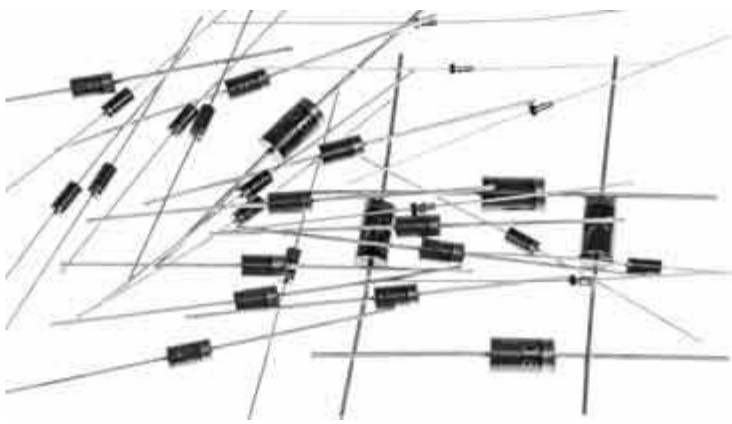
Unit V: Power Converters

PN Junction Diode

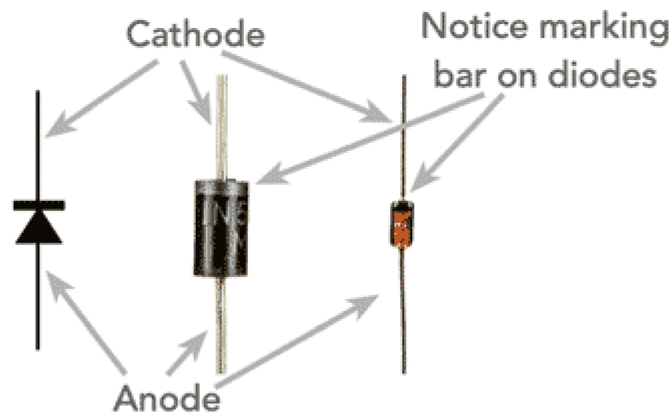
The PN junction diode is the basic semiconductor diode. It is used for many forms of rectification for current levels both large and small, as well as high and low voltage levels, and it finds many uses in all manner of electronic circuits.

The PN junction has the very useful property that electrons are only able to flow in one direction. As current consists of a flow of electrons, this means that current is allowed to flow only in one direction across the structure, but it is stopped from flowing in the other direction across the junction.
PN junction diodes can be obtained in a number of semiconductor materials - the earliest diodes tended to be made from germanium, but most of them today are silicon diodes.
The diode is simple in its basic concept, being formed from the junction of N-type and P-type materials, although in reality the manufacture and theory of operation are more complex.



Diode circuit symbol and polarity

Like any diode, the PN junction diode has two connections or electrodes. This gives it its name: "di-" meaning two and "-ode" as a shortening of electrode.
One electrode is termed the anode and the other is termed the cathode. For a current to flow across the PN diode junction it must be forward biased. Under these conditions conventional current flows from the anode to the cathode, but not the other way around.



Diode circuit symbol and physical diode orientation

It is easy to determine the polarity of many wired diodes. The "bar" on the circuit symbol corresponds to the cathode of the diode and this is often marked by a white line around the circumference of the actual diode.
When a PN junction diode is forward biased, the anode is positive with respect to the cathode, and conversely, when reverse biased the cathode is positive with respect to the anode.

Voltage polarities for PN junction diode operation
This means that when a diode is used in a circuit like a rectifier, the cathode is provides the positive output - the anode still remaining more positive as shown in the circuit below.

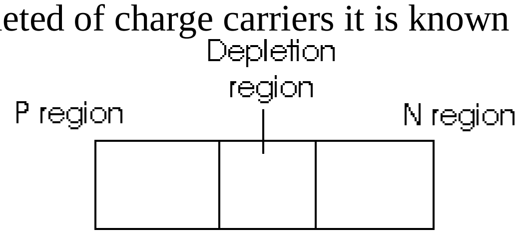
Diode rectifier showing the voltage polarities
Polarity on diode is for forward biased / conduction condition
This circuit shows how the anode of the diode is positive with respect to cathode and the cathode is connected to the output which is positive with respect to the zero volt line. In this way the voltage polarities around the circuit are maintained.

Development of the PN junction diode
The PN junction is one of the most important structures in today's electronics scene. It forms the basis of today's semiconductor technology, and was the first semiconductor device to be used. The first semiconductor diode to be used was the Cat's Whisker wireless detector used in early wireless sets. It consisted of a wire placed onto a material that was effectively a semiconductor. The point where the wire met the semiconductor then formed a small PN junction and this detected the radio signals. It was actually a form of Schottky diode, but nevertheless the earliest form of PN junction.

The diode or PN junction was the first form of semiconductor device to be investigated in the early 1940s when the first real research was undertaken into semiconductor technology. It was found that small point contact diodes were able to rectify some of the microwave frequencies used in early radar systems and as a result they soon found many uses.
Today, the PN junction has undergone a significant amount of development. Many varieties of diode are in use in a variety of applications. In addition to this, the PN junction forms the basis of much of today's semiconductor technology where it is used in transistors, FETs, and many types of integrated circuit.
The PN junction is found in many semiconductor devices today including semiconductor diodes, the bipolar transistor, junction FETs, diac, thyristor and the triac - it forms the basis of a huge amount of today's semiconductor technology.

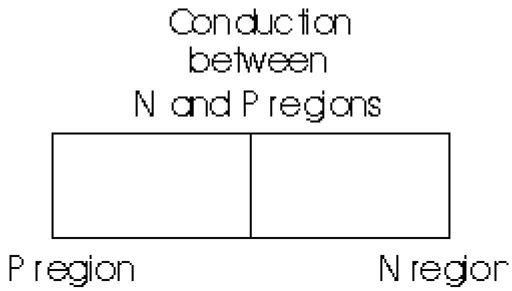
PN Junction

A PN junction is typically made from a single piece of semiconductor that has two differing areas: one is made to be P-type and the other N-type.
Accordingly the different areas of the semiconductor have different properties. The N-type semiconductor has an excess of electrons whilst the P-type has an excess of holes.
The diode can be thought of consisting of the two areas being brought into intimate contact with each other.
When this occurs the holes diffuse into the N-type area and a similar process occurs for the P-type material.
When this diffusion occurs, the flow of charges sets up an electric field that starts to hinder the flow of further charge and shortly and equilibrium state is reached and no further flow of charge occurs.
Where the two areas meet and at equilibrium there are no free holes or electrons. This means that there are no available charge carries in this region. In view of the fact that this area is depleted of charge carriers it is known as the depletion region.



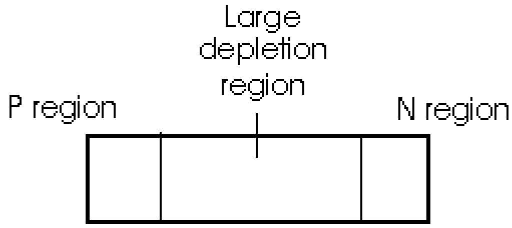
The semiconductor diode PN junction with no bias applied

The depletion region is very thin - often only few thousandths of a millimetre - but this is enough to prevent current flowing in the normal way. However it is found that different effects are noticed dependent upon the way in which the voltage is applied to the junction.



The semiconductor diode PN junction with forward bias

- ***Current Flow*** - If the voltage is applied such that the P type area becomes positive and the N type becomes negative, holes are attracted towards the negative voltage and are assisted to jump across the depletion layer. Similarly electrons move towards the positive voltage and jump the depletion layer. Even though the holes and electrons are moving in opposite directions, they carry opposite charges and as a result they represent a current flow in the same direction.
- ***No current flow*** - If a voltage is applied to the PN junction in the opposite sense no current flows. The reason for this is that the holes are attracted towards the negative potential that is applied to the P type region. Similarly the electrons are attracted towards the positive potential which is applied to the N type region. In other words the holes and electrons are attracted away from the junction itself and the depletion region increases in width. Accordingly no current flows across the PN junction.

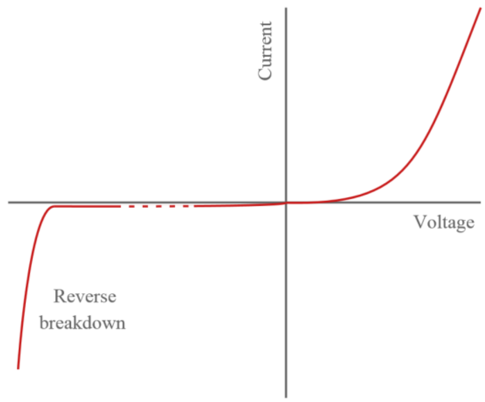


The semiconductor diode PN junction with reverse bias

PN junction characteristics

While the PN junction provides an excellent rectifying action, it is not a perfect diode having infinite resistance in the reverse direction and zero resistance in the forward direction. In order that the PN junction can be used, it is necessary to know a little about its properties and characteristics with forward and reverse bias.

Looking at the characteristic plot of the PN junction, it can be seen that in the forward direction (forward biased) it can be seen that very little current flows until a certain voltage has been reached. This represents the work that is required to enable the charge carriers to cross the depletion layer. This voltage varies from one type of semiconductor to another. For germanium it is around 0.2 or 0.3 volts and for silicon it is about 0.6 volts. It is possible to measure a voltage of about 0.6 volts across most small current diodes when they are forward biased as most diodes are silicon. A small number will show a lower voltage and are likely to be germanium. Power rectifier diodes normally have a larger voltage across them but this is partly due to the fact that there is some resistance in the silicon, and partly due to the fact that higher currents are flowing and they are operating further up the curve.



PN diode IV characteristic

In the reverse direction, a perfect diode would not allow any current to flow. In reality a small amount of current does flow, although this is likely to be very small and in the region of pico amps or microamps. It has been exaggerated on the diagram so that it can be seen. Although it is normally very low, the performance of any diode will degrade at higher temperatures and it is also found that germanium is not as good as silicon.

These reverse current results from what are called minority carriers. These are a very small number of electrons found in a P type region or holes in an N type region. Early semiconductors has relatively high levels of minority carriers, but now that the manufacture of semiconductor materials is very much better the number of minority carriers is much reduced as are the levels of reverse currents.

The basic diode PN junction is used throughout the whole of the electronics industry today. Even it its basic form as a diode, it is used in enormous quantities, but beyond that the PN junction forms the bedrock of much of today's high-tech transistors and integrated circuits. Without the PN junction, life today would be very different, and electronics would be a very different scene.

Bipolar Junction Transistor

Transistors are three terminal active devices made from different semiconductor materials that can act as either an insulator or a conductor by the application of a small signal voltage. The transistor's ability to change between these two states enables it to have two basic functions: "switching" (digital electronics) or "amplification" (analogue electronics). Then bipolar transistors have the ability to operate within three different regions:

- Active Region – the transistor operates as an amplifier and $I_c = \beta * I_b$
- Saturation – the transistor is "Fully-ON" operating as a switch and $I_c = I(saturation)$
- Cut-off – the transistor is "Fully-OFF" operating as a switch and $I_c = 0$

A Typical Bipolar Transistor

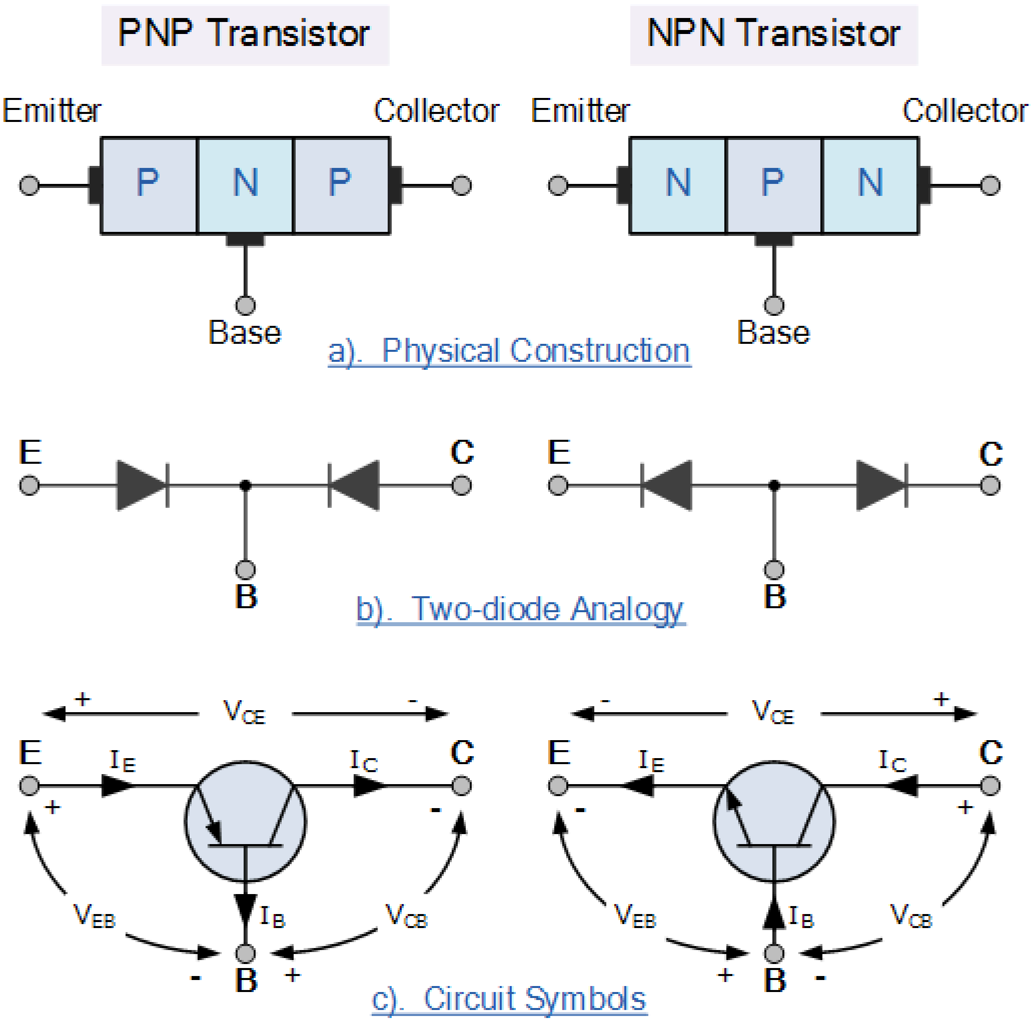
The word Transistor is a combination of the two words Transfer of Resistor which describes their mode of operation way back in their early days of electronics development. There are two basic types of bipolar transistor construction, PNP and NPN, which basically describes the physical arrangement of the P-type and N-type semiconductor materials from which they are made.

The **Bipolar Transistor** basic construction consists of two PN-junctions producing three connecting terminals with each terminal being given a name to identify it from the other two. These three terminals are known and labelled as the Emitter (E), the Base (B) and the Collector (C) respectively.

Bipolar Transistors are current regulating devices that control the amount of current flowing through them from the Emitter to the Collector terminals in proportion to the amount of biasing voltage applied to their base terminal, thus acting like a current-controlled switch. As a small current flowing into the base terminal controls a much larger collector current forming the basis of transistor action.

The principle of operation of the two transistor types PNP and NPN, is exactly the same the only difference being in their biasing and the polarity of the power supply for each type.

Bipolar Transistor Construction



a). Physical Construction
b). Two-diode Analogy
c). Circuit Symbols

The construction and circuit symbols for both the PNP and NPN bipolar transistor are given above with the arrow in the circuit symbol always showing the direction of "conventional current flow" between the base terminal and its emitter terminal. The direction of the arrow always points from the positive P-type region to the negative N-type region for both transistor types, exactly the same as for the standard diode symbol.

Bipolar Transistor Configurations

As the **Bipolar Transistor** is a three terminal device, there are basically three possible ways to connect it within an electronic circuit with one terminal being common to both the input and output. Each method of connection responding differently to its input signal within a circuit as the static characteristics of the transistor vary with each circuit arrangement.

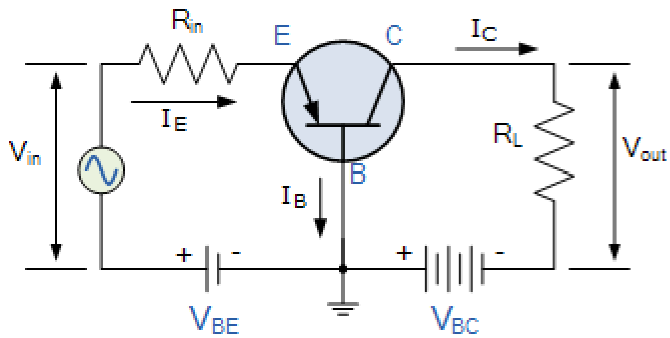
- Common Base Configuration – has Voltage Gain but no Current Gain.
- Common Emitter Configuration – has both Current and Voltage Gain.
- Common Collector Configuration – has Current Gain but no Voltage Gain.

The Common Base (CB) Configuration

As its name suggests, in the **Common Base** or grounded base configuration, the BASE connection is common to both the input signal AND the output signal. The input signal is applied between the transistors base and the emitter terminals, while the corresponding output signal is taken from between the base and the collector terminals as shown. The base terminal is grounded or can be connected to some fixed reference voltage point.

The input current flowing into the emitter is quite large as its the sum of both the base current and collector current respectively therefore, the collector current output is less than the emitter current input resulting in a current gain for this type of circuit of "1" (unity) or less, in other words the common base configuration "attenuates" the input signal.

The Common Base Transistor Circuit



This type of amplifier configuration is a non-inverting voltage amplifier circuit, in that the signal voltages Vin and Vout are "in-phase". This type of transistor arrangement is not very common due to its unusually high voltage gain characteristics. Its input characteristics represent that of a forward biased diode while the output characteristics represent that of an illuminated photo-diode.

Also this type of bipolar transistor configuration has a high ratio of output to input resistance or more importantly "load" resistance (RL) to "input" resistance (Rin) giving it a value of "Resistance Gain". Then the voltage gain (Av) for a common base configuration is therefore given as:

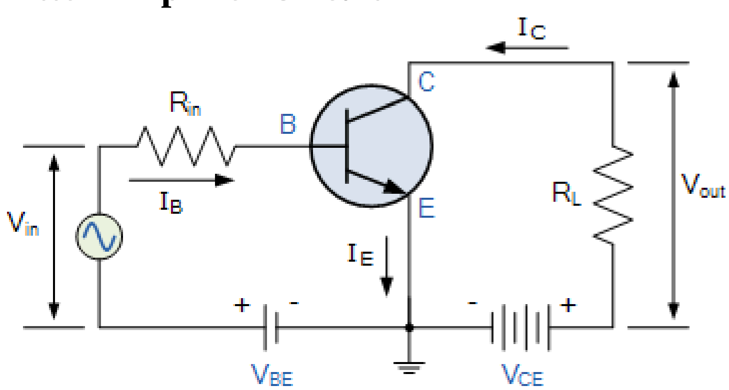
Common Base Voltage Gain

$$\mathbf{Av} = \frac{Vout}{Vin} = \frac{I_c R_L}{I_E R_{IN}}$$

Where: Ic/Ie is the current gain, alpha (α) and R_L/R_{in} is the resistance gain.
The common base circuit is generally only used in single stage amplifier circuits such as microphone pre-amplifier or radio frequency (R_f) amplifiers due to its very good high frequency response.

The Common Emitter (CE) Configuration

In the **Common Emitter** or grounded emitter configuration, the input signal is applied between the base and the emitter, while the output is taken from between the collector and the emitter as shown. This type of configuration is the most commonly used circuit for transistor based amplifiers and which represents the "normal" method of bipolar transistor connection.
The common emitter amplifier configuration produces the highest current and power gain of all the three bipolar transistor configurations. This is mainly because the input impedance is LOW as it is connected to a forward biased PN-junction, while the output impedance is HIGH as it is taken from a reverse biased PN-junction.
The Common Emitter Amplifier Circuit



In this type of configuration, the current flowing out of the transistor must be equal to the currents flowing into the transistor as the emitter current is given as Ie = Ic + Ib.
As the load resistance (R_L) is connected in series with the collector, the current gain of the common emitter transistor configuration is quite large as it is the ratio of Ic/Ib.
A transistors current gain is given the Greek symbol of Beta, (β).
As the emitter current for a common emitter configuration is defined as Ie = Ic + Ib, the ratio of Ic/Ie is called Alpha, given the Greek symbol of α. Note: that the value of Alpha will always be less than unity.

Since the electrical relationship between these three currents, Ib, Ic and Ie is determined by the physical construction of the transistor itself, any small change in the base current (Ib), will result in a much larger change in the collector current (Ic).

Then, small changes in current flowing in the base will thus control the current in the emitter-collector circuit. Typically, Beta has a value between 20 and 200 for most general purpose transistors. So if a transistor has a Beta value of say 100, then one electron will flow from the base terminal for every 100 electrons flowing between the emitter-collector terminal.

By combining the expressions for both Alpha, α and Beta, β the mathematical relationship between these parameters and therefore the current gain of the transistor can be given as:

$$\text{Alpha}, (\alpha) = \frac{I_C}{I_E} \quad \text{and} \quad \text{Beta}, (\beta) = \frac{I_C}{I_B}$$

$$\therefore I_C = \alpha.I_E = \beta.I_B$$

$$\text{as:} \quad \alpha = \frac{\beta}{\beta + 1} \qquad \beta = \frac{\alpha}{1 - \alpha}$$

$$I_E = I_C + I_B$$

Where: "Ic" is the current flowing into the collector terminal, "Ib" is the current flowing into the base terminal and "Ie" is the current flowing out of the emitter terminal.

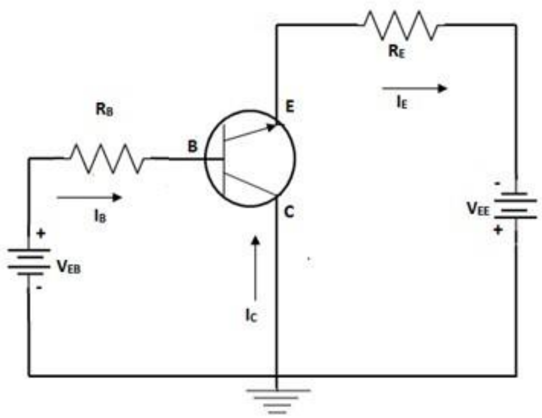
Then to summarise a little. This type of bipolar transistor configuration has a greater input impedance, current and power gain than that of the common base configuration but its voltage gain is much lower. The common emitter configuration is an inverting amplifier circuit. This means that the resulting output signal has a 180^{o} phase-shift with regards to the input voltage signal.

The Common Collector (CC) Configuration

In the **Common Collector** or grounded collector configuration, the collector is now common through the supply. The input signal is connected directly to the base, while the output is taken from the emitter load as shown. This type of configuration is commonly known as a **Voltage Follower** or **Emitter Follower** circuit.

The common collector or emitter follower configuration is very useful for impedance matching applications because of the very high input impedance, in the region of hundreds of thousands of Ohms while having relatively low output impedance.

The Common Collector Transistor Circuit



The common emitter configuration has a current gain approximately equal to the β value of the transistor itself. In the common collector configuration the load resistance is situated in series with the emitter so its current is equal to that of the emitter current.

As the emitter current is the combination of the collector AND the base current combined, the load resistance in this type of transistor configuration also has both the collector current and the input current of the base flowing through it. Then the current gain of the circuit is given as:

The Common Collector Current Gain

$$I_E = I_C + I_B$$

$$A_i = \frac{I_E}{I_B} = \frac{I_C + I_B}{I_B}$$

$$A_i = \frac{I_C}{I_B} + 1$$

$$Ai = \beta + 1$$

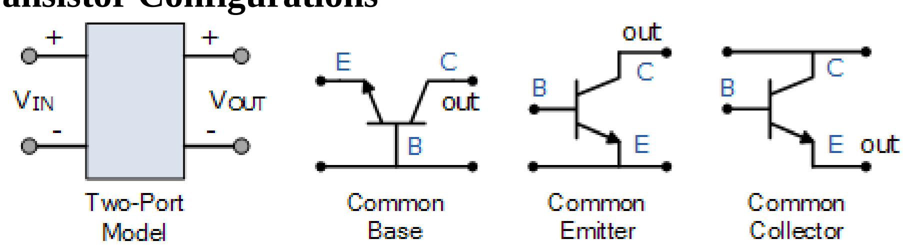
This type of bipolar transistor configuration is a non-inverting circuit in that the signal voltages of Vin and Vout are "in-phase". It has a voltage gain that is always less than "1" (unity). The load resistance of the common collector transistor receives

both the base and collector currents giving a large current gain (as with the common emitter configuration) therefore, providing good current amplification with very little voltage gain.
We can now summarize the various relationships between the transistors individual DC currents flowing through each leg and its DC current gains given above in the following table.

Relationship between DC Currents and Gains

$I_E = I_B + I_C$ $I_C = I_E - I_B$ $I_B = I_E - I_C$	$\alpha = \frac{I_C}{I_E} = \frac{\beta}{1+\beta}$ $\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$
$I_B = \frac{I_C}{\beta} = \frac{I_E}{1+\beta} = I_E(1-\alpha)$	
$I_C = \beta . I_B = \alpha . I_E$	$I_E = \frac{I_C}{\alpha} = I_B(1+\beta)$

Bipolar Transistor Summary
Then to summaries, the behavior of the bipolar transistor in each one of the above circuit configurations is very different and produces different circuit characteristics with regards to input impedance, output impedance and gain whether this is voltage gain, current gain or power gain and this is summarized in the table below.
Bipolar Transistor Configurations

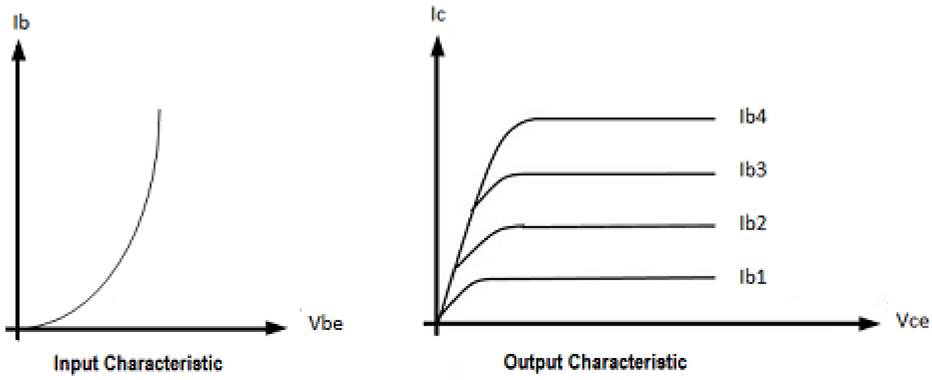


In the next tutorial about **Bipolar Transistors**, we will look at the NPN Transistor in more detail when used in the common emitter configuration as an amplifier as this

Prepared by: Mr Vishal Sharma
Asst. Prof. EE Dept., JECRC Jaipur

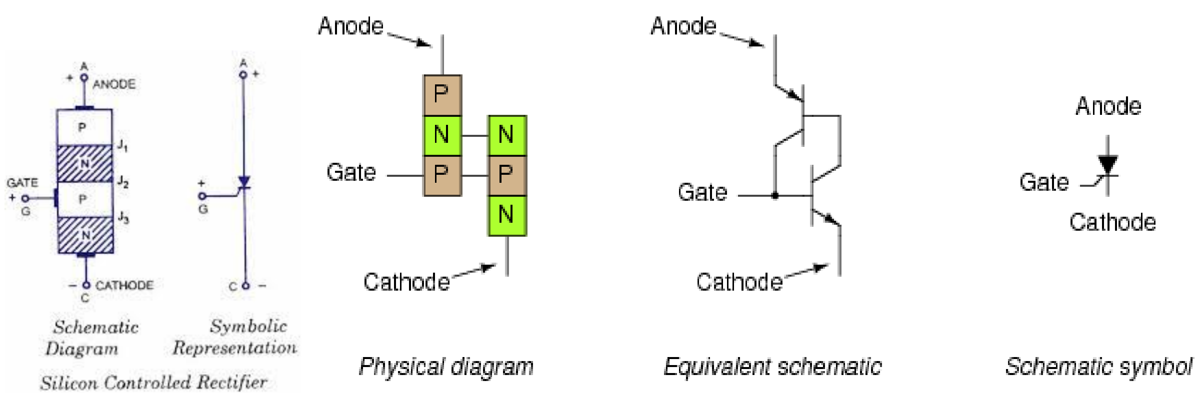
is the most widely used configuration due to its flexibility and high gain. We will also plot the output characteristics curves commonly associated with amplifier circuits as a function of the collector current to the base current.

BJT Characteristics



BJT characteristic curves

The Silicon-Controlled Rectifier (SCR)



The Silicon-Controlled Rectifier (SCR)

SCR Conduction

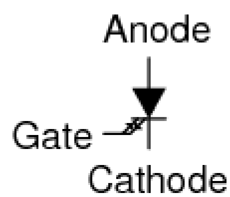
If an SCR's gate is left *floating* (disconnected), it behaves exactly as a Shockley diode. It may be latched by break over voltage or by exceeding the critical rate of voltage rise between anode and cathode, just as with the Shockley diode. Dropout is accomplished by reducing current until one or both internal transistors fall into cutoff mode, also like the Shockley diode. However, because the gate terminal connects directly to the base of the lower transistor, it may be used as an alternative means to latch the SCR. By applying a small voltage between gate and cathode, the lower transistor will be forced *on* by the resulting base current, which will cause the upper transistor to conduct, which then supplies the lower transistor's base with current so that it no longer needs to be activated by a gate voltage. The necessary gate current to initiate latch-up, of course, will be much lower than the current through the SCR from cathode to anode, so the SCR does achieve a measure of amplification.

Triggering/Firing

This method of securing SCR conduction is called *triggering or firing* and it is by far the most common way that SCRs are latched in actual practice. In fact, SCRs are usually chosen so that their break over voltage is far beyond the greatest voltage expected to be experienced from the power source so that it can be turned on *only* by an intentional voltage pulse applied to the gate.

Reverse Triggering

It should be mentioned that SCRs may *sometimes* be turned off by directly shorting their gate and cathode terminals together, or by "reverse-triggering" the gate with a negative voltage (in reference to the cathode), so that the lower transistor is forced into cutoff. I say this is "sometimes" possible because it involves shunting all of the upper transistor's collector current past the lower transistor's base. This current may be substantial, making triggered shut-off of an SCR difficult at best. A variation of the SCR, called a *Gate-Turn-Off* thyristor, or *GTO*, makes this task easier. But even with a GTO, the gate current required to turn it off may be as much as 20% of the anode (load) current! The schematic symbol for a GTO is shown in the following illustration:



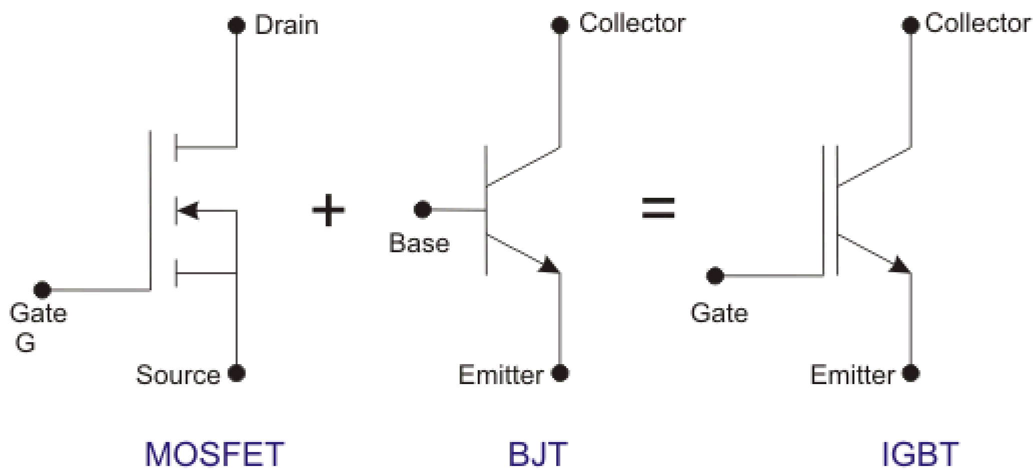
The Gate Turn-Off thyristor (GTO)

Insulated Gate Bipolar Transistor | IGBT

IGBT is a relatively new device in power electronics and before the advent of IGBT, Power MOSFETs and Power BJT were common in use in power electronic applications. Both of these devices possessed some advantages and simultaneously some disadvantages. On one hand, we had bad switching performance, low input impedance, secondary breakdown and current controlled Power BJT and on the other we had excellent conduction characteristics of it. Similarly, we had excellent switching characteristics, high input impedance, voltage controlled Power

MOSFETs, which also had bad conduction characteristics and problematic parasitic diode at higher ratings. Though the uni - polar nature of Power MOSFETs leads to low switching times, it also leads to high ON-state resistance as the voltage rating increases.

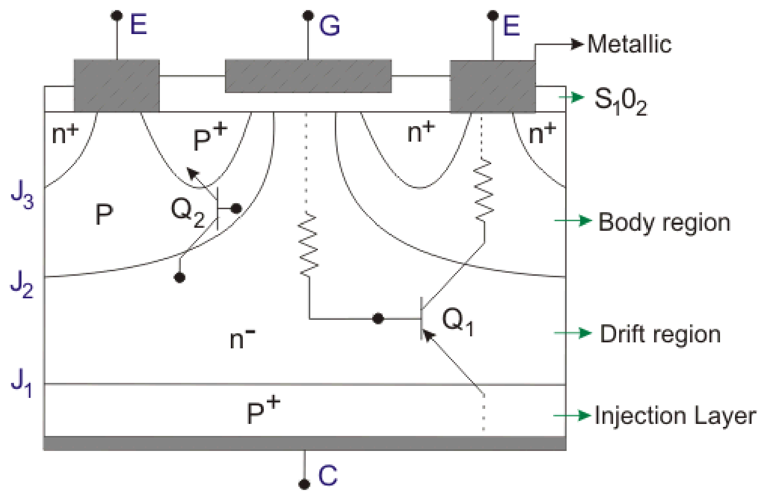
Thus the need was for such a device which had the goodness of both Power MOSFETs and Power BJT and this was when IGBT was introduced in around the early 1980s and became very popular among power electronic engineers because of its superior characteristics. IGBT has Power MOSFET like input characteristics and Power BJT like output characteristics and hence its symbol is also an amalgamation of the symbols of the two parent devices. The three terminals of IGBT are Gate, Collector and Emitter. The figure below shows the symbol of IGBT.



IGBT is known by various other names also, such as- Metal Oxide Insulated Gate Transistor (MOSIGT), Gain Modulated Field Effect Transistor (GEMFET), Conductively Modulated Field Effect Transistor (COMFET), Insulated Gate Transistor (IGT).

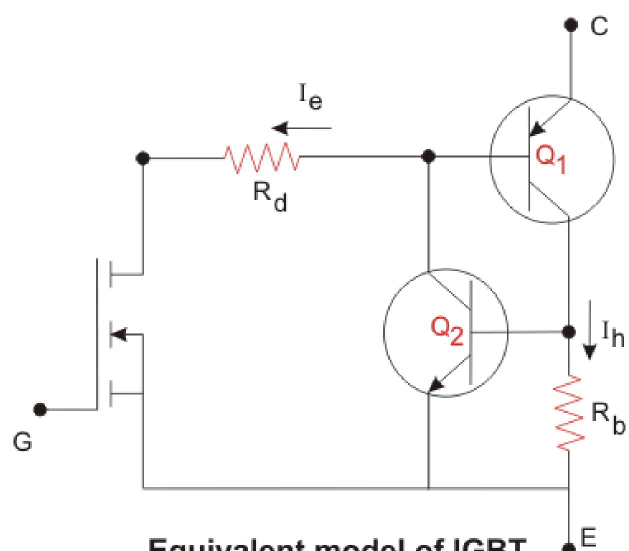
Structure of IGBT

The **structure of IGBT** is very much similar to that of PMOSFET, except one layer known as injection layer which is p^+ unlike n^+ substrate in PMOSFET. This injection layer is the key to the superior characteristics of IGBT. Other layers are called the drift and the body region. The two junctions are labeled J_1 and J_2. Figure below show the structure of n-channel IGBT.



Structure of IGBT

Upon careful observation of the structure, we'll find that there exists an n-channel MOSFET and two BJTs- Q_1 and Q_2 as shown in the figure. Q_1 is p^+n^-p BJT and Q_2 is n^-pn^+ BJT. R_d is the resistance offered by the drift region and R_b is the resistance offered by p body region. We can observe that the collector of Q_1 is same as base of Q_2 and collector of Q_2 is same as base of Q_1. Hence we can arrive at an equivalent circuit model of IGBT as shown in the figure below.



Equivalent model of IGBT

The two transistor back to back connection forms a parasitic thyristor as shown in the above figure.

N-channel IGBT turns ON when the collector is at a positive potential with respect to emitter and gate also at sufficient positive potential (>V_{GET}) with respect to emitted. This condition leads to the formation of an inversion layer just below the

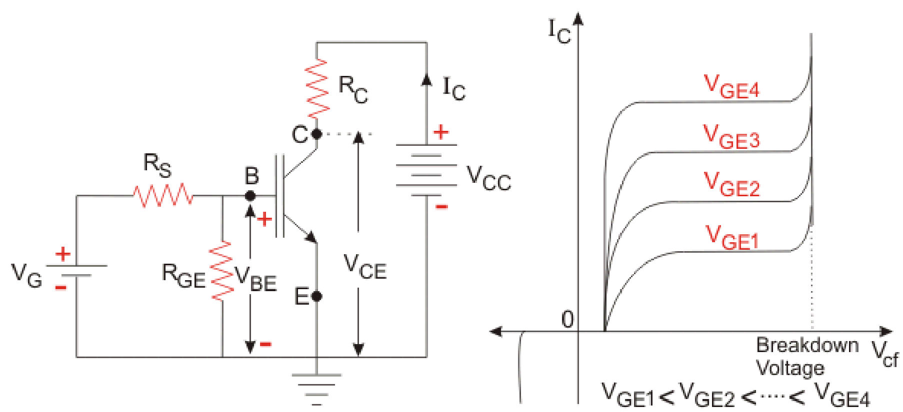
gate, leading to a channel formation and a current begins to flow from collector to emitter.
The collector current I_c in IGBT constitutes of two components- I_e and I_h. I_e is the current due to injected electrons flowing from collector to emitter through injection layer, drift layer and finally the channel formed. I_h is the hole current flowing from collector to emitter through Q_1 and body resistance R_b. Hence

$$I_c = I_e + I_h$$

Although I_h is almost negligible and hence $I_c \approx I_e$.

A peculiar phenomenon is observed in IGBT known as Latching up of IGBT. This occurs when collector current exceeds a certain threshold value (I_{CE}). In this the parasitic thyristor gets latched up and the gate terminal loses control over collector current and IGBT fails to turn off even when gate potential is reduced below V_{GET}. For turning OFF of IGBT now, we need typical commutation circuitry as in the case of forced commutation of thyristors. If the device is not turned off as soon as possible, it may get damaged.

Characteristics of IGBT
Static I-V Characteristics of IGBT
The figure below shows static i-v characteristics of an n-channel IGBT along with a circuit diagram with the parameters marked.



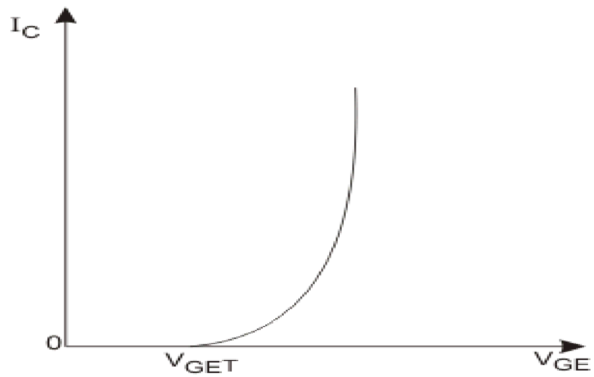
Circuit Diagram   Static I - V Characteristics

The graph is similar to that of a BJT except that the parameter which is kept constant for a plot is V_{GE} because IGBT is a voltage controlled device unlike BJT which is a current controlled device. When the device is in OFF mode (V_{CE} is positive and V_{GE}

$< V_{GET}$) the reverse voltage is blocked by J_2 and when it is reverse biased, i.e. V_{CE} is negative, J_1 blocks the voltage.

Transfer Characteristics of IGBT

Figure below shows the transfer characteristic of IGBT, which is exactly same as PMOSFET. The IGBT is in ON-state only after V_{GE} is greater than a threshold value V_{GET}.



Transfer Characteristics

Switching Characteristics of IGBT

Advantages and Disadvantages of IGBT

Advantages:-

- Lower gate drive requirements
- Low switching losses
- Small snubber circuitry requirements
- High input impedance
- Voltage controlled device
- Temperature coefficient of ON state resistance is positive and less than PMOSFET, hence less On-state voltage drop and power loss.
- Enhanced conduction due to bipolar nature
- Better Safe Operating Area

Disadvantages:-

- Cost
- Latching-up problem
- High turn off time compared to PMOSFET

Single Phase Rectifier

There are two major theories in rectification which are used to describe the nature of the output wave. They are;

1. Half-wave rectifier theory

2. Full-wave rectifier theory

HALF-WAVE RECTIFIER THEORY

In half wave rectifier, if we consider a simple sinusoidal AC voltage, either the negative half cycle or the positive half cycle of the signal is allowed to move past the rectifier circuit. Which will result in the output shown below.

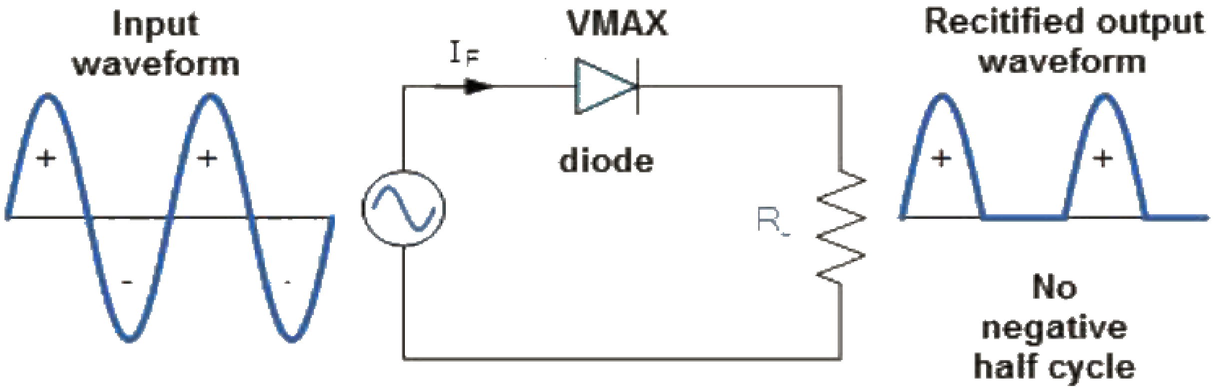


Figure 1 Half-wave rectification

FULL-WAVE RECTIFIER THEORY

In full wave rectifier, if we consider a simple sinusoidal a.c voltage, both the negative half cycle or the positive half cycle of the signal is allowed to move past the rectifier circuit with one of the halves flipped to the other halve such that we now have two positive or negatives halves following each other at the output.

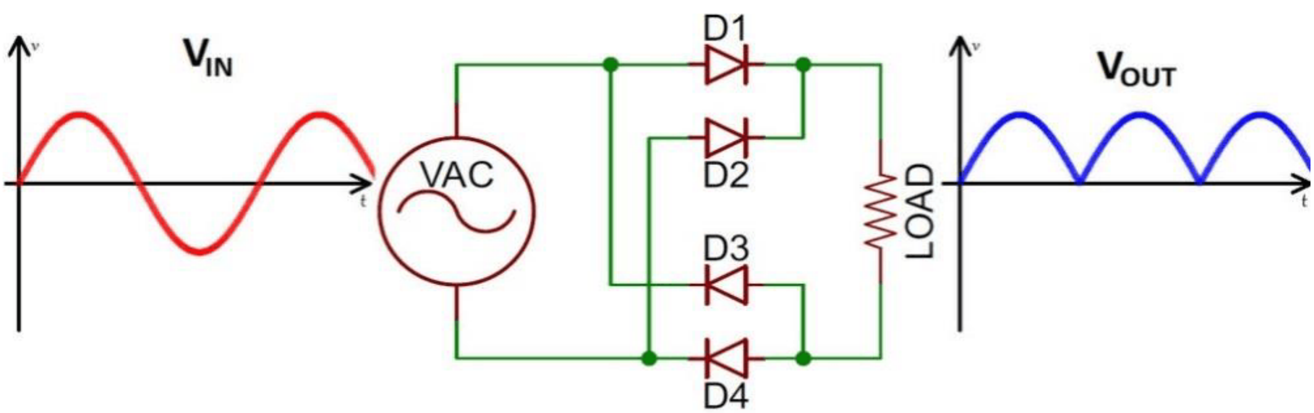


Figure 2 Full-wave rectification

TYPES OF RECTIFIERS

In the past, rectifiers are designed using vacuum tubes, anode plates and cathode plates but with the advent of semiconductor devices, rectifiers are designed using solid-state semiconductor components such as diodes and transistors. However, we will discuss briefly a classical rectifier, which was used before semiconductor devices became ubiquitous, it is called mercury-arc rectifier. Generally, there are seven types of rectifiers available in the market today, but we will only discuss three of them which are used mostly in DC power supplies for our electronic systems.

Types of Rectifiers are classified as follows;

1. Single(1) phase half wave rectifier
2. Single(1) phase full wave rectifier
3. Full wave bridge circuit
4. Three(3) phase half wave rectifier
5. Three(3) phase full wave rectifier

SINGLE PHASE HALF WAVE RECTIFIER

The circuit for this rectifier is shown in figure 4a, with a resistive load. The a.c voltage is supplied to the diode which is connected in series with a load RL.

Working Principle:

During the positive half-cycle, the input alternating current voltage, the diode is forward biased (ON) thus, it conducts. Which makes the current to pass through it. While during the negative half cycle, the diode will be reverse biased as such, it won't conduct, which means the negative half-cycle of the input voltage won't pass through it. The resulting output from the diode action will result in the output voltage shown in figure 4b.

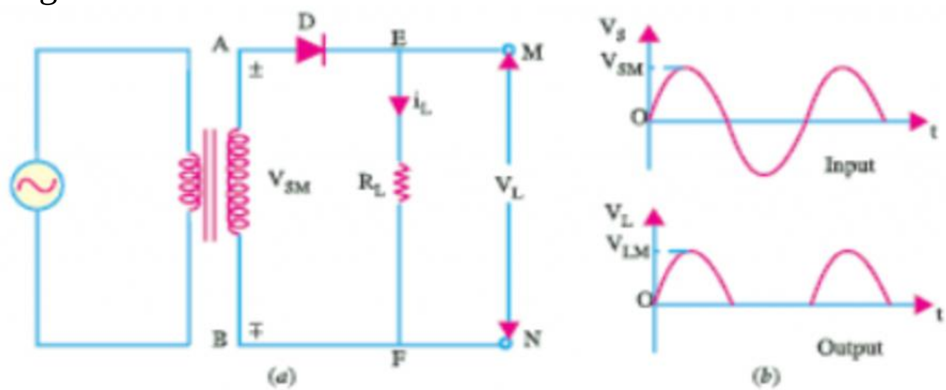


Figure 4 Single-phase half-wave rectifier

SINGLE PHASE FULL WAVE RECTIFIER

For the rectifier, two diodes work hand in hand to produce a full wave rectified input a.c voltage. Mostly, full wave rectifiers that use two diodes are always used with a center-tapped transformer. The circuit diagram is shown in figure 5a.

Working principle:

When the main supply is switched on, the ends of the transformer M and N oscillate between positive and negative half-cycle. During the positive half-cycle, the diode D1 will be forward biased which mean the positive side of the supply voltage will pass, while D2 will be reversed biased. Alternatively, during the negative half-cycle, the transformer terminal will M and N will have switched polarity making diode D2 forward biased which makes the negative component of the supply voltage to pass through it. From the figure 5b, we can observe that the frequency of the output voltage is twice the input voltage.

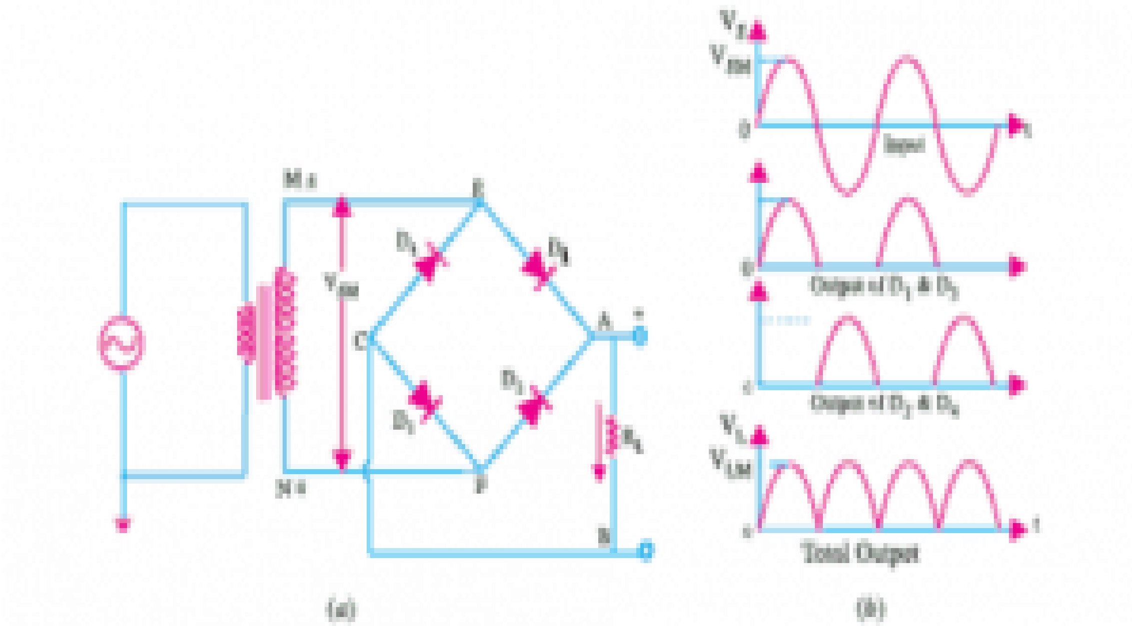


Figure 5 Single-phase full-wave rectifier

FULL-WAVE BRIDGE RECTIFIER

This standard packaged full wave rectifier is used in most DC power supplies. It consists of four diodes that switch ON or OFF depending on the current half-cycle of the supply alternating current (AC) voltage. The circuitry is shown in figure 6a. The transformer used in a full wave bridge rectifier is not center-tapped which makes more efficient than its 2-diodes counterpart. Mostly, it is found packaged in standard IC case with four terminals from figure 6c.

Working Principle

During the positive half-cycle at the terminal, M is positive while N is negative as shown in figure 6b, Diodes D1 and D2 are forward-biased (ON) which makes current to flow through them. Whereby, diodes D3 and D4 are reverse-biased which put them in, where this electricity is consumed, OFF state. Alternatively, in the negative half-cycle, M becomes negative while N is positive, this new arrangement makes diodes D3 and D4 forward-biased which makes them to conduct and current keeps flowing through the resistance RL n the same direction in both half-cycles of the input alternating current supply.

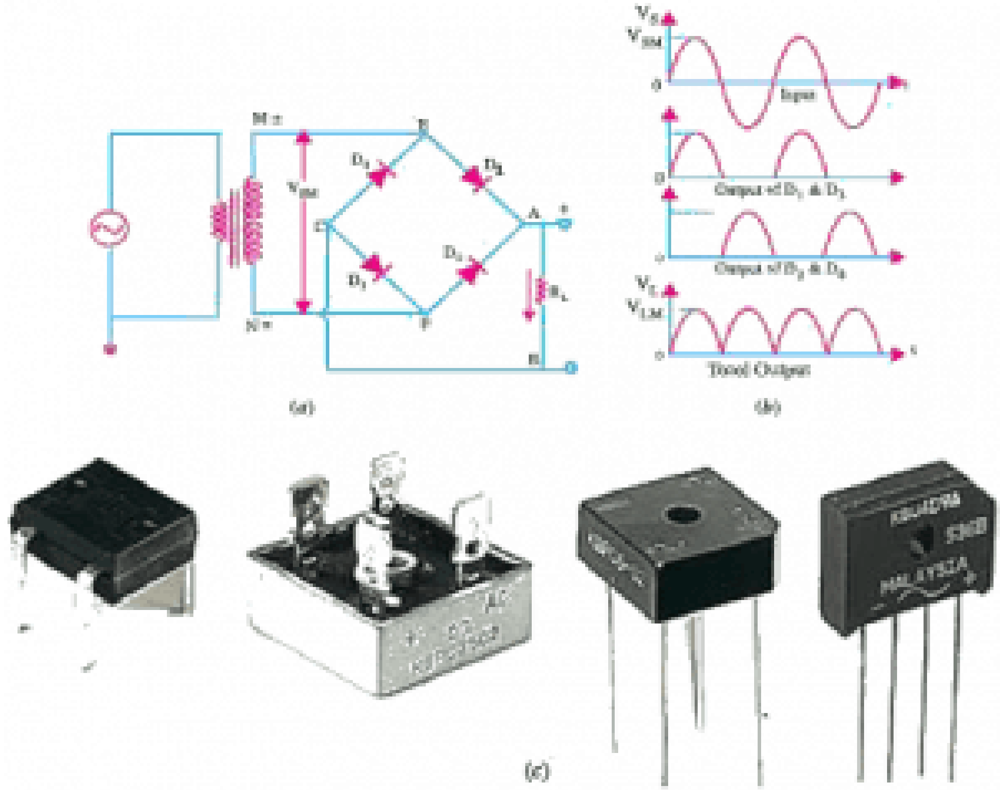


Figure 6 Full-wave bridge rectifier

APPLICATION OF RECTIFIERS

Rectifiers are applied mainly in DC power supply. Its main function in the power supply is to convert the incoming alternating current and voltage to direct current which is then filtered using a bank of capacitors and then regulated to, for example, 5V,9V, 12V and so on depending on the specification.

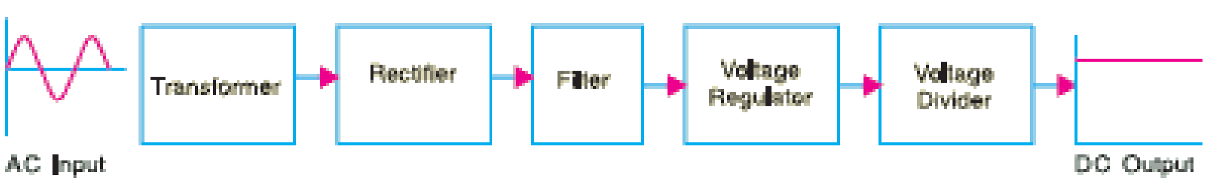


Figure 7 Power supply block diagram

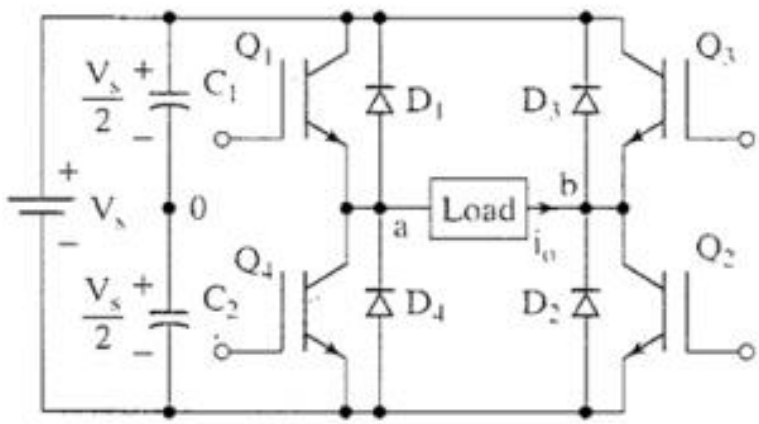
ADVANTAGES OF RECTIFIERS

1. With the advent of low-cost semiconductors in rectifiers, DC power supply has become cheaper

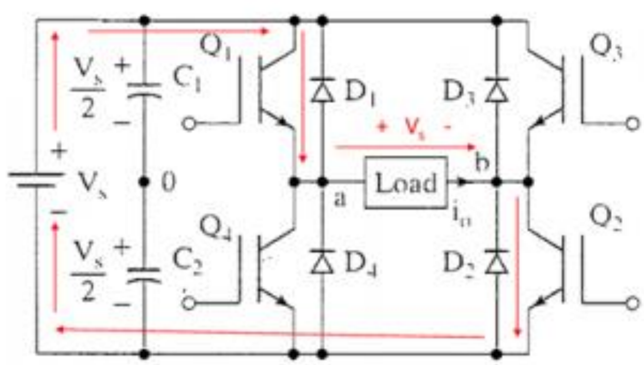
2. Rectifiers will help mitigate the usage of a center-tapped transformer which means more portable packaging
3. Rectifiers are suitable for high voltage and low voltage application
4. Rectifiers have less peak inverse voltage for each diode

Single Phase Full Bridge Inverter

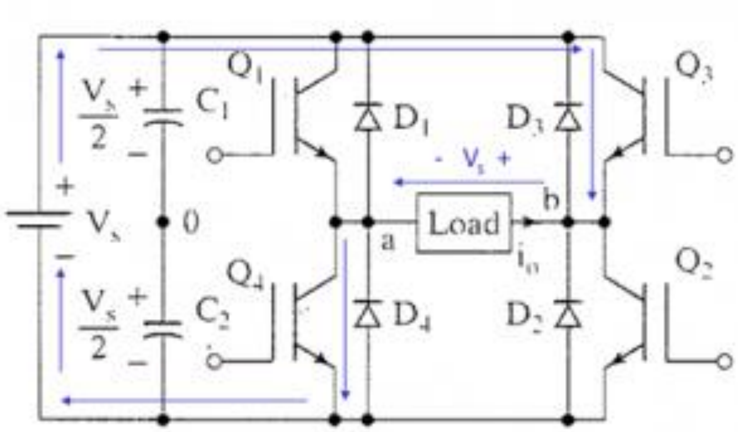
A single phase bridge DC-AC inverter is shown in Figure below. The analysis of the single phase DC-AC inverters is done taking into account following assumptions and conventions.
1) The current entering node a in Figure 8 is considered to be positive.
2) The switches S1, S2, S3 and S4 are unidirectional, i.e. they conduct current in one direction.



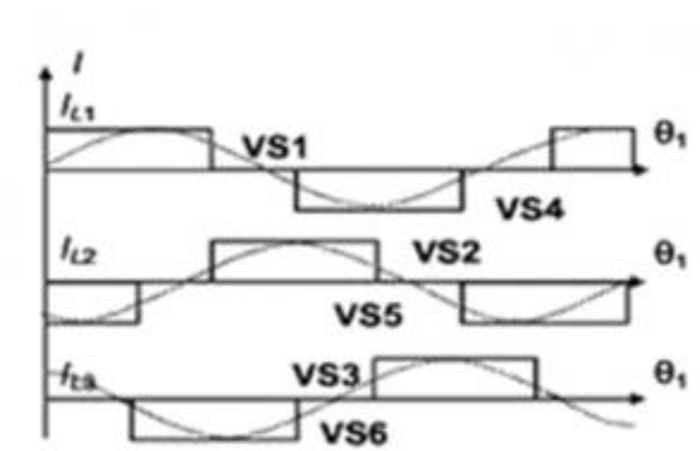
When the switches S1 and S2 are turned on simultaneously for a duration 0 ≤ t ≤ T1 , the the input voltage Vin appears across the load and the current flows from point a to b.



If the switches S3 and S4 turned on duration T1 ≤ t ≤ T2, the voltage across the load the load is reversed and the current through the load flows from point b to a.

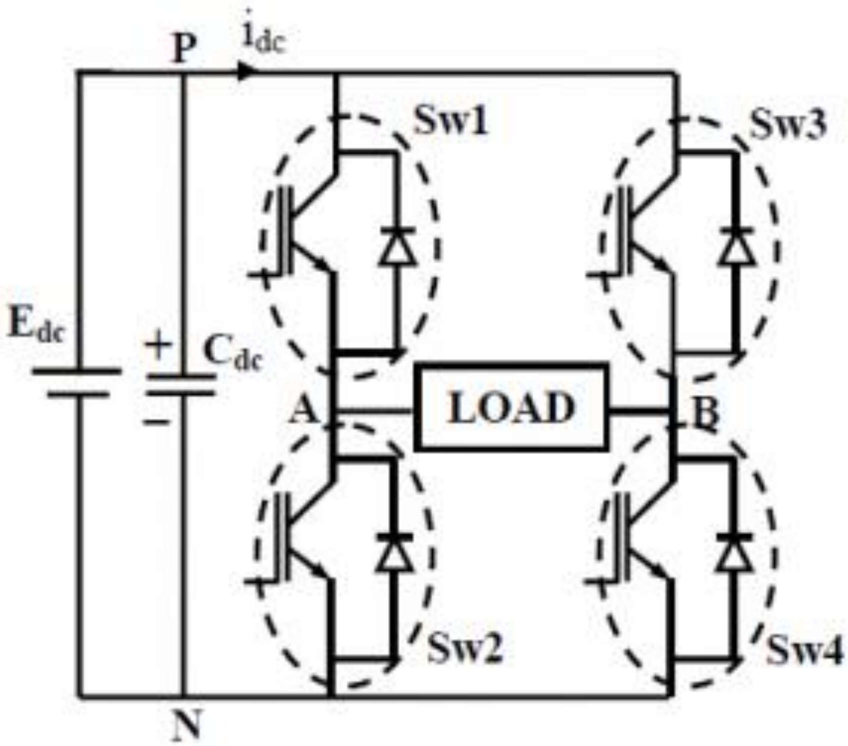


The voltage and current waveforms across the resistive load are shown in Figure below.



Single Phase Full Bridge Inverter for R-L load:

A single-phase square wave type voltage source inverter produces square shaped output voltage for a single-phase load. Such inverters have very simple control logic and the power switches need to operate at much lower frequencies compared to switches in some other types of inverters. The first generation inverters, using thyristor switches, were almost invariably square wave inverters because thyristor switches could be switched on and off only a few hundred times in a second. In contrast, the present day switches like IGBTs are much faster and used at switching frequencies of several kilohertz. Single-phase inverters mostly use half bridge or full bridge topologies. Power circuits of these topologies are shown in in Figure below.



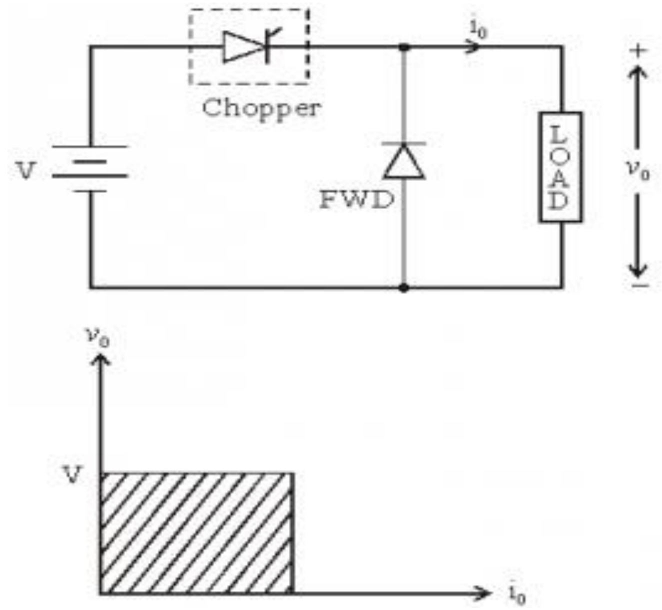
The above topology are analyzed under the assumption of ideal circuit conditions. Accordingly, it is assumed that the input dc voltage (Edc) is constant and the switches are lossless. In full bridge topology has two such legs. Each leg of the inverter consists of two series connected electronic switches shown within dotted lines in the figures. Each of these switches consists of an IGBT type controlled switch across which an uncontrolled diode is put in anti-parallel manner. These switches are capable of conducting bi-directional current but they need to block only one polarity of voltage. The junction point of the switches in each leg of the inverter serves as one output point for the load.

DC-DC Converters (Choppers)

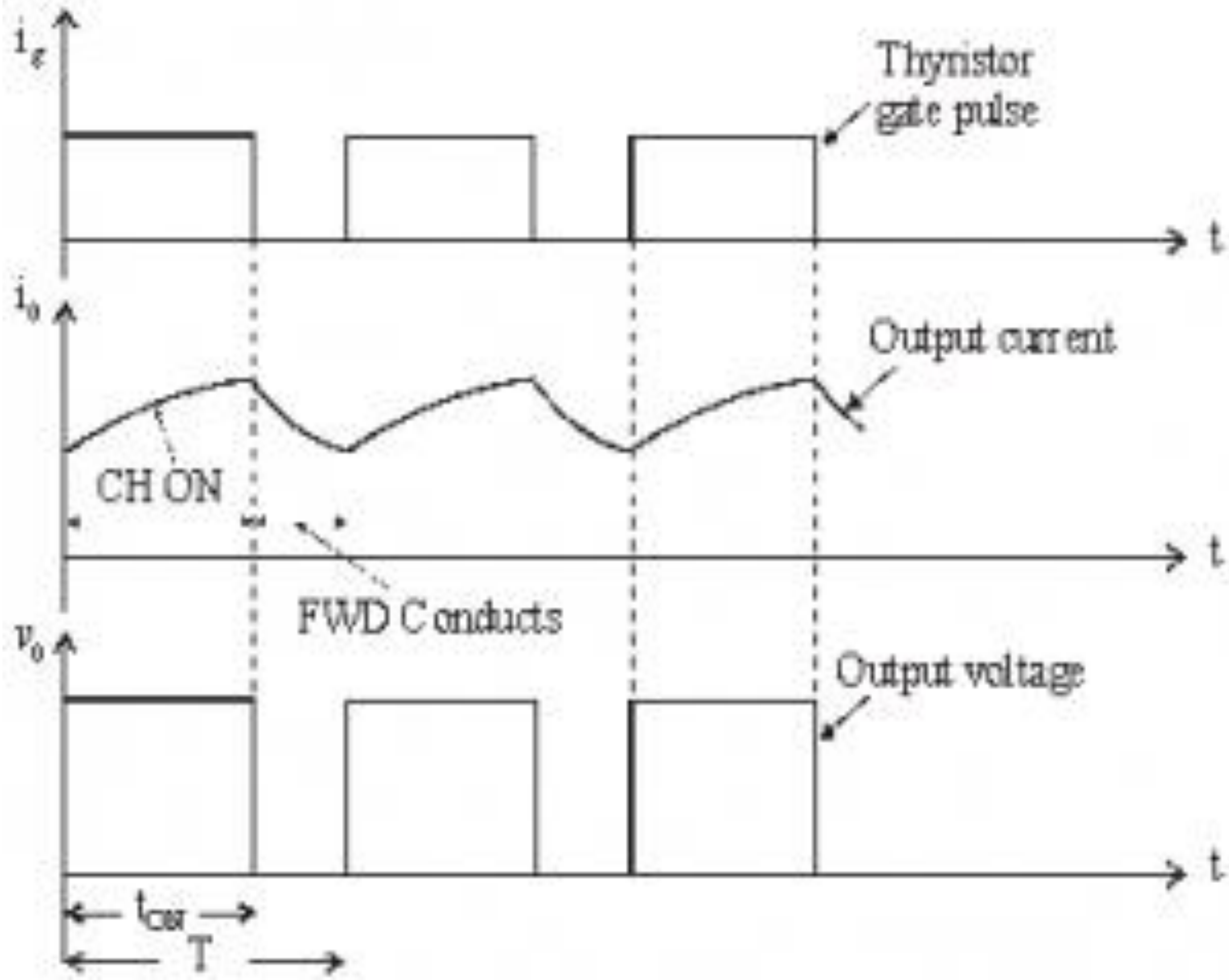
Depending upon the direction of the output current and voltage, the choppers can be classified into five classes namely
Class A [One-quadrant Operation]
Class B [One-quadrant Operation]
Class C [Two-quadrant Operation]
Class D Chopper [Two-quadrant Operation]
Class E Chopper [Four-quadrant Operation]

Class A [One-quadrant Operation]

Class A Chopper is a first quadrant chopper When chopper is ON, supply voltage V is connected across the load. When chopper is OFF, $V_0 = 0$ and the load current continues to flow in the same direction through the FWD. The average values of output voltage and current are always positive. Class A Chopper is a first quadrant chopper. When chopper is ON, supply voltage V is connected across the load. When chopper is OFF, $V_0 = 0$ and the load current continues to flow in the same direction through the FWD. The average values of output voltage and current are always positive. Class A Chopper is a step-down chopper in which power always flows form source to load. It is used to control the speed of dc motor. The output current equations obtained in step down chopper with R-L load can be used to study the performance of Class A Chopper.



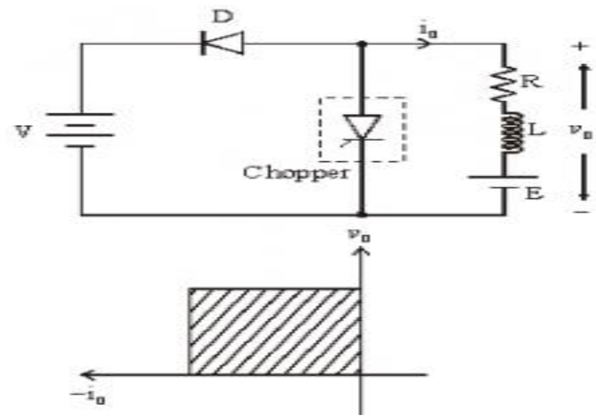
Prepared by: Mr Vishal Sharma
Asst. Prof. EE Dept., JECRC Jaipur

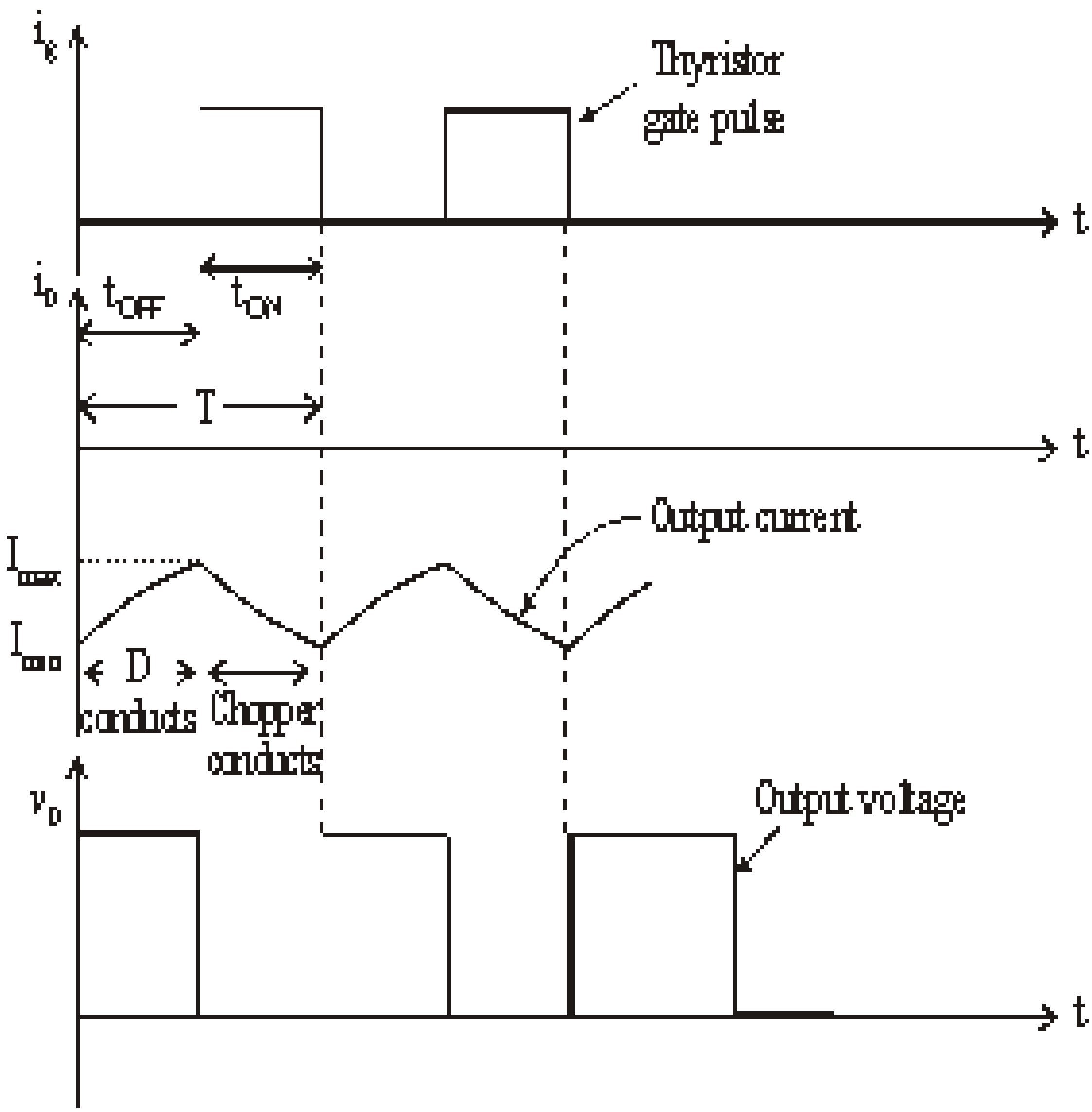


Class B [One-quadrant Operation]

Class B Chopper is a step-up chopper. When chopper is ON, E drives a current through L and R in a direction opposite to that shown in figure. During the ON period of the chopper, the inductance L stores energy. When Chopper is OFF, diode D conducts, and part of the energy stored in inductor L is returned to the supply. Average output voltage is positive. Average output current is negative. Therefore Class B Chopper operates in second quadrant. In this chopper, power flows from load to source. Class B Chopper is used for regenerative braking of dc motor.

Figure below shoes Class B chopper.





Class C [Two-quadrant Operation]

Class C Chopper can be used as a step-up or step-down chopper. Class C Chopper is a combination of Class A and Class B Choppers. For first quadrant operation, CH1 is ON or D2 conducts. For second quadrant operation, CH2 is ON or D1 conducts. When CH1 is ON, the load current is positive. The output voltage is equal to input & the load receives power from the source. When CH1 is turned OFF, energy stored in inductance L forces current to flow through the diode D2 and the output voltage is zero. Current continues to flow in positive direction. When CH2 is triggered, the voltage E forces current to flow in opposite direction through L and CH2 . The output voltage is zero. On turning OFF CH2, the energy stored in the inductance drives current through diode D1 and the supply Output voltage is V, the input current becomes negative and power flows from load to source. Average output voltage is positive Average output current can take both positive and negative values. Choppers CH1 & CH2 should not be turned ON simultaneously as it would result in short circuiting the supply. Class C Chopper can be used both for dc motor control and regenerative braking of dc motor.

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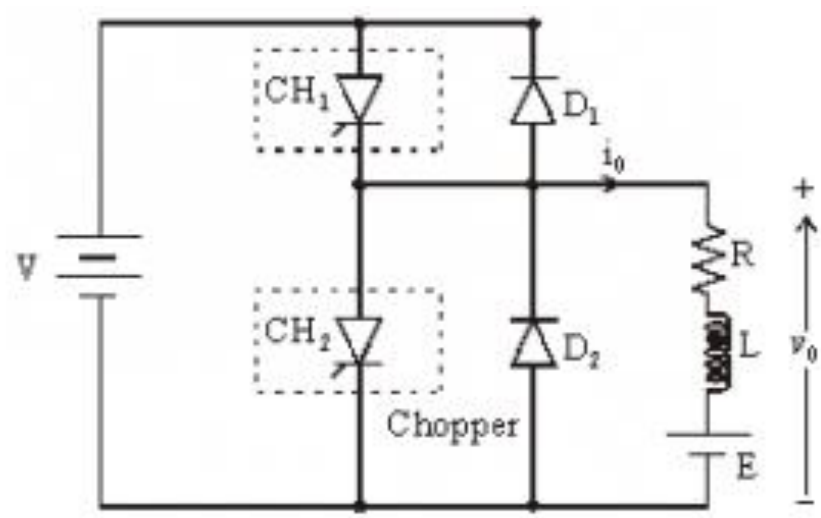
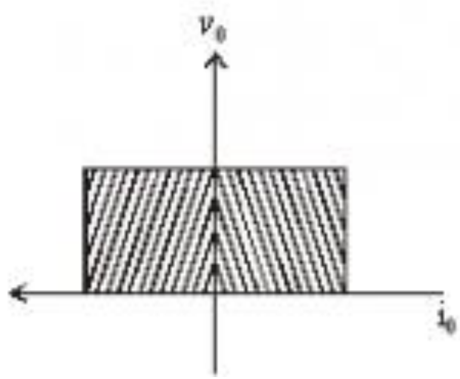
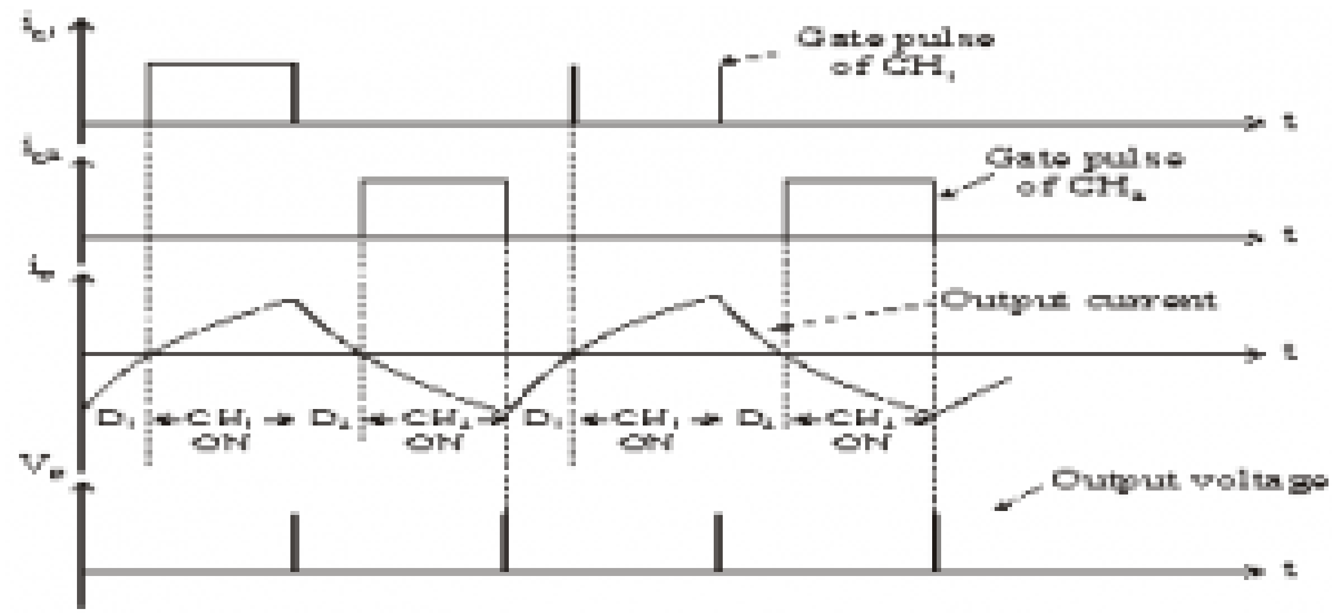




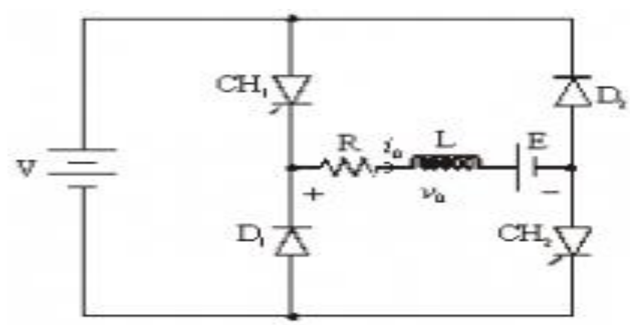
Prepared by: Mr Vishal Sharma
Asst. Prof. EE Dept., JECRC Jaipur

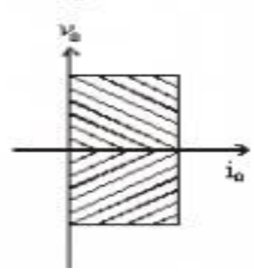


Class D Chopper [Two-quadrant Operation]

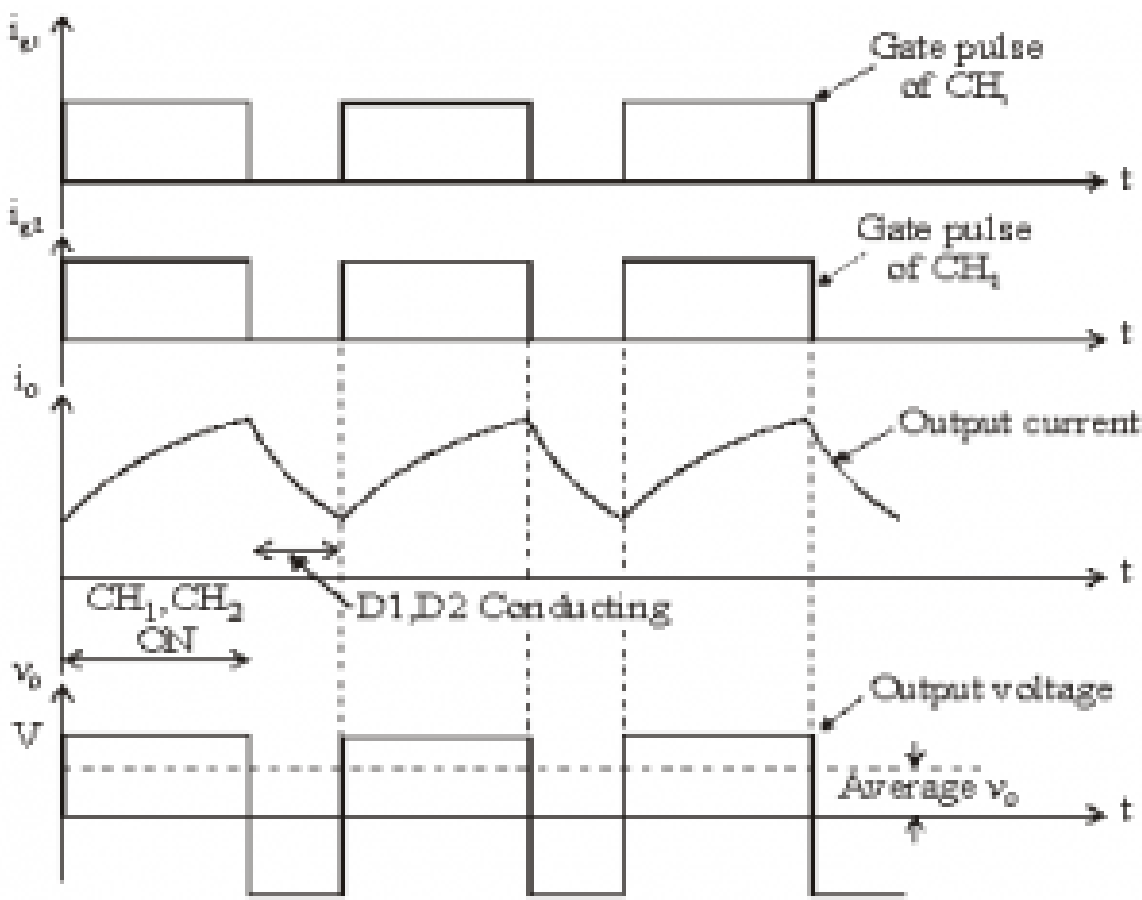
Class D is a two quadrant chopper. When both CH1 and CH2 are triggered simultaneously, the output voltage vO = V and output current flows through the load. When CH1 and CH2 are turned OFF, the load current continues to flow in the same direction through load, D1 and D2, due to the energy stored in the inductor L. Output voltage vO = – V.

Average load voltage is positive if chopper ON time is more than the OFF time Average output voltage becomes negative if $t_{ON} < t_{OFF}$. Hence the direction of load current is always positive but load voltage can be positive or negative.



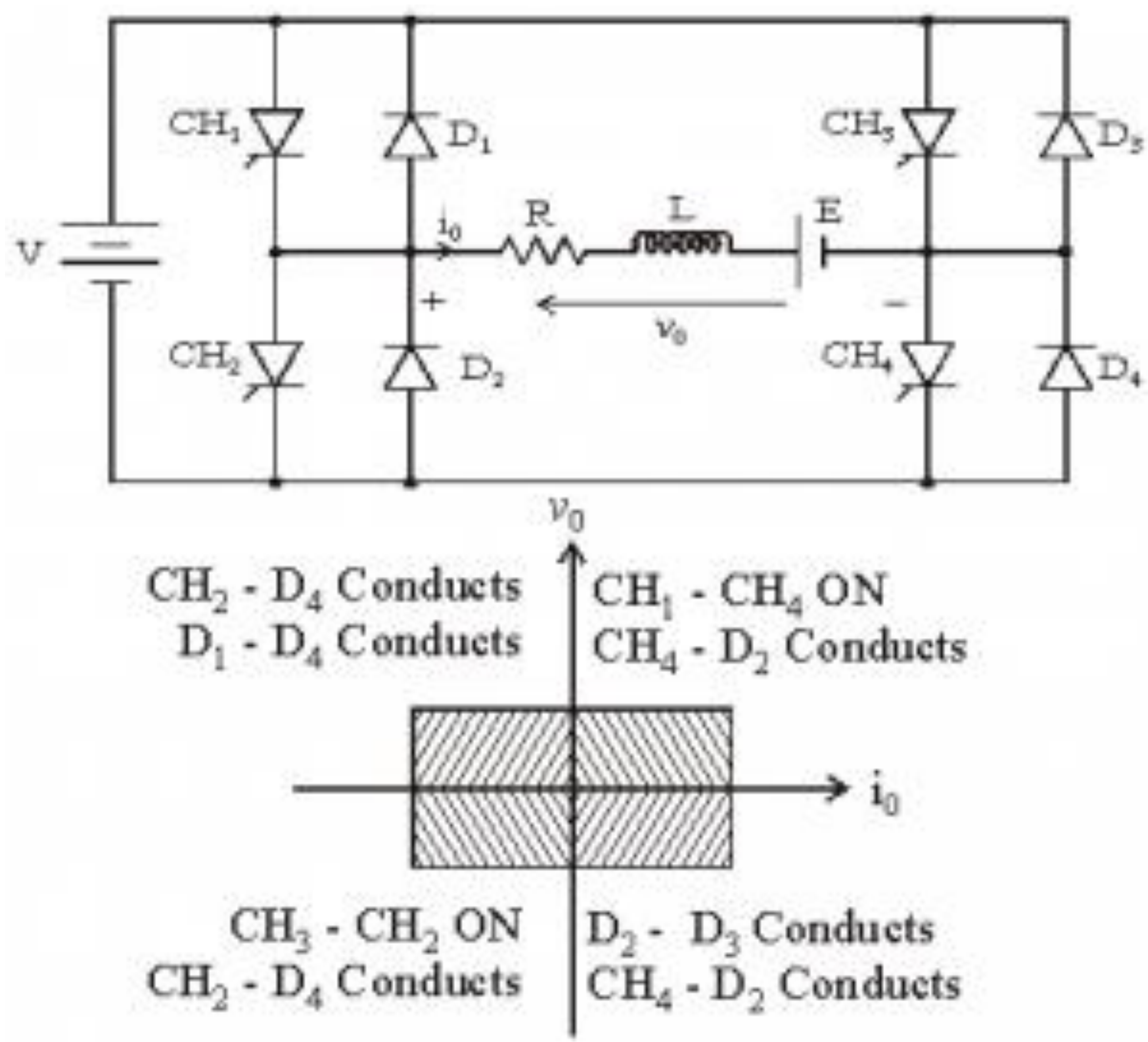


Prepared by: Mr Vishal Sharma
Asst. Prof. EE Dept., JECRC Jaipur



Class E Chopper [Four-quadrant Operation]
Class E is a four quadrant chopper When CH1 and CH4 are triggered, output current iO flows in positive direction through CH1 and CH4, and with output voltage vO = V. This gives the first quadrant operation.
When both CH1 and CH4 are OFF, the energy stored in the inductor L drives iO through D2 and D3 in the same direction, but output voltage v_O = -V. Therefore the chopper operates in the fourth quadrant. When CH2 mand CH3 are triggered, the load current iO flows in opposite direction & output voltage vO = -V. Since both i_O and v_O are negative, the chopper operates in third quadrant. When both CH2 and CH3 are OFF, the load current iO continues to flow in the same direction D1 and D4 and the output voltage vO = V. Therefore the chopper operates in second quadrant as vO is positive but iO is negative.
Figure below shows Class E chopper.

Prepared by: Mr Vishal Sharma
Asst. Prof. EE Dept., JECRC Jaipur



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Asst. Prof. EE Dept., JECRC Jaipur