Department of Electronics & Communication Engineering

Basic Electronics Notes (ECE111)
NitteDU - 2025

NITTE
(Deemed to be University)
Where there is space for every dream

August - 2025

Contents

Chapter 1

Diodes and their Applications

1.1 Background

Materials can be classified into three types as mentioned below. The Figure 1.21 shows the energy band gap of different materials.

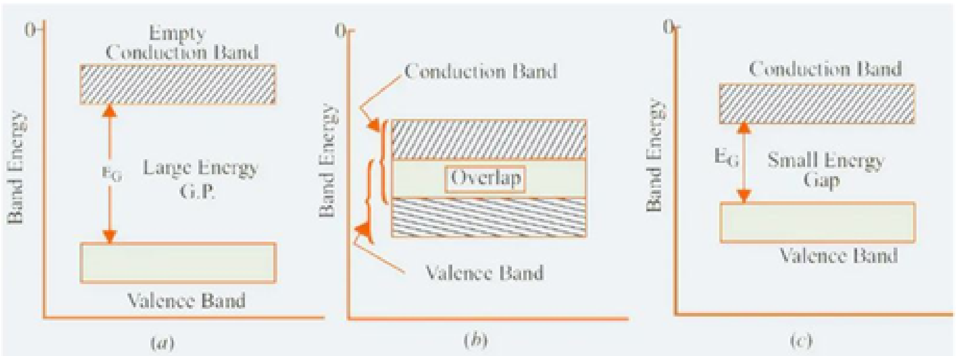


Figure 1.1: Energy Band Gap of different Materials: (a) Insulators, (b) Conductors, (c) Semiconductors

- ★ **Conductors**: Are very good carriers of electricity. They have a large number of free electrons since there is no energy gap between conduction band and valence band. E.g., Copper, Aluminium.
- ★ **Insulators**: Do not conduct electricity. There is a large energy gap between conduction band and valence band. Eg: Wood, glass.
- ★ **Semi-Conductors**: Are neither insulators, nor conductors. The band Gap between conduction band and valence band is very narrow. Eg: Germanium (Ge), Silicon (Si) conductivity lies between conductors and insulators. There are 2 types of semiconductors.
  - **Intrinsic semiconductors**: Semiconductor in its purest form is intrinsic semiconductor. It behaves as an insulator at zero temperature. At room temperature, electron hole pairs are created, due to the drift of electrons to the conduction bond. This creates a vacancy called as a 'hole'. Holes are positively charged while electrons are negatively charged.

Thus, the movement of electrons in conduction band yields electron and the movement of holes in valence band gives rises to a hole current.

- **Extrinsic semiconductors**: Are created by adding impurities (or other materials) to intrinsic semiconductors to improve conductivity or conduction nature of the materials used in diodes, transistors etc. Depending upon the type of impurities added, we have 2 types: P-type semiconductors and N-type semiconductors.
    - **P-type semiconductors**: Are produced by doping intrinsic semiconductors with trivalent impurities also known as acceptor impurities (ions). In this hole are majority charge carriers and electrons are the minority charge carriers. Eg: trivalent impurities are Boron, Aluminium.
    - **N-type semiconductors**: are generated by doping intrinsic semiconductors with pentavalent impurities. Eg: Arsenic, phosphorous. These impurities are known as donor ions. In n-type semiconductors, electrons are the majority charge carriers and holes are minority charge carriers.

NOTE:

- Active components: Transforms one form of signals to another form. Eg: Transistors, MOSFETS, OP-Amp, Gates.
- Passive Components: Diodes, Resistor (R), Inductor (L) and Capacitor (C) utilizes Power (P) or Voltage (V) from other sources.

1.2 PN DIODE

- N- type and P-type semiconductor materials are chemically combined with a special fabrication technique to form P-N junction. Such P-N junction forms a popular electronic device called P-N Junction diode.

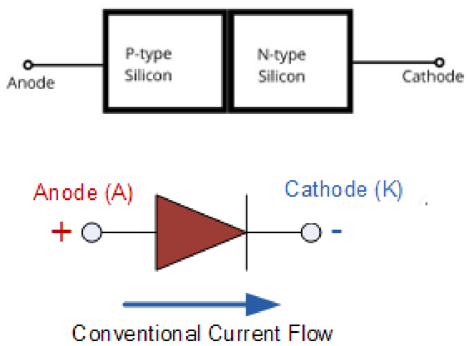


Figure 1.2: Diode Symbol

- A diode is a basic element for the number of electronic circuits.
- Diode is connected in two modes. That is Forward Bias and Reverse Bias
- P-N junction diode allows current flow when forward biased and blocks the current flow when reverse biased.

- It is a Uni-directional (one-way) device offering low-resistance when forward biased and behaving almost as open switch when reverse biased.
- Arrow head indicates the conventional direction of current flow when the diode is forward biased.
- Manufacturers provide datasets that specify the maximum forward current and reverse voltages for various types of diodes.
- Some diodes are low current diodes that are used in switching circuits. High current diodes are often used as rectifiers for ac to dc conversion.
- P-N junction diode can be get damaged if
  - A high forward current overheats the device
  - A large reverse voltage causes the junction breakdown.

1.2.1 Unbiased PN Junction Diode

- Unbiased P-N junction is the one where no external source is connected across the terminals of the device. Consider a zero bias P-N junction as shown in figure 1.3.

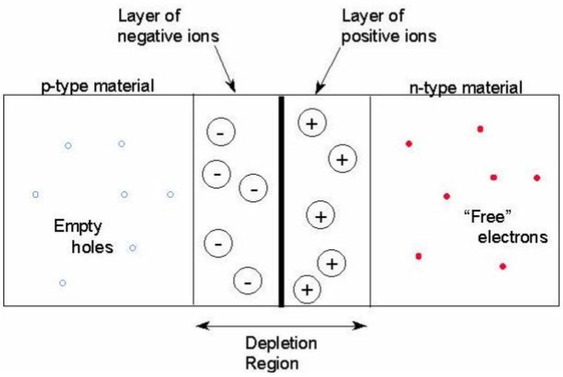


Figure 1.3: Unbaised Diode

- At N-type semiconductor, large number of free electrons are present while at P-type, small number of free electrons are present.
- Due to this high concentration of electrons at N-side, they get repelled from each other and hence try to move towards lower concentration region. Hence, the free electrons from N-side are attracted towards the holes at P-side. Thus, the free electrons move from N-side (high concentration region) to P-side (low concentration region) (called Diffusion)
- At P-type semiconductor, large number of holes are present while at N-type, semiconductor, small number of holes are present.
- Due to this high concentration of holes at P-side they get repelled and move towards lower concentration N-side. Hence, the holes from P-side are attracted towards the free electrons at N-side. Thus, the holes move from P-side (high concentration) to N-side (low concentration)

- As holes enter the N region, they recombine with the donor atoms. As donor atoms accept additional holes, they become positively charged immobile ions. Hence number of positively charged immobile ions get formed near the junction on N-side.
- Similarly the electrons diffusing from N side to P side recombine with the acceptor atoms on P side. As acceptor atoms accept additional electrons, they become negatively charged immobile ions. Such large number of negatively charged immobile ions get formed near the junction on p-side. The formation of immobile ions near the junction is shown in the Figure 1.3.
- In the region near the junction, there exists a wall of negative immobile charges on P side and a wall of positive immobile charges on N side. In this region, there are no mobile charge carriers. Such a region is depleted of the free mobile charge carriers and hence called depletion region or depletion layer.
- In equilibrium condition, the depletion region gets widened upto a point where no further electrons or holes can cross the junction. Thus depletion region acts as the barrier.
- Thus, a barrier is built up near the junction which prevents the further movement of electrons and holes. The total charge formed at the P-N junction is called barrier voltage, barrier potential or junction potential.
- The size of the barrier voltage at the P-N junction depends on the amount of doping, junction temperature and type of material used. The barrier potential for Si diode is 0.7V and for Ge is 0.3V.

1.2.2 VI Characteristics and Biasing of the Diode

- Applying an external voltage across the terminals of the P-N junction diode is known as **biasing**.
- There are two types:
  - Forward biasing
  - Reverse biasing

Forward Biased P-N Junction

- A diode is said to be **forward biased** when its **anode is connected to the positive terminal** of the battery and **cathode is connected to the negative terminal**.

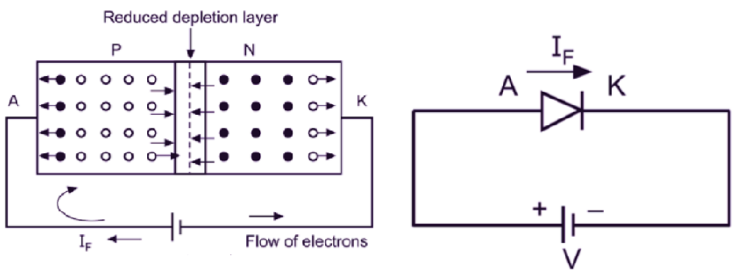


Figure 1.4: Forward Biasing of the Diode

- When the diode is forward biased, as long as the applied voltage V is less than the barrier potential, there is no conduction.
- When the applied voltage V exceeds the barrier potential, the diode becomes forward biased.
  - Holes on the P-side are repelled by the positive terminal of the battery and are driven towards the junction.
  - Electrons on the N-side are repelled by the negative terminal of the battery and move towards the junction.
- As a result, the width of the **depletion region** decreases.
- As the forward bias voltage V increases further:
  - The depletion layer reduces further.
  - Eventually, it disappears almost completely.
  - A large number of charge carriers flow across the junction.
  - This causes an **exponential rise in current**.

Reverse Biased P-N Junction

- A diode is said to be **reverse biased** when the **anode (P-region)** is connected to the **negative terminal** of the battery and the **cathode (N-region)** is connected to the **positive terminal**.

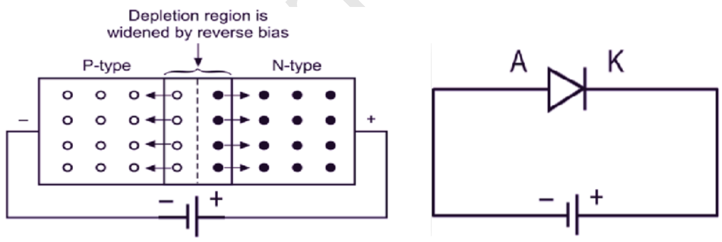


Figure 1.5: Reverse Biasing of the Diode

- Electrons from the N-region are attracted towards the positive terminal of the battery, and holes from the P-region are attracted towards the negative terminal.
- No charge carrier is able to cross the junction. As electrons and holes both move away from the junction, the depletion region widens. This creates more positive ions and hence more negative ions in the N region.
- This causes the **depletion region to widen** and the **barrier potential to increase**, reducing the flow of majority charge carriers across the junction to nearly zero.
- Due to increased barrier potential, the electrons from P-region towards the positive of battery. Similarly negative side of barrier potential drags the holes from N-region towards the negative of battery. The electrons on P-side and holes on N-side are minority charge carriers, which constitute the current in reverse biased condition. This is called the **reverse saturation current** (I_S).

- As a result, a reverse biased diode allows only a **very small reverse current**, and hence can be considered to have a **high reverse resistance**.
  - Typically in the nanoampere (nA) range for silicon diodes and microampere (µA) or milliampere (mA) for germanium diodes.
- If reverse voltage is increased, at a particular value, velocity of minority carriers increases. Due to the kinetic energy associated with the minority carriers, more minority carriers are generated when there is collision of minority carriers with the atoms. The collision make the electrons to break the co-valent bonds. These electrons are available as minority carriers and get accelerated due to high reverse voltage. They again collide with another atoms to generate more minority carriers.
- Finally large number of minority carriers move across the junction, breaking the PN junction. These large number of minority carriers give rise to a very high reverse current. This effect is called **avalanche effect** and the mechanism of destroying the junction is called **reverse breakdown** of a p-n junction.
- So, when the reverse voltage V_R is sufficiently increased, the diode enters **breakdown**.
- **Caution:** Reverse breakdown can permanently damage the diode unless the reverse current is limited by a suitable series resistor.

1.3 Forward and Reverse characteristics of the Si and Ge diode:

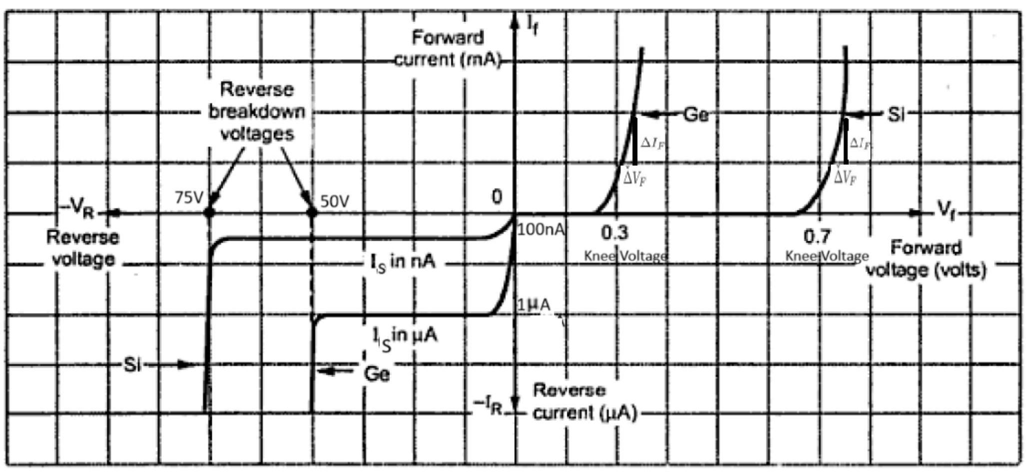


Figure 1.6: Reverse Biasing of the Diode

- V-I characteristics of PN junction is the graph of voltage applied across the PN junction and the current flowing through the PN junction. The Fig. 1.4 shows the forward biased diode.

- The applied voltage is V while the voltage across the diode is V_F. The current flowing in the circuit is the forward current I_F.The graph of forward current I_F against the forward voltage V_F across the diode is called forward characteristics of a diode.
- As long as V_F is less than knee voltage, the current flowing is very small. Practically this current is assumed to be zero.
- As V_F increases towards knee voltage, the width of depletion region goes on reducing. When V_F exceeds knee voltage, the depletion region becomes very thin and current increases suddenly. This increase in the current is exponential as shown in the Fig. 1.6
- At one point, the forward current starts increasing exponentially is called knee of the curve.
- The Fig. 1.5 shows the reverse biased diode. The reverse voltage across the diode is V_R while the current flowing is reverse current I_R flowing due to minority charge carriers. The graph of I_R against V_R is called reverse characteristics of a diode.
- As reverse voltage is increased, reverse current increases initially but after a certain voltage, the current remains constant equal to reverse saturation current I_s though reverse voltage is increased. At one point, where breakdown occurs and reverse current increases rapidly is called knee of the reverse characteristics.This is shown in the reverse **VI characteristics** of the diode in Figure 1.6

Diode Parameters

- **Forward Voltage Drop (V_F or V_K):**
  The voltage drop across the diode in forward bias condition is known as **forward voltage drop**. It is represented as V_F and is generally equal to the **knee voltage** V_K.
  Typical values:
  - Silicon (Si): 0.7 V
  - Germanium (Ge): 0.3 V
- **Maximum Forward Current ($I_{F\mathbf{max}}$):**
  It is the maximum current a diode can conduct under forward bias without causing permanent damage to the P-N junction due to overheating.
- **Reverse Breakdown Voltage (V_{BR}):**
  It is the reverse bias voltage at which the P-N junction breaks down and a large current flows, potentially damaging the diode.
  - For silicon diodes, breakdown occurs around 75 V.
  - For germanium diodes, breakdown occurs around 50 V.
- **Reverse Saturation Current (I_S):**
  It is the very small current that flows through the diode in reverse bias due to minority carriers.
  Typical values:

  - Germanium (Ge): in μA
  - Silicon (Si): in nA

- **Dynamic Resistance (r_d):**
  It is the resistance offered by the diode to changing voltages in forward bias. Also called **incremental** or **AC resistance**.
  It is given by:
  $$r_d = \frac{\Delta V_F}{\Delta I_F}$$
  From the V-I graph of the diode:
  $$\text{Slope} = \frac{\Delta I_F}{\Delta V_F} \Rightarrow r_d = \frac{1}{\text{Slope}}$$

- **Forward Resistance (R_F):**
  It is the ratio of forward voltage to forward current. Also known as **static forward resistance**:
  $$R_F = \frac{V_F}{I_F}$$

- **Reverse Resistance (R_R):**
  It is the ratio of reverse voltage to reverse current. Also called **static reverse resistance**:
  $$R_R = \frac{V_R}{I_R}$$

1.4 Diode Models

An equivalent circuit for a device is a circuit that models or simulates its electrical behavior. It is made up of basic components such as resistors and voltage sources.

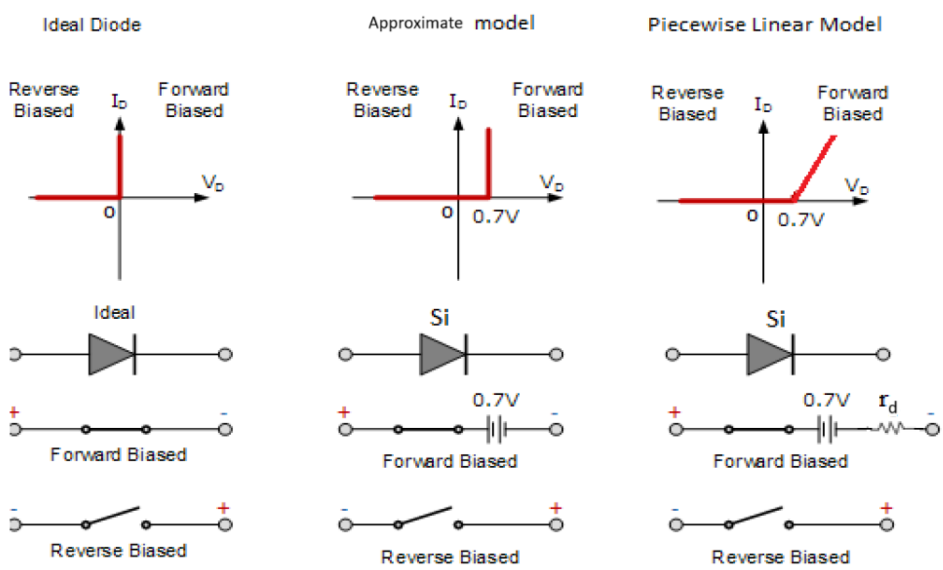


Figure 1.7: Diode Models

1. Ideal Diode Model

- In an ideal diode:
  - **Forward Voltage Drop** (V_F) $= 0$
  - **Forward Resistance** (R_F) $= 0$
  - **Reverse Resistance** (R_R) $= \infty$
  - **Reverse Current** (I_R) $= 0$
- This implies perfect conduction in forward bias and perfect insulation in reverse bias.

2. Approximate Diode Model

- The approximate model includes:
  - An ideal diode switch
  - A **voltage source** V_F **= 0.7** in series to represent the threshold voltage (barrier potential)
- It neglects the dynamic resistance (r_d) and models only the threshold behavior.

3. Piecewise Linear Model

- This model consists of:
  - An ideal diode
  - A voltage cell (threshold voltage V_F =0.7)
  - A **dynamic resistance** r_d in series
- This model provides a more accurate approximation of a real diode's forward characteristic.
- **Note:** When the actual forward characteristics of a diode are not available, this model provides a **straight-line approximation** and is called the *piecewise linear model.*

1.5 Numerical on Diodes

1. Find the value of current I in the following circuit.
   Answer: A Si diode is reverse biased.So it does not conduct.
2. For the circuit shown, calculate I_D.

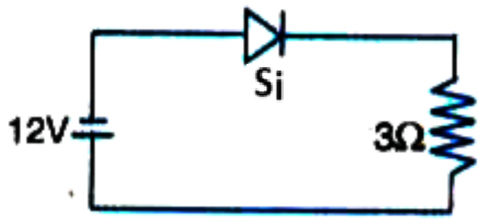


Figure 1.8: Problem 1

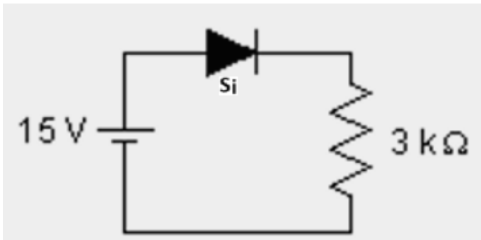


Figure 1.9: Problem 2

Solution: Applying KVL, we get:

$$15\,\mathrm{V} - 0.7\,\mathrm{V} - I_D \times 3\,\mathrm{k\Omega} = 0$$

$$I_D = \frac{15 - 0.7}{3\mathrm{k\Omega}} = \frac{14.3}{3\mathrm{k\Omega}} = 4.76\,\mathrm{mA}$$

3. For the circuit shown, calculate I_D and V_o.

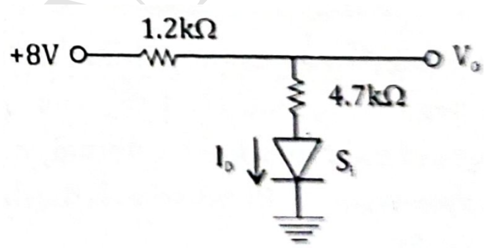


Figure 1.10: Problem 3

Solution:

Applying KVL, we get:

$$8\,\mathrm{V} - I_D \times 1.2\,\mathrm{k\Omega} - I_D \times 4.7\,\mathrm{k\Omega} - 0.7\,\mathrm{V} = 0$$

$$I_D = \frac{8 - 0.7}{(4.7 + 1.2)\,\mathrm{k\Omega}} = \frac{7.3}{5.9\,\mathrm{k\Omega}} = 1.237\,\mathrm{mA}$$

$$V_o = I_D \times 4.7 \times 10^3 + 0.7$$

$$= 1.237 \times 10^{-3} \times 4.7 \times 10^3 + 0.7 = 5.8119 + 0.7 = \underline{6.51\,\mathrm{V}}$$

4. For the circuit shown, calculate I_D and V_o.
   Solution

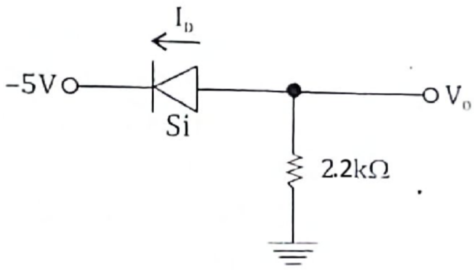


Figure 1.11: Problem 4

Applying KVL, we have:

$$-5\,\mathrm{V} + 2.2\,\mathrm{k\Omega} \times I_D + 0.7\,\mathrm{V} = 0$$

$$\therefore I_D = \frac{5-0.7}{2.2\,\mathrm{k\Omega}} = 1.95\,\mathrm{mA}$$

$$V_o = 1.95\,\mathrm{mA} \times 2.2\,\mathrm{k\Omega} = \underline{4.3\,\mathrm{V}}$$

5. For the circuit shown, calculate the current in the circuit.

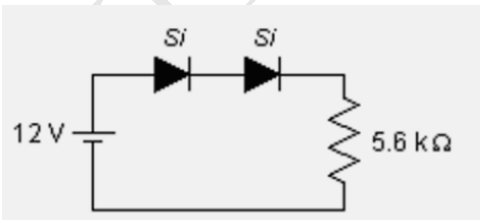


Figure 1.12: Problem 5

Solution: Applying KVL, we get:

$$12\,\mathrm{V} - 0.7\,\mathrm{V} - 0.7\,\mathrm{V} - I_D \times 5.6\,\mathrm{k\Omega} = 0$$

$$I_D = \frac{12-1.4}{5.6\mathrm{k\Omega}} = \frac{10.6}{5.6\mathrm{k\Omega}} = 1.893\,\mathrm{mA}$$

1.6 Rectifiers

- One of the most important applications of a junction diode is **rectification**.
- **Rectification** is the process of converting **alternating current (AC)** into **direct current (DC)**.

- Rectification can be performed using:
  - **Half-wave rectifier** (uses one diode)
  - **Full-wave rectifier** (uses two or four diodes)
- Depending on the type of AC supply and the configuration of the rectifier circuit, the output voltage may contain both DC and AC components. This output is called **pulsating DC** and includes **AC ripples**.
- Many applications, such as power supplies for radios, televisions, and computers, require a **steady and constant DC voltage**.
- In such applications, the output of the rectifier is passed through a **filter circuit** to reduce the ripple content and provide a smooth DC voltage.
- Filter circuits typically consist of:
  - Capacitors
  - Inductors (chokes)
  - Resistors (optional)
  - Or a combination (e.g., RC filters, LC filters)
- The filtering process generally involves the use of a **large capacitor**, which charges to the peak of the input voltage and discharges slowly, thus providing a relatively constant **DC output voltage**.
- Filter types:
  - **RC Filter**: Uses resistor and capacitor
  - **LC Filter**: Uses inductor and capacitor

1.6.1 Half Wave Rectifier (HWR)

- A Half Wave Rectifier requires only **one diode** for its construction.

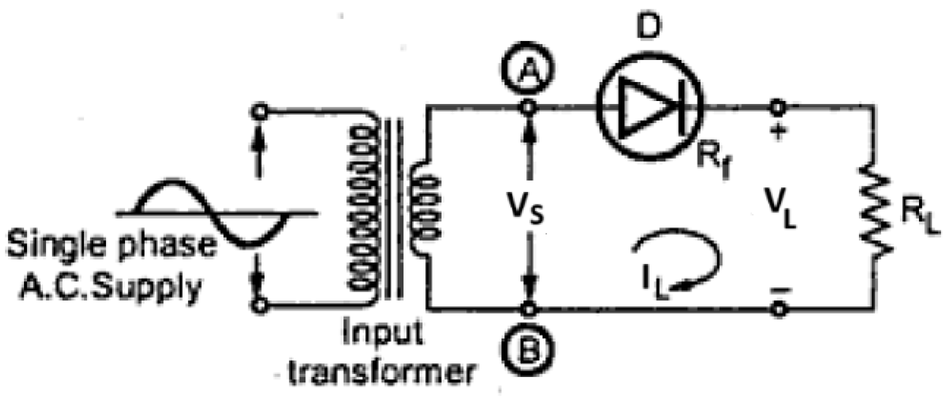


Figure 1.13: Half Wave Rectifier

- In HWR, the diode conducts only during the **positive half cycle** of the input AC signal.
- The **negative half cycle** is blocked, resulting in a unidirectional (pulsating DC) output.
- The input is a sinusoidal AC voltage. The instantaneous secondary voltage is:

$$V_s = V_m \sin \omega t \quad \text{for } 0 \leq \omega t \leq 2\pi$$

  where, $\omega = 2\pi\text{f}$, and V_m is the peak value of voltage.

Working

- During the **positive half cycle** of the input AC signal, i.e., $0 \leq \omega t \leq \pi$:
  - The secondary winding of the transformer has node A more positive than node B.
  - The diode D becomes **forward biased** and acts as a **closed switch**.
  - Current flows through the load resistor R_L, producing a voltage across it.
  - Since the load is resistive, the current waveform follows the voltage waveform.
- The **load current** is given by:

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

- Where:

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

  is the **peak value of the current**.

- The output voltage is a **pulsating DC**, and is discontinuous.
- The **average or DC value** of the output voltage or current is obtained by integrating over one full cycle.
- During the **negative half cycle**, i.e., $\pi \leq \omega t \leq 2\pi$:
  - Node A becomes negative and node B becomes positive.
  - The diode D is **reverse biased** and acts as an **open switch**.
  - No current flows through the load resistor R_L.
  - Therefore,

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

  - The load voltage is:

$$V_L = V_m \sin \omega t \quad \text{for } 0 \leq \omega t \leq \pi$$

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

Waveform

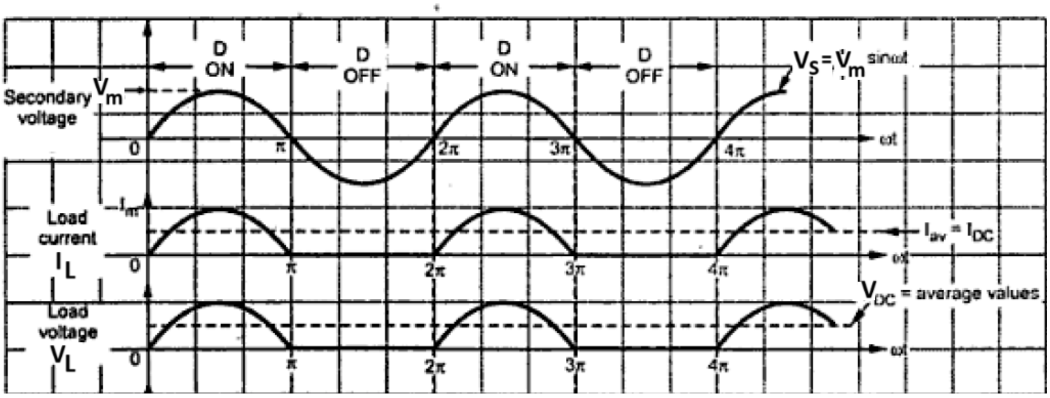


Figure 1.14: HWR Waveforms

Parameters

1. **Average DC Load Current (I_{DC})**: The average value of an alternating current is calculated as the area under the one cycle of load current I_L from 0 to 2π, divided by the period of I_L, i.e., 2π:

$$I_{DC} = \sqrt{\frac{\text{Area under the one cycle of load current } I_L}{\text{period of } I_L}}$$

$$I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} I_L \, d(\omega t)$$

Given, $I_L = I_m \sin(\omega t)$, we have:

$$I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} I_m \sin(\omega t) \, d(\omega t)$$

Since the current is zero from $\pi \leq \omega t \leq 2\pi$, the integral becomes:

$$I_{DC} = \frac{I_m}{2\pi}\int_0^{\pi} \sin(\omega t) \, d(\omega t)$$

$$I_{DC} = \frac{I_m}{2\pi}\left[-\cos(\omega t)\right]_0^{\pi}$$

$$I_{DC} = -\frac{I_m}{2\pi}\left[\cos(\pi) - \cos(0)\right]$$

$$\cos(\pi) = -1, \quad \cos(0) = 1$$

$$I_{DC} = -\frac{I_m}{2\pi}(-2)$$

$$I_{DC} = \frac{I_m}{\pi}$$

2. **Average DC Load Voltage (V_{DC}):**

   The average value of the output voltage is given by:

$$V_{DC} = \frac{1}{2\pi} \int_0^{2\pi} V_L \, d(\omega t)$$

   Given that $V_L = V_m \sin(\omega t)$, we substitute:

$$V_{DC} = \frac{1}{2\pi} \int_0^{2\pi} V_m \sin(\omega t) \, d(\omega t)$$

   Since the voltage is zero from $\pi \leq \omega t \leq 2\pi$, we split and simplify the integral:

$$V_{DC} = \frac{V_m}{2\pi} \int_0^{\pi} \sin(\omega t) \, d(\omega t)$$

$$V_{DC} = \frac{V_m}{2\pi} \left[-\cos(\omega t) \right]_0^{\pi}$$

$$V_{DC} = -\frac{V_m}{2\pi} \left[\cos(\pi) - \cos(0) \right]$$

$$\cos(\pi) = -1, \quad \cos(0) = 1$$

$$V_{DC} = -\frac{V_m}{2\pi}(-2) = \frac{V_m}{\pi}$$

$$V_{DC} = \frac{V_m}{\pi}$$

   Alternate Derivation:

   The average DC voltage can also be expressed as the product of DC load current I_{DC} and the load resistance R_L:

$$V_{DC} = I_{DC} \times R_L = \frac{I_m}{\pi} R_L$$

   Also, since:

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

   Then:

$$V_{DC} = I_{DC} \cdot R_L = \frac{V_m}{\pi(R_L + R_S + R_f)} \cdot R_L$$

$$V_{DC} = \frac{V_m}{\pi \left(1 + \frac{R_S + R_f}{R_L}\right)}$$

Since $R_S + R_f \ll R_L$, we approximate:

$$\frac{R_S + R_f}{R_L} \ll 1$$

Therefore:

$$V_{DC} = \frac{V_m}{\pi}$$

3. **RMS Value of Load Current (I_{RMS}):**

The RMS value of the load current is defined as:

$$I_{RMS} = \sqrt{\frac{(\text{Area under the one cycle of load current } I_L)^2}{\text{period of } I_L}}$$

$$I_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_L^2 \, d(\omega t)}$$

Since the current is zero for $\pi \le \omega t \le 2\pi$:

$$I_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} I_L^2 \, d(\omega t)}$$

Given $I_L = I_m \sin(\omega t)$:

$$I_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} I_m^2 \sin^2(\omega t) \, d(\omega t)}$$

Using identity $\sin^2(\omega t) = \frac{1-\cos(2\omega t)}{2}$:

$$I_{RMS} = \sqrt{\frac{I_m^2}{2\pi}\int_0^{\pi} \frac{1-\cos(2\omega t)}{2} \, d(\omega t)}$$

$$I_{RMS} = \sqrt{\frac{I_m^2}{4\pi}\left[\omega t - \frac{\sin(2\omega t)}{2}\right]_0^{\pi}}$$

$$\sin(2\pi) = 0, \quad \sin(0) = 0 \Rightarrow I_{RMS} = \sqrt{\frac{I_m^2}{4\pi}\cdot \pi} = \frac{I_m}{2}$$

$$I_{RMS} = \frac{I_m}{2}$$

4. **RMS Value of Load Voltage (V_{RMS})**

   Similarly,

$$V_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_L^2\, d(\omega t)} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} V_m^2 \sin^2(\omega t)\, d(\omega t)}$$

$$= \sqrt{\frac{V_m^2}{4\pi}\left[\omega t - \frac{\sin(2\omega t)}{2}\right]_0^{\pi}} = \sqrt{\frac{V_m^2}{4\pi}\cdot \pi} = \frac{V_m}{2}$$

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

   Alternate Derivation:

$$V_{RMS} = I_{RMS}\cdot R_L = \frac{I_m}{2}R_L \quad \text{and} \quad I_m = \frac{V_m}{R_S + R_L + R_f}$$

   So,

$$V_{RMS} = \frac{V_m}{2(R_L + R_S + R_f)}\cdot R_L$$

$$V_{RMS} = \frac{V_m}{2\left(1 + \frac{R_S+R_f}{R_L}\right)}$$

   Since $R_S + R_f \ll R_L$, we approximate:

$$\frac{R_S + R_f}{R_L} \ll 1$$

   Therefore:

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

5. **Ripple Factor (γ)**:

   Ripple factor is defined as the ratio of RMS value of AC component to DC component of the output. Ripple factor is defined as the ratio of the RMS value of the AC component to the DC component of the output:

$$\gamma = \frac{I_{\text{AC}}}{I_{\text{DC}}} = \frac{\text{RMS value of AC component of output}}{\text{DC component of output}}$$

   Here, I_{RMS} is the total RMS current of the rectifier output. It includes both AC and DC components:

$$I_{\text{RMS}}^2 = I_{\text{AC}}^2 + I_{\text{DC}}^2$$

   Solving for I_{AC}^2:

$$I_{\mathrm{AC}}^2 = I_{\mathrm{RMS}}^2 - I_{\mathrm{DC}}^2$$

Therefore, the ripple factor becomes:

$$\gamma = \frac{I_{\mathrm{AC}}}{I_{\mathrm{DC}}} = \sqrt{\frac{I_{\mathrm{RMS}}^2}{I_{\mathrm{DC}}^2} - 1}$$

Given:

$$I_{DC} = \frac{I_m}{\pi}, \quad I_{RMS} = \frac{I_m}{2} \Rightarrow \gamma = \sqrt{\frac{(I_m/2)^2}{(I_m/\pi)^2} - 1} = \sqrt{\frac{1/4}{1/\pi^2} - 1} = \sqrt{\frac{\pi^2}{4} - 1} \approx 1.21$$

Hence, ripple content in output = 121% of DC component, indicating poor rectification.

6. **Efficiency (η)**:

   Efficiency is the ratio of output DC power to input AC power:

$$\eta = \frac{P_{DC}}{P_{AC}} = \frac{\text{output DC power}}{\text{input AC power}} = \frac{I_{DC}^2 R_L}{I_{RMS}^2 (R_f + R_L)}$$

$$\eta = \frac{\left(\frac{I_m}{\pi}\right)^2 R_L}{\left(\frac{I_m}{2}\right)^2 (R_f + R_L)} = \frac{I_m^2/\pi^2}{I_m^2/4} \cdot \frac{R_L}{R_f + R_L}$$

$$= \frac{4}{\pi^2} \cdot \frac{R_L}{R_f + R_L}$$

   If $R_f \ll R_L$, then:

$$\eta \approx \frac{4}{\pi^2} = 0.406 \Rightarrow \eta \approx 40.6\%$$

   In Half Wave Rectifiers, the ripple content is high and efficiency is low. Therefore, output is not very close to pure DC.

1.6.2 Full Wave Bridge Rectifier (FWBR)

- It is a Full Wave Rectifier (FWR) circuit with four diodes.
- An AC voltage is applied to one diagonal of the bridge through a transformer, and the rectified DC output voltage is taken from the other diagonal of the bridge.

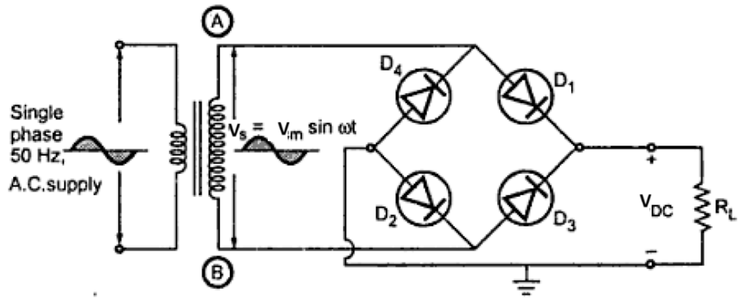


Figure 1.15: Full Wave Rectifier

Working

- During the positive half cycle of the AC input signal, node A at the secondary of the transformer is positive while node B is negative. Hence, diodes D_1 and D_2 are forward biased and conduct current, while diodes D_3 and D_4 are reverse biased and do not conduct.
- The diodes D_1 and D_2 are connected in series with the load resistance R_L, allowing current to flow through the load.
- During the negative half cycle of the AC input signal, node A becomes negative while node B becomes positive. In this case, diodes D_3 and D_4 are forward biased and conduct current, whereas diodes D_1 and D_2 are reverse biased and remain off.
- Now, diodes D_3 and D_4 conduct current through the load resistance R_L.

In a Full Wave Rectifier (FWR), load current flows during both the half cycles of the AC input signal, and in the same direction through the load resistance. As a result, the negative half cycle of the input signal is also rectified and appears above the axis in the output waveform.

The **load current** is given by:

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

Where:

$$I_m = \frac{V_m}{R_s + 2R_f + R_L}$$

is the **peak value of the current**. The load voltage is:

$$V_L = V_m \sin \omega t \quad \text{for } 0 \leq \omega t \leq \pi$$

where, V_m is the peak value of voltage.

Waveform

The input and output waveform of the Bridge rectifiers is shown in the Figure 1.16.

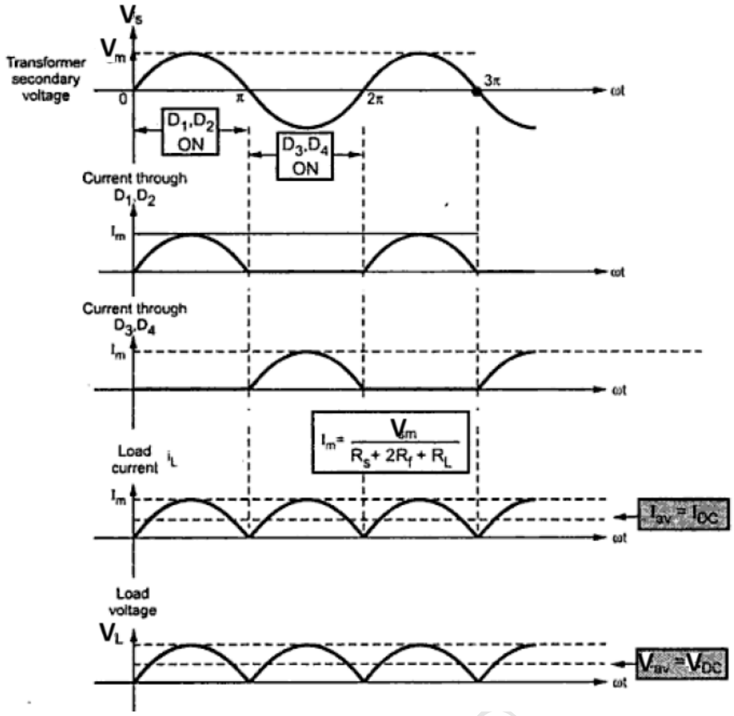


Figure 1.16: FWR Waveforms

Parameters

1. **Average Value of Load Current (I_{DC})**:

   The average value of current is given by the area under the curve of load current I_L over one full cycle:

$$
\begin{aligned}
I_{DC} &= \frac{1}{\pi}\int_0^{\pi} I_L \, d(\omega t) \\
\text{Given: } I_L &= I_m \sin\omega t \\
\Rightarrow I_{DC} &= \frac{1}{\pi}\int_0^{\pi} I_m \sin\omega t \, d(\omega t) \\
&= \frac{1}{\pi}\int_0^{\pi} I_m \sin\omega t \, d(\omega t) \\
&= \frac{I_m}{\pi}\int_0^{\pi} \sin\omega t \, d(\omega t) \\
&= \frac{I_m}{\pi}\left[-\cos\omega t\right]_0^{\pi} \\
&= \frac{I_m}{\pi}\left[-\cos\pi + \cos 0\right]
\end{aligned}
$$

Since $\cos\pi = -1$ and $\cos 0 = 1$,

$$
\begin{aligned}
I_{DC} &= \frac{I_m}{\pi}\left[-(-1)+1\right] = \frac{I_m}{\pi}\cdot 2 \\
\Rightarrow I_{DC} &= \frac{2I_m}{\pi}
\end{aligned}
$$

2. **Average DC Load Voltage (V_{DC}):**

$$
\begin{aligned}
V_{DC} &= \frac{1}{\pi}\int_0^{\pi} V_L\, d(\omega t)\\
V_L &= V_m \sin\omega t\\
V_{DC} &= \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t\, d(\omega t)\\
&= \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t\, d(\omega t)\\
&= \frac{V_m}{\pi}\int_0^{\pi} \sin\omega t\, d(\omega t)\\
&= \frac{V_m}{\pi}\left[-\cos\omega t\right]_0^{\pi}\\
&= \frac{V_m}{\pi}\left[-\cos\pi + \cos 0\right]\\
\text{Since } \cos\pi = -1 \text{ and } \cos 0 = 1,&\\
V_{DC} &= \frac{V_m}{\pi}\cdot 2 = \frac{2V_m}{\pi}
\end{aligned}
$$

Alternate Derivation:

$$V_{DC} = I_{DC} \times R_L = \frac{I_m}{\pi} R_L$$

Also, since:

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

Then:

$$V_{DC} = I_{DC} \cdot R_L = \frac{V_m}{\pi(R_L + R_S + R_f)} \cdot R_L$$

$$V_{DC} = \frac{V_m}{\pi\left(1 + \frac{R_S + R_f}{R_L}\right)}$$

Since $R_S + R_f \ll R_L$, we approximate:

$$\frac{R_S + R_f}{R_L} \ll 1$$

Therefore:

$$V_{DC} = \frac{V_m}{\pi}$$

3. **RMS Value of Load Current (I_{RMS}):**

$$
\begin{aligned}
I_{RMS} &= \sqrt{\frac{1}{\pi}\int_0^{\pi} I_L^2 \, d(\omega t)} \\
I_L &= I_m \sin \omega t \\
\Rightarrow I_{RMS} &= \sqrt{\frac{1}{\pi}\int_0^{\pi} I_m^2 \sin^2 \omega t \, d(\omega t)} \\
&= \sqrt{\frac{I_m^2}{\pi}\int_0^{\pi} \frac{1-\cos 2\omega t}{2} \, d(\omega t)} \\
&= \sqrt{\frac{I_m^2}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_0^{\pi}} \\
\text{Since } \sin 0 = \sin 2\pi = 0, \\
I_{RMS} &= \sqrt{\frac{I_m^2}{2\pi}(\pi - 0)} = \sqrt{\frac{I_m^2 \pi}{2\pi}} \\
&= \frac{I_m}{\sqrt{2}}
\end{aligned}
$$

4. **RMS Value of Load Voltage (V_{RMS})**:

$$
\begin{aligned}
V_{RMS} &= \sqrt{\frac{1}{\pi}\int_0^{\pi} V_L^2 \, d(\omega t)} \\
V_L &= V_m \sin \omega t \\
\Rightarrow V_{RMS} &= \sqrt{\frac{1}{\pi}\int_0^{\pi} V_m^2 \sin^2 \omega t \, d(\omega t)} \\
&= \sqrt{\frac{V_m^2}{\pi}\int_0^{\pi} \frac{1-\cos 2\omega t}{2} \, d(\omega t)} \\
&= \sqrt{\frac{V_m^2}{2\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_0^{\pi}} \\
\text{Since } \sin 0 = \sin 2\pi = 0, \\
V_{RMS} &= \sqrt{\frac{V_m^2}{2\pi}(\pi - 0)} = \sqrt{\frac{V_m^2 \pi}{2\pi}} \\
&= \frac{V_m}{\sqrt{2}}
\end{aligned}
$$

5. **Ripple Factor (γ)**:

   The ripple factor is defined as the ratio of the RMS value of the AC component to the DC component of the output:

$$\gamma = \frac{I_{AC}}{I_{DC}} = \sqrt{\frac{I_{AC}^2}{I_{DC}^2}}$$

$$\text{Since } I_{AC}^2 = I_{RMS}^2 - I_{DC}^2,$$

$$\Rightarrow \gamma = \sqrt{\frac{I_{RMS}^2 - I_{DC}^2}{I_{DC}^2}} = \sqrt{\frac{I_{RMS}^2}{I_{DC}^2} - 1}$$

$$\text{Substituting: } I_{RMS} = \frac{I_m}{\sqrt{2}}, \quad I_{DC} = \frac{2I_m}{\pi}$$

$$\Rightarrow \gamma = \sqrt{\frac{\left(\frac{I_m^2}{2}\right)}{\left(\frac{4I_m^2}{\pi^2}\right)} - 1}$$

$$= \sqrt{\frac{\pi^2}{8} - 1}$$

$$= \sqrt{1.2337 - 1} = \sqrt{0.2337} \approx 0.483$$

$$\Rightarrow \%\gamma = 48.3\%$$

Conclusion: The ripple content in the output is 48.3% of the DC component, i.e., $I_AC < I_{DC}$, hence it offers good rectification.

6. **Efficiency (η)**:

Efficiency is defined as the ratio of DC output power to AC input power:

$$\eta = \frac{\text{Output DC Power}}{\text{Input AC Power}} = \frac{P_{DC}}{P_{AC}}$$

$$= \frac{I_{DC}^2 R_L}{I_{RMS}^2 (R_S + 2R_f + R_L)}$$

$$\text{Substitute: } I_{DC} = \frac{2I_m}{\pi}, \quad I_{RMS} = \frac{I_m}{\sqrt{2}}$$

$$\Rightarrow \eta = \frac{\left(\frac{2I_m}{\pi}\right)^2 R_L}{\left(\frac{I_m}{\sqrt{2}}\right)^2 (R_S + 2R_f + R_L)}$$

$$= \frac{\left(\frac{4I_m^2}{\pi^2}\right) R_L}{\left(\frac{I_m^2}{2}\right) (R_S + 2R_f + R_L)}$$

$$= \frac{8}{\pi^2} \cdot \frac{R_L}{R_S + 2R_f + R_L}$$

$$\text{If } \frac{R_S + 2R_f}{R_L} \ll 1, \Rightarrow \frac{R_L}{R_S + 2R_f + R_L} \approx 1$$

$$\Rightarrow \eta \approx \frac{8}{\pi^2} \approx 0.812$$

$$\Rightarrow \%\eta \approx 81.2\%$$

Conclusion: In a Full Wave Rectifier, ripple contents are lower, and hence, the efficiency is higher.

Advantages of Full Wave Rectifier (FWR)

- DC load voltage and current are more than Half Wave Rectifier (HWR)
- Efficiency is high
- Provides large DC power output
- Ripple factor is less
- Widely used in regulated power supplies

1.7 Filter Circuits

The output from a half-wave or full-wave rectifier circuit isn't a pure direct current (DC); it contains unwanted fluctuations known as ripple. To reduce these ripples, filter circuits are introduced. These filters are placed between the rectifier and the load to help smooth the output is shown in Figure 1.17. Filter circuits are used at the output of rectifiers

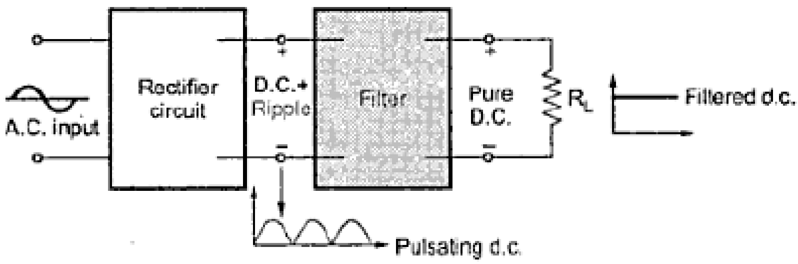


Figure 1.17: Filter Circuit

to obtain ripple-free DC voltage. They minimize the ripples in the output as much as possible. Two components used by the filter circuits are

- **Inductor Filter:** Blocks AC and allows DC to pass through. Hence, it is connected in series with the load.
- **Capacitor Filter:** Blocks DC and allows AC components to pass through. Hence, it is connected in parallel with the load.

The inductor filter is not in use now a days as inductors are bulky, costly, and consume more power, so they're not commonly used anymore.

Bridge Rectifier with Capacitor Filter

- The capacitor charges to the peak value V_m during the diode conduction period and delivers this energy during the non-conduction period to the load R_L.
- Charging time of the capacitor must be small so that it quickly reaches the peak value. The discharging time must be large so that it slowly discharges until the next peak.

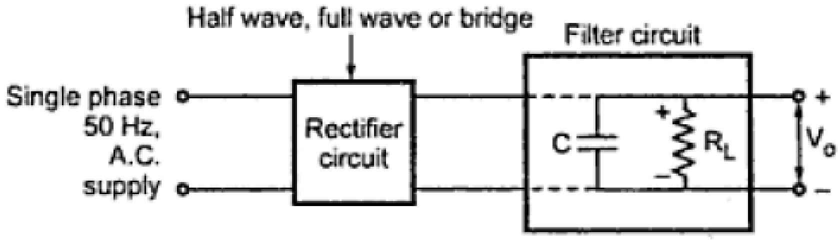


Figure 1.18: Capacitor Filter

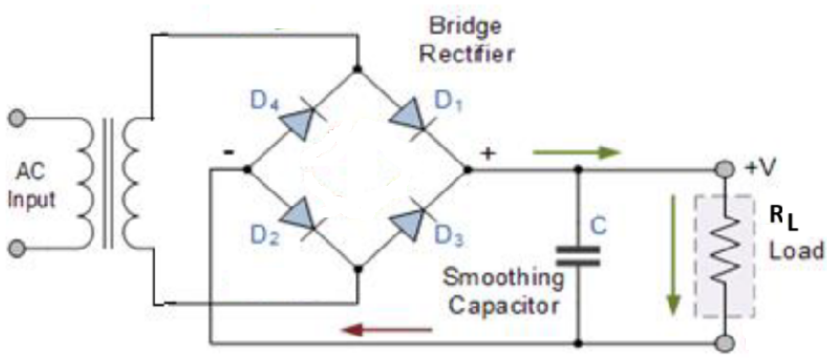


Figure 1.19: Capacitor Filter in Bridge Rectifier

- During the positive half cycle of the AC supply, diodes D_1 and D_2 conduct and charge the capacitor to the peak value V_m. They stop conducting when the transformer secondary voltage drops below V_m. This is because the capacitor voltage, which is the cathode voltage of diode becomes more positive than anode.
- So the capacitor then starts discharging through R_L, and the voltage across the capacitor falls gradually.
- The discharging of capacitor is decided by R_LC time constant which is very large and hence capacitor discharges very little from V_m
- In the next positive half cycle, when the transformer secondary voltage, becomes more than the capacitor voltage, the diodes D_3 and D_4 becomes forward biased and charges the capacitor C back to V_m
- Due to short charging time and long discharging time, the ripples in the output voltage are considerably reduced.

Time Constants

$$\text{Charging time:} \quad T_1 = 2R_fC$$
$$\text{Discharging time:} \quad T_2 = R_LC$$

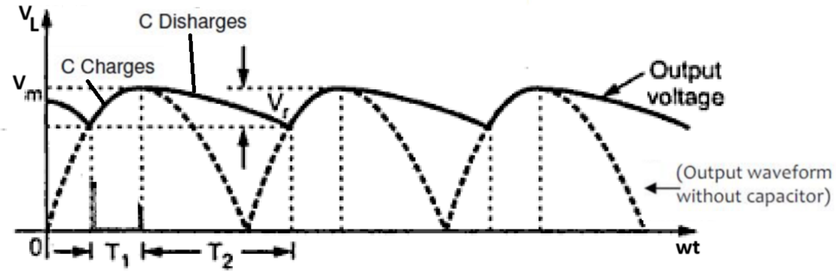


Figure 1.20: Bridge Rectifier with filter waveform

Output Voltage Variation

- **Without filter:** 0 to V_m
- **With filter:** (V_m - V_f) to V_m

This indicates that the parallel combination of R_L and C significantly reduces the ripple content in the output voltage.

Ripple Factor with Capacitor Filter

- For FWR:

$$\gamma = \frac{1}{4\sqrt{3}fCR_L}$$

By selecting a large value of C, the output can be made smoother, thereby reducing the ripple content.

1.8 Numerical on Rectifiers

1. A sinusoidal voltage of peak value 40V and frequency 50 Hz is applied to a HWR without filter. It has a load $R_L = 800\,\Omega$

   Calculate:
   a) Peak, DC and RMS value of Load current
   b) DC output power
   c) AC input power
   d) Rectifier efficiency

   Solution:

   Given: $V_m = 40\,\text{V},\ f = 50\,\text{Hz},\ R_L = 800\,\Omega,\ R_f = 8\,\Omega$

   a) Peak value of the load current I_m:

$$I_m = \frac{V_m}{R_L + R_f} = \frac{40}{800 + 8} = 49.5\,\text{mA}$$

$$I_{DC} = \frac{I_m}{\pi} = \frac{49.5}{\pi} = 15.757\,\text{mA}$$

$$I_{rms} = \frac{I_m}{2} = \frac{49.5}{2} = 24.75\,\text{mA}$$

b) DC power to load, P_{DC}:

$$P_{DC} = I_{DC}^2 \cdot R_L = (15.75 \times 10^{-3})^2 \times 800 = 198.45\,\text{mW}$$

c) AC input power P_{AC}:

$$P_{AC} = I_{rms}^2 \cdot (R_L + R_f) = (24.75 \times 10^{-3})^2 \cdot 808 = 494.95\,\text{mW}$$

d) Efficiency η:

$$\eta = \frac{P_{DC}}{P_{AC}} = \frac{198.45}{494.95} = 0.4009$$

$$\%\eta = 40.09\%$$

2. An input to a HWR is $v = 23 \sin 314t$. If $R_f = 50\,\Omega$ and $R_L = 500\,\Omega$, determine:
   - DC load voltage
   - RMS load voltage
   - DC power delivered to the load
   - Rectification efficiency

   Solution:

   Given:

   $$v = V_m \sin \omega t = 23 \sin 314t, \quad R_f = 50\,\Omega, \quad R_L = 500\,\Omega$$

   DC Load Voltage:

   $$I_{DC} = \frac{I_m}{\pi}, \quad I_m = \frac{V_m}{R_L + R_f} = \frac{23}{50 + 500} = 41.81\,\text{mA}$$

   $$I_{DC} = \frac{41.81\,\text{mA}}{\pi} = 13.31\,\text{mA}$$

   $$V_{DC} = I_{DC} \times R_L = 13.31\,\text{mA} \times 500 = 6.65\,\text{V}$$

   RMS Load Voltage:

   $$I_{rms} = \frac{I_m}{2} = \frac{41.81\,\text{mA}}{2} = 20.90\,\text{mA}$$

   $$V_{rms} = I_{rms} \times R_L = 20.90\,\text{mA} \times 500 = 10.45\,\text{V}$$

   DC Power Delivered to Load:

$$P_{DC} = I_{DC}^2 \times R_L = (13.31 \times 10^{-3})^2 \times 500 = 88.57\,\text{mW}$$

Rectification Efficiency:

$$\eta = \frac{P_{DC}}{P_{AC}} = 0.3691$$

$$\%\eta = 36.91\%$$

3. In a full wave bridge rectifier, the transformer secondary voltage is

$$V_S = 100 \sin \omega t$$

The forward resistance of each diode is $R_f = 25\,\Omega$ and load resistance is $R_L = 950\,\Omega$. Calculate:

- DC Output Voltage
- Ripple Factor
- Efficiency

Solution:

Given:

$$V_S = V_m \sin \omega t, \quad V_m = 100\,V, \quad R_f = 25\,\Omega, \quad R_L = 950\,\Omega$$

1. DC Output Voltage:

$$I_m = \frac{V_m}{2R_f + R_L} = \frac{100}{2 \times 25 + 950} = \frac{100}{1000} = 100\,\text{mA}$$

$$I_{DC} = \frac{2I_m}{\pi} = \frac{2 \times 100\,\text{mA}}{\pi} = 63.66\,\text{mA}$$

$$V_{DC} = I_{DC} \times R_L = 63.66\,\text{mA} \times 950 = 60.478\,\text{V}$$

2. Ripple Factor:

$$I_{rms} = \frac{I_m}{\sqrt{2}} = \frac{100\,\text{mA}}{\sqrt{2}} = 70.71\,\text{mA}$$

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{DC}}\right)^2 - 1} = \sqrt{\left(\frac{70.71}{63.66}\right)^2 - 1} = \sqrt{1.233 - 1} = \sqrt{0.2337} = 0.4834$$

$$\%\gamma = 48.34\%$$

3. Efficiency:

$$\eta = \frac{P_{DC}}{P_{AC}} = \frac{I_{DC}^2 \times R_L}{I_{rms}^2 \times (2R_f + R_L)}$$

$$\eta = \frac{(63.66 \times 10^{-3})^2 \times 950}{(70.71 \times 10^{-3})^2 \times 1000} = \frac{3.85}{5} = 0.77$$

$$\eta = 77\%$$

4. A bridge rectifier uses 4 diodes with an RMS input voltage of 110 V. The forward resistance of each diode is 25 Ω, and the load resistance is $R_L = 1\,\text{k}\Omega$. Find:

   - Maximum value of current
   - DC value of current through the load
   - DC load voltage

   Solution:
   Given:

$$V_{\text{rms}} = 110\,\text{V}, \quad R_f = 25\,\Omega, \quad R_L = 1000\,\Omega$$

1. Find V_m:

$$V_{\text{rms}} = \frac{V_m}{\sqrt{2}} \Rightarrow V_m = V_{\text{rms}} \times \sqrt{2} = 110 \times \sqrt{2} = 155.56\,\text{V}$$

2. Maximum value of current I_m:

$$I_m = \frac{V_m}{2R_f + R_L} = \frac{155.56}{2 \times 25 + 1000} = \frac{155.56}{1050} = 148.15\,\text{mA}$$

3. DC value of current:

$$I_{DC} = \frac{2I_m}{\pi} = \frac{2 \times 148.15\,\text{mA}}{\pi} = 94.36\,\text{mA}$$

4. DC load voltage:

$$V_{DC} = I_{DC} \times R_L = 94.36\,\text{mA} \times 1000 = 94.36\,\text{V}$$

5. Determine the ripple factor of a bridge rectifier using a capacitor filter.The load used is 2 kΩ and DC output voltage is 12 V. Assume supply frequency of 50 Hz and ideal diodes. A capacitor of 100 μF is used in the filter circuit.

   Solution:

   Given:

$$R_L = 2\,\text{k}\Omega, \quad V_{\text{DC}} = 12\,\text{V}, \quad f = 50\,\text{Hz}, \quad C = 100\,\mu\text{F}$$

Ripple factor for bridge rectifier with capacitor filter:

$$\gamma = \frac{1}{4\sqrt{3} f C R_L}$$

Substituting the values:

$$\gamma = \frac{1}{4\sqrt{3} \times 50 \times 2 \times 10^3 \times 100 \times 10^{-6}} = \frac{1}{69.28}$$

$$\gamma = 0.0144 \quad \Rightarrow \quad \%\gamma = 1.44\%$$

6. Calculate the value of capacitor C that has to be used for the filter of a bridge rectifier to get a ripple factor of 0.01. The rectifier supplies current to a load of $2\,\mathrm{k\Omega}$ and the supply frequency is $50\,\mathrm{Hz}$.

   Solution:

   Given:

$$\gamma = 0.01, \quad R_L = 2\,\mathrm{k\Omega}, \quad f = 50\,\mathrm{Hz}$$

$$\gamma = \frac{1}{4\sqrt{3}fCR_L} \Rightarrow C = \frac{1}{4\sqrt{3}fR_L\gamma}$$

   Substituting the values:

$$C = \frac{1}{4\sqrt{3} \times 50 \times 2 \times 10^3 \times 0.01} = \frac{1}{6928.203} = 1.443 \times 10^{-4}\,\mathrm{F}$$

$$C = 144.3\,\mu\mathrm{F}$$

1.9 Zener Diode

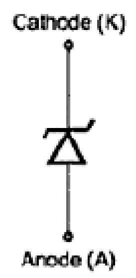


Figure 1.21: Zener Diode Symbol

- Zener diode is a special purpose diode; it is heavily doped compared to a junction diode.
- Zener diodes are designed for operation in the reverse breakdown region.
- The zener diodes have breakdown voltage range from 3 V to 200 V.

1.9.1 VI Characterstics of Zener Diode

The forward and reverse baising of the zener diode is shown in the Figure 1.22. The VI characterstics of the Zener is shown in Figure 1.23

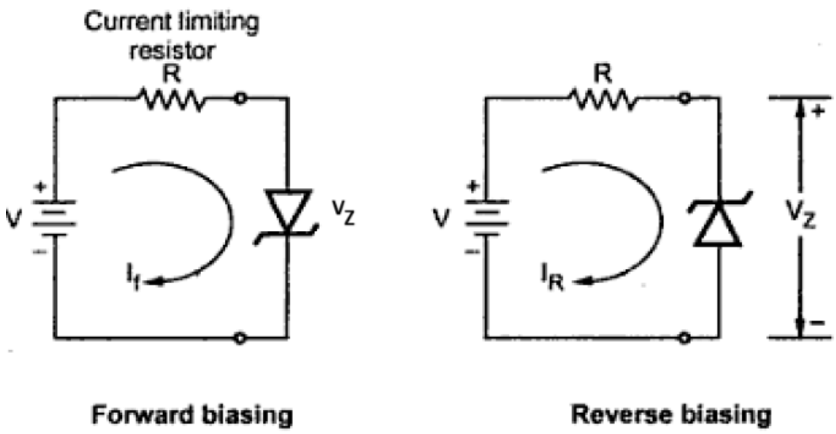


Figure 1.22: Forward and Reverse baising of the Zener diode

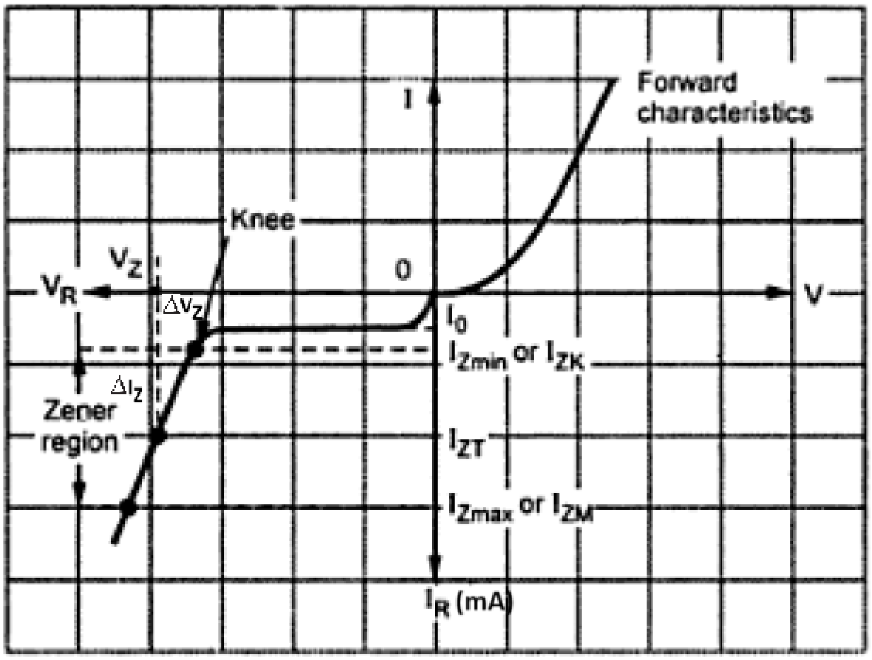


Figure 1.23: VI Characteristics of the Zener diode

- In the forward biased condition, As long as forward voltage is less than barrier voltage, the current flowing is very small. As it increases beyond this voltage the depletion region becomes very thin and current increases suddenly. This increase in the current is exponential as shown in the Fig. 1.23.
- When a narrow junction with a narrow depletion region is applied with a high reverse voltage, due to the high electric field, electrons break away from the atoms.

Hence, electron hole pairs are generated in large numbers and a sudden increase of current is ibserved. This ionization by electric field is known as **Zener breakdown**.

- When a junction diode is reverse biased, there is normally a small amount of reverse saturation current due to the minority charge carriers till the reverse voltage applied is less than the reverse breakdown voltage.
- When the reverse voltage is sufficiently increased, the junction breaks down and a large reverse current flows but the voltage across it remains almost constant.
- Under this condition, the diode may be continuously operated in reverse breakdown.
- Every zener diode has a capacity to carry current. As current increases, the power dissipation P_Z increases. If this dissipation increases beyond a certain value, the diode may get damaged.
- If the reverse current is limited by means of a suitably connected series resistor, the power dissipation in the diode can be kept to a level that will not destroy the device.
- This property of breakdown may be useful in applications such as a voltage reference source or voltage regulator.

Zener Parameters

- **Zener Breakdown Voltage (V_Z)**:
  It is the voltage beyond which there is a sharp increase in current for a small change in reverse voltage. It is the voltage across the Zener diode in the breakdown region.
- **Reverse Knee Current (I_{ZK})**:
  It is the Zener current corresponding to the knee region of the V-I characteristics.
- **Maximum Zener Current (I_{ZM})**:
  It is the maximum Zener current that can pass through the diode without damaging the device.
- **Zener Test Current (I_{ZT})**:
  It is the standard test current used for checking the working condition of a Zener diode.
- **Dynamic Resistance (r_Z)**:
  It is the ratio of the change in reverse voltage to the corresponding change in reverse current beyond the knee region.

$$r_Z = \frac{\Delta V_Z}{\Delta I_Z}$$

- **Maximum Power Dissipation (P_D)**:
  It is given by the product of the Zener breakdown voltage and the maximum Zener current:

$$P_D = V_Z \times I_{Z\_max}$$

Note: Many low power Zener diodes have a test current specified as $I_{ZT} = 20\,\text{mA}$.

1.9.2 Zener diode as a Voltage Regulator

- Voltage regulators are devices used to maintain constant voltage across a load irrespective of fluctuations in the input voltage and load currents.
- After rectification, the voltage is pulsating DC with ripples those are unwanted fluctuations.
- A filter circuit helps smoothen this, reducing ripple. But it doesn't completely eliminate it, so the result is unregulated DC.
- To achieve smooth and stable output, a regulator circuit is added after the filter. It:
  - Minimizes remaining ripple,
  - Keeps the output voltage constant even if input voltage or load conditions change.
- The output of the regulator is called DC supply.
- Zener diodes are widely used as voltage regulators to regulate the voltage across small loads.
- Zener diodes have a sharp reverse breakdown voltage, which remains nearly constant over a wide range of currents.
- They can produce a stabilized output voltage with low ripple under varying load current conditions.

Working:

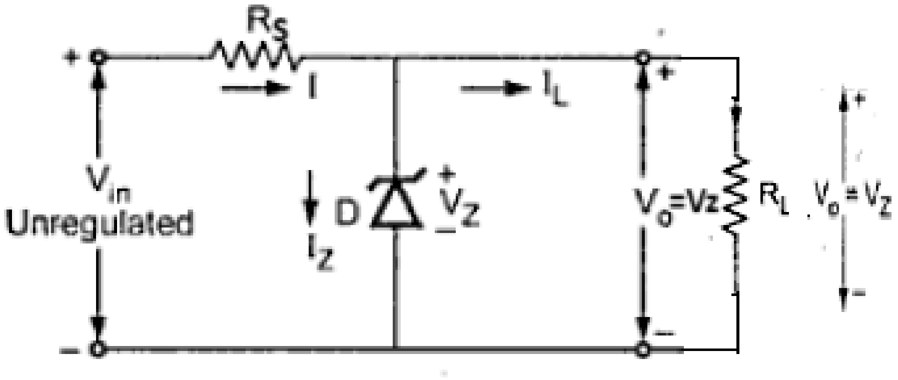


Figure 1.24: Zener Volatge Regulator

- The Zener diode is connected with its cathode terminal to the positive terminal of the DC supply, hence it is reverse biased and operates in breakdown region. The large current flows through the zener diode. Under this condition the voltage across the zener is constant and is equal to V_z.

- A resistor R_s is connected in series with the Zener diode to limit the maximum current in the circuit.
- As the voltage across the zener diode remains constant, equal to V_Z, it is connected across the load, and hence the load voltage V_o is equal to the zener voltage V_Z.
- Zener current must remain above $I_{Z(min)}$ for voltage stabilization.
- $I_{Z(max)}$ depends on the Zener's power rating.

Case 1: No Load Condition $(I_L = 0)$

- The load current is zero, so the entire current flows through the Zener diode $(I = I_Z)$

$$I = \frac{V_{in} - V_Z}{R_S} = I_z$$

- The diode dissipates maximum power.
- R_s must be chosen to keep power dissipation within safe limits.

Case 2: With Load Condition $(I_L \neq 0)$

1. **Regulation with Varying line voltage:**
   - Load R_L is connected in parallel with the Zener diode.
   - The voltage across R_L is equal to Zener voltage.

   $$V_o = V_Z \text{ is constant.}$$

   $$\therefore \quad I_L = \frac{V_o}{R_L} = \frac{V_Z}{R_L} = \text{constant}$$

   And

   $$I = \frac{V_{in} - V_Z}{R_S} = I_Z + I_L$$

   - Now if $V_{\mathbf{in}}$ **increases**, then the total current I increases. But I_L is constant as V_Z is constant. Hence, the current I_Z increases to keep I_L constant.
   - But as long as I_Z is between $I_{Z\min}$ and $I_{Z\max}$, the V_Z, i.e., output voltage V_o, is constant. Thus, the changes in input voltage get compensated and the output is maintained constant.
   - Similarly, if $V_{\mathbf{in}}$ **decreases**, then current I decreases. But to keep I_L constant, I_Z decreases. As long as I_Z is between $I_{Z\max}$ and $I_{Z\min}$, the output voltage remains constant.

   Key Note:

2. **Regulation with Varying Load:**

V_{in} increases ➔	$I = I_L + I_Z$ increases ➔	I_L is constant (V_Z/R_L) ➔	So I_Z increases ($I_Z = I - I_L$) ➔	As long $I_Z < I_{Zmax}$, V_Z is constant i.e. output voltage is constant
V_{in} decreases ➔	$I = I_L + I_Z$ decreases ➔	I_L is constant (V_Z/R_L) ➔	So I_Z decreases ($I_Z = I - I_L$) ➔	As long $I_Z > I_{Zmin}$, V_Z is constant i.e. output voltage is constant

- The input voltage V_{in} is constant, and the output voltage V_o across the load is also constant due to the Zener diode maintaining a fixed voltage V_Z. Assuming the series resistance R_s is constant, the total current I through R_s remains constant.

$$I = \frac{V_{in} - V_Z}{R_S} \quad \text{(constant)} = I_L + I_Z$$

  Where:
  - I is the total current through the resistor R_s
  - I_L is the load current through R_L
  - I_Z is the current through the Zener diode
- As the **load resistance R_L decreases**, the load current I_L increases. The voltage V_Z is constant. Hence, the current I_Z decreases to keep I constant.
- But as long as I_Z is between $I_{Z\min}$ and $I_{Z\max}$, the V_Z, i.e., output voltage V_o, is constant. Thus, the changes in input voltage get compensated and the output is maintained constant.
- Similarly, if the **load resistance R_L increases**, the load current I_L decreases. The voltage V_Z is constant. Hence, the current I_Z increases to keep I constant. As long as I_Z is between $I_{Z\max}$ and $I_{Z\min}$, the output voltage remains constant.

Key Note:

R_L increases, I_L decreases ➔	$I = \frac{V_{in} - V_Z}{R}$ constant ➔	$I_Z = I - I_L$ increases ➔	As long $I_Z < I_{Zmax}$, V_Z is constant i.e. output voltage is constant.
R_L decreases, I_L increases ➔	$I = \frac{V_{in} - V_Z}{R}$ constant ➔	$I_Z = I - I_L$ decreases ➔	As long $I_Z > I_{Zmin}$, V_Z is constant i.e. output voltage is constant.

1.10 Numerical on Zener Diode

1. A 24 V, 600 mW zener diode is used for providing a 24 V stabilized supply to a variable load from a 32 V supply. Calculate:
   (a) Value of series resistance required
   (b) Zener current when the load is 1200 Ω

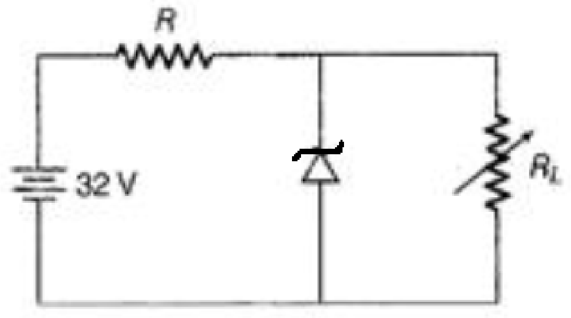


Figure 1.25: Problem 1

Given:

$$V_Z = 24\,\text{V}$$
$$P_Z = 600\,\text{mW} = 0.6\,\text{W}$$
$$V_S = 32\,\text{V}$$

(i) Value of Series Resistance R_S

When the load is disconnected ($R_L = \infty$), i.e., $I_L = 0$, then:

$$I_s = I_Z + I_L = I_Z + 0 = I_{Z\max}$$

$$I_{Z\max} = \frac{P_Z}{V_Z} = \frac{600 \times 10^{-3}}{24} = 25\,\text{mA}$$

Applying KVL:

$$V_S - I_S R_S - V_Z = 0$$

Substituting values:

$$32 - (25 \times 10^{-3})R_S - 24 = 0 \Rightarrow R_S = \frac{32 - 24}{25 \times 10^{-3}} = \frac{8}{0.025} = 320\,\Omega$$

Therefore, the value of series resistance is $\boxed{R_S = 320\,\Omega}$.

(ii) Zener Current when Load is $R_L = 1200\,\Omega$

We know:

$$V_Z = V_O = V_L = I_L \cdot R_L \Rightarrow I_L = \frac{V_Z}{R_L} = \frac{24}{1200} = 0.02\,\text{A} = 20\,\text{mA}$$

Load current is $I_L = 20\,\text{mA}$.

Now,

$$I_Z = I_S - I_L = 25\,\text{mA} - 20\,\text{mA} = 5\,\text{mA}$$

Therefore, the zener current when the load is 1200 Ω is $\boxed{I_Z = 5\,\text{mA}}$.

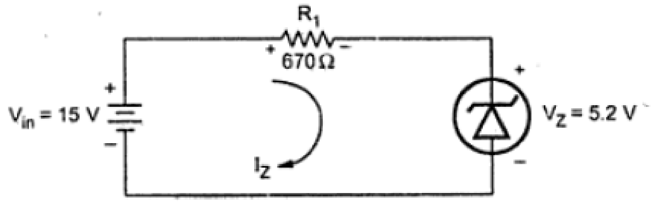


Figure 1.26: Problem 2

2. For the circuit shown, calculate the zener diode current and the power dissipation.

   Given:

$$V_{\text{in}} = 15\,\text{V}$$
$$V_Z = 5.2\,\text{V}$$
$$R_1 = 670\,\Omega$$

Solution: Applying KVL,

$$-I_Z R_1 - V_Z + V_{\text{in}} = 0$$

$$\Rightarrow I_Z = \frac{V_{\text{in}} - V_Z}{R_1} = \frac{15 - 5.2}{670} = 14.6268\,\text{mA}$$

Power Dissipation:

$$P_D = V_Z \cdot I_Z = 5.2 \times 14.6268 \times 10^{-3} = 76.059\,\text{mW}$$

Answer:
Zener current $I_Z = 14.6268\,\text{mA}$
Power dissipation $P_D = 76.059\,\text{mW}$

3. A circuit has a zener diode connected across the load with the following details. Find the source current I, the load current I_L, and the zener power dissipation P_Z.

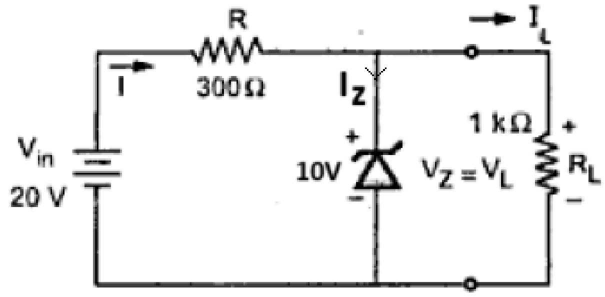


Figure 1.27: Problem 3

Given:

- Source voltage, $V_{in} = 20\,\text{V}$
- Series resistance, $R = 200\,\Omega$
- Zener voltage, $V_Z = 10\,\text{V}$
- Load resistance, $R_L = 1\,\text{k}\Omega = 1000\,\Omega$

To find: I, I_L, and zener power dissipation P_Z

Solution

Applying KVL to the input loop:

$$V_{in} - IR_S - V_Z = 0$$

$$20 - I \cdot 200 - 10 = 0 \Rightarrow I = \frac{20-10}{200} = \frac{10}{200} = 0.05\,\text{A} = 50\,\text{mA}$$

Load current:

$$V_L = V_O = I_L R_L = V_Z \Rightarrow I_L = \frac{V_Z}{R_L} = \frac{10}{1000} = 0.01\,\text{A} = 10\,\text{mA}$$

Power dissipation across Zener:

$$P_Z = V_Z \cdot I_{Zmax} = 10 \cdot 40 \times 10^{-3} = 400\,\text{mW}$$

4. In the circuit shown in Figure 1.28 determine,
a) the load current
b) the zener current
c) power dissipated in zener diode

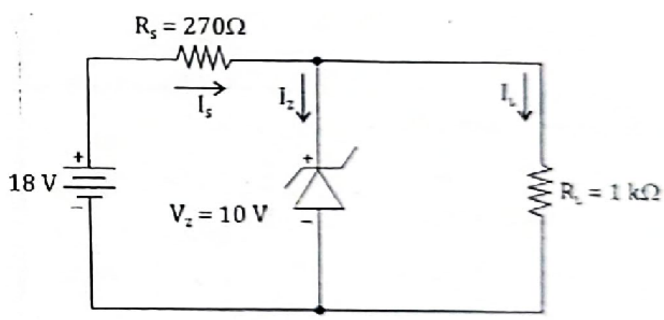


Figure 1.28: Problem 4

Solution

Given: $V_i = 18\,\text{V}, \quad R_S = 270\,\Omega$
$V_z = 10\,\text{V}, \quad R_L = 1\,\text{k}\Omega$

Source Current:

$$I_S = \frac{V_i - V_z}{R_S} = \frac{18-10}{270} = 29.62\,\text{mA}$$

(a) **Load current**

$$I_L = \frac{V_z}{R_L} = \frac{10}{1 \times 10^3} = 10\,\text{mA}$$

(b) **Zener current**

$$I_S = I_Z + I_L \Rightarrow I_Z = I_S - I_L$$

$$I_Z = 29.62 \times 10^{-3} - 10 \times 10^{-3} = 19.62\,\text{mA}$$

(c) **Power dissipated in zener diode**

$$P_Z = V_Z \cdot I_Z = 10 \times 19.62 \times 10^{-3} = 196.2\,\text{mW}$$

Chapter 2

Transistors and their Applications

2.1 Introduction of Bipolar junction transistors (BJT)

- BJT is a three-terminal device constructed using doped semiconductor materials.
- It is mainly used in amplifying and switching applications.
- It is called **bipolar** because both holes and electrons take part in the conduction of current.
- The three terminals of a BJT are:
  - E: Emitter
  - B: Base
  - C: Collector
- Two junctions present in a BJT are:
  - B–E junction (Base–Emitter)
  - C–B junction (Collector–Base)

Types of Transistors

1. **NPN transistor**: A P-type semiconductor material is sandwiched between two N-type materials.
2. **PNP transistor**: An N-type semiconductor material is sandwiched between two P-type materials.

Junction representations of NPN and PNP transistors with terminals can be illustrated in Figure 2.1 using circuit diagrams or symbolic representations.

- **Emitter**: It is highly doped and is the supplier of electrons (in NPN transistor).
- **Base**: It is thin and lightly doped.
- **Collector**: It is moderately doped and large in size. It collects the electrons emitted by the emitter (in NPN transistor).

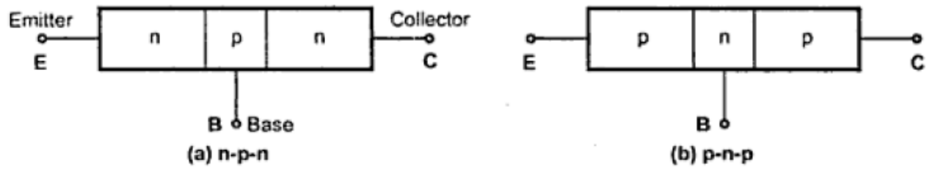


Figure 2.1: Types of Transistor

Transistor symbols:

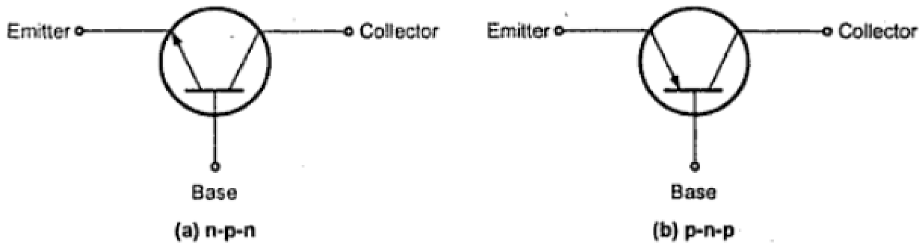


Figure 2.2: Transistor Symbols

- The arrow indicates the emitter terminal of the transistor. It also indicates the connectional direction for the current flow (P to N).
- In NPN transistor the arrowhead points outwards from base to emitter.
- In PNP transistor the arrowhead points inwards for emitter towards the base.

2.1.1 NPN Transistor Operation

Unbiased Transistor

An unbiased transistor means a transistor with no external voltage (biasing) is applied. There will be no current flowing from any of the transistor leads. Since a transistor is like two pn junction diodes connected back to back, there are depletion regions at both the junctions, emitter junction and collector junction, as shown in the Figure 2.3.

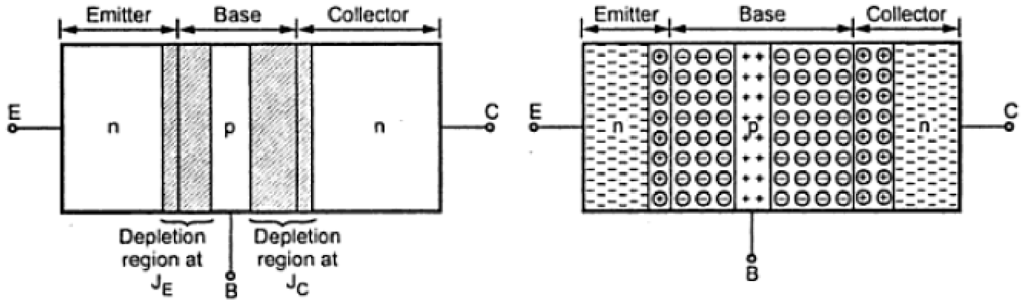


Figure 2.3: Unbiased Transistor

During diffusion process, depletion region penetrates more deeply into the lightly doped side in order to include an equal number of impurity atoms in each side of the junction. As shown in the Figure 2.3, depletion region at emitter junction penetrates less in the heavily doped emitter and extends more in the base region. Similarly, depletion region at collector junction penetrates less in the heavily doped collector and extends more in the base region. As collector is slightly less doped than the emitter, the depletion layer width at the collector junction is more than the depletion layer width at the emitter junction.

Operation of NPN Transistor with Biasing

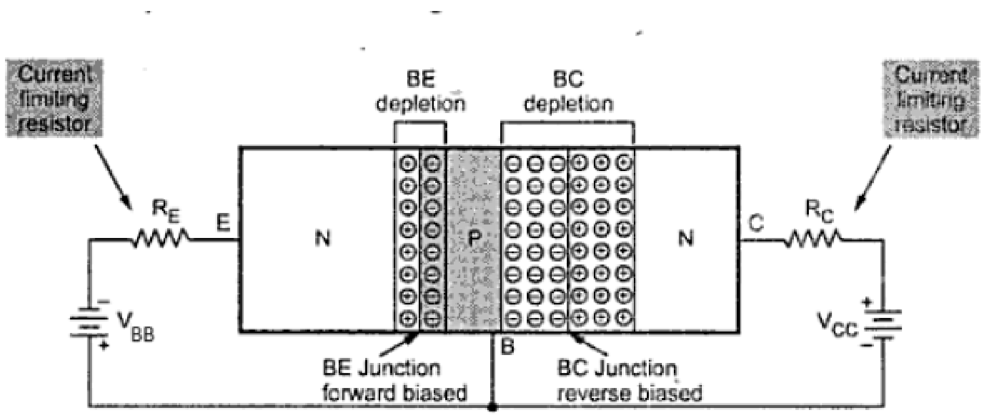


Figure 2.4: Baised Transistor

- Emitter and collector are heavily doped, whereas the base is lightly doped.
- The figure shows an NPN transistor with external bias voltages applied.
- The emitter-base (E–B) junction is forward biased by an external DC source. This reduces the barrier voltage and causes electrons in the N-type emitter to flow toward the P-type base. As a result, the depletion region at the E–B junction becomes narrow.
  (Electrons are emitted into the base region, hence the name **emitter**, and the resulting current is called **emitter current** I_E.)
- The collector-base (C–B) junction is reverse biased by the external DC source. This increases the barrier voltage and widens the C–B depletion region.
- Electrons flow from the emitter through the P-type base and combine with holes in the base. Since the base region is thin and lightly doped, only a few electrons recombine with holes to form the **base current** I_B.
- The remaining electrons reach the C–B depletion region and are drawn across the junction by the external DC bias supply. These electrons are collected in the collector region, giving rise to the **collector current** I_C.
- Thus, electron current is dominant in an NPN transistor.
- Since approximately 98% of the electrons from the emitter flow into the collector circuit and only a few recombine in the base, the base current is small and the collector current is large.

2.1.2 BJT Voltages and Currents (NPN)

Terminal Voltages

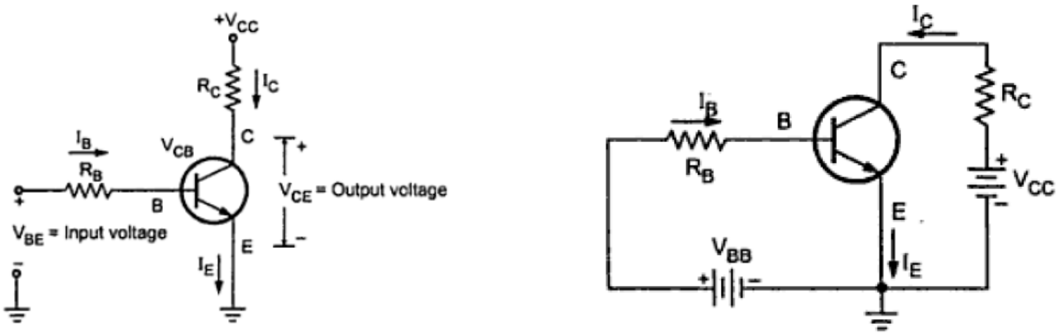


Figure 2.5: Transistor Currents and Voltages

- The direction of the arrowhead indicates the conventional current direction.
- For an NPN transistor, the base is biased with a positive voltage with respect to the emitter.
- The collector is biased with a higher positive voltage than the base.
- In the figure, V_{BB} is the base bias voltage connected through R_B, and the collector supply V_{CC} is connected through R_C.
- The negative terminals of both sources are connected to the emitter terminal.
- To ensure the collector-base junction is reverse biased, $V_{CC} > V_{BB}$ (i.e., positive on collector and negative on base).

Note:

- Typical base-emitter voltages: 0.3 V for germanium, 0.7 V for silicon.
- Typical collector voltages: 3 V to 20 V.

Transistor Currents (NPN)

- For an NPN transistor, I_B and I_C flow into the device (conventional current), and I_E flows out.
- The current relationship is:
$$I_E = I_B + I_C$$
- Electrons are the majority carriers and move opposite to the conventional current direction.
- Low-power transistors: $I_C = 1\,\text{mA}$ to $20\,\text{mA}$.

- High-power transistors: $I_C = 100\,\text{mA}$ to several amperes.

  Nearly 96% to 99% of I_E flows across the collector-base junction to become collector current I_C.

- **Common-base current gain:**

$$I_C = \alpha I_E$$

  Where, α is the **emitter to collector current gain**. It is also referred to as **common base current gain**. It is the ratio of collector current to emitter current,

$$\alpha = \frac{I_C}{I_E}, \quad \text{typically } \alpha \in [0.96 \quad to \quad 0.99]$$

  Hence, the collector current is almost equal to emitter current. In many circuits, it is assumed that $I_C \approx I_E$.

  Leakage current: Since CB junction is reverse biased, very small **reverse saturation current** I_{CBO} flows across the junction. It is known as collector to base leakage current.

- **Common-emitter current gain:**

$$I_C = \beta I_B$$

$$\beta = \frac{I_C}{I_B}, \quad \text{typically } \beta \in [25 \quad to \quad 300]$$

  Where, β is the base to collector current gain. t is also referred to as **common emitter current gain**. It is the ratio of collector to base current.

2.1.3 Relation between α and sβ:

$$I_E = I_C + I_B \tag{1}$$

and

$$\alpha = \frac{I_C}{I_E}, \quad \beta = \frac{I_C}{I_B}$$

$$I_C = \alpha I_E \tag{2}$$

Substituting 1 in 2,

$$I_C = \alpha(I_C + I_B)$$

$$I_C - \alpha I_C = \alpha I_B$$

$$I_C(1 - \alpha) = \alpha I_B$$

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

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

Also,

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

$$\text{or} \quad \beta(1-\alpha) = \alpha$$

$$\beta - \beta\alpha = \alpha$$

$$\beta = \alpha + \beta\alpha$$

$$= (1+\beta)\alpha$$

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

2.2 Numerical on Transistor Currents and Current Gain

1. Calculate I_C and I_E for a transistor that has $\alpha = 0.98$ and $I_B = 100\,\mu\text{A}$. Determine the value of β for the transistor.

   Solution:

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.98}{1-0.98} = \frac{0.98}{0.02} = 49$$
$$I_C = \beta \cdot I_B = 49 \times 100 \times 10^{-6} = 4.9\,\text{mA}$$
$$I_E = I_C + I_B = 4.9\,\text{mA} + 0.1\,\text{mA} = 5\,\text{mA}$$

2. Calculate α and β for $I_C = 1\,\text{mA}$ and $I_B = 25\,\mu\text{A}$. Determine new I_B for $I_C = 5\,\text{mA}$.

   Solution:

$$\beta = \frac{I_C}{I_B} = \frac{1\,\text{mA}}{25\,\mu\text{A}} = 40$$
$$I_E = I_C + I_B = 1.025\,\text{mA}$$
$$\alpha = \frac{I_C}{I_E} = \frac{1}{1.025} \approx 0.976$$
$$I_{B_{\text{new}}} = \frac{I_C}{\beta} = \frac{5\,\text{mA}}{40} = 125\,\mu\text{A}$$

3. Determine β and I_E for $I_B = 50\,\mu\text{A}$ and $I_C = 3.65\,\text{mA}$.

   Solution:

$$I_E = I_C + I_B = 3.65\,\text{mA} + 0.05\,\text{mA} = 3.70\,\text{mA}$$
$$\beta = \frac{I_C}{I_B} = \frac{3.65}{0.05} = 73$$

4. Given $I_C = 3\,\text{mA}$ and $I_E = 3.03\,\text{mA}$, find β. Determine new I_C if $\beta = 70$.

   Solution:

$$I_B = I_E - I_C = 3.03\,\text{mA} - 3\,\text{mA} = 0.03\,\text{mA} = 30\,\mu\text{A}$$
$$\beta = \frac{I_C}{I_B} = \frac{3}{0.03} = 100$$
$$I_{C_{\text{new}}} = \beta \cdot I_B = 70 \times 30 \times 10^{-6} = 2.1\,\text{mA}$$

5. Find I_C and I_E for $\alpha = 0.99$ and $I_B = 20\,\mu$A.
   Solution:

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.99}{0.01} = 99$$
$$I_C = \beta \cdot I_B = 99 \times 20 \times 10^{-6} = 1.98\,\text{mA}$$
$$I_E = I_C + I_B = 1.98\,\text{mA} + 0.02\,\text{mA} = 2\,\text{mA}$$

2.3 Transistor Characteristics

The graphs showing the relationship between different currents and voltages of a transistor are known as the **characteristics** of the transistor.

Types of Characteristics

- Input Characteristics
- Output Characteristics

Any transistor circuit can be designed using three types of configurations, based on the connection of transistor terminals:

- Common Emitter Configuration (CE)
- Common Base Configuration (CB)
- Common Collector Configuration (CC)

Each configuration has its own characteristic curves.

2.3.1 Common Emitter Configuration (NPN)

In this configuration, the emitter terminal is common to both input and output terminals as shown in Figure 2.6.

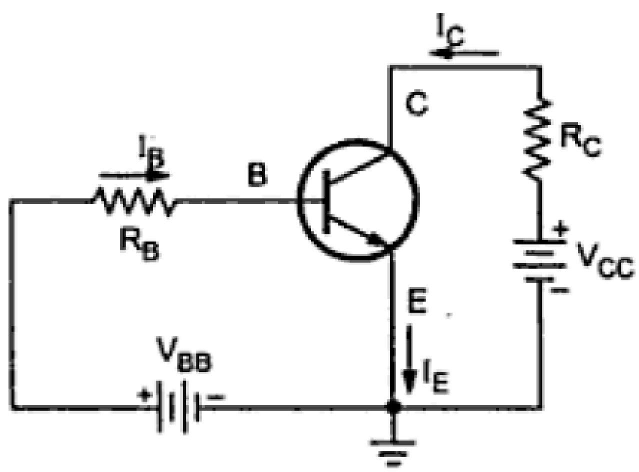


Figure 2.6: CE Configuration of NPN transistr

- Input is applied between the base-emitter (B–E) terminals, and output is taken between collector-emitter (C–E) terminals.
- This configuration is widely used as an inverting amplifier.
- It introduces a phase shift of 180° at the output.
- The B–E junction is forward biased and the C–B junction is reverse biased using supplies V_{BB} and V_{CC}.
- The negative terminal of V_{BB} repels electrons in the emitter, causing current to flow from emitter to base and then to collector.
- Input current: I_B, Output current: I_C, and $I_E = I_B + I_C$

Input Characteristics

Input characteristics are obtained by plotting input current I_B versus input voltage V_{BE} at constant output voltage V_{CE}.

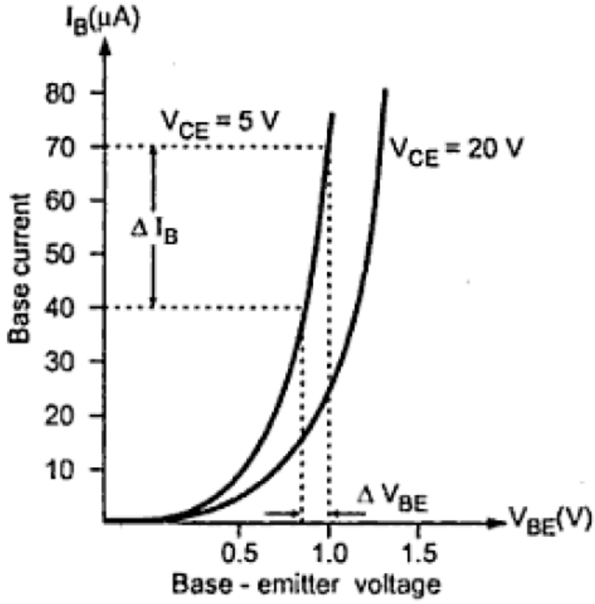


Figure 2.7: Input Characteristics of CE Configuration

- When V_{CE} is constant, after the cut in voltage, the base current (I_B) increases rapidly with a small increase in the V_{BE}. This means that dynamic input resistance is small in the CE configuration.
- Dynamic input resistance is defined as the ratio of change in base-emitter voltage to change in base current at constant V_{CE}:

$$r_i = \frac{\Delta V_{BE}}{\Delta I_B} \quad \text{(with } V_{CE} \text{ constant)}$$

- For a fixed value V_{BE}, I_B decreases as V_{CE} is increased. Alarger value of V_{CE} results in a large reverse bias at collector-base PN junction. This increases the depletion region and reduces the effective width of the base. Hence, there are fewer recombinations in the base region, reducing the base current I_B.

- This shifts the input characteristic curves to the right.

Output Characteristics

Output characteristics are obtained by plotting output current I_C versus output voltage V_{CE} at constant input current I_B.

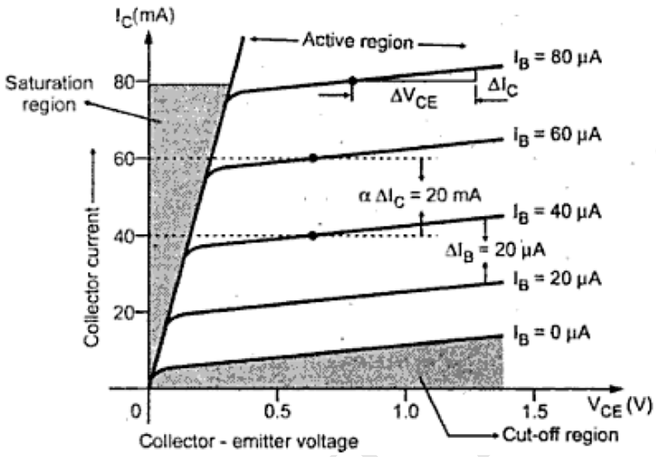


Figure 2.8: Output Characteristics of CE Configuration

- Even with constant I_B, I_C increases slightly with V_{CE}, making the slope.
- If V_{CE} exceeds a certain limit, the C–B junction breaks down, causing I_C to rise rapidly—this is the **breakdown region**.
- For the fixed value of V_{CE}, the ratio of small change in I_c, ΔI_C to small change in I_B, ΔI_B, then β is:

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

- From the output characteristics, the change in collector emitter voltage(ΔV_{CE}) causes little change in the collector current(ΔI_C) for constant base current I_B. Thus, the output dynamic resistance is high in CE configuration,

$$r_o = \frac{\Delta V_{CE}}{\Delta I_C} \quad \text{(with } I_B \text{ constant)}$$

- The output characterstics of common emitter configuration consists of three regions:
  - **Active Region**: As V_{CE} is increased, reverse bias increases. This causes the depletion region to spread more in the base region than in the collector, reducing the chances of recombination in the base. This causes collector current I_C to rise more sharply with increasing V_{CE}. B–E junction is forward biased, C–B junction is reverse biased. A transistor acts as an amplifier.

- **Saturation Region**: If the V_{CE} is reduced, the CB junction becomes forward biased, since the EB junction is already forward biased, I_C also decreases rapidly. Here both the junctions are forward biased. A transistor acts as a closed switch.
- **Cut-off Region**: When the input base current is made equal to zero, the I_C is the small leakage current. Here, both junctions are reverse-biased biased and hence no current flows through the transistor. A transistor acts as an open switch.

- In the active region, the CB junction is reverse biased. If the V_{CE} is excedes the maximum limit, width of the depletion region at the CB junction increses such that it penatrates into the base until it makes contact with EB depletion region. This condition is called **punch through effect**. When this situation occurs, breakdown of transitor occurs. That is large I_C flows and which distroys the transistor.

2.4 CE-RC Coupled Amplifier (Single Stage)

Single-stage RC coupled amplifiers are designed to improve the strength of weak signals for further amplification.

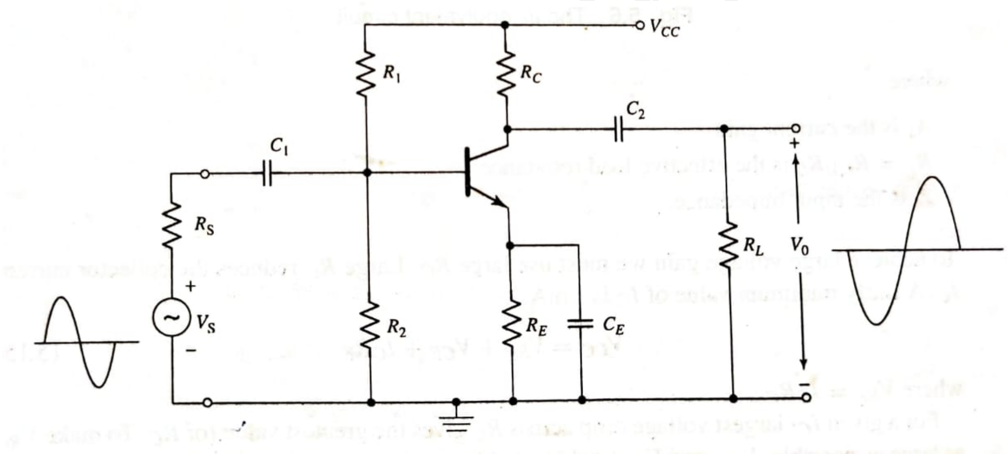


Figure 2.9: Single Stage Common Emitter RC Coupled Amplifier

Significance of the each Components

- **Input Coupling Capacitor C_1, C_2**: C_1 Couples the small signal AC, V_s to the base of the transistor. Blocks DC and allows only AC to pass, preventing external DC from affecting the transistor's biasing. If the C_1 is not connected, then the R_s is in parallel with R_2. This will reduce the bias voltage at the transistor base and alter the collector current. To avoid this and maintain the stability of bias condition coupling capacitors are connected.

- **Biasing Circuit (R_1, R_2 and R_E)**: The R_1 and R_2 provides necessary base bias using a voltage divider network to operate the transistor in the active region. It sets the proper operating point for the CE amplifier. The R_E provides bias stabilization.

- **Emitter Bypass Capacitor** C_E: Connected in parallel to R_E, it offers a low-resistance path to the amplified AC signal, thereby increasing the gain.

  Note: Without C_E, the amplified signal passes through R_E, causing a large voltage drop and reducing output voltage and gain.

- **Output Coupling Capacitor** C_2: Connected at the collector to block DC and pass AC to the load or next stage. If the R_L is connected directly to the output without connecting the C_2, the DC levels of V_{CE} and V_c will change. To avoid this Coupling capacitors are used at the output.

Phase Reversal Concept

- During the **positive half cycle** of the input signal V_s, the AC and DC voltages add together, increasing the forward bias across the base-emitter (B-E) junction. This leads to an increase in base current I_B. Consequently, the collector current increases as:

  $$I_C = \beta I_B$$

  The increase in I_C causes an increase in the voltage drop across R_C.

- Since the collector voltage is given by:

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

  An increase in I_C increases $I_C R_C$, causing V_C to decrease (i.e., move in the negative direction).

- During the **negative half cycle** of the AC input signal V_s, the AC and DC voltages oppose each other, reducing the forward bias across the B-E junction. As a result, the base current I_B decreases, which also reduces the collector current I_C.

- The reduction in I_C decreases the voltage drop $I_C R_C$ across R_C. Since:

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

  For a fixed V_{CC}, when $I_C R_C$ reduces, the collector voltage V_C increases (moves in the positive direction).

Thus, as V_s increases in the positive direction, the collector voltage V_C moves in the negative direction. Hence, we obtain a **negative half cycle** of the output voltage for a **positive half cycle** at the input.

Similarly, a **positive half cycle** is observed at the output for a **negative half cycle** at the input. Therefore, we conclude that there exists a 180° **phase shift** between the input and output voltages in a CE amplifier, making it an **inverting amplifier**.

2.5 Transistor as a Switch

A transistor can be made to operate as an ON/OFF switch.

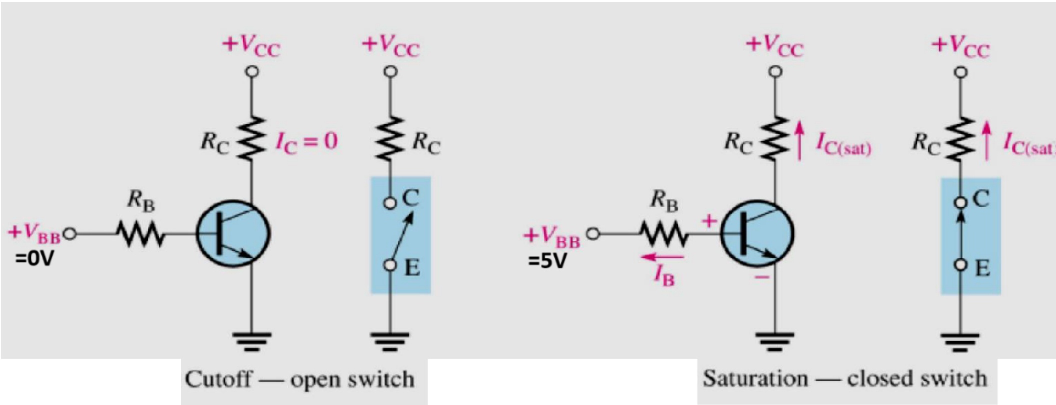


Figure 2.10: Transistor as Switch

Case 1: Cut-off State (Open Switch)

When base voltage $V_{BB} = 0V$, both the EB and CB junctions are reverse biased. No base current I_B flows. Hence, $I_C = 0$. Therefore, the collector (C) and emitter (E) terminals are open-circuited.

Output collector voltage: $V_O = V_{CC}$

Therefore, the transistor is in the cut-off state.

Case 2: Saturation State (Closed Switch)

When a higher level of base voltage V_{BB} is applied, both EB and CB junctions are forward biased. A large base current I_B flows due to $+V_{BB}$ which makes the collector current reach saturation level. Hence, collector (C) and emitter (E) terminals are short-circuited.

Output collector voltage: $V_O = 0V$

Saturation current:

$$I_{C(sat)} = \frac{V_{CC} - V_{CE}}{R_C}$$

Therefore, the transistor is in the saturation state.

2.6 Field Effect Transistor

- Field Effect Transistor known as FET is a 3-terminal semiconductor device in which current flow is only due to one of the two kinds of charge carriers namely electrons or holes. Hence, it is a unipolar device.
- BJT is a current controlled device (I_B controls I_C in CE configuration) while FET is a voltage controlled device (input voltage controls output current).
- FET construction is simple compared to BJT and uses less area in an integrated circuit (IC). It is less noisier than BJT.
- Low power consumption and are used in MOS circuits.

- Input resistance is high compared to BJT.

Two Types of FETs are:

1. **Junction Field Effect Transistor (JFET)**
2. **Metal Oxide Semiconductor Field Effect Transistor (MOSFET)**

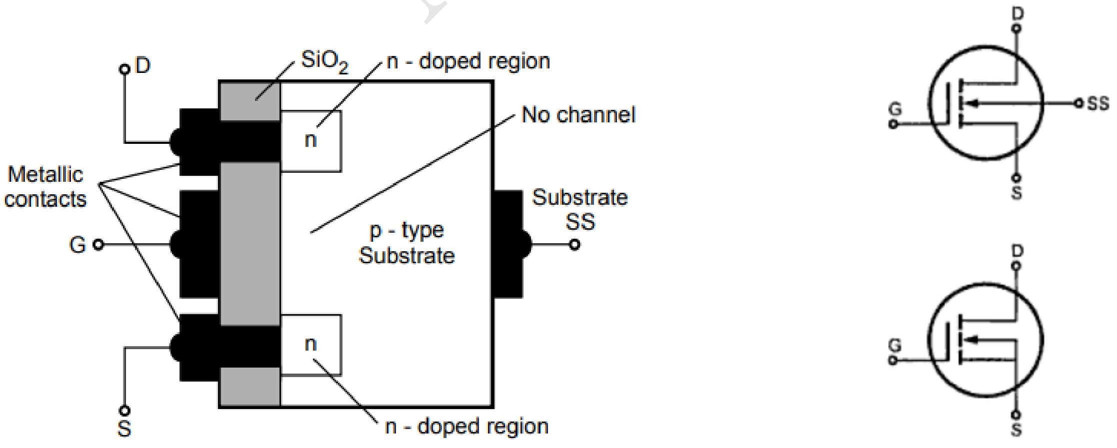
1. JFET

- n-channel JFET
- p-channel JFET

2. MOSFET

- **Depletion type**
  - n-channel
  - p-channel
- **Enhancement type**
  - n-channel
  - p-channel

2.6.1 N channel Enhancement Type Metal Oxide Semiconductor (N-EMOSFET)



(a) Structure (b) Symbol

Figure 2.11: N-EMOSFET

Basic Construction

- A slab of *p-type* material is formed from a silicon base and is referred to as substrate. The substrate is internally connected to the source terminal.

- The source and drain terminals are connected through metallic contacts to the *n-doped* regions. There is an absence of channel between the two *n-doped* regions.
- SiO_2 layer is present to isolate the gate metallic platform from drain and source terminals.

Drain and Trnasfer Characteristics of n-channel MOSFET

- If V_{GS} is set to 0V and a positive voltage is applied between drain and source terminals, the absence of an n-channel will result in a current of zero mA.
- Both V_{GS} and V_{DS} are set at some positive voltage greater than zero volts. This establishes a positive potential between the drain and gate with respect to the source.
- The positive potential at the gate will pressure the holes in the p-substrate along the edge of SiO_2 layer to leave the area and enter deeper regions of the p-substrate, as in Figure 2.12.

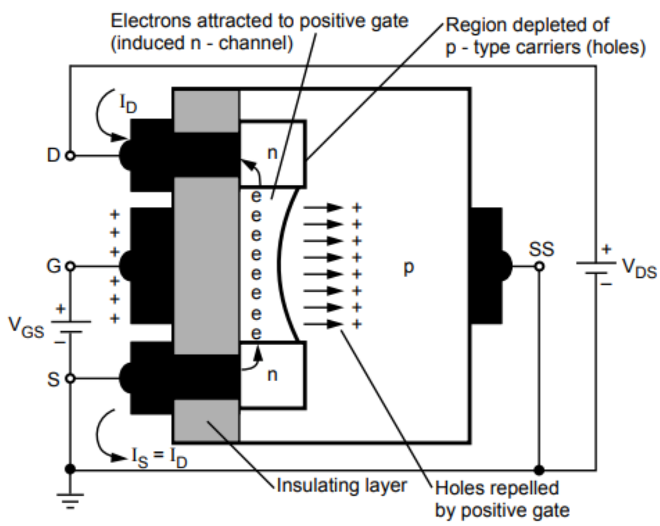


Figure 2.12: Channel formation in the NEMOSFET

- The electrons (minority carriers) in the p-substrate will be attracted to the positive gate and accumulate in the region near the surface of the SiO_2 layer.
- The SiO_2 layer and its insulating qualities will prevent the electrons from being absorbed by the gate.
- As V_{GS} increases in magnitude, the concentration of electrons near the SiO_2 surface increases until it can control the flow of current between drain and source.
- The level of V_{GS} that results in significant increase in drain current is called as **threshold voltage** V_T.

- Since the channel is non-existent with $V_{GS} = 0V$ and is enhanced by the application of positive gate-to-source voltage, this type of MOSFET is called an **enhancement type MOSFET**.
- The Figure 2.13 shows the drain characteristics of an N channel enhancement type MOSFET. Here, as V_{GS} is increased beyond the threshold level V_T, $V_{GS} > V_T$, the density of free carriers in the induced channel will increase, resulting in increased drain current I_D.

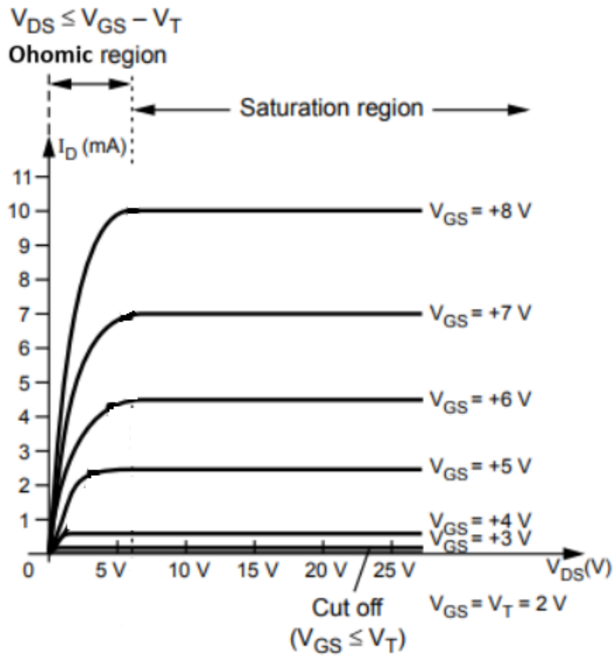


Figure 2.13: Drain Characteristics of the N-EMOSFET

- If V_{GS} is held constant, and V_{DS} is increased, the drain current I_D increases in the initial portion of the curve, and this region is called **Ohmic region**. As the V_{DS} is further increased I_D reaches a **Saturation level**. At this condition, pinching off occurs.
- When saturation occurs, the channel becomes narrow toward the drain, as shown in Figure 2.14.

- With V_{GS} held constant and V_{DS} increased, the gate-to-drain voltage V_{GD} will drop. So, the gate will be less and less positive with respect to the drain.
- This reduction in gate-to-drain voltage causes a reduction in channel width. Hence, the channel will be reduced to a point of pinch-off and a saturation condition will be established.

  Saturation Condition:

  $$V_{DS(\text{sat})} = V_{GS} - V_T$$

- When V_{DS} is less than V_T, the drain current drops to zero and hence the device shifts to **Cut off region.**

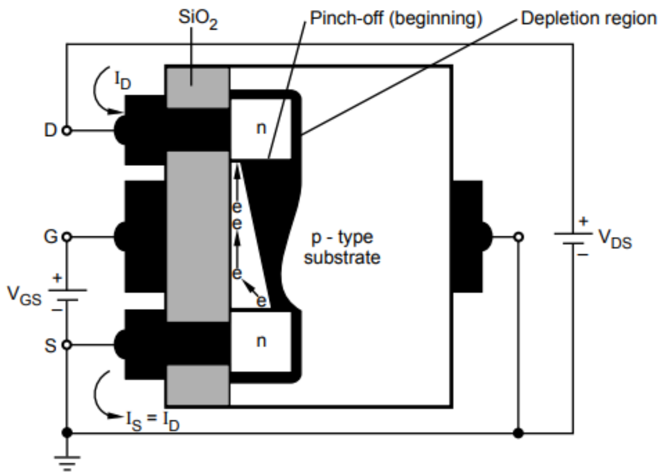


Figure 2.14: Change in channel and depletion in MOSFET

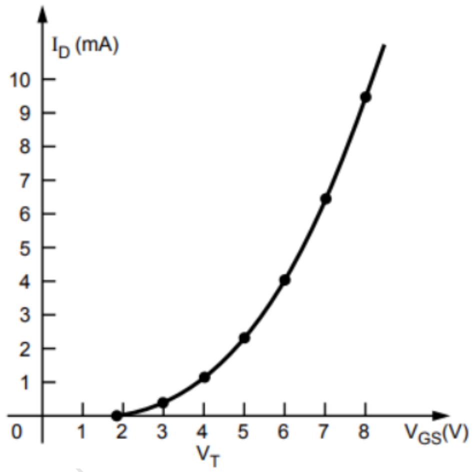


Figure 2.15: Transfer Characteristics of the NEMOSFET

The Figure 2.15 shows the Transfer characteristics of the MOSFET.

- For $V_{GS} < V_T$, $I_D = 0\,\text{mA}$
- For $V_{GS} > V_T$, I_D depends on V_{GS} and is applied by a nonlinear relation:

$$I_D = K(V_{GS} - V_T)^2$$

Where,

$$K \text{ is a constant} = 0.278 \times 10^{-3}\,\text{A/V}^2$$

$$K = \frac{I_{D(\text{ON})}}{(V_{GS} - V_T)^2}$$

2.7 CMOS Inverter

- **CMOS** → Complementary MOS. It uses two E-MOSFETs for its construction.

- A P-channel and N-channel E-MOSFET when placed on the same substrate is known as **Complementary MOS**.
- It has low input impedance, fast switching speeds and low power consumption.
- It is used in computer logic design.
- One N-type MOS (NMOS) and one P-type MOS (PMOS) are connected in pairs to form CMOS.
- Gates of the two devices are connected to form the input terminal, and the two drain terminals are connected together to form the output terminal, as shown in Figure 2.16.

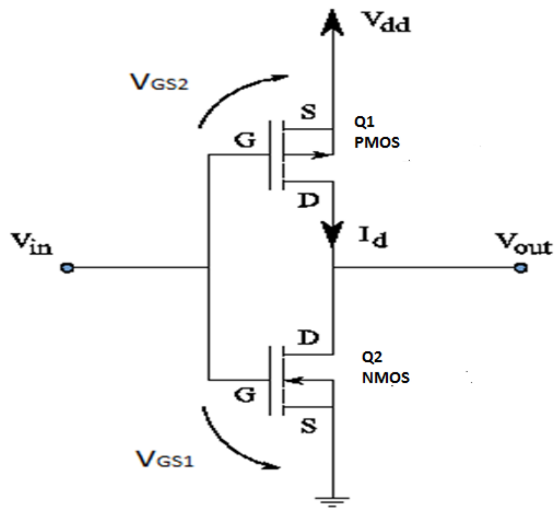


Figure 2.16: CMOS Inverter

Case 1: When $V_{\text{in}} = 5\text{V}$ (State 1)

$$V_{\text{GS2}} = V_{\text{in}} - V_{\text{DD}} = 5 - 5 = 0\text{V}$$

Hence, PMOS is non-conducting or **OFF** (open circuited). It offers high resistance.

$$V_{\text{GS1}} = V_{\text{in}} - V_{\text{G}} = 5 - 0 = 5\text{V}$$

Therefore, for $V_{\text{GS1}} = 5\text{V}$, NMOS is conducting or **ON** (short circuited to ground). It offers low resistance.

NMOS is ON with low resistance. Hence,

$$V_{\text{out}} = 0\text{V} \quad \text{(State 0)}$$

Case 2: When $V_{\text{in}} = 0\text{V}$ (State 0)

$$V_{\text{GS2}} = 0 - 5 = -5\text{V}$$

For negative gate voltage, PMOS is ON and acts as a closed switch. It conducts and offers low resistance.

$$V_{\mathrm{GS1}} = 0 - 0 = 0\mathrm{V}$$

NMOS is non-conducting for $V_{\mathrm{GS1}} = 0\mathrm{V}$.
Hence, it is **OFF** and open circuited. It offers high resistance.

$$\therefore \text{PMOS is ON with } V_{\mathrm{out}} = 5\mathrm{V} \quad \text{(State 1)}$$