ATME COLLEGE OF ENGINEERING

13th KM Stone, Bannur Road, Mysore - 570 028

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

NOTES

Course: Power Electronics

Course Code:BEE503

SEMESTER: V

AY 2024-25

INSTITUTIONAL VISION AND MISSION

VISION:

- Development of academically excellent, culturally vibrant, socially responsible and globally competent human resources.

MISSION:

- To keep pace with advancements in knowledge and make the students competitive and capable at the global level.
- To create an environment for the students to acquire the right physical, intellectual, emotional and moral foundations and shine as torchbearers of tomorrow's society.
- To strive to attain ever-higher benchmarks of educational excellence.

Department Vision and Mission

Vision:

To produce Electrical & Electronics Engineers through greatest quality of technical education, technical skill training and intellectual capacity building of individuals.

Mission:

- To provide knowledge to students that builds a strong foundation in the basic principles of electrical engineering, problem solving abilities, analytical skills, soft skills and communication skills for their overall development.
- To offer outcome based technical education.
- To encourage faculty in training & development and to offer consultancy through research & industry interaction.

Program Educational Objectives (PEOs)

PEO1:

To produce competent and ethical Electrical & Electronics Engineers who will exhibit the necessary technical and managerial skills to perform their duties in society.

PEO2:

To make graduates continuously acquire and enhance their technical and socio-economic skills.

PEO3:

To aspire graduates on Research and Consultancy activities leading to offering solutions and excel in various career paths.

PEO4:

To produce quality engineers who have the capability to work in teams and contribute to real time projects.

Program Outcomes (POs)

Engineering Graduates will be able to:

PO1: Engineering Knowledge: Apply the knowledge of mathematics, science, engineering fundamentals and an engineering specialization to the solution of complex engineering problems.

PO2: 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.

PO3: 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.

PO4: 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.

PO5: 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.

PO6: 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.

PO7: 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.

PO8: Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO9: Individual and team work: Function effectively as an individual and as a member or leader in diverse teams, and in multidisciplinary settings.

PO10: 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.

PO11: Project management and finance: Demonstrate knowledge and understanding of the engineering 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.

PO12: Life-long learning: Recognize the need for and have the preparation and ability to engage in independent and lifelong learning in the broadest context of technological change.

Program Specific Outcomes (PSOs)

The students will develop an ability to produce the following engineering traits:

PSO1: Apply the concepts of Electrical & Electronics Engineering to evaluate the performance of Power systems and also to control industrial drives using power electronics.

PSO2: Demonstrate the concepts of process control for Industrial Automation, design models for environmental and social concerns and also exhibit continuous self- learning.

Module -01: Introduction , Power Diodes, Power Rectifiers.

Structure

1.0 Introduction
1.1 Objectives
1.2 Power Electronics Applications
1.3 Power Semiconductor devices
1.4 Control Characteristics Of power Devices
1.5 Types Of Power Converters
1.6 Periphral Effects
1.7 Power Diodes
1.8 Reverse recovery characteristics
1.9 Rectifiers
1.10 Assignment Questions
1.11 Outcomes
1.12 Further Readings

1.0 INTRODUCTION TO POWER ELECTRONICS

Power Electronics is a field which combines Power (electric power), Electronics and Control systems.

Power engineering deals with the static and rotating power equipment for the generation, transmission and distribution of electric power.

Electronics deals with the study of solid state semiconductor power devices and circuits for Power conversion to meet the desired control objectives (to control the output voltage and output power).

Power electronics may be defined as the subject of applications of solid state power semiconductor devices (Thyristors) for the control and conversion of electric power.

1.1 Objectives:

- To give an overview of applications power electronics, different types of power semiconductor devices, their switching characteristics.
- To explain power diode characteristics, types, their operation and the effects of power diodes on RL circuits.
- To explain the techniques for design and analysis of single phase diode rectifier circuits.

1.2 Power Electronic Applications

1. COMMERCIAL APPLICATIONS

Heating Systems Ventilating, Air Conditioners, Central Refrigeration, Lighting, Computers and Office equipments, Uninterruptible Power Supplies (UPS), Elevators, and

2. AEROSPACE APPLICATIONS

Space shuttle power supply systems, satellite power systems, aircraft power systems.

3. TELECOMMUNICATIONS

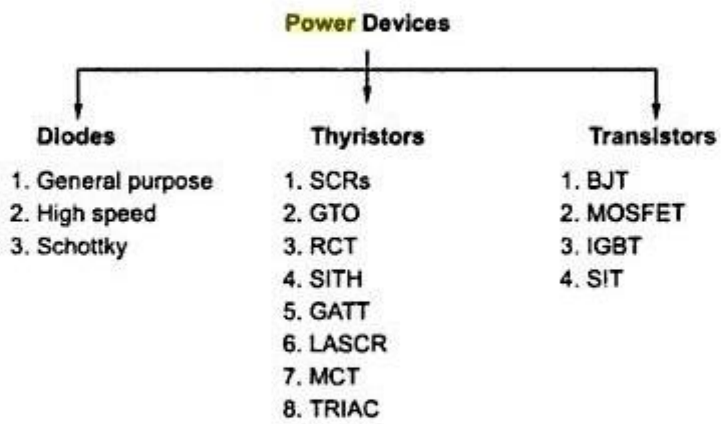
Battery chargers, power supplies (DC and UPS), mobile cell phone battery chargers.

4. TRANSPORTATION

Traction control of electric vehicles, battery chargers for electric vehicles, electric locomotives, street cars, trolley buses, automobile electronics including engine controls.

1.3 POWER SEMICONDUCTOR DEVICES

The power semiconductor devices are used as on/off switches in power control circuit. These devices are classified as follows.



A. POWER DIODES

Power diodes are made of silicon p-n junction with two terminals, anode and cathode. Diode is forward biased when anode is made positive with respect to the cathode. Diode conducts fully when the diode voltage is more than the cut-in voltage (0.7 V for Si). Conducting diode will have a small voltage drop across it.

Diode is reverse biased when cathode is made positive with respect to anode. When reverse biased, a small reverse current known as leakage current flows. This leakage current increases with increase in magnitude of reverse voltage until avalanche voltage is reached (breakdown voltage).

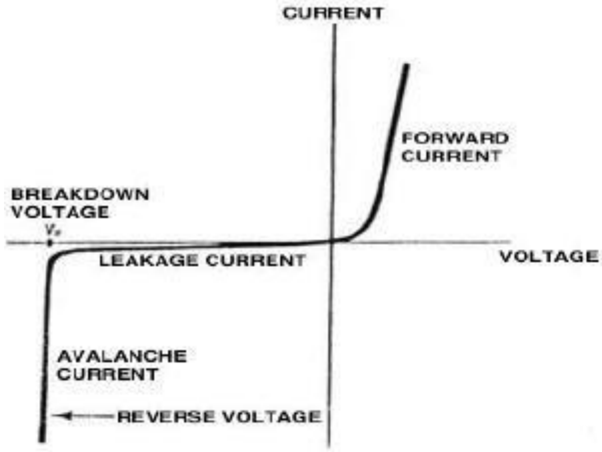


Fig.1.1 V-I Characteristics of diode.

POWER DIODES TYPES

Power diodes can be classified as

1. General purpose diodes.
2. High speed (fast recovery) diodes.
3. Schottky diode.

General Purpose Diodes

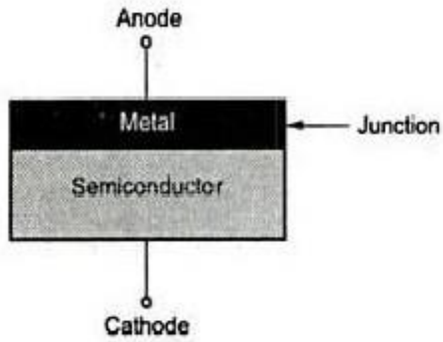
The diodes have high reverse recovery time of about 25 microsecs (μsec). They are used in low speed (frequency) applications. e.g., line commutated converters, diode rectifiers and converters for a low input frequency upto 1 KHz. Diode ratings cover a very wide range with current ratings less than 1 A to several thousand amps (2000 A) and with voltage ratings from 50 V to 5 KV. These diodes are generally manufactured by diffusion process. Alloyed type rectifier diodes are used in welding power supplies. They are most cost effective and rugged and their ratings can go upto 300A and 1KV.

Fast Recovery Diodes

The diodes have low recovery time, generally less than 5 μs. The major field of applications is in electrical power conversion i.e., in free-wheeling ac-dc and dc-ac converter circuits. Their current ratings is from less than 1 A to hundreds of amperes with voltage ratings from 50 V to about 3 KV. Use of fast recovery diodes are preferable for free-wheeling in SCR circuits because of low recovery loss, lower junction temperature and reduced di/dt. For high voltage ratings greater than 400 V they are manufactured by diffusion process and the recovery time is controlled by platinum or gold diffusion. For less than 400 V rating epitaxial diodes provide faster switching speeds than diffused diodes. Epitaxial diodes have a very narrow base width resulting in a fast recovery time of about 50 ns.

Schottky Diodes

A Schottky diode has metal (aluminium) and semi-conductor junction. A layer of metal is deposited on a thin epitaxial layer of the n-type silicon. In Schottky diode there is a larger barrier for electron flow from metal to semi-conductor. Figure shows the schotty diode.



When Schottky diode is forward biased free electrons on n-side gain enough energy to flow into the metal causing forward current. Since the metal does not have any holes there is no charge storage, decreasing the recovery time. Therefore a Schottky diode can switch-off faster than an ordinary p-n junction diode. A Schottky diode has a relatively low forward voltage drop and reverse recovery losses. The leakage current is higher than a p-n junction diode. The maximum allowable voltage is about 100 V. Current ratings vary from about 1 to 300 A. They are mostly used in low voltage and high current dc power supplies. The operating frequency may be as high 100-300 kHz as the device is suitable for high frequency application.

Comparison Between Different Types Of Diodes

General Purpose Diodes	**Fast Recovery Diodes**	**Schottky Diodes**
Upto 5000V & 3500A	Upto 3000V and 1000A	Upto 100V and 300A
Reverse recovery time – High	Reverse recovery time – Low	Reverse recovery time – Extremely low.
Turn off time - High	Turn off time - Low	Turn off time – Extremely Low
Switching frequency – Low	Switching frequency – High	Switching frequency – Very high.
V_F = 0.7V to 1.2V	V_F = 0.8V to 1.5V	$V_F \approx$0.4V to 0.6V

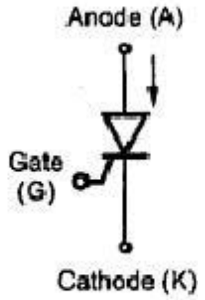
B. Thyristors

Silicon Controlled Rectifiers (SCR):

The SCR has 3- terminals namely:

Anode (A), Cathode (k) and Gate(G).

Internally it is having 4-layers p-n-p-n as shown in figure (b).



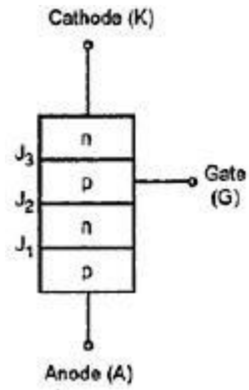


Fig.1.2 (a). Symbol Fig.1.2 (b). Structure of SCR

The word thyristor is coined from thyratron and transistor. It was invented in the year 1957 at Bell Labs.

The Thyristors can be subdivided into different types

- Forced-commutated Thyristors (Inverter grade Thyristors)
- Line-commutated Thyristors (converter-grade Thyristors)
- Gate-turn off Thyristors (GTO).
- Reverse conducting Thyristors (RCT's).
- Static Induction Thyristors (SITH).
- Gate assisted turn-off Thyristors (GATT).
- Light activated silicon controlled rectifier (LASCR) or Photo SCR's.
- MOS-Controlled Thyristors (MCT's).

C. POWER TRANSISTORS

Transistors which have high voltage and high current rating are called power transistors. Power transistors used as switching elements, are operated in saturation region resulting in a low - on state voltage drop. Switching speed of transistors is much higher than the thyristors. And they are extensively used in dc-dc and dc-ac converters with inverse parallel connected diodes to provide bi-directional current flow. However, voltage and current ratings of power transistor are much lower than the thyristors. Transistors are used in low to medium power applications. Transistors are current controlled device and to keep it in the conducting state, a continuous base current is required.

Power transistors are classified as follows

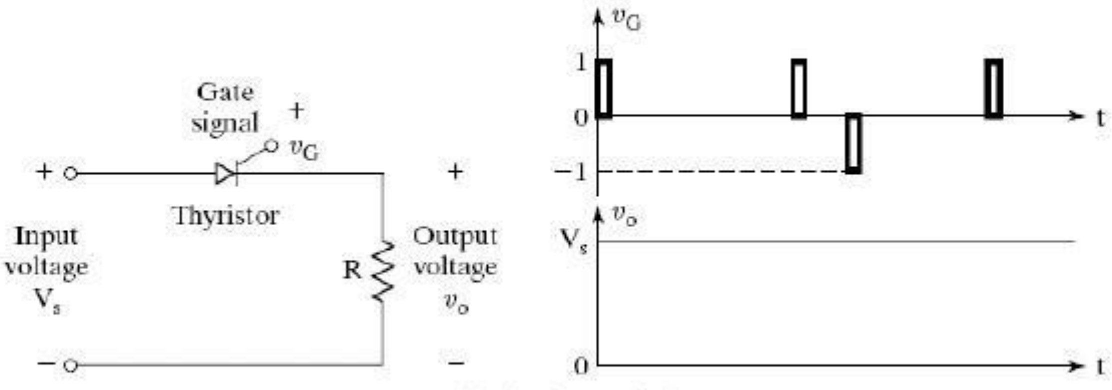
- Bi-Polar Junction Transistors (BJTs)
- Metal-Oxide Semi-Conductor Field Effect Transistors (MOSFETs)
- Insulated Gate Bi-Polar Transistors (IGBTs)

- Static Induction Transistors (SITs)

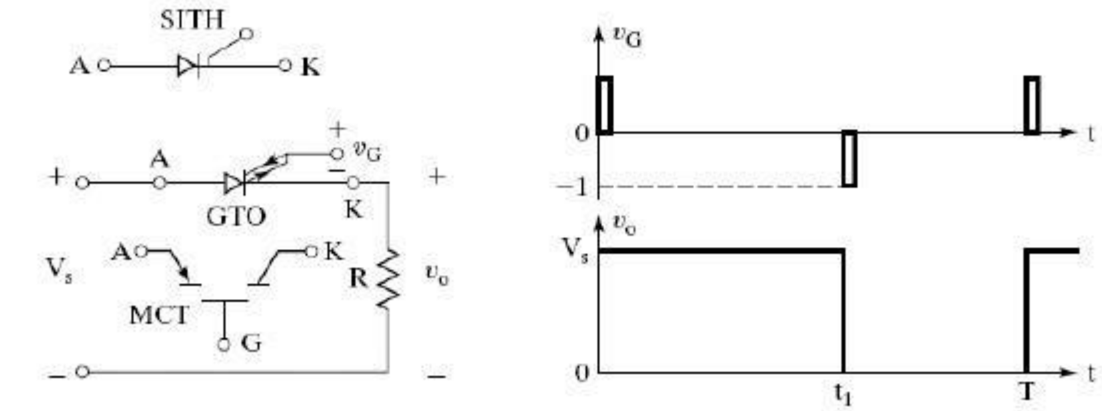
1.4 CONTROL CHARACTERISTICS OF POWER DEVICES

The power semiconductor devices are used as switches. Depending on power requirements, ratings, fastness & control circuits for different devices can be selected. The required output is obtained by varying conduction time of these switching devices.

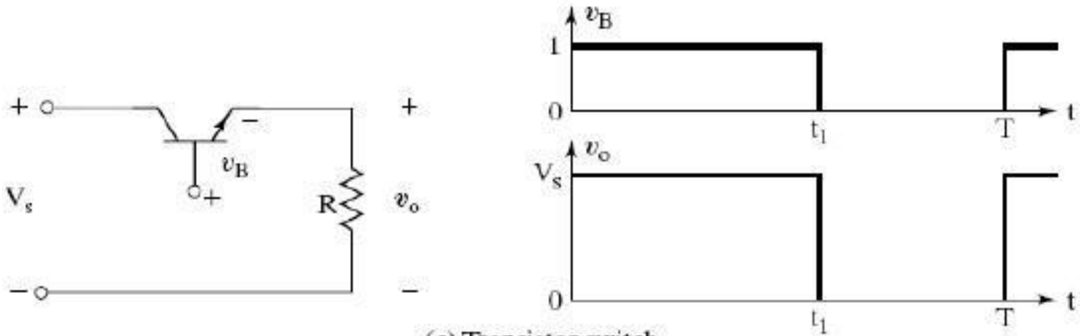
Control characteristics of Thyristors:



(a) Thyristor switch



(b) GTO/MTO/ETO/IGCT/MCT/SITH switch (For MCT, the polarity of V_G is reversed as shown)



(c) Transistor switch

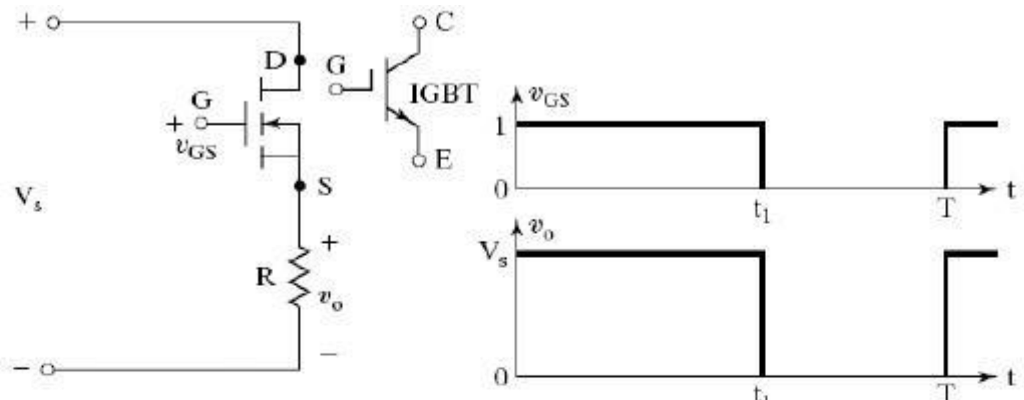


Fig1.3: Control Characteristics of Power Switching Devices

Classification of power semiconductor devices:

- Uncontrolled turn on and turn off (e.g.: diode).
- Controlled turn on and uncontrolled turn off (e.g. SCR)
- Controlled turn on and off characteristics (e.g. BJT, MOSFET, GTO, SITH, IGBT, SIT, MCT).
- Continuous gate signal requirement (e.g. BJT, MOSFET, IGBT, SIT).
- Pulse gate requirement (e.g. SCR, GTO, MCT).
- Bipolar voltage withstanding capability (e.g. SCR, GTO).
- Unipolar voltage withstanding capability (e.g. BJT, MOSFET, GTO, IGBT, MCT).
- Bidirectional current capability (e.g.: Triac, RCT).
- Unidirectional current capability (e.g. SCR, GTO, BJT, MOSFET, MCT, IGBT, SITH, SIT & Diode).

1.5 Types of Power Converters or Types of Power Electronic Circuits

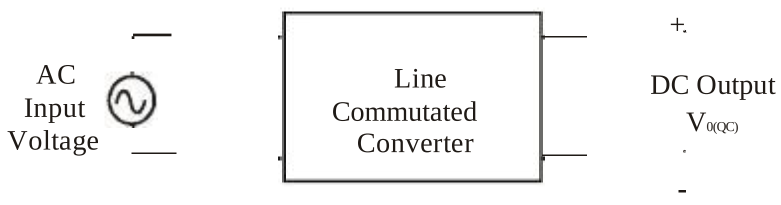
For the control of electric power supplied to the load or the equipment/machinery or for power conditioning the conversion of electric power from one form to other is necessary and the switching characteristic of power semiconductor devices (Thyristors) facilitate these conversions.

The thyristorised power converters are referred to as the static power converters and they perform the function of power conversion by converting the available input power supply in to output power of desired form.

The different types of thyristor power converters are

- Diode rectifiers (uncontrolled rectifiers).
- Line commutated converters or AC to DC converters (controlled rectifiers)
- AC voltage (RMS voltage) controllers (AC to AC converters).
- Cyclo converters (AC to AC converters at low output frequency).
- DC choppers (DC to DC converters).
- Inverters (DC to AC converters).

1. AC TO DC Converters (Rectifiers)



These are AC to DC converters. The line commutated converters are AC to DC power converters. These are also referred to as controlled rectifiers. The line commutated converters (controlled rectifiers) are used to convert a fixed voltage, fixed frequency AC power supply to obtain a variable DC output voltage. They use natural or AC line commutation of the Thyristors.

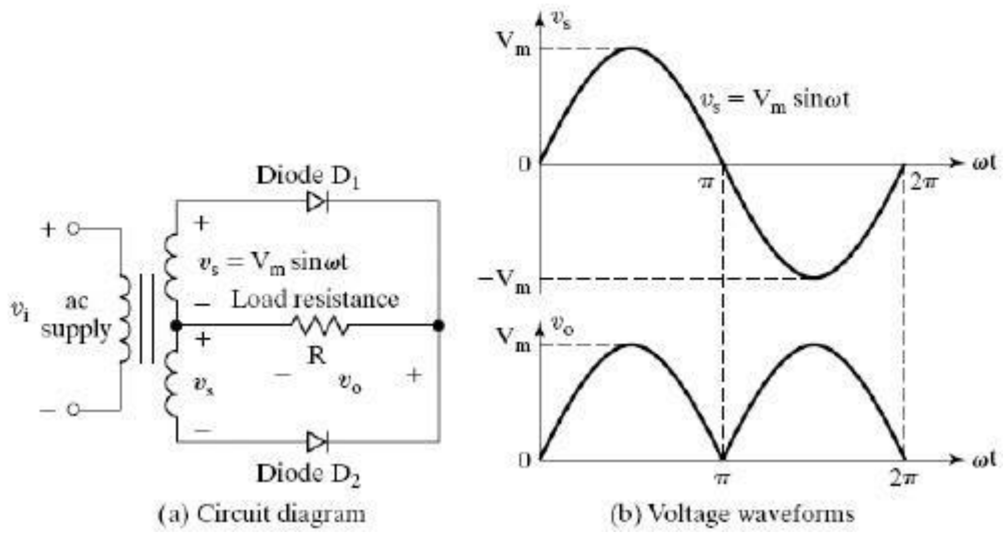


Fig1.4: A Single Phase Full Wave Uncontrolled Rectifier Circuit (Diode Full Wave Rectifier) using a Center Tapped Transformer

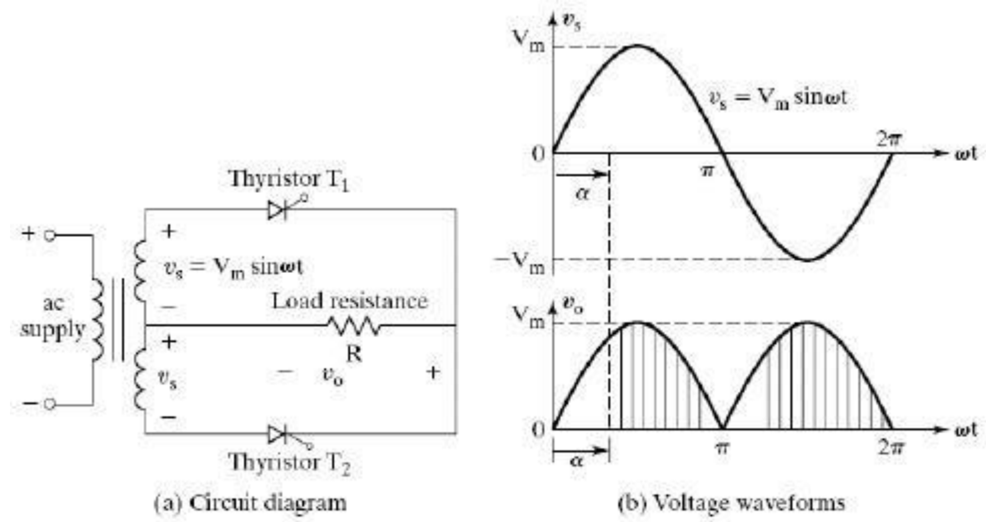


Fig: 1.5 A Single Phase Full Wave Controlled Rectifier Circuit (using SCRs) using a Center Tapped Transformer

Different types of line commutated AC to DC converters circuits are

- Diode rectifiers – Uncontrolled Rectifiers
- Controlled rectifiers using SCR's.
  - Single phase controlled rectifier.
  - Three phase controlled rectifiers.

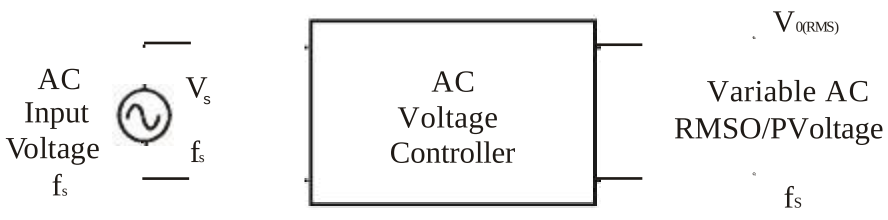
Applications of Ac To Dc Converters

AC to DC power converters are widely used in

- Speed control of DC motor in DC drives.

- UPS.
- HVDC transmission.
- Battery Chargers.

2. a. AC TO AC Converters or AC regulators.



The AC voltage controllers convert the constant frequency, fixed voltage AC supply into variable AC voltage at the same frequency using line commutation.

AC regulators (RMS voltage controllers) are mainly used for

- Speed control of AC motor.
- Speed control of fans (domestic and industrial fans).
- AC pumps.

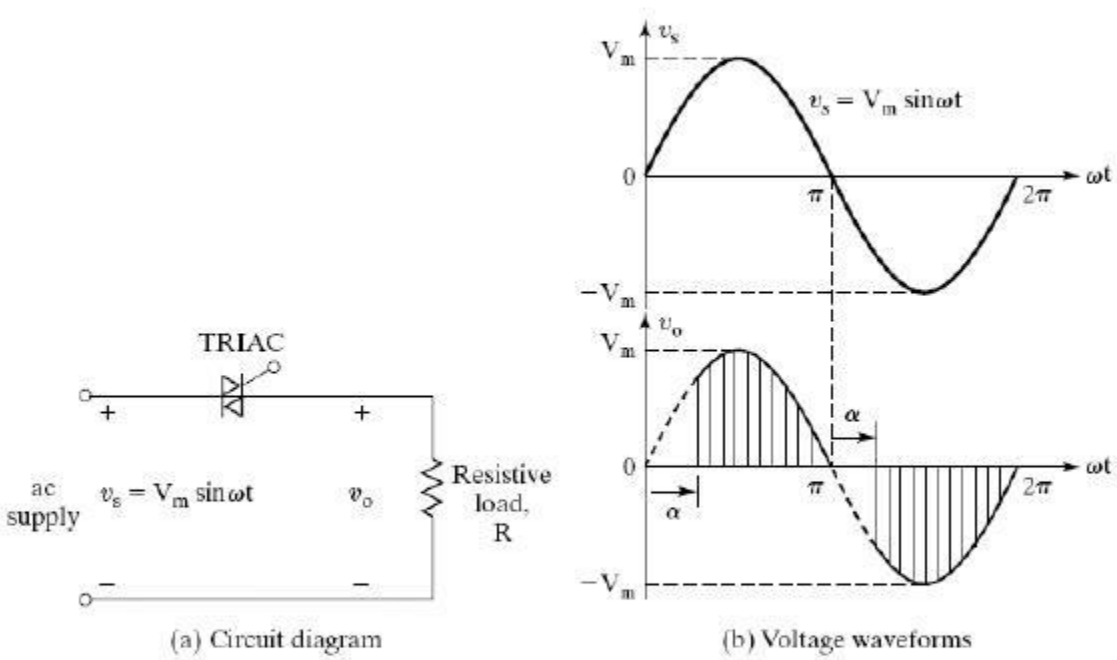
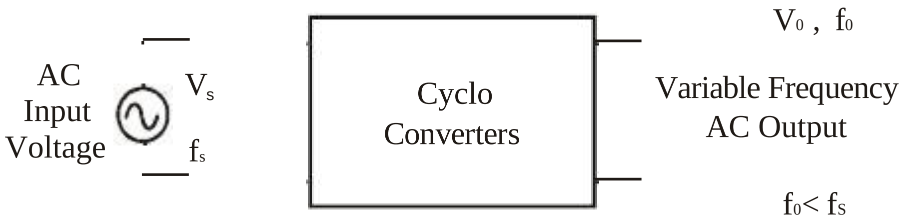


Fig.1.6: A Single Phase AC voltage Controller Circuit (AC-AC Converter using a TRIAC)

2. b. AC TO AC Converters with Low Output Frequency or CYCLO CONVERTERS

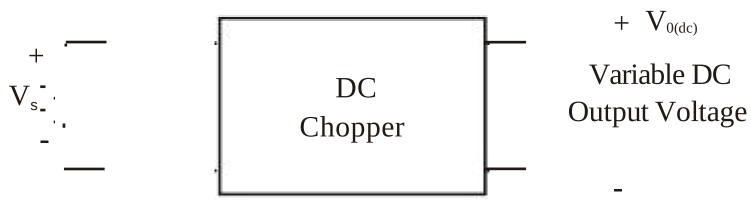


The cyclo converters convert power from a fixed voltage fixed frequency AC supply to a variable frequency and variable AC voltage at the output.

The cyclo converters generally produce output AC voltage at a lower output frequency. That is output frequency of the AC output is less than input AC supply frequency.

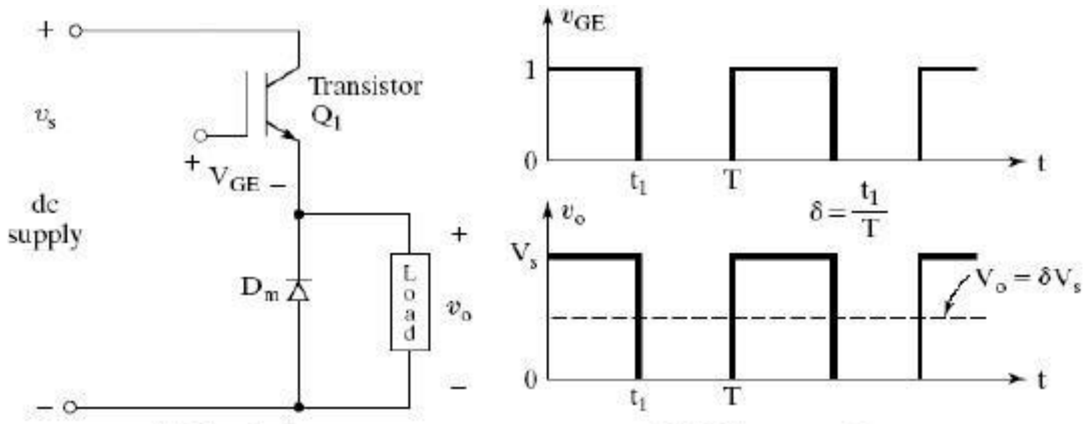
Applications of cyclo converters are traction vehicles and gearless rotary kilns.

3. CHOPPERS or DC TO DC Converters



The choppers are power circuits which obtain power from a fixed voltage DC supply and convert it into a variable DC voltage. They are also called as DC choppers or DC to DC converters. Choppers employ forced commutation to turn off the Thyristors. DC choppers are further classified into several types depending on the direction of power flow and the type of commutation. DC choppers are widely used in

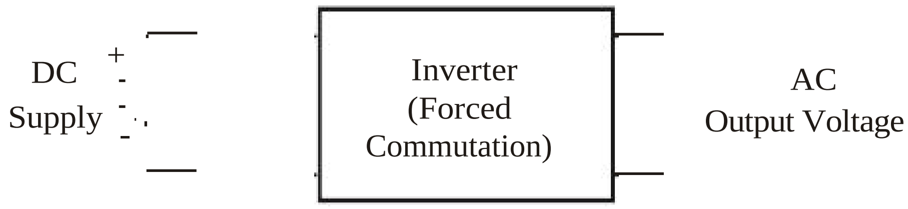
- Speed control of DC motors from a DC supply.
- DC drives for sub-urban traction.
- Switching power supplies.



(a) Circuit diagram (b) Voltage waveforms

Fig.1.7: A DC Chopper Circuit (DC-DC Converter) using IGBT

4. INVERTERS or DC TO AC Converters



The inverters are used for converting DC power from a fixed voltage DC supply into an AC output voltage of variable frequency and fixed or variable output AC voltage. The inverters also employ force commutation method to turn off the Thyristors.

Applications of inverters are in

- Industrial AC drives using induction and synchronous motors.
- Uninterrupted power supplies (UPS system) used for computers, computer labs.

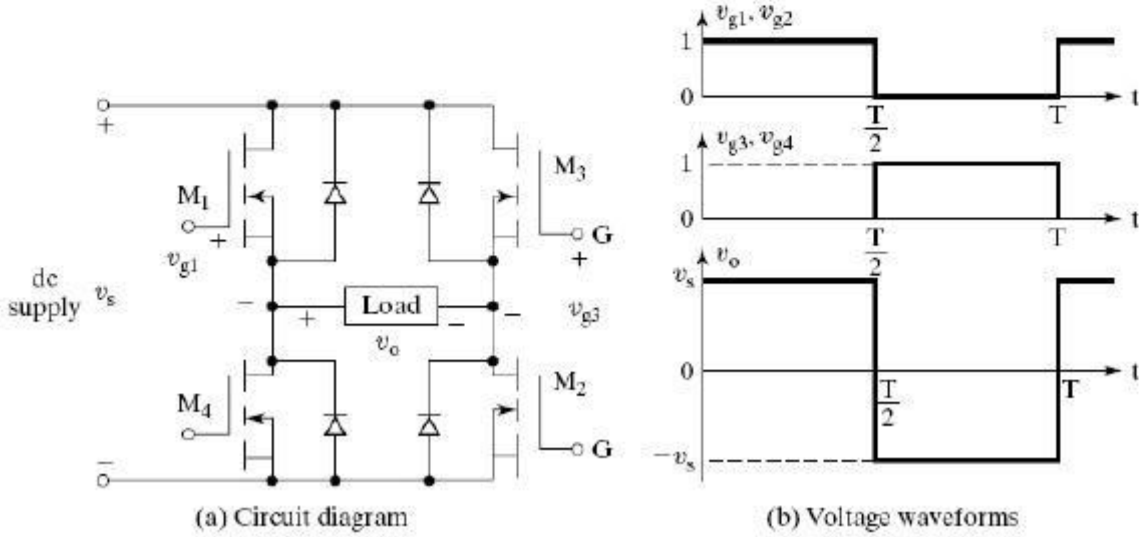


Fig.1.8: Single Phase DC-AC Converter (Inverter) using MOSFETS

1.6 Peripheral Effects

The power converter operations are based mainly on the switching of power semiconductor devices and as a result the power converters introduce current and voltage harmonics (unwanted AC signal components) into the supply system and on the output of the converters.

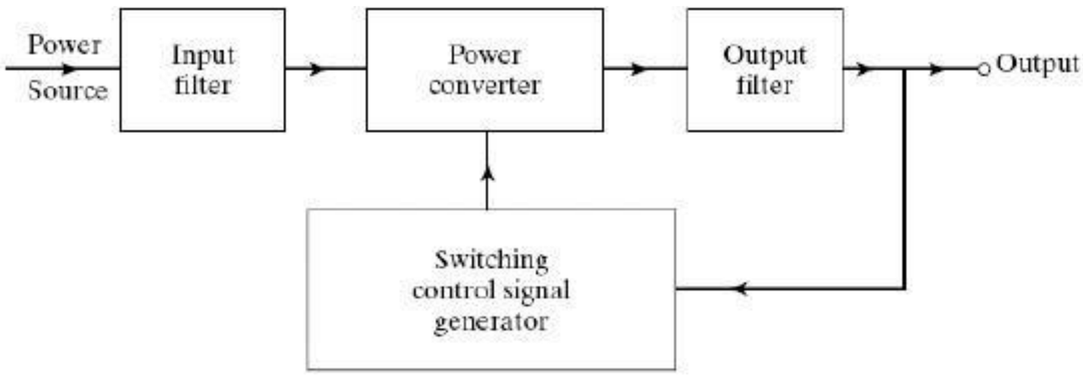


Fig.1.9: A General Power Converter System

These induced harmonics can cause problems of distortion of the output voltage, harmonic generation into the supply system, and interference with the communication and signaling circuits. It is normally necessary to introduce filters on the input side and output side of a power converter system so as to reduce the harmonic level to an acceptable magnitude. The figure below shows the block diagram of a generalized power converter with filters added. The application of power electronics to supply the sensitive electronic loads poses a challenge on the power quality issues and raises the problems and concerns to be resolved by the researchers. The input and output quantities of power converters could be either AC or DC. Factors such as total harmonic distortion (THD), displacement factor or harmonic factor

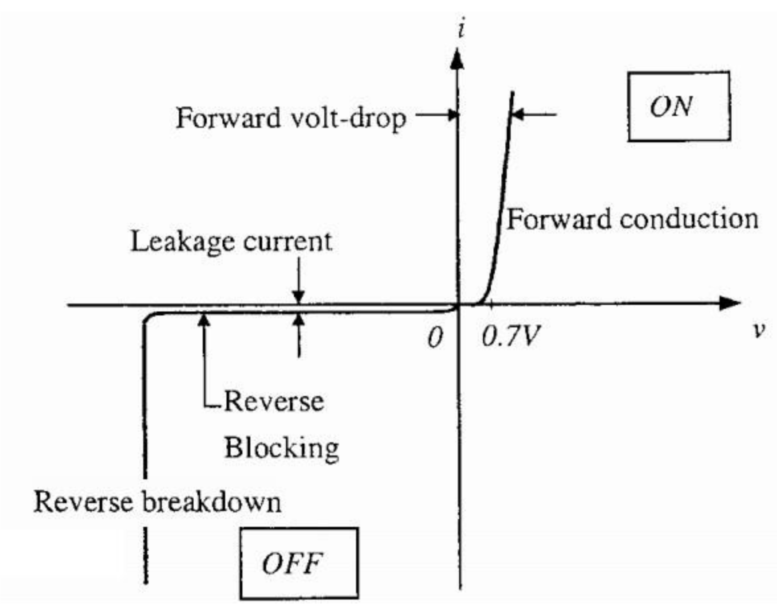
(HF), and input power factor (IPF), are measures of the quality of the waveforms. To determine these factors it is required to find the harmonic content of the waveforms. To evaluate the performance of a converter, the input and output voltages/currents of a converter are expressed in Fourier series. The quality of a power converter is judged by the quality of its voltage and current waveforms.

The control strategy for the power converters plays an important part on the harmonic generation and the output waveform distortion and can be aimed to minimize or reduce these problems. The power converters can cause radio frequency interference due to electromagnetic radiation and the gating circuits may generate erroneous signals. This interference can be avoided by proper grounding and shielding.

1.7 POWER DIODES

Introduction : Power diodes are made of silicon p-n junction with two terminals, anode and cathode. Diode is forward biased when anode is made positive with respect to the cathode. Diode conducts fully when the diode voltage is more than the cut-in voltage (0.7 V for Si). Conducting diode will have a small voltage drop across it. Diode is reverse biased when cathode is made positive with respect to anode. When reverse biased, a small reverse current known as leakage current flows. This leakage current increases with increase in magnitude of reverse voltage until avalanche voltage is reached (breakdown voltage).

Fig shows V-I Characteristics of diode.



Forward Voltage Drop:

- Is the forward-conducting junction level
- The forward voltage drop is due to the forward resistance of the junction.
- forward volt drop is across the junction
-

Reverse Leakage Current:

Thermal agitation does break some of the bonds in the crystal, resulting in minority carriers, Which permit a small reverse current flow, i.e. leakage current.

1.8 Reverse Recovery Characteristics

When a diode is in forward conduction mode, a sudden reversal of the polarity of the applied voltage would not stop the diode current at once. But the diode continues to conduct in the opposite direction due to minority carriers that remain stored in pn-junction and the bulk semiconductor material. Fig.2 shows the effect of minority carriers on the turn off characteristics of the power diode.

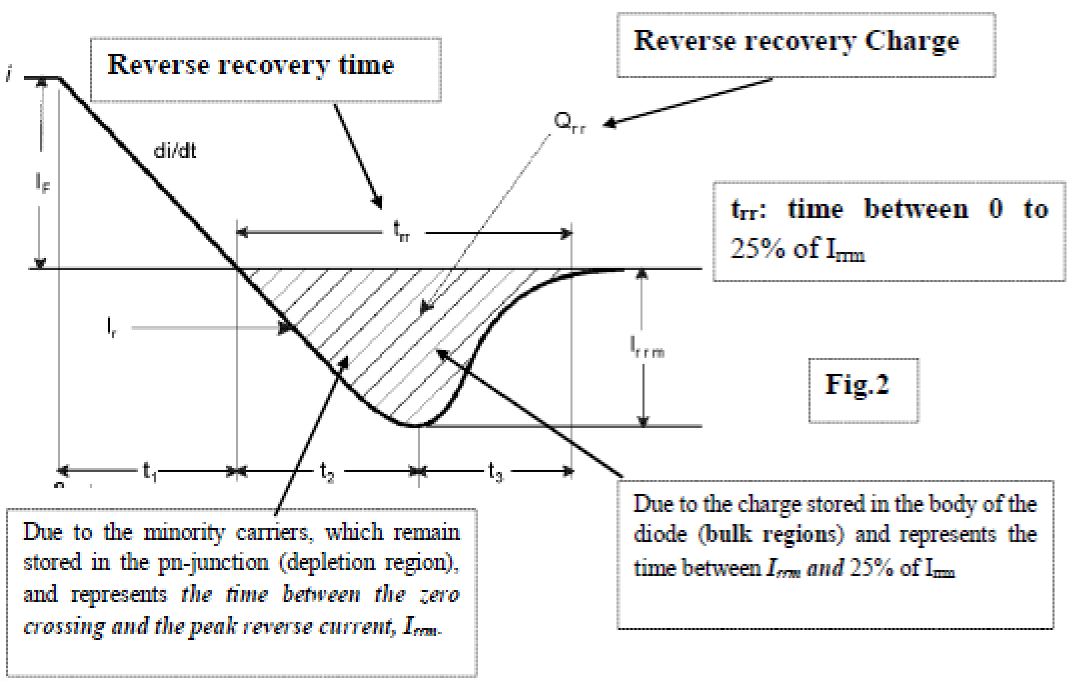


Fig.2

The charge carriers (holes & electrons) require a certain time to recombine with opposite n charges and to be neutralized; this time is called the **reverse recovery time trr o**f the diode. From Fig.2, one can found the following relationships:

$t_{rr} = t_2 + t_3 \quad I_{rr} = t_2 \frac{di}{dt}$ then $Q_{rr} = \frac{1}{2} I_{rrm} t_2 + \frac{1}{2} I_{rrm} t_3 = \frac{1}{2} I_{rrm} t_{rr}$

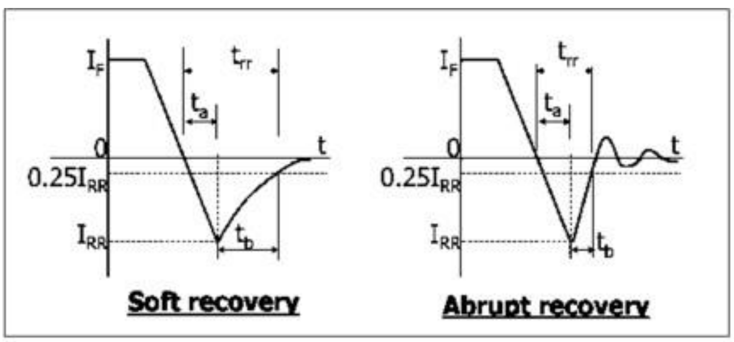
$$I_{rrm} \cong \frac{2Q_{rr}}{t_{rr}} = t_2 \frac{di}{dt}$$

For Fast recovery :

$$t_3 \ll t_2 \rightarrow t_2 = t_{rr} \rightarrow t_{rr} = \sqrt{\frac{2Q_{rr}}{\frac{di}{dt}}}$$

Hence, $I_{rrm} = \sqrt{2Q_{rr} \frac{di}{dt}}$

The fast decay of negative current creates an inductive drop that adds with the reverse blocking voltage VR as illustrate in Fig.3.There are two types of reverse recovery characteristics of junction diodes: **Soft recovery and Fast recovery** where, the **softness factor, SF** is the ratio of t2/t3.



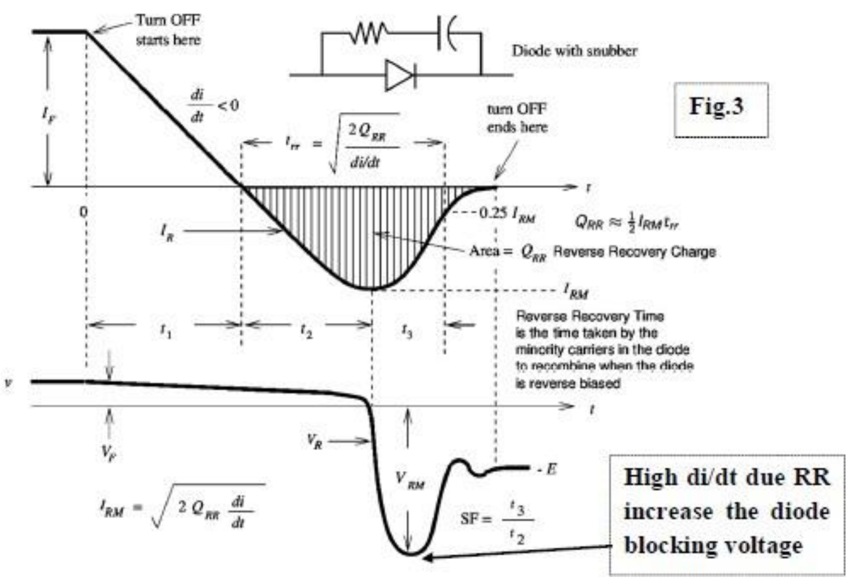


Fig.3

Hence, the blocking voltage across the diode increases to: $V_{rrm} = V_{rr} + V_R$ where, Vrr is reverse recovery voltage due to the fast decay in the negativecurrent and equal to: $V_{rr} = L\frac{di}{dt}$

Based on the diode reverse recovery characteristics power diode are classified into:

- Standard Recovery (General) Diodes
- Fast Recovery Diodes
- Schottky Diodes
- Silicon Carbide Diodes.

For high frequency rectifier applications, Fast recovery and Schottky Diodes are generally used because of their short reverse recovery time and low voltage drop in their forward bias condition

General Purpose Diodes

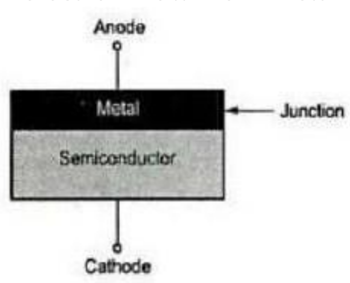
The diodes have high reverse recovery time of about 25 microsecs (µsec). They are used in low speed (frequency) applications. e.g., line commutated converters, diode rectifiers and converters for a low input frequency upto 1 KHz. Diode ratings cover a very wide range with current ratings less than 1 A to several thousand amps (2000 A) and with voltage ratings from 50 V to 5 KV. These diodes are generally manufactured by diffusion process. Alloyed type rectifier diodes are used in welding power supplies. They are most cost effective and rugged and their ratings can go up to 300A and 1KV.

Fast Recovery Diodes:

The diodes have low recovery time, generally less than 5µs. The major field of applications is in electrical power conversion i.e., in free-wheeling ac-dc and dc-ac converter circuits. Their current ratings is from less than 1 A to hundreds of amperes with voltage ratings from 50 V to about 3 KV. Use of fast recovery diodes are preferable for freewheeling in SCR circuits because of low recovery loss, lower junction temperature and reduced di/dt. For high voltage ratings greater than 400V they are manufactured by diffusion process and the recovery time is controlled by platinum or gold diffusion. For less than 400 V rating epitaxial diodes provide faster switching speeds than diffused diodes. Epitaxial diodes have a very narrow base width resulting in a fast recovery time of about 50 ns.

Schottky Diodes :

A Schottky diode has metal (aluminium) and semi-conductor junction. A layer of metal is deposited on a thin epitaxial layer of the n-type silicon. In Schottky diode there is a larger barrier for electron flow from metal to semi-conductor. Figure shows the Schottky diode.

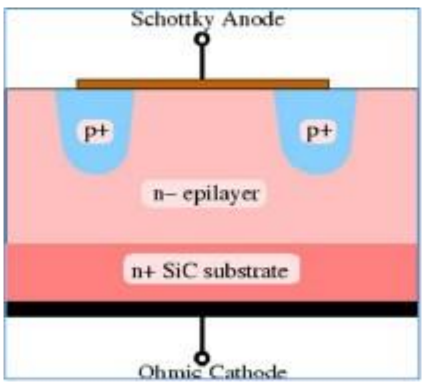


When Schottky diode is forward biased free electrons on n-side gain enough energy to flow into the metal causing forward current. Since the metal does not have any holes there is no charge storage, decreasing the recovery time. Therefore, a Schottky diode can switch-off faster than an ordinary p-n junction diode. A Schottky diode has a relatively low forward voltage drop and reverse recovery losses. The leakage current is higher than a p-n junction diode. The maximum allowable voltage is about 100 V. Current ratings vary from about 1 to 300 A. They are mostly used in low voltage and high current dc power supplies. The operating frequency may be as high 100-300 kHz as the device is suitable for high frequency application.

Silicon Carbide SiC Schottky Barrier Diode (SBD)

SiC (Silicon Carbide) is a compound semiconductor comprised of silicon (Si) and carbon (C). Compared to Si, SiC has

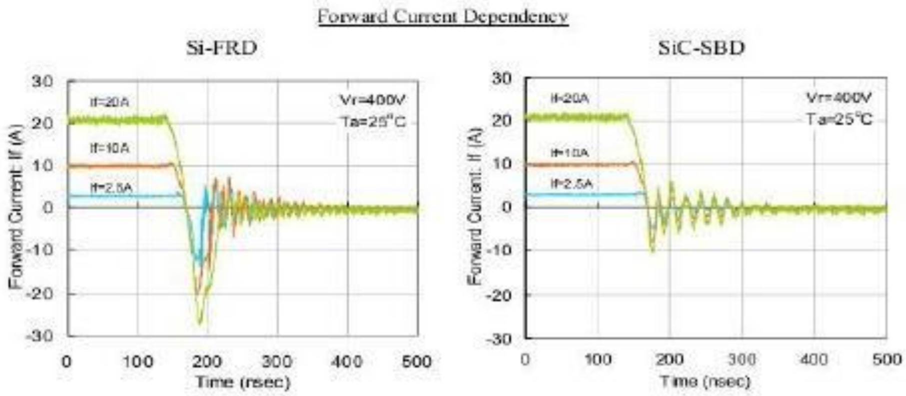
- ✓ Ten times the dielectric breakdown field strength.
- ✓ Three times the bandgap.
- ✓ Three times the thermal conductivity.



Both p-type and n-type regions, which are necessary to fashion device structures in a semiconductor materials, can be formed in SiC. These properties make SiC an attractive material from which to manufacture power devices that can far exceed the performance of their Si counterparts. SiC devices can withstand ***higher breakdown voltage, have lower resistivity, and can operate at higher temperature***. SiC SBDs (Schottky barrier diodes) with breakdown voltage from 600V (which far exceeds the upper limit for silicon SBDs) and up are readily available. Compared to silicon FRDs (fast recovery diodes),

- ✓ SiC SBDs have much lower reverse recovery current and recovery time, hence dramatically lower recovery loss and noise emission. Furthermore, unlike silicon FRDs, these characteristics do not change significantly over current and operating temperature ranges.
- ✓ SiC SBDs allow system designers to improve efficiency, lower cost and size of heat sink, increasing switching frequency to reduce size of magnetics and its cost, etc.

SiC-SBDs have similar threshold voltage as Si- FRDs, i.e., a little less than 1V.



Reverse recovery characteristics of SiC-SBD

Si fast P-N junction diodes (e.g. FRDs: fast recovery diodes) have high transient current at the moment the junction voltage switches from the forward to the reverse direction, resulting in significant switching loss. This is due to minority carriers stored in the drift layer during conduction phase when forward voltage is applied. The higher the forward current (or temperature), the longer the recovery time and the larger the recovery current.

In contrast, since SiC-SBDs are majority carrier (unipolar) devices that use no minority carriers for electrical conduction, they do not store minority carrier s. The reverse recovery current in SiC SBDs is only to discharge junction capacitance. Thus the switching loss is substantially lower compared to that in Si-FRDs. The transient current is nearly independent of temperatures and forward currents, and thereby achieves stable fast recovery in any environment. This also means SiC-SBDs generate less noise from the recovery current.

A typical comparison between different types of diodes is shown in the table below:

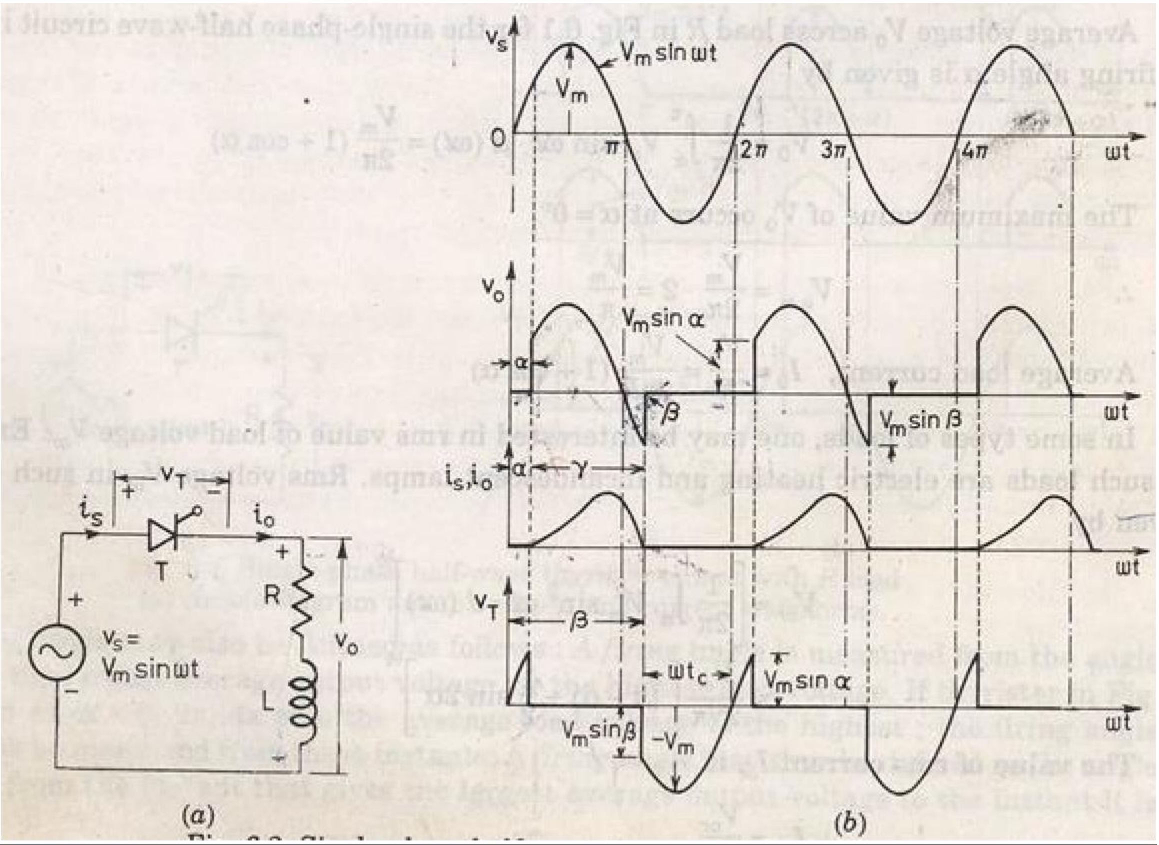
Standard Recovery Diodes	Fast Recovery Diodes	Schottky Diodes	Silicon Carbide Diodes.
Upto 5000V & 3500A	Upto 3000V and 1000A	Upto 100V and 300A	Upto 600V and 200A
Reverse recovery time –High t_{rr} ~=25μs.	Reverse recovery time – Low $t_{rr} \leq 5$μs.	Reverse recovery time – Extremely low. trr is typically around few ns	have extremely fast switching behaviour with ultra-low trr
Typically used in rectifiers at power frequencies i.e., at 50Hz or 60 Hz.	Typically operating at higher frequencies as freewheeling diodes.	Typically operating at higher frequencies as freewheeling diodes.	Typically operating at higher frequencies as freewheeling diodes.
V_F = 0.7V to 1.2V	V_F = 0.8V to 1.5V	V_F = 0.4V to 0.6V	V_F <0.5V

1.10 DIODE RECTIFIER

Rectifier are used to convert A.C to D.C supply.

Rectifiers can be classified as single phase rectifier and three phase rectifier. Single phase rectifier are classified as 1-Φ half wave and 1-Φ full wave rectifier. Three phase rectifier are classified as 3-Φ half wave rectifier and 3-Φ full wave rectifier. 1-Φ Full wave rectifier are classified as1-Φ mid point type and 1-Φ bridge type rectifier. 1-Φ bridge type rectifier are classified as 1-Φ half controlled and 1-Φ full controlled rectifier. 3-Φ full wave rectifier are again classified as 3-Φ mid point type and 3-Φ bridge type rectifier. 3-Φ bridge type rectifier are again divided as 3-Φ half controlled rectifier and 3-Φ full controlled rectifier.

Single phase half wave circuit with R-L load



Output current i_o rises gradually. After some time i_o reaches a maximum value and then begins to decrease.

At π, v_o=0 but i_o is not zero because of the load inductance L. After π interval SCR is reverse biased but load current is not less then the holding current.

At β>π, i_o reduces to zero and SCR is turned off.

At 2π+β SCR triggers again

α is the firing angle.

β is the extinction angle.

$v = \beta - \alpha = conduction\ angle$

Analysis for V_T.

At $\omega t = /, V_T = V_m sin /$

During $= / \ to\ /,\ V_T = 0$;

When $= /,\ V_T = V_m sin /$;

$$V_m \sin \omega t = Ri_0 + L\frac{di_0}{dt}$$

$$i_s = \frac{V_m}{\sqrt{R^2 + X^2}} \sin(\omega\, t - \phi)$$

Where,

$$\phi = \tan^{-1}\frac{X}{R}$$

$$X = \omega L$$

Where $/$ is the angle by which I_s lags V_s. The

transient component can be obtained as

$$Ri_t + L\frac{di_0}{dt} = 0$$

So $i_t = Ae^{-(Rt/L)}$

$i_0 = i_s + i_t$

$$\frac{V_m}{z}\sin(\omega t - /) + Ae^{-(Rt/L)}$$

Where $z = \sqrt{R^2 + X^2}$

At $\alpha = \omega t, i_o = 0$;

$$0 = \frac{Vm}{z}\sin(\alpha - /) + Ae^{-(R\alpha/L\omega)};$$

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

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

Therefore,

$\omega t = \beta, i_0 = 0;$

So $\sin(\beta - \alpha) = \sin(\alpha - /)e^{-(\beta-\alpha)/(\omega L)}$

β can obtained from the above equation.

The average load voltage can be given by

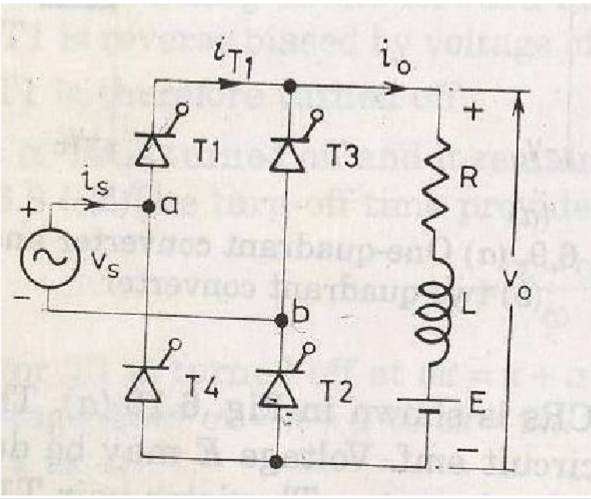
$$V_0 = \frac{1}{2\pi}\int_{\alpha}^{\beta} V_m \sin\omega t d(\omega t)$$

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

Average load current

$$I_0 = \frac{V_m}{2\pi R}(\cos\alpha - \cos\beta)$$

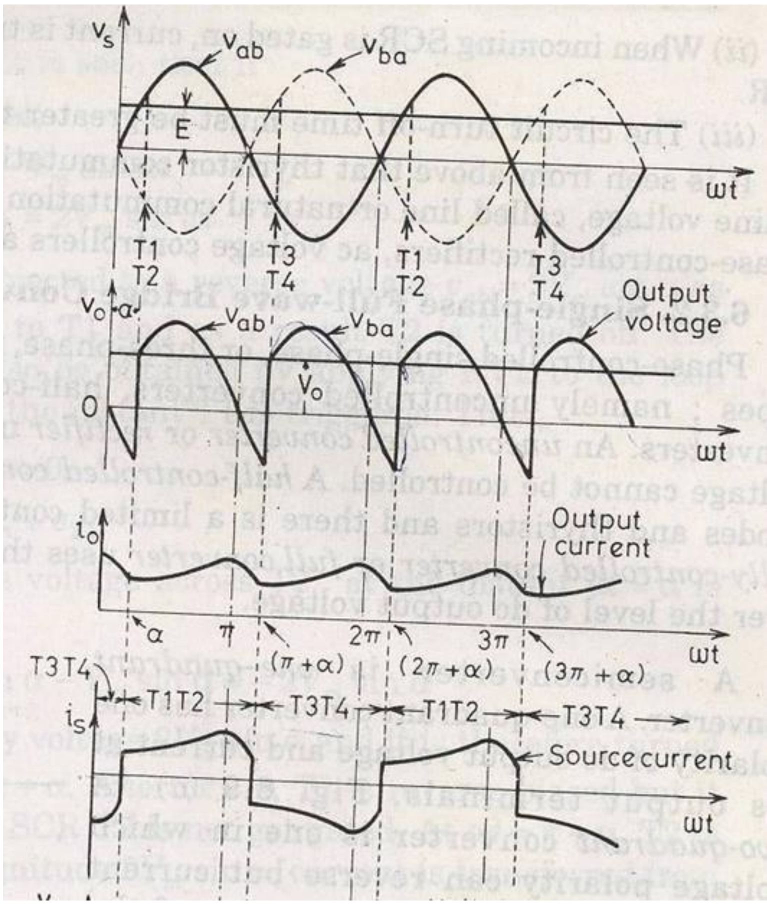
Single phase full converter



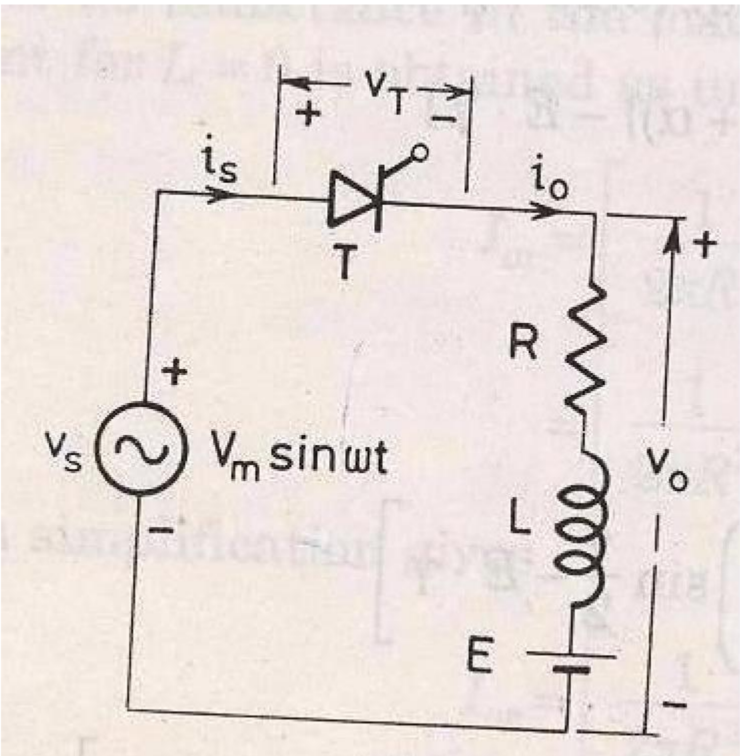
$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\beta} V_m \sin(\omega t) d(\omega t)$$

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

T_1,T_2 triggered at α and π radian latter T_3, T_4 are triggered.



Single phase half wave circuit with RLE load



The minimum value of firing angle is

$$V_m \sin(\omega t) = E$$

So,

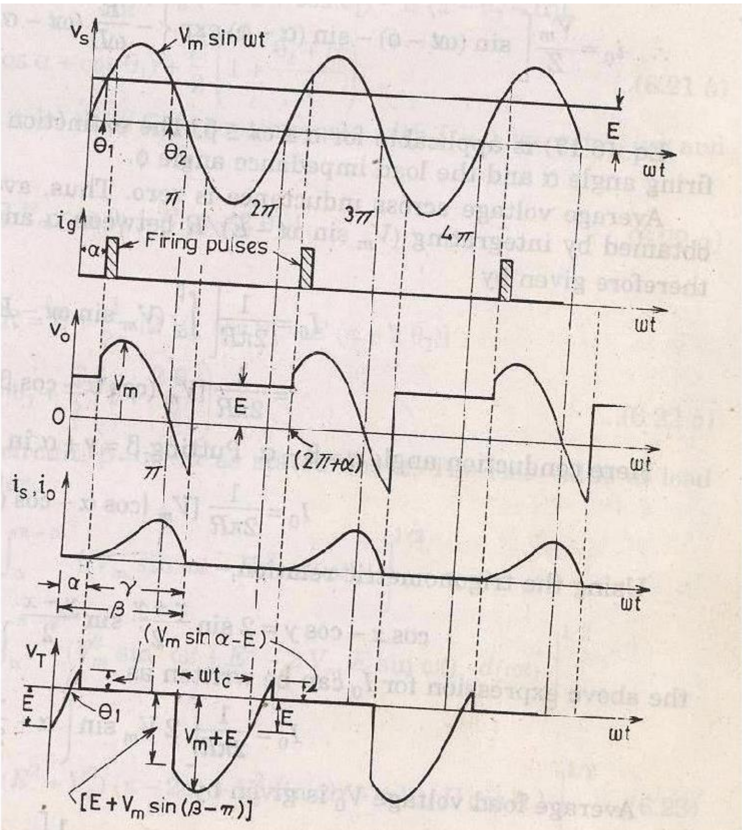
$$\theta_1 = \sin^{-1} \frac{E}{V_m}$$

Maximum value of firing angle

$$\theta_2 = \pi - \theta_2$$

The voltage differential equation is

$$V_m \sin(\omega t) = R i_0 + L\frac{di_0}{dt} + E$$



$$i_s = i_{s1} + i_{s2}$$

Due to source volt

$$i_{s1} = \frac{V_m}{Z} \sin(\omega t - \phi)$$

Due to DC counter emf

$i_{s2} = -(E / R)$

$i_t = Ae^{-(R/L)t}$

Thus the total current is given by

$i_{s1} + i_{s2} + i_t$

$= \frac{V_m}{Z}\sin(\omega t - \phi) - \frac{E}{R} + Ae^{-(R/L)t}$

$i_{s0} = \frac{V_m}{Z}\sin(\omega t - \phi) - \frac{E}{R} + Ae^{-(R/L)t}$

$At \omega t = \alpha, i_0 = 0$

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

So

$$i_0 = \frac{V_m}{Z}[\sin(\omega t - \phi) - \sin(\alpha - \phi)e^{\{\frac{-R}{\omega L}(\omega t - \alpha)\}} - \frac{E}{R}[1 - e^{\{\frac{-R}{\omega L}(\omega t - \alpha)\}}]$$

Average voltage across the inductance is zero. Average value of load current is

$$I_0 = \frac{1}{2\pi R}\int_\alpha^\beta (V_m \sin\omega t - E)\, d(\omega t)$$

$$= \frac{1}{2\pi R}[V_m(\cos\alpha - \cos\beta) - E(\beta - \alpha)]$$

Conduction angle $\nu = \beta - \alpha$

$\Rightarrow \beta = \alpha + v$

$$I_0 = \frac{1}{2\pi R}[V_m(\cos\alpha - \cos(\alpha + v)) - E(v)]$$

$$\cos A - \cos B = 2\sin\frac{A+B}{2}\sin\frac{A-B}{2}$$

So

$$I_0 = \frac{1}{2\pi R}[2V_m \sin(\alpha + \frac{v}{2})\sin\frac{v}{2} - E.\nu]$$

$\nu = E + I_0 R$

$= E + \frac{1}{2\pi}[2V_m \sin(\alpha + \frac{\nu}{2})\sin\frac{\nu}{2} - E.\nu]$

$= E(1 - \frac{\nu}{2\pi}) + [\frac{V_m}{\pi}\sin(\alpha + \frac{\nu}{2})\sin\frac{\nu}{2}]$

If load inductance L is zero then

$\beta = \theta_2$

And $\nu = \beta - \alpha = \theta_2 - \alpha$

But $\theta_2 = \pi - \theta_1$

So $\beta = \theta_2 = \pi - \theta_1$

And $\nu = \pi - \theta_1 - \alpha$

So average current will be

$$I_0 = \frac{1}{2\pi R}[V_m(\cos\alpha - \cos(\pi - \theta_1)) - E(\pi - \theta_1 - \alpha)]$$

So $V_0 = E + I_0 R$

$$= \frac{V_m}{2\pi}(\cos\alpha + \cos\theta_1) + \frac{E}{2}(1 + \frac{\theta_1 + \alpha}{\pi})$$

For no inductance rms value of load current

$$I_0 = [\frac{1}{2\pi R^2}\int_{\alpha}^{\pi-\alpha}(V_m \sin(\omega t) - E)^2 d(\omega t)]^{1/2}$$

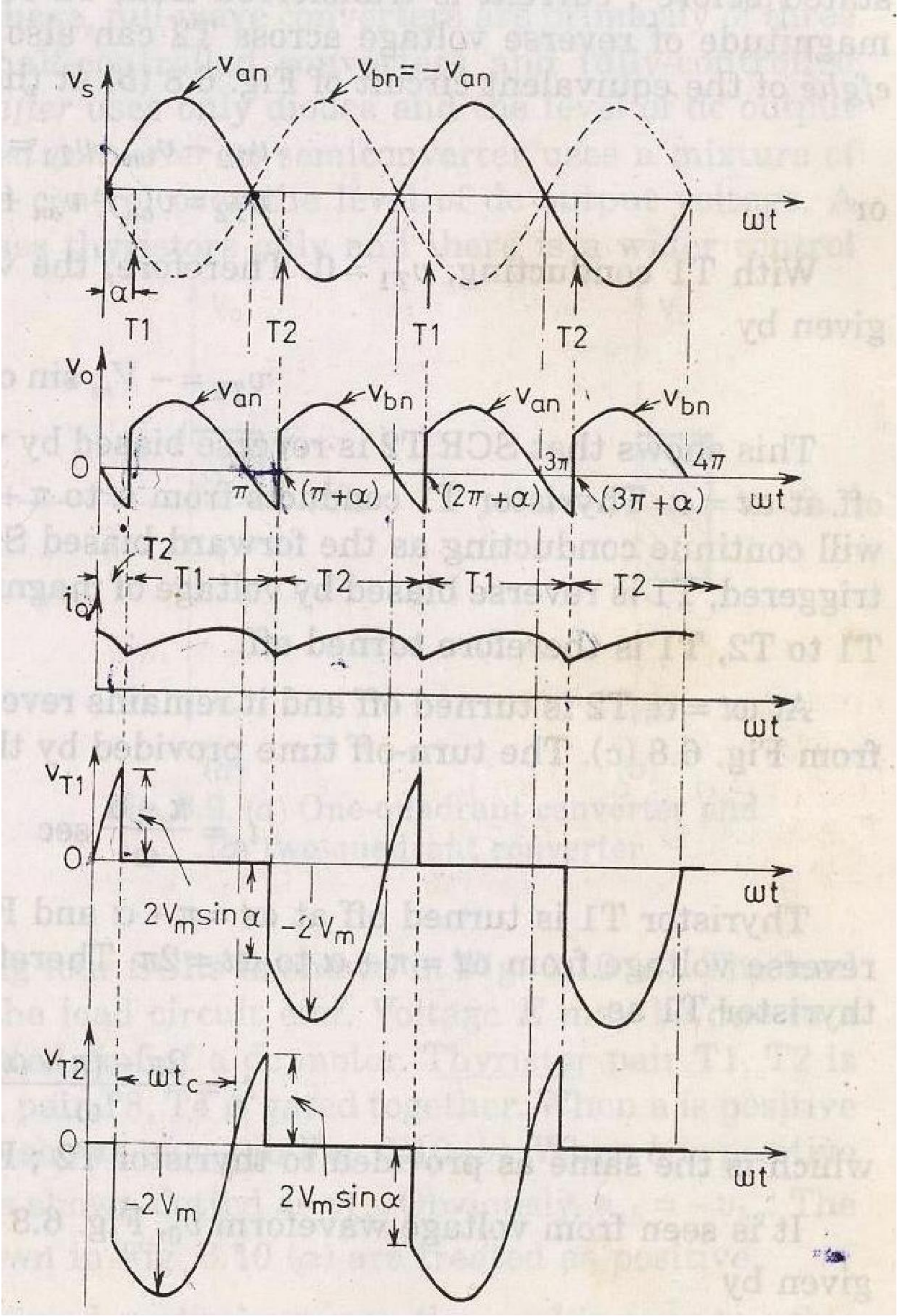
Power delivered to load

$$P = I_{or}^2 R + I_0 E$$

Supply power factor

$$Pf = \frac{I_{or}^2 R + I_0 E}{V_s I_{or}}$$

Single phase full wave converter:

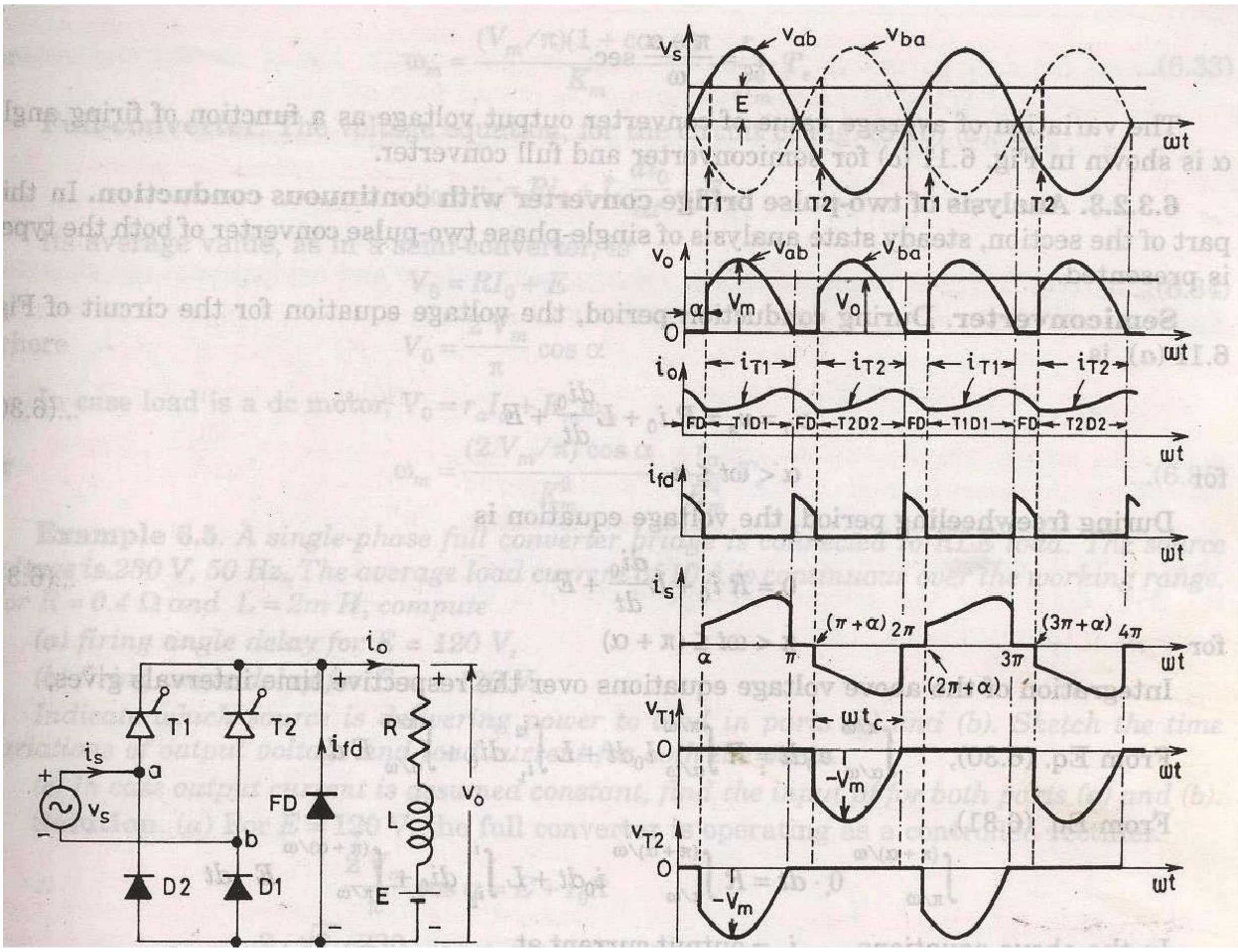


v_s
v_{an}
$v_{bn} = -v_{an}$
ωt
α
T1
T2
T1
T2
v_o
v_{an}
v_{bn}
v_{an}
v_{bn}
O
π
$(\pi+\alpha)$
$(2\pi+\alpha)$
3π
$(3\pi+\alpha)$
4π
ωt
T2
T1
T2
T1
T2
i_o
ωt
v_{T1}
O
$2V_m \sin\alpha$
$-2V_m$
ωt
v_{T2}
ωt_c
O
$-2V_m$
$2V_m \sin\alpha$
ωt

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

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

Single phase semi converter:



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

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

full converter:

steady state analysis

$$V_s = Ri_o + L\frac{di_0}{dt} + E$$

$$V_0 = RI_0 + E$$

$$V_0 = \frac{2V_m}{\pi}\cos\alpha$$

So in case of DC motor load

$$V_0 = r_a I_a + \alpha_m \omega_m$$

So $$\omega_m = \frac{\frac{2V_m}{\pi}\cos\alpha - r_a I_a}{\alpha_m}$$

$$T = \alpha_m I_a$$

$$\Rightarrow I_a = \frac{T_e}{\alpha_m}$$

Put $$I_a = \frac{T_e}{\alpha_m}$$

So $$\omega_m = \frac{(\frac{2V_m}{\pi})\cos\alpha}{\alpha_m} - \frac{r_a T_e}{\alpha_m^2}$$

1.7 Recommended questions:

1. State important applications of power electronics
2. What is a static power converter? Name the different types of power converters and mention their functions.
3. Give the list of power electronic circuits of different input / output requirements.
4. What are the peripheral effects of power electronic equipments? What are the remedies for them?
5. What are the peripheral effects of power electronic equipments? What are the remedies for them?

1.8 Generic Skills / Outcomes:

- To get an overview of power electronics and its history of development.
- Various applications of power converters such as UPS, Inverters, DC motor control.

1.9 Further Redaing

1. http://books.google.co.in/books/about/Power_Electronics.html?id=-WqvjxMXClAC
2. http://www.flipkart.com/power-electronic-2ed/p/itmczynuyqnbvzzj
3. http://www.scribd.com/doc/36550374/Power-Electronics-Notes
4. http://elearning.vtu.ac.in/EC42.html
5. http://www.onlinevideolecture.com/electrical-engineering/nptel-iit-bombay/power-electronics/?course_id=510

MODULE-2

POWER TRANSISTORS

Structure

2.0 Introduction
2.1 Objectives
2.2 Bipolar Junction Transistor
2.3 Transistor as switch
2.4 Switching Characterstics
2.5 Switching Limits
2.6 Power Mosfet
2.7 Assignment Questions
2.8 Outcomes
2.9 Further Readings

2.0 Introduction

Power transistors are devices that have controlled turn-on and turn-off characteristics. These devices are used a switching devices and are operated in the saturation region resulting in low on-state voltage drop. They are turned on when a current signal is given to base or control terminal. The transistor remains on so long as the control signal is present.

Power transistors are classified as follows

- Bipolar junction transistors(BJTs)
- Metal-oxide semiconductor filed-effect transistors(MOSFETs)
- Static Induction transistors(SITs)
- Insulated-gate bipolar transistors(IGBTs)

2.1 Objectives:

- To explain different power transistors, their steady state and switching characteristics and limitations.

2.2Bipolar Junction Transistors

The need for a large blocking voltage in the off state and a high current carrying capability in the on state means that a power BJT must have substantially different structure than its small signal equivalent. The modified structure leads to significant differences in the I-V characteristics and switching behavior between power transistors and its logic level counterpart.

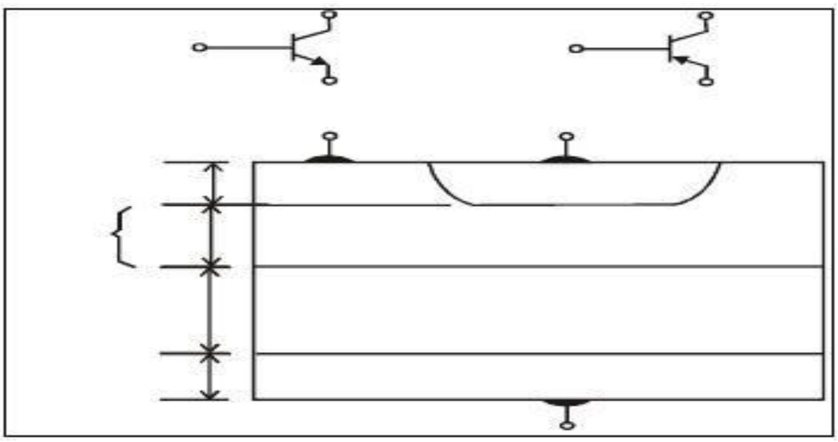
Basic Operating Principle of a Bipolar Junction Transistor

A junction transistor consists of a semiconductor crystal in which a p type region is sandwiched between two n type regions. This is called an n-p-n transistor. Alternatively an n type region may be placed in between two p type regions to give a p-n-p transistor. Fig shows the circuit symbols and schematic representations of an n-p-n and a p-n-p transistor. The terminals of a transistor are called Emitter (E), Base (B) & Collector (C) as shown in the figure.

When a biasing voltage VBB of appropriate polarity is applied across the junction JBE the potential barrier at this junction reduces and at one point the junction becomes forward biased. The current crossing this junction is governed by the forward biased p-n junction equation for a given collector emitter voltage. The base current iB is related to the recombination of minority carriers injected into the base from the emitter. The rate of recombination is directly proportional to the amount of excess minority carrier stored in the base. Since, in a normal transistor the emitter is much more heavily doped compared to the base the current crossing J B BE is almost entirely determined by the excess minority carrier distribution in the base. Thus, it can be concluded that the relationship between iBB and VBE will be similar to the i-v characteristics of a p-n junction diode. VCE, however have some effect on this characteristic. As VCE increases reverse bias of JCB increases and the depletion region at JCB moves deeper into the base. The effective base width thus reduces, reducing the rate of recombination in the base region and hence the base current. Therefore iB for a given V B BE reduces with increasing VCE

Power Transistor Structure

If we recall the structure of conventional transistor we see a thin p-layer is sandwiched between two n-layers or vice versa to form a three terminal device with the terminals named as Emitter, Base and Collector. The structure of a power transistor is as shown below.



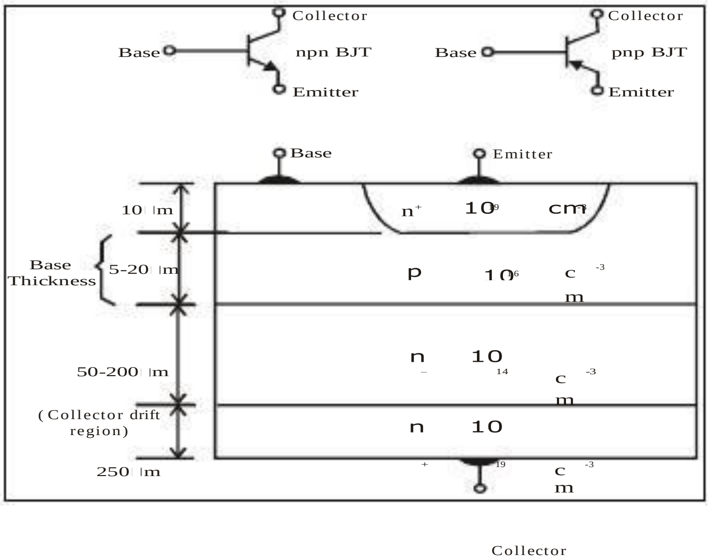


Fig.2.1: Structure of Power Transistor

The difference in the two structures is obvious.

A power transistor is a vertically oriented four layer structure of alternating p-type and n-type. The vertical structure is preferred because it maximizes the cross sectional area and through which the current in the device is flowing. This also minimizes on-state resistance and thus power dissipation in the transistor.

The doping of emitter layer and collector layer is quite large typically 10^{19} cm^{-3}. A special layer called the collector drift region (n^-) has a light doping level of 10^{14}.

The thickness of the drift region determines the breakdown voltage of the transistor. The base thickness is made as small as possible in order to have good amplification capabilities, however if the base thickness is small the breakdown voltage capability of the transistor is compromised.

Steady State Characteristics

Figure 3(a) shows the circuit to obtain the steady state characteristics. Fig 3(b) shows the input characteristics of the transistor which is a plot of I_B versus V_{BE} . Fig 3(c) shows the output characteristics of the transistor which is a plot I_C versus V_{CE} . The characteristics shown are that for a signal level transistor.

The power transistor has steady state characteristics almost similar to signal level transistors except that the V-I characteristics has a region of quasi saturation as shown by figure 4.

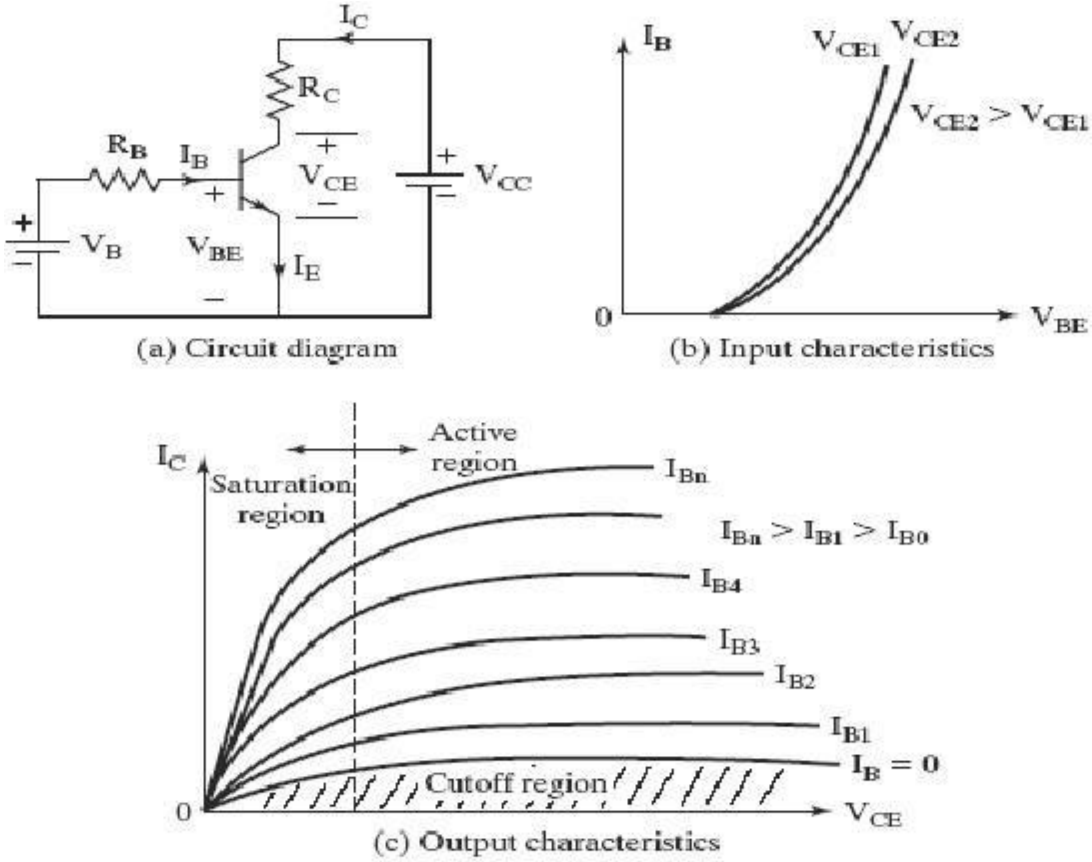


Fig 2.2. Steady State Characteristics of Power Transistor

There are four regions clearly shown: Cutoff region, Active region, quasi saturation and hard saturation. The cutoff region is the area where base current is almost zero. Hence no collector current flows and transistor is off. In the quasi saturation and hard saturation, the base drive is applied and transistor is said to be on. Hence collector current flows depending upon the load.

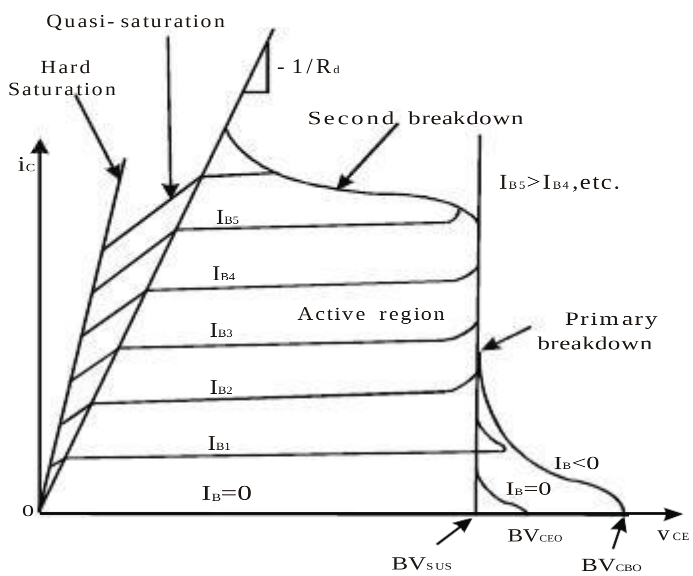


Fig. 2.3: Characteristics of NPN Power Transistors

The power BJT is never operated in the active region (i.e. as an amplifier) it is always operated between cutoff and saturation. The BV_{SUS} is the maximum collector to emitter voltage that can be sustained when BJT is carrying substantial collector current. The BV_{CEO} is the maximum collector to emitter breakdown voltage that can be sustained when base current is zero and BV_{CBO} is the collector base breakdown voltage when the emitter is open circuited.

The primary breakdown shown takes place because of avalanche breakdown of collector base junction. Large power dissipation normally leads to primary breakdown.

The second breakdown shown is due to localized thermal runaway.

Transfer Characteristics

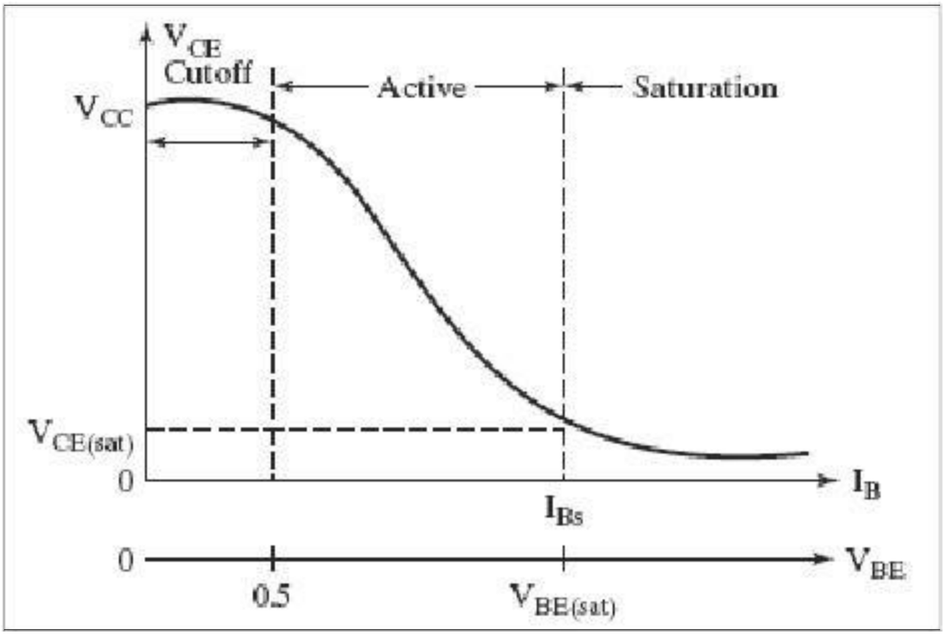


Fig. 2.4: Transfer Characteristics

B

$$I_E = I_C + I_B$$

$$\beta = h_{fE} = \frac{I_C}{I_B}$$

$$I_C = \beta I_B + I_{CEO}$$

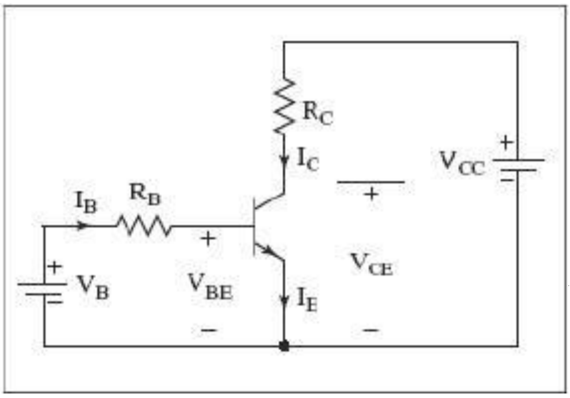
$$\alpha = \frac{\beta}{\beta + 1}$$

$$\beta = \frac{\alpha}{1 - \alpha}$$

2.3 Transistor as a Switch

The transistor is used as a switch therefore it is used only between saturation and cutoff.

From fig. 5 we can write the following equations



\Fig. 2.5: Transistor Switch

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

$$V_C = V_{CE} = V_{CC} - I_C R_C$$

$$V_C = V_{CC} - \beta \frac{R_C \; V_B - V_{BE}}{R_B}$$

$$V_{CE} = V_{CB} + V_{BE}$$

$$V_{CB} = V_{CE} - V_{BE} \qquad ....$$

Equation (1) shows that as long as V_{CE} □ V_{BE} the CBJ is reverse biased and transistor is in active region, The maximum collector current in the active region, which can be obtained by setting V_{CB} □ 0 and V_{BE} □ V_{CE} is given as

$$I_{CM} = \frac{V_{CC} - V_{CE}}{R_C} \qquad \therefore \quad I_{BM} = \frac{I_{CM}}{\beta_F}$$

If the base current is increased above I_{BM} ,V_{BE} increases, the collector current increases and V_{CE} falls belowV_{BE} . This continues until the CBJ is forward biased with V_{BC} of about 0.4 to 0.5V, the transistor than goes into saturation. The transistor saturation may be defined as the point above which any increase in the base current does not increase the collector current significantly.

In saturation, the collector current remains almost constant. If the collector emitter voltage is V_{CEsat} the collector current is

$$I_{CS} = \frac{V_{CC} - V_{CESAT}}{R_C}$$

$$I_{BS} = \frac{I_{CS}}{\beta}$$

Normally the circuit is designed so that I_B is higher that I_{BS} . The ratio of I_B to I_{BS} is called to overdrive factor ODF.

$$ODF = \frac{I_B}{I_{BS}}$$

The ratio of I_{CS} to I_B is called as forced β .

$$\beta_{forced} = \frac{I_{CS}}{I_B}$$

2.4 Switching Characteristics

A forward biased p-n junction exhibits two parallel capacitances; a depletion layer capacitance and a diffusion capacitance. On the other hand, a reverse biased p-n junction has only depletion capacitance. Under steady state the capacitances do not play any role. However under transient conditions, they influence turn-on and turn-off behavior of the transistor.

$I_{BS} = \frac{V_B - V_{BE(sat)}}{} = \frac{5 - 0.7}{} = 4.76mA$

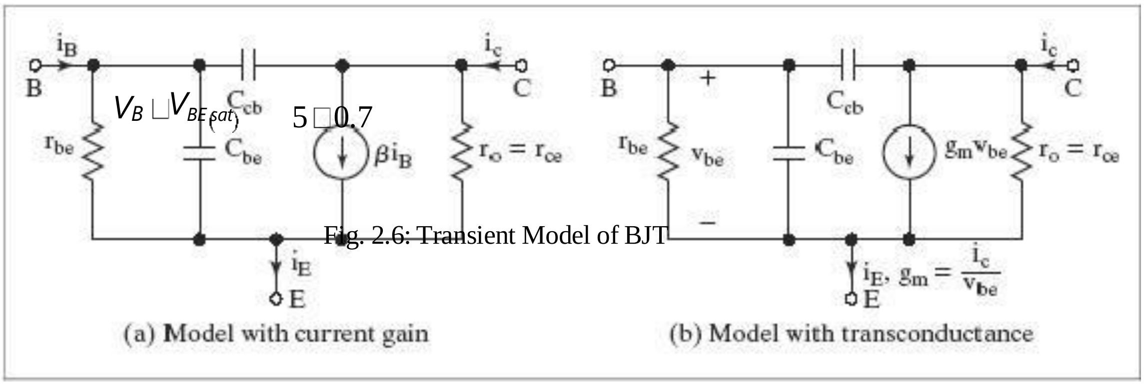


Fig. 2.6: Transient Model of BJT

The drift region in a power transistor is introduced in order to block large forward voltage. However, one effect of introducing the drift region is the appearance of a “quasi saturation region” in the output i-v characteristics of a power transistor. In the quasi saturation state the drift region is not completely shorted out by “conductivity modulation” by excess carriers from the base region. In offers a resistance which is a function of the base current. Although the base current retain some control over collector current in this state the value of dc current gain reduces substantially due to increased effective base width. Another effect of introducing the drift region is to make the VCE saturation voltage depend linearly on the collector current in the hard saturation region due to the ohmic resistance of the “conductivity modulated” drift region.

FBOSOA compactly represents the safe operating limits of a power transistor in terms of maximum forward current, maximum forward voltage, maximum average & instantaneous power dissipation and second break down limits. It is most useful in designing the switching trajectory of a power transistor

For safe switching operation, however it is not sufficient to merely restrict the switching power loss. It will be necessary to restrict the switching trajectory (an instantaneous plot of ic vs VCE during switching with time as a parameter) within the FBSOA /RBSOA region corresponding to a pulse width greater than TSW (ON) or TSW (OFF)

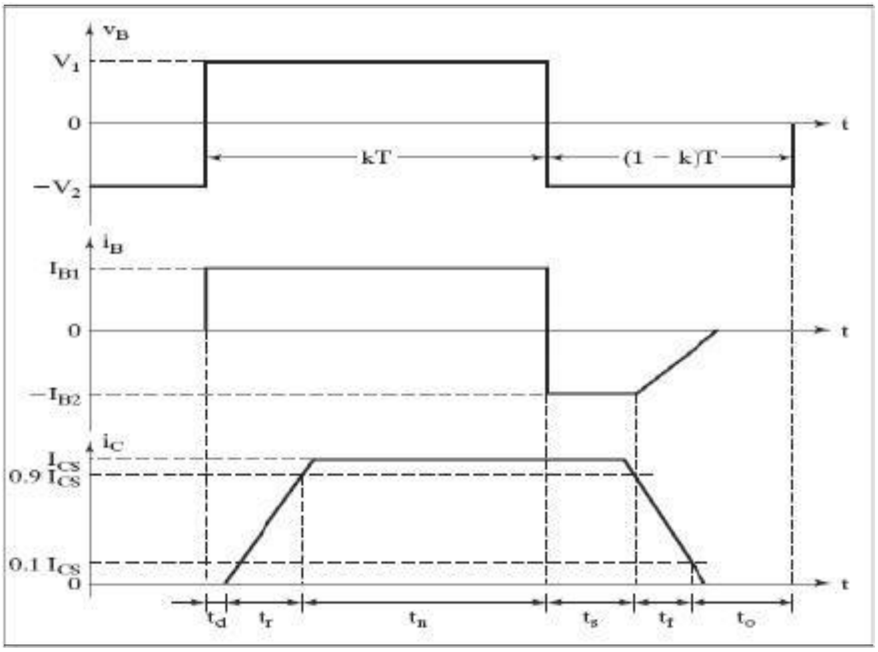


Fig. 2.7: Switching Times of BJT

Due to internal capacitances, the transistor does not turn on instantly. As the voltage V_B rises from zero to V_1 and the base current rises to I_{B1}, the collector current does not respond immediately. There is a delay known as delay time td, before any collector current flows. The delay is due to the time required to charge up the BEJ to the forward bias voltage V_{BE}(0.7V). The collector current rises to the steady value of I_{CS} and this time is called rise time t_r.

The base current is normally more than that required to saturate the transistor. As a result excess minority carrier charge is stored in the base region. The higher the ODF, the greater is the amount of extra charge stored in the base. This extra charge which is called the saturating charge is proportional to the excess base drive.

This extra charge which is called the saturating charge is proportional to the excess base drive and the corresponding current I_e.

$$I_e = I_B - \frac{I_{CS}}{\beta} = ODF.I_{BS} - I_{BS} = I_{BS}\ \ ODF - 1$$

When the input voltage is reversed from V_1 to -V_2, the reverse current –I_{B2} helps to discharge the base. Without –I_{B2} the saturating charge has to be removed entirely due to recombination and the storage time t_s would be longer.

Once the extra charge is removed, BEJ charges to the input voltage –V_2 and the base current falls to zero. t_f depends on the time constant which is determined by the reverse biased BEJ capacitance.

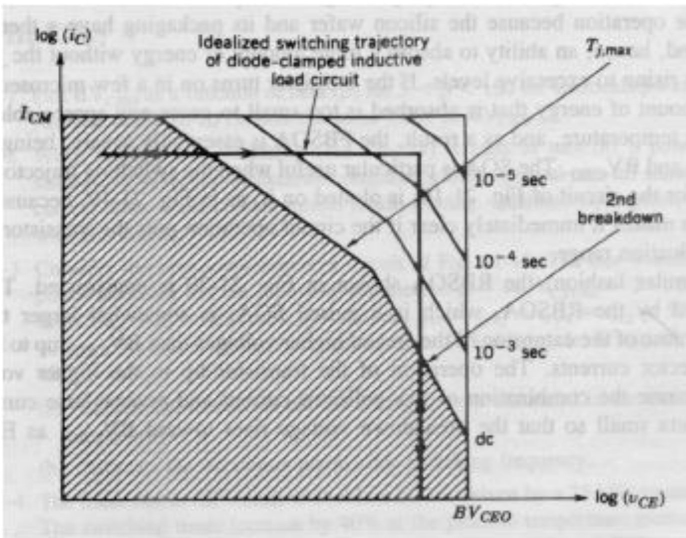
2.5 Switching Limits

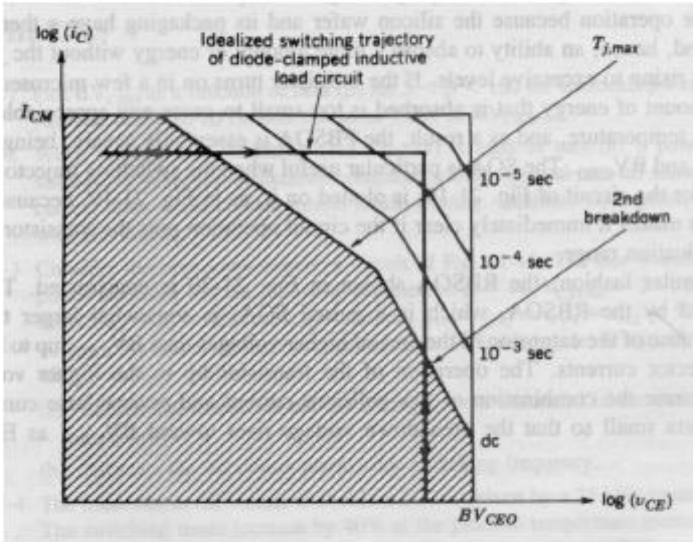
1. Second Breakdown

It is a destructive phenomenon that results from the current flow to a small portion of the base, producing localized hot spots. If the energy in these hot spots is sufficient the excessive localized heating may damage the transistor. Thus secondary breakdown is caused by a localized thermal runaway. The SB occurs at certain combinations of voltage, current and time. Since time is involved, the secondary breakdown is basically an energy dependent phenomenon.

2. Forward Biased Safe Operating Area FBSOA

During turn-on and on-state conditions, the average junction temperature and second breakdown limit the power handling capability of a transistor. The manufacturer usually provides the FBSOA curves under specified test conditions. FBSOA indicates the $I_c - V_{ce}$ limits of the transistor and for reliable operation the transistor must not be subjected to greater power dissipation than that shown by the FBSOA curve.





The dc FBSOA is shown as shaded area and the expansion of the area for pulsed operation of the BJT with shorter switching times which leads to larger FBSOA. The second break down boundary represents the maximum permissible combinations of voltage and current without getting into the region of $i_c - v_{ce}$ plane where second breakdown may occur. The final portion of the boundary of the FBSOA is breakdown voltage limit BV_{CEO} .

3. Reverse Biased Safe Operating Area RBSOA

During turn-off, a high current and high voltage must be sustained by the transistor, in most cases with the base-emitter junction reverse biased. The collector emitter voltage must be held to a safe level at or below a specified value of collector current. The manufacturer provide $I_c - V_{ce}$ limits during reverse-biased turn off as reverse biased safe area (RBSOA).

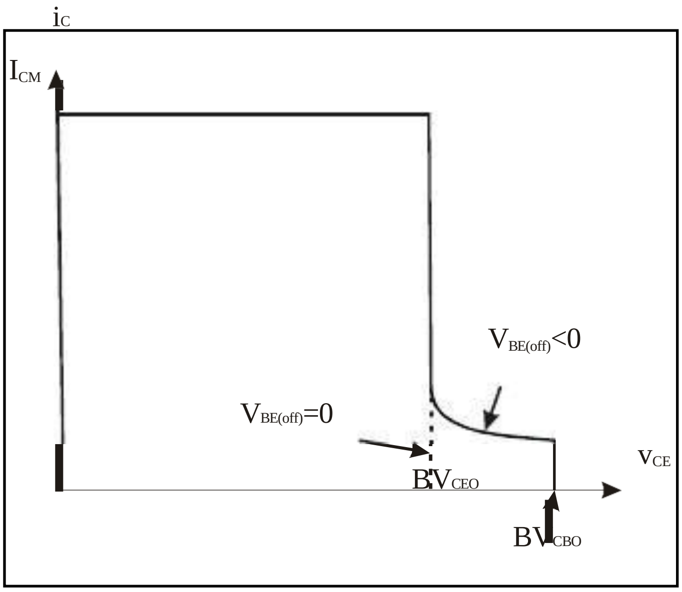


Fig.2.8: RBSOA of a Power BJT

The area encompassed by the RBSOA is somewhat larger than FBSOA because of the extension of the area of higher voltages than BV_{CEO} upto BV_{CBO} at low collector currents.

This operation of the transistor upto higher voltage is possible because the combination of low collector current and reverse base current has made the beta so small that break down voltage rises towards BV_{CBO} .

4. Power Derating

The thermal equivalent is shown. If the total average power loss is P_T,

The case temperature is $T_c = T_j - PT_{jc}$.

The sink temperature is $T_s = T_c - PT_{CS}$

The ambient temperature is T_A $T_S - P_T R_{SA}$ and $T_j - T_A$ T

The maximum power dissipation in P_T is specified at T_C □ $25^0 C$.

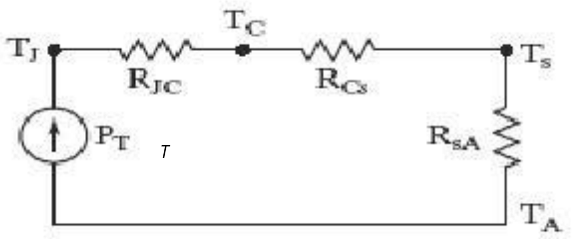


Fig.2.9: Thermal Equivalent Circuit of Transistor

5. Breakdown Voltages

A break down voltage is defined as the absolute maximum voltage between two terminals with the third terminal open, shorted or biased in either forward or reverse direction.

BV_{SUS} : The maximum voltage between the collector and emitter that can be sustained across the transistor when it is carrying substantial collector current.

BV_{CEO} : The maximum voltage between the collector and emitter terminal with base open circuited.

BV_{CBO} : This is the collector to base break down voltage when emitter is open circuited.

6. Base Drive Control

This is required to optimize the base drive of transistor. Optimization is required to increase switching speeds. t_{on} can be reduced by allowing base current peaking during turn-be increased to a sufficiently high value to maintain the transistor in quasi-saturation region. t_{off} can be reduced by reversing base current and allowing base current peaking during turn off since increasing I_{B2} decreases storage time.

A typical waveform for base current is shown.

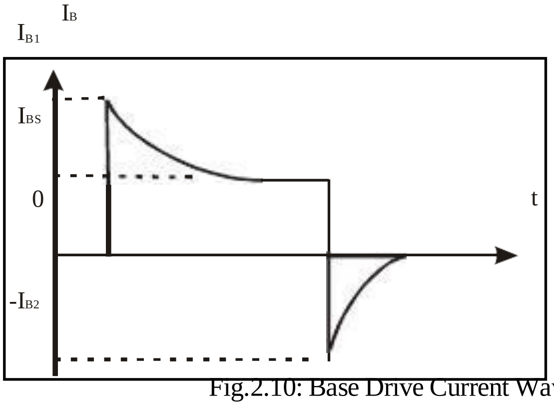


Fig.2.10: Base Drive Current Waveform

Some common types of optimizing base drive of transistor are

- Turn-on Control.
- Turn-off Control.
- Proportional Base Control.
- Antisaturation Control

Turn-On Control

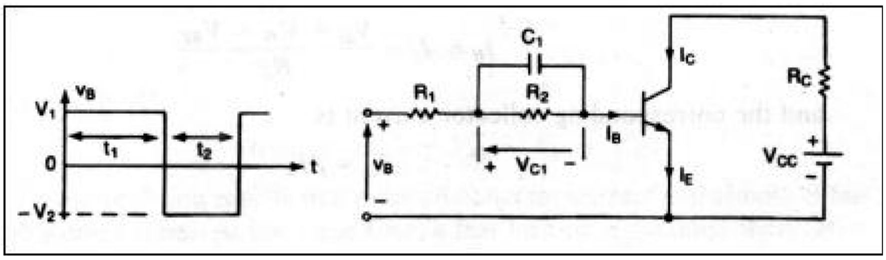


Fig. 2.11: Base current peaking during turn-on

Turn-Off Control

If the input voltage is changed to during turn-off the capacitor voltage V_C is added to V_2 as reverse voltage across the transistor. There will be base current peaking during turn off. As the capacitor C_1 discharges, the reverse voltage will be reduced to a steady state value, V_2. If different turn-on and turn-off characteristics are required, a turn-off circuit using C_2, R_3 & R_4 may be added. The diode D_1 isolates the forward base drive circuit from the reverse base drive circuit during turn off.

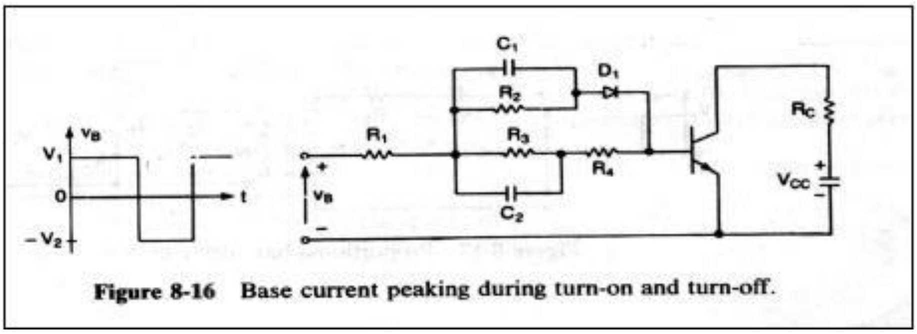


Fig: 2.12. Base current peaking during turn-on and turn-off

Proportional Base Control

This type of control has advantages over the constant drive circuit. If the collector current changes due to change in load demand, the base drive current is changed in proportion to collector current.

When switch S_1 is turned on a pulse current of short duration would flow through the base of transistor Q_1 and Q_1 is turned on into saturation. Once the collector current starts to flow, a corresponding base current is induced due to transformer action. The transistor would latch on itself and S_1 can be turned off. The turns ratio is $\frac{N_2}{N_1} \quad \frac{I_C}{I_B}$

of the circuit, the magnetizing current which must be much smaller than the collector current should be as small as possible. The switch S_1 can be implemented by a small signal trans and additional arrangement is necessary to discharge capacitor C_1 and reset the transformer core during turn-off of the power transistor.

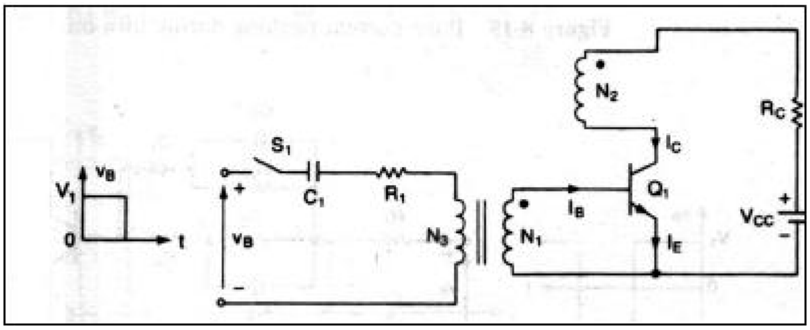


Fig.2.13: Proportional base drive circuit

Antisaturation Control

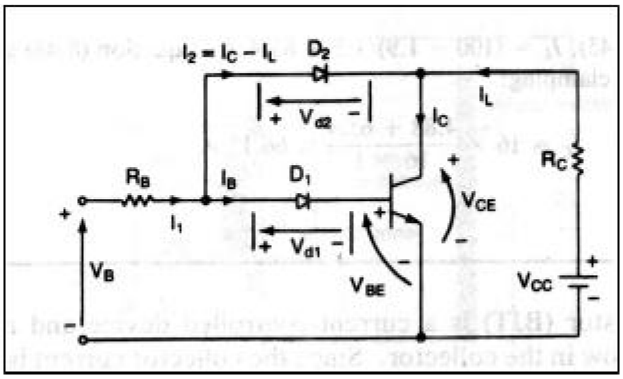


Fig:2.14: Collector Clamping Circuit

If a transistor is driven hard, the storage time which is proportional to the base current increases and the switching speed is reduced. The storage time can be reduced by operating the transistor in soft saturation rather than hard saturation. This can be accomplished by clamping CE voltage to a pre-determined level and the collector current is given by

$$I_C = \frac{V_{CC} - V_{CM}}{R_C}.$$

Where V_{CM} is the clamping voltage and V_{CM} V_{CE} .

The base current which is adequate to drive the transistor hard, can be found from $I_B = I_1 = \frac{V_B - V_{D1} - V_{BE}}{R_B}$ and the corresponding collector current is I_C I_L I_B .

The clamping action thus results a reduced collector current and almost elimination of the storage time. At the same time, a fast turn-on is accomplished.

However, due to increased V_{CE}, the on-state power dissipation in the transistor is increased, whereas the switching power loss is decreased.

ADVANTAGES OF BJT'S

- BJT's have high switching frequencies since their turn-on and turn-off time is low.
- The turn-on losses of a BJT are small.
- BJT has controlled turn-on and turn-off characteristics since base drive control is possible.
- BJT does not require commutation circuits.

DEMERITS OF BJT

- Drive circuit of BJT is complex.
- It has the problem of charge storage which sets a limit on switching frequencies.

It cannot be used in parallel operation due to problems of negative temperature coefficient.

2.6 POWER MOSFETS

MOSFET stands for metal oxide semiconductor field effect transistor. There are two types of MOSFET

- Depletion type MOSFET
- Enhancement type MOSFET

Depletion Type MOSFET

Construction

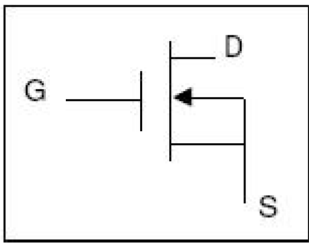


Fig.2.15 Symbol of n-channel depletion type MOSFET

It consists of a highly doped p-type substrate into which two blocks of heavily doped n-type material are diffused to form a source and drain. A n-channel is formed by diffusing between source and drain. A thin layer of SiO_2 is grown over the entire surface and holes are cut in SiO_2 to make contact with n-type blocks. The gate is also connected to a metal contact surface but remains insulated from the n-channel by the SiO_2 layer. SiO_2 layer results in an extremely high input impedance of the order of 10^{10} to 10^{15} Ω for this area.

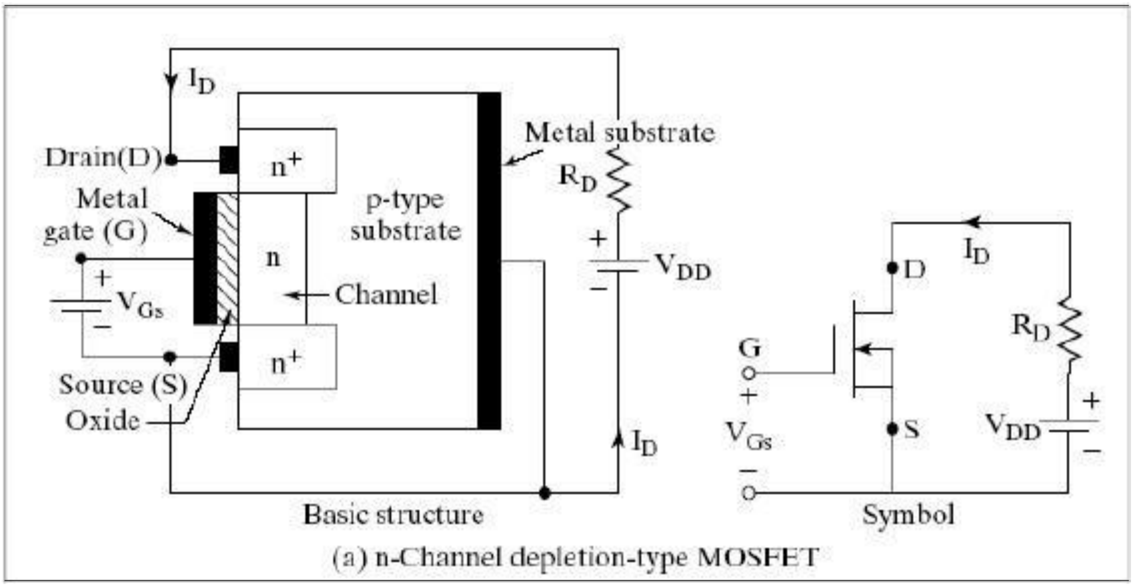


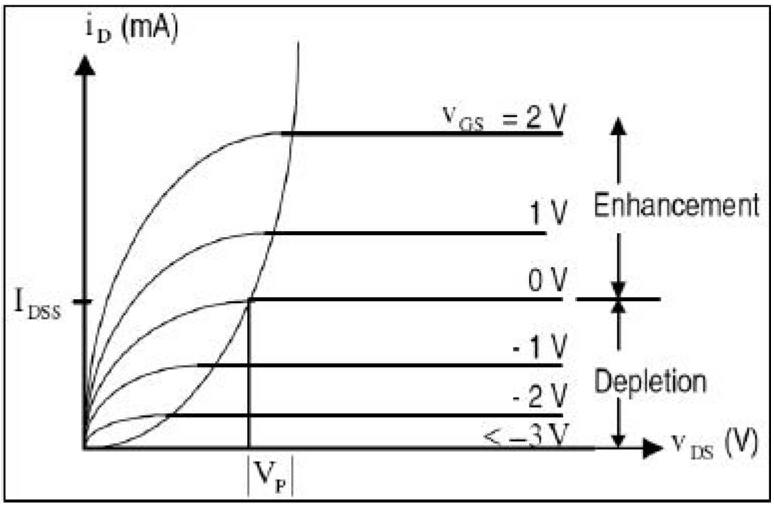
Fig.2.16: Structure of n-channel depletion type MOSFET

Operation

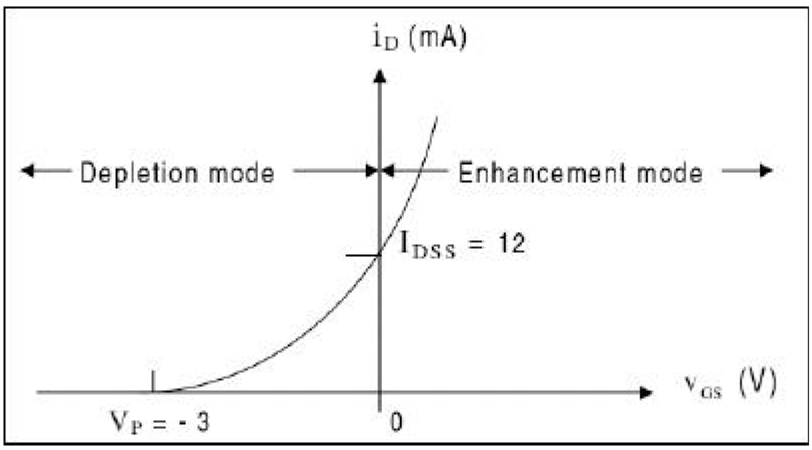
When V_{GS} □ $0V$ and V_{DS} is applied and current flows from drain to source similar to JFET. When V_{GS} □ $-1V$, the negative potential will tend to pressure electrons towards the p-type substrate and attracts hole from p-type substrate. Therefore recombination occurs and will reduce the number of free electrons in the n-channel for conduction. Therefore with increased negative gate voltage I_D reduces.

For positive values, V_{gs} , additional electrons from p-substrate will flow into the channel and establish new carriers which will result in an increase in drain current with positive gate voltage.

Drain Characteristics



Transfer Characteristics

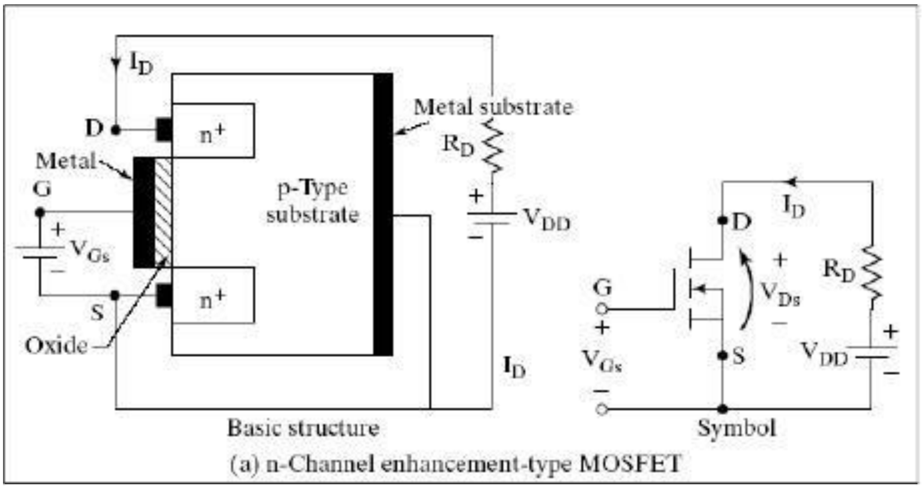


Enhancement Type MOSFET

Here current control in an n-channel device is now affected by positive gate to source voltage rather than the range of negative voltages of JFET's and depletion type MOSFET.

Basic Construction

A slab of p-type material is formed and two n-regions are formed in the substrate. The source and drain terminals are connected through metallic contacts to n-doped regions, but the absence of a channel between the doped n-regions. The SiO_2 layer is still present to isolate the gate metallic platform from the region between drain and source, but now it is separated by a section of p-type material.



(a) n-Channel enhancement-type MOSFET

Fig. 2.17: Structure of n-channel enhancement type MOSFET

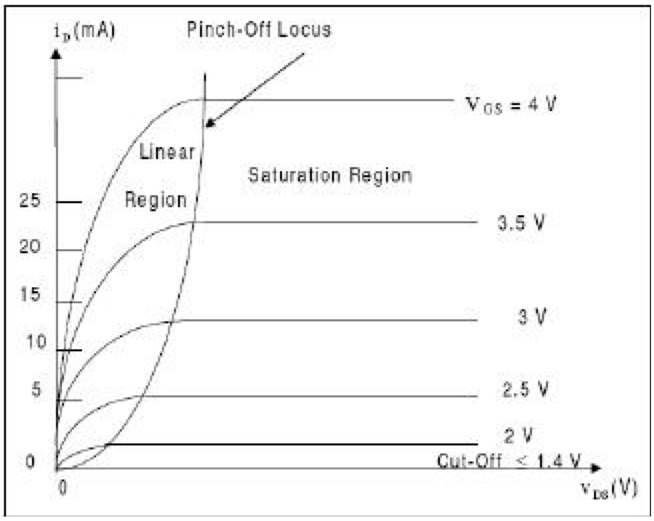
Operation

If $V_{GS} = 0V$ and a voltage is applied between the drain and source, the absence of a n-channel will result in a current of effectively zero amperes. With V_{DS} set at some positive voltage and V_{GS} set at 0V, there are two reverse biased p-n junction between the n-doped regions and p substrate to oppose any significant flow between drain and source.

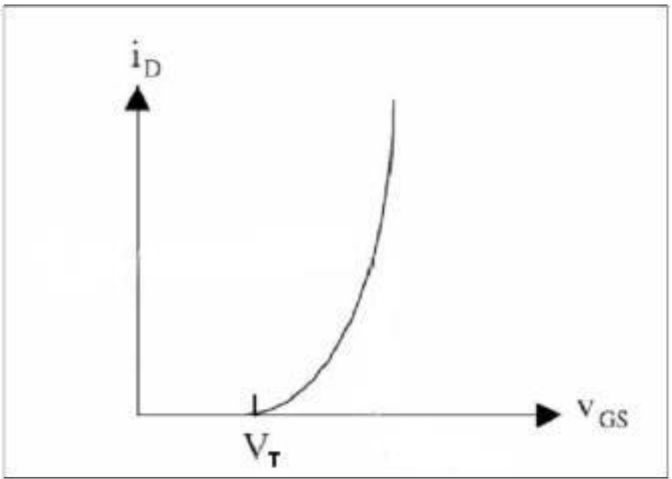
If both V_{DS} and V_{GS} have been set at some positive voltage, then positive potential at the gate will pressure the holes in the p-substrate along the edge of SiO_2 layer to leave the area and enter deeper region of p-substrate. However the electrons in the p-substrate will be attracted to the positive gate and accumulate in the region near the surface of the SiO_2 layer. The negative carriers will not be absorbed due to insulating SiO_2 layer, forming an inversion layer which results in current flow from drain to source.

The level of V_{GS} that result in significant increase in drain current is called threshold voltage V_T . As V_{GS} increases the density of free carriers will increase resulting in increased level of drain current. If V_{GS} is constant V_{DS} is increased; the drain current will eventually reach a saturation level as occurred in JFET.

Drain Characteristics

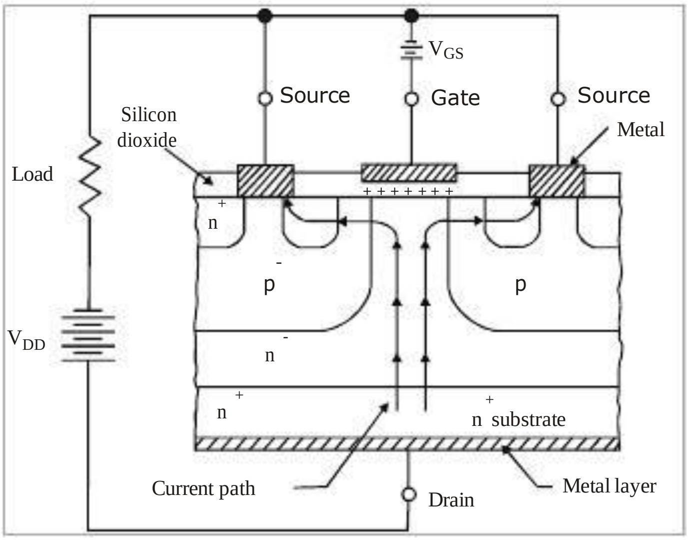


Transfer Characteristics



Power MOSFET’S

Power MOSFET’s are generally of enhancement type only. This MOSFET is turned ‘ON’ when a voltage is applied between gate and source. The MOSFET can be turned ‘OFF’ by removing the gate to source voltage. Thus gate has control over the conduction of the MOSFET. The turn-on and turn-off times of MOSFET’s are very small. Hence they operate at very high frequencies; hence MOSFET’s are preferred in applications such as choppers and inverters. Since only voltage drive (gate-source) is required, the drive circuits of MOSFET are very simple. The paralleling of MOSFET’s is easier due to their positive temperature coefficient. But MOSFTS's have high on-state resistance hence for higher currents; losses in the MOSFET's are substantially increased. Hence MOSFET's are used for low power applications.



Construction

Power MOSFET's have additional features to handle larger powers. On the n substrate high resistivity n^{-} layer is epitaxially grown. The thickness of n^{-} layer determines the voltage blocking capability of the device. On the other side of n substrate, a metal layer is deposited to form the drain terminal. Now p^{-} regions are diffused in the epitaxially grown n^{-} layer. Further n regions are diffused in the p^{-} regions as shown. SiO_2 layer is added, which is then etched so as to fit metallic source and gate terminals.

A power MOSFET actually consists of a parallel connection of thousands of basic MOSFET cells on the same single chip of silicon.

When gate circuit voltage is zero and V_{DD} is present, $n-\bar{p}$ junctions are reverse biased and no current flows from drain to source. When gate terminal is made positive with respect to source, an electric field is established and electrons from n^{-} channel in the p^{-} regions. Therefore a current from drain to source is established.

Power MOSFET conduction is due to majority carriers therefore time delays caused by removal of recombination of minority carriers is removed.

Because of the drift region the ON state drop of MOSFET increases. The thickness of the drift region determines the breakdown voltage of MOSFET. As seen a parasitic BJT is formed, since emitter base is shorted to source it does not conduct.

Switching Characteristics

The switching model of MOSFET's is as shown in the figure 6(a). The various inter electrode capacitance of the MOSFET which cannot be ignored during high frequency switching are represented by C_{gs}, C_{gd} & C_{ds} . The switching waveforms are as shown in figure **7.** The turn on time t_d is the time that is required to charge the input capacitance to the threshold voltage level. The rise time t_r is the gate charging time from this threshold level to the full gate voltage V_{gsp} . The turn off delay time t_{doff} is the time required for the input capacitance to discharge from overdriving the voltage V_1 to the pinch off region. The fall time is the time required for the input capacitance to discharge from pinch off region to the threshold voltage. Thus basically switching ON and OFF depend on the charging time of the input gate capacitance.

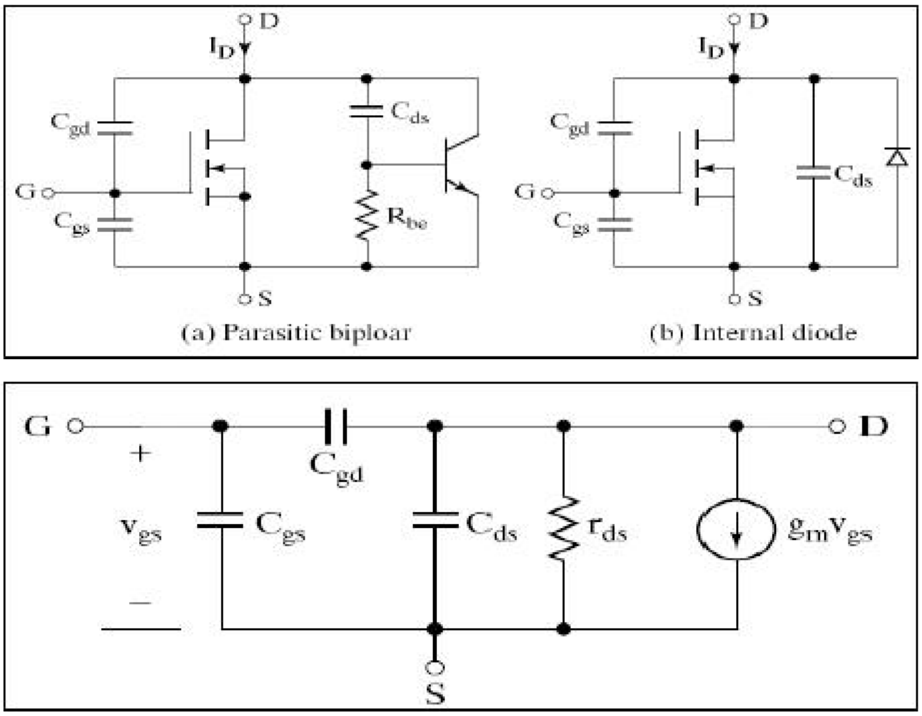


Fig.2.18: Switching model of MOSFET

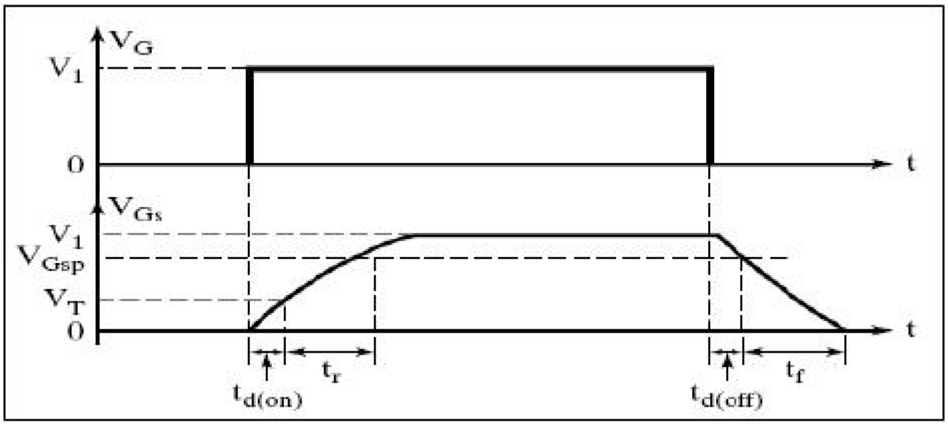


Fig2.19: Switching waveforms and times of Power MOSFET

Gate Drive

The turn-on time can be reduced by connecting a RC circuit as shown to charge the capacitance faster. When the gate voltage is turned on, the initial charging current of the capacitance is

$$I_G = \frac{V_G}{R_S}.$$

The steady state value of gate voltage is

$$V_{GS} = \frac{R_G V_G}{R_S + R_1 / R_G}.$$

Where R_S is the internal resistance of gate drive force.

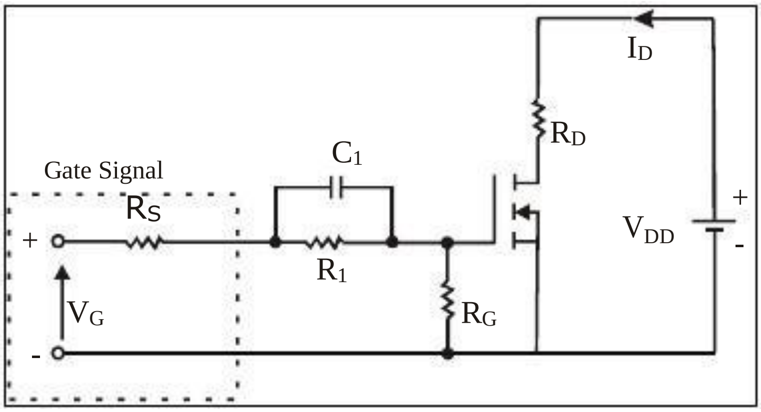


Fig.2.20: Fast turn on gate drive circuit 1

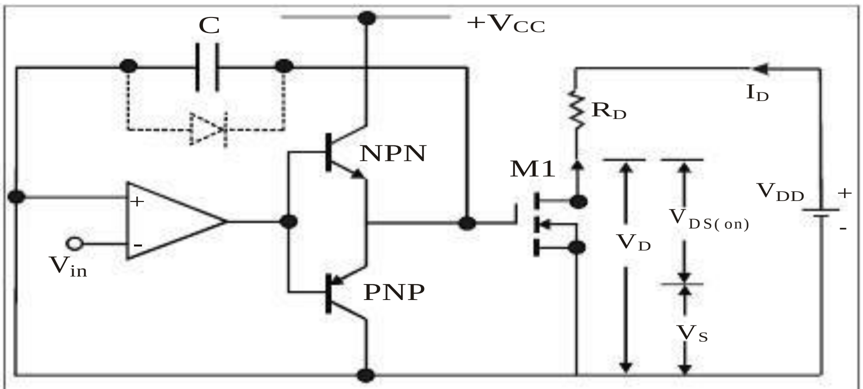


Fig.2.21: Fast turn on gate drive circuit 2

The above circuit is used in order to achieve switching speeds of the order of 100nsec or less. The above circuit as low output impedance and the ability to sink and source large currents. A totem poll arrangement that is capable of sourcing and sinking a large current is achieved by the PNP and NPN transistors. These transistors act as emitter followers and offer a low output impedance. These transistors operate in the linear region therefore minimize the delay time. The gate signal of the power MOSFET may be generated by an op-amp. Let V_{in} be a negative voltage and initially assume that the MOSFET is off therefore the non-inverting terminal of the op-amp is at zero potential. The op-amp output is high therefore the NPN transistor is on and is a source of a large current since it is an emitter follower. This enables the gate-source capacitance C_{gs} to quickly charge upto the gate voltage required to turn-on the power MOSFET. Thus high speeds are achieved. When V_{in} becomes positive the output of op-amp becomes negative the PNP transistor turns-on and the gate-source capacitor quickly discharges through the PNP transistor. Thus the PNP transistor acts as a current sink and the MOSFET is quickly turned-off. The capacitor C helps in regulating the rate of rise and fall of the gate voltage thereby controlling the rate of rise and fall of MOSFET drain current. This can be explained as follows

- The drain-source voltage $V_{DS} = V_{DD} - I_D R_D$.
- If I_D increases V_{DS} reduces. Therefore the positive terminal of op-amp which is tied to the source terminal of the MOSFET feels this reduction and this reduction is transmitted to gate through the capacitor ‘C’ and the gate voltage reduces and the drain current is regulated by this reduction.

Comparison of MOSFET with BJT

- Power MOSFETS have lower switching losses but its on-resistance and conduction losses are more. A BJT has higher switching loss bit lower conduction loss. So at high frequency applications power MOSFET is the obvious choice. But at lower operating frequencies BJT is superior.
- MOSFET has positive temperature coefficient for resistance. This makes parallel operation of MOSFET’s easy. If a MOSFET shares increased current initially, it heats up faster, its resistance increases and this increased resistance causes this current to shift to other devices in parallel. A BJT is a negative temperature coefficient, so current shaving resistors are necessary during parallel operation of BJT’s.
- In MOSFET secondary breakdown does not occur because it have positive temperature coefficient. But BJT exhibits negative temperature coefficient which results in secondary breakdown.
- Power MOSFET’s in higher voltage ratings have more conduction losses.
- Power MOSFET’s have lower ratings compared to BJT’s . Power MOSFET’s ⟶ 500V to 140A, BJT ⟶ 1200V, 800A.

2.7 Recommended questions:

1. Explain the control characteristics of the following semiconductor devices
   1) Power BJT 3) MOSFET 4) IGBT
2. Give the comparison between MOSFET and BJT.
3. Draw the circuit symbol of IGBT. Compare its advantages over MOSFET

4. Draw the switching model and switching waveforms of a power MOSFET, define the various switching applications.
5. With a circuit diagram and waveforms of base circuit voltage, base current and collector current under saturation for a power transistor, show the delay that occurs during the turn-ON and turn – OFF.
6. Explain the terms Overdrive factor (ODF) and forced beta for a power transistor for switching applications?
7. Explain the switching characteristics of BJT.
8. Explain the steady and switching characteristics of MOSFET.

2.8 Generic Skills / Outcomes:

- Explain steady state, switching characteristics and gate control requirements of different power transistors and their limitations.

2.9 Further Reading

1. http://books.google.co.in/books/about/Power_Electronics.html?id=-WqvjxMXClAC
2. http://www.flipkart.com/power-electronic-2ed/p/itmczynuyqnbvzzj
3. http://www.scribd.com/doc/36550374/Power-Electronics-Notes
4. http://elearning.vtu.ac.in/EC42.html
5. http://www.onlinevideolecture.com/electrical-engineering/nptel-iit-bombay/power-electronics/?course_id=510

MODULE - 3
THYRISTORS

Structure

3.0 Introduction
3.1 Objectives
3.2 Silicon Controlled Rectifier
3.3 Thyristor Gate Characteristics
3.4 Quantitative Analysis
3.5 Switching Characteristics
3.6 Gate Trigger Methods
3.7 Assignment Questions
3.8 Outcomes
3.9 Further Readings

3.0 Introduction

A thyristor is the most important type of power semiconductor devices. They are extensively used in power electronic circuits. They are operated as bi-stable switches from non-conducting to conducting state.

A thyristor is a four layer, semiconductor of p-n-p-n structure with three p-n junctions. It has three terminals, the anode, cathode and the gate.

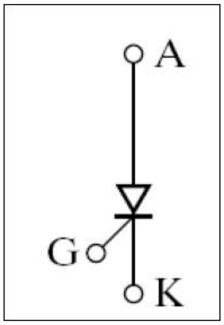
The word thyristor is coined from thyratron and transistor. It was invented in the year 1957 at Bell Labs. The Different types of Thyristors are

- Silicon Controlled Rectifier (SCR).
- TRIAC
- DIAC
- Gate Turn Off Thyristor

3.1Objectives:

- To explain different types of Thyristors, their gate characteristics and gate control requirements.

3.2 Silicon Controlled Rectifier (SCR)



The SCR is a four layer three terminal device with junctions as shown. The construction of SCR shows that the gate terminal is kept nearer the cathode. The approximate thickness of each layer and doping densities are as indicated in the figure. In terms of their lateral dimensions Thyristors are the largest semiconductor devices made. A complete silicon wafer as large as ten centimeter in diameter may be used to make a single high power thyristor.

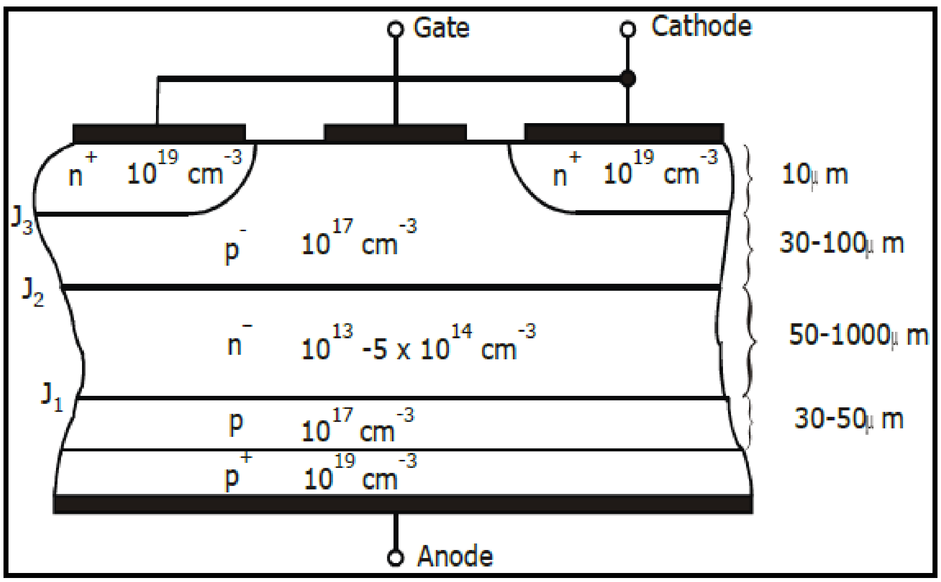


Fig.3.1: Structure of a generic thyristor

Qualitative Analysis

When the anode is made positive with respect the cathode junctions 1 3 *J* & *J* are forward biased and junction 2 *J* is reverse biased. With anode to cathode voltage *AK V* being small, only leakage current flows through the device. The SCR is then said to be in the forward blocking state. If *AK V* is further increased to a large value, the reverse biased junction 2 *J* will breakdown due to avalanche effect resulting in a large current through the device. The voltage at which this phenomenon occurs is called the forward breakdown voltage *BO V* .

Since the other junctions 1 3 *J* & *J* are already forward biased, there will be free movement of carriers across all three junctions resulting in a large forward anode current. Once the SCR is switched on, the voltage drop across it is very small, typically 1 to 1.5V. The anode current is limited only by the external impedance present in the circuit.

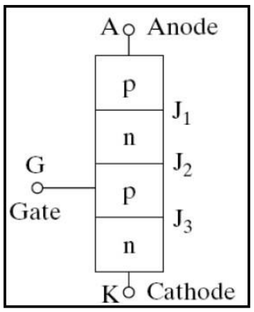
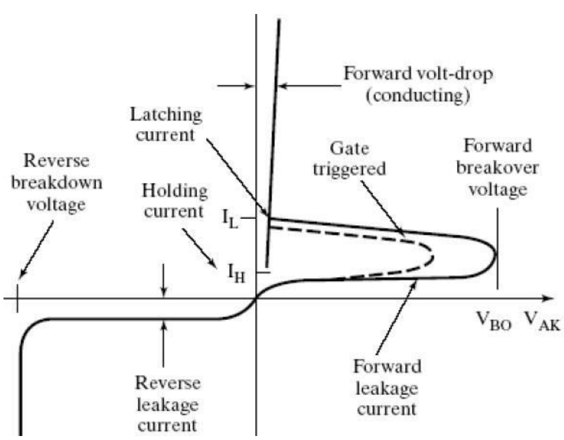


Fig.3.2: Simplified model of a thyristor

Although an SCR can be turned on by increasing the forward voltage beyond *BO V* , in practice, the forward voltage is maintained well below *BO V* and the SCR is turned on by applying a positive voltage between gate and cathode.

With the application of positive gate voltage, theleakage current through the junction 2 *J* is increased. This is because the resulting gate current consists mainly of electron flow from cathode to gate. Since the bottom end layer is heavily doped as compared to the p-layer, due to the applied voltage, some of these electrons reach junction 2 *J* and add to the minority carrier concentration in the p-layer. This raises the reverse leakage current and results in breakdown of junction 2 *J* even though the applied forward voltage is less than the breakdown voltage *BO V* . With increase in gate current
breakdown occurs earlier.

V-I Characteristics

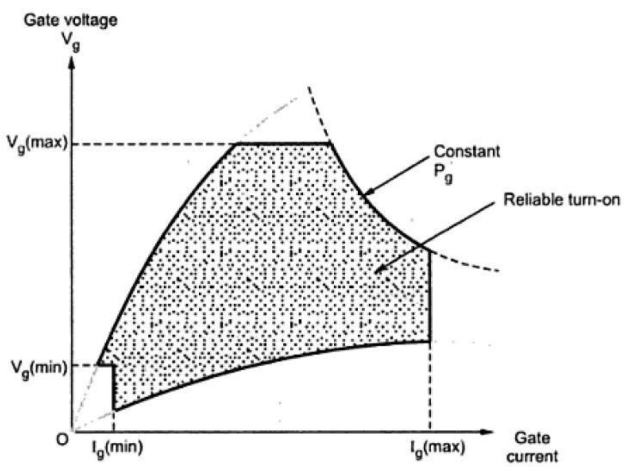


A typical V-I characteristics of a thyristor is shown above. In the reverse direction the thyristor appears similar to a reverse biased diode which conducts very little current until avalanche breakdown occurs. In the forward direction the thyristor has two stable states ormodes of operation that are connected together by an unstable mode that appears as anegative resistance on the V-I characteristics. The low current high voltage region is the 1forward blocking state or the off state and the low voltage high current mode is the on state.

For the forward blocking state the quantity of interest is the forward blocking voltage *BO V* which is defined for zero gate current. If a positive gate current is applied to a thyristor then the transition or break over to the on state will occur at smaller values of anode to cathode voltage as shown. Although not indicated the gate current does not have to be a dc current but instead can be a pulse of current having some minimum time duration. This ability to switch the thyristor by means of a current pulse is the reason for wide spread applications of the device.

Holding Current *H I*
After an SCR has been switched to the on state a certain minimum value of anode +current is required to maintain the thyristor in this low impedance state. If the anode current is reduced below the critical holding current value, the thyristor cannot maintain the current through it and reverts to its off state usually *I* is associated with turn off the device.
Latching Current *L I*
After the SCR has switched on, there is a minimum current required to sustain conduction. This current is called the latching current. *L I* associated with turn on and is usually greater than holding current.

3.3 Thyristor Gate Characteristics



The gate voltage is plotted with respect to gate current in the above characteristics. Ig(max) is the maximum gate current that can flow through the thyristor without damaging it Similarly Vg(max) is the maximum gate voltage to be applied. Similarly Vg (min) and Ig(min) are minimum gate voltage and current, below which thyristor will not be turned-on. Hence to turn-on the thyristor successfully the gate current and voltage should be

$$I_{g(min)} < I_g < I_{g(max)}$$

$$V_{g\,(min)} < V_g < V_{g\,(max)}$$

The characteristic of Fig. also shows the curve for constant gate power (Pg). Thus for reliable turn-on, the (Vg, Ig) point must lie in the shaded area in Fig. 3.6. It turns-on thyristor successfully. Note that any spurious voltage/current spikes at the gate must be less than Vg (min) and Ig(min) to avoid false triggering of the thyristor. The gate characteristics shown in Fig. 3.6 are for DC values of gate voltage and current.

Instead of applying a continuous (DC) gate drive, the pulsed gate drive is used. The gate voltage and current are applied in the form of high frequency pulses. The frequency of these pulses is upto l0 kHz. Hence the width of the pulse can be upto 100 micro seconds. The pulsed gate drive is applied for following reasons (advantages):

i) The thyristor has small turn-on time i.e. upto 5 microseconds. Hence a pulse of gate drive is sufficient to turn-on the thyristor.

ii) Once thyristor turns-on, there is no need of gate drive. Hence gate drive in the form of pulses is suitable.

iii) The DC gate voltage and current increases losses in the thyristor. Pulsed gate drive has reduced losses.

iv) The pulsed gate drive can be easily passed through isolation transformers to isolate thyristor and trigger circuit.

Requirement of Gate Drive

The gate drive has to satisfy the following requirements

: i) The maximum gate power should not be exceeded by gate drive, otherwise thyristor will be damaged

. ii) The gate voltage and current should be within the limits specified by gate characteristics (Fig. 3.6) for successful turn-on

. iii) The gate drive should be preferably pulsed. In case of pulsed drive the following relation must be satisfied: (Maximum gate power x pulse width) x (Pulse frequency) ≤ Allowable average gate power

iv) The width of the pulse should be sufficient to turn-on the thyristor successfully.

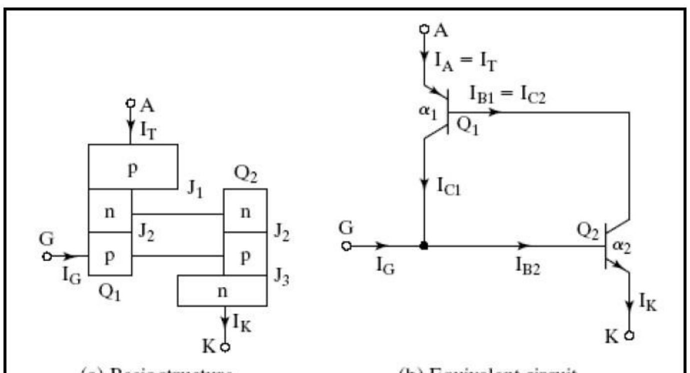
v) The gate drive should be isolated electrically from the thyristor. This avoids any damage to the trigger circuit if in case thyristor is damaged.

vi) The gate drive should not exceed permissible negative gate to cathode voltage, otherwise the thyristor is damaged.

vii) The gate drive circuit should not sink current out of the thyristor after turn-on.

3.4 Quantitative Analysis

Two Transistor Model



(a) Basic structure (b) Equivalent circuit

The general transistor equations are,

$$I_C = \beta I_B + \; 1+\beta \; I_{CBO}$$

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

$$I_E = I_C + I_B$$

$$I_B = I_E \; 1-\alpha \; - I_{CBO}$$

The SCR can be considered to be made up of two transistors as shown in above figure. Considering PNP transistor of the equivalent circuit,

$$I_{E_1} = I_A, I_C = I_{C_1}, \alpha = \alpha_1, I_{CBO} = I_{CBO_1}, I_B = I_{B_1}$$

$$\therefore \quad I_{B_1} = I_A \; 1-\alpha_1 \; - I_{CBO_1} \quad ---$$

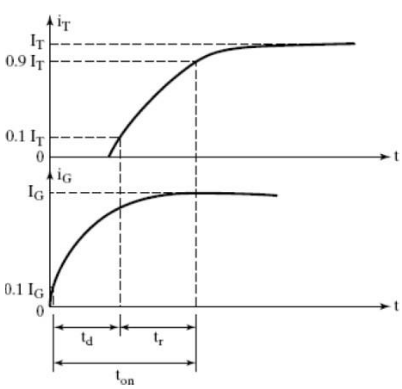
From the equivalent circuit, we see that

$$\therefore \quad I_{C_2} = I_{B_1}$$

$$\Rightarrow \quad I_A = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{1- \; \alpha_1 + \alpha_2}$$

3.5 Switching Characteristics (Dynamic characteristics)

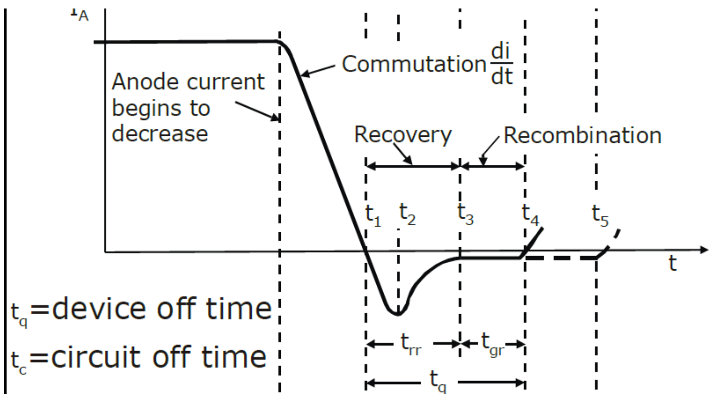
Thyristor Turn-ON Characteristics



When the SCR is turned on with the application of the gate signal, the SCR does not conduct fully at the instant of application of the gate trigger pulse. In the beginning, there is no appreciable increase in the SCR anode current, which is because, only a small portion of the

silicon pellet in the immediate vicinity of the gate electrode starts conducting. The duration between 90% of the peak gate trigger pulse and the instant the forward voltage has fallen to 90% of its initial value is called the gate controlled / trigger delay time *gd t* . It is also defined as the duration between 90% of the gate trigger pulse and the instant at which the anode current rises to 10% of its peak value. *gd t* is usually in the range of 1 sec.

Thyristor Turn OFF Characteristics



When an SCR is turned on by the gate signal, the gate loses control over the device and the device can be brought back to the blocking state only by reducing the forward current to a level below that of the holding current. In AC circuits, however, the current goes through a natural zero value and the device will automatically switch off. But in DC circuits, where no neutral zero value of current exists, the forward current is reduced by applying a reverse voltage across anode and cathode and thus forcing the current through the SCR to zero.

As in the case of diodes, the SCR has a reverse recovery time *rr t* which is due to charge storage in the junctions of the SCR. These excess carriers take some time for recombination resulting in the gate recovery time or reverse recombination time *gr t* . Thus, the turn-off time *q t* is the sum of the durations for which reverse recovery current flows after the application of reverse voltage and the time required for the recombination of all excess carriers present. At the end of the turn off time, a depletion layer develops across 2 *J* and the junction can now withstand the forward voltage. The turn off time is dependent on the anode current, the magnitude of reverse *g V* applied ad the magnitude and rate of application of the forward voltage. The turn off time for converte grade SCR's is 50 to 100 sec and that for inverter grade SCR's is 10 to 20 sec.

To ensure that SCR has successfully turned off , it is required that the circuit off time *c t* be greater than SCR turn off time *q t* .

Thyristor Turn ON

Thermal Turn on: If the temperature of the thyristor is high, there will be an increase in charge carriers which would increase the leakage current. This would cause an increase in 1 & 2 and the thyristor may turn on. This type of turn on many cause thermal run away and is usually avoided.

Light: If light be allowed to fall on the junctions of a thyristor, charge carrier concentration would increase which may turn on the SCR.

LASCR: Light activated SCRs are turned on by allowing light to strike the silicon wafer.

High Voltage Triggering: This is triggering without application of gate voltage with only application of a large voltage across the anode-cathode such that it is greater than the forward breakdown voltage *BO V* **.** This type of turn on is destructive and should be avoided.

Gate Triggering: Gate triggering is the method practically employed to turn-on the thyristor. Gate triggering will be discussed in detail later.

dv

dt

Triggering: Under transient conditions, the capacitances of the p-n junction will influence the characteristics of a thyristor. If the thyristor is in the blocking state, a rapidly rising voltage applied across the device would cause a high current to flow through the device resulting in turn-on. If

*j*2 *i* is the current throught the junction 2 *j* and

*j*2 *C* is the junction capacitance and

*j*2 *V* is the voltage across 2 *j* , then

$$i_{j_2} = \frac{dq_2}{dt} = \frac{d}{dt} \; C_{j_2} V_{j_2} \; = \frac{C_{j_2} dV_{J2}}{dt} + V_{j_2} \frac{dC_{j_2}}{dt}$$

Thyristor Ratings

VOLTAGE RATINGS

V_{DWM} : This specifies the peak off state working forward voltage of the device. This specifies the maximum forward off state voltage which the thyristor can withstand during its working.

V_{DRM} : This is the peak repetitive off state forward voltage that the thyristor can block repeatedly in the forward direction (transient).

V_{DSM} : This is the peak off state surge / non-repetitive forward voltage that will occur across the thyristor.

V_{RWM} : This the peak reverse working voltage that the thyristor can withstand in the reverse direction.

V_{RRM} : It is the peak repetitive reverse voltage. It is defined as the maximum permissible instantaneous value of repetitive applied reverse voltage that the thyristor can block in reverse direction.

V_{RSM} : Peak surge reverse voltage. This rating occurs for transient conditions for a specified time duration.

V_T : On state voltage drop and is dependent on junction temperature.

V_{TM} : Peak on state voltage. This is specified for a particular anode current and junction temperature.

$\frac{dv}{dt}$ rating: This is the maximum rate of rise of anode voltage that the SCR has to withstand and which will not trigger the device without gate signal (refer dv

Current Rating

$I_{Taverage}$: This is the on state average current which is specified at a particular temperature.

I_{TRMS} : This is the on-state RMS current.

Latching current, I_L : After the SCR has switched on, there is a minimum current required to sustain conduction. This current is called the latching current. I_L associated with turn on and is usually greater than holding current

Holding current, I_H : After an SCR has been switched to the on state a certain minimum value of anode current is required to maintain the thyristor in this low impedance state. If the anode current is reduced below the critical holding current value, the thyristor cannot maintain the current through it and reverts to its off state usually $I_{\square}$ is associated with turn off the device.

$\frac{di}{dt}$ rating: This is a non repetitive rate of rise of on-state current. This maximum value of rate of rise of current is which the thyristor can withstand without destruction. When thyristor is switched on, conduction starts at a place near the gate. This small area of conduction spreads rapidly and if rate of rise of anode current di

carriers, local hotspots will be formed near the gate due to high current density

Gate Specifications

I_{GT} : This is the required gate current to trigger the SCR. This is usually specified as a DC value.

V_{GT} : This is the specified value of gate voltage to turn on the SCR (dc value).

V_{GD} : This is the value of gate voltage, to switch from off state to on state. A value below this will keep the SCR in off state.

Q_{RR} : Amount of charge carriers which have to be recovered during the turn off process.

Rthjc : Thermal resistance between junction and outer case of the device.

3.6 Gate Triggering Methods

Types

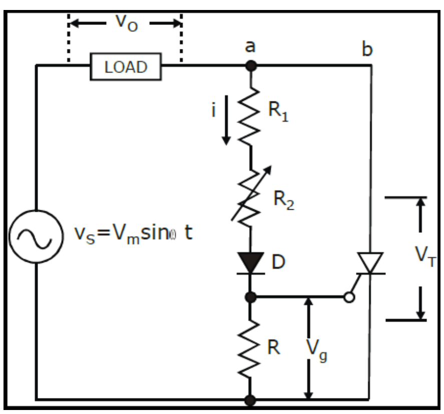
The different methods of gate triggering are the following

- R-triggering.
- RC triggering.
- UJT triggering

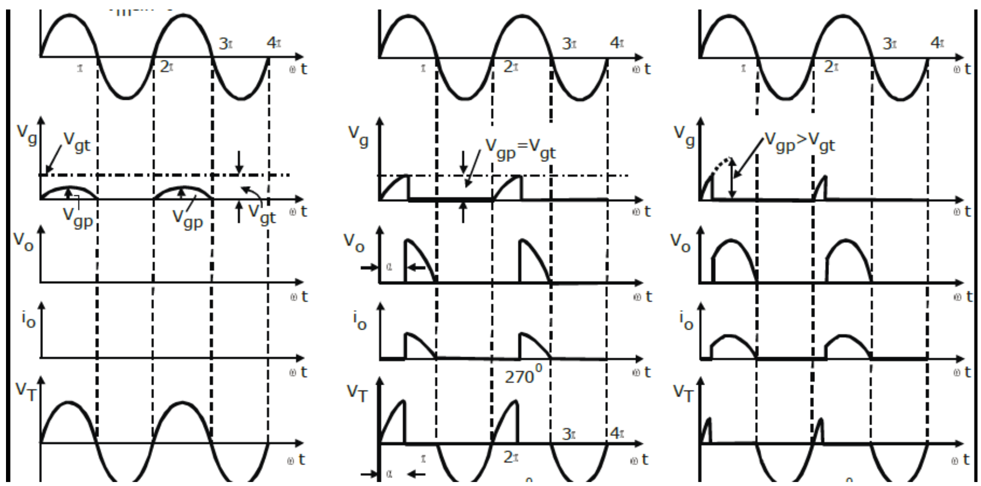
Resistance Triggering

A simple resistance triggering circuit is as shown. The resistor 1 *R* limits the current through the gate of the SCR. 2 *R* is the variable resistance added to the circuit to achieve control over the triggering angle of SCR. Resistor 'R' is a stabilizing resistor. The diode D is required to ensure that no negative voltage reaches the gate of the

SC



R.



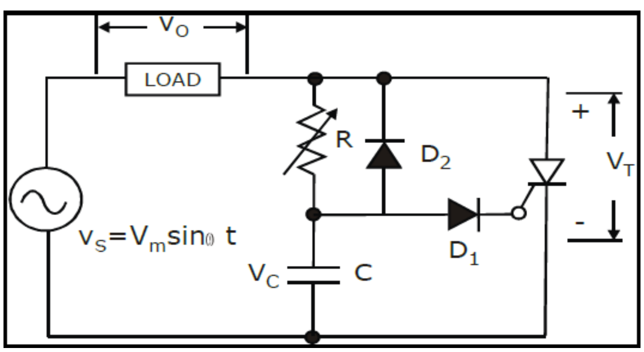
Resistance Capacitance Triggering

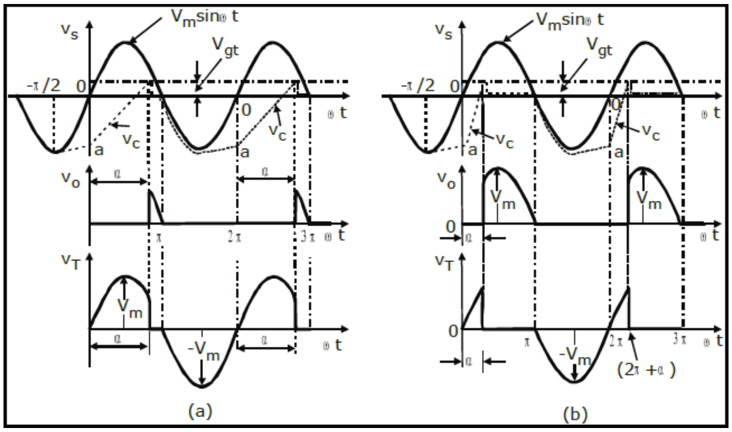
RC Half Wave

Capacitor 'C' in the circuit is connected to shift the phase of the gate voltage. 1 *D* is used to prevent negative voltage from reaching the gate cathode of SCR.

In the negative half cycle, the capacitor charges to the peak negative voltage of the supply *m V* through the diode 2 *D* . The capacitor maintains this voltage across it, till the supply voltage crosses zero. As the supply becomes positive, the capacitor charges through resistor 'R' from initial voltage of *m V* , to a positive value.

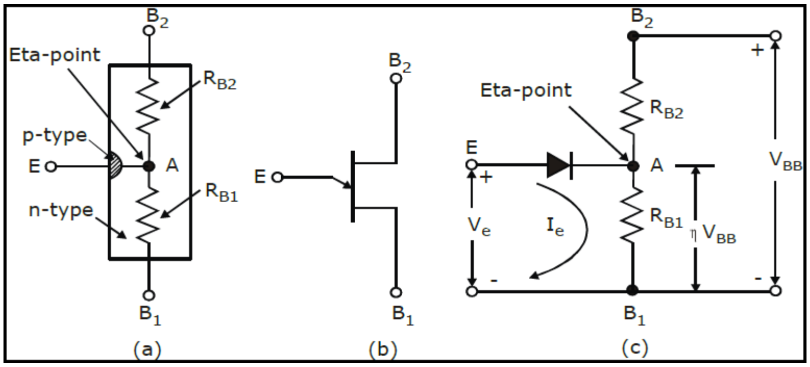
When the capacitor voltage is equal to the gate trigger voltage of the SCR, the SCR is fired and the capacitor voltage is clamped to a small positive value.





Case 1: R Large.
When the resistor 'R' is large, the time taken for the capacitance to charge from *m V* to *gt V* is large, resulting in larger firing angle and lower load voltage.
Case 2: R Small
When 'R' is set to a smaller value, the capacitor charges at a faster rate towards *gt V* resulting in early triggering of SCR and hence *L V* is more. When the SCR triggers, the voltage drop across it falls to 1 – 1.5V. This in turn lowers, the voltage across R & C. Low voltage across the SCR during conduction period keeps the capacitor discharge during the positive half cycle.

UNI-JUNCTION TRANSISTOR (UJT)



UJT is an n-type silicon bar in which p-type emitter is embedded. It has three terminals base1, base2 and emitter 'E'. Between 1 *B* and 2 *B* UJT behaves like ordinary resistor and the internal resistances are given as *B*1 *R* and *B*2 *R* with emitter open *BB B*1 *B*2 *R R R* . Usually the p-region is heavily doped and n-region is lightly doped. The equivalent circuit of UJT is as shown. When *BB V* is applied across 1 *B* and 2 *B* , we find that potential at A is

Operation

When voltage *BB V* is applied between emitter 'E' with base 1 1 *B* as reference and the emitter voltage *E V* is less than *D BE V V* the UJT does not conduct. *D BB V V* is designated as *P V* which is the value of voltage required to turn on the UJT. Once *E V* is equal to *P BE D V V V* , then UJT is forward biased and it conducts.

The peak point is the point at which peak current *P I* flows and the peak voltage *P V* is across the UJT. After peak point the current increases but voltage across device drops, this is due to the fact that emitter starts to inject holes into the lower doped n-region. Since p-region is heavily doped compared to n-region. Also holes have a longer life time, therefore number of carriers in the base region increases rapidly. Thus potential at 'A' falls but current *E I* increases rapidly. *B*1 *R* acts as a decreasing resistance.

The negative resistance region of UJT is between peak point and valley point. After valley point, the device acts as a normal diode since the base region is saturated and *B*1 *R* does not decrease again.

$$V_{AB1} = \frac{V_{BB} R_{B1}}{R_{B1} + R_{B2}} = \eta V_{BB} \left[\eta = \frac{R_{B1}}{R_{B1} + R_{B2}} \right]$$

(i) Expression for period of oscillation„t"

The period of oscillation of the UJT can be derived based on the voltage across the capacitor. Here we assume that the period of charging of the capacitor is lot larger than than the discharging time. Using initial and final value theorem for voltage across a capacitor, we get

$$V_C = V_{final} + V_{initial} - V_{final} \quad e^{-t/RC}$$

$$t = T, V_C = V_P, V_{initial} = V_V, V_{final} = V_{BB}$$

Therefore $\quad V_P = V_{BB} + V_V - V_{BB} \quad e^{-T/RC}$

$$\Rightarrow \qquad T = RC \log_e \left(\frac{V_{BB} - V_V}{V_{BB} - V_P} \right)$$

If

$$V_V < V_{BB},$$

$$T = RC \ln \left(\frac{V_{BB}}{V_{BB} - V_P} \right)$$

$$T = RC \ln \left[\frac{1}{1 - \eta} \right]$$

3.7 Assignment Questions

1 Distinguish between latching current and holding current.
2. Converter grade and inverter grade thyristors
3. Thyristor turn off and circuit turn off time
4. Peak repetitive forward blocking voltage $i^2 t$ rating
5. Explain the turn on and turn of dynamic characteristics of thyristor
6. A string of series connected thyristors is to withstand a DC voltage of 12 KV. The maximum leakage current and recovery charge differences of a thyristors are 12 mA and 120 µC respectively. A de-rating factor of 20% is applied for the steady state and dynamic (transient) voltage sharing of the thyristors. If the maximum steady sate voltage is 1000V, determine 1) the steady voltage sharing resistor R for each thyristor. 2) the transient voltage capacitor C1 for each thryristor
7. A SCR is to operate in a circuit where the supply voltage is 200 VDC. The dv/dt should be limited to 100 V/ µs. Series R and C are connected across the SCR for limiting dv/dt. The maximum discharge current from C into the SCR, if and when it is turned ON is to be limited to 100 A. Using an approximate expression, obtain the values of R and C.
8. With the circuit diagram and relevant waveforms,

3.8 Generic Skills / Outcomes:

- Discuss different types of Thyristors, their operation, gate characteristics and gate control requirements.

3.9 Further Reading

1. http://books.google.co.in/books/about/Power_Electronics.html?id=-WqvjxMXClAC
2. http://www.flipkart.com/power-electronic-2ed/p/itmczynuyqnbvzzj
3. http://www.scribd.com/doc/36550374/Power-Electronics-Notes
4. http://elearning.vtu.ac.in/EC42.html
5. http://www.onlinevideolecture.com/electrical-engineering/nptel-iit-bombay/power-electronics/?course_id=510

Module 4(a)

CONTROLLED RECTIFIERS

Structure

4.0 Introduction
4.1 Objectives
4.2 Line Commutated AC to DC Converters
4.3 Application Of Phase Controlled Rectifiers
4.4 Single Phase Half Wave Rectifier
4.5 Assignment Questions
4.6 Outcomes
4.7 Further Reading

4.0 Introduction

Thyristors are semicontrolled devices which can be turned ON by applying a current pulse at its gate terminal at a desired instance. However, they cannot be turned off from the gate terminals. Therefore, the fully controlled converter continues to exhibit load dependent output voltage / current waveforms as in the case of their uncontrolled counterpart. However, since the thyristor can block forward voltage, the output voltage / current magnitude can be controlled by controlling the turn on instants of the thyristors. Working principle of thyristors based single phase fully controlled converters will be explained first in the case of a single thyristor halfwave rectifier circuit supplying an R or R-L load. However, such converters are rarely used in practice.

Full bridge is the most popular configuration used with single phase fully controlled rectifiers. Analysis and performance of this rectifier supplying an R-L-E load (which may represent a dc motor) will be studied in detail in this

4.1 Objectives:

- To explain the design, analysis techniques, performance parameters and characteristics of controlled rectifiers

4.2 Line Commutated AC to DC converters

Type of input: Fixed voltage, fixed frequency ac power supply.

• Type of output: Variable dc output voltage

• Type of commutation: Natural / AC line commutation

Different types of Line Commutated Converters

• AC to DC Converters (Phase controlled rectifiers)

• AC to AC converters (AC voltage controllers)

• AC to AC converters (Cyclo converters) at low output frequency

Differences Between Diode Rectifiers & Phase Controlled Rectifiers

• The diode rectifiers are referred to as uncontrolled rectifiers .

• The diode rectifiers give a fixed dc output voltage .

• Each diode conducts for one half cycle.

• Diode conduction angle = 1800 or radians.

• We cannot control the dc output voltage or the average dc load current in a diode rectifier circuit

4.3 Applications of Phase Controlled Rectifiers

• DC motor control in steel mills, paper and textile mills employing dc motor drives.

• AC fed traction system using dc traction motor.

• Electro-chemical and electro-metallurgical processes.

• Magnet power supplies.

• Portable hand tool drives

Classification of Phase Controlled Rectifiers

• Single Phase Controlled Rectifiers.

• Three Phase Controlled Rectifiers

4.3.1 Different types of Single Phase Controlled Rectifiers.

• Half wave controlled rectifiers.

• Full wave controlled rectifiers.

• Using a center tapped transformer.

• Full wave bridge circuit.

• Semi converter.

• Full converter.

Different Types of Three Phase Controlled Rectifiers

• Half wave controlled rectifiers.

• Full wave controlled rectifiers.

• Semi converter (half controlled bridge converter).

• Full converter (fully controlled bridge converter).

4.4 Principle of Phase Controlled Rectifier Operation Single Phase Half-Wave Thyristor

Converter with a Resistive Load

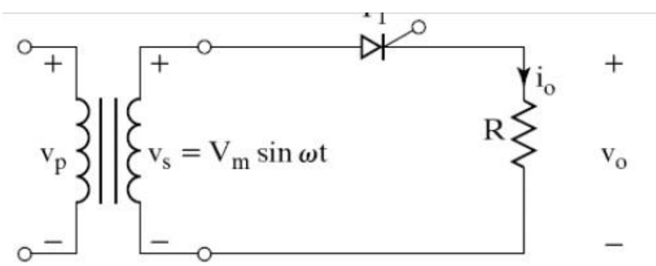
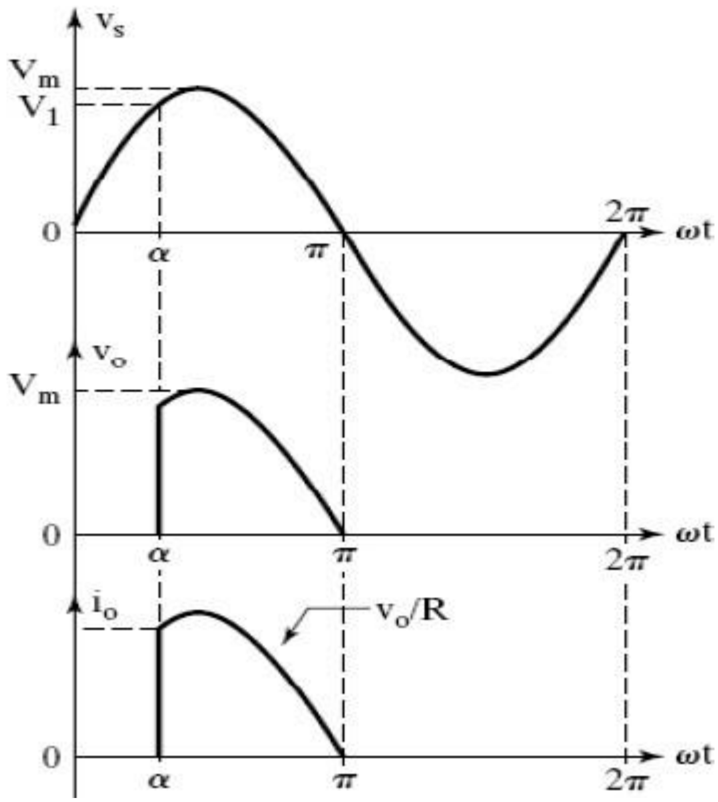


Fig. shows the circuit diagram of a single phase fully controlled halfwave rectifier supplying a purely resistive load. At $\omega t = 0$ when the input supply voltage becomes positive the thyristor T becomes forward biased. However, unlike a diode, it does not turn ON till a gate pulse is applied at $\omega t = \alpha$. During the period $0 < \omega t \leq \alpha$ the thyristor blocks the supply voltage and the load voltage remains zero as shown in Consequently, no load current flows during this interval. As soon as a gate pulse is applied to the thyristor at $\omega t = \alpha$ it turns ON. The voltage across the thyristor collapses to almost zero and the full supply voltage appears across the load. From this point onwards the load voltage follows the supply voltage. The load being purely resistive the load current i_O is proportional to the load voltage. At $\omega t = \pi$ as the supply voltage passes through the negative going zero crossing the load voltage and hence the load current becomes zero and tries to reverse direction. In the process the thyristor undergoes reverse recovery and starts blocking the negative supply voltage. Therefore, the load voltage and the load current remains clamped at zero till the thyristor is fired again at $\omega t = 2\pi + \alpha$. The same process repeats there after.



Equations:

$v_s = V_m \sin\omega t =$ i/p ac supply voltage

$V_m =$ max. value of i/p ac supply voltage

$V_S = \frac{V_m}{\sqrt{2}} =$ RMS value of i/p ac supply voltage

$v_O = v_L =$ output voltage across the load

When the thyristor is triggered at $\omega t = \alpha$

$v_O = v_L = V_m \sin\omega t;\ \omega t = \alpha$ to π

$i_O = i_L = \frac{v_O}{R} =$ Load current; $\omega t = \alpha$ to π

To Derive an Expression for the Average (DC) Output Voltage across the Load

Maximum average (dc) o/p voltage is obtained when 0 and the maximum dc output voltage

$$V_{O\ dc} = V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} v_O.d\ \ \omega t\ ;$$

$$v_O = V_m \sin\omega t\ for\ \ \omega t = \alpha\ \ to\ \ \pi$$

$$V_{O\ dc} = V_{dc} = \frac{1}{2\pi}\int_\alpha^{\pi} V_m \sin\omega t.d\ \ \omega t$$

$$V_{O\ dc} = \frac{1}{2\pi}\int_\alpha^{\pi} V_m \sin\omega t.d\ \ \omega t$$

$$V_{O\ dc} = \frac{V_m}{2\pi}\int_\alpha^{\pi} \sin\omega t.d\ \ \omega t$$

$$V_{O\ dc} = \frac{V_m}{2\pi}\int_\alpha^{\pi} \sin\omega t.d\ \ \omega t$$

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

$$V_{O\ dc} = \frac{V_m}{2\pi}\ \ -\cos\pi + \cos\alpha\ \ ;\ \ \cos\pi = -1$$

$$V_{O\ dc} = \frac{V_m}{2\pi}\ \ 1 + \cos\alpha\ \ \ ;\ V_m = \sqrt{2}V_S$$

To Derive an Expression for the RMS Value of Output Voltage of a Single Phase Half Wave Controlled Rectifier with Resistive Load

The RMS output voltage is given by

$$V_{O\ RMS} = \left[\frac{1}{2\pi} \int_0^{2\pi} v_O^2 . d\ \ \omega t \right]$$

Output voltage $v_O = V_m \sin \omega t$; for $\omega t = \alpha$ to π

$$V_{O\ RMS} = \left[\frac{1}{2\pi} \int_\alpha^{\pi} V_m^2 \sin^2 \omega t . d\ \ \omega t \right]^{\frac{1}{2}}$$

By substituting $\sin^2 \omega t = \dfrac{1-\cos 2\omega t}{2}$, we get

$$V_{O\ RMS} = \left[\frac{1}{2\pi} \int_\alpha^{\pi} V_m^2 \frac{1-\cos 2\omega t}{2} . d\ \ \omega t \right]^{\frac{1}{2}}$$

$$V_{O\ RMS} = \frac{V_m}{2} \left[\frac{1}{\pi} \left(\pi - \alpha\ - \frac{\sin 2\pi - \sin 2\alpha}{2} \right) \right]^{\frac{1}{2}} ; \sin 2\pi = 0$$

Performance Parameters of Phase Controlled Rectifiers

Output dc power (avg. or dc o/p power delivered to the load)

$$P_{O\,dc} = V_{O\,dc} \times I_{O\,dc} \;;\; i.e.,\; P_{dc} = V_{dc} \times I_{dc}$$

Where

$V_{O\,dc} = V_{dc} =$ avg./ dc value of o/p voltage.

$I_{O\,dc} = I_{dc} =$ avg./dc value of o/p current

Output ac power

$$P_{O\,ac} = V_{O\,RMS} \times I_{O\,RMS}$$

Efficiency of Rectification (Rectification Ratio)

$$\text{Efficiency } \eta = \frac{P_{O\,dc}}{P_{O\,ac}};\; \%\text{ Efficiency } \eta = \frac{P_{O\,dc}}{P_{O\,ac}} \times 100$$

The o/p voltage consists of two components

The dc component $V_{O\,dc}$

The ac /ripple component $V_{ac} = V_{r(ms)}$

Output ac power

$$P_{O\,ac} = V_{O\,RMS} \times I_{O\,RMS}$$

Efficiency of Rectification (Rectification Ratio)

$$\text{Efficiency } \eta = \frac{P_{O\,dc}}{P_{O\,ac}};\; \%\text{ Efficiency } \eta = \frac{P_{O\,dc}}{P_{O\,ac}} \times 100$$

The o/p voltage consists of two components

The dc component $V_{O\,dc}$

The ac /ripple component $V_{ac} = V_{r(ms)}$

The Ripple Factor (RF) w.r.t output voltage waveform

$$r_v = RF = \frac{V_{r(rms)}}{V_{O(dc)}} = \frac{V_{ac}}{V_{dc}}$$

$$r_v = \frac{\sqrt{V_{O(RMS)}^2 - V_{O(dc)}^2}}{V_{O(dc)}} = \sqrt{\left[\frac{V_{O(RMS)}}{V_{O(dc)}}\right]^2 - 1}$$

$$r_v = \sqrt{FF^2 - 1}$$

Current Ripple Factor $r_i = \frac{I_{r\ rms}}{I_{O\ dc}} = \frac{I_{ac}}{I_{dc}}$

Where $I_{r\ rms} = I_{ac} = \sqrt{I_{O\ RMS}^2 - I_{O\ dc}^2}$

$V_{r\ pp}$ = peak to peak ac ripple output voltage

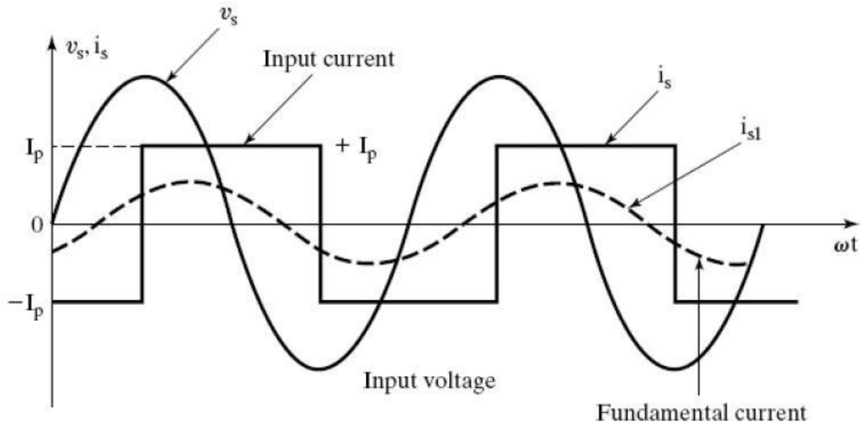
$$V_{r\ pp} = V_{O\ \max} - V_{O\ \min}$$

$I_{r\ pp}$ = peak to peak ac ripple load current

$$I_{r\ pp} = I_{O\ \max} - I_{O\ \min}$$

Transformer Utilization Factor (TUF)

$$TUF = \frac{P_{O\ dc}}{V_S \times I_S}$$



Harmonic Factor (HF) or Total Harmonic Distortion Factor

$$HF = \left[\frac{I_S^2 - I_{S1}^2}{I_{S1}^2}\right]^{\frac{1}{2}} = \left[\left(\frac{I_S}{I_{S1}}\right)^2 - 1\right]^{\frac{1}{2}}$$

Where

$I_S =$ RMS value of input supply current.

$I_{S1} =$ RMS value of fundamental component of the i/p supply current.

Input Power Factor (PF)

$$PF = \frac{V_S I_{S1}}{V_S I_S}\cos\phi = \frac{I_{S1}}{I_S}\cos\phi$$

The Crest Factor (CF)

$$CF = \frac{I_{S\ peak}}{I_S} = \frac{\text{Peak input supply current}}{\text{RMS input supply current}}$$

For an Ideal Controlled Rectifier

$FF = 1;\ \eta = 100\%\ ;\ V_{ac} = V_{r\ rms} = 0\ ;\ TUF = 1;$

$RF = r_v = 0\ ;\ HF = THD = 0;\ \ PF = DPF = 1$

4.5 Recommended questions:

1. Give the classification of converters, based on: a) Quadrant operation b) Number of current pulse c) supply input. Give examples in each case.

2. With neat circuit diagram and wave forms, explain the working of 1 phase HWR using SCR for R-load. Derive the expressions for V_{dc} and I_{dc}.

4.6 Generic Skills / Outcomes:

- Explain designing, analysis techniques and characteristics of thyristor controlled rectifiers.

4.7 Further Readings

1. http://books.google.co.in/books/about/Power_Electronics.html?id=-WqvjxMXClAC
2. http://www.flipkart.com/power-electronic-2ed/p/itmczynuyqnbvzzj
3. http://www.scribd.com/doc/36550374/Power-Electronics-Notes
4. http://elearning.vtu.ac.in/EC42.html
5. http://www.onlinevideolecture.com/electrical-engineering/nptel-iit-bombay/power-electronics/?course_id=510

MODULE 4(b)

AC VOLTAGE CONTROLLER

Structure

4.0 Introduction
4.1 Objectives
4.2 Phase Control
4.3 Type of Ac Voltage Controllers
4.4 Principle of On-Off Control Technique
4.5 Principle of AC Phase Control
4.6 Single Phase Full Wave Ac Voltage Controller
4.7 Single Phase Full Wave Ac Voltage Controller(Bidirectional)
4.8 Recommended Questions
4.9 Outcomes
4.10 Further Readings

4.0 INTRODUCTION

AC voltage controllers (ac line voltage controllers) are employed to vary the RMS value of the alternating voltage applied to a load circuit by introducing Thyristors between the load and a constant voltage ac source. The RMS value of alternating voltage applied to a load circuit is controlled by controlling the triggering angle of the Thyristors in the ac voltage controller circuits.

In brief, an ac voltage controller is a type of thyristor power converter which is used to convert a fixed voltage, fixed frequency ac input supply to obtain a variable voltage ac output. The RMS value of the ac output voltage and the ac power flow to the load is controlled by varying (adjusting) the trigger angle ‘α’.

There are two different types of thyristor control used in practice to control the ac power flow.

- On-Off control
- Phase control

These are the two ac output voltage control techniques.

In On-Off control technique Thyristors are used as switches to connect the load circuit to the ac supply (source) for a few cycles of the input ac supply and then to disconnect it for few input cycles. The Thyristors thus act as a high speed contactor (or high speed ac switch).

4.1 OBJECTIVES

- To explain the design, analysis techniques, performance parameters and characteristics of AC Voltage controllers

4.2 Phase Control

In phase control the Thyristors are used as switches to connect the load circuit to the input ac supply, for a part of every input cycle. That is the ac supply voltage is chopped using Thyristors during a part of each input cycle.

The thyristor switch is turned on for a part of every half cycle, so that input supply voltage appears across the load and then turned off during the remaining part of input half cycle to disconnect the ac supply from the load.

By controlling the phase angle or the trigger angle ‘’ (delay angle), the output RMS voltage across the load can be controlled. The trigger delay angle ‘’ is defined as the phase angle (the value of t) at which the thyristor turns on and the load current begins to flow.

Thyristor ac voltage controllers use ac line commutation or ac phase commutation. Thyristors in ac voltage controllers are line commutated (phase commutated) since the input supply is ac. When the input ac voltage reverses and becomes negative during the negative half cycle the current flowing through the conducting thyristor decreases and falls to zero. Thus the ON thyristor naturally turns off, when the device current falls to zero.

Phase control Thyristors which are relatively inexpensive, converter grade Thyristors which are slower than fast switching inverter grade Thyristors are normally used.

For applications upto 400Hz, if Triacs are available to meet the voltage and current ratings of a particular application, Triacs are more commonly used.

Due to ac line commutation or natural commutation, there is no need of extra commutation circuitry or components and the circuits for ac voltage controllers are very simple.

Due to the nature of the output waveforms, the analysis, derivations of expressions for performance parameters are not simple, especially for the phase controlled ac voltage controllers with RL load. But however most of the practical loads are of the RL type and hence RL load should be considered in the analysis and design of ac voltage controller circuits.

4.3 Type of Ac Voltage Controllers

The ac voltage controllers are classified into two types based on the type of input ac supply applied to the circuit.

- Single Phase AC Controllers.
- Three Phase AC Controllers.

Single phase ac controllers operate with single phase ac supply voltage of 230V RMS at 50Hz in our country. Three phase ac controllers operate with 3 phase ac supply of 400V RMS at 50Hz supply frequency.

Each type of controller may be sub divided into Uni-directional or half wave ac controller.

Bi-directional or full wave ac controller.

In brief different types of ac voltage controllers are

Single phase half wave ac voltage controller (uni-directional controller).

Single phase full wave ac voltage controller (bi-directional controller).

Three phase half wave ac voltage controller (uni-directional controller).

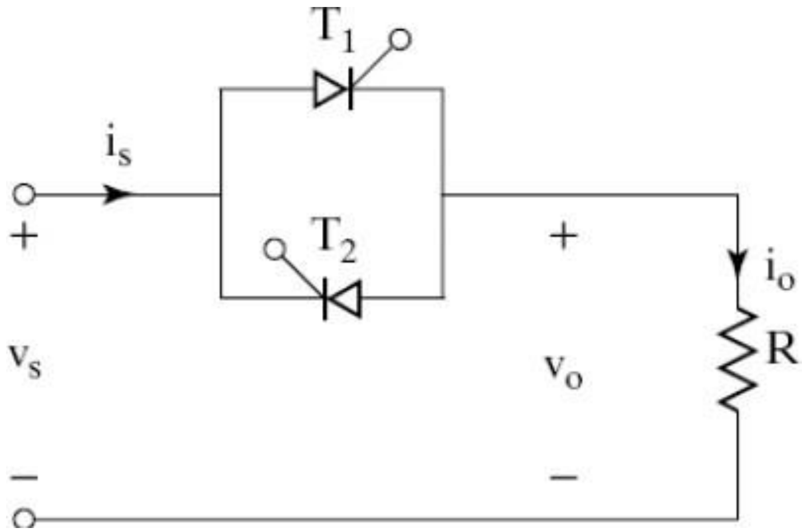
Three phase full wave ac voltage controller (bi-directional controller).

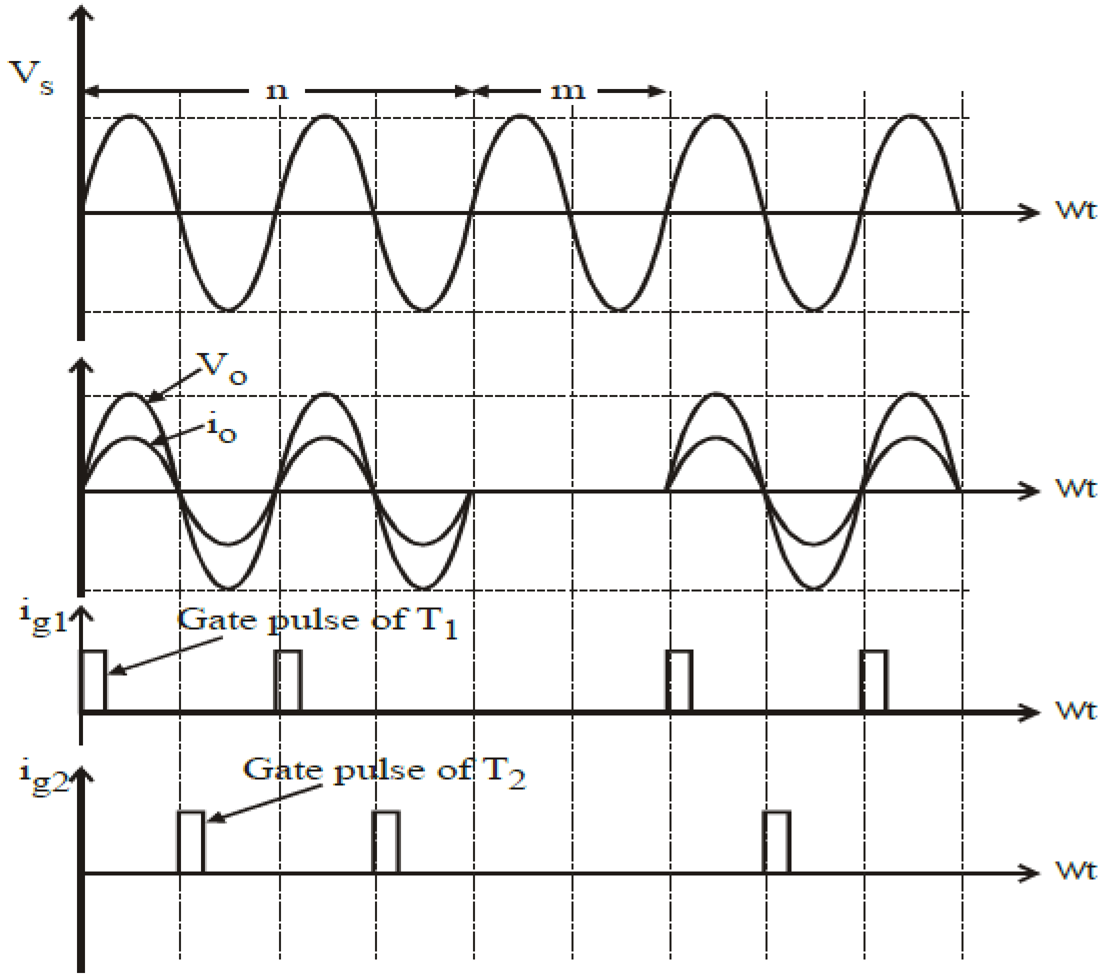
Applications of Ac Voltage Controllers

- Lighting / Illumination control in ac power circuits.
- Induction heating.
- Industrial heating & Domestic heating.
- Transformer tap changing (on load transformer tap changing).
- Speed control of induction motors (single phase and poly phase ac induction motor
- control).
- AC magnet controls.

4.4 Principle of On-Off Control Technique (Integral Cycle Control)

The basic principle of on-off control technique is explained with reference to a single phase full wave ac voltage controller circuit shown below. The thyristor switches 1 *T* and 2 *T* are turned on by applying appropriate gate trigger pulses to connect the input ac supply to the load for 'n' number of input cycles during the time interval *ON t* . The thyristor switches 1 *T* and 2 *T* are turned off by blocking the gate trigger pulses for 'm' number of input cycles during the time interval *OFF t* . The ac controller ON time *ON t* usually consists of an integral number of input cycles.


T1
T2
is
io
R
+
vs
−
+
vo
−



Example

Referring to the waveforms of ON-OFF control technique in the above diagram, Two input cycles. Thyristors are turned ON during for two input cycles. n ON t One input cycle. Thyristors are turned OFF during for one input cycle m OFF t Thyristors are turned ON precisely at the zero voltage crossings of the input supply.

The thyristor 1 *T* is turned on at the beginning of each positive half cycle by applying the gate trigger pulses to 1 *T* as shown, during the ON time *ON t* . The load current flows in the positive direction, which is the downward direction as shown in the circuit diagram when 1 *T* conducts. The thyristor 2 *T* is turned on at the beginning of each negative half cycle, by applying gating signal to the gate of 2 *T* , during *ON t* . The load current flows in the reverse direction, which is the upward direction when 2 *T* conducts. Thus we obtain a bi-directional load current flow (alternating load current flow) in a ac voltage controller circuit, by triggering the thyristors alternately. This type of control is used in applications which have high mechanical inertia and high thermal time constant (Industrial heating and speed control of ac motors). Due to zero voltage and zero current switching of Thyristors, the harmonics generated by switching actions are reduced.

(i) To derive an expression for the rms value of output voltage, for on-off control method.

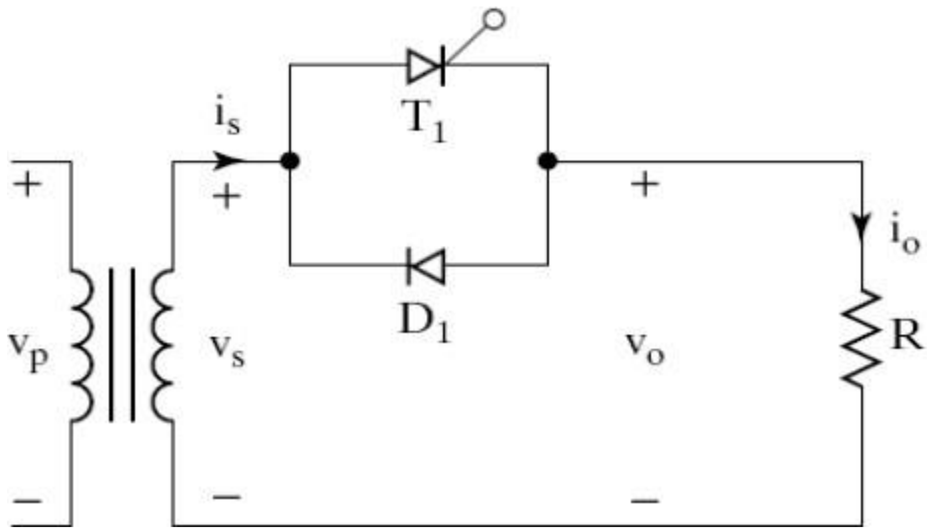
$$\text{Output RMS voltage} \quad V_{O\,RMS} = \sqrt{\frac{1}{\omega T_O} \int_{\omega t=0}^{\omega t_{ON}} V_m^{\,2} Sin^2 \omega t . d \;\; \omega t}$$

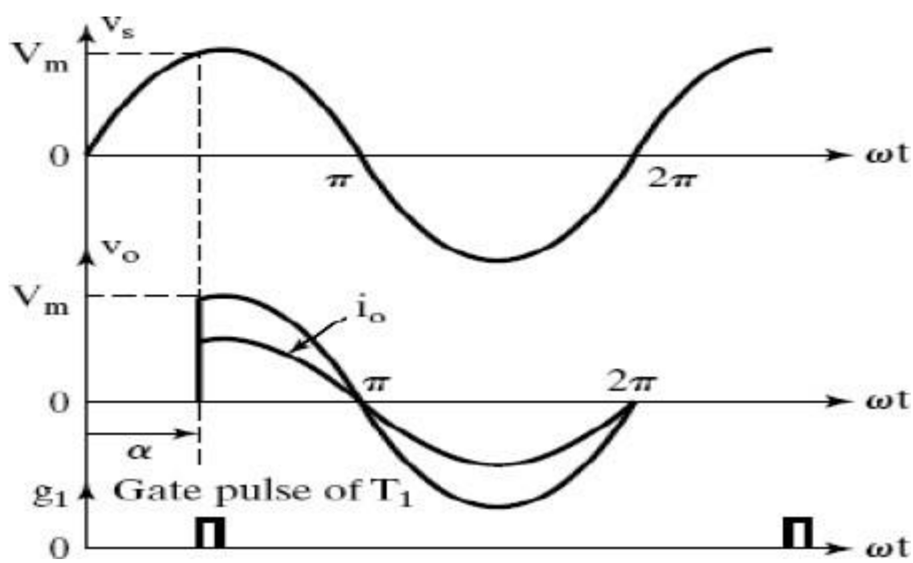
$$V_{O\,RMS} = \sqrt{\frac{V_m^{\,2}}{\omega T_O} \int_{0}^{\omega t_{ON}} Sin^2 \omega t . d \;\; \omega t}$$

$$V_{O\,RMS} = \sqrt{\frac{V_m^{\,2}}{2\omega T_O} \left[\;\; \omega t_{ON} - 0 \;\; - \frac{\sin 2\omega t_{ON} - \sin 0}{2} \right]}$$

4.5 Principle of AC Phase Control

The basic principle of ac phase control technique is explained with reference to a single phase half wave ac voltage controller (unidirectional controller) circuit shown in the below figure. The half wave ac controller uses one thyristor and one diode connected in parallel across each other in opposite direction that is anode of thyristor 1 T is connected to the cathode of diode 1 D and the cathode of 1 T is connected to the anode of 1 D . The output voltage across the load esistor 'R' and hence the ac power flow to the load is controlled by varying the trigger angle. The trigger angle or the delay angle ' ' refers to the value of t or the instant at which the thyristor 1 T is triggered to turn it ON, by applying a suitable gate trigger pulse between the gate and cathode lead. The thyristor 1 T is forward biased during the positive half cycle of input ac supply. It can be triggered and made to conduct by applying a suitable gate trigger pulse only during the positive half cycle of input supply. When 1 T is triggered it conducts and the load current flows through the thyristor 1 T , the load and through the transformer secondary winding.





Disadvantages of single phase half wave ac voltage controller

The output load voltage has a DC component because the two halves of the output voltage waveform are not symmetrical with respect to '0' level. The input supply current waveform also has a DC component (average value) which can result in the problem of core saturation of the input supply transformer. The half wave ac voltage controller using a single thyristor and a single diode provides control on the thyristor only in one half cycle of the input supply. Hence ac power flow to the load can be controlled only in one half cycle. Half wave ac voltage controller gives limited range of RMS output voltage control. Because the RMS value of ac output voltage can be varied from a maximum of 100% of *S V* at a trigger angle 0 to a low of 70.7% of *S V* at Radians . These drawbacks of single phase half wave ac voltage controller can be over come by using a single phase full wave ac voltage controller.

Applications of rms Voltage Controller

- Speed control of induction motor (polyphase ac induction motor).
- Heater control circuits (industrial heating).
- Welding power control.
- Induction heating.
- On load transformer tap changing.
- Lighting control in ac circuits.
- Ac magnet controls

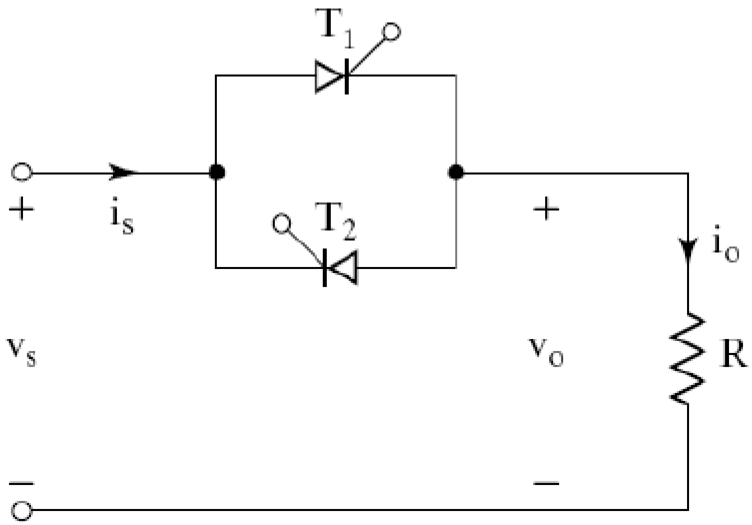
4.6 Single Phase Full Wave Ac Voltage Controller (Ac Regulator) or Rms Voltage Controller with Resistive Load

Single phase full wave ac voltage controller circuit using two SCRs or a single triac is generally used in most of the ac control applications. The ac power flow to the load can be controlled in both the half cycles by varying the trigger angle' '**.**The RMS value of load voltage can be varied by varying the trigger angle ' '**.** The input supply current is alternating i the case of a full wave ac voltage controller and due to the symmetrical nature of the input supply current waveform there is no dc component of input supply current i.e., the average value of the input supply current is zero.

A single phase full wave ac voltage controller with a resistive load is shown in the figure below. It is possible to control the ac power flow to the load in both the half cycles by adjusting the trigger angle' '. Hence the full wave ac voltage controller is also referred to as to a bi-directional controller.

The thyristor 1 *T* is forward biased during the positive half cycle of the input supply voltage. The thyristor 1 *T* is triggered at a delay angle of ' ' 0 radians . Considering the ON thyristor 1 *T* as an ideal closed switch the input supply voltage appears across the load resistor *L R* and the output voltage *O S v v* during *t* to radians. The load current flows through the ON thyristor 1 *T* and through the load resistor *L R* in the downward direction during the conduction time of 1 *T* from *t* to radians.

At *t* , when the input voltage falls to zero the thyristor current (which is flowing through the load resistor *L R*) falls to zero and hence 1 *T* naturally turns off . No current flows in the circuit during *t* to . The thyristor 2 *T* is forward biased during the negative cycle of input supply and

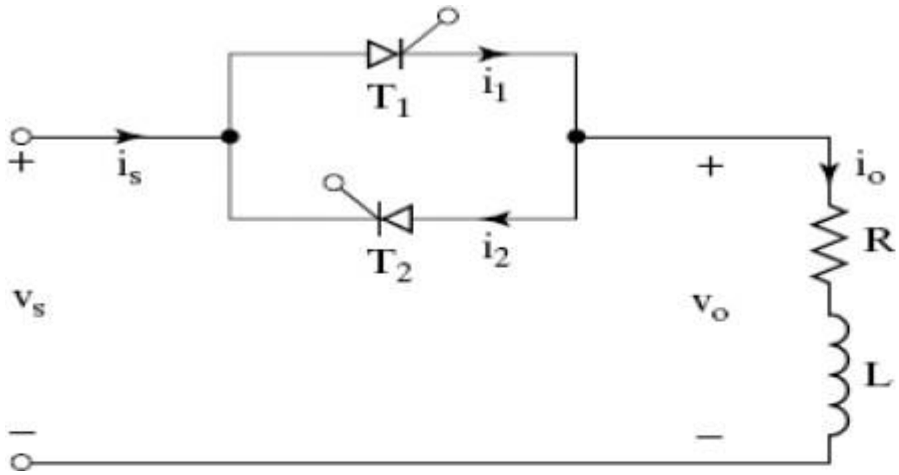


when thyristor 2 *T* is triggered at a delay angle , the output voltage follows the negative halfcycle of input from *t* to 2 . When 2 *T* is ON, the load current flows in the reverse direction (upward direction) through 2 *T* during *t* to 2 radians. The time interval (spacing) between the gate trigger pulses of 1 *T* and 2 *T* is kept at radians or 1800. At *t* 2 the input supply voltage falls to zero and hence the load current also falls to zero and thyristor 2 *T* turn off naturally.

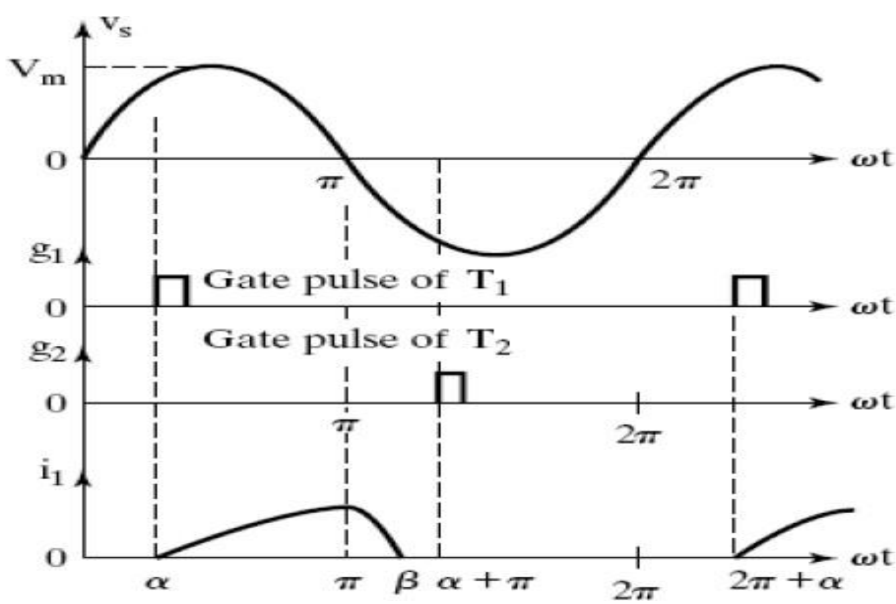
4.7 Single Phase Full Wave Ac Voltage Controller (Bidirectional Controller) With RL Load

In this section we will discuss the operation and performance of a single phase full wave ac voltage controller with RL load. In practice most of the loads are of RL type. For example if we consider a single phase full wave ac voltage controller controlling the speed of a single phase ac induction motor, the load which is the induction motor winding is an RL type of load, where R represents the motor winding resistance and L represents the motor winding inductance. A single phase full wave ac voltage controller circuit (bidirectional controller) with an RL load using two thyristors 1 *T* and 2 *T* (1 *T* and 2 *T* are two SCRs) connected in parallel is shown in the figure below. In place of two thyristors a single Triac can be used to implement a full wave ac controller, if a suitable Traic is available for the desired RMS load current and the RMS output voltage ratings.

The thyristor 1 *T* is forward biased during the positive half cycle of input supply. Let us assume that 1 *T* is triggered at *t* , by applying a suitable gate trigger pulse to 1 *T* during the positive half cycle of input supply. The output voltage across the load follows the input supply voltage when 1 *T* is ON. The load current *O i* flows through the thyristor 1 *T* and through the load in the downward direction. This load current pulse flowing through 1 *T* can be considered as the positive current pulse. Due to the inductance in the load, the load current *O I* flowing through 1 *T* would not fall to zero at *t* , when the input supply voltage starts to become negative.



The thyristor 1 *T* will continue to conduct the load current until all the inductive energy stored in the load inductor L is completely utilized and the load current through 1 *T* falls to zero at *t* , where is referred to as the Extinction angle, (the value of *t*) at which the load current falls to zero. The extinction angle is measured from the point of the beginning of the positive half cycle of input supply to the point where the load current falls to zero. The thyristor 1 *T* conducts from *t* to . The conduction angle of 1 *T* is , which depends on the delay angle and the load impedance angle . The waveforms of the input supply voltage, the gate trigger pulses of 1 *T* and 2 *T* , the thyristor current, the load current and the load voltage waveforms appear as shown in the figure below



Note

The RMS value of the output voltage and the load current may be varied by varying the trigger angle . This circuit, AC RMS voltage controller can be used to regulate the RMS voltage across the terminals of an ac motor (induction motor). It can be used to control the temperature of a furnace by varying the RMS output voltage.

For very large load inductance 'L' the SCR may fail to commutate, after it is triggered and the load voltage will be a full sine wave (similar to the applied input supply voltage and the output control will be lost) as long as the gating signals are applied to the thyristors 1 T and 2 T . The load current waveform will appear as a full continuous sine wave and the load current waveform lags behind the output sine wave by the load power factor angle.

4.8 Recommended questions

1. Discuss the operation of a single phase controller supplying a resistive load, and controlled by the on-off method of control. Also highlight the advantages and disadvantages of such a control. Draw the relevant waveforms.

2. What phase angle control is as applied to single phase controllers? Highlight the advantages and disadvantages of such a method of control. Draw all the wave forms.

3. What are the effects of load inductance on the performance of voltage controllers?

4. Explain the meaning of extinction angle as applied to single phase controllers supplying inductive load with the help of waveforms.

5. What are unidirectional controllers? Explain the operation of the same with the help of waveforms and obtain the expression for the RMS value of the output voltage. What are the advantage and disadvantages of unidirectional controllers?

6. What are bi-directional controllers explain the operation of the same with the help of waveforms and obtain the expression for the R<S value of the output voltage. RMS value of thyristor current. What are the advantages of bi-directional controllers?

7. The AC Voltage controller shown below is used for heating a resistive load of 5 Ω and the input voltage Vs = 120 V (rms). The thyristor switch is on for n=125 cycles and is off for m = 75 cycles. Determine the RMS output voltage Vo, the input factor and the average and RMS thyristor current

4.9 Generic Skills / Outcomes

- Discuss the principle of operation of single phase and three phase AC voltage controllers.

4.10 Further Reading

1. **"Thyristorized Power Controllers" -** G. K. Dubey S. R. Doradla, A. Joshi and Rmk Sinha New age international (P) ltd reprint 1999.

2. **"Power Electronics" -** Cynil W. Lander 3rd edition, MGH 2003.

MODULE-5(a)
DC-DC COVERTER

STRUCTURE

5.0 Introduction
5.1 Objectives
5.2 Principle of Step-down Chopper
5.3 Principle of Step-up Chopper
5.4 Classification of Choppers
5.5 Impulse Commutated Chopper
5.6 Recommended questions
5.7 Outcomes
5.8 Further Readings

5.0 INTRODUCTION

Chopper is a static device.

• A variable dc voltage is obtained from a constant dc voltage source.

• Also known as dc-to-dc converter.

• Widely used for motor control.

• Also used in regenerative braking.

• Thyristor converter offers greater efficiency, faster response, lower maintenance, smaller size and smooth control.

Choppers are of Two Types

- Step-down choppers.
- Step-up choppers.

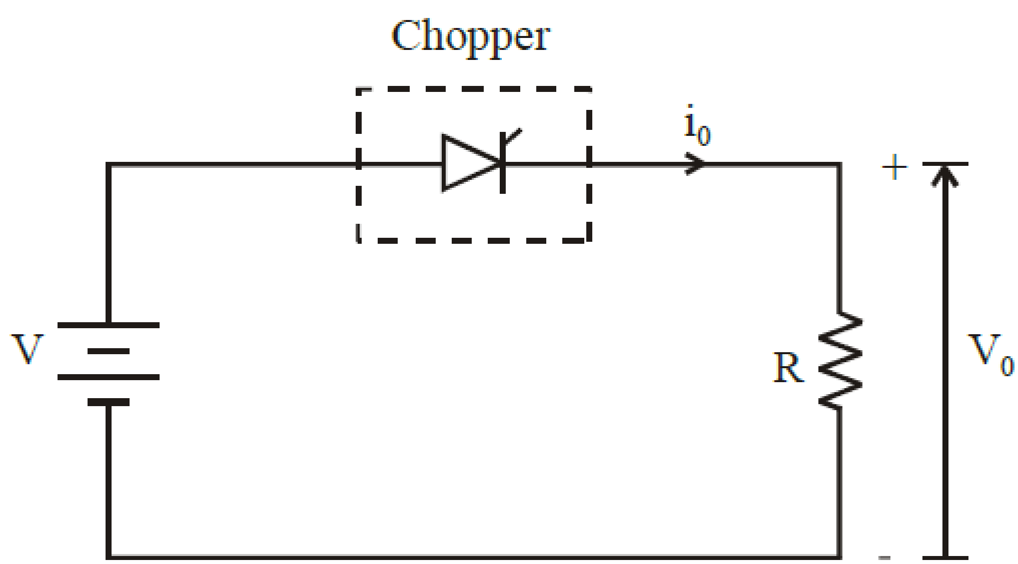
In step down chopper output voltage is less than input voltage.

In step up chopper output voltage is more than input voltage

5.1 **OBJECTIVES**

- ✓ To explain the design, analysis techniques, performance parameters and characteristics of DC-DC converters,operation of various chopper commutation circuits.

5.2 Principle of Step-down Chopper

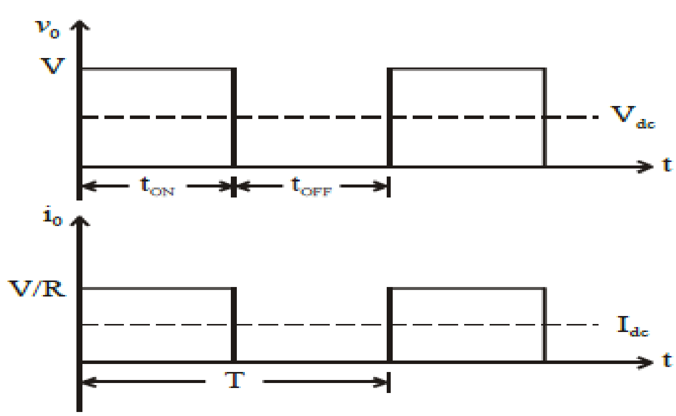


A step-down chopper with resistive load.

• The thyristor in the circuit acts as a switch.

• When thyristor is ON, supply voltage appears across the load

• When thyristor is OFF, the voltage across the load will be zero.



Methods of Control

• The output dc voltage can be varied by the following methods.

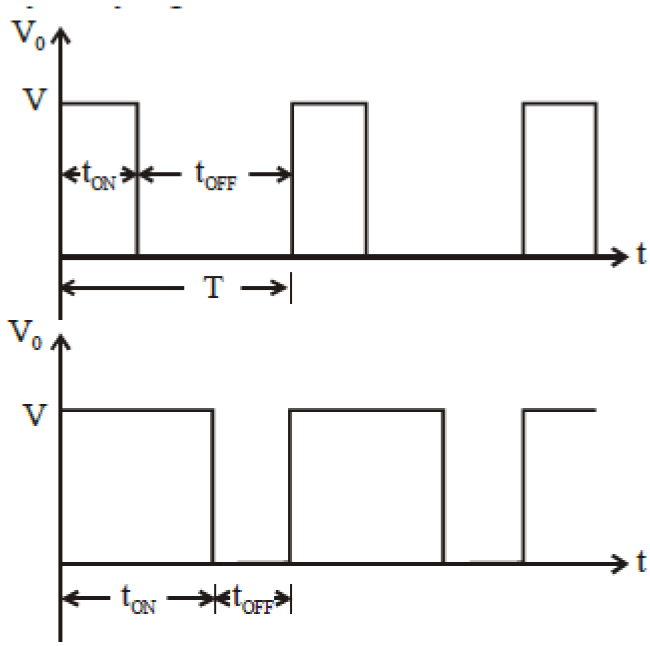
– Pulse width modulation control or constant frequency operation.

– Variable frequency control.

Pulse Width Modulation

• t_{ON} is varied keeping chopping frequency '*f*' & chopping period 'T' constant.

• Output voltage is varied by varying the ON time *tON*

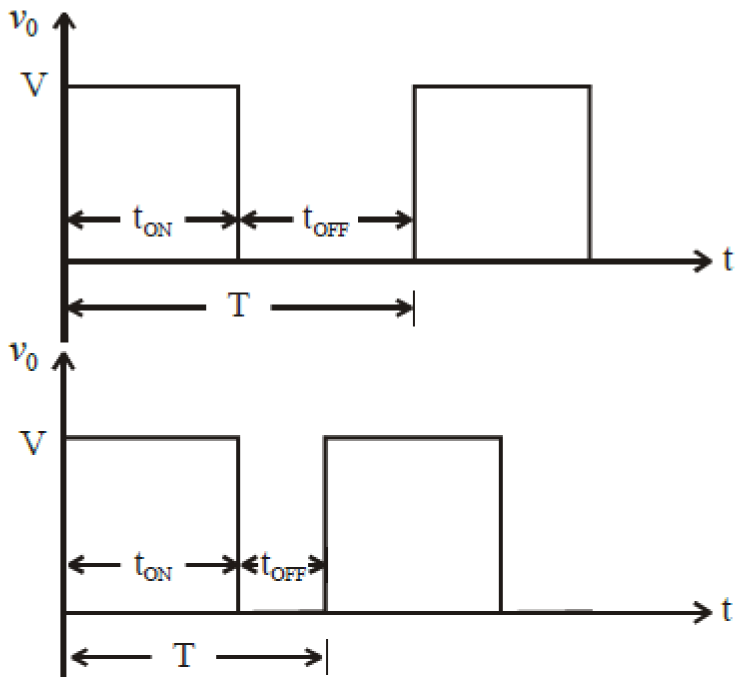


Variable Frequency Control

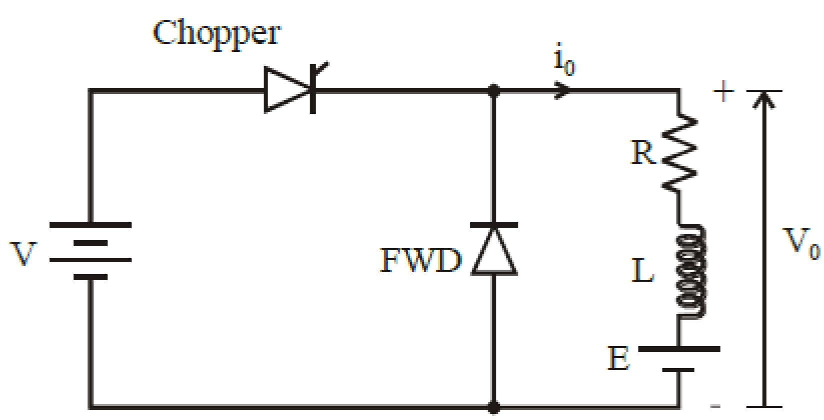
• Chopping frequency '*f*' is varied keeping either *tON* or *tOFF* constant.

• To obtain full output voltage range, frequency has to be varied over a wide range.

• This method produces harmonics in the output and for large *tOFF* load current may become discontinuous



5.2.1 Step-down Chopper with R-L Load



When chopper is ON, supply is connected across load.

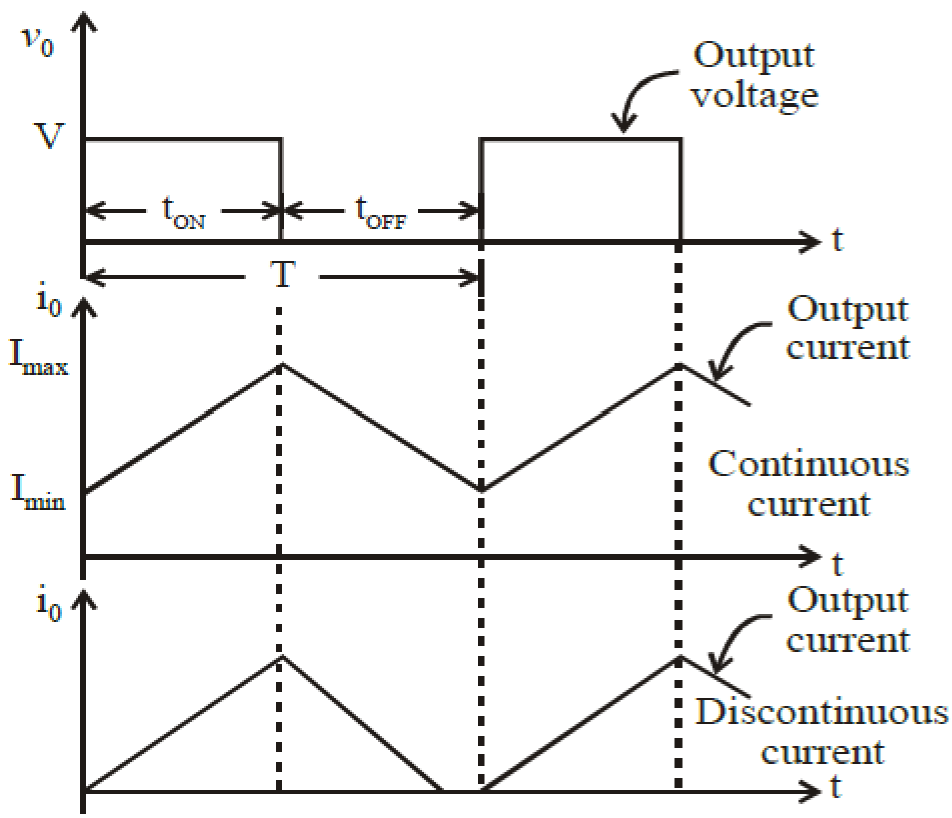
Current flows from supply to load.

When chopper is OFF, load current continues to flow in the same direction through FWD due to energy stored in inductor *‘L’*.

Load current can be continuous or discontinuous depending on the values of *‘L’* and duty cycle *‘d’*

For a continuous current operation, load current varies between two limits *Imax* and *Imin*

When current becomes equal to *Imax* the chopper is turned-off and it is turned-on when current reduces to *Imin.*



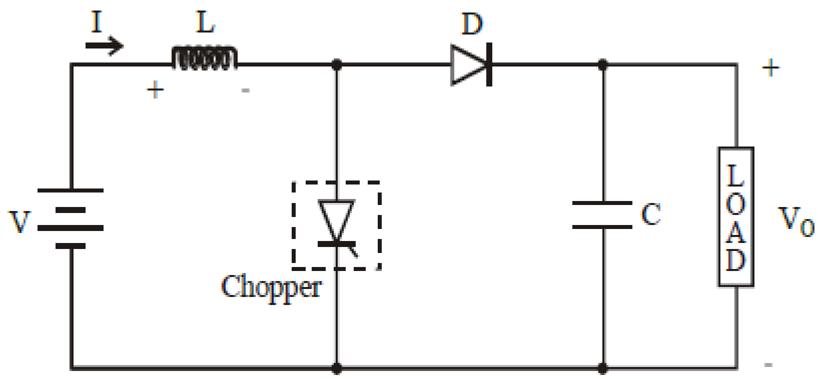
5.3 Principle of Step-up Chopper

Step-up chopper is used to obtain a load voltage higher than the input voltage *V*.

The values of *L* and *C* are chosen depending upon the requirement of output voltage and current.

When the chopper is *ON*, the inductor *L* is connected across the supply.

The inductor current *‘I’* rises and the inductor stores energy during the *ON* time of the chopper, *Ton*. When the chopper is off, the inductor current *I* is forced to flow through the diode *D* and load for a period, *tOFF*.



The current tends to decrease resulting in reversing the polarity of induced EMF in *L*.
Therefore voltage across load is given by

A large capacitor 'C' connected across the load, will provide a continuous output voltage.

- Diode *D* prevents any current flow from capacitor to the source.
- Step up choppers are used for regenerative braking of dc motors.

(i) Expression For Output Voltage

$$VIt_{ON} = V_O - V \;\; It_{OFF}$$

$$V_O = \frac{V \;\; t_{ON} + t_{OFF}}{t_{OFF}}$$

$$V_O = V\left(\frac{T}{T - t_{ON}}\right)$$

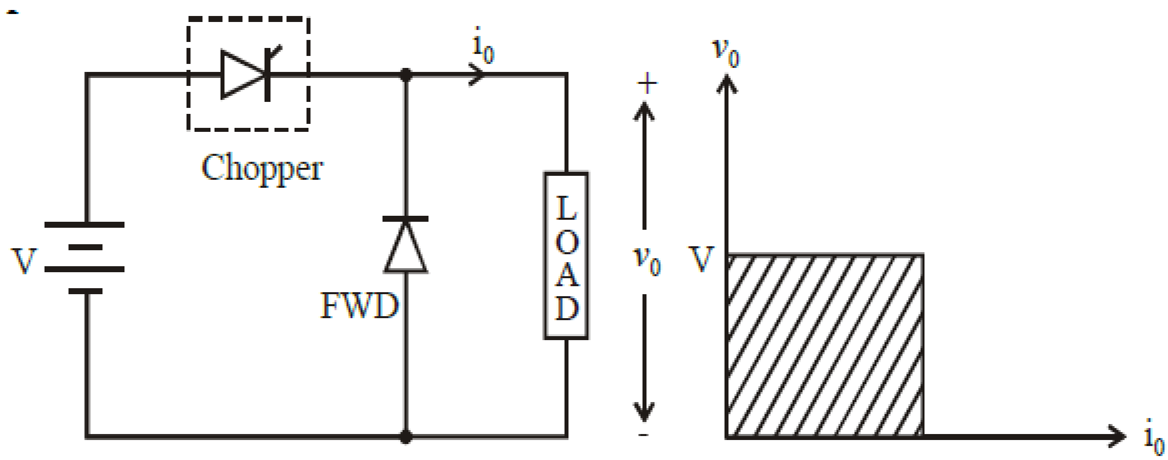
Performance Parameters

- The thyristor requires a certain minimum time to turn *ON* and turn *OFF*.
- Duty cycle *d* can be varied only between a min. & max. value, limiting the min. and max. value of the output voltage.
- Ripple in the load current depends inversely on the chopping frequency, *f*.
- To reduce the load ripple current, frequency should be as high as possible.

5.4 Classification of Choppers

Choppers are classified as
- Class A Chopper
- Class B Chopper
- Class C Chopper
- Class D Chopper
- Class E Chopper

1. Class A Chopper



When chopper is *ON*, supply voltage *V* is connected across the load.

• When chopper is OFF, *v*O = 0 and the load current continues to flow in the same direction through the FWD.

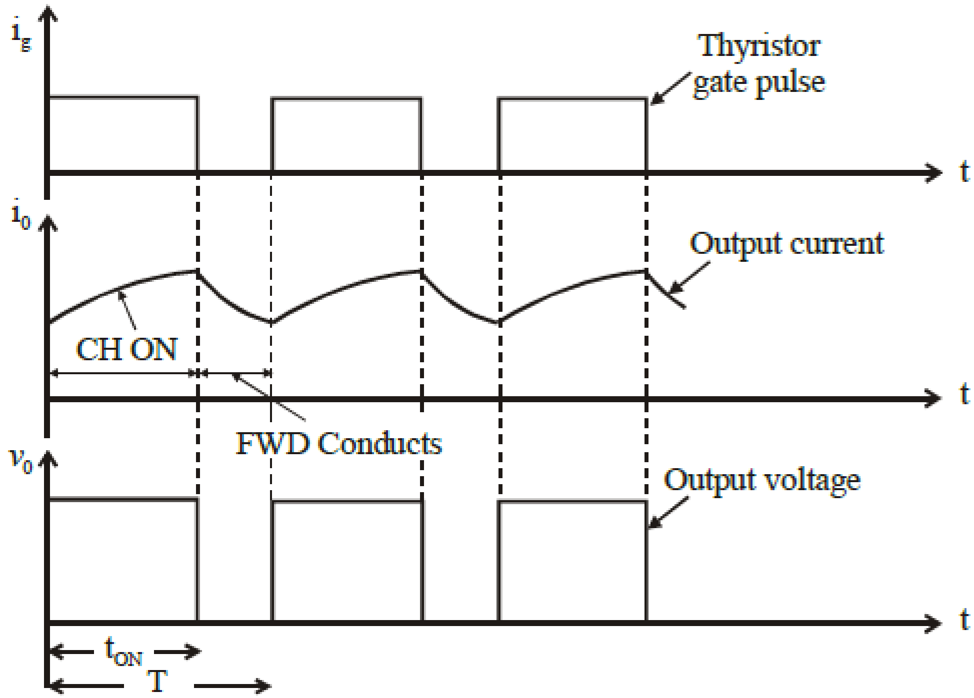
• The average values of output voltage and current are always positive.

• *Class A Chopper* is a first quadrant chopper .

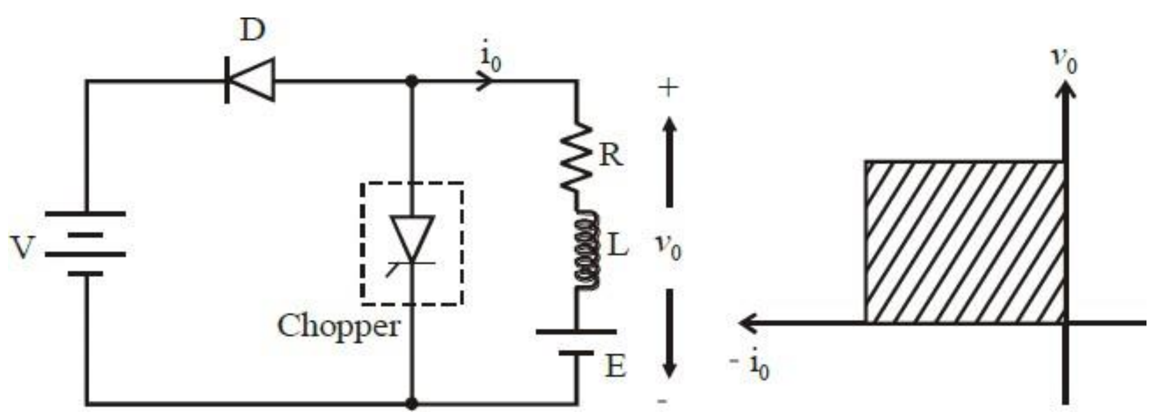
• *Class A Chopper* is a step-down chopper in which power always flows form source to load.

• It is used to control the speed of dc motor.

• The output current equations obtained in step down chopper with *R-L* load can be used to study the performance of *Class A Chopper*.



2. Class B Chopper



When chopper is ON, *E* drives a current through *L* and R in a direction opposite to that shown in figure.

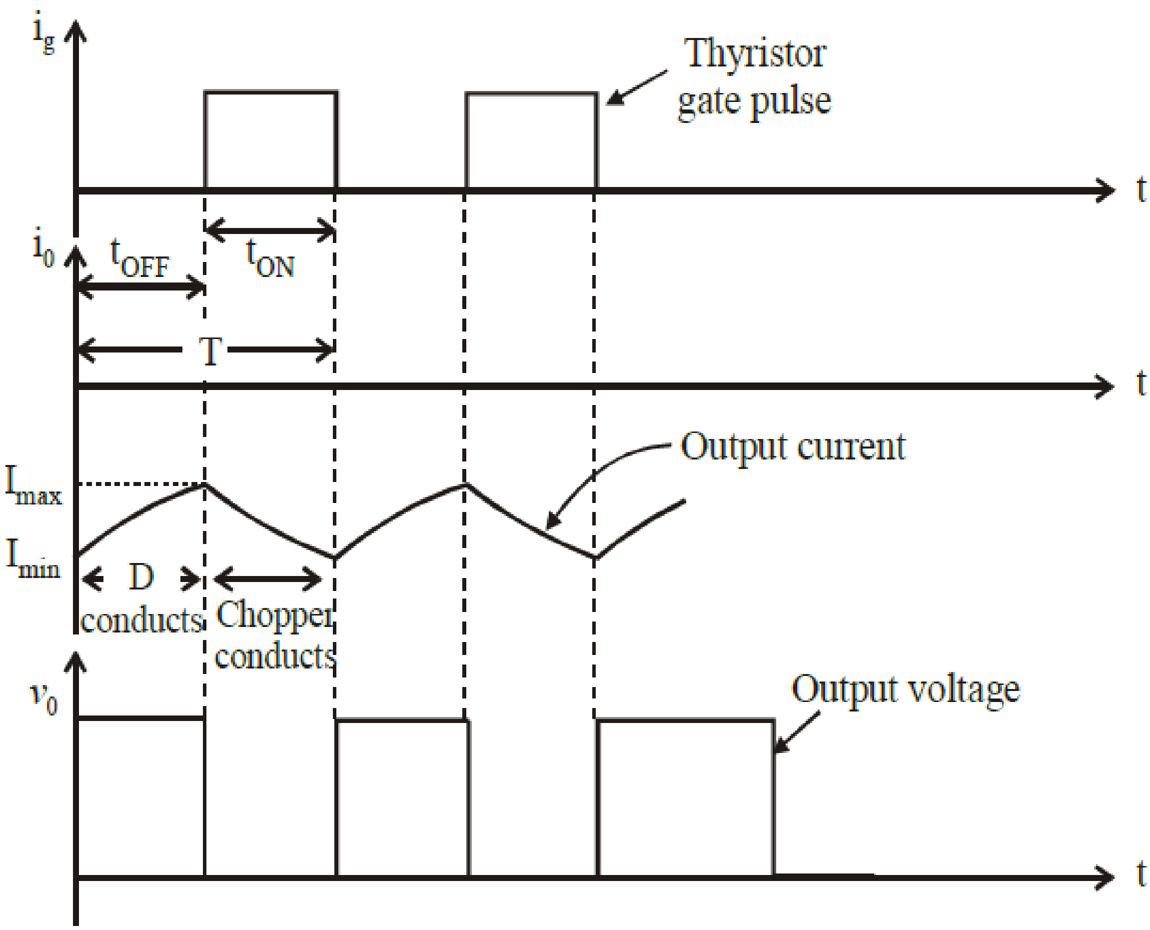
• During the ON period of the chopper, the inductance *L* stores energy.

• When Chopper is OFF, diode *D* conducts, and part of the energy stored in inductor *L* is returned to the supply.

• Average output voltage is positive.

• Average output current is negative.

• Therefore Class B Chopper operates in second quadrant.
• In this chopper, power flows from load to source.
• Class B Chopper is used for regenerative braking of dc motor.
• Class B Chopper is a step-up chopper



(i) Expression for Output Current

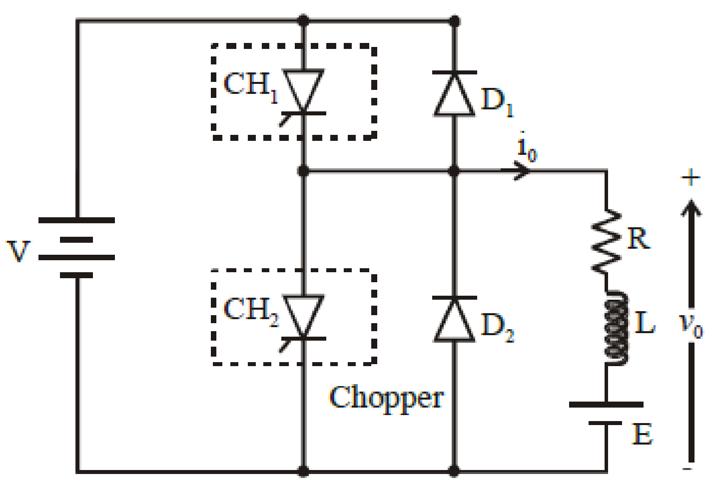
$$\therefore \quad i_O(t) = \frac{V-E}{R}\left(1-e^{-\frac{R}{L}t}\right) + I_{\min} e^{-\frac{R}{L}t} \quad 0 < t < t_{OFF}$$

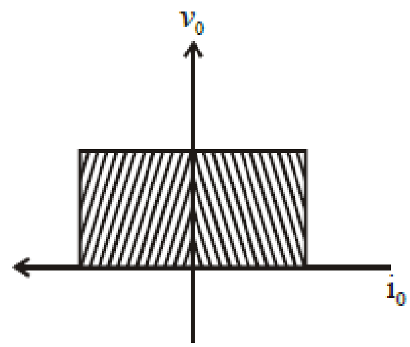
At $t = t_{OFF}$ $\quad i_O(t) = I_{\max}$

$$I_{\max} = \frac{V-E}{R}\left(1-e^{-\frac{R}{L}t_{OFF}}\right) + I_{\min} e^{-\frac{R}{L}t_{OFF}}$$

$$\therefore \quad I_{\min} = I_{\max} e^{-\frac{R}{L}t_{ON}} - \frac{E}{R}\left(1-e^{-\frac{R}{L}t_{ON}}\right)$$

3. Class C Chopper





Class C Chopper is a combination of Class A and Class B Choppers.

- For first quadrant operation, CH1 is ON or D2 conducts.
- For second quadrant operation, CH2 is ON or D1 conducts.
- When CH1 is ON, the load current is positive.

• The output voltage is equal to ‘V’ & the load receives power from the source.

• When CH1 is turned OFF, energy stored in inductance L forces current to flow through the diode D2 and the output voltage is zero.

• Current continues to flow in positive direction.

• When CH2 is triggered, the voltage E forces current to flow in opposite direction through L and CH2 .

• The output voltage is zero.

• On turning OFF CH2 , the energy stored in the inductance drives current through diode D1 and the supply

• Output voltage is V, the input current becomes negative and power flows from load to source.

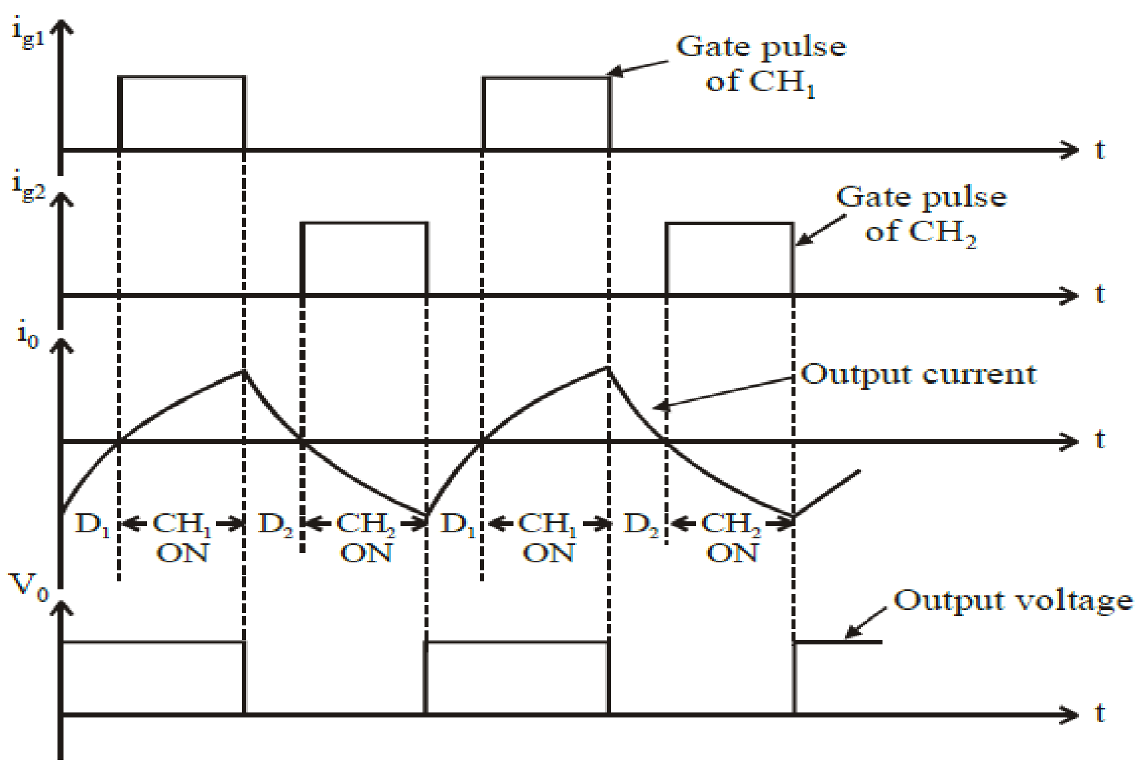
• Average output voltage is positive

• Average output current can take both positive and negative values.

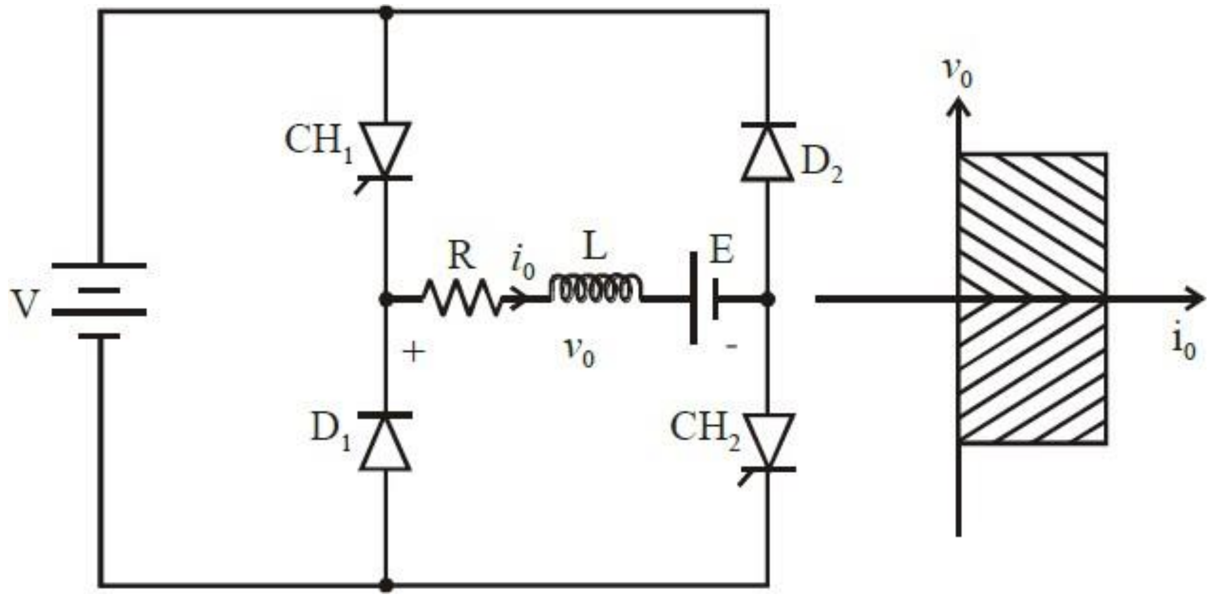
• Choppers CH1 & CH2 should not be turned ON simultaneously as it would result in short circuiting the supply.

• Class C Chopper can be used both for dc motor control and regenerative braking of dc motor.

• Class C Chopper can be used as a step-up or step-down chopper



4. Class D Chopper



Class D is a two quadrant chopper.

• When both CH1 and CH2 are triggered simultaneously, the output voltage vO = V and output current flows through the load.

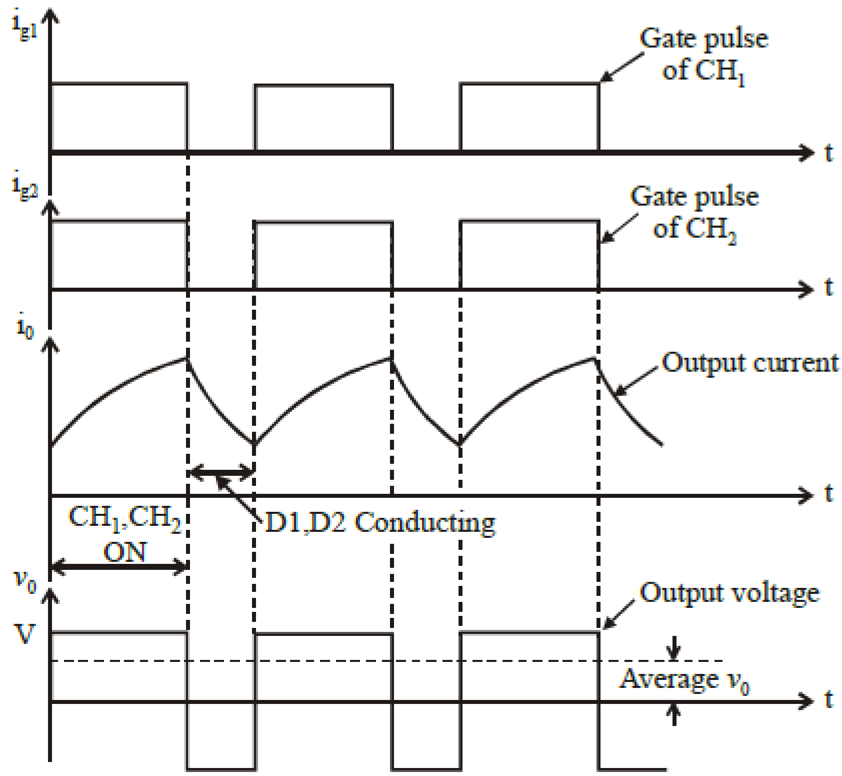
• When CH1 and CH2 are turned OFF, the load current continues to flow in the same direction through load, D1 and D2 , due to the energy stored in the inductor L.

• Output voltage vO = - V .

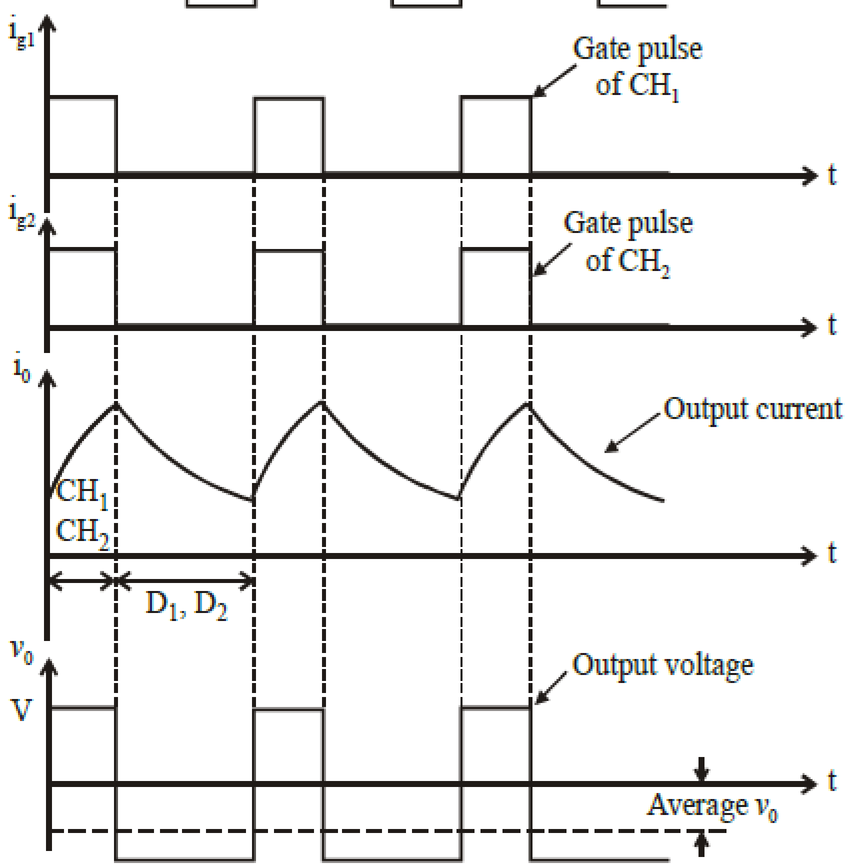
• Average load voltage is positive if chopper ON time is more than the OFF time

• Average output voltage becomes negative if tON < tOFF .

• Hence the direction of load current is always positive but load voltage can be positive or negative

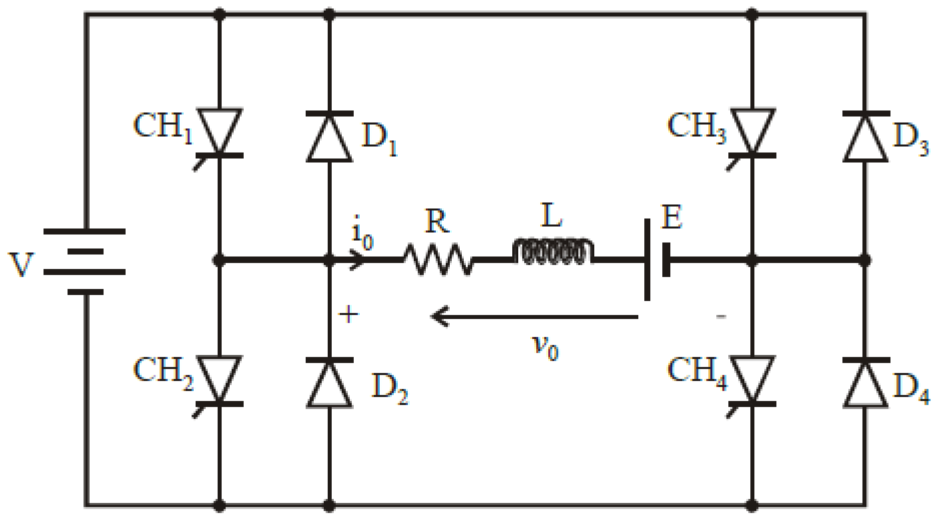


ig1
Gate pulse of CH1
t
ig2
Gate pulse of CH2
t
i0
Output current
t
CH1,CH2 ON
D1,D2 Conducting
v0
V
Output voltage
Average v0
t



ig1
Gate pulse of CH1
t
ig2
Gate pulse of CH2
t
i0
Output current
CH1
CH2
D1, D2
t
v0
V
Output voltage
t
Average v0

5. Class E Chopper



Class E is a four quadrant chopper

• When CH1 and CH4 are triggered, output current iO flows in positive direction through CH1 and CH4, and with output voltage vO = V.

• This gives the first quadrant operation.

• When both CH1 and CH4 are OFF, the energy stored in the inductor L drives iO through D2 and D3 in the same direction, but output voltage vO = -V.

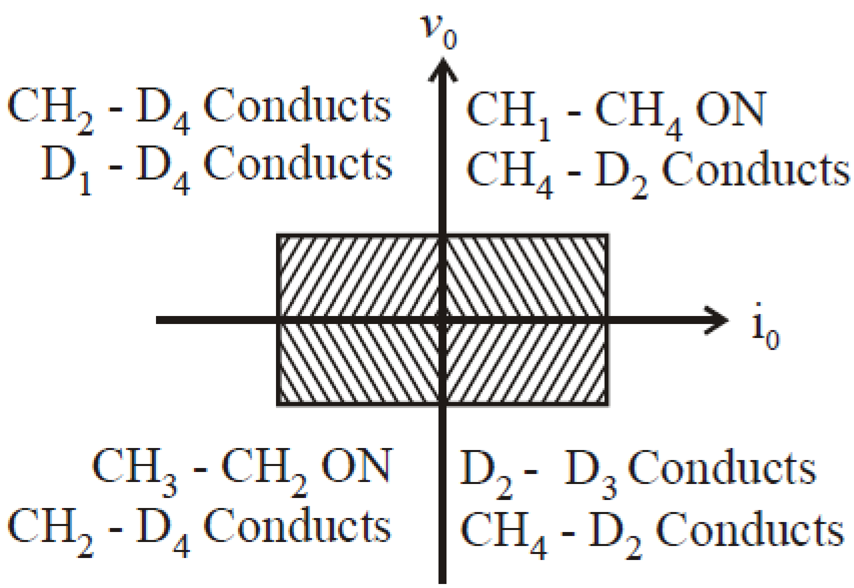
• Therefore the chopper operates in the fourth quadrant.

• When CH2 and CH3 are triggered, the load current iO flows in opposite direction & output voltage vO = -V.

• Since both iO and vO are negative, the chopper operates in third quadrant.

• When both CH2 and CH3 are OFF, the load current iO continues to flow in the same direction D1 and D4 and the output voltage vO = V.

• Therefore the chopper operates in second quadrant as vO is positive but iO is negative.



Effect Of Source & Load Inductance

- The source inductance should be as small as possible to limit the transient voltage.
- Also source inductance may cause commutation problem for the chopper.
- Usually an input filter is used to overcome the problem of source inductance.
- The load ripple current is inversely proportional to load inductance and chopping frequency.
- Peak load current depends on load inductance.
- To limit the load ripple current, a smoothing inductor is connected in series with the load.

5.6 Recommended questions

1. Explain the principle of operation of a chopper. Briefly explain time-ratio control and PWM as applied to chopper

2. Explain the working of step down shopper. Determine its performance factors, VA, Vo rms, efficiency and Ri the effective input resistane

3. Explain the working of step done chopper for RLE load. Obtain the expressions for minimum load current I1max load current I2, peak – peak load ripple current di avg value of load current Ia, the rms load current Io and Ri.

4. Give the classification of stem down converters. Explain with the help of circuit diagram one-quadrant and four quadrant converters.

5. The step down chopper has a resistive load of R=10ohm and the input voltage is Vs=220V. When the converter switch remain ON its voltage drop is Vch=2V and the chopping frequency is 1 KHz. If the duty cycle is 50% determine a) the avg output voltage VA, b) the rms output voltage Vo c) the converter efficiency d) the effective input resistance Ri of the converter.

6. Explain the working of step-up chopper. Determine its performance factors.

5.7 Generic Skills / Outcomes

- ✓ Discuss the principle of operation of single phase and three phase DC –DC converters

5.8 Further Reading

1. **"Power Electronics" -** M. H. Rashid 3rd edition, PHI / Pearson publisher 2004.

2. **"Power Electronics" -** M. D. Singh and Kanchandani K.B. TMH publisher, 2nd Ed. 2007.

3. **"Thyristorized Power Controllers" -** G. K. Dubey S. R. Doradla, A. Joshi and Rmk Sinha New age international (P) ltd reprint 1999.

DC-AC CONVERTERS

Structure

5.0 Introduction
5.1 Objectives
5.2 Classification of Inverters
5.3 Principle of Operation
5.4 Half bridge inverter with Inductive load
5.5 Fourier analysis of the Load Voltage Waveform
5.6 Performance parameters of inverters
5.7 Single Phase Bridge Inverter
5.8 Single Phase Bridge Inverter with RL Load
5.9 Comparison of half bridge and full bridge inverters
5.10 Principle of Operation of CSI
5.11 Variable DC link Inverter
5.12 Recommended questions
5.13 Outcomes
5.14 Further Readings

5.0 INTRODUCTION

The converters which converts the power into ac power popularly known as the inverters. The application areas for the inverters include the uninterrupted power supply (UPS), the ac motor speed controllers, etc.

The inverters can be classified based on a number of factors like, the nature of output waveform (sine, square, quasi square, PWM etc), the power devices being used (thyristor transistor, MOSFETs IGBTs), the configuration being used, (series. parallel, half bridge, Full bridge), the type of commutation circuit that is being employed and Voltage source and current source inverters.

The Thyristorised inverters use SCRs as power switches. Because the input source of power is pure de in nature, forced commutation circuit is an essential part of Thyristorised inverters. The commutation circuits must be carefully designed to ensure a successful commutation of SCRs. The addition of the commutation circuit makes the Thyristorised inverters bulky and costly. The size and the cost of the circuit can be reduced to some extent if the operating frequency is increased but then the inverter grade thyristors which are special thyristors manufactured to operate at a higher frequency must be used, which are costly.

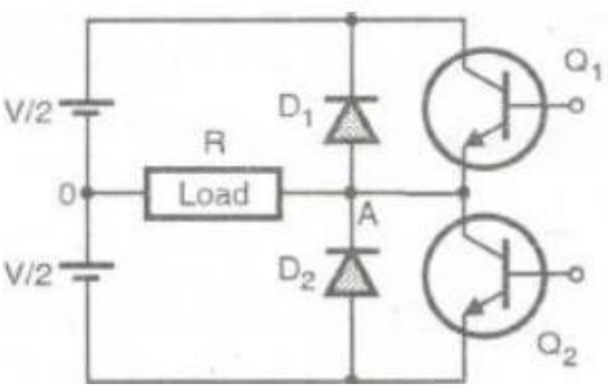
5.1 OBJECTIVES:

- ✓ To explain the design, analysis techniques, performance parameters and characteristics of DC-AC converters

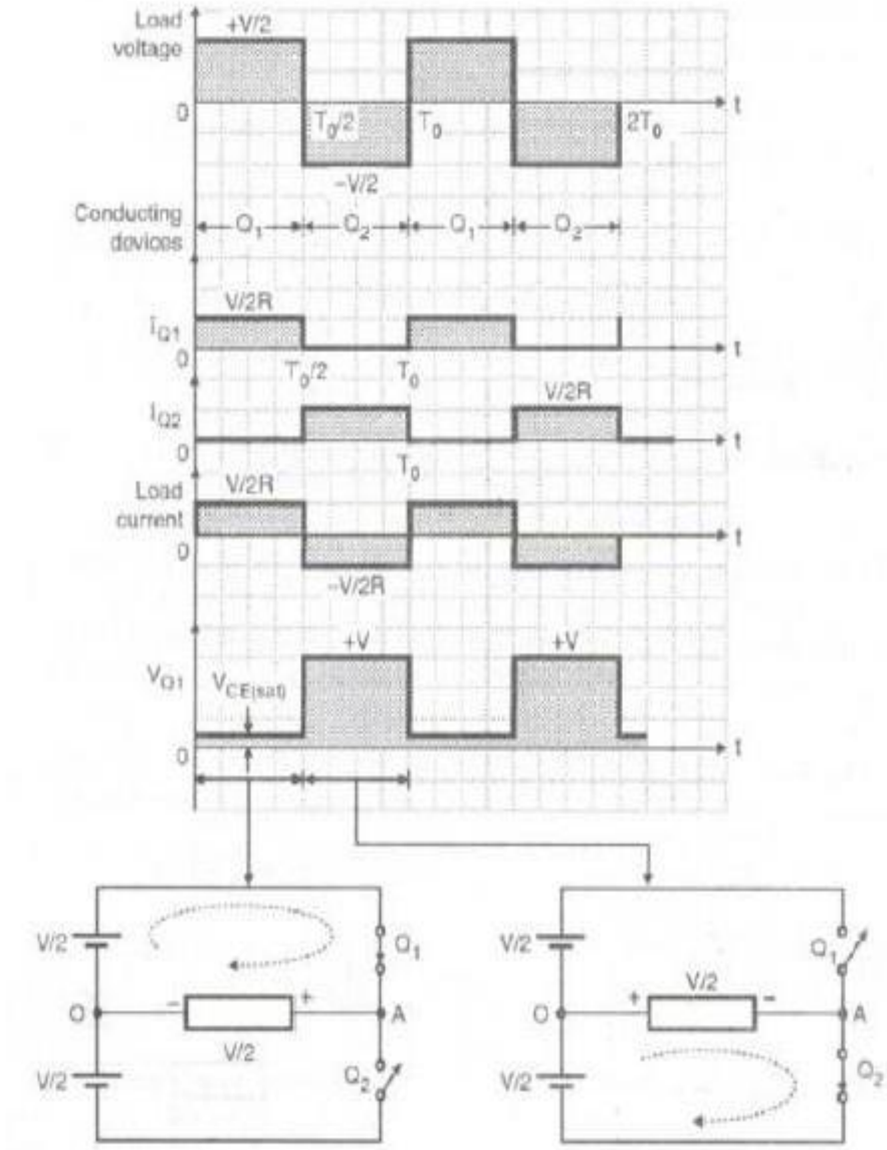
5.2 Classification of Inverters

There are different basis of classification of inverters. Inverters are broadly classified as current source inverter and voltage source inverters. Moreover it can be classified on the basis of devices used (SCR or gate commutation devices), circuit configuration (half bridge or full bridge), nature of output voltage (square, quasi square or sine wave), type of circuit (switched mode PWM or resonant converters) etc.

5.3 Principle of Operation



1. The principle of single phase transistorised inverters can be explained with the help of Fig. The configuration is known as the half bridge configuration**.**
2. The transistor Q1 is turned on for a time T0/2, which makes the instantaneous voltage across the load Vo = V*12.*
3. If transistor Q2 is turned on at the instant T0/2 by turning Q1 off then -V/2 appears across the load.

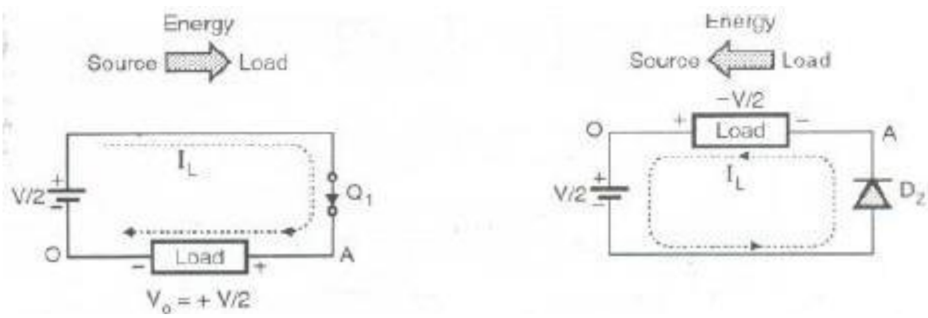


5.4 Half bridge inverter with Inductive load

Operation with inductive load:

Let us divide the operation into four intervals. We start explanation from the second lime interval II to t2 because at the beginning of this interval transistor Q1 will start conducting.

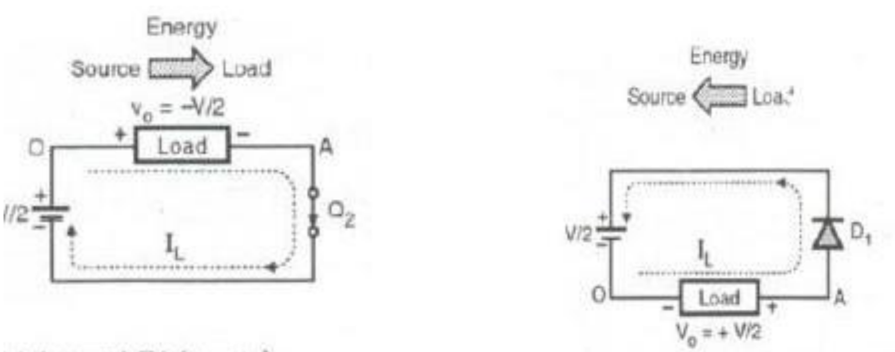
Interval II (tl - t2): Q1 is turned on at instant tl, the load voltage is equal to + V/2 and the positive load current increases gradually. At instant t2 the load current reaches the peak value. The transistor Q1 is turned off at this instant. Due to the same polarity of load voltage and load current the energy is stored by the load. Refer Fig. 8.3(a).



Interval III (t2- t3): Due to inductive load, the load current direction will be maintained same even after Q1 is turned off. The self induced voltage across the load will be negative. The load current flows through lower half of the supply and D2 as shown in Fig. 8.3(b). In this interval the stored energy in load is fed back to the lower half of the source and the load voltage is clamped to -V/2.

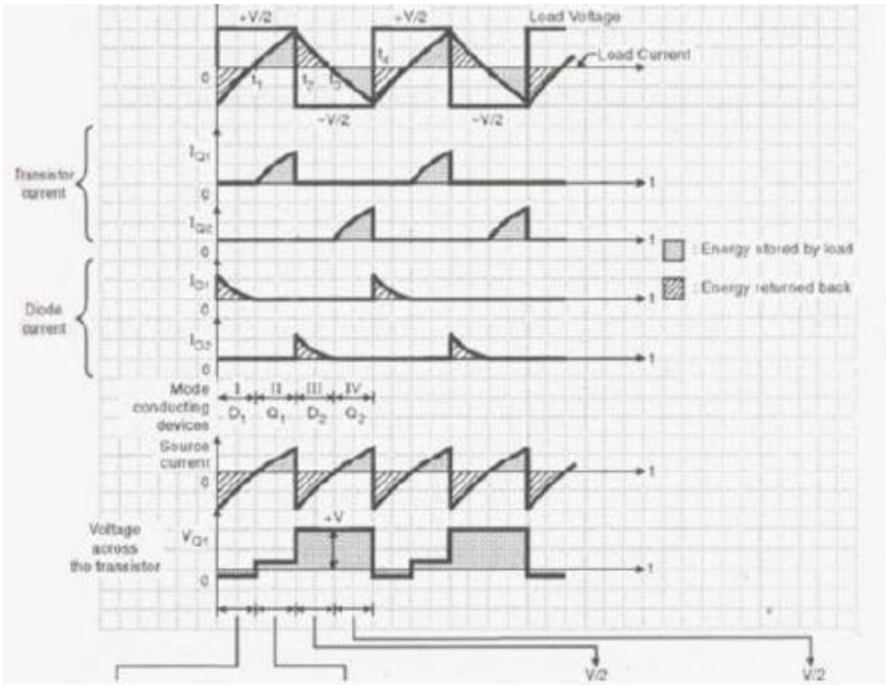
Interval IV (t3 - t4):

At the instant t3, the load current goes to zero, indicating that all the stored energy has been returned back to the lower half of supply. At instant t3 ' Q2 ‘is turned on. This will produce a negative load voltage v0 = - V/2 and a negative load current. Load current reaches a negative peak at the end of this interval. (See Fig. 8.4(a)).



(a) Interval IV $(t_3 - t_4)$

(b) Interval I $(t_0 - t_1)$



Interval I (t4 to t5) or (t0 to t1)

Conduction period of the transistors depends upon the load power, factor. For purely inductive load, a transistor conducts only for T0/2 or 90 o. Depending on the load power factor, that conduction period of the transistor will vary between 90 to 1800 (1800 for purely resistive load).

5.5 Fourier analysis of the Load Voltage Waveform of a Half Bridge Inverter

Assumptions:

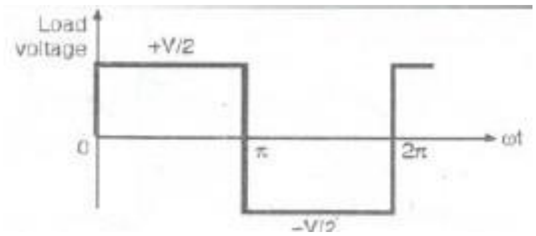
• The load voltage waveform is a perfect square wave with a zero average value.

• The load voltage waveform does not depend on the type of load.

• an, bn and cn are the Fourier coefficients.

• ɵn is the displacement angle for the nth harmonic component of output voltage.

• Total dc input voltage to the inverter is V volts.



RMS output voltage

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

$$= \left\{ \frac{V^2}{4\pi} \times \pi \right\}^{1/2}$$

$$V_{o\,rms} = \frac{V}{2} \text{ volts}$$

RMS value of fundamental component of output voltage

As the fundamental component is a sinewave, its rms value is given by,

$$V_{o1\,rms} = \frac{2V}{\sqrt{2}\,\pi} = \frac{\sqrt{2}\,V}{\pi} = 0.45\ V$$

5.6 Performance parameters of inverters

The output of practical inverters contains harmonics and the quality of an inverter is normally evaluated in terms of following performance parameters:

- Harmonic factor of nth harmonic.
- Total harmonic distortion.
- Distortion factor.
- Lowest order harmonic.

***Harmonic factor of nth harmonics HFn*:**

The harmonic factor is a measure of contribution of indivisual harmonics. It is defined as the ratio of the rms voltage of a particular harmonic component to the rms value of fundamental component.

Total harmonic distortion, THD: It is a measure of closeness in shape between a waveform and its fundamental component (sinusoidal waveform). THD = 0 means sinusoidal wave.

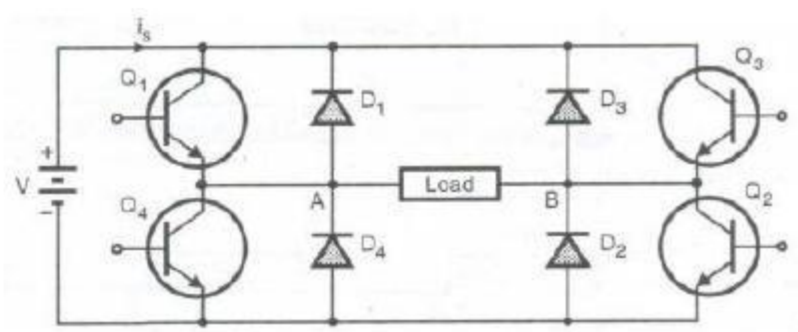
Distortion Factor, DF

DF indicates the amount of HD that remains in a particular waveform after the harmonics of that waveform have been subjected to the second order attenuation (i.e. divided by n2)

Lowest-orderharmonic,LOH

LOH is that harmonic component whose frequency is closest to the fundamental one. Its amplitude is normally > 3% of the fundamental component. High LOH is desired.

5.7 Single Phase Bridge Inverter



A single phase bridge inverter is shown in Fig.8.7. It consists of four transistors. These transistors are turned on and off in pairs of Q1, Q2 and Q3 Q4.

In order to develop a positive voltage + V across the load, the transistors Q1, and O2 are turned on simultaneously whereas to have a negative voltage - V across the load we need to turn on the devices Q3 and Q4.

Diodes D1, D2, D3, and D4 are known as the feedback diodes, because energy feedback takes place through these diodes when the load is inductive.

Operation with resistive load

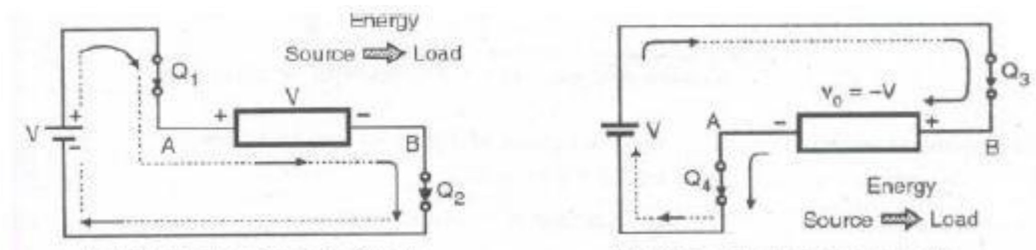
With the purely resistive load the bridge inverter operates in two different intervals In one cycle of the output.

Mode I (0 - T0/2*):*

The transistors 01 and O2 conduct simultaneously in this mode. The load voltage is + V and load current flows from A to B. The equivalent circuit for mode 1 is as shown in Fig. 8.8 (A). At t = To/2 , 0, and Q2 are turned off and Q3 and Q4 are turned on.

At t = T0/2, Q3 and Q4 are turned on and Q1 and Q2 are turned off. The load voltage is –V and load current flows from B to A. The equivalent circuit for mode II is as shown in Fig. 9.5.1(b). At t = To, Q3 and Q4 are turned off and Q1 and Q2 are turned on again.

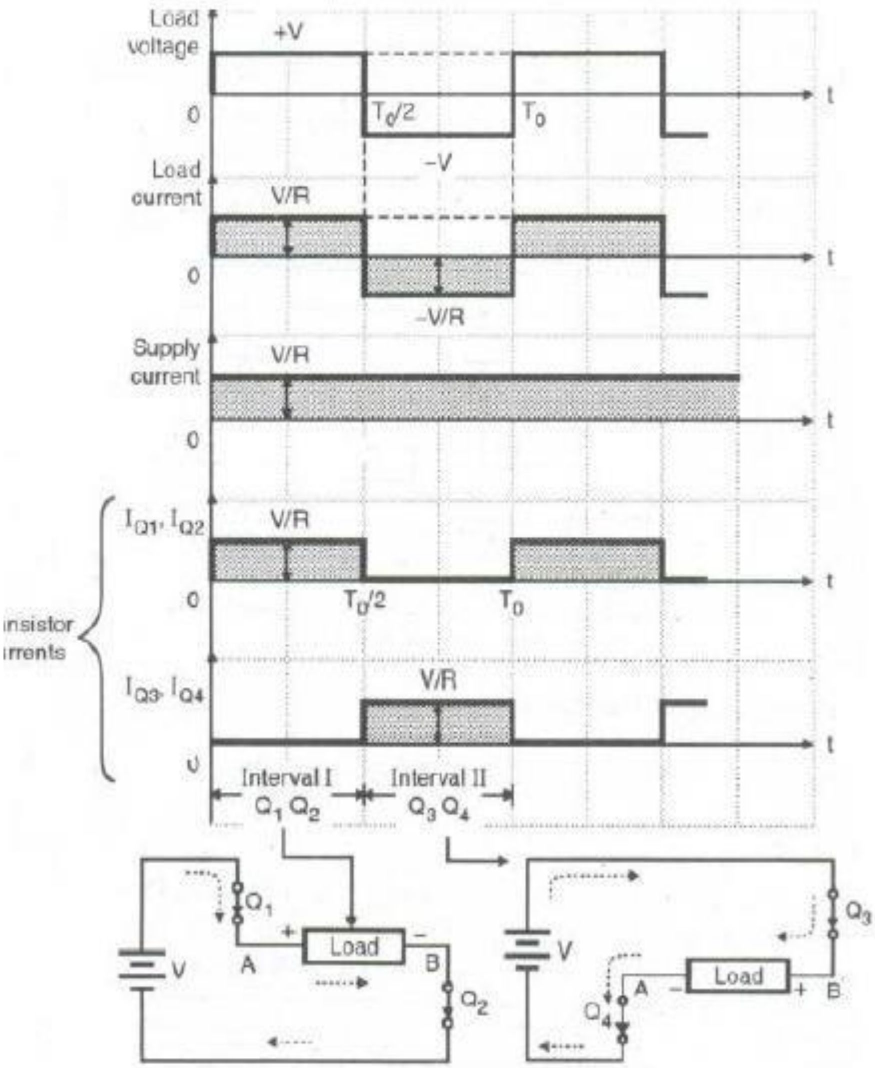
• As the load is resistive it does not store any energy. Therefore the feedback diodes are not effective here.



(a) Mode I equivalent circuit (b) Mode II equivalent circuit

• The voltage and current waveforms with resistive load are as shown in Fig.

The important observations from the waveforms of Fig as follows:
(i) The load current is in phase with the load voltage
(ii) The conduction period for each transistor is 1t radians or 1800
(iii) Peak current through each transistor = V/R.
(iv) Average current through each transistor = V/2R
(v) Peak forward voltage across each transistor = V volts.



5.8 Single Phase Bridge Inverter with RL Load

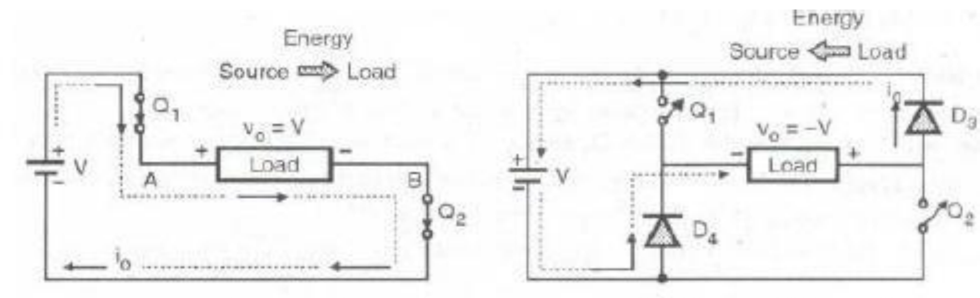
The operation of the circuit can be divided into four intervals or modes. The waveforms are as shown in Fig.

Interval I (t1 – t2):

At instant tl, the pair of transistors Q1 and Q2 is turned on. The transistors are assumed to be ideal switches. Therefore point A gets connected to positive point of dc source V through Q, and point B gets connected to negative point of input supply.

The output voltage Vo == + V as shown in Fig 8.11(a). The load current starts increasing exponentially due to the inductive nature of the load.

The instantaneous current through Q1 and Q2 is equal to the instantaneous load current. The energy is stored into the inductive load during this interval of operation.



(a) Interval I ($t_1 - t_2$) (b) Interval II ($t_2 - t_3$)

Interval II (t2 - t3) :

• At instant t2 both the transistors Q1 and Q2 are turned off. But the load current does not reduce to 0 instantaneously, due to its inductive nature.

• So in order to maintain the flow of current in the same direction there is a self induced voltage across the load. The polarity of this voltage is exactly opposite to that in the previous mode.

• Thus output voltage becomes negative equal to - V. But the load current continues to now in the same direction, through D3 andD4 as shown in Fig. 8.11(b).

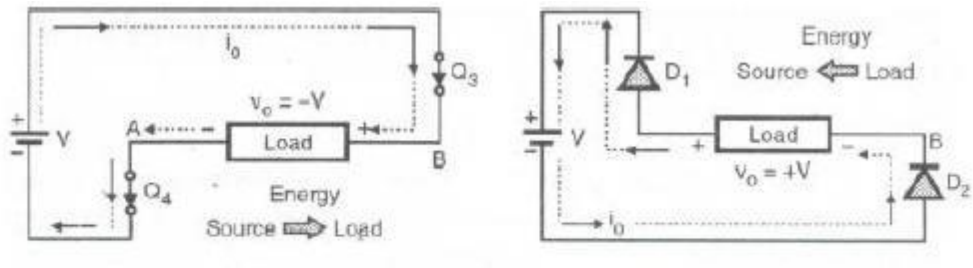
• Thus the stored energy in the load inductance is returned back to the source in this mode. The diodes D1 to D4 are therefore known as the feedback diodes.

• The load current decreases exponentially and goes to 0 at instant t3 when all the energy stored ill the load is returned back to supply. D3 and D4 are turned off at t3·

Interval III (t3 – t4)

• At instant t3 ' Q3 and Q4 are turned on simultaneously. The load voltage remains negative equal to - V but the direction of load current will reverse and become negative.

• The current increases exponentially in the negative direction. And the load again stores energy) in this mode of operation. This is as shown in Fig.



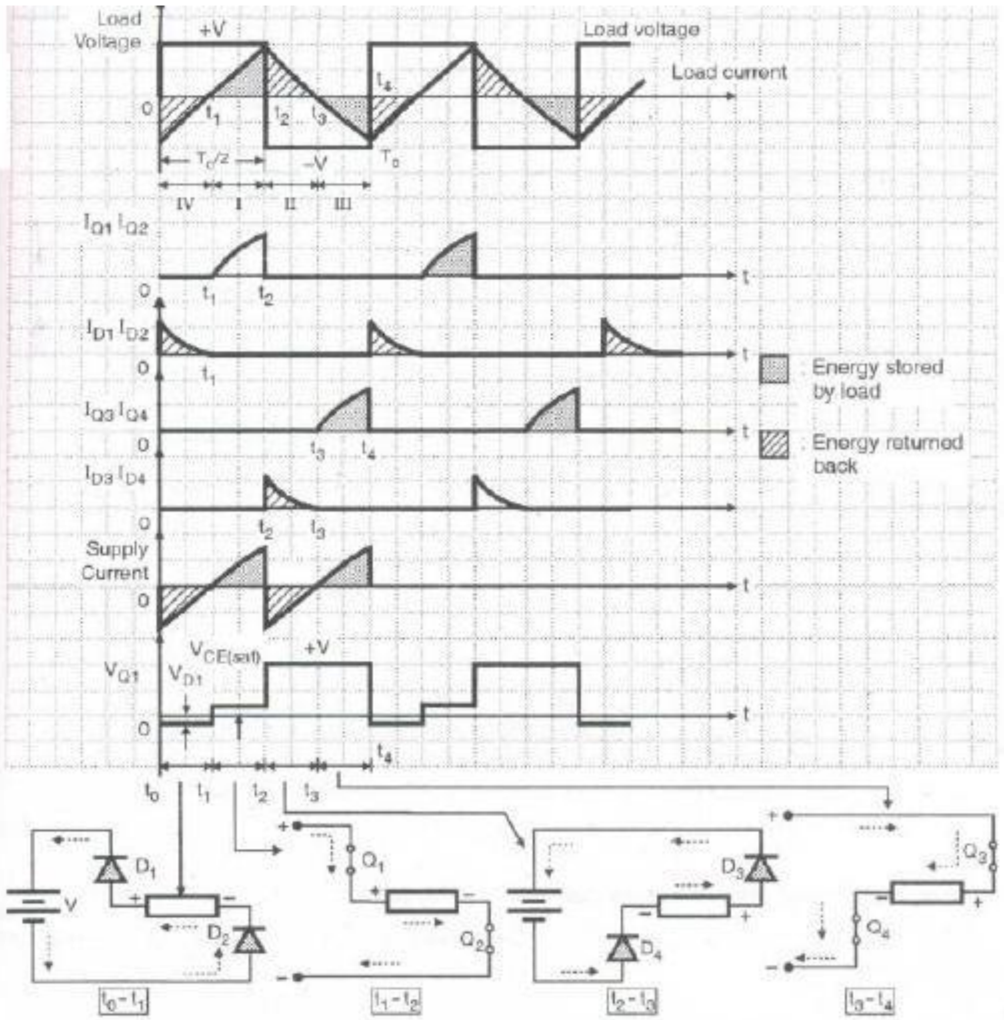
(a) Interval III ($t_3 - t_4$) (b) Interval IV (t_4 to t_5) or ($t_0 - t_1$)

Interval IV (t4 to t5) or (t0 to t1)

• At instant t4 or to the transistors Q3 and Q4 are turned off. The load inductance tries to maintain the load current in the same direction, by inducing a positive load voltage.
• This will forward bias the diodes D) and D2. The load stored energy is returned back to the input dc supply. The load voltage Vo = + V but the load current remains negative and decrease exponentially towards 0. This is as shown in Fig. 8.12(b).
• At t5 or t1 the load current goes to zero and transistors Q1 and Q2 can be turned on again.

Conduction period of devices:

• The conduction period with a very highly inductive load, will be T*01*4 or 90 0 for all the transistors as well as the diodes.
• The conduction period of transistors will increase towards To/2.*or* 1800 with increase in th1 load power factor. (i.e., as the load becomes more and more resistive).

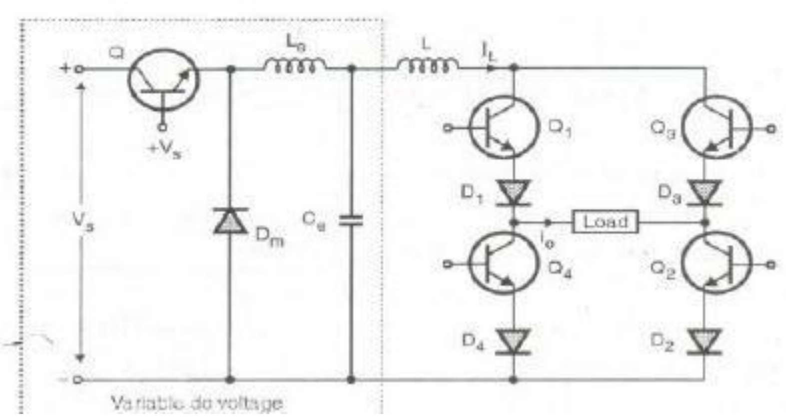


5.9 Comparison of half bridge and full bridge inverters

Sr. No.	Parameter	Half bridge	Full bridge
1	Need of an output transformer	Not needed	Not needed
2	Number of transistors required to be used.	Two	Four
3	Efficiency	High	High
4	Voltage across the nonconducting transistor	V Volts	V Volts
5	Output voltage waveform	Square, Quasi square or PWM	Square, Quasi square or PWM
6	Current rating of power device	Equal to the load current	Equal to the load current
7	Number of devices conducting simultaneously	One	Two
8	Necessity of dead band to avoid cross conduction	Yes	Yes

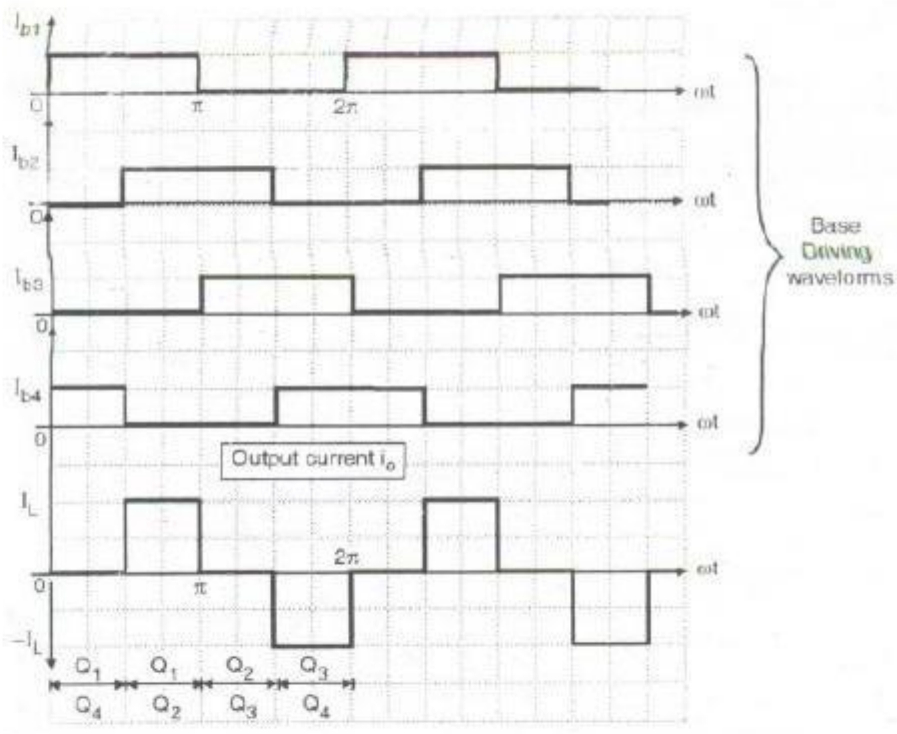
5.10 Principle of Operation of CSI

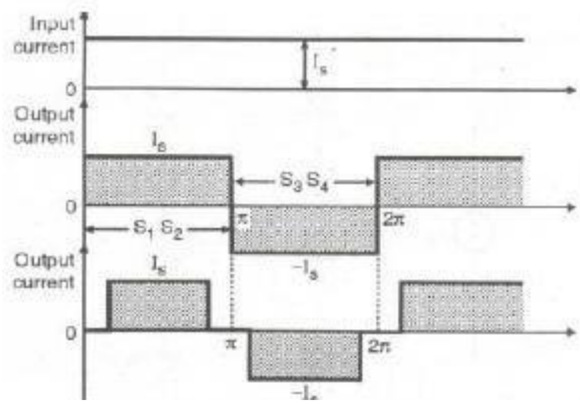
The circuit diagram of current source inverter is shown in Fig. The variable dc voltage source is converted into variable current source by using inductance L.



The current IL supplied to the single phase transistorised inverter is adjusted by the combination of variable dc voltage and inductance L.
The waveforms of base currents and output current io are as shown in Fig. 8.15. When transistors Q1 and Q2 conduct simultaneously, the output current is positive and equal to + IL. When transistors Q3 and Q4 conduct simultaneously the output current io = - IL.
But io = 0 when the transistors from same arm i.e. Q(Q4 or Q2 Q3 conduct simultaneously.

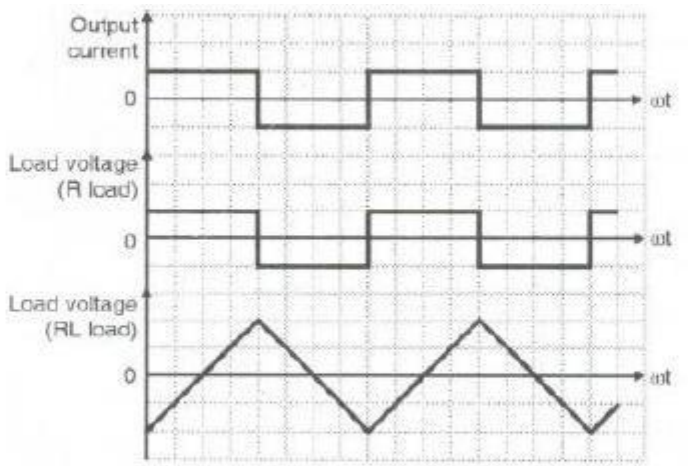
The output current waveform of Fig.is a quasi-square waveform. But it is possible to
Obtain a square wave load current by changing the pattern of base driving signals. Such waveforms are shown in Fig.





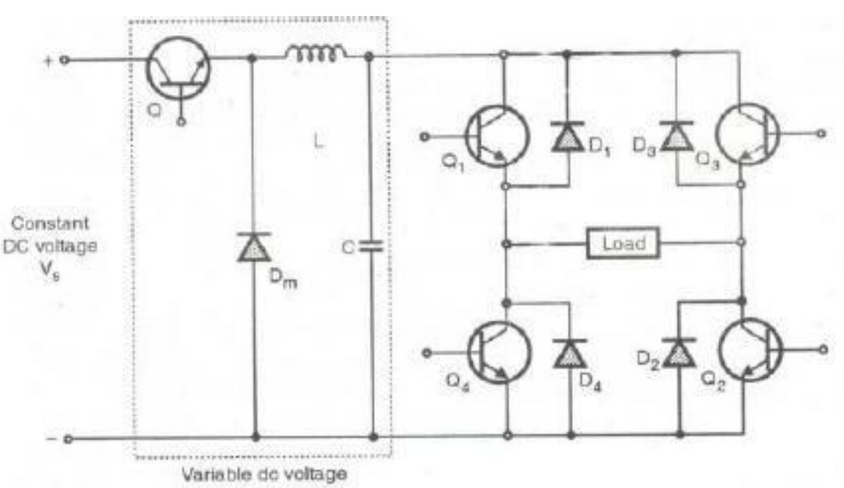
Load Voltage:

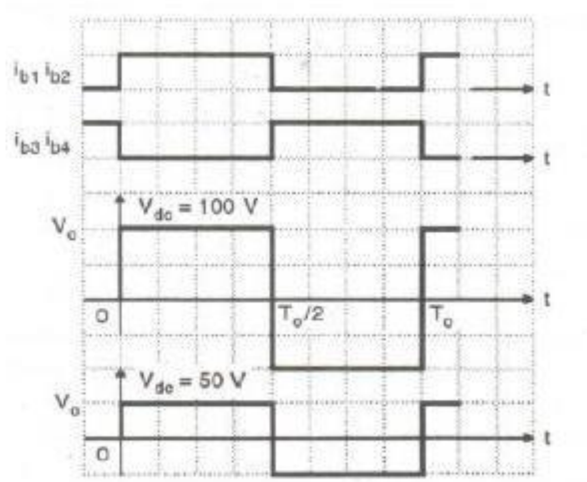
• The load current waveform in CSI has a defined shape, as it is a square waveform in this case. But the load voltage waveform will be dependent entirely on the nature of the load.
• The load voltage with the resistive load will be a square wave, whereas with a highly inductive load it will be a triangular waveform. The load voltage will contain frequency components at the inverter frequency f, equal to l/T and other components at multiples of inverter frequency.
• The load voltage waveforms for different types of loads are shown in Fig.



5.11 Variable DC link Inverter

The circuit diagram of a variable DC-link inverter is shown in Fig. This circuit can be divided into two parts namely a block giving a variable DC voltage and the second part being the bridge inverter itself.





The components Q, Dm, Land C give out a variable DC output. L and C are the filter components. This variable DC voltage acts as the supply voltage for the bridge inverter.

The pulse width (conduction period) of the transistors is maintained constant and the variation in output voltage is obtained by varying the DC voltage.

The output voltage waveforms with a resistive load for different dc input voltages are shown in Fig.

We know that for a square wave inverter, the rms value of output voltage is given by,

V0 (rms) = Vdc volts

Hence by varying Vdc, we can vary V0 (rms)

One important advantage of variable DC link inverters is that it is possible to eliminate or reduce certain harmonic components from the output voltage waveform.

The disadvantage is that an extra converter stage is required to obtain a variable DC voltage from a fixed DC. This converter can be a chopper

Three Phase DC-AC Inverters:

Three Phase DC-AC Converters Three phase inverters are normally used for high power applications. The advantages of a three phase inverter are:

- The frequency of the output voltage waveform depends on the switching rate of the switches and hence can be varied over a wide range.
- The direction of rotation of the motor can be reversed by changing the output phase sequence of the inverter.
- The ac output voltage can be controlled by varying the dc link voltage.

The general configuration of a three phase DC-AC inverter is shown in Figure 1. Two types of control signals can be applied to the switches:

- 180^o conduction

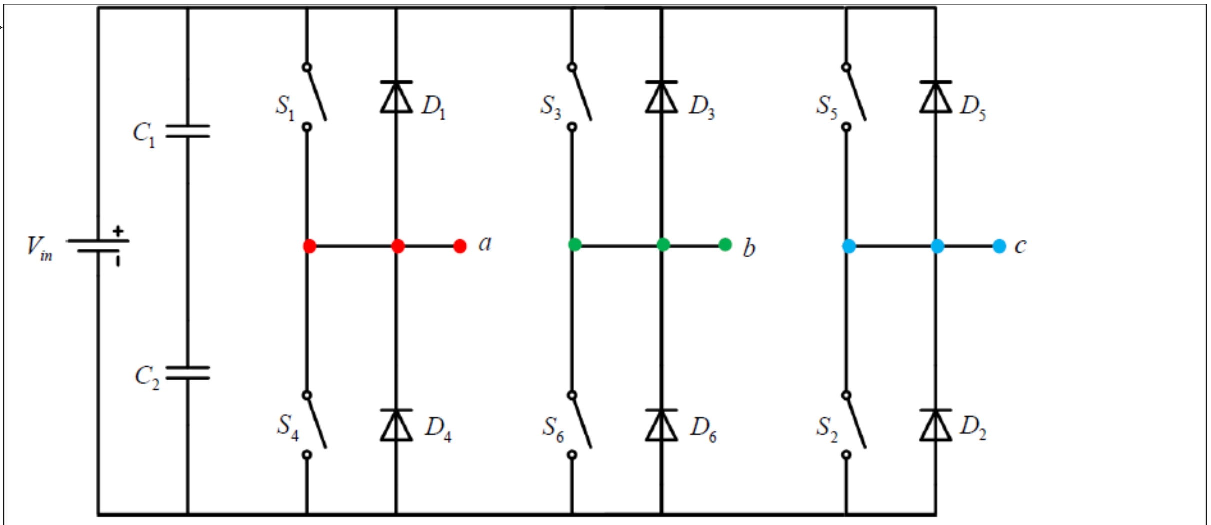
➢ 

Figure 1: Configuration of a Three-Phase DC-AC Inverter

180-Degree Conduction with Star Connected Resistive Load

The configuration of the three phase inverter with star connected resistive load is shown in **Figure** 2. The following convention is followed:
A current leaving a node point ***a***, ***b*** or ***c*** and entering the neutral point ***n*** is assumed to be positive.
All the three resistances are equal, Ra= Rb= Rc= R

In this mode of operation each switch conducts for 180o. Hence, at any instant of time ***three switches*** remain ***on***. When is S1 ***on***, the terminal ***a*** gets connected to the positive terminal of input DC source. Similarly, when S4 is ***on***, terminal ***a*** gets connected to the negative terminal of input DC source. There are six possible modes of operation in a cycle and each mode is of 60o duration and the explanation of each mode is as follows:

Mode 1**:** In this mode the switches s5,s6 and s1 are turned ***on*** for time interval $0 < \omega t < \pi/3$ As a result of this the terminals ***a*** and ***c*** are connected to the positive terminal of the input DC source and the terminal ***b*** is connected to the negative terminal of the DC source. The current flow through Ra,Rb and Rc is shown in **Figure 3a** and the equivalent circuit is shown in **Figure 3b**. The equivalent resistance of the circuit shown in **Figure 3b** is

$$R_{eq} = R + \frac{R}{2} = \frac{3R}{2}$$

The current delivered by the DC input source is

$$i = \frac{V_{in}}{R_{eq}} = \frac{2}{3}\frac{V_{in}}{R}$$

The currents and are ia and ib

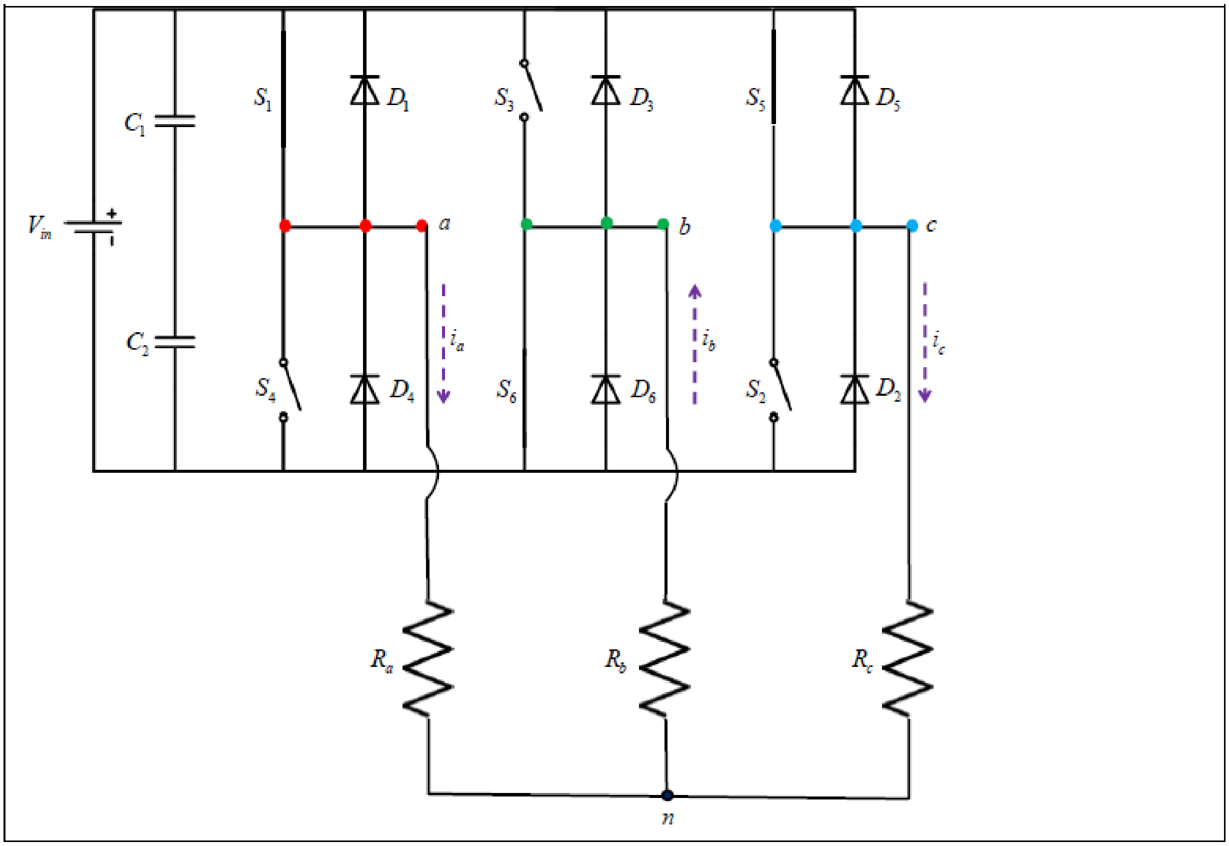
$$i_a = i_c = \frac{1}{3}\frac{V_{in}}{R}$$

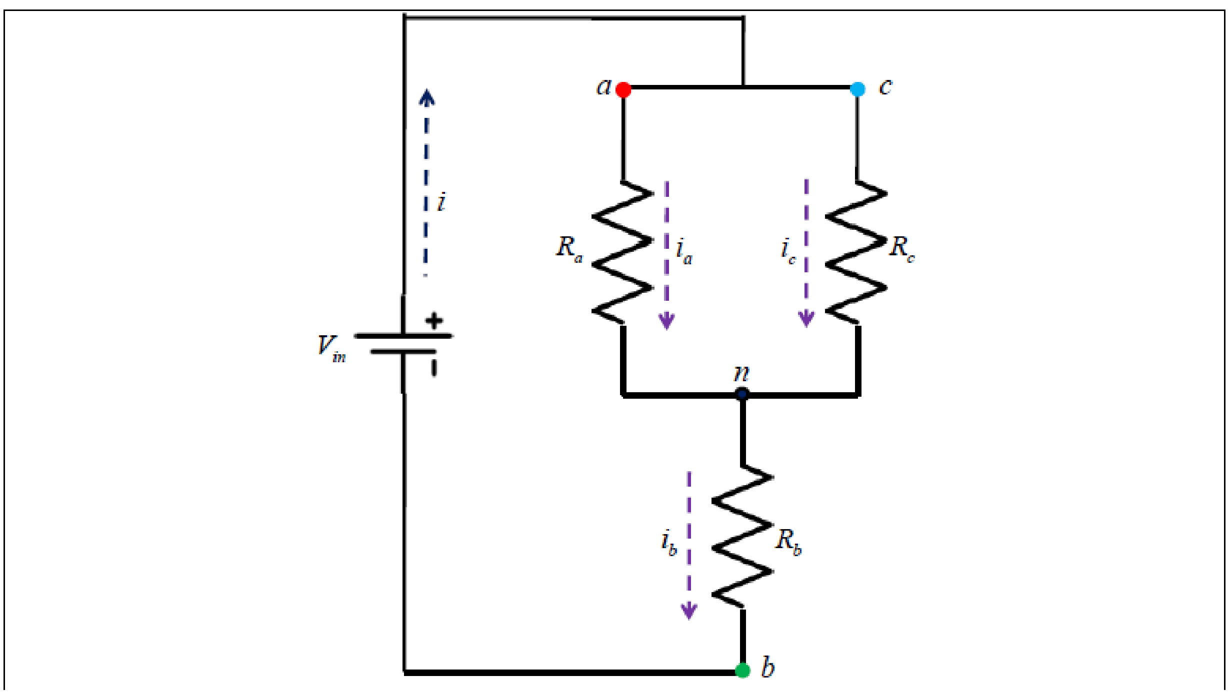
Keeping the current convention in mind, the current is ib

$$i_b = -i = -\frac{2}{3}\frac{V_{in}}{R}$$

Having determined the currents through each branch, the voltage across each branch is

$$v_{an} = v_{cn} = i_a R = \frac{V_{in}}{3};\ v_{bn} = i_b R = -\frac{2V_{in}}{3}$$



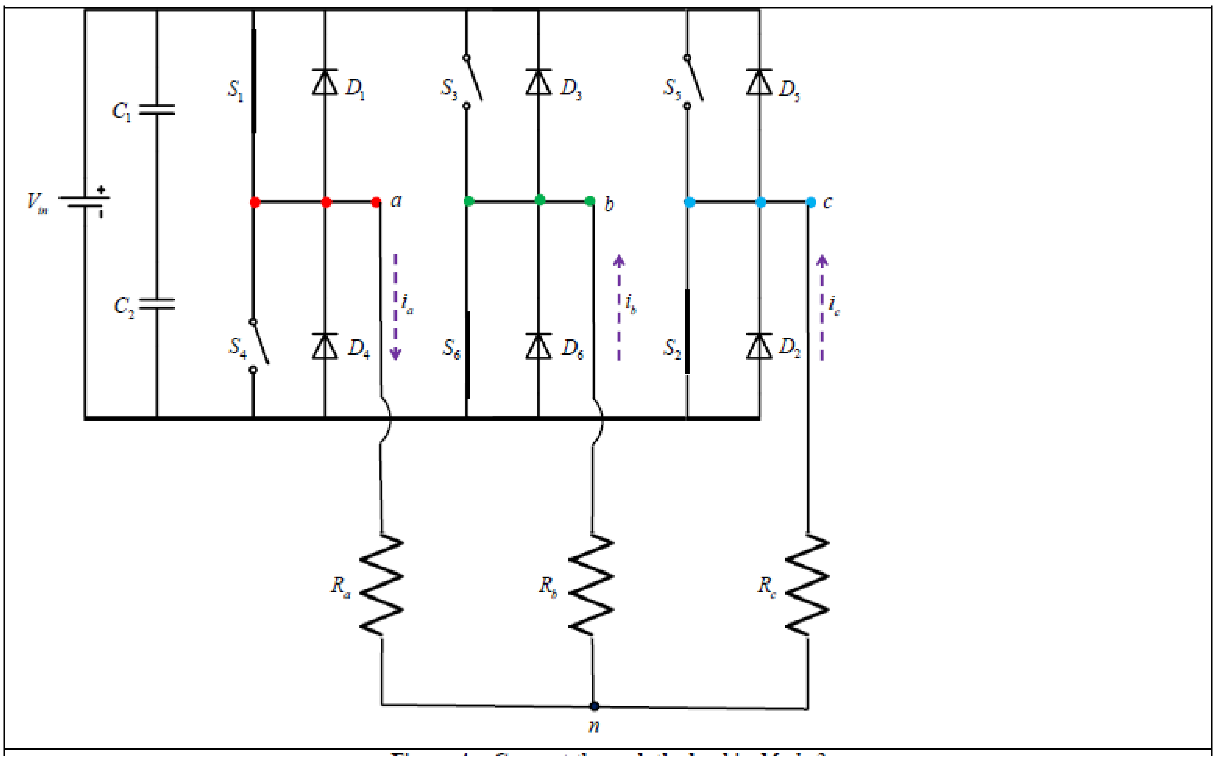


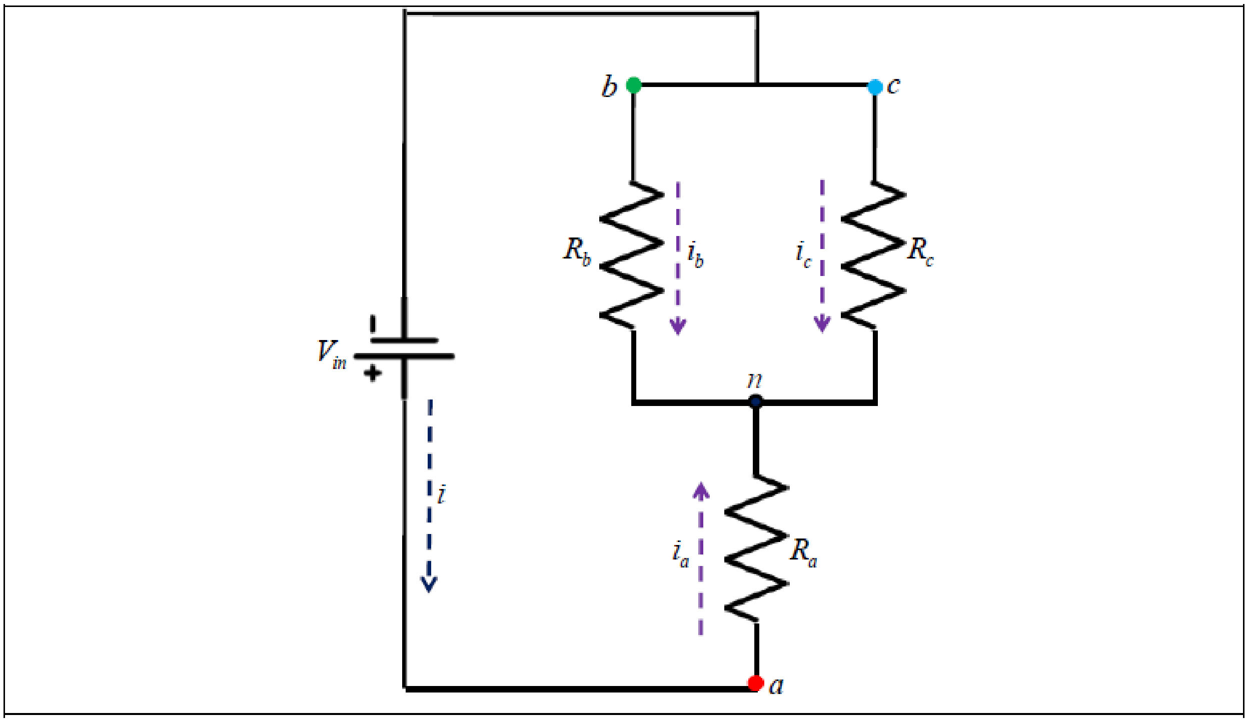
.

Mode 2**:** In this mode the switches s6,s1 and s2 are turned ***on*** for time interval π/3< ωt< 2π/3. The current flow and the equivalent circuits are shown in **Figure 4a** and **Figure 4b** respectively. Following the reasoning given for ***mode 1***, the currents through each branch and the voltage drops are given by

$$i_b = i_c = \frac{1}{3}\frac{V_{in}}{R};\ i_a = -\frac{2}{3}\frac{V_{in}}{R}$$

$$v_{bn} = v_{cn} = \frac{V_{in}}{3};\ v_{an} = -\frac{2V_{in}}{3}$$

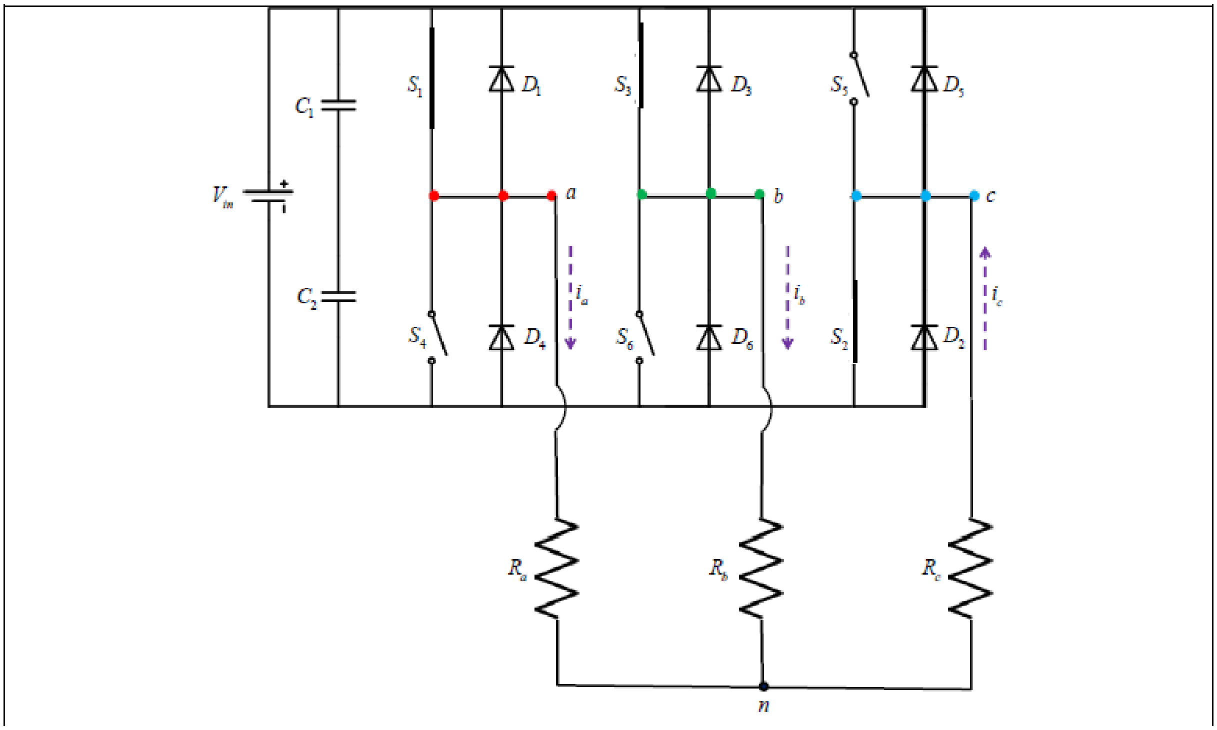


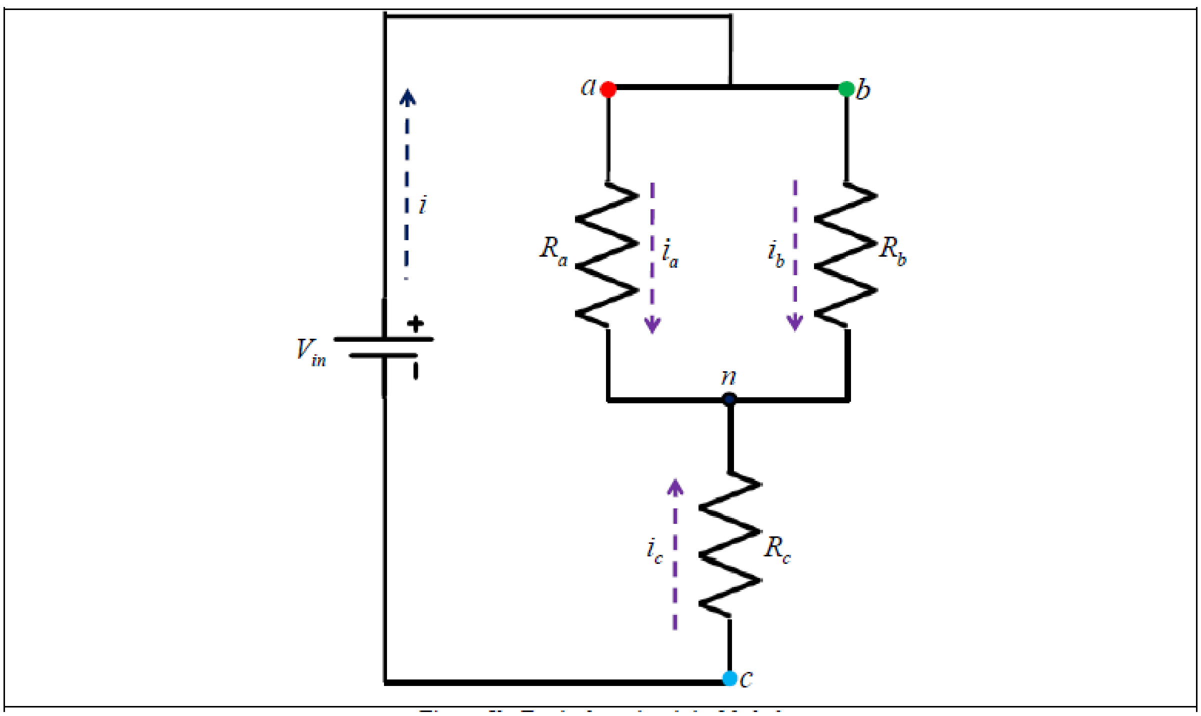


Mode 3*:** In this mode the switches s1,s2 and s3 are turned ***on for time interval 2π/3< ωt< π. . The current flow and the equivalent circuits are shown in **Figure 5a** and **figure 5b** respectively. The magnitudes of currents and voltages are:

$$i_a = i_b = \frac{1}{3}\frac{V_{in}}{R};\ i_c = -\frac{2}{3}\frac{V_{in}}{R}$$

$$v_{an} = v_{bn} = \frac{V_{in}}{3};\ v_{cn} = -\frac{2V_{in}}{3}$$





For ***modes 4, 5*** and ***6*** the equivalent circuits will be same as ***modes 1, 2*** and ***3*** respectively. The voltages and currents for each mode are:

$$\left.\begin{aligned} i_a = i_c &= -\frac{1}{3}\frac{V_{in}}{R};\ i_b = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{cn} &= -\frac{V_{in}}{3}; V_{bn} = \frac{2V_{in}}{3} \end{aligned}\right\} \text{for } \textbf{\textit{mode 4}}$$

$$\left.\begin{aligned} i_b = i_c &= -\frac{1}{3}\frac{V_{in}}{R};\ i_a = \frac{2}{3}\frac{V_{in}}{R} \\ v_{bn} = v_{cn} &= -\frac{V_{in}}{3}; V_{an} = \frac{2V_{in}}{3} \end{aligned}\right\} \text{for } \textbf{\textit{mode5}}$$

$$\left.\begin{aligned} i_a = i_b &= -\frac{1}{3}\frac{V_{in}}{R};\ i_c = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{bn} &= -\frac{V_{in}}{3}; V_{cn} = \frac{2V_{in}}{3} \end{aligned}\right\} \text{for } \textbf{\textit{mode 6}}$$

The plots of the phase voltages (V_{an} ,V_{bn} and V_{cn}) and the currents (I_a , I_b and I_c) are shown in **Figure 6**. Having known the phase voltages, the line voltages can also be determined as:

$$v_{ab} = v_{an} - v_{bn}$$
$$v_{bc} = v_{bn} - v_{cn}$$
$$v_{ca} = v_{cn} - v_{an}$$

The plots of line voltages are also shown in **Figure 6** and the phase and line voltages can be expressed in terms of Fourier series as:

$$v_{an} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1 + \sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin(n\omega t)$$
$$v_{bn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1 + \sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \frac{2n\pi}{3}\right)$$
$$v_{cn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1 + \sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \frac{4n\pi}{3}\right)$$

$$v_{ab} = v_{an} - v_{bn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t + \frac{n\pi}{6}\right)$$
$$v_{bc} = v_{bn} - v_{cn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t - \frac{n\pi}{2}\right)$$
$$v_{ca} = v_{cn} - v_{an} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t - \frac{7n\pi}{6}\right)$$

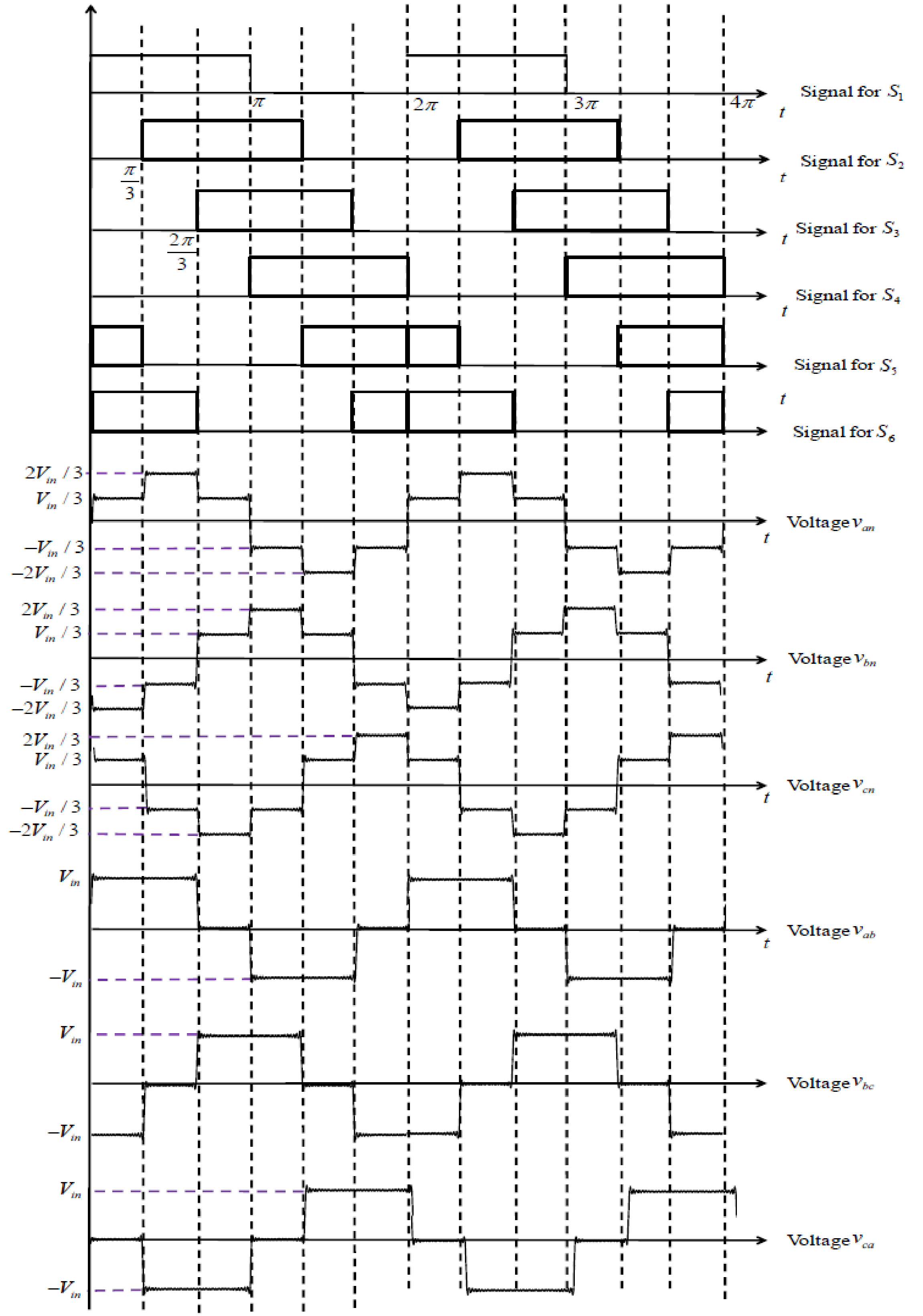


Figure 6: Voltage waveforms for Resistive load for 180°

5.12 Recommended questions

1. What are the differences between half and full bridge inverters?
2. What are the purposes of feedback diodes in inverters?
3. What are the arrangements for obtaining three phase output voltages?
4. What are the methods for voltage control within the inverters?
5. What are the methods of voltage control of I-phase inverters? Explain them briefly.
6. What are the main differences between VSI and CSI?
7. With a neat circuit diagram, explain single phase CSI?
8. The single phase half bridge inverter has a resistive load of R= 2.4 Ω and the dc input voltage is Vs=48V Determine a) the rms output voltage at the fundamental frequency Vo1 b) The output power Po c) the average and peak currents of each transistor d) the peak reverse blocking voltage Vbr of each transistor e) the THD f) the DF g) the HF and DF of the LOH.

5.13 Generic Skills / Outcomes

- ✓ Discuss the principle of operation of single phase and three phase DC –AC converters

5.14 Further Reading

1. **"Power Electronics" -** M. D. Singh and Kanchandani K.B. TMH publisher, 2nd Ed. 2007.

2. **"Thyristorized Power Controllers" -** G. K. Dubey S. R. Doradla, A. Joshi and Rmk Sinha New age international (P) ltd reprint 1999.

3. **"Power Electronics" -** Cynil W. Lander 3rd edition, MGH 2003.