1

Introduction

General

In this fast developing society, *electronics* has come to stay as the most important branch of engineering. Electronic devices are being used in almost all the industries for quality control and automation and they are fast replacing the present vast army of workers engaged in processing and assembling in the factories. Great strides taken in the industrial applications of electronics during the recent years have demonstrated that this versatile tool can be of great importance in increasing production, efficiency and control.

The rapid growth of electronic technology offers a formidable challenge to the beginner, who may be almost paralysed by the mass of details. However, the mastery of fundamentals can simplify the learning process to a great extent. The purpose of this chapter is to present the elementary knowledge in order to enable the readers to follow the subsequent chapters.

1.1 Electronics

The branch of engineering which deals with current conduction through a vacuum or gas or semiconductor is known as ***electronics.**

Electronics essentially deals with electronic devices and their utilisation. An *electronic device* is that in which current flows through a vacuum or gas or semiconductor. Such devices have valuable properties which enable them to function and behave as the friend of man today.

Importance. Electronics has gained much importance due to its numerous applications in industry. The electronic devices are capable of performing the following functions :

(*i*) **Rectification.** The conversion of a.c. into d.c. is called *rectification.* Electronic devices can convert a.c. power into d.c. power (See Fig. 1.1) with very high efficiency. This d.c. supply can be used for charging storage batteries, field supply of d.c. generators, electroplating etc.

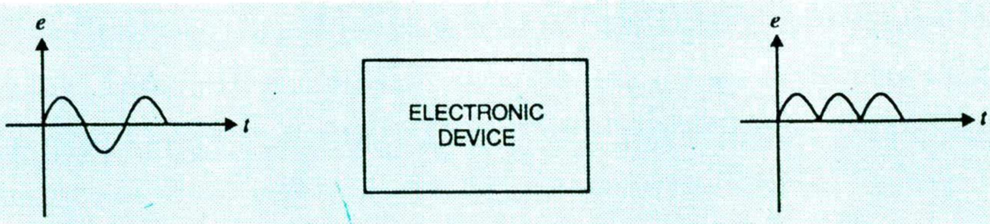

Fig. 1.1

* The word *electronics* derives its name from electron present in all materials.

(*ii*) **Amplification.** The process of raising the strength of a weak signal is known as *amplification*. Electronic devices can accomplish the job of amplification and thus act as amplifiers (See Fig. 1.2). The amplifiers are used in a wide variety of ways. For example, an amplifier is used in a radio-set where the weak signal is amplified so that it can be heard loudly. Similarly, amplifiers are used in public address system, television etc.

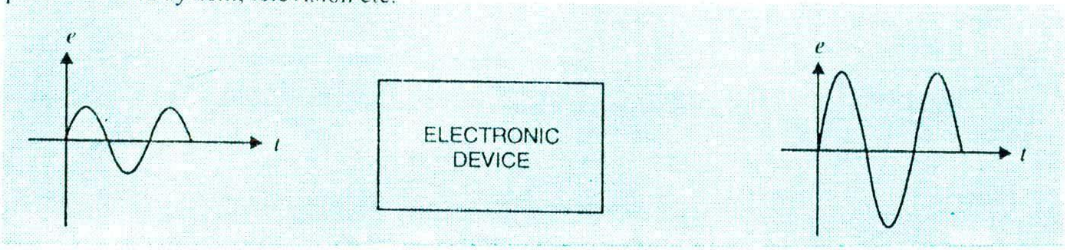

Fig. 1.2

(*iii*) **Control.** Electronic devices find wide applications in automatic control. For example, speed of a motor, voltage across a refrigerator etc. can be automatically controlled with the help of such devices.

(*iv*) **Generation.** Electronic devices can convert d.c. power into a.c. power of any frequency (See Fig. 1.3). When performing this function, they are known as *oscillators*. The oscillators are used in a wide variety of ways. For example, electronic high frequency heating is used for annealing and hardening.

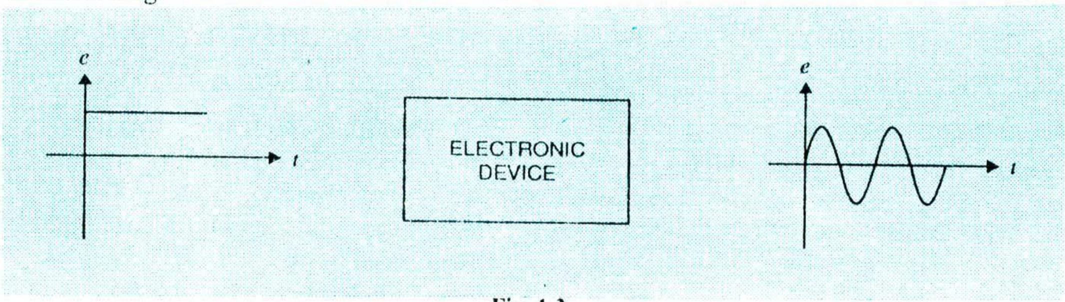

Fig. 1.3

(*v*) **Conversion of light into electricity.** Electronic devices can convert light into electricity. This conversion of light into electricity is known as *photo-electricity*. Photo-electric devices are used in Burglar alarms, sound recording on motion pictures *etc*.

(*vi*) **Conversion of electricity into light.** Electronic devices can convert electricity into light. This valuable property is utilised in television and radar.

1.2 Atomic Structure

According to the modern theory, matter is electrical in nature. All the materials are composed of very small particles called *atoms*. The atoms are the building bricks of all matter. An atom consists of a central *nucleus* of positive charge around which small negatively charged particles, called *electrons* revolve in different paths or orbits.

(1) **Nucleus.** It is the central part of an atom and *contains *protons* and *neutrons*. A proton is a positively charged particle, while the neutron has the same mass as the proton, but has no charge.

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* Although the nucleus of an atom is of complex structure, yet for the purpose of understanding electronics, this simplified picture of the nucleus is adequate.

Therefore, the nucleus of an atom is positively charged. The sum of protons and neutrons constitutes the entire weight of an atom and is called atomic weight. It is because the particles in the extra nucleus (*i.e.* electrons) have negligible weight as compared to protons or neutrons.

∴ atomic weight = no. of protons + no. of neutrons

(2) **Extra nucleus.** It is the outer part of an atom and contains *electrons* only. An electron is a negatively charged particle having negligible mass. The charge on an electron is equal but opposite to that on a proton. Also, the number of electrons is equal to the number of protons in an atom under ordinary conditions. Therefore, an atom is neutral as a whole. The number of electrons or protons in an atom is called *atomic number i.e.*

atomic number = no. of protons or electrons in an atom

The electrons in an atom revolve round the nucleus in different orbits or paths. The number and arrangement of electrons in any orbit is determined by the following rules :

(*i*) The number of electrons in any orbit is given by $2n^2$ where n is the number of the orbit. For example,

First orbit contains $2 \times 1^2 = 2$ electrons

Second orbit contains $2 \times 2^2 = 8$ electrons

Third orbit contains $2 \times 3^2 = 18$ electrons

and so on.

(*ii*) The last orbit cannot have more than 8 electrons.

(*iii*) The last but one orbit cannot have more than 18 electrons.

1.3 Structure of Elements

We have seen that all atoms are made up of protons, neutrons and electrons. The difference between various types of elements is due to the different number and arrangement of these particles within their atoms. For example, the structure* of copper atom is different from that of carbon atom and hence the two elements have different properties.

The atomic structure can be easily built up if we know the atomic weight and atomic number of the element. Thus taking the case of copper atom,

Atomic weight = 64

Atomic number = 29

∴ No. of protons = No. of electrons = 29

and No. of neutrons = 64 − 29 = 35

Fig. 1.4 shows the structure of copper atom. It has 29 electrons which are arranged in different orbits as follows. The first orbit will have 2 electrons, the second 8 electrons, the third 18 electrons and the fourth orbit will have 1 electron. The atomic structure of all known elements can be shown in this way and the reader is advised to try for a few commonly used elements.

1.4 The Electron

Since electronics deals with tiny particles called electrons, these small particles require detailed study. As discussed before, an electron is a negatively charged particle having negligible mass. Some of the important properties of an electron are :

(*i*) Charge on an electron, $e = 1.602 \times 10^{-19}$ coulomb

* The number and arrangement of protons, neutrons and electrons.

(*ii*) Mass of an electron, $m = 9.0 \times 10^{-31}$ kg

(*iii*) Radius of an electron, $r = 1.9 \times 10^{-15}$ metre

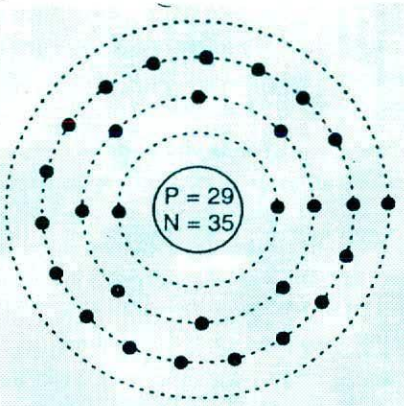


Fig. 1.4

The ratio *e/m* of an electron is 1.77×10^{11} coulombs/kg. This means that mass of an electron is very small as compared to its charge. It is due to this property of an electron that it is very mobile and is greatly influenced by electric or magnetic fields.

1.5 Energy of an Electron

An electron moving round the nucleus possesses two types of energies viz. kinetic energy due to its motion and potential energy due to the charge on the nucleus. The total energy of the electron is the sum of these two energies. The energy of an electron increases as its distance from the nucleus increases. Thus, an electron in the second orbit possesses more energy than the electron in the first orbit; electron in the third orbit has higher energy than in the second orbit. It is clear that electrons in the last orbit possess very high energy as compared to the electrons in the inner orbits. These last orbit electrons play an important role in determining the physical, chemical and electrical properties of a material.

1.6 Valence Electrons

***The electrons in the outermost orbit of an atom are known as* valence electrons.**

The outermost orbit can have a maximum of 8 electrons *i.e.* the maximum number of valence electrons can be 8. The valence electrons determine the physical and chemical properties of a material. These electrons determine whether or not the material is chemically active; metal or non-metal or, a gas or solid. These electrons also determine the electrical properties of a material.

On the basis of electrical conductivity, materials are generally classified into *conductors, insulators* and *semi-conductors*. As a rough rule, one can determine the electrical behaviour of a material from the number of valence electrons as under :

(*i*) When the number of valence electrons of an atom is less than 4 (*i.e.* half of the maximum eight electrons), the material is usually *a metal and a conductor*. Examples are sodium, magnesium and aluminium which have 1, 2 and 3 valence electrons respectively (See Fig. 1.5).

(*ii*) When the number of valence electrons of an atom is more than 4, the material is usually *a non-metal and an insulator*. Examples are nitrogen, sulphur and neon which have 5, 6 and 8 valence electrons respectively (See Fig. 1.6).

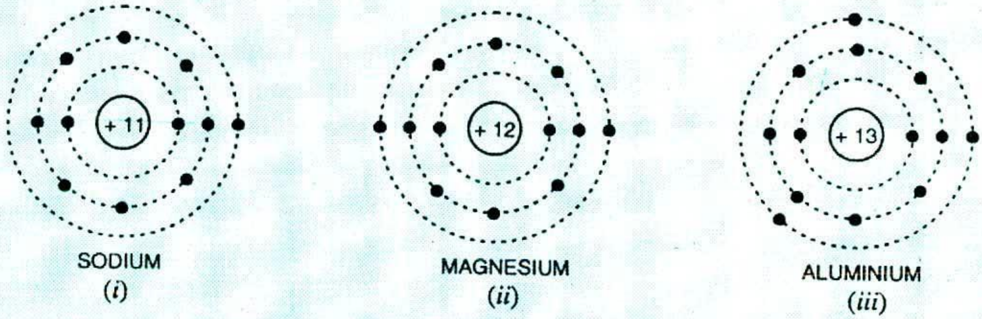


Fig. 1.5

(*iii*) When the number of valence electrons of an atom is 4 (*i.e.* exactly one-half of the maximum 8 electrons), the material has both metal and non-metal properties and is usually a

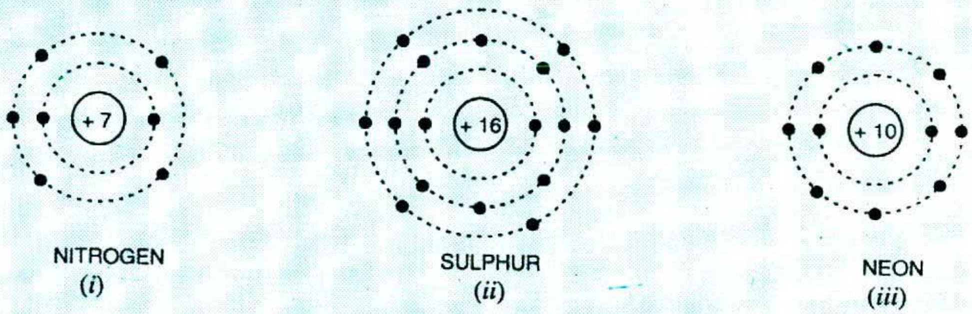


Fig. 1.6

semi-conductor. Examples are carbon, silicon and germanium (See Fig. 1.7).

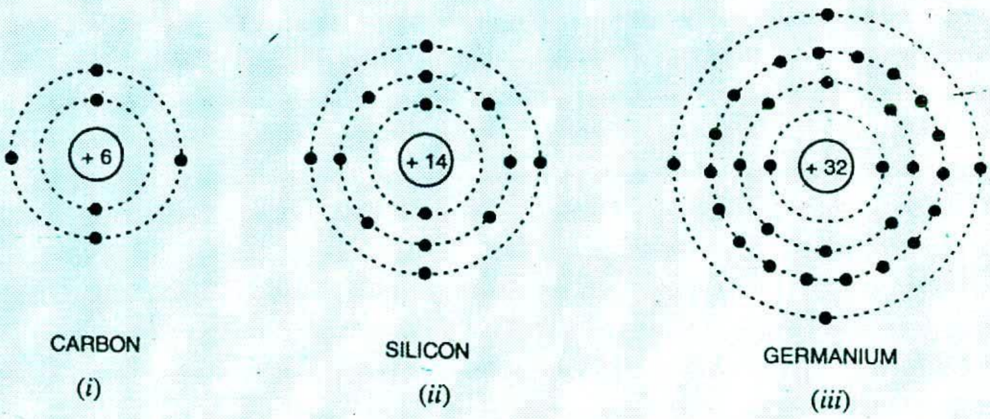


Fig. 1.7

1.7 Free Electrons

The valence electrons of different materials possess different energies. The greater the energy of a valence electron, the lesser it is bound to the nucleus. In certain substances, particularly metals, the valence electrons possess so much energy that they are very loosely attached to the nucleus. These loosely attached valence electrons move at random within the material and are called *free electrons*.

The valence electrons which are very loosely attached to the nucleus are known as **free electrons.**

The free electrons can be easily removed or detached by applying a small amount of external energy. As a matter of fact, these are the free electrons which determine the electrical conductivity of a material. On this basis, conductors, insulators and semiconductors can be defined as under :

(*i*) A *conductor* is a substance which has a large number of free electrons. When potential difference is applied across a conductor, the free electrons move towards the positive terminal of supply, constituting electric current.

(*ii*) An *insulator* is a substance which has practically no free electrons at ordinary temperature. Therefore, an insulator does not conduct current under the influence of potential difference.

(*iii*) A *semiconductor* is a substance which has very few free electrons at room temperature. Consequently, under the influence of potential difference, a semiconductor *practically* conducts no current.

1.8 Voltage Source

Any device that produces voltage output continuously is known as a *voltage source*. There are two types of voltage sources, namely ; direct voltage source and alternating voltage source.

(*i*) **Direct voltage source.** A device which produces direct voltage output continuously is called *a direct voltage source*. Common examples are cells and d.c. generators. An important characteristic of a direct voltage source is that it maintains the same polarity of the output voltage *i.e.* positive and negative terminals remain the same. When load resistance R_L is connected across such a source, *current flows from positive terminal to negative terminal *via* the load [See Fig. 1.8 (*i*)]. This is called *direct current* because it has just one direction. The current has one direction as the source maintains the same polarity of output voltage. The opposition to load current inside the d.c. source is known as *internal resistance* R_i. The equivalent circuit of a d.c. source is the generated *e.m.f.* E_g in series with internal resistance R_i of the source as shown in Fig. 1.8 (*ii*). Referring to Fig. 1.8 (*i*), it is clear that :

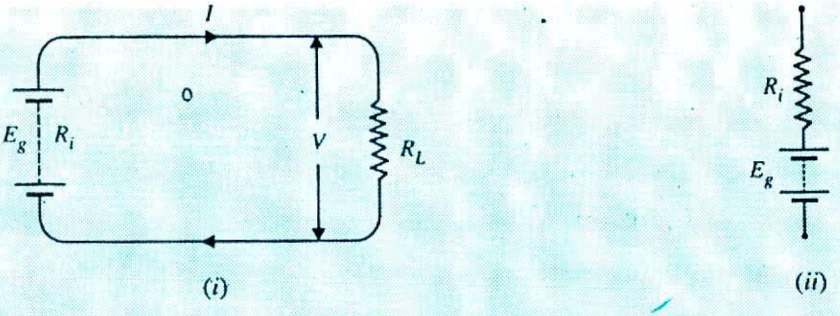


Fig. 1.8

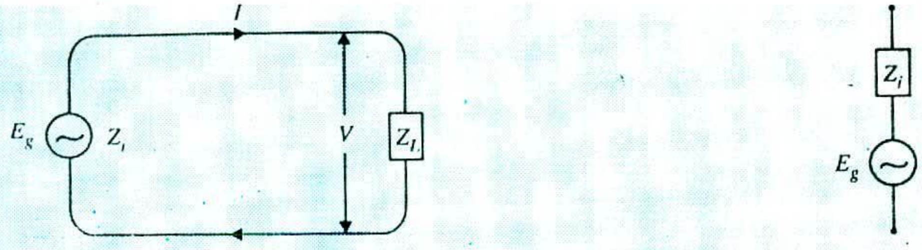
$$\text{Load current, } I = \frac{E_g}{R_L + R_i}$$

$$\text{Terminal voltage, } V = (E_g - I R_i) \quad \text{or} \quad I R_L$$

(*ii*) **Alternating voltage source.** A device which produces alternating voltage output continuously is known as *alternating voltage source e.g.* a.c. generator. An important characteristic of alternating voltage source is that it periodically reverses the polarity of the output voltage. When load

* This is the conventional current. However, the flow of electrons will be in the opposite direction.

impedance Z_l is connected across such a source, current flows through the circuit that periodically reverses in direction. This is called *alternating current.*



(i) (ii)

Fig. 1.9

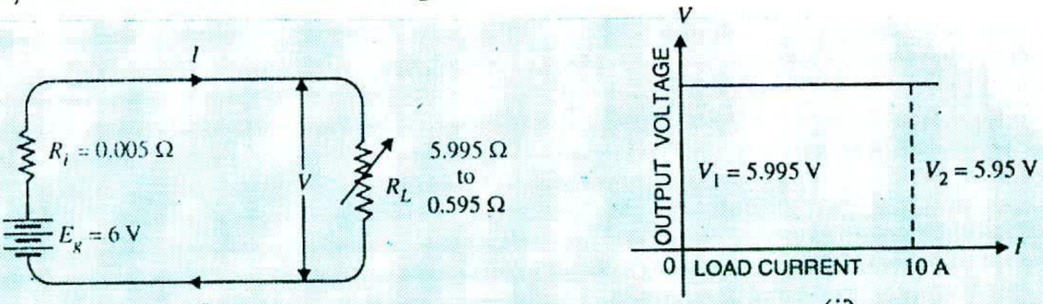
The opposition to load current inside the a.c. source is called its *internal impedance* Z_i. The equivalent circuit of an a.c. source is the generated *e.m.f.* E_g *(r.m.s.)* in series with internal impedance Z_i of the source as shown in Fig. 1.9 (*ii*). Referring to Fig. 1.9 (*i*), it is clear that :

$$\text{Load current, } I\,(r.m.s.) = \frac{E_g}{Z_L + Z_i}$$

$$\text{Terminal voltage, } V = (E_g - I Z_i)^* \quad \text{or} \quad I Z_L$$

1.9 Constant Voltage Source

*A voltage source which has very low internal **impedance as compared with external load impedance is known as a* **constant voltage source.**



(i) (ii)

Fig. 1.10

In such a case, the output voltage nearly remains the same when load current changes. Fig. 1.10 (*i*) illustrates a constant voltage source. It is a d.c. source of 6 V with internal resistance R_i = 0.005 Ω. If the load current varies over a wide range of 1 to 10 A, for any of these values, the internal drop across R_i (= 0.005 Ω) is less than 0.05 volt. Therefore, he voltage output of the source is between 5.995 to 5.95 volts. 'his can be considered constant voltage compared with the wide ariations in load current.

Fig. 1.11

Fig. 1.10 (*ii*) shows the graph for a constant voltage source. may be seen that the output voltage remains constant inspite of

Vector difference since a.c. quantities are vector quantities.

* resistance in case of a d.c. source.

the changes in load current. Thus as the load current changes from 0 to 10 A, the output voltage essentially remains the same (*i.e.* $V_1 = V_2$). A constant voltage source is represented as shown in Fig. 1.11.

Example 1.1. *A lead acid battery fitted in a truck develops 24V and has an internal resistance of 0.01 Ω It is used to supply current to head lights etc. If the total load is equal to 100 watts, find :*

(i) voltage drop in internal resistance

(ii) terminal voltage

Solution.

Generated voltage, $E_g = 24$ V

Internal resistance, $R_i = 0.01\ \Omega$

Power supplied, $P = 100$ watts

(*i*) Let I be the load current.

Now $P = E_g \times I$ (∵ For an ideal source, $V \simeq E_g$)

$$\therefore \quad I = \frac{P}{E_g} = \frac{100}{24} = 4.17 \text{ A}$$

$\therefore$ Voltage drop $= I R_i = 4.17 \times 0.01 =$ **0.0417 V**

(*ii*) Terminal Voltage, $V = E_g - I R_i$

$= 24 - 0.0417 =$ **23.96 V**

Comments : It is clear from the above example that when internal resistance of the source is quite small, the voltage drop in internal resistance is very low. Therefore, the terminal voltage substantially remains constant and the source behaves as a constant voltage source irrespective of load current variations.

1.10 Constant Current Source

*A voltage source that has a very high internal *impedance as compared with external load impedance is considered as a* **constant current source.**

In such a case, the load current nearly remains the same when the output voltage changes. Fig. 1.12 (*i*) illustrates a constant current source. It is a d.c. source of 1000 V with internal resistance $R_i = 900$ kΩ. Here, load R_L varies over 3 : 1 range from 50 kΩ to 150 kΩ. Over this variation of load R_L, the circuit current I is essentially constant at 1.05 to 0.95 mA or approximately 1 mA. It may be noted that output voltage V varies approximately in the same 3 : 1 range as R_L, although load current essentially remains **constant at 1mA. The beautiful example of a constant current source is found in vacuum tube circuits where the tube acts as a generator having internal resistance as high as 1 MΩ.

Fig. 1.12 (*ii*) shows the graph of a constant current source. It is clear that current remains constant even when the output voltage changes substantially. The following points may be noted regard-

* resistance in case of a d.c. source.

** Now $I = \dfrac{E_g}{R_L + R_i}$. Since $R_i >> R_L$, $I = \dfrac{E_g}{R_i}$

As both E_g and R_i are constant, I is constant.

ing the constant current source :

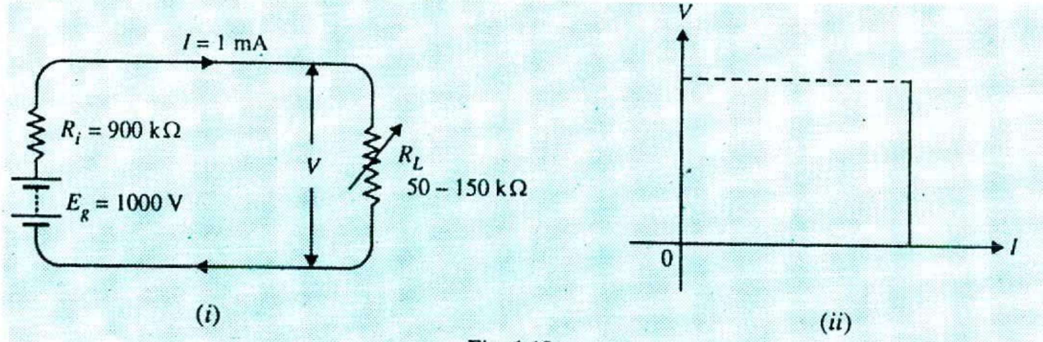


Fig. 1.12

(i) Due to high internal resistance of the source, the load current remains essentially constant as the load R_L is varied.

(ii) The output voltage varies approximately in the same range as R_L, although current remains constant.

(iii) The output voltage V is much less than the generated voltage E_g because of high $I R_i$ drop.

Fig. 1.13 shows the symbol of a constant current source.

Fig. 1.13

Example 1.2. *A d.c. source generating 500 V has an internal resistance of 1000 Ω Find the load current if load resistance is (i) 10 Ω (ii) 50 Ω and (iii) 100 Ω*

Solution.

Generated voltage, $E_g = 500$ V

Internal resistance, $R_i = 1000\ \Omega$

(i) When $R_L = 10\ \Omega$

$$\text{Load current, } I = \frac{E_g}{R_L + R_i} = \frac{500}{10 + 1000} = \mathbf{0.495\ A}$$

(ii) When $R_L = 50\ \Omega$

$$\text{Load current, } I = \frac{500}{50 + 1000} = \mathbf{0.476\ A}$$

(iii) When $R_L = 100\ \Omega$

$$\text{Load current, } I = \frac{500}{100 + 1000} = \mathbf{0.454\ A}$$

It is clear from the above example that load current is essentially constant since $R_i >> R_L$.

1.11 Conversion of Voltage Source into Current Source

Fig. 1.14 shows a constant voltage source with voltage V and internal resistance R_i. Fig. 1.15 shows its equivalent current source. It can be easily shown that the two circuits behave electrically the same way under all conditions.

(i) If in Fig. 1.14, the load is open-circuited (*i.e.* $R_L \to \infty$), then voltage across terminals A and B is V. If in Fig. 1.15, the load is open-circuited (*i.e.* $R_L \to \infty$), then all current I (= V/R_i) flows through R_i, yielding voltage across terminals AB = $I R_i = V$. Note that open-circuited voltage across AB is V for both the circuits and hence they are electrically equivalent.

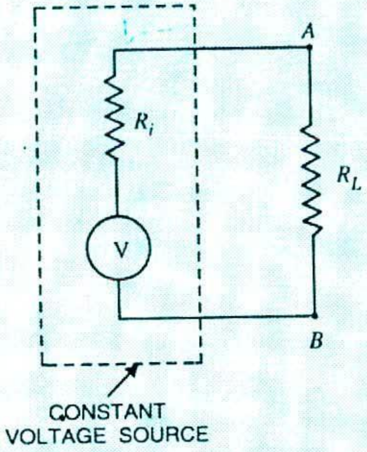


Fig. 1.14

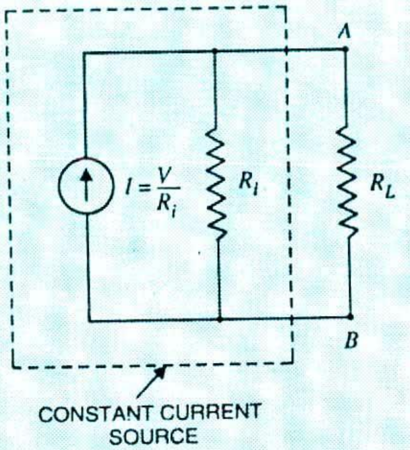


Fig. 1.15

(*ii*) If in Fig. 1.14, the load is short-circuited (*i.e.* $R_L = 0$), the short circuit current is given by;

$$I_{short} = \frac{V}{R_i}$$

If in Fig. 1.15, the load is short-circuited (*i.e.* $R_L = 0$), the current I (= V/R_i) bypasses R_i in favour of short-circuit. It is clear that current (= V/R_i) is the same for the two circuits and hence they are electrically equivalent.

Thus to convert a constant voltage source into a constant current source, the following procedure may be adopted :

(*a*) Place a short-circuit across the two terminals in question (terminals AB in the present case) and find the short-circuit current. Let it be I. Then I is the current supplied by the equivalent current source.

(*b*) Measure the resistance at the terminals with load removed and sources of e.m.f.s replaced by their internal resistances if any. Let this resistance be R.

(*c*) Then equivalent current source can be represented by a single current source of magnitude I in parallel with resistance R.

Note. To convert a current source of magnitude I in parallel with resistance R into voltage source,

$$\text{Voltage of voltage source, } V = IR$$

$$\text{Resistance of voltage source, } R = R$$

Thus voltage source will be represented as voltage V in series with resistance R.

Example 1.3. *Convert the constant voltage source shown in Fig. 1.16 into constant current source.*

Solution. The solution involves the following steps :

(*i*) Place a short across AB in Fig. 1.16 and find the short-circuit current I.

$$\text{Clearly, } I = 10/10 = 1 \text{ A}$$

Therefore, the equivalent current source has a magnitude of 1 A.

(*ii*) Measure the resistance at terminals *AB* with load *removed and 10 V source replaced by its internal resistance. The 10 V source has negligible resistance so that resistance at terminals *AB* is $R = 10\ \Omega$.

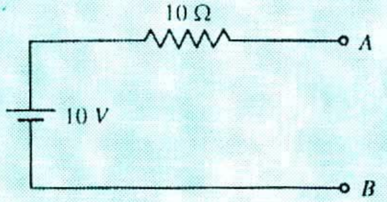


Fig. 1.16

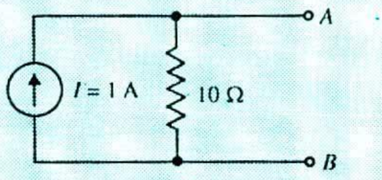


Fig. 1.17

(*iii*) The equivalent current source is a source of 1 A in parallel with a resistance of 10 Ω as shown in Fig. 1.17.

Example 1.4. *Convert the constant current source in Fig. 1.18 into equivalent voltage source.*

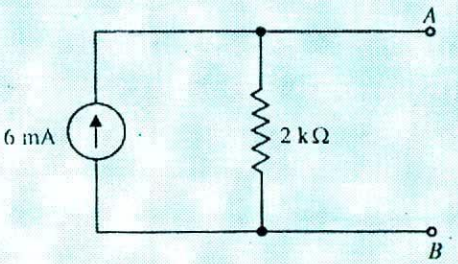


Fig. 1.18

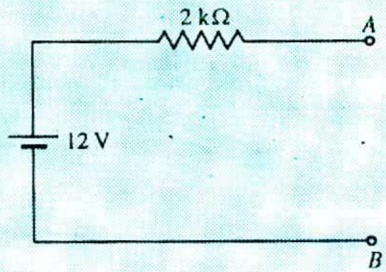


Fig. 1.19

Solution. The solution involves the following steps :

(*i*) To get the voltage of the voltage source, multiply the current of the current source by the internal resistance *i.e.*

Voltage of voltage source $= IR = 6\ \text{mA} \times 2\ \text{k}\Omega = 12\text{V}$

(*ii*) The internal resistance of voltage source is 2 k Ω.

The equivalent voltage source is a source of 12 V in series with a resistance of 2 k Ω as shown in Fig. 1.19.

Note. The voltage source should be placed with +ve terminal in the direction of current flow.

1.12 Maximum Power Transfer Theorem

When load is connected across a voltage source, power is transferred from the source to the load. The amount of power transferred will depend upon the load resistance. If load resistance R_L is made equal to the internal resistance R_i of the source, then maximum power is transferred to the load R_L. This is known as *maximum power transfer theorem* and can be stated as follows :

Maximum power is transferred from a source to a load when the load resistance is made equal to the internal resistance of the source.

This applies to d.c. as well as a.c. power.**

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* Fortunately, no load is connected across *AB*. Had there been load across *AB*, it would have been removed.

** As power is concerned with resistance only, therefore, this is true for both a.c. and d.c. power.

To prove this theorem mathematically, consider a voltage source of generated voltage E and internal resistance R_i and delivering power to a load resistance R_L [See Fig. 1.20 (*i*)]. The current I flowing through the circuit is given by ;

$$I = \frac{E}{R_L + R_i}$$

Power delivered to the load, $P = I^2 R_L = \left(\frac{E}{R_L + R_i}\right)^2 R_L$ ...(*i*)

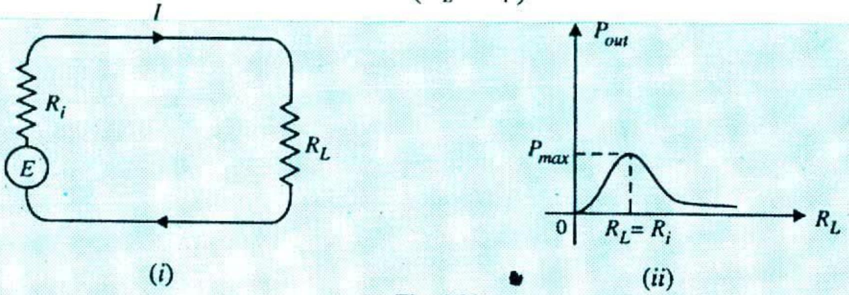

Fig. 1.20

For a given source, generated voltage E and internal resistance R_i are constant. Therefore, power delivered to the load depends upon R_L. In order to find the value of R_L for which the value of P is maximum, it is necessary to differentiate eq. (*i*) w.r.t. R_L and set the result equal to zero.

Thus, $$\frac{dP}{dR_L} = E^2\left[\frac{(R_L + R_i)^2 - 2R_L(R_L + R_i)}{(R_L + R_i)^4}\right] = 0$$

or $$(R_L + R_i)^2 - 2R_L(R_L + R_i) = 0$$

or $$(R_L + R_i)(R_L + R_i - 2R_L) = 0$$

or $$(R_L + R_i)(R_i - R_L) = 0$$

Since $(R_L + R_i)$ cannot be zero,

$\therefore$ $$R_i - R_L = 0$$

or $$R_L = R_i$$

i.e. *Load resistance* = *Internal resistance*

Thus, for maximum power transfer, load resistance R_L must be equal to the internal resistance R_i of the source.

Under such conditions, the load is said to be *matched* to the source. Fig. 1.20 (*ii*) shows a graph of power delivered to R_L as a function of R_L. It may be mentioned that efficiency of maximum power transfer is *50% as one-half of the total generated power is dissipated in the internal resistance R_i of the source.

Applications. Electric power systems never operate for maximum power transfer because of low efficiency and high voltage drops between generated voltage and load. However, in the electronic circuits, maximum power transfer is usually desirable. For instance, in a public address sys-

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* Efficiency $= \frac{\text{output power}}{\text{input power}} = \frac{I^2 R_L}{I^2(R_L + R_i)}$

$= R_L/2R_L = 1/2 = 50\%$ $(\because R_L = R_i)$

tem, it is desirable to have load (*i.e.* speaker) "matched" to the amplifier so that there is maximum transference of power from the amplifier to the speaker. In such situations, efficiency is *sacrificed at the cost of high power transfer.

Example 1.5. *A generator develops 200 V and has an internal resistance of 100 Ω. Find the power delivered to a load of (i) 100 Ω (ii) 300 Ω. Comment on the result.*

Solution.

Generated voltage, $E = 200$ V

Internal resistance, $R_i = 100\ \Omega$

(*i*) When load $R_L = 100\ \Omega$

$$\text{Load current, } I = \frac{E}{R_L + R_i} = \frac{200}{100 + 100} = 1 \text{ A}$$

$\therefore$ Power delivered to load $= I^2 R_L = (1)^2 \times 100 =$ **100 watts**

Total power generated $= I^2 (R_L + R_i) = 1^2 (100 + 100) = 200$ watts

Thus, out of 200 W power developed by the generator, only 100W has reached the load *i.e.* efficiency is 50% only.

(*ii*) When load $R_L = 300\ \Omega$

$$\text{Load current, } I = \frac{E}{R_L + R_i} = \frac{200}{300 + 100} = 0.5 \text{ A}$$

Power delivered to load $= I^2 R_L = (0.5)^2 \times 300 =$ **75 watts**

Total power generated $= I^2 (R_L + R_i) = (0.5)^2 (300 + 100) = 100$ watts

Thus, out of 100 watts of power produced by the generator, 75 watts is transferred to the load i.e. efficiency is 75%.

Comments. Although in case of $R_L = R_i$, a large power (100 W) is transferred to the load, but there is a big wastage of power in the generator. On the other hand, when R_L is *not* equal to R_i, the power transfer is less (75 W) but smaller part is wasted in the generator *i.e.* efficiency is high. Thus, it depends upon a particular situation as to what the load should be. If we want to transfer maximum power (*e.g.* in amplifiers) irrespective of efficiency, we should make $R_L = R_i$. However, if efficiency is more important (*e.g.* in power systems), then internal resistance of the source should be considerably smaller than the load resistance.

Example 1.6. *An audio amplifier produces an alternating output of 12 V before the connection to a load. The amplifier has an equivalent resistance of 15 Ω at the output. What resistance the load need to have to produce maximum power ? Also calculate the power output under this condition.*

Solution. In order to produce maximum power, the load (*e.g.* a speaker) should have a resistance of 15 Ω to match the amplifier. The equivalent circuit is shown in Fig. 1.21.

$\therefore$ Load required, $R_L =$ **15 Ω**

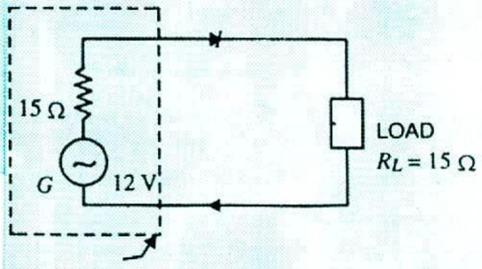


Fig. 1.21

* Electronic devices develop small power. Therefore, if too much efficiency is sought, a large number of such devices will have to be connected in series to get the desired output. This will distort the output as well as increase the cost and size of equipment.

$$\text{Circuit current, } I = \frac{V}{R_T} = \frac{12}{15 + 15} = 0.4 \text{ A}$$

$$\text{Power delivered to load, } P = I^2 R_L = (0.4)^2 \times 15 = \mathbf{2.4 \text{ W}}$$

Example 1.7. *For the a.c. generator shown in Fig. 1.22 (i), find (i) the value of load so that maximum power is transferred to the load (ii) the value of maximum power.*

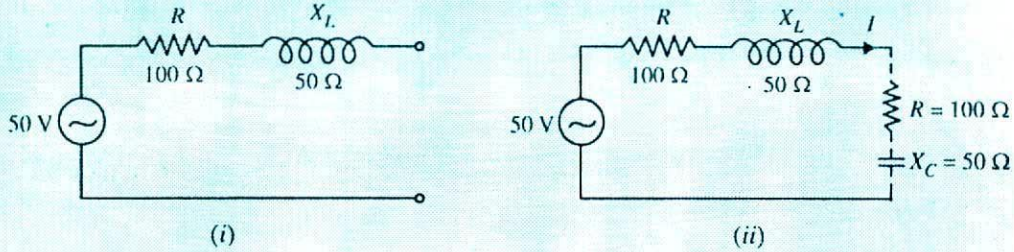


Fig. 1.22

Solution.

(*i*) In a.c. system, maximum power is delivered to the load impedance (Z_L) when load impedance is conjugate of the internal impedance (Z_i) of the source. Now in the problem, $Z_i = (100 + j50)\Omega$. For maximum power transfer, the load impedance should be conjugate of internal impedance. *i.e.* Z_L should be $(100 - j50)$ Ω. This is shown in dotted lines in Fig. 1.22 (*ii*).

$$\therefore \quad Z_L = \mathbf{(100 - j50)\ \Omega}$$

(*ii*) Total impedance, $Z_T = Z_i + Z_L = (100 + j50) + (100 - j50) = 200\ \Omega$*

$$\text{Circuit current, } I = \frac{V}{Z_T} = \frac{50}{200} = 0.25 \text{ A}$$

Maximum power transferred to the load = $I^2 R_L = (0.25)^2 \times 100 =$ **6.25 W**

1.13 Thevenin's Theorem

Sometimes it is desirable to find a particular branch current in a circuit as the resistance of that branch is varied while all other resistances and voltage sources remain constant. For instance, in the circuit shown in Fig. 1.23, it may be desired to find the current through R_L for five values of R_L, assuming that R_1, R_2, R_3 and E remain constant. In such situations, the **solution can be obtained readily by applying *Thevenin's theorem* stated below :

Any two-terminal network containing a number of e.m.f. sources and resistances can be replaced by an equivalent series circuit having a voltage source E_0 in series with a resistance R_0 where,

E_0 = open circuited voltage between the two terminals.

R_0 = the resistance between two terminals of the circuit obtained by looking "in" at the terminals with load removed and voltage sources replaced by their internal resistances, if any.

To understand the use of this theorem, consider the two-terminal circuit shown in Fig. 1.23. The circuit enclosed in the dotted box can be replaced by one voltage E_0 in series with resistance R_0 as shown in Fig. 1.24. The behaviour at the terminals AB and $A'B'$ is the same for the two circuits,

* Note that by making internal impedance and load impedance conjugate, the reactive terms cancel. The circuit then consists of internal and external resistances only. This is quite logical because power is only consumed in resistances as reactances (X_L or X_C) consume no power.

** Solution can also be obtained by applying Kirchhoff's laws but it requires a lot of labour.

independent of the values of R_L connected across the terminals.

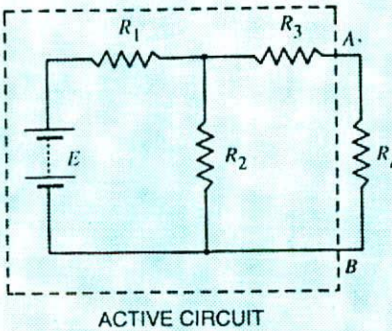


Fig. 1.23

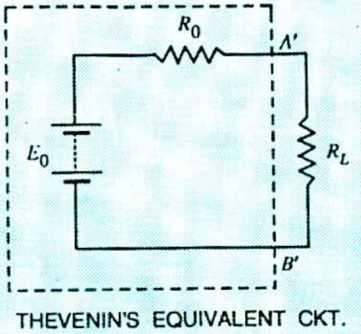


Fig. 1.24

(*i*) **Finding E_0.** This is the voltage between terminals A and B of the circuit when load R_L is removed. Fig. 1.25 shows the circuit with load removed. The voltage drop across R_2 is the desired voltage E_0.

$$\text{Current through } R_2 = \frac{E}{R_1 + R_2}$$

$$\therefore \quad \text{Voltage across } R_2,\ E_0 = \left(\frac{E}{R_1 + R_2}\right) R_2$$

Thus, voltage E_0 is determined.

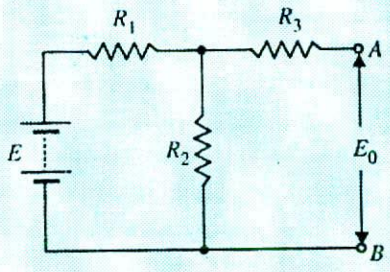


Fig. 1.25

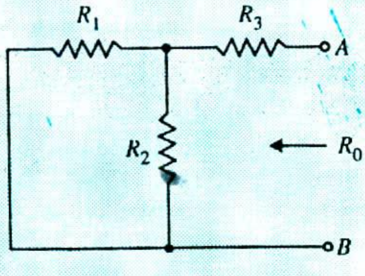


Fig. 1.26

(*ii*) **Finding R_0.** This is the resistance between terminals A and B with load removed and e.m.f. reduced to zero (See Fig. 1.26).

$\therefore$ Resistance between terminals A and B is

$$R_0 = \text{parallel combination of } R_1 \text{ and } R_2 \text{ in series with } R_3$$

$$= \frac{R_1 R_2}{R_1 + R_2} + R_3$$

Thus, the value of R_0 is determined. Once the values of E_0 and R_0 are determined, then the current through the load resistance R_L can be found out easily (Refer to Fig. 1.24).

Example 1.8. *Using Thevenin's theorem, find the current through 100 Ω resistance connected across terminals A and B in the circuit of Fig. 1.27.*

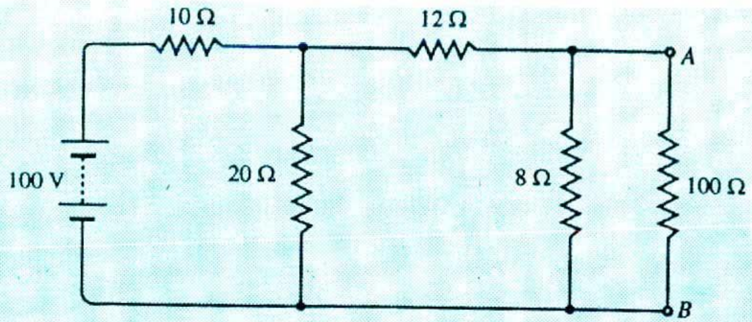


Fig. 1.27

Solution.

(*i*) **Finding E_0.** It is the voltage across terminals *A* and *B* with 100 W resistance removed as shown in Fig. 1.28.

$$E_0 = (\text{Current through } 8\ W)\ ´\ 8\ W = 2.5^*\ ´\ 8 = 20\ V$$

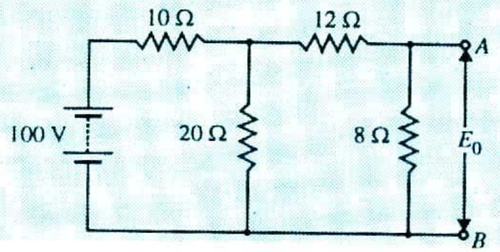


Fig. 1.28

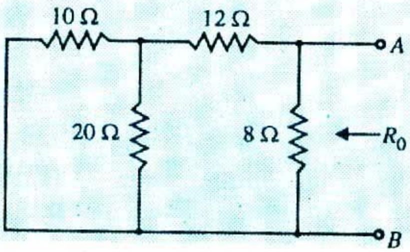


Fig. 1.29

(*ii*) **Finding R_0.** It is the resistance between terminals *A* and *B* with 100 W removed and voltage source short circuited as shown in Fig. 1.29.

R_0 = resistance looking in at terminals *A* and *B* in Fig. 1.29

$$= \frac{\left[\frac{10 \times 20}{10 + 20} + 12\right] 8}{\left[\frac{10 \times 20}{10 + 20} + 12\right] + 8}$$

= 5.6 W

Therefore, Thevenin's equivalent circuit will be as shown in Fig. 1.30. Now, current through 100 W resistance connected across terminals *A* and *B* can be found by applying Ohm's law.

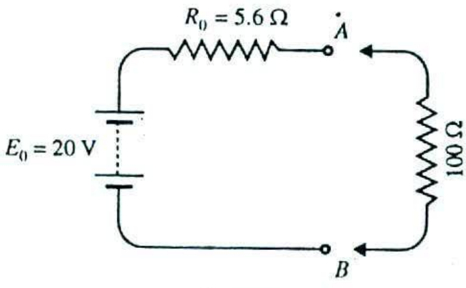


Fig. 1.30

$$\text{Current through 100 W resistor} = \frac{E_0}{R_0 + R_L} = \frac{20}{5.6 + 100} = \mathbf{0.19\ A}$$

Example 1.9. *Find the Thevenin s equivalent circuit for Fig. 1.31.*

Solution. The Thevenin's voltage E_0 is the voltage across terminals *A* and *B*. This voltage is

* By solving this series-parallel circuit.

equal to the voltage across R_3. It is because terminals A and B are open circuited and there is no current flowing through R_2 and hence no voltage drop across it.

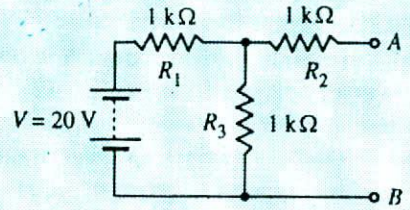


Fig. 1.31

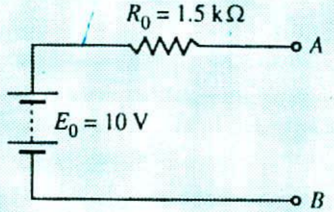


Fig. 1.32

$$\therefore \quad E_0 = \text{Voltage across } R_3$$

$$= \frac{R_3}{R_1 + R_3} \times V = \frac{1}{1+1} \times 20 = 10 \text{ V}$$

The Thevenin's resistance R_0 is the resistance measured between terminals A and B with no load (*i.e.* open at terminals A and B) and voltage source replaced by a short circuit.

$$\therefore \quad R_0 = R_2 + \frac{R_1 R_3}{R_1 + R_3} = 1 + \frac{1 \times 1}{1+1} = 1.5 \text{ k}\Omega$$

Therefore, Thevenin's equivalent circuit will be as shown in Fig. 1.32.

Example 1.10. *Calculate the value of load resistance R_L to which maximum power may be transferred from the circuit shown in Fig. 1.33 (i). Also find the maximum power.*

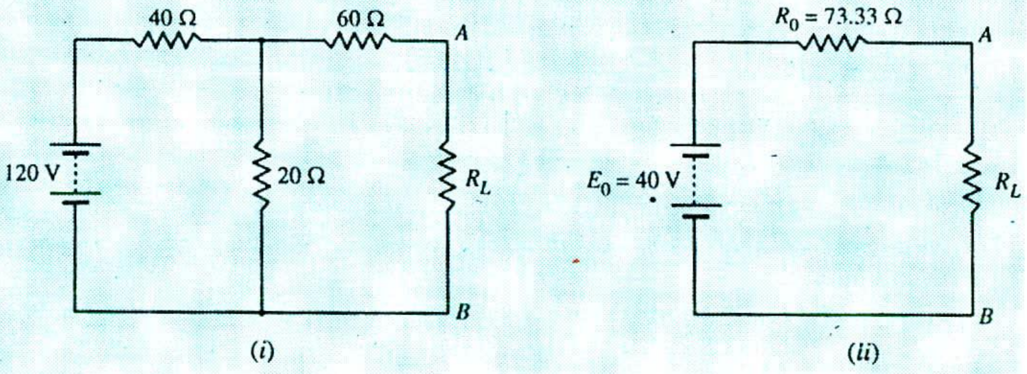


Fig. 1.33

Solution. We shall first find Thevenin's equivalent circuit to the left of terminals AB in Fig. 1.33 (*i*).

$$E_0 = \text{Voltage across terminals } AB \text{ with } R_L \text{ removed}$$

$$= \frac{120}{40 + 20} \times 20 = 40 \text{ V}$$

R_0 = Resistance between terminals A and B with R_L removed and 120 V source replaced by a short

$$= 60 + (40\ \Omega \parallel 20\ \Omega) = 60 + (40 \times 20/60) = 73.33\ \Omega$$

The Thevenin's equivalent circuit to the left of terminals AB in Fig. 1.33 (*i*) is E_0 (= 40 V) in series with R_0 (= 73.33 Ω). When R_L is connected between terminals A and B, the circuit becomes as shown in Fig. 1.33 (*ii*). It is clear that maximum power will be transferred when

$$R_L = R_0 = 73.33\ \Omega$$

$$\text{Maximum power to load} = \frac{E_0^2}{4R_L} = \frac{(40)^2}{4 \times 73.33} = \mathbf{5.45\ W}$$

Comments. This shows another advantage of Thevenin's equivalent circuit of a network. Once Thevenin's equivalent resistance R_0 is calculated, it shows at a glance the condition for maximum power transfer. Yet Thevenin's equivalent circuit conveys another information. Thus referring to Fig. 1.33 (*ii*), the maximum voltage that can appear across terminals A and B is 40 V. This is not so obvious from the original circuit shown in Fig. 1.33 (*i*).

1.14 Norton's Theorem

Fig. 1.34 (*i*) shows a network enclosed in a box with two terminals A and B brought out. The network in the box may contain any number of resistors and e.m.f. sources connected in any manner. But according to Norton, the entire circuit behind terminals A and B can be replaced by a current source of output I_N in parallel with a single resistance R_N as shown in Fig. 1.34 (*ii*). The value of I_N is determined as mentioned in Norton's theorem. The resistance R_N is the same as Thevenin's resistance R_0. Once Norton's equivalent circuit is determined [See Fig. 1.34 (*ii*)], then current through any load R_L connected across terminals AB can be readily obtained.

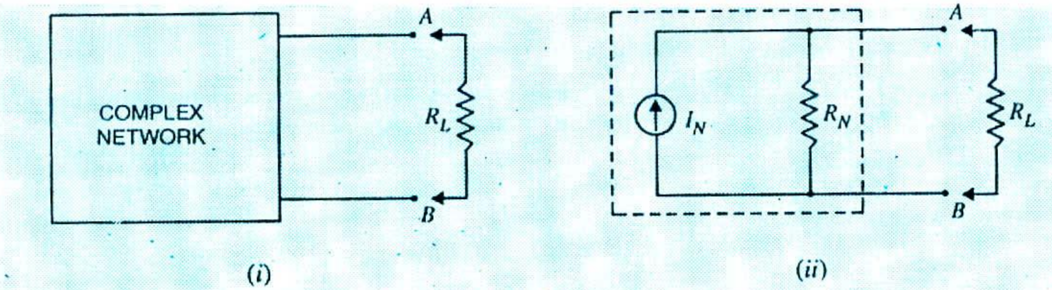


Fig. 1.34

Hence Norton's theorem as applied to d.c. circuits may be stated as under :

Any network having two terminals A and B can be replaced by a current source of output I_N in parallel with a resistance R_N.

(*i*) *The output I_N of the current source is equal to the current that would flow through AB when A and B are short circuited.*

(*ii*) *The resistance R_N is the resistance of the network measured between terminals A and B with load (R_L) removed and sources of e.m.f. replaced by their internal resistances, if any.*

Norton's theorem is *converse* of Thevenin's theorem in that Norton equivalent circuit uses a current generator instead of voltage generator and resistance R_N (which is the same as R_0) in parallel with the generator instead of being in series with it.

Illustration. Fig. 1.35 illustrates the application of Norton's theorem. As far as circuit behind terminals AB is concerned [See Fig. 1.35 (*i*)], it can be replaced by a current source of output I_N in parallel with a resistance R_N as shown in Fig. 1.35 (*iv*). The output I_N of the current generator is equal to the current that would flow through AB when terminals A and B are short-circuited as shown in Fig. 1.35 (*ii*). The load R' on the source when terminals AB are short-circuited is given by;

$$R' = R_1 + \frac{R_2 R_3}{R_2 + R_3} = \frac{R_1 R_2 + R_1 R_3 + R_2 R_3}{R_2 + R_3}$$

$$\text{Source current, } I' = \frac{V}{R'} = \frac{V(R_2 + R_3)}{R_1 R_2 + R_1 R_3 + R_2 R_3}$$

$$\text{Short-circuit current, } I_N = \text{Current in } R_2 \text{ in Fig. 1.35 } (ii)$$

$$= I' \times \frac{R_3}{R_2 + R_3} = \frac{V R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3}$$

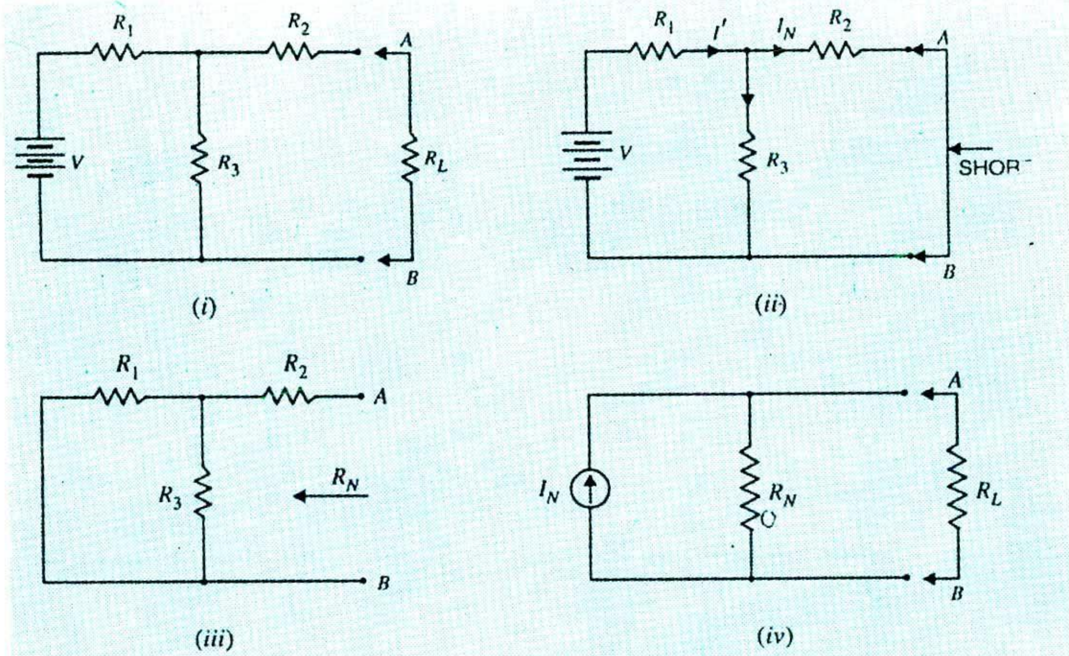


Fig. 1.35

To find R_N, remove the load R_L and replace the voltage source by a short circuit because its resistance is assumed zero [See Fig. 1.35 (*iii*)].

$$\therefore \quad R_N = \text{Resistance at terminals } AB \text{ in Fig. 1.35 } (iii).$$

$$= R_2 + \frac{R_1 R_3}{R_1 + R_3}$$

Thus the values of I_N and R_N are known. The Norton equivalent circuit will be as shown in Fig. 1.35 (*iv*).

Example 1.11. *Using Norton's theorem, find the current in 8 Ω resistor in the network shown in Fig. 1.36 (i).*

Solution. We shall reduce the network to the left of AB in Fig. 1.36 (*i*) to Norton's equivalent circuit. For this purpose, we are required to find I_N and R_N.

(*i*) With load (*i.e.*, 8 Ω) removed and terminals AB short circuited [See Fig. 1.36 (*ii*)], the current that flows through AB is equal to I_N. Referring to Fig. 1.36 (*ii*),

$$\text{Load on the source} = 4\ \Omega + 5\ \Omega \parallel 6\ \Omega$$

$$= 4 + \frac{5 \times 6}{5 + 6} = 6.727\ \Omega$$

Source current, $I' = 40/6.727 = 5.94$ A

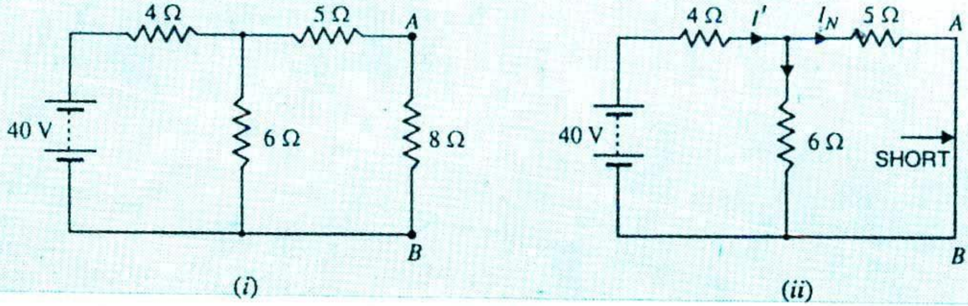


Fig. 1.36

∴ Short-circuit current in AB, $I_N = I' \times \frac{6}{6+5} = 5.94 \times 6/11 = 3.24$ A

(*ii*) With load (*i.e.*, 8 Ω) removed and battery replaced by a short (since its internal resistance is assumed zero), the resistance at terminals AB is equal to R_N as shown in Fig. 1.37 (*i*).

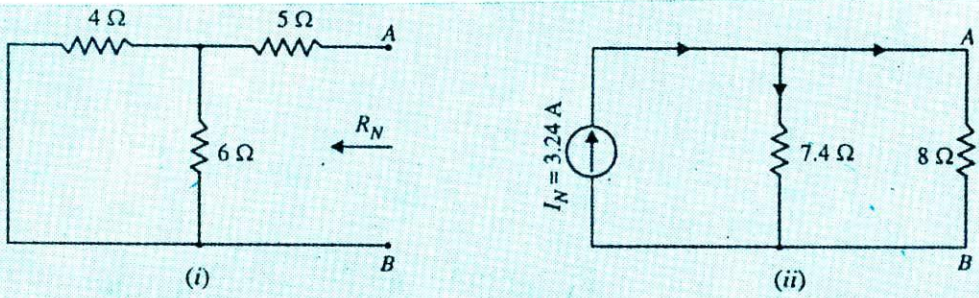


Fig. 1.37

$$R_N = 5\,\Omega + 4\,\Omega \,||\, 6\,\Omega = 5 + \frac{4 \times 6}{4+6} = 7.4\,\Omega$$

The Norton's equivalent circuit behind terminals AB is I_N (= 3.24 A) in parallel with R_N (= 7.4 Ω). When load (*i.e.*, 8 Ω) is connected across terminals AB, the circuit becomes as shown in Fig. 1.37 (*ii*). The current source is supplying current to two resistors 7.4 Ω and 8 Ω in parallel.

∴ Current in 8 Ω resistor $= 3.24 \times \frac{7.4}{8+7.4} =$ **1.55 A**

Example 1.12. *Show that when Thevenin's equivalent circuit of a network is converted into Norton's equivalent circuit, $I_N = E_0/R_0$ and $R_N = R_0$. Here E_0 and R_0 are Thevenin voltage and Thevenin resistance respectively.*

Solution. Fig. 1.38 (*i*) shows a network enclosed in a box with two terminals A and B brought out. Thevenin's equivalent circuit of this network will be as shown in Fig. 1.38 (*ii*). To find Norton's equivalent circuit, we are to find I_N and R_N. Referring to Fig. 1.38 (*ii*),

I_N = Current flowing through short-circuited AB in Fig. 1.38 (*ii*)

$= E_0/R_0$

R_N = Resistance at terminals AB in Fig. 1.38 (*ii*)

$= R_0$

Fig. 1.38 (*iii*) shows Norton's equivalent circuit. Hence we arrive at the following two important conclusions :

(*i*) To convert Thevenin's equivalent circuit into Norton's equivalent circuit,

$$I_N = E_0/R_0 \quad ; \quad R_N = R_0$$

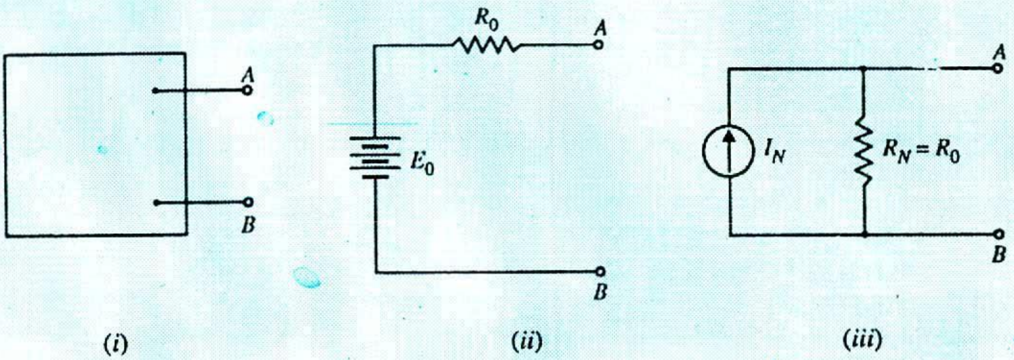


Fig. 1.38

(*ii*) To convert Norton's equivalent circuit into Thevenin's equivalent circuit,

$$E_0 = I_N R_N \quad ; \quad R_0 = R_N$$

1.15 Chassis and Ground

It is the usual practice to mount the electronic components on a metal base called *chassis*. For example, in Fig. 1.39, the voltage source and resistors are connected to the chassis. As the resistance of chassis is very low, therefore, it provides a conducting path and may be considered as a piece of wire.

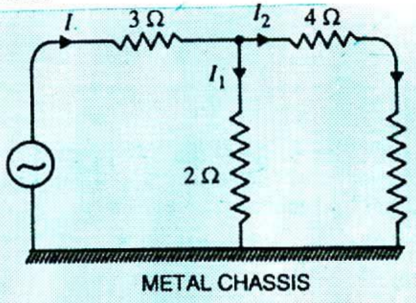


Fig. 1.39

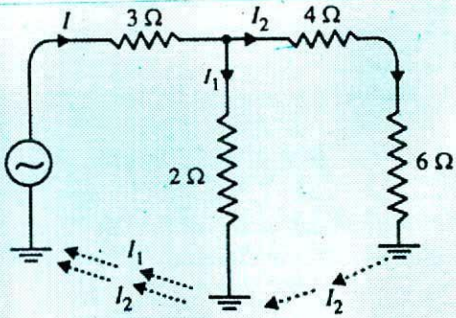


Fig. 1.40

It is customary to refer to the chassis as *ground.* Fig. 1.40 shows the symbol for chassis. It may be seen that all points connected to chassis are shown as grounded and represent the same potential. The adoption of this scheme (*i.e.* showing points of same potential as grounded) often simplifies the electronic circuits. In our further discussion, we shall frequently use this scheme.

Multiple-Choice Questions

1. The outermost orbit of an atom can have a maximum of .... electrons.
   (*i*) 8 (*ii*) 6
   (*iii*) 4 (*iv*) 3
2. When the outermost orbit of an atom has less than 4 electrons, the material is generally a ....
   (*i*) non-metal (*ii*) metal
   (*iii*) semiconductor (*iv*) none of above
3. The valence electrons have ....

(i) very small energy
(ii) least energy
(iii) maximum energy
(iv) none of the above

4. A large number of free electrons exist in ....
(i) semiconductors (ii) metals
(iii) insulators (iv) non-metals

5. An ideal voltage source has .... internal resistance.
(i) small (ii) large
(iii) infinite (iv) zero

6. An ideal current source has .... internal resistance.
(i) infinite (ii) zero
(iii) small (iv) none of the above

7. Maximum power is transferred if load resistance is equal to .... of the source.
(i) half the internal resistance
(ii) internal resistance
(iii) twice the internal resistance
(iv) none of the above

8. Efficiency at maximum power transfer is ....
(i) 75% (ii) 25%
(iii) 90% (iv) 50%

9. When the outermost orbit of an atom has exactly 4 valence electrons, the material is generally ....
(i) a metal (ii) a non-metal
(iii) a semiconductor
(iv) an insulator

10. Thevenin's theorem replaces a complicated circuit facing a load by an ....
(i) ideal voltage source and parallel resistor
(ii) ideal current source and parallel resistor
(iii) ideal current source and series resistor
(iv) ideal voltage source and series resistor

11. The output voltage of an ideal voltage source is ....
(i) zero
(ii) constant
(iii) dependent on load resistance
(iv) dependent on internal resistance

12. The current output of an ideal current source is ....
(i) zero
(ii) constant
(iii) dependent on load resistance
(iv) dependent on internal resistance

13. Norton's theorem replaces a complicated circuit facing a load by an ....
(i) ideal voltage source and parallel resistor
(ii) ideal current source and parallel resistor
(iii) ideal voltage source and series resistor
(iv) ideal current source and series resistor

14. The practical example of ideal voltage source is ....
(i) lead-acid cell (ii) dry cell
(iii) Daniel cell (iv) none of the above

15. The speed of electrons in vacuum is .... than in a conductor.
(i) less (ii) much more
(iii) much less (iv) none of the above

16. Maximum power will be transferred from a source of 10 Ω resistance to a load of ....
(i) 5 Ω (ii) 20 Ω
(iii) 10 Ω (iv) 40 Ω

17. When the outermost orbit of an atom has more than 4 electrons, the material is generally a ....
(i) metal (ii) non-metal
(iii) semiconductor (iv) none of the above

18. An ideal source consists of 5 V in series with 10 kΩ resistance. The current magnitude of equivalent current source is ....
(i) 2 mA (ii) 3.5 mA
(iii) 0.5 mA (iv) none of the above

19. To get Thevenin voltage, you have to ....
(i) short the load resistor
(ii) open the load resistor
(iii) short the voltage source
(iv) open the voltage source

20. To get the Norton current, you have to ....
(i) short the load resistor
(ii) open the load resistor
(iii) short the voltage source
(iv) open the voltage source

21. The open-circuited voltage at the terminals

of load R_L in a network is 30 V. Under the conditions of maximum power transfer, the load voltage will be ....

(*i*) 30 V (*ii*) 10 V
(*iii*) 5 V (*iv*) 15 V

22. Under the conditions of maximum power transfer, a voltage source is delivering a power of 30 W to the load. The power produced by the source is ....

(*i*) 45 W (*ii*) 60 W
(*iii*) 30 W (*iv*) 90 W

23. The maximum power transfer theorem is used in ....

(*i*) electronic circuits
(*ii*) power system
(*iii*) home lighting circuits
(*iv*) none of the above

24. The Norton resistance of a network is 20 Ω and the shorted-load current is 2 A. If the network is loaded by a resistance equal to 20 Ω, the current through the load will be ....

(*i*) 2 A (*ii*) 0.5 A
(*iii*) 4 A (*iv*) 1 A

25. The Norton current is sometimes called the ....

(*i*) shorted-load current
(*ii*) open-load current
(*iii*) Thevenin current
(*iv*) Thevenin voltage

Answers to Multiple-Choice Questions

1. (*i*)	**2.** (*ii*)	**3.** (*iii*)	**4.** (*ii*)	**5.** (*iv*)
6. (*i*)	**7.** (*ii*)	**8.** (*iv*)	**9.** (*iii*)	**10.** (*iv*)
11. (*ii*)	**12.** (*ii*)	**13.** (*ii*)	**14.** (*i*)	**15.** (*ii*)
16. (*iii*)	**17.** (*ii*)	**18.** (*iii*)	**19.** (*ii*)	**20.** (*i*)
21. (*iv*)	**22.** (*ii*)	**23.** (*i*)	**24.** (*iv*)	**25.** (*i*)

Chapter Review Topics

1. What is electronics ? Mention some important applications of electronics.
2. Describe briefly the structure of atom.
3. Explain how valence electrons determine the electrical properties of a material.
4. Explain constant voltage and current sources. What is their utility ?
5. Derive the condition for transfer of maximum power from a source to a load.
6. State and explain Thevenin's theorem.
7. Write short notes on the following :
(*i*) Atomic structure (*ii*) Valence electrons (*iii*) Free electrons

Problems

1. A dry battery developing 12 V has an internal resistance of 10 Ω. Find the output current if load is (*i*) 100 Ω (*ii*) 10 Ω (*iii*) 2 Ω and (*iv*) 1 Ω. **[(*i*) 0.1A (*ii*) 0.6A (*iii*) 1A (*iv*) 1.1A]**
2. Convert the current source in Fig. 1.41 into the equivalent voltage source.
[36 V in series with 900 Ω]

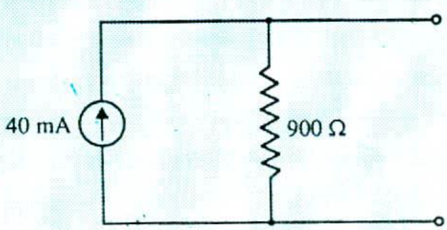


Fig. 1.41

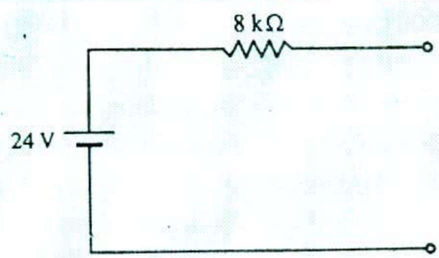


Fig. 1.42

3. Convert the voltage source in Fig. 1.42 into equivalent current source.

[3 mA in parallel with 8 kΩ]

4. Using Norton's Theorem, find the current in branch *AB* containing 6 Ω resistor of the network shown in Fig. 1.43. **[0.466 A]**

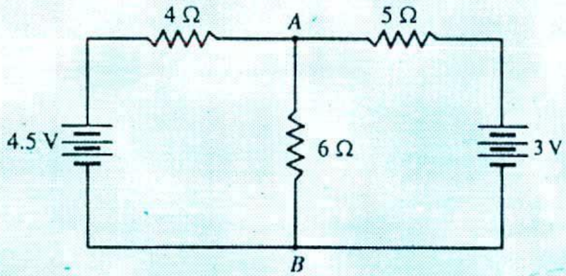


Fig. 1.43

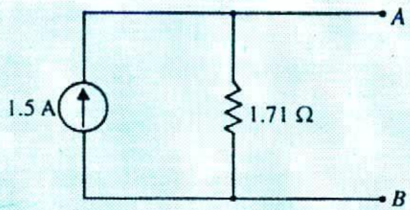


Fig. 1.44

5. Fig. 1.44 shows Norton's equivalent circuit of a network behind terminals *A* and *B*. Convert it into Thevenin's equivalent circuit. **[2.56 V in series with 1.71 Ω]**

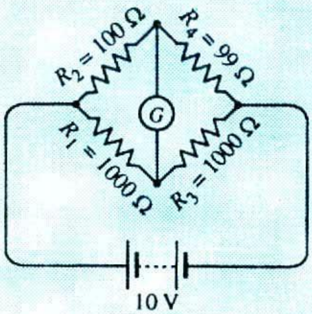


Fig. 1.45

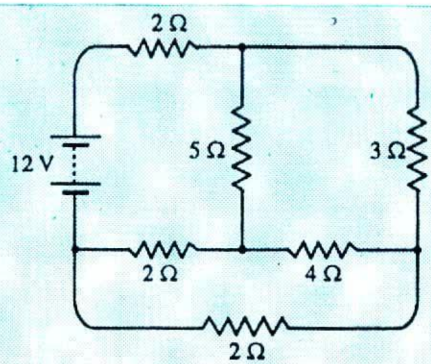


Fig. 1.46

6. A power amplifier has an internal resistance of 5 Ω and develops open circuited voltage of 12 V. Find the efficiency and power transferred to a load of (*i*) 20 Ω (*ii*) 5 Ω.

[(*i*) 80%, 4.6 W (*ii*) 50%, 7.2 W]

7. Using Thevenin's theorem, find the current through the galvanometer in the Wheatstone bridge shown in Fig. 1.45. **[38.6 μA]**

8. Using Thevenin's theorem, find the current through 4 Ω resistor in the circuit of Fig. 1.46. **[0.305A]**

Discussion Questions

1. Why are free electrons most important for electronics ?
2. Why do insulators not have any free electrons ?
3. Where do you apply Thevenin's theorem ?
4. Why is maximum power transfer theorem important in electronic circuits ?
5. What are the practical applications of a constant current source ?

2

Electron Emission

Introduction

The reader is familiar with the current conduction (*i.e.* flow of electrons) through a conductor. The valence electrons of the conductor atoms are loosely bound to the atomic nuclei. At room temperature, the thermal energy in the conductor is adequate to break the bonds of the valence electrons and leave them unattached to any one nucleus. These unbound electrons move at random within the conductor and are known as *free electrons*. If an electric field is applied across the conductor, these free electrons move through the conductor in an orderly manner, thus constituting electric current. This is how these free electrons move through the conductor or electric current flows through a wire.

Many electronic devices depend for their operation on the movement of electrons in an evacuated space. For this purpose, the free electrons must be ejected from the surface of metallic conductor by supplying sufficient energy from some external source. This is known as *electron emission*. The emitted electrons can be made to move in vacuum under the influence of an electric field, thus constituting electric current in vacuum. In this chapter, we shall confine our attention to the various aspects of electron emission.

2.1 Electron Emission

The liberation of electrons from the surface of a substance is known as **electron emission.**

For electron emission, metals are used because they have many free electrons. If a piece of metal is investigated at room temperature, the random motion of free electrons is as shown in Fig. 2.1. However, these electrons are free only to the extent that they may transfer from one atom to another within the metal but they cannot leave the metal surface to provide electron emission. It is because the free electrons that start at the surface of metal find behind them positive nuclei pulling them back and none pulling forward. Thus at the surface of a metal, a free electron encounters forces that prevent it to leave the metal. In other words, the metallic surface offers a barrier to free electrons and is known as *surface barrier*.

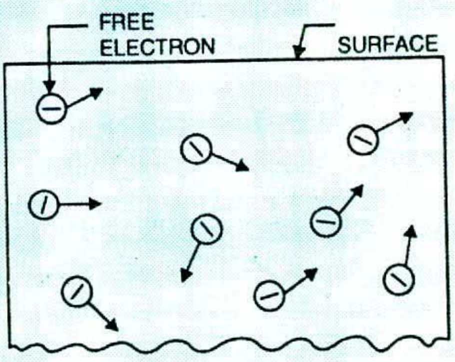


Fig. 2.1

However, if sufficient external energy is given to the free electron, its kinetic energy is increased and thus electron will cross over the surface barrier to leave the metal. This additional energy required by an electron to overcome the surface barrier of the metal is called *work function* of the metal.

The amount of additional energy required to emit an electron from a metallic surface is known as **work function** *of that metal.*

Thus, if the total energy required to liberate an electron from a metal is 4 eV* and the energy already possessed by the electron is 0.5 eV, then additional energy required (*i.e.*, work function) is 4 – 0.5 = 3.5 eV. The work function of pure metals varies roughly from 2 to 6 eV. It depends upon the nature of metal, its purity and the conditions of its surface. It may be noted that it is desirable that metal used for electron emission should have low work function so that a small amount of energy is required to cause emission of electrons.

2.2 Types of Electron Emission

The electron emission from the surface of a metal is possible only if sufficient additional energy (*equal to the work function of the metal*) is supplied from some external source. This external energy may come from a variety of sources such as heat energy, energy stored in electric field, light energy or kinetic energy of the electric charges bombarding the metal surface. Accordingly, there are following four principal methods of obtaining electron emission from the surface of a metal :

(*i*) **Thermionic emission.** In this method, the metal is heated to sufficient temperature (about 2500°C) to enable the free electrons to leave the metal surface. The number of electrons emitted depends upon the temperature. The higher the temperature, the greater is the emission of electrons. This type of emission is employed in vacuum tubes.

(*ii*) **Field emission.** In this method, a strong electric field (*i.e.* a high positive voltage) is applied at the metal surface which pulls the free electrons out of metal because of the attraction of positive field. The stronger the electric field, the greater is the electron emission.

(*iii*) **Photo-electric emission.** In this method, the energy of light falling upon the metal surface is transferred to the free electrons within the metal to enable them to leave the surface. The greater the intensity (*i.e.* brightness) of light beam falling on the metal surface, the greater is the photo-electric emission.

(*iv*) **Secondary emission.** In this method, a high velocity beam of electrons strikes the metal surface and causes the free electrons of the metal to be knocked out from the surface.

2.3 Thermionic Emission

The process of electron emission from a metal surface by supplying thermal energy to it is known as **thermionic emission.**

At ordinary temperatures, the energy possessed by free electrons in the metal is inadequate to cause them to escape from the surface. When heat is applied to the metal, some of heat energy is

---

* Work function is the additional energy required for the liberation of electrons. Therefore, it should have the conventional unit of energy *i.e.* Joules. But this unit is very large for computing electronics work. Therefore, in practice, a smaller unit called *electron volt* (abbreviated as eV) is used.

One electron-volt is the amount of energy acquired by an electron when it is accelerated through a potential difference of 1 V.

Thus, if an electron moves from a point of 0 potential to a point of +10V, then amount of energy acquired by the electron is 10 *eV*.

Since charge on an electron $= 1.602 \times 10^{-19}$ C and voltage = 1 V,

$\therefore$ 1 electron-volt $= Q\,V = (1.602 \times 10^{-19}) \times 1$ J

or 1 eV $= 1.602 \times 10^{-19}$ J

converted into kinetic energy, causing accelerated motion of free electrons. When the temperature rises sufficiently, these electrons acquire additional energy equal to the work function of the metal. Consequently, they overcome the restraining surface barrier and leave the metal surface.

Metals *with lower work function* will require less additional energy and, therefore, will emit electrons at lower temperatures. The commonly used materials for electron emission are *tungsten, thoriated tungsten* and *metallic oxides of barium and strontium*. It may be added here that high temperatures are necessary to cause thermionic emission. For example, pure tungsten must be heated to about 2300°C to get electron emission. However, oxide coated emitters need only 750°C to cause thermionic emission.

Richardson-Dushman equation. The amount of thermionic emission increases rapidly as the emitter temperature is raised. The emission current density is given by Richardson-Dushman equation given below :

$$J_s = A\,T^2\,e^{-\frac{b}{T}}\ \text{amp/m}^2 \qquad ...(i)$$

where J_s = emission current density *i.e.* current per square metre of the emitting surface

T = absolute temperature of emitter in K

A = constant, depending upon the type of emitter and is measured in amp/m²/K²

b = a constant for the emitter

e = natural logarithmic base

The value of b is constant for a metal and is given by ;

$$b = \frac{\phi e}{k}$$

where ϕ = work function of emitter

e = electron charge = 1.602×10^{-19} coulomb

k = Boltzmann's constant = 1.38×10^{-23} J/K

$$\therefore \qquad b = \frac{\phi \times 1.602 \times 10^{-19}}{1.38 \times 10^{-23}} = 11600\,\phi\ \text{K}$$

Putting the value of b in exp. (i), we get,

$$J_s = A T^2 e^{-\frac{11600\,\phi}{T}} \qquad ...(ii)$$

The following points may be noted from eqn. (ii) :

(i) The emission is markedly affected by temperature changes. Doubling the temperature of an emitter may increase electron emission by more than 10^7 times. For instance, emission from pure tungsten metal is about 10^{-6} ampere per sq. cm. at 1300°C but rises to enormous value of about 100 amperes when temperature is raised to 2900°C.

(ii) Small changes in the work function of the emitter can produce enormous effects on emission. Halving the work function has exactly the same effect as doubling the temperature.

Example 2.1. *A tungsten filament consists of a cylindrical cathode 5 cm long and 0.01 cm in diameter. If the operating temperature is 2500 K, find the emission current. Given that* $A = 60.2 \times 10^4\ A/m^2/K^2$, $\phi = 4.517$ *eV.*

Solution. $A = 60.2 \times 10^4$ amp/m^2/K^2, $T = 2500$ K, $\phi = 4.517$ eV

$\therefore$ $b = 11600\,\phi\,\text{K} = 11600 \times 4.517\,\text{K} = 52400\,\text{K}$

Using Richardson-Dushman equation, emission current density is given by ;

$$J_s = AT^2 e^{-\frac{b}{T}}\ \text{amp/m}^2 = 60.2 \times 10^4 \times (2500)^2 \times (2.718)^{-\frac{52400}{2500}}$$

$$= 0.3 \times 10^4\ \text{amp/m}^2$$

Surface area of cathode, $a = \pi\, d\, l = 3.146 \times 0.01 \times 5 = 0.157\ \text{cm}^2 = 0.157 \times 10^{-4}\ \text{m}^2$

$\therefore$ Emission current $= J_s \times a = (0.3 \times 10^4) \times (0.157 \times 10^{-4}) = \mathbf{0.047\ A}$

Example 2.2. *A tungsten wire of unknown composition emits 0.1 amp/cm² at a temperature of 1900 K. Find the work function of tungsten filament. Determine whether the tungsten is pure or contaminated with substance of lower work function. Given that A = 60.2 amp/cm²/K².*

Solution. $J_s = 0.1$ amp/cm^2 ; $A = 60.2$ amp/cm^2/K^2 ; $T = 1900$ K

Let ϕ electron-volt be the work function of the filament.

$\therefore$ $b = 11600\,\phi\,\text{K}$

Using Richardson-Dushman equation, emission current density is given by ;

$$J_s = A\,T^2 e^{-\frac{b}{T}}\ \text{amp/cm}^2$$

or $$0.1 = 60.2 \times (1900)^2 \times e^{-\frac{11600\phi}{1900}}$$

or $$e^{-\frac{11600\phi}{1900}} = \frac{0.1}{60.2 \times (1900)^2} = 4.6 \times 10^{-10}$$

or $$e^{-6.1\,\phi} = 4.6 \times 10^{-10}$$

or $$-6.1\,\phi \log_e e = \log_e 4.6 - 10 \log_e 10$$

or $$-6.1\,\phi = 1.526 - 23.02$$

$\therefore$ $$\phi = \frac{1.526 - 23.02}{-6.1} = \mathbf{3.56\ eV}$$

Since the work function of pure tungsten is 4.52 eV, the sample must be contaminated. Thoriated tungsten has a work function ranging from 2.63 eV to 4.52 eV, depending upon the percentage of metallic thorium. Therefore, the sample is most likely to be thoriated tungsten.

2.4 Thermionic Emitter

The substance used for electron emission is known as an *emitter* or *cathode*. The cathode is heated in an evacuated space to emit electrons. If the cathode were heated to the required temperature in open air, it would burn up because of the presence of oxygen in the air. A cathode should have the following properties :

(*i*) **Low work function.** The substance selected as cathode should have low work function so that electron emission takes place by applying small amount of heat energy *i.e.* at low temperatures.

(*ii*) **High melting point.** As electron emission takes place at very high temperatures (>1500°C), therefore, the substance used as a cathode should have high melting point. For a material such as copper, which has the advantage of a low work function, it is seen that it cannot be used as a cathode because it melts at 810°C. Consequently, it will vaporise before it begins to emit electrons.

(*iii*) **High mechanical strength.** The emitter should have high mechanical strength to withstand the bombardment of positive ions. In any vacuum tube, no matter how careful the evacuation, there are always present some gas molecules which may form ions by impact with electrons when current flows. Under the influence of electric field, the positive ions strike the cathode. If high voltages are used, the cathode is subjected to considerable bombardment and may be damaged.

2.5 Commonly Used Thermionic Emitters

The high temperatures needed for satisfactory thermionic emission in vacuum tubes limit the number of suitable emitters to such substances as *tungsten, thoriated tungsten* and certain *oxide coated metals*.

(*i*) **Tungsten.** It was the earliest material used as a cathode and has a slightly higher work function (4.52 eV). The important factors in its favour are : high melting point (3650 K), greater mechanical strength and longer life. The disadvantages are : high operating temperature (2500 K), high work function and low emission efficiency. Therefore, it is used in applications involving voltages exceeding 5 kV *e.g.* in X-ray tubes.

(*ii*) **Thoriated tungsten.** A mixture of two metals may have a lower work function than either of the pure metals alone. Thus, a tungsten emitter with a small quantity of thorium has a work function of 2.63 eV, compared with 3.4 eV for thorium and 4.52 eV for tungsten. At the same time, thoriated tungsten provides thermionic emission at lower temperature (1700°C) with consequent reduction in the heating power required.

In the manufacture of this type of cathode, tungsten filament is impregnated with thorium oxide and heated to a very high temperature (1850°C to 2500°C). The thorium oxide is reduced to metallic thorium and coats the filament surface with a thin layer of thorium. Thoriated tungsten cathodes are used for intermediate power tubes at voltages between 500 to 5000 volts.

(*iii*) **Oxide-coated cathode.** The cathode of this *type consists of a nickel ribbon coated with barium and strontium oxides. The oxide-coated cathode has low work function (1.1 eV), operates at comparatively low temperature (750°C) and has high emission efficiency. However, the principal limitation of oxide-coated cathode is that it cannot withstand high voltages. Therefore, it is mostly used in receiving tubes or where voltages involved do not exceed 1000 volts.

S.No.	Emitter	Work Function	Operating temperature	Emission efficiency
1	*Tungsten*	4.52 eV	2327°C	4 mA/watt
2	*Thoriated tungsten*	2.63 eV	1700°C	60 mA/watt
3	*Oxide-coated*	1.1 eV	750°C	200 mA/watt

2.6 Cathode Construction

As cathode is sealed in vacuum, therefore, the most convenient way to heat it is electrically. On this basis, the thermionic cathodes are divided into two types viz directly heated cathode and indirectly heated cathode.

(*i*) **Directly heated cathode.** In this type, the cathode consists of oxide-coated nickel ribbon, called the **filament. The heating current is directly passed through this ribbon which emits the

* Oxides of any alkaline-earth metal (*e.g.* calcium, strontium, barium etc.) have very good emission characteristics. In the manufacture of this type of emitter, the base metal (*e.g.* nickel) is first coated with a mixture of strontium and barium carbonates. It is then heated to a high temperature in vacuum glass tube until the carbonates decompose into oxides. By proper heating, a layer of oxides of barium and strontium is coated over the cathode surface to give oxide-coated emitter.

** *Filament.* The term filament (literally means a thin wire) denotes the element through which the cathode heating current flows. In case of directly heated, cathode is itself the filament. If indirectly heated, heater is the filament.

electrons. Fig. 2.2 (*i*) shows the structure of directly heated cathode whereas Fig. 2.2 (*ii*) shows its symbol.

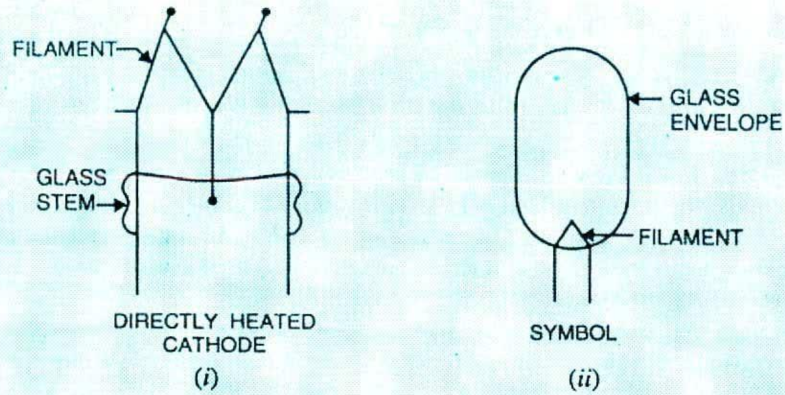


Fig. 2.2

The directly heated cathode is more efficient in converting heating power into thermionic emission. Therefore, it is generally used in power tubes that need large amounts of emission and in small tubes operated from batteries where efficiency and quick heating are important. The principal limitation of this type of cathode is that any variation in heater voltage affects the electron emission and thus produces *hum* in the circuit.

(*ii*) **Indirectly heated cathode.** In this type, the cathode consists of a thin metal sleeve coated with barium and strontium oxides. A filament or heater is enclosed within the sleeve and insulated from it. There is no electrical connection between the heater and the cathode. The heating current is passed through the heater and the cathode is heated indirectly through heat transfer from the heater element. Fig. 2.3 (*i*) shows the structure of indirectly heated cathode whereas Fig. 2.3 (*ii*) shows its symbol.

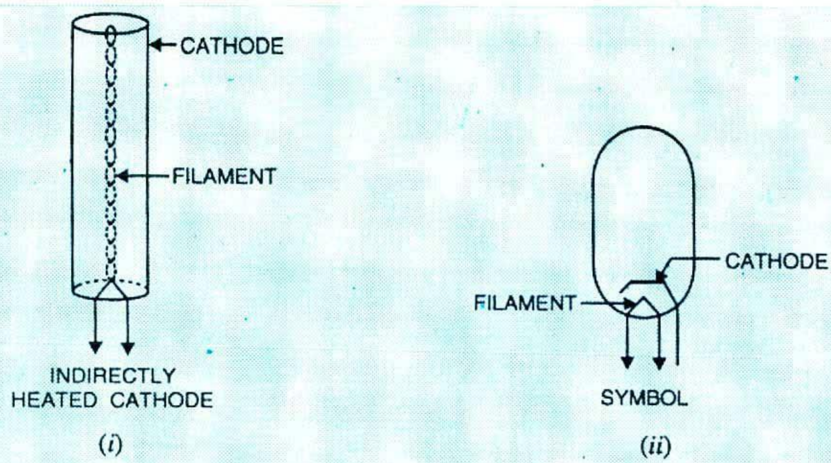


Fig. 2.3

Indirectly heated cathode has many advantages. As cathode is completely separated from the heating circuit, therefore, it can be readily connected to any desired potential as needed, independent of the heater potential. Furthermore, because of relatively large mass of cylindrical cathode, it takes time to heat or cool and as such does not introduce hum due to heater voltage fluctuations. Finally, a.c. can be used in the heater circuit to simplify the power requirements. Almost all modern receiving tubes use this type of cathode.

2.7 Field Emission

The process of electron emission by the application of strong electric field at the surface of a metal is known as **field emission.**

When a metal surface is placed close to a high voltage conductor which is positive *w.r.t.* the metal surface, the electric field exerts attractive force on the free electrons in the metal. If the positive potential is great enough, it succeeds in overcoming the restraining forces of the metal surface and the free electrons will be emitted from the metal surface as shown in Fig. 2.4.

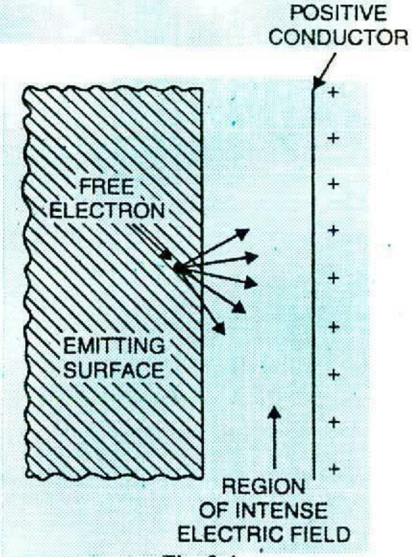


Fig. 2.4

Very intense electric field is required to produce field emission. Usually, a voltage of the order of a million volts per centimetre distance between the emitting surface and the positive conductor is necessary to cause field emission. Field emission can be obtained at temperatures much lower (*e.g.* room temperature) than required for thermionic emission and, therefore, it is also sometimes called *cold cathode emission* or *auto electronic emission.*

2.8 Secondary Emission

Electron emission from a metallic surface by the bombardment of high-speed electrons or other particles is known as **secondary emission.**

When high-speed electrons suddenly strike a metallic surface, they may give some or all of their kinetic energy to the free electrons in the metal. If the energy of the striking electrons is sufficient, it may cause free electrons to escape from the metal surface. This phenomenon is called *secondary emission.* The electrons that strike the metal are called *primary electrons* while the emitted electrons are known as *secondary electrons.* The intensity of secondary emission depends upon the emitter material, mass and energy of the bombarding particles.

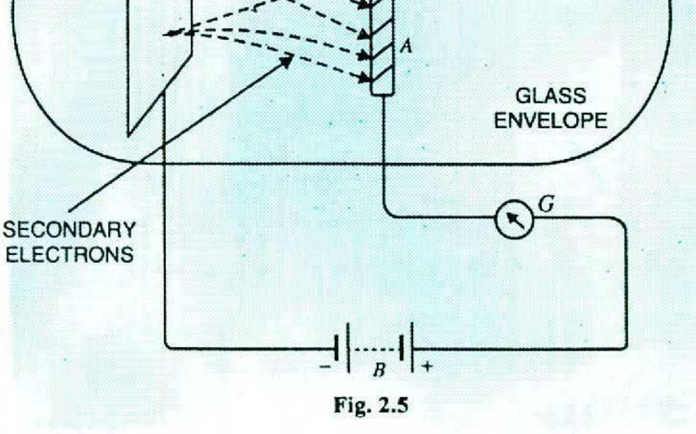


Fig. 2.5

The principle of secondary emission is illustrated in Fig. 2.5. An evacuated glass envelope contains an emitting surface *E*, the collecting anode *A* and a source of primary electrons *S*. The anode is maintained at positive potential *w.r.t.* the emitting surface by battery B. When the primary electrons strike the emitting surface E, they knock out secondary electrons which are attracted to the anode and constitute a flow of current. This current may be measured by connecting a sensitive galvanometer G in the anode circuit.

The effects of secondary emission are very undesirable in many electronic devices. For example, in a tetrode valve, secondary emission is responsible for the negative resistance. In some electronic devices, however, secondary emission effects are utilised *e.g.* *electron multiplier, cathode ray tube etc.

2.9 Photo Electric Emission

Electron emission from a metallic surface by the application of light is known as **photo electric emission.**

When a beam of light strikes the surface of certain metals (*e.g.* potassium, sodium, cesium), the energy of photons of light is transferred to the free electrons within the metal. If the energy of the striking photons is greater than the work function of the metal, then free electrons will be knocked out from the surface of the metal. The emitted electrons are known as *photo electrons* and the phenomenon is known as *photoelectric emission.* The amount of photoelectric emission depends upon the intensity of light falling upon the emitter and frequency of radiations. The greater the intensity and frequency of radiations, the greater is the photo electric emission. Photo-electric emission is utilised in photo tubes which form the basis of television and sound films.

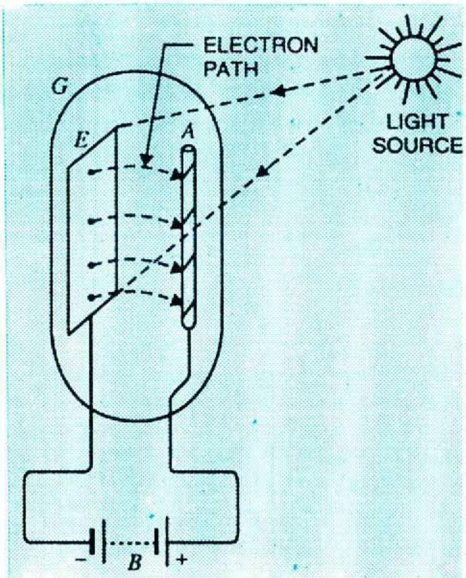


Fig. 2.6

Fig. 2.6 illustrates the phenomenon of photoelectric emission. The emitter E and anode A are enclosed in an evacuated glass envelope G. A battery B maintains the anode at positive potential w.r.t. emitter. When light of suitable intensity and frequency falls on the emitter, electrons are ejected from its surface. These electrons are attracted by the positive anode to constitute current in the circuit. It may be noted that current will exist in the circuit so long as illumination is maintained.

Multiple-Choice Questions

1. Work function of metals is generally measured in ....
   (*i*) joules (*ii*) electron-volt
   (*iii*) watt-hour (*iv*) watt
2. The operating temperature of an oxide-coated emitter is about ....
   (*i*) 750°C (*ii*) 1200°C
   (*iii*) 2300°C (*iv*) 3650°C
3. .... is used in high voltage (> 10 kV) applications.
   (*i*) tungsten emitter
   (*ii*) oxide-coated emitter

* An interesting aspect of secondary emission is that a high-speed bombarding electron may liberate as many as 10 "secondary electrons". This amounts to a multiplication of electron flow by a ratio as great as 10 and is utilised in current multiplier devices.

(*iii*) thoriated-tungsten emitter
(*iv*) none of the above

4. A desirable characteristic of an emitter is that it should have .... work function.
(*i*) large (*ii*) very large
(*iii*) small (*iv*) none of the above

5. The thermionic emitter that has the highest operating temperature is ....
(*i*) oxide-coated (*ii*) thoriated-tungsten
(*iii*) tungsten (*iv*) none of the above

6. If the temperature of an emitter is increased two times, the electron emission is ....
(*i*) increased two times
(*ii*) increased four times
(*iii*) increased several million times
(*iv*) none of the above

7. In X-ray tubes, ... emitter is used.
(*i*) thoriated tungsten
(*ii*) tungsten
(*iii*) oxide-coated
(*iv*) none of the above

8. The life of an oxide-coated emitter is about ....
(*i*) 500 hours (*ii*) 1000 hours
(*iii*) 200 hours (*iv*) 10,000 hours

9. The electrons emitted by a thermionic emitter are called ....
(*i*) free electrons
(*ii*) loose electrons
(*iii*) thermionic electrons
(*iv*) bound electrons

10. The work function of an oxide-coated emitter is about ....
(*i*) 1.1 eV (*ii*) 4 eV
(*iii*) 2.63 eV (*iv*) 4.52 eV

11. The warm-up time of a directly heated cathode is .... that of indirectly heated cathode.
(*i*) more than (*ii*) less than
(*iii*) same as (*iv*) data incomplete

12. The most commonly used emitter in the tubes of a radio receiver is ....
(*i*) tungsten (*ii*) thoriated-tungsten
(*iii*) oxide-coated (*iv*) none of the above

13. Field emission is utilised in ....
(*i*) vacuum tubes
(*ii*) TV picture tubes
(*iii*) gas-filled tubes
(*iv*) mercury pool devices

14. Oxide-coated emitters have electron emission of .... per watt of heating power.
(*i*) 5-10 mA (*ii*) 40-90 mA
(*iii*) 50-100 mA (*iv*) 150-1000 mA

15. The oxide-coated cathodes can be used for voltages upto ....
(*i*) 1000 V (*ii*) 3000 V
(*iii*) 4000 V (*iv*) 10,000 V

Answers to Multiple-Choice Questions

1. (*ii*)	**2.** (*i*)	**3.** (*i*)	**4.** (*iii*)	**5.** (*iii*)
6. (*iii*)	**7.** (*ii*)	**8.** (*iv*)	**9.** (*iii*)	**10.** (*i*)
11. (*ii*)	**12.** (*iii*)	**13.** (*iv*)	**14.** (*iv*)	**15.** (*i*)

Chapter Review Topics

1. What is electron emission ? Explain the terms : surface barrier and work function.
2. What general conditions must be satisfied before an electron can escape from the surface of a material ?
3. Name and explain briefly four practical ways by which electron emission can occur.
4. What are the materials used for thermionic emitters ? Compare the relative merits of each.
5. Discuss briefly construction and relative advantages of directly and indirectly heated cathodes.

Problems

1. An oxide-coated emitter has a surface area of 0.157 cm^2. If the operating temperature is 110 K, find the emission current. Given A = 100 $A/m^2/K^2$, work function = 1.04 eV. **[0.0352 A]**
2. A tungsten filament of unknown composition emits 1000 A/m^2 at an operating temperature of 1900 K. Find the work function of tungsten filament. Given $A = 60.2 \times 10^4$ $A/m^2/K^2$. **[3.44 eV]**
3. Calculate the total emission available from barium-strontium oxide emitter, 10 cm long and 0.01 cm in diameter, operated at 1900 K. Given that $A = 10^{-12}$ $Amp/cm^2/K^2$ and b = 12,000. **[0.345 A]**

Discussion Questions

1. Why does electron emission not occur at room temperature ?
2. Why are high temperatures necessary for thermionic emission ?
3. Why are electron emitters heated electrically ?
4. Why are thermionic emitters heated in vacuum ?
5. Why are tungsten and thoriated tungsten cathodes always of directly heated type ?
6. Why cannot oxide-coated cathodes be used for voltages exceeding 1000 volts?
7. Why do directly heated cathodes introduce hum in the circuit ?
8. Why are directly heated cathodes used in high power applications ?

3

Vacuum Tubes

Introduction

The vacuum tube has been described as the most important single piece of equipment introduced into electrical engineering during the twentieth century. Its development has produced a new branch of engineering called electronics. The applications of vacuum tubes are so varied that this "miracle tool" has won a place in the industrial and commercial fields. These tubes have been finding wide applications in radio, long distance telephones, sound motion pictures, television, radar, electronic computers and industrial automation. Though vacuum tubes have been replaced by *semi-conductor devices, they are still used at many places in the electronic circuits.

Despite the wide variety of tasks that vacuum tubes are doing—despite the complexity of some electronic equipment—the basic construction and principles of operation of tubes are quite simple to understand. In this chapter, we shall focus our attention on some important types of vacuum tubes with special reference to their operation and characteristics.

3.1 Vacuum Tube

An electronic device in which the flow of electrons is through vacuum is known as a **vacuum tube.**

A vacuum tube usually contains a *cathode* which is the electron emitter ; an *anode* (also called *plate*) which is the electron collector and one or more electrodes (called *grids*) for controlling the flow of electrons between cathode and plate. These electrodes are housed in a highly evacuated glass envelope. The plate is held at positive potential w.r.t. cathode so that emitted electrons are attracted to plate to provide current in vacuum. The ability of vacuum tubes to conduct current in vacuum enables them to perform different functions.

Classification of vacuum tubes. There are several ways of classifying vacuum tubes. However, according to the number of electrodes, vacuum tubes are classified as under :

(*i*) Vacuum diode (*ii*) Vacuum triode

(*iii*) Vacuum tetrode (*iv*) Vacuum pentode

The diode, triode, tetrode and pentode contain 2, 3, 4 and 5 electrodes respectively. It may be noted here that heater is not counted as electrode because it is merely an incandescent filament to heat the cathode electrically. There are two principal electrodes, namely : *cathode* and *anode* present in every tube. The other electrodes, if any, are called grids. One of them called *control grid* is used to control the flow of electrons between cathode and plate. The others are called *screen grids* and are generally held at some constant potential and serve to alter the characteristics of the tube.

* These are covered in later chapters.

3.2 Vacuum Diode

In 1904, Sir J.A. Fleming (1849-1945), an English Physicist, invented first vacuum diode, called the *Fleming's Valve*. Fleming's valve was so insensitive that it found little immediate applications. Many improvements have been made in the vacuum diode since the invention of the first crude model.

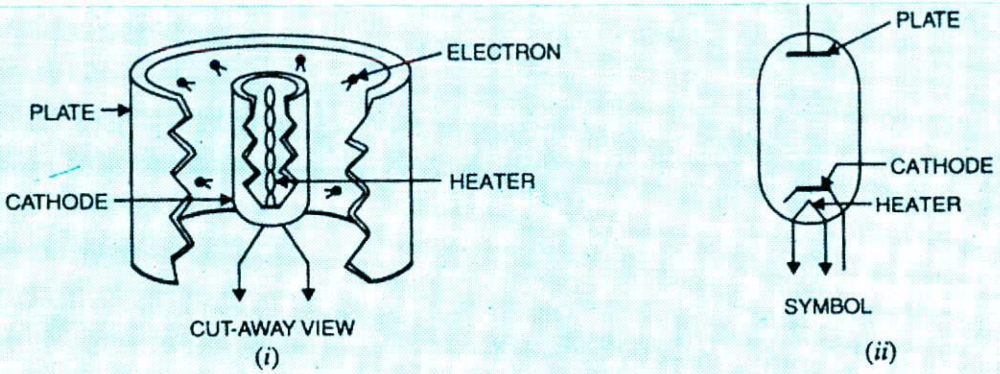


Fig. 3.1

Construction. A vacuum diode consists of two electrodes, a *cathode* and an *anode* (or *plate*) enclosed in a highly evacuated glass envelope. The cathode is in the form of nickel cylinder coated with barium and strontium oxides and is heated indirectly to provide electron emission. The anode is generally a hollow cylinder made of *nickel or molybdenum and surrounds the cathode. Fig. 3.1 (*i*) shows the construction of vacuum diode whereas Fig. 3.1 (*ii*) shows its symbol. Note the symbol of diode where plate is represented by straight line, cathode by a straight line with sides folded down and heater by inverted V.

Operation. When the cathode is heated by passing electric current through the heater, it emits a large number of electrons. The behaviour of these emitted electrons will depend upon the anode potential w.r.t. cathode. If the anode is at zero potential *w.r.t.* cathode as shown in Fig. 3.2 (*i*), the emitted electrons simply cannot go to plate as the latter is neutral. Therefore, circuit current is zero.

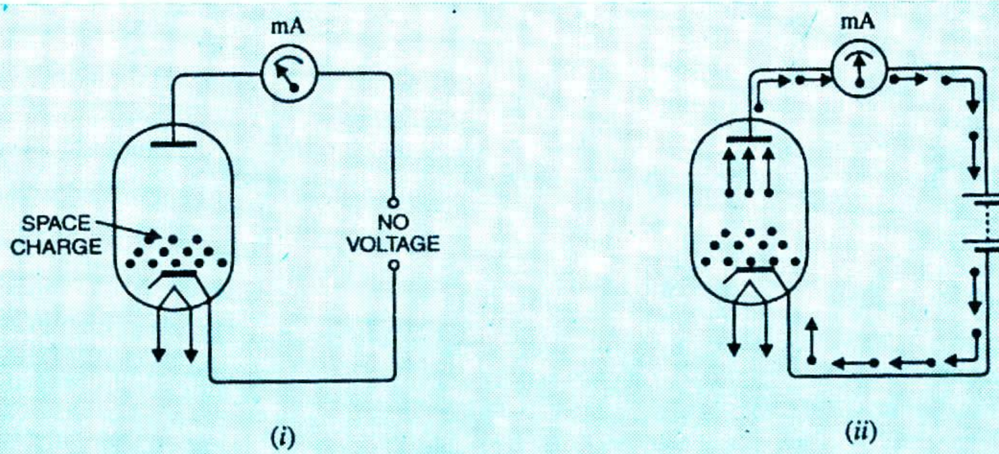


Fig. 3.2

* Other materials such as graphite, tantalum, iron may be used.

However, the emitted electrons start accumulating near the cathode and form a cloud of electrons. This is known as *space charge*. It is so called because the space near the cathode is charged (negatively). It may be noted that a stage is reached when the number of electrons forming the space charge becomes *constant for a given operating temperature. In this way, space charge becomes a source of electrons that can be attracted to the plate if the latter is held at appropriate potential.

If the plate is made positive *w.r.t.* cathode as shown in Fig. 3.2 (*ii*), then electrons from the space charge are attracted to the plate. These electrons flow from cathode to plate to constitute what is known as *plate current*. Upon reaching the plate, these electrons continue to flow through the external circuit made up of the connecting wires, meter and battery. They finally return to the cathode, thus making up the supply of electrons lost by emission. If the positive potential on the plate is increased, the plate current also increases since more electrons will be pulled from the space charge to the plate.

If the anode is made negative *w.r.t.* cathode as shown in Fig. 3.3, the emitted electrons are repelled back and no current flows in the circuit. The current cannot flow in the opposite direction because neither plate is hot enough to emit electrons nor it is made of suitable material for electron emission.

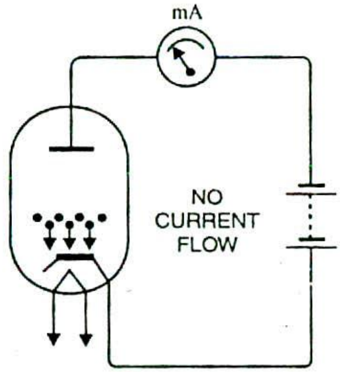


Fig. 3.3

The following conclusions may be drawn from the diode valve operation :

(*i*) The current flows in the diode only when plate is made positive *w.r.t.* cathode. No current can flow when plate is negative *w.r.t.* cathode.

(*ii*) Electron flow within a diode takes place only from cathode to plate and never from plate to cathode. This unidirectional conduction enables the diode to act like a switch or **valve, automatically starting or stopping conduction depending upon whether the plate is positive or negative *w.r.t.* cathode. This property permits the diode to act as a *rectifier*, changing alternating current into direct current. We shall discuss the operation of rectifiers in chapter 4.

3.3 Characteristics of Vacuum Diode

The most important characteristic of a vacuum diode is the plate characteristic which gives the *relation between plate voltage and plate current for a given cathode temperature*. The circuit arrangement for determining the plate characteristics of an indirectly heated vacuum diode is shown in Fig. 3.4 (*i*). The cathode temperature can be changed by varying R_1 connected in the heater circuit. The plate voltage can be varied to desired value by means of resistor R_2 arranged as potential divider in the plate circuit. Keeping the cathode temperature constant, say at T_1, the plate voltage is varied in steps from zero by means of potential divider. Corresponding to each value of plate voltage, the value of plate current is noted. Then curve is drawn, taking plate voltage along X-axis and plate

* The emitted electrons go to form space charge and leave the cathode positively charged. The combined effect of negative space charge and positive cathode is to send some of the electrons from space charge back to the cathode. But in the meanwhile, more electrons are emitted by the cathode. In fact, soon a dynamic equilibrium is established when the number of electrons emitted is equal to the number of electrons attracted back to cathode.

** Diode conducts from cathode to anode and that too when its plate is positive *w.r.t.* cathode. This is true of all tubes. This property has given the tubes an alternative name of valves. Just as valve operates in one direction, similarly vacuum tubes conduct in one direction *i.e.* from cathode to plate.

current along Y-axis. This gives the plate characteristic at cathode temperature T_1 as shown in Fig. 3.4 (*ii*). Following similar procedure, plate characteristics at various cathode temperatures can be obtained. The following points may be noted from the plate characteristics :

(*i*) All the curves are *coincident at low plate-voltage where the negative space charge is most effective in limiting plate current. This low-plate voltage region [*i.e.* region *oa* in Fig. 3.4 (*ii*)] is known as *space charge limited region*. In this region, the plate current increases as the plate voltage is increased, because more positive plate attracts electrons from the space charge at a greater rate. In the space charge limited region, the plate current is given by the relation ;

$$I_b = K E_b^{3/2}$$

where K is a constant whose value depends upon the shape of electrodes and geometry of tube. This relation is known as *Child's law*. It is clear that in space charge limited region, the plate current I_b is completely controlled by plate voltage E_b and is independent of cathode temperature.

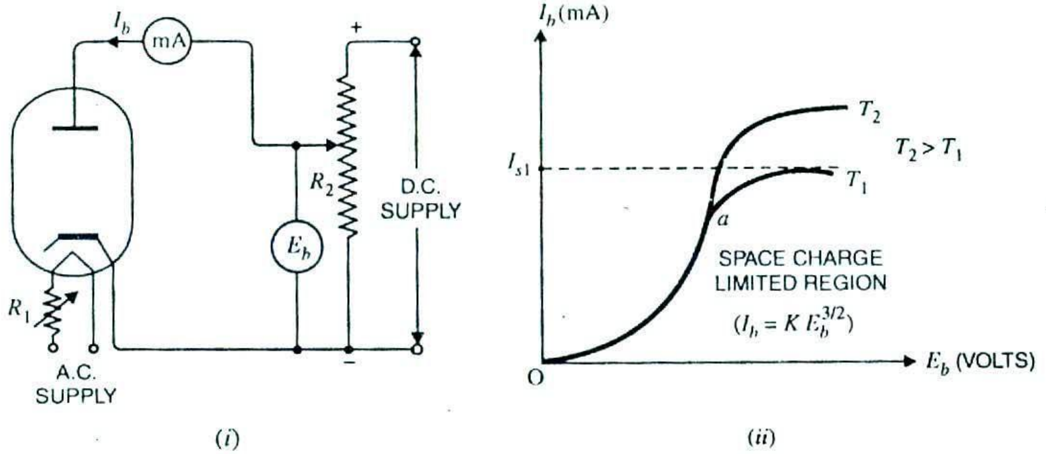


Fig. 3.4

(*ii*) As plate voltage is made progressively higher, greater portion of electrons from space charge is attracted to plate and eventually at some plate voltage, the space charge is completely eliminated. Under such conditions, the entire supply of emitted electrons (for a given cathode temperature) is attracted to the plate. Therefore, beyond this point, plate current becomes constant and does not increase even if the plate voltage is increased. This maximum plate current is called ***saturation*** *current*. In Fig. 3.4 (*ii*), I_{s1} is the saturation current at cathode temperature T_1.

(*iii*) If the cathode temperature is raised (say from T_1 to T_2), the rate of emission is increased. Consequently, the saturation point is raised.

Example 3.1. *The plate current in a diode is 10 mA at plate voltage of 100V when operating in the space charge limited region. What is the plate voltage necessary to double the plate current ?*

Solution.

$$I_{b1} = 10 \text{ mA}, \quad E_{b1} = 100\text{V}, \quad I_{b2} = 20 \text{ mA}, \quad E_{b2} = ?$$

According to Child's law,

---

* At low voltages, so few electrons are pulled out of the space charge that even at reduced cathode temperature, the cathode can supply sufficient number of electrons.

$$I_{b1} \propto E_{b1}^{3/2}$$

$$I_{b2} \propto E_{b2}^{3/2}$$

$$\therefore \quad I_{b1}/I_{b2} = (E_{b1}/E_{b2})^{3/2}$$

$$10/20 = (100/E_{b2})^{3/2}$$

$$\frac{1}{2} = \frac{100 \times 10}{E_{b2}^{3/2}}$$

$$\text{or} \quad E_{b2}^{3/2} = 2000$$

$$\therefore \quad E_{b2} = \mathbf{158.7\ volts}$$

3.4 Plate Resistance of Diode

We have seen that plate current flowing through a vacuum diode varies as the plate voltage is changed. Therefore, a diode may be considered as having internal resistance that limits the amount of plate current flow. This internal resistance offered by the diode is known as its *plate resistance*. It may be noted that negative space charge is *mainly responsible for the plate resistance of diode. This resistance is not the same for direct current as for alternating current. Accordingly; like any other vacuum tube, diode has two types of resistances, namely : *d.c. plate resistance* and *a.c. plate resistance.*

(*i*) **d.c. plate resistance.** *The resistance offered by the diode to direct current is known as* **d.c. plate resistance.**

Its value can be calculated by finding the ratio of total d.c. plate voltage across diode to the resulting current. Fig. 3.5 shows the typical plate characteristic of a vacuum diode. At point P on the curve, the plate voltage is OA and the corresponding plate current is OB. The d.c. plate resistance R_b is given by ;

$$R_b = \frac{OA}{OB}$$

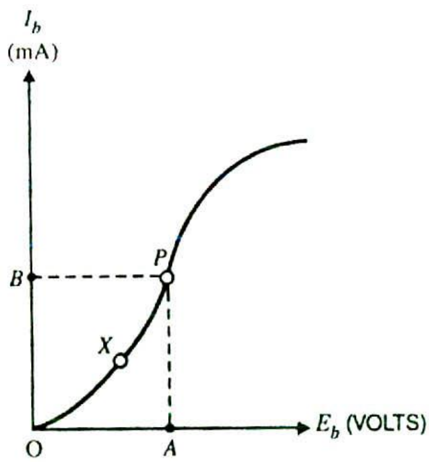


Fig. 3.5

As plate characteristic is not a straight line, therefore, d.c. plate resistance is not constant but depends upon the operating point. Thus plate resistance at point X is different from that at point P. Hence, d.c. plate resistance must be determined at the actual operating point.

(*ii*) **a.c. plate resistance.** It is the resistance offered by the diode to alternating current and may be defined as under :

The ratio of a small change in plate voltage across a diode to the resulting change in plate current is known as **a.c. plate resistance** *i.e.*

$$\text{a.c. plate resistance, } r_p = \frac{\Delta E_b}{\Delta I_b}$$

As tubes are generally used with a.c. or varying potentials, therefore, a.c. plate resistance is much more important than d.c. plate resistance. The a.c. plate resistance can be determined from plate characteristic by considering the small change of plate voltage half way on each side of the operating point. For example, in Fig. 3.6, the a.c. plate resistance at operating point P can be found by considering small equal changes of plate voltage on either side of the operating point (*i.e.* $AB = AC$).

* Although it may depend to a lesser extent upon the physical size and spacing of electrodes.

Change in plate voltage = BC

Change in plate current = YZ

∴ a.c. plate resistance at P is

$$r_p = \frac{BC}{YZ}$$

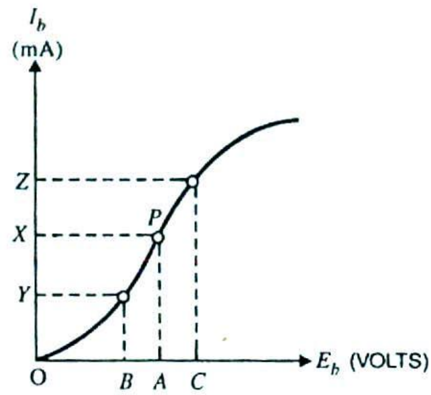
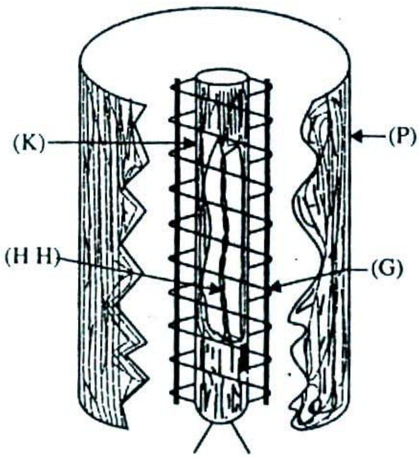


Fig. 3.6

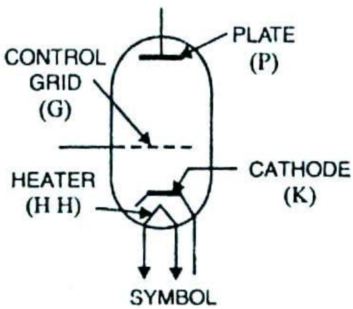
3.5 Vacuum Triode

In 1906, Dr. Lee De Forest (1873 – 1961), an American scientist placed a third electrode in the form of wire mesh between the cathode and plate of a vacuum diode. The resulting device was called *triode*. So important was this discovery that it ushered in the electronics industry as we know it to-day.

Construction. As the name implies, a triode has three electrodes, namely : *cathode, plate* and *control grid*. The cathode is located at the centre of the tube and is surrounded by control grid which is in turn surrounded by plate. The cathode and plate have similar construction as for a diode. The control grid consists of a fine wire mesh placed very close to the cathode. The spacing between the turns of the mesh are wide enough so that the passage of electrons from cathode to plate is not obstructed by the grid. The electrons attracted to plate from cathode go through the openings in the grid. Fig. 3.7 (*i*) shows the cut-away view of triode whereas Fig. 3.7 (*ii*) shows its symbol. The dotted line between plate and cathode in the symbol represents the control grid.



(*i*)



(*ii*)

Fig. 3.7

Action of control grid. The electrons emitted by the cathode pass through the openings of control grid to reach the plate. As the control grid is much closer to the cathode than the plate, therefore, a small voltage on the control grid has much more control on the electron flow than a comparatively high voltage on the plate. This places the control grid in a commanding position to control the plate current flowing in the triode. Fig. 3.8 shows the action of the control grid in a triode at different grid voltages, assuming the plate potential remains unaltered.

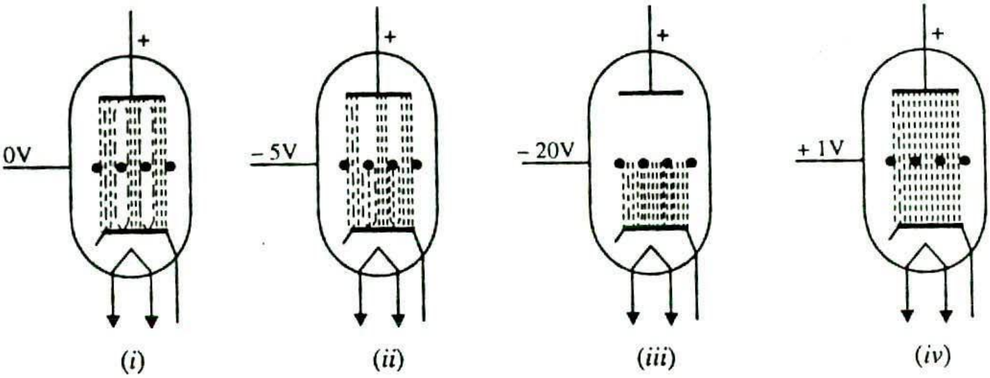


Fig. 3.8

(*i*) When the control grid is at zero potential *w.r.t.* cathode as shown in Fig. 3.8 (*i*), the triode valve just behaves like a diode. This is not surprising since under these conditions, the presence of control grid does not affect the electric field between plate and cathode.

(*ii*) If the control grid is placed at some negative potential (say – 5 V) *w.r.t.* cathode as shown in Fig. 3.8 (*ii*), it has repelling effect on the electrons flowing towards the plate. Consequently, fewer electrons reach the plate, thereby reducing the plate current. It may be added that due to the advantageous position of control grid, the reduction in plate current is much more than could be by some larger plate potential.

(*iii*) As the negative potential on the grid (called *grid bias*) is increased, the plate current decreases continuously. If sufficient negative voltage (say – 20 V) is placed on the grid, all the electrons are repelled towards cathode. Consequently, the plate current becomes zero and the triode is said to be *cut off* [See Fig. 3.8 (*iii*)].

The smallest negative grid voltage, for a given plate voltage, at which plate current becomes zero is known as **grid cut off** *or* **cut off bias.**

(*iv*) If the control grid is made slightly positive (say + 1V) *w.r.t.* cathode as shown in Fig. 3.8 (*iv*), the helping electrostatic fields of plate and grid will accelerate the electrons towards the plate. Therefore, plate current is increased and at the same time some of the electrons are attracted to grid to constitute grid current. The grid current is undesirable because it causes power loss in the grid circuit. *Therefore, grid is always kept at *negative potential w.r.t. cathode.*

Conclusion. From the above discussion, it is concluded that a slight change in grid potential brings about a large change in plate current. To affect the same change in plate current without changing the grid potential, a much larger plate potential is needed. In fact, this remarkable current controlling property of control grid is responsible for the widespread use of triodes as amplifiers.

3.6 Triode Characteristics

The graphical representations of relationship between plate current, plate voltage and grid voltage under normal operating conditions are known as *triode characteristics*. Assuming the **cathode temperature to be constant, the plate current in a triode depends upon plate and grid potentials *i.e.*

* This is fully explained in the chapter on vacuum tube amplifiers.

** The filament is supplied with the specified voltage recommended by the manufacturer. Therefore, cathode temperature remains constant.

$$I_b = f(E_b, E_c)$$

There are three variables and, therefore, we require a three-dimensional surface to represent the relation among all the three quantities at a time. However, this paper is two dimensional and for convenience, relation is found between any two quantities while the third quantity is kept constant. Accordingly; there will be three characteristics *viz plate characteristic i.e.* I_b/E_b curve at constant E_c, *mutual characteristic i.e.* I_b / E_c curve at constant E_b and *constant current characteristic i.e.* E_b/E_c curve at constant I_b. The triode characteristics can be obtained under two sets of conditions, namely;

(*i*) **Static conditions** *i.e.* when various d.c. voltages are applied to the triode electrodes and there is no load in the plate circuit and no signal at the input. Under such conditions, the plate potential remains static or constant and is independent of plate current. The curves obtained under static conditions are known as *static characteristics*.

(*ii*) **Dynamic conditions** *i.e.* when signal is applied in the grid circuit and load is inserted in the plate circuit. Under such conditions, the plate current flowing through the load causes a voltage drop in it. Consequently, the plate potential does not remain static or constant but varies with plate current. The curves obtained under this condition are known as *dynamic characteristics*. It may be mentioned here that dynamic characteristics represent the actual operating conditions since a practical triode circuit has signal in the input and load in the plate circuit.

3.7 Static Characteristics of Triode

Fig. 3.9 shows the experimental arrangement for determining the static characteristics of a triode. The plate voltage can be maintained constant at any desired value by resistor R_1 arranged as potential divider. The grid can be given any positive or negative potential *w.r.t.* cathode with the help of reversing switch *RS*.

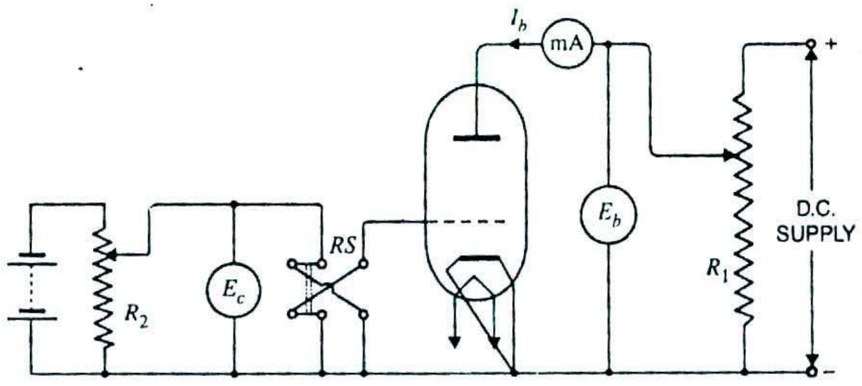


Fig. 3.9

1. Plate characteristic. *It is the curve between plate voltage E_b and plate current I_b of a triode at constant grid voltage E_c.*

For determining the static plate characteristics, refer to the circuit diagram shown in Fig. 3.9. Firstly, the grid voltage is set at zero *i.e.* $E_c = 0$ V. Keeping the grid voltage constant at this value, the plate voltage is changed in steps and the corresponding values of I_b are noted on the milliammeter connected in the plate circuit. The E_b/I_b readings are plotted on the graph. This gives the plate characteristic at $E_c = 0$ V. The experiment is repeated with $E_c = -2$ V, and then $E_c = -4$ V etc. Thus, a family of plate characteristics is obtained at different grid voltages as shown in Fig. 3.10. The following points may be noted from these characteristics :

(*i*) The characteristics are drawn for negative values of grid voltage only as practically a triode is always operated at negative grid voltage.

(*ii*) The characteristics are curved over the lower portion but fairly linear in the upper portion. It is because at low plate voltage, the plate current rises slowly but at high plate voltages, it increases *appreciably.

(*iii*) The curves are approximately equally spaced for equal differences of grid voltages.

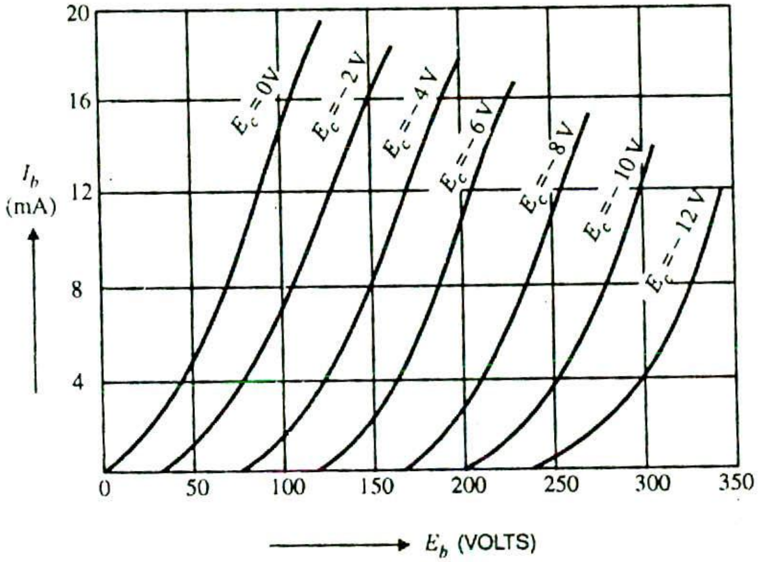


Fig. 3.10

2. ****Mutual characteristic.** *It is the curve between plate current I_b and grid voltage E_c at constant plate voltage E_b.*

For determining the static mutual characteristics of a triode, the circuit of Fig. 3.9 can be used. The slider on R_1 is adjusted to give a constant value of plate voltage, say 200 volts. Keeping the plate voltage constant at this value, the grid voltage is changed from zero to negative values in steps. The corresponding values of plate current I_b are noted on the milliammeter connected in the plate circuit. The I_b/E_c readings are plotted on the graph. This gives the mutual characteristic at $E_b = 200$ V. The experiment is repeated with $E_b = 150$ V and $E_b = 100$ V etc. Thus a family of mutual characteristics at different plate voltages is obtained as shown in Fig. 3.11. *It may be seen that mutual characteristics convey the same information as the plate characteristics.* Often either of the two is used to study the performance of triode in a circuit.

3. **Constant current characteristic.** *It is the curve between plate voltage E_b and grid voltage E_c at constant plate current I_b.*

For determining the constant current characteristics, the experimental arrangement of Fig. 3.9 can be employed. However, this curve is relatively unimportant from the practical point of view and is seldom used.

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* At low plate voltage, electrons having passed through the grid are slowed down and in most cases return to the grid. Hence, plate current increase is slow. However, at large plate potential, the electrons are accelerated after passing through the grid, thereby increasing plate current.

** So called because they express the mutual relationship between input (grid) and output (plate) circuits.

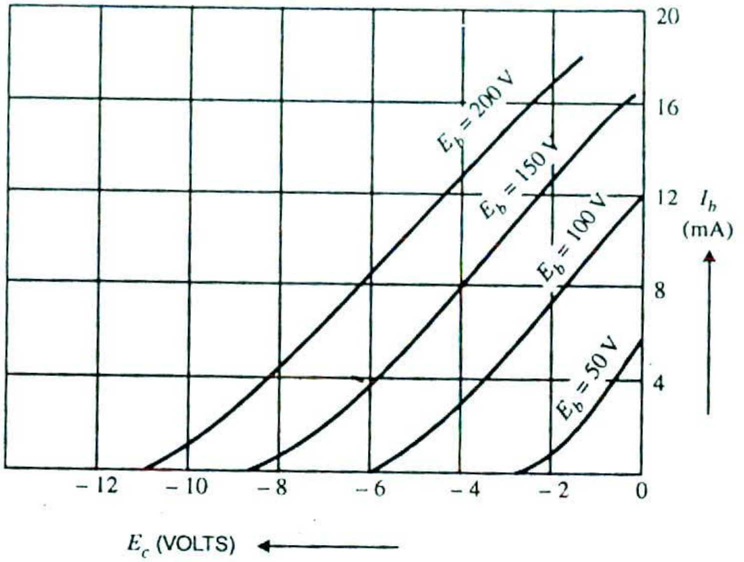


Fig. 3.11

3.8 Vacuum Tube Constants

In the design of a vacuum tube, several factors such as shape of electrodes, spacing between electrodes etc. are taken into account. It is these factors which determine the behaviour of the tube in a circuit. The design factors are summarised by a series of numbers, called *tube* or *valve constants*. All major valve manufacturers publish manuals in which these constants are listed. The three most important tube constants are the *amplification factor, a.c. plate resistance* and *transconductance*.

(*i*) **amplification factor (μ).** The amplification factor of a tube is a measure of the effectiveness of grid voltage relative to the plate voltage in controlling the plate current. It is represented by Greek letter μ and may be defined as under :

The ratio of small change in plate voltage (ΔE_b) to a small change in grid voltage (ΔE_c) of a triode at constant plate current is known as **amplification factor** *i.e.*

$$\text{Amplification factor, } \mu = \frac{{}^{*}\Delta E_b}{\Delta E_c} \text{ at constant } I_b$$

For instance, suppose a 40 volt change in plate voltage brings about a change of 1 mA in plate current and the same plate current change (1 mA) is obtained by changing the grid voltage by 2 volts. Then it becomes clear that the effect of grid voltage on the plate current is 20 times as large as the plate voltage effect. In other words, the amplification factor of the tube is 40/2 = 20. If a tube has higher amplification factor, it means that effect of grid voltage on the plate current is greater relative to the plate voltage.

The amplification factor of a tube primarily depends upon grid structure and to a lesser extent on the shape of electrodes and their spacing. The closer spacing of the grid wires or greater distance between grid and plate results in a higher amplification factor. Triodes are classified as *low μ triodes*

* The simplest method to determine amplification factor is to change the plate voltage by small amount (ΔE_b), record the change in plate current, and then change the grid voltage (in opposite direction) by an amount ΔE_c just sufficient to restore the plate current to the previous value. Then,

$$\mu = \Delta E_b / \Delta E_c$$

(3), *medium* μ *triodes* (20) *and high* μ *triodes* (100).

(*ii*) ***a.c. plate resistance** (r_p). It is the opposition offered by the tube to the flow of electrons from cathode to plate when varying voltages are applied to the electrodes. It may be defined as under :

The ratio of small change in plate voltage (ΔE_b) *to the resulting small change in plate current* (ΔI_b) *at constant grid voltage is known as* **a.c. plate resistance** *i.e.*

$$\text{a.c. plate resistance, } r_p = \frac{\Delta E_b}{\Delta I_b} \text{ at constant } E_c$$

The a.c. plate resistance indicates how the plate voltage influences the plate current at constant grid voltage. For example, if 20 V change of plate voltage brings about 2.5 mA change in plate current at constant grid voltage, then r_p = 20V/ 2.5 mA = 8000 Ω. The a.c. plate resistance of a tube depends upon the type of emitter, the geometry of tube and the space charge. It should be noted that a.c. plate resistance will vary—depending upon the operating point. A.C. plate resistance of triodes ranges from as low as 300 ohms for low μ tubes to approximately 100,000 ohms for high μ tubes.

(*iii*) **Transconductance or mutual conductance** (g_m)

The **transconductance or mutual conductance indicates the effectiveness of grid potential in changing the plate current. Therefore, it is the most important of the three valve constants and may be defined as under :

The ratio of small change in plate current (ΔI_b) *to the small change in grid voltage* (ΔE_c) *at constant plate voltage is known as* **transconductance** *or* **mutual conductance** *i.e.*

$$\text{Mutual conductance, } g_m = \frac{\Delta I_b}{\Delta E_c} \text{ at constant } E_b$$

As g_m is a ratio of current to voltage, therefore, it should be expressed in the units of *mho* (ohm spelled backward).

Since vacuum tubes are low-current devices, the transconductance will be a fraction of 1 mho. Therefore, it is more convenient to express g_m in micromho (μ mho). Note that 1 mho = 10^6 μ mho. Thus, if a 1 V change of grid voltage in a valve produces 3 mA (*i.e.*, 0.003 A) change in plate current, then,

$$\text{Transconductance, } g_m = \frac{0.003 \text{ A}}{1 \text{ V}} \times 10^6 = 3000 \ \mu \text{ mho}$$

3.9 Relationship between μ, r_p and g_m

$$\text{We know, } \mu = \frac{\Delta E_b}{\Delta E_c}$$

Multiplying and dividing the numerator and denominator on the R.H.S. by I_b, we get,

$$\mu = \frac{\Delta E_b}{\Delta E_c} \times \frac{\Delta I_b}{\Delta I_b} = \frac{\Delta E_b}{\Delta I_b} \times \frac{\Delta I_b}{\Delta E_c}$$

$$\therefore \quad \mu = r_p \times g_m$$

i.e. amplification factor = plate resistance × mutual conductance

* A tube has d.c. plate resistance also which is the opposition by the tube to the direct current flow. However, a.c. plate resistance is more significant in a practical circuit.

** Conductance means the ability to conduct. By changing the grid voltage, the conduction ability of plate circuit can be changed. Therefore, conductance is transferred from grid circuit and hence the name *transconductance*. When a change in one circuit produces a change in another circuit, mutual relation is said to exist. Hence, transconductance is sometimes called *mutual conductance*.

It is obvious from this relation that if we know any two values, we can find the third.

It is worthwhile to give passing reference to the importance of transconductance g_m. In practical circuits, as shown in later chapters, it is impossible to achieve *full amplification of the valve due to the voltage drop in its own internal resistance. Therefore, in order to obtain maximum amplification, the tube should have high μ and low r_p *i.e.*, μ/r_p should be as high as possible. But this ratio is equal to g_m, the transconductance of the tube. Hence, it is the g_m which decides the extent of amplification by the tube. Therefore, this constant has assumed much significance and is widely used in the design of electronic equipment.

3.10 Valve Constants from Characteristics

Although valve constants can be found by making measurements, yet in practice they are determined from the characteristics as a matter of convenience. As plate characteristics and mutual characteristics of a triode convey the same information, therefore, either of the two can be used for the determination of valve constants. However, plate characteristics are frequently used for the purpose as they present the data in a more useful form.

Fig. 3.12 shows the typical plate characteristics of a triode. Suppose we want to find the three valve constants at the operating point *A* on E_c = – 8V. The construction procedure is as follows. First follow the - 8 V curve down to a convenient point *B*. From point *B*, draw a horizontal line to intersect the next grid curve (*i.e.*, – 10 V curve) at point *C*. Now, draw a vertical line from *C* until it intersects the – 8 V grid voltage curve again at point *D*. With this construction, the valve constants can be readily determined.

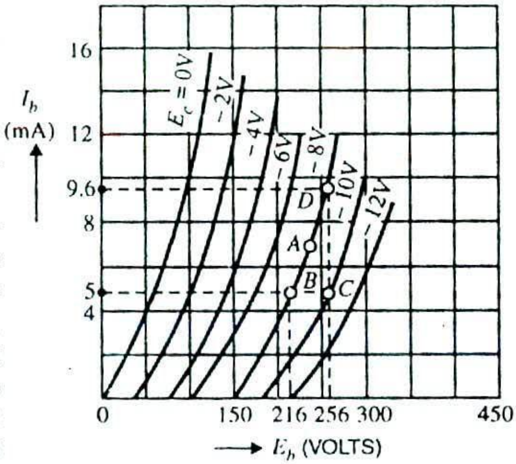


Fig. 3.12

(*i*) **Determination of μ :** The operating point is :

at B, I_b = 5 mA,	E_b = 216 V,	E_c = – 8 V
at D, I_b = 9.6mA,	E_b = 256 V,	E_c = – 8 V
at C, I_b = 5 mA,	E_b = 256 V,	E_c = – 10 V

It is clear that by moving from *B* to *D*, the plate current is changed by 4.6 mA (*i.e.* 9.6 – 5 = 4.6 mA) and the plate voltage by 40 V (*i.e.* 256 – 216 = 40 V). The same change (4.6 mA) in plate current is brought about by moving from *D* to *C* *i.e.* changing grid voltage from –8 V to – 10 V or by 2 V. It follows, therefore, that a change of 2 V in the grid potential has produced the same effect on plate current as 40 V change in plate voltage.

$$\therefore \quad \text{Amplification factor, } \mu = \frac{\Delta E_b}{\Delta E_c} = \frac{40}{2} = 20$$

(*ii*) **Determination of r_p.** If we move from point *B* to *D* along a constant grid voltage of – 8 V,

* Ideally, a voltage E_c applied in the grid circuit should appear as μE_c in the plate circuit.

$$\left(\because \mu = \frac{E_b}{E_c} \text{ or } E_b = \mu E_c \right)$$

However, due to voltage drop in r_p, the voltage available in the plate circuit is less than μE_c.

the plate current changes by 4.6 mA and plate voltage by 40 V. In other words, at constant grid voltage (*i.e.* – 8 V), a change of 40 V in plate voltage produces 4.6 mA change in plate current.

$$\therefore \quad \text{Plate resistance, } r_p = \frac{\Delta E_b}{\Delta I_b} = \frac{40 \text{ V}}{4.6 \text{ mA}} = 8695 \ \Omega$$

(*iii*) **Determination of g_m.** If we move from D to C, the plate voltage remains constant at 256 V. However, the grid voltage changes from – 8 V to – 10 V *i.e.* by 2 V and plate current from 9.6 mA to 5 mA *i.e.* by 4.6 mA. In other words, a change of 2 V on the grid produces a change of 4.6 mA in the plate current.

$$\therefore \quad \text{Mutual conductance, } g_m = \frac{\Delta I_b}{\Delta E_c} = \frac{4.6 \text{ mA}}{2 \text{ V}} = \frac{0.0046}{2} \times 10^6 \ \mu \text{ mho} = 2300 \ \mu \text{ mho}$$

Example 3.2. *Find the mutual conductance of a triode if $\mu = 20$ and $r_p = 8000 \ \Omega$.*

Solution. $\mu = 20, \quad r_p = 8000 \ \Omega, \quad g_m = ?$

We know $\mu = r_p \times g_m$

or $20 = 8000 \times g_m$

$$\therefore \quad g_m = \frac{20}{8000} \text{ mho} = \frac{20}{8000} \times 10^6 \ \mu \text{ mho} = \mathbf{2500 \ \mu \ mho}$$

Example 3.3. *The following readings were obtained from the linear portions of the static characteristics of a vacuum triode :*

E_b	*150 V*	*150 V*	*100 V*
I_b	*12 mA*	*5 mA*	*7.5 mA*
E_c	*– 1.5 V*	*– 3 V*	*– 1.5 V*

Calculate : (i) a.c. plate resistance (ii) mutual conductance and (iii) amplification factor.

Solution.

(*i*) With E_c constant at – 1.5 V, the reduction of plate voltage from 150 V to 100 V reduces the plate current from 12 mA to 7.5 mA *i.e.*

Change in plate voltage, $\Delta E_b = 150 - 100 = 50 \text{ V}$

Change in plate current, $\Delta I_b = 12 - 7.5 = 4.5 \text{ mA}$

$$\therefore \quad \text{Plate resistance, } r_p = \frac{\Delta E_b}{\Delta I_b} = \frac{50 \text{ V}}{4.5 \text{ mA}} = \mathbf{11.1 \ k\Omega}$$

(*ii*) With E_b constant at 150 V, plate current increases from 5 mA to 12 mA as the grid voltage is changed from – 3 V to – 1.5 V *i.e.*

$$\Delta I_b = 12 - 5 = 7 \text{ mA} \quad ; \quad \Delta E_c = (-1.5) - (-3) = 1.5 \text{ V}$$

$$\therefore \quad \text{Mutual conductance, } g_m = \frac{\Delta I_b}{\Delta E_c} = \frac{7 \text{ mA}}{1.5 \text{ V}} = \frac{0.007}{1.5} \times 10^6 \ \mu \text{ mho} = \mathbf{4666 \ \mu \ mho}$$

(*iii*) Amplification factor, $\mu = r_p \times g_m = 11.1 \ k\Omega \times 4666 \ \mu \text{ mho} = \mathbf{52}$

Example 3.4. *The plate current characteristic of a triode is represented by the following expression :*

$$I_b = 0.003 \ (E_b + 30E_c)^{1.5} \ mA$$

where I_b is the plate current in mA, E_b and E_c are the plate and grid voltages in volts respectively. Determine mathematically the values of (i) mutual conductance (ii) amplification factor and (iii) the plate resistance for the triode at the point where $E_b = 250$ V and $E_c = -3$ V.

Solution. The operating point has $E_b = 250$ V and $E_c = -3$ V.

$$I_b = 0.003\,(E_b + 30E_c)^{1.5} \text{ mA}$$

or
$$I_b = 0.003 \times 10^{-3} \times (E_b + 30E_c)^{1.5} \text{ A} \quad ...(i)$$

(*i*) **Mutual conductance.** Differentiating equation (*i*) *w.r.t.* E_c, keeping E_b constant, we get,

$$\frac{\Delta I_b}{\Delta E_c} = 0.003 \times 10^{-3} \times 1.5\,(E_b + 30E_c)^{1/2} \times 30$$

$$= 0.003 \times 10^{-3} \times 1.5 \times 30\,\sqrt{(250 + 30 \times -3)}$$

$$= 1.7 \times 10^{-3} \text{ A/V or mho} = 1.7 \times 10^{-3} \times 10^{6}\ \mu \text{ mho}$$

$$= \mathbf{1700\ \mu\ mho}$$

(*ii*) **Amplification factor.** Differentiating eq. (*i*) *w.r.t.* E_c, keeping I_b constant, we get,

$$0 = 0.003 \times 10^{-3} \times 1.5\,(E_b + 30E_c)^{1/2}\left(\frac{\Delta E_b}{\Delta E_c} + 30\right)$$

or
$$0 = 0.0045 \times 10^{-3}\,\sqrt{250 + 30(-3)} \times (\mu + 30)$$

$\therefore$
$$\mu = -\mathbf{30}$$

The negative sign indicates that the two voltages (*i.e.* E_b and E_c) are in opposite direction.

(*iii*) **Plate resistance**

$$\mu = r_p \times g_m$$

$\therefore$
$$r_p = \frac{\mu}{g_m} = \frac{30}{1700 \times 10^{-6}}\ \Omega = \mathbf{17647\ \Omega}$$

3.11 Dynamic Characteristics

The graphical relations between I_b, E_b and E_c when the triode contains load in the plate circuit are known as **dynamic characteristics of triode.**

The static characteristics drawn in Art. 3.7 are applicable only for a static or constant potential. These were obtained with the plate of the tube directly connected to d.c. supply voltage. However, in actual practice, some load R_L is always connected in the plate circuit as shown in Fig. 3.13. The plate current flowing through the load causes a voltage drop I_bR_L across it. Consequently, the plate potential will be less than the supply voltage. For any given plate current I_b, the plate voltage is :

$$E_b = E_{bb} - I_b R_L \quad ...(i)$$

If the grid voltage changes, plate current I_b also changes which in turn varies the plate voltage E_b. Hence, while drawing the dynamic characteristics, the effect of load in the plate circuit must be taken into account.

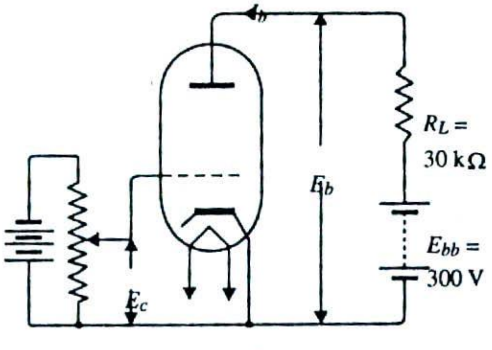


Fig. 3.13

1. Dynamic plate characteristics. When load R_L is connected in the plate circuit, the relation between E_b and I_b is given by the equation :

$$E_b = E_{bb} - I_b R_L$$

As E_{bb} and R_L are fixed values, therefore, it is a first degree equation and hence can be represented by a straight line on the static plate characteristics. This line is known as *load line* and determines the $E_b - I_b$ points for any given value of plate load. *Therefore, combination of static plate characteristics and load line is the dynamic plate characteristics of triode.*

To add load line to the static plate characteristics, we need only two points. These two points can be located as under :

(*i*) *Maximum E_b point.* When plate current $I_b = 0$, then from eq. (*i*), $E_b = E_{bb}$ (= 300 V in this case). This gives the first point *B* on the voltage axis corresponding to $E_b = E_{bb}$.

(*ii*) *Maximum I_b point.* When plate voltage E_b is zero, then from eq. (*i*), we get,

$$0 = E_{bb} - I_b R_L$$

$$\therefore \quad \text{Max. } I_b = \frac{E_{bb}}{R_L} = \frac{300 \text{ V}}{30 \text{ k}\Omega} = 10 \text{ mA}$$

This gives the second point *A* on the plate current axis. By joining these two points, the load line *AB* is constructed (See Fig. 3.14).

With the construction of load line on the static plate characteristics, we get the dynamic plate characteristics. These characteristics indicate the operating conditions of triode. Thus, if it is desired to find the plate current and plate voltage at a grid voltage $E_c = -2$ V, then the intersection of load line *AB* to − 2 V characteristic (point *C*) will give the desired results—E_b on *X*-axis and I_b on *Y*-axis.

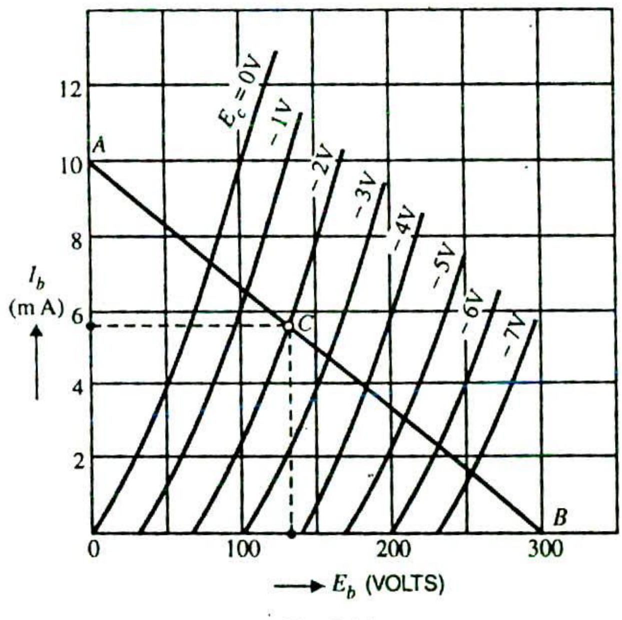


Fig. 3.14

2. Dynamic mutual characteristic. It may appear that by adding load line to the static mutual characteristic, we shall get dynamic mutual characteristic. But this is *not true* since mutual dynamic characteristic is not a straight line. The simple method is to use the static plate characteristics with the load line added and pick off the plate current values corresponding to various grid voltages as shown in Fig. 3.15.

The steps in the construction of mutual dynamic characteristic are :

(*i*) Draw the load line for the given supply voltage and load resistance on the static plate characteristics as shown in Fig. 3.15 (*ii*).

(*ii*) At each point of intersection of load line with E_c, transfer this point as indicated by the direction of arrows.

(*iii*) Join these points through a suitable curve as shown in Fig. 3.15 (*i*). This gives the dynamic mutual characteristic.

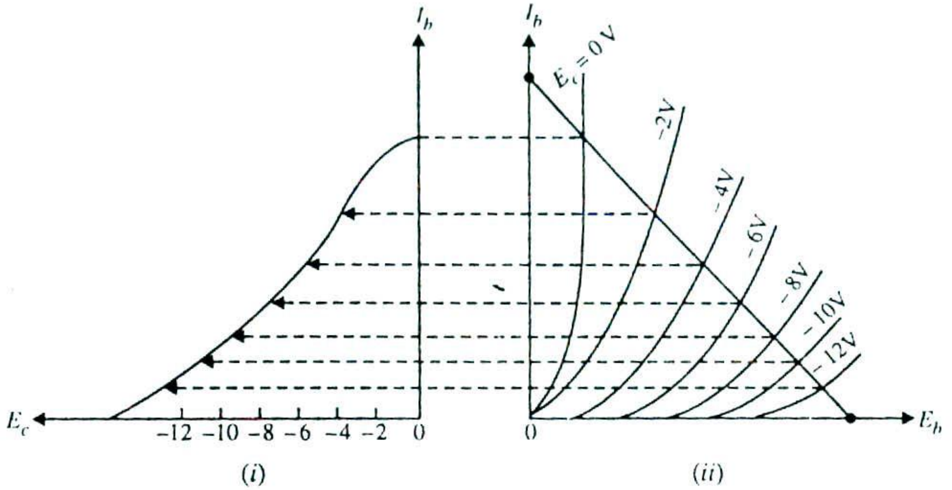


Fig. 3.15

3.12 Applications of triode

The main application of a triode is that it raises the strength of a weak signal and thus acts as an *amplifier*. The weak signal is applied in the grid circuit and amplified output is taken from the plate circuit. Fig. 3.16 shows the circuit of a basic triode amplifier. We have already seen that grid has much more influence on the plate current as compared to the plate itself. When a load resistance R_L is placed in series with the plate circuit, the voltage drop produced across the resistance is a function of plate current and hence, is controlled by the grid voltage. Thus, a small change in the grid voltage (or signal) can cause a large change in plate current and hence voltage available across R_L will be much more than the grid voltage. In other words, the signal voltage applied in the grid circuit appears in the amplified form in the plate circuit of the valve. It may be noted that grid being **always* maintained at negative potential *w.r.t.* cathode, the amplification takes place without any current or power consumption in the grid circuit.

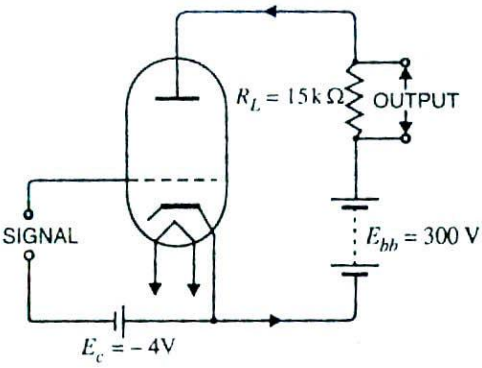


Fig. 3.16

Suppose the triode under discussion has $g_m = 1500\ \mu$ mho and $R_L = 15\ k\Omega$. If a signal of 1 volt is applied at the grid, it will give a plate current of 1 V × 1500 μ mho = 1.5 mA

$$\therefore \quad \text{Output voltage} = \text{plate current} \times R_L$$
$$= 1.5\ \text{mA} \times 15\ k\Omega = 22.5\ \text{V}$$

Thus a small signal of 1 V applied in the grid circuit appears as 22.5 V in the plate circuit. In this way, the triode has been able to raise the voltage level of the signal from 1 V to 22.5 V *i.e.* by a factor

* The grid is always maintained at negative potential w.r.t. cathode. In order that grid may not be driven positive during positive half cycle of signal, a battery E_c is connected in the grid circuit as shown in Fig. 3.16. This will be further explained in the chapter on vacuum tube amplifiers.

of 22.5. Hence triode acts as amplifier. The detailed discussion regarding amplifiers shall appear in chapter 4.

3.13 Limitations of Triode

The invention of triode by De Forest opened such vast new fields that for many years electronics engineers were busily engaged in exploring its possibilities. However, when it was used as an amplifier, it presented two serious drawbacks namely ; *interelectrode capacitance* and *insufficient amplification.*

(*i*) **Interelectrode capacitance.** Capacitance exists between any two conducting surfaces separated by an insulating medium. As triode electrodes are made of metals and evacuated space between any two of them presents insulation, therefore, capacitance must exist between grid and cathode (C_{gk}), grid and plate (C_{pg}) and plate and cathode (C_{pk}). These capacitances are called *interelectrode capacitances* (See Fig. 3.17). Interelectrode capacitances are quite small, ranging from 2 to 12 picofarads.

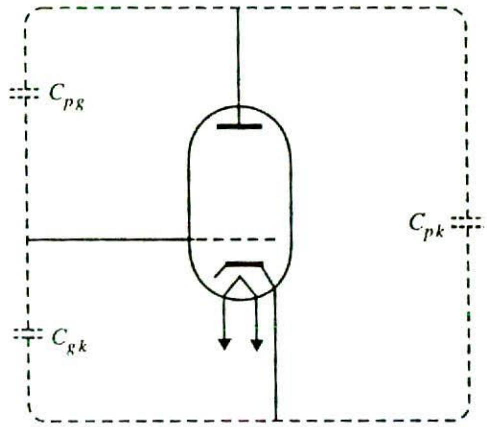


Fig. 3.17

At low frequencies, their effects are quite negligible. *However, at high frequencies, particularly plate to grid capacitance C_{pg} introduces serious complications.*

$$\text{Plate-grid reactance, } X_{C_{pg}} = \frac{1}{C_{pg} \cdot \omega} = \frac{1}{2\pi f . C_{pg}}$$

The plate to grid capacitance C_{pg}, especially has the property of feeding back energy from the plate circuit (*output*) to the grid circuit (*input*). At high frequencies, the value of $X_{C_{pg}}$ is quite low so that a part of the plate energy will be fed back to the grid circuit through C_{pg}. This capacitive feedback is negative and reduces the amplification at high frequencies. It is due to this reason that triodes are generally used for amplifying low frequency [< 20 kHz] signals.

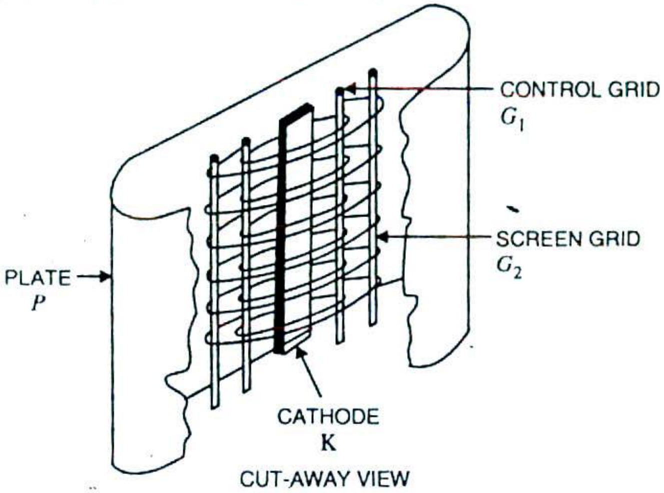
(*ii*) **Insufficient amplification.** The amplification factor of a triode is generally small and does not exceed 100. The amplification factor μ of a valve can be high if the effect of control grid on plate current is quite large as compared to that of plate. But this is not so in case of triode due to insufficient shielding between plate and cathode. The control grid which is to provide the necessary shielding allows a part of electric field to penetrate through it.

However, if control grid is to be made more effective in controlling the plate current, the electric field from plate to cathode should be shielded as effectively as possible. This can be achieved by having a control grid with very finely spaced spiral. But there is a limit to it since in a very finely spaced spiral grid, the electrons will encounter difficulty in passing through the grid openings and consequently, the plate current will be reduced. *This puts a limit to the effectiveness of control grid.* Therefore, amplification factor of a triode is low.

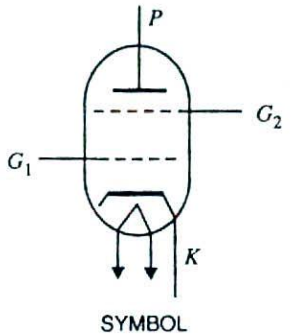
3.14 Tetrode Valve

Although triode can make amplification, it presents the major limitation that plate-to-grid capacitance (C_{pg}) causes feedback particularly at higher frequencies. The plate-to-grid capacitance of a triode can be reduced by inserting an additional grid, called the *screen grid*, between control grid and plate. Such a four-electrode valve is known as *tetrode.*

Construction. The tetrode is a four-electrode valve. It contains a *plate, cathode, control grid* G_1 *and screen grid* G_2. The construction of screen grid is somewhat similar to control grid and is placed between plate and control grid. The screen grid is operated at fixed positive potential w.r.t. cathode, but somewhat lower than the plate voltage. The cut-away sketch and symbol of tetrode are shown in Figs. 3.18 (*i*) and 3.18 (*ii*) respectively.



(*i*)



(*ii*)

Fig. 3.18

The main purpose of screen grid is to screen or shield the plate from the control grid in order to reduce plate-to-grid capacitance. This can be easily understood by referring to Fig. 3.19. With the addition of screen grid, capacitance exists between plate and screen grid (C_1) and between screen grid and control grid (C_2). These two capacitances are in series and, therefore, the total capacitance between plate and control grid is reduced. It has been found that plate to grid capacitance in a tetrode is reduced to about 0.01 pF. This reduced C_{pg} nearly eliminates all the capacitive feedback from plate circuit to grid circuit.

Operation. The working of tetrode is similar to triode with the additional action of screen grid. Like triode, control grid in a tetrode is placed at a small negative potential while the plate is at a fairly positive potential w.r.t. cathode. The screen grid is also kept at positive *potential *w.r.t.* cathode but somewhat lower than plate voltage.

When cathode is heated, it emits electrons by thermionic emission. The path for emitted electrons inside the tube is from the cathode, through the control grid, and through the spaces in the screen grid to be collected by the plate. Most of the emitted electrons reach the plate, forming a plate current flow. However, some electrons are attracted by the screen grid to constitute screen grid current. Therefore, in a tetrode, the cathode emission produces a *screen grid current* as

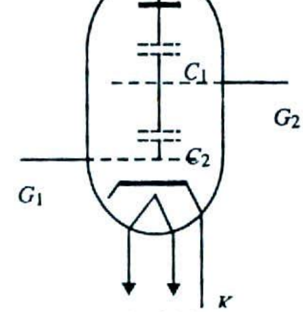


Fig. 3.19

* If the screen grid is connected to cathode, the purpose of reducing plate to grid capacitance is served but it introduces another undesirable effect. As cathode is at negative potential w.r.t. plate, therefore, screen will also be negative w.r.t. plate. The result would be that flow of electrons from cathode to plate would be retarded due to repulsion of screen grid. This difficulty is overcome by making the screen grid positive w.r.t. cathode -

well as plate current. Although screen grid current serves no useful purpose, it is only a small part of the total emission current.

As the screen grid acts as an *electrostatic shield* between the plate and control grid, therefore, change in plate voltage has little effect on the magnitude of plate current. On the other hand, the control grid retains control over the plate current. Thus, the addition of screen grid makes the plate voltage less effective in controlling the plate current without affecting the effectiveness of the control grid. In other words, amplification factor is increased.

3.15 Tetrode Characteristics

Characteristic curves of a tetrode can be obtained in the same manner as were obtained for a triode. However, more significant for tetrode's performance is the *plate characteristics*. The plate characteristic of a tetrode gives the relationship between plate current (I_b) and the plate voltage (E_b) at constant grid voltage and at some fixed screen grid voltage. The circuit diagram for the determination of plate characteristics of a tetrode is shown in Fig. 3.20.

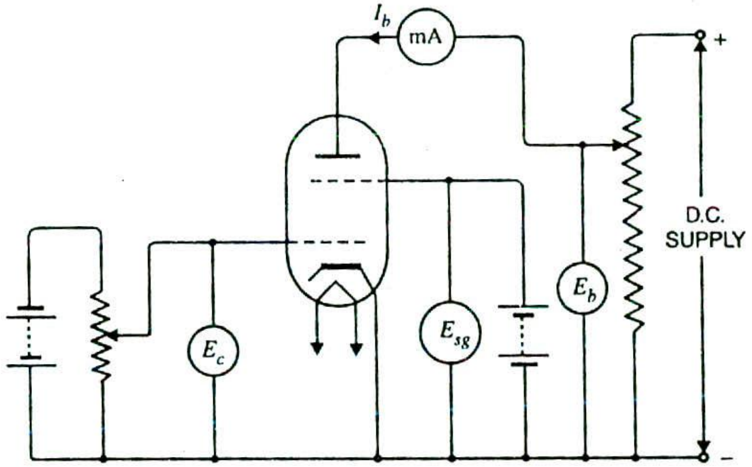


Fig. 3.20

With the control grid voltage held constant, say – 2 V and the screen grid voltage held constant at some positive value (say E_{sg} = 100 V), the plate voltage is varied from zero to maximum. Corresponding to each value of plate voltage, the plate current is noted. The variations in plate current with plate potential are then plotted on a graph. This gives the plate characteristic of tetrode at $E_c = -2$ V and screen grid voltage = 100 V.

The experiment is repeated with $E_c = -4$ V and $E_c = -6$ V etc. Thus a family of plate characteristics is obtained as shown in Fig. 3.21. It may be noted that this family of plate characteristics of tetrode is valid only for screen voltage chosen *i.e.* 100 V in this case. If the plate characteristics for any other screen grid voltage are desired, a new family of curves may be obtained by keeping the screen grid voltage fixed at the new value.

The following points may be noted from the tetrode characteristics :

(*i*) **Portion ab :** For the portion *ab* of the characteristic, the plate current increases with the increase in plate voltage. Although during this portion, plate voltage is less than screen grid voltage, yet most of the electrons manage to reach the plate. This results in the increase in plate current.

(*ii*) **Portion bc :** For the portion *bc* of the curve, the plate current decreases with the increase in plate voltage. The decrease in plate current (*i.e.* dip in the curve) is due to the phenomenon known as *secondary emission*. Although even now plate potential is less than screen grid potential, the electrons are speeded up sufficiently to cause electron emission from the plate material itself. The emitted electrons are called secondary electrons and the process is known as secondary emission. These secondary electrons are immediately attracted by the screen grid because its voltage is more positive than that of the plate. As the secondary electrons flow in opposite direction to plate current, therefore, plate current is *reduced. *This explains why during the portion bc of the curve, the plate current decreases though plate potential is increasing.* This region where an increase in plate voltage causes a decrease in plate current is known as *negative resistance region.* This behaviour of tetrode leads to undesirable effects during amplification.

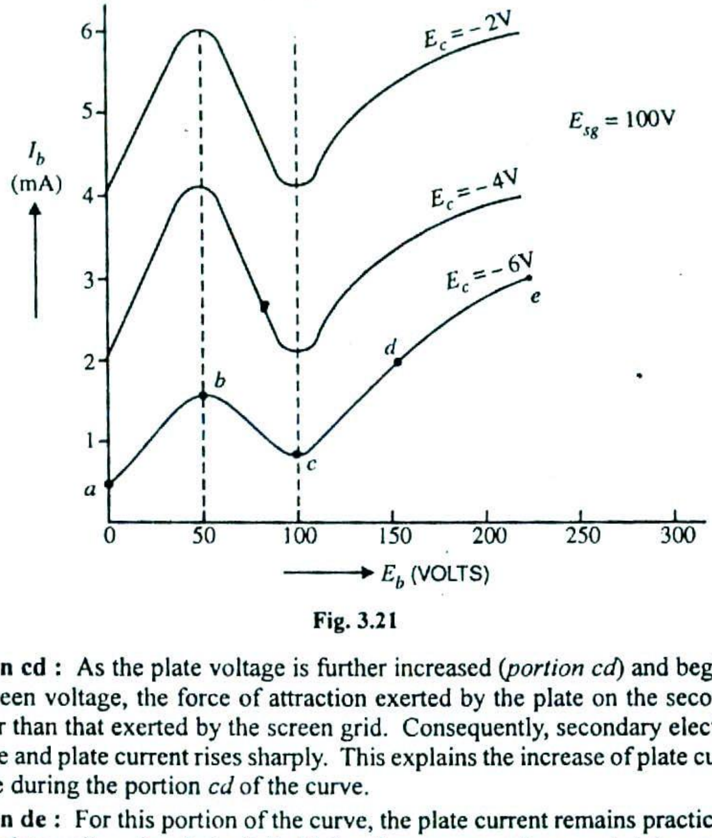


Fig. 3.21

(*iii*) **Portion cd :** As the plate voltage is further increased (*portion cd*) and begins to approach the value of screen voltage, the force of attraction exerted by the plate on the secondary electrons becomes greater than that exerted by the screen grid. Consequently, secondary electrons are pulled back by the plate and plate current rises sharply. This explains the increase of plate current with plate voltage increase during the portion *cd* of the curve.

(*iv*) **Portion de :** For this portion of the curve, the plate current remains practically constant. It is because now plate voltage is substantially higher than screen voltage and plate practically collects all the electrons from the cathode.

3.16 Tetrode Constants

Tetrode constants have the same meaning as for triodes. However, their values are different from that of a triode due to the presence of screen grid. We shall now consider each tetrode constant in turn.

(*i*) **a.c. plate resistance (r_p).** Because of the shielding effect of screen grid, plate voltage has little effect on plate current. Consequently, a much greater change in plate voltage is required to produce the same change in plate current *than* would be necessary in a triode. Therefore, the a.c. plate resistance ($\Delta E_b / \Delta I_b$) of a tetrode is much greater than that of a triode. The tetrode resistance is of the order of 70 kΩ to 100 kΩ.

* The secondary emission also takes place in the triode, but since the plate in a triode is the only positive electrode, the secondary electrons are attracted back by the plate.

(*ii*) **Amplification factor** (μ). It has already been discussed that control grid of a tetrode has about the same effect in controlling the plate current as in a triode. But in a tetrode, the plate potential has very little effect on plate current as compared to triode. Clearly, the amplification factor ($\Delta E_b / \Delta E_c$) of a tetrode will be higher than that of a triode. The amplification factor of a tetrode is about 500 compared to a triode whose μ varies from 10 to 100.

(*iii*) **Transconductance** (g_m). The transconductance is given by $g_m = \mu / r_p$. Although the μ of a tetrode is high, the r_p is also extremely high. The increase in amplification factor for the tetrode is offset by the greater increase in plate resistance. Consequently, the mutual conductance of a tetrode is *slightly* less than for a triode. The usual value of tetrode transconductance is of the order of 1000 to 1500 μmho, which is about the same as for a triode.

3.17 Limitation of Tetrode

The disadvantage of a tetrode is the reduction of plate current due to secondary emission. In normal operation, with an a.c. signal applied to the grid circuit, the plate voltage of tetrode varies from instant to instant. As the screen grid voltage is likely to be greater than plate voltage during some *part of a.c. signal, the secondary electrons are attracted by the screen. Thus a current opposite to plate current starts flowing in the tetrode as shown in Fig. 3.22. This reduces the plate current.

The phenomenon of reduction of plate current in a tetrode due to secondary emission is known as ****dynatron effect.**

The dip in E_b/I_b characteristic of a tetrode is due to dynatron effect. The result is that tetrode operation is limited to a small portion of E_b/I_b curve. In this region, a high supply voltage is necessary to prevent secondary emission. For this reason, tetrode is obsolete these days and has been replaced by pentode.

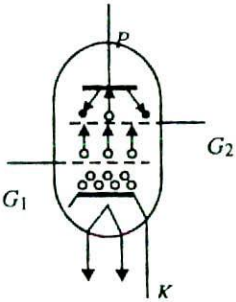


Fig. 3.22

Example 3.5. *A tetrode vacuum tube is operated in a circuit for the type shown in Fig. 3.23 and has the following values :*

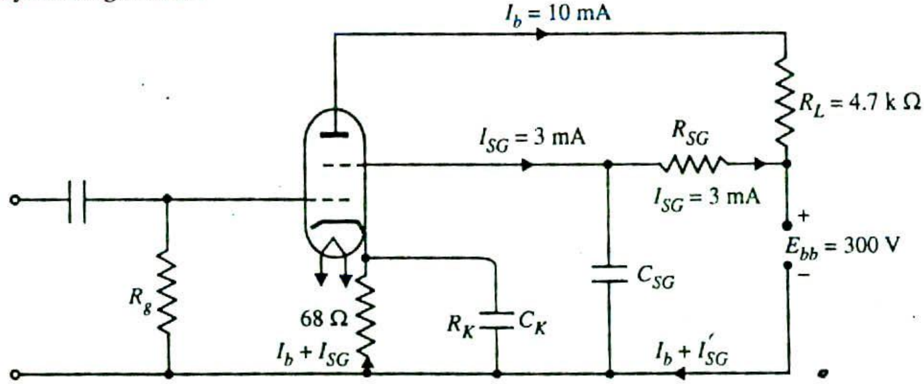


Fig. 3.23

* This does happen in an actual tetrode during the positive half-cycle of the signal when a large plate current is flowing. This large current results in a big voltage drop across load R_L and consequently plate voltage is reduced to a low value. But screen grid voltage is generally kept high (200 V as compared to E_{bb} = 300 V) in order that it may attract sufficient number of electrons for plate, thus increasing μ and r_p. Hence, plate voltage falls below screen grid voltage during most part of the positive half-cycle of the signal.

** Since the plate acts here as a source of electrons, the region is known as dynatron region.

$E_{bb} = 300\ V$; $R_L = 4.7\ k\Omega$; $R_K = 68\ \Omega$

$I_b = 10\ mA$; $I_{sg} = 3\ mA$

(i) Explain the function of R_{SG} *and* C_{SG}.

(ii) What is the zero signal plate-cathode voltage?

(iii) What is grid-cathode bias ?

(iv) If the screen voltage is to be 150V, what value of screen dropping resistor R_{SG} *will be required ?*

Solution.

(*i*) In actual practice, the desired d.c. operating voltage for the screen grid is obtained from the plate supply voltage E_{bb} with the help of resistor R_{SG}. The screen grid is connected to the plate supply through the resistance R_{SG}. By having a suitable value of R_{SG}, the desired positive potential can be obtained on the screen grid. The capacitor C_{SG} is connected from the screen to the ground to provide the a.c. grounding for the screen.

(*ii*) Zero signal plate - cathode voltage

$$= E_{bb} - I_b R_L = 300 - 10\ \text{mA} \times 4.7\ \text{k}\Omega$$
$$= 300 - 47 = \mathbf{253\ V}$$

(*iii*) The current flowing through cathode resistance R_K is $(I_b + I_{SG})$.

$$\therefore \quad \text{grid - cathode bias} = -R_K (I_b + I_{SG}) = -68\ (13\ \text{mA})$$
$$= -68 \times (13 \times 10^{-3}\ \text{A}) = \mathbf{-0.884\ V}$$

(*iv*) Plate supply voltage = Screen grid voltage + drop in R_{SG}

or $$E_{bb} = V_{SG} + I_{SG} R_{SG}$$

or $$R_{SG} = \frac{E_{bb} - V_{SG}}{I_{SG}} = \frac{300 - 150}{3\ \text{mA}} = \frac{150\ \text{V}}{3\ \text{mA}} = \mathbf{50\ k\Omega}$$

3.18 Pentode Valve

In order to eliminate the undesirable effects of secondary emission, an additional grid, called *suppressor grid*, is inserted inbetween the plate and screen grid of tetrode. This gives the five-electrode valve, called *Pentode*. Thus, a pentode contains a cathode, a plate and three grids. The grid closest to the cathode is the control grid G_1, and next is the screen grid G_2 and the third is supressor grid G_3. The suppressor grid is connected to the cathode and serves to suppress the effects of secondary emission. Fig. 3.24 (*i*) shows the physical construction of pentode whereas Fig. 3.24 (*ii*) shows its symbol.

Action of suppressor grid. The working of pentode is similar to tetrode with the additional action of suppressor grid. The suppressor grid performs the following functions :

(*i*) *Suppresses secondary emission effects.* As the suppressor grid is connected to the cathode, therefore, it is at substantial negative potential *w.r.t.* plate. The electrons from cathode still produce secondary emission as they hit the plate with high speeds. But now the secondary electrons are no longer attracted to the screen grid. As soon as the secondary electrons are emitted by the plate, they are repelled back by the negative suppressor grid. Thus the effects of secondary emission are *suppressed and the 'dip' in the plate characteristic of tetrode is eliminated.

(*ii*) *Increases amplification factor.* The presence of suppressor grid provides further shielding

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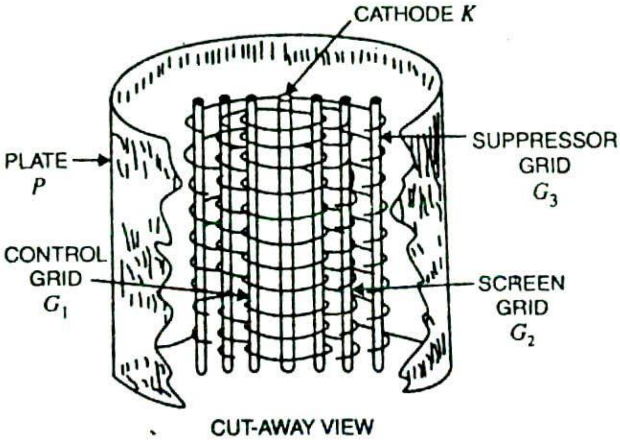
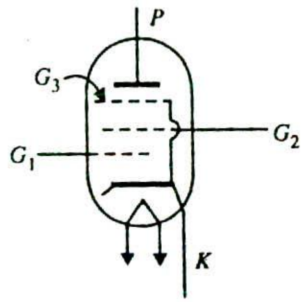
* The reader may note that suppressor grid does not prevent secondary emission by the plate. Rather it eliminates the effects of secondary emission.

between plate and control grid. This puts the control grid in a more commanding position and hence amplification factor is increased.



(*i*)



(*ii*)

Fig. 3.24

(*iii*) *Reduces* C_{gp}. The suppressor grid further reduces grid to plate capacitance. This completely eliminates the feedback action.

3.19 Pentode Characteristics

The plate characteristics of a pentode can be obtained by using the same circuit as for tetrode. Fig. 3.25 shows a family of plate characteristics of a typical pentode.

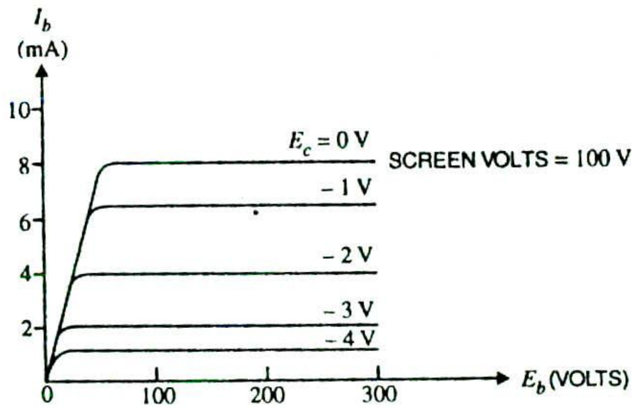


Fig. 3.25

The following points may be noted from the pentode characteristics :

(*i*) Over the major portion of the characteristics, plate current is largely independent of plate voltage changes. Therefore, pentode may be thought as a *constant current device*. A pentode is generally operated in this region.

(*ii*) The *dip* found in the plate characteristics of tetrode is eliminated in the pentode plate characteristics.

(*iii*) The characteristics are non-linear below the knee of the curve.

Pentode constants. Due to additional shielding action of suppressor grid, the plate potential in a pentode has even less effect on the plate current than in a tetrode. Therefore, a pentode has higher amplification factor and plate resistance than a tetrode. Again because of extremely high amplification factor and plate resistance, the g_m which is the ratio of the two, is comparable in value to both the triode and tetrode. Typical values of pentode constants are :

Amplification factor, 1000 to 5000

Plate resistance, 0.5 to 2 MΩ

Transconductance, 1000 to 9000 μ mho

3.20 Comparison of Valve Constants

Below is given the comparison of valve constants of triode, tetrode and pentode for facility of reference.

S.No.	Particular	Triode	Tetrode	Pentode
1	Amplification factor (μ)	10 to 100	Range around 500	1000 to 5000
2	Plate resistance (r_p)	3000 Ω to 1000 kΩ	70 to 1000 kΩ	0.5 to 2 MΩ
3	Transconductance (g_m)	About 2500 μ mho	About 1000 μ mho	1000 to 9000 μ mho

3.21 Limitations in the Operating Conditions of Tubes

The vacuum tubes discussed so far shall give satisfactory performance in a circuit if they are operated under proper conditions. Any deviation may result in the damage of the tube. Therefore, the tube manufacturers publish manuals indicating the limitations in the operating conditions of tubes. The important ones are *peak inverse voltage, maximum plate current* and *maximum plate dissipation.*

(*i*) **Peak inverse voltage.** In the normal situation, the plate of a tube is positive *w.r.t.* cathode and current flows from cathode to plate. However, if the tube is supplied with small reverse potential (*i.e.* plate is negative and cathode is positive), normally no current will flow. As the reverse potential is increased, a stage may reach when the electric field becomes strong enough to *tear* electrons out of the cold plate. As a result, current starts flowing in the reverse direction *i.e.* from plate to cathode. This is undesirable and may damage the tube or other circuit elements. *The maximum reverse voltage that can be applied across the tube without conduction in the reverse direction is known as* **peak inverse voltage.**

The peak inverse voltage is always specified in tube manuals. Care should be taken that this rating is never exceeded in a tube.

(*ii*) **Maximum plate current.** It is the highest instantaneous plate current that a tube can safely carry without damage to the cathode and without undue voltage drop in the tube. This value is also listed in tube manuals by the manufacturers.

(*iii*) **Maximum plate dissipation.** It is maximum power that a tube can handle without overheating. During the tube operation, electrons from cathode bombard the plate. The kinetic energy of these electrons is converted into heat, thus raising the temperature of plate structure. If the heat is produced faster than the plate can dissipate it, the temperature will rise to such a point as to either melt the plate or cause electron emission from the plate. Therefore, heat produced must be dissipated in order to keep the plate temperature within safe limits.

3.22 Why Current in Vacuum ?

The reader must have noted that there are two advantages in using a vacuum tube to provide current.

(*i*) The emitted electrons can flow only in one direction from cathode to anode inside the tube.

In other words, current will flow only when anode is positive *w.r.t.* cathode. Hence when an alternating voltage is applied between anode and cathode, the current will flow only during the half cycles which make anode positive *w.r.t.* cathode. As a result, the tube can serve as a rectifier, changing alternating current to direct current.

(*ii*) The amount of plate current can be effectively controlled by the control grid. A small change in grid potential produces a very large change in plate current. Therefore, the tube can be used as an amplifier to raise the strength of a weak signal.

The above conditions cannot be realised if current flows through a wire.

3.23 Causes of Tube Failure

A vacuum tube is basically a low-current device as the electron flow is limited by the amount of thermionic emission from the cathode. Most of vacuum tubes carry less than 100 mA. There are several reasons why vacuum tubes become defective. Some of the more common reasons are :

(*i*) **Filament Failure.** Filament wires gradually lose molecules, weaken at one point and burn out. Too much filamant current may also burn out the wire. The open filament can be checked with an ohmmeter, with power off.

(*ii*) **Tube becomes gassy.** If the envelope leaks, air is drawn into the tube. The internal elements give off gas when overheated by excessive current.

(*iii*) **Loose elements.** When elements are not welded properly, they vibrate, causing opens or short circuits in the tubes.

Multiple-Choice Questions

1. The two principal electrodes present in every vacuum tube are ....
   (*i*) plate and grid
   (*ii*) plate and cathode
   (*iii*) cathode and grid
   (*iv*) none of the above

2. A vacuum diode can be used as a ....
   (*i*) rectifier (*ii*) amplifier
   (*iii*) oscillator (*iv*) none of the above

3. The plate current in a vacuum diode depends upon ....
   (*i*) cathode temperature only
   (*ii*) plate voltage only
   (*iii*) both plate voltage and cathode temperature
   (*iv*) none of the above

4. The control grid in a triode is ....
   (*i*) very near to plate
   (*ii*) very near to cathode
   (*iii*) mid-way between plate and cathode
   (*iv*) none of the above

5. A pentode is essentially .... device.
   (*i*) a constant current
   (*ii*) a constant voltage
   (*iii*) neither constant voltage nor constant current
   (*iv*) data incomplete

6. The internal resistance of a tube is mainly due to ....
   (*i*) space charge (*ii*) vacuum
   (*iii*) plate potential (*iv*) none of the above

7. More noise is generated in a pentode than in a triode due to the presence of ....
   (*i*) space charge (*ii*) heater
   (*iii*) more number of electrodes
   (*iv*) none of the above

8. The grid-to-plate capacitance is least in .... valve.
   (*i*) triode (*ii*) tetrode
   (*iii*) pentode (*iv*) none of the above

9. The negative resistance characteristic of a tetrode is due to ....
   (*i*) secondary emission

(ii) plate being positive w.r.t. cathode

(iii) control grid being negative w.r.t. cathode

(iv) none of the above

10. A triode is normally operated with control grid at .... potential w.r.t. cathode.

(i) positive (ii) zero

(iii) high positive (iv) negative

11. The screen grid potential is kept .... plate potential.

(i) somewhat higher than

(ii) somewhat lower than

(iii) same as

(iv) at zero potential w.r.t.

12. The voltage on the suppressor grid of a pentode is generally ....

(i) positive w.r.t. cathode

(ii) zero w.r.t. cathode

(iii) negative w.r.t. cathode

(iv) none of the above

13. The unit of transconductance is ....

(i) ohm (ii) volt

(iii) mho/m (iv) mho

14. The tube whose plate characteristics resemble with the output characteristics of a transistor is ....

(i) triode valve (ii) tetrode valve

(iii) pentode valve (iv) diode valve

15. A vacuum tube will conduct only if its plate is .... w.r.t. cathode.

(i) positive (ii) negative

(iii) at zero potential

(iv) none of the above

16. For a given plate voltage, if negative potential on the control grid of a triode is increased, the plate current ....

(i) increases (ii) decreases

(iii) remains the same

(iv) cannot say

17. A hard tube is defined as a tube with ....

(i) a tungsten filament

(ii) a metal envelope

(iii) a gas in the envelope

(iv) no gas in the envelope

18. For proper high frequency amplification, we use ....

(i) triode (ii) tetrode

(iii) pentode (iv) none of the above

19. The real measure of valve's amplification capability is its ....

(i) transconductance

(ii) plate resistance

(iii) amplification factor

(iv) none of the above

20. The transconductance of a pentode is .... that of a triode.

(i) more than (ii) less than

(iii) same as (iv) none of the above

21. What will be the transconductance of a tube having $\mu = 20$ and $r_p = 8000\ \Omega$?

(i) 1400 μ mho (ii) 2500 μ mho

(iii) 800 μ mho (iv) none of the above

22. If a 20 V change in plate voltage of a triode brings about 2 mA change in plate current at constant grid voltage, then a.c. plate resistance of the triode is ....

(i) 5 kΩ (ii) 20 kΩ

(iii) 2 kΩ (iv) 10 kΩ

23. The transconductance of a tube is 3 mA/volt. What is its value in micromhos ?

(i) 3000 μ mho (ii) 6000 μ mho

(iii) 1333 μ mho (iv) none of the above

24. The values of μ and r_p of a tube are increased two-fold. The change in its transconductance will be ....

(i) four-fold (ii) three-fold

(iii) no change (iv) eight-fold

25. What is the amplification factor of a triode if its plate resistance is 15 kΩ and transconductance is 4000 μ mho ?

(i) 30 (ii) 60

(iii) 90 (iv) 180

Answers to Multiple-Choice Questions

1. (ii)	2. (i)	3. (iii)	4. (ii)	5. (i)
6. (i)	7. (iii)	8. (iii)	9. (i)	10. (iv)
11. (ii)	12. (ii)	13. (iv)	14. (iii)	15. (i)
16. (ii)	17. (iv)	18. (iii)	19. (i)	20. (iii)
21. (ii)	22. (iv)	23. (i)	24. (iii)	25. (ii)

Chapter Review Topics

1. Explain the construction and working of a vacuum diode.
2. Explain the formation of space charge. What is the effect of cathode temperature on space charge ?
3. Give the procedure for determining the plate characteristics of a vacuum diode. What inferences you draw from these characteristics ?
4. Explain the terms d.c. plate resistance and a.c. plate resistance of a vacuum tube.
5. Describe the construction and working of a vacuum triode.
6. Give the procedure of determining the static plate characteristics and mutual characteristics of a vacuum triode. What inferences do you draw from these curves ?
7. Define plate resistance, transconductance and amplification factor of a triode and establish the relationship among them.
8. How will you obtain dynamic plate characteristics of a triode ?
9. Discuss the limitations of triode.
10. Explain the construction and working of (*i*) tetrode valve (*ii*) pentode valve.

Problems

1. A triode passes a plate current of 4.5 mA at a plate voltage of 300 V and grid voltage of – 10 V. If the plate voltage is reduced to 250 V but grid voltage increased to – 7.5 V, the plate current remains unchanged. Find the amplification factor of triode. **[20]**
2. If a triode has mutual conductance of 1.5 mA/V and anode slope resistance of 12 kΩ, calculate the amplification factor. **[18]**
3. A triode passes a plate current of 10 mA at $E_b = 200$ V, $E_c = 0$ V. If $E_c = -4$ V, $E_b = 100$ V, then $I_b =$ 5 mA. Find (*i*) plate resistance (*ii*) amplification factor (*iii*) mutual conductance. **[(*i*) 20 k Ω (*ii*) 25 (*iii*) 1250 μ mho]**
4. Two plate characteristics for a triode are obtained from the following data :

Grid Voltage = 0

Plate voltage (*volts*)	0	25	50	75	100	125
Plate current (*mA*)	0	2.5	5.4	8.8	12.8	17.4

Grid Voltage = – 4 V

Plate voltage (*volts*)	45	75	100	125	150
Plate current (*mA*)	0	1.5	4.0	6.9	10.3

Draw the characteristics and find the values of three valve constants.

[g_m = 2.2 mA/V, μ = 16, r_p = 7.25 k Ω]

5. A triode passes a plate current of 5 mA at plate voltage of 150 V and grid voltage of – 2 V. If the grid voltage is changed to – 3.5V, the plate current drops to 3.2 mA but can be restored to 5 mA by increasing plate voltage to 195 V. Calculate (*i*) mutual conductance (*ii*) a.c. plate resistance and (*iii*) amplification factor. **[(*i*) 1200 μmho (*ii*) 25 kΩ (*iii*) 30]**

Discussion Questions

1. Why is vacuum tube used to provide current ?
2. Why is vacuum diode operated in the space charge limited region ?
3. Why is a.c. plate resistance of a vacuum tube more significant than d.c. plate resistance ?
4. Why is control grid of a tube always held at negative potential ?
5. Why secondary emission effects introduce complications in tetrode and not in triode and pentode?
6. Why has a pentode a higher amplification factor and a higher plate resistance than a tetrode or triode?
7. Why transconductance has about the same value in triode, tetrode and pentode ?
8. Why is transconductance a real measure of valve's amplification capability ?

4

Vacuum Tube Rectifiers

Introduction

The electric power is almost exclusively generated, transmitted and distributed in the form of alternating current as an economical proposition. However, for many applications, we require d.c. supply. For example, for the successful operation of all electron tubes and semiconductor devices, d.c. supply is needed. Batteries cannot be used for the purpose as they are costly and require frequent replacement. Therefore, it is necessary to convert available a.c. supply into the required d.c. supply. This is achieved by an electronic device known as *rectifier*.

Though conversion of a.c. into d.c. can be accomplished by mechanical devices such as motor-generator sets, rotary converters *etc.*, yet rectifiers are mostly used for this purpose due to their simplicity, cheapness, efficiency, longer life and noiseless operation. In this chapter, we shall deal with vacuum tube rectifiers and their increasing applications in electronic equipment.

4.1 Rectifier

An electronic device that converts alternating current into direct current is called a **rectifier.**

A rectifier changes a.c. into d.c. by eliminating the negative half-cycles of the alternating voltage. It may be thought of as a *switch* that closes a load circuit during the positive half-cycle of a.c. supply and opens the circuit during the negative half-cycle. Therefore, a rectifier provides one-way path for electric current *i.e.* conduction takes place in one direction only. It is in this way that a rectifier converts an alternating current into unidirectional current.

4.2 Vacuum Diode as Rectifier

It has already been discussed that when the plate of a diode is positive w.r.t. cathode, current flows in the plate circuit whereas no current flows when plate is negative w.r.t. cathode. This unidirectional characteristic of diode permits it to be used as a rectifier. Although there is no switch in a diode, yet it behaves in a quite similar way.

Fig. 4.1 shows the action of a vacuum diode as a rectifier. During the positive half-cycle of a.c. supply, plate is positive *w.r.t.* cathode [See Fig. 4.1 (*i*)] and diode conducts current in the circuit. This corresponds to the closure of switch. However, during the negative half-cycle of a.c. supply, plate is negative *w.r.t.* cathode [See Fig. 4.1 (*ii*)] and hence no current conduction takes place. This corresponds to the opening of the switch. The result of this action of diode is that current always flows in one direction in the load. As a matter of fact, the characteristic of diode to conduct current in one direction renders it suitable to be used as a rectifier.

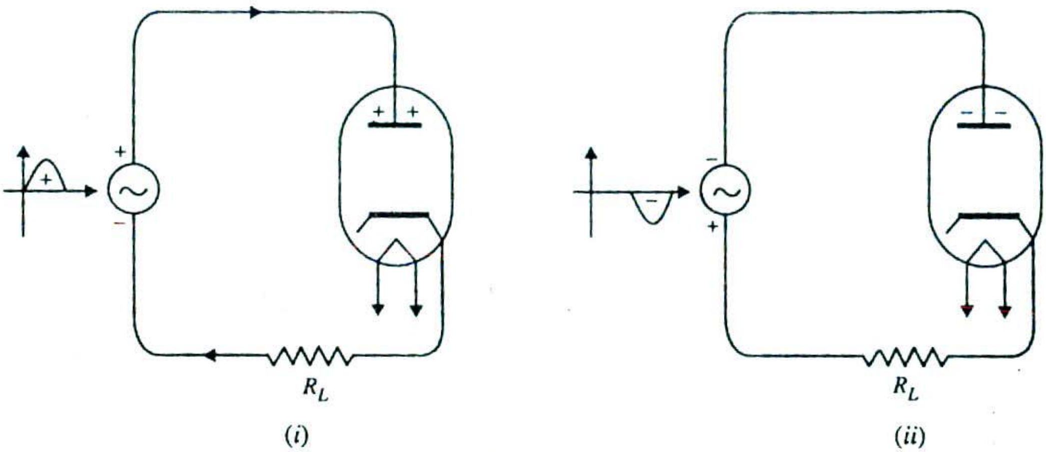


Fig. 4.1

4.3 Single-Phase Vacuum Tube Rectifiers

Broadly, single-phase vacuum tube rectifiers may be classified into two categories *viz.* *half-wave rectifier* and *full-wave rectifier*. A half-wave rectifier conducts only on the positive half-cycles of input a.c. voltage *i.e.* it uses one half-cycle of a.c. input voltage to produce d.c. output. On the other hand, a full-wave rectifier conducts on both half-cycles (*positive* and *negative*) of a.c. input i.e. it uses both half-cycles of input a.c. voltage to produce d.c. output. Obviously, a full-wave rectifier circuit can supply more d.c. output power than the equivalent half-wave rectifier.

Before discussing the various rectifier circuits, the reader may keep the following points in mind :

(*i*) The available a.c. supply has a nominal phase voltage of 230V r.m.s. and frequency 50Hz.

(*ii*) Usually, a.c. supply to be rectified is supplied through a transformer for two reasons. Firstly, a transformer allows us to step up or down the a.c. voltage. Secondly, it isolates the rectifier circuit from power line and thus reduces the risk of electric shock.

4.4 Half-wave Rectifier

A half-wave rectifier employs a single diode as shown in Fig. 4.2. The a.c. supply to be rectified is applied through a power transformer in series with diode valve and load resistance R_L. The transformer has two secondary windings. One is the high voltage winding and supplies a.c. voltage to the diode for rectification. The other is low voltage winding and supplies low-voltage a.c. to the heater of the cathode.

Operation. The a.c. voltage to be rectified appears across the secondary winding *PQ*. During the positive half-cycle of a.c. supply, the end *P* of the secondary winding (and hence the plate) becomes positive *w.r.t.* end *Q* (*i.e.* cathode). Therefore, diode conducts and the *conventional current* flows from plate to cathode and then via load resistance R_L to the end *Q*. Note that current is flowing from *A* to *B* in the load. However, during the negative half-cycle of a.c. supply, end *P* is negative and end *Q* positive. This makes the plate negative *w.r.t.* cathode and hence diode does not conduct. Again for the next positive half-cycle, diode conducts and current flows through the load from *A* to *B*. Therefore, current through R_L is unidirectional *i.e.* it always flows from *A* to *B*, though after every half-cycle. Consequently, d.c. output is obtained across the load.

It may be noted that although the output across load is unidirectional, it is not steady because of continuous changes in amplitude (See Fig. 4.3). Therefore, the output from a rectifier is pulsating *d.c. These pulsations are removed with the help of *filter circuit* to obtain steady d.c. output.

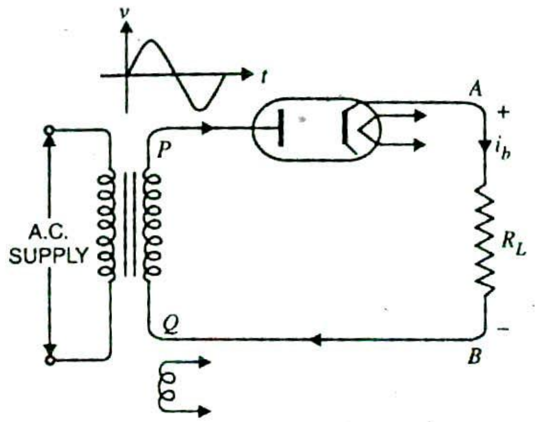


Fig. 4.2

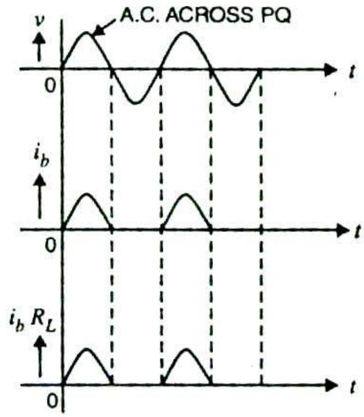


Fig. 4.3

Note the rippple in the d.c. output has the same frequency as that of a.c. input voltage. Therefore, the ripple frequency of half-wave rectifier for 50 Hz a.c. power line voltage is 50 Hz.

4.5 Rectification Efficiency of Half-wave Rectifier

The basic function of a rectifier is to convert alternating current into direct current. Therefore, it is very important to know how efficient the rectifier is to convert input a.c. power into d.c. power.

The ratio of d.c. power output to the a.c. power input in a rectifier is known as **rectification efficiency** *i.e.*

$$\text{Rectification efficiency, } \eta = \frac{\text{d.c. output power}}{\text{a.c. input power}}$$

Consider a half-wave rectifier circuit shown in Fig. 4.4. Suppose the input a.c. voltage (*i.e.* across secondary of the transformer) is $v = V_m \sin\theta$. Let r_p and R_L be the plate resistance and load resistance respectively. For the positive half-cycle of a.c. input voltage, the diode conducts whereas for negative half-cycle, no conduction takes place. The waveform of output current is shown in Fig. 4.5.

Maximum value of current through load is

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

d.c. output power. As the output current is pulsating d.c., therefore, we shall have to find the *average value* in order to determine the d.c. power. For a half-wave rectified current wave,

$$\text{Average current, } I_{av} = I_{dc} = \frac{I_m}{\pi}$$

---

* To ascertain the polarities of d.c. output voltage, see the direction of conventional current flow in the load R_L. This current flows from the positive terminal to the negative terminal. Therefore, end *A* of load is positive and end *B* negative.

$\therefore$ d.c. output power, $P_{dc} = I_{dc}^2 R_L = \left(\frac{I_m}{\pi}\right)^2 R_L$

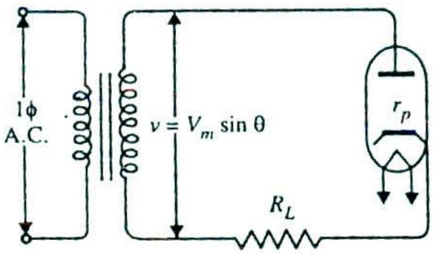


Fig. 4.4

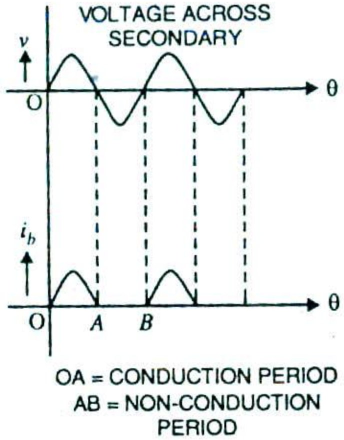


Fig. 4.5

a.c. power input. The a.c. input power is dissipated in plate resistance r_p and load resistance R_L. For a half-wave rectified current wave,

$$\text{r.m.s. value of current, } I_{r.m.s} = \frac{I_m}{2}$$

$$\text{a.c. input power, } P_{ac} = I_{rms}^2 (r_p + R_L) = \frac{I_m^2}{4}(r_p + R_L)$$

$$\therefore \text{ Rectification efficiency, } \eta = \frac{P_{dc}}{P_{ac}} = \frac{\left(\frac{I_m}{\pi}\right)^2 R_L}{\frac{I_m^2}{4}(r_p + R_L)}$$

$$= \frac{0.406}{1 + \frac{r_p}{R_L}} \quad \text{...(i)}$$

It is obvious from exp. (*i*) that if R_L is much larger than r_p, then r_p/R_L can be neglected as compared to 1 and efficiency of rectification will be maximum *i.e.*

Max. rectification efficiency, η = 40.6%

This shows that in half-wave rectification, maximum 40.6% of a.c. input power can be converted into d.c. power. Due to poor efficiency of half-wave rectifier, it is rarely used in practice.

Example 4.1. *A half-wave rectifier uses a diode with* $r_p = 300\ \Omega$. *If the input a.c. is 200 V (r.m.s.) and load is a resistance of 1200 Ω, calculate* I_{dc}, $I_{r.m.s.}$ *and the rectification efficiency.*

Solution.

Plate resistance, $r_p = 300\ \Omega$

Load resistance, $R_L = 1200\ \Omega$

Max. value of a.c. input, $V_m = 200 \times \sqrt{2}$ V

$\therefore$ Max. value of current, $I_m = \dfrac{V_m}{(r_p + R_L)} = \dfrac{200\sqrt{2}}{(300 + 1200)} = 0.189 \text{ A} = 189 \text{ mA}$

$$I_{dc} = I_m/\pi = 189/\pi = \mathbf{60\ mA}$$

$$I_{r.m.s.} = I_m/2 = 189/2 = \mathbf{94.5\ mA}$$

d.c. output power, $P_{dc} = I_{dc}^2 \times R_L = (0.06)^2 \times 1200 = 4.32 \text{ W}$

a.c. input power, $P_{ac} = I_{rms}^2 (r_p + R_L) = (0.0945)^2 \times 1500 = 13.39 \text{ W}$

Rectification efficiency $= \dfrac{P_{dc}}{P_{ac}} \times 100 = \dfrac{4.32}{13.39} \times 100 = \mathbf{32.26\%}$

Example 4.2. *A half-wave rectifier is used to supply 100 V d.c. to a load of 800 Ω. The diode has a plate resistance of 200 Ω. Calculate :*

(*i*) *a.c. voltage required*

(*ii*) *efficiency of rectification*

Solution.

Plate resistance, $r_p = 200\ \Omega$

Load resistance, $R_L = 800\ \Omega$

D.C. output voltage, $E_{dc} = 100 \text{ V}$

(*i*) Let V_m be the maximum value of a.c. voltage required.

Now $$E_{dc} = I_{dc} \times R_L = \frac{V_m}{\pi (r_p + R_L)} \times R_L$$

or $$100 = \frac{V_m}{\pi (200 + 800)} \times 800$$

$\therefore$ $$V_m = \frac{\pi (200 + 800)\, 100}{800} = \mathbf{393\ V}$$

Hence a.c. voltage of maximum value of 393V is required.

(*ii*) Rectification efficiency $= \dfrac{0.406}{1 + \dfrac{r_p}{R_L}} = \dfrac{0.406}{1 + \dfrac{200}{800}} = 0.325 = \mathbf{32.5\%}$

Example 4.3. *A vacuum tube half-wave rectifier with a.c. and d.c. instruments is shown in Fig. 4.6. Find the readings of :*

(*i*) *a moving coil permanent magnet ammeter (d.c.)*

(*ii*) *a.c. ammeter*

(*iii*) *wattmeter*

Solution.

(*i*) **Voltage across transformer secondary,** $e_s = 1000 \sin \omega t$

$\therefore$ Max. value, $V_m = 1000 \text{ V}$

Max. current, $I_m = \dfrac{V_m}{r_p + R_L} = \dfrac{1000}{(500 + 4500)} = 0.2 \text{ A} = 200 \text{ mA}$

$\therefore$ $$I_{dc} = I_m/\pi = 200/\pi = \mathbf{63.7\ mA}$$

$\therefore$ The d.c. ammeter reads 63.7 mA.

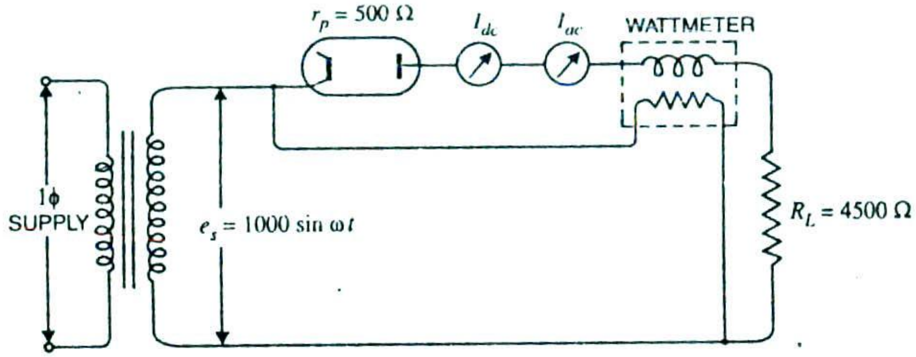


Fig. 4.6

(*ii*) $$I_{ac} = I_{r.m.s.} = I_m/2 = 200/2 = \mathbf{100\ mA}$$

∴ The a.c. ammeter reads 100 mA.

(*iii*) The wattmeter is connected in such a way that it reads the entire power supplied to the diode and load.

∴ Wattmeter reading, $W = (I_{rms})^2 (r_p + R_L)$

$$= \left(\frac{100}{1000}\right)^2 \times (500 + 4500) = \mathbf{50\ watts}$$

4.6 Disadvantages of Half-Wave Rectifier

Half-wave rectification is seldom used in practice because of the following drawbacks :

(*i*) The rectification efficiency is low.

(*ii*) The d.c. output is small.

(*iii*) The secondary of the transformer carries the rectified current, thus producing direct magnetisation of the transformer core.

(*iv*) Because of short heavy pulses of current, the heating of transformer windings is large compared to the current delivered.

4.7 Vacuum Tube Full-wave Rectifiers

In a full-wave rectifier, current flows through the load in the same direction for both half-cycles of a.c. input voltage. The full wave rectification can be achieved with the help of two diodes working alternately. For positive half-cycle of a.c. input voltage, one diode supplies current to the load and for the negative half-cycle, the other diode does so; the current being always in the same direction through the load. There are two types of circuits commonly used for full-wave rectification viz.

(*i*) Centre-tap full-wave rectifier

(*ii*) Full-wave bridge rectifier

It may be noted that use of transformer is essential for full-wave rectification though it is optional for half-wave rectification.

4.8 Centre-tap Full-wave Rectifier

A centre-tap full-wave rectifier may employ either (*i*) two diode circuit or (*ii*) double-diode circuit. We shall discuss each type of circuit in turn.

1. Two diode circuit. This circuit uses two single diodes *A* and *B* as shown in Fig. 4.7. The plates of two diodes are connected to the opposite ends of the centre-tapped secondary of power transformer. The two cathodes are tied together and the common junction D is connected to one side of load resistance R_L. The other end of R_L is connected to the centre-tap C of the secondary winding. With this arrangement, only *one-half* of transformer secondary voltage appears between the plate and cathode of each diode.

Operation. When positive half of a.c. supply appears across the secondary winding, end P becomes positive and end Q negative. This makes the plate of diode A positive and that of diode B negative *w.r.t.* cathode. Therefore, current conduction takes place in the circuit due to diode A only while diode B does not conduct. The path of *conventional current* is along *PADCP* and is shown by the dotted arrows. Note that current is pulsating and its direction through load R_L is from D to C. During negative half-cycle, end P becomes negative and end Q positive. Hence, diode B will conduct and diode A does not. The path of *conventional current* is along *QBDCQ* and is shown by solid arrows. Note that again the direction of current through load R_L is from D to C.

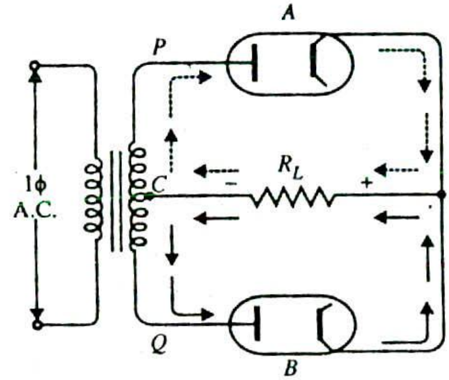


Fig. 4.7

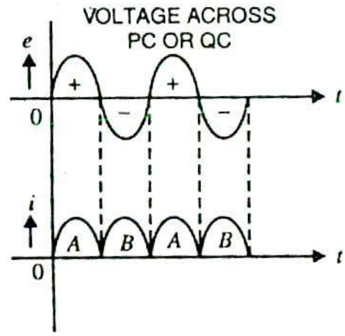


Fig. 4.8

The reader should note carefully that current flow through load R_L is in the same direction for both half-cycles of a.c. input voltage (See Fig. 4.8). Therefore, d.c. output is obtained across R_L. Also, the polarities of d.c. voltage across R_L should be noted.

Disadvantages

(*i*) It is sometimes difficult to locate the centre-tap on the secondary winding.

(*ii*) The d.c. output is small as each diode utilises only one-half of the transformer secondary voltage.

(*iii*) The diodes used must have high *peak inverse voltage*. It is because when the diode is not conducting, *whole of secondary voltage appears across it in the reverse direction.

2. Double-diode circuit. Sometimes, two separate diodes are put in one envelope so that the two plates share a common cathode. The valve is then known as a *double-diode* as shown in Fig. 4.9. The two plates A and B are connected to the opposite ends of centre-tapped secondary of power transformer. The load resistance R_L is connected between the centre-tap and the cathode.

---

* Refer to Fig. 4.7. When diode A is conducting, its cathode is positive almost to the peak of secondary voltage and the cathode of B is at the same potential. But the plate of B is negative to the peak of secondary voltage. Therefore, an inverse voltage equal to the maximum secondary voltage appears across the non-conducting diode B.

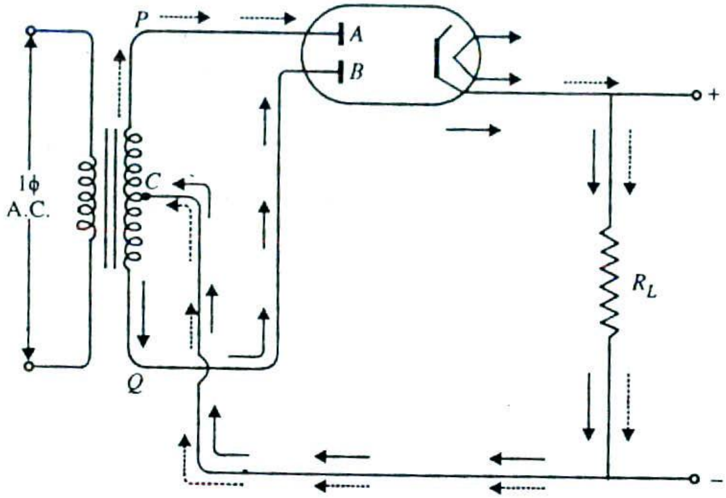


Fig. 4.9

Operation. The working of this circuit is exactly similar to that of two diode circuit. During the positive half-cycle of a.c. voltage, end P of secondary winding is positive and end Q negative. Therefore, plate A conducts while plate B does not. This is shown by dotted arrows. However, during the negative half-cycle, plate B conducts whereas plate A does not. This is shown by solid arrows. It may be noted that current through load resistance R_L is in the same direction for both half-cycles of input a.c. and hence d.c. output appears across the load. This circuit also carries the disadvantages of two diode circuit.

4.9 Full-wave Bridge Rectifier

The need for centre-tapped power transformer is eliminated in the bridge rectifier circuit as shown in Fig. 4.10. It contains four diodes to form a bridge circuit and hence the name. The a.c. supply to be rectified is applied to the diagonally opposite ends of the bridge through the transformer. Between the other two ends, load resistance R_L is connected. As we shall see, for each half-cycle (positive or negative) of a.c. input, two diodes in series carry the current in the same direction through the load. Therefore, the circuit gives full-wave rectification.

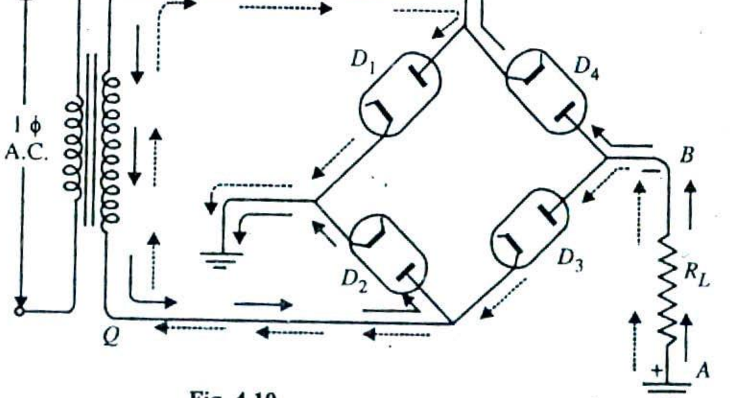


Fig. 4.10

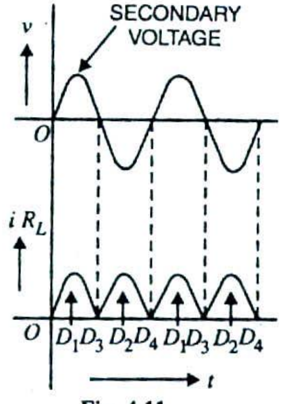


Fig. 4.11

Operation. During the positive half-cycle of a.c. supply, suppose the top end P of transformer secondary becomes positive and the bottom end Q negative. This places the voltages on the cathodes and plates of four diodes as under :

Plate of diode D_1 positive *w.r.t.* cathode

Plate of diode D_3 positive *w.r.t.* cathode

Plate of diode D_2 negative *w.r.t.* cathode

Plate of diode D_4 negative *w.r.t.* cathode

As only that diode conducts which has its plate positive w.r.t. cathode, therefore, only diodes D_1 and D_3 will conduct. These two diodes will be in series through load R_L as shown in Fig. 4.12. The conventional current flow is shown by dotted arrows. It is clear that end A of the load resistance R_L will be positive and end B negative.

During the negative half of a.c. supply, the top end P of the transformer secondary becomes negative and bottom end Q positive. This places the voltages on the plates and cathodes of four diodes as under :

Plate of diode D_2 positive *w.r.t.* its cathode

Plate of diode D_4 positive *w.r.t.* its cathode

Plate of diode D_1 negative *w.r.t.* its cathode

Plate of diode D_3 negative *w.r.t.* its cathode

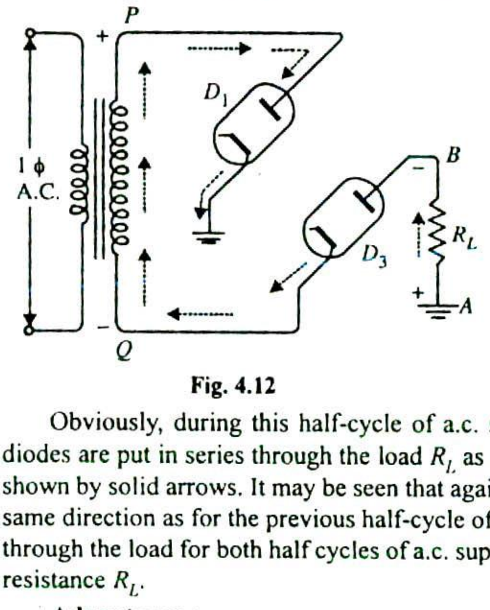


Fig. 4.12

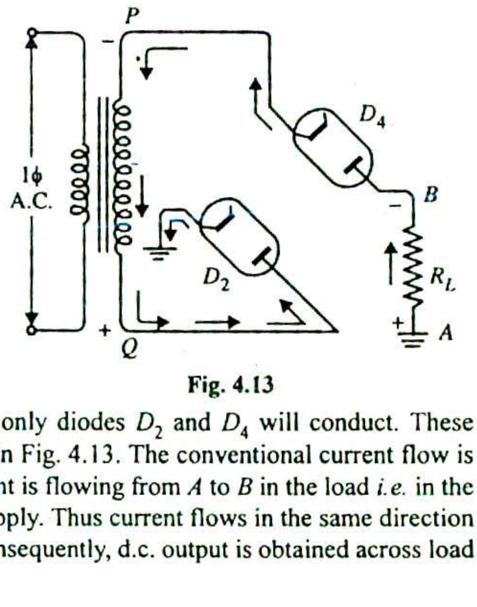


Fig. 4.13

Obviously, during this half-cycle of a.c. supply, only diodes D_2 and D_4 will conduct. These diodes are put in series through the load R_L as shown in Fig. 4.13. The conventional current flow is shown by solid arrows. It may be seen that again current is flowing from A to B in the load *i.e.* in the same direction as for the previous half-cycle of a.c. supply. Thus current flows in the same direction through the load for both half cycles of a.c. supply. Consequently, d.c. output is obtained across load resistance R_L.

Advantages :

(*i*) The need for the centre-tap on the secondary of the transformer is eliminated.

(*ii*) The output voltage is nearly *twice that of the centre-tap circuit for a given power transformer.

(*iii*) The peak inverse voltage is one-half that of centre-tap circuit.

---

* Because full voltage of transformer secondary is applied across the two conducting diodes during each a.c. half-cycle. However, in centre-tap circuit, only half of secondary voltage is utilised for rectification.

Disadvantages :

(*i*) It requires four diodes instead of two.

(*ii*) As two diodes in series carry the load current during each half-cycle, therefore, tube voltage drop is increased. This reduces the output voltage. In any case, output is much more than the equivalent centre-tap circuit.

(*iii*) The cathodes of the rectifier tubes are at different potentials. This does not permit the use of double-diode and necessitates a separate heater supply for each of the four tubes.

4.10 Rectification Efficiency of Full-wave Rectifier

Consider a full-wave rectified current wave shown in Fig. 4.14. Let the input a.c. voltage (across secondary of transformer) be $v = V_m \sin\theta$. Let us further assume that r_p and R_L are the plate resistance and load resistance respectively.

Maximum current through load is

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

d.c. power output. As the output current waveform is pulsating d.c., therefore, we shall have to find the average value of current over one cycle.

For a full-wave rectified current wave,

$$\text{Average current, } I_{av} = I_{dc} = \frac{2\,I_m}{\pi}$$

$$\therefore \quad \text{d.c. output power, } P_{dc} = I_{dc}^2\, R_L = \left(\frac{2\,I_m}{\pi}\right)^2 \times R_L$$

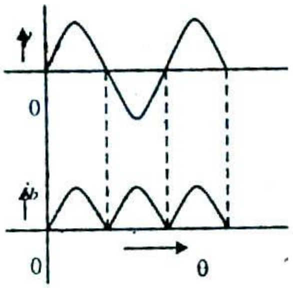


Fig. 4.14

a.c. power input. The a.c. input power is dissipated in plate resistance r_p and load R_L. For a full-wave rectified current wave,

R.M.S. value of current is

$$I_{rms} = \frac{I_m}{\sqrt{2}}$$

$$\therefore \quad \text{a.c. power input, } P_{ac} = I_{rms}^2\,(r_p + R_L) = \frac{I_m^2}{2}\,(r_p + R_L)$$

$\therefore$ Rectification efficiency is

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{\left(\frac{2\,I_m}{\pi}\right)^2 \times R_L}{\frac{I_m^2}{2}\,(r_p + R_L)} = \frac{0.812}{1 + \frac{r_p}{R_L}}$$

If $R_L >> r_p$, then efficiency will be maximum and is equal to 81.2%. This is double the efficiency due to half-wave rectifier. In other words, a full-wave rectifier is twice as effective as a half-wave rectifier.

Example 4.4. *A full-wave, 1-phase rectifier employs two vacuum diodes, the internal resistance of each diode may be assumed constant at 500 Ω. The transformer r.m.s. secondary voltage from centre tap to each of secondary end is 300 V and load has a resistance of 2000 Ω. Find:*

(i) d.c. power output *(ii) a.c. power input* *(iii) rectification efficiency*

Solution.

$$\text{Diode resistance, } r_p = 500\ \Omega$$

Load resistance, $R_L = 2000\ \Omega$

Max. value of a.c. voltage, $V_m = 300 \times \sqrt{2}$ V

Maximum value of current, $I_m = \dfrac{V_m}{r_p + R_L} = \dfrac{300 \times \sqrt{2}}{500 + 2000} = 0.17$ A

(*i*) $$I_{dc} = \frac{2\,I_m}{\pi} = \frac{2 \times 0.17}{\pi} = 0.108 \text{ A}$$

$\therefore$ d.c. power output, $P_{dc} = I_{dc}^2 \times R_L = (0.108)^2 \times 2000 =$ **23.32 watts**

(*ii*) R.M.S. value of load current, $I_{rms} = \dfrac{I_m}{\sqrt{2}} = \dfrac{0.17}{\sqrt{2}} = 0.12$ A

$\therefore$ a.c. power input, $P_{ac} = I_{rms}^2 (r_p + R_L)$

$= (0.12)^2 \times (500 + 2000) =$ **36 watts**

(*iii*) Rectification efficiency $= \dfrac{P_{dc}}{P_{ac}} \times 100 = \dfrac{23.32}{36} \times 100 =$ **64.8%**

Example 4.5. *A full-wave rectifier with a.c. and d.c. instruments is shown in Fig. 4.15. Calculate the readings of : (i) d.c. ammeter (ii) a.c. ammeter.*

Solution.

Max. value of input voltage, $V_m = 1000$ V

$$\therefore \quad I_m = \frac{V_m}{r_p + R_L} = \frac{1000}{500 + 4500} = 0.2 \text{ A} = 200 \text{ mA}$$

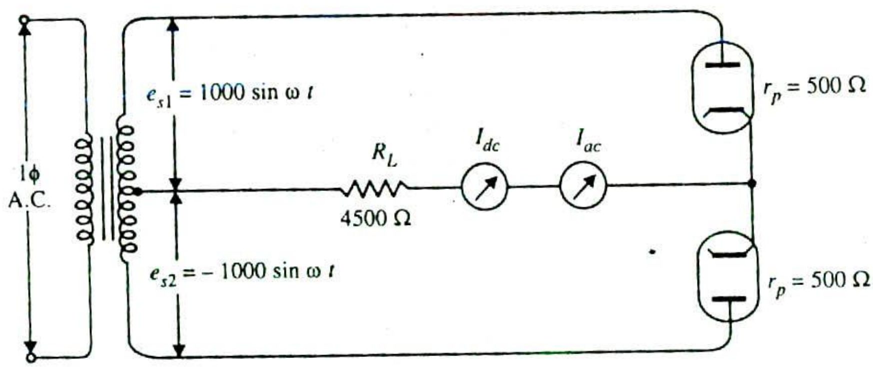


Fig. 4.15

(*i*) $$I_{dc} = \frac{2\,I_m}{\pi} = \frac{2\,(200)}{\pi} = \mathbf{127.3\ mA}$$

$\therefore$ The d.c. ammeter reads 127.3 mA.

(*ii*) $$I_{ac} = I_{rms} = \frac{I_m}{\sqrt{2}} = \frac{200}{\sqrt{2}} = \mathbf{141.4\ mA}$$

$\therefore$ The a.c. ammeter reads 141.4 mA.

4.11 Advantages of Full-Wave Rectifier

The advantages of a full-wave rectifier as compared to a half-wave rectifier are :

(*i*) It produces a more constant rectified output as compared to a half-wave rectifier.

(*ii*) It has higher rectification efficiency.

(*iii*) The ripple frequency is double the frequency of the a.c. input voltage. Since higher ripple frequency is easier to filter, smaller capacitors are required for filter circuits.

(*iv*) There is no resultant transformer-core magnetisation due to direct current flow through the secondary of the transformer. It is because of cancellation of direct current flowing in each half of the transformer secondary in opposite directions.

4.12 Filter Circuits

The output of a rectifier has pulsating character *i.e.* it contains d.c. and a.c. components. The uses of such a pulsating direct voltage are limited to charging batteries, running d.c. motors etc. However, in electronic circuits, we need a d.c. voltage that is constant in value. In order to get constant d.c. voltage, a filter circuit is installed between the rectifier output and load R_L as shown in Fig. 4.16.

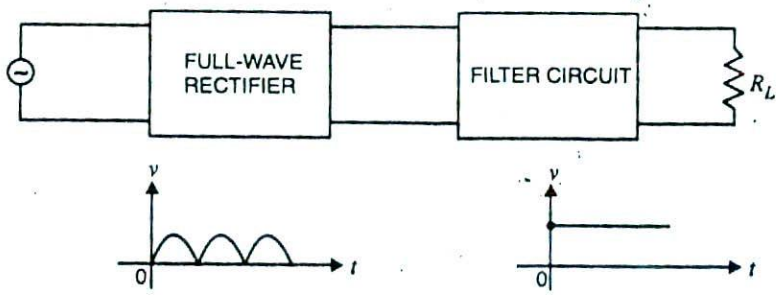


Fig. 4.16

The filter circuit removes or filters out the a.c. component from the rectifier output and allows only the d.c. component to reach the load. Thus, a constant d.c. voltage appears across the load. The most commonly used filter circuits are :

(*i*) capacitor filter (*ii*) choke input filter (*iii*) capacitor input filter

The operation of these filters is discussed in detail in chapter 9.

4.13 D.C. Power Supply

The d.c. power supply is a combination of three basic elements *viz. transformer, full-wave rectifier* and *filter circuit.* Fig. 4.17 shows a typical power supply for a radio receiver.

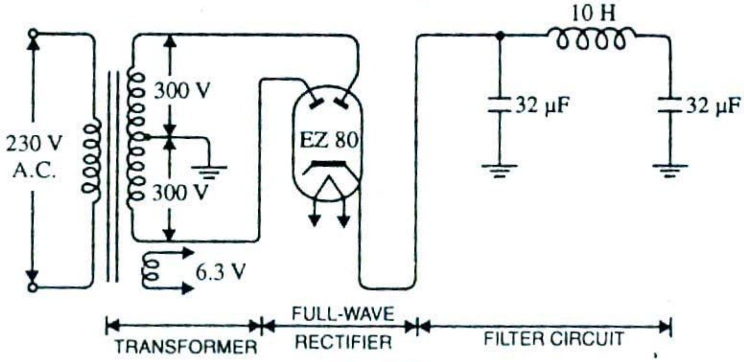


Fig. 4.17

Transformer is used to change the a.c. line voltage to the proper magnitude for the power-supply operation. The full-wave rectification is done by double-diode. The output from the rectifier has a pulsating character. The pulsations in the rectifier output are reduced to minimum value by the capacitor input filter.

Multiple-Choice Questions

1. The output of a rectifier is ....
   (*i*) pulsating d.c. (*ii*) pure d.c.
   (*iii*) pure a.c. (*iv*) none of the above
2. A vacuum diode acts as a .... switch.
   (*i*) bi-directional (*ii*) controlled
   (*iii*) unidirectional (*iv*) none of the above
3. The maximum efficiency of a full-wave rectifier is ....
   (*i*) 40.6% (*ii*) 20.3%
   (*iii*) 90% (*iv*) 81.2%
4. The most important consideration in a vacuum tube rectifier is ....
   (*i*) filament voltage rating
   (*ii*) PIV rating
   (*iii*) plate voltage rating
   (*iv*) none of the above
5. The d.c. output of a bridge type rectifier is nearly .... that of centre-tap rectifier for a given transformer.
   (*i*) twice (*ii*) thrice
   (*iii*) four times (*iv*) five times
6. In a centre-tap full-wave rectifier, ... transformer secondary voltage is utilised.
   (*i*) full (*ii*) one-third
   (*iii*) one-half (*iv*) one-eighth
7. The maximum efficiency of a half-wave rectifier is ....
   (*i*) 20.3% (*ii*) 80.6%
   (*iii*) 50% (*iv*) 40.6%
8. Transformer is essential in a .... rectifier.
   (*i*) bridge type (*ii*) half-wave
   (*iii*) centre-tap (*iv*) none of the above
9. In a full-wave rectifier, if a.c. supply is 50 Hz, then a.c. ripple in the output is ....
   (*i*) 50 Hz (*ii*) 100 Hz
   (*iii*) 25 Hz (*iv*) 200 Hz
10. A bridge type rectifier uses .... diodes.
    (*i*) four (*ii*) two
    (*iii*) three (*iv*) six
11. For the same d.c. output, centre-tap rectifier should have .... PIV as compared to bridge type rectifier.
    (*i*) same (*ii*) smaller
    (*iii*) higher (*iv*) none of the above
12. For high voltage applications, we use ....
    (*i*) centre-tap rectifier
    (*ii*) bridge type rectifier
    (*iii*) half-wave rectifier
    (*iv*) none of the above
13. The power supply in a radio receiver generally uses .... filter.
    (*i*) capacitor input
    (*ii*) choke input
    (*iii*) resistance
    (*iv*) none of the above
14. In filter circuits, we generally use .... capacitors.
    (*i*) mica (*ii*) paper
    (*iii*) air (*iv*) electrolytic
15. In a half-wave rectifier, if a.c. supply is 50 Hz, then a.c. ripple in the output is ....
    (*i*) 100 Hz (*ii*) 25 Hz
    (*iii*) 50 Hz (*iv*) 12.5 Hz
16. The d.c. output of a bridge type rectifier is .... that of equivalent centre-tap rectifier.
    (*i*) the same as (*ii*) more than
    (*iii*) less than (*iv*) none of the above
17. The values of L and C in filter circuits for a half-wave rectifier are .... as compared to that of a full-wave rectifier.
    (*i*) the same as (*ii*) more

(*iii*) less (*iv*) none of the above

18. In a centre-tap rectifier, if voltage between one end of secondary and centre-tap is 300 V peak, then PIV is..............
   (*i*) 600 V (*ii*) 300 V
   (*iii*) 150 V (*iv*) 1200 V

19. Capacitor input filter is .... choke input filter.
   (*i*) as efficient as
   (*ii*) more efficient than
   (*iii*) less efficient than
   (*iv*) none of the above

20. Full-wave rectification is .... half-wave rectification.
   (*i*) easier to filter than
   (*ii*) difficult to filter than
   (*iii*) as easier to filter as
   (*iv*) none of the above

Answers to Multiple-Choice Questions

1. (*i*)	**2.** (*iii*)	**3.** (*iv*)	**4.** (*ii*)	**5.** (*i*)
6. (*iii*)	**7.** (*iv*)	**8.** (*iii*)	**9.** (*ii*)	**10.** (*i*)
11. (*iii*)	**12.** (*ii*)	**13.** (*i*)	**14.** (*iv*)	**15.** (*iii*)
16. (*ii*)	**17.** (*ii*)	**18.** (*i*)	**19.** (*ii*)	**20.** (*i*)

Chapter Review Topics

1. What is a rectifier ? Explain how a vacuum diode acts as a rectifier.
2. Describe the working of a vacuum tube half-wave rectifier.
3. Derive an expression for the efficiency of half-wave rectification in terms of tube resistance r_p and load resistance R_L.
4. With neat sketches, explain the working of following full-wave rectifiers :
   (*i*) double-diode circuit (*ii*) two diode circuit
   (*iii*) bridge circuit
5. Deduce an expression for the efficiency of full-wave rectification.
6. What is a filter circuit ?
7. Give the circuit diagram of a typical radio d.c. power supply.

Discussion Questions

1. Why is half-wave rectifier used for applications requiring a small current drain ?
2. Why is a transformer necessary for full-wave rectification ?
3. Why cannot you use two double diodes in a bridge rectifier circuit ?
4. The transformer in a centre-tap circuit has usually a high step-up ratio between primary and secondary windings. Explain why ?
5. Where do you use bridge rectifier circuit ?

5

Vacuum Tube Amplifiers

Introduction

The process of raising the strength of a weak signal is known as amplification and the device which accomplishes this job is called an *amplifier*. The phenomenon of amplification is necessary throughout radio communication systems. For example, the radio waves picked up by the receiving antenna possess extremely small power say, of the order of milliwatts. However, they must be amplified to several watts in order to produce adequate loudspeaker response in the radio receiver. Similarly, the sound output from a microphone is a fraction of a watt and must be amplified hundreds of times to make it possible to fill a stadium with sound. As a matter of fact, amplifiers find wide applications in industrial and commercial fields *e.g.* in television, inter-communication system, radio receivers etc. Fortunately, the characteristics of vacuum tubes reveal that they can do the job of amplification. The purpose of this chapter is to show how vacuum tubes may be utilised to amplify voltage or power most efficiently.

5.1 Vacuum Tube Amplifiers

The amplifiers employing vacuum tubes for raising the strength of a weak signal are known as **vacuum tube amplifiers.**

Only grid-controlled vacuum tubes *e.g.* triode, tetrode, pentode etc. can act as amplifiers. The weak signal is applied between control grid and cathode and the amplified output is obtained across the load in the plate circuit. The amplifying property of a grid-controlled tube is due to the fact that a small change in grid voltage causes a relatively large change in plate current and hence greater output is obtained across the load in the plate circuit *i.e.* grid voltage is amplified.

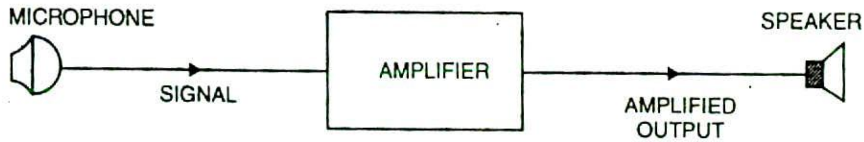


Fig. 5.1

It should be noted that an amplifier amplifies only the electrical signal. This electrical signal to be amplified may be directly available or converted into electrical by some suitable device. For example, Fig. 5.1 shows the single line diagram of a public address system. The microphone converts the sound waves into equivalent electrical waves. These electrical waves (called the *signal*) are applied to the input terminals of the amplifier *i.e.* between control grid and cathode of the tube. The signal appears in the amplified form at the output terminals *i.e.* in the plate circuit. The amplified electrical signal is converted into sound waves by the speaker connected in the plate circuit of the tube.

5.2 Faithful Amplification

The most important requirement of an amplifier is that it should do faithful amplification *i.e.* it should increase the magnitude of signal and the general shape of the signal should not change. In other words, the amplified output should be similar in every respect to the input (*i.e. signal*) except for the amplitude which should be as great as possible.

In order to achieve faithful amplification, the control grid of the amplifying tube should be kept at *negative potential w.r.t. cathode* at all times. To do so, a d.c. voltage is applied in the grid circuit in addition to the signal voltage as shown in Fig. 5.2. This d.c. voltage is known as *grid bias* (E_c) and its magnitude is such that it always keeps the grid negative *w.r.t.* cathode regardless of the polarity of the signal.

Why is grid bias necessary ? The reader may wonder why grid bias battery E_c is necessary for faithful amplification. Assume for a moment, that it is absent and only signal (a.c.) is applied in the grid circuit. The alternating signal will make the grid alternately positive and negative w.r.t. cathode. Whenever the input signal goes positive, the grid will draw current. The grid current flow results in the following effects :

(*i*) It distorts the linearity of I_b/E_c characteristic, thus leading to distorted amplification.

(*ii*) It requires certain amount of power (*i.e.* grid voltage × grid current) which it extracts from the input signal. Generally, the input signal is too weak to supply the power and consequently* distorted amplification takes place.

For these reasons, no grid current should flow during any portion of the cycle of the input signal. The bias battery E_c ensures this function. The bias voltage is always of sufficient magnitude and of such polarity as to maintain grid negative *w.r.t.* cathode at all times.

5.3 Triode as an Amplifier

Fig. 5.2 shows the basic triode amplifier circuit. The weak signal e_g is applied in the grid circuit and useful output is obtained across the load R_L connected in the plate circuit. The bias battery E_c ensures the grid to be always negative *w.r.t.* cathode. The weak signal voltage produces a **large change in plate current. As the value of R_L is quite high, therefore, a large voltage drop occurs across it. Thus, a weak signal applied in the grid circuit appears in the amplified form in the plate circuit. It is in this way that a triode acts as an amplifier.

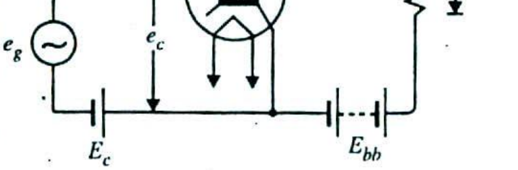


Fig. 5.2

Illustration. The action of triode as an amplifier can be made more illustrative if we consider the typical circuit values as shown in Fig. 5.3 (*i*). Thus an alternating signal e_g equal to 4 V peak amplitude has been applied in the grid circuit of triode in series with a fixed bias voltage E_c from a 4-volt battery. The total instantaneous voltage

* Only over the linear portion of I_b/E_c curve, variations of e_g produce proportional changes in I_b. However, with grid current flow, the I_b/E_c curve deviates from linearity.

** We have already seen that grid is in a commanding position and a small voltage placed on it produces a large change in plate current.

between grid and cathode (e_c) is equal to the algebraic sum of e_g and E_c *i.e.*

$$e_c = E_c + e_g$$

In our example, $E_c = -4$ V and the signal voltage e_g varies between + 4 V and – 4 V. Therefore, the total instantaneous grid voltage e_c will vary between 0 and – 8 V. It is clear that grid is never driven positive *w.r.t.* cathode and hence this circuit arrangement will give faithful amplification. Let us suppose that load $R_L = 20$ k Ω.

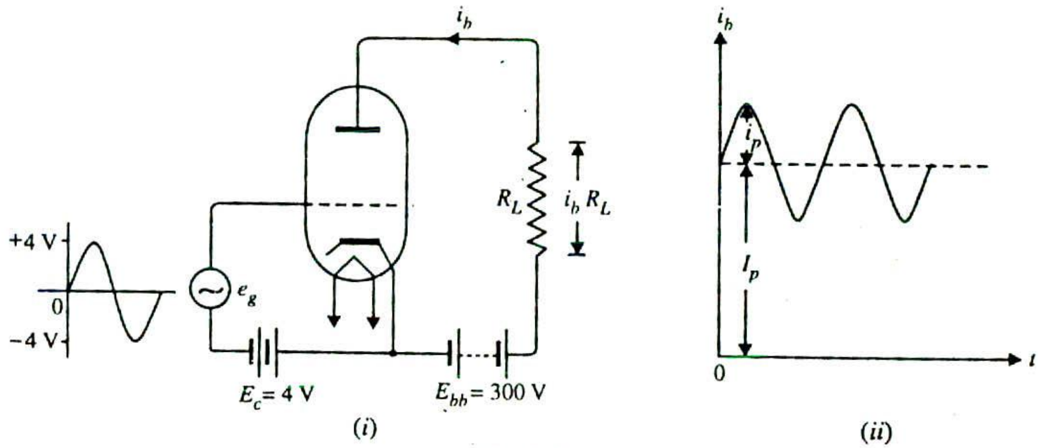


Fig. 5.3

Consider some numerical values given in the table below. Only three conditions of signal voltage (*viz.* 0 V, + 1 V and + 2 V) are considered. Let us assume that corresponding to these three conditions, the plate current is respectively 3 mA, 4 mA and 5 mA.

S. No.	e_g	E_c	e_c	i_b	$i_b R_L$
1	0V	– 4V	– 4V	3 mA	60V
2	+ 1V	– 4V	– 3V	4 mA	80V
3	+ 2V	– 4V	– 2V	5 mA	100V

It is clear that change of signal voltage from + 1V to + 2V has produced a change of 100 – 80 = 20V across R_L. Thus a small change of only 1V in the signal has changed the voltage across R_L by 20V — an amplification of 20 times.

The following points may be noted :

(*i*) When no signal is applied, d.c. plate current (I_p) flows in the circuit due to grid bias E_c. However, when the signal is applied, the plate current varies above and below I_p in accordance with the input. Therefore, with the signal applied, the total plate current i_b [See Fig. 5.3 (*ii*)] is given by ;

$$i_b = I_p + i_p$$

where I_p = zero signal plate current

i_p = a.c. component due to signal voltage

(*ii*) The *useful output of the tube is the voltage drop across R_L due to a.c. component i_p *i.e.*

* The d.c. component fixes the biasing conditions only. It is the a.c. component which produces useful output. Suppose at any instant the signal voltage is such that plate current increases from $i_b = I_p$ to $i_b = I_p + i_p$

$$\therefore \text{Voltage amplification} = \frac{\text{change in voltage across } R_L}{\text{signal voltage}} = \frac{(I_p + i_p)R_L - I_p R_L}{\text{signal voltage}} = \frac{i_p R_L}{\text{signal voltage}}$$

$$\text{Useful output} = i_p R_L$$

$$\therefore \quad \text{Voltage amplification} = \frac{i_p R_L}{\text{signal voltage}}$$

5.4 Graphical Analysis of Triode Amplifier

The function of triode as an amplifier can also be explained graphically. Suppose a signal of peak voltage E_g is applied in the grid circuit in series with grid bias voltage E_c ; E_c being greater than signal peak voltage E_g so that grid is always negative *w.r.t.* cathode. The total instantaneous grid voltage will be the algebraic sum of E_c and signal voltage at any instant.

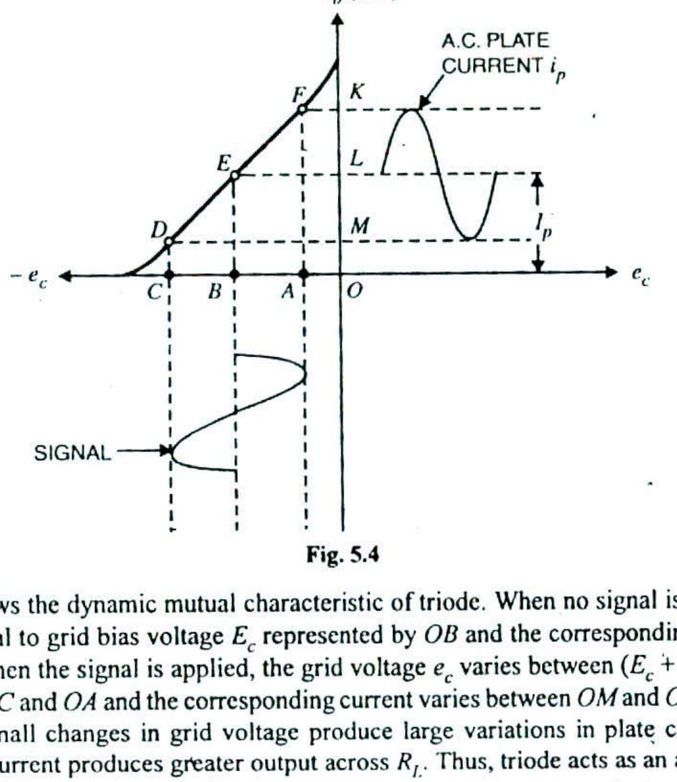


Fig. 5.4

Fig. 5.4 shows the dynamic mutual characteristic of triode. When no signal is applied, the grid voltage e_c is equal to grid bias voltage E_c represented by *OB* and the corresponding plate current is *OL*. However, when the signal is applied, the grid voltage e_c varies between $(E_c + E_g)$ and $(E_c - E_g)$ represented by *OC* and *OA* and the corresponding current varies between *OM* and *OK*. It is clear from the graph that small changes in grid voltage produce large variations in plate current. This large change in plate current produces greater output across R_L. Thus, triode acts as an amplifier.

Operating point. The values of plate current and grid voltage (bias) in the absence of signal determine the operating point. Thus, in Fig. 5.4, *E* is the operating point. It is called so because the signal variations take place about this point. For faithful amplification, the operating point should be so chosen that the variations of input signal are accommodated within the linear portion of the characteristic. Referring to Fig. 5.4, it is clear that by selecting the operating point *E*, the variations of the input signal are accommodated within the linear portion *DF* of the characteristic. Consequently, output current waveform has the same shape as the input signal, resulting in faithful amplification.

5.5 Phase Reversal

In the triode amplifier, there is a phase difference of 180° between the input (*i.e.* signal) voltage and output voltage. In other words, the positive half-cycle of the signal appears as amplified negative-half in the output while the negative half-cycle of the signal appears as amplified positive-half in the output. This is known as *phase reversal*. This fact can be easily explained by referring to Fig. 5.5.

$$\text{Output voltage, } e_b = E_{bb} - i_b R_L$$

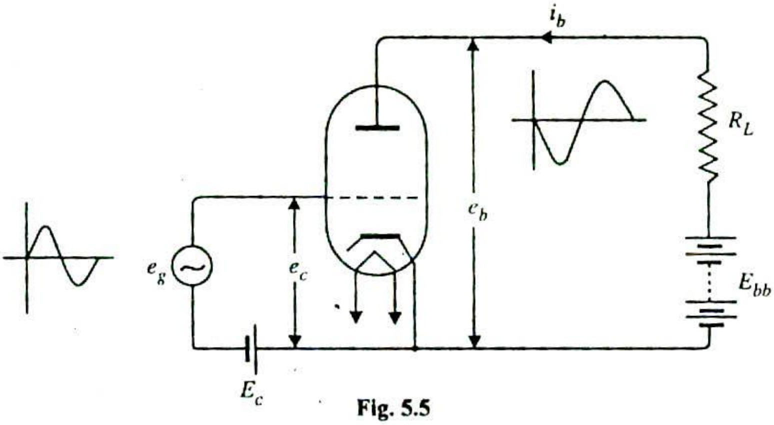


Fig. 5.5

When the signal is increasing in the positive half-cycle, the net grid voltage e_c becomes less negative. The result is that plate current i_b increases and so does the voltage drop $i_b R_L$. As E_{bb} is constant, therefore, output voltage e_b decreases. In other words, as the signal is increasing in the positive half-cycle, the output is increasing in the negative sense *i.e.* output is 180° out of phase with the input. Similarly, when the signal goes in the negative-half cycle, the plate current decreases and hence voltage drop $i_b R_L$ also decreases. This results in the increased voltage output e_b. In other words, as the signal is increasing in the negative half cycle, the output is increasing in the positive sense. *It may be noted that amplification is not affected by this phase reversal.*

5.6 A.C. Equivalent Circuit of Triode

Fig. 5.6 (*i*) shows the triode amplifier circuit. Let us assume that triode has amplification factor μ, a.c. plate resistance r_p and plate load R_L. When the signal e_g is applied, the plate current consists of (*i*) *quiescent current I_p and (*ii*) an a.c. component i_p. The useful output of the tube is the voltage drop across R_L due to the a.c. component i_p.

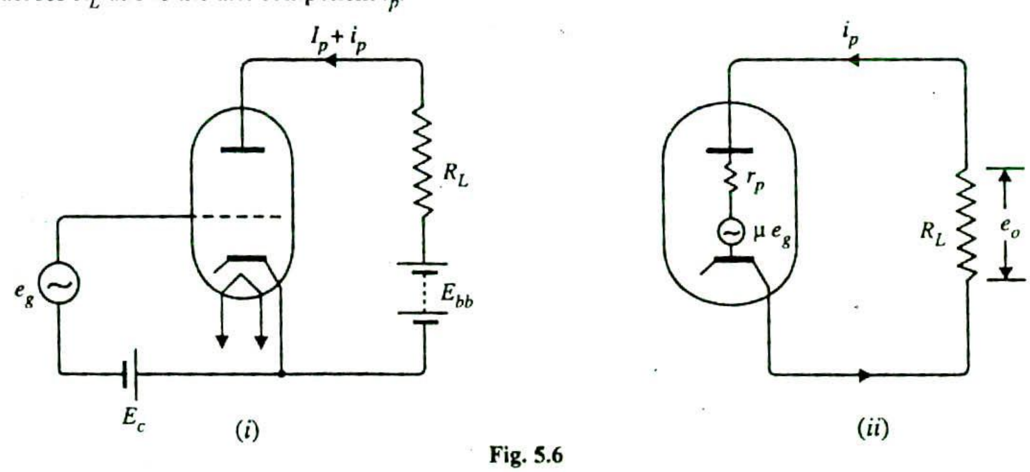


Fig. 5.6

* Zero signal plate current is also called quiescent current. Quiescent means silent. Therefore, it is the plate current when triode is silent *i.e.* in the absence of signal.

So far as the flow of *a.c. in the tube is concerned, the equivalent circuit is as shown in Fig. 5.6 (*ii*). The signal voltage e_g appears as $\mu\, e_g$ in the plate circuit. Therefore, between plate and cathode, an imaginary a.c. generator of voltage $\mu\, e_g$ is incorporated. The a.c. plate resistance is in series with plate load R_L. The a.c. output e_o is obtained across load R_L.

Voltage gain. The ratio of output voltage to the input signal voltage is known as *voltage gain i.e.*

$$\text{Voltage gain} = \frac{\text{Output voltage}}{\text{Signal voltage}}$$

Referring to the equivalent circuit of triode in Fig. 5.6 (*ii*), we get,

$$i_p = \frac{\mu\, e_g}{r_p + R_L}$$

$$\text{Output voltage, } e_o = i_p\, R_L = \left(\frac{-\mu\, e_g}{r_p + R_L}\right) R_L$$

$$\therefore \quad \text{Voltage gain, } A_v = e_o/e_g$$

$$= \frac{\left(\frac{\mu\, e_g}{r_p + R_L}\right) R_L}{e_g}$$

$$\therefore \quad A_v = \frac{\mu\, R_L}{r_p + R_L} \qquad \text{...(i)}$$

The following points may be noted :

(*i*) The voltage gain has no unit *i.e.* it is a number.

(*ii*) The voltage gain A_v is less than μ. It is because some voltage is dropped across the internal resistance r_p of the tube. If $r_p = 0$, then $A_v = \mu$.

(*iii*) For a non-resistive load,

$$A_v = \frac{\mu\, Z_L}{r_p + Z_L}$$

Example 5.1. *A triode used as an amplifier has an amplification factor of 20 and a.c. plate resistance of 10 kΩ. The load resistance is 15 kΩ. Find the voltage gain of the amplifier.*

Solution. $\mu = 20, \quad r_p = 10\text{ k}\Omega, \quad R_L = 15\text{ k}\Omega$

$$\therefore \quad \text{Voltage gain, } {}^{**}A_v = \frac{\mu\, R_L}{r_p + R_L} = \frac{20 \times 15}{10 + 15} = \mathbf{12}$$

Example 5.2. *A 12 AU7 triode used as an amplifier has $\mu = 20$ and $r_p = 10$ kΩ. The load resistance is 15 kΩ. The signal voltage applied to the grid has a 3-volt peak swing. Find (i) voltage gain (ii) load current and (iii) output voltage.*

Solution. Fig. 5.7 shows the conditions of the problem.

$$\mu = 20, \quad r_p = 10\text{ k}\Omega, \quad R_L = 15\text{ k}\Omega, \quad E_g = 3\ V$$

(*i*) $$\text{Voltage Gain, } A_v = \frac{\mu\, R_L}{r_p + R_L} = \frac{20 \times 15}{10 + 15} = \mathbf{12}$$

---

* The d.c. components of current and voltage merely serve to fix the operating point and so long as they are present in their proper amount, they may be ignored while calculating the flow of a.c.

** While using this relation, the units of R_L and r_p must be the same.

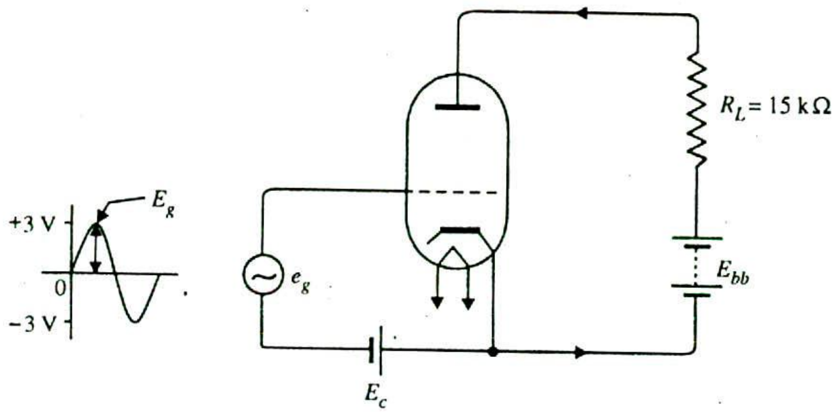


Fig. 5.7

(*ii*) Load current (r.m.s.), $I_P = \dfrac{\dfrac{\mu E_g}{\sqrt{2}}}{r_p + R_L} = \dfrac{20 \times 3 \times 0.707}{(10+15)\times 10^3} = \mathbf{1.69 \times 10^{-3}\ A}$

(*iii*) Output voltage $= I_P \times R_L$

$= 1.69 \times 10^{-3}\ A \times 15\ k\Omega = \mathbf{25.35\ V}$

Example 5.3. *The voltage gain of an amplifier using triode is 30 with load resistance of 50 kΩ and 34 with load resistance of 85 kΩ. Calculate the parameters of the triode.*

Solution.

When load resistance $R_L = 50\ k\Omega$

$$A_v = \frac{\mu R_L}{r_p + R_L}$$

or
$$30 = \frac{\mu \times 50}{r_p + 50}$$

or
$$30\, r_p + 1500 = 50\,\mu \quad \ldots(i)$$

When load resistance $R_L = 85\ k\Omega$

$$34 = \frac{\mu \times 85}{r_p + 85}$$

or
$$34\, r_p + 2890 = 85\,\mu \quad \ldots(ii)$$

Solving eqs. (*i*) and (*ii*), we get, $\mu = \mathbf{42}$ and $r_p = \mathbf{20\ k\Omega}$

$$\therefore \quad g_m = \frac{\mu}{r_p} = \frac{42}{20000\ \Omega} = \mathbf{21 \times 10^{-4}\ mho}$$

Example 5.4. *A triode of plate resistance of 2400 Ω and an amplification factor of 6 feeds a load of 3000 Ω. When the r.m.s. value of a sinusoidal voltage applied to the grid is 9V, what is the a.c. power developed in the load ?*

Solution.

R.M.S. value of a.c. plate current, $I_p = \dfrac{\mu E_g}{r_p + R_L}$

Here $\mu = 6;\ E_g = 9\ V;\ r_p = 2400\ \Omega;\ R_L = 3000\ \Omega$

$\therefore$ Plate current (*r.m.s.*), $I_p = \dfrac{6 \times 9}{2400 + 3000} = \dfrac{54}{5400} = 0.01\ \text{A}$

A.C. power in load $= I_p^2 R_L = (0.01)^2 \times 3000 =$ **0.3 W**

5.7 Self-biasing of Triode

In the absence of signal, the d.c. voltage that exists between control grid and cathode, making grid negative w.r.t. cathode, is known as **grid bias.**

It has already been explained that for faithful amplification, no current should flow in the grid circuit. This is possible only if the *net* grid-cathode voltage is always negative. In the circuit drawn so far, this was achieved by using a battery E_c in the grid circuit. However, the use of such a grid bias battery is undesirable because of its high cost and frequent replacement. Therefore, in practice, the d.c. component of plate current of the triode is itself used for obtaining grid bias voltage. Under such conditions, the triode is said to be self-biased.

The method of obtaining grid bias by using d.c. component of plate current in a triode is known as **self-biasing.**

The two most commonly used methods of self-biasing of a triode are ; *cathode bias* and *grid leak bias.* We shall discuss these two methods in turn.

(*i*) **Cathode bias.** This is the most common arrangement of obtaining grid bias in valves acting as amplifiers. In this method, a resistance R_k (called *cathode resistor*) is placed in series with the cathode circuit as shown in Fig. 5.8. The d.c. plate current I_p flowing through R_k produces a d.c. voltage drop I_pR_k across it, making control grid negative *w.r.t.* cathode. This is because the conventional plate current flows through R_k from point *P* to *Q*, thus making point *Q* (*i.e.* control grid) negative *w.r.t.* point *P* (*i.e.* cathode).

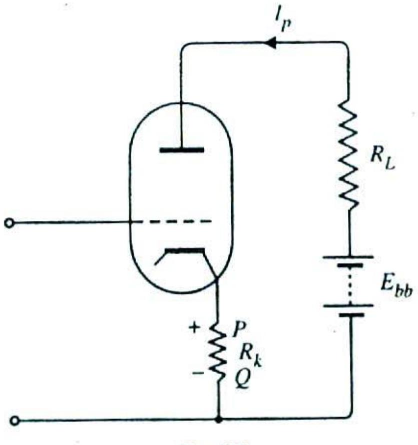


Fig. 5.8

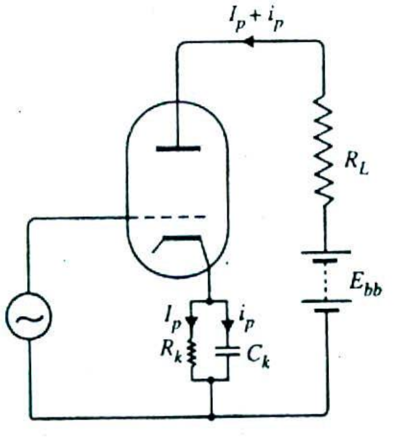


Fig. 5.9

It is very important that grid bias voltage (I_pR_k) should remain constant whether the signal is applied or not. When no signal is applied (See Fig. 5.8), the d.c. plate current I_p establishes a fixed grid bias. However, when an a.c. signal is applied, an a.c. component i_p flows in the plate circuit in addition to d.c. component I_p. The total plate current ($I_p + i_p$) flowing through R_k produces varying grid bias across R_k. In order to keep grid bias voltage fixed during the application of signal, a by-pass capacitor C_k is connected in parallel with R_k as shown in Fig. 5.9. The capacitor C_k provides an easy path for a.c. component i_p of plate current whereas the d.c. component I_p flows through R_k, thus producing a fixed grid bias voltage I_pR_k.

(*ii*) **Grid leak bias.** In this method, bias voltage is obtained by means of a capacitor C_g and high resistance R_g placed in the grid circuit as shown in Fig. 5.10. The resistance R_g is known as grid leak resistor because a small grid current leaks through it to establish grid bias.

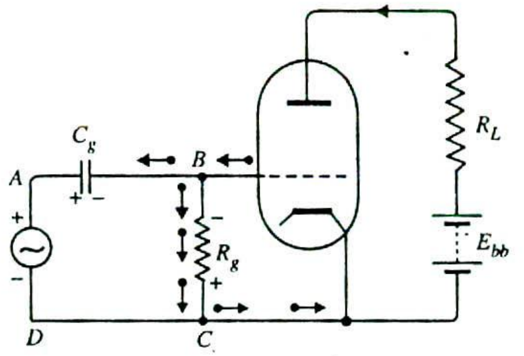


Fig. 5.10

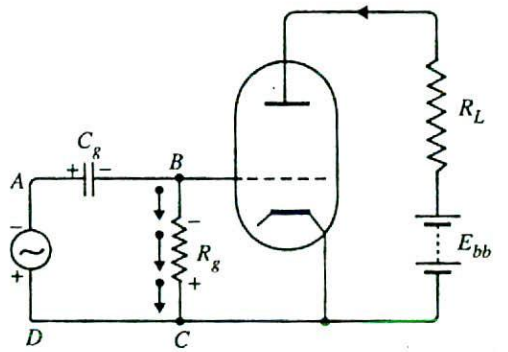


Fig. 5.11

When no signal is applied, there is no grid bias voltage because the grid current is zero and has no voltage drop across R_g. However, when an a.c. signal is applied in the grid circuit, this makes the grid alternately positive and negative *w.r.t.* cathode. During the positive half of the signal [See Fig. 5.10], the electrons are drawn by the capacitor C_g, thus making them to flow through R_g. This makes point *B* (*i.e.* grid) negative *w.r.t.* point *C* (*i.e.* cathode) and establishes the necessary grid bias. It may be noted here that the electrons flowing through R_g continue their journey to cathode and through the valve. During the negative half of signal [See Fig. 5.11], no further electrons are drawn by the grid. Some of the electrons already collected on the capacitor C_g leak through R_g, again making point *B* negative *w.r.t.* cathode.

5.8 Practical Circuit of Triode Amplifier

Figure 5.12 shows the practical circuit of a triode amplifier. The functions of the various components of the circuit are briefly discussed below :

(*i*) *Cathode resistor* R_k. The cathode resistor R_k is used to properly bias the triode. Its value ranges from 2 kΩ to 10 kΩ depending upon the design considerations.

(*ii*) *By-pass capacitor* C_k. The by-pass capacitor C_k (1 – 4 μ*F*) is connected across R_k. Its function is to provide a low reactance path to the a.c. signal. If C_k were not used, a varying voltage will develop across R_k on the application of signal. This will change the bias voltage, resulting in unfaithful amplification.

(*iii*) *Grid leak resistor* R_g. Some of the millions of electrons that travel from cathode get stuck up at the grid, thus making it too much negative. The grid leak resistor R_g (≃ 1 MΩ) provides an easy path for such electrons to return to the cathode. If R_g were not used, the grid would be driven to such a high negative potential by the electrons striking it that plate current may be cut off.

(*iv*) *Coupling Capacitor* C_c. The coupling capacitor C_c (0.01 to 0.1 μ*F*) is used to connect one stage of amplification to the next stage. Its function is to prevent the steady anode voltage of the first valve from reaching the grid of the second valve and thus overloading it.

(v) *Input capacitor* C_{in}. An input capacitor C_{in} is used to couple the signal to the grid of the tube. If it were not used, the signal source resistance would come across R_g and thus change the bias conditions. This capacitor allows only a.c. signal to flow but isolates the signal source from R_g.

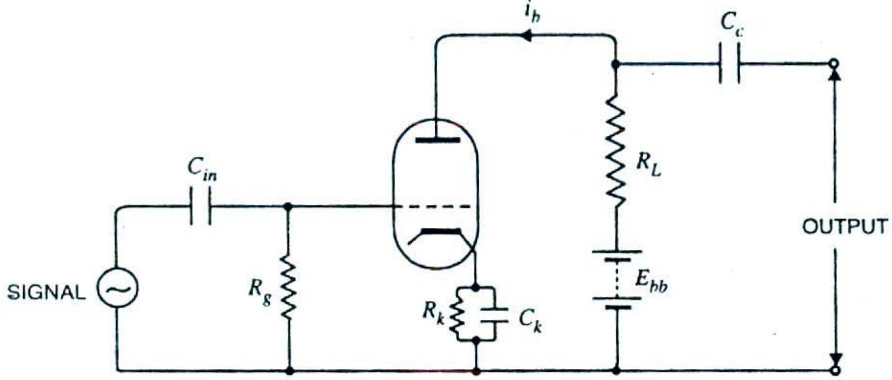


Fig. 5.12

Figure 5.13 shows the simplified and practical way of drawing the amplifier circuit. Note that output may be obtained* either (*i*) across R_L or (*ii*) across the terminals 1 and 2. In either case, the magnitude of the output will be the same.

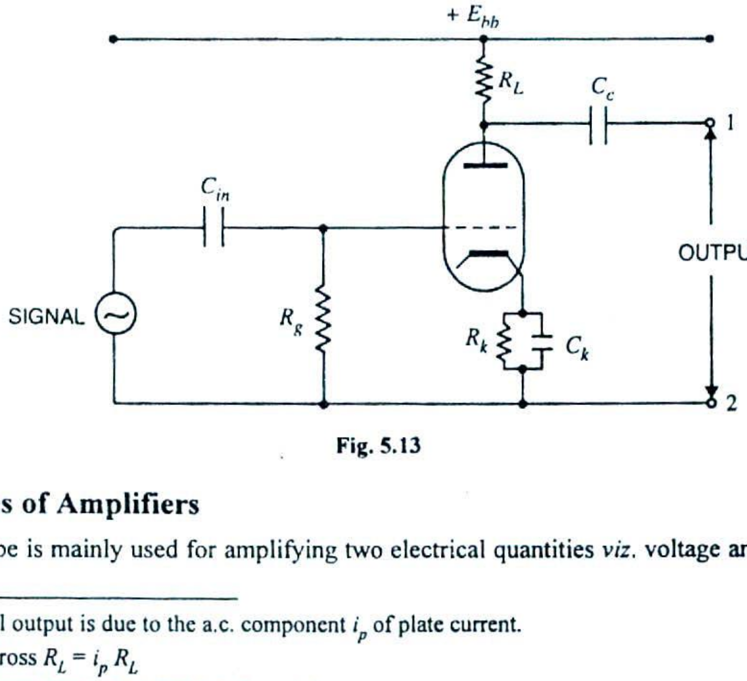


Fig. 5.13

5.9 Types of Amplifiers

A vacuum tube is mainly used for amplifying two electrical quantities *viz.* voltage and power. Ac-

* The useful output is due to the a.c. component i_p of plate current.

Output across $R_L = i_p R_L$ ...(*i*)

Output across terminals 1 and 2 $= E_{bb} - i_p R_L$

Since E_{bb} cannot pass through capacitor C_c,

$\therefore$ Output across terminals 1 and 2 $= - i_p R_L$ ...(*ii*)

Note that output across terminals 1 and 2 is the same as across R_L. The negative sign in exp. (*ii*) indicates the phase reversal.

cordingly, there are two types of amplifiers namely; *voltage amplifiers* and *power amplifiers*.

(*i*) *Voltage amplifier*. Its main function is to raise the voltage level of the signal. Although a voltage amplifier may also build up power to some extent, but this is of secondary interest. The design of voltage amplifier incorporates two features *viz*., high amplification factor μ and high plate resistance R_L. The result is that output voltage is considerably higher than the input voltage.

(*ii*) *Power amplifier.* Its main function is to raise the power level of the signal. Although the voltage level may be built up to some extent but this is of secondary interest. The power amplifier is designed to have small μ and low R_L. This results in the large plate current and hence greater power output.

5.10 Classification of Amplifiers

Voltage or power amplifiers may be classified in several*ways. However, they (**particularly power amplifiers) are frequently classified according to their *mode of operation i.e.* plate current flow during various parts of the signal. The flow of plate current would obviously depend upon the grid bias voltage and the signal magnitude. On the basis of plate current flow during various parts of the signal, the amplifiers are classified as *class A amplifiers*, *class B amplifiers* and *class C amplifiers*.

1. Class A amplifiers. The amplifiers in which the grid bias is so chosen that plate current flows during whole of the signal cycle are known as *class A amplifiers*. Clearly, for this to happen, the amplifier tube must operate on the linear portion of the dynamic characteristic as shown in Fig. 5.14. An inspection of the figure reveals that input signal is faithfully reproduced in the output.

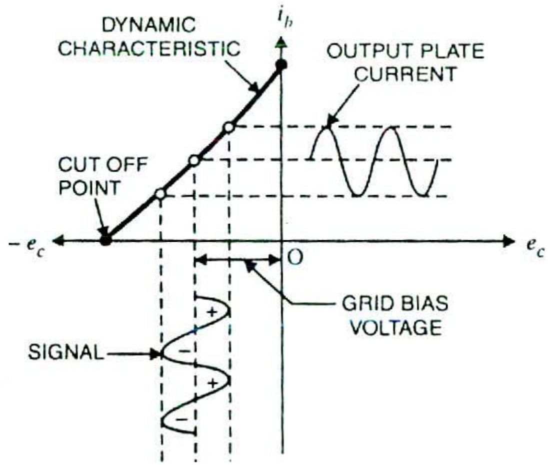


Fig. 5.14

Advantages :

(*i*) There is little distortion *i.e.* output wave shape is exactly similar to the input wave shape, though much amplified.

(*ii*) The power amplification is almost infinite. The class A amplifier is always operated at a negative grid bias. Consequently, no grid current flows and the power amplification, which is the ratio of output power divided by input power (almost zero) is, therefore, very high.

Disadvantages :

(*i*) They have †low efficiency (about 25%). The remaining power (75%) is dissipated in the valve.

---

* They may be classified as to signal frequency (*e.g.* audio frequency, high frequency amplifiers), *methods of coupling* (*e.g.* R-C coupled, transformer-coupled amplifiers) *etc.*

** Voltage amplifiers are usually operated in class *A* operation only.

† Amplifier efficiency $= \dfrac{\text{a.c. power output}}{\text{d.c. power input}}$

The plate current flows at all times in class A operation. At low values of grid voltage, the a.c. component of plate current is very small as compared to zero signal plate current. The result is that a.c. power component is comparatively a small fraction of d.c. power input.

(*ii*) Due to poor efficiency, the output is quite low.

Class A amplifiers are used where distortionless output is the prime requisite *e.g.* voltage amplifiers, audio power amplifiers.

2. Class B amplifiers. The amplifiers in which the grid bias is so chosen that plate current flows during the positive half cycle of the signal only are known as *class B amplifiers*. Obviously, for this to happen, the grid is biased near to cut off value as shown in Fig. 5.15. An inspection of the figure reveals that plate current flows during positive half-cycles of signal only. However, during negative half-cycles of the signal, the grid is driven so much negative that no plate current flow is possible.

Advantages :

(*i*) The efficiency of operation is fairly good (about 50%). As the grid is biased to cut off value, therefore, plate current flows only when the signal is applied. Consequently, most of the plate current represents power.

(*ii*) Due to improved efficiency, fairly good power output is obtained.

Disadvantages :

(*i*) The output is distorted since negative half-cycles of input do not appear in the output.

(*ii*) The power amplification is less than that of class A amplifier.

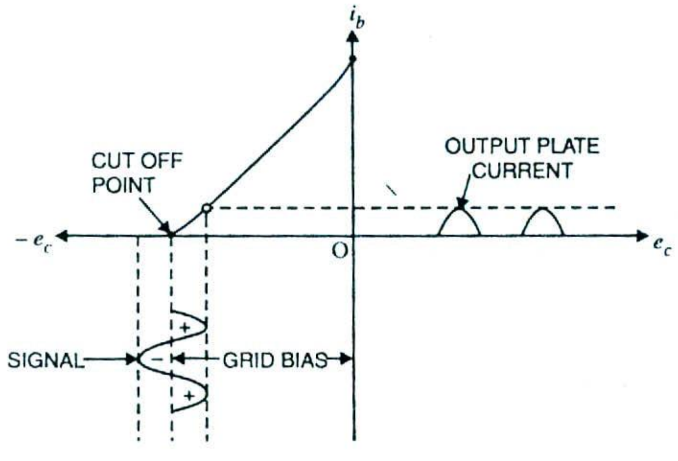


Fig. 5.15

Applications :

In class *B* operation, the output waveform of the positive half-cycles is fairly good but negative half-cycles do not appear at all. However, it is possible to arrange two class *B* tubes in a circuit known as *push-pull circuit*. One tube amplifies the positive half-cycle of the signal and the other tube amplifies the negative half-cycle. In this way, both half-cycles of the input signal appear in the output with the added advantages of higher output and efficiency. Push-pull circuit is, therefore, widely used for power amplification.

3. Class *C* amplifiers. The amplifiers in which grid bias is greater than cut off value so that plate current flows for less than half of the input signal cycle are known as *class C amplifiers*. The class *C* operation is illustrated graphically in Fig. 5.16 where the grid is operated at a negative high value of grid bias. The features of Class *C* amplifiers are high distortion, high power output and excellent efficiency (about 75%). Because of their inherent distortion, the use of class *C* amplifiers is only limited to oscillators and final stages of radio transmitters where higher efficiency rather than distortion is important.

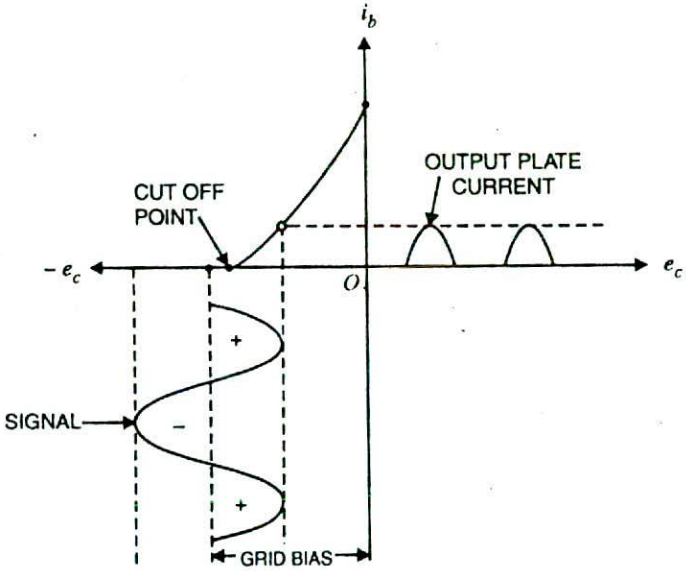


Fig. 5.16

5.11 Amplifier Coupling Methods

The output from a *single amplifier stage is usually insufficient to drive an output device such as a loudspeaker. Additional amplification over two or three stages is generally necessary. To accomplish this, output of each amplifier stage is electrically *coupled* to the grid of the next amplifier tube as shown in Fig. 5.17. The manner in which the output of one stage is fed for amplification to the next stage is called coupling. There are several methods of coupling one stage of amplification to another. In each method, the object is

(*i*) to transfer a.c. output of one stage to the input of the next stage.

(*ii*) to isolate the **d.c. conditions of one stage from the other.

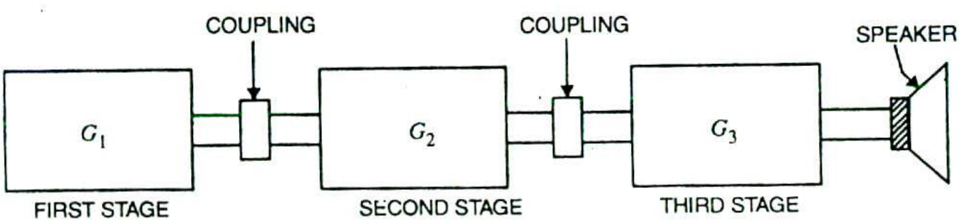


Fig. 5.17

Fig. 5.17 shows three stages of amplification. If the gains of respective stages are G_1, G_2 and G_3, then the total gain G is given by ;

* A single amplifier stage consists of a single triode (or any other grid-controlled tube) and associated circuit such as plate load, grid bias circuit *etc.*

** except for direct coupled amplifiers.

$$G = G_1 \times G_2 \times G_3$$

The most commonly used coupling methods are *R-C coupling, impedance coupling* and *transformer coupling*.

5.12 Resistance-Capacitance (R-C) Coupled Amplifiers

This is the most popular type of coupling and is employed in the voltage amplification stage. Fig. 5.18 shows two stages of *R-C* coupled amplifier. A resistance R_L is used as a plate load and capacitor C_c (0.01 to 0.1 μF) is used to connect the output of one stage to the grid of the next stage. Here, R_L and C_c form the coupling network and hence the name *R-C* coupled amplifier. The $R_k - C_k$ combination forms the biasing network. The input capacitor C_{in} allows only the a.c. signal to flow.

Operation. When the input signal of r.m.s. value E_g is applied to the grid of first valve V_1, it appears in the amplified form across plate load R_L. The output across R_L of valve V_1 is given to the grid of valve V_2 through the coupling capacitor C_c. The second stage further does amplification. It may be added here that coupling capacitor performs two useful functions *viz* :

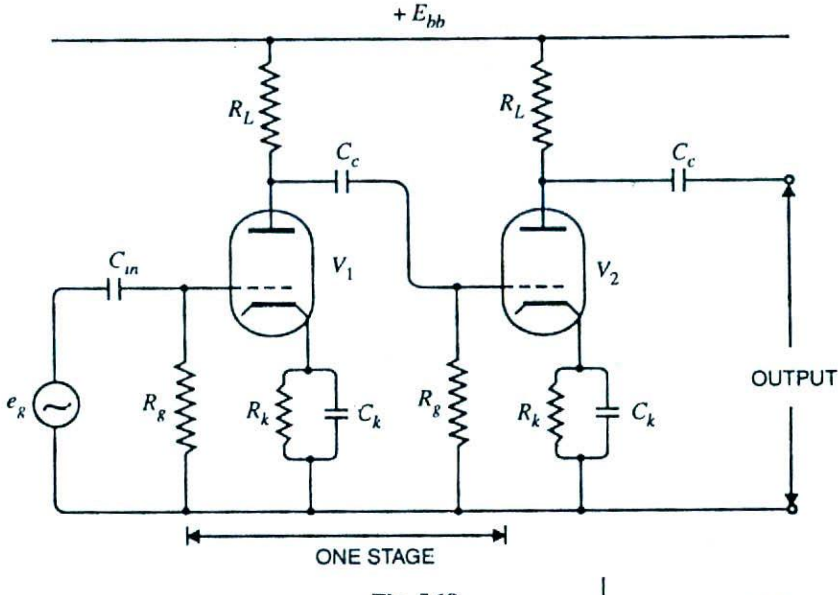


Fig. 5.18

(*i*) it offers low reactance to a.c. ; allowing a.c. output of V_1 to be transferred to the grid of V_2.

(*ii*) it *prevents the high positive voltage on the plate of V_1 from reaching the grid of next valve V_2 since a capacitor can only pass a.c.

Frequency response. The voltage gain of an amplifier varies with signal frequency. The curve between voltage gain and signal frequency of an amplifier is known as *frequency response*. Fig. 5.19 shows the frequency response of an *R-C*

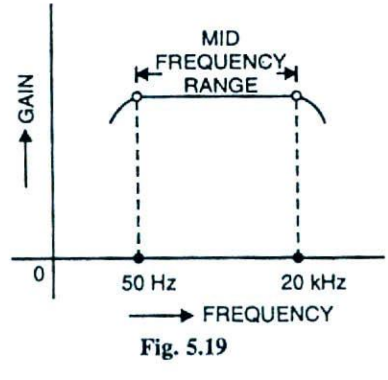


Fig. 5.19

* If C_c is not used, then full positive voltage of valve V_1 will be applied to the grid of valve V_2. This will result in extremely high value of grid current in V_2 and the grid structure would probably melt. Moreover, unfaithful amplification will result as grid is driven positive.

coupled amplifier. The following points may be noted :

(*i*) The gain is small at *low frequencies* (<50Hz). It is because C_c offers very high reactance at low frequencies and, therefore, part of a.c. output of the first stage is lost across it.

(*ii*) The gain is constant in the *mid-frequency* range (50 Hz–20 kHz). This is also the audio frequency range e.g. music, speech etc.

(*iii*) The gain is small at high frequencies due to the *shunting effect of plate to cathode capacitance.

Advantages :

(*i*) An *R-C* coupled amplifier has lower cost since it employs resistors and capacitors which are quite cheap.

(*ii*) It occupies less space and weight since modern resistors and capacitors are quite small and extremely light.

(*iii*) It has better frequency response. It is because the gain in mid-frequency region, which is the region of most importance for speech, music etc., is nearly constant.

Disadvantages :

(*i*) The gain of an *R-C* coupled amplifier is comparatively small. It is because the effect of loading of the next stage is appreciable which results in the lower effective load and hence less gain.

(*ii*) They tend to become noisy with the passage of time.

(*iii*) Impedance matching is poor.

Applications. R-C coupled amplifiers are used for voltage amplification e.g. in the initial stages of public address system or in the initial stages of a radio receiver.

5.13 Choke-Capacitance Coupled Amplifiers

A choke-capacitance amplifier differs from *R-C* coupled amplifier only in respect of load. The load for choke-capacitance amplifier is a choke coil of large inductance and negligible resistance. Fig. 5.20 shows the two stages of a choke-capacitance coupled amplifier. The circuit is similar to *R-C* coupled amplifier except that the load is a choke coil *L* instead of high resistance. Here, L-C_c forms the coupling network and hence the name choke-capacitance coupled amplifier.

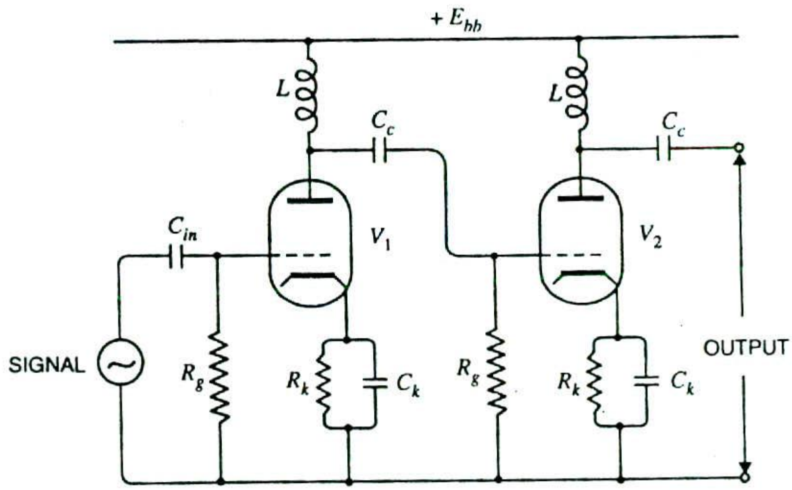


Fig. 5.20

* The effect of plate-cathode capacitance is that load resistance is shunted by an a.c. path. The greater the frequency, lower is the impedance of this shunting path. Therefore, effective load impedance is reduced and hence the gain.

When the signal is applied to grid of first valve V_1, it appears in the amplified form across plate load L. The output across L of valve V_1 is given to the grid of the next valve V_2 through coupling capacitor C_c. The second stage renders further amplification.

Advantages :

(*i*) Lesser supply voltage E_{bb} is required. It is because there is a very little d.c. voltage drop in L due to d.c. plate current flow.

(*ii*) Very little d.c. power is wasted in inductive load L as it possesses small resistance.

(*iii*) Higher voltage amplification can be obtained.

Disadvantages :

(*i*) Frequency response is poorer than *R-C* coupling.

(*ii*) More costly due to high cost of choke.

(*iii*) Core saturation effects of choke due to direct current.

Due to poor frequency response, *L-C* coupling is rarely employed except for amplifying a narrow range of frequencies.

5.14 Transformer Coupled Amplifiers

This type of coupling is mostly employed for power amplification. Fig. 5.21 shows two stages of transformer coupled amplifier. A transformer T (called *coupling transformer*) is used to feed the output of one stage to the input of the next stage. The primary P of this transformer is made plate load of valve V_1 and its secondary S gives the input to the grid of the next valve V_2.

Operation. When an a.c. signal is applied to the grid of first valve V_1, this causes an amplified a.c. to flow through the plate circuit of V_1 and hence primary P of the coupling transformer. The inductive reactance of transformer primary multiplied by the plate current (r.m.s. value) gives the output voltage appearing in the plate circuit of valve V_1. This amplified voltage in the primary is transferred to the input of the next stage by transformer secondary as shown in Fig. 5.21. The second stage does amplification in an exactly similar way.

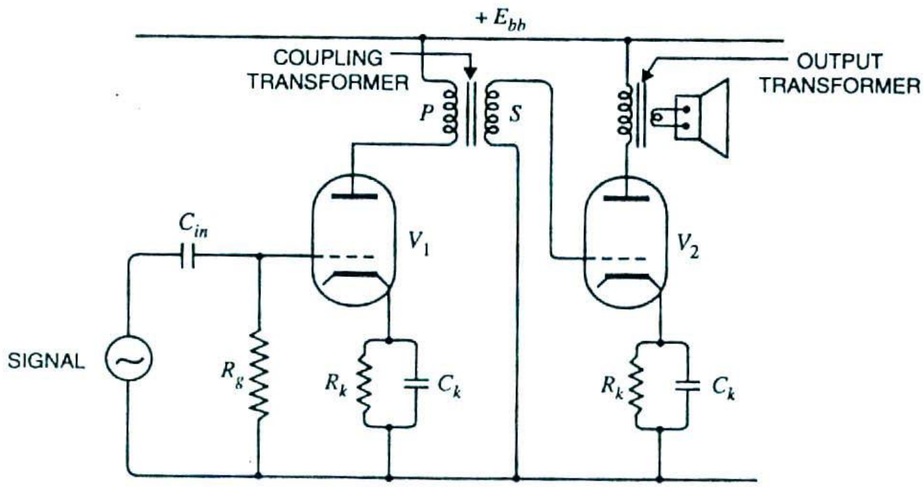


Fig. 5.21

Frequency response. The frequency response of a transformer coupled amplifier is shown in Fig. 5.22. It is clear from the curve that frequency response is very poor. This can be explained as under :

Output voltage across P = Plate load × plate current

= Reactance of primary P × plate current

The reactance of primary P depends upon frequency. Lower is the frequency, lesser is the plate load and hence smaller is the gain. This results in a disproportionate amplification of frequencies in a complete signal such as music, with lower frequencies getting amplified to smaller extent and higher frequencies to greater extent.

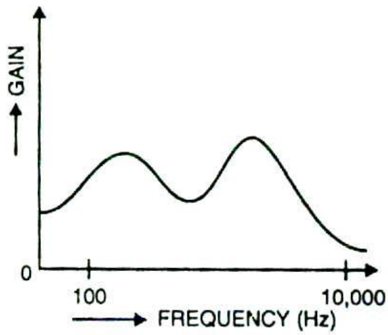


Fig. 5.22

Advantages :

(*i*) High gain can be obtained by using step-up coupling transformer.

(*ii*) An excellent impedance matching can be achieved in a transformer coupled amplifier.

Disadvantages :

(*i*) It gives poor frequency response.

(*ii*) Coupling transformers are bulky and fairly expensive.

(*iii*) Frequency distortion is higher i.e. low frequency signals are less amplified as compared to high frequency signals.

Applications. It is used for power amplification e.g. in the output stage. It is because in the output stage of an amplifier, we want to transfer power (rather than voltage) to a load. Maximum power can be transferred only by impedance matching which is excellently done by transformer coupled amplifiers.

Example 5.5. *The parameters of a certain power triode are $\mu = 20$, $r_p = 1000\ \Omega$. If a loudspeaker having a resistance of $10\ \Omega$ is to be supplied through a transformer from this triode, find (i) transformation ratio for transfer of maximum power (ii) the power supplied to the speaker when the r.m.s. value of signal voltage is 8V.*

Solution. Fig. 5.23 (*i*) shows triode supplying power to the loudspeaker through a transformer.

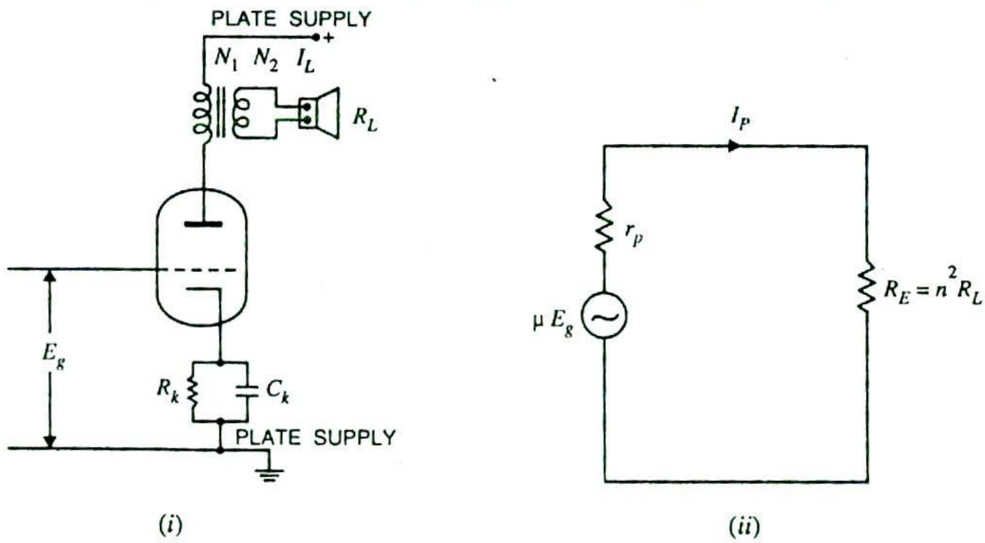


Fig. 5.23

Let I_L = r.m.s. value of secondary current

I_p = r.m.s. value of a.c. component of plate current

R_L = resistance of the loudspeaker

$$n = \frac{N_1}{N_2} = \frac{\text{No. of primary turns}}{\text{No. of secondary turns}}$$

R_E = equivalent resistance of loudspeaker referred to primary $= n^2 R_L$

The equivalent circuit of triode power amplifier is shown in Fig. 5.23 (*ii*).

(*i*) In order to transfer maximum power to the speaker,

$$r_p = n^2 R_L$$

or

$$n = \sqrt{\frac{r_p}{R_L}} = \sqrt{\frac{1000}{10}} = \mathbf{10}$$

(*ii*) Maximum power absorbed by the load (*i.e.*, speaker) is

$$P_{max} = I_p^2 R_E = \left(\frac{\mu E_g}{r_p + R_E}\right)^2 R_E$$

$$= \left(\frac{\mu E_g}{2 r_p}\right)^2 r_p \qquad (\because R_E = r_p)$$

$$\therefore \quad P_{max} = \frac{(\mu E_g)^2}{4 r_p} = \frac{(20 \times 8)^2}{4 \times 1000} = \mathbf{6.4\ W}$$

5.15 Stages of a Practical Power Amplifier

A practical power amplifier has two main stages of amplification *viz.* voltage amplification stage and output stage [See Fig. 5.24].

(*i*) *Voltage amplification stage.* Here, the voltage level of the weak signal is raised by employing two or more than two stages of voltage amplification. Generally, *R-C* coupled amplifiers are used.

(*ii*) *Output stage.* This is the final stage and feeds power directly to the load *e.g.* speaker. This stage essentially consists of a power amplifier and its purpose is to transfer maximum power to the load.

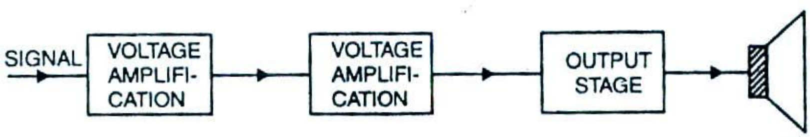


Fig. 5.24

As power handled by the output stage is quite large, therefore, current in the output stage is quite high. If a single tube is used, it can only be employed as a class *A* amplifier for *faithful amplification. But the power efficiency of class *A* operation is very low. In order to have high efficiency, the output stage generally employs two tubes in class *B* operation. This is known as *push-pull* arrange-

* It is because only in class *A* operation, the complete signal (+ *ve* and – *ve* half) is obtained in the output.

ment. One tube amplifies the positive half-cycle of the signal and the other tube amplifies the negative half-cycle of the signal.

5.16 Push-Pull Amplifier

The power efficiency of a class *A* amplifier is quite low (about 25%). In order to increase the efficiency in power amplification, two tubes are used in **push-pull* arrangement in the output stage. One tube amplifies the positive half-cycle of the signal while the other tube amplifies the negative half-cycle of the signal.

Circuit details. Fig. 5.25 shows the circuit where two tubes V_1 and V_2 are used in push-pull. Both the tubes are operated in class *B* operation *i.e.* plate current is nearly zero in the absence of the signal. The centre-tapped secondary of the input transformer T_1 supplies equal and opposite voltages to the grid circuits of the two tubes. The output transformer T_2 has centre-tapped primary. The output is taken across the secondary of output transformer T_2.

Operation. Suppose during the positive half cycle of the signal (*marked* 1), the end *A* of the input transformer is positive and end *B* is negative. This will make the grid of valve V_1 more **positive and that of valve V_2 more negative. Thus valve V_1 conducts (solid arrow heads) and valve V_2 is †cut off. Therefore, this half-cycle of the signal is amplified by valve V_1 and appears in upper half of the output transformer primary. In the next half-cycle of the signal (*marked* 2), valve V_2 conducts (dotted arrow heads) and valve V_1 is cut off. Therefore, this half-cycle of the signal is amplified by valve V_2 and appears in the lower half of output transformer primary.

The plate currents flow on alternate half-cycle of the signal through the centre-tapped primary of the output transformer and since they are in opposite direction, the effect is the same as a normal sine wave a.c. (See Fig. 5.25). This induces voltage in the secondary of the output transformer.

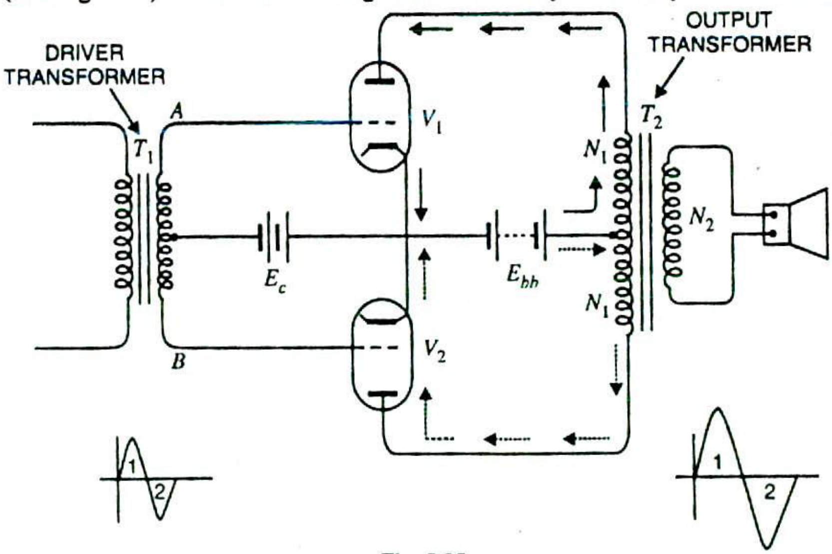


Fig. 5.25

* So called because when one tube is *pushing* (conduction), the other is *pulling* (stopping conduction).

** This does not mean that either grid will actually become positive. It cannot happen because the d.c. grid bias keeps both grids at a negative potential.

† Both valves are operating in class *B* operation *i.e.* they are biased to cut off. Here, grid of valve V_1 becomes less negative and grid of valve V_2 more negative. Hence V_2 does not conduct.

Advantages :

(*i*) The efficiency is much higher (about 80%).

(*ii*) As d.c. plate currents of the two tubes flow in opposite directions in the two halves of the output transformer primary, therefore, core saturation effect is eliminated.

(*iii*) For the same plate dissipation, the output power is nearly 5 times that of a single tube amplifier.

(*iv*) The signal input voltage is divided between the two halves of the input transformer. Therefore, the input circuit can handle double the grid voltage of single tube operating as class *A* amplifier.

Disadvantages :

(*i*) Two tubes have to be used.

(*ii*) There may be unequal amplification of two halves of the signal if the parameters (μ, g_m, r_p) of the two tubes are not equal.

Applications. It is used in the final stages of a power amplifier *e.g.* public address system.

Multiple-Choice Questions

1. For faithful amplification, the control grid should be .... *w.r.t.* cathode.
   (*i*) positive (*ii*) at zero potential
   (*iii*) negative (*iv*) none of the above
2. The actual voltage gain of a triode amplifier is less than μ due to ....
   (*i*) grid being negative *w.r.t.* cathode
   (*ii*) voltage drop in the a.c. resistance of the tube
   (*iii*) plate being positive *w.r.t.* cathode
   (*iv*) none of the above
3. The output and input voltages of a grounded cathode amplifier have a phase difference of ....
   (*i*) 90° (*ii*) 0°
   (*iii*) 270° (*iv*) 180°
4. A voltage amplifier is designed to have ....
   (*i*) high μ and R_L
   (*ii*) high r_p and low R_L
   (*iii*) low μ and high R_L
   (*iv*) none of the above
5. The best frequency response is provided by........
   (*i*) transformer coupling
   (*ii*) direct coupling
   (*iii*) R.C. coupling
   (*iv*) impedance coupling
6. The output stage of a practical amplifier always employs ....
   (*i*) R.C. coupling
   (*ii*) direct coupling
   (*iii*) transformer coupling
   (*iv*) impedance coupling
7. Voltage amplifiers are operated as .... amplifiers.
   (*i*) class A (*ii*) class C
   (*iii*) class B (*iv*) none of the above
8. The plate efficiency of class *A* amplifier is about ....
   (*i*) 50% (*ii*) 70%
   (*iii*) 5% (*iv*) 30%
9. .... operation results in severe distortion.
   (*i*) Class C (*ii*) Class A
   (*iii*) Class B (*iv*) none of the above
10. The best tube for high-frequency application is ....
    (*i*) triode valve (*ii*) pentode valve
    (*iii*) tetrode valve (*iv*) none of the above
11. The maximum plate efficiency for class B operation is ....
    (*i*) 50% (*ii*) 40%
    (*iii*) 78.5% (*iv*) 35%
12. The input impedance of a vacuum tube amplifier is ....
    (*i*) zero (*ii*) small
    (*iii*) large (*iv*) data insufficient
13. In a vacuum tube amplifier, grid bias is provided by ....

(*i*) a bias battery
(*ii*) a bias resistor
(*iii*) mains a.c. voltage
(*iv*) none of the above

14. The magnitude of bias voltage is determined by ....
(*i*) plate supply voltage
(*ii*) filament voltage
(*iii*) load resistance
(*iv*) magnitude of signal

15. If no bias is employed in a vacuum tube amplifier, then ....
(*i*) plate current may increase
(*ii*) there will be distortion in the output
(*iii*) electron emission will not be proper
(*iv*) tube may burn

16. If a single tube is used in the output stage of a practical amplifier, it must have .... operation.
(*i*) class A (*ii*) class B
(*iii*) class C (*iv*) none of the above

17. In order to obtain maximum voltage gain, ... coupling should be employed.
(*i*) RC (*ii*) direct
(*iii*) transformer (*iv*) impedance

18. Power amplifiers are generally operated in .... operation.
(*i*) class A (*ii*) class B
(*iii*) class C (*iv*) none of the above

19. For the same plate dissipation, the output power of a class B push-pull amplifier is nearly .... that of a class *A* amplifier.
(*i*) 2 times (*ii*) 3 times
(*iii*) 2.4 times (*iv*) 5 times

20. Direct coupling is used for .... amplification.
(*i*) very low frequency
(*ii*) audio frequency
(*iii*) radio frequency
(*iv*) ultra high frequency

Answers to Multiple-Choice Questions

1. (*iii*)	**2.** (*ii*)	**3.** (*iv*)	**4.** (*i*)	**5.** (*ii*)
6. (*ii*)	**7.** (*i*)	**8.** (*iv*)	**9.** (*i*)	**10.** (*ii*)
11. (*iii*)	**12.** (*iii*)	**13.** (*ii*)	**14.** (*iv*)	**15.** (*ii*)
16. (*i*)	**17.** (*iii*)	**18.** (*ii*)	**19.** (*iv*)	**20.** (*i*)

Chapter Review Topics

1. What do you understand by vacuum tube amplifier ? Explain the action of a triode amplifier.
2. What do you mean by faithful amplification ? How will you achieve it in a vacuum tube amplifier ?
3. Describe the action of triode amplifier graphically.
4. Obtain the a.c. equivalent circuit of a triode and hence derive the expression for voltage gain.
5. What do you understand by triode biasing ? Explain any two methods of self-biasing a triode.
6. Draw the circuit of a practical triode amplifier and explain the function of each component.
7. What do you understand by coupling of amplifiers ? What is its need ?
8. Describe the characteristics of class *A*, *B* and *C* amplifiers.
9. Describe the circuit details, working, advantages and disadvantages of : (*i*) *R-C* coupled amplifiers. (*ii*) Choke-capacitance coupled amplifiers. (*iii*) Transformer-coupled amplifiers.
10. Explain the working of a push-pull amplifier with a neat sketch. What are the advantages and disadvantages of this circuit ?
11. Write short notes on the following :
(*i*) Operating point (*ii*) Phase reversal (*iii*) Stages of a practical power amplifier.

Problems

1. Find the voltage gain of a triode amplifier if $\mu = 30$, $r_p = 20$ kΩ and plate load $R_L = 10$ kΩ. **[10]**
2. Find the output voltage for a triode amplifier if $r_p = 20$ kΩ, $R_L = 10$ kΩ and input voltage = 5 V. Take $\mu = 50$. **[43.3V]**
3. A triode amplifier has mutual conductance 0.5 mA/V and plate resistance $r_p = 13$ kΩ. Find (*i*) the voltage amplification for a resistive load of 40 kΩ (*ii*) the power output when a sinusoidal signal of peak value 2V is applied to the grid. **[(*i*) 4.9 (*ii*) 1.2 mW]**
4. The slope of I_b/E_b characteristic of a triode is 0.2 mA/volt and that of I_b/E_c characteristic 1.3 mA/volt. If plate load $R_l = 8$ kΩ, find the voltage amplification. **[4]**
5. A pentode having a mutual conductance of 1 mA/V and a.c. plate resistance of 800 kΩ is used as a voltage amplifier with a resistive load of 50 kΩ. Calculate the voltage amplification obtained. **[47]**
6. The peak value of a sinusoidal voltage applied to the grid of a triode is 1V. The valve has a plate resistance of 9kΩ and an amplification factor 18 and the load resistance is 20 kΩ. Find (*i*) the r.m.s. value of alternating component of plate current (*ii*) the r.m.s. value of alternating voltage across the load and (*iii*) the voltage amplification of the system. **[(*i*) 0.439 mA (*ii*) 8.78 V (*iii*) 12.4]**
7. A triode has an amplification factor of 20 and a.c. plate resistance of 10 kΩ. Determine the r.m.s. value of a.c. component of voltage across a purely resistive load of 50 kΩ when an r.m.s. voltage of 1.8 V is applied between grid and cathode. **[30V]**
8. A triode has the following parameters : $r_p = 4$ kΩ and $g_m = 3$mA/V. This triode is to supply power to a loudspeaker through an ideal transformer. If the resistance of loudspeaker is 20 Ω, calculate (*i*) the ratio of transformation for maximum power transfer and (*ii*) the power supplied to the speaker when the signal voltage applied to the grid has an r.m.s. value of 2V. **[(*i*) 14.14 : 1 (*ii*) 36 mW]**

Discussion Questions

1. Why cannot vacuum diode do amplification ?
2. Why is coupling necessary in multistage amplifiers ?
3. Why are voltage amplifiers always operated in class *A* operation ?
4. Why are power amplifiers generally operated in class *B* operation ?
5. Why is the efficiency of class *A* operation low ?
6. Why is transformer coupling used for power amplification ?

6

Gas-Filled Tubes

Introduction

In the vacuum tubes we have been discussing so far, the electrons flow from cathode to anode in vacuum. In such tubes, extreme care is taken to produce as perfect a vacuum as possible to prevent ionisation of gases and the resulting large uncontrolled currents. It may be recalled that the secret of triode is the fine control of free electrons within valve by the electrostatic fields of grid and anode. If gas is present even in small amount, the electrons flowing from cathode to anode will cause ionisation of the gas. The ionised molecules would interfere with the control and make the device useless as an amplifier.

In certain applications, fine control of electrons within the valve is of less importance than the efficient handling and turning on and off of heavy currents. In such situations, some inert gases (*e.g.* argon, neon, helium) at low pressures are purposely introduced into the valve envelope. Such tubes are known as *gas-filled tubes*. The gas-filled tubes are capable of doing various jobs that vacuum tubes cannot perform and which are especially useful in industrial and control circuits. In this chapter, we shall focus our attention on some important types of gas-filled tubes with special reference to their characteristic properties.

6.1 Gas-Filled Tubes

A **gas-filled** *tube is essentially a vacuum tube having a small amount of some inert gas at low pressure.*

The gas pressure in a gas-filled tube usually ranges from 10mm of Hg to 50mm. The construction of gas-filled tubes is similar to that of vacuum tubes, except that the cathodes, grids and anodes are usually larger in order to carry heavier current. However, the characteristic properties of the two are markedly different. Firstly, a gas-filled tube can conduct much *more current than the equivalent vacuum tube. It is because the electrons flowing from cathode to anode collide with gas molecules and ionise them *i.e.* knock out electrons from them. The additional electrons flow to the anode together with the original electrons, resulting in the increase in plate current. Secondly, a gas filled tube has far less control on the electrons in the tube than that of vacuum tube. Once the ionisation starts, the control of gas-filled tube is tremendously reduced.

Classification. Gas-filled tubes are usually classified according to the type of electron emission employed. On this basis, they may be classified into two types namely; *cold-cathode type* and *hot-cathode type.*

* The ability of a gas-filled tube to carry large current is, of course, no recommendation in itself. A copper wire will do the same thing and with better efficiency. But a gas filled tube has one special ability which the wire does not possess ; the ability to carry current in one direction.

Cold-cathode type. In this type of gas-filled tubes, the cathode is not heated as in a vacuum tube. The ionisation of the gas is caused by the energy available from natural sources such as cosmic rays, sun rays or radioactive particles in air. These natural sources are the underlying reasons for the start of conduction in cold-cathode gas tubes. Most cold-cathode tubes are used as diodes.

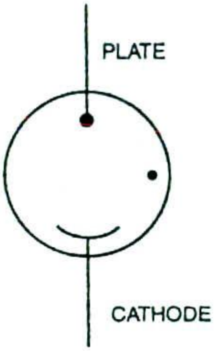


Fig. 6.1

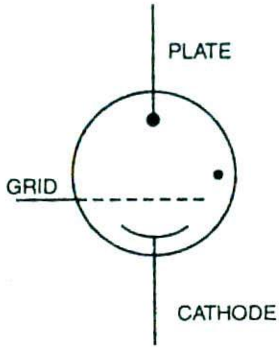


Fig. 6.2

Fig. 6.1 shows the schematic symbol for a cold-cathode gas diode, known as *glow tube*. The dot within the circle indicates the presence of gas. Fig. 6.2 shows the schematic symbol of cold-cathode gas triode, known as *grid glow tube*.

Hot-cathode type. In this type of gas-filled tubes, the cathode is heated just as in an ordinary vacuum tube. The electrons flowing from cathode to plate cause ionisation of the gas molecules. Such tubes are used as diodes, triodes and tetrodes.

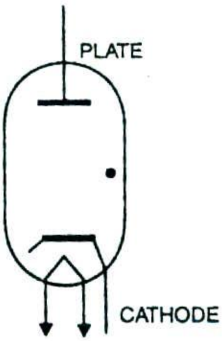


Fig. 6.3

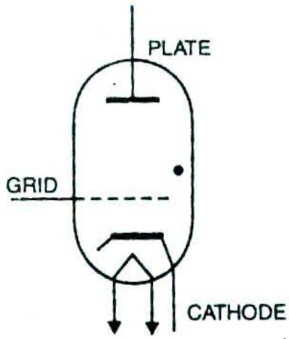


Fig. 6.4

Fig. 6.3 shows the schematic symbol of a hot-cathode gas diode, known as *phanotron* whereas Fig. 6.4 shows the symbol of hot-cathode gas triode, known as *thyratron*.

6.2 Conduction in a Gas

A gas under ordinary pressure is a perfect insulator and cannot conduct current. However, if the gas pressure is low, it is possible to produce a large number of free electrons in the gas by the process of ionisation and thus cause the gas to become a conductor. This is precisely what happens in gas-filled tubes. The current conduction in a gas at low pressure can be beautifully illustrated by referring to the hot-cathode gas diode shown in Fig. 6.5. The space between cathode and anode of the tube contains gas molecules. When cathode is heated, it emits a large number of electrons. These electrons form a cloud of electrons near the cathode, called **space charge.** If anode is made positive *w.r.t.*

cathode, the electrons (black dots) from the space charge speed towards the anode and collide with gas molecules (white circles) in the tube.

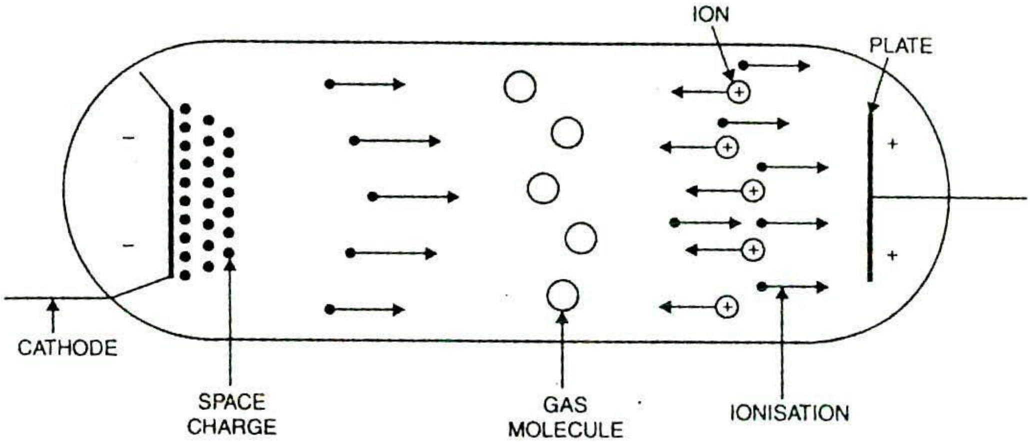


Fig. 6.5

If the anode-cathode voltage is low, the electrons do not possess the necessary energy to cause ionisation of the gas. Therefore, the plate current flow in the tube is only due to the electrons emitted by the cathode. As the anode-cathode voltage is increased, the electrons acquire more speed and energy and a point-called *ionisation voltage* is reached, where ionisation of the gas starts. The ionisation of gas produces free electrons and positive gas ions (white circles with +ve signs). The additional free electrons flow to the anode together with the original electrons, thus increasing plate current. However, the increase in plate current due to these added electrons is practically negligible. But the major effect is that the positive gas ions slowly drift towards the cathode and neutralise the space charge. Consequently, the resistance of the tube decreases, resulting in large plate current. *Hence, it is due to the neutralisation of space charge by the positive gas ions that plate current in a gas tube is too much increased.*

The following points may be noted regarding the conduction in a gas at low pressure :

(*i*) At low anode-cathode voltage, the ionisation of the gas does not occur and the plate current is about the same as for a vacuum tube at the same anode voltage.

(*ii*) At some anode-cathode voltage, called ionisation voltage, ionisation of the gas takes place. The plate current increases dramatically to a large value due to the neutralisation of space charge by the positive gas ions. The ionisation voltage depends upon the type and pressure of gas in the tube.

(*iii*) Once ionisation has started, it is maintained at anode-cathode voltage much lower than ionisation voltage. However, minimum anode-cathode voltage, called *deionising voltage*, exists below which ionisation cannot be maintained. Under such conditions, the positive gas ions combine with electrons to form neutral gas molecules and conduction stops. Because of this switching action, a gas-filled tube can be used as an electronic switch.

6.3 Cold-Cathode Gas Diode

Fig. 6.6 shows the cut-away view of cold-cathode gas diode. It essentially consists of two electrodes, cathode and anode, mounted fairly close together in an envelope filled with some inert gas at low pressure. The anode is in the form of a thin wire whereas cathode is of cylindrical metallic surface having oxide coating. The anode is always held at positive potential *w.r.t.* cathode.

Operation. Fig. 6.7 shows a circuit that can be used to investigate the operation of cold-cathode gas diode. Electric conduction through the tube passes through three successive discharge phases *viz.* Townsend discharge, the glow discharge and the arc discharge.

(*i*) **Townsend discharge.** At low anode-cathode voltage, the tube conducts an extremely small current (1mA). It is because the cathode is cold and as such no source of electrons is present. However, natural sources (*e.g.* cosmic rays *etc.*) cause some ionisation of the gas, creating a few free electrons. These electrons move towards the anode to constitute a small current. This stage of conduction is known as **Townsend discharge.* In this phase of conduction, no visible light is associated.

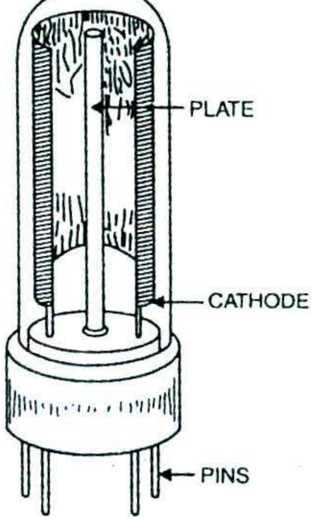


Fig. 6.6

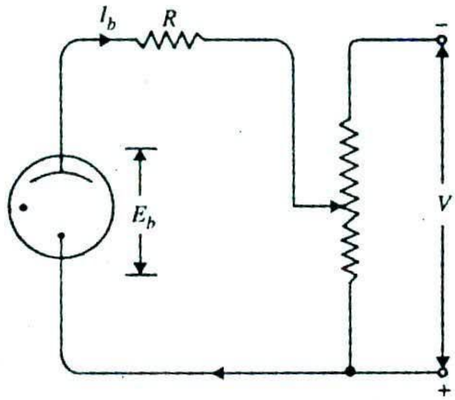


Fig. 6.7

(*ii*) **Glow discharge.** As the anode-cathode voltage is increased, the electrons acquire more and more energy. At some voltage, known as *ionisation voltage*, ionisation of the gas starts and the tube current rises to a large value. The voltage across the tube drops to a low value, which remains constant regardless of the plate current. At the same time, glow is seen in the gas and on a portion of the cathode. This phase of conduction is known as *glow discharge.*

The fact that glow tube maintains constant voltage across it in the glow discharge region needs some explanation. In this region, any increase in supply voltage causes more current to flow; the drop across series resistance *R* increases but the voltage E_b across the tube remains constant. As the current increases, the degree of ionisation increases and the glow covers a greater part of cathode surface and hence the ionised gas path between cathode and anode has greater area of cross-section. As resistance is inversely proportional to the area of cross-section, therefore, resistance of the tube decreases. Hence, the voltage across the tube remains constant. Reverse is also true should the supply voltage decrease. Thus in the glow discharge region, the resistance of the tube changes so as to maintain constant voltage across it.

(*iii*) **Arc discharge.** Once the cathode glow covers the entire surface of the cathode, the *x*-sectional area of gas path cannot increase further. This region is known as *abnormal glow.* If the current density is further increased, the discharge becomes an arc.

* The volt-ampere characteristics of glow tube were first investigated by J. S. Townsend in 1901 and hence the name.

6.4 Characteristics of Cold-Cathode Diode

The volt-ampere characteristic of a cold-cathode diode is shown in Fig. 6.8. At low anode-cathode voltage, the tube current is very small (1mA) and is due to the ionisation of gas molecules by the natural sources. This stage of conduction upto voltage B is known as *Townsend discharge* and is non-self maintained discharge because it requires an external source to cause ionisation. At some critical voltage such as B, the tube fires and the voltage across the tube drops (from B to C) and remains constant regardless of plate current. This is the start of second conduction and is known as *glow discharge*. In this region (C to D), voltage across the tube remains constant even if the plate current increases.

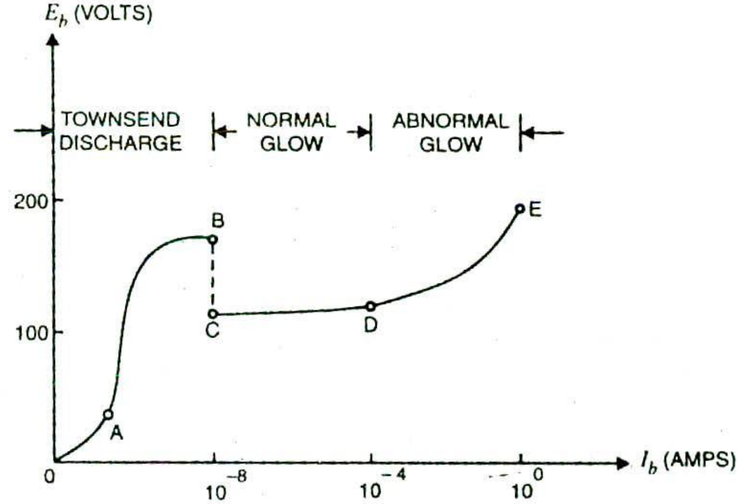


Fig. 6.8

After the glow discharge, the voltage across the tube no longer remains constant. Now, if the supply voltage is raised, not only will the circuit current increase but the voltage across the tube will start to rise again. This stage of conduction (D to E) is known as *abnormal glow*.

6.5 Applications of Glow Tubes

The outstanding characteristic of a cold-cathode gas diode (or glow tube) to maintain constant voltage across it in the glow discharge region renders it suitable for many industrial and control applications. A few of such applications are mentioned below :

(*i*) *As a voltage regulating tube*. A glow tube maintains constant voltage across it in the glow discharge region. This characteristic permits it to be used as a voltage regulating tube. Fig. 6.9 shows a simple circuit commonly used to maintain constant voltage across a load. The glow tube (*VR* tube) is connected in parallel with the load R_L across which constant voltage is desired. So long as the tube operates in the glow discharge region, it will maintain constant voltage (= 150V) across the load. The extra voltage is dropped across the series resistance R.

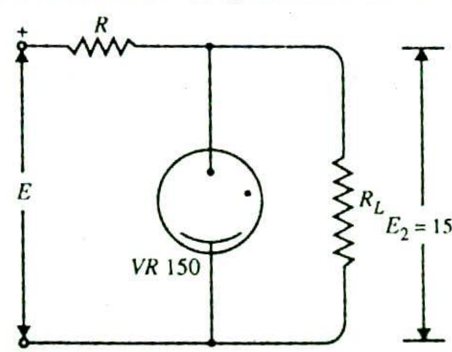


Fig. 6.9

(*ii*) *As a polarity indicator.* As the cathode is surrounded by a characteristic glow, therefore, it can be useful to indicate the polarity of a direct voltage.

(*iii*) *As an electronic switch*, which closes at ionisation potential, permitting a large current to flow, and opens at the deionising voltage, blocking the current flow.

(*iv*) *As a radio frequency field detector.* A strong radio-frequency field is capable of ionising the gas without direct connection to the tube. Therefore, the tube can indicate the presence of radio frequency field.

6.6 Hot-Cathode Gas Diode

A hot-cathode gas diode is frequently used as a rectifier for moderate voltages because of high efficiency and better regulation. A hot-cathode gas diode consists of an oxide-coated cathode and a metallic anode enclosed in a glass envelope containing some inert gas under reduced pressure. For proper operation of the tube, anode is always held at a positive potential *w.r.t.* cathode.

Operation. Fig. 6.10 shows a circuit that can be used to investigate the operation of a hot-cathode gas diode. When cathode is heated, a large number of electrons are emitted. At low anode-cathode voltage, the tube conducts very small current. Under such conditions, the gas is not ionised and the tube acts similar to a vacuum diode — the voltage across the tube increases with plate current. This action continues until anode-cathode voltage becomes equal to the ionisation potential of the gas. Once this potential is reached, the gas begins to ionise, creating free electrons and positive gas ions. The positive gas ions move towards the cathode and tend to neutralise the space charge, thus decreasing the internal resistance of the tube. If now the plate voltage is increased, the plate current also increases due to increased degree of ionisation. This further reduces the tube resistance. As a result, increase in plate current is offset by the decrease in tube resistance *and the voltage across the tube remains constant.* Therefore, in a hot-cathode gas diode, not only the internal drop within the tube is small but also it remains constant. For this reason, a gas diode has better efficiency and regulation than for a vacuum diode when used as a rectifier.

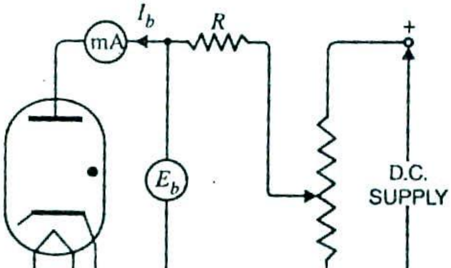


Fig. 6.10

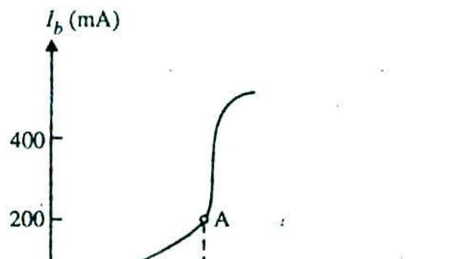


Fig. 6.11

Plate Characteristics. Fig. 6.10 shows the circuit that can be used to determine the volt-ampere (E_b/I_b) characteristics of a hot-cathode gas diode. The series resistance R is used to limit the current to reach a dangerously high value. Fig. 6.11 shows the plate characteristic of hot-cathode diode. It is clear that at first, plate current rises slowly with increase in anode-cathode voltage. However, at some voltage, known as ionisation voltage (point A), the plate current rises sharply and the voltage drop across the tube remains constant. The extra voltage is dropped across the series resistance R. Any attempt to raise the anode-cathode voltage above the ionising value is fruitless. Increasing the voltage E_b above point A results in higher plate current (I_b) and large drop across R but the voltage E_b across the tube remains constant.

6.7 Thyratron

A hot-cathode gas triode is known by the trade name *thyratron*. As discussed before, a gas diode fires at a fixed plate potential, depending upon the type of gas used and gas pressure. Very often it is necessary to control the plate potential at which the tube is to fire. Such a control is obviously impossible with a gas diode. However, if a third electrode, known as *control grid* is introduced in a gas diode, this control is possible. The tube is then known as hot-cathode gas triode or thyratron. By controlling the negative potential on the control grid, the tube can be fired at any plate potential.

Construction. Figs. 6.12 (*i*) and 6.12 (*ii*) respectively show the cut-away view and schematic symbol of a thyratron. It consists of three electrodes, namely; *cathode, anode* and *control grid* enclosed in a glass envelope containing some inert gas at low pressure. The cathode and anode are approximately planar. The control grid of thyratron has a special structure quite different from that of a vacuum tube. It consists of a metal cylinder surrounding the cathode with one or more perforated discs known as *grid baffles* near the centre.

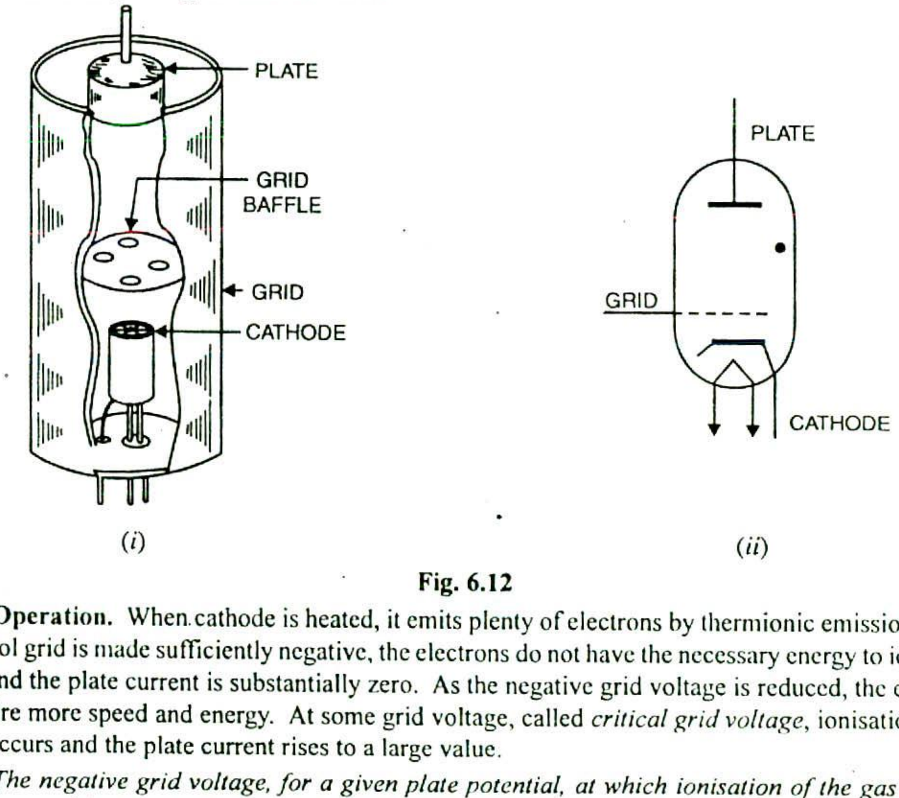


Fig. 6.12

Operation. When cathode is heated, it emits plenty of electrons by thermionic emission. If the control grid is made sufficiently negative, the electrons do not have the necessary energy to ionise the gas and the plate current is substantially zero. As the negative grid voltage is reduced, the electrons acquire more speed and energy. At some grid voltage, called *critical grid voltage*, ionisation of the gas occurs and the plate current rises to a large value.

The negative grid voltage, for a given plate potential, at which ionisation of the gas starts is known as **critical grid voltage.**

At critical grid voltage, gas ionises, creating free electrons and positive gas ions. The positive ions tend to neutralise the space charge, resulting in large plate current. In addition, these positive ions are attracted by the negative grid and neutralise the normal negative field of the grid, thereby preventing the grid from exerting any further control on the plate current of the tube. The grid now loses all control and the tube behaves as a diode. *Therefore, the function of control grid is only to start the conduction of anode current.* Once the conduction is started, the tube acts as a gas diode. It is important to realise the usefulness of control grid. We have seen that the ionisation does not start at low values of plate current. In a gas diode, it requires that the plate potential should be increased until sufficient plate current is flowing to cause ionisation. However, by adjusting the negative voltage on the grid, the desired plate current can be obtained to cause ionisation.

It may be mentioned here that once the thyratron fires, the only way to stop conduction is to reduce plate voltage to zero for a period *long enough for deionisation of the gas in the tube.

6.8 Applications of Thyratron

As the grid voltage has no control over the magnitude of plate current once the thyratron fires, therefore, it cannot be used as an amplifier like a vacuum triode. However, because of its triggering action, it is useful in switching and relay applications. Thyratrons are also used as controlled rectifiers for controlling the amount of d.c. power fed to the load. They are also used in motor control circuits.

Multiple-Choice Questions

1. A gas diode can conduct .... the equivalent vacuum diode for the same plate voltage.
   (*i*) less current than
   (*ii*) more current than
   (*iii*) same current as
   (*iv*) none of the above
2. A gas-filled tube has .... resistance before ionisation.
   (*i*) very high (*ii*) small
   (*iii*) very small (*iv*) zero
3. The PIV of a hot cathode gas diode is .... the equivalent vacuum diode.
   (*i*) the same as that of
   (*ii*) more than that of
   (*iii*) less than that of
   (*iv*) none of the above
4. The anode-to-cathode potential of a gas-filled tube at which gas deionises and stops conduction is called ....potential.
   (*i*) extinction (*ii*) striking
   (*iii*) ionising (*iv*) none of the above
5. A thyratron can be used as ....
   (*i*) an oscillator (*ii*) an amplifier
   (*iii*) a controlled switch
   (*iv*) none of the above
6. The internal resistance of a gas-filled tube is .... that of a vacuum tube.
   (*i*) the same as (*ii*) more than
   (*iii*) less than (*iv*) none of the above
7. A cold cathode tube is generally used as a ....
   (*i*) diode (*ii*) triode
   (*iii*) tetrode (*iv*) pentode
8. Conduction in a cold cathode tube is started by ....
   (*i*) thermionic emission
   (*ii*) secondary emission
   (*iii*) natural sources
   (*iv*) none of the above
9. The cathode heating time of thermionic gas diode is .... that of a vacuum diode.
   (*i*) the same as (*ii*) much more than
   (*iii*) much less than (*iv*) none of the above
10. The solid state equivalent of thyratron is ....
    (*i*) FET (*ii*) transistor
    (*iii*) SCR (*iv*) crystal diode
11. The solid state equivalent of cold cathode diode is ....
    (*i*) zener diode (*ii*) crystal diode
    (*iii*) LED (*iv*) transistor
12. The noise in a gas-filled tube is .... that in a vacuum tube.
    (*i*) the same as (*ii*) more than
    (*iii*) less than (*iv*) none of the above
13. The ionisation potential in a gas diode depends upon ....
    (*i*) plate current
    (*ii*) cathode construction
    (*iii*) size of the tube

* 100 to 1000 μ sec.

(*iv*) type and pressure of gas

14. If the gas pressure in a gas-filled diode is increased, its PIV rating ....
    (*i*) remains the same
    (*ii*) is increased
    (*iii*) is decreased
    (*iv*) none of the above

15. Once a thyratron is fired, its control grid .... over the plate current.
    (*i*) loses all control
    (*ii*) exercises fine control
    (*iii*) exercises rough control
    (*iv*) none of the above

16. To stop conduction in a thyratron, the .... voltage should be reduced to zero.
    (*i*) grid (*ii*) plate
    (*iii*) filament (*iv*) none of the above

17. Ionisation of cold cathode diode takes place at .... plate potential compared to hot cathode gas diode.
    (*i*) the same (*ii*) much higher
    (*iii*) much lesser (*iv*) none of the above

18. A gas-filled tube has .... internal resistance after ionisation.
    (*i*) low (*ii*) high
    (*iii*) very high (*iv*) moderate

19. The gas-filled tubes can handle .... peak inverse voltage (PIV) as compared to equivalent vacuum tubes.
    (*i*) more (*ii*) less
    (*iii*) the same (*iv*) none of the above

20. A cold cathode diode is used as .... tube.
    (*i*) a rectifier
    (*ii*) a power-controlled
    (*iii*) a regulating
    (*iv*) an amplifier

Answers to Multiple-Choice Questions

1. (*ii*)	**2.** (*i*)	**3.** (*iii*)	**4.** (*i*)	**5.** (*iii*)
6. (*iii*)	**7.** (*i*)	**8.** (*iii*)	**9.** (*ii*)	**10.** (*iii*)
11. (*i*)	**12.** (*ii*)	**13.** (*iv*)	**14.** (*iii*)	**15.** (*i*)
16. (*ii*)	**17.** (*ii*)	**18.** (*i*)	**19.** (*ii*)	**20.** (*iii*)

Chapter Review Topics

1. Explain the differences between a gas tube and equivalent vacuum tube.
2. Explain how ionisation takes place in a hot-gas diode. How does current conduction take place in such a tube ?
3. Give the schematic symbols of glow tube, hot-cathode gas diode and thyratron.
4. Explain the construction, operation and characteristics of a glow tube.
5. Discuss some applications of glow tubes.
6. What is a thyratron ? How does it differ from a vacuum triode ?
7. Write short notes on the following :
    (*i*) Characteristics of hot-cathode gas diode
    (*ii*) Applications of thyratrons

Discussion Questions

1. What are the advantages of gas tubes over vacuum tubes ?
2. What is the difference between the action of thyratron and vacuum triode ?
3. Why cannot thyratrons be used as rectifiers for high voltages ?
4. Can gas diodes be used as rectifiers for high voltages ?
5. What is the drawback of a gas diode compared to a thyratron ?

7

Atomic Structure

Introduction

The study of atomic structure is of considerable importance for electronics engineering. Unfortunately, the size of an atom is so small that it is virtually impossible to see it even with the most powerful microscope. Therefore, we have to employ indirect method for the study of its structure. The method consists of studying the properties of atom experimentally. After this, a *guess* is made regarding the possible structure of atom, which should satisfy the properties studied experimentally.

Various scientists have given different theories regarding the structure of atom. However, for the purpose of understanding electronics, the study of Bohr's atomic model is adequate. Although numerous refinements on Bohr's atomic model have since been made, we still believe in the laws that Bohr applied to the atomic world. In this chapter, we shall deal with Bohr's atomic model in order to understand the problems facing the electronic world.

7.1 Bohr's Atomic Model

In 1913, Neils Bohr, Danish Physicist gave clear explanation of atomic structure. According to Bohr:

(*i*) An atom consists of a positively charged nucleus around which negatively charged electrons revolve in different *circular orbits*.

(*ii*) The electrons can revolve round the nucleus only in certain permitted orbits i.e. orbits of certain radii are allowed.

(*iii*) The electrons in each permitted orbit have a certain fixed amount of energy. The larger the orbit (*i.e.* larger radius), the greater is the energy of electrons.

(*iv*) If an electron is given additional energy (*e.g.* heat, light etc.), it is lifted to the higher orbit. The atom is said to be in a state of *excitation*. This state does not last long, because the electron soon falls back to the original lower orbit. As it falls, it gives back the acquired energy in the form of heat, light or other radiations.

Fig. 7.1 shows the structure of silicon atom. It has 14 electrons. Two electrons revolve in the first orbit, 8 in the second orbit and 4 in the third orbit. The first, second, third orbits etc. are also known as K, L, M orbits respectively.

These electrons can revolve only in permitted orbits (*i.e.* orbits of *radii r_1, r_2 and r_3) and not in any arbitrary orbit. Thus, all radii between r_1 and r_2 or between r_2 and r_3 are forbidden. Each orbit has fixed amount of energy associated with it. If an electron in the first orbit is to be lifted to the

* The values of radii are determined from quantum considerations.

second orbit, just the *right amount of energy should be supplied to it. When this electron jumps from the second orbit to first, it will give back the acquired energy in the form of electromagnetic radiations.

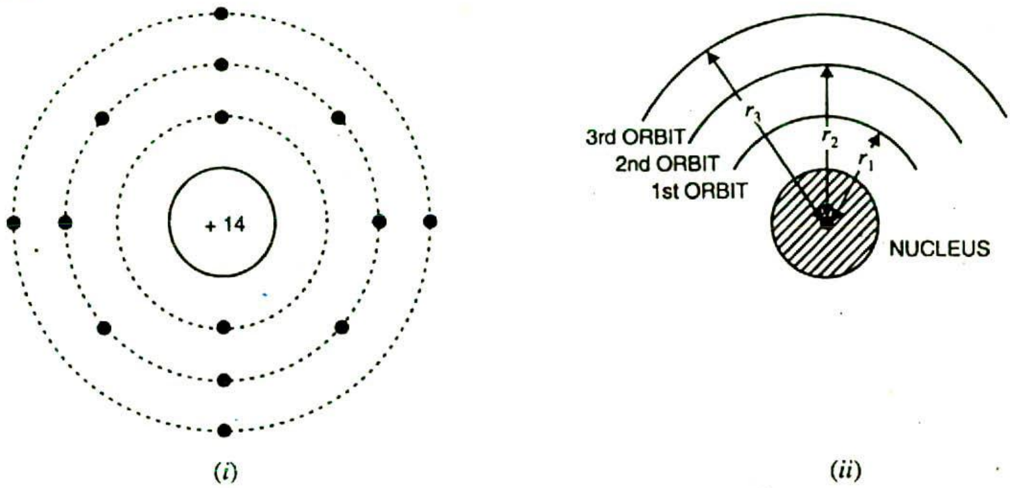


Fig. 7.1

7.2 Energy Levels

It has already been discussed that each orbit has fixed amount of energy associated with it. The electrons moving in a particular orbit possess the energy of that orbit. The larger the orbit, the greater is its energy. It becomes clear that outer orbit electrons possess more energy than the inner orbit electrons.

A convenient way of representing the energy of different orbits is shown in Fig. 7.2 (*ii*). This is known as energy level diagram. The first orbit represents the *first energy level*, the second orbit indicates the *second energy level* and so on. The larger the orbit of an electron, the greater is its energy and higher is the energy level.

The 3rd orbit represent the higher is the energy level.

Fig. 7.2

* So that its total energy is equal to that of second orbit.

7.3 Energy Bands

In case of a single isolated atom, the electrons in any orbit possess definite energy. However, an atom in a solid is greatly influenced by the closely-packed neighbouring atoms. The result is that the electron in any orbit of such an atom can have a range of energies rather than a single energy. This is known as *energy band*.

The range of energies possessed by an electron in a solid is known as **energy band.**

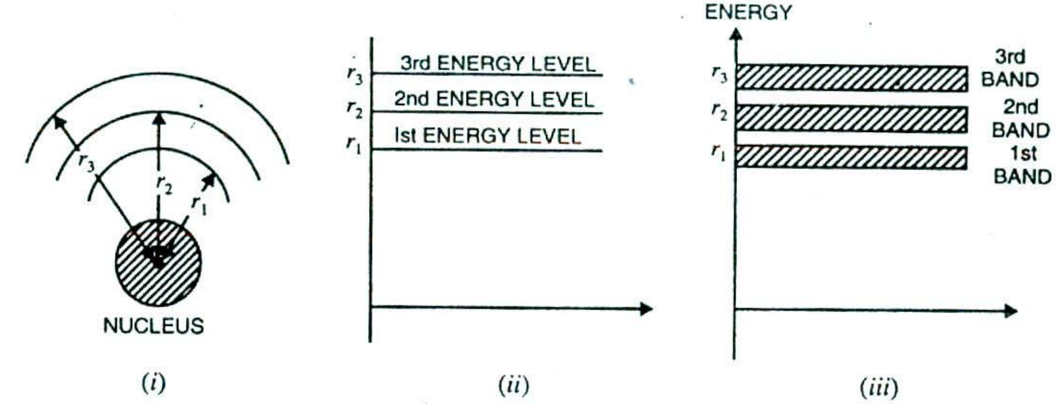


Fig. 7.3

The concept of energy band can be easily understood by referring to Fig. 7.3. Fig. 7.3 (*ii*) shows the energy levels of a single isolated atom of silicon. Each orbit of an atom has a single energy. Therefore, an electron can have only single energy corresponding to the orbit in which it exists. However, when the atom is in a solid, the electron in any orbit can have a range of energies. For instance, electrons in the first orbit have slightly different energies because no two electrons in this orbit see exactly the same charge environment. Since there are millions of first orbit electrons, the slightly different energy levels form a band, called 1st energy band [See Fig. 7.3 (*iii*)]. The electrons in the first orbit can have any energy range in this band. Similarly, second orbit electrons form second energy band and so on.

7.4 Important Energy Bands in Solids

As discussed before, individual *K, L, M* etc. energy levels of an isolated atom are converted into corresponding bands when the atom is in a solid. Though there are a number of energy bands in solids, the following are of particular importance [See Fig 7.4] :

(*i*) **Valence band.** *The range of energies (i.e. band) possessed by valence electrons is known as* **valence band.**

The electrons in the outermost orbit of an atom are known as valence electrons. In a normal atom, valence band has the electrons of highest energy. This band may be completely or partially filled. For instance, in case of inert gases, the valence band is full whereas for other materials, it is only partially filled. The partially filled band can accommodate more electrons.

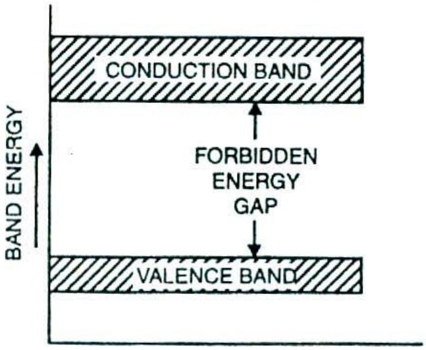


Fig. 7.4

(*ii*) **Conduction band.** In certain materials (*e.g.* metals), the valence electrons are loosely attached to the nucleus. Even at ordinary temperature, some of the valence electrons may get detached to become free electrons. In fact, it is these free electrons which are responsible for the conduction of current in a conductor. For this reason, they are called *conduction electrons.*

The range of energies (i.e. band) possessed by conduction band electrons is known as **conduction band.**

All electrons in the conduction band are free electrons. If a substance has empty conduction band, it means current conduction is not possible in that substance. Generally, insulators have empty conduction band. On the other hand, it is partially filled for conductors.

(*iii*) **Forbidden energy gap.** *The separation between conduction band and valence band on the energy level diagram is known as* **forbidden energy gap.**

No electron of a solid can stay in a forbidden energy gap as there is no allowed energy state in this region. The width of the forbidden energy gap is a measure of the bondage of valence electrons to the atom. The greater the energy gap, more tightly the valence electrons are bound to the nucleus. In order to push an electron from valence band to the conduction band (*i.e.* to make the valence electron free), external energy equal to the forbidden energy gap must be supplied.

7.5 Classification of Solids and Energy Bands

We know that some solids are good conductors of electricity while others are insulators. There is also an intermediate class of semiconductors. The difference in the behaviour of solids as regards their electrical conductivity can be beautifully explained in terms of energy bands. The electrons in the lower energy band are tightly bound to the nucleus and play no part in the conduction process. However, the valence and conduction bands are of particular importance in ascertaining the electrical behaviour of various solids.

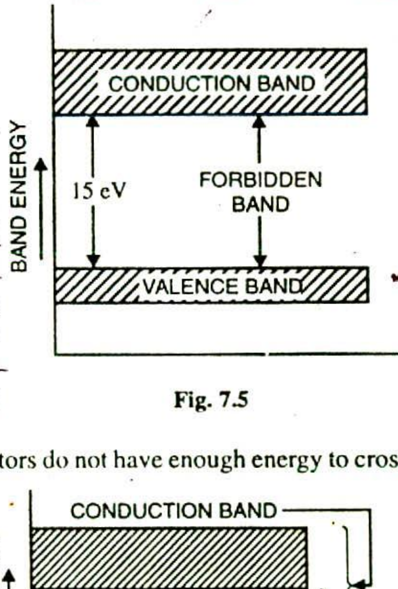


Fig. 7.5

(*i*) **Insulators.** Insulators (*e.g.* wood, glass etc.) are those substances which do not allow the passage of electric current through them. In terms of energy band, the valence band is full while the conduction band is empty. Further, the energy gap between valence and conduction bands is very large (≃ 15 eV) as shown in Fig. 7.5. Therefore, a very high electric field is required to push the valence electrons to the conduction band. For this reason, the electrical conductivity of such materials is extremely small and may be regarded as nil under ordinary conditions.

At room temperature, the valence electrons of the insulators do not have enough energy to cross over to the conduction band. However, when the temperature is raised, some of the valence electrons may acquire enough energy to cross over to the conduction band. Hence, the resistance of an insulator decreases with the increase in temperature *i.e.* an insulator has negative temperature co-efficient of resistance.

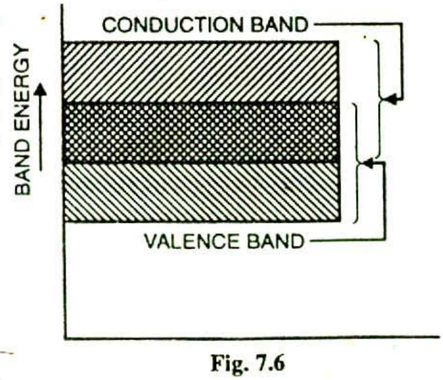


Fig. 7.6

(*ii*) **Conductors.** Conductors (*e.g.* copper, aluminium) are those substances which easily allow the passage of electric current through them. It is because there are a large number of free electrons available in a conductor. In terms of energy band, the valence and conduction bands overlap each other as shown in Fig. 7.6. Due to this overlapping, a slight potential difference across a conductor causes the free electrons to constitute electric current. Thus, the electrical behaviour of conductors can be satisfactorily explained by the band energy theory of materials.

(*iii*) **Semicondutors.** Semiconductors (*e.g.* germanium, silicon etc.) are those substances whose electrical conductivity lies inbetween conductors and insulators. In terms of energy band, the valence band is almost filled and conduction band is almost empty. Further, the energy gap between valence and conduction bands is very small as shown in Fig. 7.7. Therefore, comparatively smaller electric field (smaller than insulators but much greater than conductors) is required to push the electrons from the valence band to the conduction band. In short, a semiconductor has :

(*a*) almost full valence band

(*b*) almost empty conduction band

(*c*) small energy gap ($\simeq$ 1 eV) between valence and conduction bands.

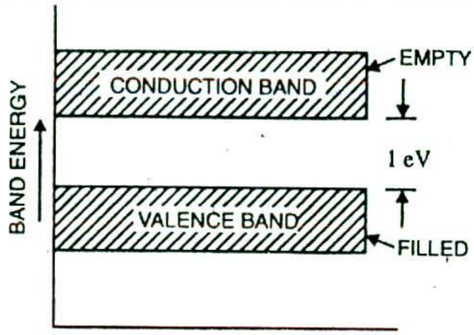


Fig. 7.7

At low temperature, the valence band is completely full and conduction band is completely empty. Therefore, a semiconductor virtually behaves as an insulator at low temperatures. However, even at room temperature, some electrons (about one electron for 10^{10} atoms) cross over to the conduction band, imparting little conductivity to the semiconductor. As the temperature is increased, more valence electrons cross over to the conduction band and the conductivity increases. This shows that electrical conductivity of a semiconductor increases with the rise in temperature *i.e.* a semiconductor has negative temperature co-efficient of resistance.

Multiple-Choice Questions

1. The electrons in the third orbit of an atom have .... energy than the electrons in the second orbit.
   (*i*) more (*ii*) less
   (*iii*) the same (*iv*) none of the above
2. When an electron jumps from higher orbit to a lower orbit, it .... energy.
   (*i*) absorbs
   (*ii*) emits
   (*iii*) sometimes emits, sometimes absorbs
   (*iv*) none of the above
3. Which of the following is quantized according to Bohr's theory of atom ?
   (*i*) linear momentum of electron
   (*ii*) linear velocity of electron
   (*iii*) angular momentum of electron
   (*iv*) angular velocity of electron
4. A semiconductor has .... band.
   (*i*) almost empty valence
   (*ii*) almost empty conduction
   (*iii*) almost full conduction
   (*iv*) none of the above
5. The electrons in the conduction band are known as ....
   (*i*) bound electrons
   (*ii*) valence electrons
   (*iii*) free electrons
   (*iv*) none of the above
6. In insulators, the energy gap between valence and conduction bands is ....
   (*i*) very large (*ii*) zero
   (*iii*) very small (*iv*) none of the above
7. In a conductor, the energy gap between valence and conduction bands is ....
   (*i*) large (*ii*) very large
   (*iii*) very small (*iv*) none of the above
8. According to Bohr's theory of atom, an electron can move in an orbit of ....

(i) any radius

(ii) certain radius

(iii) some range of radii

(iv) none of the above

9. In a semiconductor, the energy gap between valence and conduction bands is about ....

(i) 15 eV (ii) 100 eV

(iii) 50 eV (iv) 1 eV

10. The energy gap between valence and conduction bands in insulators is about ....

(i) 15 eV (ii) 1.5 eV

(iii) zero (iv) 0.5 eV

Answers to Multiple-Choice Questions

1. (i)	2. (ii)	3. (iii)	4. (ii)	5. (iii)
6. (i)	7. (iii)	8. (ii)	9. (iv)	10. (i)

Chapter Review Topics

1. Explain the salient features of Bohr's atomic model.
2. Explain the concept of energy bands in solids.
3. Describe the valence band, conduction band and forbidden energy gap with the help of energy level diagram.
4. Give the energy band description of conductors, semiconductors and insulators.

Discussion Questions

1. Why is the energy of an electron more in higher orbits ?
2. What is the concept of energy band ?
3. Why do conduction band electrons possess very high energy ?
4. Why are valence electrons of a material so important ?
5. What is the difference between energy level and energy band ?

8

Semiconductor Physics

Introduction

Certain substances like germanium, silicon, carbon etc. are neither good conductors like copper nor insulators like glass. In other words, the resistivity of these materials lies inbetween conductors and insulators. Such substances are classified as *semiconductors*. Semiconductors have some useful properties and are being extensively used in electronic circuits. For instance, *transistor*—a semiconductor device is fast replacing bulky vacuum tubes in almost all applications. Transistors are only one of the family of semiconductor devices ; many other semiconductor devices are becoming increasingly popular. In this chapter, we shall focus our attention on the different aspects of semiconductors.

8.1 Semiconductor

It is not easy to define a semiconductor if we want to take into account all its physical characteristics. However, generally, a semiconductor is defined on the basis of electrical conductivity as under :

A **semiconductor** *is a substance which has resistivity (10^{-4} to 0.5 Ωm) inbetween conductors and insulators e.g. germanium, silicon, selenium, carbon etc.*

The reader may wonder, when a semiconductor is neither a good conductor nor an insulator, then why not to classify it as a *resistance material* ? The answer shall be readily available if we study the following table :

S.No.	Substance	Nature	Resistivity
1	Copper	good conductor	1.7×10^{-8} Ω m
2	Germanium	semiconductor	0.6 Ω m
3	Glass	insulator	9×10^{11} Ω m
4	Nichrome	resistance material	10^{-4} Ω m

Comparing the resistivities of above materials, it is apparent that the resistivity of germanium (semiconductor) is quite high as compared to copper (conductor) but it is quite low when compared with glass (insulator). This shows that resistivity of a semiconductor lies inbetween conductors and insulators. However, it will be wrong to consider the semiconductor as a resistance material. For example, nichrome, which is one of the highest resistance material, has resistivity much lower than germanium. This shows that electrically germanium cannot be regarded as a conductor or insulator or a resistance material. This gave such substances like germanium the name of semiconductors.

It is interesting to note that it is not the resistivity alone that decides whether a substance is semiconductor or not. For example, it is just possible to prepare an alloy whose resistivity falls within the range of semiconductors but the alloy cannot be regarded as a semiconductor. In fact, semiconductors have a number of peculiar properties which distinguish them from conductors, insulators and resistance materials.

Properties of Semiconductors

(*i*) The resistivity of a semiconductor is less than an insulator but more than a conductor.

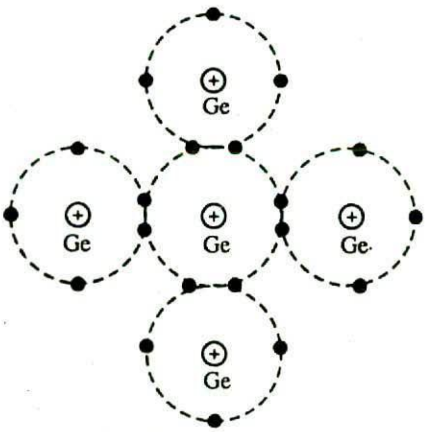
(*ii*) Semiconductors have *negative temperature co-efficient of resistance i.e.* the resistance of a semiconductor decreases with the increase in temperature and *vice-versa.* For example, germanium is actually an insulator at low temperatures but it becomes a good conductor at high temperatures.

(*iii*) When a suitable metallic impurity (*e.g.* arsenic, gallium etc.) is added to a semiconductor, its current conducting properties change appreciably. This property is most important and is discussed later in detail.

8.2 Bonds in Semiconductors

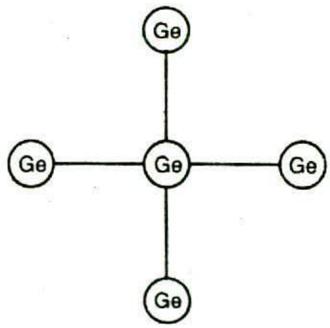
The atoms of every element are held together by the bonding action of valence electrons. This bonding is due to the fact that it is the tendency of each atom to complete its last orbit by acquiring 8 electrons in it. However, in most of the substances, the last orbit is incomplete *i.e.* the last orbit does not have 8 electrons. This makes the atom active to enter into bargain with other atoms to acquire 8 electrons in the last orbit. To do so, the atom may lose, gain or share valence electrons with other atoms. In semiconductors, bonds are formed by sharing of valence electrons. Such bonds are called *co-valent bonds.* In the formation of a co-valent bond, each atom contributes equal number of valence electrons and the contributed electrons are shared by the atoms engaged in the formation of the bond.

Fig. 8.1 shows the co-valent bonds among germanium atoms. A germanium atom has *4 valence electrons. It is the tendency of each germanium atom to have 8 electrons in the last orbit. To do so,



COVALENT BONDS AMONG Ge ATOMS

(*i*)



BONDING DIAGRAM

(*ii*)

Fig. 8.1

* A germanium atom has 32 electrons. First orbit has 2 electrons, second 8 electrons, third 18 electrons and the fourth orbit has 4 electrons.

each germanium atom positions itself between four other germanium atoms as shown in Fig. 8.1 (*i*). Each neighbouring atom shares one valence electron with the central atom. In this business of sharing, the central atom completes its last orbit by having 8 electrons revolving round the nucleus. In this way, the central atom sets up co-valent bonds. Fig. 8.1 (*ii*) shows the bonding diagram.

The following points may be noted regarding the co-valent bonds :

(*i*) Co-valent bonds are formed by sharing of valence electrons.

(*ii*) In the formation of co-valent bond, each valence electron of an atom forms direct bond with the valence electron of an adjacent atom. In other words, valence electrons are associated with particular atoms. For this reason, valence electrons in a semiconductor are not free.

8.3 Crystals

A substance in which the atoms or molecules are arranged in an orderly pattern is known as a *crystal*. All semi-conductors have crystalline structure. For example, referring to Fig. 8.1, it is clear that each atom is surrounded by neighbouring atoms in a repetitive manner. Therefore, a piece of germanium is generally called germanium crystal.

8.4 Commonly Used Semiconductors

There are many semiconductors available, but very few of them have a practical application in electronics. The two most frequently used materials are *germanium* (Ge) and *silicon* (Si). It is because the energy required to break their co-valent bonds (*i.e.* energy required to release an electron from their valence bonds) is very small; being 0.7 eV for germanium and 1.1 eV for silicon. Therefore, we shall discuss these two semiconductors in detail.

(*i*) **Germanium.** Germanium has become the model substance among the semiconductors; the main reason being that it can be purified relatively well and crystallised easily. Germanium is an earth element and was discovered in 1886. It is recovered from the ash of certain coals or from the flue dust of zinc smelters. Generally, recovered germanium is in the form of germanium dioxide powder which is then reduced to pure germanium.

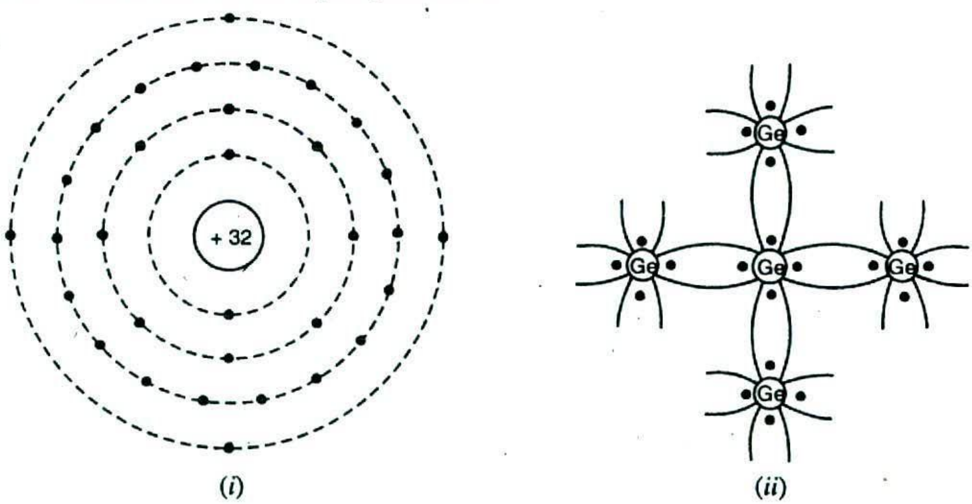
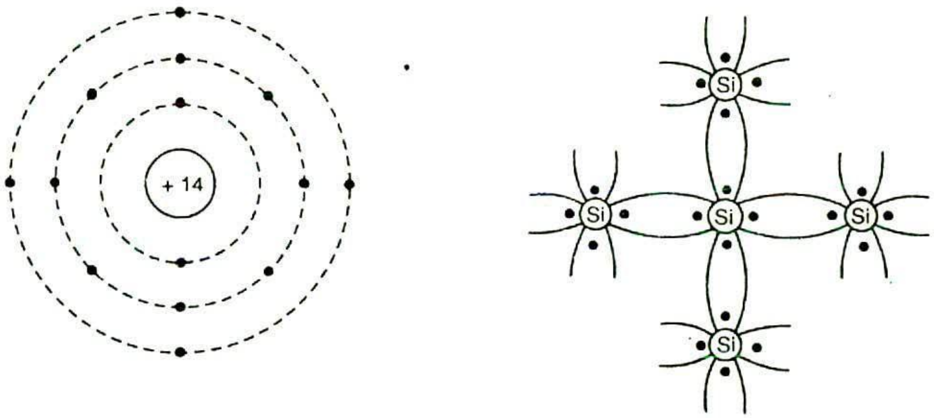


Fig. 8.2

The atomic number of germanium is 32. Therefore, it has 32 protons and 32 electrons. Two electrons are in the first orbit, eight electrons in the second, eighteen electrons in the third and four electrons in the outer or valence orbit [See Fig. 8.2 (*i*)]. It is clear that germanium atom has four valence electrons *i.e.*, it is a tetravalent element. Fig. 8.2 (*ii*) shows how the various germanium atoms are held through co-valent bonds. As the atoms are arranged in an orderly pattern, therefore, germanium has crystalline structure.

(*ii*) **Silicon.** Silicon is an element in most of the common rocks. Actually, sand is silicon dioxide. The silicon compounds are chemically reduced to silicon which is 100% pure for use as a semiconductor.



(*i*) (*ii*)

Fig. 8.3

The atomic number of silicon is 14. Therefore, it has 14 protons and 14 electrons. Two electrons are in the first orbit, eight electrons in the second orbit and four electrons in the third orbit [See Fig. 8.3 (*i*)]. It is clear that silicon atom has four valence electrons *i.e.* it is a tetravalent element. Fig. 8.3 (*ii*) shows how various silicon atoms are held through co-valent bonds. Like germanium, silicon atoms are also arranged in an orderly manner. Therefore, silicon has crystalline structure.

8.5 Energy Band Description of Semiconductors

It has already been discussed that a semiconductor is a substance whose resistivity lies between conductors and insulators. The resistivity is of the order of 10^{-4} to 0.5 ohm metre. However, a semiconductor can be defined much more comprehensively on the basis of energy bands as under :

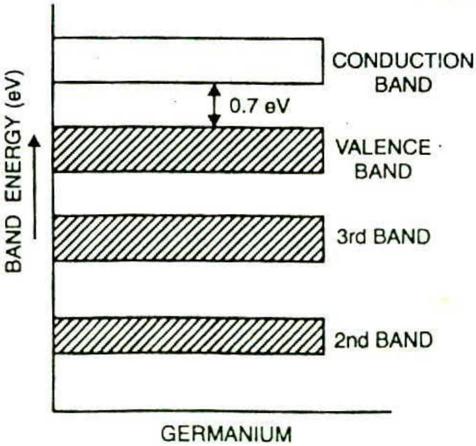


Fig. 8.4

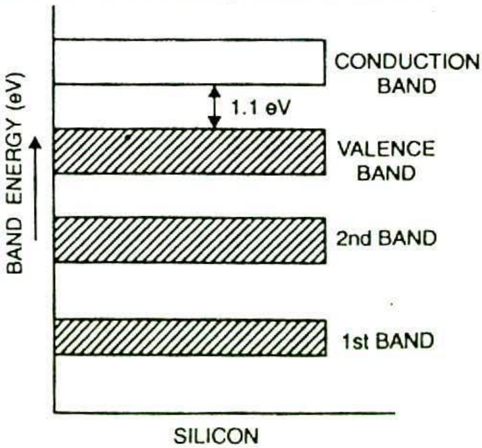


Fig. 8.5

A **semiconductor** *is a substance which has almost filled valence band and nearly empty conduction band with a very small energy gap (≃ 1 eV) separating the two.*

Figs. 8.4 and 8.5 show the energy band diagrams of germanium and silicon respectively. It may be seen that forbidden energy gap is very small; being 1.1 eV for silicon and 0.7 eV for germanium. Therefore, relatively small energy is needed by their valence electrons to cross over to the conduction band. Even at room temperature, some of the valence electrons may acquire sufficient energy to enter into the conduction band and thus become free electrons. However, at this temperature, the number of free electrons available is very *small. Therefore, at room temperature, a piece of germanium or silicon is neither a good conductor nor an insulator. For this reason, such substances are called *semiconductors*.

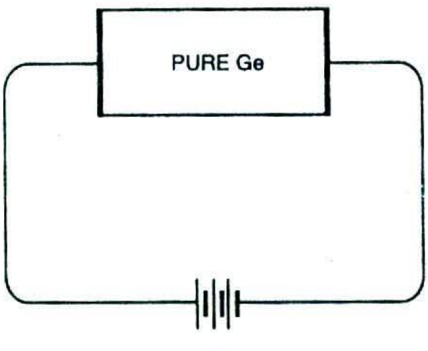
The energy band description is extremely helpful in understanding the current flow through a semiconductor. Therefore, we shall frequently use this concept in our further discussion.

8.6 Effect of Temperature on Semiconductors

The electrical conductivity of a semiconductor changes appreciably with temperature variations. This is a very important point to keep in mind.

(*i*) **At absolute zero.** At absolute zero temperature, all the electrons are tightly held by the semiconductor atoms. The inner orbit electrons are bound whereas the valence electrons are engaged in co-valent bonding. At this temperature, the co-valent bonds are very strong and there are no free electrons. Therefore, the semiconductor crystal behaves as a perfect insulator [See Fig. 8.6 (*i*)].

In terms of energy band description, the valence band is filled and there is a large energy gap between valence band and conduction band. Therefore, no valence electron can reach the conduction band to become free electron. It is due to the non-availability of free electrons that a semiconductor behaves as an insulator.



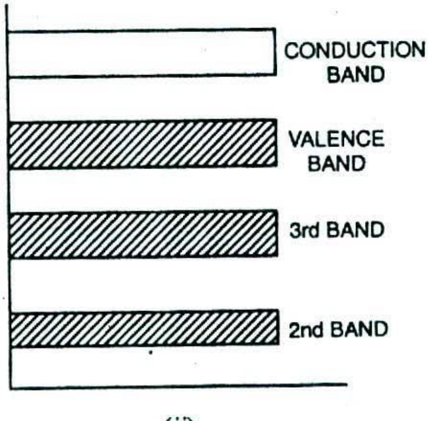
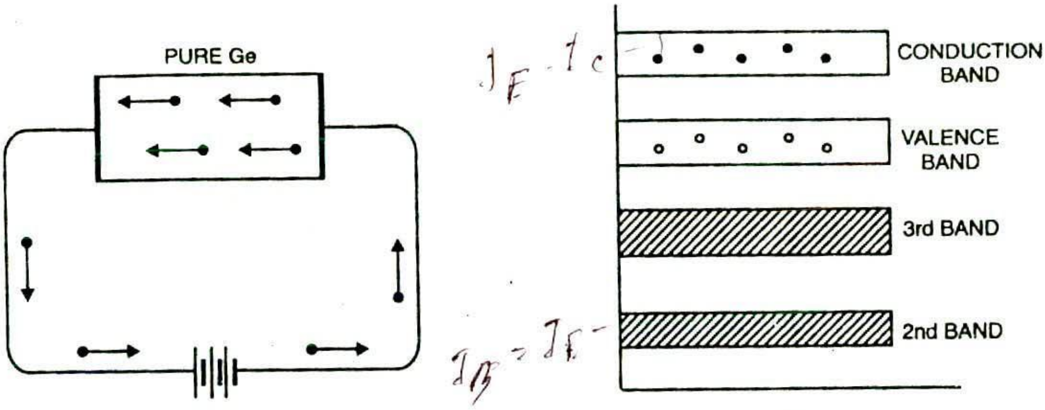


Fig. 8.6

(*ii*) **Above absolute zero.** When the temperature is raised, some of the covalent bonds in the semiconductor break due to the thermal energy supplied. The breaking of bonds sets those electrons *free* which are engaged in the formation of these bonds. The result is that a few free electrons exist in the semiconductor. These free electrons can constitute a tiny electric current if potential difference is applied across the semiconductor crystal [See Fig. 8.7 (*i*)]. *This shows that the resistance of a semi-*

* Out of 10^{10} semiconductor atoms, one atom provides a free electron.

conductor decreases with the rise in temperature i.e. it has negative temperature coefficient of resistance. It may be added that at room temperature, current through a semiconductor is too small to be of any practical value.



(*i*) (*ii*)

Fig. 8.7

Fig. 8.7 (*ii*) shows the energy band diagram. As the temperature is raised, some of the valence electrons acquire sufficient energy to enter into the conduction band and thus become free electrons. Under the influence of electric field, these free electrons will constitute electric current. It may be noted that each time a valence electron enters into the conduction band, a *hole* is created in the valence band. As we shall see in the next article, holes also contribute to current. In fact, hole current is the most significant concept in semiconductors.

8.7 Hole Current

At room temperature, some of the co-valent bonds in pure semiconductor break, setting up free electrons. Under the influence of electric field, these free electrons constitute electric current. At the same time, another current – the hole current – also flows in the semiconductor. When a covalent bond is broken due to thermal energy, the removal of one electron leaves a vacancy *i.e.* a missing electron in the covalent bond. This missing electron is called a *hole which acts as a positive charge. For one electron set free, one hole is created. Therefore, thermal energy creates *hole-electron pairs*; there being as many holes as the free electrons. The current conduction by holes can be explained as follows :

The hole shows a missing electron. Suppose the valence electron at *L* (See Fig. 8.8) has become free electron due to thermal energy. This creates a hole in the co-valent bond at *L*. The hole is a strong centre of attraction **for the electron. A valence electron (say at *M*) from nearby co-valent bond comes to fill in the hole at *L*. This results in the creation of hole at *M*. Another valence electron (say at *N*) in turn may leave its bond to fill the hole at *M*, thus creating a hole at *N*. Thus the hole having a positive charge has moved from *L* to *N* *i.e.* towards the negative terminal of supply. This constitutes *hole current*.

It may be noted that hole current is due to the movement of †valence electrons from one co-

* Note that hole acts as a virtual charge, although there is no physical charge on it.

** There is a strong tendency of semiconductor crystal to form co-valent bonds. Therefore, a hole attracts an electron from the neighbouring atom.

† Unlike the normal current which is by free electrons.

valent bond to another bond. The reader may wonder why to call it a hole current when the conduction is again by electrons (of course *valence electrons* !). The answer is that the basic reason for current flow is the presence of holes in the co-valent bonds. Therefore, it is more appropriate to consider the current as the movement of holes.

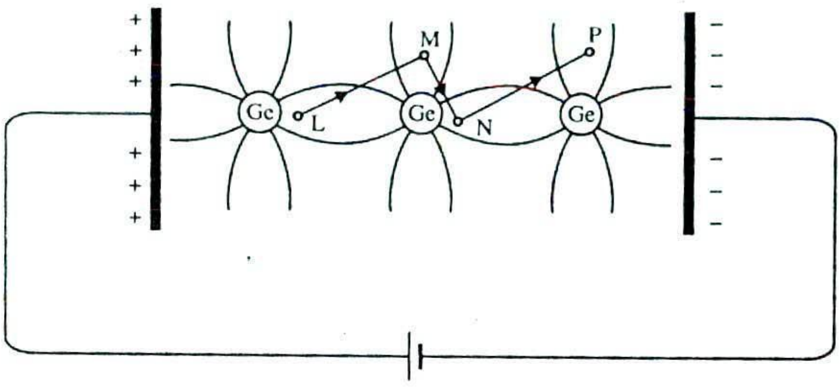


Fig. 8.8

Energy band description. The hole current can be beautifully explained in terms of energy bands. Suppose due to thermal energy, an electron leaves the valence band to enter into the conduction band as shown in Fig. 8.9.

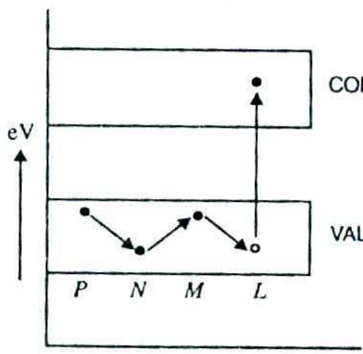


Fig. 8.9

This leaves a vacancy at *L*. Now the valence electron at *M* comes to fill the hole at *L*. The result is that hole disappears at *L* and appears at *M*. Next, the valence electron at *N* moves into the hole at *M*. Consequently, hole is created at *N*. It is clear that valence electrons move along the path *PNML* whereas holes move in the opposite direction *i.e.* along the path *LMNP*.

8.8 Intrinsic Semiconductor

A semiconductor in an extremely pure form is known as an **intrinsic semiconductor.**

In an intrinsic semiconductor, even at room temperature, hole-electron pairs are created. When electric field is applied across an intrinsic semiconductor, the current conduction takes place by two processes, namely ; by *free electrons* and *holes* as shown in Fig. 8.10. The free electrons are produced due to the breaking up of some covalent bonds by thermal energy. At the same time, holes are created in the covalent bonds. Under the influence of electric field, conduction through the semiconductor is by both free electrons and holes. Therefore, the total current inside the semiconductor is the sum of currents due to free electrons and holes.

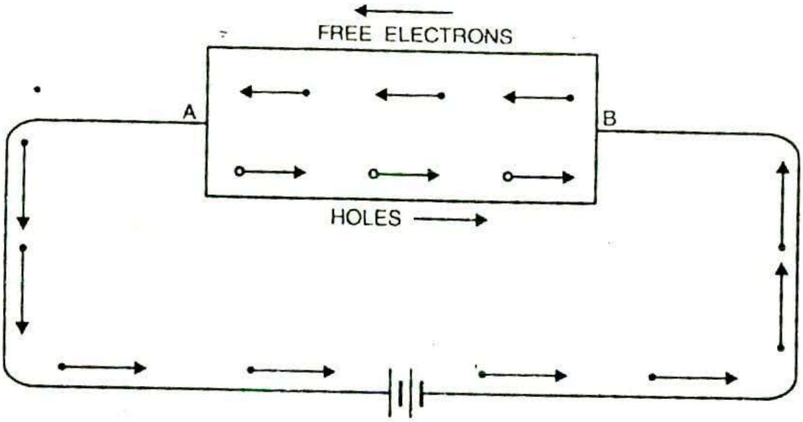


Fig. 8.10

It may be noted that current in the external wires is fully electronic *i.e.* by electrons. What about the holes ? Referring to Fig. 8.10, holes being positively charged move towards the negative terminal of supply. As the holes reach the negative terminal *B*, electrons enter the semiconductor crystal near the terminal and combine with holes, thus cancelling them. At the same time, the loosely held electrons near the positive terminal *A* are attracted away from their atoms into the positive terminal. This creates new holes near the positive terminal which again drift towards the negative terminal.

8.9 Extrinsic Semiconductor

The intrinsic semiconductor has little current conduction capability at room temperature. To be useful in electronic devices, the pure semiconductor must be altered so as to significantly increase its conducting properties. This is achieved by adding a small amount of suitable impurity to a semiconductor. It is then called *impurity or extrinsic semiconductor*. The process of adding impurities to a semiconductor is known as *doping*. The amount and type of such impurities have to be closely controlled during the preparation of extrinsic semiconductor. Generally, for 10^8 atoms of semiconductor, one impurity atom is added.

The purpose of adding impurity is to increase either the number of free electrons or holes in the semiconductor crystal. As we shall see, if a pentavalent impurity (having 5 valence electrons) is added to the semiconductor, a large number of free electrons are produced in the semiconductor. On the other hand, addition of trivalent impurity (having 3 valence electrons) creates a large number of holes in the semiconductor crystal. Depending upon the type of impurity added, extrinsic semiconductors are classified into :

(*i*) *n*-type semiconductor (*ii*) *p*-type semiconductor

8.10 *n*-type Semiconductor

When a small amount of pentavalent impurity is added to a pure semiconductor, it is known as **n-type semiconductor.**

The addition of pentavalent impurity provides a large number of free electrons in the semiconductor crystal. Typical examples of pentavalent impurities are *arsenic* (At. No. 33) and *antimony* (At. No. 51). Such impurities which produce *n*-type semiconductor are known as *donor impurities* because they donate or provide free electrons to the semiconductor crystal.

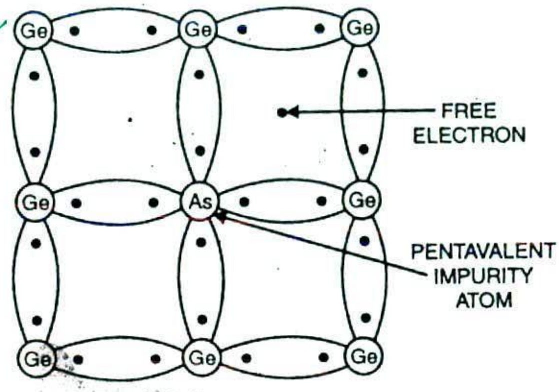


Fig. 8.11

To explain the formation of n-type semiconductor, consider a pure germanium crystal. We know that germanium atom has four valence electrons. When a small amount of pentavalent impurity like arsenic is added to germanium crystal, a large number of free electrons become available in the crystal. The reason is simple. Arsenic is pentavalent *i.e.* its atom has five valence electrons. An arsenic atom fits in the germanium crystal in such a way that its four valence electrons form covalent bonds with four germanium atoms. The *fifth* valence electron of arsenic atom finds no place in covalent bonds and is thus free as shown in Fig. 8.11. Therefore, for each arsenic atom added, one free electron will be available in the germanium crystal. Though each arsenic atom provides one free electron, yet an extremely small amount of arsenic impurity provides enough atoms to supply millions of free electrons.

Fig. 8.12 shows the energy band description of n-type semi-conductor. The addition of pentavalent impurity has produced a number of conduction band electrons *i.e.*, free electrons. The four valence electrons of pentavalent atom form covalent bonds with four neighbouring germanium atoms. The fifth left over valence electron of the pentavalent atom cannot be accommodated in the valence band and travels to the conduction band. The following points may be noted carefully :

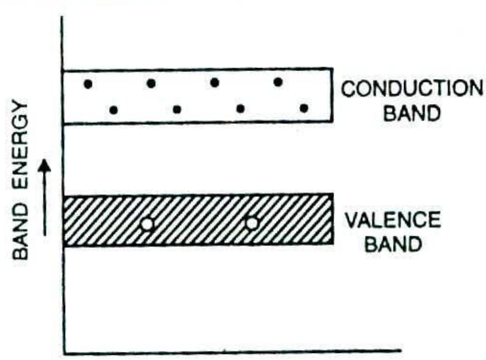


Fig. 8.12

(*i*) Many new free electrons are produced by the addition of pentavalent impurity.

(*ii*) Thermal energy of room temperature still generates a few hole-electron pairs. However, the number of free electrons provided by the pentavalent impurity far exceeds the number of holes. It is due to this predominance of electrons over holes that it is called n-type semiconductor (n stands for negative).

n-type conductivity. The current conduction in an n-type semiconductor is *predominantly* by free electrons *i.e.* negative charges and is called *n-type or electron type conductivity*. To understand n-type conductivity, refer to Fig. 8.13. When p.d. is applied across the n-type semiconductor, the free electrons (donated by impurity) in the crystal will be directed towards the positive terminal, constituting electric current. As the current flow through the crystal is by free electrons which are carriers of negative charge, therefore, this type of conductivity is called negative or n-type conductivity. It may be noted that conduction is just as in ordinary metals like copper.

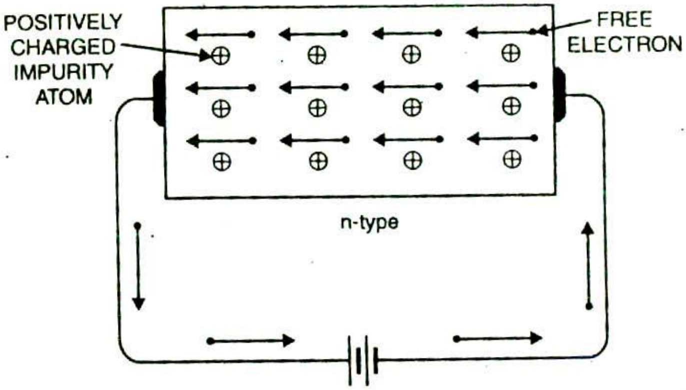


Fig. 8.13

8.11 *p*-type Semiconductor

***When a small amount of trivalent impurity is added to a pure semiconductor, it is called* p-type semiconductor.**

The addition of trivalent impurity provides a large number of holes in the semiconductor. Typical examples of trivalent impurities are *gallium* (At. No. 31) and *indium* (At. No. 49). Such impurities which produce *p*-type semiconductor are known as *acceptor impurities* because the holes created can accept the electrons.

To explain the formation of *p*-type semiconductor, consider a pure germanium crystal. When a small amount of trivalent impurity like gallium is added to germanium crystal, there exists a large number of holes in the crystal. The reason is simple. Gallium is trivalent *i.e.* its atom has three valence electrons. Each atom of gallium fits into the germanium crystal but now only three co-valent bonds can be formed. It is because three valence electrons of gallium atom can form only three single co-valent bonds with three germanium atoms as shown in Fig. 8.14. In the fourth co-valent bond, only germanium atom contributes one valence electron while gallium has no valence electron to contribute as all its three valence electrons are already engaged in the co-valent bonds with neighbouring germanium atoms. In other words, fourth bond is incomplete; being short of one electron. This missing electron is called a *hole*. Therefore, for each gallium atom added, one hole is created. A small amount of gallium provides millions of holes.

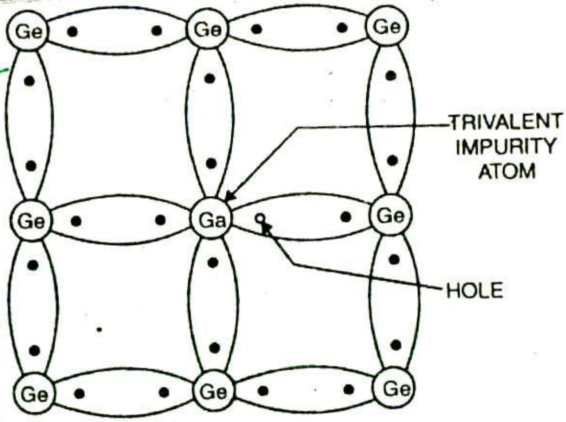


Fig. 8.14

Fig. 8.15 shows the energy band description of the *p*-type semiconductor. The addition of trivalent impurity has produced a large number of holes. However, there are a few conduction band electrons due to thermal energy associated with room temperature. But the holes far outnumber the conduction band electrons. It is due to the predominance of holes over free electrons that it is called *p*-type semiconductor (*p* stands for positive).

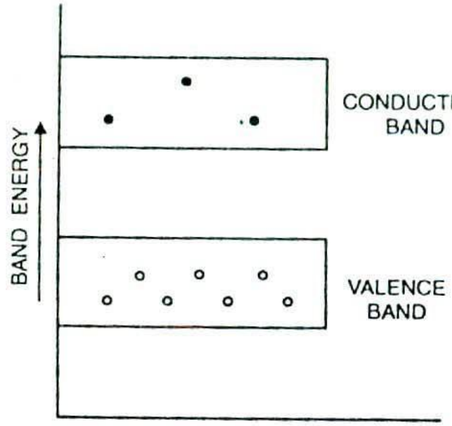


Fig. 8.15

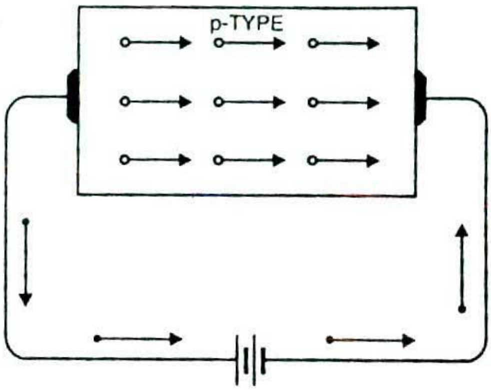


Fig. 8.16

***p*-type conductivity.** The current conduction in *p*-type semiconductor is predominantly by holes *i.e.* positive charges and is called *p-type* or *hole-type conductivity.* To understand *p*-type conductivity, refer to Fig. 8.16. When *p.d.* is applied to the *p*-type semiconductor, the holes (donated by the impurity) are shifted from one co-valent bond to another. As the holes are positively charged, therefore, they are directed towards the negative terminal, constituting what is known as hole current. It may be noted that in *p*-type conductivity, the valence electrons move from one co-valent bond to another unlike the *n*-type where current conduction is by free electrons.

8.12 Charge on *n*-type and *p*-type Semiconductors

As discussed before, in *n*-type semiconductor, current conduction is due to excess of electrons whereas in a *p*-type semiconductor, conduction is by holes. The reader may think that *n*-type material has a net negative charge and *p*-type a net positive charge. But this conclusion is wrong. It is true that *n*-type semiconductor has excess of electrons but these extra electrons were supplied by the atoms of donor impurity and each atom of donor impurity is electrically neutral. When the impurity atom is added, the term "excess electrons" refers to an excess with regard to the number of electrons needed to fill the co-valent bonds in the semiconductor crystal. The extra electrons are free electrons and increase the conductivity of the semiconductor. The situation with regard to *p*-type semiconductor is also similar. *It follows, therefore, that n-type as well as p-type semiconductor is electrically neutral.*

8.13 Majority and Minority Carriers

It has already been discussed that due to the effect of impurity, *n*-type material has a large number of free electrons whereas *p*-type material has a large number of holes. However, it may be recalled that even at room temperature, some of the co-valent bonds break, thus releasing an equal number of free electrons and holes. An *n*-type material has its share of electron-hole pairs (released due to breaking of bonds at room temperature) but in addition has a much larger quantity of free electrons due to the effect of impurity. These impurity-caused free electrons are not associated with holes. Consequently, an *n*-type material has a large number of free electrons and a small number of holes as shown in Fig. 8.17 (*i*). The free electrons in this case are considered *majority carriers — since the majority portion of current in n*-type material is by the flow of free electrons — and the holes are the *minority carriers*.

Similarly, in a *p*-type material, holes outnumber the free electrons as shown in Fig. 8.17 (*ii*). Therefore, holes are the majority carriers and free electrons are the minority carriers.

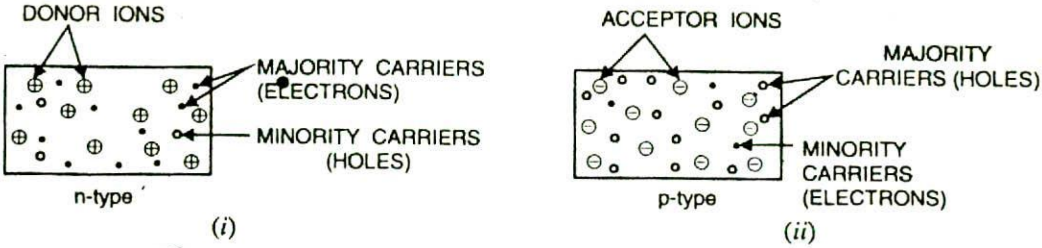


Fig. 8.17

8.14 *pn* Junction

When a p-type semiconductor is suitably joined to n-type semiconductor, the contact surface is called **pn junction.**

Most semiconductor devices contain one or more *pn* junctions. The *pn* junction is of great importance because it is in effect, the *control element* for semiconductor devices. A thorough knowledge of the formation and properties of *pn* junction can enable the reader to understand the semiconductor devices.

Formation of *pn* junction. In actual practice, the characteristic properties of *pn* junction will not be apparent if a *p*-type block is just brought in contact with *n*-type block. In fact, *pn* junction is fabricated by special techniques. One common method of making *pn* junction is called *alloying*. In this method, a small block of indium (trivalent impurity) is placed on an *n*-type germanium slab as shown in Fig. 8.18 (*i*). The system is then heated to a temperature of about 500°C. The indium and some of the germanium melt to form a small puddle of molten germanium-indium mixture as shown in Fig. 8.18 (*ii*). The temperature is then lowered and puddle begins to solidify. Under proper conditions, the atoms of indium impurity will be suitably adjusted in the germanium slab to form a single crystal. The addition of indium overcomes the excess of electrons in the *n*-type germanium to such an extent that it creates a *p*-type region.

As the process goes on, the remaining molten mixture becomes increasingly rich in indium. When all germanium has been redeposited, the remaining material appears as indium button which is frozen on to the outer surface of the crystallised portion as shown in Fig. 8.18 (*iii*). This button serves as a suitable base for soldering on leads.

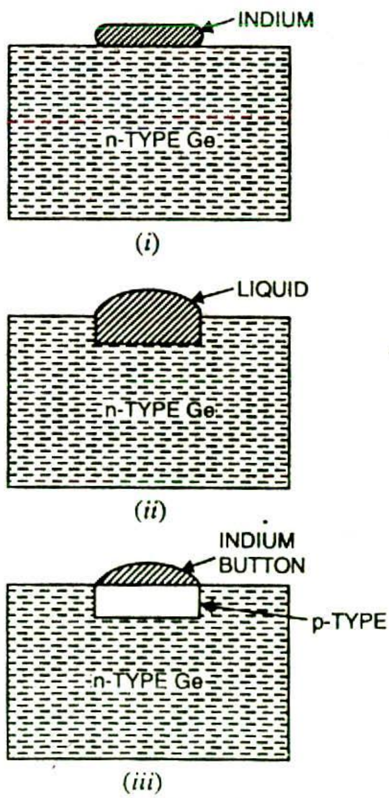


Fig. 8.18

8.15 Properties of pn Junction

To explain the properties of a *pn* junction, consider two types of materials; one *p*-type and the other *n*-type as shown in Fig 8.19. In this figure, left side material is a *p*-type semiconductor having *negative acceptor ions and positively charged holes. The right side material is *n*-type semiconductor having **positive donor ions and free electrons.

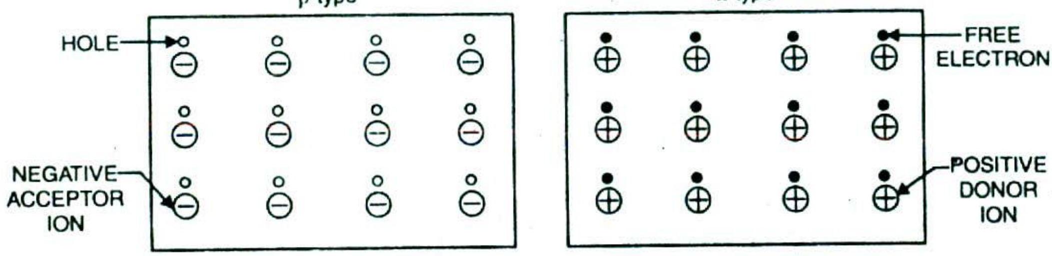


Fig. 8.19

Now, suppose the two pieces are suitably treated to form *pn* junction. Keep in mind that *n*-type material has a high concentration of free electrons while *p*-type material has a high concentration of holes. Therefore, at the junction, there is a tendency for the free electrons to *diffuse* over to the *p*-side and holes to the *n*-side. This process is called *diffusion*. As the free electrons move across the junction from *n*-type to *p*-type, positive donor ions are uncovered *i.e.* they are robbed of free electrons. Hence, a positive charge is built on the *n*-side of the junction. At the same time, the free electrons cross the junction and uncover the negative acceptor ions by filling in the holes. Therefore, a net negative charge is established on *p*-side of the junction. When a sufficient number of donor and acceptor ions is uncovered, further diffusion is prevented. It is because now positive charge on *n*-side repels holes to cross from *p*-type to *n*-type and negative charge on *p*-side repels free electrons to enter from *n*-type to *p*-type. Thus, a barrier is set up against further movement of charge carriers *i.e.* holes and electrons. This is called *potential barrier or junction barrier* V_0. The potential barrier is of the order of 0.1 to 0.3 volt. The potential distribution diagram is shown in Fig. 8.20. It is clear from the diagram that a potential barrier V_0 is set up which gives rise to electric field. This field prevents the respective majority carriers from crossing the barrier region.

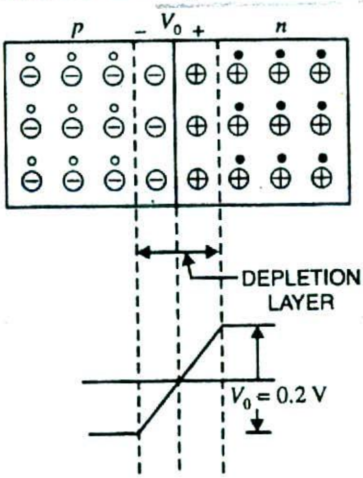


Fig. 8.20

It should be noted that outside this barrier on each side of the junction, the material is still neutral. Only inside the barrier, there is positive charge on *n*-side and negative charge on *p*-side. This region is called *depletion layer*. It is called so because the mobile charge carriers (*i.e.* free electrons and holes) have been depleted (*i.e.* emptied) in this region.

8.16 Applying Voltage Across pn Junction

The potential difference across a *pn* junction can be applied in two ways, namely; *forward biasing* and *reverse biasing*.

1. Forward biasing. *When external voltage applied to the junction is in such a direction that it cancels the potential barrier, thus permiting current flow, it is called* **forward biasing.**

* The acceptor impurity atom is short of one electorn. Therefore, it becomes a negative ion.

** The donor impurity atom donates one electron to the crystal and becomes a positive ion.

To apply forward bias, connect positive terminal of the battery to *p*-type and negative terminal to *n*-type as shown in Fig. 8.21. The applied forward potential establishes an electric field which acts against the field due to potential barrier. Therefore, the resultant field is weakened and the barrier height is reduced at the junction as shown in Fig. 8.21. As potential barrier voltage is very small (0.1 to 0.3 V), therefore, a small forward voltage is sufficient to completely eliminate the barrier. Once the potential barrier is eliminated by the forward voltage, junction resistance becomes almost zero and a low resistance path is established for the entire circuit. Therefore, current flows in the circuit. This is called *forward current.* With forward bias to *pn* junction, the following points are worth noting :

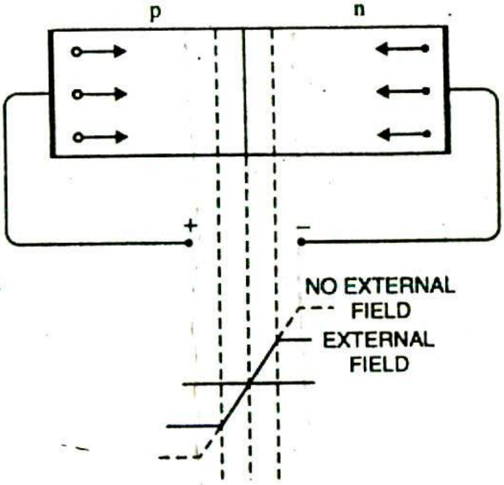


Fig. 8.21

(*i*) The potential barrier is reduced and at some forward voltage (0.1 to 0.3 V), it is eliminated altogether.

(*ii*) The junction offers low resistance (called *forward resistance,* R_f) to current flow.

(*iii*) Current flows in the circuit due to the establishment of low resistance path. The magnitude of current depends upon the applied forward voltage.

2. Reverse biasing. *When the external voltage applied to the junction is in such a direction that potential barrier is increased, it is called* **reverse biasing.**

To apply reverse bias, connect negative terminal of the battery to *p*-type and positive terminal to *n*-type as shown in Fig. 8.22. It is clear that applied reverse voltage establishes an electric field which acts in the same direction as the field due to potential barrier. Therefore, the resultant field at the junction is strengthened and the barrier height is increased as shown in Fig. 8.22. The increased potential barrier prevents the flow of charge carriers across the junction. Thus, a high resistance path is established for the entire circuit and hence the current does not flow. With reverse bias to *pn* junction, the following points are worth noting :

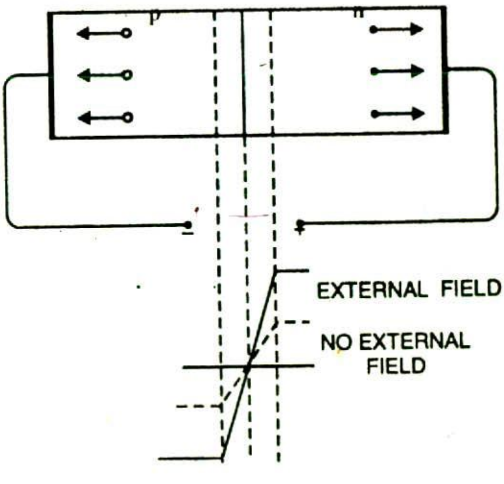


Fig. 8.22

(*i*) The potential barrier is increased.

(*ii*) The junction offers very high resistance (called *reverse resistance,* R_r) to current flow.

(*iii*) No current flows in the circuit due to the establishment of high resistance path.

Conclusion. From the above discussion, it follows that with reverse bias to the junction, a high resistance path is established and hence no current flow occurs. On the other hand, with forward bias to the junction, a low resistance path is set up and hence current flows in the circuit.

8.17 Current Flow in a Forward Biased pn Junction

We shall now see how current flows across *pn* junction when it is forward biased. Fig. 8.23 shows a forward biased *pn* junction. Under the influence of forward voltage, the free electrons in *n*-type move *towards the junction, leaving behind positively charged atoms. However, more electrons arrive from the negative battery terminal and enter the *n*-region to take up their places. As the free electrons reach the junction, they become **valence electrons. As valence electrons, they move through the holes in the *p*-region. The valence electrons move towards left in the *p*-region which is equivalent to the holes moving to right. When the valence electrons reach the left end of the crystal, they flow into the positive terminal of the battery.

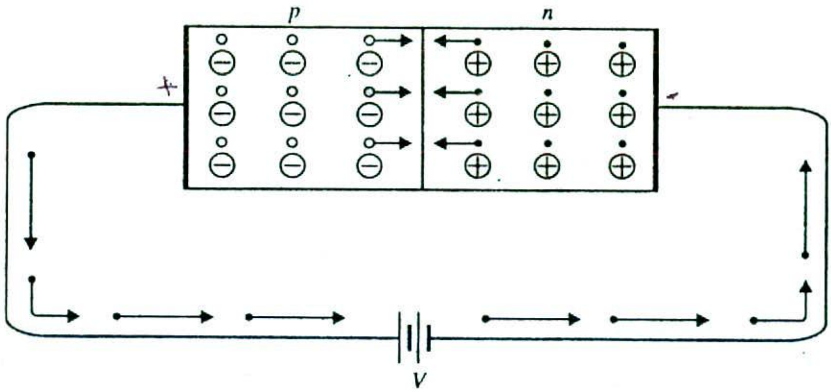


Fig. 8.23

The mechanism of current flow in a forward biased *pn* junction can be summed up as under :

(*i*) The free electrons from the negative terminal continue to pour into the *n*-region while the free electrons in the *n*-region move towards the junction.

(*ii*) The electrons travel through the *n*-region as free-electrons *i.e.* current in *n*-region is by free electrons.

(*iii*) When these electrons reach the junction, they combine with holes and become valence electrons.

(*iv*) The electrons travel through *p*-region as valence electrons *i.e.* current in the *p*-region is by holes.

(*v*) When these valence electrons reach the left end of crystal, they flow into the positive terminal of the battery.

From the above discussion, it is concluded that in *n*-type region, current is carried by free electrons whereas in *p*-type region, it is carried by holes. However, in the external connecting wires, the current is carried by free electrons.

8.18 Volt-Ampere Characteristics of *pn* Junction

Volt-ampere or *V-I* characteristic of a *pn* junction (also called a *crystal or semiconductor diode*) is the curve between voltage across the junction and the circuit current. Usually, voltage is taken along *x*-axis and current along *y*-axis. Fig. 8.24 shows the †circuit arrangement for determining the *V-I*

* Note that negative terminal of battery is connected to *n*-type. It repels the free electrons in *n*-type towards the junction.

** A hole is in the co-valent bond. When a free electron combines with a hole, it becomes a valence electron.

† *R* is the current limiting resistance. It prevents the forward current from exceeding the permitted value.

characteristics of a *pn* junction. The characteristics can be studied under three heads, namely; *zero external voltage*, *forward bias* and *reverse bias*.

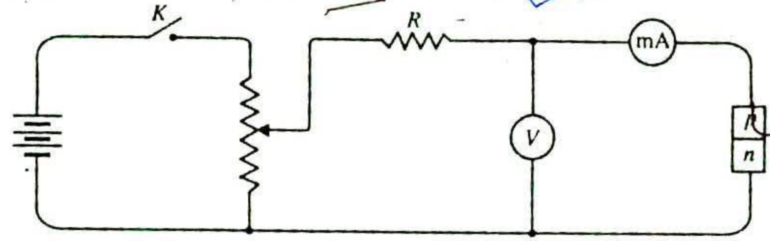


Fig. 8.24

(*i*) **Zero external voltage.** When the external voltage is zero, *i.e.* circuit is open at *K*, the potential barrier at the junction does not permit current flow. Therefore, the circuit current is zero as indicated by point *O* in Fig. 8.25.

(*ii*) **Forward bias.** With forward bias to the *pn* junction *i.e. p*-type connected to positive terminal and *n*-type connected to negative terminal, the potential barrier is reduced. At some forward voltage (0.7 V for Si and 0.3 V for Ge), the potential barrier is altogether eliminated and current starts flowing in the circuit. From now onwards, the current increases with the increase in forward voltage. Thus, a rising curve *OB* is obtained with forward bias as shown in Fig. 8.25. From the forward characteristic, it is seen that at first (*region OA*),the current increases very slowly and the curve is non-linear. It is because the external applied voltage is used up in overcoming the potential barrier. However, once the external voltage exceeds the potential barrier voltage, the *pn* junction behaves like an ordinary conductor. Therefore, the current rises very sharply with increase in external voltage (*region AB on the curve*). The curve is almost linear.

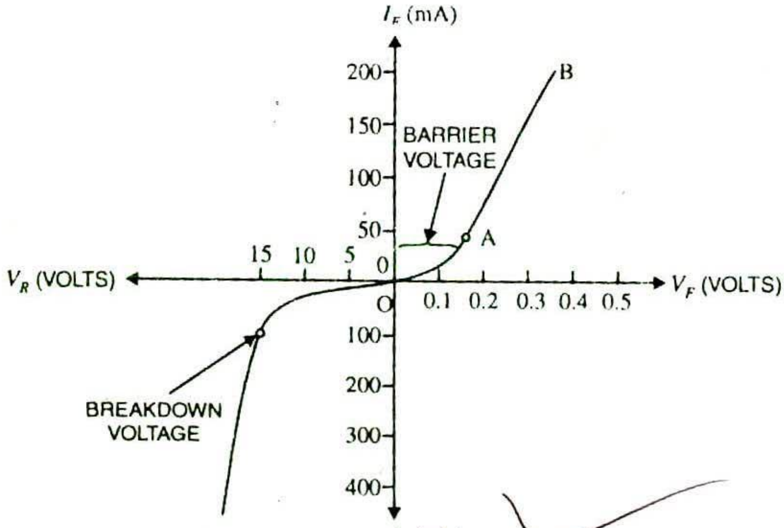


Fig. 8.25

(*iii*) **Reverse bias.** With reverse bias to the *pn* junction *i.e. p*-type connected to negative terminal and *n*-type connected to positive terminal, potential barrier at the junction is increased. Therefore, the junction resistance becomes very high and practically no current flows through the circuit.

However, in practice, a very small current (of the order of μ*A*) flows in the circuit with reverse bias as shown in the reverse characteristic. This is called *reverse *saturation current* (I_s) and is due to the minority carriers. It may be recalled that there are a few free electrons in *p*-type material and a few holes in *n*-type material. These undesirable free electrons in *p*-type and holes in *n*-type are called *minority carriers*. As shown in Fig. 8.26, to these minority carriers, the applied reverse bias appears as forward bias. Therefore, a **small current flows in the reverse direction.

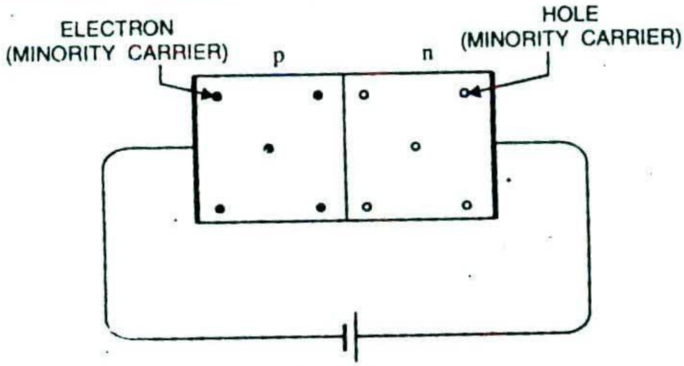


Fig. 8.26

If reverse voltage is increased continuously, the kinetic energy of electrons (minority carriers) may become high enough to knock out electrons from the semiconductor atoms. At this stage *breakdown* of the junction occurs, characterised by a sudden rise of reverse current and a sudden fall of the resistance of barrier region. This may destroy the junction permanently.

Note. The forward current through a *pn* junction is due to the *majority carriers* produced by the impurity. However, reverse current is due to the *minority carriers* produced due to breaking of some co-valent bonds at room temperature.

8.19 Important Terms

Two important terms often used with *pn* junction (*i.e.* crystal diode) are *breakdown voltage* and *knee voltage*. We shall now explain these two terms in detail.

(*i*) **Breakdown voltage.** *It is the minimum reverse voltage at which pn junction breaks down with sudden rise in reverse current.*

Under normal reverse voltage, a very little reverse current flows through a *pn* junction. However, if the reverse voltage attains a high value, the junction may break down with sudden rise in reverse current. For understanding this point, refer to Fig. 8.27. Even at room temperature, some hole-electron pairs (minority carriers) are produced in the depletion layer as shown in Fig. 8.27 (*i*). With reverse bias, the electrons move towards the positive terminal of supply. At large reverse voltage, these electrons acquire high enough velocities to dislodge valence electrons from semiconductor atoms as shown in Fig. 8.27 (*ii*). The newly liberated electrons in turn free other valence electrons. In this way, we get an *avalanche* of free electrons. Therefore, the *pn* junction conducts a very large reverse current.

Once the breakdown voltage is reached, the high reverse current may damage the junction. There-

* The term saturation comes from the fact that it reaches its maximum level quickly and does not significantly change with the increase in reverse voltage.

** Reverse current increases with reverse voltage but can generally be regarded as negligible over the working range of voltages.

fore, care should be taken that reverse voltage across a *pn* junction is always less than the breakdown voltage.

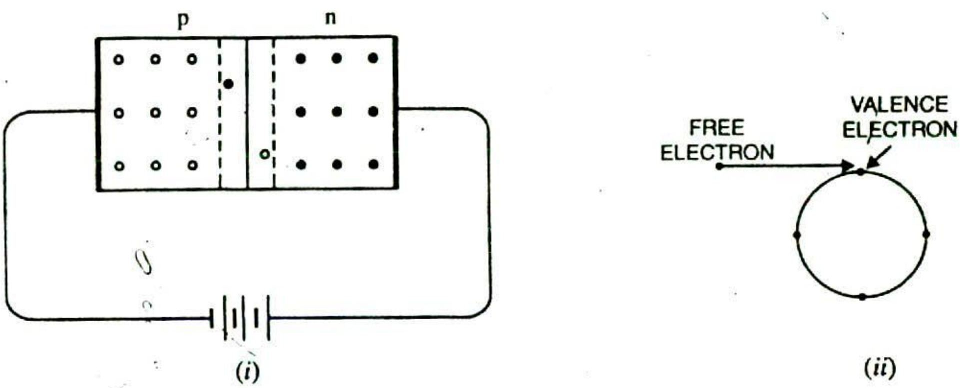


Fig. 8.27

(vi) Knee voltage. *It is the forward voltage at which the current through the junction starts to increase rapidly.*

When a diode is forward biased, it conducts current very slowly until we overcome the potential barrier. For silicon *pn* junction, potential barrier is 0.7 V whereas it is 0.3 V for germanium junction. It is clear from Fig. 8.28 that knee voltage for silicon diode is 0.7 V and 0.3 V for germanium diode.

Once the applied forward voltage exceeds the knee voltage, the current starts increasing rapidly. It may be added here that in order to get useful current through a *pn* junction, the applied voltage must be more than the knee voltage.

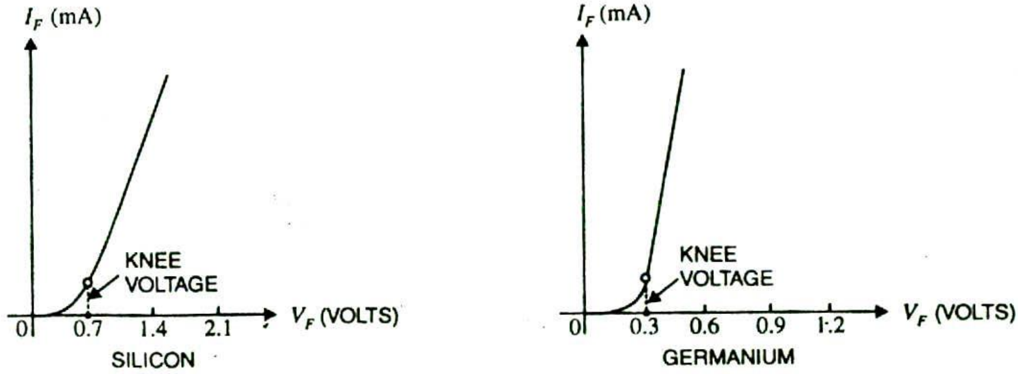


Fig. 8.28

Note. The potential barrier voltage is also known as *turn-on voltage*. This is obtained by taking the straight line portion of the forward characteristic and extending it back to the horizontal axis.

8.20 Limitations in the Operating Conditions of *pn* Junction

Every *pn* junction has limiting values of *maximum forward current, peak inverse voltage* and *maximum power rating*. The *pn* junction will give satisfactory performance if it is operated within these limiting values. However, if these values are exceeded, the *pn* junction may be destroyed due to excessive heat.

(*i*) *Maximum forward current.* It is the highest instantaneous forward current that a *pn* junction can conduct without damage to the junction. Manufacturers' data sheet usually specifies this rating. If the forward current in a *pn* junction is more than this rating, the junction will be destroyed due to overheating.

(*ii*) *Peak inverse voltage (PIV).* It is the maximum reverse voltage that can be applied to the *pn* junction without damage to the junction. If the reverse voltage across the junction exceeds its PIV, the junction may be destroyed due to excessive heat. The peak inverse voltage is of particular importance in rectifier service. A *pn* junction *i.e.* a crystal diode is used as a rectifier to change alternating current into direct current. In such applications, care should be taken that reverse voltage across the diode during negative half-cycle of a.c. does not exceed the PIV of diode.

(*iii*) *Maximum power rating.* It is the maximum power that can be dissipated at the junction without damaging it. The power dissipated at the junction is equal to the product of junction current and the voltage across the junction. This is a very important consideration and is invariably specified by the manufacturer in the data sheet.

Multiple-Choice Questions

1. A semiconductor is formed by .... bonds.
   (*i*) covalent (*ii*) electrovalent
   (*iii*) co-ordinate (*iv*) none of the above
2. A semiconductor has .... temperature co-efficient of resistance.
   (*i*) positive (*ii*) zero
   (*iii*) negative (*iv*) none of the above
3. The most commonly used semiconductor is ....
   (*i*) germanium (*ii*) silicon
   (*iii*) carbon (*iv*) sulphur
4. A semiconductor has generally .... valence electrons.
   (*i*) 2 (*ii*) 3
   (*iii*) 6 (*iv*) 4
5. The resistivity of pure germanium under standard conditions is about ....
   (*i*) $6 \times 10^4\ \Omega$ cm (*ii*) $60\ \Omega$ cm
   (*iii*) $3 \times 10^6\ \Omega$ cm (*iv*) $6 \times 10^{-4}\ \Omega$ cm
6. The resistivity of pure silicon is about ....
   (*i*) $100\ \Omega$ cm (*ii*) $6000\ \Omega$ cm
   (*iii*) $3 \times 10^5\ \Omega$ cm (*iv*) $1.6 \times 10^{-8}\ \Omega$ cm
7. When a pure semiconductor is heated, its resistance ....
   (*i*) goes up
   (*ii*) goes down
   (*iii*) remains the same
   (*iv*) cannot say
8. The strength of a semiconductor crystal comes from ....
   (*i*) forces between nuclei
   (*ii*) forces between protons
   (*iii*) electron-pair bonds
   (*iv*) none of the above
9. When a pentavalent impurity is added to a pure semiconductor, it becomes ....
   (*i*) an insulator
   (*ii*) an intrinsic semiconductor
   (*iii*) *p*-type semiconductor
   (*iv*) *n*-type semiconductor
10. Addition of pentavalent impurity to a semiconductor creates many ....
    (*i*) free electrons (*ii*) holes
    (*iii*) valence electrons
    (*iv*) bound electrons
11. A pentavalent impurity has .... valence electrons.
    (*i*) 3 (*ii*) 5
    (*iii*) 4 (*iv*) 6
12. An *n*-type semiconductor is ....
    (*i*) positively charged
    (*ii*) negatively charged

(*iii*) electrically neutral
(*iv*) none of the above

13. A trivalent impurity has .... valence electrons.
(*i*) 4 (*ii*) 5
(*iii*) 6 (*iv*) 3

14. Addition of trivalent impurity to a semiconductor creates many ....
(*i*) holes (*ii*) free electrons
(*iii*) valence electrons
(*iv*) bound electrons

15. A hole in a semiconductor is defined as ....
(*i*) a free electron
(*ii*) the incomplete part of an electron pair bond
(*iii*) a free proton
(*iv*) a free neutron

16. The impurity level in an extrinsic semiconductor is about .... of pure semiconductor.
(*i*) 10 atoms for 10^8 atoms
(*ii*) 1 atom for 10^8 atoms
(*iii*) 1 atom for 10^4 atoms
(*iv*) 1 atom for 100 atoms

17. As the doping to a pure semiconductor increases, the bulk resistance of the semiconductor ....
(*i*) remains the same
(*ii*) increases
(*iii*) decreases
(*iv*) none of the above

18. A hole and electron in close proximity would tend to ....
(*i*) repel each other
(*ii*) attract each other
(*iii*) have no effect on each other
(*iv*) none of the above

19. In a semiconductor, current conduction is due ....
(*i*) only to holes
(*ii*) only to free electrons
(*iii*) to holes and free electrons
(*iv*) none of the above

20. The random motion of holes and free electrons due to thermal agitation is called ....
(*i*) diffusion (*ii*) pressure
(*iii*) ionisation (*iv*) none of the above

21. A forward biased *pn* junction has a resistance of the ....
(*i*) order of Ω (*ii*) order of kΩ
(*iii*) order of MΩ (*iv*) none of the above

22. The battery connections required to forward bias a *pn* junction are ....
(*i*) +ve terminal to *p* and –ve terminal to *n*
(*ii*) –ve terminal to *p* and +ve terminal to *n*
(*iii*) –ve terminal to *p* and –ve terminal to *n*
(*iv*) none of the above

23. The barrier voltage at a *pn* junction for germanium is about ....
(*i*) 3.5 V (*ii*) 3V
(*iii*) zero (*iv*) 0.3 V

24. In the depletion region of a *pn* junction, there is a shortage of ....
(*i*) acceptor ions (*ii*) holes and electrons
(*iii*) donor ions (*iv*) none of the above

25. A reverse biased *pn* junction has ....
(*i*) very narrow depletion layer
(*ii*) almost no current
(*iii*) very low resistance
(*iv*) large current flow

26. A *pn* junction acts as a ....
(*i*) controlled switch
(*ii*) bidirectional switch
(*iii*) unidirectional switch
(*iv*) none of the above

27. A reverse biased *pn* junction has resistance of the........
(*i*) order of Ω (*ii*) order of kΩ
(*iii*) order of MΩ (*iv*) none of the above

28. The leakage current across a *pn* junction is due to ....
(*i*) minority carriers
(*ii*) majority carriers
(*iii*) junction capacitance
(*iv*) none of the above

29. When the temperature of an extrinsic semiconductor is increased, the pronounced effect is on ....
   (*i*) junction capacitance
   (*ii*) minority carriers
   (*iii*) majority carriers
   (*iv*) none of the above

30. With forward bias to a *pn* junction, the width of depletion layer ....
   (*i*) decreases (*ii*) increases
   (*iii*) remains the same
   (*iv*) none of the above

31. The leakage current in a *pn* junction is of the order of ....
   (*i*) A (*ii*) mA
   (*iii*) kA (*iv*) μA

32. In an intrinsic semiconductor, the number of free electrons ....
   (*i*) equals the number of holes
   (*ii*) is greater than the number of holes
   (*iii*) is less than the number of holes
   (*iv*) none of the above

33. At room temperature, an intrinsic semiconductor has ....
   (*i*) many holes only
   (*ii*) a few free electrons and holes
   (*iii*) many free electrons only
   (*iv*) no holes or free electrons

34. At absolute temperature, an intrinsic semiconductor has ....
   (*i*) a few free electrons
   (*ii*) many holes
   (*iii*) many free electrons
   (*iv*) no holes or free electrons

35. At room temperature, an intrinsic silicon crystal acts approximately as ....
   (*i*) a battery
   (*ii*) a conductor
   (*iii*) an insulator
   (*iv*) a piece of copper wire

Answers to Multiple-Choice Questions

1. (*i*)	**2.** (*iii*)	**3.** (*ii*)	**4.** (*iv*)	**5.** (*ii*)
6. (*ii*)	**7.** (*ii*)	**8.** (*iii*)	**9.** (*iv*)	**10.** (*i*)
11. (*ii*)	**12.** (*iii*)	**13.** (*iv*)	**14.** (*i*)	**15.** (*ii*)
16. (*ii*)	**17.** (*iii*)	**18.** (*ii*)	**19.** (*iii*)	**20.** (*i*)
21. (*i*)	**22.** (*i*)	**23.** (*iv*)	**24.** (*ii*)	**25.** (*ii*)
26. (*iii*)	**27.** (*iii*)	**28.** (*i*)	**29.** (*ii*)	**30.** (*i*)
31. (*iv*)	**32.** (*i*)	**33.** (*ii*)	**34.** (*iv*)	**35.** (*iii*)

Chapter Review Topics

1. What do you understand by a semi-conductor ? Discuss some important properties of semiconductors.
2. Which are the most commonly used semiconductors and why ?
3. Give the energy band description of semiconductors.
4. Discuss the effect of temperature on semiconductors.
5. Give the mechanism of hole current flow in a semiconductor.
6. What do you understand by intrinsic and extrinsic semiconductors ?
7. What is a *pn* junction ? Explain the formation of potential barrier in a *pn* junction.
8. Discuss the behaviour of a *pn* junction under forward and reverse biasing.

9. Draw and explain the V-I characteristics of a *pn* junction.

10. Write short notes on the following :

   (*i*) Breakdown voltage

   (*ii*) Knee voltage

   (*iii*) Limitations in the operating conditions of *pn* junction

Discussion Questions

1. Why is a semiconductor an insulator at ordinary temperature ?
2. Why are electron carriers present in *p*-type semiconductor ?
3. Why is silicon preferred to germanium in the manufacture of semiconductor devices ?
4. What is the importance of peak inverse voltage ?

9

Semiconductor Diode

Introduction

It has already been discussed in the previous chapter that a *pn* junction conducts current easily when forward biased and practically no current flows when it is reverse biased. This unilateral conduction characteristic of *pn* junction (*i.e.* semiconductor diode) is similar to that of a vacuum diode. Therefore, like a vacuum diode, a semiconductor diode can also accomplish the job of *rectification i.e.* change alternating to direct current. However, semiconductor diodes have become more *popular as they are smaller in size, cheaper and robust and usually operate with greater efficiency. In this chapter, we shall focus our attention on the circuit performance and applications of semiconductor diodes.

9.1 Semiconductor Diode

A pn junction is known as a **semi-conductor** *or* **crystal diode.** ✓

The outstanding property of a crystal diode to conduct current in one direction only permits it to be used as a rectifier. A crystal diode is usually represented by the schematic symbol shown in Fig. 9.1. The arrow in the symbol indicates the direction of easier conventional current flow.

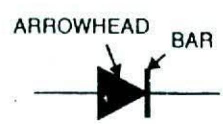


Fig. 9.1

A crystal diode has two terminals. When it is connected in a circuit, one thing to decide is whether the diode is forward or reverse biased. There is an easy rule to ascertain it. If the external circuit is trying to push the conventional current in the direction of arrow, the diode is forward biased. On the other hand, if the conventional current is trying to flow opposite to arrowhead, the diode is reverse biased. Putting in simple words :

(*i*) If *arrowhead* of diode symbol is *positive w.r.t. bar* of the symbol, the diode is forward biased.

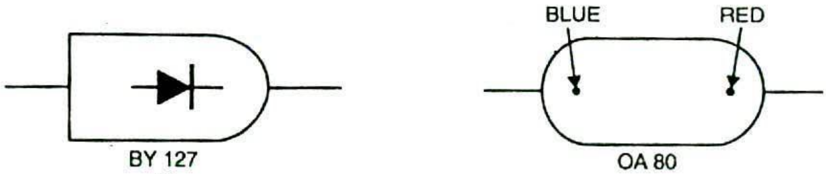
(*ii*) If the *arrowhead* of diode symbol is *negative w.r.t. bar*, the diode is reverse biased.

Identification of crystal diode terminals. While using a crystal diode, it is often necessary to know which end is arrowhead and which end is bar. For this purpose, the following methods are available :

* On the other hand, vacuum diodes can withstand high reverse voltages and can operate at fairly high temperatures.

** So called because *pn* junction is grown out of a crystal.

(*i*) Some manufacturers actually paint the symbol on the body of the diode *e.g. BY*127, *BY*114 crystal diodes manufactured by *BEL* [See Fig. 9.2 (*i*)].



(*i*) (*ii*)

Fig. 9.2

(*ii*) Sometimes, red and blue marks are used on the body of the crystal diode. Red mark denotes arrow whereas blue mark indicates bar *e.g. OA80* crystal diode [See Fig. 9.2 (*ii*)].

9.2 Crystal Diode as a Rectifier

Fig. 9.3 illustrates the rectifying action of a crystal diode. The a.c. input voltage to be rectified, the diode and load R_L are connected in series. The d.c. output is obtained across the load as explained in the following discussion. During the positive half-cycle of a.c. input voltage, the arrowhead becomes positive *w.r.t.* bar. Therefore, diode is forward biased and conducts current in the circuit. The result is that positive half-cycle of input voltage appears across R_L as shown. However, during the negative half-cycle of input a.c. voltage, the diode becomes reverse biased because now the arrowhead is negative *w.r.t.* bar. Therefore, diode does not conduct and no voltage appears across load R_L. The result is that output consists of positive half-cycles of input a.c. voltage while the negative half-cycles are suppressed. In this way, crystal diode has been able to do rectification i.e. change a.c. into d.c. It may be seen that output across R_L is pulsating d.c.

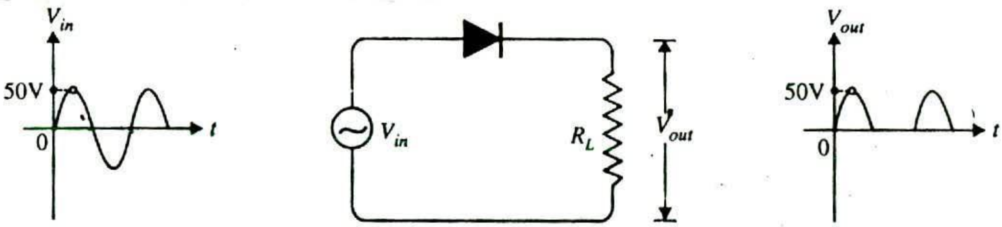
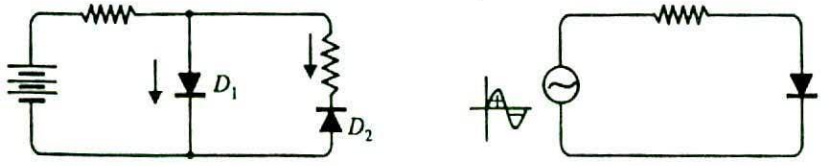


Fig. 9.3

It is interesting to see that behaviour of diode is like a *switch*. When the diode is forward biased, it behaves like a closed switch and connects the a.c. supply to the load R_L. However, when the diode is reverse biased, it behaves like an open switch and disconnects the a.c. supply from the load R_L. This switching action of diode permits only the positive half-cycles of input a.c. voltage to appear across R_L.

Example 9.1. *In each diode circuit of Fig. 9.4, find whether the diodes are forward or reverse biased.*



(*i*) (*ii*)

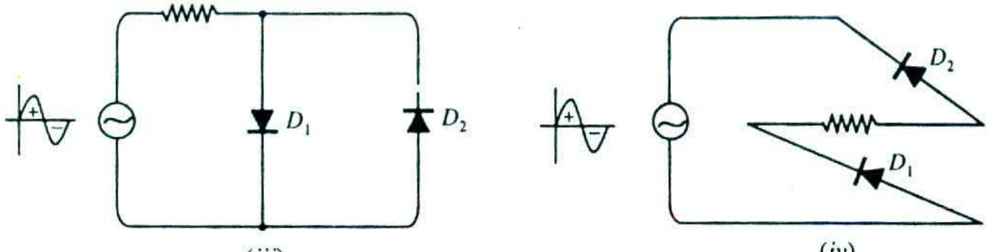


Fig. 9.4

Solution.

(*i*) Refer to Fig. 9.4 (*i*). The conventional current coming out of battery flows in the branch circuits. In diode D_1, the conventional current flows in the direction of arrowhead and hence this diode is forward biased. However, in diode D_2,the conventional current flows opposite to arrowhead and hence this diode is reverse biased.

(*ii*) Refer to Fig. 9.4 (*ii*). During the positive half-cycle of input a.c. voltage, the conventional current flows in the direction of arrowhead and hence diode is forward biased. However, during the negative half-cycle of input a.c. voltage, the diode is reverse biased.

(*iii*) Refer to Fig. 9.4 (*iii*). During the positive half-cycle of input a.c. voltage, conventional current flows in the direction of arrowhead in D_1 but it flows opposite to arrowhead in D_2. Therefore, during positive half-cycle, diode D_1 is forward biased and diode D_2 reverse biased. However, during the negative half-cycle of input a.c. voltage, diode D_2 is forward biased and D_1 is reverse biased.

(*iv*) Refer to Fig. 9.4 (*iv*). During the positive half-cycle of input a.c. voltage, both the diodes are reverse biased. However, during the negative half-cycle of input a.c. voltage, both the diodes are forward biased.

9.3 Resistance of Crystal Diode

It has already been discussed that a forward biased diode conducts easily whereas a reverse biased diode practically conducts no current. It means that *forward resistance* of a diode is quite small as compared with its *reverse resistance*.

1. Forward resistance. The resistance offered by the diode to forward bias is known as *forward resistance*. This resistance is not the same for the flow of direct current as for the changing current. Accordingly; this resistance is of two types, namely; *d.c. forward resistance* and *a.c. forward resistance*.

(*i*) *d.c. forward resistance.* It is the opposition offered by the diode to the direct current. It is measured by the ratio of d.c. voltage across the diode to the resulting d.c. current through it. Thus, referring to the forward characteristic in Fig. 9.5, it is clear that when forward voltage is OA, the forward current is OB.

$$\therefore \quad \text{d.c. forward resistance, } R_f = \frac{OA}{OB}$$

(*ii*) *a.c. forward resistance.* It is the opposition offered by the diode to the changing forward current. It is measured by the ratio of change in voltage across diode to the resulting change in current through it *i.e.*

$$\text{a.c. forward resistance} = \frac{\text{Change in voltage across diode}}{\text{Corresponding change in current through diode}}$$

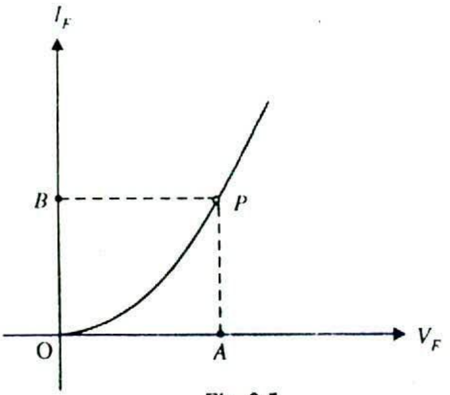


Fig. 9.5

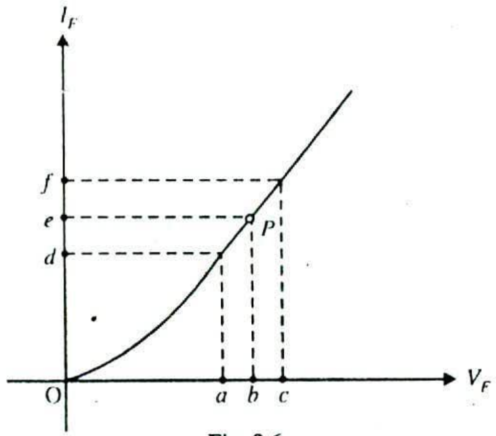


Fig. 9.6

The a.c. forward resistance is more significant as the diodes are generally used with alternating voltages. The a.c. forward resistance can be determined from the forward characteristic as shown in Fig. 9.6. If P is the operating point at any instant, then forward voltage is *ob* and forward current is *oe*. To find the a.c. forward resistance, vary the forward voltage on both sides of the operating point equally as shown in Fig. 9.6 where $ab = bc$. It is clear from this figure that :

For forward voltage *oa*, circuit current is *od*.

For forward voltage *oc*, circuit current is *of*.

$$\therefore \quad \text{a.c. forward resistance} = \frac{\text{Change in forward voltage}}{\text{Change in forward current}} = \frac{oc - oa}{of - od} = \frac{ac}{df}$$

It may be mentioned here that forward resistance of a crystal diode is very small, ranging from 1 to 25 Ω.

2. Reverse resistance. The resistance offered by the diode to the reverse bias is known as *reverse resistance*. It can be d.c. reverse resistance or a.c. reverse resistance depending upon whether the reverse bias is direct or changing voltage. Ideally, the reverse resistance of a diode is infinite. However, in practice, the reverse resistance is not infinite because for any value of reverse bias, there does exist a small leakage current. It may be emphasised here that reverse resistance is very large compared to the forward resistance. In germanium diodes, the ratio of reverse to forward resistance is 40000 : 1 while for silicon this ratio is 1000000 : 1.

9.4 Equivalent Circuit of Crystal Diode

It is generally profitable to replace a device or system by its equivalent circuit. An equivalent circuit of a device (*e.g* crystal diode, transistor etc) is a combination of electric elements, which when connected in a circuit, acts exactly as does the device when connected in the same circuit. Once the device is replaced by its equivalent circuit, the resulting network can be solved by traditional circuit analysis techniques. We shall now find the equivalent circuit of a crystal diode.

(*i*) ***Approximate Equivalent circuit.** When the forward voltage V_F is applied across a diode, it will not conduct till the potential barrier V_0 at the junction is overcome. When the forward voltage exceeds the potential barrier voltage, the diode starts conducting as shown in Fig. 9.7 (*i*). The forward current I_f flowing through the diode causes a voltage drop in its internal resistance r_f. Therefore, the forward voltage V_F applied across the *actual* diode has to overcome :

* We assume here that *V*/*I* characteristic of crystal diode is linear.

(i) potential barrier V_0

(ii) internal drop $I_f r_f$

$$\therefore \quad V_F = V_0 + I_f r_f$$

For a silicon diode, $V_0 = 0.7$ V whereas for a germanium diode, $V_0 = 0.3$ V.

Therefore, approximate equivalent circuit for a crystal diode is a switch in series with a battery V_0 and internal resistance r_f as shown in Fig. 9.7 (ii). This approximate equivalent circuit of a diode is very helpful in studying the performance of the diode in a circuit.

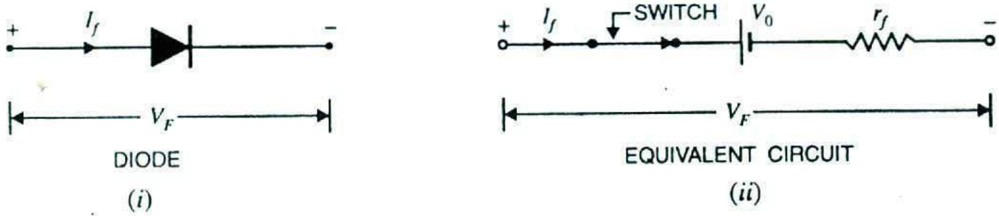


Fig. 9.7

(ii) **Simplified Equivalent circuit.** For most applications, the internal resistance r_f of the crystal diode can be ignored in comparison to other elements in the equivalent circuit. The equivalent circuit then reduces to the one shown in Fig. 9.8 (ii). This simplified equivalent circuit of the crystal diode is frequently used in diode-circuit analysis.

Fig. 9.8

(iii) **Ideal diode model.** An ideal diode is one which behaves as a perfect conductor when forward biased and as a perfect insulator when reverse biased. Obviously, in such a hypothetical situation, forward resistance $r_f = 0$ and potential barrier V_0 is considered negligible. It may be mentioned here that although ideal diode is never found in practice, yet diode circuit analysis is made on this basis. *Therefore, while discussing diode circuits, the diode will be assumed ideal unless and until stated otherwise.*

9.5 Crystal Diode Equivalent Circuits

It is desirable to sum up the various models of crystal diode equivalent circuit in the tabular form (See Page 141).

Example 9.2. *An a.c. voltage of peak value 20 V is connected in series with a silicon diode and load resistance of 500 Ω. If the forward resistance of diode is 10 Ω, find :*

(i) peak current through diode *(ii) peak output voltage*

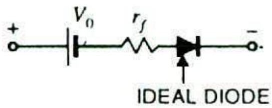
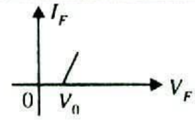
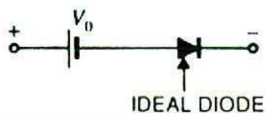
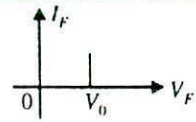
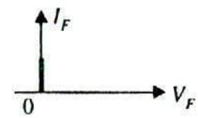
What will be these values if the diode is assumed to be ideal ?

Solution.

Peak input voltage = 20 V

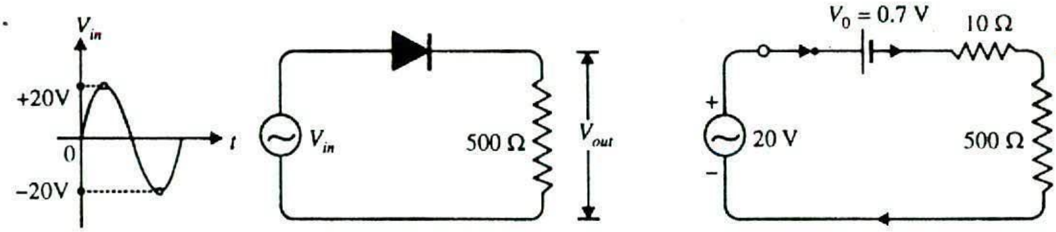
Forward resistance, r_f = 10 Ω

Load resistance, R_L = 500 Ω

S.No.	Type	Model	Characteristic
1.	Approximate model		
2.	Simplified model		
3.	Ideal Model		

Potential barrier voltage, $V_0 = 0.7$ V

The diode will conduct during the positive half-cycles of a.c. input voltage only. The equivalent circuit is shown in Fig. 9.9 (*ii*).



(*i*) (*ii*)

Fig. 9.9

(*i*) The peak current through the diode will occur at the instant when the input voltage reaches positive peak *i.e.* $V_{in} = V_F = 20$ V.

$$\therefore \quad V_F = V_0 + (I_f)_{peak}\,[r_f + R_L] \quad \text{...(i)}$$

$$\text{or} \quad (I_f)_{peak} = \frac{V_F - V_0}{r_f + R_L} = \frac{20 - 0.7}{10 + 500} = \frac{19.3}{510}\text{ A} = \mathbf{37.8\ mA}$$

(*ii*) Peak output voltage $= (I_f)_{peak} \times R_L = 37.8\text{ mA} \times 500\ \Omega = \mathbf{18.9\ V}$

Ideal diode. For an ideal diode, put $V_0 = 0$ and $r_f = 0$ in equation (*i*).

$$\therefore \quad V_F = (I_f)_{peak} \times R_L$$

$$\text{or} \quad (I_f)_{peak} = \frac{V_F}{R_L} = \frac{20\text{ V}}{500\ \Omega} = \mathbf{40\ mA}$$

Peak output voltage $= (I_f)_{peak} \times R_L = 40\text{ mA} \times 500\ \Omega = \mathbf{20\ V}$

Comments. It is clear from the above example that output voltage is *nearly* the same whether the actual diode is used or the diode is considered ideal. This is due to the fact that input voltage is quite large as compared with V_0 and voltage drop in r_f. Therefore, nearly the whole input forward voltage appears across the load. For this reason, diode circuit analysis is generally made on the ideal diode basis.

Example 9.3. *Find the current through the diode in the circuit shown in Fig. 9.10 (i). Assume the diode to be ideal.*

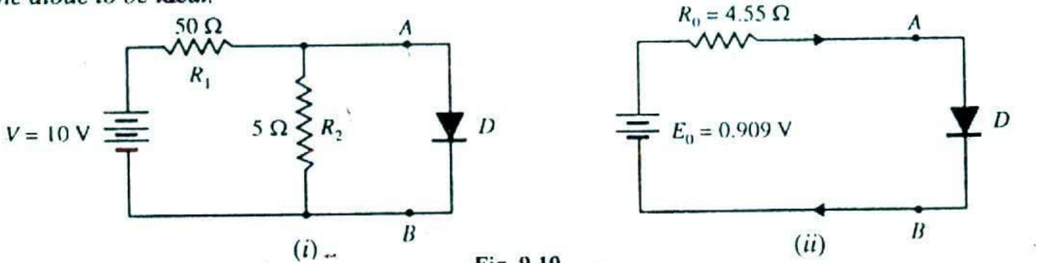


Fig. 9.10

Solution. We shall use Thevenin's theorem to find current in the diode. Referring to Fig. 9.10 (i),

$$E_0 = \text{Thevenin's voltage}$$
$$= \text{Open circuited voltage across } AB \text{ with diode removed}$$
$$= \frac{R_2}{R_1 + R_2} \times V = \frac{5}{50 + 5} \times 10 = 0.909 \text{ V}$$

$$R_0 = \text{Thevenin's resistance}$$
= Resistance at terminals AB with diode removed and battery replaced by a short circuit
$$= \frac{R_1 R_2}{R_1 + R_2} = \frac{50 \times 5}{50 + 5} = 4.55 \ \Omega$$

Fig. 9.10 (ii) shows Thevenin's equivalent circuit. Since the diode is ideal, it has zero resistance.

$$\therefore \quad \text{Current through diode} = \frac{E_0}{R_0} = \frac{0.909}{4.55} = 0.2 \text{ A} = \mathbf{200 \text{ mA}}$$

Example 9.4. *Calculate the current through 48 Ω resistor in the circuit shown in Fig. 9.11 (i). Assume the diodes to be of silicon and forward resistance of each diode is 1 Ω.*

Solution. Diodes D_1 and D_3 are forward biased while diodes D_2 and D_4 are reverse biased. We can, therefore, consider the branches containing diodes D_2 and D_4 as "open". Replacing diodes D_1 and D_3 by their equivalent circuits and making the branches containing diodes D_2 and D_4 open, we get the circuit shown in Fig. 9.11 (ii). Note that for a silicon diode, the barrier voltage is 0.7 V.

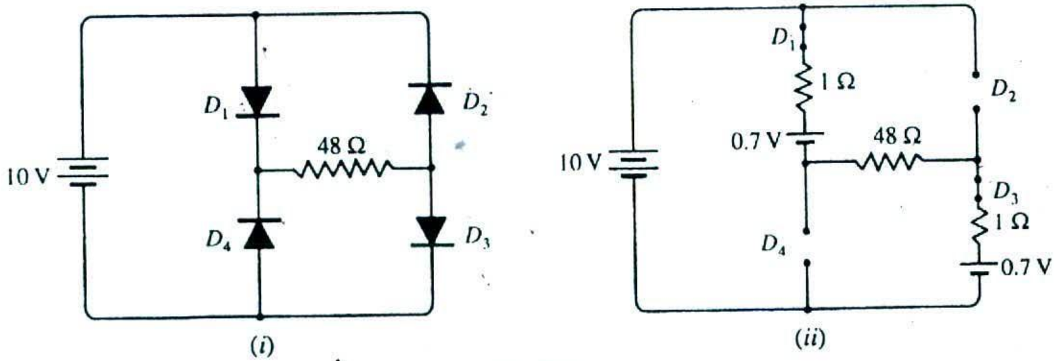


Fig. 9.11

$$\text{Net circuit voltage} = 10 - 0.7 - 0.7 = 8.6 \text{ V}$$
$$\text{Total circuit resistance} = 1 + 48 + 1 = 50 \ \Omega$$

∴ Circuit current = 8.6/50 = 0.172 A = **172 mA**

Example 9.5. *Determine the current I in the circuit shown in Fig. 9.12 (i). Assume the diodes to be of silicon and forward resistance of diodes to be zero.*

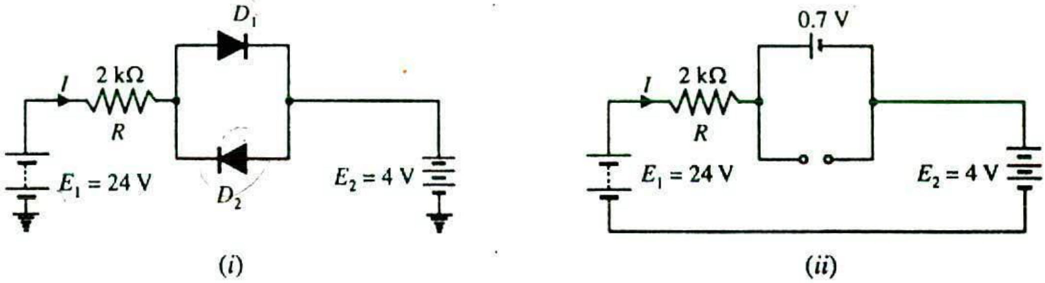


Fig. 9.12

Solution. The conditions of the problem suggest that diode D_1 is forward biased and diode D_2 is reverse biased. We can, therefore, consider the branch containing diode D_2 as open as shown in Fig. 9.12 (*ii*). Further, diode D_1 can be replaced by its simplified equivalent circuit.

$$\therefore \quad I = \frac{E_1 - E_2 - V_0}{R} = \frac{24 - 4 - 0.7}{2 \text{ k}\Omega} = \frac{19.3 \text{ V}}{2 \text{ k}\Omega} = \mathbf{9.65 \text{ mA}}$$

Example 9.6. *Find the voltage V_A in the circuit shown in Fig. 19.13 (i). Use simplified model.*

Solution. It appears that when the applied voltage is switched on, both the diodes will turn "on". But that is not so. When voltage is applied, germanium diode (V_0 = 0.3 V) will turn on first and a level of 0.3 V is maintained across the parallel circuit. The silicon diode never gets the opportunity to have 0.7 V across it and, therefore, remains in open-circuit state as shown in Fig. 9.13 (*ii*).

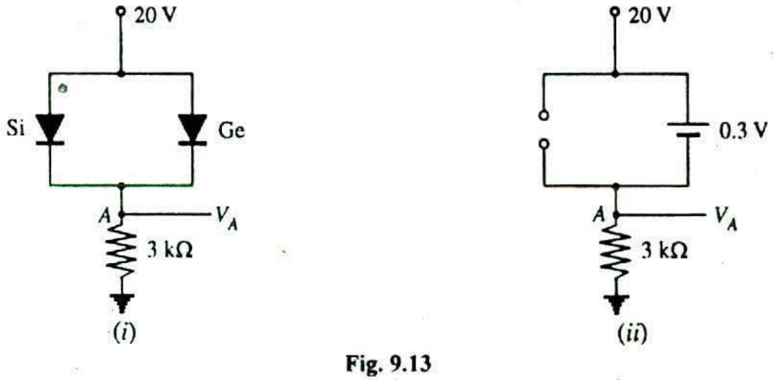


Fig. 9.13

$$\therefore \quad V_A = 20 - 0.3 = \mathbf{19.7 \text{ V}}$$

Example 9.7. *Find V_Q and I_D in the network shown in Fig. 9.14 (i). Use simplified model.*

Solution. Replace the diodes by their simplified models. The resulting circuit will be as shown in Fig. 9.14 (*ii*). By symmetry, current in each branch is I_D so that current in branch *CD* is $2I_D$. Applying Kirchhoff's voltage law to the closed circuit *ABCDA*, we have,

$$-0.7 - I_D \times 2 - 2\,I_D \times 2 + 10 = 0 \qquad (I_D \text{ in mA})$$

or $$6\,I_D = 9.3$$

$$\therefore \quad I_D = \frac{9.3}{6} = \mathbf{1.55 \text{ mA}}$$

$$V_Q = (2\,I_D) \times 2\text{ k}\Omega = (2 \times 1.55\text{ mA}) \times 2\text{ k}\Omega = \mathbf{6.2\ V}$$

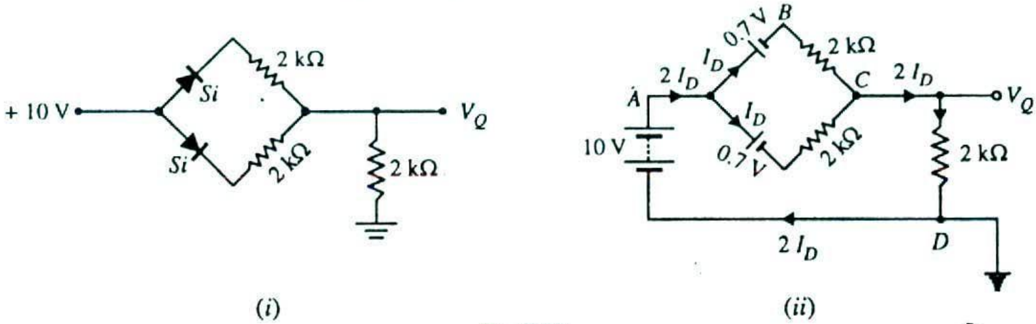


Fig. 9.14

Example 9.8. *Determine current through each diode in the circuit shown in Fig. 9.15 (i). Use simplified model. Assume diodes to be similar.*

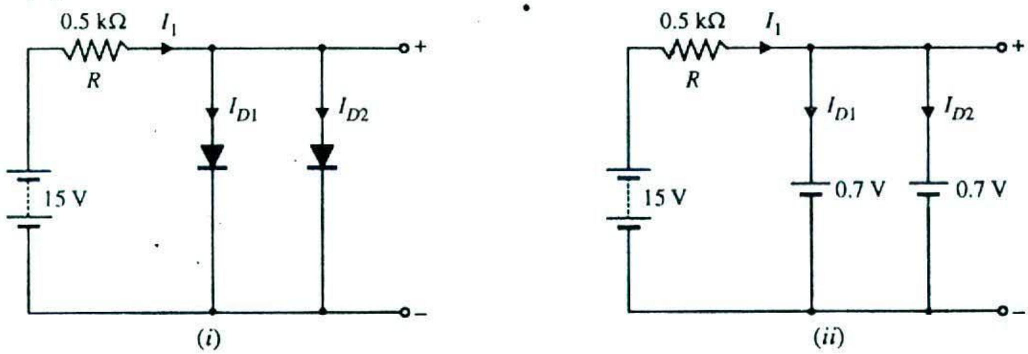


Fig. 9.15

Solution. The applied voltage forward biases each diode so that they conduct current in the same direction. Fig. 9.15 (*ii*) shows the equivalent circuit using simplified model. Referring to Fig. 9.15 (*ii*),

$$I_1 = \frac{\text{Voltage across } R}{R} = \frac{15 - 0.7}{0.5\text{ k}\Omega} = 28.6\text{ mA}$$

Since the diodes are similar, $I_{D1} = I_{D2} = \frac{I_1}{2} = \frac{28.6}{2} = \mathbf{14.3\ mA}$

Comments. Note the use of placing the diodes in parallel. If the current rating of each diode is 20 mA and a single diode is used in this circuit, a current of 28.6 mA would flow through the diode, thus damaging the device. By placing them in parallel, the current is limited to a safe value of 14.3 mA for the same terminal voltage.

9.6 Important Terms

While discussing the diode circuits, the reader will generally come across the following terms :

(*i*) **Forward current.** It is the current flowing through a forward biased diode. Every diode has a maximum value of forward current which it can safely carry. If this value is exceeded, the diode may be destroyed due to excessive heat. For this reason, the manufacturers' data sheet specifies the maximum forward current that a diode can handle safely.

(*ii*) **Peak inverse voltage.** *It is the maximum reverse voltage that a diode can withstand without destroying the junction.*

If the reverse voltage across a diode exceeds this value, the reverse current increases sharply and breaks down the junction due to excessive heat. Peak inverse voltage is extremely important when diode is used as a rectifier. In rectifier service, it has to be ensured that reverse voltage across the diode does not exceed its PIV during the negative half-cycle of input a.c. voltage. As a matter of fact, PIV consideration is generally the deciding factor in diode rectifier circuits. The peak inverse voltage may be between 10V and 10 kV depending upon the type of diode.

(*iii*) **Reverse current or leakage current.** It is the current that flows through a reverse biased diode. This current is due to the minority carriers. Under normal operating voltages, the reverse current is quite small. Its value is extremely small (< 1μ A) for silicon diodes but it is appreciable (≃ 100 μA) for germanium diodes.

It may be noted that the reverse current is usually very small as compared with forward current. For example, the forward current for a typical diode might range upto 100 mA while the reverse current might be only a few μA—a ratio of many thousands between forward and reverse currents.

9.7 Crystal Diode Rectifiers

For reasons associated with economics of generation and transmission, the electric power available is usually an a.c. supply. The supply voltage varies sinusoidally and has a frequency of 50 Hz. It is used for lighting, heating and electric motors. But there are many applications (*e.g.* electronic circuits) where d.c. supply is needed. When such a d.c. supply is required, the mains a.c. supply is rectified by using crystal diodes. The following two rectifier circuits can be used :

(*i*) Half-wave rectifier (*ii*) Full-wave rectifier

9.8 Half-Wave Rectifier

In half-wave rectification, the rectifier conducts current only during the positive half-cycles of input a.c. supply. The negative half-cycles of a.c. supply are suppressed *i.e.* during negative half-cycles, no current is conducted and hence no voltage appears across the load. Therefore, current always flows in one direction (*i.e.* d.c.) through the load though after every half-cycle.

Circuit details. Fig. 9.16 shows the circuit where a single crystal diode acts as a half-wave rectifier. The a.c. supply to be rectified is applied in series with the diode and load resistance R_L. Generally, a.c. supply is given through a transformer. The use of transformer permits two advantages. Firstly, it allows us to step up or step down the a.c. input voltage as the situation demands. Secondly, the transformer isolates the rectifier circuit from power line and thus reduces the risk of electric shock.

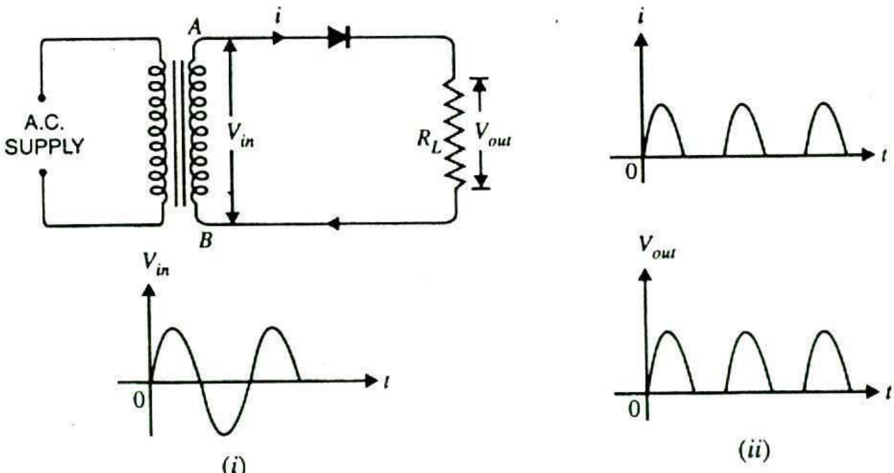


Fig. 9.16

Operation. The a.c. voltage across the secondary winding AB changes polarities after every half-cycle. During the positive half-cycle of input a.c. voltage, end A becomes positive *w.r.t.* end B. This makes the diode forward biased and hence it conducts current. During the negative half-cycle, end A is negative *w.r.t.* end B. Under this condition, the diode is reverse biased and it conducts no current. Therefore, current flows through the diode during positive half-cycles of input a.c. voltage only ; it is blocked during the negative half-cycles [See Fig. 9.16 (*ii*)]. In this way, current flows through load R_L always in the same direction. Hence d.c. output is obtained across R_L. It may be noted that output across the load is pulsating d.c. These pulsations in the output are further smoothened with the help of *filter circuits* discussed later.

Disadvantages : The main disadvantages of a half-wave rectifier are :

(*i*) The pulsating current in the load contains alternating component whose basic frequency is equal to the supply frequency. Therefore, an elaborate filtering is required to produce steady direct current.

(*ii*) The a.c. supply delivers power only half the time. Therefore, the output is low.

9.9 Efficiency of Half-Wave Rectifier

The ratio of d.c. power output to the applied input a.c. power is known as **rectifier efficiency** *i.e.*

$$\text{Rectifier efficiency, } \eta = \frac{\text{d.c. power output}}{\text{Input a.c. power}}$$

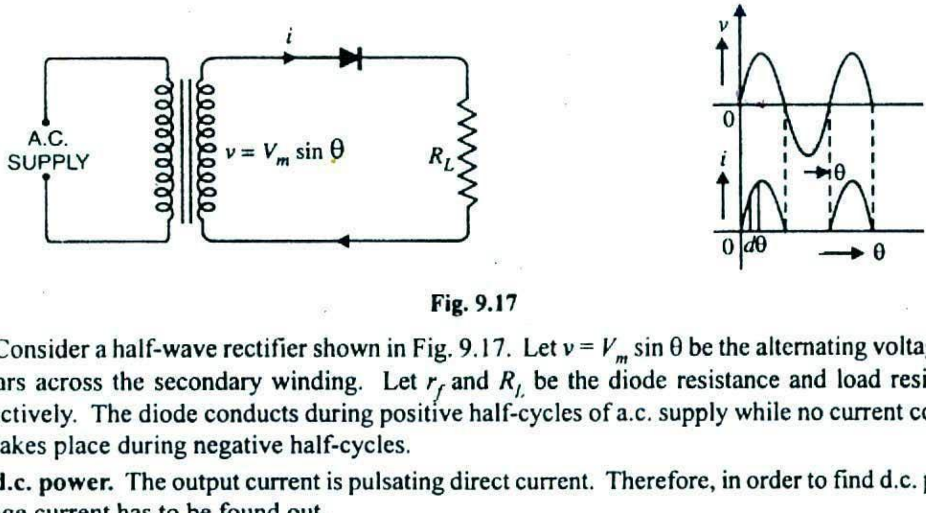


Fig. 9.17

Consider a half-wave rectifier shown in Fig. 9.17. Let $v = V_m \sin\theta$ be the alternating voltage that appears across the secondary winding. Let r_f and R_L be the diode resistance and load resistance respectively. The diode conducts during positive half-cycles of a.c. supply while no current conduction takes place during negative half-cycles.

d.c. power. The output current is pulsating direct current. Therefore, in order to find d.c. power, average current has to be found out.

$$*I_{av} = I_{dc} = \frac{1}{2\pi}\int_0^{\pi} i\, d\theta = \frac{1}{2\pi}\int_0^{\pi} \frac{V_m \sin\theta}{r_f + R_L}\, d\theta$$

$$= \frac{V_m}{2\pi(r_f + R_L)}\int_0^{\pi} \sin\theta\, d\theta = \frac{V_m}{2\pi(r_f + R_L)}[-\cos\theta]_0^{\pi}$$

$$= \frac{V_m}{2\pi(r_f + R_L)} \times 2 = \frac{V_m}{(r_f + R_L)} \times \frac{1}{\pi}$$

---

* Average value $= \dfrac{\text{Area under the curve over a cycle}}{\text{Base}} = \dfrac{\int_0^{\pi} i\, d\theta}{2\pi}$

$$= \frac{* I_m}{\pi} \qquad \left[\because I_m = \frac{V_m}{(r_f + R_L)}\right]$$

$\therefore$ d.c. power, $P_{dc} = I_{dc}^2 \times R_L = \left(\frac{I_m}{\pi}\right)^2 \times R_L$ ...(*i*)

a.c. power input : The a.c. power input is given by ;

$$P_{ac} = I_{rms}^2 (r_f + R_L)$$

For a half-wave rectified wave, $I_{rms} = I_m/2$

$$\therefore \quad P_{ac} = \left(\frac{I_m}{2}\right)^2 \times (r_f + R_L) \quad ...(ii)$$

$$\therefore \quad \text{Rectifier efficiency} = \frac{\text{d.c. output power}}{\text{a.c. input power}} = \frac{(I_m/\pi)^2 \times R_L}{(I_m/2)^2 (r_f + R_L)}$$

$$= \frac{0.406 R_L}{r_f + R_L} = \frac{0.406}{1 + \frac{r_f}{R_L}}$$

The efficiency will be maximum if r_f is negligible as compared to R_L.

$\therefore$ Max. rectifier efficiency = 40.6%

This shows that in half-wave rectification, a maximum of 40.6% of a.c. power is converted into d.c. power.

Example 9.9. *The applied input a.c. power to a half-wave rectifier is 100 watts. The d.c. output power obtained is 40 watts.*

(*i*) *What is the rectification efficiency ?*

(*ii*) *What happens to remaining 60 watts ?*

Solution.

$$(i) \quad \text{Rectification efficiency} = \frac{\text{d.c. output power}}{\text{a.c. input power}} = \frac{40}{100} = 0.4 = \mathbf{40\%}$$

(*ii*) 40% efficiency of rectification does not mean that 60% of power is lost in the rectifier circuit. In fact, a crystal diode consumes little power due to its small internal resistance. The 100 W a.c. power is contained as 50 watts in positive half-cycles and 50 watts in negative half-cycles. The 50 watts in the negative half-cycles are not supplied at all. Only 50 watts in the positive half-cycles are converted into 40 watts.

$$\therefore \quad \text{Power efficiency} = \frac{40}{50} \times 100 = 80\%$$

Although 100 watts of a.c. power was supplied, the half-wave rectifier accepted only 50 watts and converted it into 40 watts d.c. power. Therefore, it is appropriate to say that efficiency of rectification is 40% and *not* 80% which is power efficiency.

Example 9.10. *An a.c. supply of 230 V is applied to a half wave rectifier circuit through a transformer of turn ratio 10 : 1. Find* (*i*) *the output d.c. voltage and* (*ii*) *the peak inverse voltage. Assume the diode to be ideal.*

---

* It may be remembered that the *area of one-half cycle of a sinusoidal wave* is twice the peak value. Thus in this case, peak value is I_m and, therefore, area of one-half cycle is $2 I_m$.

$$\therefore \quad I_{av} = I_{dc} = \frac{2 I_m}{2\pi} = \frac{I_m}{\pi}$$

Solution.

Primary to secondary turns is

$$\frac{N_1}{N_2} = 10$$

R.M.S. primary voltage

$$= 230 \text{ V}$$

∴ Max. primary voltage is

$$V_{pm} = (\sqrt{2}) \times \text{r.m.s. primary voltage}$$

$$= (\sqrt{2}) \times 230 = 325.3 \text{ V}$$

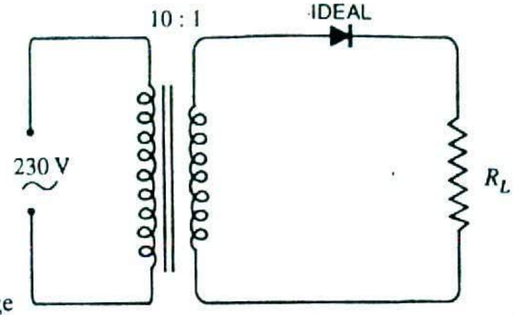


Fig. 9.18

Max. secondary voltage is

$$V_{sm} = V_{pm} \times \frac{N_2}{N_1} = 325.3 \times \frac{1}{10} = 32.53 \text{ V}$$

(*i*) $$I_{d.c.} = \frac{I_m}{\pi}$$

∴ $$V_{dc} = \frac{I_m}{\pi} \times R_L = \frac{V_{sm}}{\pi} = \frac{32.53}{\pi} = \mathbf{10.36\ V}$$

(*ii*) During the negative half-cycle of a.c. supply, the diode is reverse biased and hence conducts no current. Therefore, the maximum secondary voltage appears across the diode.

∴ Peak inverse voltage = **32.53 V**

Example 9.11. *A crystal diode having internal resistance $r_f = 20\Omega$ is used for half-wave rectification. If the applied voltage $v = 50 \sin \omega t$ and load resistance $R_L = 800\ \Omega$, find :*

(*i*) I_m, I_{dc}, I_{rms} (*ii*) *a.c. power input and d.c. power output*

(*iii*) *d.c. output voltage* (*iv*) *efficiency of rectification*

Solution.

$$v = 50 \sin \omega t$$

∴ Maximum voltage, $V_m = 50$ V

(*i*) $$I_m = \frac{V_m}{r_f + R_L} = \frac{50}{20 + 800} = 0.061 \text{ A} = \mathbf{61\ mA}$$

$$I_{dc} = I_m/\pi = 61/\pi = \mathbf{19.4\ mA}$$

$$I_{rms} = I_m/2 = 61/2 = \mathbf{30.5\ mA}$$

(*ii*) $$\text{a.c. power input} = (I_{rms})^2 \times (r_f + R_L) = \left(\frac{30.5}{1000}\right)^2 \times (20 + 800) = \mathbf{0.763\ watt}$$

$$\text{d.c. power output} = I_{dc}^2 \times R_L = \left(\frac{19.4}{1000}\right)^2 \times 800 = \mathbf{0.301\ watt}$$

(*iii*) $$\text{d.c. output voltage} = I_{dc} R_L = 19.4 \text{ mA} \times 800\ \Omega = \mathbf{15.52\ volts}$$

(*iv*) $$\text{efficiency of rectification} = \frac{0.301}{0.763} \times 100 = \mathbf{39.5\%}$$

Example 9.12. *A half-wave rectifier is used to supply 50V d.c. to a resistive load of 800 Ω. The diode has a resistance of 25 Ω. Calculate a.c. voltage required.*

Solution.

Output d.c. voltage, $V_{dc} = 50$ V

Diode resistance, $r_f = 25\ \Omega$

Load resistance, $R_L = 800\ \Omega$

Let V_m be the maximum value of a.c. voltage required.

$$\therefore \quad V_{dc} = I_{dc} \times R_L$$

$$= \frac{I_m}{\pi} \times R_L = \frac{V_m}{\pi(r_f + R_L)} \times R_L \qquad \left[\because I_m = \frac{V_m}{r_f + R_L}\right]$$

or
$$50 = \frac{V_m}{\pi(25 + 800)} \times 800$$

$$\therefore \quad V_m = \frac{\pi \times 825 \times 50}{800} = \mathbf{162\ V}$$

Hence a.c. voltage of maximum value 162 V is required.

9.10 Full-Wave Rectifier

In full-wave rectification, current flows through the load in the same direction for both half-cycles of input a.c. voltage. This can be achieved with two diodes working alternately. For the positive half-cycle of input voltage, one diode supplies current to the load and for the negative half-cycle, the other diode does so ; current being always in the same direction through the load. Therefore, a full-wave rectifier utilises both half-cycles of input a.c. voltage to produce the d.c. output. The following two circuits are commonly used for full-wave rectification :

(*i*) Centre-tap full-wave rectifier (*ii*) Full-wave bridge rectifier

9.11 Centre-Tap Full-Wave Rectifier

The circuit employs two diodes D_1 and D_2 as shown in Fig. 9.19. A centre tapped secondary winding *AB* is used with two diodes connected so that each uses one half-cycle of input a.c. voltage. In other words, diode D_1 utilises the a.c. voltage appearing across the upper half (*OA*) of secondary winding for rectification while diode D_2 uses the lower half winding *OB*.

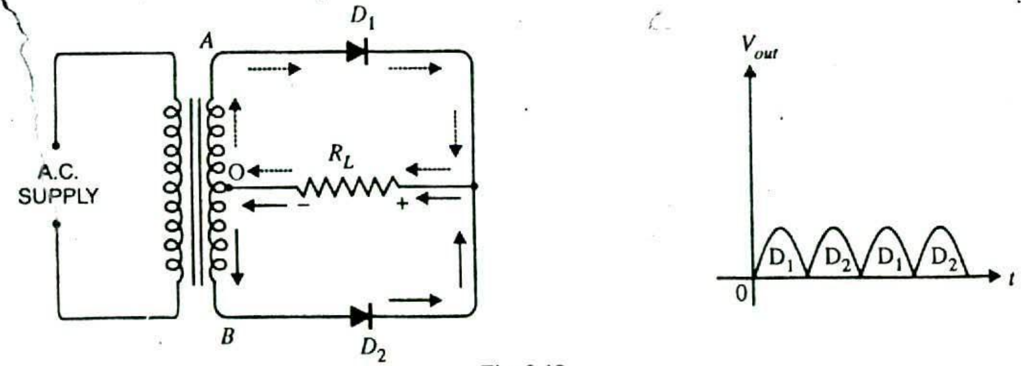


Fig. 9.19

Operation. During the positive half-cycle of secondary voltage, the end *A* of the secondary winding becomes positive and end *B* negative. This makes the diode D_1 forward biased and diode D_2 reverse biased. Therefore, diode D_1 conducts while diode D_2 does not. The conventional current flow is through diode D_1, load resistor R_L and the upper half of secondary winding as shown by the dotted arrows. During the negative half-cycle, end *A* of the secondary winding becomes negative and end B positive. Therefore, diode D_2 conducts while diode D_1 does not. The conventional current flow is through diode D_2, load R_L and lower half winding as shown by solid arrows. Referring to Fig. 9.19, it may be seen that current in the load R_L is *in the same direction* for both half-cycles of input a.c. voltage. Therefore, d.c. is obtained across the load R_L. Also, the polarities of the d.c. output across the load should be noted.

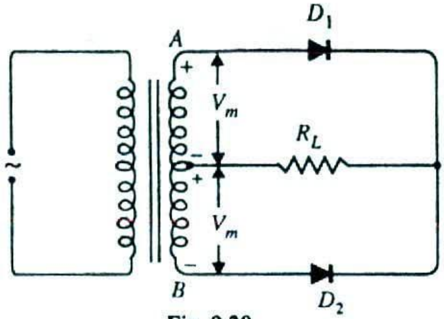


Fig. 9.20

Peak inverse voltage. Suppose V_m is the maximum voltage across the half secondary winding. Fig. 9.20 shows the circuit at the instant secondary voltage reaches its maximum value in the positive direction. At this instant, diode D_1 is conducting while diode D_2 is non-conducting. Therefore, whole of the secondary voltage appears across the non-conducting diode. Consequently, the peak inverse voltage is twice the maximum voltage across the half-secondary winding *i.e.*

$$\text{PIV} = 2\,V_m$$

Disadvantages

(*i*) It is difficult to locate the centre tap on the secondary winding.

(*ii*) The d.c. output is small as each diode utilises only one-half of the transformer secondary voltage.

(*iii*) The diodes used must have high peak inverse voltage.

9.12 Full-Wave Bridge Rectifier

The need for a centre tapped power transformer is eliminated in the bridge rectifier. It contains four diodes D_1, D_2, D_3 and D_4 connected to form bridge as shown in Fig. 9.21. The a.c. supply to be rectified is applied to the diagonally opposite ends of the bridge through the transformer. Between other two ends of the bridge, the load resistance R_L is connected.

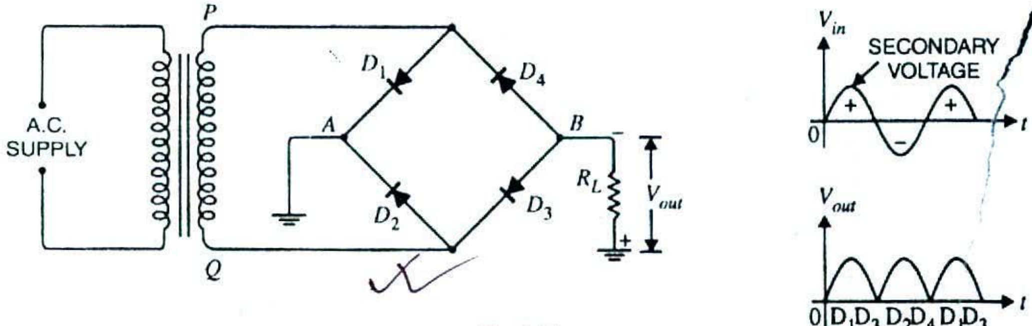


Fig. 9.21

Operation. During the positive half-cycle of secondary voltage, the end P of the secondary winding becomes positive and end Q negative. This makes diodes D_1 and D_3 forward biased while diodes D_2 and D_4 are reverse biased. Therefore, only diodes D_1 and D_3 conduct. These two diodes will be in series through the load R_L as shown in Fig. 9.22 (*i*). The conventional current flow is shown by dotted arrows. It may be seen that current flows from A to B through the load R_L.

During the negative half-cycle of secondary voltage, end P becomes negative and end Q positive. This makes diodes D_2 and D_4 forward biased whereas diodes D_1 and D_3 are reverse biased. Therefore, only diodes D_2 and D_4 conduct. These two diodes will be in series through the load R_L as shown in Fig. 9.22 (*ii*). The current flow is shown by the solid arrows. It may be seen that again current flows from A to B through the load *i.e.* in the same direction as for the positive half-cycle. Therefore, d.c. output is obtained across load R_L.

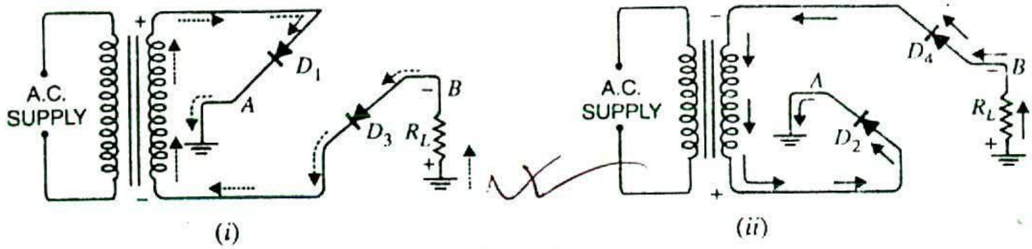


Fig. 9.22

Peak inverse voltage. The peak inverse voltage (PIV) of each diode is equal to the maximum secondary voltage of transformer. Suppose during positive half cycle of input a.c., end P of secondary is positive and end Q negative. Under such conditions, diodes D_1 and D_3 are forward biased while diodes D_2 and D_4 are reverse biased. Since the diodes are considered ideal, diodes D_1 and D_3 can be replaced by wires as shown in Fig 9.23 (*i*). This circuit is the same as shown in Fig. 9.23 (*ii*).

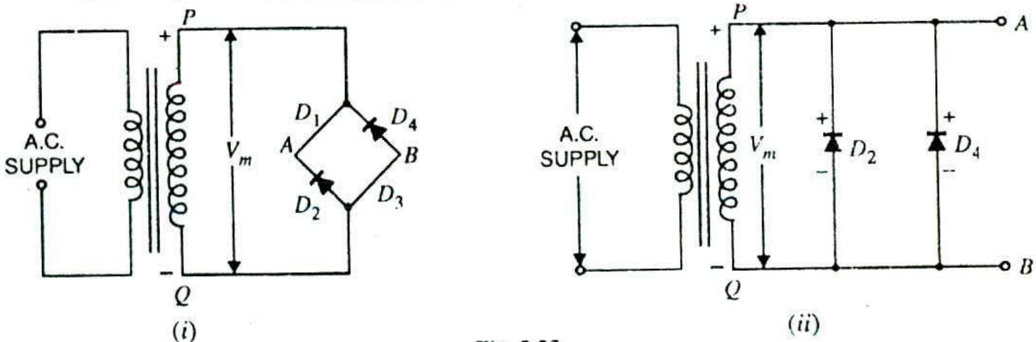


Fig. 9.23

Refering to Fig. 9.23 (*ii*), it is clear that two reverse biased diodes (*i.e.*, D_2 and D_4) and the secondary of transformer are in parallel. Hence PIV of each diode (D_2 and D_4) is equal to the maximum voltage (V_m) across the secondary. Similarly, during the next half cycle, D_2 and D_4 are forward biased while D_1 and D_3 will be reverse biased. It is easy to see that reverse voltage across D_1 and D_3 is equal to V_m.

Advantages

(*i*) The need for centre-tapped transformer is eliminated.

(*ii*) The output is twice that of the centre-tap circuit for the same secondary voltage.

(*iii*) The PIV is one-half that of the centre-tap circuit (for same d.c. output).

Disadvantages

(*i*) It requires four diodes.

(*ii*) As during each half-cycle of a.c. input two diodes that conduct are in series, therefore, voltage drop in the internal resistance of the rectifying unit will be twice as great as in the centre tap circuit. This is objectionable when secondary voltage is small.

9.13 Efficiency of Full-Wave Rectifier

Fig. 9.24 shows the process of full-wave rectification. Let $v = V_m \sin \theta$ be the a.c. voltage to be rectified. Let r_f and R_L be the diode resistance and load resistance respectively. Obviously, the rectifier will conduct current through the load in the same direction for both half-cycles of input a.c. voltage. The instantaneous current i is given by ;

$$i = \frac{v}{r_f + R_L} = \frac{V_m \sin\theta}{r_f + R_L}$$

d.c. output power. The output current is pulsating direct current. Therefore, in order to find the d.c. power, average current has to be found out. From the elementary knowledge of electrical engineering,

$$I_{dc} = \frac{2I_m}{\pi}$$

$\therefore$ d.c. power output, $P_{dc} = I_{dc}^2 \times R_L = \left(\frac{2I_m}{\pi}\right)^2 \times R_L$ ...(*i*)

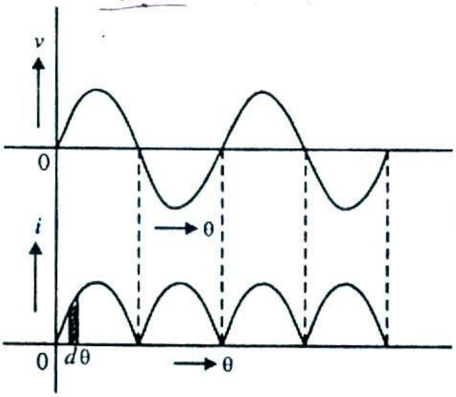


Fig. 9.24

a.c. input power. The a.c. input power is given by ;

$$P_{ac} = I_{rms}^2 (r_f + R_L)$$

For a full-wave rectified wave, we have,

$$I_{rms} = I_m/\sqrt{2}$$

$\therefore$ $P_{ac} = \left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f + R_L)$ ... (*ii*)

$\therefore$ Full-wave rectification efficiency is

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{(2I_m/\pi)^2 R_L}{\left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f + R_L)}$$

$$= \frac{8}{\pi^2} \times \frac{R_L}{(r_f + R_L)} = \frac{0.812\, R_L}{r_f + R_L} = \frac{0.812}{1 + \frac{r_f}{R_L}}$$

The efficiency will be maximum if r_f is negligible as compared to R_L.

$\therefore$ Maximum efficiency = 81.2%

This is double the efficiency due to half-wave rectifier. Therefore, a full-wave rectifier is twice as effective as a half-wave rectifier.

Example 9.13. *A full-wave rectifier uses two diodes, the internal resistance of each diode may be assumed constant at 20 Ω. The transformer r.m.s. secondary voltage from centre tap to each end of secondary is 50 V and load resistance is 980 Ω. Find :*

(*i*) *the mean load current* (*ii*) *the r.m.s. value of load current*

Solution.

$$r_f = 20\ \Omega,\quad R_L = 980\ \Omega$$

$$\text{Max. a.c. voltage, } V_m = 50 \times \sqrt{2} = 70.7\ \text{V}$$

$$\text{Max. load current, } I_m = \frac{V_m}{r_f + R_L} = \frac{70.7\ \text{V}}{(20 + 980)\ \Omega} = 70.7\ \text{mA}$$

(*i*) $$\text{Mean load current, } I_{dc} = \frac{2 I_m}{\pi} = \frac{2 \times 70.7}{\pi} = \mathbf{45\ mA}$$

(*ii*) R.M.S. value of load current is

$$I_{rms} = \frac{I_m}{\sqrt{2}} = \frac{70.7}{\sqrt{2}} = \mathbf{50\ mA}$$

Example 9.14. *In the centre-tap circuit shown in Fig. 9.25, the diodes are assumed to be ideal i.e. having zero internal resistance. Find :*

(*i*) *d.c. output voltage* (*ii*) *peak inverse voltage* (*iii*) *rectification efficiency.*

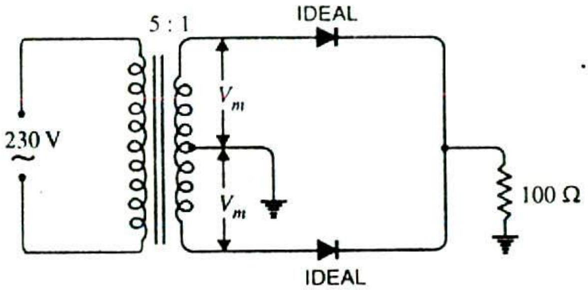


Fig. 9.25

Solution.

Primary to secondary turns, $N_1/N_2 = 5$

R.M.S. primary voltage = 230 V

∴ R.M.S. secondary voltage

$$= 230 \times (1/5) = 46\ \text{V}$$

Maximum voltage across secondary

$$= 46 \times \sqrt{2} = 65\text{V}$$

Maximum voltage across half secondary winding is

$$V_m = 65/2 = 32.5\ \text{V}$$

(*i*) $$\text{Average current, } I_{dc} = \frac{2 V_m}{\pi R_L} = \frac{2 \times 32.5}{\pi \times 100} = 0.207\ \text{A}$$

∴ $$\text{d.c. output voltage, } V_{dc} = I_{dc} \times R_L = 0.207 \times 100 = \mathbf{20.7\ V}$$

(*ii*) The peak inverse voltage is equal to the maximum secondary voltage, *i.e.*

$$PIV = \mathbf{65\ V}$$

(*iii*) $$\text{Rectification efficiency} = \frac{0.812}{1 + \frac{r_f}{R_L}}$$

$$\text{Since } r_f = 0$$

∴ $$\text{Rectification efficiency} = \mathbf{81.2\ \%}$$

Example 9.15. *In the bridge type circuit shown in Fig. 9.26, the diodes are assumed to be ideal. Find :*

(*i*) *d.c. output voltage* (*ii*) *peak inverse voltage* (*iii*) *output frequency*

Assume primary to secondary turns to be 4.

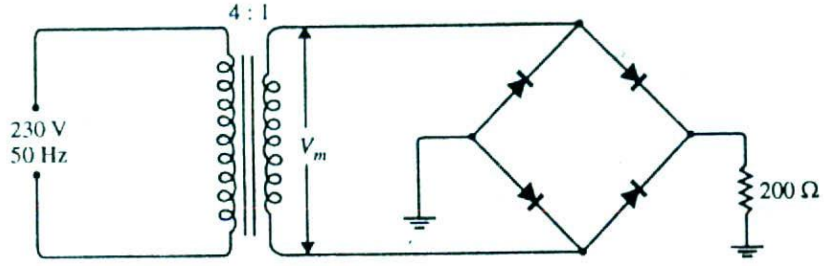


Fig. 9.26

Solution.

Primary/secondary turns, $N_1/N_2 = 4$

R.M.S. primary voltage $= 230$ V

$\therefore$ R.M.S. secondary voltage $= 230\,(N_2/N_1) = 230 \times (1/4) = 57.5$ V

Maximum voltage across secondary is

$$V_m = 57.5 \times \sqrt{2} = 81.3 \text{ V}$$

(*i*) Average current, $I_{dc} = \dfrac{2V_m}{\pi R_L} = \dfrac{2 \times 81.3}{\pi \times 200} = 0.26$ A

$\therefore$ d.c. output voltage, $V_{dc} = I_{dc} \times R_L = 0.26 \times 200 = \mathbf{52\ V}$

(*ii*) The peak inverse voltage is equal to the maximum secondary voltage *i.e.*

$$PIV = \mathbf{81.3\ V}$$

(*iii*) In full-wave rectification, there are two output pulses for each complete cycle of the input a.c. voltage. Therefore, the output frequency is twice that of the a.c. supply frequency *i.e.*

$$f_{out} = 2 \times f_{in} = 2 \times 50 = \mathbf{100\ Hz}$$

Example 9.16. *Fig. 9.27 (i) and Fig. 9.27 (ii) show the centre-tap and bridge type circuits having the same load resistance and transformer turn ratio. The primary of each is connected to 230V, 50 Hz supply.*

(*i*) *Find the d.c. voltage in each case.*

(*ii*) *PIV for each case for the same d.c. output. Assume the diodes to be ideal.*

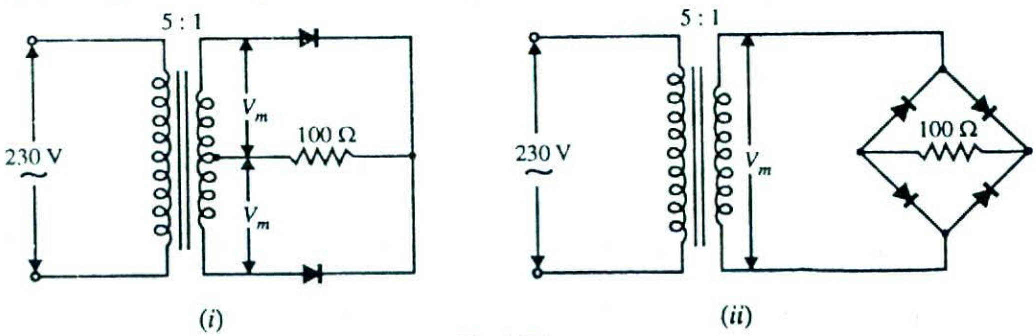


Fig. 9.27

Solution.

(*i*) **D.C. output voltage**

Centre-tap circuit

$$\text{R.M.S. secondary voltage} = 230 \times 1/5 = 46 \text{ V}$$

$$\text{Max. voltage across secondary} = 46 \times \sqrt{2} = 65 \text{ V}$$

Max. voltage appearing across half secondary winding is

$$V_m = 65/2 = 32.5 \text{ V}$$

$$\text{Average current, } I_{dc} = \frac{2 V_m}{\pi R_L}$$

$$\text{D.C. output voltage, } V_{dc} = I_{dc} \times R_L = \frac{2 V_m}{\pi R_L} \times R_L$$

$$= \frac{2 V_m}{\pi} = \frac{2 \times 32.5}{\pi} = \mathbf{20.7 \text{ V}}$$

Bridge Circuit

$$\text{Max. voltage across secondary, } V_m = 65 \text{ V}$$

$$\text{D.C. output voltage, } V_{dc} = I_{dc} R_L = \frac{2 V_m}{\pi R_L} \times R_L = \frac{2 V_m}{\pi} = \frac{2 \times 65}{\pi} = \mathbf{41.4 \text{ V}}$$

This shows that for the same secondary voltage, the d.c. output voltage of bridge circuit is twice that of the centre-tap circuit.

(*ii*) **PIV for same d.c. output voltage**

The d.c. output voltage of the two circuits will be the same if V_m (*i.e.* max. voltage utilised by each circuit for conversion into d.c.) is the same. For this to happen, the turn ratio of the transformers should be as shown in Fig. 9.28.

Centre-tap circuit

$$\text{R.M.S. secondary voltage} = 230 \times 1/5 = 46 \text{ V}$$

$$\text{Max. voltage across secondary} = 46 \times \sqrt{2} = 65 \text{ V}$$

Max. voltage across half secondary winding is

$$V_m = 65/2 = 32.5 \text{ V}$$

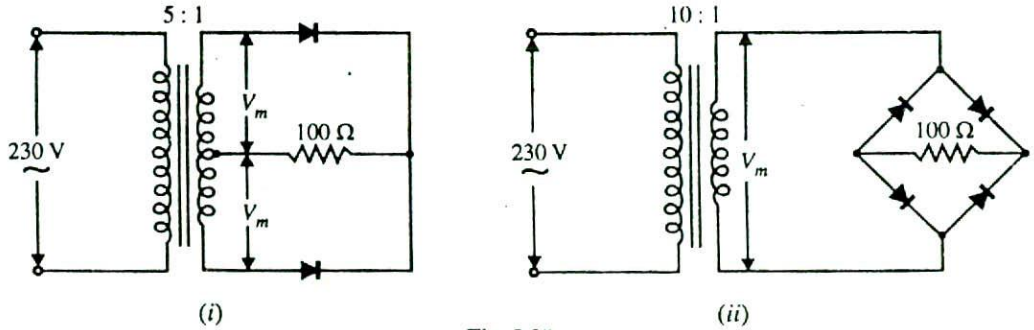


Fig. 9.28

$$\therefore \quad PIV = 2 V_m = 2 \times 32.5 = \mathbf{65 \text{ V}}$$

Bridge type circuit

$$\text{R.M.S. secondary voltage} = 230 \times 1/10 = 23 \text{ V}$$

$$\text{Max. voltage across secondary, } V_m = 23 \times \sqrt{2} = 32.5 \text{ V}$$

$\therefore \qquad PIV = V_m = \mathbf{32.5\ V}$

This shows that for the same d.c. output voltage, *PIV* of bridge circuit is half that of centre-tap circuit. This is a distinct advantage of bridge circuit.

Example 9.17. *The four diodes used in a bridge rectifier circuit have forward resistances which may be considered constant at 1Ω and infinite reverse resistance. The alternating supply voltage is 240 V r.m.s. and load resistance is 480 Ω. Calculate (i) mean load current and (ii) power dissipated in each diode.*

Solution.

$$\text{Max. a.c. voltage, } V_m = 240 \times \sqrt{2}\ \text{V}$$

(*i*) At any instant in the bridge rectifier, two diodes in series are conducting. Therefore, total circuit resistance = $2\,r_f + R_L$.

$$\text{Max. load current, } I_m = \frac{V_m}{2\,r_f + R_L} = \frac{240 \times \sqrt{2}}{2 \times 1 + 480} = 0.7\ \text{A}$$

$$\therefore \qquad \text{Mean load current, } I_{dc} = \frac{2\,I_m}{\pi} = \frac{2 \times 0.7}{\pi} = \mathbf{0.45\ A}$$

(*ii*) Since each diode conducts only half a cycle, diode r.m.s. current is :

$$I_{r.m.s.} = I_m/2 = 0.7/2 = 0.35\ \text{A}$$

$$\text{Power dissipated in each diode} = I^2_{r.m.s.} \times r_f = (0.35)^2 \times 1 = \mathbf{0.123\ W}$$

9.14 Nature of Rectifier Output

It has already been discussed that the output of a rectifier is pulsating d.c. as shown in Fig. 9.29. In fact, if such a waveform is carefully analysed, it will be found that it contains a d.c. component and an a.c. component. The a.c. component is responsible for the *pulsations in the wave. The reader may wonder how a pulsating d.c. voltage can have an a.c. component when the voltage never becomes negative. The answer is that any wave which varies in a regular manner has an a.c. component.

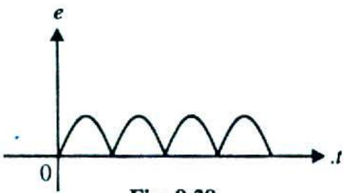


Fig. 9.29

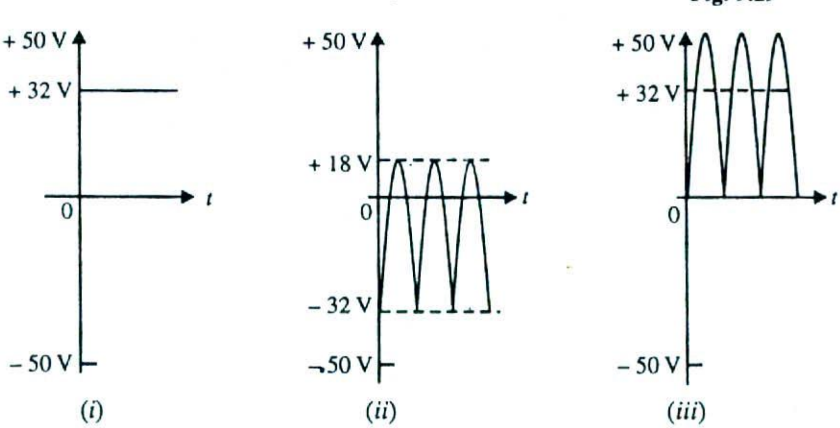


Fig. 9.30

* Means changing output voltage.

The fact that a pulsating d.c. contains both d.c. and a.c. components can be beautifully illustrated by referring to Fig. 9.30. Fig. 9.30 (*i*) shows a pure d.c. component, whereas Fig. 9.30 (*ii*) shows the *a.c. component. If these two waves are added together, the resulting wave will be as shown in Fig. 9.30 (*iii*). It is clear that the wave shown in Fig. 9.30 (*iii*) never becomes negative, although it contains both a.c. and d.c. components. The striking resemblance between the rectifier output wave shown in Fig. 9.29 and the wave shown in Fig. 9.30 (*iii*) may be noted.

It follows, therefore, that a pulsating output of a rectifier contains a d.c. component and an a.c. component.

9.15 Ripple Factor

The output of a rectifier consists of a d.c. component and an a.c. component (also known as *ripple*). The a.c. component is undesirable and accounts for the pulsations in the rectifier output. The effectiveness of a rectifier depends upon the magnitude of a.c. component in the output ; the smaller this component, the more effective is the rectifier.

The ratio of r.m.s. value of a.c. component to the d.c. component in the rectifier output is known as **ripple factor** *i.e.*

$$\text{Ripple factor} = \frac{\text{r.m.s. value of a.c. component}}{\text{value of d.c. component}} = \frac{I_{ac}}{I_{dc}}$$

Therefore, ripple factor is very important in deciding the effectiveness of a rectifier. The smaller the ripple factor, the lesser the effective a.c. component and hence more effective is the rectifier.

Mathematical analysis. The output current of a rectifier contains d.c. as well as a.c. component. The undesired a.c. component has a frequency of 100 Hz (*i.e.* double the supply frequency 50 Hz) and is called the *ripple* (See Fig. 9.31). It is a fluctuation superimposed on the d.c. component.

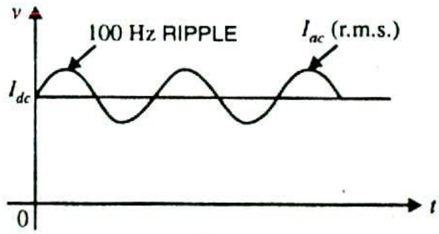


Fig. 9.31

By definition, the effective (*i.e.* r.m.s.) value of total load current is given by ;

$$I_{rms} = \sqrt{I_{dc}^2 + I_{ac}^2}$$

or

$$I_{ac} = \sqrt{I_{rms}^2 - I_{dc}^2}$$

Dividing throughout by I_{dc}, we get,

$$\frac{I_{ac}}{I_{dc}} = \frac{1}{I_{dc}}\sqrt{I_{rms}^2 - I_{dc}^2}$$

But I_{ac}/I_{dc} is the ripple factor.

$$\therefore \quad \text{Ripple factor} = \frac{1}{I_{dc}}\sqrt{I_{rms}^2 - I_{dc}^2} = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

(*i*) **For half-wave rectification.** In half-wave rectification,

$$I_{rms} = I_m/2 \quad ; \quad I_{dc} = I_m/\pi$$

$$\therefore \quad \text{Ripple factor} = \sqrt{\left(\frac{I_m/2}{I_m/\pi}\right)^2 - 1} = 1.21$$

* Although the a.c. component is not a sine-wave, yet it is alternating one.

It is clear that a.c. component exceeds the d.c. component in the output of a half-wave rectifier. This results in greater pulsations in the output. Therefore, half-wave rectifier is ineffective for conversion of a.c. into d.c.

(*ii*) **For full-wave rectification.** In full-wave rectification,

$$I_{rms} = \frac{I_m}{\sqrt{2}} \quad ; \quad I_{dc} = \frac{2\,I_m}{\pi}$$

$$\therefore \quad \text{Ripple factor} = \sqrt{\left(\frac{I_m/\sqrt{2}}{2\,I_m/\pi}\right)^2 - 1} = 0.48$$

$$i.e. \quad \frac{\text{effective a.c. component}}{\text{d.c. component}} = 0.48$$

This shows that in the output of a full-wave rectifier, the d.c. component is more than the a.c. component. Consequently, the pulsations in the output will be less than in half-wave rectifier. For this reason, full-wave rectification is invariably used for conversion of a.c. into d.c.

Example 9.18. *A power supply A delivers 10 V dc with a ripple of 0.5 V r.m.s. while the power supply B delivers 25 V dc with a ripple of 1 mV r.m.s. Which is better power supply ?*

Solution. The lower the ripple factor of a power supply, the better it is.

For power supply A

$$\text{Ripple factor} = \frac{V_{ac(r.m.s.)}}{V_{dc}} = \frac{0.5}{10} \times 100 = 5\%$$

For power supply B

$$\text{Ripple factor} = \frac{V_{ac(r.m.s.)}}{V_{dc}} = \frac{0.001}{25} \times 100 = 0.004\%$$

Clearly, power supply *B* is better.

9.16 Comparison of Rectifiers

S. No.	Particulars	Half-wave	Centre-tap	Bridge type
1	No. of diodes	1	2	4
2	Transformer necessary	no	yes	no
3	Max. efficiency	40.6%	81.2%	81.2%
4	Ripple factor	1.21	0.48	0.48
5	Output frequency	f_{in}	$2 f_{in}$	$2 f_{in}$
6	Peak inverse voltage	V_m	$2 V_m$	V_m

9.17 Filter Circuits

Generally, a rectifier is required to produce pure d.c. supply for using at various places in the electronic circuits. However, the output of a rectifier has pulsating *character *i.e.* it contains a.c. and d.c. components. The a.c. component is undesirable and must be kept away from the load. To do so, a *filter circuit* is used which removes (or *filters out*) the a.c. component and allows only the d.c. component to reach the load.

A filter circuit *is a device which removes the a.c. component of rectifier output but allows the d.c. component to reach the load.*

* If such a d.c. is applied in an electronic circuit, it will produce a *hum*.

Obviously, a filter circuit should be installed between the rectifier and the load as shown in Fig. 9.32. A filter circuit is generally a combination of inductors (L) and capacitors (C). The filtering action of L and C depends upon the basic electrical principles. A capacitor passes a.c. readily but does not *pass d.c. at all. On the other hand, an inductor **opposes a.c. but allows d.c. to pass through it. It then becomes clear that suitable network of L and C can effectively remove the a.c. component, allowing the d.c. component to reach the load.

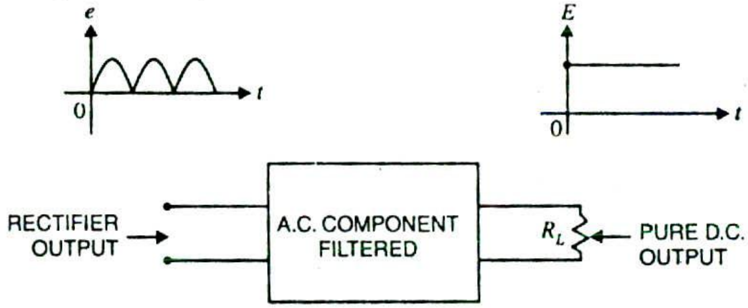


Fig. 9.32

9.18 Types of Filter Circuits

The most commonly used filter circuits are *capacitor filter*, *choke input filter* and *capacitor input filter or π-filter*. We shall discuss these filters in turn.

(*i*) **Capacitor filter.** Fig. 9.33 (*ii*) shows a typical capacitor filter circuit. It consists of a capacitor C placed across the rectifier output in parallel with load R_L. The pulsating direct voltage of the rectifier is applied across the capacitor. As the rectifier voltage increases, it charges the capacitor and also supplies current to the load. At the end of quarter cycle [Point A in Fig. 9.33 (*iii*)], the capacitor is charged to the peak value V_m of the rectifier voltage. Now, the rectifier voltage starts to decrease. As this occurs, the capacitor discharges through the load and voltage across it (*i.e.* across parallel combination of R-C) decreases as shown by the line AB in Fig. 9.33 (*iii*). The voltage across load will decrease only slightly because immediately the next voltage peak comes and recharges the capacitor. This process is repeated again and again and the output voltage waveform becomes $ABCDEFG$. It may be seen that very little ripple is left in the output. Moreover, output voltage is higher as it remains substantially near the peak value of rectifier output voltage.

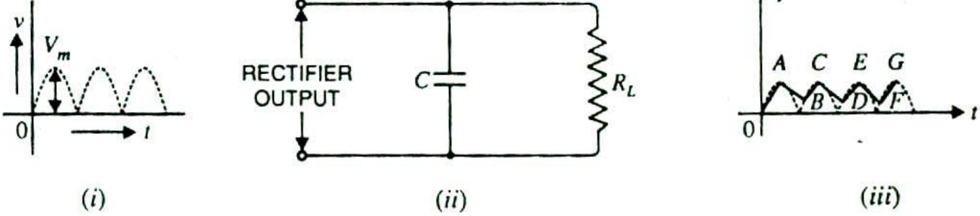


Fig. 9.33

* A capacitor offers infinite reactance to d.c. For d.c., $f = 0$.

$$\therefore \quad X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 0 \times C} = \infty$$

Hence, a capacitor does not allow d.c. to pass through it.

** We know $X_L = 2\pi f L$. For d.c., $f = 0$ and, therefore, $X_L = 0$. Hence inductor passes d.c. quite readily. For a.c., it offers opposition and drops a part of it.

The capacitor filter circuit is extremely popular because of its low cost, small size, little weight and good characteristics. For small load currents (say upto 50 mA), this type of filter is preferred. It is commonly used in transistor radio battery eliminators.

(*ii*) **Choke input filter.** Fig. 9.34 shows a typical choke input filter circuit. It consists of a *choke *L* connected in series with the rectifier output and a filter capacitor *C* across the load. Only a single filter section is shown, but several identical sections are often used to reduce the pulsations as effectively as possible.

The pulsating output of the rectifier is applied across terminals 1 and 2 of the filter circuit. As discussed before, the pulsating output of rectifier contains a.c. and d.c. components. The choke offers high opposition to the passage of a.c. component but negligible opposition to the d.c. component. The result is that most of the a.c. component appears across the choke while whole of d.c. component passes through the choke on its way to load. This results in the reduced pulsations at terminal 3.

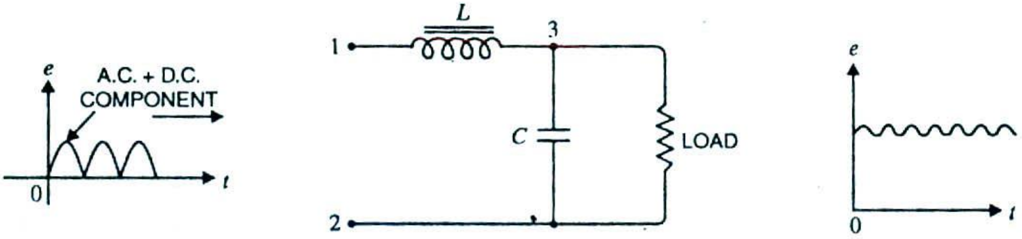


Fig. 9.34

At terminal 3, the rectifier output contains d.c. component and the remaining part of a.c. component which has managed to pass through the choke. Now, the low reactance of filter capacitor bypasses the a.c. component but prevents the d.c. component to flow through it. Therefore, only d.c. component reaches the load. In this way, the filter circuit has filtered out the a.c. component from the rectifier output, allowing d.c. component to reach the load.

(*iii*) **Capacitor input filter** *or* **π-filter.** Fig. 9.35 shows a typical capacitor input filter or **π-filter. It consists of a filter capacitor C_1 connected across the rectifier output, a choke *L* in series and another filter capacitor C_2 connected across the load. Only one filter section is shown but several identical sections are often used to improve the smoothing action.

The pulsating output from the rectifier is applied across the input terminals (*i.e.* terminals 1 and 2) of the filter. The filtering action of the three components *viz* C_1, *L* and C_2 of this filter is described below :

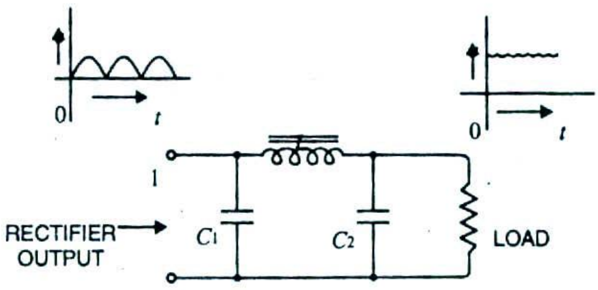


Fig. 9.35

(*a*) The *filter capacitor* C_1 offers low reactance to a.c. component of rectifier output while it offers infinite reactance to the d.c. component. Therefore, capacitor C_1 bypasses an appreciable amount of a.c. component while the d.c. component continues its journey to the choke *L*.

* The shorthand name of inductor coil is choke.

** The shape of the circuit diagram of this filter circuit appears like Greek letter π (pi) and hence the name π-filter.

(*b*) The *choke L* offers high reactance to the a.c. component but it offers almost zero reactance to the d.c. component. Therefore, it allows the d.c. component to flow through it, while the *unbypassed a.c. component is blocked.

(*c*) The *filter capacitor* C_2 bypasses the a.c. component which the choke has failed to block. Therefore, only d.c. component appears across the load and that is what we desire.

Example 9.19. *The choke of Fig. 9.36 has a d.c. resistance of 25 Ω. What is the d.c. voltage if the full-wave signal into the choke has a peak value of 25.7 V ?*

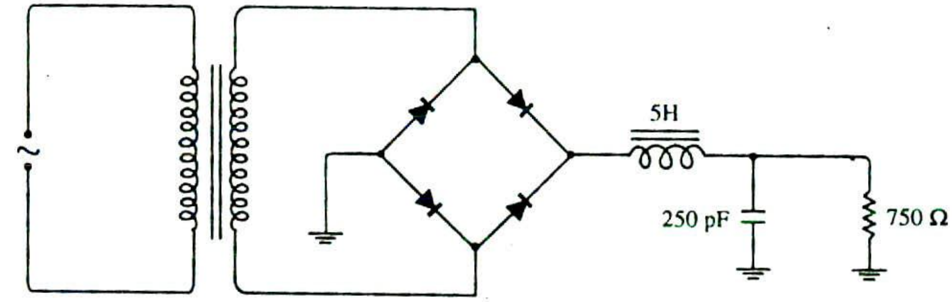


Fig 9.36

Solution. The output of a full-wave rectifier has a d.c. component and an a.c. component. Due to the presence of a.c. component, the rectifier output has a pulsating character as shown in Fig. 9.37. The maximum value of the pulsating output is V_m and d.c. component is $V'_{DC} = 2\ V_m/\pi$.

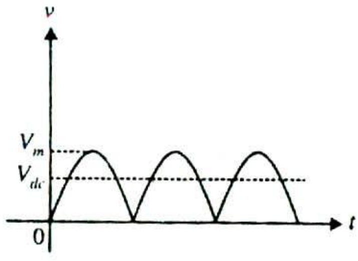


Fig. 9.37

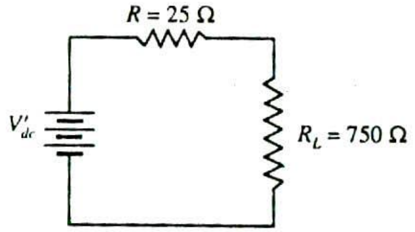


Fig. 9.38

For d.c. component V'_{DC}, the choke resistance is in series with the load as shown in Fig. 9.38.

$$\therefore \quad \text{Voltage across load, } V_{DC} = \frac{V'_{DC}}{R + R_L} \times R_L$$

$$\text{In our example, } V'_{DC} = \frac{2V_m}{\pi} = \frac{2 \times 25.7}{\pi} = 16.4 \text{ V}$$

$$\therefore \quad \text{Voltage across load, } V_{DC} = \frac{V'_{DC}}{R + R_L} \times R_L = \frac{16.4}{25 + 750} \times 750 = \mathbf{15.9\ V}$$

The voltage across the load is 15.9 V dc *plus* a small ripple.

9.19 Voltage Stabilisation

A rectifier with an appropriate filter serves as a good source of d.c. output. However, the major disadvantage of such a power supply is that the output voltage changes with the variations in the input

* That part of a.c. component which could not be bypassed by capacitor C_1.

voltage or load. Thus, if the input voltage increases, the d.c. output voltage of the rectifier also increases. Similarly, if the load current increases, the output voltage falls due to the voltage drop in the rectifying element, filter chokes, transformer winding etc In many electronic applications, it is desired that the output voltage should remain constant regardless of the variations in the input voltage or load. In order to ensure this, a voltage stabilising device, called voltage stabiliser is used. Several stabilising circuits have been designed but only *zener diode* as a voltage stabiliser will be discussed.

9.20 Zener Diode

It has already been discussed that when the reverse bias on a crystal diode is increased, a critical voltage, called *breakdown voltage* is reached where the reverse current increases sharply to a high value. The breakdown region is the knee of the reverse characteristic as shown in Fig. 9.39. The satisfactory explanation of this breakdown of the junction was first given by the American scientist C. Zener. Therefore, the breakdown voltage is sometimes called, *zener voltage* and the sudden increase in current is known as zener current.

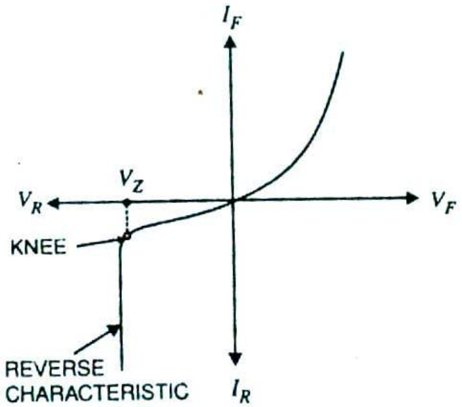


Fig. 9.39

The breakdown or zener voltage depends upon the amount of doping. If the diode is heavily doped, depletion layer will be thin and consequently the breakdown of the junction will occur at a lower reverse voltage. On the other hand, a lightly doped diode has a higher breakdown voltage. When an ordinary crystal diode is properly doped so that it has a sharp breakdown voltage, it is called a zener diode.

A properly doped crystal diode which has a sharp breakdown voltage is known as a **zener diode.**

Fig. 9.40 shows the symbol of a zener diode. It may be seen that it is just like an ordinary diode except that the bar is turned into *z*-shape. The following points may be noted about the zener diode:

(*i*) A zener diode is like an ordinary diode except that it is properly doped so as to have a sharp breakdown voltage.

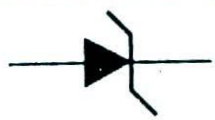


Fig. 9.40

(*ii*) A zener diode is always reverse connected *i.e.* it is always reverse biased.

(*iii*) A zener diode has sharp breakdown voltage, called zener voltage V_Z.

(*iv*) When forward biased, its characteristics are just those of ordinary diode.

(*v*) The zener diode is not immediately burnt just because it has entered the *breakdown region. As long as the external circuit connected to the diode limits the diode current to less than *burn out* value, the diode will not burn out.

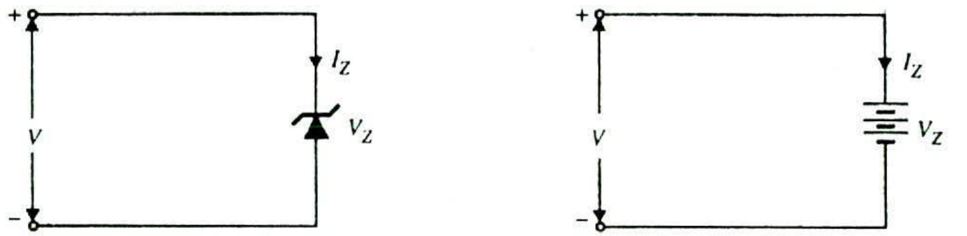
9.21 Equivalent Circuit of Zener Diode

The analysis of circuits using zener diodes can be made quite easily by replacing the zener diode by its equivalent circuit.

(*i*) **"On" state.** When reverse voltage across a zener diode is equal to or more than breakdown voltage V_Z, the current increases very sharply. In this region, the curve is almost vertical. It means

* The current is limited only by both external resistance and the power dissipation of zener diode.

that voltage across zener diode is constant at V_Z even though the current through it changes. Therefore, in the breakdown region, an *ideal zener diode can be represented by a battery of voltage V_Z as shown in Fig. 9.41 (*ii*). Under such conditions, the zener diode is said to be in the "ON" state.



(*i*)
$V \geq V_Z$

(*ii*)
Equivalent circuit of zener for "on" state

Fig. 9.41

(*ii*) **"OFF" state.** When the reverse voltage across the zener diode is less than V_Z but greater than 0 V, the zener diode is in the "OFF" state. Under such conditions, the zener diode can be represented by an open-circuit as shown in Fig. 9.42 (*ii*).

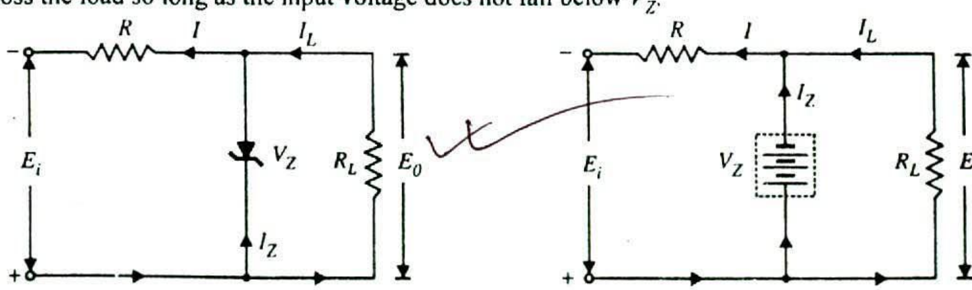
(*i*)
$V_Z > V > 0$

(*ii*)
Equivalent circuit of zener for "off" state

Fig. 9.42

9.22 Zener Diode as Voltage Stabiliser

A zener diode can be used as a voltage regulator to provide a constant voltage from a source whose voltage may vary over sufficient range. The circuit arrangement is shown in Fig. 9.43 (*i*). The zener diode of zener voltage V_Z is reverse connected across the load R_L across which constant output is desired. The series resistance R absorbs the output voltage fluctuations so as to maintain constant voltage across the load. It may be noted that the zener will maintain a constant voltage V_Z (= E_0) across the load so long as the input voltage does not fall below V_Z.



(*i*)

(*ii*)

Fig. 9.43

* This assumption is fairly reasonable as the impedance of zener diode is quite small in the breakdown region.

When the circuit is properly designed, the load voltage E_0 remains essentially constant (equal to V_Z) even though the input voltage E_i and load resistance R_L may vary over a wide range.

(*i*) Suppose the input voltage increases. Since the zener is in the breakdown region, the zener diode is equivalent to a battery V_Z as shown in Fig. 9.43 (*ii*). It is clear that output voltage remains constant at $V_Z (= E_0)$. The excess voltage is dropped across the series resistance R. This will cause an increase in the value of total current I. The zener will conduct the increase of current in I while the load current remains constant. Hence, output voltage E_0 remains constant irrespective of the changes in the input voltage E_i.

(*ii*) Now suppose that input voltage is constant but the load resistance R_L decreases. This will cause an increase in load current. The extra current cannot come from the source because drop in R (and hence source current I) will not change as the zener is within its regulating range. The additional load current will come from a decrease in zener current I_Z. Consequently, the output voltage stays at constant value.

Voltage drop across $R = E_i - E_0$

Current through R, $I = I_Z + I_L$

Applying Ohm's law, we have,

$$R = \frac{E_i - E_0}{I_Z + I_L}$$

9.23 Solving Zener Diode Circuits

The analysis of zener diode circuits is quite similar to that applied to the analysis of semiconductor diodes. The first step is to determine the state of zener diode *i.e.*, whether the zener is in the "on" state or "off" state. Next, the zener is replaced by its appropriate model. Finally, the unknown quantities are determined from the resulting circuit.

1. E_i and R_L fixed. This is the simplest case and is shown in Fig. 9.44 (*i*). Here the applied voltage E_i as well as load R_L is fixed. The first step is to find the state of zener diode. This can be determined by removing the zener from the circuit and calculating the voltage V across the resulting open-circuit as shown in Fig. 9.44 (*ii*).

$$V = E_0 = \frac{R_L E_i}{R + R_L}$$

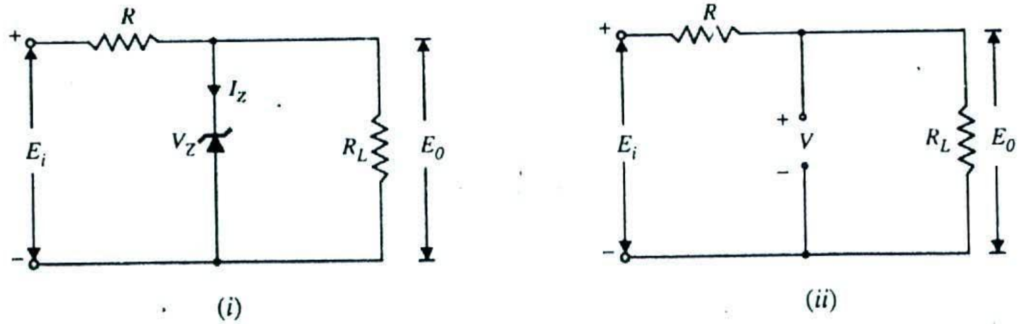


Fig. 9.44

If $V \geq V_Z$, the zener diode is in the "on" state and its equivalent model can be substituted as shown in Fig. 9.45 (*i*). If $V < V_Z$, the diode is in the "off" state as shown in Fig. 9.45 (*ii*).

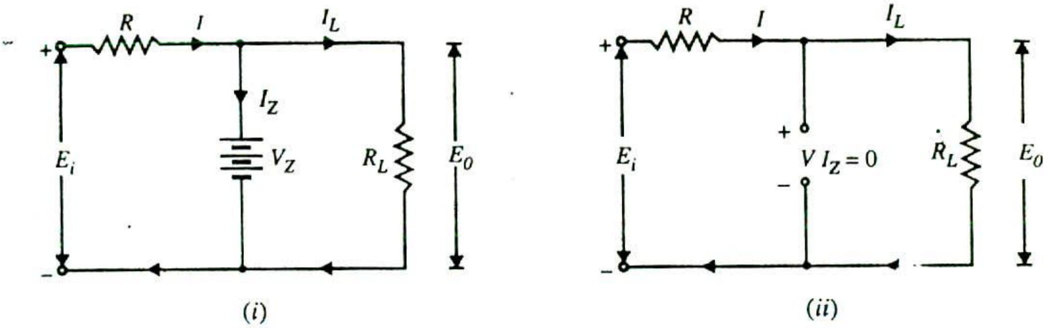


Fig. 9.45

(*i*) **On state.** Referring to circuit shown in Fig. 9.45 (*i*),

$$E_0 = V_Z$$

$$I_Z = I - I_L \quad \text{where } I_L = \frac{E_0}{R_L} \text{ and } I = \frac{E_i - E_0}{R}$$

Power dissipated in zener, $P_Z = V_Z I_Z$

(*ii*) **Off state.** Referring to the circuit shown in Fig. 9.45 (*ii*),

$$I = I_L \quad \text{and} \quad I_Z = 0$$

$$V_R = E_i - E_0 \quad \text{and} \quad V = E_0 \quad (V < V_Z)$$

$$\therefore \quad P_Z = V I_Z = V(0) = 0$$

2. Fixed E_i and Variable R_L. This case is shown in Fig. 9.46. Here the applied voltage (E_i) is fixed while load resistance R_L (and hence load current I_L) changes. Note that there is a definite range of R_L values (and hence I_L values) which will ensure the zener diode to be in "on" state. Let us calculate that range of values.

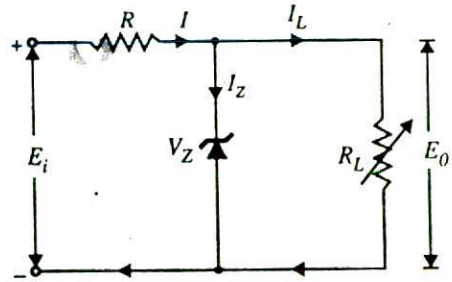


Fig. 9.46

(*i*) **R_{Lmin} and I_{Lmax}.** Once the zener is in the "on" state, load voltage E_0 (= V_Z) is constant. As a result, when load resistance is minimum (*i.e.*, R_{Lmin}), load current will be maximum ($I_L = E_0/R_L$). In order to find the minimum load resistance that will turn the zener on, we simply calculate the value of R_L that will result in $E_0 = V_Z$ *i.e.*,

$$E_0 = V_Z = \frac{{}^*R_L E_i}{R + R_L}$$

$$\therefore \quad R_{Lmin} = \frac{R V_Z}{E_i - V_Z} \quad \text{...(i)}$$

This is the minimum value of load resistance that will ensure that zener is in the "on" state. Any value of load resistance less than this value will result in a voltage E_0 across the load less than V_Z and the zener will be in the "off" state.

---

* If you remove the zener in the circuit shown in Fig. 9.46, then voltage V across the open-circuit is

$$V = \frac{R_L E_i}{R + R_L}$$

The zener will be turned on when $V = V_Z$.

Clearly ;
$$I_{Lmax} = \frac{E_0}{R_{Lmin}} = \frac{V_Z}{R_{Lmin}}$$

(*ii*) $\mathbf{I_{Lmin}}$ **and** $\mathbf{R_{Lmax}}$. It is easy to see that when load resistance is maximum, load current is minimum.

Now, Zener current, $I_Z = I - I_L$

When the zener is in the "on" state, I remains *fixed. This means that when I_L is maximum, I_Z will be minimum. On the other hand, when I_L is minimum, I_Z is maximum. If the maximum current that a zener can carry safely is **I_{ZM}, then,

$$I_{Lmin} = I - I_{ZM}$$

and
$$R_{Lmax} = \frac{E_0}{I_{Lmin}} = \frac{V_Z}{I_{Lmin}}$$

If the load resistance exceeds this limiting value, the current through zener will exceed I_{ZM} and the device may burn out.

3. Fixed $\mathbf{R_L}$ and Variable $\mathbf{E_i}$. This case is shown in Fig. 9.47. Here the load resistance R_L is fixed while the applied voltage (E_i) changes. Note that there is a definite range of E_i values that will ensure that zener diode is in the "on" state. Let us calculate that range of values.

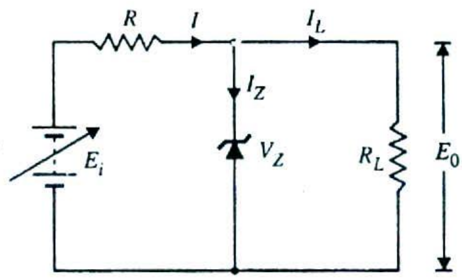


Fig. 9.47

(*i*) $\mathbf{E_i}$ (*min*). To determine the minimum applied voltage that will turn the zener on, simply calculate the value of E_i that will result in load voltage $E_0 = V_Z$ *i.e.*,

$$E_0 = V_Z = \frac{R_L E_i}{R + R_L}$$

$$\therefore \quad E_{i\,(min)} = \frac{(R + R_L) V_Z}{R_L}$$

(*ii*) $\mathbf{E_i}$ (*max*)

Now, Current through R, $I = I_Z + I_L$

Since I_L $(= E_0/R_L = V_Z/R_L)$ is fixed, the value of I will be maximum when zener current is maximum *i.e.*,

$$I_{max} = I_{ZM} + I_L$$

Now
$$E_i = I R + E_0$$

Since E_0 $(= V_Z)$ is constant, the input voltage will be maximum when I is maximum.

$$\therefore \quad E_{i\,(max)} = I_{max} R + V_Z$$

Example 9.20. *For the circuit shown in Fig. 9.48 (i), find :*

(i) the output voltage *(ii) the voltage drop across series resistance*

(iii) the current through zener diode

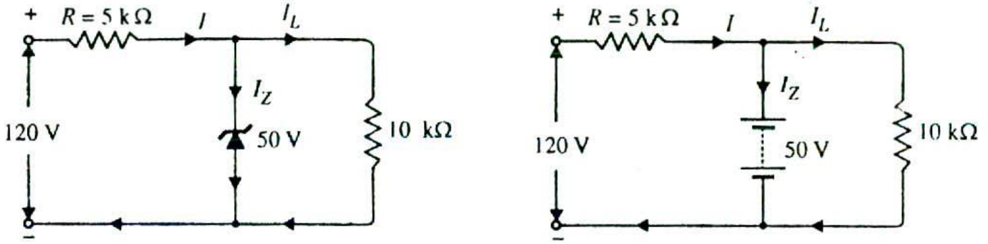
Solution. If you remove the zener diode in Fig. 9.48 (*i*), the voltage V across the open-circuit is given by ;

* Voltage across R, $V_R = E_i - E_0$ and $I = V_R/R$. As E_i and E_0 are fixed, I remains the same.

** Max. power dissipation in zener, $P_{ZM} = V_Z I_{ZM}$

$$V = \frac{R_L E_i}{R + R_L} = \frac{10 \times 120}{5 + 10} = 80 \text{ V}$$

Since voltage across zener diode is greater than V_Z (= 50 V), the zener is in the "on" state. It can, therefore, be represented by a battery of 50 V as shown in Fig. 9.48 (*ii*).



(*i*) (*ii*)

Fig. 9.48

(*i*) Referring to Fig. 9.48 (*ii*),

Output voltage $= V_Z = \mathbf{50\ V}$

(*ii*) Voltage drop across R = Input voltage $- V_Z = 120 - 50 = \mathbf{70\ V}$

(*iii*) Load current, $I_L = V_Z/R_L = 50 \text{ V}/10 \text{ k}\Omega = 5 \text{ mA}$

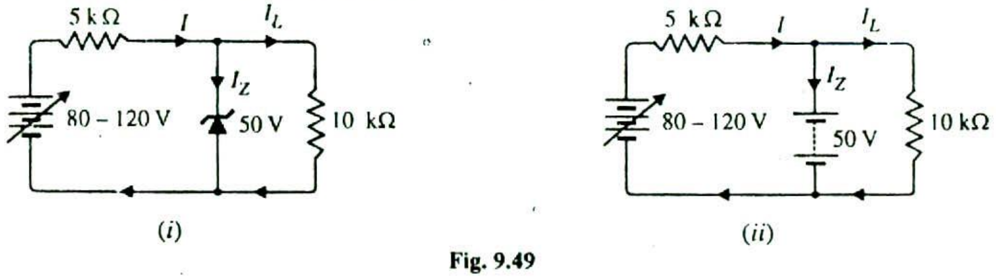
Current through R, $I = \dfrac{70 \text{ V}}{5 \text{ k}\Omega} = 14 \text{ mA}$

Applying Kirchhoff's first law, $I = I_L + I_Z$

$\therefore$ Zener current, $I_Z = I - I_L = 14 - 5 = \mathbf{9\ mA}$

Example 9.21. *For the circuit shown in Fig. 9.49 (i), find the maximum and minimum values of zener diode current.*

Solution. The first step is to determine the state of the zener diode. It is easy to see that for the given range of voltages (80 – 120 V), the voltage across the zener is greater than V_Z (= 50 V). Hence the zener diode will be in the "on" state for this range of applied voltages. Consequently, it can be replaced by a battery of 50 V as shown in Fig. 9.49 (*ii*).



(*i*) (*ii*)

Fig. 9.49

Maximum zener current. The zener will conduct *maximum current when the input voltage is maximum *i.e.* 120 V. Under such conditions :

Voltage across 5 kΩ $= 120 - 50 = 70$ V

* $I_Z = I - I_L$. Since I_L (= V_Z/R_L) is fixed, I_Z will be maximum when I is maximum.

Now, $I = \dfrac{E_i - E_0}{R} = \dfrac{E_i - V_Z}{R}$. Since V_Z (= E_0) and R are fixed, I will be maximum when E_i is maximum and *vice-versa*.

$$\text{Current through } 5\text{ k}\Omega,\ I = \frac{70\text{ V}}{5\text{ k}\Omega} = 14\text{ mA}$$

$$\text{Load current, } I_L = \frac{50\text{ V}}{10\text{ k}\Omega} = 5\text{ mA}$$

Applying Kirchhoff's first law, $I = I_L + I_Z$

$\therefore$ Zener current, $I_Z = I - I_L = 14 - 5 = \mathbf{9\ mA}$

Minimum Zener current. The zener will conduct minimum current when the input voltage is minimum *i.e.* 80 V. Under such conditions, we have,

Voltage across 5 kΩ $= 80 - 50 = 30$ V

$$\text{Current through } 5\text{ k}\Omega,\ I = \frac{30\text{ V}}{5\text{ k}\Omega} = 6\text{ mA}$$

Load current, $I_L = 5$ mA

$\therefore$ Zener current, $I_Z = I - I_L = 6 - 5 = \mathbf{1\ mA}$

Example 9.22. *A 7.2 V zener is used in the circuit shown in Fig. 9.50 and the load current is to vary from 12 to 100 mA. Find the value of series resistance R to maintain a voltage of 7.2 V across the load. The input voltage is constant at 12V and the minimum zener current is 10 mA.*

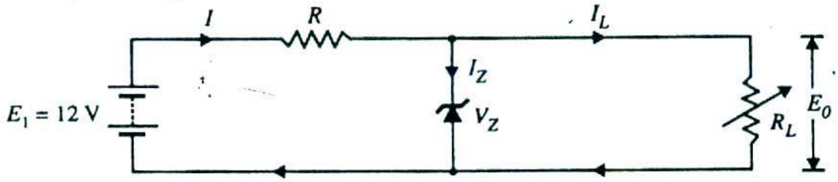


Fig. 9.50

Solution. $E_i = 12\text{ V};\quad V_Z = 7.2\text{ V}$

$$R = \frac{E_i - E_0}{I_Z + I_L}$$

The voltage across R is to remain constant at 12 – 7.2 = 4.8 V as the load current changes from 12 to 100 mA. The minimum zener current will occur when the load current is maximum.

$$\therefore \quad R = \frac{E_i - E_0}{(I_Z)_{min} + (I_L)_{max}} = \frac{12\text{ V} - 7.2\text{ V}}{(10 + 100)\text{ mA}} = \frac{4.8\text{ V}}{110\text{ mA}} = \mathbf{43.5\ \Omega}$$

If R = 43.5 Ω is inserted in the circuit, the output voltage will remain constant over the regulating range. As the load current I_L decreases, the zener current I_Z will increase to such a value that $I_Z + I_L$ = 110 mA. Note that if load resistance is open-circuited, then I_L = 0 and zener current becomes 110 mA.

Example 9.23. *The zener diode shown in Fig. 9.51 has V_Z = 18 V. The voltage across the load stays at 18 V as long as I_Z is maintained between 200 mA and 2 A. Find the value of series resistance R so that E_0 remains 18 V while input voltage E_i is free to vary between 22 V to 28V.*

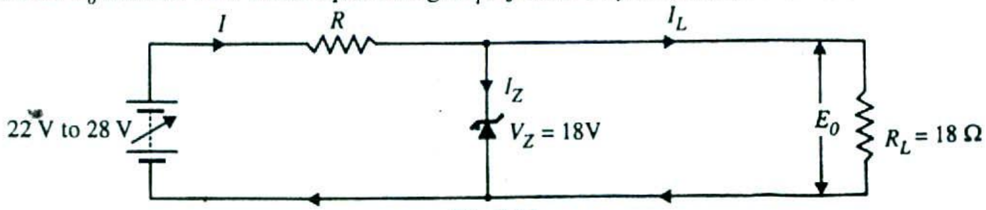


Fig 9.51

Solution. The zener current will be minimum (*i.e.* 200 mA) when the input voltage is minimum (*i.e.* 22 V). The load current stays at constant value $I_L = V_Z / R_L = 18 \text{ V}/18\ \Omega = 1 \text{ A} = 1000 \text{ mA}$.

$$\therefore \quad R = \frac{E_i - E_0}{(I_Z)_{min} + (I_L)_{max}} = \frac{(22 - 18) \text{ V}}{(200 + 1000) \text{ mA}} = \frac{4 \text{ V}}{1200 \text{ mA}} = \mathbf{3.33\ \Omega}$$

Example 9.24. *A 10-V zener diode is used to regulate the voltage across a variable load resistor. The input voltage varies between 13 V and 16 V and the load current varies between 10 mA and 85 mA. The minimum zener current is 15 mA. Calculate the value of series resistance R.*

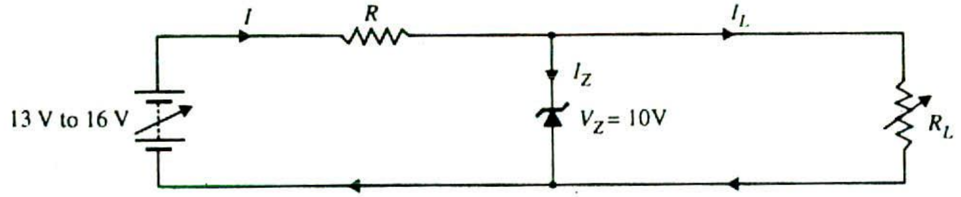


Fig. 9.52

Solution. The zener will conduct minimum current (*i.e.* 15 mA) when input voltage is minimum (*i.e.* 13 V).

$$\therefore \quad R = \frac{E_i - E_0}{(I_Z)_{min} + (I_L)_{max}} = \frac{(13 - 10) \text{ V}}{(15 + 85) \text{ mA}} = \frac{3 \text{ V}}{100 \text{ mA}} = \mathbf{30\ \Omega}$$

Example 9.25. *The circuit of Fig. 9.53 uses two zener diodes, each rated at 15 V, 200 mA. If the circuit is connected to a 45-volt unregulated supply, determine :*

(i) The regulated output voltage *(ii) The value of series resistance R*

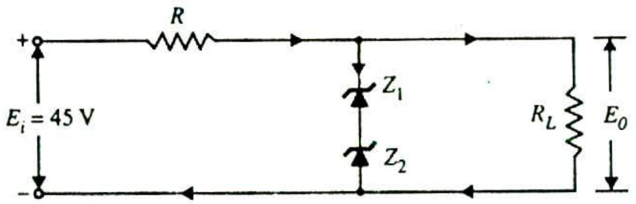


Fig. 9.53

Solution. When the desired regulated output voltage is higher than the rated voltage of the zener, two or more zeners are connected in series as shown in Fig. 9.53. However, in such circuits, care must be taken to select those zeners that have the same current rating.

Current rating of each zener, $I_Z = 200$ mA

Voltage rating of each zener, $V_Z = 15$ V

Input voltage, $E_i = 45$ V

(*i*) Regulated output voltage, $E_0 = 15 + 15 = \mathbf{30\ V}$

(*ii*) Series resistance, $R = \dfrac{E_i - E_0}{I_Z} = \dfrac{45 - 30}{200 \text{ mA}} = \dfrac{15 \text{ V}}{200 \text{ mA}} = \mathbf{75\ \Omega}$

Example 9.26. *What value of series resistance is required when three 10-watt, 10-volt, 1000 mA zener diodes are connected in series to obtain a 30-volt regulated output from a 45 volt d.c. power source ?*

Solution. Fig. 9.54 shows the desired circuit. The worst case is at no load because then zeners carry the maximum current.

Voltage rating of each zener, V_Z = 10 V

Current rating of each zener, I_Z = 1000 mA

Input unregulated voltage, E_i = 45 V

Regulated output voltage, E_0 = 10 + 10 + 10 = 30 V

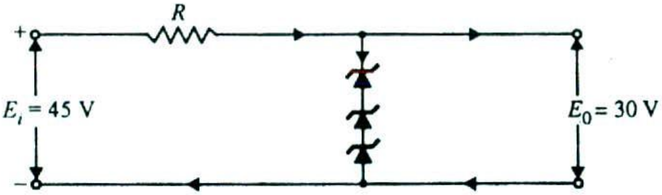


Fig. 9.54

Let R ohms be the required series resistance.

$$\text{Voltage across } R = E_i - E_0 = 45 - 30 = 15 \text{ V}$$

$$\therefore \quad R = \frac{E_i - E_0}{I_Z} = \frac{15 \text{ V}}{1000 \text{ mA}} = \mathbf{15\ \Omega}$$

Example 9.27. *Over what range of input voltage will the zener circuit shown in Fig. 9.55 maintain 30 V across 2000 Ω load, assuming that series resistance R = 200 Ω and zener current rating is 25 mA ?*

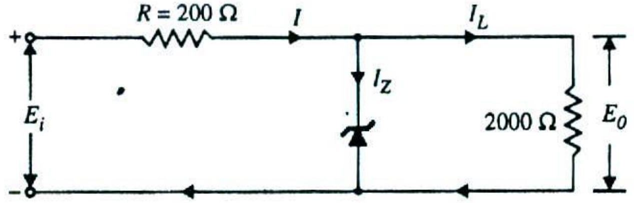


Fig. 9.55

Solution. The minimum input voltage required will be when $I_Z = 0$. Under this condition,

$$I_L = I = \frac{30 \text{ V}}{2000\ \Omega} = 15 \text{ mA}$$

$$\therefore \quad \text{Minimum input voltage} = 30 + IR = 30 + 15 \text{ mA} \times 200\ \Omega$$

$$= 30 + 3 = \mathbf{33\ V}$$

The maximum input voltage required will be when $I_Z = 25$ mA. Under this condition

$$I = I_L + I_Z = 15 + 25 = 40 \text{ mA}$$

$$\therefore \quad \text{Max. input voltage} = 30 + IR$$

$$= 30 + 40 \text{ mA} \times 200\ \Omega$$

$$= 30 + 8 = \mathbf{38\ V}$$

Therefore, the input voltage range over which the circuit will maintain 30 V across the load is **33 V to 38 V.**

Example 9.28. *In the circuit shown in Fig. 9.56, the voltage across the load is to be maintained at 12 V as load current varies from 0 to 200 mA. Design the regulator. Also find the maximum wattage rating of zener diode.*

Solution. By designing the regulator here means to find the values of V_Z and R. Since the load voltage is to be maintained at 12 V, we will use a zener diode of zener voltage 12 V *i.e.*,

$$V_Z = \mathbf{12\ V}$$

The voltage across R is to remain constant at 16 − 12 = 4 V as the load current changes from 0 to 200 mA. The minimum zener current will occur when the load current is maximum.

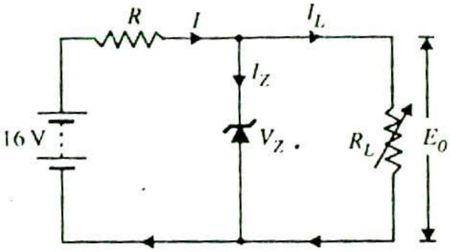


Fig. 9.56

$$\therefore \quad R = \frac{E_i - E_0}{(I_Z)_{min} + (I_L)_{max}} = \frac{16 - 12}{(0 + 200)\ \text{mA}} = \frac{4\ \text{V}}{200\ \text{mA}} = \mathbf{20\ \Omega}$$

Maximum power rating of zener is

$$P_{ZM} = V_Z I_{ZM} = (12\ \text{V})(200\ \text{mA}) = \mathbf{2.4\ W}$$

9.24 Crystal Diodes versus Vacuum Diodes

Semiconductor diodes (or crystal diodes) have a number of advantages and disadvantages as compared to their electron-tube counterparts (*i.e.*, vacuum diodes).

Advantages :

(*i*) They are smaller, more rugged and have a longer life.

(*ii*) They are simpler and inherently cheaper.

(*iii*) They require no filament power. As a result, they produce less heat than the equivalent vacuum diodes.

Disadvantages :

(*i*) They are extremely heat sensitive. Even a slight rise in temperature increases the current appreciably. Should the temperature *exceed the rated value of the diode, the increased flow of current may produce enough heat to ruin the *pn* junction. On the other hand, vacuum diodes function normally over a wide range of temperature changes.

It may be noted that silicon is better than germanium as a semiconductor material. Whereas a germanium diode should not be operated at temperatures higher than 80°C, silicon diodes may operate safely at temperatures upto about 200°C.

(*ii*) They can handle small currents and low inverse voltages as compared to vacuum diodes.

(*iii*) They cannot stand an overload even for a short period. Any slight overload, even a transient pulse, may permanently damage the crystal diode. On the other hand, vacuum diodes can stand an overload for a short period and when the overload is removed, the tube will generally recover.

Multiple-Choice Questions

1. A crystal diode has ....
   (*i*) one *pn* junction
   (*ii*) two *pn* junctions
   (*iii*) three *pn* junctions
   (*iv*) none of the above

2. A crystal diode has forward resistance of the order of ....
   (*i*) kΩ (*ii*) Ω
   (*iii*) MΩ (*iv*) none of the above

3. If the arrow of crystal diode symbol is posi-

* Even when soldering the leads of a crystal diode, care must be taken not to permit heat from the soldering device to reach the crystal diode.

tive w.r.t. bar, then diode is .... biased.
(*i*) forward
(*ii*) reverse
(*iii*) either forward or reverse
(*iv*) none of the above

4. The reverse current in a diode is of the order of ....
(*i*) kA (*ii*) mA
(*iii*) μA (*iv*) A

5. The forward voltage drop across a silicon diode is about ....
(*i*) 2.5 V (*ii*) 3 V
(*iii*) 10 V (*iv*) 0.7 V

6. A crystal diode is used as ....
(*i*) an amplifier (*ii*) a rectifier
(*iii*) an oscillator (*iv*) a voltage regulator

7. The d.c. resistance of a crystal diode is .... its a.c. resistance.
(*i*) the same as (*ii*) more than
(*iii*) less than (*iv*) none of the above

8. An ideal crystal diode is one which behaves as a perfect .... when forward biased.
(*i*) conductor
(*ii*) insulator
(*iii*) resistance material
(*iv*) none of the above

9. The ratio of reverse resistance and forward resistance of a germanium crystal diode is about ....
(*i*) 1 : 1 (*ii*) 100 : 1
(*iii*) 1000 : 1 (*iv*) 40000 : 1

10. The leakage current in a crystal diode is due to ....
(*i*) minority carriers
(*ii*) majority carriers
(*iii*) junction capacitance
(*iv*) none of the above

11. If the temperature of a crystal diode increases, then leakage current ....
(*i*) remains the same
(*ii*) decreases
(*iii*) increases
(*iv*) becomes zero

12. The PIV rating of a crystal diode is .... that of equivalent vacuum diode.
(*i*) the same as (*ii*) lower than
(*iii*) more than (*iv*) none of the above

13. If the doping level of a crystal diode is increased, the breakdown voltage ....
(*i*) remains the same
(*ii*) is increased
(*iii*) is decreased
(*iv*) none of the above

14. The knee voltage of a crystal diode is approximately equal to ....
(*i*) applied voltage
(*ii*) breakdown voltage
(*iii*) forward voltage
(*iv*) barrier potential

15. When the graph between current through and voltage across a device is a straight line, the device is referred to as ....
(*i*) linear (*ii*) active
(*iii*) nonlinear (*iv*) passive

16. When the crystal diode current is large, the bias is ....
(*i*) forward (*ii*) inverse
(*iii*) poor (*iv*) reverse

17. A crystal diode is a .... device.
(*i*) non-linear (*ii*) bilateral
(*iii*) linear (*iv*) none of the above

18. A crystal diode utilises .... characteristic for rectification.
(*i*) reverse
(*ii*) forward
(*iii*) forward or reverse
(*iv*) none of the above

19. When a crystal diode is used as a rectifier, the most important consideration is ....
(*i*) forward characteristic
(*ii*) doping level
(*iii*) reverse characteristic
(*iv*) PIV rating

20. If the doping level in a crystal diode is in-

creased, the width of depletion layer ....
- (i) remains the same
- (ii) is decreased
- (iii) is increased
- (iv) none of the above

21. A zener diode has ....
- (i) one *pn* junction
- (ii) two *pn* junctions
- (iii) three *pn* junctions
- (iv) none of the above

22. A zener diode is used as ....
- (i) an amplifier (ii) a voltage regulator
- (iii) a rectifier (iv) a multivibrator

23. The doping level in a zener diode is .... that of a crystal diode.
- (i) the same as (ii) less than
- (iii) more than (iv) none of the above

24. A zener diode is always .... connected.
- (i) reverse
- (ii) forward
- (iii) either reverse or forward
- (iv) none of the above

25. A zener diode utilises .... characteristic for its operation.
- (i) forward
- (ii) reverse
- (iii) both forward and reverse
- (iv) none of the above

26. In the breakdown region, a zener diode behaves like a .... source.
- (i) constant voltage
- (ii) constant current
- (iii) constant resistance
- (iv) none of the above

27. A zener diode is destroyed if it ....
- (i) is forward biased
- (ii) is reverse biased
- (iii) carries more than rated current
- (iv) none of the above

28. A series resistance is connected in the zener circuit to ....
- (i) properly reverse bias the zener
- (ii) protect the zener
- (iii) properly forward bias the zener
- (iv) none of the above

29. A zener diode is .... device.
- (i) a non-linear (ii) a linear
- (iii) an amplifying (iv) none of the above

30. A zener diode has .... breakdown voltage.
- (i) undefined (ii) sharp
- (iii) zero (iv) none of the above

31. .... rectifier has the lowest forward resistance.
- (i) solid state (ii) vacuum tube
- (iii) gas tube (iv) none of the above

32. Mains a.c. power is converted into d.c. power for ....
- (i) lighting purposes
- (ii) heaters
- (iii) using in electronic equipment
- (iv) none of the above

33. The disadvantage of a half-wave rectifier is that the ....
- (i) components are expensive
- (ii) diodes must have a higher power rating
- (iii) output is difficult to filter
- (iv) none of the above

34. If the a.c. input to a half-wave rectifier has an r.m.s. value of $400/\sqrt{2}$ volts, then diode PIV rating is ....
- (i) $400/\sqrt{2}$ V (ii) 400 V
- (iii) $400 \times \sqrt{2}$ V (iv) none of the above

35. The ripple factor of a half-wave rectifier is ....
- (i) 2 (ii) 1.21
- (iii) 2.5 (iv) 0.48

36. There is a need of transformer for ....
- (i) half-wave rectifier
- (ii) centre-tap full-wave rectifier
- (iii) bridge full-wave rectifier
- (iv) none of the above

37. The *PIV* rating of each diode in a bridge rectifier is .... that of the equivalent centre-tap rectifier.

(*i*) one-half (*ii*) the same as
(*iii*) twice (*iv*) four times

38. For the same secondary voltage, the output voltage from a centre-tap rectifier is .... than that of bridge rectifier.
(*i*) twice (*ii*) thrice
(*iii*) four times (*iv*) one-half

39. If the PIV rating of a diode is exceeded, ...
(*i*) the diode conducts poorly
(*ii*) the diode is destroyed
(*iii*) the diode behaves as zener diode
(*iv*) none of the above

40. A 10 V power supply would use .... as filter capacitor.
(*i*) paper capacitor (*ii*) mica capacitor
(*iii*) electrolytic capacitor
(*iv*) air capacitor

41. A 1000 V power supply would use .... as a filter capacitor.
(*i*) paper capacitor
(*ii*) air capacitor
(*iii*) mica capacitor
(*iv*) electrolytic capacitor

42. The ...... filter circuit results in the best voltage regulation.
(*i*) choke input
(*ii*) capacitor input
(*iii*) resistance input
(*iv*) none of the above

43. A half-wave rectifier has an input voltage of 240 V r.m.s. If the step-down transformer has a turns ratio of 8 : 1, what is the peak load voltage ? Ignore diode drop.
(*i*) 27.5 V (*ii*) 86.5 V
(*iii*) 30 V (*iv*) 42.5 V

44. The maximum efficiency of a half-wave rectifier is ....
(*i*) 40.6% (*ii*) 81.2%
(*iii*) 50% (*iv*) 25%

45. The most widely used rectifier is ....
(*i*) half-wave rectifier
(*ii*) centre-tap full-wave rectifier
(*iii*) bridge full-wave rectifier
(*iv*) none of the above

Answers to Multiple-Choice Questions

1. (*i*)	**2.** (*ii*)	**3.** (*i*)	**4.** (*iii*)	**5.** (*iv*)
6. (*ii*)	**7.** (*iii*)	**8.** (*i*)	**9.** (*iv*)	**10.** (*i*)
11. (*iii*)	**12.** (*ii*)	**13.** (*iii*)	**14.** (*iv*)	**15.** (*i*)
16. (*i*)	**17.** (*i*)	**18.** (*ii*)	**19.** (*iv*)	**20.** (*iii*)
21. (*i*)	**22.** (*ii*)	**23.** (*iii*)	**24.** (*i*)	**25.** (*ii*)
26. (*i*)	**27.** (*iii*)	**28.** (*ii*)	**29.** (*i*)	**30.** (*ii*)
31. (*i*)	**32.** (*iii*)	**33.** (*iii*)	**34.** (*ii*)	**35.** (*iv*)
36. (*ii*)	**37.** (*i*)	**38.** (*iv*)	**39.** (*ii*)	**40.** (*iii*)
41. (*i*)	**42.** (*i*)	**43.** (*iv*)	**44.** (*i*)	**45.** (*iii*)

Chapter Review Topics

1. What is a crystal diode ? Explain its rectifying action.
2. Draw the graphic symbol of crystal diode and explain its significance. How the polarities of crystal diode are identified ?
3. What do you understand by the d.c. and a.c. resistance of a crystal diode ? How will you determine them from the *V-I* characteristic of a crystal diode ?
4. Draw the equivalent circuit of a crystal diode.
5. Discuss the importance of peak inverse voltage in rectifier service.
6. Describe a half-wave rectifier using a crystal diode.
7. Derive an expression for the efficiency of a half-wave rectifier.

8. With a neat sketch, explain the working of (*i*) Centre-tap full-wave rectifier (*ii*) Full-wave bridge rectifier.
9. Derive an expression for the efficiency for a full-wave rectifier.
10. Write a short note about the nature of rectifier output.
11. What is a ripple factor ? What is its value for a half-wave and full-wave rectifier ?
12. Describe the action of the following filter circuits : (*i*) capacitor filter (*ii*) choke input filter (*iii*) capacitor input filter.
13. What is a zener diode ? Draw the equivalent circuit of an ideal zener in the breakdown region.
14. Explain how zener diode maintains constant voltage across the load.

Problems

1. What is the current in the circuit in Fig. 9.57 ? Assume the diode to be ideal. **[10 mA]**

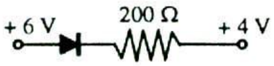


Fig. 9.57

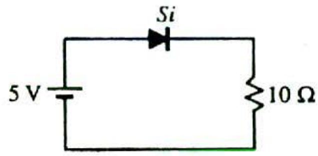


Fig. 9.58

2. Using equivalent circuit, determine the current in the circuit shown in Fig. 9.58. Assume the forward resistance of the diode to be 2 Ω. **[358 mA]**
3. Find the voltage V_A and current I in the circuit shown in Fig. 9.59. Use simplified model. **[14 V; 2 mA]**
4. Determine the magnitude of V_A in the circuit shown in Fig. 9.60. **[9.5 V]**
5. A half-wave rectifier uses a transformer of turn ratio 4 : 1. If the primary voltage is 240 V (r.m.s.), find (*i*) d.c. output voltage (*ii*) peak inverse voltage. Assume the diode to be ideal. **[(*i*) 27 V (*ii*) 85 V]**

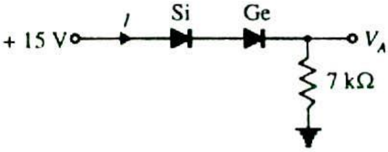


Fig. 9.59

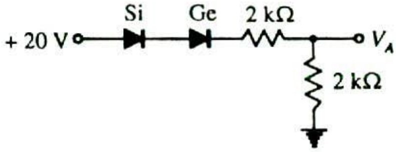


Fig. 9.60

6. A half-wave rectifier uses a transformer of turn ratio 2 : 1. The load resistance is 500 Ω. If the primary voltage (r.m.s.) is 240 V, find (*i*) d.c. output voltage (*ii*) peak inverse voltage. **[(*i*) 54 V (*ii*) 170 V]**

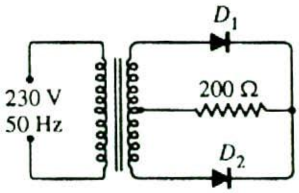


Fig. 9.61

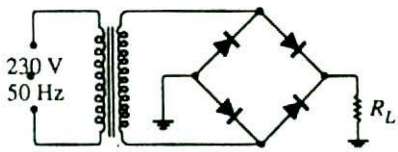


Fig. 9.62

7. In Fig. 9.61, the maximum voltage across half of secondary winding is 50 V. Find (*i*) the average load voltage (*ii*) peak inverse voltage (*iii*) output frequency. Assume the diodes to be ideal.
[(*i*) 31.8 V (*ii*) 100 V (*iii*) 100 Hz]
8. In Fig. 9.62, the maximum secondary voltage is 136 V. Find (*i*) the d.c. load voltage (*ii*) peak inverse voltage (*iii*) output frequency. **[(*i*) 86.6 V (*ii*) 136 V (*iii*) 100 Hz]**

9. In the circuit shown in Fig. 9.63, is zener diode in the on or off state ? [Off]

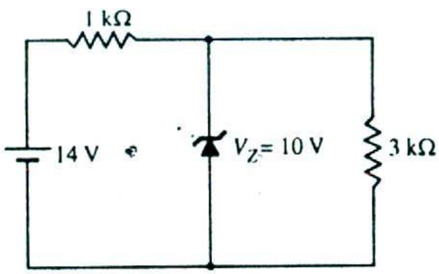


Fig. 9.63

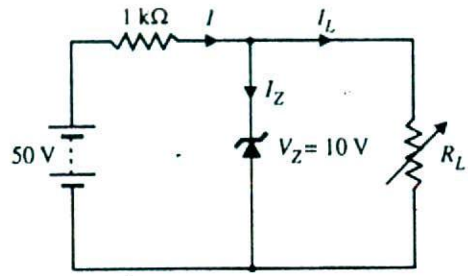


Fig. 9.64

10. In the circuit shown in Fig. 9.64, determine the range of R_L that will result in a constant voltage of 10 V across R_L. [250 Ω to 1.25 kΩ]

Discussion Questions

1. Why are diodes not operated in the breakdown region in rectifier service ?
2. Why do we use transformers in rectifier service ?
3. Why is *PIV* important in rectifier service ?
4. Why is zener diode used as a voltage regulator ?
5. Why is capacitor input filter preferred to choke input filter ?