NEAR EAST UNIVERSITY

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POWER ELECTRONICS TURN-OFF DEVICE CONVERTERS

Graduation Project
EE – 400

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Nicosia - 2007

ACKNOWLEDGEMENT

In the name of Almighty ALLAH, the compassionate and merciful.

I am grateful for the many encouraging and favourable comments from my advisor honourable Dr. Ozgur Cemal, who is my advisor as well. Because of his suggestions, patient and consistence support, I would be able to complete my project. I am thankful to him for his co-operation and guidance throughout my study of engineering.

I would like to acknowledge to my parents especially to my father, Syed Mehboob Alam, who has brought all of his efforts to support me, without knowing the return and who has patiently encouraged me to be the best everywhere. I am thankful to them for their moral support and pray which paved the way for my success

I would like to mention these two personalities, who really inspired me, Dr. Erdal Onurhan and especially Madam Filiz Alshanabley. I am thankful to them for their co-operation in my studies. They have been very kind and helping to me.

I can not regret all my friends especially Nauman Sharif, Munam Awais and Mirza Irfan Anjum. I am thankful to them for their help and support. I found them available in every moment whenever, I was in need of any kind of help and assistance during my stay in Cyprus.

ABSTRACT

Power electronics deals with the applications of solid-state electronics for the control and conversion of electric power. Conversion techniques require the switching on and off power switching devices. Low level electronics circuits, which normally consist of integrated circuits and discrete components, generate the required gating signals for the power devices. Integrated circuits and discrete components are being replaced by microprocessors and signal processing ICs.

An ideal power device should have no switching –on and –off limitations in terms of turn-on time, turn-off time, current, and voltage handling capabilities. Power semi conductor technology is rapidly developing fast switching power devices with increasing voltage and current limits. Power switching devices such as power BJTs, power MOSFETs, SITs, IGBTs MCTs, SITHs, SCRs, GTOs, ETOs, IGCTs, and other semiconductor devices are finding increasing applications in a wide range of products. With the availability of faster switching devices, the application of modern microprocessors and digital signal processing in synthesizing the control strategy for gating power devices to meet the conversion specifications are widening the scope of power electronics. (The study of controlling with microprocessor is beyond the scope of the topic). The power electronics revolution has gained momentum, since the early 1990s.

Engineering concerned with the supply and utilization of electricity need to be aware of the effects which power electronic equipment has on both the supply and load.

The fundamental of power electronics are well established and they do not change rapidly. However, the devices characteristics are continuously being improved and new devices are added. Power electronics, which employs the bottom-up approach, covers device characteristics conversion techniques first and then applications. It emphasizes the fundamental principles of power electronics.

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INTRODUCTION

Power electronics has applications within the whole field of electrical energy systems. The great extent of power electronics is due to a number of advantages which electronic apparatus generally has over its electromechanical counterparts. Power electronics has revolutionized the field of energy consumption.

The power electronics revolution has gained momentum, since 1990s. Within next 20 years, power electronics will shape and condition the electricity somewhere between its generation and all its users.

In chapter one, we gave a brief introduction about power electronics, its history, field of applications and advantages. It gives an idea about the relationship of power electronics with power, electronics, and control.

In chapter two, we discussed about the turn off devices. This chapter includes the characteristics, behavior, structure, advantages and disadvantages. These devices are used in power applications as switching devices. The development of theory and application relies heavily on waveforms and transient responses

Finally, in chapter three, we talked about converters. Converters in terms of voltage and current source. A converter is an operative unit, consisting of semiconductor devices and necessary auxiliaries, used for changing one or more of the characteristics of an electric power system. It can change voltage and current levels, frequency and number of phases. Electronic switches are also regarded as converters. Converters in terms of rectifiers and inverters, with voltage and current sources, are discussed in detail. Single phase and three phase rectifiers, as well as, inverters are discussed, by giving the input wave forms, output across the load and circuitry used.

CHAPTER 1

POWER ELECTRONICS

1.1 What is power electronics?

Power electronics refers to the conversion of electrical energy for power applications by power semiconductor devices where these devices operate as switches. Advantages of silicon controlled rectifiers abbreviated as SCR's led to the development of a new area of application called power electronics.

Power electronics combine power, electronics and control:

- Power: power deals with the static and rotating power equipment for the generation, transmission and distribution of electrical energy.
- Electronics: electronics deals with the solid-state devices and circuits for signal processing to meet the desired control objectives.
- Control: control deals with the steady-state and dynamic characteristics of closed-loop systems.

Thus, power electronics may be defined as the application of solid-state electronics for the control and conversion of electrical power. The interrelationship of power electronics with power, control and electronics is depicted in figure below:

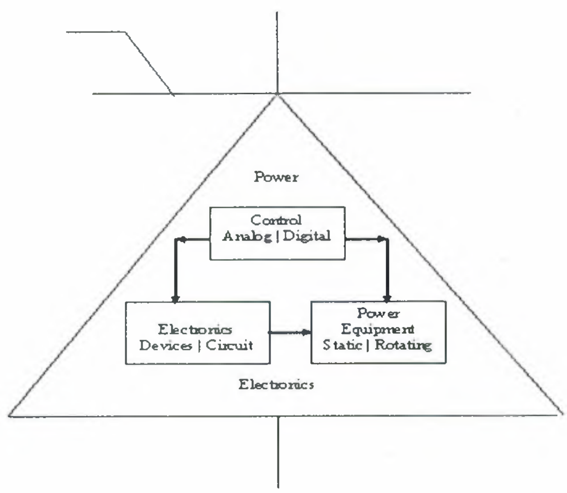


Figure 1.1 Relationships of power electronics to power, electronics and control

1.2 History of Power Electronics

The history of power electronics began with the introduction of mercury arc rectifiers in 1900. Then the metal tank rectifier, grid-controlled vacuum-tube rectifier, ignitron, phanotron and thyratron were introduced gradually. These devices were applied for power control until the 1950s.

The first electronic revolution began in1948 with the invention of the silicon transistor at Bell Telephone Laboratories by Bardeen, Brattain and Shockley. Most of today's advanced electronic technologies are traceable to that invention.

Microelectronics evolved over the years from the silicon semiconductors. The next breakthrough in 1956 was also from Bell laboratories: the invention of the PNPN triggering transistor, which was defined as a silicon-controlled rectifier (SCR).

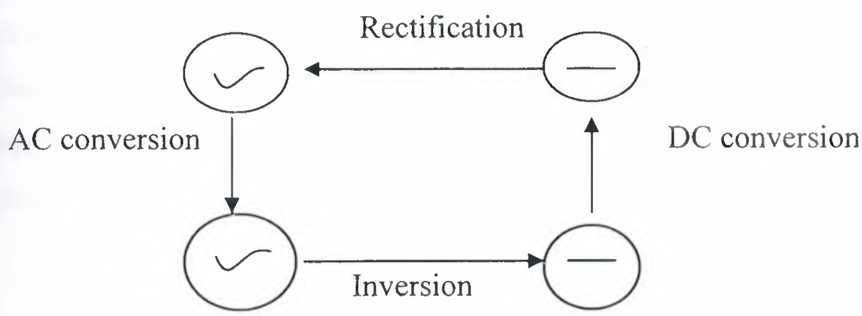
The second electronics evolution began in 1958 with the development of the commercial thyristor by the General Electric Company. That was the beginning of a new era of power electronics. Since then, many different types of power semiconductor devices and conversion techniques have been introduced. The power electronics revolution has gained momentum since the late 1980s and early 1990s. a chronological history of power electronics is shown in figure

1.3 Main tasks of power electronics

Power electronics has application has application that supports the whole field of electrical power systems with the range from a few VA / watts to thousands micro VA / micro watts. The main task of power electronics is to control and convert electrical power from one to another.

The four main forms of conversions of electrical power:

1- AC to DC
2- DC to AC
3- DC to DC
4- AC to AC



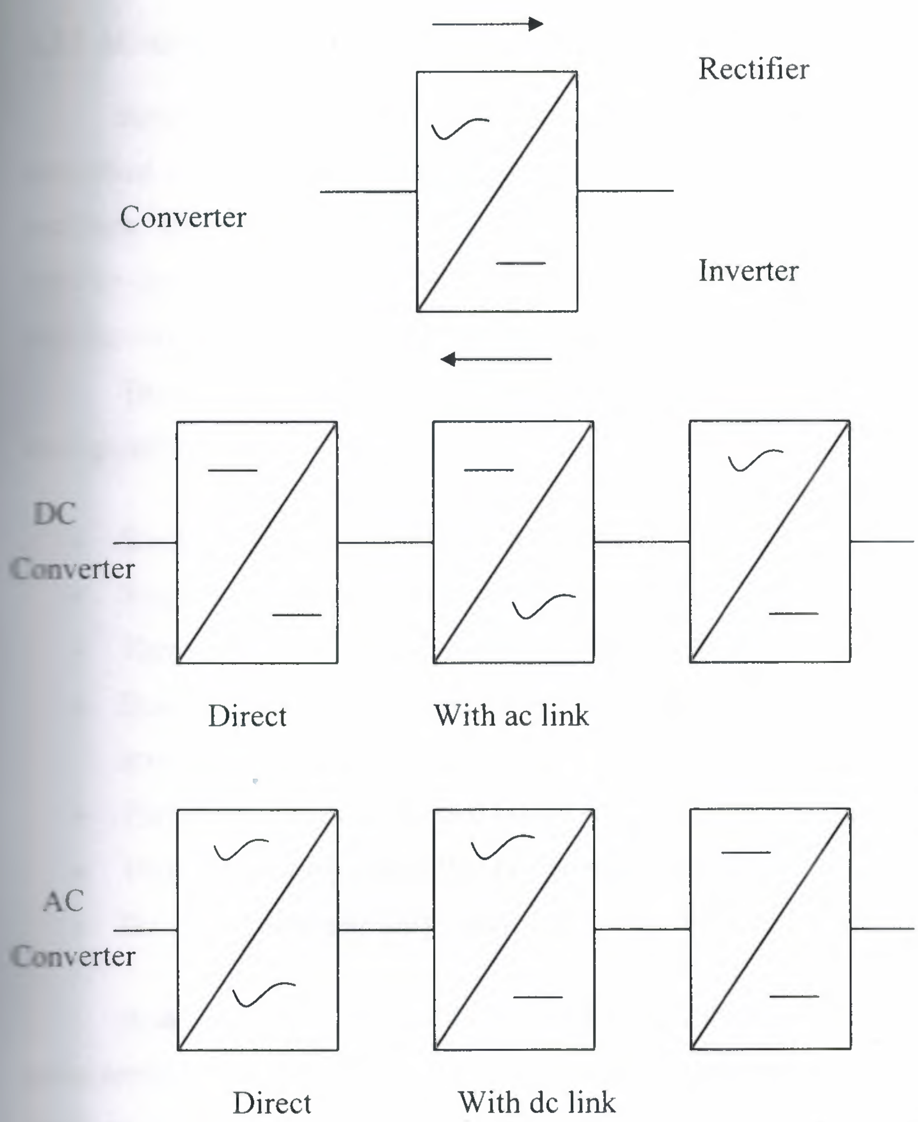


Figure 1.2 Conversion of electrical power

Electrical power converter is the term that is used to refer to a power electronic that convert voltage and current from one form to another.

The converters can be classified as:

1- Rectifiers
2- ac to dc converters
3- inverters converting dc to ac
4- chopper or a switch mode power supply that converts dc to another dc
5- cyclo converters and inverters converting ac to another ac
6- static switches

For this purpose SCR's and other power electronic devices are used as starter switches.

1.3.1 AC-to-DC Converters (Rectifiers)

Rectifiers can be classified as uncontrolled and controlled rectifiers, and the controlled rectifiers can be further divided into semi-controlled and fully-controlled rectifiers. Uncontrolled rectifier circuits are built with diodes, and fully-controlled rectifier circuits are built with SCRs. Both diodes and SCRs are used in semi-controlled rectifier circuits.

There are several configurations of rectifier circuits. The popular rectifier configurations are listed below.

- Single-phase semi-controlled bridge rectifier,
- Single-phase fully-controlled bridge rectifier,
- Three-phase three-pulse, star-connected rectifier,
- Double three-phase, three-pulse star-connected rectifiers with inter-phase transformer (IPT),
- Three-phase semi-controlled bridge rectifier,
- Three-phase fully-controlled bridge rectifier and
- Double three-phase fully-controlled bridge rectifiers with IPT.

Apart from the configurations listed above, there are series-connected and 12-pulse rectifiers for delivering high power output. Power rating of a single-phase rectifier tends to be lower than 10 kW. Three-phase bridge rectifiers are used for delivering higher power output, up to 500 kW at 500 V dc or even more. For low voltage, high current applications, and a pair of three-phase, three-pulse rectifiers interconnected by an inter-phase transformer (IPT) is used. For a high current output, rectifiers with IPT are preferred to connecting devices directly in parallel. There are many applications for rectifiers. Some of them are:

- Variable speed dc drives,
- Battery chargers,
- DC power supplies and Power supply for a specific application like electroplating

1.3.2 DC-to-AC Converters

The converter that changes a dc voltage to an alternating voltage is called an inverter. Earlier inverters were built with SCRs. Since the circuitry required to turn the SCR off tends to be complex, other power semiconductor devices such as bipolar junction transistors, power MOSFETs, insulated gate bipolar transistors (IGBT) and MOS-controlled thyristors (MCTs) are used nowadays. Currently only the inverters with a high power rating, such as 500 kW or higher, are likely to be built with either SCRs or gate turn-off thyristors (GTOs). There are many inverter circuits and the techniques for controlling an inverter vary in complexity. Some of the applications of an inverter are listed below:

- Emergency lighting systems,
- AC variable speed drives,
- Uninterrupted power supplies, and
- Frequency converters.

1.3.3 DC-to -DC Converters

When the SCR came into use, a dc-to-dc converter circuit was called a chopper. Nowadays, an SCR is rarely used in a dc-to-dc converter. Either a power BJT or a power MOSFET is normally used in such a converter and this converter is called a switch-mode power supply. A switch-mode power supply can be of one of the types listed below:

- Step-down switch-mode power supply,
- Step-up chopper,
- Fly-back converter and
- Resonant converter.

The typical applications for a switch-mode power supply or a chopper are:

- DC drive
- Battery charger and
- DC power supply.

1.3.4 AC-to-AC Converters

A cycloconverter or a cycloinverter converts an ac voltage, such as the mains supply, to another ac voltage. The amplitude and the frequency of input voltage to a cycloconverter tend to be fixed values, whereas both the amplitude and the frequency of output voltage of a cycloconverter tend to be variable. On the other hand, the circuit that converts an ac voltage to another ac voltage at the same frequency is known as an ac-chopper.

A typical application of a cycloconverter is to use it for controlling the speed of ac traction motor and most of these cycloconverters have a high power output, of the order a few megawatts and SCRs are used in these circuits. In contrast, low cost, low power cycloconverters for low power ac motors are also in use and many of these circuits tend to use triacs in place of SCRs. Unlike an SCR which conducts in only one direction, a triac is capable of conducting in either direction and like an SCR; it is also a three terminal device. It may be noted that the use of a cycloconverter is not as common as that of an inverter and a cycloinverter is rarely used.

1.3.5 Static switches

Because the power devices can be operated as static switches or contractors, the supply to these switches could be either ac or dc and the switches are called as ac static

1.4 Basic principles of power electronics

A quantitative understanding of the basic principles of power electronics is best achieved if the circuit components are realized in such a way that their function can be described by simple mathematical expressions.

1.5 Application of power electronics

The demand for control of electrical power for electric motor drive systems and industrial control existed for many years, and this led to early development of the Ward-Leonard system to obtain a variable dc voltage for control of dc motor drives. Power electronics has revolutionized the concept of power control for power conversion and for control of electric motor drives.

Power electronics are based primarily on the switching of power semiconductor devices. With the development of power semiconductor technology, the power handling capabilities and switching speed of the power devices have improved tremendously.

Power electronics has application within the whole field of electrical energy systems. The great extent of power electronics is due to a number of advantages which electronic apparatus generally has over its electromechanical counterparts.

Table1.1 Some applications of power electronics

Field of energy application	**Type of converter**	**Application**
Production	Rectifiers Frequency converters Rectifiers Frequency converters Electronic switch	Auxiliary power systems in power plants Converters for alternative energy source
Transmission	Rectifiers Inverters Electronic switches AC converters	High voltage dc (HVDC) Phase compensation
Distribution	Electronic switches Rectifiers Inverters Electronic switches	Electronic tap-changers DC networks AC networks Uninterruptible power systems
Consumption	Rectifiers Frequency converters AC converters DC converters	DC motor drives Field supplies Power supplies Battery charges Galvano rectifiers AC motor drives Induction heating Magnetic stirrers Light dimmers Traction motors Battery charges

Power electronics equipment is cheaper, lighter and smaller, and has great efficiency and more general availability. Also relevant is the fact that it can be easily controlled from microprocessors and computers, and that its performance can meet high demands from, say, industrial process and electric networks, problems which were earlier completely unrealistic can now be solved by means of power electronics. The development of microprocessor and microcomputer technology has a great impact on the control and synthesizing the control strategy for the power semiconductor devices. Modern power electronic equipment uses

1- power semiconductors that can be regarded as muscle
2- microelectronics that have the power and intelligence of brain

Power electronics have already found an important place in modern technology and now used in a great variety of high power products, including

- Heat controls
- Motor controls
- Vehicle propulsion systems and
- High-voltage direct current (HVDC) systems.
- Power supplies
- Light controls

It is difficult to draw the flexible ac transmissions (FACTs) boundaries for the application of power electronics. Especially with the present trends in the development of power devices and microprocessors
Some applications of power electronics, in the field of energy, are given in the table in the table 1.1.

1.6 Additional insight into power electronics

There are several striking features of power electronics, the foremost among them being the extensive use of inductors and capacitors. In many applications of power electronics, an inductor may carry a high current at a high frequency. The implications of operating an inductor in this manner are quite a few, such as necessitating the use of litz wire in place of single-stranded or multi-stranded copper wire at frequencies above 50 kHz, using a proper core to limit the losses in the core, and shielding the inductor properly so that the fringing that occurs at the air-gaps in the magnetic path does not lead to electromagnetic interference. Usually the capacitors used in a power electronic application are also stressed. It is typical for a capacitor to be operated at a high frequency with current surges passing through it periodically. This means that the current rating of the capacitor at the operating frequency should be checked before its use. In addition, it may be preferable if the capacitor has self-healing property. Hence an inductor or a capacitor has to be selected or designed with care, taking into account the operating conditions, before its use in a power electronic circuit.

In many power electronic circuits, diodes play a crucial role. A normal power diode is usually designed to be operated at 400 Hz or less. Many of the inverter and switch-mode power supply circuits operate at a much higher frequency and these circuits need diodes that turn ON and OFF fast. In addition, it is also desired that the turning-off process of a diode should not create undesirable electrical transients in the circuit. Since there are several types of diodes available, selection of a proper diode is very important for reliable operation of a circuit.

Analysis of power electronic circuits tends to be quite complicated, because these circuits rarely operate in steady-state. Traditionally steady-state response refers to the state of a circuit characterized by either a dc response or a sinusoidal response. Most of the power electronic circuits have a periodic response, but this response is not usually sinusoidal. Typically, the repetitive or the periodic response contains both a steady-state part due to the forcing function and a transient part due to the poles of the network. Since the responses are no sinusoidal, harmonic analysis is often necessary. In order to obtain the time response, it may be necessary to resort to the use of a computer program.

Power electronics is a subject of interdisciplinary nature. To design and build control circuitry of a power electronic application, one needs knowledge of several areas, which are listed below.

- Design of analogue and digital electronic circuits, to build the control circuitry.
- Microcontrollers and digital signal processors for use in sophisticated applications.
- Many power electronic circuits have an electrical machine as their load. In ac variable speed drive, it may be a reluctance motor, an induction motor or a synchronous motor. In a dc variable speed drive, it is usually a dc shunt motor.
- In a circuit such as an inverter, a transformer may be connected at its output and the transformer may have to operate with a non sinusoidal waveform at its input.
- A pulse transformer with a ferrite core is used commonly to transfer the gate signal to the power semiconductor device. A ferrite-cored transformer with a relatively higher power output is also used in an application such as a high frequency inverter.

- Many power electronic systems are operated with negative feedback. A linear controller such as a PI controller is used in relatively simple applications, whereas a controller based on digital or state-variable feedback techniques is used in more sophisticated applications.
- Computer simulation is often necessary to optimize the design of a power electronic system. In order to simulate, knowledge of software package such as MATLAB and the know-how to model nonlinear systems may be necessary.

The study of power electronics is an exciting and a challenging experience. The scope for applying power electronics is growing at a fast pace. New devices keep coming into the market, sustaining development work in power electronics.

1.7 Advantages

Microelectronics revolution gave us the ability to process a huge amount of information at incredible speed. The power electronics revolution is giving us the ability to shape and control large amounts of power with ever-increasing efficiency. Due to the marriage of power electronics, the muscle, with microelectronics, the brain, many potential applications of power electronics are now emerging and this trend will continue. Within the next 30 year, power electronics will shape and condition electricity somewhere in the transmission network between its generation and all its users.

1.8 Summery

As the technology for the power semiconductor devices and integrated circuits develops, the potential for the applications of power electronics becomes wider. There are already many power semiconductor devices that are commercially available; however, the development is all direction is continuing. The power converters fall generally into six categories: (1) AC-DC Converters (2) AC-AC Converters (3) DC_DC Converters (4) DC-AC Converters (5) Static Switches. The design of power electronics circuits requires designing the power and control circuits.

CHAPTER 2

TURN-OFF DEVICES

2.1 Turn-off devices

Those devices, which have controlled turn-on and turn-off characteristics i.e. the devices which can be turned off as well, by gate control, are called turn-off devices.

There are 13 types of thyristors. Only the GTOs, SITHs, MTOs, ETOs, IGCTs, and MCTs are gate turn-off devices. Each type has advantages and disadvantages. Also, BJTs, MOSFETs, SITs, IGBTs, and COOLMOS stand into the category of turn- off devices. Their characteristics, operation, and the behaviour, is discussed in this chapter.

2.2 Thyristor

2.2.1 Introduction

The thyristor is a solid-state semiconductor device with four layers of alternating N and P-type material. They act as a switch, conducting when their gate receives a current pulse, and continue to conduct for as long as they are forward biased.

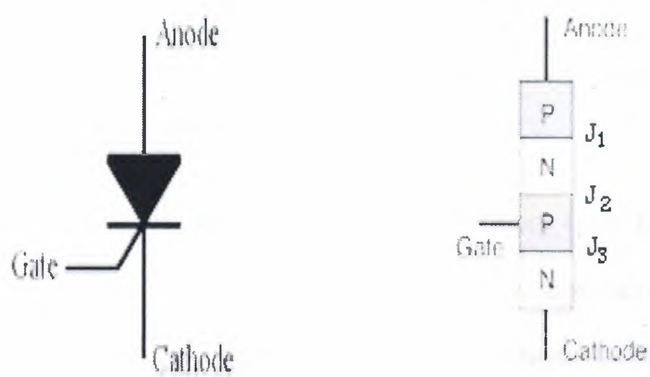


Figure 2.1 Thyristor symbol and three pn-junctions

Conventional thyristors are designed without gate-controlled turn-off capability, in which case the thyristor can recover from its conducting state to nonconducting state only when the current is brought to zero by other means. Gate turn-off thyristors are designed to have both turn-on and turn-off capability.

2.2.2 Thyristor turn-on

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

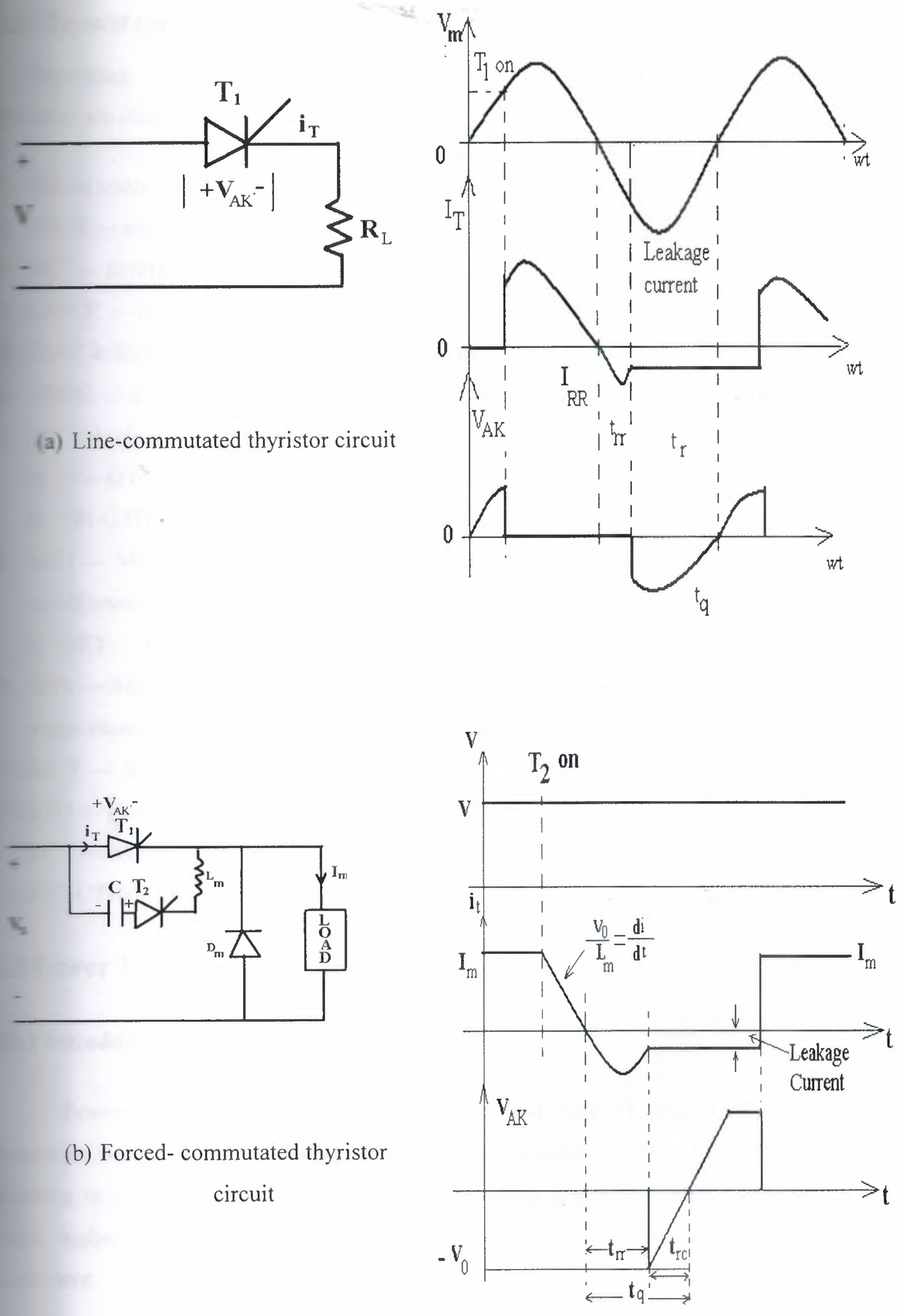
1. Thermals
2. Light
3. High voltage
4. dv/dt
5. Gate current

2.2.3 Thyristor turn-off

A thyristor that is in the on state is turned off by reducing the forward current to a level below the holding current I_H. There are various techniques for turning off a thyristor. In all the commutation techniques, the anode gate is maintained below the holding current for a sufficiently long time, so that all the excess carriers in the four layers are swept out or recombined.

Due to two outer pn-junctions, J_1 and $J3$, the turn-off characteristics would be similar to that of diode, exhibiting reverse recovery time t_{rr} and peak reverse recovery current I_{RR}. I_{RR} can be much greater than the normal reverse blocking current I_R The turn-off characteristics are shown in figure 2.2a and b for a line-commutated circuit and forced-commutated circuit, respectively.

The turn-off time t_q is the sum of reverse recovery time t_{rr} and recombination time t_{rc}. At the end of turn-off, a depletion layer develops across junction J_2 and thyristor recovers its ability to withstand forward voltage. In all the combination techniques, a reverse voltage applied across the thyristor during the turn-off process.



(a) Line-commutated thyristor circuit

(b) Forced- commutated thyristor circuit

Figure 2.2: Turn-off characteristics

2.2.4 Types of thyristors

Depending on the physical construction, and turn-on and turn-off behavior, thyristors are classified into 13 categories:

1) Silicon controlled rectifier (SCR)
2) ASCR — asymmetrical SCR
3) RCT — reverse conducting thyristor
4) LASCR — light activated SCR, or LTT — light triggered thyristor
5) DIAC & SIDAC — both forms of trigger devices
6) TRIAC — a bidirectional switching device containing two thyristor structures
7) GTO (thyristor) — gate turn-off thyristor
   a) MA-GTO — Modified anode gate turn-off thyristor
   b) DB-GTO — Distributed buffer gate turn-off thyristor
8) MCT — MOSFET controlled thyristor containing two additional FET structures for on/off control.
   a) BRT — Base Resistance Controlled Thyristor
9) SITh — Static induction thyristor, or FCTh — Field controlled thyristor containing a gate structure that can shut down anode current flow.
10) IGCT — Integrated gate-commutated thyristor
11) ETO — Emitter turn-off (control) thyristor
12) BCT — Bidirectional phase controlled thyristor
13) FET-CTHs — FET-controlled thyristors

2.3 Power Transistors

2.3.1 Introduction

Power transistors have controlled turn-on and turn-off characteristics. The transistors which are used as switching elements are operated in the saturation region, resulting in a low on-state voltage drop. The switching speed of modern transistor is much higher than that of thyristors and they are extensively employed in dc-ac converters.

2.3.2 Types of power Transistors

The power transistors are broadly classified into five categories:

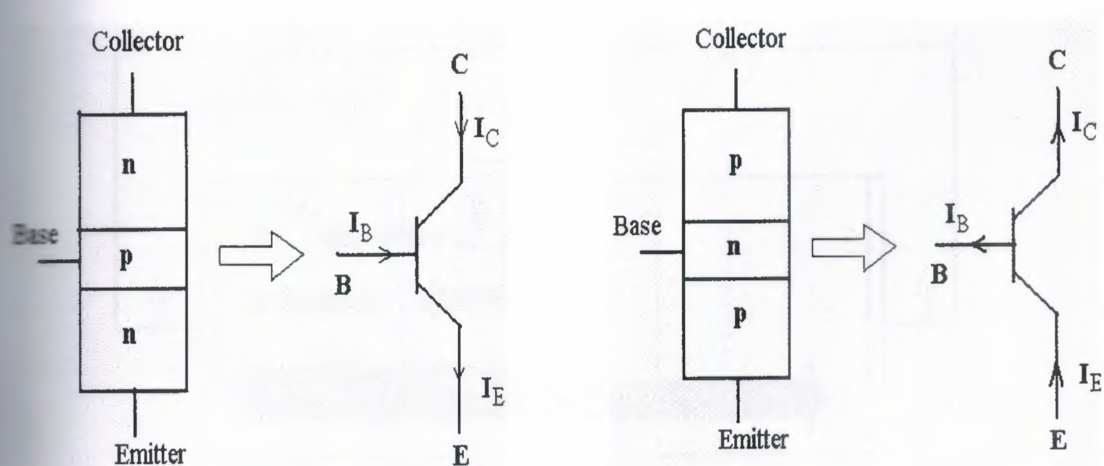
1) Bipolar junction transistors (BJTs)
2) Metal-oxide-semiconductor field-effect transistors (MOFETs)
3) Static induction transistors (SITs)
4) Insulated-gate bipolar transistors (IGBTs)
5) COOLMOS

These can be assumed as ideal switches to explain the power conversion techniques.

2.4 Bipolar Junction Transistors (BJT)

2.4.1 Structure and principle of operation

A bipolar junction transistor is formed by adding a second p- or n-region to a pn-junction diode. With two n-regions and one p-region, two junctions are formed and it is known as NPN-transistor, as shown in figure 2.3(a). With two p-regions and one n-region, it is called a PNP-transistor, as shown in figure 2.3(b). The three terminals are named as collector, emitter, and base. A bipolar transistor has two junctions, collector-base junction (CBJ) and base-emitter junction (BEJ). The device is called "bipolar" since its operation involves both types of mobile carriers, electrons and holes.



(a) NPN-Transistor (b) PNP-transistor

Figure 2.3 Bipolar transistor

There are two n^+-regions for the emitter of NPN-type transistor and two p^+-regions for the emitter of NPN-type transistor. For an NPN-type the emitter side n-layer is made wide, as shown in figure 2.4, the p-base is narrow, and the collector side n-layer is narrow and heavily doped. For a PNP-type, the emitter side p-layer is made wide, the n-base is narrow, and the collector side p-layer is narrow and heavily doped. The base and collector currents flow through two parallel paths, resulting in a low on- state collector-emitter resistance, $R_{CE(ON)}$.

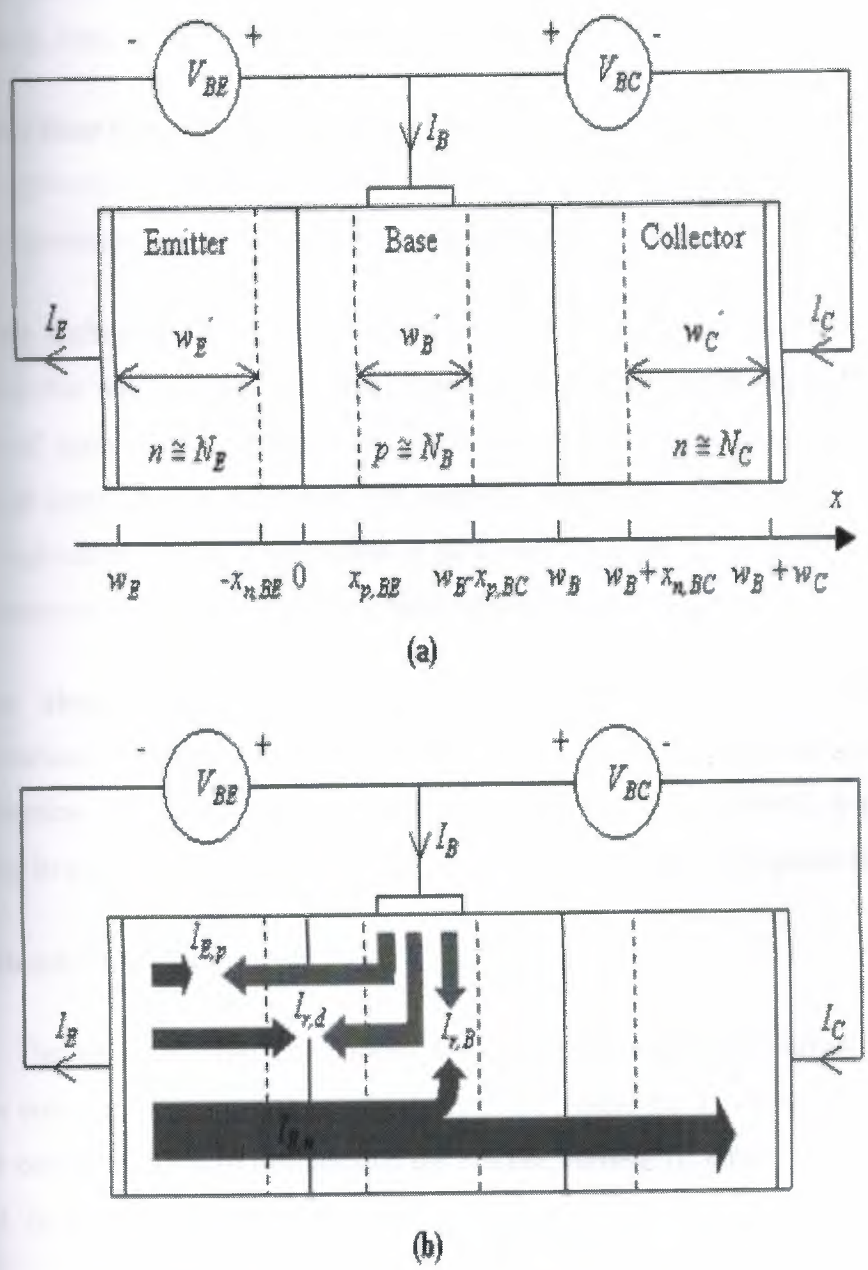


Figure 2.4 (a) Structure and sign convention of a n-p-n bipolar junction transistor.
(b) Electron and hole flow under forward active bias, $V_{BE} > 0$ and $V_{BC} = 0$.

2.4.2 BJT Configurations

There is a very brief look at the three basic ways in which a bipolar junction transistor (BJT) can be used. In each case, one terminal is common to both the input and output signal. All the circuits shown here are without bias circuits and power supplies for clarity.

Common Emitter Configuration: Here the emitter terminal is common to both the input and output signal. The arrangement is the same for a PNP transistor. Used in this way the transistor has the advantages of medium input impedance, medium output impedance, high voltage gain and high current gain.

Common Base Configuration: Here the base is the common terminal. Used frequently for RF applications, this stage has the following properties. Low input impedance, high output impedance, unity (or less) current gain and high voltage gain.

Common Collector Configuration: This last configuration is also more commonly known as the emitter follower. This is because the input signal applied at the base is "followed" quite closely at the emitter with a voltage gain close to unity. The properties are a high input impedance, a very low output impedance, a unity (or less) voltage gain and a high current gain. This circuit is also used extensively as a "buffer" converting impedances or for feeding or driving long cables or low impedance loads.

A note about Phase Shifts: In both the common base and emitter follower configurations, the input and output signals are in phase, but with the common emitter configuration only, the input and output signals are phase inverted, a positive input resulting in a negative output and vice versa. This is also known as phase displacement.

2.4.3 Steady-State Characteristics

The base and collector current are positive if a positive current goes into the base or collector contact. The emitter current is positive for a current coming out of the emitter contact. This also implies that the emitter current, I_E, equals the sum of the base current, I_B, and the collector current, I_C:

$$I_B = I_C + I_B \tag{2.1}$$

The base-emitter voltage and the base-collector voltage are positive if a positive voltage is applied to the base contact relative to the emitter and collector respectively.

We consider here only the forward active bias mode of operation, obtained by forward biasing the base-emitter junction and reverse biasing the base-collector junction. To simplify the discussion further, we also set $V_{CE} = 0$.. Electrons diffuse from the emitter into the base and holes diffuse from the base into the emitter. This carrier diffusion is identical to that in a p-n junction. However, what is different is that the electrons can diffuse as minority carriers through the quasi-neutral base. Once the electrons arrive at the base-collector depletion region, they are swept through the depletion layer due to the electric field. These electrons contribute to the collector current. In addition, there are two more currents, the base recombination current, indicated on Figure 2.5 by the vertical arrow, and the base-emitter depletion layer recombination current, $I_{r,d}$, (not shown).

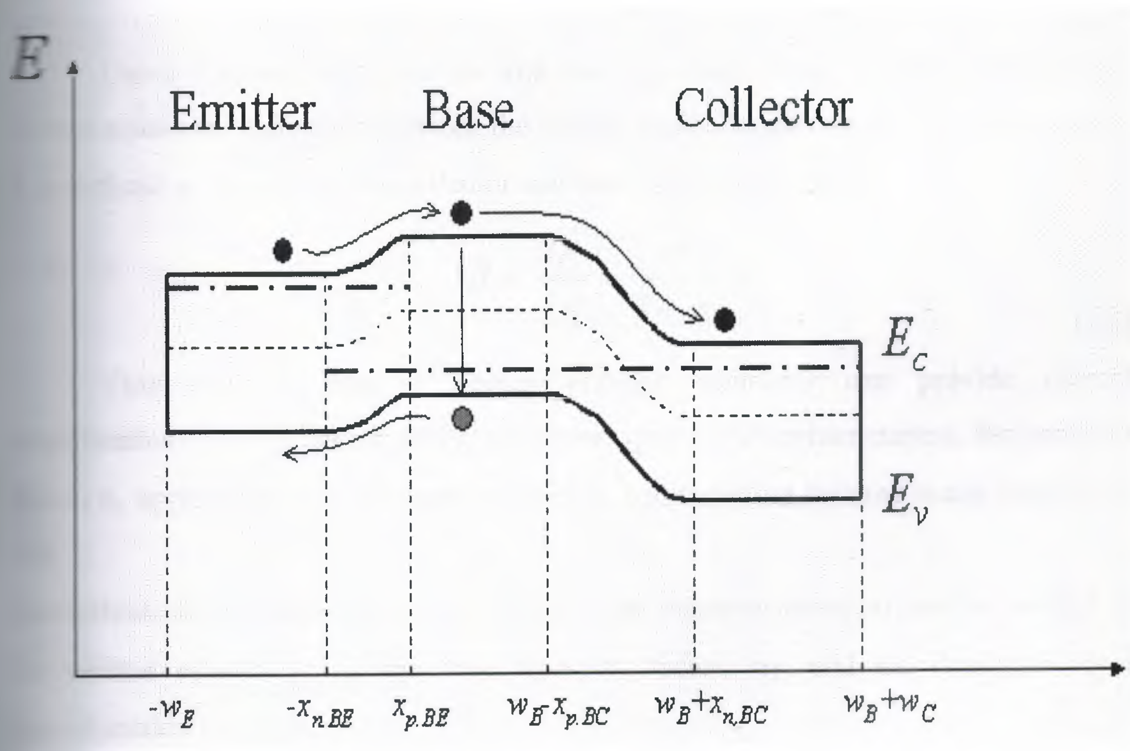


Figure 2.5: Energy band diagram of a bipolar transistor biased in the forward active mode.

The total emitter current is the sum of the electron diffusion current, $I_{E,n}$, the hole diffusion current, $I_{E,p}$ and the base-emitter depletion layer recombination current, $I_{r,d}$.

$$I_E = I_{E,n} + I_{E,p} + I_{r,d} \tag{2.2}$$

The total collector current is the electron diffusion current, $I_{E,n}$, minus the base recombination current, $I_{r,B}$.

$$I_C = I_{E,n} - I_{r,B} \tag{2.3}$$

The base current is the sum of the hole diffusion current, $I_{E,p}$, the base recombination current, $I_{r,B}$ and the base-emitter depletion layer recombination current, $I_{r,d}$.

$$I_B = I_{E,p} + I_{r,B} + I_{r,d} \tag{2.4}$$

The transport factor, α, is defined as the ratio of the collector and emitter current:

$$\alpha = \frac{I_C}{I_E} \tag{2.5}$$

Using Kirchoff's current law and the sign convention, we find that the base current equals the difference between the emitter and collector current. The current gain, β, is defined as the ratio of the collector and base current and equals:

$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha} \tag{2.6}$$

This explains how a bipolar junction transistor can provide current amplification. If the collector current is almost equal to the emitter current, the transport factor, α, approaches one. The current gain, β, can therefore become much larger than one.

To facilitate further analysis, we now rewrite the transport factor, α, as the product of the emitter efficiency, γ_E, the base transport factor, α_T, and the depletion layer recombination factor, δ_r.

$$\alpha = \alpha_T \, \gamma_E \, \delta_r \tag{2.7}$$

The emitter efficiency, γ_E, is defined as the ratio of the electron current in the emitter, $I_{E,n}$, to the sum of the electron and hole current diffusing across the base-emitter junction, $I_{E,n} + I_{E,p}$.

$$\gamma_E = \frac{I_{E,n}}{I_{E,n} + I_{E,p}} \tag{2.8}$$

$$\alpha_T = \frac{I_{E,n} - I_{r,B}}{I_{E,n}} \tag{2.9}$$

Recombination in the depletion-region of the base-emitter junction further reduces the current gain, as it increases the emitter current without increasing the collector current. The depletion layer recombination factor, δ_r, equals the ratio of the current due to electron and hole diffusion across the base-emitter junction to the total emitter current:

$$\delta_r = \frac{I_E - I_{r,d}}{I_E} \tag{2.10}$$

A bipolar junction transistor, (BJT) is very versatile. It can be used in many ways, as an amplifier, a switch or an oscillator and many other uses too. Before an input signal is applied its operating conditions need to be set. This is achieved with a suitable bias circuit. A bias circuit allows the operating conditions of a transistor to be defined, so that it will operate over a pre-determined range. This is normally achieved by applying a small fixed dc voltage to the input terminals of a transistor.

Bias design can take a mathematical approach or can be simplified using transistor characteristic curves. The characteristic curves predict the performance of a BJT. There are three curves, an input characteristic curve, a transfer characteristic curve and an output characteristic curve. Of these curves, the most useful for amplifier design is the output characteristics curve. The output characteristic curves for a BJT are a graph displaying the output voltages and currents for different input currents. The linear (straight) part of the curve needs is utilized for an amplifier or oscillator. For use as a switch, a transistor is biased at the extremities of the graph, these conditions are known as "cut-off" and "saturation".

Simple Bias Circuit: The simplest bias circuit is shown below. It consists only of a fixed bias resistor and load resistor. The BJT is operating in common emitter mode. The dc current gain or beta, h_{FE} is the ratio of dc collector current divided by dc base current. The values of Rb and Rc can be determined by either mathematical approach or by using the output characteristic curves.

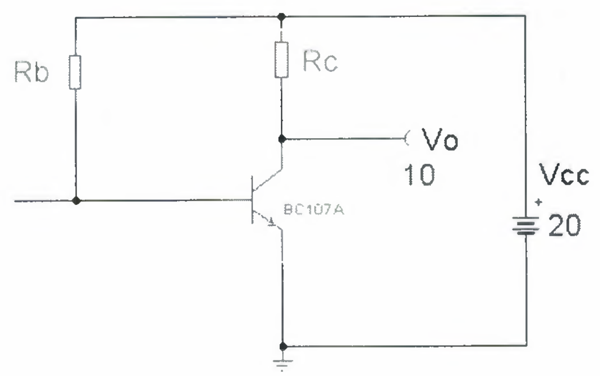


Figure 2.6 Circuit diagram

Input Characteristic Curves: It is worthwhile looking at a typical input characteristic curve for a small signal BJT. The following is the input characteristic for a transistor in common emitter mode; it is a plot of input base emitter voltage verses base current. It is shown with both x and y axis slightly zoomed.

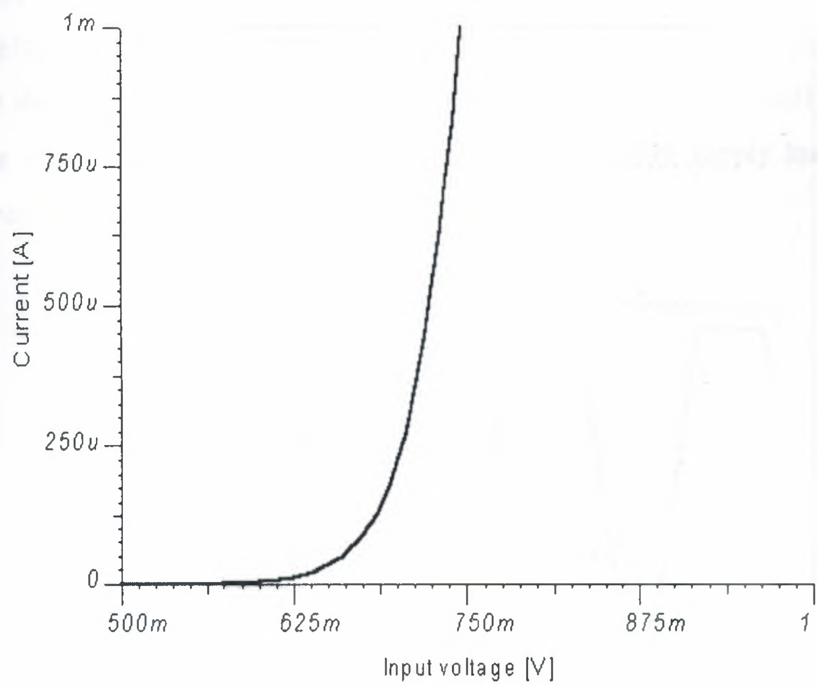


Figure 2.7 Input characteristics

Output Characteristic Curves: For each transistor configuration, common emitter, common base and emitter follower the output curves are slightly different. Typical output characteristics for a BJT in common emitter mode are shown below:-

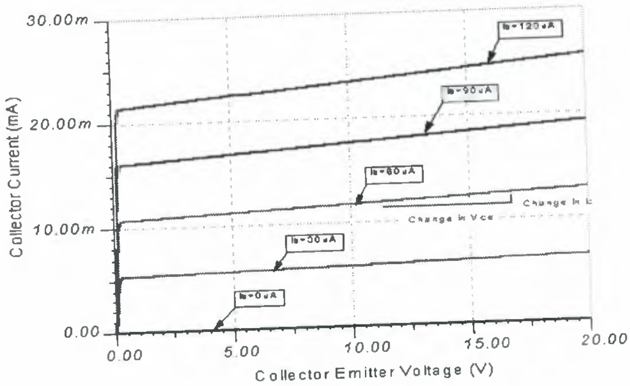


Figure 2.8 output characteristics

After the initial bend, the curves approximate a straight line. The slope or gradient of each line represents the output impedance, for a particular input base current. So what has all this got to do with biasing? Take, for example the middle curve. The collector emitter voltage is displayed up to 20 volts. Let's assume that we have a single stage amplifier, working in common emitter mode, and the supply voltage is 10 volts. The output terminal is the collector; the input is the base, the bias conditions is set anywhere on the flat part of the graph. However, imagine the bias is set so that the collector voltage is 2 volts. If the output signal is 4 volts peak to peak then, depending on whether the transistor used is a PNP or NPN, then one half cycle will be amplified cleanly, the other cycle will approach the limits of the power supply and will "clip". This is shown below:

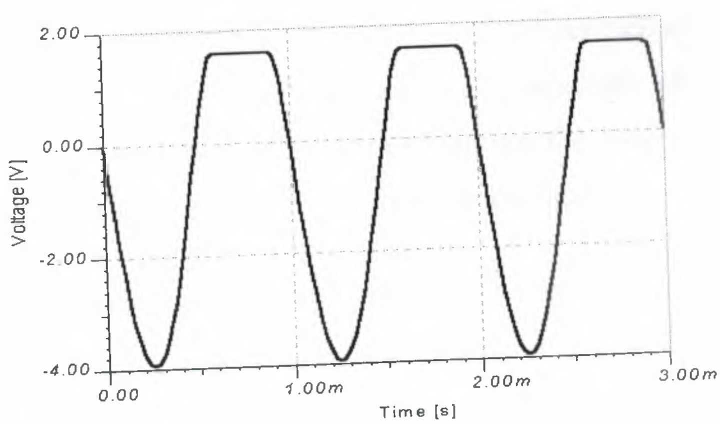


Figure 2.9: O/P Waveform with clipping on positive half cycle

Figure 2.9 shows a 4 volt peak to peak waveform with clipping on the positive half cycle. This is caused by setting the bias at a value other than half the supply voltage.

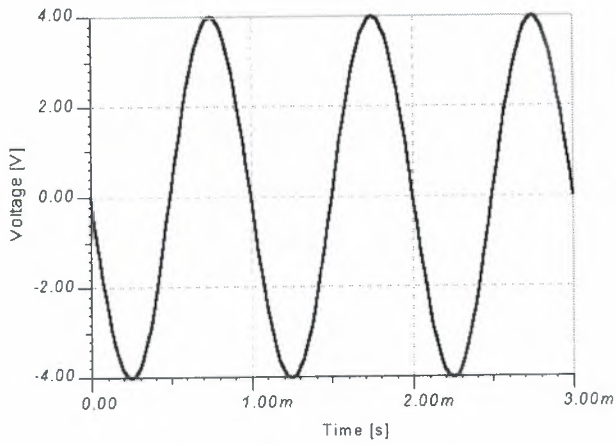


Figure 2.10: O/P Waveform, when bias is set for the value of supply voltage.

Figure 2.10 shows the same amplifier, but here the bias is set so that collector voltage is half the value of the supply voltage. Hence, it is a good idea to set the bias for a single stage amplifier to half the supply voltage, as this allows maximum output voltage swing in both directions of an output waveform.

2.4.4 Switching Limits

Second breakdown (SB): The SB, which is a destructive phenomenon, 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 may damage the transistor. Thus secondary breakdown is caused by the localized thermal runaway, resulting from high current concentrations. The current concentration may be caused by the defects in the transistor structure. The SB occurs at certain combination of voltage, current, and time. Because the time is involved, the secondary breakdown is basically an energy dependent phenomenon.

Forward-biased safe operating area (FBSOA): During turn-on and on-state conditions, the average junction temperature and second breakdown limits the power handling capability of transistor. The manufacturers usually provide the FBSOA curves under specified test conditions.

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 to emitter junction reverse biased. The collector-emitter voltage must be held to a safe level at, or below, a specified value of collector current.

Breakdown voltages: A breakdown 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. At breakdown the voltage remains relatively constant, where the current rises rapidly. The following breakdown voltages are quoted by the manufactures:

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

$V_{CEV} or V_{CEX}$: The maximum voltage between the collector terminal and emitter terminal at a specified negative voltage applied between base and emitter.

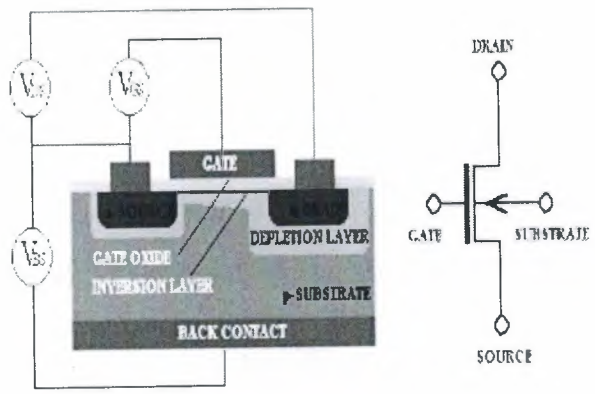
$V_{CEO(SUS)}$: The maximum sustaining voltage between the collector terminal and emitter terminal with the base open circuited. This rating is specified at the maximum collector current and voltage, appearing simultaneously across the device with a specified value of load inductance.

2.5 Power MOSFETs

2.5.1 Introduction

Power MOSFET (Metal-oxide-semiconductor field - effect transistor) is a voltage-controlled device and requires only a small input current. The switching speed is very high and the switching times are of the order of nanosecond. Power MOSFETs find increasing applications in low-power high-frequency converters. MOSFETs do not have the problems of second breakdown phenomena as do BJTs. However, MOSFETs have the problems of electrostatic discharge and require special care in handling. In addition, it is relatively difficult to protect them under short-circuited fault conditions. 10^9 to $10^{11}\,\Omega$

The cross-section of MOSFETs known as vertical (V) MOSFETs is shown in figure 2.11(a).MOSFETs require low gate energy, and have a very fast switching speed and low switching losses. The input resistance is very high, 10^9 to$10^{11}\Omega$. MOSFETs, however, suffer from the disadvantage of high forward on-state resistance and hence high on-state losses, which make them less attractive as power devices.



(a) (b)

Figure2.11 (a) Cross-section and (b) circuit symbol of an *n*-type Metal-Oxide-Semiconductor-Field-Effect-Transistor (MOSFET)

2.5.2 Steady-state characteristics

The MOSFETs are voltage-controlled devices and have very high input impedance. The gate draws a very small leakage current, on the order of nanoamperes. The current gain, which is the ratio of drain current I_D, to the input gate current I_G, is typically on the order of10^9. However, the current gain is not an important parameter. The transconductance, which is the ratio of drain current to the gate voltage, defines the transfer characteristics and is a very important parameter. The output characteristics of a MOSFET are shown in the figure2.20.

There are three regions of operation:

(1) Cut-off region, where $V_{GS} \le V_T$

(2) Pinch-off or saturation region, where $V_{DS} \ge V_{GS} - V_T$. The pinch-off occurs at

$V_{DS} = V_{GS} - V_T$

(3) Linear region, where $V_{DS} \leq V_{GS} - V_T$

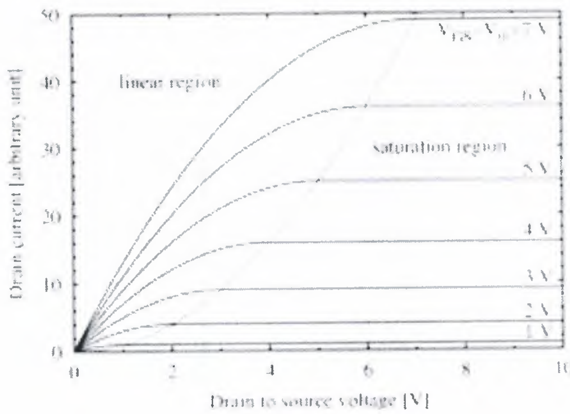
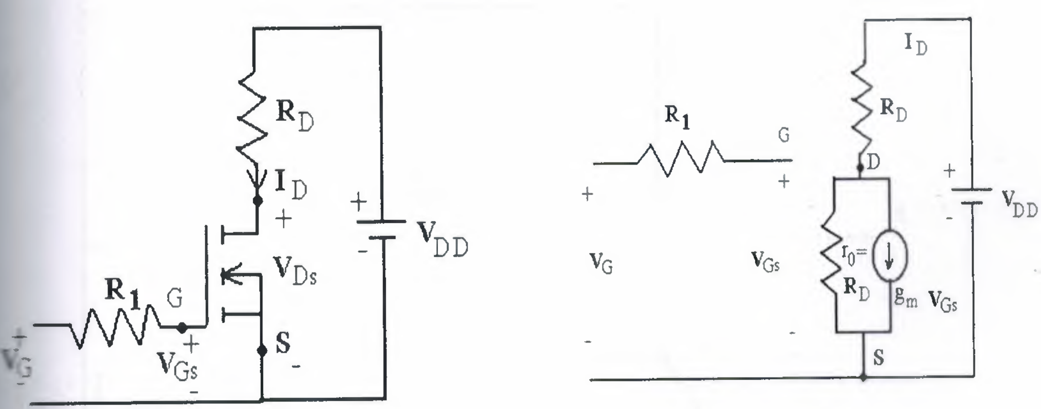


Figure2.12 Output characteristics of MOSFET

Due to high drain current and low drain voltage, the power MOSFETs are operated in the linear region for switching actions. In the saturation region, the drain current remains almost constant for any increase in the value of V_{DS} and the transistors are used in this region for voltage amplification. The steady-state model is shown in the figure 2.13.



(a) circuit diagram (b) Equivalent circuit

Figure 2.13 Steady-state switching model of MOSFETs

The transconductance g_m is defined as

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

The output resistance $r_0 = R_{DS}$, which is defined as

$$R_{DS} = \frac{\Delta V_{DS}}{\Delta I_D}$$

is normally very high in the pinch-off region, and is very small in the linear region.

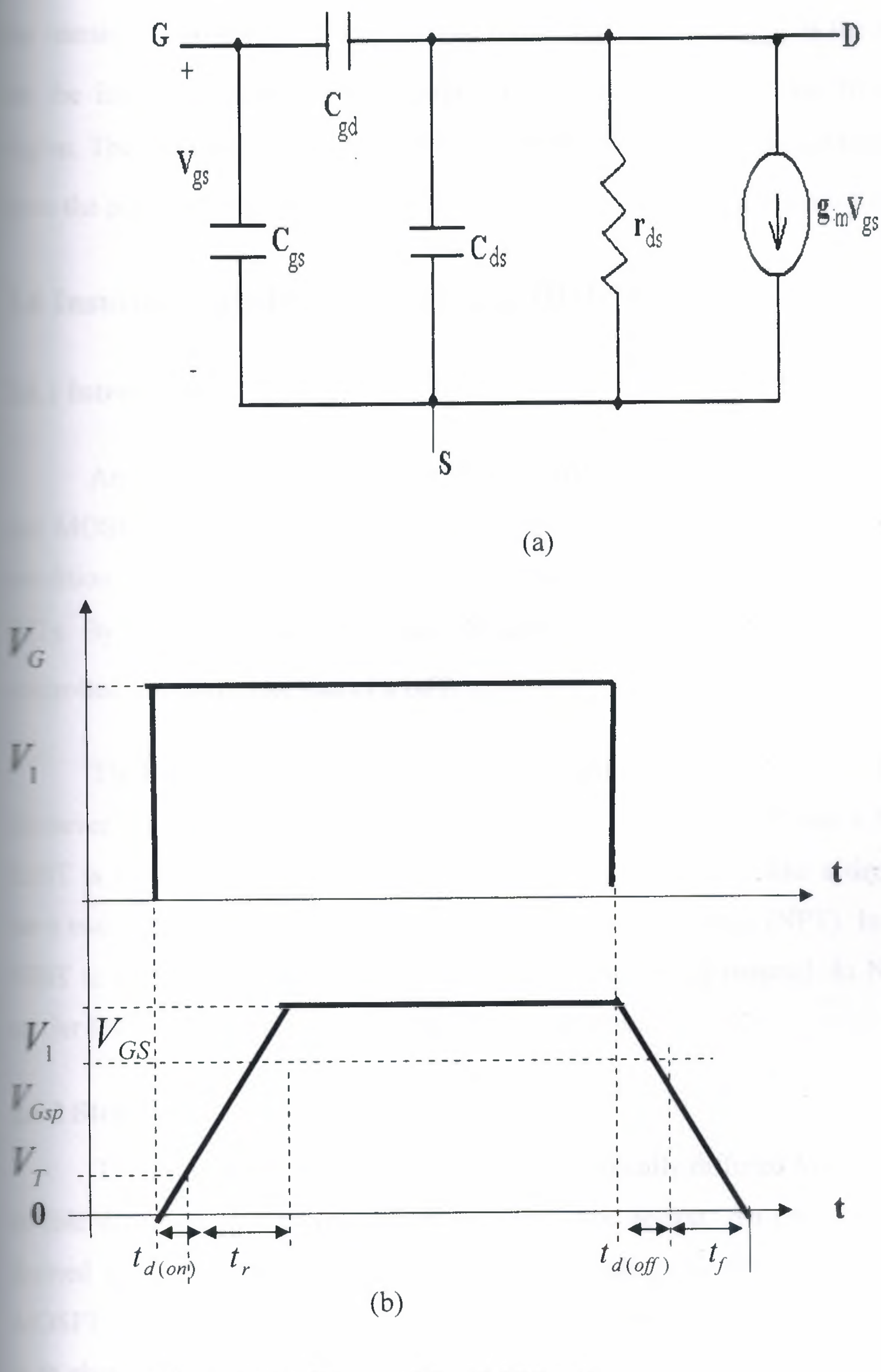


Figure 2.14 (a) Switching model of MOS and
(b) Switching waveforms and times

The switching model of MOSFETs and typical switching waveforms and times are shown in figure 2.14. The turn-on delay $t_{d(on)}$ is the time that is required to charge the input capacitance to threshold voltage level. The rise time t_r is the gate charging time from the threshold level to the full-gate voltage V_{GSP} , which is required to drive the transistor into the linear region. The turn-off delay time $t_{d(off)}$ is the time required for the input capacitance to discharge from overdrive gate voltage to the pinch-off region. The fall time t_F is the time that is required for the input capacitance to discharge from the pinch-off region to threshold voltage. If $V_{GS} \leq V_T$, the transistor turns off.

2.6 Insulated gate bipolar transistor (IGBTs)

2.6.1 Introduction

An insulated gate bipolar transistor (IGBT) combines the advantages of BJTs and MOSFETs. An IGBT has high input impedance, like MOSFETs, and low on state condition losses, like BJTs. However, there is no second breakdown problem, as with BJTs. By chip design and structure, the equivalent drain-to-source resistance R_{DS} is controlled to behave like that of a BJT.

The silicon cross section of an IGBT is almost identical to that of a MOSFET. However, the performance of an IGBT is closer to that of a BJT than a MOSFET. An IGBT is made of four alternate PNPN layers, and could latch like a thyristor. IGBTs have two structures: punch-through (PT) and no punch-through (NPT). In PT structure, IGBT is designed in such a way that its switching time is reduced. In NPT structure, carrier life time is kept more than that of a PT structure.

2.6.2 Structure

The structure is very similar to that of a vertically diffused MOSFET featuring a double diffusion of a p-type region and an n-type region. An inversion layer can be formed under the gate by applying the correct voltage to the gate contact as with a MOSFET. The main difference is the use of a p^+ substrate layer for the drain. The effect is to change this into a bipolar device as this p-type region injects holes into the n-type drift region.Fig.2.6 shows the structure of a typical n-channel IGBT.

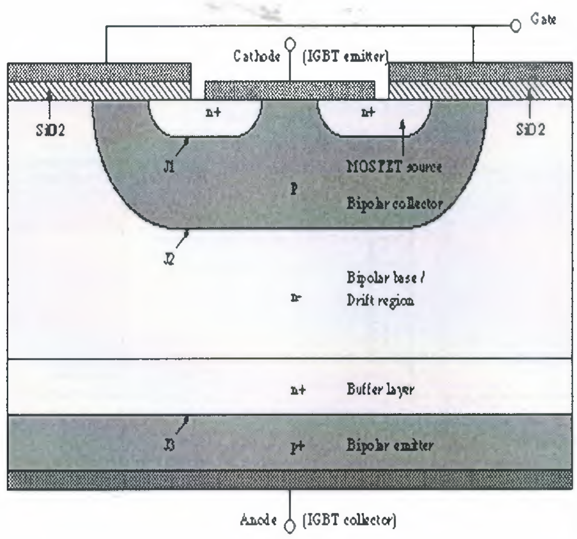
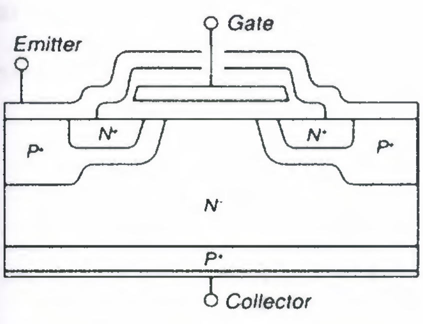


Figure 2.15 A typical IGBT structure

2.6.3 Characteristics

An IGBT is a voltage-controlled device similar to the power MOSFETs. An IGBT is turned on by applying a positive gate voltage and is turned off by removing the gate voltage. It requires a very simple drive circuit. It has lower switching and conducting losses while sharing many of the appealing features of power MOSFETs, such as ease of gate drive, peak current, capability, and ruggedness. An IGBT is inherently faster than a BJT. However, the switching speed of IGBT is inferior to that of MOSFETs.



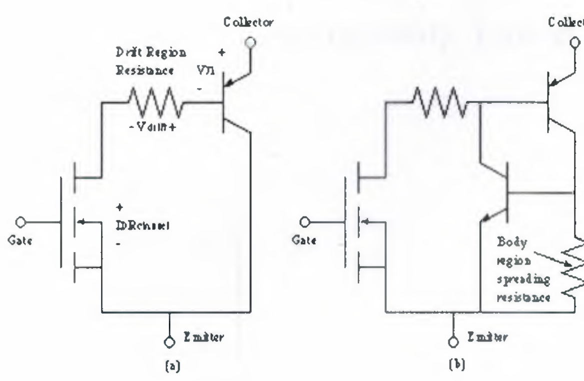


Figure 2.16 (a) Cross section (b) Symbol and circuit for an IGBT

The three terminals are gate, collector, and emitter instead of gate, drain, and source for an MOSFET, as shown in figure 2.16a. The symbol and circuit of an IGBT is shown in the figure 2.16b. The typical output characteristics of collector current versus collector emitter voltage are also shown in the figure2.17 for various gate-emitter voltages.

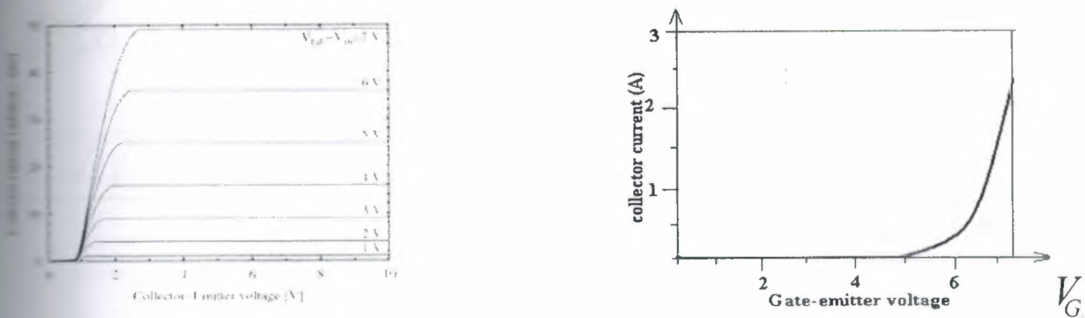


Figure 2.17 Typical output and transfer characteristics of IGBTs

The parameters and their symbols are similar to that of MOSFETs, except that the subscripts for source and drain are changed to emitter and collector, respectively. IGBTs are finding increasing applications in medium-power applications such as dc and ac motor drives, power supplies, solid-state relays, and contractors.

2.7 SITs

SIT (Static Induction Transistor) is high power, high frequency device. It is a vertical structure device with short multichannels. SIT has short channel length, low GATE series resistance, low gate-source capacitance & small thermal resistance. Thus, it is not subject to area limitations and is suitable for high-speed, high-power operation. It has low noise, low distortion and high audio frequency power capability. Turn-on & Turn-off time are very small typically in 0.25microsecs**.**

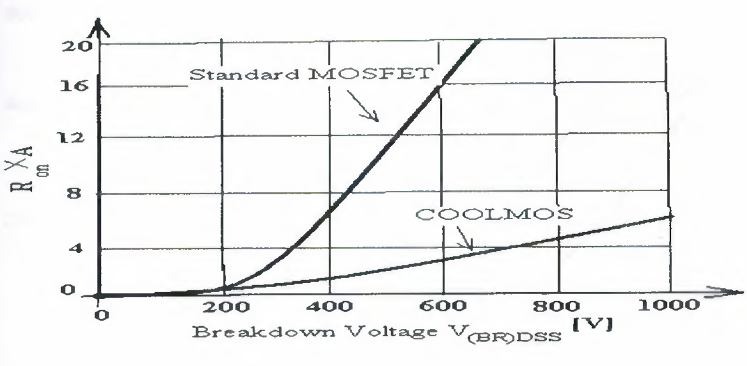
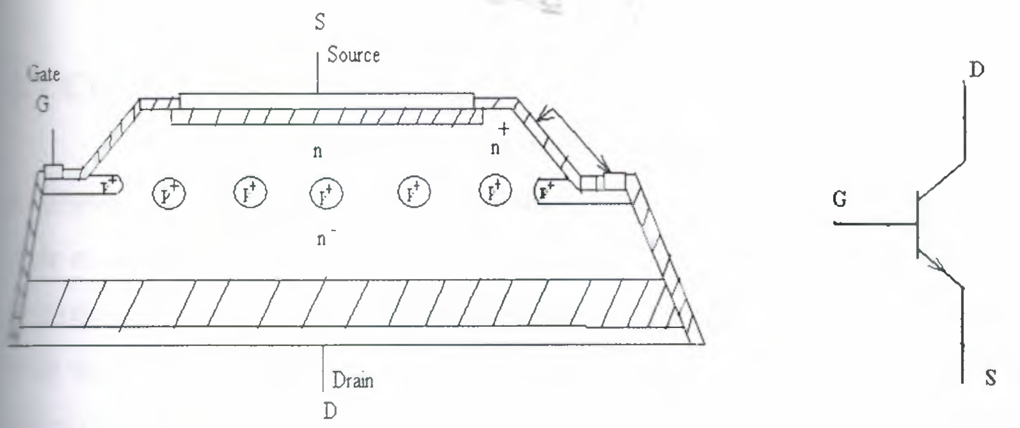


Figure2.18 The linear relationship between blocking voltage and on-resistance



(a) Cross section (b) symbol

Figure2.19. Cross section and symbol for SITs.

The on-state drop is high, typically 90V for a 180-A device and 18V for an 18-Adevice. An SIT normally is an on device, and a negative voltage holds it off. Normally on-state characteristics and the high on-state drop limit its application for general power conversions. The typical characteristics are shown in figure 2.20. An electro statically induced potential barrier controls the current in static induction devices. The SITs can operate with the power of 100 KVA at 100 KHz or 10 VA at 100 GHz. The current ratings of SITs can be up to 1200 V, 300 A, and the switching speed can be up to 1200 V, 300 A, and the switching speed can be as high as 100 k Hz. It is most suitable for high-power, high-frequency applications (e.g. audio, VHF/UHF, and microwave amplifiers).

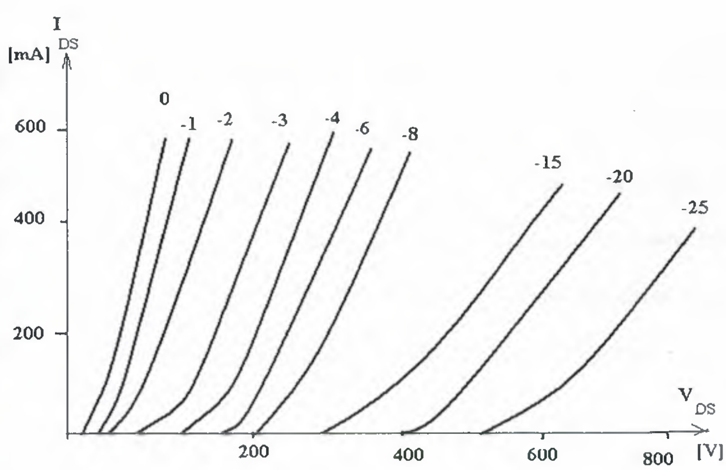


Figure 2.20 Typical characteristics of SITs.

2.7 COOLMOS

COOLMOS is a new technology for high voltage power MOSFETs, implements a compensation structure in the vertical drift region of a MOSFET to improve the on-state resistance. It has a lower on-state resistance for the same package compared with that of other MOSFETs. The conduction losses are at least five times less as compared with the conventional MOSFETs technology. It is capable of handling two or three times more output power and the act chip area is approximately five times smaller than that of a standard MOSFET. In the **figure** 2.21, the cross section of a COOLMOS is depicted.

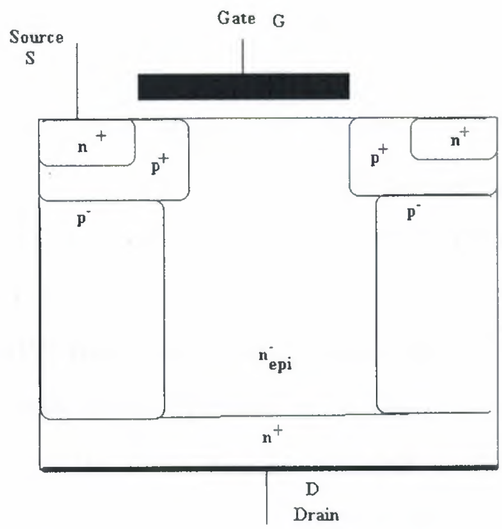


Figure 2.21: cross section of a COOLMOS

The COOLMOS devices can be used in application unto power range of 2 kVA such as power supplies for workstations and server, uninterruptible power supplies (UPS), high-voltage converters for microwave and medical systems, induction ovens, and welding equipment. These devices can replace conventional power MOSFETs in all applications in most cases without power adoption. At switching frequencies above 100 kHz, COOLMOS devices offer a superior current handling capability such as smallest required chip area at a given current. The devices have advantage of an intrinsic inverse diode.

2.8 GTOs

A GTO (gate turn off thyristor) is a device with full gate control and similar high current/voltage rating of a SCR. The GTO has the highest power rating and the best trade-off between the blocking voltage and the conduction loss of any fully controllable switch. However, GTOs' dynamic performance is poor. A GTO is slow in both turn-on and turn-off. It lacks FBSOA and has poor RBSOA so it requires snubber to control dv/dt during the turn-off transition and di/dt during turn-on transition.

The GTO's static parameters are excellent: low conduction loss due to double-sided minority carrier injection, high blocking voltage and low cost due to the capability of fabrication on a large single wafer. However, its dynamic performance is poor. The requirements of a dv/dt snubber during turn-off operation, a di/dt snubber during turn-on operation and minimum on and off times make the GTO difficult to use.

Figure 2-22 (a) shows the cell structure and the doping profile of a typical high power GTO. It is a three terminal, four-layer PNPN structure with a lightly doped N- voltage-blocking layer in the center. The electrode on the external P+ layer is called the anode where the current is normally flowing into the device. The electrode on the external N+ layer is called the cathode from where the current is normally flowing out. The electrode on the internal P layer (p-base) is called the gate, which is used for control.

The operation principle of a GTO can be understood through its equivalent circuit model shown in Figure 2-22 (b). The PNP transistor represents the GTO's top three layers, while the NPN transistor represents the GTO's bottom three layers. Since the n- layer serves as the base of the PNP and the collector of the NPN, and the internal P layer serves as the base of the NPN and the collector of the PNP, the two transistors are cross coupled. This structure has two stable states: ON and OFF, which are determined by its gate control.

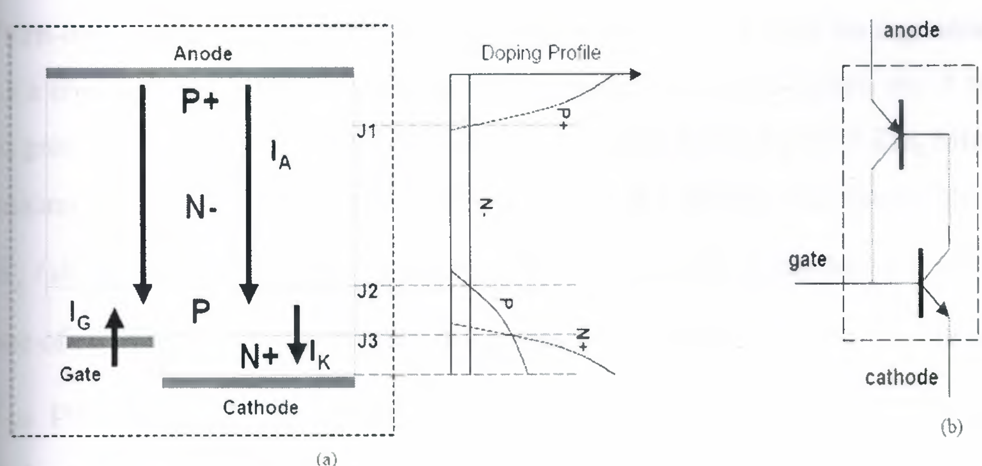


Figure 2-22 (a) GTO cell structure and its doping profile; (b) The GTO's equivalent circuit model

A GTO like an SCR can be turned on by applying a positive gate signal. However, a GTO can be turned off by a negative gate signal. A GTO is a nonlatching device and can be built with current and voltage ratings similar to those of an SCR. A GTO is turned on by applying a short positive pulse and turned off by a short negative pulse to its gate.

The GTOs have these advantages over SCRs:

1) Elimination of commutating components in forced commutation, resulting in reduction in cost, weight, and volume.
2) Reduction in acoustic and electro-magnetic noise due to the elimination of commutation chokes
3) Faster turn-off, permitting high-switching frequencies
4) Improved efficiency of converters.

In low power applications, GTOs have the following advantages over bipolar transistors:

1) A higher voltage capability
2) A high ratio of peak surge current to average current, typically 10:1
3) A high ratio of peak controllable current to average current
4) A high on-state gain (anode current and gate current).
5) A pulsed gate signal of the short duration

Under surge conditions, a GTO goes into deeper saturation due to regeneration action. On the other hand, a bipolar transistor tends to come out of saturation.

Turn-on: The GTO has a highly interdigited gate structure with no regenerative gates. As a consequence, a large initial gate trigger pulse is required to turn on. A typical turn on gate pulse and its important parameters are shown in the figure 7.22a. Minimum and maximum values of I_{GM} can be derived from the device data sheet. The values of di_g / dt is given in device characteristics of the data sheet, against turn-on time. The rate of rise of gate current di_g / dt affects the device turn-on losses. The duration of the I_{GM} pulse should not be less than half the minimum of time given in data sheet ratings. A longer period is required if the anode current di / dt is low such that I_{GM} is maintained until a sufficient level of anode current is established.

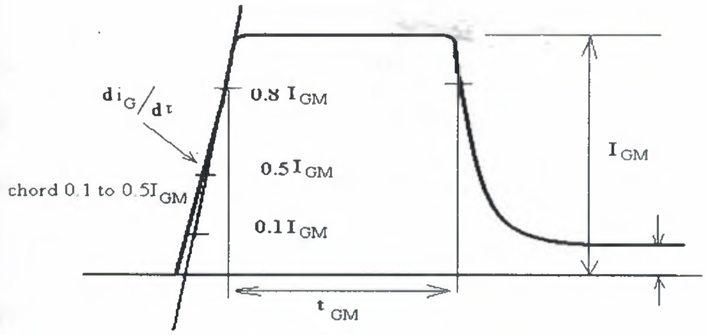


Figure 2.22a: The typical turn-on pulse

On-state: once the GTO is turned on, forward gate current must be continued for the whole of the conduction period to ensure the device remains in conduction during the on period. The on-state gate current should be at least 1% of the turn-on pulse to ensure that the gate does not unlatch.

Turn-off: the turn-off performance of a GTO is greatly influenced by the characteristics of the turn-off circuit. Thus, the characteristics of the turn-off circuit must match the deice requirements. The turn-off process involves the extraction of the gate charge, the gate avalanche period, and the anode current decay. The amount of the charge extraction is a device parameter and its value is not significantly affected by the external circuit conditions. The initial peak turn-off current and turn-off time, which are important parameters of the turning-off process, depend on the external circuit components. A typical anode current versus the turn-off pulse is shown in figure 2.22b. The device data sheet gives typical values for I_{GQ}. The GTO has a long turn-off, tail-off current at the end of the turn-off and next turn-on must wait until the residual charge on the anode side is dissipated through recombination process.

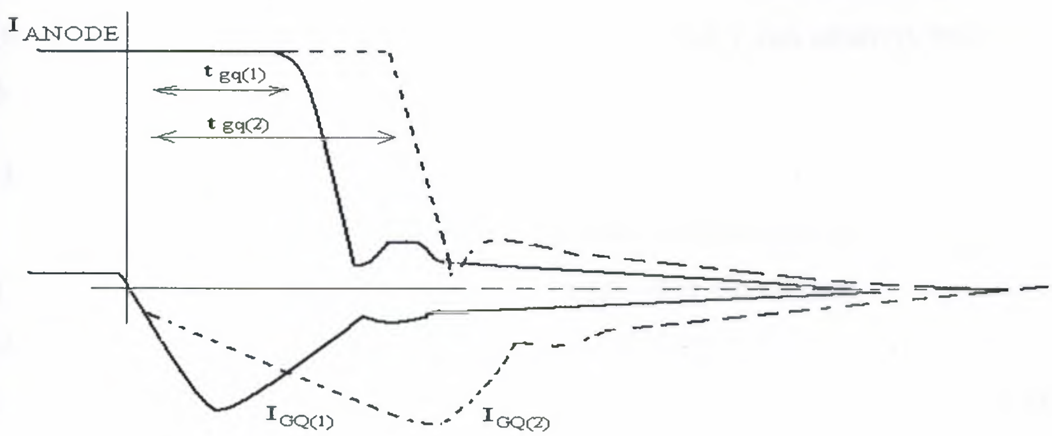
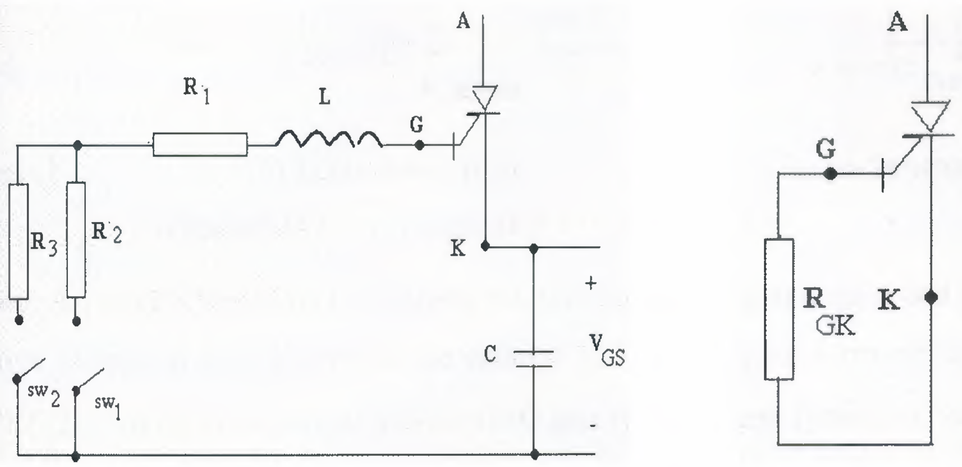


Figure 2.22b Typical anode current versus turn-off pulse

Because a GTO requires a large turn-off current, charged capacitor C is normally used to provide the required turn-off gate current. Inductor L limits the turn-off di/dt of the gate current through the circuit formed by R_1, R_2, SW_1, and L. the gate circuit supply voltage V_{GS} should be selected to give the required value of V_{GQ}. The value of R_1 and R_2 should also be minimized. A turn-off circuit arrangement of a GTO is shown in figure 2.23a



(a) Turn-off circuit (b) Gate-Cathode resistance, R_{GK}

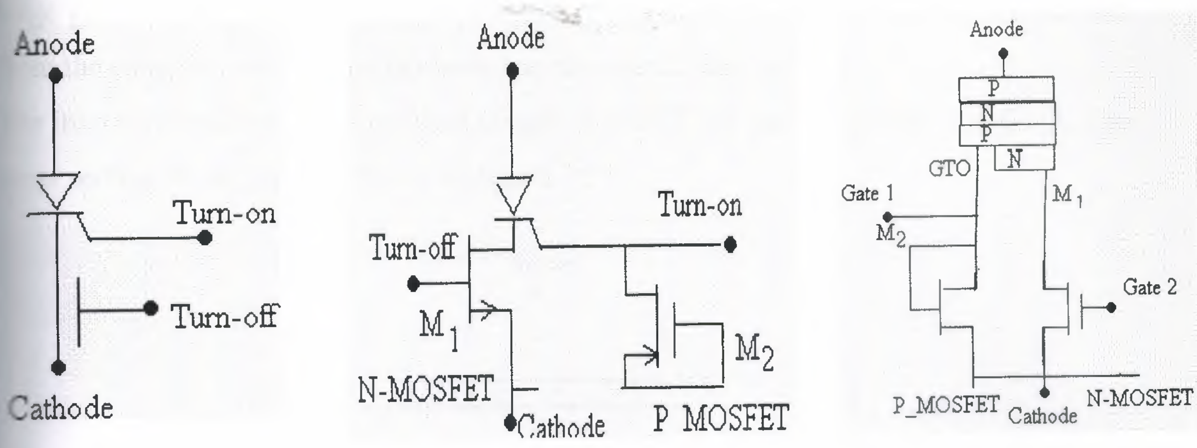
Figure 2.23 A GTO turn-off circuit

During the off-state period, which begins after the fall of the tail current to zero, the gat should ideally remain reverse biased. This reverse bias ensures maximum blocking capability.

A GTO has low gain during turn-off, typically six, and requires a relatively high negative current pulse to turn off. It has higher on-state voltage than that of SCRs. GTOs are mostly used in voltage source converters in which a fast recovery antiparallel diode is required across each GTO.

2.9 ETOs

The ETO is a MOS-GTO hybrid device that combines the advantages of both the GTO and MOSFET. The ETO symbol, its equivalent circuit, and the pn-structure are shown in the figure2.24. ETO has two gates: one normal gate for turn-on and one with a series MOSFET for turn-off. High power ETOs with a current rating of up to 4 kA and a voltage rating of up to 6 kV have been demonstrated.



(a) Symbol (b) Equivalent circuit (c) pn-Structure

Figure2.24 Emitter turn-off (ETO) thyristor

Turn-on: An ETO is turned on by applying positive voltages to gates, gate1 and gate 2. a positive voltage to gate 2 turns on the cathode MOSFET Q_E and turns off the gate MOSFET Q_G. An injection current into the GTO gate (through gate 1) turns on the ETO due to the existence of the GTO.

Turns-off: When a turn-off negative voltage signal is applied to the cathode MOSFET Q_E, it is turned off and transfers all the current away from the cathode into the base via gate MOSFET Q_G. This stops the regeneration latching process and results in a fast turn-off.

It is important to note that both the cathode MOSFET Q_E and the gate MOSFET Q_G are not subjected to high-voltage stress, no matter how high the voltage is on the ETO. This is due to the fact that the internal structure of the GTO's gate-cathode is a PN-junction. The disadvantage of series

MOSFET is that it has to carry the main GTO current and it increases the total voltage drop by about 0.3 to 0.5 V and corresponding losses. Similar to a GTO the ETO has a long turn-off tail of current at the end of the turn-off and the next turn-on must wait until the residual charge on the anode side is dissipated through the recombination process.

2.10 IGCTs

The IGCT integrates a gate-commutated thyristor (GCT) with a multilayered printed circuit board gate drive. The GCT is a hard switched GTO with a very fast and large gate current pulse, as large as the full-rated current that draws out all the current from the cathode into the gate in about 1 μs to ensure a fast turn-off.

The internal structure and equivalent circuit of a GCT are similar to that of a GTO. The cross section of an IGCT is shown in figure 2.25.

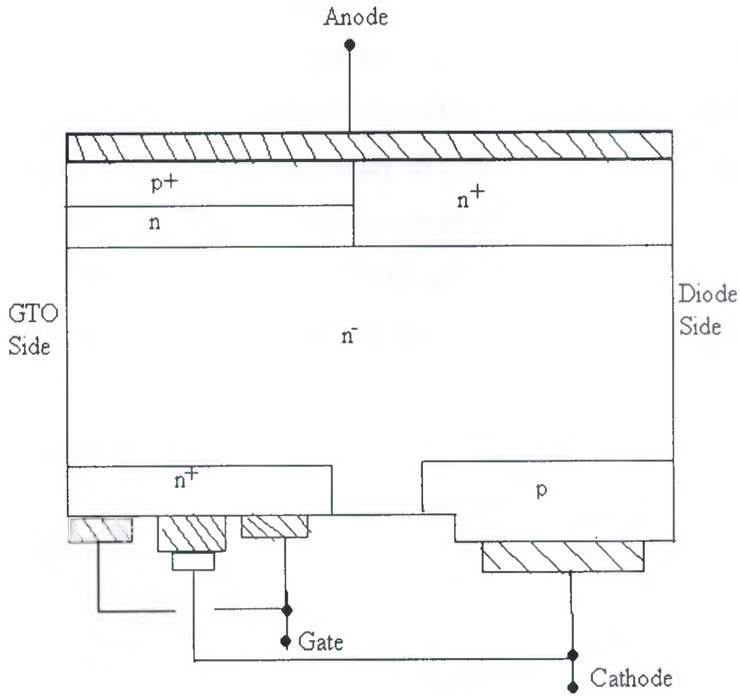


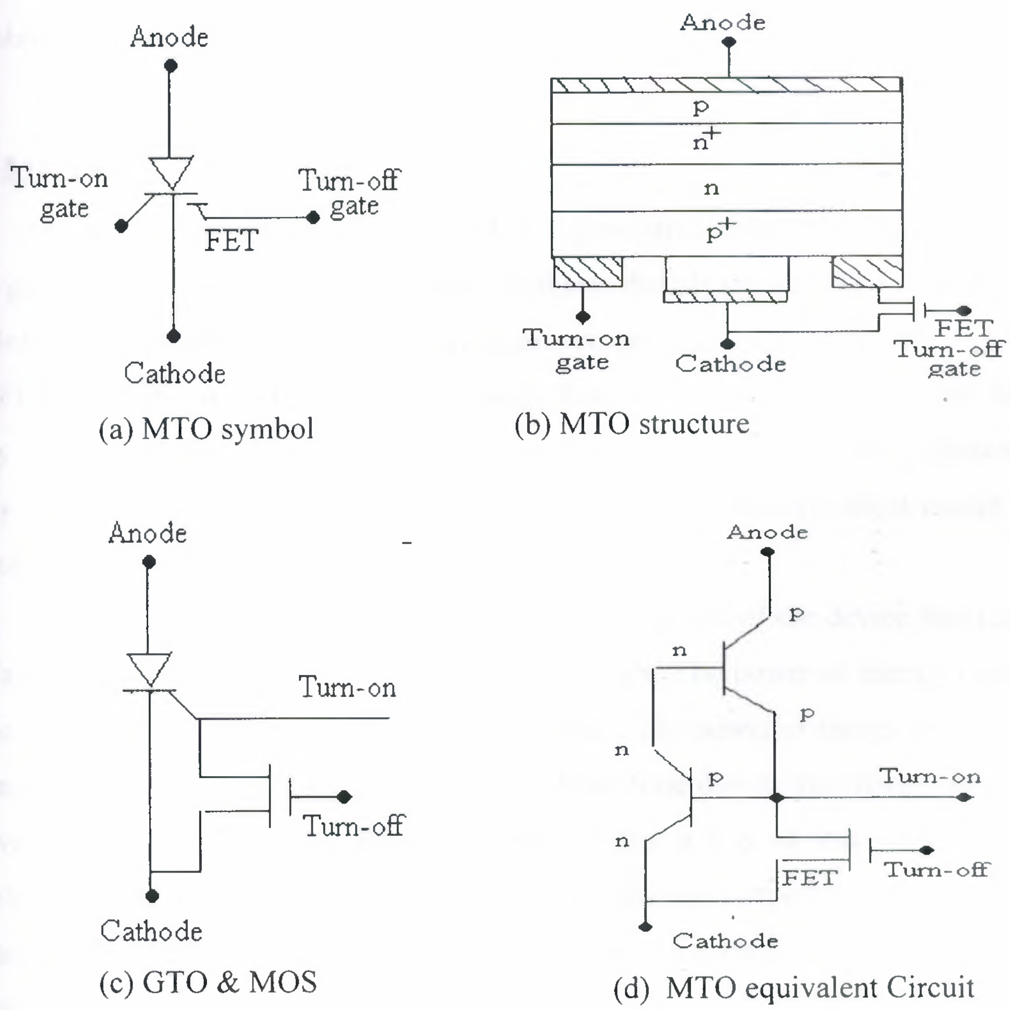
Figure 2.25. Cross section of IGCT with reverse diode

Turn-on: Similar to a GTO, the IGCT is turned on by applying the turn-on current to its gate.

Turn-off: The IGCT is turned off by a multilayer gate-driver circuit board that can supply a fast rising turn-off pulse, for example, a gate current of 4 kA/μs with a gate cathode voltage of 20V only. With this rate of gate current, the cathode-side npn-transistor is totally turned off within about within about 1 μs and the anode side onp-transistor is effectively left with an open base and it is turned-off almost immediately. Due to a very short duration pulse, the gate-drive energy is greatly reduced and the gate-drive energy consumption is minimized. The gate-drive power requirement isw decreased by a factor of five compared with that of the GTO. To apply a fast rising and high-great current, the IGCT incorporates a special effort to reduce the inductance of the gate circuitry as low as possible. This feature is also necessary for gate-drive circuits of the MTO and ETO.

2.11 MTOs

The MTO was developed by Silicon power company (SPCO). It is a combination of a GTO and MOSFET, which together overcome the limitations of the GTO turn-off ability. The main drawback of GTOs is that they require a high-pulse-current drive circuit for the low impedance gate. The gate circuit must provide the gate turn-off-current whose typical peak amplitude is 35% of the current to be controlled. The MTO provides the same functionality as GTO but uses a gate drive that needs to supply only the signal level voltage necessary to turn MOS transistor on and off. Figure 2.21 shows the symbol, structure, and equivalent circuit of the MTO. Its strictURE is similar to that of a GTO and retains the GTO's advantage of high voltage (up to 10 kV) and high current (up to 4000 A). MTOs can be used in high-power application ranging from 1 to 20 MVA



(a) MTO symbol (b) MTO structure

(c) GTO & MOS (d) MTO equivalent Circuit

Figure2.26 MTO turn-off (MOS) thyristor

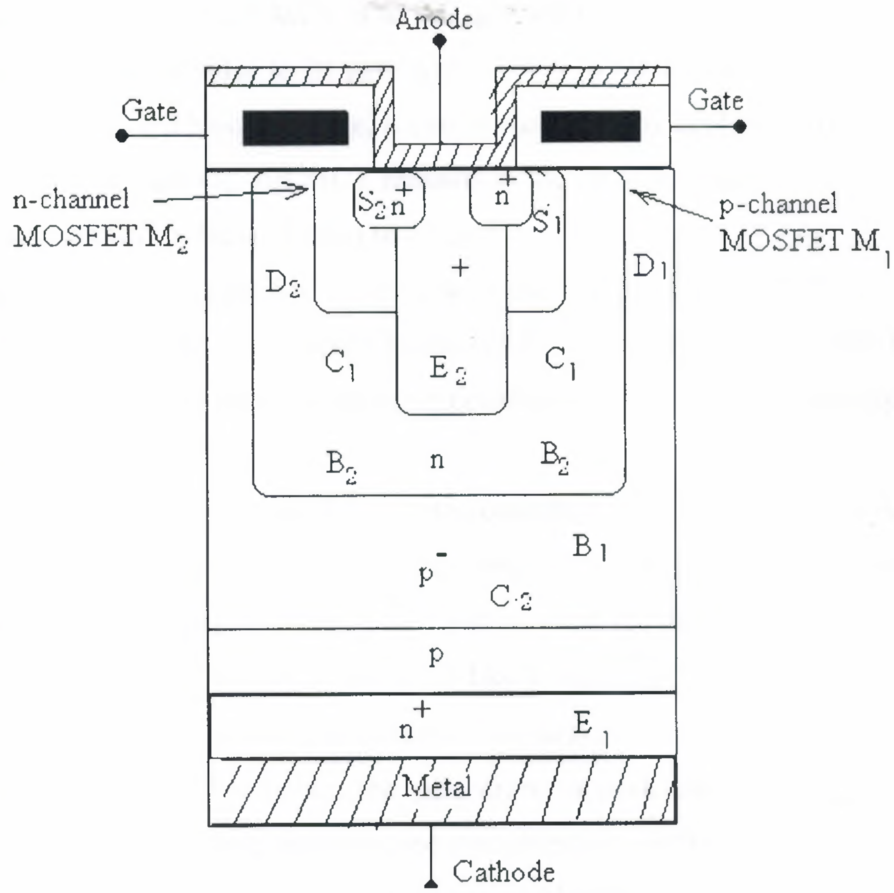
Turn-on: Like a GTO, the MTO is turned on by applying gate current pulse to the turn-on gate. Turn-on pulse turns on the npn-transistor Q_1, which then turns on the pnp-transistor Q_2 and latches on the MTO.

Turn-off: To turn-off the MTO, a gate pulse voltage is applied to the MOSFET gate. Turning on the MOSFETs shorts the emitter and base of the npn-transistor Q_1, thereby stopping the latching process. In contrast, a GTO is turned off by sweeping enough current out of the emitter base of the npn-transistor with a large negative pulse to stop the regenerative latching action. As a result, MTO turns off much faster than a GTO and the losses associated with the storage time are almost eliminated. Also the MTO has a higher dv/dt and requires much smaller snubber components. Similar to a GTO, the MTO has a long turn-off tail of current at the end of the turn-off and the next turn0on must wait until the residual charge on the anode side is dissipated through the recombination process.

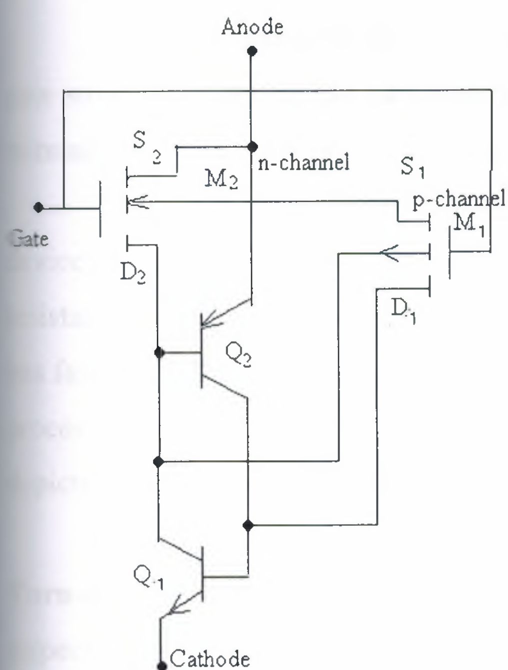
2.12 MCTs

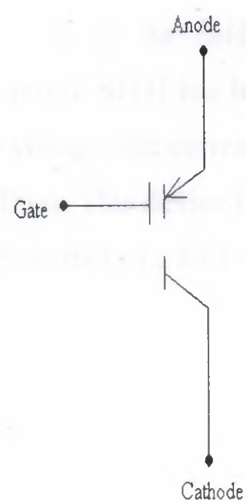
An MCT combines the features of a regenerative four-layer thyristor and a MOS-gate structure. Like the IGBT, which combines the advantages of bipolar junction and field-effect structures, an MCT is an improvement over a thyristor with a pair of MOSFETs to turn on and turn off. Although there are several devices in the MCT family with the distinct combinations of channel and gate structures, the p-channel is widely reported in literature. A schematic of a p-MCT cell, its equivalent circuit and symbol is shown in figure 2.24a, b & c.

The MOS structure is spread across the entire surface of the device that results in a fast turn-on and turn-off with low switching losses. The power or energy required for the turn-on and turn-off with low-switching losses. The power or energy required for the turn-on and turn-off is very small, and the delay time due to the charge storage is also very small. As a latching thyristor device, it has a low on-state voltage drop. Therefore, the MCT has the potential to be the near-ultimate turn-off thyristor with low on-state and switching losses, and a fast-switching speed for applications in high-power converters.



(a) Schematic





(b) Equivalent Circuit (c) Symbol

Figure 2.27 Schematic and equivalent circuit for p-channel MCTs.

Turn-on: When a p-channel MCT is in the forward blocking state, it can be turned on by applying a negative pulse to its gate with respect to the anode. When the n-channel MCT is in the forward blocking state, it can be turned on by applying a pulse to its gate with respect to the cathode. An MCT remains in the on-state until the device current is reversed or a turn-off pulse is applied to its gate.

Turn-off: When a p-channel MCT is in the on-state, it can be turned off by applying a positive pulse to its gate with respect to the anode. When an n-channel MCT is in the on-state, it can be turned off by applying a negative pulse to its gate with respect to the cathode

The MCT can be operated as a gate-controlled device if its current is less than the peak controllable current. Attempting to turn off the MCT at currents higher than its rated peak controllable current may result in destroying the device. For higher values of current, the MCT has to be commutated off like a standard SCR. The gate pulse width are not critical for smaller device currents. For larger currents, the width of turn-off pulse should be larger. Moreover, the gate draws a peak current during turn-off. In many applications, including inverters and converters, a continuous gate pulse over the entire on or off period is required to avoid state ambiguity.

2.13 SITHs

The static induction thyristor (SI-thyristor, SITH) is a thyristor with a buried gate structure in which the gate electrodes are placed in n-base region. Since they are normally on-state, gate electrodes must be negatively biased to hold off-state.

The SITH (static induction thyristor), are also known as the field-controlled device (FCD). A SITH is a minority carrier device. As a result, SITH has low on-state resistance or voltage drop and it can be made with higher voltage and current ratings. It has faster switching speed and high dv/dt and di/dt capabilities. This device is extremely process sensitive. The cross section, equivalent circuit and symbol of a half SITH cell is depicted in the figure 7.25a, b, and c respectively.

Turn-on: A SITH is normally turned on by applying a positive gate voltage with respect to the cathode. The SITH switching on rapidly, providing the gate current and voltage drive is sufficient.

Turn-off: A SITH is normally turned-off by applying a negative voltage with respect to the cathode.

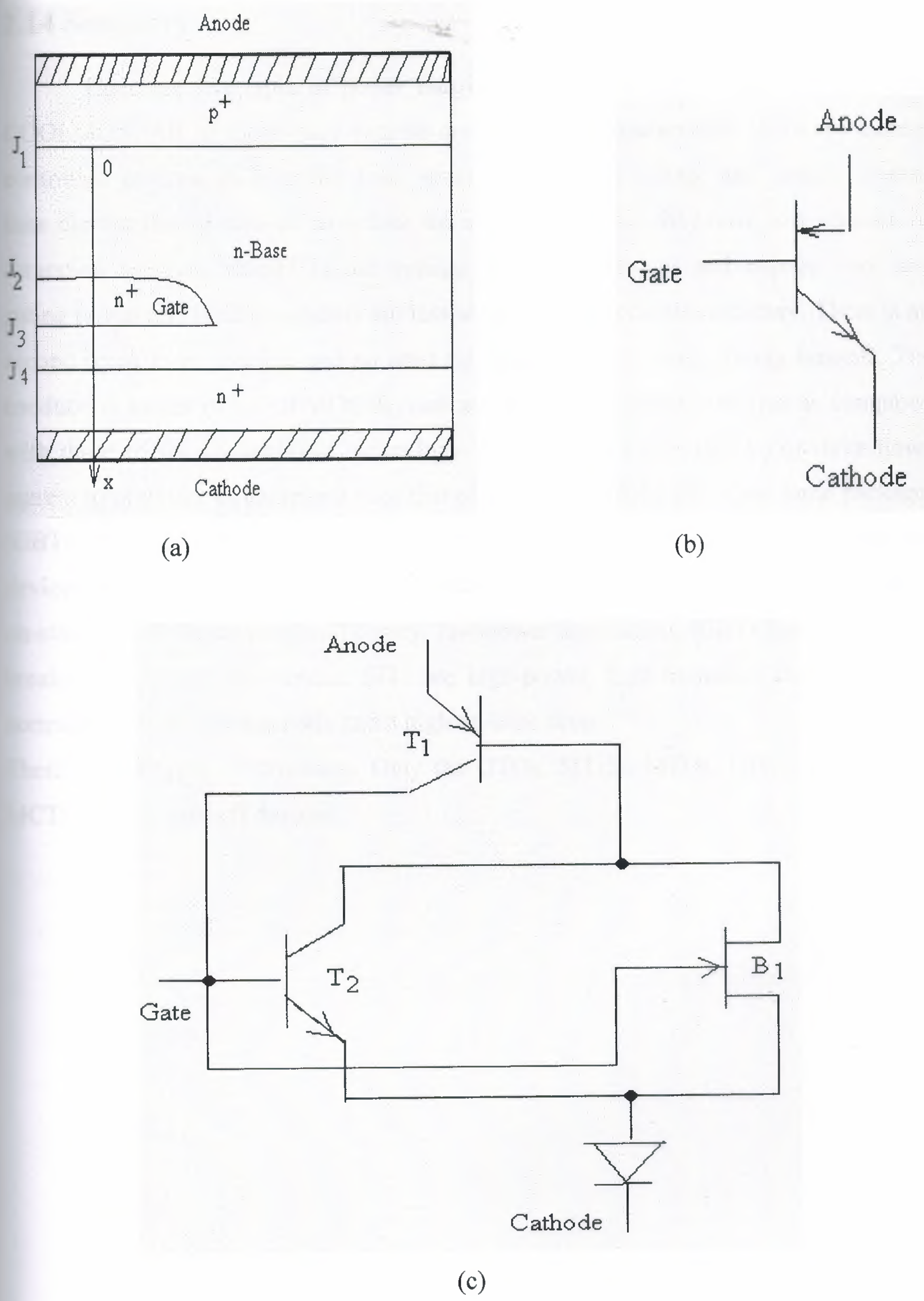


Figure 2.28: (a) Cross-section of half cell (b) SITH symbol (c) equivalent circuit

2.14 Summery

There are five types of power transistors: BJTs, MOSFETs, SITs, IGBTs, and COOLMOS. All of these have turn-on and turn-off characteristics. BJTs are current controlled devices. BJTs suffer from second breakdown voltage and require reverse base current during turn-off to reduce the storage time, but they have low on-state or saturation voltage. MOSFETs are voltage controlled devices and require very low gating power and their parameters are less sensitive to junction temperature. There is no second breakdown problem and no need for negative gate voltage during turn-off. The conduction losses of COOLMOS devices are reduced by a factor of five as compared with those of the conventional technology. It is capable to handle two or three times more output power as compared with that of a standard MOSFET of the same package. IGBTs which combine the advantages of BJTs and MOSFETs are voltage-controlled devices and have low on-state voltage similar to BJTs, COOLMOS, which has very low on-state loss, is used in high-efficiency, low-power application. IGBTs have no second breakdown voltage phenomena. SITs are high-power, high-frequency devices. They, normally have on-characteristic and a high on-state drop.

There are 13 types of thyristors. Only the GTOs, SITHs, MTOs, ETOs, IGCTs, and MCTs are gate turn-off devices

CHAPTER THREE

CONVERTERS

Rectifiers and inverters are the converters that are used for the conversion of ac pulsating to dc and dc to ac respectively. Here, it is given a brief illustration about them which encloses the circuitry used in them, input output waveforms and, their working principles

The output of a converter depends on the switching pattern of the converter switches and the input voltage (or current). Similar to a linear system, the output quantities of a converter can be expressed in terms of the input quantities, by spectrum multiplication. The arrangement of a single-phase converter is shown in figure 3.1a. if $V_i(\theta)$ and $I_i(\theta)$ are the input voltage and current, respectively, the corresponding output voltage and current are $V_0(\theta)$ and $I_0(\theta)$, respectively. The input could be either a voltage source or a current source.

Voltage Source: For a voltage source, the output voltage $V_0(\theta)$ can be related to input voltage $V_i(\theta)$ by

$$V_i(\theta) = S(\theta)V_i(\theta) \tag{3.1}$$

Where $S(\theta)$ is the switching function of the converter, as shown in the figure 3.1b. $S(\theta)$ depends on the type of converter and the gating pattern of the switches. If g_1, g_2, g_3 and g_4 are the gating signals for switches Q_1, Q_2, Q_3 and Q_4 respectively, the switching function is

$$S(\theta) = g_1 - g_4 = g^2 - g^3 \tag{3.2}$$

Neglecting the losses in the converter switches and using power balance gives us

$$V_i(\theta)\ I_i(\theta) = V_0(\theta)\ I_0(\theta)$$

$$= S(\theta) = \frac{V_0(\theta)}{V_i(\theta)} = \frac{I_i(\theta)}{I_0(\theta)}$$

$$I_i(\theta) = S(\theta)\ I_0(\theta) \tag{3.3}$$

Once $S(\theta)$ is known, $V_0(\theta)$ divided by the load impedance gives $I_0(\theta)$; and then $I_i(\theta)$ can be found from the preceding equation.

Current Source. In the case of current source, the input current remains constant, $I_i(\theta) = I_i$, and the output current $I_0(\theta)$ can be related to input current I_i,

$$I_0(\theta) = S(\theta)\, I_i$$

$$V_0(\theta)\, I_0(\theta) = V_i(\theta)\, I_i(\theta)$$

Which gives

$$V_i(\theta) = S(\theta)\, V_0(\theta)$$

$$S(\theta) = \frac{V_i(\theta)}{V_0(\theta)} = \frac{I_0(\theta)}{I_i(\theta)} \tag{3.4}$$

3.1 Rectifiers

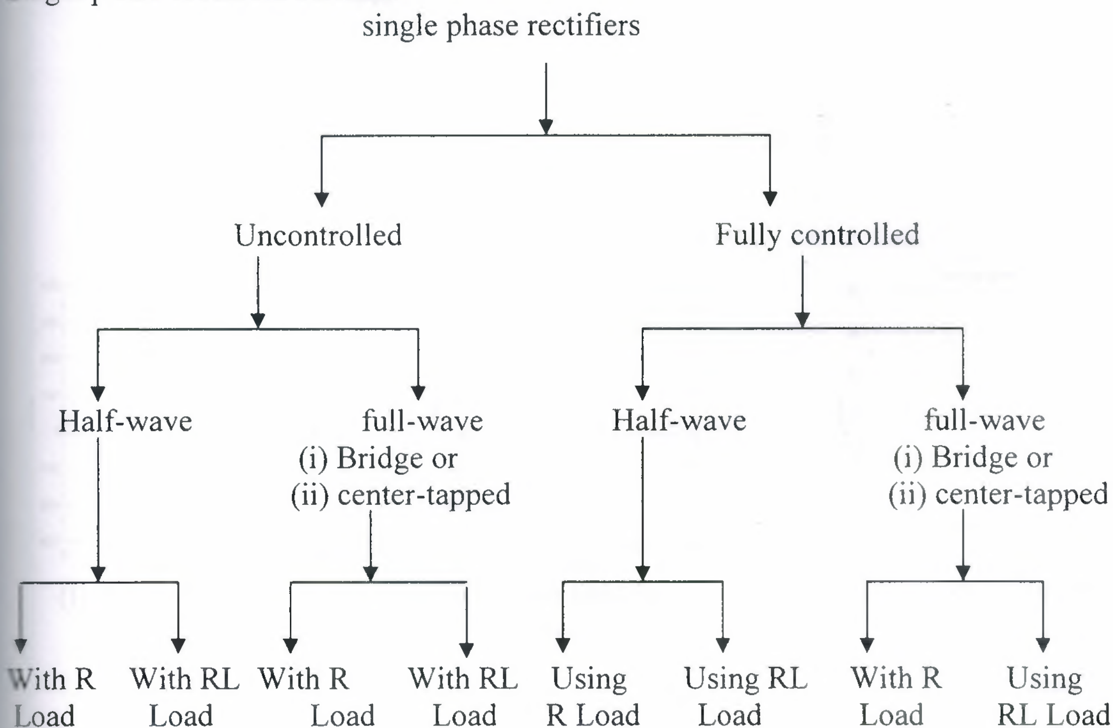
A rectifier is circuit that converts an ac signal into a unidirectional. A rectifier is a type of ac-dc converter. Depending on the type of input supply, the rectifiers are classified into two types:

(a) Single Phase rectifiers

(b) Three Phase rectifiers

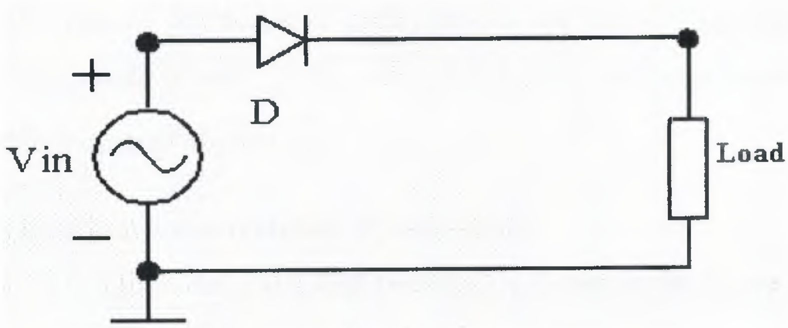
3.2 Single Phase Rectifiers

Single phase rectifiers include:

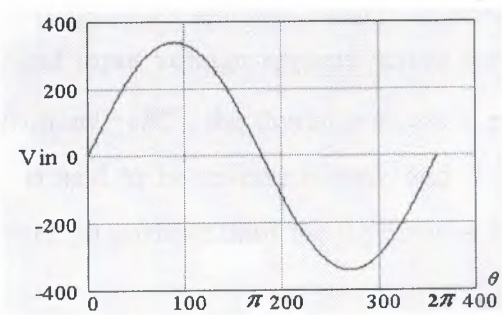


3.2.1 Single phase half wave rectifiers (Uncontrolled):

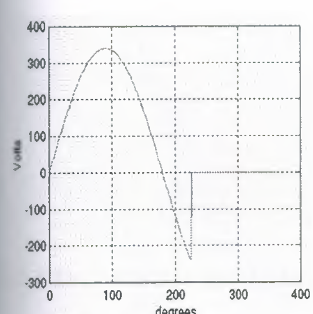
A single phase half wave rectifier is the simplest type, but it is not normally used in industrial applications. However, it is useful in understanding the principle of rectifier operation. As shown in circuit diagram 3.1a, with a load (resistive or inductive). During the positive half cycle of the input voltage, diode D conducts and input voltage appears across the load, during the negative half cycle of the input voltage, the diode is in the blocking condition and the output voltage is zero. The waveforms for the input voltage and output voltage and current across the resistor are shown in figure 3.1b & c.



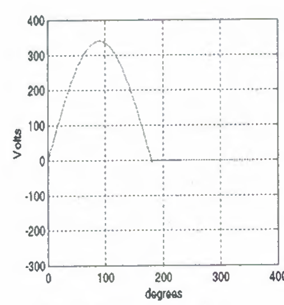
a) Circuit Diagram



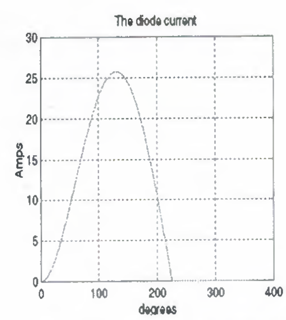
(b) I/P wave form



(i) When load is Inductive



(ii) When load is Resistive



(iii) Output Current

(c) O/P Waveforms

Figure 3.1: Single phase half wave circuitry for uncontrolled rectification

3.2.2 Single phase full wave rectifier (uncontrolled):

A full wave rectifier circuit with a center tapped transformer is show in figure 3.2a.Each half of the transformer with its diode acts as a half wave rectifier and the output of a full wave rectifier is shown in figure 3.2b. The average output voltage is

$$V_{dc} = \frac{2}{T}\int_{0}^{\frac{T}{2}} V_m Sin\omega t \ \mathrm{dt} = \frac{2V_m}{\pi} = 0.6366\ V_m \qquad (3.5)$$

Instead of using a center tapped transformer, four diodes can be used. During the positive half cycle of the input voltage, the power is supplied to the load through the diodes D1 & D2. During the negative cycle, diodes D3 and D4 conduct. The peak inverse voltage of a diode is only V_m. This circuit is known as bridge rectifier, and it is commonly used in industrial application.

3.2.3 Single phase half wave rectifiers (Controlled):

A circuit with a thyristor and a load (resistor) is shown in the figure 3.4a. During the positive half cycle of input voltage, the thyristor anode is positive with respect to its cathode and the thyristor is said to be forward biased. When thyristor T is fired at $\varpi t = \alpha$, thyristor conducts and input voltage appears across the load. When the input voltage starts to be negative at $\varpi t = 180°$, the thyristor anode is negative with respect to its cathode and thyristor T is said to be reverse biased; and it is turned off. The time after the input voltage starts to go positive until the thyristor is fired at $\varpi t = \alpha$ is called the delay or firing angle α .

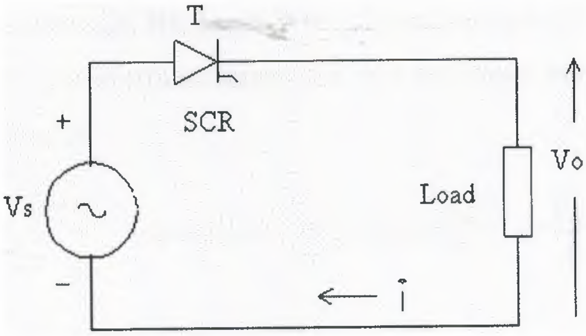
If V_m is the peak input voltage, the average output voltage V_{dc} is

$$V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\pi} VmSin\omega t \ \mathrm{d}(\omega t) = \frac{V_m}{2\pi}[-Cos\omega t]_{\alpha}^{\pi}$$

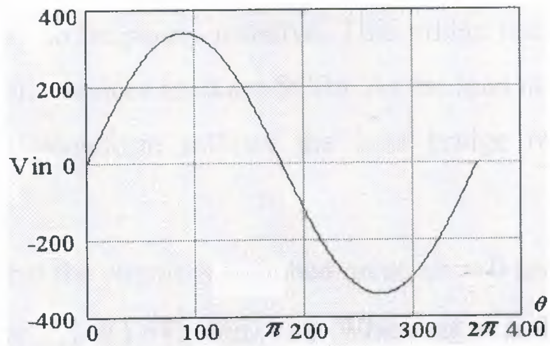
$$= \frac{V_m}{2\pi}(1+\mathrm{Cos}\,\alpha) \qquad (3.6)$$

The maximum output voltage is

$$V_{dc} = \frac{V_m}{2\pi} \qquad (3.7)$$

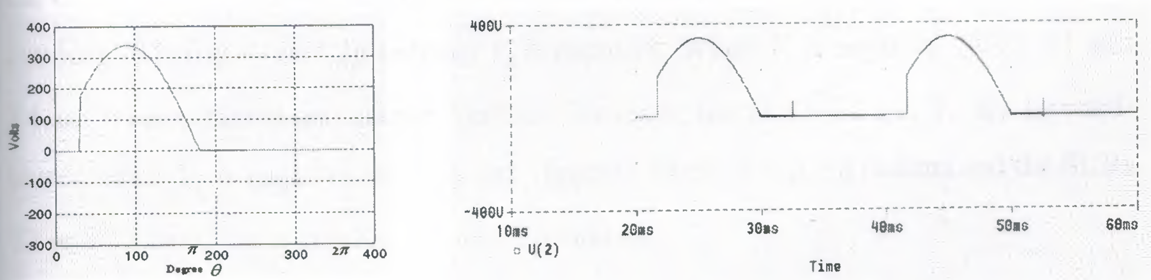


(a) Circuit Diagram



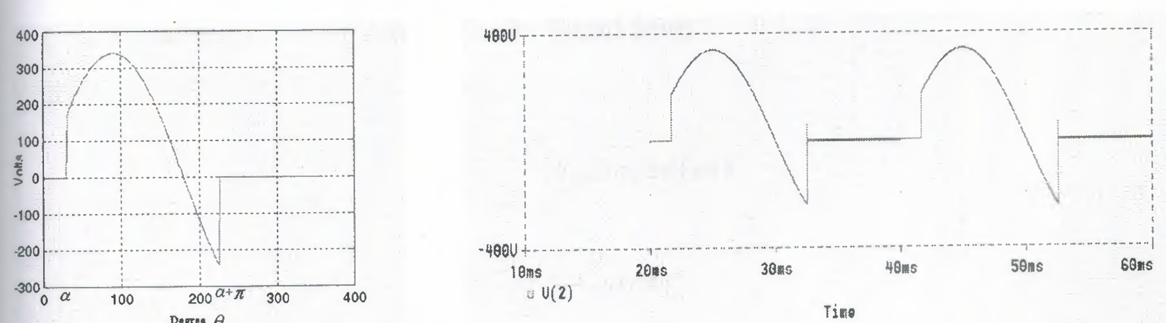
(b) I/P wave form

When the load is resistive, then output waveform is;



(c) O/P waveform, when load is resistive

When load is inductive, output wave form is;



(d) O/P waveform, when load is inductive

Figure 3.2: Single phase half wave circuit for controlled rectification

When the load is inductive i.e. RL load: When there is an inductive load in the circuit then we have the output waveform as across the load as follows and the output waveform across RL load is

$$V_{dc}=\frac{1}{2\pi}\int_{\alpha}^{\alpha+\pi} V_m Son\omega t d(\omega t)\ \frac{V_m}{2\pi}[-Cos\omega t]_{\alpha}^{\alpha+\pi} \quad =\frac{V_m}{\pi}Cos\alpha \tag{3.8}$$

3.2.4 Single phase fully controlled rectifiers:

The operation of a fully-controlled bridge rectifier circuit is explained in this program. The load is set to be purely resistive. This bridge rectifier is called as fully-controlled, because all the devices used are SCRs. As the load is purely resistive in first case, the load current waveform follows the load bridge rectifier output voltage waveform.

Let us assume that the circuit is switched on at $\omega t = 0$ and let the firing angle be a. Let the supply voltage $V_s(\omega t) = V_m$ Sin (ωt). When ωt = a, the SCRs T1 and T4 get triggered and they start conducting since they are forward-biased. These two SCRs continue to conduct till ωt = p. When ωt = p radians, the supply voltage falls to zero and the current through the SCRs T1 and T4 falls below the holding level and they cease to conduct. When p < ωt < 2p radians, V_s is negative. When V_s is negative, SCRs T1 and T4 are reverse-biased and cannot conduct. However, the SCRs T2 and T3 are forward-biased when V_s is negative and they get triggered when ωt = p + a radians and the SCRs T2 and T3 continue to conduct till ωt = 2p radians.

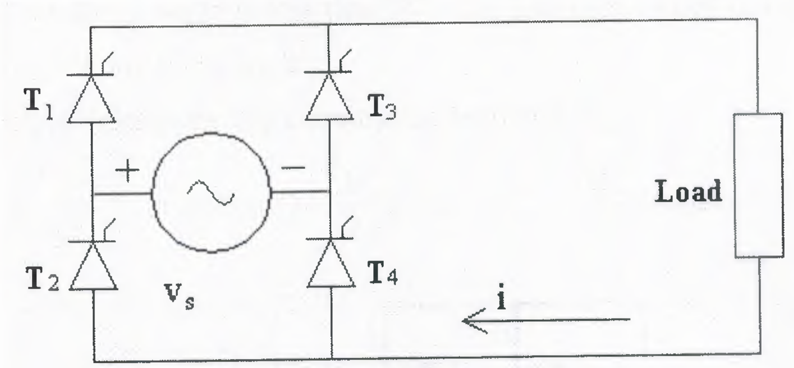
During the periods defined by 0 < ωt < a, and p < ωt < p + a, no SCR is in conduction and the output voltage is zero. The conduction in the load is discontinuous.

The average output voltage can be found from

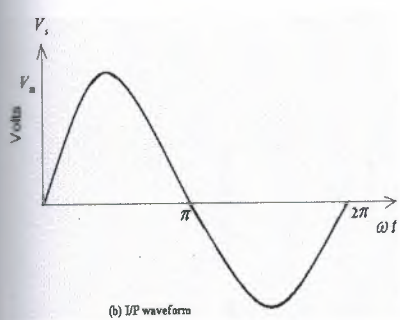
$$V_{dc}=\frac{2}{2\pi}\int_{\alpha}^{\pi} V_m Sin\omega t d(\omega t)$$

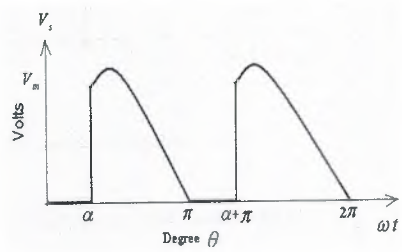
$$=\frac{2V_m}{2\pi}[-Cos\omega t]_{\alpha}^{\pi}$$

$$=\frac{V_m}{\pi}(1+Cos\alpha) \tag{3.9}$$



(a) Circuit diagram





(b) I/P Waveform

(c) O/P Wave form

Figure 3.3: Single phase fully controlled rectifier

In second case, when there is RL load across the SCRs instead of resistive load then, for this circuit, V_s is a sinusoidal voltage source. When it is positive, the SCRs T1 and T $_3$ can be triggered and then current flows from V_s through SCR T1, load inductor L, load resistor R, SCR T_3 and back into the source. In the next half-cycle, the other pair of SCRs conducts.

The main purpose of this circuit is to provide a variable dc output voltage, which is brought about by varying the firing angle. Let $V_s = V_m$ Sin wt, with $0 < \omega t < 360^o$. If $\omega t = 30^o$ when T1 and T_3 are triggered, then the firing angle is said to be 30^o. In this instance the other pair is triggered when $\omega t = 210^o$. Usually the description of this circuit is based on the assumption that the load inductance is sufficiently large to keep the load current continuous and ripple-free.

It is assumed here that the load inductance is quite large. The animation is correct only if the firing angle is less than 90°. The programs under simulation section will run correctly for any firing angle.

The average output voltage for this circuitry can be found as

$$V_{dc} = \frac{2}{2\pi}\int_{\alpha}^{\alpha+\pi} V_m Sin\omega t d(\omega t) = \frac{2V_m}{2\pi}[-Cos\omega t]_{\alpha}^{\alpha+\pi} = \frac{2V_m}{\pi} Cos\alpha \tag{3.10}$$

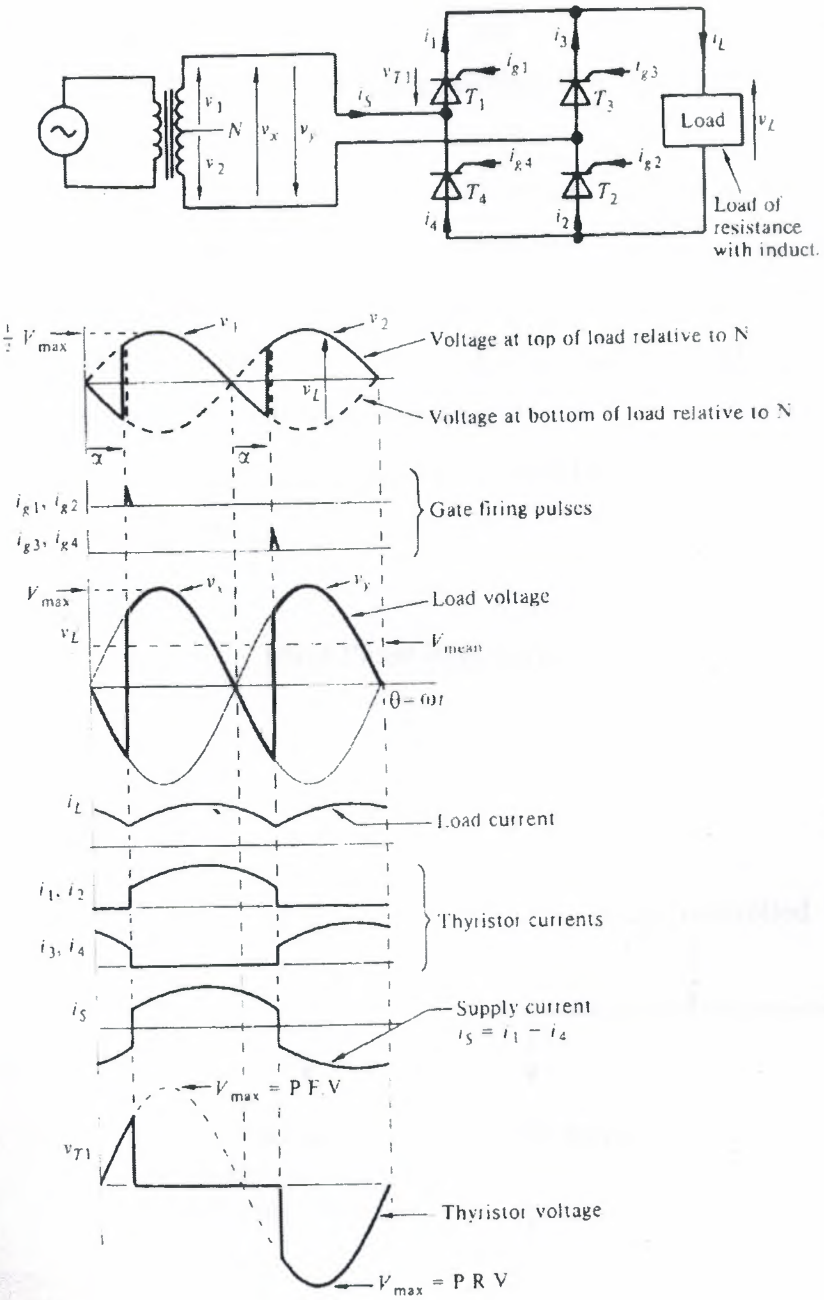


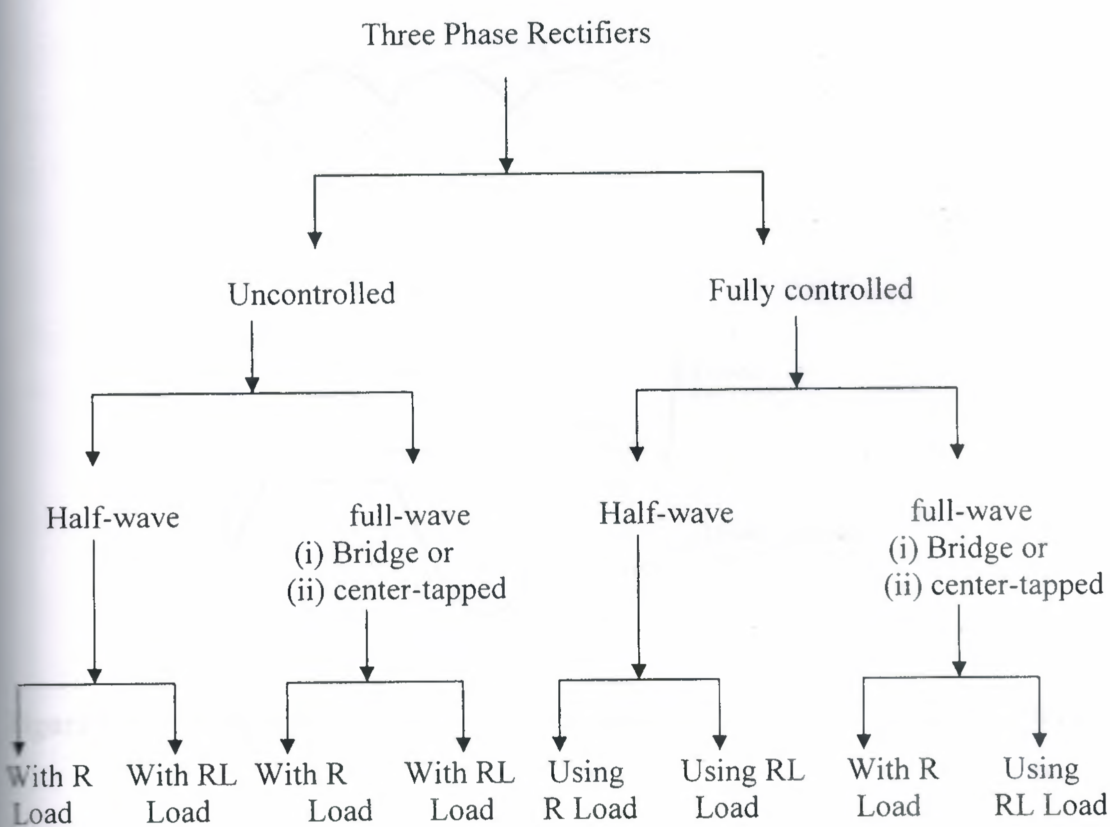
Figure 3.4 :Fully controlled Single-phase Bridge., connection and waveforms

3.3 Three-phase rectification:

Diode rectifiers provide a fixed output voltage only. To obtain controlled output voltages, phase-control thyristor are used instead of diodes. The output voltage of thyristor rectifiers is varied by controlling the delay or firing angle of thyristors. A phase-control thyristor (or we can say SCRs) is turned on by applying a short pulse to its gate and turned off due to natural or line commutation; and in case of highly inductive load, it is turned off by firing another thyristor of the rectifier during the negative half cycle of input voltage.

Three phase-controlled rectifiers are simple and less expensive; and the efficiency of these rectifiers is, in general, above 95 %. Because these rectifiers convert from ac to dc, these controlled rectifiers are also called ac-dc converters and are used extensively in industrial application, especially in variable speed drives, ranging from fractional horsepower to megawatt power level.

The three phase converters can be classified into the below mentioned types, depending on the input supply:



Furthermore, we can subdivide controlled converters into

(a) Semi converters: A semi converter is a one quadrant converter and it has one polarity of output voltage and current.

(b) Full converter: A full converter is a two-quadrant converter and the polarity of its output voltage can be either positive or negative. However, the output current of full converter has one polarity only.

(c) Dual converter: A dual converter can operate in four quadrants; and both the output current and voltage can be either positive or negative.

3.3.1 Three phase half wave Converter:

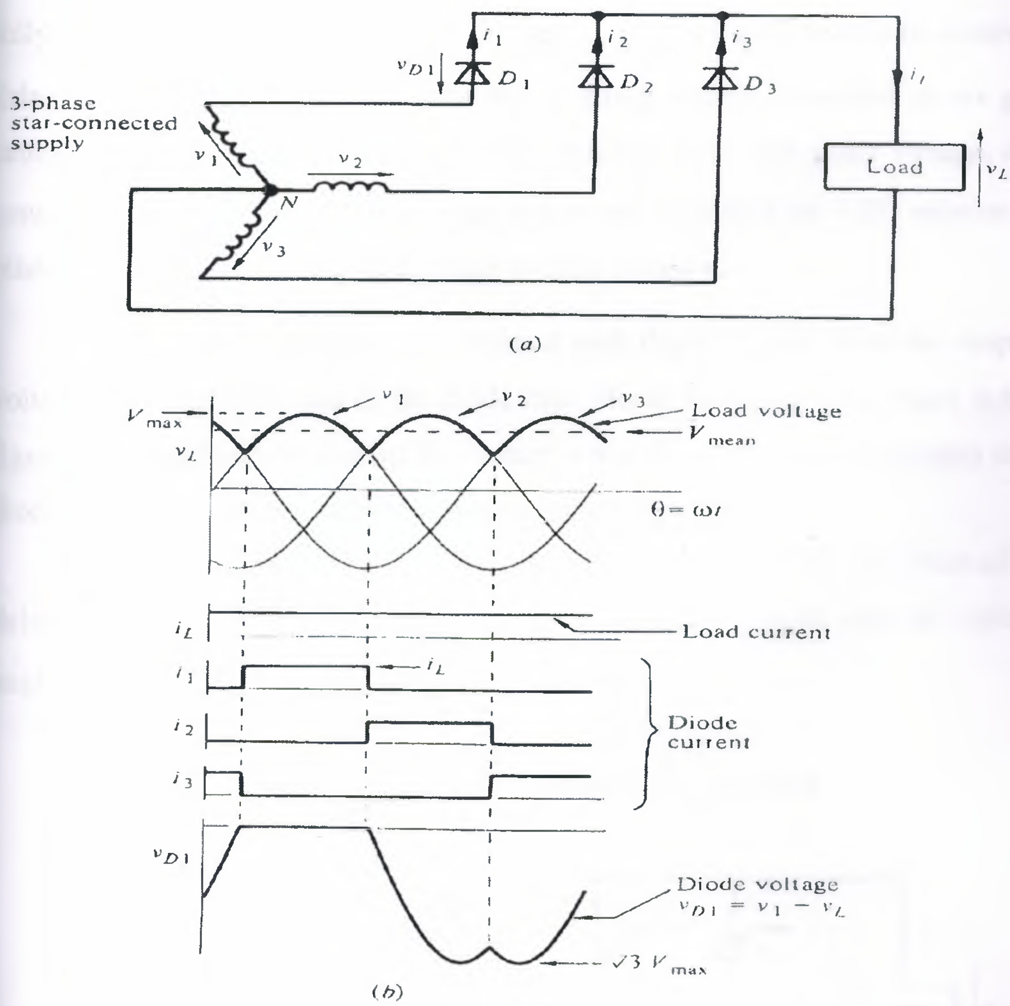


Figure 3.5: Three-phase half-wave circuit using diodes (a) Connection (b) waveform

The connection of the three phase half-wave circuit is shown is figure3.5, each supply phase being connected to the load via diode and as in all half-wave connection, the load current being returned to the supply neutral.

The circuit functions in a manner such that only one diode is conducting at any given instant, that one which is connected to the phase having the highest instantaneous value. This results in the load voltage V_L having the waveform, as shown in figure3.5, which is the top of the successive phase voltages.

The mean value of the load voltage is given by

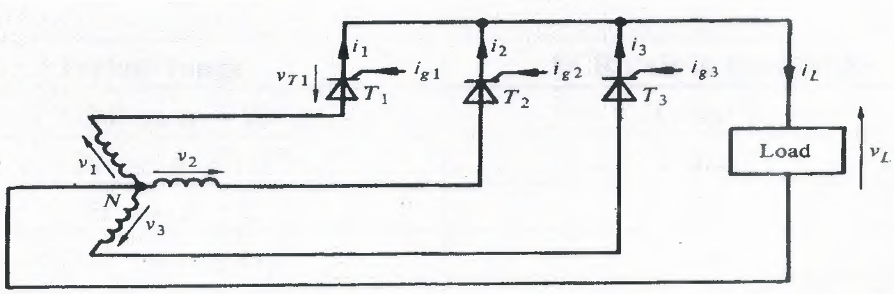
$$V_{dc} = \frac{1}{2\pi/3}\int_{\pi/6}^{5\pi/6} V_m Sin\omega t d(\omega t) = \frac{3\sqrt{3}}{2\pi} V_m \qquad (3.11)$$

When the diodes, in figure 3.6, are replaced by the thyristor the circuit becomes fully controlled, with the mean load voltage i.e. V_{dc} being adjustable by control of the firing delay angle α. Each thyristor has a firing circuit connected to its gate and cathode, producing a firing pulse relative in position to its own phase voltage. A master control will ensure that the three gate pulses are displayed by $120°$ relative to each other, giving the same firing delay angle to each thyristor.

The firing delay angle α is defined such that it is zero when the output mean voltage is a maximum, that is, the diode case. Hence the firing delay angle α shown in figure 3.6 is defined relative to the instant when the supply phase voltages cross and diodes would commutate naturally, not the supply voltage zero.

The load voltage wave forms of figure 3.6 © & (d) show the effect of a larger delay angle, the voltage having instantaneous negative periods after the firing delay angle $\alpha = 30°$. The mean load voltage is given by

$$V_{dc} = \frac{1}{2\pi/3}\int_{\alpha+\pi/6}^{\alpha+5\pi/6} V_m Sin\omega t d(\omega t) = \frac{3\sqrt{3}}{2\pi} V_m Cos\alpha \qquad (3.12)$$



(a)

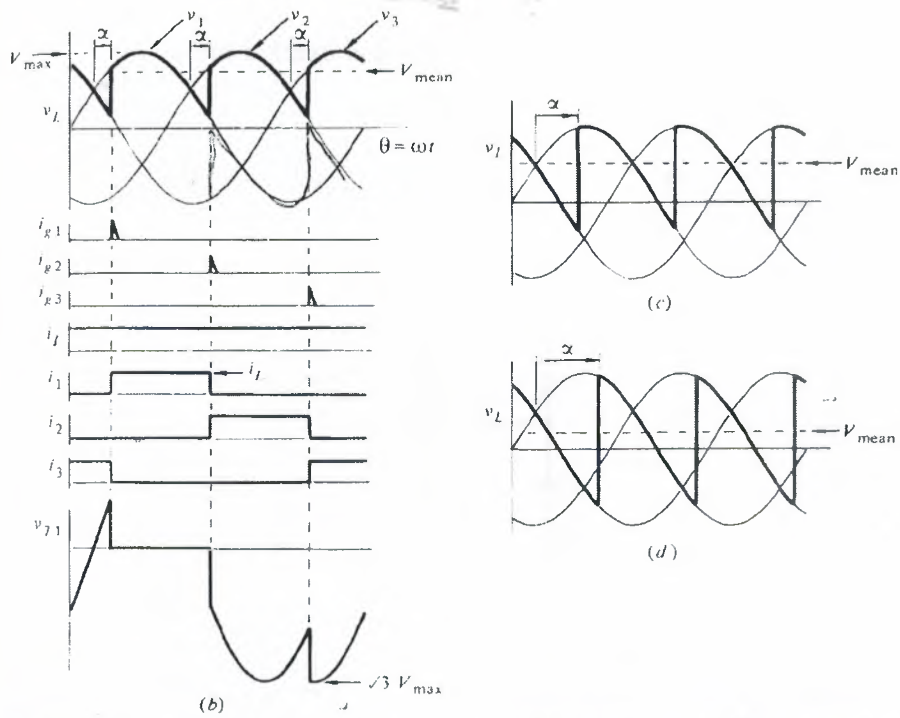


Figure3.6 Three-phase half-wave controlled circuit using thyristors (a).Connection (b) Wave-forms with small firing delay angle.

(c) and (d) Load voltage waveform with large delay angle.

3.3.2 Three phase full wave Converter:

A full converter circuit with highly inductive load, as shown in figure 3.5a, is known as a three phase bridge rectifier. The thyristor are fired at an interval of $\pi/3$. At $\omega t = \pi/6 + \alpha$, thyristor T_6 is already conducting and thyristor T_1 is turned on. During interval $(\pi/6 + \alpha) \leq \omega t \geq (\pi/2 + \alpha)$, thyristor T_1 and T_6 conduct and output voltage appear across the load. At $\omega t = \pi/2 + \alpha$, thyristor T_2 is fired and thyristor T_6 is reverse biased immediately. During interval $\pi/2 + \alpha \leq \omega t \geq (5\pi/6 + \alpha)$, thyristor T_1 and T_2 conduct and output voltage appear across the load.

Period, range	**SCR Pair in conduction**
$\alpha + 30^{\circ}$ to $\alpha + 90^{\circ}$	T_1 and T_6
$\alpha + 90^{\circ}$ to $\alpha + 150^{\circ}$	T_1 and T_2
$\alpha + 150^{\circ}$ to $\alpha + 210^{\circ}$	T_2 and T_3
$\alpha + 210^{\circ}$ to $\alpha + 270^{\circ}$	T_3 and T_4
$\alpha + 270^{\circ}$ to $\alpha + 330^{\circ}$	T_4 and T_5
$\alpha + 330^{\circ}$ to $\alpha + 360^{\circ}$ and $\alpha + 0^{\circ}$ to $\alpha + 30^{\circ}$	T_5 and T_6

The average output voltage is found from

$$V_{dc} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha}\sqrt{3}V_m Sin\omega t d(\omega t) = \frac{3\sqrt{3}}{\pi}V_m Cos\alpha \tag{3.13}$$

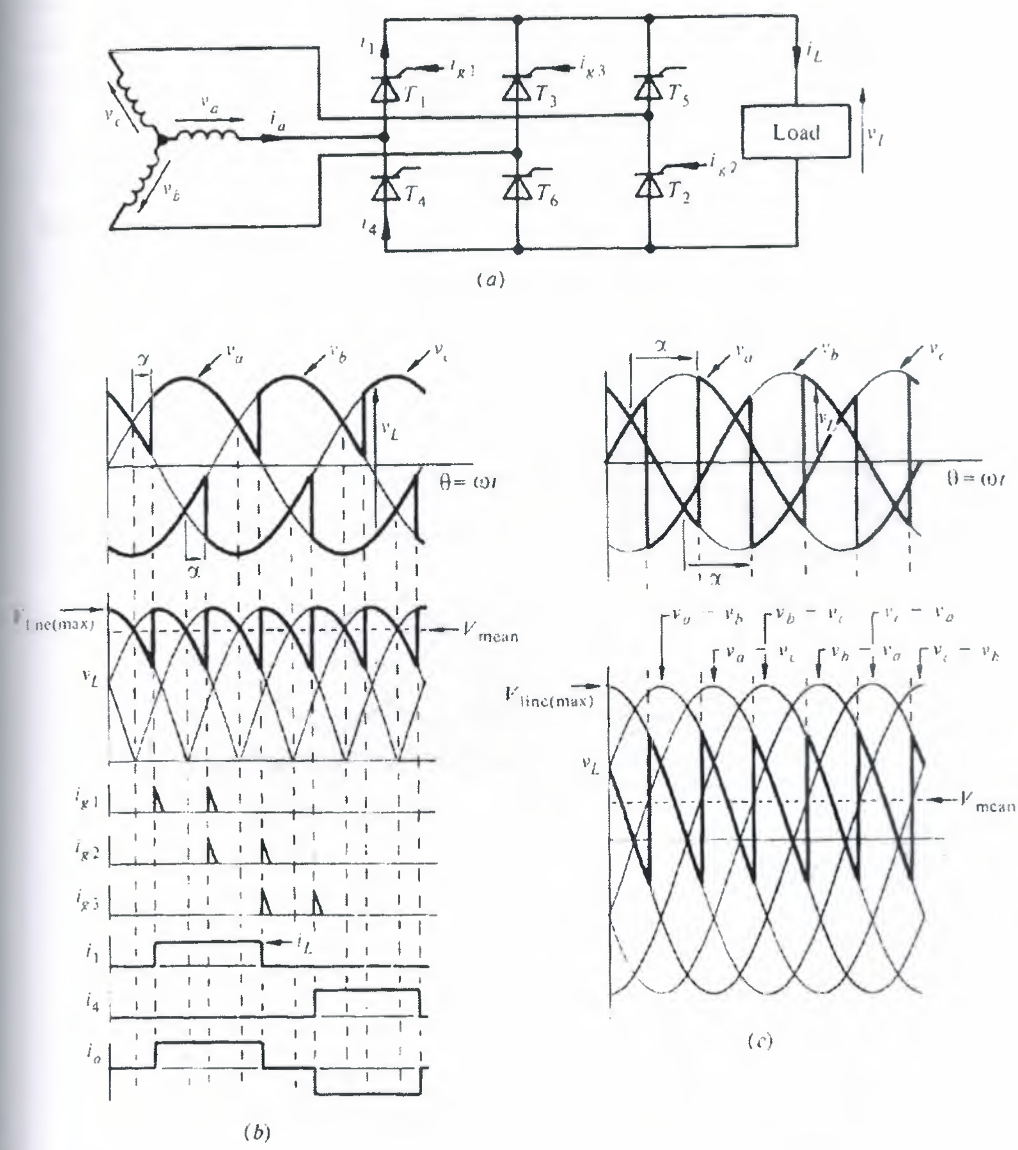


Figure 3.7 Fully-controlled three-phase bridge (a) connection (b) Waveforms with small firing delay (c) voltage wave with large firing delay

A three phase bridge rectifier is commonly used in high power applications. A full wave rectifier is shown in the figure 3.5a. it can operate with or without a transformer and gives six pulse ripples on the output voltage. The diodes are numbered in order of conduction sequences and each one conducts for 120°. The conduction sequence for diodes is D_1 - D_2, $D_3 - D_2$, $D_3 - D_4$, $D_5 - D_4$, $D_5 - D_6$, and $D_1 - D_6$. The waveforms and conduction times of diodes are shown in figure 3.554.

Period, range	**Diode Pair in conduction**
30° to 90°	D_1 and D_6
90° to 150°	D_1 and D_2
150° to 210°	D_2 and D_3
210° to 270°	D_3 and D_4
270° to 330°	D_4 and D_5
330° to 360° and 0° to 30°	D_5 and D_6

If V_m is the peak value of the phase voltage, then the average output voltage found from

$$V_{dc} = \frac{2}{2\pi/6}\int_0^{\frac{\pi}{6}} \sqrt{3}V_m \, Cos\,\omega t \, d(\omega t) = \frac{3\sqrt{3}V_m}{\pi} = 1.654\,V_m \qquad (3.14)$$

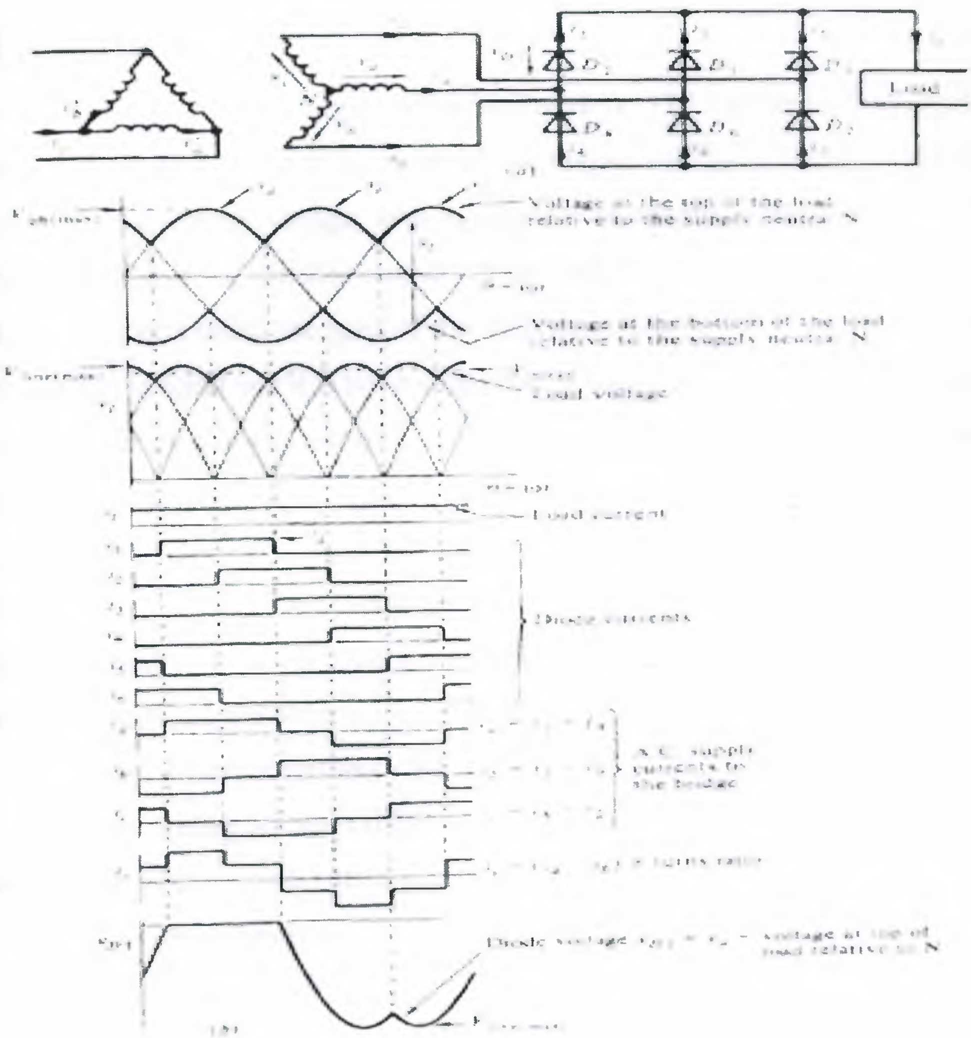


Figure 3.8 Three-phase bridge circuit (a) connection (b) Waveform

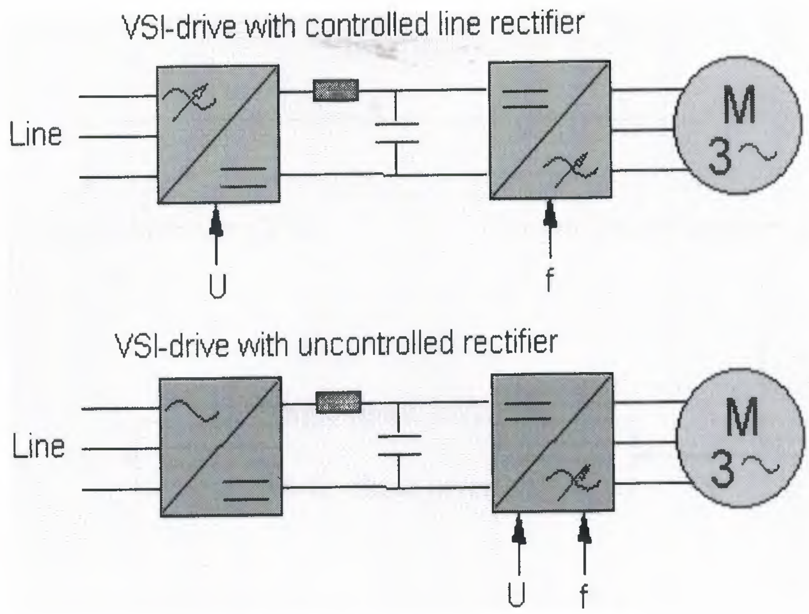


Figure 3.9 Block diagram

3.4 Inverters:

DC-to-ac converters are known as inverters. The function of an inverter is to change a dc input voltage to a symmetric ac output voltage of desired magnitude and frequency. The output voltage to a symmetric ac output voltage could be fixed or variable frequency. A variable output voltage can be obtained by varying the input dc voltage and maintaining the gain of the inverter constant. On the other hand, if the dc input voltage is fixed and it is not controllable, a variable output voltage can be obtained by varying the gain of the inverter. The inverter gain may be defined as the ratio of the ac output voltage to dc input voltage.

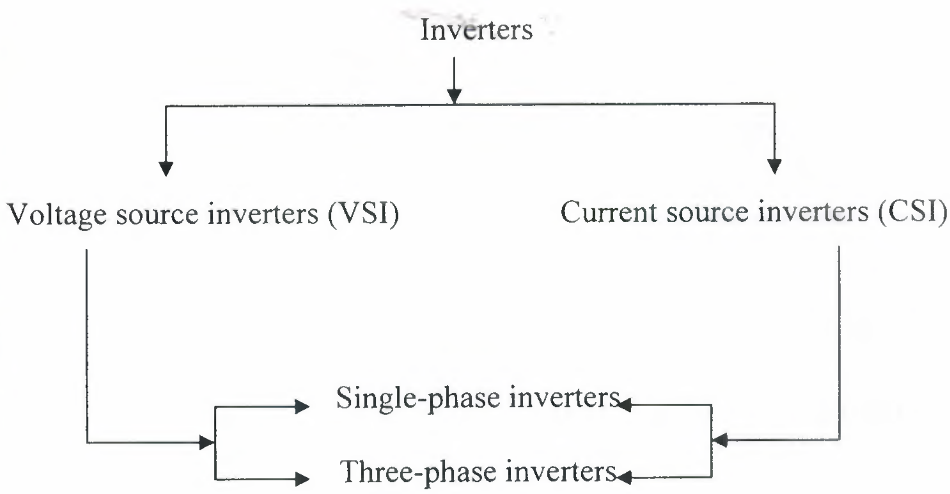
Inverters are widely used in industrial applications (e.g. variable-speed ac motor drives, induction heating, standby power supplies, and uninterruptible power supplies).the input may be a battery, fuel cell, solar cell, or other dc source.

There are two kinds of inverters, under discussion:

1. Voltage source inverters (VSI)
2. current source inverters (CSI)

Further, each of them is classified into two categories:

a) Single-Phase Inverters
b) Three-Phase Inverters



3.5 Voltage Source Inverters

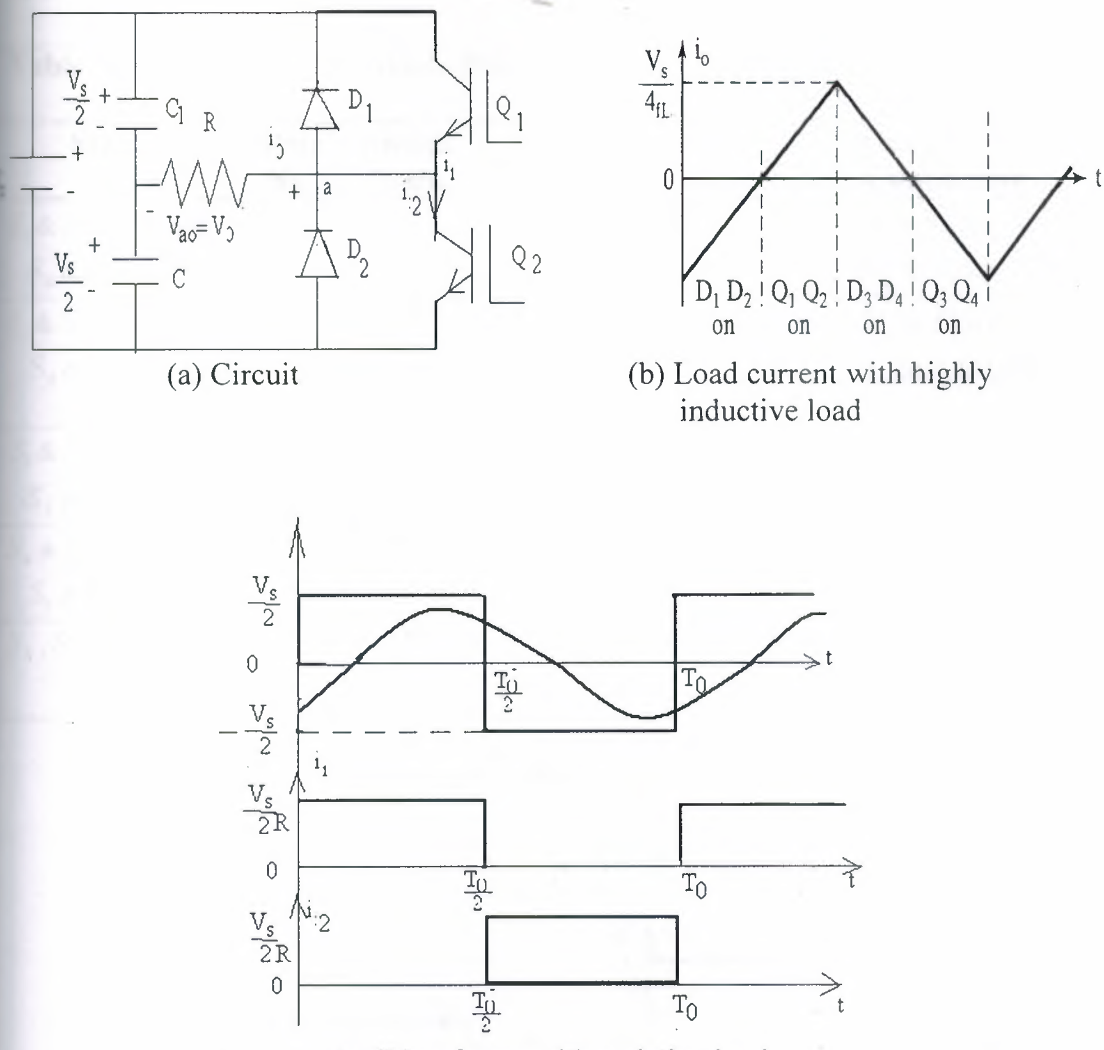
Voltage source inverters are fed from a voltage source and the load current is forced to fluctuate from positive to negative, and vice versa. To cope with inductive loads, the power switches with free wheeling diode are required. These are most commonly used type of inverters. The output voltage is maintained constant on the inverter and the output current is forced to change

3.5.1 Single Phase Inverters:

Single Phase half bridge inverter: The principle of single-phase inverters is depicted through Figure 3.4545. The inverter circuit consists of two choppers. When only transistor Q_1 is turned on for a time $T_0/2$, the instantaneous voltage across the load v_0 is $V_s/2$. If transistor Q_2 only is turned on for a time $T_0/2$, $-V_s/2$ appear across the load. The circuit must be designed such a way that Q_1 and Q_2 are not turned on at the same time. The waveforms for the output voltage and transistor currents with a resistive load are shown in figure 3.10 this inverter requires a three-wire dc source, and when a transistor is off, its reverse voltage is V_S instead of $V_s/2$. This inverter is known as *half bridge inverter*.

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

$$V_0 = \left(\frac{2}{T_0}\int_0^{T_0/2}\frac{V_s^2}{4}\,dt\right)^{1/2} = \frac{V_S}{2} \tag{3.15}$$



(a) Circuit

(b) Load current with highly inductive load

(c) Waveforms with resistive load

Figure 3.10 Single phase half-bridge inverter

Single-Phase Full-Bridge Inverter: A single-phase inverter is shown in figure 3.11(a) consists of four choppers. When transistors Q_1 and Q_2 are turned on simultaneously, the input voltage V_S appears across the load. If transistors Q_3 and Q_4 are turned on at the same time, the voltage across the load is reversed and is -V_S.

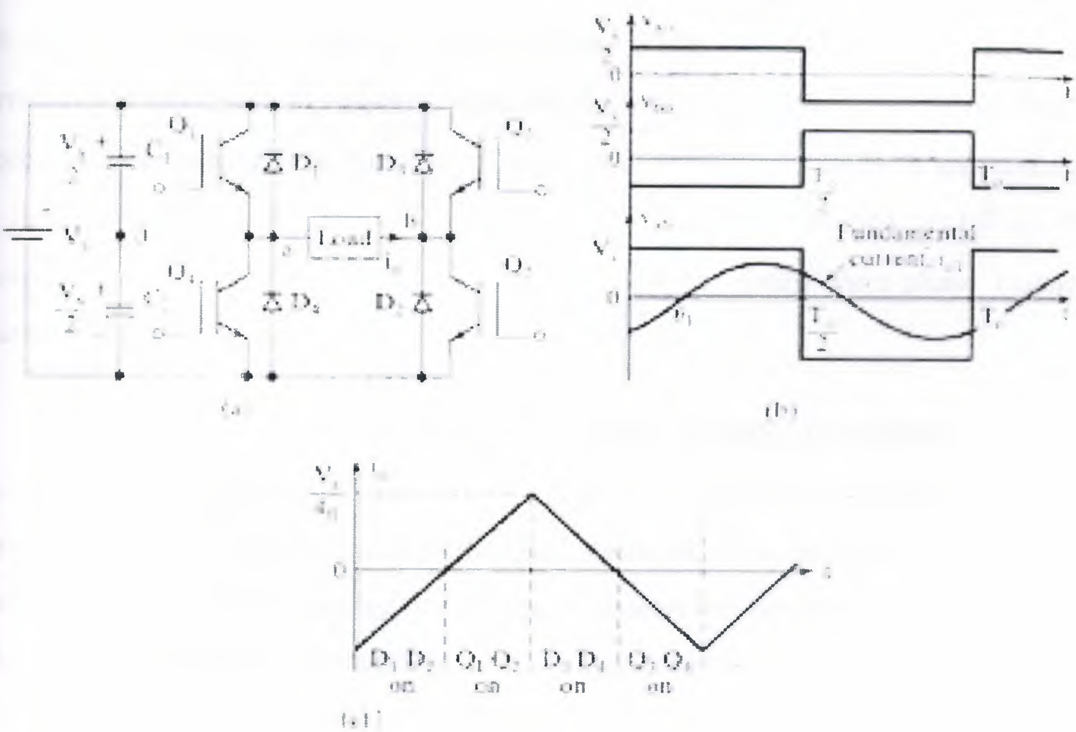
The waveform for the output voltage is shown in figure 3.11 (b). Five switch states are given in table 3.1. Transistors Q_1, Q_4 act as the switching devices S_1, S_4 respectively. If two switches: one upper and one lower conduct at the same time such that the output voltage is $\pm V_S$, the switching state is 1, where as if these switches are off at the same time, the switch state is 0.

Table 3.1 Switch States for Single-Phase Full-Bridge Voltage Source Inverter(VSI)

State	State No.	Switch State	V_{a0}	V_{b0}	V_0	Components Conducting
S_1 & S_2 are on and S_4 & S_3 are off	1	10	$V_s/2$	$-V_s/2$	V_S	S_1 & S_2 if $i_0>0$ D_1 & D_2 if $i_0<0$
S_1 & S_2 are off and S_4 & S_3 are on	2	01	$-V_s/2$	$V_s/2$	$-V_S$	D_4 & D_3 if $i_0>0$ S_4 & S_3 If $i_0<0$
S_1 & S_3 are on and S_4 & S_2 are off	3	11	$V_s/2$	$V_s/2$	0	S_1 & D_3 if $i_0>0$ S_3 & D_1 if $i_0<0$
S_4 & S_2 are on and S_1 & S_3 are off	4	00	$-V_s/2$	$-V_s/2$	0	S_2 & D_4 if $i_0>0$ S_4 & D_2 if<0
S_4, S_2, S_1, S_3 are all off	5	Off	$-V_s/2$ $V_s/2$	$V_s/2$ $-V_s/2$	$-V_S$ V_S	D_4 & D_3 if $i_0>0$ D_4 & D_2 if $i_0<0$

The rms output voltage can be found from

$$V_0 = \left(\frac{2}{T_0} \int_0^{T_0/2} V_S^2 \, dt \right)^{1/2} = V_S \qquad (3.16)$$



(a) Circuit (b) Waveforms with resistive load
(c) Load current with highly inductive load

Figure 3.11 Single-Phase Full-Bridge Inverter

3.5.2 Three-Phase Inverters:

Three-phase inverters are normally used for high-power applications. Three single-phase half (or full)-bridge inverters can be connected in parallel to form the configuration of a three-phase inverter. The gating signals of single-phase inverters should be advanced or delayed by 120° with respect to each other to obtain three-phase balanced (fundamental) voltages. The transformer primary windings must be isolated from each other, whereas the secondary windings may be connected in Y or delta. This arrangement requires three-single-phase transformers, 12 transistors, and 12 diodes. If the output voltages of single-phase inverters are not perfectly balanced in magnitudes and phases, the three-phase output voltages are unbalanced.

A three-phase output can be obtained from a configuration of six transistors and six diodes. There are two types of control signals which are developed in order to apply the transistors: 180° conduction or 120° conduction.

180-Degree Conduction: The 180° conduction has better utilization of the switches and is the preferred method. Each transistor conducts for 180°. Three transistors remain on at any instant of time. When transistor Q_1 is switched on, terminal a is connected to the positive terminal of the dc input voltage. When transistor Q_4 is switched on, terminal a is brought to the negative terminal of the dc source. There are six methods of operation in a cycle and the duration of each mode is 60°. The transistors are numbered in the sequence of gating the transistors (e.g. 123, 234,345, 456, 561, and 612). The gating signals are shifted from each other by 60° to obtain three-phase balanced (fundamental) voltages.

The switches of any leg of inverter ($S_1 and S_4$, $S_3 and S_6$, or $S_3 and S_6$) cannot be switched on simultaneously; this would result in a short circuit across the dc link voltage supply. Similarly, to avoid undefined states and thus undefined ac output line voltages, the switches of any leg of the inverter cannot be switched off simultaneously; this can result in voltages that depend on the respective line current polarity.

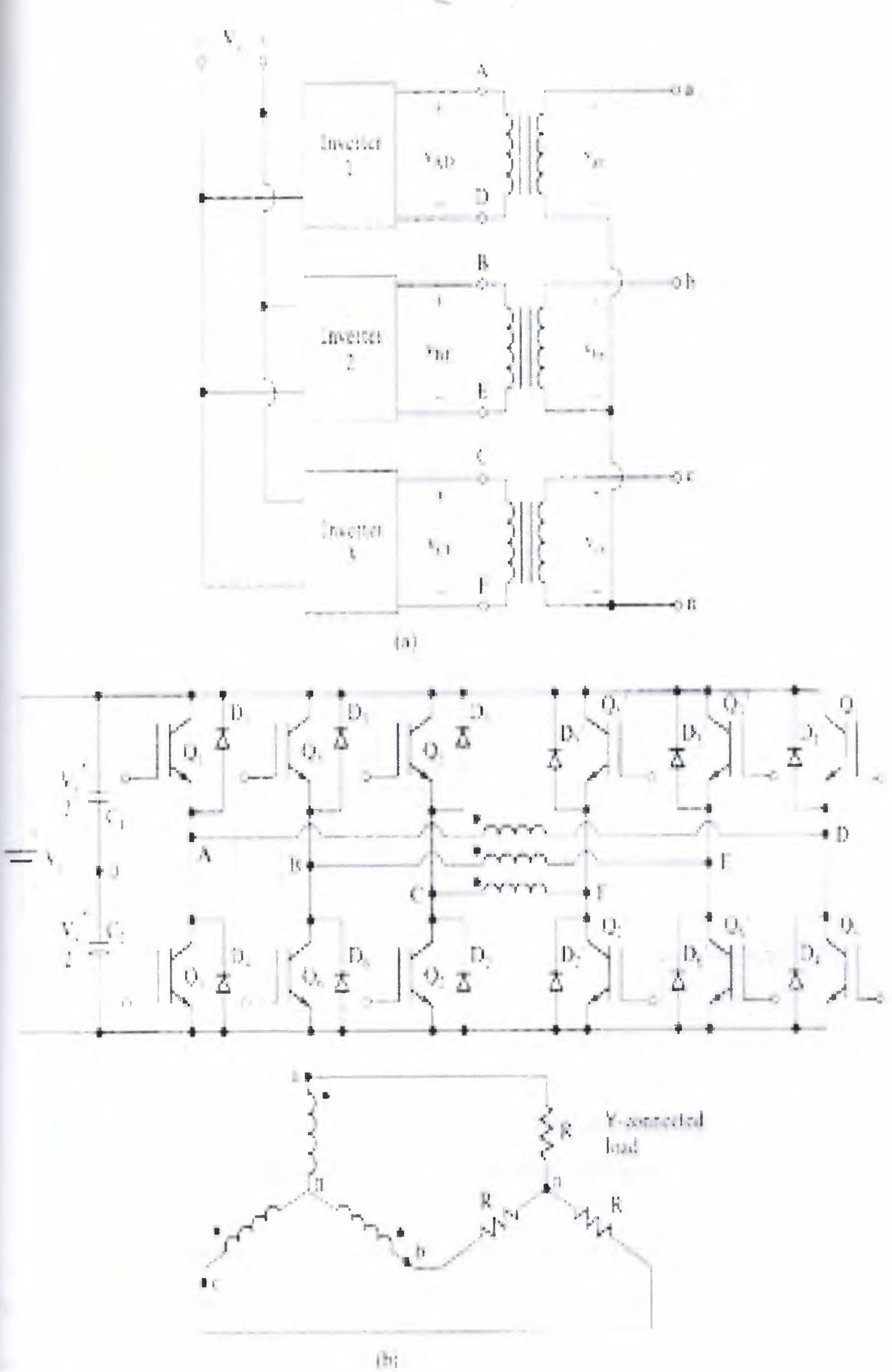
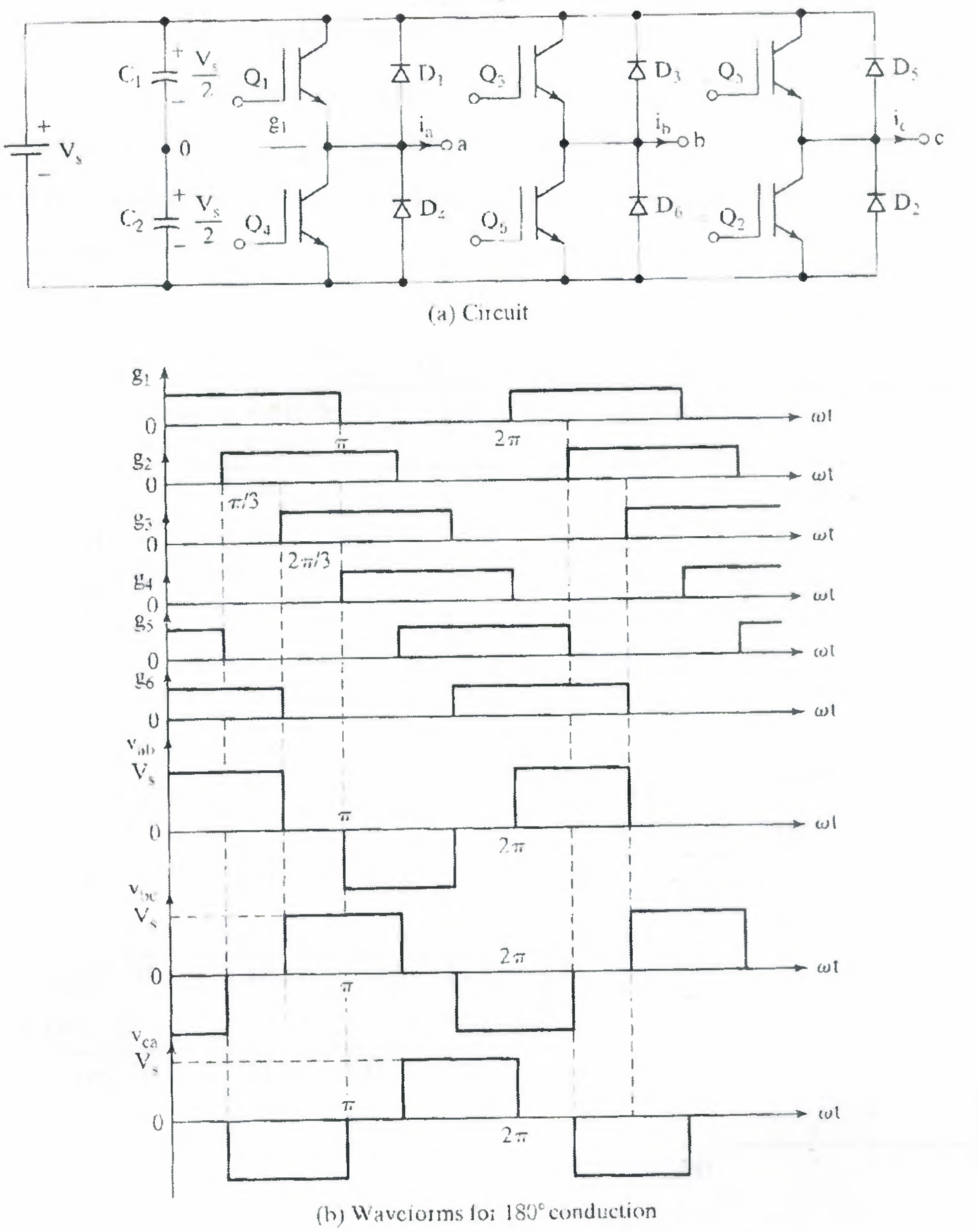


Figure 3.12 Three-phase inverter formed by three single-phase inverter
(a) Schematic (b) Circuit diagram



(a) Circuit (b) Waveforms for 180° conduction

Figure 3.13 Three-phase bridge inverter.

Table 3.2 shows eight valid switch states. Transistors Q_1, Q_6 act as the switching devices S_1, S_6 respectively. If two switches: one upper and one lower conduct at the same time such that output voltage is $\pm V_s$, the switch state is 1, whereas if these switches are off at the same time that the output voltage is 0. States 1 to 6 produce nonzero output voltages. States 7 and 8 produces zero line voltages and the line currents freewheel through either the upper or the lower freewheeling diodes. the inverters move from one state to another in order to generate the voltage waveform.

For a delta connected load, the phase currents can be obtained directly from the line to line voltages. Once the phase currents are known, the line currents can be determined. For a Y-connected load, the line-to-neutral voltages must be determined to find the line (or phase) currents.

Table 3.2 Switch States for Three-Phase Voltage Source Inverter (VSI)

State	**State No.**	**Switch States**	V_{ab}	V_{bc}	V_{ca}	**Space Vector**
S_1, S_2, S_6 are on & S_3, S_4, S_5 are off	1	100	V_S	0	$-V_S$	V_1=1+j0.57= $2/\sqrt{3}\angle 30°$
S_1, S_2, S_3,are on & S_4, S_5, S_6 are off	2	110	0	V_S	$-V_S$	V_2=j1.55= $2/\sqrt{3}\angle 90°$
S_2, S_3, S_4 are on & S_5, S_6, S_1 are off	3	010	$-V_S$	V_S	0	V_3=1+j0.577 $=2/\sqrt{3}\angle 150°$
S_3, S_4, S_5 are on & S_6, S_1, S_2 are off	4	011	$-V_S$	0	V_S	V_4= -1-.j577 $=2/\sqrt{3}\angle 210°$
S_1, S_2, S_3 are off & S_4, S_5, S_6 are on	5	001	0	$-V_S$	V_S	V_5=-j1.55= $2/\sqrt{3}\angle 270°$
S_6, S_1, S_5 are on & S_4, S_3, S_2 are off	6	101	V_S	$-V_S$	0	V_6=1-j0.57= $2/\sqrt{3}\angle 210°$
S_1, S_3, S_5 are on & S_6, S_2, S_4 are off	7	111	0	0	0	V_7=0
S_2, S_4, S_6 are on & S_1, S_3, S_5 are off	8	000	0	0	0	V_0=0

120-Degree Conduction: In this type of control, each transistor conducts for $120°$. Only two transistors remain on at any instant of time. The conduction sequence of transistors is 61, 12, 23, 34, 45, 56, and 61. There are three modes of operation in one half cycle and the equivalent circuits and their output across the load is depicted in the figure 3.14

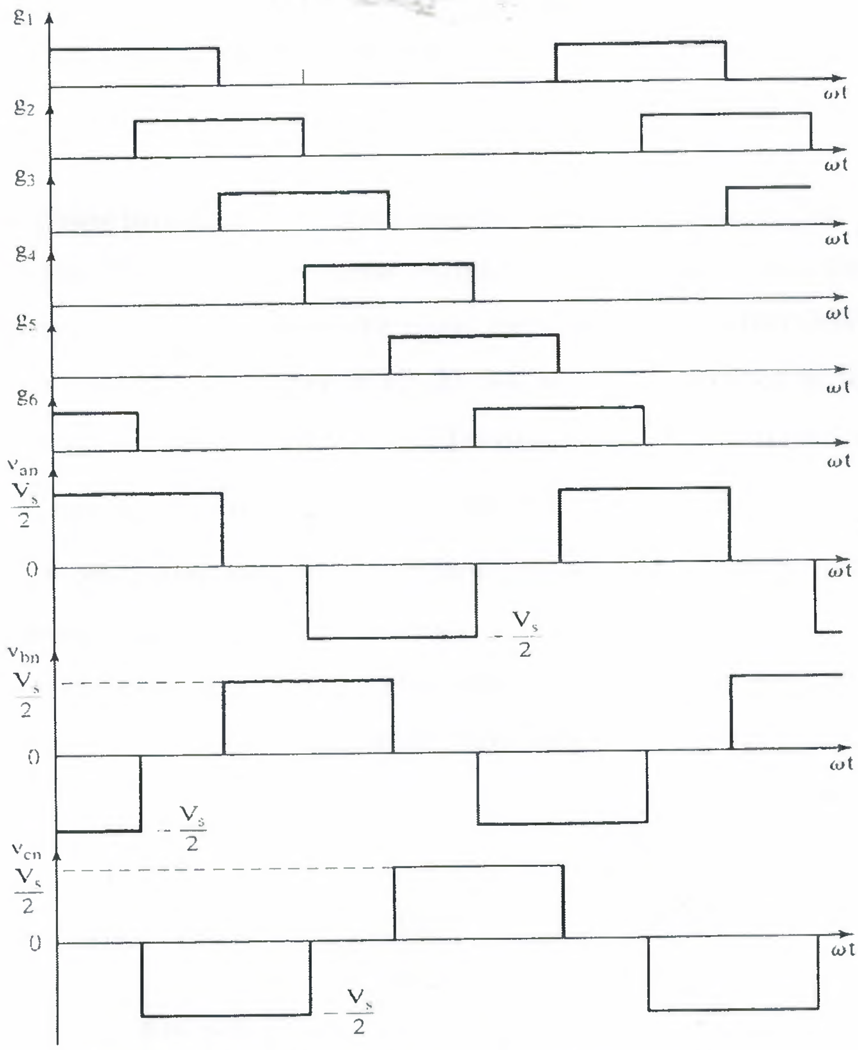


Figure 3.14 Gating signals for120°conduction

3.6 Current-Source Inverters

In current-source inverters (CSI), the input behaves as a current source. The output current is maintained constant irrespective of the load on the inverter and the output voltage is forced to change.

Or, inverters can be defined as:

The phase control is made to function in such a way that DC link current is maintained constant and equal to a reference value provided to controller. So, the inverters act as an AC source.

The advantages of the CSI are.

1) The input dc current is controlled and limited, misfiring of switching devices or short circuit, would not be a serious problem.
2) The peak current of power devices is limited

3) The commutation circuits for thyristors are simpler
4) It has the ability to handle reactive or regenerative load without free wheeling diodes.

3.6.1 Single-phase inverters: The circuit diagram of a single-phase inverter is shown in the figure 3.15a. There is a continuous current flow from the source, therefore two switches always conduct; one from the upper switches and the other from the lower switches. The conduction sequence is 12, 23, 34, and 41 as depicted in figure 3.15b. The switch states are shown in table 3.3. Transistors Q_1, Q_4 in figure 3.15a act as switching devices S_1, S_4 respectively. If two switches, one upper and one lower conduct at the same time such that the output current is $\pm I_L$, the switch state is 1; whereas if these switches are off at the same time, the switch state is 0. The output current waveform is shown in figure 3.15c. The diodes in series with the transistors are required to block the reverse voltages on the transistors.

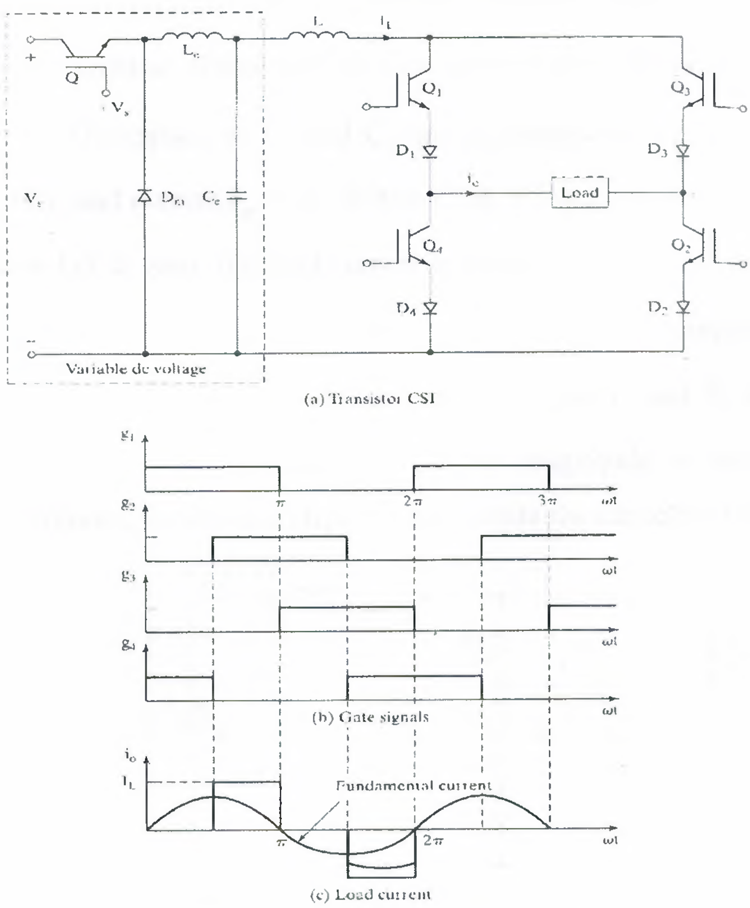


Figure 3.15: Single-phase current source
(a)Transistor CSI (b) Gate signal (c) Load current

When two devices in different arms conduct, the source current I_L flows through the load. When two devices in the same arm conduct, the source current is bypassed from the load. The load current can be expressed as

$$i_0 = \sum_{n=1,3,5,,,,}^{\infty} \frac{4I_L}{n\pi} Sin\frac{n\delta}{2} Sinn(\omega t) \tag{3.17}$$

Table 3.3 Switch States for a Full-Bridge Single-Phase Current Source Inverter (CSI)

State	State No.	Switch State S_1, S_2, S_3, S_4	i_0	Components conducting
S_1, S_2 are on & S_4, S_3 are off	1	1100	I_L	S_1 & S_2, D_1 & D_2
S_3, S_4 are on & S_1, S_2 are off	2	0011	$-I_L$	S_3 & S_4, D_3 & D_4
S_1, S_4 are on & S_3, S_2 are off	3	1001	0	S_1 & S_4, D_1 & D_4
S_3, S_2 are on & S_1, S_4 are off	4	0110	0	S_3 & S_2, D_3 & D_2

Single-phase thyristor current source inverter: A current source inverter that utilizes capacitors to turn off switching devices such as thyristor is shown in the **figure 3.44.** When T_1 and T_2 are conducting and capacitors C_1 & C_2 are charged with polarity. Firing of thyristor T_3 and T_4 reverse biases thyristors T_1 and T_2. T_1 and T_2 are turned off by impulse commutation. The current now flows through T_3 C_1 D_1, load, and D_2 C_2 T_4. The capacitors C_1 and C_2 are discharged and recharged at a constant rate determined by load current $I_m = I_L$. When C_1 & C_2 are charged to the load voltage and their currents fall to zero, the load current is transferred from diode D_1 to D_3 and D_2 to D_4. D_1 and D_2 are turned off when the load current is completely reversed. The capacitor is now ready to turn off T_3 and T_4 if thyristor T_1 and T_2 are fired in next half cycle. The commutation time depends on the magnitude of load current and load voltage. The diodes, as shown in figure 3.16, isolate the capacitor from the load voltage.

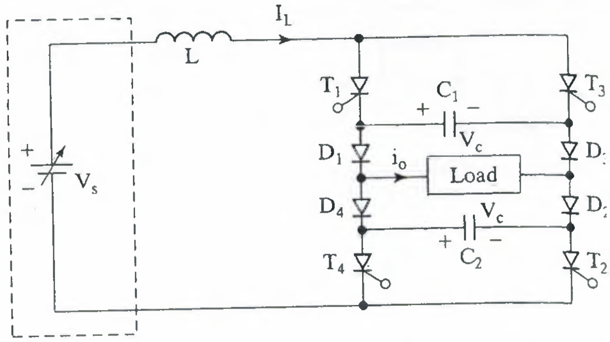


Figure 3.16: Single-phase thyristor current-source inverter.

3.7 Three-phase Current Source Inverters

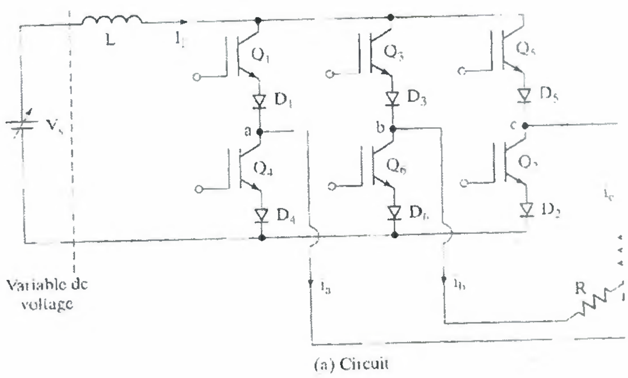
Figure 3.17a shows the circuit diagram of a three-phase current source inverter. The waveforms for gating signals and line currents for Y-connected load are shown in figure 3.17b. At any instant, only two thyristor conducts at the same time. Each device conducts for 120°. The instantaneous currents for phase a of a Y-connected load can be expressed as

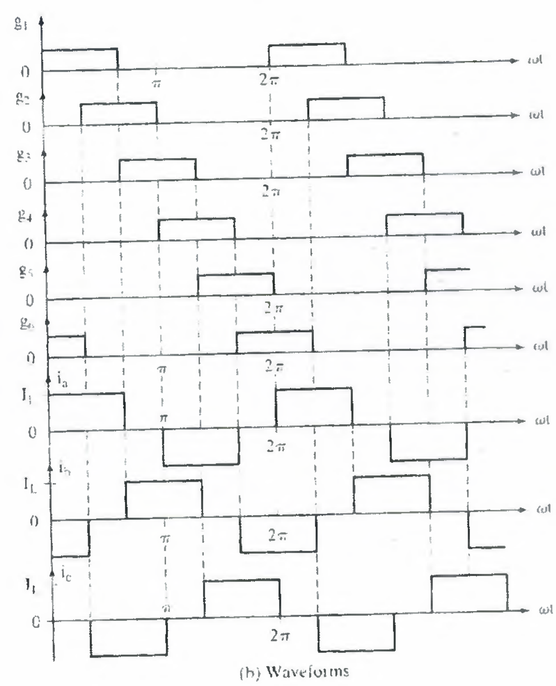
$$i_0 = \sum_{n=1,3,5,,,}^{\infty} \frac{4I_L}{n\pi} Sin\frac{n\pi}{3} Sinn(\omega t + \frac{\pi}{6}) \qquad (3.18)$$

The instantaneous currents for phase a of a delta-connected load is given by

$$i_0 = \sum_{n=1,3,5,,,}^{\infty} \frac{4I_L}{\sqrt{3}n\pi} Sin\frac{n\pi}{3} Sin(n\omega t) \qquad (3.19)$$

(a) Circuit





(b) Waveforms

Figure 3.17 Three-phase current source transistor inverter.

3.8 CSI vs VSI

The CSI is a dual of a VSI. The line-to-line voltage is similar in shape to the line current of CSI. In a VSI, the load current depends on the load impedance, whereas load voltage in a CSI depends on the load impedance. For this reason, diodes are connected in series with switching devices to protect them from transient voltages due to load current switching.

A CSI requires a relatively larger reactive to exhibit current-source haracteristics and an extra converter stage to control the current. The dynamic response is slower. Due to current transfer from one pair of switches to another, an output filter is required to suppress the output voltage spikes.

3.9 Summery

Converters are used in order to change or transfer the energy from one form into another. For this purpose semiconductor devices are used. In low power applications, single phase converters are being used, e.g. the half wave rectifier which is the simplest power electronic circuit that is used in low-cost power supplies for electronics like radio. The performance of a full wave converter is significantly improved compared with that of a half –wave. An inductive load can make the load current continuous

An ac output voltage can be obtained by alternatively connecting the positive and negative terminals of the dc source across the load by turning on and off the switching devices accordingly.

Three-phase converters are normally used for high power applications, like in industrial applications. The phase-controlled converters are simple and less expensive; and the efficiency is high.

CONCLUSION

The design of power electronics circuit requires designing the power and control circuits. BJTs, MOSFETs, SITs, IGBTs, and COOLMOS are the types of power transistors; all of them have turn-on and turn-on characteristics. BJTs are current controlled devices whereas MOSFETs, IGCTs COOLMOS are voltage source devices. There are 13 types of thyristors only 6 of them, GTOs, SITHs, MTOs, ETOs, IGCTs, and MCTs, are gate turn-off devices. Each type has advantages and disadvantages.

Converters are used in order to change or transfer the energy from one form into another. For this purpose semiconductor devices are used. In low power applications, single phase converters are being used. Three-phase converters are used for high power applications, like in industrial applications. The phase-controlled converters are simple and less expensive; and the efficiency is more than 95 %.

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