

ATME COLLEGE OF ENGINEERING

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



A T M E

College of Engineering

**DEPARTMENT OF ELECTRICAL & ELECTRONICS
ENGINEERING**

NOTES

COURSE: Analog Electronic Circuits

COURSE CODE: 1BEE302

SEMESTER: III

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

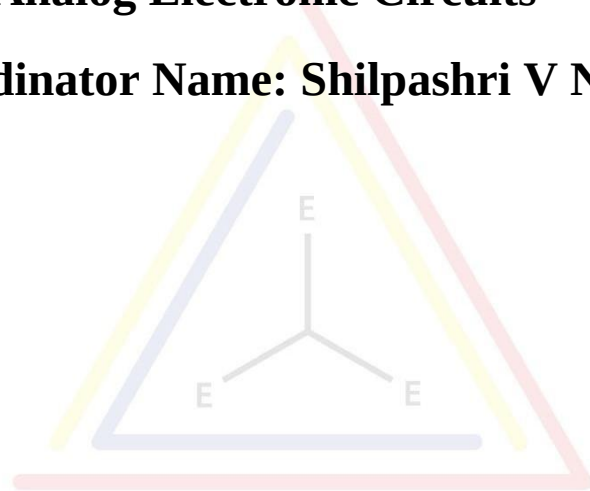
NOTES

Academic Year: 2026-27

Course Code: 1BEE302

Course Title: Analog Electronic Circuits

Course Co-ordinator Name: Shilpashri V N



Department of EEE
Emitting Elite Energy

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

Vision of the Institute Development of academically excellent, culturally vibrant, socially responsible and globally competent human resources. Mission of the Institute • To keep pace with advancements in knowledge and make the students competitive and capable at the global level. • To create an environment for the students to acquire the right physical, intellectual, emotional and moral foundations and shine as torch-bearers of tomorrow's society. • To strive to attain ever-higher benchmarks of educational excellence	Vision of the Department To create Electrical and Electronics Engineers who excel to be technically competent and fulfil the cultural and social aspirations of the society. Mission of the Department • To provide knowledge to students that builds a strong foundation in the basic principles of electrical engineering, problem solving abilities, analytical skills, soft skills and communication skills for their overall development. • To offer outcome based technical education. • To encourage faculty in training & development and to offer consultancy through research & industry interaction.
Program Educational Objectives (PEO's) • PEO1: To produce competent and ethical Electrical and Electronics Engineers who will exhibit the necessary technical and managerial skills to perform their duties in society. • PEO2: To make graduates continuously acquire and enhance their technical and socio-economic skills. • PEO3: To aspire graduates on R&D activities leading to offering solutions and excel in various career paths. • PEO4: To produce quality engineers who have the capability to work in teams and contribute to real time projects.	Program Specific Outcomes (PSO's) • PSO1: Apply the concepts of Electrical & Electronics Engineering to evaluate the performance of power systems and also to control industrial drives using power electronics. • PSO2: Demonstrate the concepts of process control for Industrial Automation, design models for environmental and social concerns and also exhibit continuous self- learning.

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Program Outcomes (PO's)

PO1: Engineering Knowledge: Apply knowledge of mathematics, natural science, computing, engineering fundamentals and an engineering specialization as specified in WK1 to WK4 respectively to develop to the solution of complex engineering problems.

PO2: Problem Analysis: Identify, formulate, review research literature and analyze complex engineering problems reaching substantiated conclusions with consideration for sustainable development. (WK1 to WK4)

PO3: Design/Development of Solutions: Design creative solutions for complex engineering problems and design/develop systems/components/processes to meet identified needs with consideration for the public health and safety, whole-life cost, net zero carbon, culture, society and environment as required. (WK5)

PO4: Conduct Investigations of Complex Problems: Conduct investigations of complex engineering problems using research-based knowledge including design of experiments, modelling, analysis & interpretation of data to provide valid conclusions. (WK8).

PO5: Engineering Tool Usage: Create, select and apply appropriate techniques, resources and modern engineering & IT tools, including prediction and modelling recognizing their limitations to solve complex engineering problems. (WK2 and WK6)

PO6: The Engineer and The World: Analyze and evaluate societal and environmental aspects while solving complex engineering problems for its impact on sustainability with reference to economy, health, safety, legal framework, culture and environment. (WK1, WK5, and WK7).

PO7: Ethics: Apply ethical principles and commit to professional ethics, human values, diversity and inclusion; adhere to national & international laws. (WK9)

PO8: Individual and Collaborative Team work: Function effectively as an individual, and as a member or leader in diverse/multi-disciplinary teams.

PO9: Communication: Communicate effectively and inclusively within the engineering community and society at large, such as being able to comprehend and write effective reports and design documentation, make effective presentations considering cultural, language, and learning differences

PO10: Project Management and Finance: Apply knowledge and understanding of engineering management principles and economic decision-making and apply these to one's own work, as a member and leader in a team, and to manage projects and in multidisciplinary environments.

PO11: Life-Long Learning: Recognize the need for, and have the preparation and ability for i) independent and life-long learning ii) adaptability to new and emerging technologies and iii) critical thinking in the broadest context of technological change. (WK8)

Module – I

Semiconductor Diode: Introduction, semiconductor materials, working principle and forward and reverse bias conditions, resistance levels, diode equivalent circuit, transition and diffusion capacitance, reverse recovery time. Half-wave and full-wave rectifiers, necessity of clippers and clampers, different types of clippers and clampers. Zenor diode, power Supply and series and parallel Voltage Regulators. Light emitting diodes (LEDs)

Bipolar Junction Transistors: Introduction, NPN and PNP transistors, construction, operation. Characteristics of common base (CB), common emitter (CE) and common collector configuration, cutoff region, active region, and saturation region. Relation between collector current, base current and emitter current.

Semiconductor Diode:

A **semiconductor** is a material which has electrical conductivity to a degree between that of a metal (such as copper) and that of an insulator (such as glass). Semiconductors are the foundation of modern electronics, including transistors, solar cells, light-emitting diodes (LEDs), quantum dots and digital and analog integrated circuits.

Diode – Di + ode

Di means two and ode means electrode. So physical contact of two electrodes is known as diode and its important function is alternative current to direct current.

INTRINSIC SEMICONDUCTOR

An intrinsic semiconductor is one, which is pure enough that impurities do not appreciably affect its electrical behavior. In this case, all carriers are created due to thermally or optically excited electrons from the full valence band into the empty conduction band.

Thus equal numbers of electrons and holes are present in an intrinsic semiconductor. Electrons and holes flow in opposite directions in an electric field, though they contribute to current in the same direction since they are oppositely charged. Hole current and electron current are not necessarily equal in an intrinsic semiconductor, however, because electrons and holes have different effective masses (crystalline analogues to free inertial masses).

The concentration of carriers is strongly dependent on the temperature. At low temperatures, the valence band is completely full making the material an insulator.

Both silicon and germanium are tetravalent, i.e. each has four electrons (valence electrons) in their outermost shell. Both elements crystallize with a diamond-like structure, i.e. in such a way that each atom in the crystal is inside a tetrahedron formed by the four atoms which are closest to it. Each atom shares its four valence electrons with its four immediate neighbours, so that each atom is involved in four covalent bonds.

EXTRINSIC SEMICONDUCTOR

An extrinsic semiconductor is one that has been doped with impurities to modify the number and type of free charge carriers. An extrinsic semiconductor is a semiconductor that has been *doped*, that is, into which a doping agent has been introduced, giving it different electrical properties than the intrinsic (pure) semiconductor.

Doping involves adding dopant atoms to an intrinsic semiconductor, which changes the electron and hole carrier concentrations of the semiconductor at thermal equilibrium. Dominant carrier concentrations in an extrinsic semiconductor classify it as either an n-type or p-type semiconductor. The electrical properties of extrinsic semiconductors make them essential components of many electronic devices.

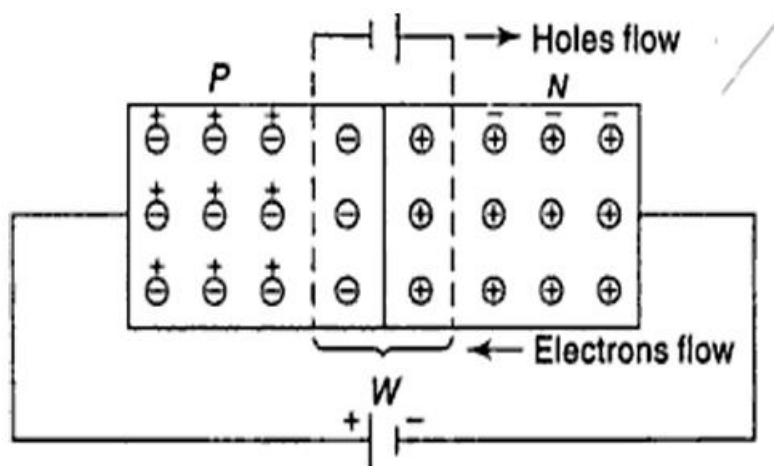
A pure or intrinsic conductor has thermally generated holes and electrons. However these are relatively few in number. An enormous increase in the number of charge carriers can be achieved by introducing impurities into the semiconductor in a controlled manner.

The result is the formation of an extrinsic semiconductor. This process is referred to as doping. There are basically two types of impurities: donor impurities and acceptor impurities. Donor impurities are made up of atoms (arsenic for example) which have five valence electrons. Acceptor impurities are made up of atoms (gallium for example) which have three valence electrons.

FORWARD BIAS CONDITION

When positive terminal of the battery is connected to the P-type and negative terminal to N-type of the PN junction diode that is known as forward bias condition.

Operation



The applied potential in external battery acts in opposition to the internal potential barrier which disturbs the equilibrium.

As soon as equilibrium is disturbed by the application of an external voltage, the Fermi level is no longer continuous across the junction. Under the forward bias condition the applied positive

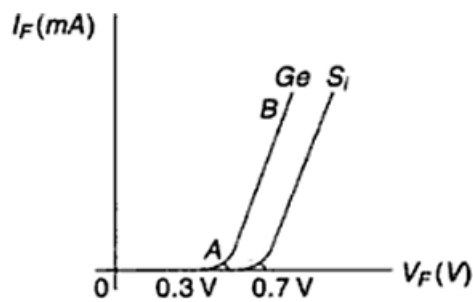
potential repels the holes in P type region so that the holes move towards the junction and the applied positive potential repels the electrons in N type region so that the electrons move towards the junction. When the applied potential is more than the internal barrier potential the depletion region and internal potential barrier disappear.

V-I Characteristics

As the forward voltage increased for $V_F < V_0$, the forward current I_F almost zero because the potential barrier prevents the holes from P region and electrons from N region to flow across the depletion region in opposite direction.

For $V_F > V_0$, the potential barrier at the junction completely disappears and hence, the holes cross the junction from P to N type and electrons cross the junction to opposite direction, resulting large current flow in external circuit.

A feature noted here is the cut in voltage or threshold voltage V_F below which the current is very small.



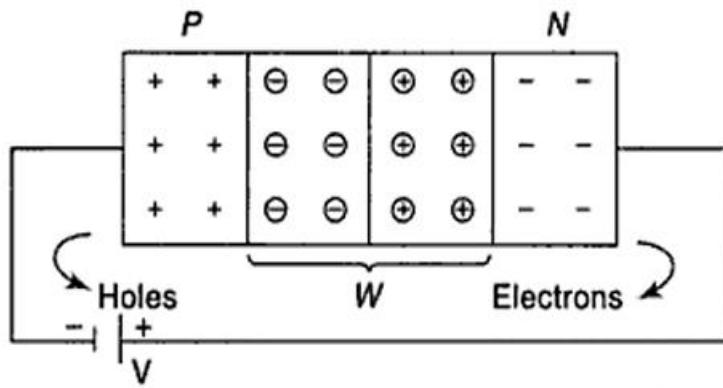
Cut in voltage is 0.3V for germanium and 0.7 for silicon.

REVERSE BIAS CONDITION

When the negative terminal of the battery is connected to the P-type and positive terminal to N-type of the PN junction diode that is known as forward bias condition.

Operation

The holes from the majority carriers of the P side move towards the negative terminal of the battery and electrons which from the majority carrier of the N side are attracted towards the positive terminal of the battery.



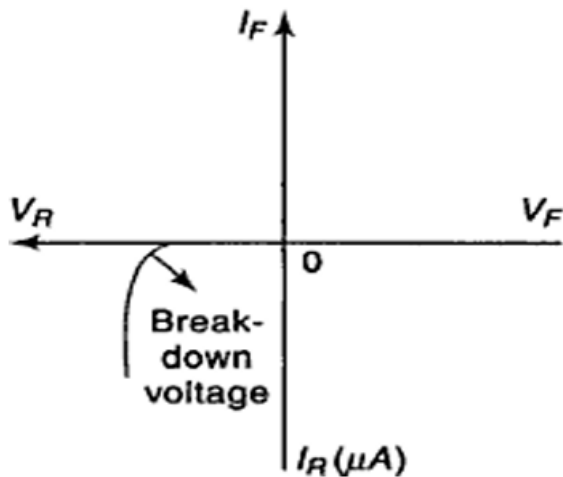
Hence, the width of the depletion region which is depleted of mobile charge carriers increases. Thus, the electric field produced by applied reverse bias, is in the same direction as the electric field of the potential barrier. Hence the resultant potential barrier is increased which prevents the flow of majority carriers in both directions.

The depletion width W is proportional to under reverse bias.

V-I characteristics

Theoretically no current flow in the external circuit. But in practice a very small amount of current of the order of few microamperes flows under reverse bias.

Electrons forming covalent bonds of semiconductor atoms in the P and N type regions may absorb sufficient energy from heat and light to cause breaking covalent bonds. So electron hole pairs continuously produced.



Consequently the minority carriers electrons in the P region and holes in the N region, wander over to the junction and flow towards their majority carrier side giving rise a small reverse current.

This current is known as reverse saturation current I_0 . The magnitude of this current is depends on the temperature because minority carrier is thermally broken covalent bonds.

TRANSITION AND DIFFUSION CAPACITANCES

1. Maximum Forward Current

The Maximum Forward Current ($I_F(\max)$) is as its name implies the maximum forward current allowed to flow through the device. When the diode is conducting in the forward bias condition, it has a very small "ON" resistance across the PN junction and therefore, power is dissipated across this junction (Ohm's Law) in the form of heat.

Then, exceeding its ($I_F(\max)$) value will cause more heat to be generated across the junction and the diode will fail due to thermal overload, usually with destructive consequences. When operating diodes around their maximum current ratings it is always best to provide additional cooling to dissipate the heat produced by the diode.

For example, our small 1N4148 signal diode has a maximum current rating of about 150mA with a power dissipation of 500mW at 25°C. Then a resistor must be used in series with the diode to limit the forward current, ($I_F(\max)$) through it to below this value.

2. Peak Inverse Voltage

The Peak Inverse Voltage (PIV) or Maximum Reverse Voltage ($V_R(\max)$), is the maximum allowable Reverse operating voltage that can be applied across the diode without reverse breakdown and damage occurring to the device. This rating therefore, is usually less than the "avalanche breakdown" level on the reverse bias characteristic curve. Typical values of $V_R(\max)$ range from a few volts to thousands of volts and must be considered when replacing a diode.

The peak inverse voltage is an important parameter and is mainly used for rectifying diodes in AC rectifier circuits with reference to the amplitude of the voltage were the sinusoidal waveform changes from a positive to a negative value on each and every cycle.

3. Forward Power Dissipation

Signal diodes have a Forward Power Dissipation, ($P_D(\max)$) rating. This rating is the maximum possible power dissipation of the diode when it is forward biased (conducting). When current flows through the signal diode the biasing of the PN junction is not perfect and offers some resistance to the flow of current resulting in power being dissipated (lost) in the diode in the form of heat.

As small signal diodes are nonlinear devices the resistance of the PN junction is not constant, it is a dynamic property then we cannot use Ohms Law to define the power in terms of current and resistance or voltage and resistance as we can for resistors. Then to find the power that will be dissipated by the diode we must multiply the voltage drop across it times the current flowing through it: $P_D = V \times I$

4. Maximum Operating Temperature

The Maximum Operating Temperature actually relates to the Junction Temperature (T_J) of the diode and is related to maximum power dissipation. It is the maximum temperature allowable before the structure of the diode deteriorates and is expressed in units of degrees centigrade per Watt, ($^{\circ}\text{C}/\text{W}$).

This value is linked closely to the maximum forward current of the device so that at this value the temperature of the junction is not exceeded. However, the maximum forward current will also depend upon the ambient temperature in which the device is operating so the maximum forward current is usually quoted for two or more ambient temperature values such as 25°C or 70°C.

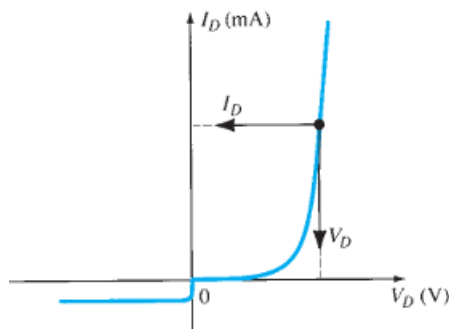
RESISTANCE LEVELS

As the operating point of a diode moves from one region to another the resistance of the diode will also change due to the nonlinear shape of the characteristic curve. It will be demonstrated in the next few paragraphs that the type of applied voltage or signal will define the resistance level of interest. Three different levels will be introduced in this section, which will appear again as we examine other devices. It is therefore paramount that their determination be clearly understood.

DC or Static Resistance

The application of a dc voltage to a circuit containing a semiconductor diode will result in an operating point on the characteristic curve that will not change with time. The resistance of the diode at the operating point can be found simply by finding the corresponding levels of V_D and I_D as shown in Figure below and applying the following equation:

$$R_D = \frac{V_D}{I_D}$$



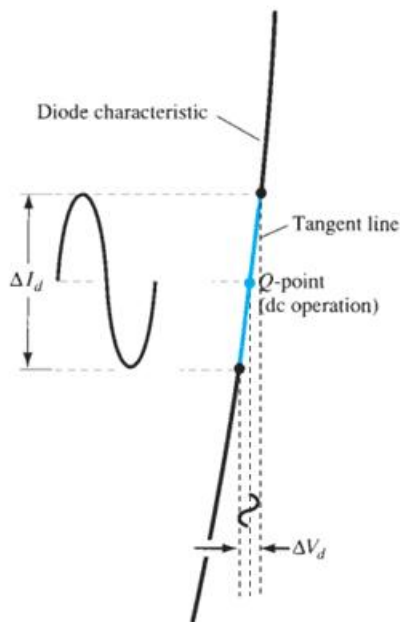
The dc resistance levels at the knee and below will be greater than the resistance levels obtained for the vertical rise section of the characteristics. The resistance levels in the reverse-bias region will naturally be quite high. Since ohmmeters typically employ a relatively constant-current source, the resistance determined will be at a preset current level (typically, a few milliamperes).

In general, therefore, the higher the current through a diode, the lower is the dc resistance level. Typically, the dc resistance of a diode in the active (most utilized) will range from about 10Ω to 80Ω .

AC or Dynamic Resistance

If a sinusoidal rather than a dc input is applied, the situation will change completely. The varying input will move the instantaneous operating point up and down a region of the characteristics and thus defines a specific change in current and voltage as shown in Figure. With no applied varying

signal, the point of operation would be the Q -point appearing on Figure, determined by the applied dc levels. The designation Q-point is derived from the word quiescent, which means “still or unvarying.”



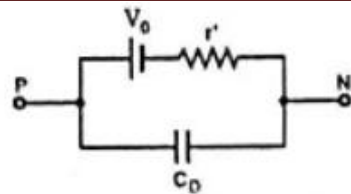
A straight line drawn tangent to the curve through the Q -point as shown in Fig. 1.26 will define a particular change in voltage and current that can be used to determine the ac or dynamic resistance for this region of the diode characteristics. An effort should be made to keep the change in voltage and current as small as possible and equidistant to either side of the Q -point. In equation form,

$$r_d = \frac{\Delta V_d}{\Delta I_d}$$

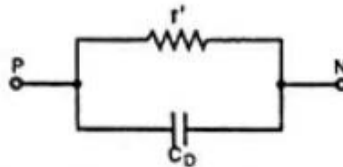
Where signifies a finite change in the quantity. The steeper the slope, the lower is the value of r_d for the same change in I_d and the lower is the resistance. The ac resistance in the vertical-rise region of the characteristic is therefore quite small, whereas the ac resistance is much higher at low current levels.

DIODE EQUIVALENT CIRCUITS

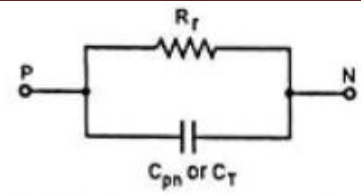
It is usually advantageous to replace a device or system by its equivalent circuit. An equivalent circuit of a device or a system is a combination of electric elements properly chosen to best represent the actual terminal characteristics of the device or the system. Once the equivalent circuit is determined, the device can be replaced by its Equivalent Circuit of a Diode without severely affecting the behavior of the overall system.



(a) Equivalent Circuit For Forward Biased Diode



(b) AC Equivalent Circuit For Forward Biased Diode



(c) Equivalent Circuit For Reverse Biased Diode

We have seen that a forward-biased junction offers a dynamic or ac resistance $r' = (r + r_B)$ and possesses diffusion capacitance C_D which comes into picture only when frequency of the applied voltage is very high. Hence, it can be represented by the Equivalent Circuit of a Diode shown in Fig.(a).

An opposing battery has been connected in series with r' to account for the junction barrier potential V_0 . The complete equivalent circuits for a forward biased diode is shown in Fig.(a).

The equivalent circuits for the forward-biased diode may be modified to form a small-signal ac equivalent circuits. This circuit is employed for diodes which are maintained in a forward-bias condition, but which are subjected to small variations in voltage V and current I . The small-signal ac Equivalent Circuit of a Diode is drawn [Fig.b)] by dropping the opposing battery representing the junction barrier potential V_0 from the circuit shown in Fig.(a).

A reverse-biased diode can be simply represented by the reverse resistance R_r in parallel with the depletion layer capacitance C_{pn} or C_T . This is illustrated in Fig.(c).

REVERSE RECOVERY TIME

It is the period during which a diode continues to conduct in reverse after switching from forward to reverse bias.

Reverse recovery time occurs when a diode transitions from forward bias (conducting) to reverse bias (non-conducting). Ideally, a diode should stop conducting immediately when the voltage is reversed, but due to stored charge carriers (electrons and holes) in the junction, the diode continues to conduct a reverse current for a short period

During this time:

- Initial Reverse Current: Immediately after voltage reversal, the current remains high as stored carriers are swept out of the junction.
- Peak Reverse Current (I_{rr}): The current reaches a maximum due to the rapid removal of excess carriers.
- Decay Phase: The reverse current decreases exponentially as carriers recombine.
- Steady-State Reverse Current: Eventually, the current stabilizes at the reverse saturation current level

Factors Affecting Reverse Recovery Time

Several parameters influence t_{rr} :

- Doping Levels: Higher doping accelerates carrier recombination, reducing t_{rr} .
- Junction Capacitance: Lower capacitance allows faster removal of carriers.
- Temperature: Higher temperatures can increase carrier mobility but may slow recombination.
- Forward Current: Higher forward currents store more charge, increasing t_{rr}

Diode Types and t_{rr} :

- PN Junction Diodes: Exhibit significant reverse recovery time due to minority carrier storage.
- Fast Recovery Diodes (FRD): Engineered to reduce t_{rr} using techniques like heavy metal implantation to trap carriers.
- Schottky Barrier Diodes (SBD): Unipolar devices that do not rely on minority carriers, resulting in nearly zero reverse recovery time

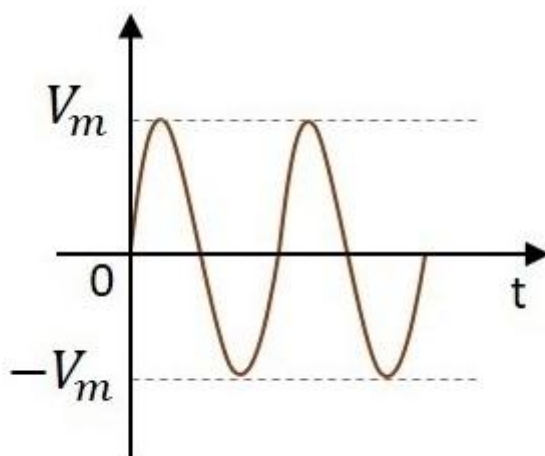
Design Implications:

Reverse recovery time is critical in high-speed switching circuits and power electronics, such as inverters and switching power supplies. A long t_{rr} can cause:

- Increased switching losses
- Higher electromagnetic interference (EMI)
- Potential voltage overshoot in circuits

RECTIFIERS

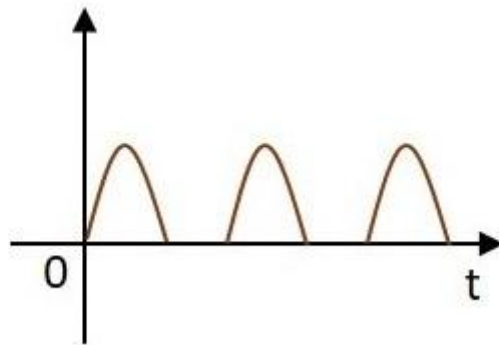
An alternating current has the property to change its state continuously. This is understood by observing the sine wave by which an alternating current is indicated. It raises in its positive direction goes to a peak positive value, reduces from there to normal and again goes to negative portion and reaches the negative peak and again gets back to normal and goes on.



During its journey in the formation of wave, we can observe that the wave goes in positive and negative directions. Actually it alters completely and hence the name alternating current.

But during the process of rectification, this alternating current is changed into direct current DC.

The wave which flows in both positive and negative direction till then, will get its direction restricted only to positive direction, when converted to DC. Hence the current is allowed to flow only in positive direction and resisted in negative direction, just as in the figure below.



The circuit which does rectification is called as a Rectifier circuit. A diode is used as a rectifier, to construct a rectifier circuit.

Types of Rectifier circuits

There are two main types of rectifier circuits, depending upon their output. They are

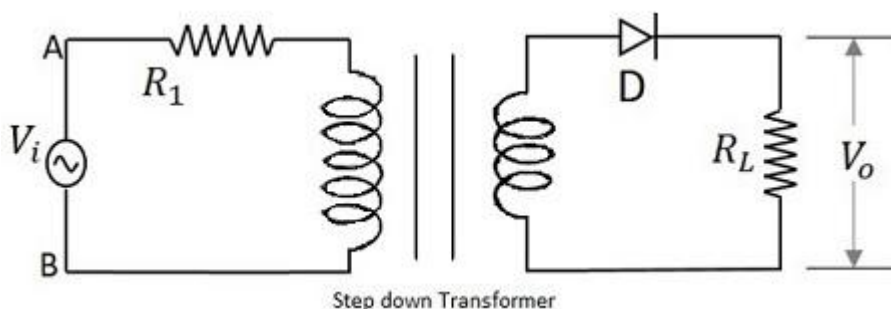
- Half-wave Rectifier
- Full-wave Rectifier

A Half-wave rectifier circuit rectifies only positive half cycles of the input supply whereas a Full-wave rectifier circuit rectifies both positive and negative half cycles of the input supply.

Half-Wave Rectifier

The name half-wave rectifier itself states that the rectification is done only for half of the cycle. The AC signal is given through an input transformer which steps up or down according to the usage. Mostly a step down transformer is used in rectifier circuits, so as to reduce the input voltage.

The input signal given to the transformer is passed through a PN junction diode which acts as a rectifier. This diode converts the AC voltage into pulsating dc for only the positive half cycles of the input. A load resistor is connected at the end of the circuit. The figure below shows the circuit of a half wave rectifier.



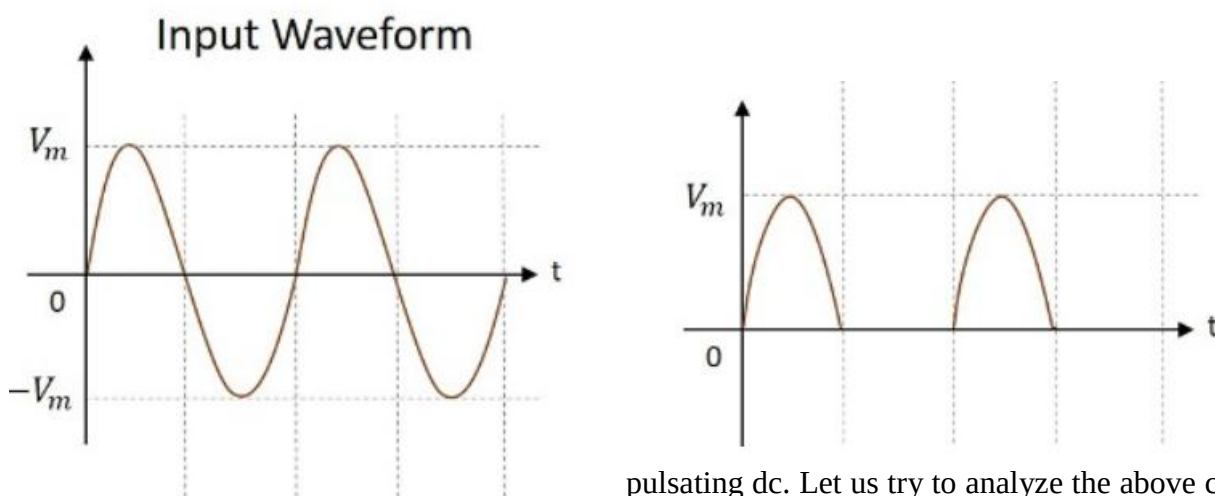
Working:

The input signal is given to the transformer which reduces the voltage levels. The output from the transformer is given to the diode which acts as a rectifier. This diode gets ON (conducts) for positive half cycles of input signal. Hence a current flows in the circuit and there will be a voltage drop across the load resistor. The diode gets OFF (doesn't conduct) for negative half cycles and hence the output for negative half cycles will be, $i_D=0$ and $V_o=0$.

Hence the output is present for positive half cycles of the input voltage only (neglecting the reverse leakage current). This output will be pulsating which is taken across the load resistor.

Waveforms:

The input and output waveforms are as shown in the following figure.



pulsating dc. Let us try to analyze the above circuit by understanding few values which are obtained from the output of half wave rectifier.

Analysis of Half-Wave Rectifier:

To analyze a half-wave rectifier circuit, let us consider the equation of input voltage.

$$v_i = V_m \sin \omega t$$

V_m is the maximum value of supply voltage.

Let us assume that the diode is ideal.

The current i in the diode or the load resistor R_L is given by

$$i = I_m \sin \omega t \quad \text{for} \quad 0 \leq \omega t \leq 2\pi$$

$$i = 0 \quad \text{for} \quad \pi \leq \omega t \leq 2\pi$$

Where

$$I_m = \frac{V_m}{R_f + R_L}$$

DC Output Current

The average current I_{dc} is given by

$$\begin{aligned} I_{dc} &= \frac{1}{2\pi} \int_0^{2\pi} i \, d(\omega t) \\ &= \frac{1}{2\pi} \left[\int_0^{\pi} I_m \sin \omega t \, d(\omega t) + \int_{\pi}^{2\pi} 0 \, d(\omega t) \right] \\ &= \frac{1}{2\pi} [I_m \{-\cos \omega t\}_0^{\pi}] \\ &= \frac{1}{2\pi} [I_m \{+1 - (-1)\}] = \frac{I_m}{\pi} = 0.318 I_m \end{aligned}$$

Substituting the value of I_m , we get

$$I_{dc} = \frac{V_m}{\pi (R_f + R_L)}$$

If $R_L \gg R_f$, then

$$I_{dc} = \frac{V_m}{\pi R_L} = 0.318 \frac{V_m}{R_L}$$

DC Output Voltage

The DC output voltage is given by

$$\begin{aligned} V_{dc} &= I_{dc} \times R_L = \frac{I_m}{\pi} \times R_L \\ &= \frac{V_m \times R_L}{\pi (R_f + R_L)} = \frac{V_m}{\pi \{1 + (R_f/R_L)\}} \end{aligned}$$

If $R_L \gg R_f$, then

$$V_{dc} = \frac{V_m}{\pi} = 0.318V_m$$

RMS Current and Voltage

The value of RMS current is given by

$$\begin{aligned} I_{rms} &= \left[\frac{1}{2\pi} \int_0^{2\pi} i^2 d(\omega t) \right]^{\frac{1}{2}} \\ I_{rms} &= \left[\frac{1}{2\pi} \int_0^{2\pi} I_m^2 \sin^2 \omega t d(\omega t) + \frac{1}{2\pi} \int_{\pi}^{2\pi} 0 d(\omega t) \right]^{\frac{1}{2}} \\ &= \left[\frac{I_m^2}{2\pi} \int_0^{\pi} \left(\frac{1 - \cos 2\omega t}{2} \right) d(\omega t) \right]^{\frac{1}{2}} \\ &= \left[\frac{I_m^2}{4\pi} \left\{ (\omega t) - \frac{\sin 2\omega t}{2} \right\}_0^{\pi} \right]^{\frac{1}{2}} \\ &= \left[\frac{I_m^2}{4\pi} \left\{ \pi - 0 - \frac{\sin 2\pi}{2} + \sin 0 \right\} \right]^{\frac{1}{2}} \\ &= \left[\frac{I_m^2}{4\pi} \right]^{\frac{1}{2}} = \frac{I_m}{2} \\ &= \frac{V_m}{2(R_f + R_L)} \end{aligned}$$

RMS voltage across the load is

$$V_{rms} = I_{rms} \times R_L = \frac{V_m \times R_L}{2(R_f + R_L)}$$

$$= \frac{V_m}{2\{1 + (R_f/R_L)\}}$$

If $R_L \gg R_f$, then

$$V_{rms} = \frac{V_m}{2}$$

Rectifier Efficiency:

Any circuit needs to be efficient in its working for a better output. To calculate the efficiency of a half wave rectifier, the ratio of the output power to the input power has to be considered.

The rectifier efficiency is defined as

$$\eta = \frac{\text{d.c. power delivered to the load}}{\text{a.c. input power from transformer secondary}} = \frac{P_{ac}}{P_{dc}}$$

Now

$$P_{dc} = (I_{dc})^2 \times R_L = \frac{I_m R_L}{\pi^2}$$

Further

$$P_{ac} = P_a + P_r$$

Where

$$P_a = \text{power dissipated at the junction of diode}$$

$$= I_{rms}^2 \times R_f = \frac{I_m^2}{4} \times R_f$$

And

$$P_r = \text{power dissipated in the load resistance}$$

$$= I_{rms}^2 \times R_L = \frac{I_m^2}{4} \times R_L$$

$$P_{ac} = \frac{I_m^2}{4} \times R_f + \frac{I_m^2}{4} \times R_L = \frac{I_m^2}{4} (R_f + R_L)$$

From both the expressions of P_{ac} and P_{dc} , we can write

$$\begin{aligned} \eta &= \frac{I_m^2 R_L / \pi^2}{I_m^2 (R_f + R_L) / 4} = \frac{4}{\pi^2} \frac{R_L}{(R_f + R_L)} \\ &= \frac{4}{\pi^2} \frac{1}{\{1 + (R_f/R_L)\}} = \frac{0.406}{\{1 + (R_f/R_L)\}} \end{aligned}$$

Percentage rectifier efficiency

$$\eta = \frac{40.6}{\{1 + (R_f/R_L)\}}$$

Theoretically, the maximum value of rectifier efficiency of a half wave rectifier is 40.6% when $R_f/R_L = 0$

Further, the efficiency may be calculated in the following way

$$\begin{aligned} \eta &= \frac{P_{dc}}{P_{ac}} = \frac{(I_{dc})^2 R_L}{(I_{rms})^2 R_L} = \frac{(V_{dc}/R_L)^2 R_L}{(V_{rms}/R_L)^2 R_L} = \frac{(V_{dc})^2}{(V_{rms})^2} \\ &= \frac{(V_m/\pi)^2}{(V_m/2)^2} = \frac{4}{\pi^2} = 0.406 \\ &= 40.6\% \end{aligned}$$

Ripple Factor:

The rectified output contains some amount of AC component present in it, in the form of ripples. This is understood by observing the output waveform of the half wave rectifier. To get a pure dc, we need to have an idea on this component.

The ripple factor gives the waviness of the rectified output. It is denoted by γ . This can be defined as the ratio of the effective value of ac component of voltage or current to the direct value or average value.

$$\gamma = \frac{\text{ripple voltage}}{\text{d.c voltage}} = \frac{\text{rms value of a.c. component}}{\text{d.c. value of wave}} = \frac{(V_r)_{rms}}{V_{dc}}$$

Here,

$$(V_r)_{rms} = \sqrt{V_{rms}^2 - V_{dc}^2}$$

Therefore,

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

Now,

$$\begin{aligned} V_{rms} &= \left[\frac{1}{2\pi} \int_0^{2\pi} V_m^2 \sin^2 \omega t \, d(\omega t) \right]^{\frac{1}{2}} \\ &= V_m \left[\frac{1}{4\pi} \int_0^{\pi} (1 - \cos 2\omega t) \, d(\omega t) \right]^{\frac{1}{2}} = \frac{V_m}{2} \\ V_{dc} = V_{av} &= \frac{1}{2\pi} \left[\int_0^{\pi} V_m \sin \omega t \, d(\omega t) + \int_0^{2\pi} 0 \, d(\omega t) \right] \\ &= \frac{V_m}{2\pi} [-\cos \omega t]_0^{\pi} = \frac{V_m}{\pi} \\ \gamma &= \sqrt{\left[\left\{ \frac{(V_m/2)}{(V_m/\pi)} \right\}^2 - 1 \right]} = \sqrt{\left\{ \left(\frac{\pi}{2} \right)^2 - 1 \right\}} = 1.21 \end{aligned}$$

The ripple factor is also defined as

$$\gamma = \frac{(I_r)_{rms}}{I_{dc}}$$

Regulation:

The current through the load may vary depending upon the load resistance. But even at such condition, we expect our output voltage which is taken across that load resistor, to be constant. So, our voltage needs to be regulated even under different load conditions.

The variation of D.C. output voltage with change in D.C. load current is defined as the Regulation. The percentage regulation is calculated as follows.

$$\text{Percentage regulation} = \frac{V_{no\ load} - V_{full\ load}}{V_{full\ load}} \times 100\%$$

The lower the percentage regulation, the better would be the power supply. An ideal power supply will have a zero percentage regulation.

Full Wave Rectifiers

A Rectifier circuit that rectifies both the positive and negative half cycles can be termed as a full wave rectifier as it rectifies the complete cycle. The construction of a full wave rectifier can be made in two types.

They are

- Center-tapped Full wave rectifier
- Bridge full wave rectifier

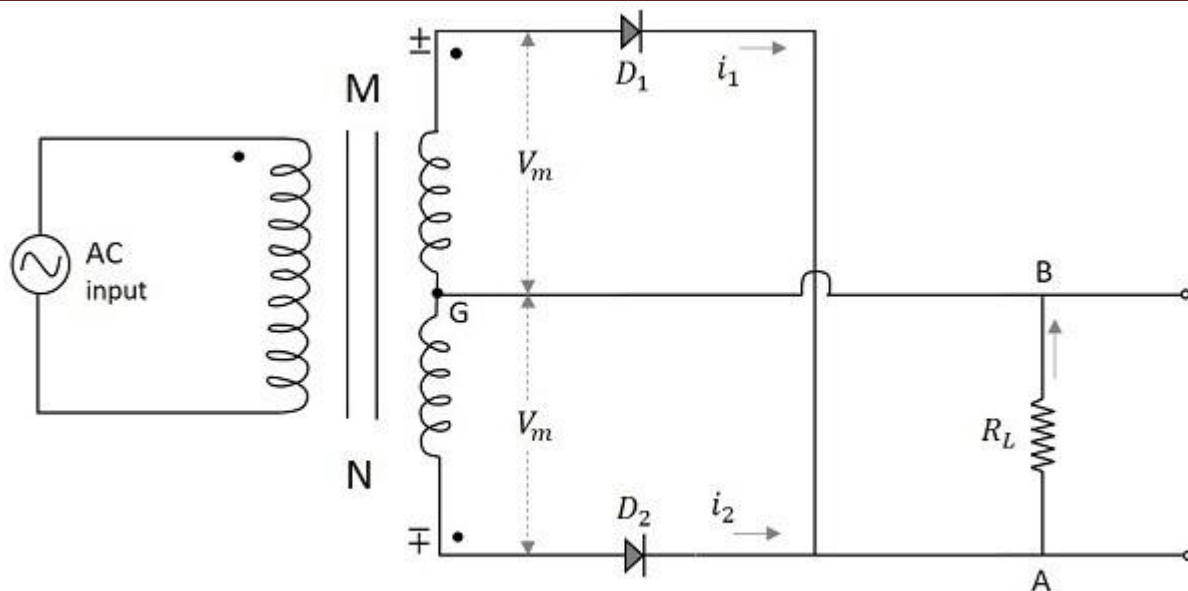
Center-tapped Full-Wave Rectifier

A rectifier circuit whose transformer secondary is tapped to get the desired output voltage, using two diodes alternatively, to rectify the complete cycle is called as a Center-tapped Full wave rectifier circuit. The transformer is center tapped here unlike the other cases.

The features of a center-tapping transformer are –

- The tapping is done by drawing a lead at the mid-point on the secondary winding. This winding is split into two equal halves by doing so.
- The voltage at the tapped mid-point is zero. This forms a neutral point.
- The center tapping provides two separate output voltages which are equal in magnitude but opposite in polarity to each other.
- A number of tapings can be drawn out to obtain different levels of voltages.

The center-tapped transformer with two rectifier diodes is used in the construction of a Center-tapped full wave rectifier. The circuit diagram of a center tapped full wave rectifier is as shown below.

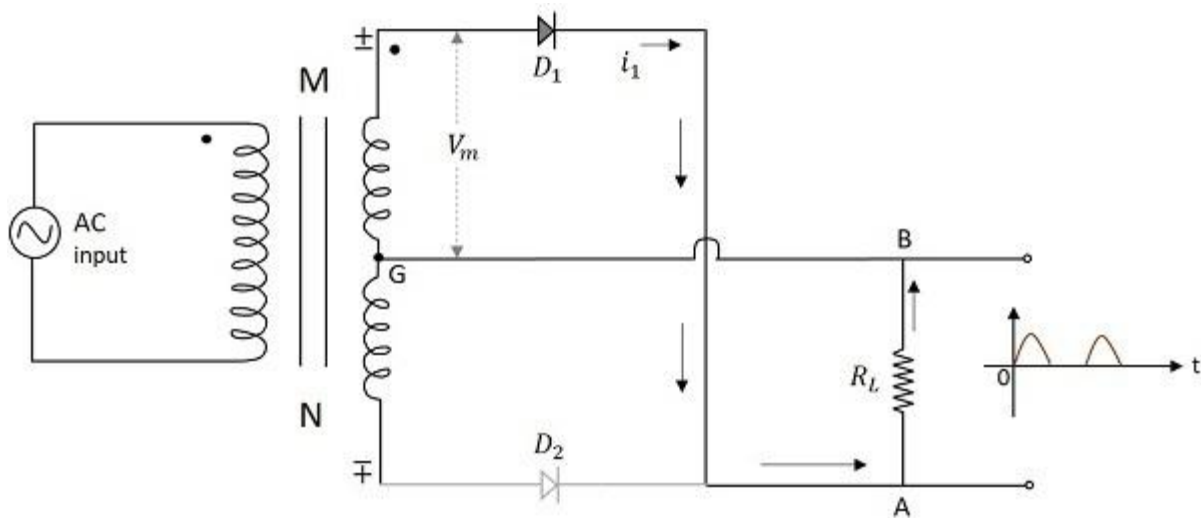


Circuit diagram of a center-tapped full wave rectifier

Working:

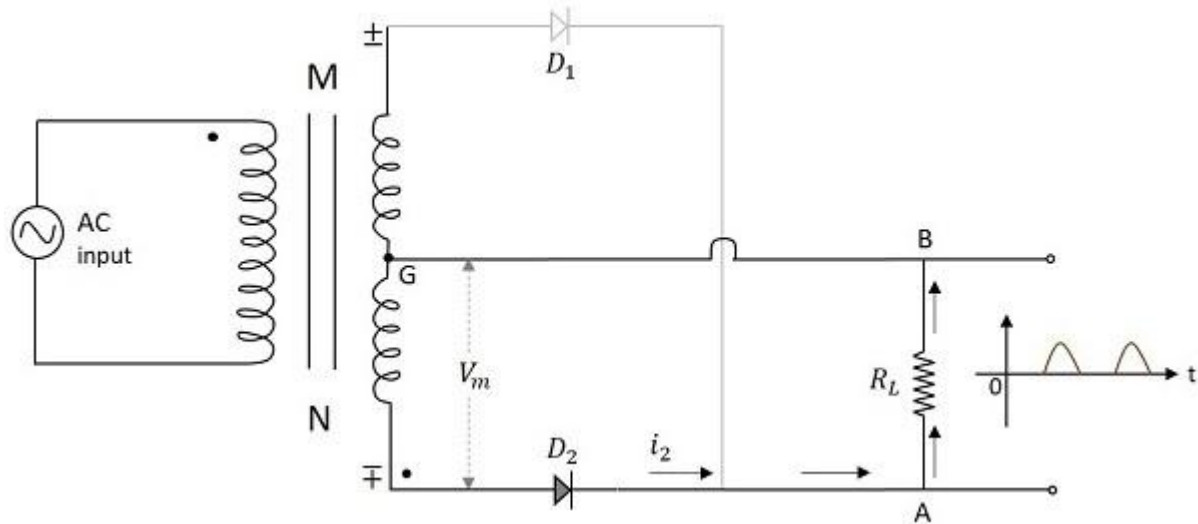
The working of a center-tapped full wave rectifier can be understood by the above figure. When the positive half cycle of the input voltage is applied, the point M at the transformer secondary becomes positive with respect to the point N.

This makes the diode D_1 forward biased. Hence current i_1 flows through the load resistor from A to B. We now have the positive half cycles in the output



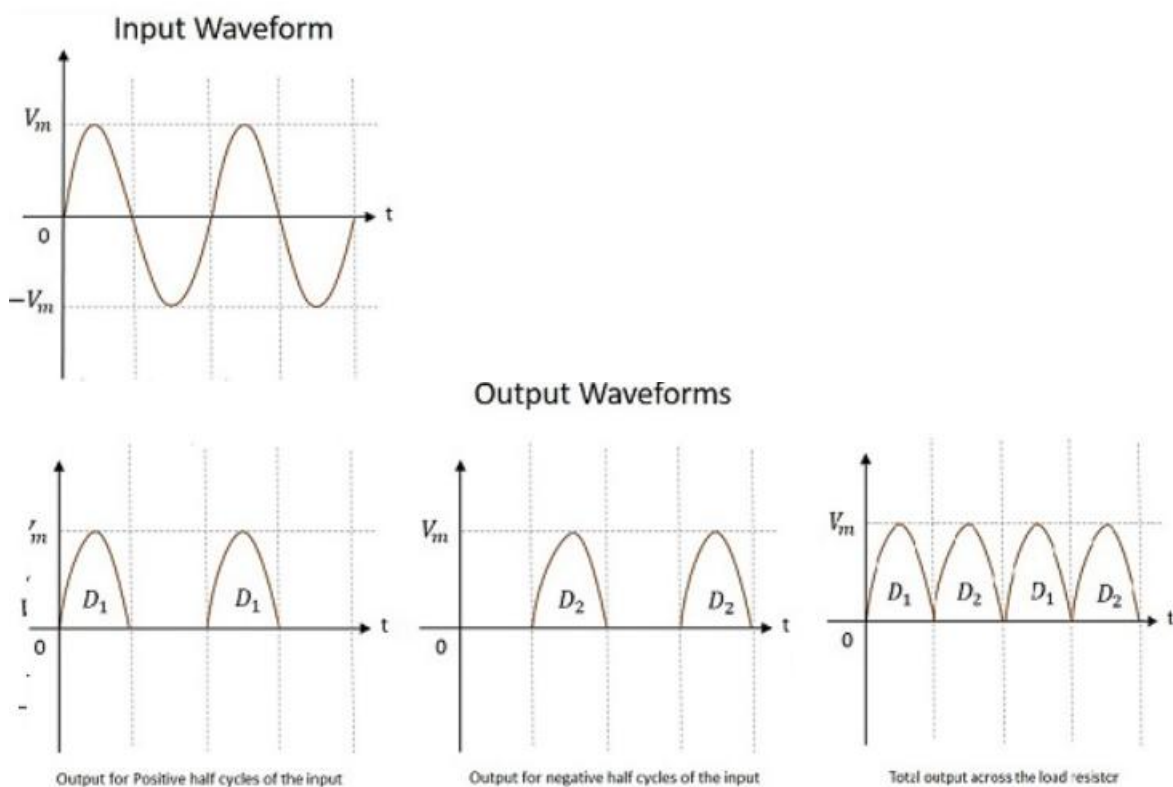
When the negative half cycle of the input voltage is applied, the point M at the transformer secondary becomes negative with respect to the point N. This makes the diode D_2 forward biased.

Hence current i_2 flows through the load resistor from A to B. We now have the positive half cycles in the output, even during the negative half cycles of the input.



Waveforms:

The input and output waveforms of the center-tapped full wave rectifier are as follows.



From the above figure it is evident that the output is obtained for both the positive and negative half cycles. It is also observed that the output across the load resistor is in the same direction for both the half cycles.

Peak Inverse Voltage:

As the maximum voltage across half secondary winding is V_m , the whole of the secondary voltage appears across the non-conducting diode. Hence the peak inverse voltage is twice the maximum voltage across the half-secondary winding, i.e. $PIV = 2V_m$

Disadvantages:

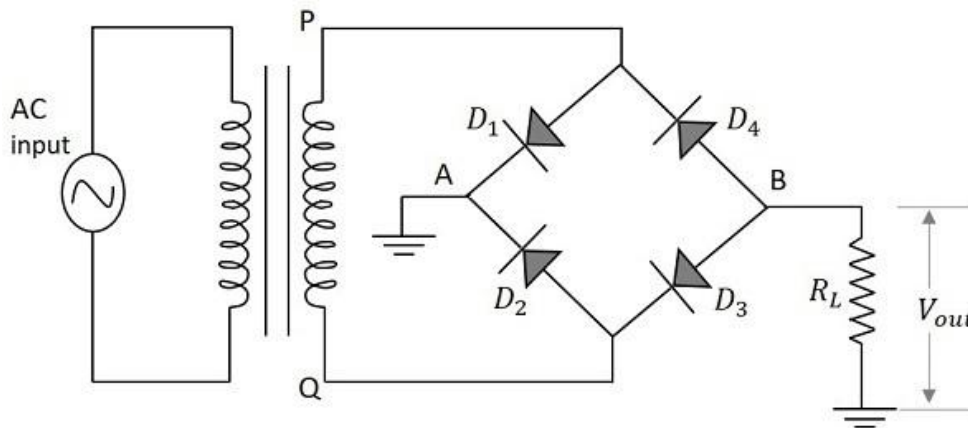
There are few disadvantages for a center-tapped full wave rectifier such as –

- Location of center-tapping is difficult
- The dc output voltage is small
- PIV of the diodes should be high

Bridge Full-Wave Rectifier

This is such a full wave rectifier circuit which utilizes four diodes connected in bridge form so as not only to produce the output during the full cycle of input, but also to eliminate the disadvantages of the center-tapped full wave rectifier circuit.

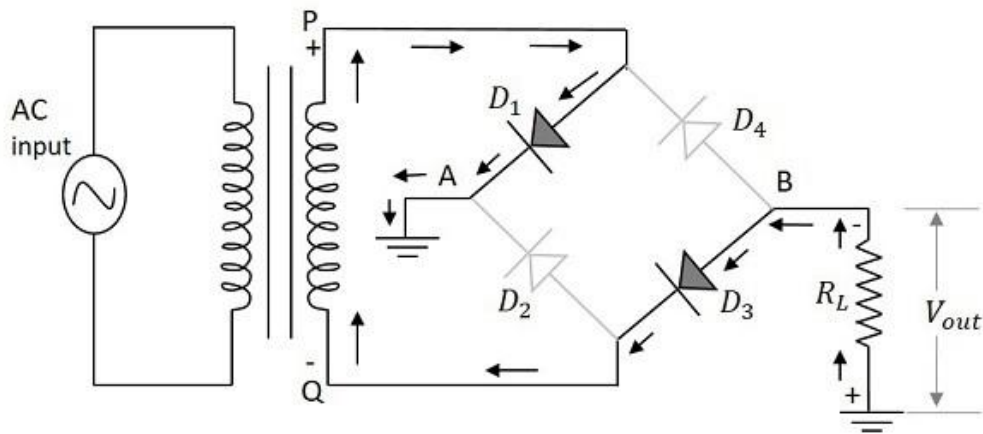
There is no need of any center-tapping of the transformer in this circuit. Four diodes called D1, D2, D3 and D4 are used in constructing a bridge type network so that two of the diodes conduct for one half cycle and two conduct for the other half cycle of the input supply. The circuit of a bridge full wave rectifier is as shown in the following figure.

**Working:**

The full wave rectifier with four diodes connected in bridge circuit is employed to get a better full wave output response. When the positive half cycle of the input supply is given, point P becomes positive with respect to the point Q.

This makes the diode D1 and D3 forward biased while D2 and D4 reverse biased. These two diodes will now be in series with the load resistor.

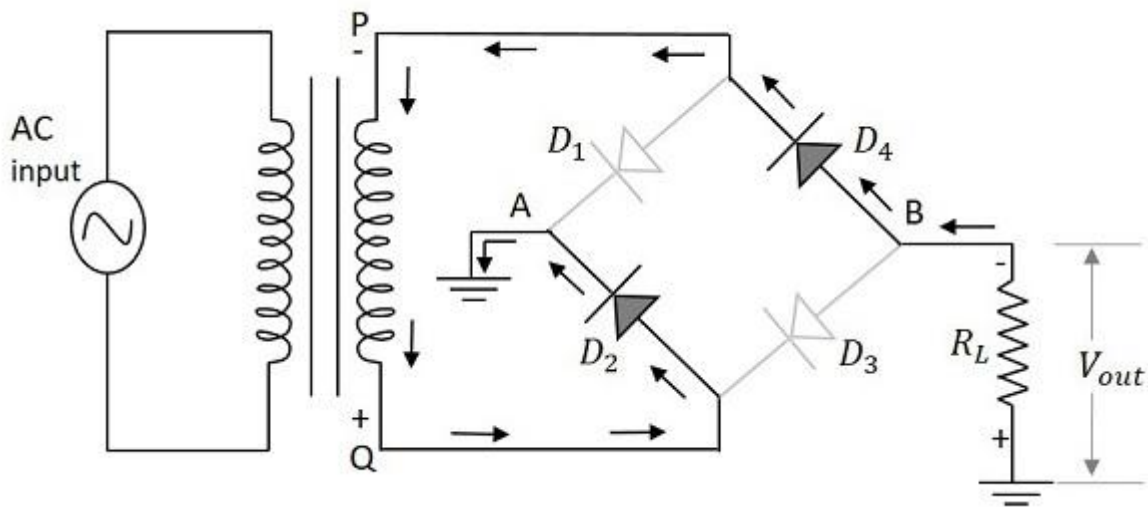
The following figure indicates this along with the conventional current flow in the circuit.



Hence the diodes D_1 and D_3 conduct during the positive half cycle of the input supply to produce the output along the load resistor. As two diodes work in order to produce the output, the voltage will be twice the output voltage of the center tapped full wave rectifier.

When the negative half cycle of the input supply is given, point P becomes negative with respect to the point Q . This makes the diode D_1 and D_3 reverse biased while D_2 and D_4 forward biased. These two diodes will now be in series with the load resistor.

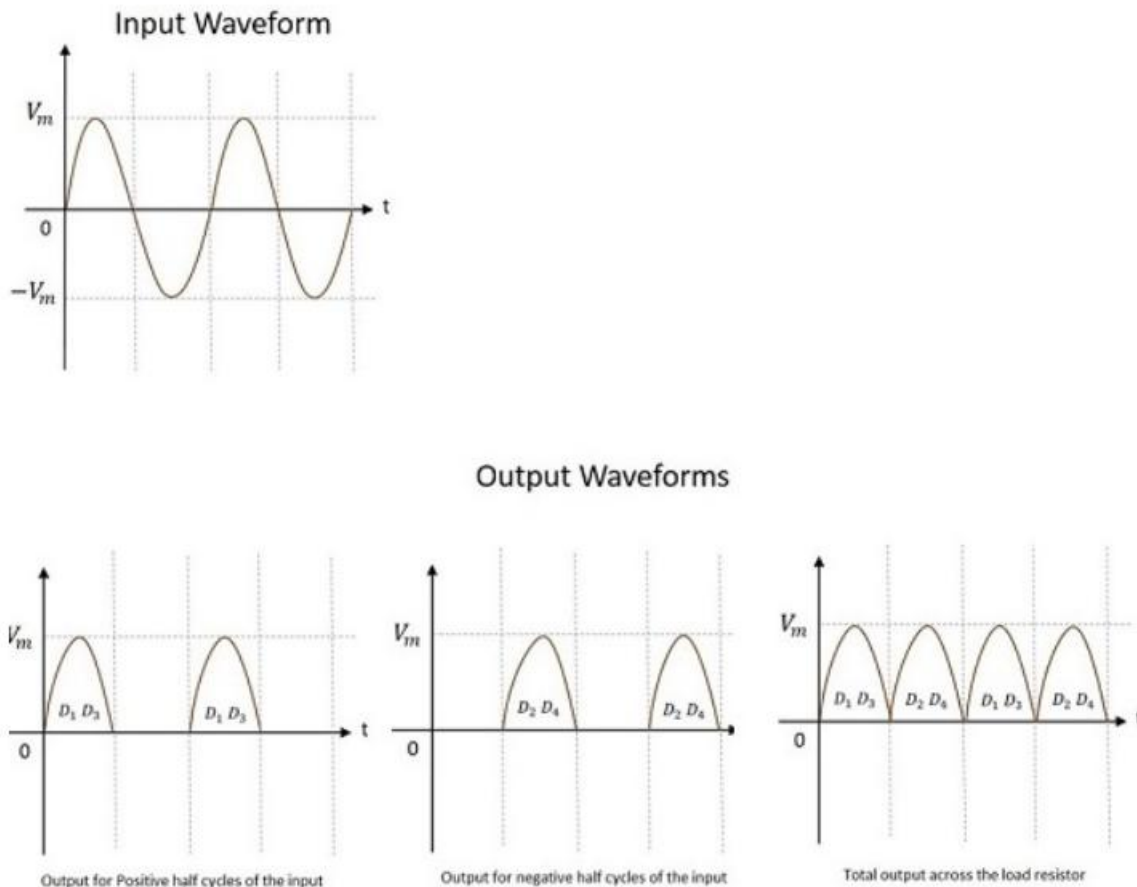
The following figure indicates this along with the conventional current flow in the circuit.



Hence the diodes D_2 and D_4 conduct during the negative half cycle of the input supply to produce the output along the load resistor. Here also two diodes work to produce the output voltage. The current flows in the same direction as during the positive half cycle of the input.

Waveforms:

The input and output waveforms of the center-tapped full wave rectifier are as follows.



From the above figure, it is evident that the output is obtained for both the positive and negative half cycles. It is also observed that the output across the load resistor is in the same direction for both the half cycles.

Peak Inverse Voltage:

Whenever two of the diodes are being in parallel to the secondary of the transformer, the maximum secondary voltage across the transformer appears at the non-conducting diodes which makes the PIV of the rectifier circuit. Hence the peak inverse voltage is the maximum voltage across the secondary winding, i.e. $PIV = 2V_m$

Advantages:

There are many advantages for a bridge full wave rectifier, such as –

- No need of center-tapping.
- The dc output voltage is twice that of the center-tapper FWR.
- PIV of the diodes is of the half value that of the center-tapper FWR.
- The design of the circuit is easier with better output.

Analysis of Full-Wave Rectifier:

In order to analyze a full wave rectifier circuit, let us assume the input voltage V_i as,

$$V_i = V_m \sin \omega t$$

The current i_1 through the load resistor R_L is given by

$$i_1 = I_m \sin \omega t \quad \text{for } 0 \leq \omega t \leq \pi$$

$$i_1 = 0 \quad \text{for } \pi \leq \omega t \leq 2\pi$$

Where

$$I_m = \frac{V_m}{R_f + R_L}$$

R_f being the diode resistance in ON condition.

Similarly, the current i_2 flowing through diode D_2 and load resistor R_L is given by,

$$i_2 = 0 \quad \text{for } 0 \leq \omega t \leq \pi$$

$$i_2 = I_m \sin \omega t \quad \text{for } \pi \leq \omega t \leq 2\pi$$

The total current flowing through R_L is the sum of the two currents i_1 and i_2 i.e.

$$i = i_1 + i_2$$

D.C. or Average Current

The average value of output current that a D.C. ammeter will indicate is given by

$$\begin{aligned} I_{dc} &= \frac{1}{2\pi} \int_0^{2\pi} i_1 d(\omega t) + \frac{1}{2\pi} \int_0^{2\pi} i_2 d(\omega t) \\ &= \frac{1}{2\pi} \int_0^\pi I_m \sin \omega t d(\omega t) + 0 + 0 + \\ &\quad \frac{1}{2\pi} \int_\pi^{2\pi} I_m \sin \omega t d(\omega t) \\ &= \frac{I_m}{\pi} + \frac{I_m}{\pi} = \frac{2I_m}{\pi} = 0.636I_m \end{aligned}$$

This is double the value of a half wave rectifier.

D.C. Output Voltage

The dc output voltage across load is given by

$$V_{dc} = I_{dc} \times R_L = \frac{2I_m R_L}{\pi} = 0.636 I_m R_L$$

Thus the dc output voltage is twice that of a half wave rectifier.

RMS Current

The RMS value of the current is given by

$$I_{rms} = \left[\frac{1}{\pi} \int_0^{\pi} i^2 d(\omega t) \right]^{\frac{1}{2}}$$

Since current is of the two same form in the two halves

$$\begin{aligned} &= \left[\frac{I_m^2}{\pi} \int_0^{\pi} \sin^2 \omega t d(\omega t) \right]^{\frac{1}{2}} \\ &= \frac{I_m}{\sqrt{2}} \end{aligned}$$

- -

Rectifier Efficiency

The rectifier efficiency is defined as

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

Now,

$$P_{dc} = (V_{dc})^2 / R_L = (2V_m / \pi)^2$$

And,

$$P_{ac} = (V_{rms})^2 / R_L = (V_m / \sqrt{2})^2$$

Therefore,

$$\begin{aligned}\eta &= \frac{P_{dc}}{P_{ac}} = \frac{(2V_m / \pi)^2}{(V_m / \sqrt{2})^2} = \frac{8}{\pi^2} \\ &= 0.812 = 81.2\%\end{aligned}$$

The rectifier efficiency can be calculated as follows –

The dc output power,

$$P_{dc} = I_{dc}^2 R_L = \frac{4I_m^2}{\pi^2} \times R_L$$

The ac input power,

$$P_{ac} = I_{rms}^2 (R_f + R_L) = \frac{I_m^2}{2} (R_f + R_L)$$

Therefore,

$$\begin{aligned} \eta &= \frac{4I_m^2 R_L / \pi^2}{I_m^2 (R_f + R_L) / 2} = \frac{8}{\pi^2} \frac{R_L}{(R_f + R_L)} \\ &= \frac{0.812}{\{1 + (R_f / R_L)\}} \end{aligned}$$

Therefore, Percentage Efficiency is

$$\begin{aligned} &= \frac{0.812}{1 + (R_f / R_L)} \\ &= 81.2\% \quad \text{if } R_f = 0 \end{aligned}$$

Thus, a full-wave rectifier has efficiency twice that of half wave rectifier.

Ripple Factor

The form factor of rectified output voltage of a full wave rectifier is given by

$$F = \frac{I_{rms}}{I_{dc}} = \frac{I_m/\sqrt{2}}{2I_m/\pi} = 1.11$$

The ripple factor γ is defined as (using ac circuit theory)

$$\begin{aligned}\gamma &= \left[\left(\frac{I_{rms}}{I_{dc}} \right)^2 - 1 \right]^{\frac{1}{2}} = (F^2 - 1)^{\frac{1}{2}} \\ &= \left[(1.11)^2 - 1 \right]^{\frac{1}{2}} = 0.48\end{aligned}$$

Regulation

The dc output voltage is given by

$$\begin{aligned}V_{dc} &= \frac{2I_m R_L}{\pi} = \frac{2V_m R_L}{\pi(R_f + R_L)} \\ &= \frac{2V_m}{\pi} \left[1 - \frac{R_f}{R_f + R_L} \right] = \frac{2V_m}{\pi} - I_{dc} R_f\end{aligned}$$

Transformer Utilization Factor

The TUF of a half wave rectifier is 0.287

There are two secondary windings in a center-tapped rectifier and hence the TUF of centertapped full wave rectifier is

$$\begin{aligned}(TUF)_{avg} &= \frac{P_{dc}}{V - A \text{ rating of a transformer}} \\ &= \frac{(TUF)_p + (TUF)_s + (TUF)_s}{3} \\ &= \frac{0.812 + 0.287 + 0.287}{3} = 0.693\end{aligned}$$

Diode Clipping Circuits or Limiting Circuits:

Clipping circuits are used to **remove a portion of a time varying input signal without distorting the remaining part of the applied waveform**. One simple example of a clipper is a **half-wave rectifier** which transfers only one half cycle of the input to the output, while clipping off the other half cycle. By changing orientation of the diode in the circuit, positive or negative portion of the input signal can be clipped off.

A. Shunt or Parallel Clipper:

In parallel clipper the diode appears in the **parallel branch or shunt** with the applied input signal. The Fig.1.1 shows a shunt clipper with bias or reference voltage V_R .

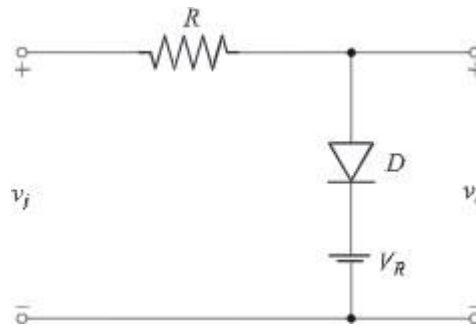


Fig.1.1: Shunt Clipper

The input signal can be any periodic signal such as sine, square, triangle etc. with peak value V_M greater than reference voltage V_R . If $V_M < V_R$, the clipping does not take place. Just before the diode conducts, the current through R is zero and hence input signal V_I is directly available at the anode of the diode as shown in Fig.1.2.

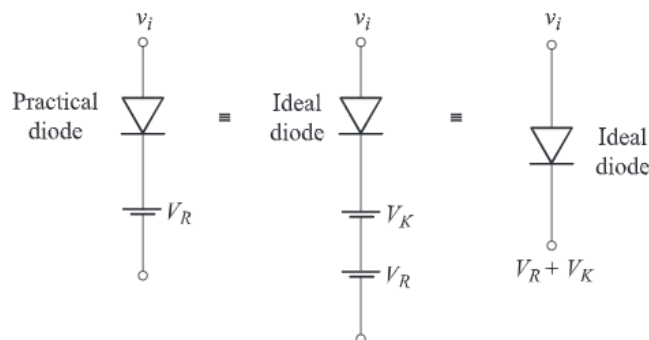


Fig.1.2: Voltage at diode terminals

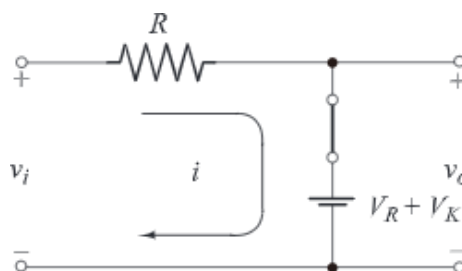


Fig.1.3 (a): Diode Conduction

For the ideal diode to conduct, it is enough that the anode voltage just equals the cathode voltage. For the circuit in Fig.1.1 the diode conducts for $v_I \geq V_R + V_K$. The equivalent circuit during the diode conduction is shown in Fig.1.3 (a).

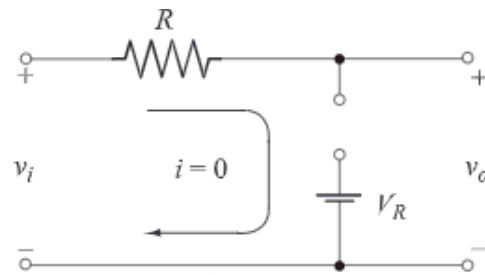


Fig.1.3 (b): Diode Off

From the circuit of Fig.1.3 (a) we find that

$$v_O = V_R + V_K \text{ for } v_I \geq V_R + V_K \text{-----(1)}$$

For $v_I \leq V_R + V_K$, the diode is off and the equivalent circuit is shown in Fig.1.3 (b). By applying KVL to the circuit we get,

$$v_i - iR - v_o = 0$$

$$v_o = v_i, \text{ for } v_i \leq V_R + V_K \text{-----(2)}$$

The output waveforms are shown in Fig.1.4. The circuit clips off a portion of the input signal which lies above $V_R + V_K$ and retains the remaining part as it is.

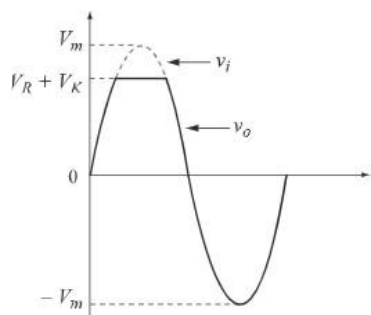


Fig.1.4: Waveforms of shunt clipper with positive clipping.

Transfer Characteristics:

The transfer characteristics are obtained by plotting v_o as a function of v_i . Transfer characteristics can be easily constructed by evaluating slope $\Delta v_o / \Delta v_i$.

For $v_i \geq V_R + V_K$ from equation (1), $v_o = V_R + V_K = \text{constant}$

$$\Delta v_o = 0$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 0 \text{ ----- (3)}$$

for $v_i \leq V_R + V_K$, from equation (2), $v_o = v_i$

$$\Delta v_o = \Delta v_i$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 1 \text{ ----- (4)}$$

The Fig.1.5 shows the transfer characteristics of shunt clipper along with output waveform for sinusoidal input.

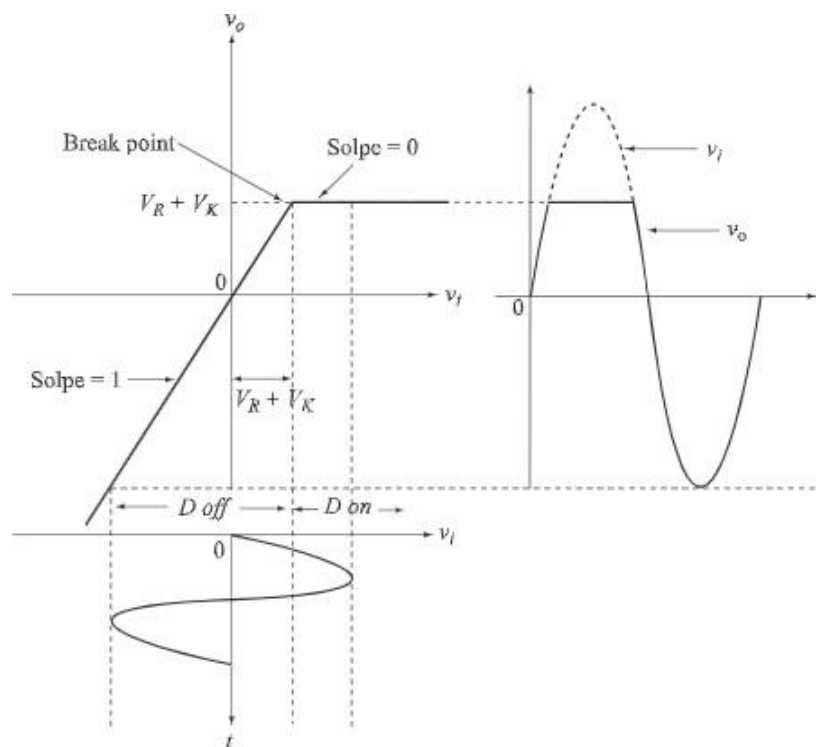


Fig.1.5: Transfer characteristics and output waveform of shunt clipper.

B. Series Clipper:

In series clipper the diode appears in series with the input or it appears in the series branch as shown in Fig.1.6. The voltage on diode terminals is shown in Fig.1.7.

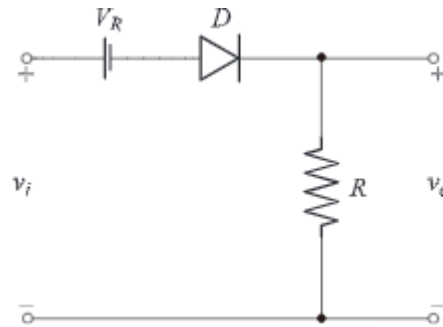


Fig.1.6: Series Clipper.

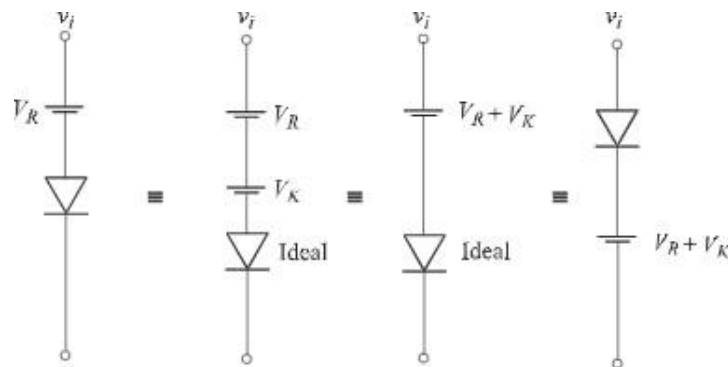


Fig.1.6: Voltage on Diode Terminals.

The diode conducts for $v_i \geq V_R + V_K$. The equivalent circuit during diode conduction is shown in Fig.1.7 (a).

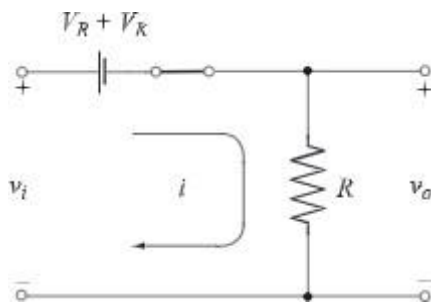


Fig.1.7 (a): Diode Conduction

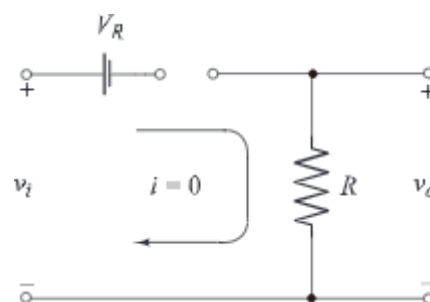


Fig.1.7 (b): Diode Off

Applying KVL to the circuit shown in Fig.1.7 (a) we have,

$$v_i - [V_R + V_K] - v_o = 0$$

$$v_o = v_i - [V_R + V_K] \quad \text{for } v_i \geq V_R + V_K \text{----- (5)}$$

Since $V_R + V_K$ is constant

$$\Delta v_o = \Delta v_i$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 1$$

From equation (5), when $v_i = v_m$,

$$v_o = v_m - [V_R + V_K] \text{----- (6)}$$

For $v_i \leq V_R + V_K$, the diode is off and the equivalent circuit is shown in Fig.1.7 (b). By applying KVL to the circuit we get,

$$v_o = iR = 0$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 0 \text{----- (7)}$$

The transfer characteristics and the output voltage waveform are shown in Fig.1.8.

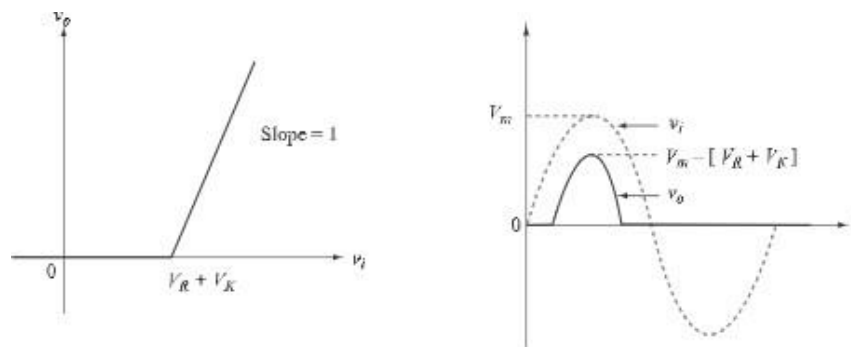


Fig.1.8: Transfer Characteristics and Output voltage Waveform.

C. Clipping at Two Independent Levels (Double ended clipper):

Two shunt clippers can be combined to obtain clipping at two independent levels. The Fig.1.9 shows the double ended clipper circuit which uses two reference voltages.

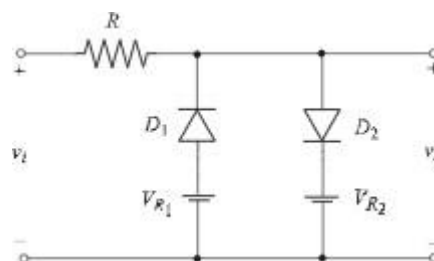
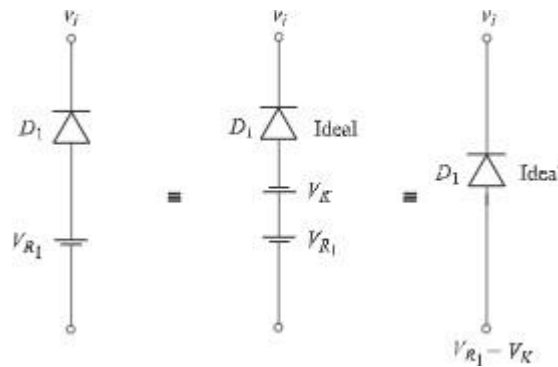


Fig.1.9: Double ended clipper circuit.

Note that V_{R1} and V_{R2} are positive. V_{R1} forward biases D_1 and V_{R2} reverse biases D_2 and also $V_{R2} > V_{R1}$. The voltages on the terminals of diode D_1 is shown in Fig.1.10.


 Fig.1.10: Terminal Voltages on D_1

The diode D_1 conducts for $v_i \leq V_{R1} - V_K$. The equivalent circuit is shown in Fig.1.11 (a). We can find that;

$$v_o = V_{R1} - V_K \quad \text{for } v_i \leq V_{R1} - V_K$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 0 \text{ ----- (8)}$$

The diode D_2 conducts for $v_i \geq V_{R2} + V_K$. The equivalent circuit is shown in Fig.1.11 (b). We can find that;

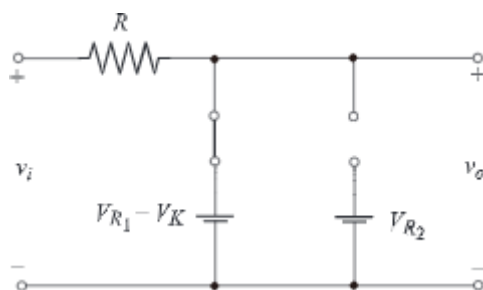
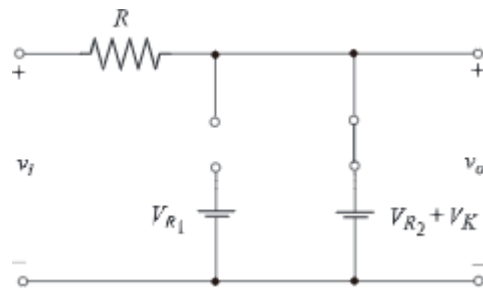
$$v_o = V_{R2} + V_K \quad \text{for } v_i \geq V_{R2} + V_K$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 0 \text{ ----- (9)}$$

For $(V_{R1} - V_K) < v_i < (V_{R2} + V_K)$, neither D_1 nor D_2 conducts. The equivalent circuit is shown in Fig.1.11 (c). From the circuit we get;

$$v_o = v_i$$

$$\text{Hence slope } \frac{\Delta v_o}{\Delta v_i} = 1 \text{ ----- (10)}$$


 Fig.1.11 (a): Equivalent circuit for $v_i \leq V_{R1} - V_K$

 Fig.1.11 (b): Equivalent circuit for $v_i \geq V_{R2} + V_K$

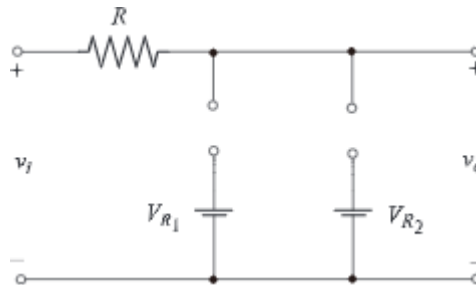


Fig.1.11 (c): Equivalent circuit for $(V_{R1} - V_K) < v_i < (V_{R2} + V_K)$.

Table 1.1: Summary on Operation of Double ended clipper.

Input voltage	Diode status	Output voltage	Slope
$v_i \leq V_{R1} - V_K$	D_1 on D_2 off	$v_o = V_{R1} - V_K$	0
$V_{R1} - V_K < v_i < V_{R2} + V_K$	D_1 off D_2 off	$v_o = v_i$	1
$v_i \geq V_{R2} + V_K$	D_1 off D_2 on	$v_o = V_{R2} + V_K$	0

The transfer characteristics along with output waveforms are shown in Fig.1.12.

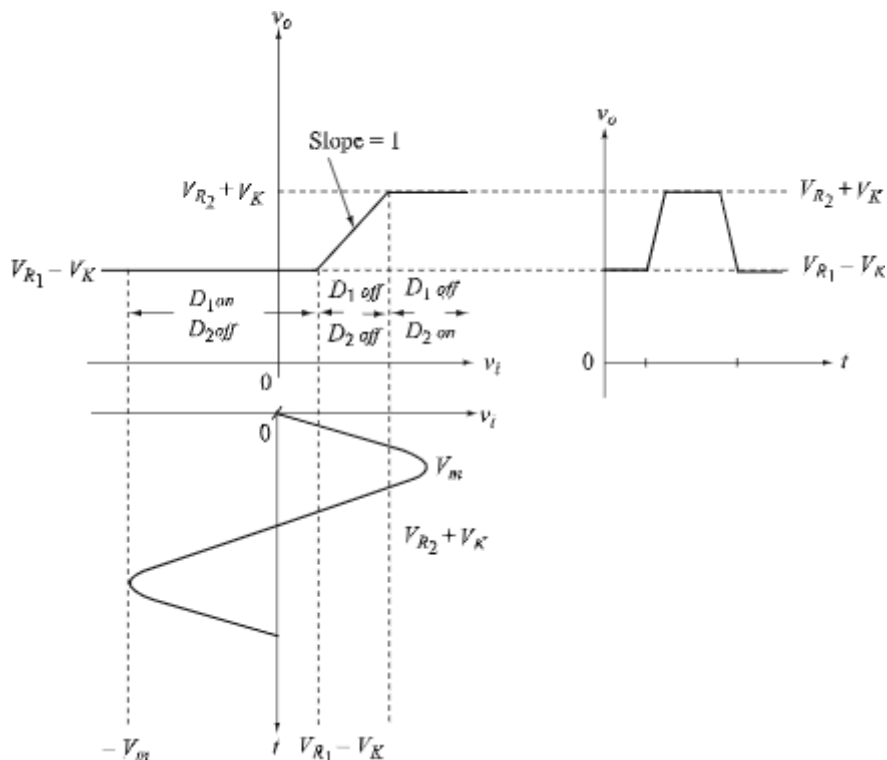


Fig.1.12: Transfer characteristics and output voltage waveform.

Clamping Circuits:

Clamping circuits are used to **add dc level** to the input signal. Clamping circuits are also called as **dc inserters or dc restorers**. Clamping circuits uses **diode, resistor and capacitor**.

Negative Clamper:

The circuit of negative clamper is shown in Fig.1.13. A simple negative clamper circuit is used to add a negative level to the ac output. The following assumptions are made while analysing the clamper circuit.

1. The diode is ideal in behaviour.
2. The time constant $\tau = RC$ is designed to very large by selecting large values of **R** and **C**.

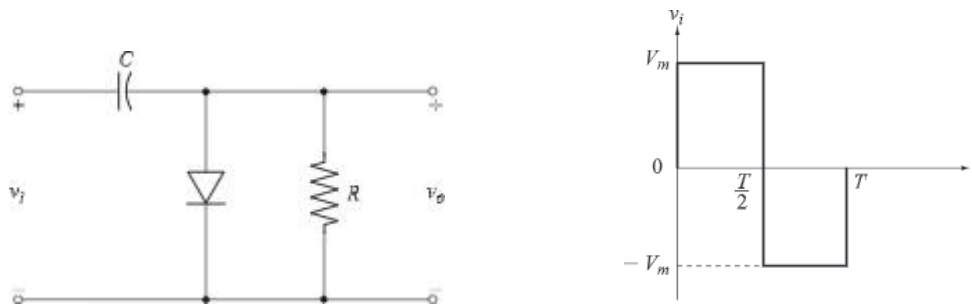


Fig.1.13: Negative clamper circuit.

The input is square wave which swings between the $\pm V_M$ with a period of $T = 1/f$. During the positive half cycle of the input the diode conducts and charges the capacitor. The charging time constant is $\tau_f = r_f C$. Since the diode resistance is very small $\tau_f \ll T/2$ and hence capacitor gets charged quickly to the peak value V_M of the input signal V_I . The equivalent circuit during diode conduction is shown in Fig.1.14 (a).

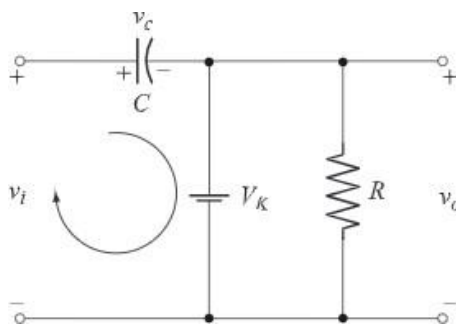


Fig.1.14 (a): Diode is ON

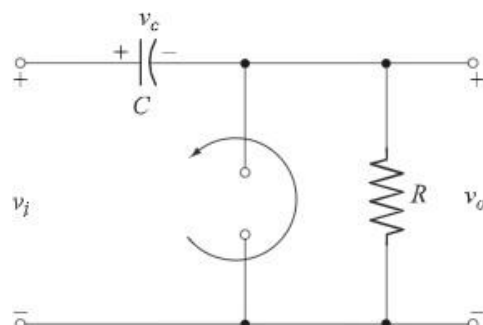


Fig.1.14 (b): Diode is OFF

Apply KVL to the circuit shown in Fig.1.14 (a) we get;

$$v_i - v_c - V_K = 0 \text{ -----(11)}$$

$$v_c = V_K - v_i$$

$$\text{When } v_i = V_M; v_c = V_K - V_M \text{-----(12)}$$

During the negative half cycle of the input supply, the diode turns off. Now the capacitor discharges into R. The discharge time constant is $\tau = RC$. The capacitor should not loose much of charge during discharge. To meet this requirement, the values of R & C are selected such that $5\tau \gg T/2 = 5RC \gg T/2$.

The equivalent circuit during the capacitor discharge is shown in Fig.1.14 (b). Apply the KVL for the circuit we get;

$$v_i - v_c - v_o = 0 \text{----- (13)}$$

$$v_o = v_i - v_c$$

$$\text{When } v_c = V_M - V_K; v_o = v_i - [V_M - V_K] \text{----- (14)}$$

Table 1.2: Output voltage levels of negative clamper

Input voltage level v_i	Output voltage level	
	Practical diode $v_o = v_i - [V_m - V_K]$	Ideal diode $v_o = v_i - V_m$
0	$-[V_m - V_K]$	$-V_m$
V_m	V_K	0
$-V_m$	$-2V_m + V_K$	$-2V_m$

The output voltage waveforms of negative clamper circuit are shown in Fig.1.15. From the waveforms we can observe that;

$$\text{Peak to peak input voltage} = \text{peak to peak output voltage} = 2 V_M$$

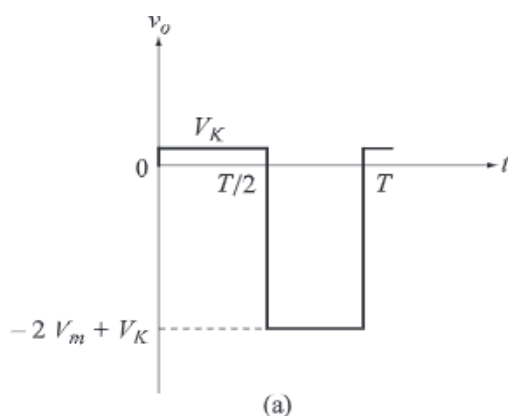


Fig.1.15 (a): Output waveform for Practical diode

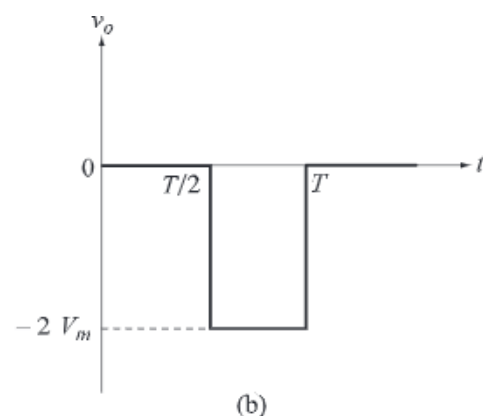


Fig.1.14 (b): Output waveform for Ideal diode

Positive Clamper:

The positive clamper circuit is obtained by **reversing the diode** direction in the negative clamper circuit. The positive clamper circuit is shown in Fig.1.16. The positive clamper circuit adds the **positive dc level** to the input signal.

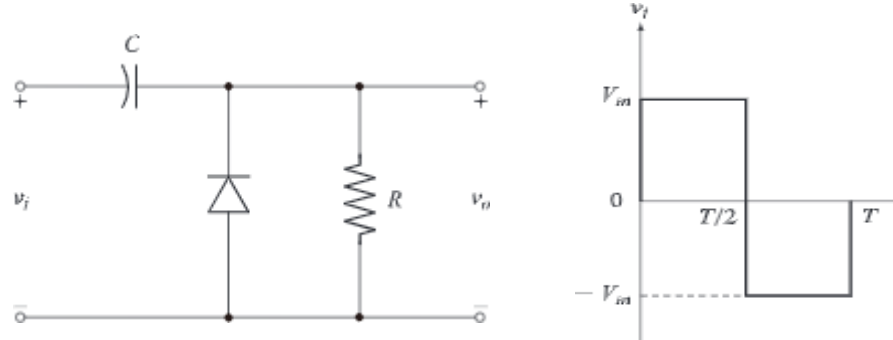
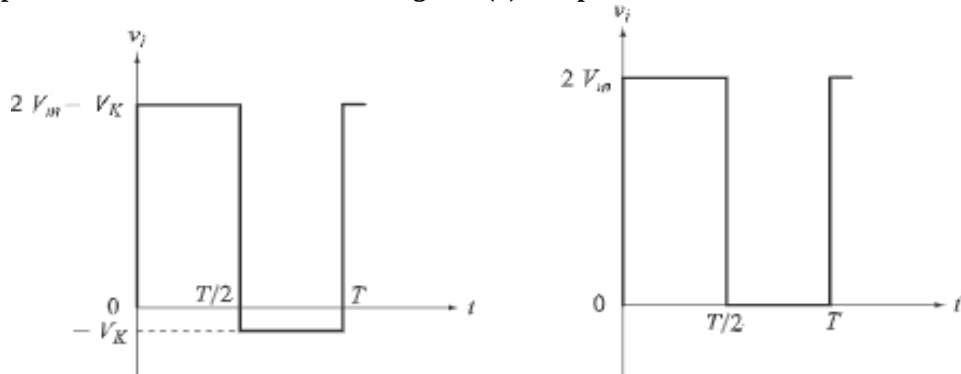


Fig.1.16: Positive clamper circuit

During the negative half cycle of the input supply, the diode gets forward biased and almost instantaneously capacitor gets charged equal to the maximum value V_M of the input signal. The capacitor once charged acts as a battery of voltage V_M . This is because RC time constant is very large hence capacitor holds its entire charge all the time.

In the positive half cycle the diode is reverse biased and the capacitor gets discharging through load resistance. Due to large time constant, it hardly gets discharged during the positive half cycle of the input supply. The waveforms of positive clamper circuit are shown in Fig.1.17.

Fig.1.17 (a): Output waveform for Practical diode Fig.1.17 (b): Output waveform for Ideal diode Table 1.3:



Output voltage levels of negative clamper

Input voltage level v_i	Output voltage level	
	Practical diode $v_o = v_i + [V_m - V_K]$	Ideal diode $v_o = v_i + V_m$
0	$V_m - V_K$	V_m
V_m	$2V_m - V_K$	$2V_m$
$-V_m$	$-V_K$	0

ZENER DIODE

A Zener diode is a special type of diode that allows current to flow in reverse when a set voltage, called Zener voltage, is exceeded.

Zener diode is basically like an ordinary PN junction diode but normally operated in reverse biased condition. But ordinary PN junction diode connected in reverse biased condition is not used as Zener diode practically. A Zener diode is a specially designed, highly doped PN junction diode.

Working Principle of Zener Diode

When a PN junction diode is reverse biased, the depletion layer widens. Continuously increasing the reverse bias voltage across the diode makes this layer even wider. Simultaneously, a constant reverse saturation current flows due to minority carriers.

At a specific reverse voltage, minority carriers gain enough kinetic energy from the strong electric field. These energetic electrons collide with stationary ions in the depletion layer, releasing more electrons. The process continues, generating additional free electrons through cumulative collisions. Due to this commutative phenomenon, very soon, huge free electrons get created in the depletion layer, and the entire diode will become conductive. This type of breakdown of the depletion layer is known as avalanche breakdown, but this breakdown is not quite sharp.

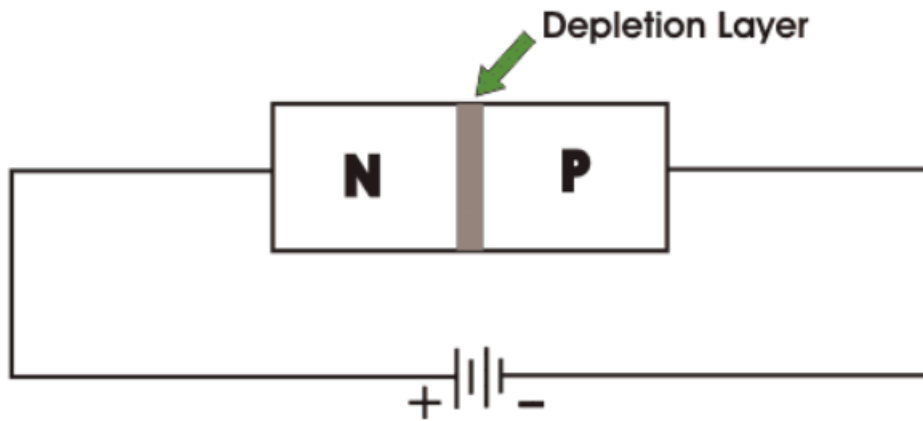
The thinner depletion layer causes a high voltage gradient or electric field strength. Increasing the reverse voltage further leads to a point where electrons break free from covalent bonds, making the region conductive. This is the Zener breakdown. The voltage at which this breakdown occurs is called Zener voltage. If the applied reverse voltage across the diode is more than Zener voltage, the diode provides a conductive path to the current through it hence, there is no chance of further avalanche breakdown in it.

Theoretically, Zener breakdown occurs at a lower voltage level than avalanche breakdown in a diode, especially doped for Zener breakdown. The Zener breakdown is much sharper than avalanche breakdown. The Zener voltage of the diode gets adjusted during manufacturing with the help of required and proper doping.

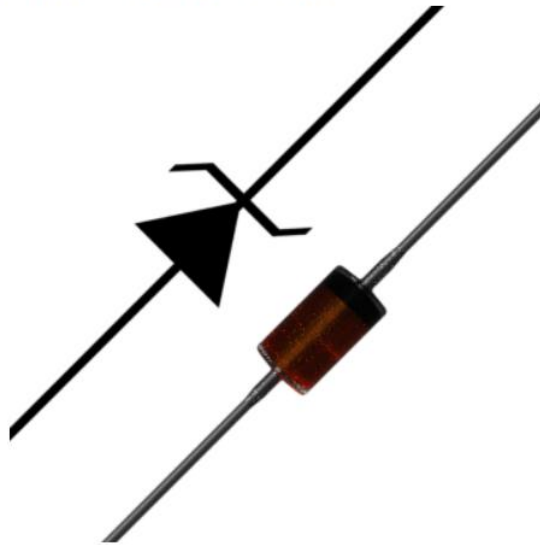
When a zener diode is connected across a voltage source, and the source voltage is more than Zener voltage, the voltage across a Zener diode remain fixed irrespective of the source voltage. Although at that condition current through the diode can be of any value depending on the load connected with the diode. That is why we use a Zener diode mainly for controlling voltage in different circuits.

Zener Diode Circuit

Zener Diode is nothing but a single diode connected in a reverse bias, we have already stated that. A diode connected in reverse bias position in a circuit is shown below,

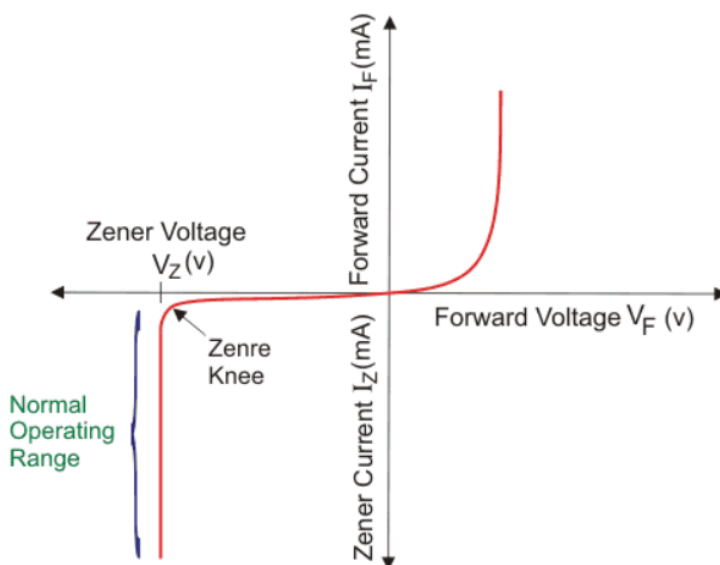


The circuit symbol of a Zener diode is also shown below.



Characteristics of a Zener Diode

Now, discussing about the diode circuits we should look through the graphical representation of the operation of the zener diode. Normally, it is called the V-I characteristics of a Zener diode.



The above diagram shows the V-I characteristics of a zener diode. When the diode is connected in forward bias, this diode acts as a normal diode but when the reverse bias voltage is greater than zener voltage, a sharp breakdown takes place. In the V-I characteristics above V_z is the zener voltage. It is also the knee voltage because at this point the current increases very rapidly.

LIGHT EMITTING DIODES

The increasing use of digital displays in calculators, watches, and all forms of instrumentation has contributed to an extensive interest in structures that emit light when properly biased. The two types in common use to perform this function are the light-emitting diode (LED) and the liquid-crystal display (LCD).

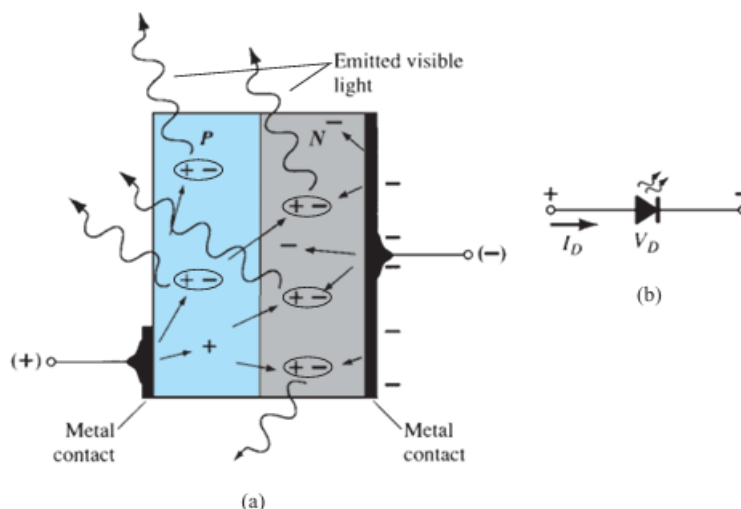
As the name implies, the light-emitting diode is a diode that gives off visible or invisible (infrared) light when energized. In any forward-biased p – n junction there is, within the structure and primarily close to the junction, a recombination of holes and electrons. This recombination requires that the energy possessed by the unbound free electrons be transferred to another state. In all semiconductor p – n junctions some of this energy is given off in the form of heat and some in the form of photons.

In Si and Ge diodes the greater percentage of the energy converted during recombination at the junction is dissipated in the form of heat within the structure, and the emitted light is insignificant.

For this reason, silicon and germanium are not used in the construction of LED devices.

On the other hand: Diodes constructed of GaAs emit light in the infrared (invisible) zone during the recombination process at the p–n junction.

The basic construction of an LED appears in Fig. below with the standard symbol used for the device. The external metallic conducting surface connected to the p -type material is smaller to permit the emergence of the maximum number of photons of light energy when the device is forward-biased. Note in the figure that the recombination of the injected carriers due to the forward-biased junction results in emitted light at the site of the recombination.



It is interesting to note that invisible light has a lower frequency spectrum than visible light. In general, when one talks about the response of electroluminescent devices, one references their wavelength rather than their frequency.

The two quantities are related by the following equation:

$$\lambda = \frac{c}{f} \quad (\text{m})$$

where $c = 3 \times 10^8$ m/s (the speed of light in a vacuum)
 f = frequency in Hertz
 λ = wavelength in meters.

SERIES AND PARALLEL VOLTAGE REGULATORS

For a Power supply to produce a constant output voltage, irrespective of the input voltage variations or the load current variations, there is a need for a voltage regulator.

A voltage regulator is such a device that maintains constant output voltage, instead of any kind of fluctuations in the input voltage being applied or any variations in current, drawn by the load.

Types of Regulators

Regulators can be classified into different categories, depending upon their working and type of connection.

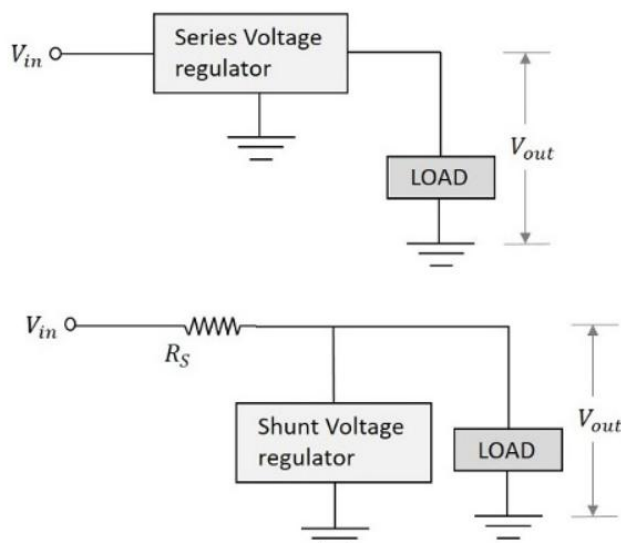
Depending upon the type of regulation, the regulators are mainly divided into two types namely, line and load regulators.

- Line Regulator – The regulator which regulates the output voltage to be constant, in spite of input line variations, it is called as Line regulator.
- Load Regulator – The regulator which regulates the output voltage to be constant, in spite of the variations in load at the output, it is called as Load regulator.

Depending upon the type of connection, there are two type of voltage regulators. They are

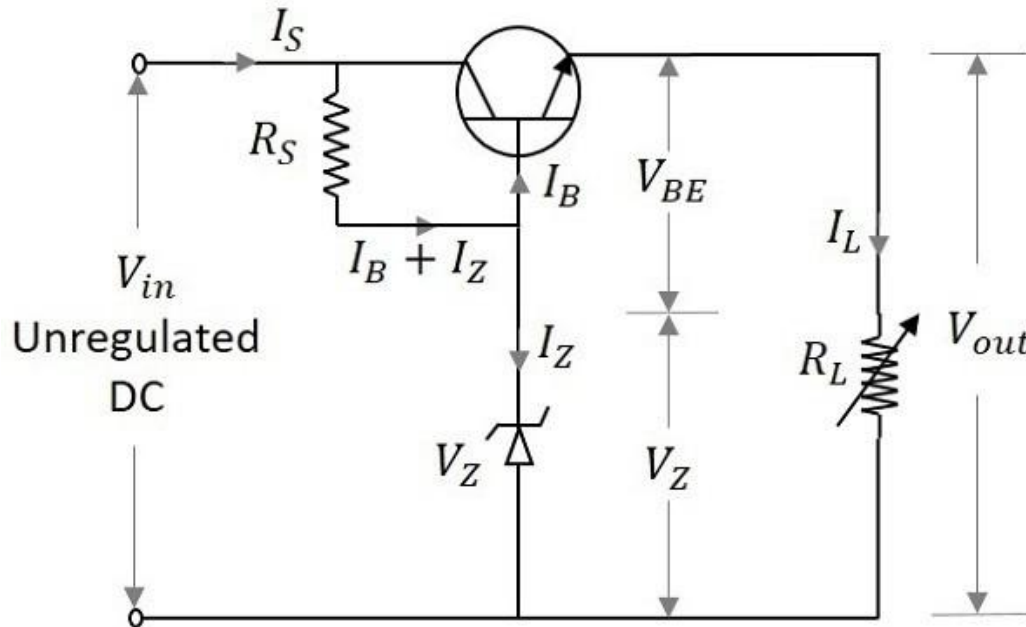
- Series voltage regulator
- Shunt voltage regulator

The arrangement of them in a circuit will be just as in the following figures.



Series Voltage Regulator

This regulator has a transistor in series to the Zener regulator and both in parallel to the load. The transistor works as a variable resistor regulating its collector emitter voltage in order to maintain the output voltage constant. The figure below shows the transistor series voltage regulator.



With the input operating conditions, the current through the base of the transistor changes. This effects the voltage across the base emitter junction of the transistor V_{BE} . The output voltage is maintained by the Zener voltage V_Z which is constant. As both of them are maintained equal, any change in the input supply is indicated by the change in emitter base voltage V_{BE} .

Hence the output voltage V_o can be understood as

$$V_o = V_Z + V_{BE}$$

Working of Series Voltage Regulator

The working of a series voltage regulator shall be considered for input and load variations. If the input voltage is increased, the output voltage also increases. But this in turn makes the voltage across the collector base junction V_{BE} to decrease, as the Zener voltage V_Z remains constant.

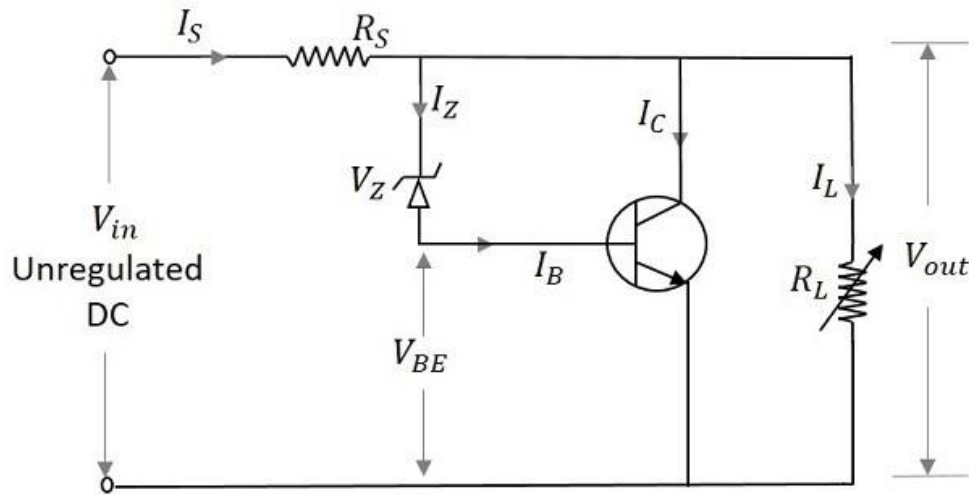
The conduction decreases as the resistance across emitter collector region increases. This further increases the voltage across collector emitter junction V_{CE} thus reducing the output voltage V_o . This will be similar when the input voltage decreases.

When the load changes occur, which means if the resistance of the load decreases, increasing the load current I_L , the output voltage V_o decreases, increasing the emitter base voltage V_{BE} .

With the increase in the emitter base voltage V_{BE} the conduction increases reducing the emitter collector resistance. This in turn increases the input current which compensates the decrease in the load resistance. This will be similar when the load current increases.

Shunt Voltage Regulator

A transistor shunt regulator circuit is formed by connecting a resistor in series with the input and a transistor whose base and collector are connected by a Zener diode that regulates, both in parallel with the load. The figure below shows the circuit diagram of a transistor shunt regulator.



Working of Shunt Voltage Regulator

If the input voltage increases, the V_{BE} and V_O also gets increased. But this happens initially. Actually when V_{in} increases, the current I_{in} also increases. This current when flows through R_S , causes a voltage drop V_S across the series resistor, which also gets increased with V_{in} . But this makes V_O to decrease. Now this decrease in V_O compensates the initial increase maintaining it to be constant. Hence V_O is maintained constant. If the output voltage decreases instead, the reverse happens.

If the load resistance decreases, there should be decrease in the output voltage V_O . The current through the load increases. This makes the base current and collector current of the transistor to decrease. The voltage across the series resistor becomes low, as the current flows heavily. The input current will be constant.

The output voltage appears will be the difference between the applied voltage V_i and the series voltage drop V_s . Hence the output voltage will be increased to compensate the initial decrease and hence maintained constant. The reverse happens if the load resistance increases.

BIPOLAR JUNCTION TRANSISTORS

The transistor is a solid state device, whose operation depends upon the flow of electric charge carriers within the solid. Transistor is capable of amplification and in most respect it is analogous to a vacuum triode. The main difference between two is that the transistor is a current controlled device whereas vacuum triode is a voltage controlled device. The transistor is only about 6 decade old, yet it is replacing vacuum triode in almost all applications.

The reasons are obviously its advantages over vacuum tubes such as

- Compact size
- Light weight
- Rugged construction
- More resistive to shocks and vibrations
- Instantaneous operation (no heating required)
- Low operating voltage
- High operating efficiency (no heat loss)
- Long life

However, transistors, in comparison to vacuum triodes, have some drawbacks also such as loud hum noise, restricted operating temperature (up to 750C) and operating frequency (up to a few MHz only).

- The transistor was developed by Dr.Shockley along with Bell Laboratories team in 1951
- The transistor is a main building block of all modern electronic systems
- It is a three terminal device whose output current, voltage and power are controlled by its input current
- In communication systems it is the primary component in the amplifier
- An amplifier is a circuit that is used to increase the strength of an ac signal
- Basically there are two types of transistors
 - Bipolar junction transistor
 - Field effect transistor
- The important property of the transistor is that it can raise the strength of a weak signal
- This property is called amplification
- Transistors are used in digital computers, satellites, mobile phones and other communication systems, control systems etc.,
- A transistor consists of two P-N junction

- The junction are formed by sandwiching either p-type or n-type semiconductor layers between a pair of opposite types which is shown below

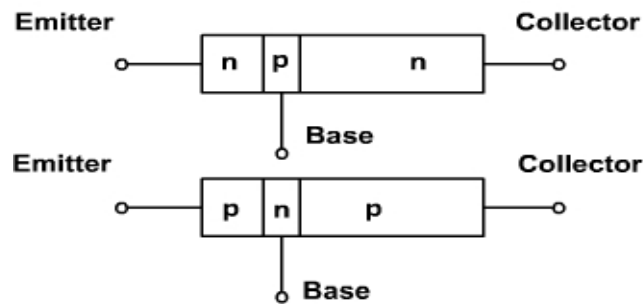
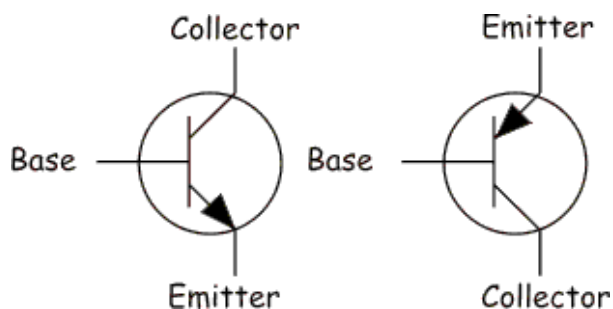


Fig: transistor

TRANSISTOR CONSTRUCTION

- A transistor has three regions known as emitter, base and collector
- Emitter:** it is a region situated in one side of a transistor, which supplies charge carriers (ie., electrons and holes) to the other two regions
- Emitter is heavily doped region
- Base:** It is the middle region that forms two P-N junction in the transistor
- The base of the transistor is thin as compared to the emitter and is a lightly doped region
- Collector:** It is a region situated in the other side of a transistor (ie., side opposite to the emitter) which collects the charge carriers.
- The collector of the transistor is always larger than the emitter and base of a transistor.
- The doping level of the collector is intermediate between the heavy doping of emitter and the light doping of the base

TRANSISTOR SYMBOLS



The transistor symbol carries an arrow head in the emitter pointing from the P- region towards the N- region

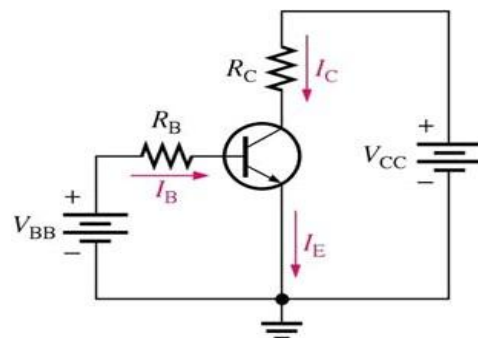
- The arrow head indicates the direction of a conventional current flow in a transistor
- The direction of arrow heads at the emitter in NPN and PNP transistor is opposite to each other
- The PNP transistor is a complement of the NPN transistor
- In NPN transistor the majority carriers are free electrons, while in PNP transistor these are the holes

UNBIASED TRANSISTORS

- A transistor with three terminals (Emitter, Base, Collector) left open is called an unbiased transistor or an open — circuited transistor
- The diffusion of free electrons across the junction produces two depletion layers
- The barrier potential of three layers is approximately 0.7v for silicon transistor and 0.3v for germanium transistor
- Since the regions have different doping levels therefore the layers do not have the same width
- The emitter base depletion layer penetrates slightly into the emitter as it is a heavily doped region where as it penetrates deeply into the base as it is a lightly doped region
- Similarly the collector- base depletion layer penetrates more into the base region and less into the collector region
- The emitter- base depletion layer width is smaller than the that of collector base depletion layer
- The unbiased transistor is never used in actual practice. Because of this we went for transistor biasing

OPERATION OF NPN TRANSISTOR

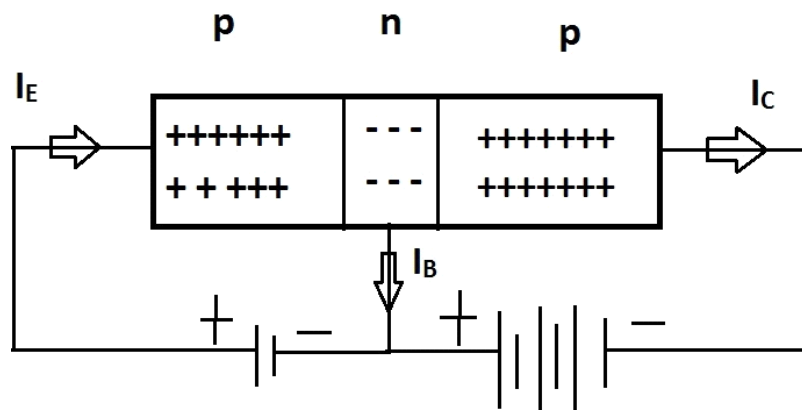
The NPN transistor is biased in forward active mode ie., emitter — base of transistor is forward biased and collector base junction is reverse biased



(a) npn

- The emitter — base junction is forward biased only if V is greater than barrier potential which is 0.7v for silicon and 0.3v for germanium transistor
- The forward bias on the emitter- base junction causes the free electrons in the N —type emitter to flow towards the base region. This constitutes the emitter current. Direction of conventional current is opposite to the flow of electrons
- Electrons after reaching the base region tend to combine with the holes
- If these free electron combine with holes in the base, they constitute base current.
- Most of the free electrons do not combine with the holes in the base
- This is because of the fact that the base and the width is made extremely small and electrons do not get sufficient holes for recombination
- Thus most of the electrons will diffuse to the collector region and constitutes collector current. This collector current is also called injected current, because of this current is produced due to electrons injected from the emitter region
- There is another component of collector current due to the thermal generated carriers.
- This is called as reverse saturation current and is quite small

OPERATION OF PNP TRANSISTOR



p-n-p transistor

- Operation of a PNP transistor is similar to npn transistor
- The current within the PNP transistor is due to the movement of holes where as, in an NPN transistor it is due to the movement of free electrons
- In PNP transistor, its emitter — base junction is forward biased and collector base junction is reverse biased.
- The forward bias on the emitter — base junction causes the holes in the emitter

region to flow towards the base region. This constitutes the emitter current

- The holes after reaching the base region, combine with the electrons in the base and constitutes base current.
- Most of the holes do not combine with the electrons in the base region
- This is due to the fact that base width is made extremely small, and holes does not get sufficient electrons for recombination.
- Thus most of the holes diffuse to the collector region and constitutes collector region
- This current is called injected current, because it is produced due to the holes injected from the emitter region
- There is small component of collector current due to the thermally generated carriers
- This is called reverse saturation current.

TRANSISTOR CURRENTS

- We know that direction of conventional current is always opposite to the electron current in any electronic device.
- However, the direction of a conventional current is same as that of a hole current in a PNP transistor

Emitter current

Base current

Collector current

- Since the base current is very small

TRANSISTOR CONFIGURATIONS

- A transistor is a three terminal device, but we require four terminals (two for input and two for output) for connecting it in a circuit.
- Hence one of the terminal is made common to the input and output circuits.
- The common terminal is grounded
- There are three types of configuration for the operation of a transistor

Common base configuration (CB)

- This is also called grounded base configuration
- In this configuration emitter is the input terminal, collector is the output terminal and base is the common terminal

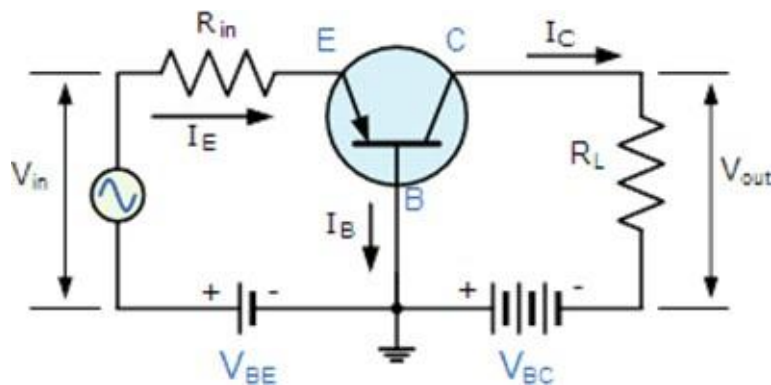
Common emitter configuration (CE)

- This is also called grounded emitter configuration
- In this configuration base is the input terminal, collector is the output terminal and emitter is the common terminal

Common collector configuration (CC)

- This is also called grounded collector configuration
- In this configuration, base is the input terminal, emitter is the output terminal and collector is the common terminal.

Common base configuration (CB)



- The input is connected between emitter and base and output is connected across collector and base
- The emitter – base junction is forward biased and collector – base junction is reverse biased.
- The emitter current, flows in the input circuit and the collector current flows in the output circuit.
- The ratio of the collector current to the emitter current is called current amplification factor.
- If there is no input ac signal, then the ratio of collector current to emitter current is called dc alpha

- The ratio of change in the collector current to change in the emitter current is known as ac alpha

Common-emitter current gain=Common-base current gain

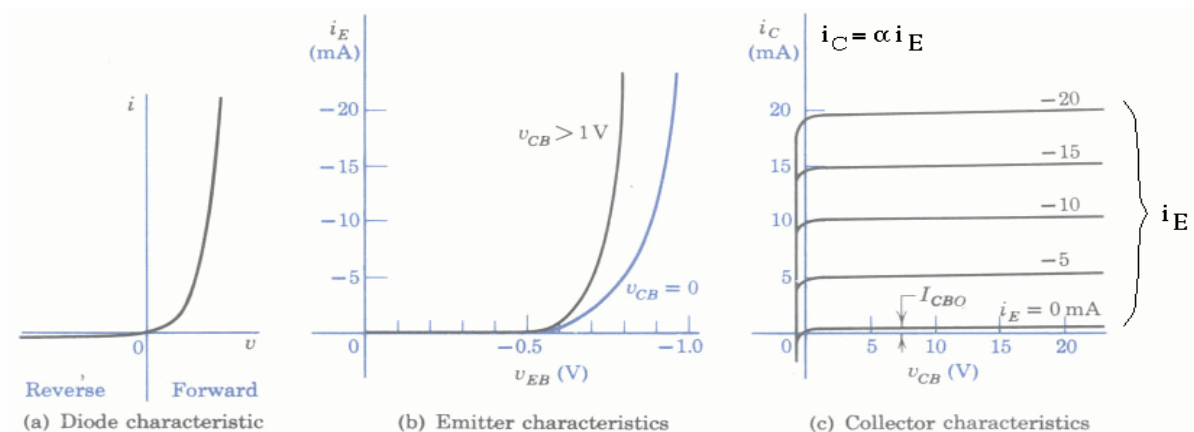
- The input characteristics look like the characteristics of a forward-biased diode. Note that V_{BE} varies only slightly, so we often ignore these characteristics and assume:

Common approximation: $V_{BE} = V_o = 0.65 \text{ to } 0.7\text{V}$

- The higher the value of better the transistor. It can be increased by making the base thin and lightly doped.
- The collector current consists of two parts transistor action. I.e., component depending upon the emitter current, which is produced by majority carriers
- The leakage current due to the movement of the minority carriers across base collector junction

CHARACTERISTICS OF CB CONFIGURATION

- The performance of transistors determined from their characteristic curves that relate different d.c currents and voltages of a transistor
- Such curves are known as static characteristics curves
- There are two important characteristics of a transistor
 - Input characteristics
 - Output characteristics



INPUT CHARACTERISTICS

The curve drawn between emitter current and emitter — base voltage for a given value of collector — base voltage is known as input characteristics. It reduces the chances of recombination of electrons with the holes in the base region. Hence current gain increases with increase in collector — base voltage. The concentration gradient of minority carriers within

the base increases.

This increases the emitter current. For extremely collector voltage, the effective base width may be reduced to zero, resulting in voltage breakdown of a transistor. This phenomenon is known as punch through. The emitter current increases rapidly with small increase in which means low input resistance. Because input resistance of a transistor is the reciprocal of the slope of the input characteristics

Base width modulation (or) Early effect

In a transistor, since the emitter — base junction is forward biased there is no effect on the width of the depletion region. However, since collector — base junction is reverse biased as the reverse bias voltage across the collector — base junction increase the width of the depletion region also increases.

Since the base is lightly doped the depletion region penetrates deeper into the base region. This reduces the effective width of the base region. This variation or modulation of the effective base width by the collector voltage is known as base width modulation or early effect. The decrease in base width by the collector voltage has the following three effects.

OUTPUT CHARACTERISTICS

The curve drawn between collector current and collector — base voltage, for a given value of emitter current is known as output characteristics

ACTIVE REGION:

- There is a very small increase in with increase in
- This is because the increase in expands the collector — base depletion region and shorten the distance between two depletion region
- Hence due to the early effect does not increase very much with increase in
- Although, the collector current is independent of if is increased beyond a certain value, eventually increases rapidly because of avalanche effects
- This condition is called punch – through or reach – through
- When it occurs large current can flow destroying the device

CUT – OFF REGION:

- small collector current flows even when emitter current
- this is the collector leakage current

SATURATION REGION:

- Collector current flows even when the external applied voltage is reduced to zero. There is a low barrier potential existing at the collector — base junction and this assists in the flow of collector current

COMMON – EMITTER CONFIGURATION

- The input is connected between base and emitter, while output is connected between collector and emitter
- Emitter is common to both input and output circuits.
- The bias voltage applied are V_{ce} and V_{be} .
- The emitter-base junction is forward biased and collector-emitter junction is reverse biased.
- The base current I_b flows in the input circuit and collector current I_c flows in the output circuit.
- CE is commonly used because its current, Voltage, Power gain are quite high and output to input impedance ratio is moderate
- The rate of change in collector current to change in base current is called amplification factor β .
- The current gain in the common-emitter circuit is called BETA (β). Beta is the relationship of collector current (output current) to base current (input current).
- Two voltages are applied respectively to the base B and collector C with respect to the common emitter E .
- Same as the CB configuration, here in the CE configuration, the BE junction is forward biased while the CB junction is reverse biased. The voltages of CB and CE configurations are related by:

$$V_{CE} = V_{CB} + V_{BE}, \quad \text{or} \quad V_{CB} = V_{CE} - V_{BE}$$

- The base current is treated as the input current, and the collector current is treated as the output current:

$$I_C = \alpha I_E + I_{CB0} = \alpha(I_C + I_B) + I_{CB0} \approx \alpha(I_C + I_B)$$

- Solving this equation for collector current, we get the relationship between the output collector current and the input base current:

$$I_C = \frac{\alpha}{1 - \alpha} I_B + \frac{1}{1 - \alpha} I_{CB0} = \beta I_B + (\beta + 1) I_{CB0} = \beta I_B + I_{ce0} \approx \beta I_B$$

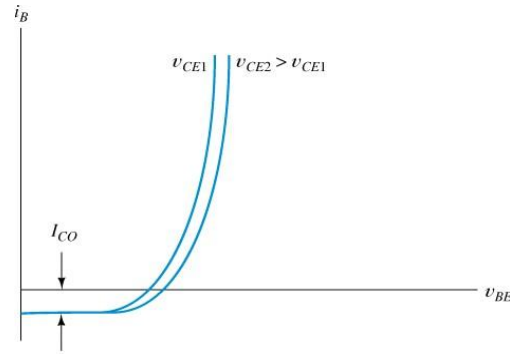
- Here we have also defined the CE *current gain* or *current transfer ratio*

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

- Which is approximately the ratio of the output current and the input current. The two parameters α and β are related by:

$$\beta = \frac{\alpha}{1 - \alpha}, \quad \alpha = \frac{\beta}{1 + \beta}, \quad 1 + \beta = \frac{1}{1 - \alpha}, \quad 1 - \alpha = \frac{1}{1 + \beta}$$

Characteristics of CE configuration



(a) Input characteristics

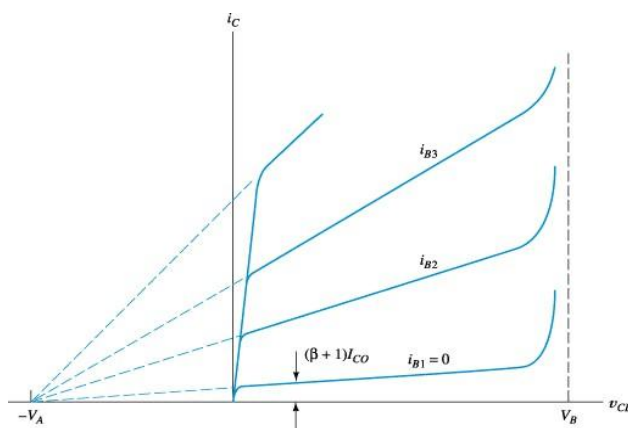
Input Characteristics

- Same as in the case of common-base configuration, the junction of the common-emitter configuration can also be considered as a forward biased diode, the current-voltage characteristics is similar to that of a diode:

$$I_B = f(V_{BE}, V_{CE}) \approx f(V_{BE}) = I_0(e^{V_{BE}/V_T} - 1)$$

- The Curve drawn between base current and base-emitter voltage for a given value of collector-emitter voltage is known as input characteristics.
- The input characteristics of CE transistors are similar to those of a forward biased diode because the base-emitter region of the transistor is forward-biased.
- Input Resistance is larger in CE configuration than in CB configuration.
This is because the I/P current increases less rapidly with increase in Vbe.
- An increment in value of Vce causes the input current to be lower for a given level of Vbe.
- This is explained on the basis of early effect.
- As a result of early effect, more charge carriers from the emitter flows across the collector-base junction and flow out through the based lead.

Output Characteristics



(b) Output characteristics

$$I_C = f(I_B, V_{CE}) \approx f(I_B) = \beta I_B \quad (\text{in linear region})$$

- It is the curve drawn between collector current I_C and collector-emitter voltage V_{CE} for a given value of base current I_B .
- The collector current I_C varies with V_{CE} and becomes a constant.
- Output characteristics in CE configuration has some slope while CB configuration has almost horizontal characteristics.
- This indicates that output resistance in case of CE configuration is less than that in CB configuration.

Active Region

- For small values of base current, the effect of collector voltage V_C over I_C is small but for large values of I_B , this effect increases.
- The shape of the characteristic is same as CB configuration
- The difference that I_C is larger than input current
- Thus, the current gain is greater than unity.

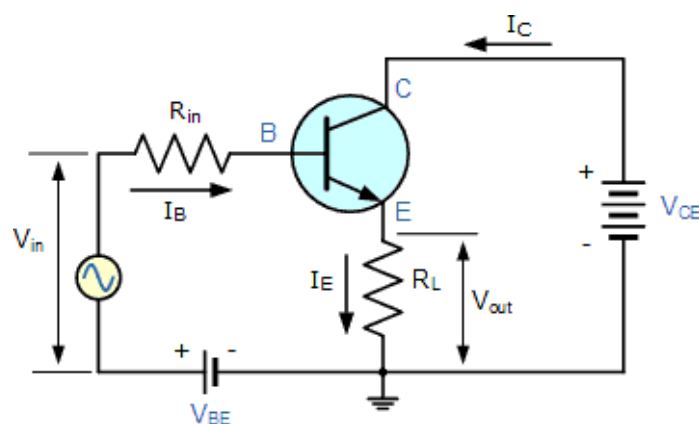
Saturation Region

- With low values of V_{CE} , the transistor is said to be operated in saturation region and in this region, base current I_B does not correspond to I_C ,

Cut off Region

- A small amount of collector current I_C flows even when $I_B=0$, This is called emitter leakage current.

Common Collector Configuration:



- Input is applied between base and collector while output is applied between emitter and collector.
- The collector forms the terminal common to both the input and output.
GAIN is a term used to describe the amplification capabilities of an amplifier. It is basically a ratio of output to input. The current gain for the three transistor configurations

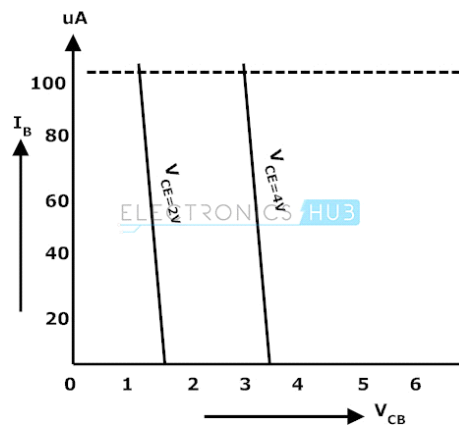
$$\alpha = \frac{\Delta I_C}{\Delta I_E}$$

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

$$\gamma = \frac{\Delta I_E}{\Delta I_B}$$

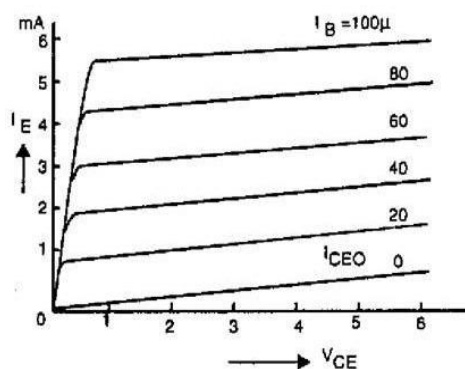
(CB, CE, and CC) are ALPHA(a), BETA (b), and GAMMA (g), respectively.

Input Characteristics



- To determine the i/p characteristics V_{ce} is kept at a suitable fixed value.
- The base collector voltage V_{bc} is increased in equal steps and the corresponding increase in I_b is noted.
- This is repeated for different fixed values of V_{ce} .

Output Characteristics

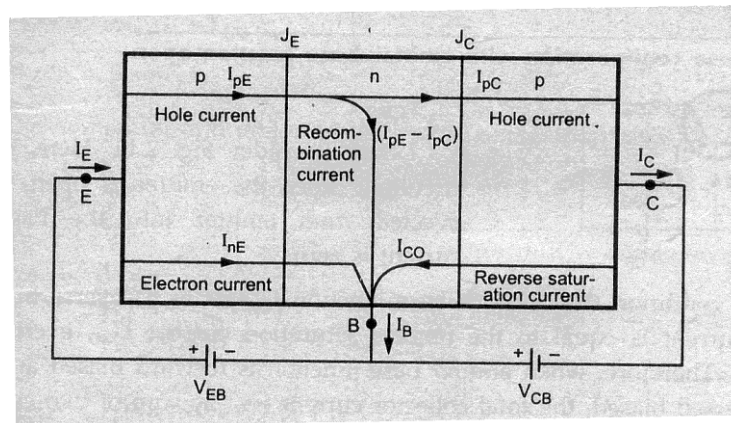


Transistor Current Components

- In the figure we show the various components which flow across the forward-biased emitter junction and the reverse-biased collector junction.
- The emitter current I_E consists of hole current I_{pE} (holes crossing from the emitter into

base) and electron current I_{nE} (electron crossing from base into the emitter).

- The ratio of hole to electron currents, I_{pE} / I_{nE} , crossing the emitter junction is proportional to the ratio of the conductivity of the p material to that of the n material.
- In the commercial transistor the doping of the emitter is made much larger than the doping of the base.
- This feature ensures (in a p-n-p transistor) that the emitter current consists almost entirely of the holes.
- Such a situation is desired since the current which results from electrons crossing the emitter junction from base to emitter does not contribute carriers which can reach the collector.
- Not all the holes crossing the emitter junction J_E reach the collector junction J_C because some of them combine with the electrons in the n — type base.
- If I_{pC} is the hole current at J_C , there must be a bulk recombination current I_{pE} - I_{pC} leaving the base (actually, electrons enter the base region through the base lead to supply those charges which have been lost by recombination with the holes injected into the base across J_E).



If the emitter were open-circuited so that $I_E = 0$, then I_{pC} would be zero.

- Under these circumstances, the base and collector would act as a reverse-biased diode, and the collector current I_C would equal the reverse saturation current I_{CO} . If $I_E \neq 0$, then
- From figure, we note that

$$I_C = I_{CO} - I_{pC}$$

- For a p-n-p transistor, I_{CO} consists of holes moving across J_C from left to right (base to collector) and electrons crossing J_C in the opposite direction.
- Since the assumed reference direction for I_{CO} in figure is from right to left, then for a p-n-p transistor, I_{CO} is negative. For an n-p-n transistor, I_{CO} is positive.