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 Though vacuum tubes have been replaced by *semi-conductor devices, they are still used at many places in the electronic circuits.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 a 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*

*These are covered in later chapters.

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.

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.

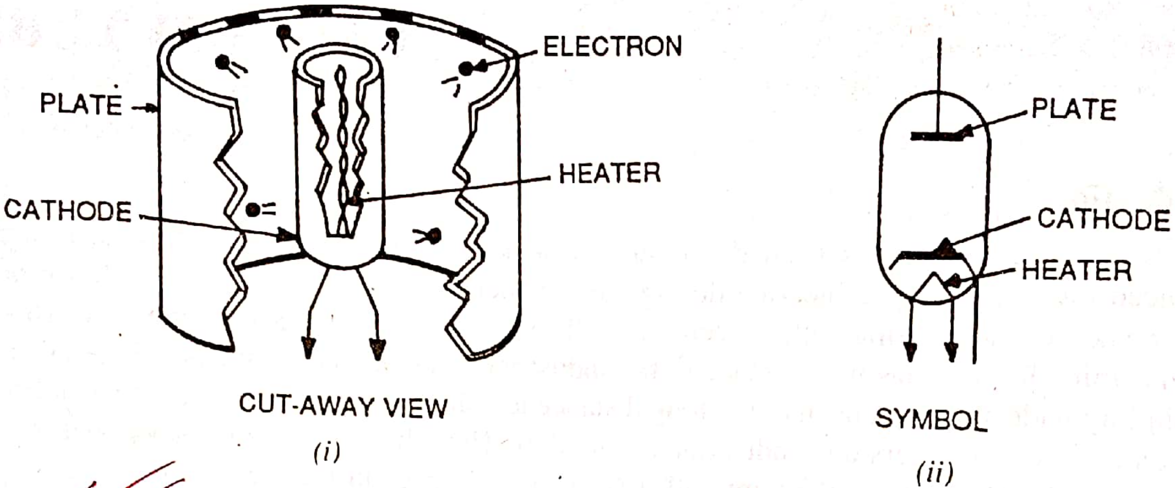

Fig. 3.1

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,

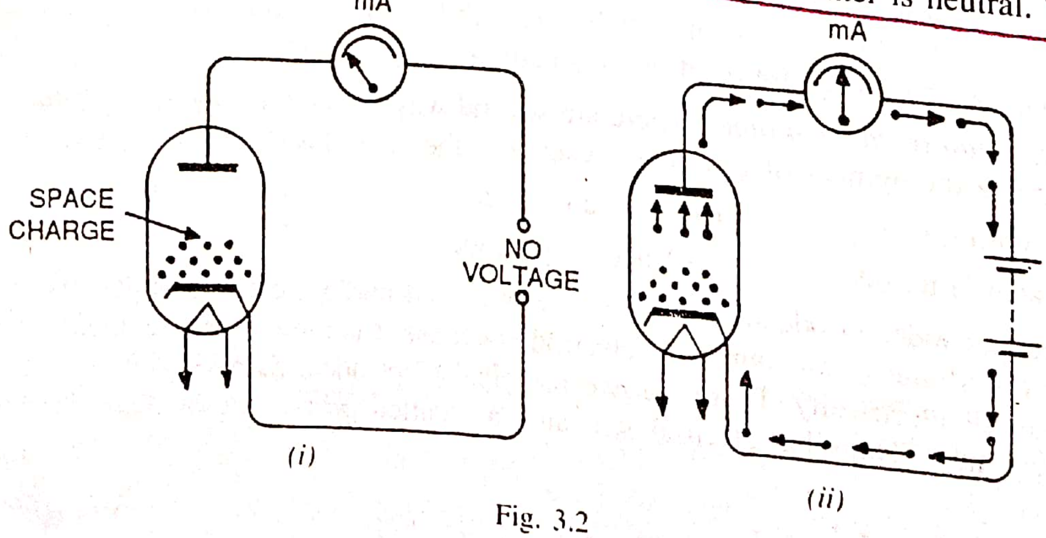

Fig. 3.2

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

circuit current is zero. 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.

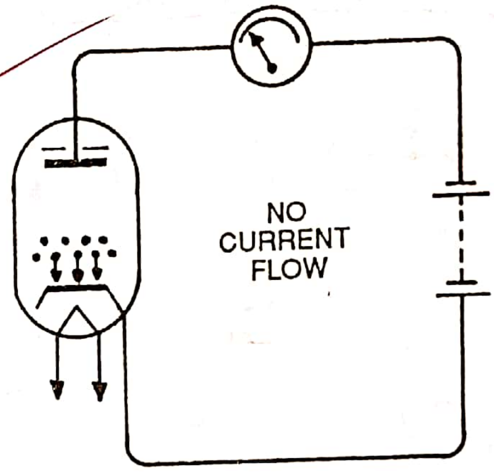

Fig. 3.3

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.

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*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.

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 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

$$I_b = KE_b^{\ 3/2}$$

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 place current I_b is completely controlled by plate voltage E_b and is independent of cathode temperature.

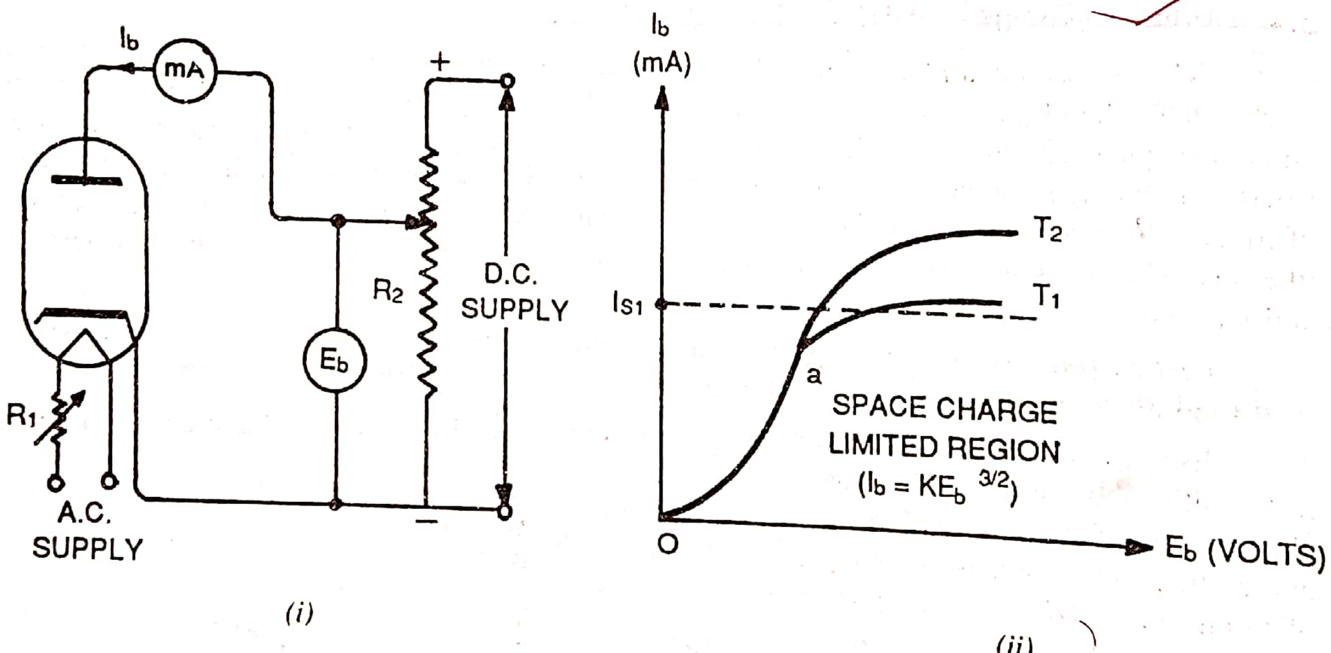


Fig. 3.4

(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 ?*

* 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.

Solution

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

According to Child's law,

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

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

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

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

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

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

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

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

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

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.

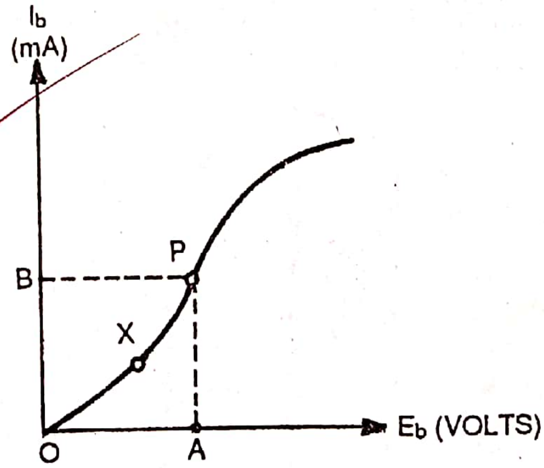


Fig. 3.5

(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.*

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

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

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.* $AB = AC$).

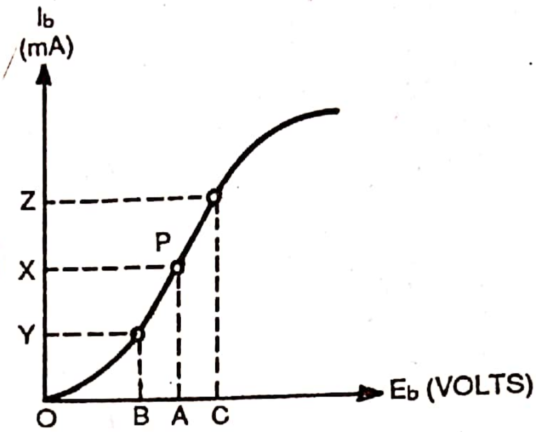


Fig. 3.6

Change in plate voltage = BC

Change in plate current = YZ

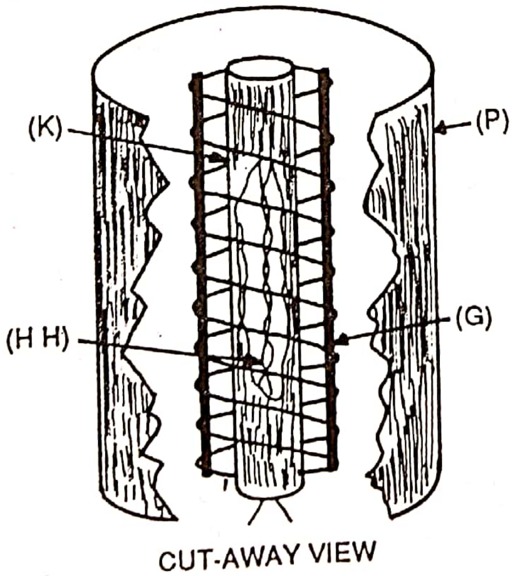
$\therefore$ a.c. plate resistance at P

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

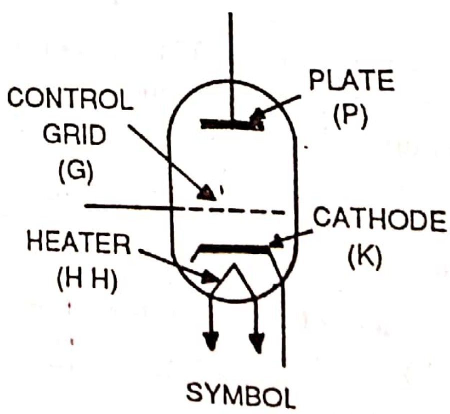
3.5 Vacuum Triode

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



(i)



(ii)

Fig. 3.7

(ii) shows its symbol. The dotted line between plate and cathode in the symbol represents the control grid.

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.

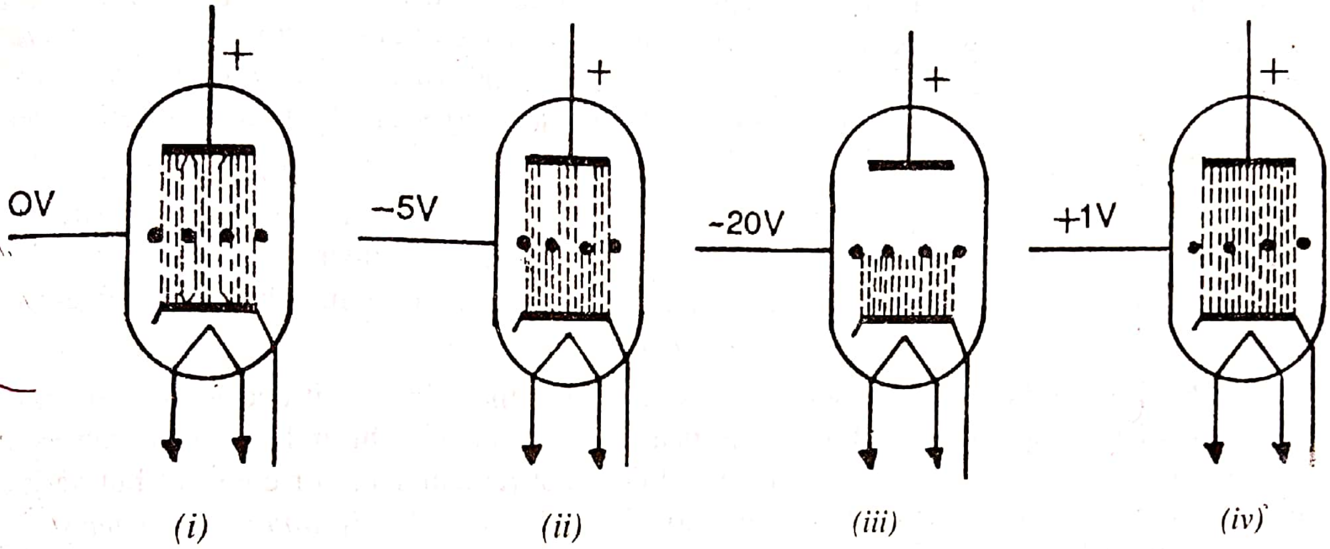


Fig. 3.8

(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 − 5V) *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 − 20V) 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.

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

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

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 characteristics 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*.

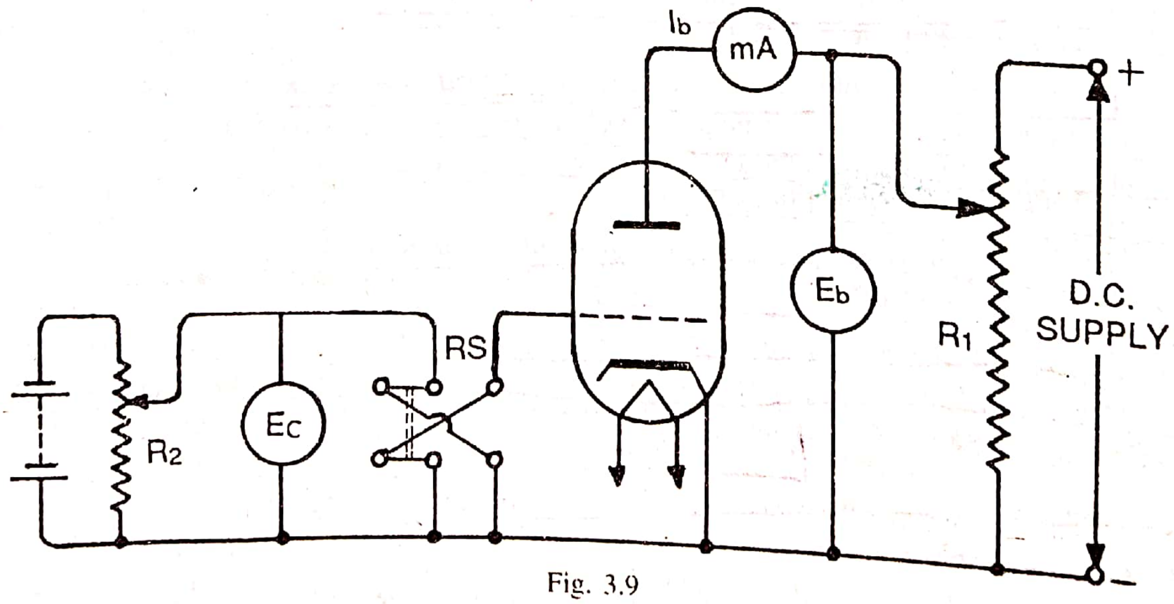

Fig. 3.9

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

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.* $E_c = 0$. 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 $E_c = 0$. 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.

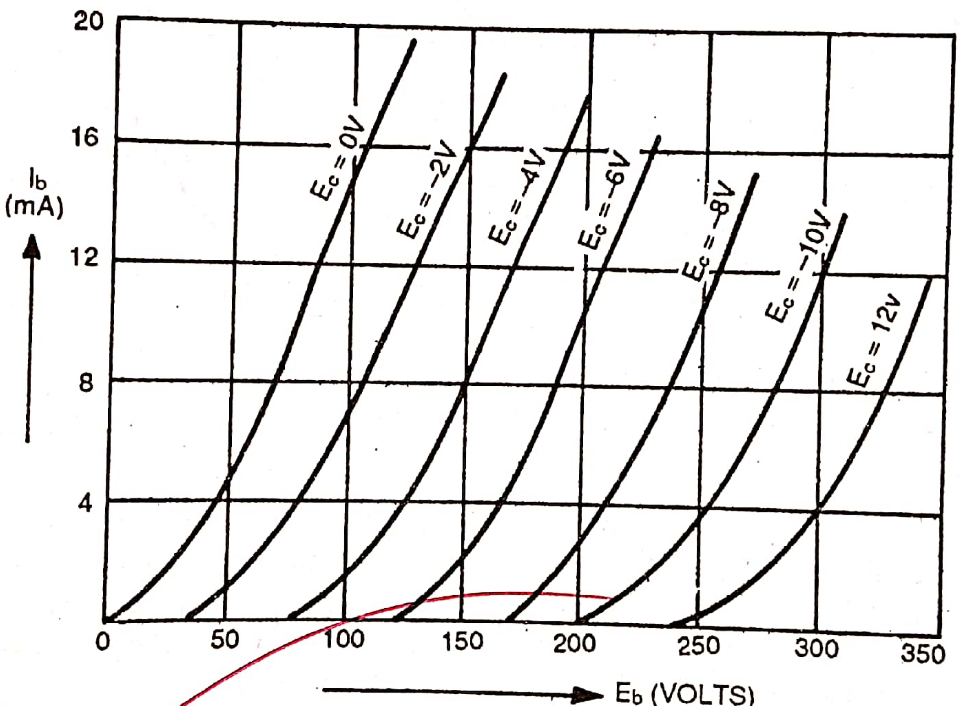

Fig. 3.10

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 characteristic at different plate voltages is obtained as shown in Fig. 3.11. *It may be*

*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.

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.

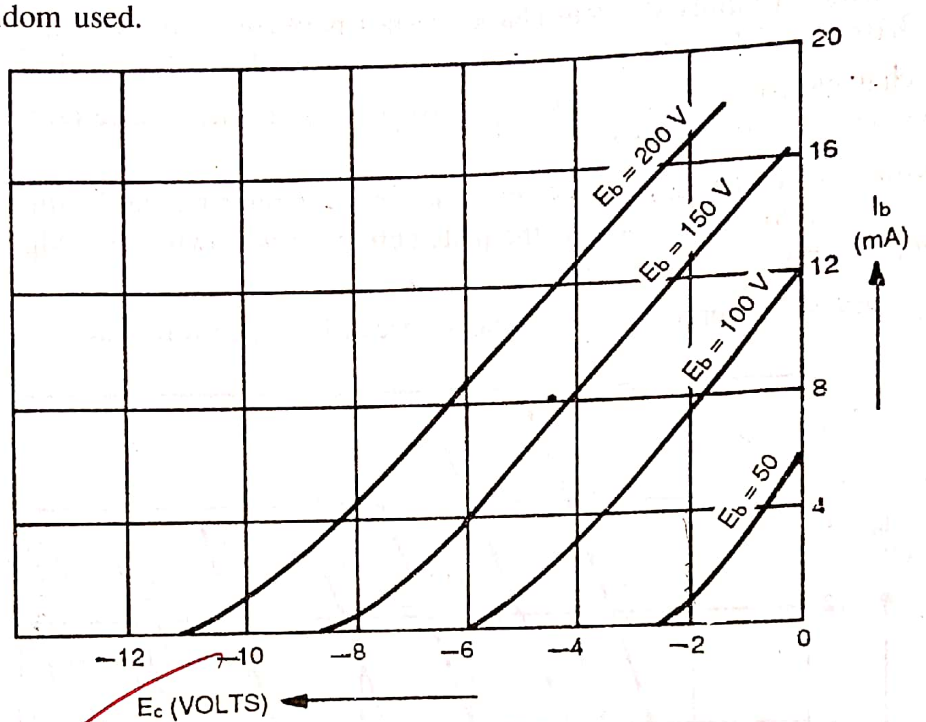

Fig. 3.11

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.*

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

*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 previous value, then

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

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 (1mA) 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* (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.*

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

The a.c. plate resistance indicates how the plate voltage influences the plate current at constant grid voltage. For example, if 20V 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.*

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

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

However, this unit is too large for practical purposes and hence a smaller unit called micromho (μ mho) is generally used. Note that 1 mho = 10^6 μ mho. Thus if a 2V change of grid voltage in a valve produces 3mA (*i.e.* 0.003A) change in plate current, then,

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* 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*.

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

3.9 Relationship between μ, r_p and g_m

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,

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

$\therefore$

$$\mu = r_p \times g_m$$

i.e. amplification factor = plate resistance $\times$ 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 loss 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 $E_c = -8$V. The construction procedure is as follows. First follow the -8V curve down to a convenient point B. From point B, draw a horizontal line to intersect the next grid curve (*i.e.*, -10V curve) at point C. Now, draw a vertical line from C until it intersects the -8V grid voltage curve again at point D. With this construction, the valve constants can be readily determined.

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

at B, $I_b = 5$ mA,	$E_b = 216$V,	$E_c = -8$V
at D, $I_b = 9.6$mA,	$E_b = 256$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 4.6mA (*i.e.* 9.6-5 = 4.6mA) and the plate voltage by 40V (*i.e.* 256 − 216 = 40V). The same change (4.6mA) in plate current is brought about by moving from D to C *i.e.* changing grid voltage from − 8V to

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

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

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

- 10V or by 2V. It follows, therefore, that a change of 2V in the grid potential has produced the same effect on plate current as 40V change in plate voltage.

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

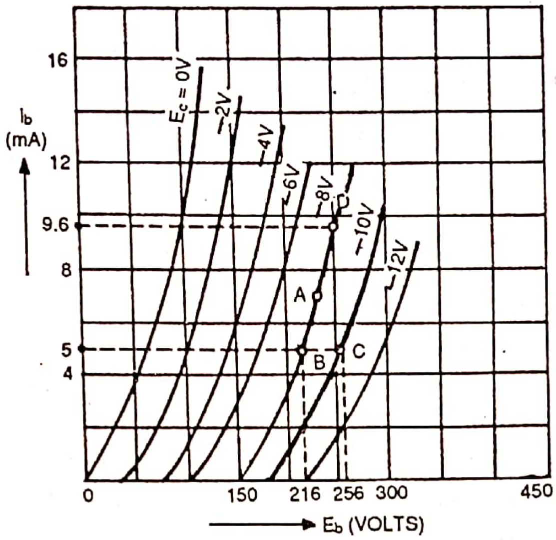

Fig. 3.12

(*ii*) **Determination of r_p.** If we move from point *B* to *D* along a constant grid voltage of − 8V, the plate current changes by 4.6mA and plate voltage by 40V. In other words, at constant grid voltage (*i.e.* − 8V), a change of 40V in plate voltage produces 4.6mA change in plate current.

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

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

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

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 $\quad \mu = r_p \times g_m$

or $\quad 20 = 8000 \times g_m$

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

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

E_b	$150V$	$150V$	$100V$
I_b	$12mA$	$5mA$	$7.5mA$
E_c	$-1.5V$	$-3V$	$-1.5V$

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

Solution

(i) With E_c constant at – 1.5V, the reduction of plate voltage from 150V to 100V reduces the plate current from 12 mA to 7.5mA *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 150V, plate current increases from 5mA to 12mA as the grid voltage is changed from – 3V to – 1.5V *i.e.*

$$\Delta I_b = 12 - 5 = 7\text{mA}$$

$$\Delta E_c = (-3) - (-1.5) = 1.5\text{V}$$

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

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

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

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

where I_b is the plate current in mA, E_b and E_c are the plate and grid voltages 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 = 250V and E_c = – 3V.

Solution

The operating point has $E_b = 250\text{V}$ and $E_c = -3\text{V}$

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

or

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

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

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

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

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

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

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

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

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**

$$\mu = r_p \times g_m$$

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

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 state 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 :

$$E_b = E_{bb} - I_bR_L \quad \ldots (i)$$

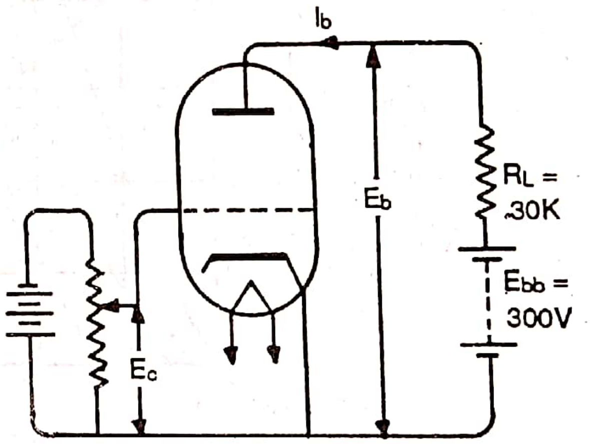

Fig. 3.13

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.

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)*, $E_b = E_{bb}$ (= 300V 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,

$$0 = E_{bb} - I_bR_L$$

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

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 $E_c = -2V$, then the intersection of load line AB to $-2V$ characteristics (point C) will give the desired results–E_b on X-axis and I_b on Y-axis.

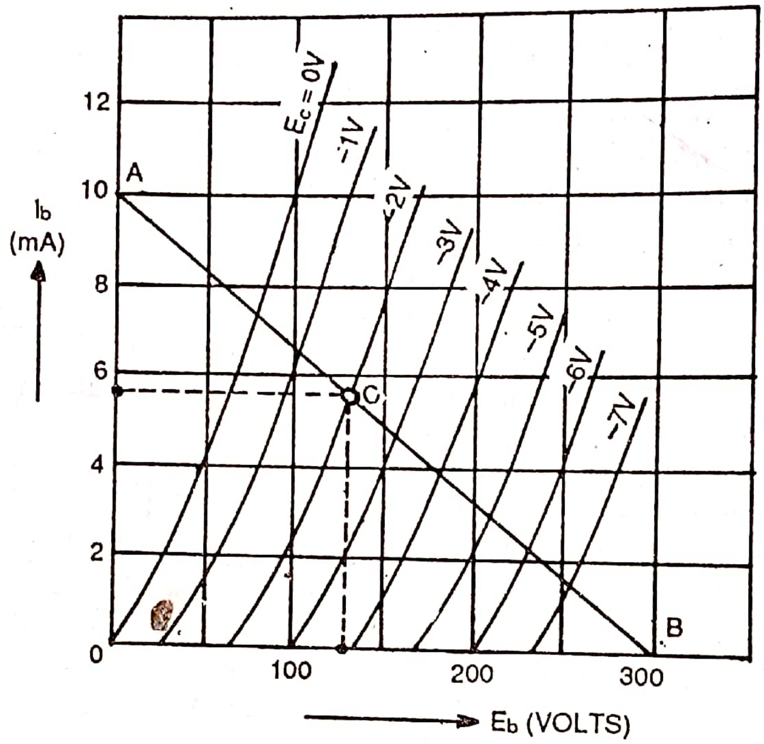

Fig. 3.14

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

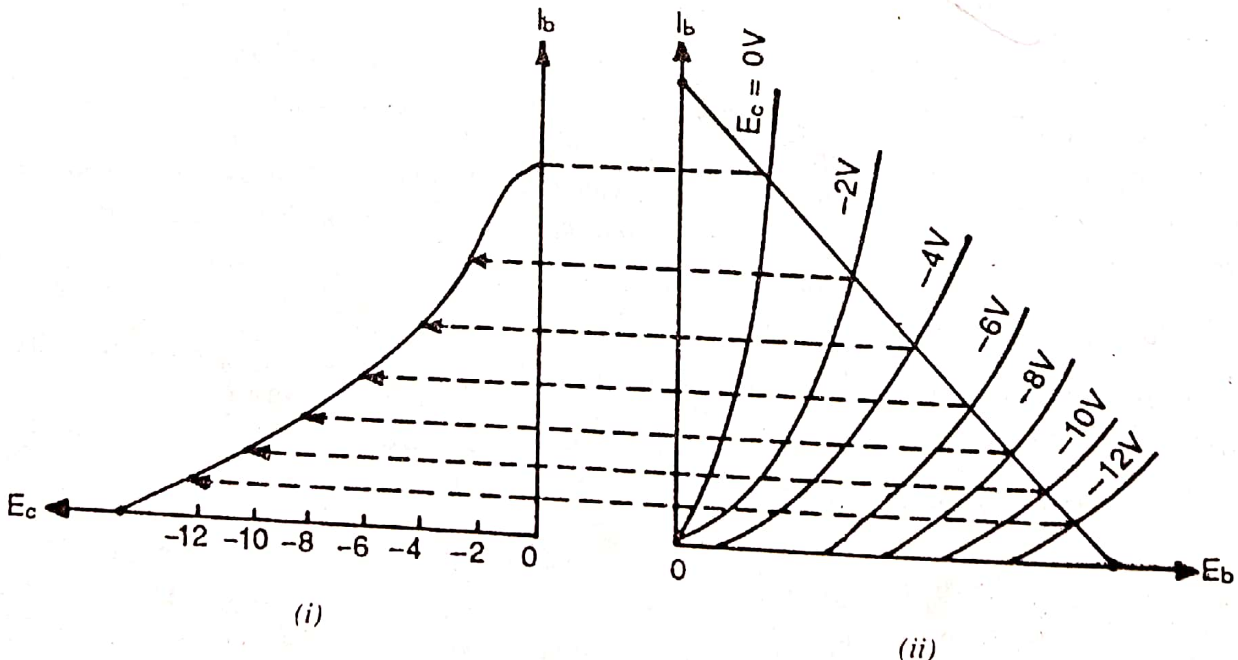

Fig. 3.15

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 *(ii)*. This gives the dynamic mutual characteristic.

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.

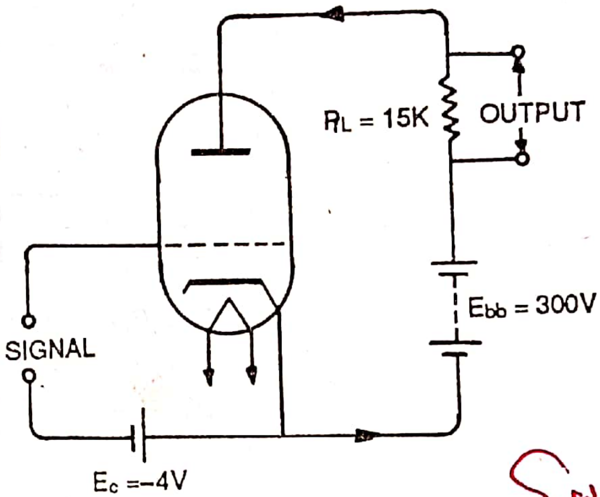

Fig. 3.16

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

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

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

*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.

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.

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

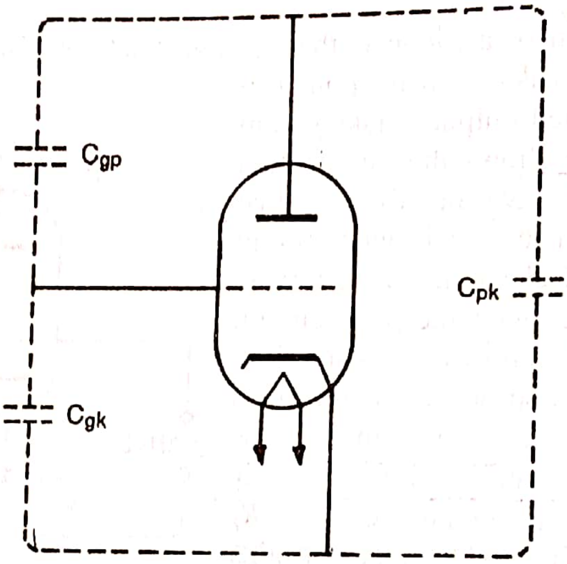

Fig. 3.17

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

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_{Cpg} 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.

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3.14 Tetrode Valve

Although triode can make amplification, it presents the major limitations 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.

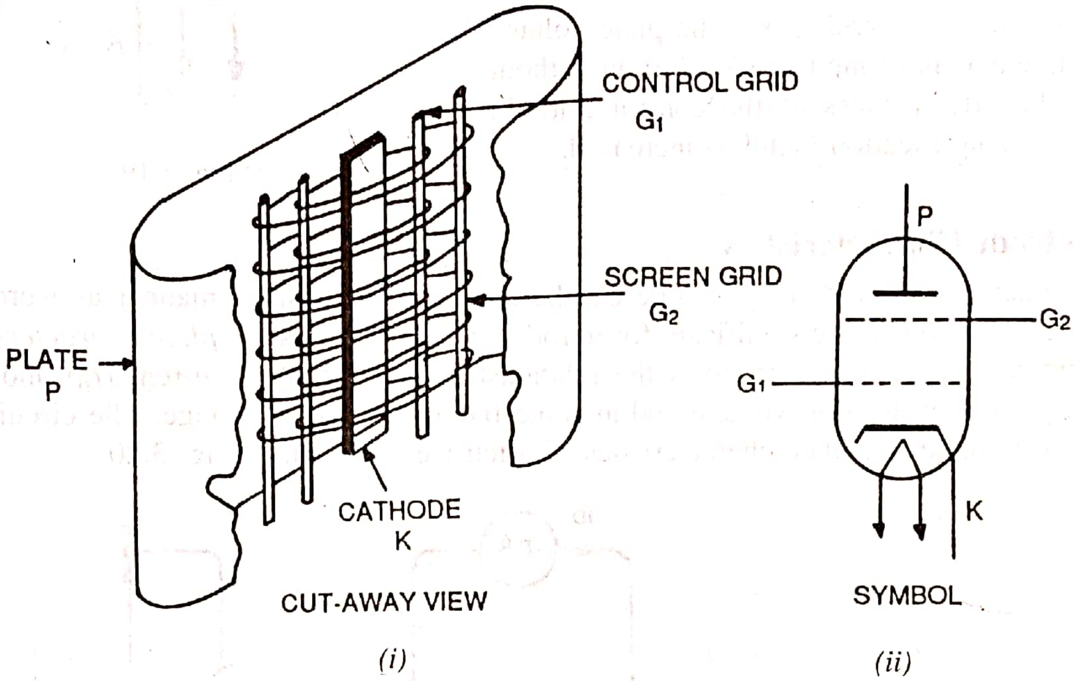

Fig. 3.18

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 0.01pF. 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

* 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.

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 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 effecting the effectiveness of the control grid. In other words, amplification factor is increased.

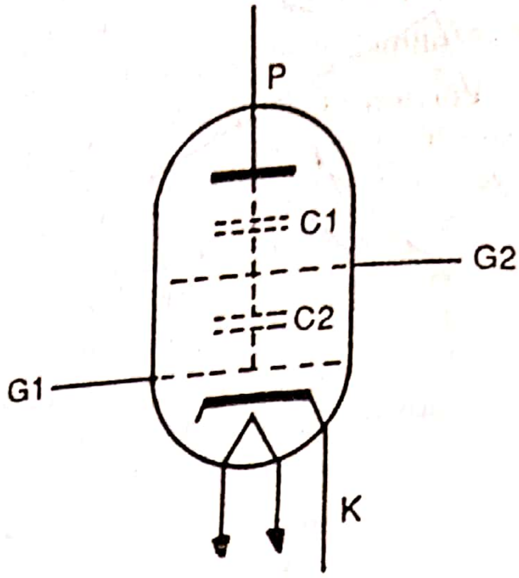

Fig. 3.19

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.

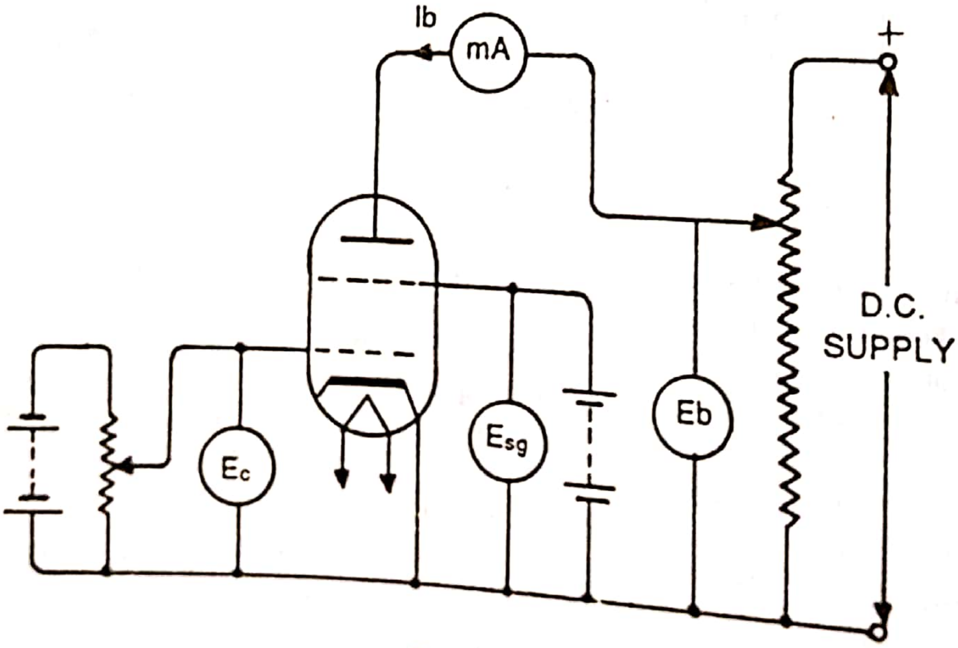

Fig. 3.20

With the control grid voltage held constant, say − 2V and the screen grid voltage held constant at some positive value (say E_{sg} = 100V), 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 = − 2V and screen grid voltage = 100V.

The experiment is repeated with E_c = − 4V and E_c = − 6V *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.* 100V 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.

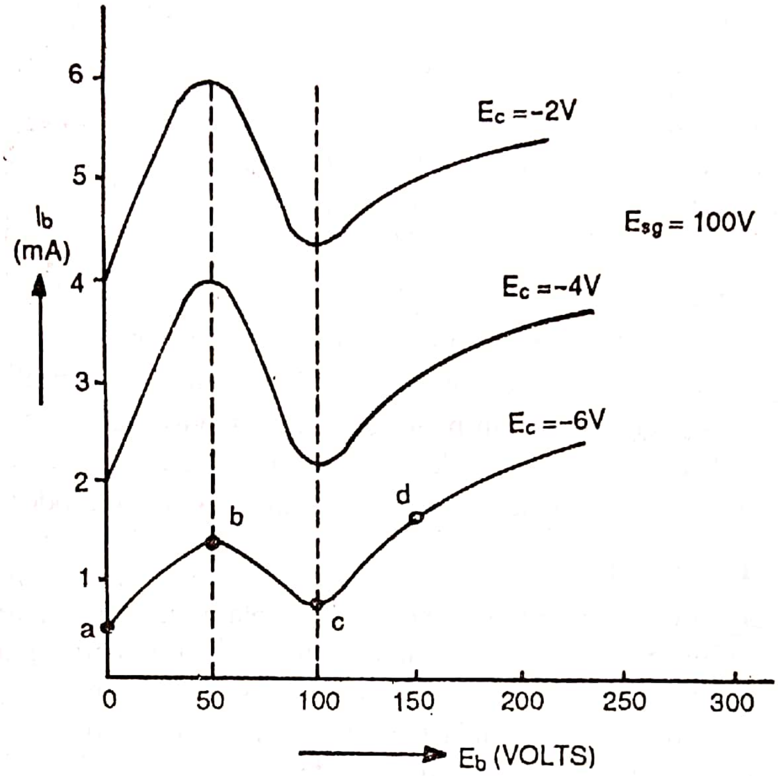

Fig. 3.21

(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.

(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.

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*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.