Department of Electronics & Communication Engineering

Basic Electronics Notes (ECE111)
NitteDU - 2025

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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.

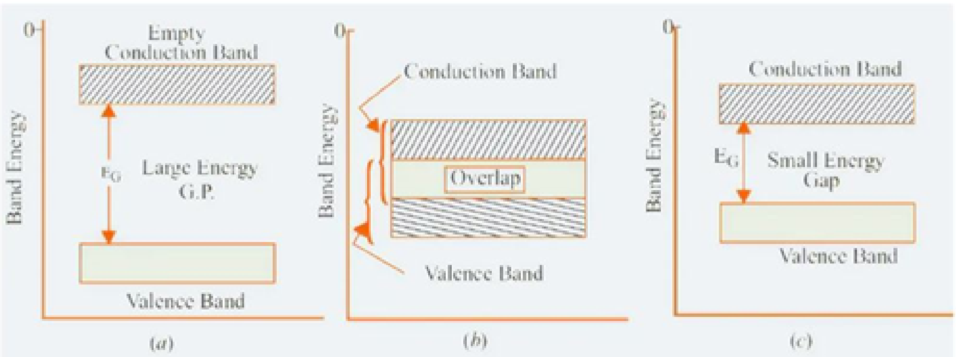

Figure 1.1: Energy Band Gap of different Materials: (a) Insulators, (b) Conductors, (c) Semiconductors

★ **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.

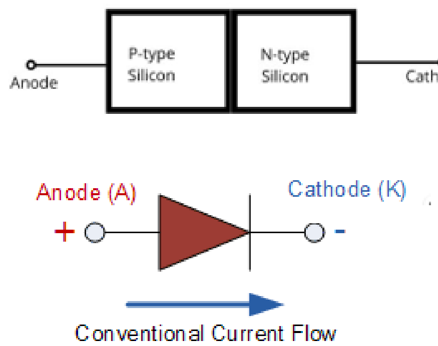

Figure 1.2: Diode Symbol

- 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.

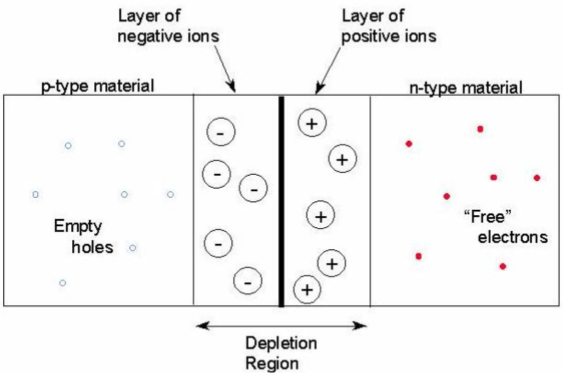

Figure 1.3: Unbaised Diode

- 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**.

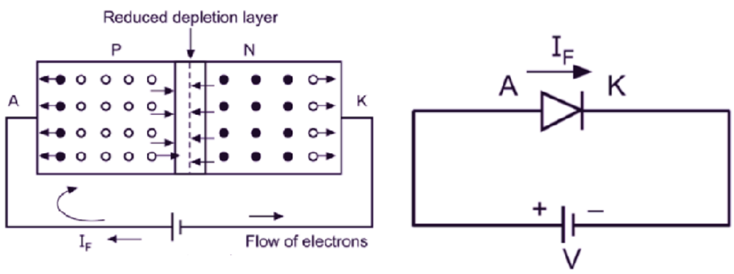

Figure 1.4: Forward Biasing of the Diode

- 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**.

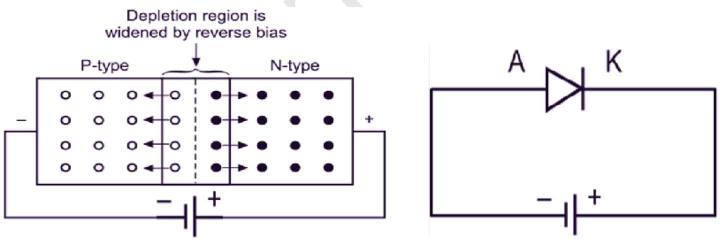

Figure 1.5: Reverse Biasing of the Diode

- 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:

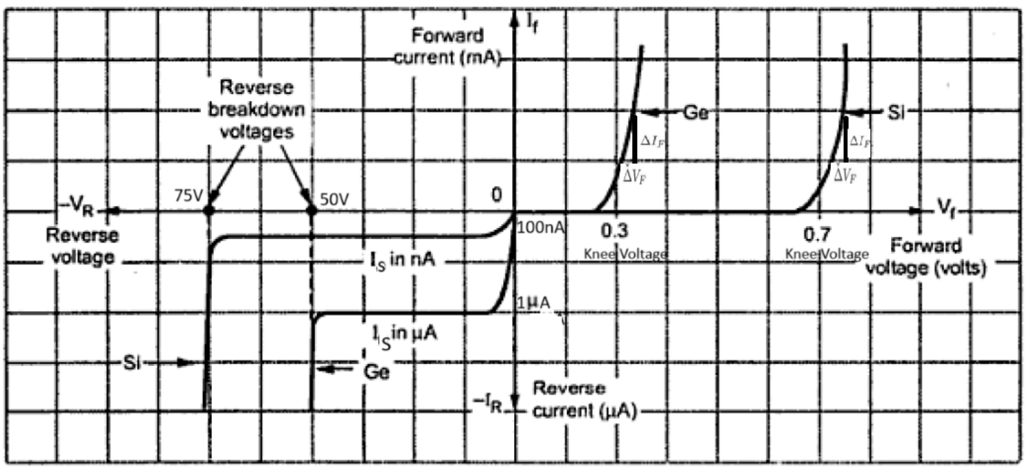

Figure 1.6: Reverse Biasing of the Diode

- 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.

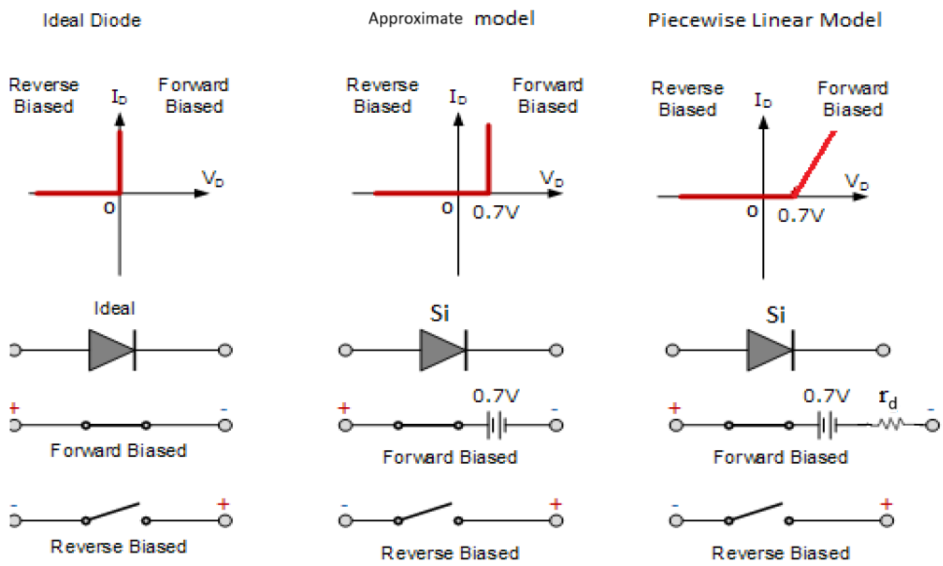

Figure 1.7: Diode Models

1. Ideal Diode Model

- In an ideal diode:
  - **Forward Voltage Drop** (V_F) = 0
  - **Forward Resistance** (R_F) = 0
  - **Reverse Resistance** (R_R) = ∞
  - **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.

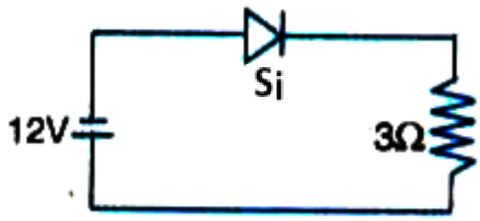

Figure 1.8: Problem 1

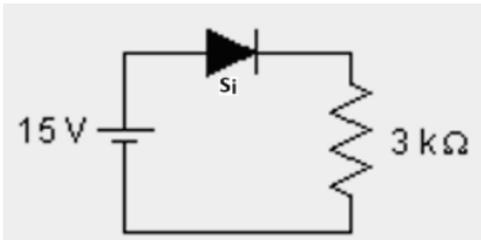

Figure 1.9: Problem 2

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.

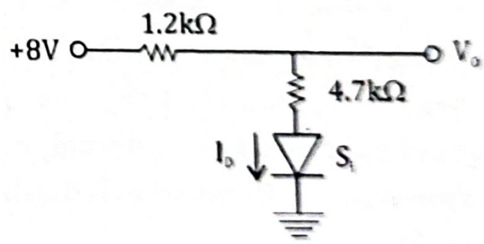

Figure 1.10: Problem 3

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

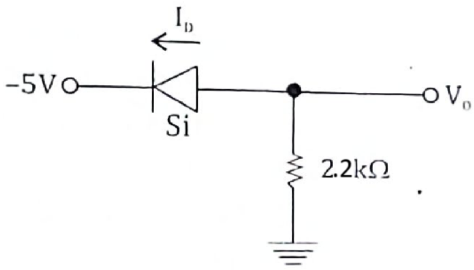

Figure 1.11: Problem 4

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.

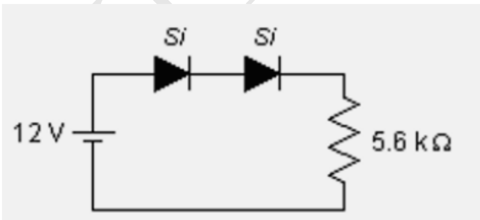

Figure 1.12: Problem 5

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.

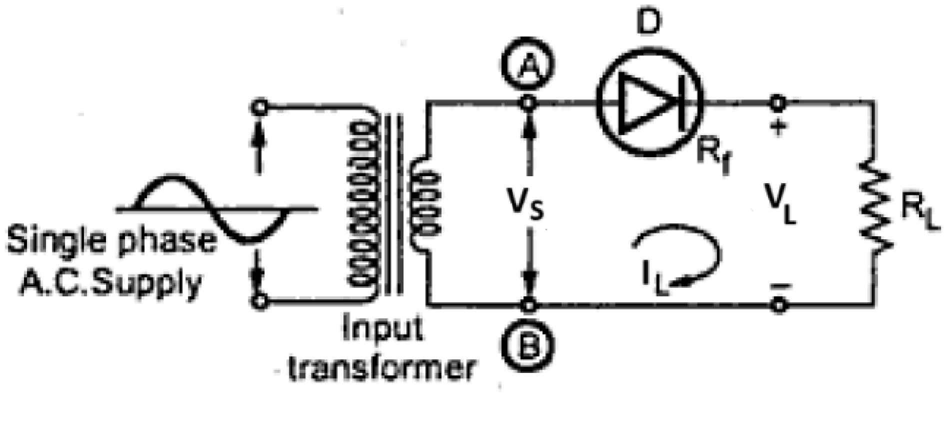

Figure 1.13: Half Wave Rectifier

- 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, $\omega = 2\pi$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

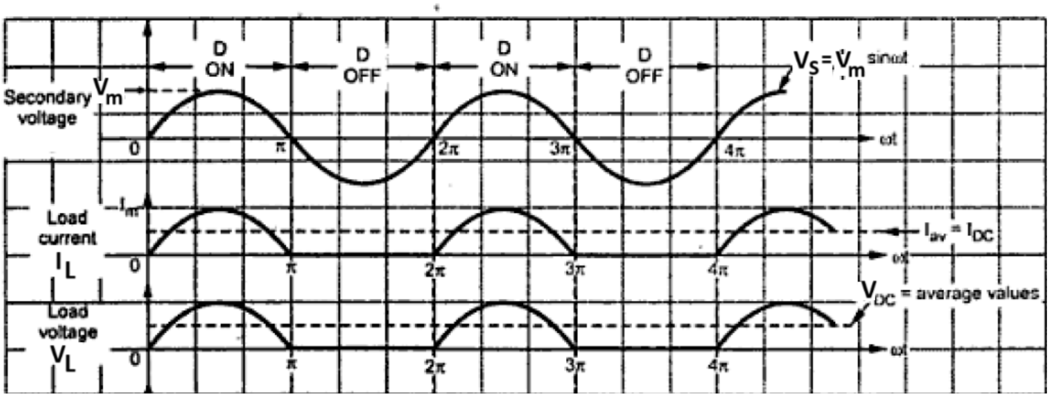

Figure 1.14: HWR Waveforms

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:

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

Therefore, the ripple factor becomes:

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

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.

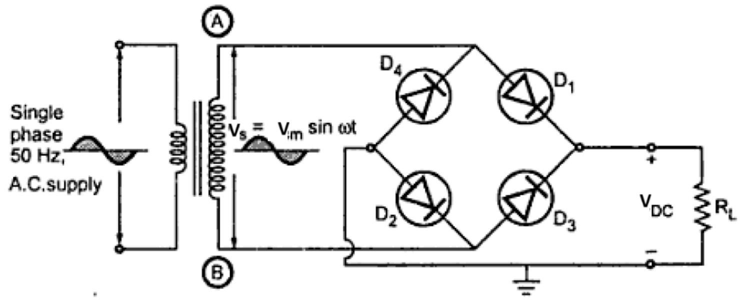

Figure 1.15: Full Wave Rectifier

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.

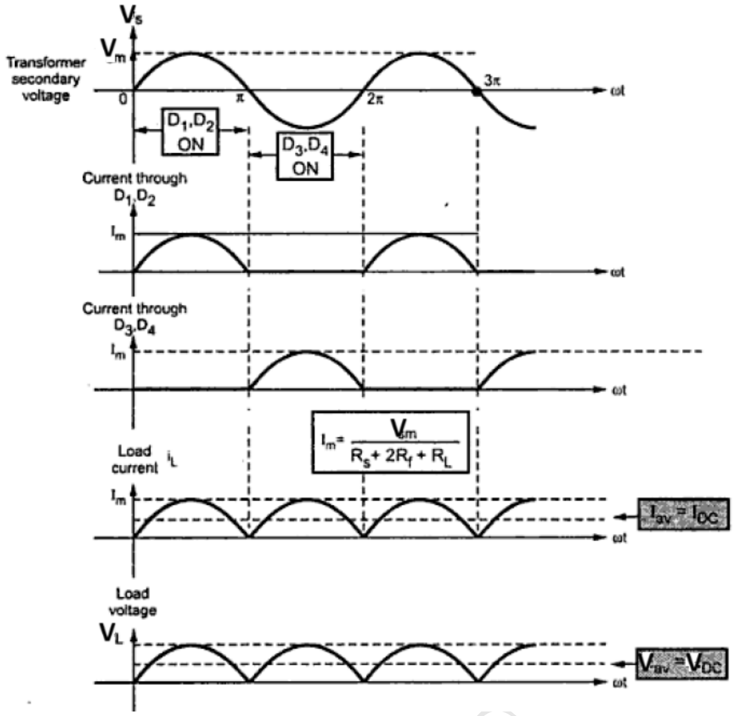

Figure 1.16: FWR Waveforms

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

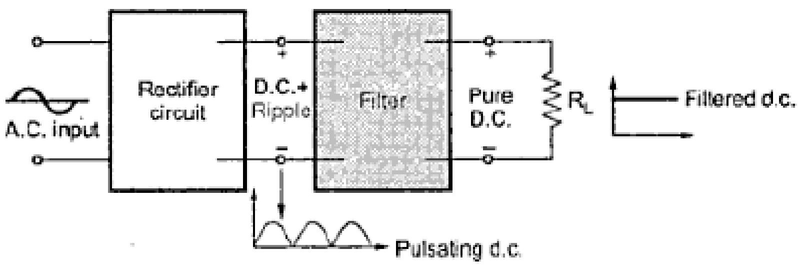

Figure 1.17: Filter Circuit

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.

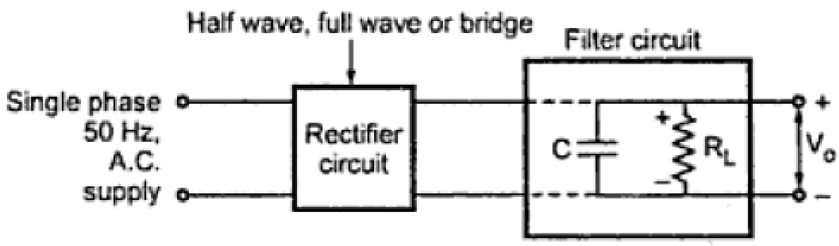

Figure 1.18: Capacitor Filter

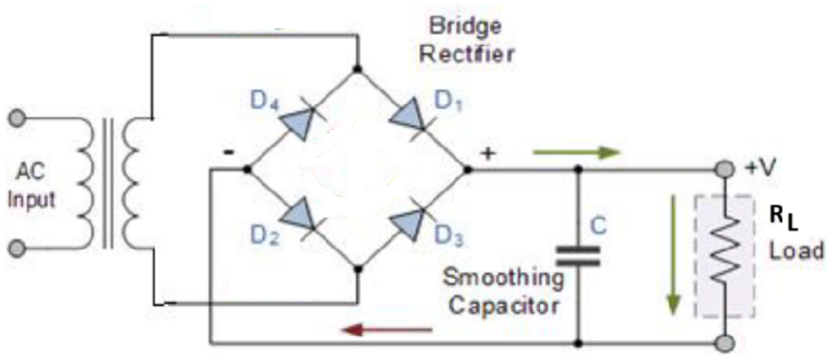

Figure 1.19: Capacitor Filter in Bridge Rectifier

- 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

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

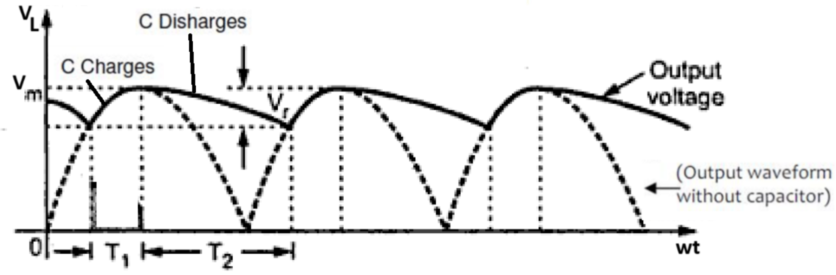

Figure 1.20: Bridge Rectifier with filter waveform

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
   - Rectification efficiency
   - DC power delivered to the load

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:

$$\eta = \frac{1}{1 + \frac{R_f}{R_L}} = \frac{1}{1 + \frac{50}{500}} = \frac{1}{1.1} = 0.909$$

$$\%\eta = 0.909 \times 0.406 = 0.3691 = 36.91\%$$

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:

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

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 $2\,\text{k}\Omega$ and the supply frequency is $50\,\text{Hz}$.

   Solution:

   Given:

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

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

   Substituting the values:

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

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

1.9 Zener Diode

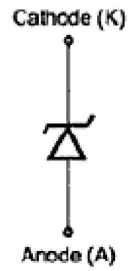

Figure 1.21: Zener Diode Symbol

- 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 biasing of the zener diode is shown in the Figure 1.22. The VI characterstics of the Zener is shown in Figure 1.23

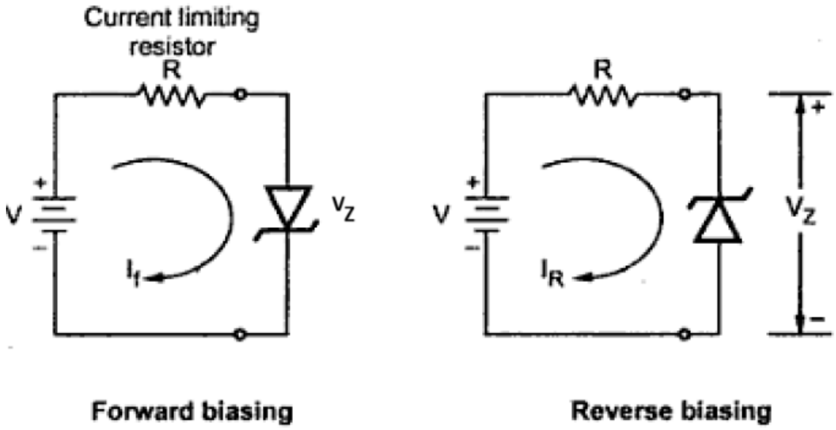

Figure 1.22: Forward and Reverse baising of the Zener diode

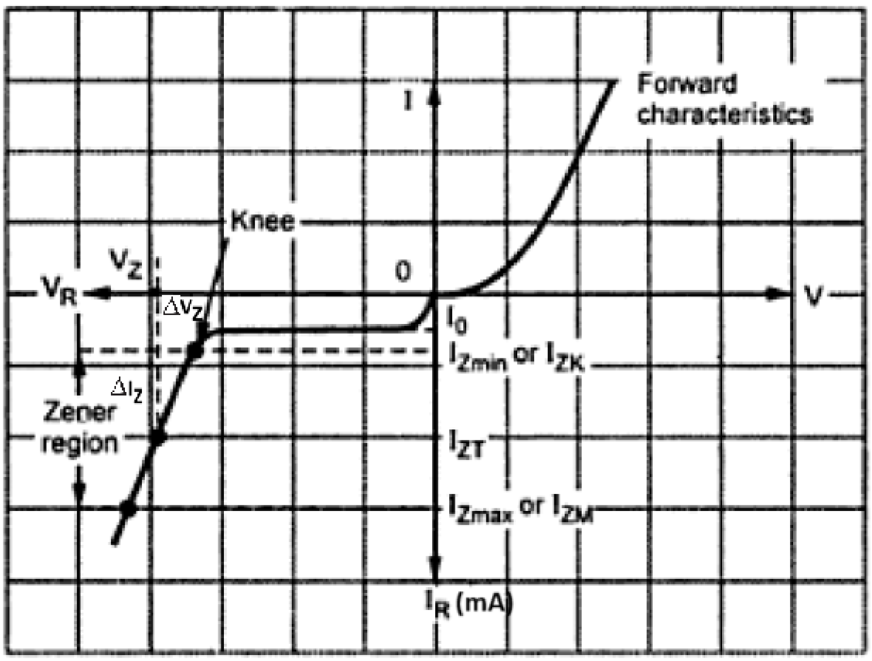

Figure 1.23: VI Characteristics of the Zener diode

- In the forward biased condition, the normal rectifier diode and the zener diode operate in similar fashion. But the zener diode is designed to be operated in the reverse biased condition.
- 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, thus converting the depletion region from an insulating material into a conducting material. 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 (I_s) 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. The change from a low value to large value of current is very sharp and is called the **zener knee** of the curve.
- At this knee, a breakdown is said to occur in the device. The revese bais voltage at which the breakdown occurs is called **zener breakdown viltage,** denoted as V_Z.
- Under this condition, the diode may be continuously operated in reverse breakdown.
- The current corresponding to a knee point is called **zener knee current** and it is the minimum current a zener must carry to operate in the reverse breakdown region. It is denoted as I_{ZK} **or** $I_{Z\mathbf{min}}$**.**
- From the bottom of the knee, the zener breakdown voltage remains almost constant, though it increases slightly as the zener current I_Z increases. The current at which the nominal zener breakdown voltage is specified is called **zener test current**, denoted as I_{ZT}**.**
- Every zener diode has a capacity to carry current. As current increases, the power dissipation $P_Z = V_Z \cdot I_Z$ increases. If this dissipation increases beyond a certain value, the diode may get damaged. The maximum current a zener diode can carry safely is called **zener maximum current** and is denoted as I_{ZM} **or** $I_{Z\mathbf{max}}$**.**
- 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 $I_{ZT} = 20\,\mathrm{mA}$.

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:

- 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.

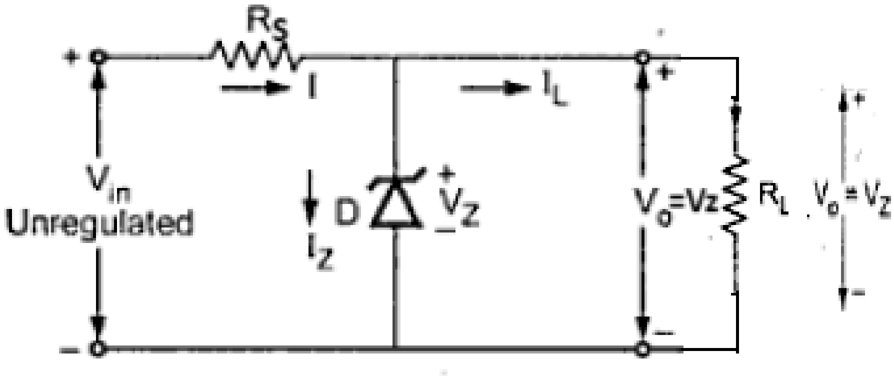

Figure 1.24: Zener Volatge Regulator

- By passing a small current through the diode from a voltage source via a suitable current limiting resistor R_s, the Zener diode will conduct sufficient current to maintain a voltage drop V_o.
- 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 $I_{Z\text{min}}$ and $I_{Z\text{max}}$, 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 $I_{Z\text{max}}$ and $I_{Z\text{min}}$, the output voltage remains constant.

2. **Regulation with Varying Load:**
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 $I_{Z\text{min}}$ and $I_{Z\text{max}}$, 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 $I_{Z\text{max}}$ and $I_{Z\text{min}}$, the output voltage remains 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 $1200\,\Omega$

Given:

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

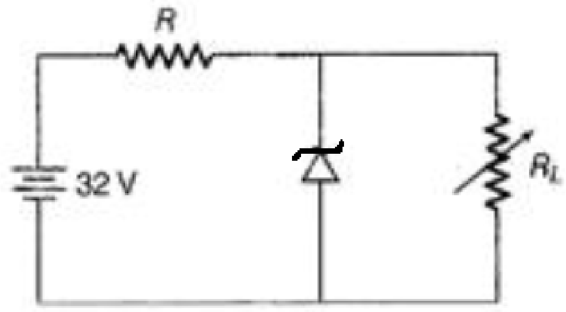

Figure 1.25: Problem 1

(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 $\boxed{I_Z = 5\,\text{mA}}$.

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

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

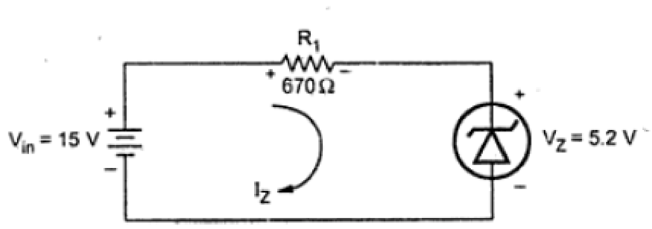

Figure 1.26: Problem 2

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.

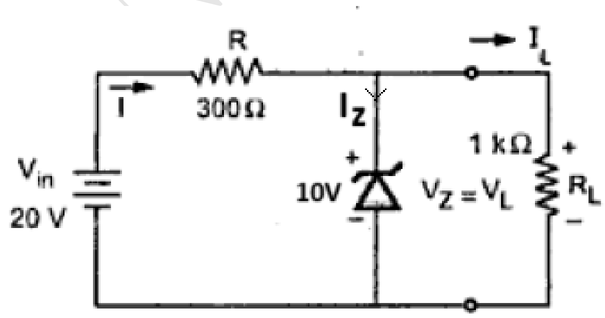

Figure 1.27: Problem 3

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

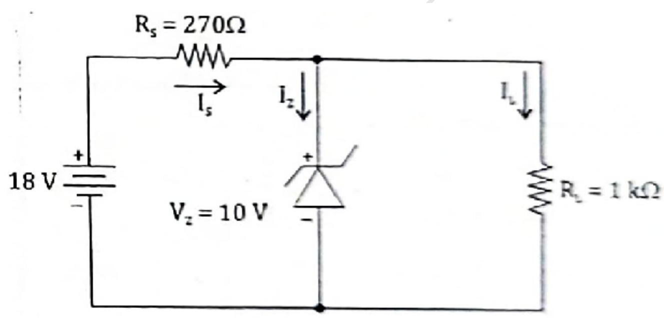

Figure 1.28: Problem 4

Solution

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

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**

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