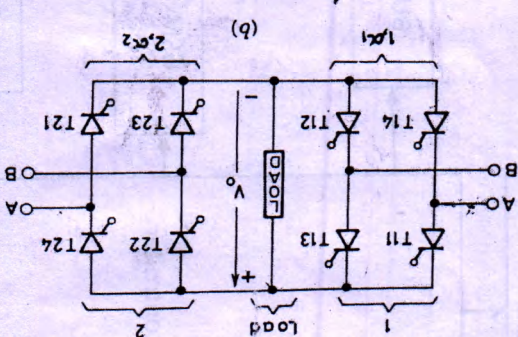
* This dual converter has two functional modes

- i) Non-circulating current mode
- ii) Circulating current mode.

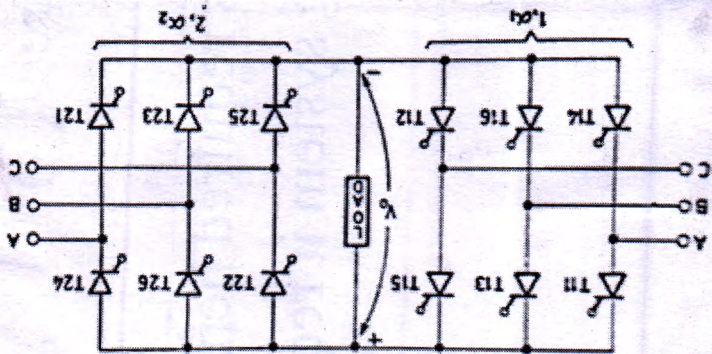
* Figure below represents the non-circulating types of dual converter using 1 ϕ and 3 ϕ configurations.



a) Quadrant Operation



b) 1 ϕ system - non-circulating mode



c) 3 ϕ system - Non-circulating mode

i) Non-Circulating Current Mode:

- * Here there are two converters, Conv 1 and Conv 2.
- * In this mode, only one converter is in operation at a time and it alone carries the entire load.
- * Here only one converter receives the firing pulses from the trigger control.
- * Suppose converter 1 is in operation and is supplying the load current, converter 2 is in off condition.
- * In order to turn-on converter 2, firing pulses of converter 1 is removed and made to turn-off.
- * After a delay time, converter 2 is turned on.
- * It should be ensured that during changeover from one converter to the other, the load current must decay to zero.

ii) Circulating Current Mode:

- * Here both the converters operate at a time with the condition,

$$\alpha_1 + \alpha_2 = 180^\circ$$

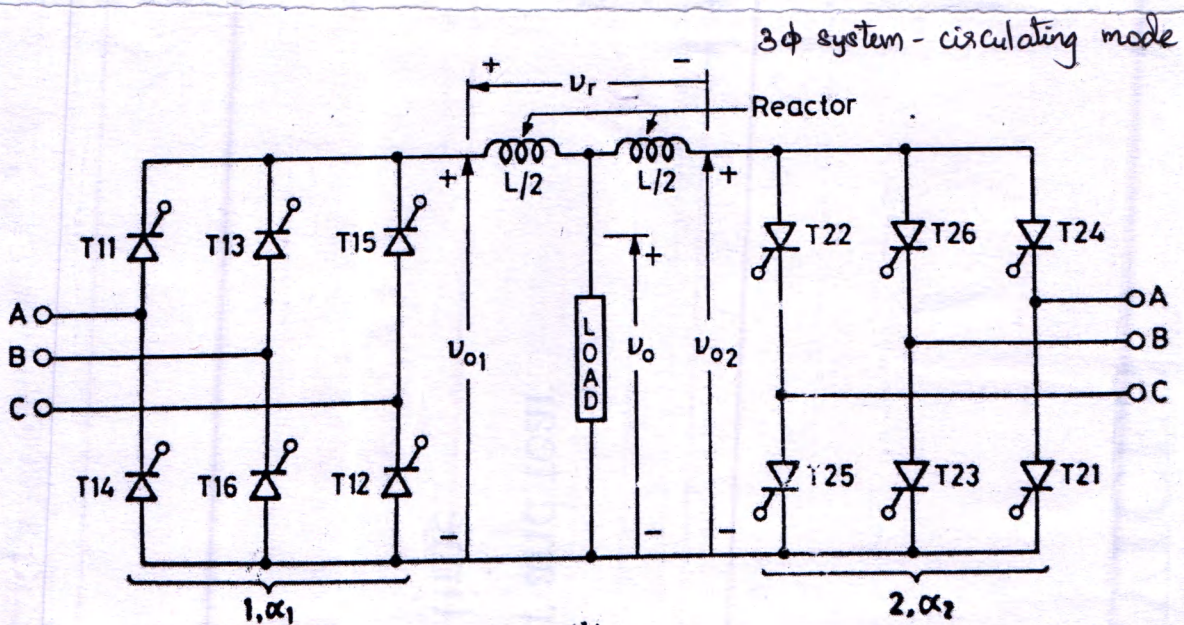
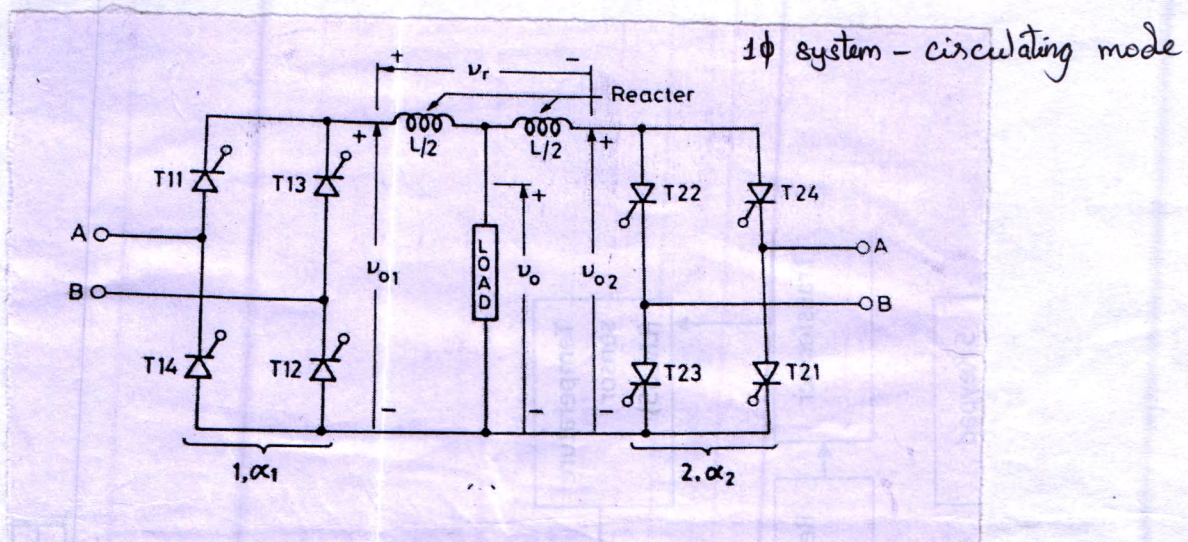
- * Where α_1 and α_2 are the firing pulses of converter 1 and converter 2 respectively.
- * In this mode, when α_1 is 60° , then α_2 should be 120° .
- * So converter 1 is working as a rectifier and converter 2 as an inverter.
- * Though the V_o at the terminals of both converters 1 and 2 has the same average value and has the same polarity, their

instantaneous output voltage waveforms, however are not similar.

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

* This circulating current is limited by the reactor.

* Even by interchanging the α_1 and α_2 values, converter operation also reverses. [$\alpha_1 = 100^\circ$ and $\alpha_2 = 80^\circ$, Conv 1 as inverter and Conv 2 as rectifier].



MODULE 4 INVERTER

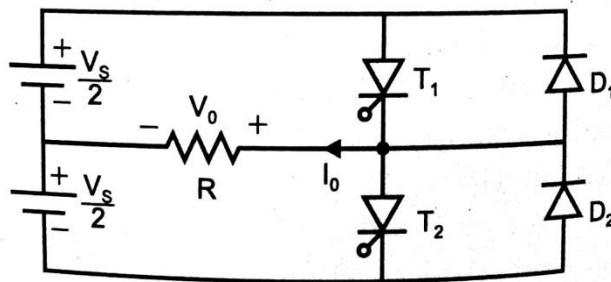
Single Phase Voltage Source Inverter

Single phase voltage source inverter are classified into two types. They are

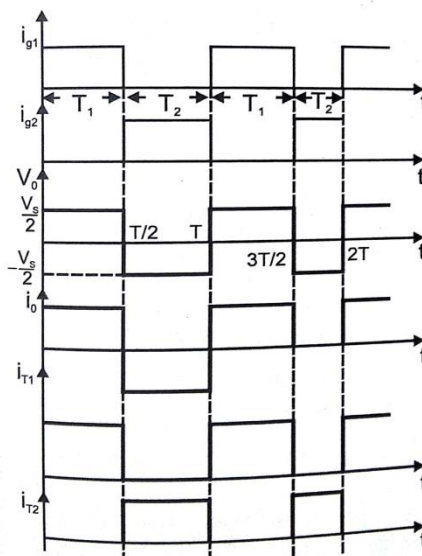
1. Single phase Half bridge Inverter
2. Single phase Full bridge Inverter

Single Phase Half Bridge Inverter

- In a single phase half bridge inverter, the gate signal i_{g1} & i_{g2} are applied to thyristor T_1 and T_2 respectively in order to turn it ON.



- The T_1 & T_2 should not be turned ON at the same time because it will causes short circuit of the gate voltages.
- This circuit consists of two thyristors T_1 & T_2 , Two Diodes D_1 & D_2 and three wire DC supply $V_s/2$.



- During the time 0 to $T/2$ thyristor T_1 is turned ON by applying the gate signal i_{g1} . The voltage across the resistive load is $V_s/2$ due to upper voltage source.
- At $t=T/2$ Thyristor T_1 is turn OFF by forced commutation and Thyristor T_2 is turned ON. During the time $T/2$ to T . The voltage across the resistive load is $(-V_s/2)$.
- The load voltage wave form is of amplitude $V_s/2$ and frequency of $1/T$ Hz.

- For resistive load, output(load) voltage V_o and load current i_o are in phase with each other.
- The diode D_1 & D_2 are connected in antiparallel with the Thyristor. These Diodes are active when Inductive load are used and it carries the current when thyristor are turned OFF.

(i) The RMS output voltage

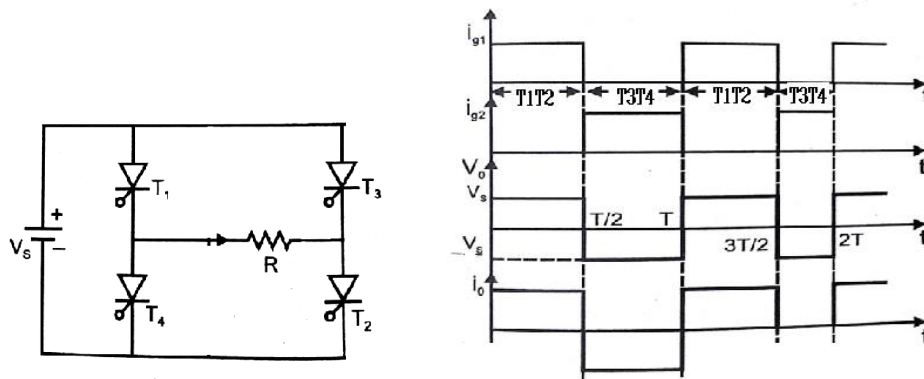
$$\begin{aligned}
 V_{\text{orms}} &= \left[\frac{1}{T} \int_0^T \left(\frac{V_s}{2} \right)^2 ds \right]^{\frac{1}{2}} \\
 &= \left[\frac{1}{T} \int_0^T \left(\frac{V_s^2}{4} \right) dt \right]^{\frac{1}{2}} \\
 &= \left[\frac{V_s^2}{4T} \int_0^T dt \right]^{\frac{1}{2}} = \left[\frac{V_s^2}{4T} \cdot T \right]^{\frac{1}{2}} = \frac{V_s}{2} \\
 \boxed{V_{\text{orms}} &= \frac{V_s}{2}}
 \end{aligned}$$

(ii) The instantaneous output voltage is
 $V_o = 0$

Single Phase Full Bridge Inverter

R Load:

- Now let us consider a single phase full bridge inverter with R load.
- In a single phase full bridge inverter, the gate signal $ig1$ & $ig2$ are applied to thyristor T_1T_2 and T_3T_4 respectively in order to turn it ON.



- Full bridge circuit consists of four Thyristor T_1, T_2, T_3 & T_4 .
- At $t=0$, T_1 & T_2 are forward biased and turned ON when gate pulse is applied. The voltage across the resistive load is positive($+V_s$). Since the Load current is in-phase with load voltage the I_o is also positive.

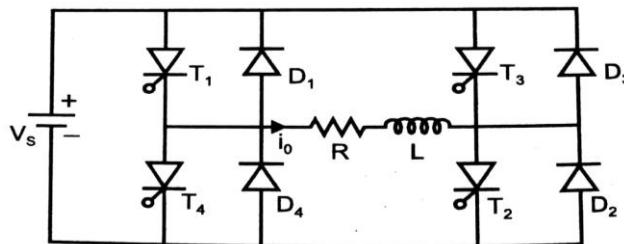
$$V_s - T_1 - R - T_2 - V_s$$

- At $t = -T/2$, T_1 & T_2 are turned OFF by forced commutation and Thyristor T_3 & T_4 are turned ON. The voltage across the resistive load is negative ($-V_s$). Since the Load current is in-phase with load voltage the I_o is also negative.

$$V_s - T_3 - R - T_4 - V_s$$

RL Load:

- Now let us consider a single phase full bridge inverter with RL load.
- In a single phase full bridge inverter, the gate signal $ig1$ & $ig2$ are applied to thyristor T_1T_2 and T_3T_4 respectively in order to turn it ON.

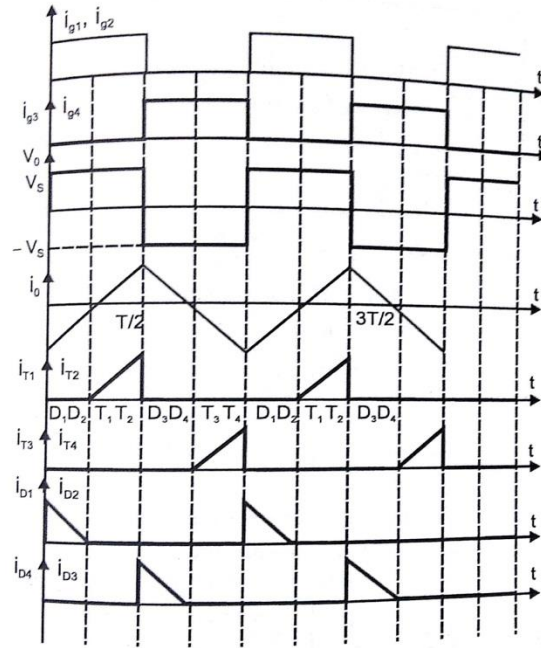


- Full bridge circuit consists of four Thyristor T_1 , T_2 , T_3 & T_4 and four Diodes D_1 , D_2 , D_3 & D_4 . Before $t=0$ thyristor T_3 and T_4 are conducting and load current i_o is negative.
- At $t=0$, Thyristor T_3 & T_4 are turned OFF and load current i_o should be positive. Due to Inductive load the load current I_o cannot change its direction immediately.
- After $t=0$ the diode D_1 & D_2 starts conducting the load current i_o flow against the supply voltage V_s .
- At $t=0$, T_1 & T_2 will not turned ON because T_1 & T_2 are reverse biased by voltage across diode D_1 & D_2 .
- When current through D_1 & D_2 are falls to zero. T_1 & T_2 are forward biased and turned ON. I_o becomes positive.

$$V_s - T_1 - R - L - T_2 - V_s$$

- At $t = -T/2$, T_1 & T_2 are OFF by forced commutation. I_o cannot reverse direction immediately. D_3 & D_4 starts conducting after $t=T/2$, through T_3 & T_4 are gated will not turn ON.
- The voltage drop across D_3 & D_4 are fall to zero, T_3 & T_4 are turned ON. Now load current i_o is negative.

$$V_s - T_3 - L - R - T_4 - V_s$$



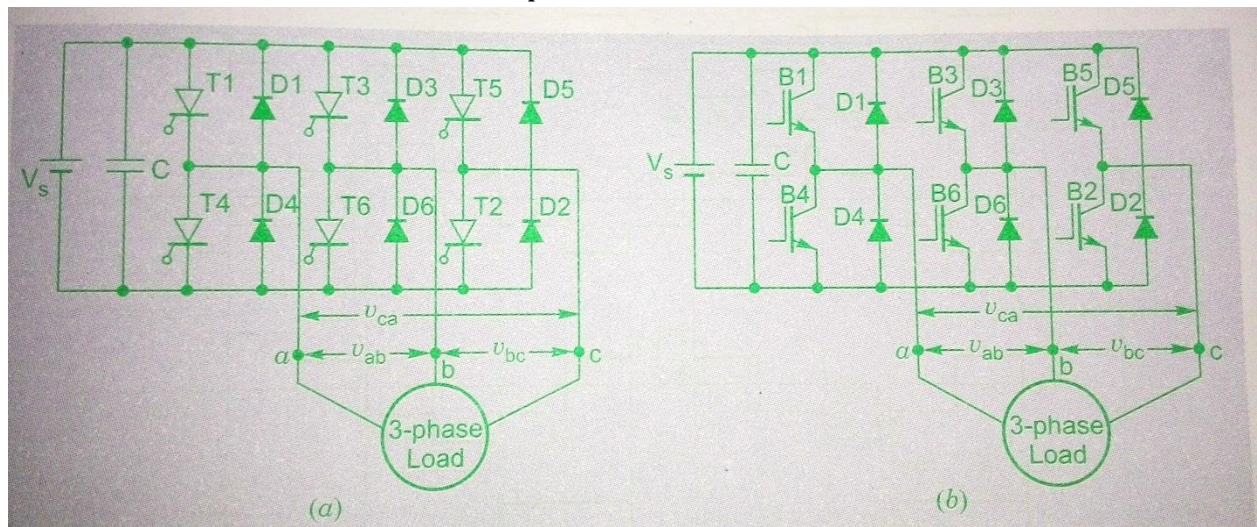
- The rms output voltage(V_{orms}) is given by

$$\begin{aligned}
 V_{\text{orms}} &= \left[\frac{1}{T} \int_0^T V_s^2 dt \right]^{\frac{1}{2}} \\
 &= \left[\frac{V_s^2}{T} \int_0^T dt \right]^{\frac{1}{2}} = \left[\frac{V_s^2}{T} \cdot T \right]^{\frac{1}{2}} = V_s \\
 \boxed{V_{\text{orms}} = V_s}
 \end{aligned}$$

THREE PHASE INVERTER

Three Phase Bridge Inverters:

- For providing adjustable frequency power to industrial applications, three phase inverters are more common than single phase inverters.
- A basic three phase inverter is a six step bridge inverter. It uses a minimum of six Thyristors.
- In inverter terminology a step is defined as a change in the firing from one Thyristor to the next Thyristor in proper sequence.
- For one cycle of 360° each step would be of 60° interval for a six step inverter. This means that Thyristor are gated at regular interval of 60° in proper sequence.
- Thus three phase inverter are classified into two modes, namely
 1. 180° mode of operation
 2. 120° mode of operation



180 DEGREE MODE OF OPERATON:

- In this mode of operation, each SCR conducts for 180° of a cycle.
- Thyristors pair in each arm (T_1, T_4); (T_3, T_6); (T_5, T_2) are turned ON with a time interval of 180. It means that T_1 conducts for 180° and T_4 for next 180° of a cycle.
- Thyristors in the upper group, i.e.; T_1, T_3, T_5 conduct at an interval of 120° . It implies that

If,

T_1 is fired at $wt = 0^\circ$,

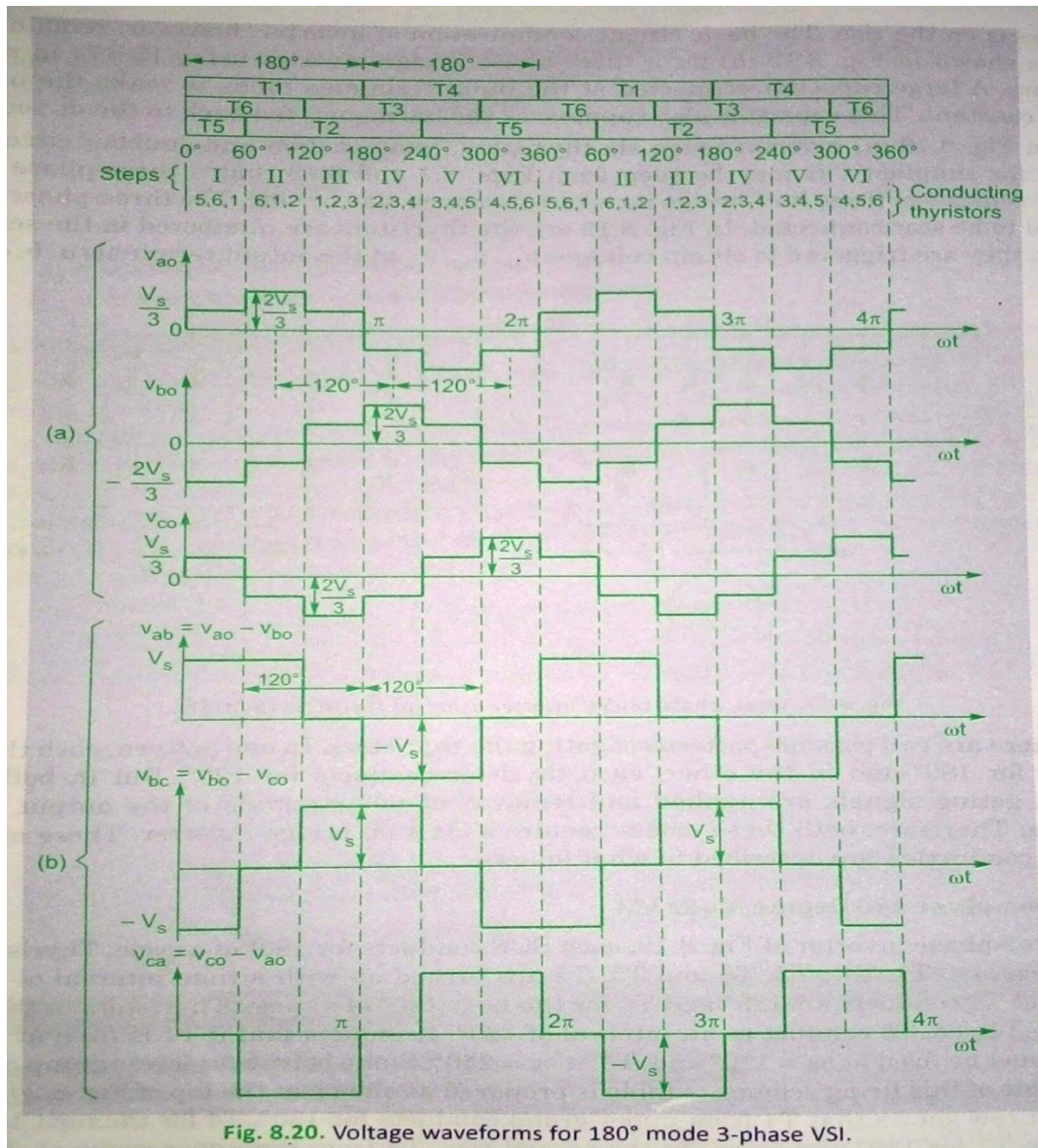
then,

T_3 must be fired at $wt = 120^\circ$

and

T_5 at $wt = 240^\circ$.
- Same is true for lower group of SCR's T_4, T_6 and T_2 .

- On the basis of this firing scheme, the table is prepared as shown.



T1, T2, T3 for step 3;
T2, T3, T4 for step 4 and so on.

(Note: 561, 612, 123, 234, 345, 456, 561,.....)

- It is seen from table that in every step of 60° duration, only 3 SCR's are conducting one from upper group and two from lower group or vice versa.
- The circuit models for step 1 to 4 are shown in figure.
- During step 1, Thyristors 5,6,1 are conducting. These are shown as closed switches and non-conducting SCR's 2,3,4 are as open switches in figure.

The load terminals a and c are connected to positive bus of dc source whereas terminal b is connected to the negative bus of dc source.

The load voltage is $V_{ab}=V_{cb}=V_s$ in magnitude. The magnitude of line to neutral voltages can be obtained as follows.

During step 1:

During step 2:

These output voltages are plotted in figure, in this manner, the variation of phase voltages V_{ao} , V_{bo} , V_{co} , as obtained in figure up to step 4. And similarly for other steps, is plotted in figure. It is clear that for each cycle of output voltage of each phase six steps are required and each step has a duration of 60 degrees.

The line voltage $V_{ab}=V_{ao}-V_{bo}$, $V_{bc}=V_{bo}-V_{co}$, $V_{ca}=V_{co}-V_{ao}$ are plotted.

Modes	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
5, 6, 1	$\frac{V_s}{3}$	$\frac{-2V_s}{3}$	$\frac{V_s}{3}$	V_s	$-V_s$	0
6, 1, 2	$\frac{2V_s}{3}$	$\frac{-V_s}{3}$	$\frac{-V_s}{3}$	V_s	0	$-V_s$
1, 2, 3	$\frac{V_s}{3}$	$\frac{V_s}{3}$	$\frac{-2V_s}{3}$	0	V_s	$-V_s$
2, 3, 4	$\frac{-V_s}{3}$	$\frac{2V_s}{3}$	$\frac{-V_s}{3}$	$-V_s$	V_s	0
3, 4, 5	$\frac{-2V_s}{3}$	$\frac{V_s}{3}$	$\frac{V_s}{3}$	$-V_s$	0	V_s
4, 5, 6	$\frac{-V_s}{3}$	$\frac{-V_s}{3}$	$\frac{2V_s}{3}$	0	$-V_s$	V_s

120 DEGREE MODE OF OPERATION:

- In this mode of operation, each SCR conducts for 180° of a cycle.
- Thyristors pair in each arm (T_1, T_4); (T_3, T_6); (T_5, T_2) are turned ON with a time interval of 180. It means that T_1 conducts for 180° and T_4 for next 180° of a cycle.
- Thyristors in the upper group, i.e.; T_1, T_3, T_5 conduct at an interval of 120°. It implies that
If,
 T_1 is fired at $wt = 0^\circ$,
then,
 T_3 must be fired at $wt = 120^\circ$
and
 T_5 at $wt = 240^\circ$.
- Same is true for lower group of SCR's T_4, T_6 and T_2 .
- On the basis of this firing scheme, the table is prepared as shown.

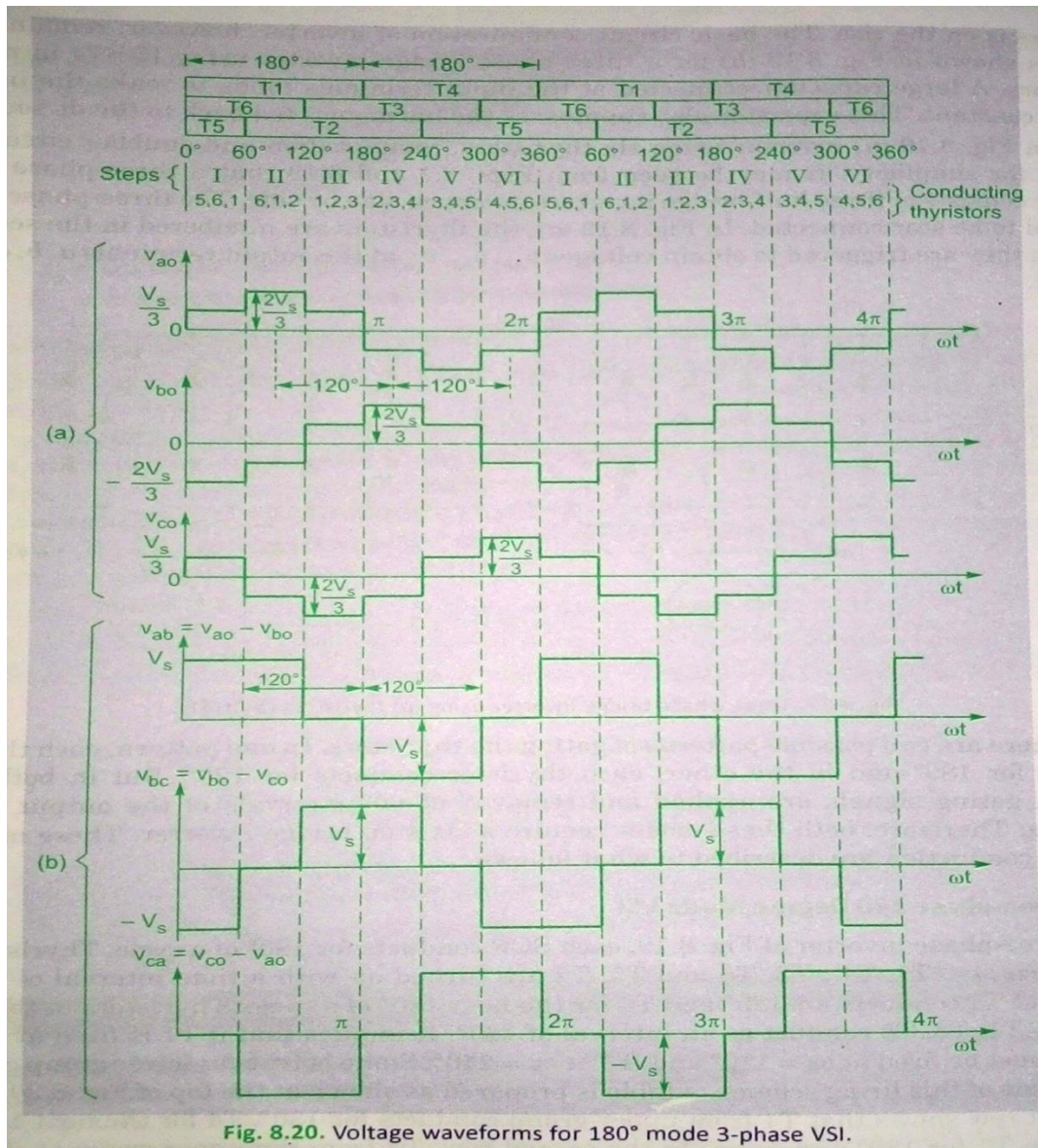


Fig. 8.20. Voltage waveforms for 180° mode 3-phase VSI.

- In this table, first row shows that T_1 from upper group conducts for 180°, T_4 for next 180° and then again T_1 for 180° and so on.
- In the second row, T_3 from the upper group is shown to start conducting 120° after T_1 starts conducting. After T_3 conducts for 180°, T_6 conduct for next 180° and again T_3 for next 180° and so on.
- Further, in the third row, T_5 from the upper group starts conducting 120° after T_3 or 240° after T_1 . After T_5 conducts for 180°, T_2 conducts for next 180°, T_5 for next 180 degrees and so on. In this manner the pattern of firing the 6 SCR's is identified.
- The table shows that
 T_5, T_6, T_1 should be gated for step 1;
 T_6, T_1, T_2 for step 2;
 T_1, T_2, T_3 for step 3;
 T_2, T_3, T_4 for step 4 and so on.

(Note: 561, 612, 123, 234, 345, 456, 561,.....)

- It is seen from table that in every step of 60° duration, only 3 SCR's are conducting one from upper group and two from lower group or vice versa.
- The circuit models for step 1 to 4 are shown in figure.
- During step 1, Thyristors 5,6,1 are conducting. These are shown as closed switches and non-conducting SCR's 2,3,4 are as open switches in figure.

The load terminals a and c are connected to positive bus of dc source whereas terminal b is connected to the negative bus of dc source.

The load voltage is $V_{ab}=V_{cb}=V_s$ in magnitude. The magnitude of line to neutral voltages can be obtained as follows.

During step 1:

During step 2:

These output voltages are plotted in figure, in this manner, the variation of phase voltages V_{ao} , V_{bo} , V_{co} , as obtained in figure up to step 4. And similarly for other steps, is plotted in figure. It is clear that for each cycle of output voltage of each phase six steps are required and each step has a duration of 60 degrees.

The line voltage $V_{ab}=V_{ao}-V_{bo}$, $V_{bc}=V_{bo}-V_{co}$, $V_{ca}=V_{co}-V_{ao}$ are plotted.

Modes	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
T_1, T_6	$\frac{V_s}{2}$	$\frac{-V_s}{2}$	0	V_s	$\frac{-V_s}{2}$	$\frac{-V_s}{2}$
T_1, T_2	$\frac{V_s}{2}$	0	$\frac{-V_s}{2}$	$\frac{V_s}{2}$	$\frac{V_s}{2}$	$-V_s$
T_2, T_3	0	$\frac{V_s}{2}$	$\frac{-V_s}{2}$	$\frac{-V_s}{2}$	V_s	$\frac{-V_s}{2}$
T_3, T_4	$\frac{-V_s}{2}$	$\frac{V_s}{2}$	0	$-V_s$	$\frac{V_s}{2}$	$\frac{V_s}{2}$
T_4, T_5	$\frac{-V_s}{2}$	0	$\frac{V_s}{2}$	$\frac{-V_s}{2}$	$\frac{-V_s}{2}$	V_s
T_5, T_6	0	$\frac{-V_s}{2}$	$\frac{V_s}{2}$	$\frac{V_s}{2}$	$-V_s$	$\frac{V_s}{2}$

MODULE 5

PWM Inverter :

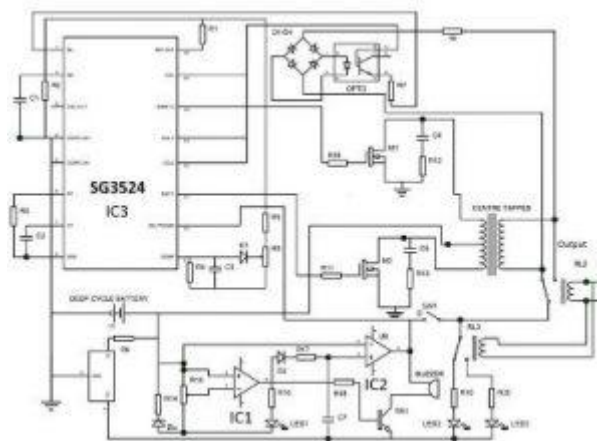
Types and Their Applications

Pulse Width Modulated inverters(PWM inverter) replaced the older versions of inverters and has a wide range of applications. Practically these are used in the power electronics circuits. The inverters based on the PWM technology possess MOSFETs in the switching stage of the output. Most of the inverters available nowadays possess this PWM technology and are capable of producing ac voltage for varying magnitudes and frequencies. There are multiple protection and control circuits in these types of inverters. The implementation of PWM technology in the inverters makes it suitable and ideal for the distinct loads connected.

What is a PWM Inverter?

An inverter whose functionality depends upon the pulse width modulation technology is referred to as PWM inverters. These are capable of maintaining the output voltages as the rated voltages depending on the country irrespective of the type of load connected. This can be achieved by changing the switching frequency width at the oscillator.

Circuit diagram of PWM inverter is given in the below diagram



There are various circuits used in the PWM inverters. Some of them are listed below

Battery Charging Current Sensor Circuit

The purpose of this circuit is to sense the current utilized in charging the battery and maintain it at the rated value. It is important to avoid the fluctuations to protect the batteries' shelf life.

Battery Voltage Sensing Circuit

This circuit is used to sense the voltage required to charge the battery when it is exhausted and begin trickle charging of the battery once it gets fully charged.

AC Mains Sensing Circuit

This circuit is to sense the availability of AC mains. If it is available then the inverter will be in a state of charging and in the absence of mains the inverter will be in battery mode.

Soft Start Circuit

It is used to delay the charging for 8 to 10 seconds after resuming the power. It is to protect the MOSFETs from the high currents. This is also referred to as Mains delay.

Change Over Circuit

Based on the mains availability this circuit switches the operation of the inverter between the battery and the charging modes.

Shut Down Circuit

This circuit is to monitor the inverter closely and shut it down whenever any abnormality incurred.

PWM Controller Circuit

To regulate the voltage at the output this controller is used. The circuit needs to perform PWM operations are incorporated in the IC's and these are present in this circuit.

Battery Charging Circuit

The process of charging a battery in the inverter is controlled by this circuit. The output generated by the sensing circuit of the mains and the sensor circuits of the battery is the inputs for this circuit.

Oscillator Circuit

This circuit is incorporated with the IC of PWM. It is used to generate the switching frequencies.

Driver Circuit

The output of the inverter gets driven by this circuit based on the switching signal of frequency generated. It is similar to that of a preamplifier circuit.

Output Section

This output section comprises a step-up transformer and it is used to drive the load.

Working Principle

An inverter designing involves various topologies of power circuits and the methods to control the voltage. The most concentrated part of the inverter is its waveform generated at the output. For the purpose of filtering the waveform inductors and the capacitors are used. In order to reduce the harmonics from the output low pass filters are used.

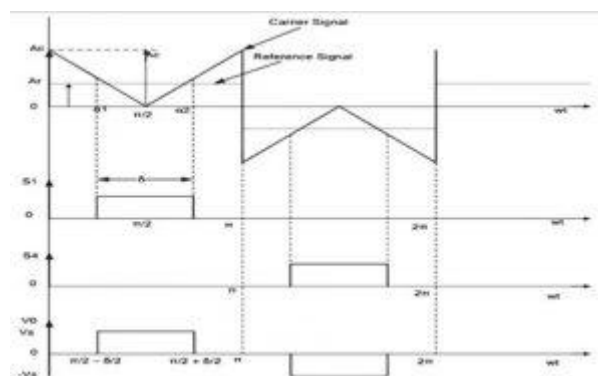
If the inverter possesses a fixed value of output frequencies resonant filters are used. For the adjustable frequencies at the output, filters are tuned above the maximum value of fundamental frequency. PWM technology changes the square wave characteristics. The pulses used for switching are modulated and regulated before it supplied to the connected load. When there is no requirement for voltage control fixed width of the pulse is used.

PWM Inverter Types & Waveforms

The technique of PWM in an inverter comprises of two signals. One signal is for the reference and the other will be the carrier. The pulse required for switching the mode of the inverter can be generated by the comparison among those two signals. There are various PWM techniques.

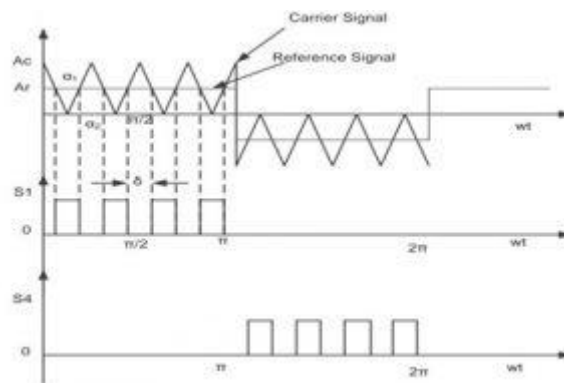
Single Pulse Width Modulation (SPWM)

For every half cycle, there is only one pulse available to control the technique. The square wave signal will be for reference and a triangular wave will be the carrier. The gate pulse generated will be the result of the comparison of the carrier and the reference signals. Higher harmonics is the major drawback of this technique.



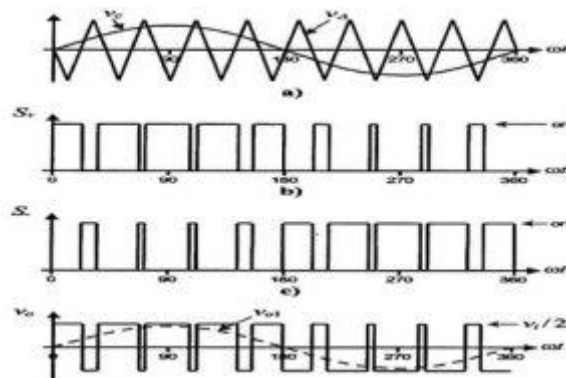
Multiple Pulse Width Modulation (MPWM)

MPWM technique is used to overcome the drawback of SPWM. Instead of a single pulse, multiple pulses are used for every half cycle of the voltage at the output. The frequency at the output is controlled by controlling the frequency of the carrier.



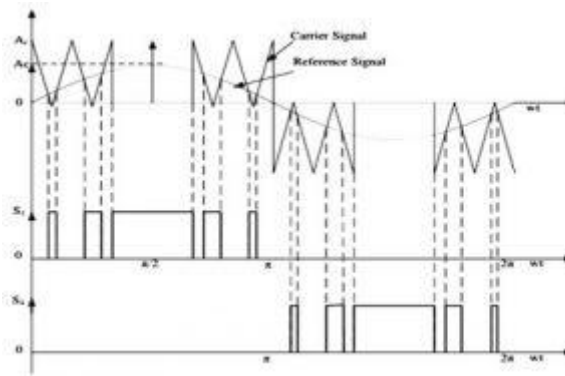
Sinusoidal Pulse Width Modulation

In this type of PWM technique, instead of a square wave, a sine wave is used as a reference and the carrier will be a triangular wave. The sine wave will be the output and its RMS value of voltage is controlled by the modulation index.



Modified Sinusoidal Pulse Width Modulation

The carrier wave is applied for the first and the last sixty-degree interval per every half cycle. This modification is introduced to improve the harmonic characteristics. It decreases the loss due to switching and increases the fundamental component.



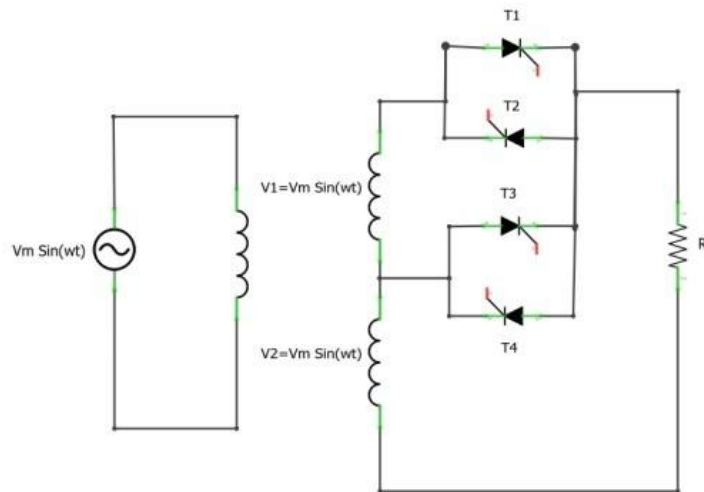
Applications

Most commonly PWM inverters are utilized in the speed AC drives where the speed of the drive is dependent on the variation in the frequency of the applied voltage. Majorly the circuits in power electronics can be controlled by using PWM signals. To generate the signals in analog form from digital devices like microcontrollers, the PWM technique is beneficial. Further, there are various applications where PWM technology is used in different circuits.

Two stage sequence control AC voltage controller with R load:

In this we will use set of thyristor connected antiparallel means we will use four thyristor in this circuit. The source voltage will provide the ac voltage which will consist of primary winding and secondary winding. The secondary winding will be center tapped the two winding will be mutual connected. The voltage from the one winding will be $V_1 = V_m \sin \omega t$ and voltage across second winding will $V_2 = V_m \sin \omega t$

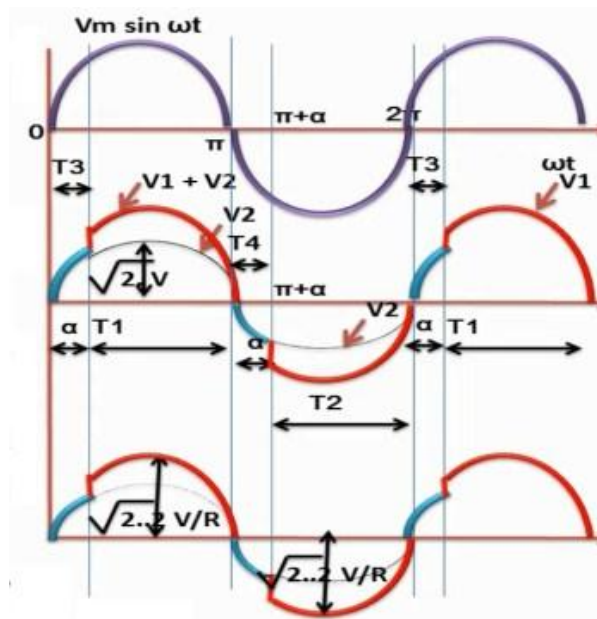
The circuit is connected with the resistive load at output.



Working:

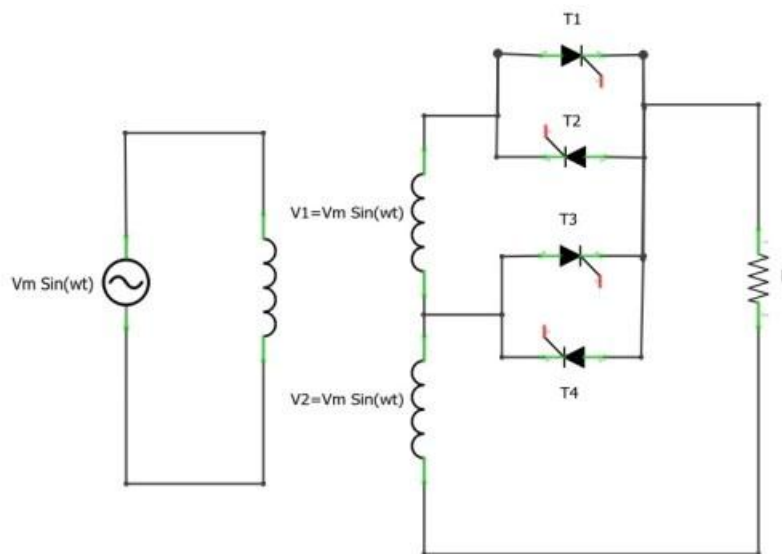
The thyristor T3 and T4 will only work when the $\omega t = 0$ means when the firing angle α will be equal to zero. The thyristor T1 and T2 will work when at particular angle the pulse is provided means their firing angle will be at certain phase. When we start the supply from the source voltage when positive cycle will occur and $\omega t = 0$ then thyristor 3 will conduct and the current will pass from thyristor 3. The voltage will be from the secondary winding V2 and the source current will flow from thyristor T3 when α will be equal to zero when the ωt will be equal to α then we will provide trigger pulse at the gate of T1 then thyristor 3 will off and thyristor one will conduct at this time then the voltage will be from $V1 + V2$ and the source current will flow in T1. The wave will go in upward direction after trigger pulse. This is because first there is only one voltage which was V1 and now we have two voltages which are $V1 + V2$ the complete secondary winding will work.

When a negative cycle will come from the source the primary and lower secondary will start working the voltage will be V2 when we will provide trigger pulse at T4 it will start conducting. The output voltage will start in reverse direction and the ωt will be equal to π . The output current will be also in reverse direction. When a trigger pulse will be given at the gate of the T2 then the output voltage will be equal to $V1 + V2$.



Multistage sequence control of Voltage:

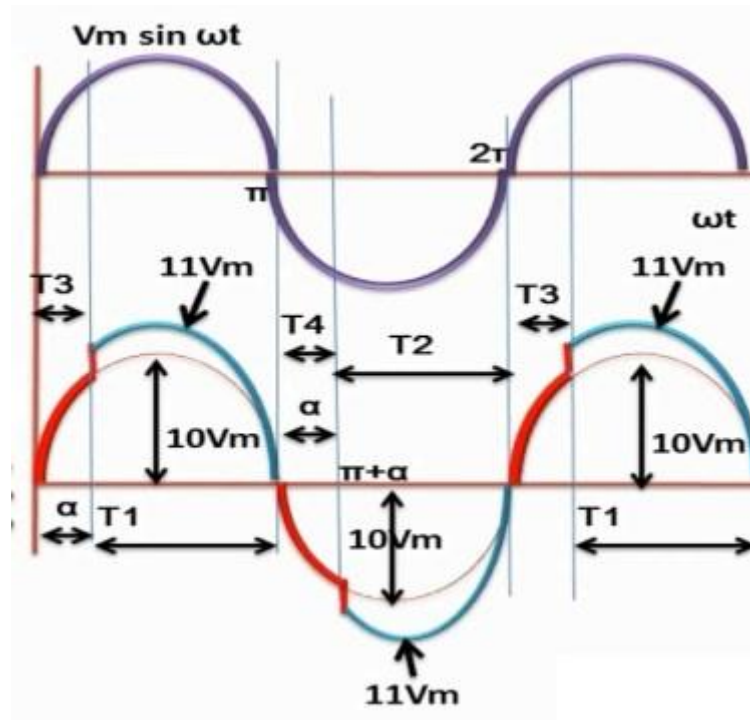
The controller will be connected in multistage. There will be separate voltage at the secondary of the winding such that 1V at one winding, 2V at second winding and 8V at third winding.



Working:

When the source voltage is applied the source current will start flowing from thyristor T3 and it will start working and with T3. The T1 and T2 will start working at α angle. The voltage will be $10V_m$ which is the sum of 2 and 8 volt. In positive cycle the upper portion of the secondary winding when the trigger voltage will be applied at the thyristor T1 and will start conducting. Then the output voltage will be the sum of all winding voltages

which are 1, 2 and 8V which is equal to 11V. when a negative cycle will occur the thyristor T4 will start conducting. The output voltage will be the sum of 2 and 8 which is equal to 10V. When trigger pulse will be applied at thyristor T2 and will start conducting at $\pi + \alpha$. When T1 and T2 will conduct we will add all the winding voltage and when T3 and T4 will conduct we will add only two winding.



6 Module

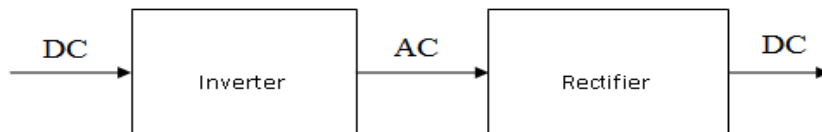
DC-DC converters—stepdown and step up choppers—single-quadrant, two-quadrant& four quadrant chopper—pulse width modulation & current limit control in dc-dc converters. Switching regulators—buck, boost&buck-boost—continuous conduction mode only—waveforms—design of filter inductance& capacitance

DC-DC converter (Chopper)

- Many industrial applications require power from dc voltage source
- E.g.: subway cars, trolley buses, battery operated vehicles, battery charging etc...
- The conversion of fixed dc voltage to an adjustable dc output voltage through the use of semiconductor devices can be carried out by the use of two types dc to dc converter given below
 - AC link chopper
 - DC chopper

AC link chopper: Dc first converted to ac by using an inverter

- Dc first converted to ac by using an inverter
- Ac is then stepped up or down by using a transformer
- Which is then converted back to dc by using a diode rectifier
- As the conversion is in two stages, dc to ac and then ac to dc, ac link chopper is costly, bulky and less efficient



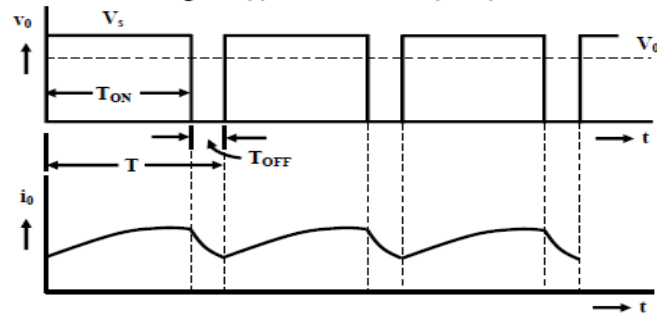
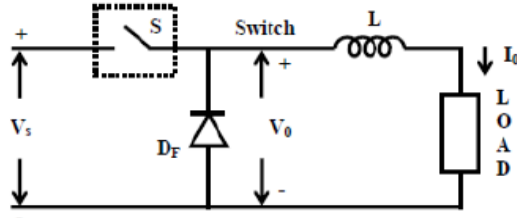
DC chopper

- *Chopper is a static device that convert fixed dc input voltage to a variable dc output voltage*
- Dc equivalent of an ac transformer
- Involves one stage conversion — more efficient



Step-down chopper

- A chopper is a high speed on/off semiconductor switch
- It connect source to load and disconnect the load from source at a fast speed
- Chopper is represented by a switch SW inside a dotted rectangle



- During the period T_{on} , chopper is on and load voltage is equal to source voltage V_s
- During the interval T_{off} , chopper is off, load current flows through the freewheeling diode FD
- As a result load terminal are short circuited by the FD and load voltage is therefore zero during T_{off}
- In this manner a chopped dc voltage is produced at the load terminal
- During T_{on} , load current rises whereas during T_{off} , load current decays

$$V_o = \frac{T_{on}}{T_{on} + T_{off}} V_s = \frac{T_{on}}{T} V = \alpha V_s$$

- T_{on} = on-time; T_{off} = off-time
- $T = T_{on} + T_{off}$ = Chopping period
- Duty cycle

$$\alpha = \frac{T_{on}}{T}$$

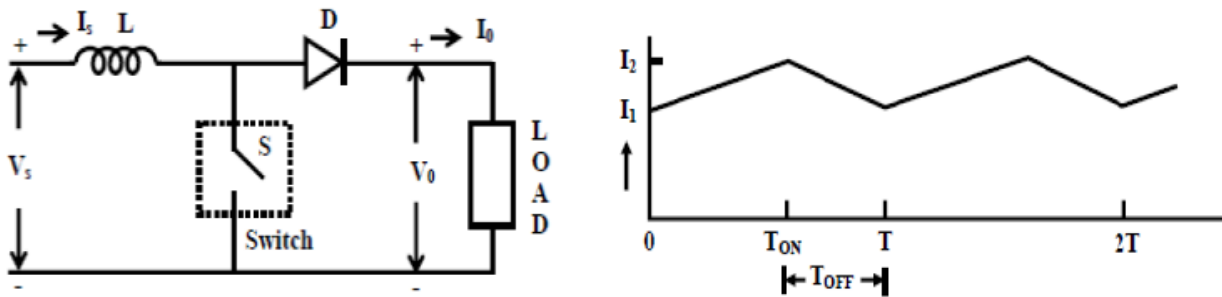
- Thus load voltage can be controlled by varying duty cycle

$$V_o = f \cdot T_{on} \cdot V_s$$

- Where f is the chopping frequency
- *Average output voltage is always less than the input voltage hence called as step down chopper*

Step-up chopper

- *Average output voltage greater than input voltage can be obtained by using a chopper known as step-up chopper*
- A large inductor L in series with the source voltage is essential



- When chopper is on, inductor stores energy
- When chopper is off as the inductor current cannot die down instantaneously, this current is forced to flow through the diode and load for a time T_{off}
- As the current tends to decrease polarity of the emf induced in the L is reversed
- As a result voltage across the load becomes

$$V_o = V_s + L \frac{di}{dt}$$
 exceeds the source voltage
- In this manner circuit acts as a step up chopper
- Assuming linear variation of output current the energy input to inductor from the source during T_{on} is

$$\begin{aligned}
 W_{in} &= (\text{voltage across } L)(\text{average current through } L)T_{on} \\
 &= V_s \cdot \left(\frac{I_1 + I_2}{2} \right) T_{on}
 \end{aligned}$$

- During T_{off} , when chopper is off, the energy released by the inductor to the load is

$$\begin{aligned}
 W_{off} &= (\text{voltage across } L)(\text{average current through } L)T_{off} \\
 &= (V_o - V_s) \cdot \left(\frac{I_1 + I_2}{2} \right) T_{off}
 \end{aligned}$$

- Considering the system to be lossless, these two energies will be equal

$$V_s \left(\frac{I_1 + I_2}{2} \right) T_{on} = (V_o - V_s) \left(\frac{I_1 + I_2}{2} \right) T_{off}$$

$$V_s \cdot T_{on} = V_o \cdot T_{off} - V_s \cdot T_{off}$$

$$V_o \cdot T_{off} = V_s (T_{on} + T_{off}) = V_s \cdot T$$

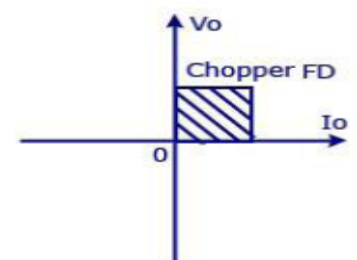
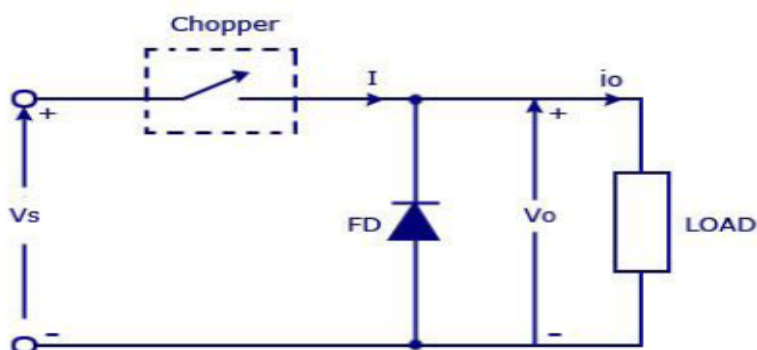
$$V_o = V_s \frac{T}{T_{off}} = V_s \frac{T}{T - T_{on}} = V_s \frac{1}{1 - \alpha}$$

Types of chopper circuit

- Power semiconductor devices used in chopper circuit are unidirectional devices
- Polarities of output voltage and direction of output current is therefore restricted
- A chopper can however operate in any of the four quadrant, by an appropriate arrangements of the semiconductor devices
- This characteristics of their operation in any of the four quadrant form the basis of their classification as type-A, type-B etc... or class A, class B etc...

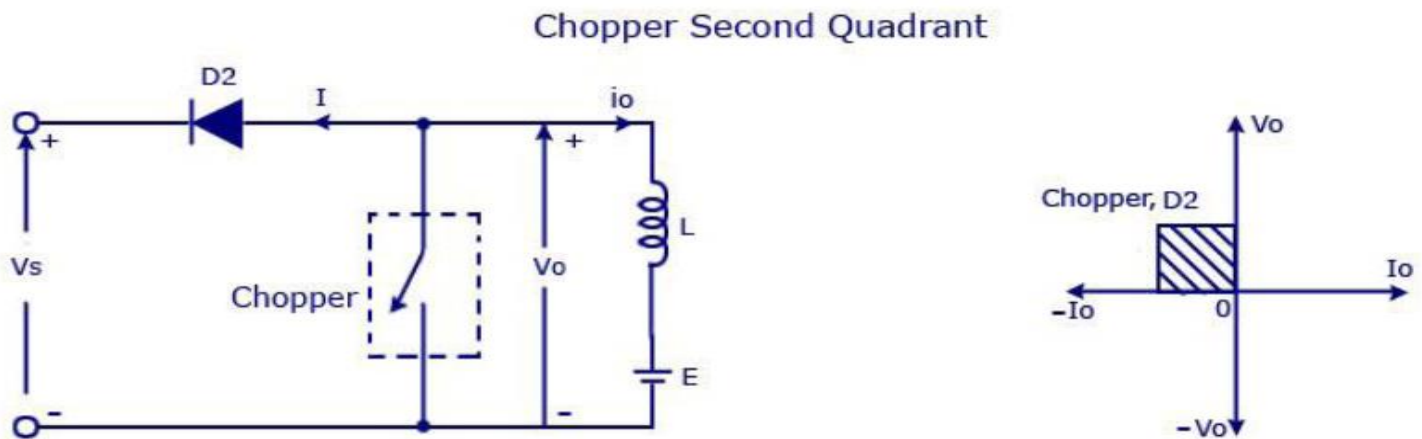
First quadrant or Type-A Chopper

Chopper First Quadrant



- When chopper CH1 is on, $V_o = V_s$ and current i_o flows in the direction as shown
- When CH1 is off, $V_o = 0$, but i_o in the load continues to flowing in the same direction through freewheeling diode FD
- It is thus seen that average value of both load voltage and current are always +ve
- The power flow is always from source to load
- This chopper is also called step down chopper

Second quadrant or Type-B Chopper

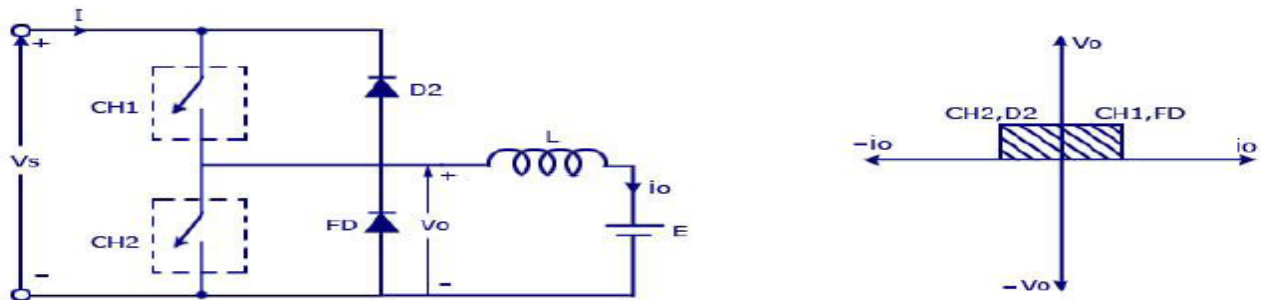


- Load must contain a dc source like a battery in this chopper
- When CH2 is on, $v_o = 0$ but load voltage E drives current through L and CH2
- Inductance L store energy during T_{on} of CH2
- When CH2 is off, $v_o = E + L(di/dt)$, exceeds source voltage V_s
- As a result diode $D2$ is forward biased and begins conduction, thus allowing power to flow to the source
- Chopper CH2 may be on or off, current I_o flows out of the load, current I_o is therefore treated as -ve
- Since V_o is always +ve and I_o is -ve power flow is from load to source
- As load voltage $V_o = E + L(di/dt)$ is more than source voltage V_s , type B chopper is known as step-up chopper

Two-quadrant type-A or Type-C

- Obtained by connecting Type-A and Type-B in parallel
- Output voltage V_o is always +ve because of the presence of freewheeling diode FD across the load
- When CH2 is on, or freewheeling diode FD conducts output voltage $V_o=0$

Chopper Two Quadrant



- When CH2 is on or diode D2 conducts, output voltage $V_o=V_s$
- The load current I_o can however reverse its direction
- Load current is +ve when CH1 is on or FD conducts
- Load current is -ve when CH2 is on or D2 conducts
- In other words, CH1 and FD operate together as type-A chopper in first quadrant
- CH2 and D2 operate together as type-B chopper in second quadrant
- Average load voltage is always +ve, but average load current can be +ve or -ve
- This type of chopper operation is used for motoring and regenerative braking of dc motors

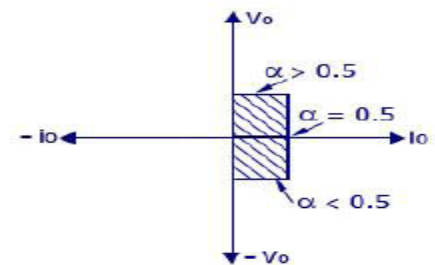
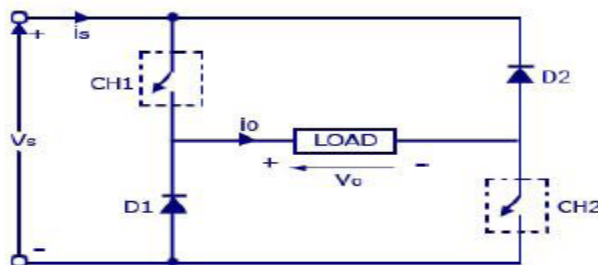
In short

This type of chopper is obtained by connecting type-A and type-B choppers in parallel as shown in Fig. 7.8 (a). The output voltage V_o is always positive because of the presence of freewheeling diode FD across the load. When chopper CH2 is on, or freewheeling diode FD conducts, output voltage $v_o = 0$ and in case chopper CH1 is on or diode D2 conducts, output voltage $v_o = V_s$. The load current i_o can, however, reverse its direction. Current i_o flows in the arrow direction marked in Fig. 7.8 (a), i.e. load current is positive when CH1 is on or FD conducts. Load current is negative if CH2 is on or D2 conducts. In other words, CH1 and FD operate together as type-A chopper in first quadrant. Likewise, CH2 and D2 operate together as type-B chopper in second quadrant.

Average load voltage is always positive but average load current may be positive or negative as explained above. Therefore, power flow may be from source to load (first-quadrant operation) or from load to source (second-quadrant operation). Choppers CH1 and CH2 should not be on simultaneously as this would lead to a direct short circuit on the supply lines. This type of chopper configuration is used for motoring and regenerative braking of dc motors. The operating region of this type of chopper is shown in Fig. 7.8 (b) by hatched area in first and second quadrants.

Two-quadrant Type-B or Type-D

Two Quadrant Type B-chopper or D-chopper Circuit

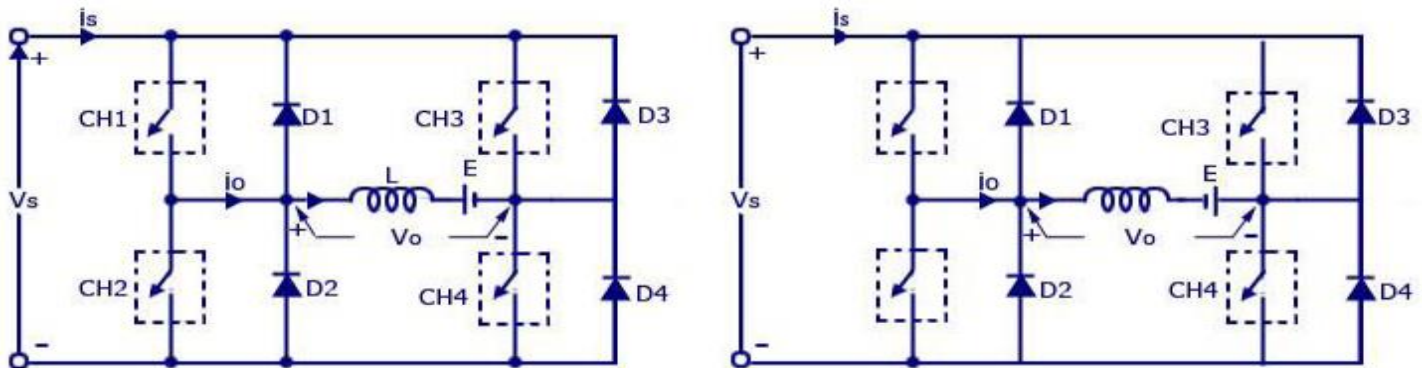


www.CircuitsToday.com

- $T_{on} > T_{off}$, $\alpha > 0.5$, V_o is +ve
- $T_{on} < T_{off}$, $\alpha < 0.5$, V_o is -ve
- $T_{on} = T_{off}$, $\alpha = 0$, $V_o = 0$
- The out put voltage $V_o = V_s$ when both CH1 and CH2 are on
- And $V_o = -V_s$, when both choppers are off but both diodes D1 and D2 conducts
- Average output voltage V_o is +ve when chopper turn on time is more than their turn off time
- The direction of load current is always +ve, because choppers and diodes can conduct current only in one direction
- As average values of both V_o and I_o are +ve, chopper operation in first quadrant is obtained

Four quadrant chopper, Type-E

E-type Chopper Circuit Diagram With Load emf E and E Reversed



- Consist of four semiconductor switches, CH1 to CH4 and four diodes from D1 to D4 in anti-parallel
- Numbering of chopper corresponds to their respective quadrant of operation

First quadrant:

- CH4 is kept on, CH3 is kept off and CH1 is operated
- With CH1 and CH4 on, load voltage $V_o = V_s$ and load current begins to flow
- V_o and I_o are +ve giving first quadrant operation
- CH1 is off, +ve current freewheels through CH4, D2

Second quadrant:

- CH2 is operated, CH1, CH3 and CH4 are kept off
- With CH2 on, reverse current flows through L, CH2, D4 and E
- Inductance L stores energy during the time CH2 on
- When CH2 is turned off, current is fed back to source through D1, D4
- V_o is +ve but I_o is -ve, second quadrant operation of chopper
- For second quadrant operation load must contain emf E



Third quadrant:

- CH1 is kept off, CH2 is kept on and CH3 is operated
- Polarity of load emf must be reversed for this quadrant of operation
- When CH3 is on, load gets connected to source V_s so that both V_o and I_o are $-ve$ leading to 3rd quadrant of operation
- When CH3 is turned off, $-ve$ current freewheels through CH2, D4

Fourth quadrant:

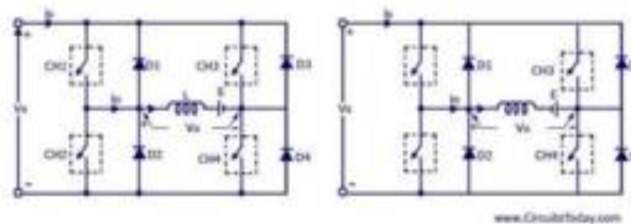
- CH4 is operated and other devices are kept off
- With CH4 on, $+ve$ current flows through CH4, D2, L and E

FOUR QUADRANT CHOPPER, TYPE-E

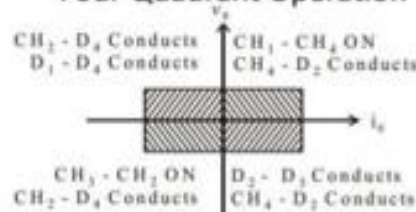
- Inductance L stores energy during the time CH4 is on
- When CH4 is turned off, current is fed back to source through diodes D2, D3
- Load voltage is $-ve$ but load current is $+ve$

Type-E chopper or the Fourth-Quadrant Chopper

E-type Chopper Circuit Diagram With Load emf E and E Reversed



Four Quadrant Operation



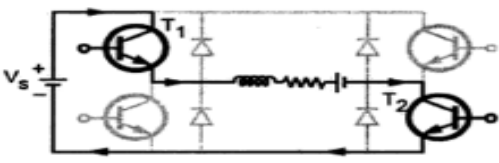
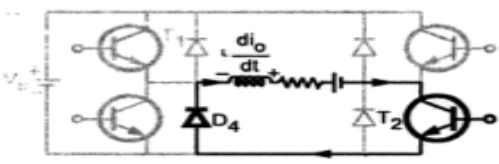
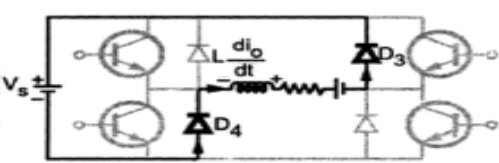
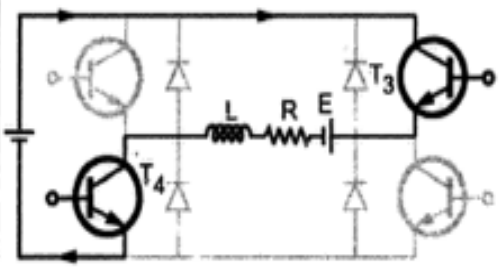
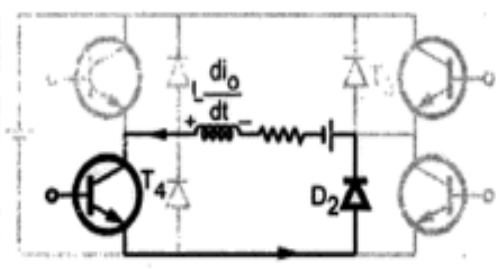
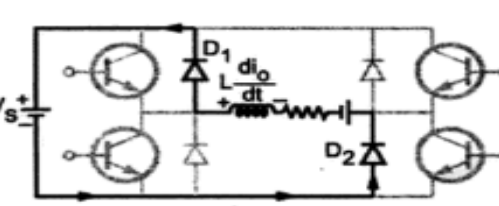
Equivalent circuit	Quadrant	Description
	I Forward motoring or rectifying.	T_1 and T_2 conducts load consumes the power from the source.
	I Forward motoring.	T_1 turned off but T_2 conducts. Hence current i_o flows through T_2 and D_4 . Load inductor induces voltage as shown freewheeling action takes place.
	IV Inverting operation i_o positive v_o negative.	T_2 is turned off. Hence inductance forces current through D_3 and D_4 . This current flows through supply. load energy is fed to the supply.
	III Rectifying operation motor rotates in opposite direction.	To reverse the direction of rotation of the motor, T_3 and T_4 are turned on. v_o and i_o both are negative. E is shown negative since motor rotates in opposite direction.
	III Freewheeling operation motor rotates in the same direction.	T_3 is turned off, but T_4 remains on. To maintain the current in the same direction inductance generates voltage and i_o flows in same direction through D_2 and T_4 . This is freewheeling action.
	II Inverting operation i_o negative v_o positive.	T_4 is turned off. Hence inductance forces current through D_1 and D_2 . This current flows through supply. load energy is fed to the supply.

Table 4.5.3 Operation of four quadrant chopper

Four quadrant chopper has the capability to operate in all the four quadrants. Hence it is used in reversible dc drives. The braking is regenerative. Hence four quadrant chopper drives are highly efficient. Their dynamic response is also fast.

Control strategies

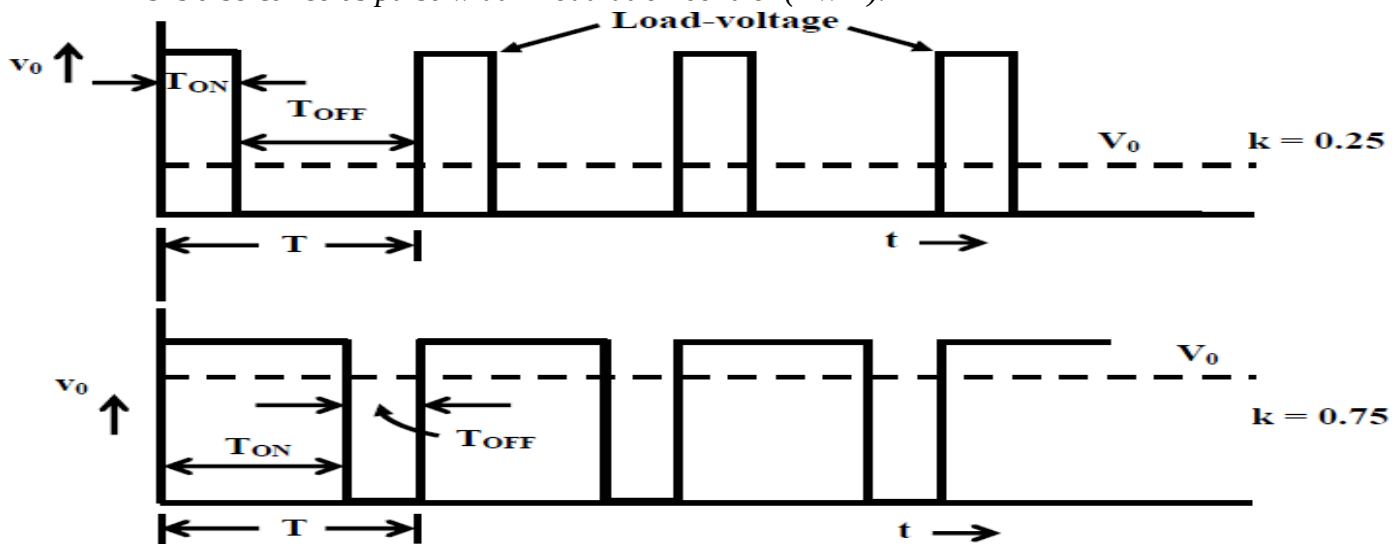
- The average value of the output voltage can be varied by opening and closing the semiconductor switch
- The two types of control strategies (schemes) are employed in all cases. These are:
 - (a) Time-ratio control, and
 - (b) Current limit control

Time-ratio Control

- In the time ratio control the value of the duty ratio, $T_{ON}/T=k$ is varied.
- There are two ways, which are constant frequency operation, and variable frequency operation.

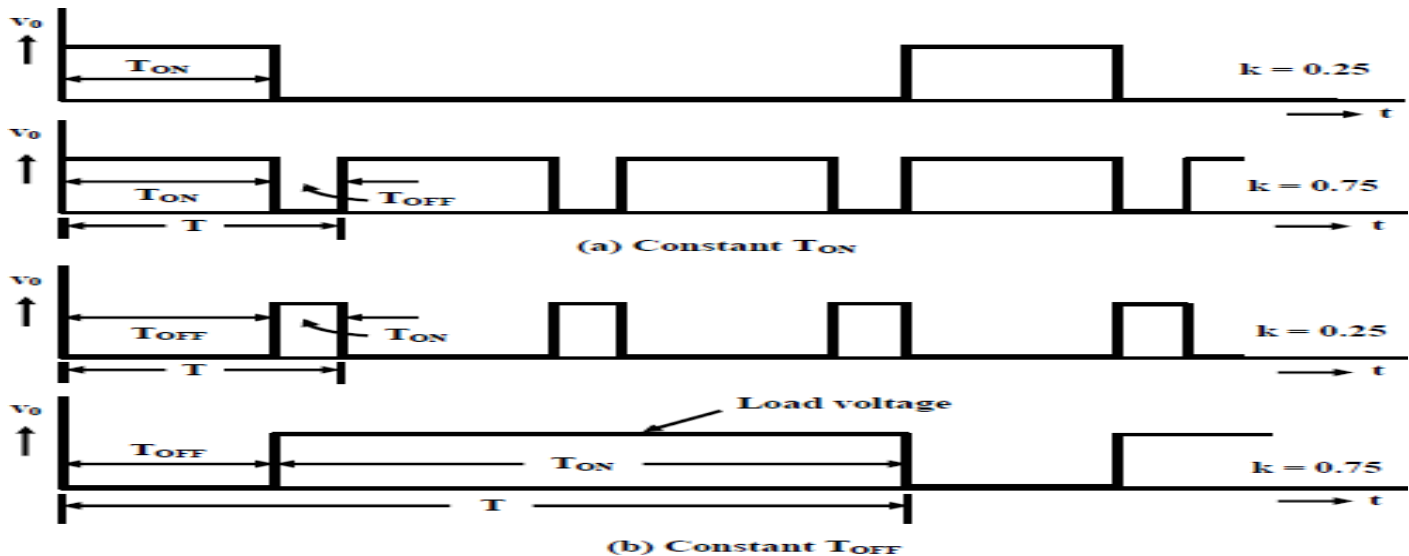
Constant Frequency Operation

- In this control strategy, the ON time, is varied, keeping the frequency ($f=1/T$), or time period T is constant.
- This is also called as *pulse width modulation control (PWM)*.



Variable Frequency Operation

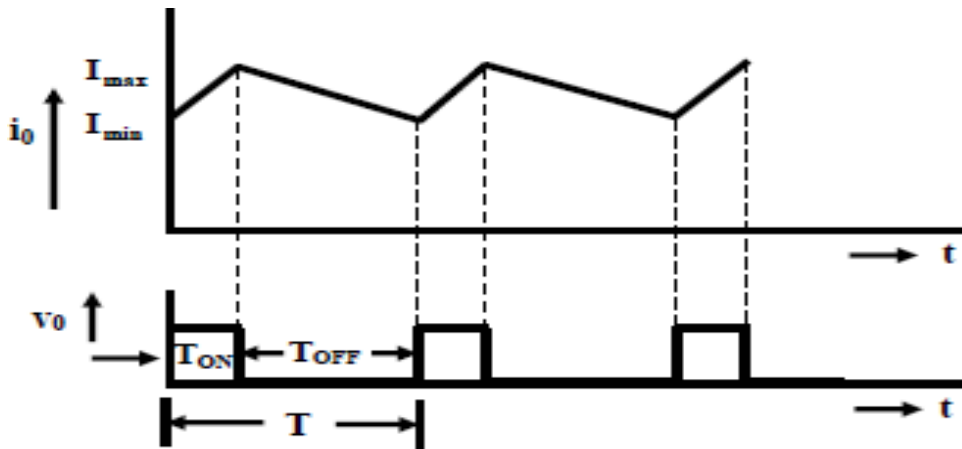
- In this control strategy, the frequency ($f=1/T$), or time period T is varied, keeping either
 - (a) the ON time, constant, or
 - (b) the OFF time, constant.
- This is also called as frequency modulation control.
- Two cases with (a) the ON time, constant, and (b) the OFF time, constant, with variable frequency or time period are shown in Fig.
- The output voltage can be varied in both cases, with the change in duty ratio, T_{on}/T



- There are major disadvantages in this control strategy. These are:
 - The frequency has to be varied over a wide range for the control of output voltage in frequency modulation. Filter design for such wide frequency variation is, therefore, quite difficult.
 - For the control of a duty ratio, frequency variation would be wide. As such, there is a possibility of interference with systems using certain frequencies, such as signaling and telephone line, in frequency modulation technique.
 - The large OFF time in frequency modulation technique, may make the load current discontinuous, which is undesirable.
 - Thus, the constant frequency system using PWM is the preferred scheme for dc-dc converters (choppers).

Current-limit control

- As can be observed from the current waveforms for the types of dc-dc converters described earlier, the current changes between the maximum and minimum values, if it (current) is continuous.
- In the current limit control strategy, the switch in dc-dc converter (chopper) is turned ON and OFF, so that the current is maintained between two (upper and lower) limits. When the current exceeds upper (maximum) limit, the switch is turned OFF.
- During OFF period, the current freewheels in say, buck converter (dc-dc) through the diode, DF, and decreases exponentially.
- When it reaches lower (minimum) limit, the switch is turned ON.
- This type of control is possible, either with constant frequency, or constant ON time.
- This is used only, when the load has energy storage elements, i.e. inductance, L .
- The reference values are load current or load voltage.
- In this case, the current is continuous, varying between I_{max} and I_{min} , which decides the frequency used for switching.
- The ripple in the load current can be reduced, if the difference between the upper and lower limits is reduced, thereby making it minimum.
- This in turn increases the frequency, thereby increasing the switching losses.



Switching regulators

- DC converters can be used as switching mode regulators to convert a dc voltage, normally unregulated to a regulated dc voltage
- The regulation is normally achieved by PWM at a fixed frequency and the switching device is normally BJT, MOSFET or IGBT
- The ripple content is normally reduced by an LC filter
- There are four basic topologies of switching regulators

Buck regulator

Boost regulator

Buck-boost regulator

Cuk regulator

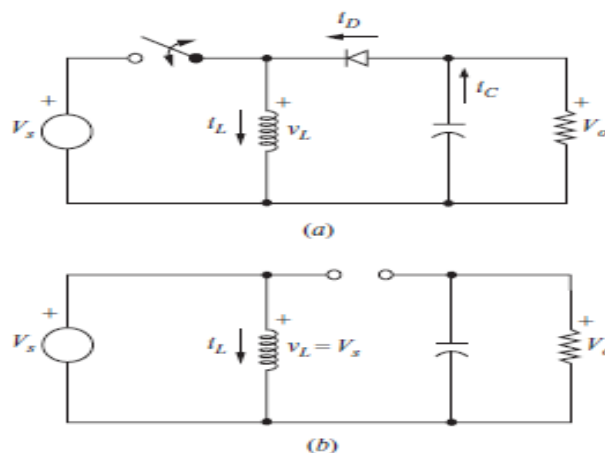
6.6 THE BUCK-BOOST CONVERTER

Another basic switched-mode converter is the buck-boost converter shown in Fig. 6-11. The output voltage of the buck-boost converter can be either higher or lower than the input voltage.

Voltage and Current Relationships

Assumptions made about the operation of the converter are as follows:

1. The circuit is operating in the steady state.
2. The inductor current is continuous.
3. The capacitor is large enough to assume a constant output voltage.
4. The switch is closed for time DT and open for $(1-D)T$.
5. The components are ideal.



Analysis for the Switch Closed When the switch is closed, the voltage across the inductor is

$$v_L = V_s = L \frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V_s}{L}$$

The rate of change of inductor current is a constant, indicating a linearly increasing inductor current. The preceding equation can be expressed as

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_s}{L}$$

Solving for Δi_L when the switch is closed gives

$$(\Delta i_L)_{\text{closed}} = \frac{V_s DT}{L} \quad (6-45)$$

Analysis for the Switch Open When the switch is open, the current in the inductor cannot change instantaneously, resulting in a forward-biased diode and current into the resistor and capacitor. In this condition, the voltage across the inductor is

$$v_L = V_o = L \frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V_o}{L}$$

Again, the rate of change of inductor current is constant, and the change in current is

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_o}{L}$$

Solving for Δi_L ,

$$(\Delta i_L)_{\text{open}} = \frac{V_o(1-D)T}{L} \quad (6-46)$$

Again, the rate of change of inductor current is constant, and the change in current is

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_o}{L}$$

Solving for Δi_L ,

$$(\Delta i_L)_{\text{open}} = \frac{V_o(1-D)T}{L} \quad (6-46)$$

For steady-state operation, the net change in inductor current must be zero over one period. Using Eqs. (6-45) and (6-46),

$$(\Delta i_L)_{\text{closed}} + (\Delta i_L)_{\text{open}} = 0$$

$$\frac{V_s DT}{L} + \frac{V_o(1-D)T}{L} = 0$$

Solving for V_o ,

$$\boxed{V_o = -V_s \left(\frac{D}{1-D} \right)} \quad (6-47)$$

INDUCTOR CURRENT , DESIGN OF FILTER INDUCTANCE OR CRITICAL INDUCTANCE

source voltage. Output voltage magnitude of the buck-boost converter can be less than that of the source or greater than the source, depending on the duty ratio of the switch. If $D > 0.5$, the output voltage is larger than the input; and if $D < 0.5$, the output is smaller than the input. Therefore, this circuit combines the capabilities of the buck and boost converters. Polarity reversal on the output may be a disadvantage in some applications, however. Voltage and current waveforms are shown in Fig. 6-12.

Note that the source is never connected directly to the load in the buck-boost converter. Energy is stored in the inductor when the switch is closed and transferred to the load when the switch is open. Hence, the buck-boost converter is also referred to as an *indirect* converter.

Power absorbed by the load must be the same as that supplied by the source, where

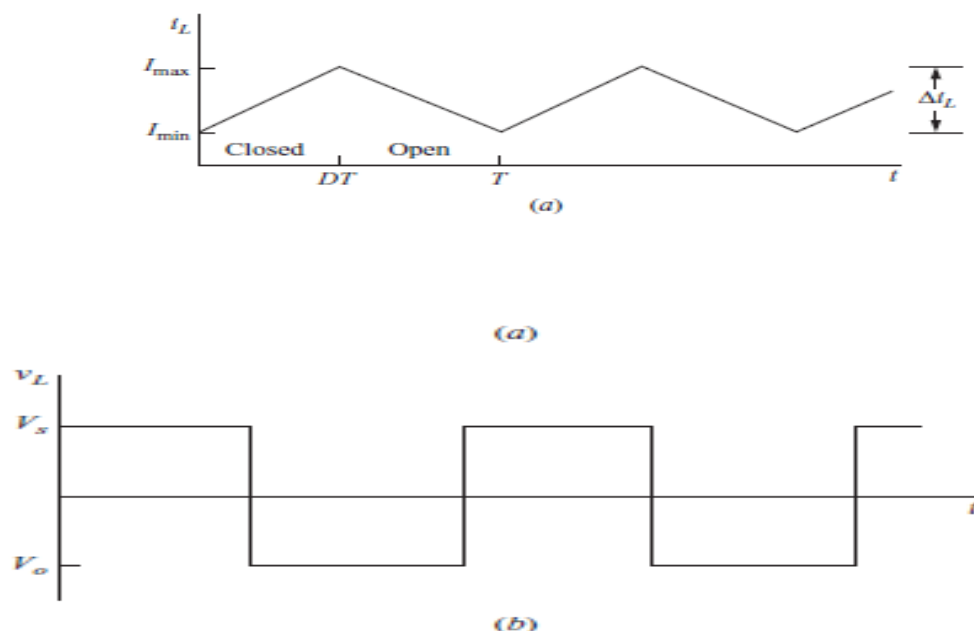


Figure 6-12 Buck-boost converter waveforms. (a) Inductor current; (b) Inductor voltage; (c) Diode current; (d) Capacitor current.

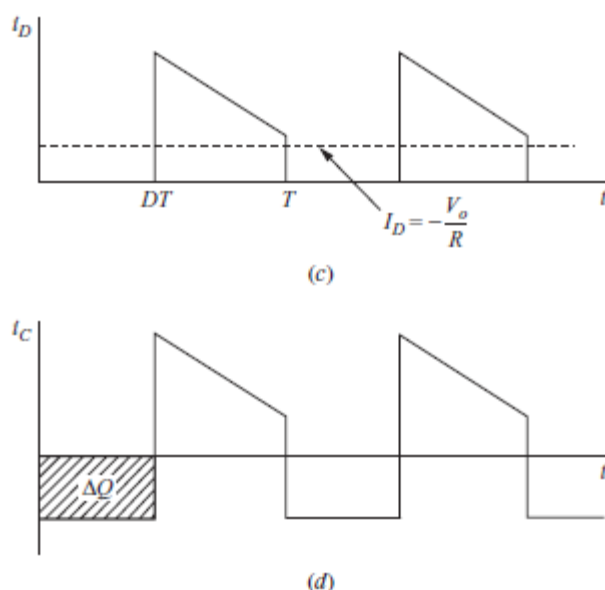


Figure 6-12 (continued)

Figure 6-12 (continued)

$$P_o = \frac{V_o^2}{R}$$
$$P_s = V_s I_s$$
$$\frac{V_o^2}{R} = V_s I_s$$

Average source current is related to average inductor current by

$$I_s = I_L D$$

resulting in

$$\frac{V_o^2}{R} = V_s I_L D$$

Substituting for V_o using Eq. (6-47) and solving for I_L , we find

$$I_L = \frac{V_o^2}{V_s R D} = \frac{P_o}{V_s D} = \frac{V_s D}{R(1-D)^2} \quad (6-49)$$

Maximum and minimum inductor currents are determined using Eqs. (6-45) and (6-49).

$$I_{\max} = I_L + \frac{\Delta i_L}{2} = \frac{V_s D}{R(1-D)^2} + \frac{V_s D T}{2L} \quad (6-50)$$

$$I_{\min} = I_L - \frac{\Delta i_L}{2} = \frac{V_s D}{R(1-D)^2} - \frac{V_s D T}{2L} \quad (6-51)$$

$$(Lf)_{\min} = \frac{(1-D)^2 R}{2} \quad (6-52)$$

or

$$L_{\min} = \frac{(1-D)^2 R}{2f} \quad (6-53)$$

where f is the switching frequency.

Output Voltage Ripple

The output voltage ripple for the buck-boost converter is computed from capacitor current waveform of Fig. 6-12d.

$$|\Delta Q| = \left(\frac{V_o}{R} \right) DT = C \Delta V_o$$

Solving for ΔV_o ,

$$\Delta V_o = \frac{V_o D T}{RC} = \frac{V_o D}{RCf}$$

or

$$\frac{\Delta V_o}{V_o} = \frac{D}{RCf} \quad (6-54)$$

Refer your class notes for buck and boost regulator derivation