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ELECTRICITY AND ELECTRONICS

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PART ONE: BASIC ELECTRICITY

1. Electricity and Magnetism

1.1 Electricity and materials

(1) What is electricity

When we rub a glass stick with a dry silk cloth, the glass stick attracts small pieces of paper. This is due to electricity produced in the glass stick.

On the other hand, it is ascertained that there is the same quantity of electricity in the silk cloth but it is different from that in the glass stick. We named the electricity in the glass stick positive electricity (+) and that in the silk cloth negative electricity (-).

(2) The structure of matter

Our world is full of a great many substances that we call matter. There are three states of matter. These are the solid state, such as stones; the liquid state, such as water; and the gaseous state, such as air.

Well, what is matter made of? Take a drop of water. It has certain properties which we recognize as peculiar to water. Divide this drop and you have two smaller drops. Each droplet still has the properties of water. Continue dividing droplets until you come to a particle so small that it can be divided no further. This particle is still water and exhibits all its properties. The smallest particle of matter that retains the properties of that matter is called *a molecule*.

It was found that it is possible to break down a water molecule into two gases, oxygen and hydrogen. Note however that these gases don't resemble the original water. The molecule seems to be made up of simpler substances. If the substance cannot be broken down any further, it is called an element. The smallest particle of an element is called *an atom*.

Once it was shown that the atom could be broken up scientists delved deeper into its secrets. As a result the electron theory of the structure of matter was set forth.

According to the electron theory, all matter is composed mainly of three types of particles. These are:

(i) the electron, a particle carrying a negative electrical charge,

(ii) the proton, a particle carrying a positive electrical charge,

(iii) the neutron, a particle that carries no electrical charge.

All atoms are composed of these particles; atoms differ from one another in the number of particles they contain and in the arrangement of these particles.

According to Niels Bohr, a Danish scientist, the atom is composed of a central nucleus, which is surrounded by revolving electrons, somewhat as our sun is surrounded by revolving planets (see Fig. 1-1). An atom of one element differs from atoms of any other in the number of protons contained in the nucleus. The number of protons in the nucleus is called the atomic number of the element hydrogen.

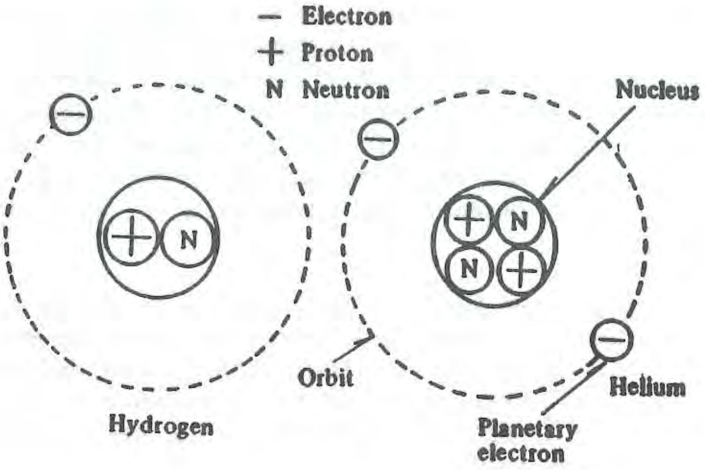


Fig.1-1 Structure of an atom

The negative charge of the planetary electron is equal and opposite to the positive charge of the proton. The positive charge of the nucleus is exactly neutralized by the negative charges of the planetary electrons revolving about it. That is, atom has no external electrical charge.

Now let us turn our attention to the electrons revolving around the nucleus. As previously stated, the normal atom has one planetary electron for each proton in the nucleus. Thus, the number of such electrons will vary from one for hydrogen to 92 for uranium and higher for the new elements. These electrons do not revolve around the nucleus in a disorderly fashion. They follow concentric paths, called orbits, about the nucleus in a manner somewhat similar to the orbiting of planets around the sun of our solar system. The planets are held in their orbits by the gravitational attraction between them and the sun.

Similarly, the electrons of an atom are held in their orbits by the electrostatic attraction between the positive electrical charges carried by the proton of the nucleus and the negative electrical charges carried by the electrons.

(3) Free electron

In the structure of an atom, particularly atoms of metals such as copper and silver, the electron in the outer most orbit is held very loosely and frequently leaves its parent neucleus and wanders off as a "free electron". This is caused by heat, light or electricity. The greater the number of free electrons, the greater will be the electron current.

1.2 Electric charge and electric quantity

(1) Electric charge

In a normal atom the positive charges of the protons in the nucleus are neutralized by the negative charges of planetary electrons. Hence a normal atom is neutral, that is, it has no external electrical charge (Fig. 1-2, (a)). When a neutral atom loses one of its electrons, it now has more positive than negative charges. Hence the overall effect is to give the atom a positive charge. In other words, it becomes a positive ion. (Fig. 1-2(b)). If an extra electron attaches itself to a neutral atom, there would be a negative charge. The atom would become a negative ion. (Fig. 1-2(c)).

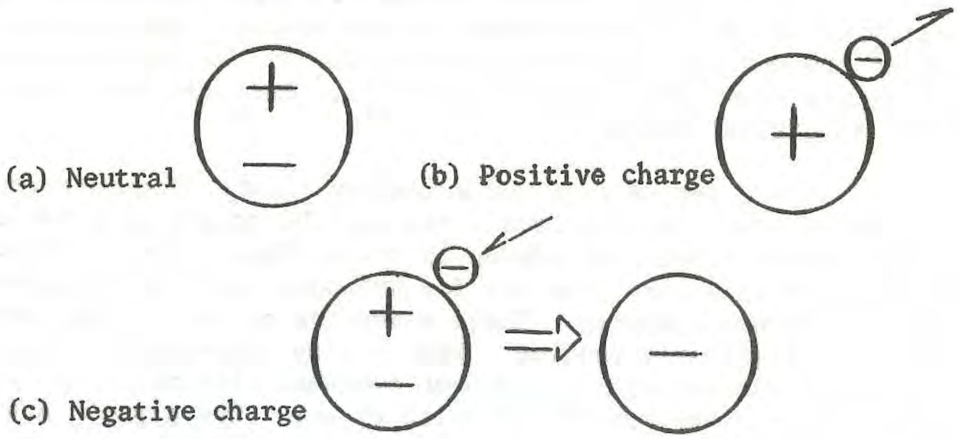
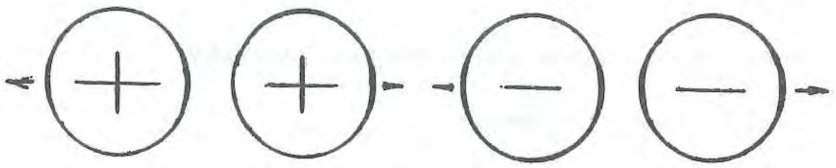
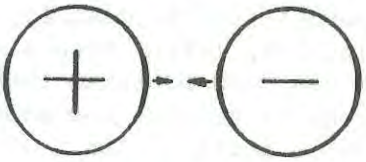


Fig.1-2 Electric charge

When two charged particles are brought near each other, they interact. If they both have positive charge or both negative charge, the particles tend to repel each other. If, on the other hand, the two particles have opposite charges, that is, one is positive and the other negative, they attract each other. (Fig. 1-3).



(a) Repeling power



(b) Attraction power

Fig.1-3 The nature of electricity

(2) Electric quantity

The electron is the basic charged particle, but since the charge of one electron is very small, a coulomb is used as a practical unit for measuring the quantity of electric charge. A coulomb is equal to the combined charges of 6.25 x 10^8 electrons. The charge of one electrons 1.602 x^{-19}C.

$$IC = \frac{1}{1.602 \times 10^{-19}} = 6.25 \times 10^{18} \text{electron}$$

1.3 Electric current, voltage, resistance

(1) Electric current

When we talk of electric current, we mean electrons in motion. When the electrons flow in one direction only, it is called the direct current (abbreviated DC).

The electrons may flow, alternately, first in one direction and then in the other. Such a current is known as the alternating current (abbreviated AC).

(2) Voltage

As shown in Fig. 1-4(a) when the connection is made between a positive charged plate and a negative charged plate by an electric wire, the electric current flows from A to B. This is because a kind of electrical pressure exists between A to B. The electric current is like a water flow. It can be understood easily by looking at Fig. 1-4(b).

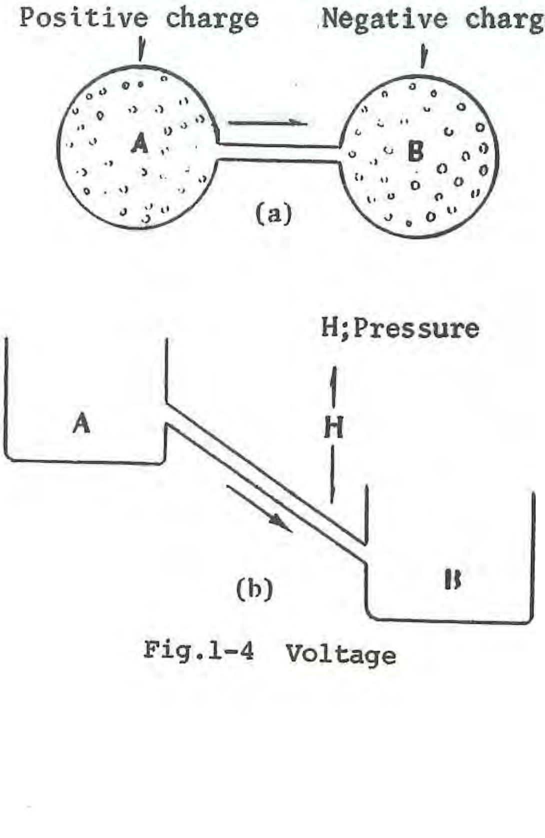


Fig.1-4 Voltage

The electrical pressure, that is the difference of electrical potentials, is called voltage. An electric current will not flow without voltage.

(3) Resistance

Resistance is the opposition to the flow of electric current. A number of factors determine the resistance that a substance offers to the flow of electric current.

The materials which have little resistance to the flow of current are called conductors and they are used to carrying or conducting electricity. Insulators are materials which offer great resistance to the flow of current and so they are used to block or insulate against the flow of current.

Both conductors and insulators conduct current but in vastly different amounts; the current flow in an insulator is so small that it is usually considered to equal zero.

Resistance is affected by the length of the material. The longer an object, the greater its resistance. Another factor is the cross-sectional area of the object, which is the area of the exposed end if we slice through the material at right angles to its length. The greater the cross-sectional area, the lower the resistance to current flow.

Resistance is also affected by the temperature. Metals generally offer higher resistance at higher temperature. Certain non-metallic substances, such as carbon, on the other hand, offer lower resistance at higher temperatures.

Specific resistance of some conductors (Unit; x $10^{-6}\Omega$cm at 20°C)

Silver	1.62
Copper	1.69
Gold	2.4
Aluminum	2.62
Tungsten	5.48
Zinc	6.1
Nickel	6.9
Iron	10.0
Platinum	10.5

As shown in the above table, metals are usually the best conductors. Carbon and ordinary water are non-metallic materials which are sometimes used as conductors, while such materials as glass, paper, rubber, ceramics and certain plastics are commonly used as insulators. The relationship between resistance and dimension of the conductor can be expressed as follows;

$$R = P \frac{L}{A}$$

R; Resistance of conductor

L; Length of conductor

A; Sectional area

P; Specific resistance of conductor of 1 cm length and 1 cm^2 area

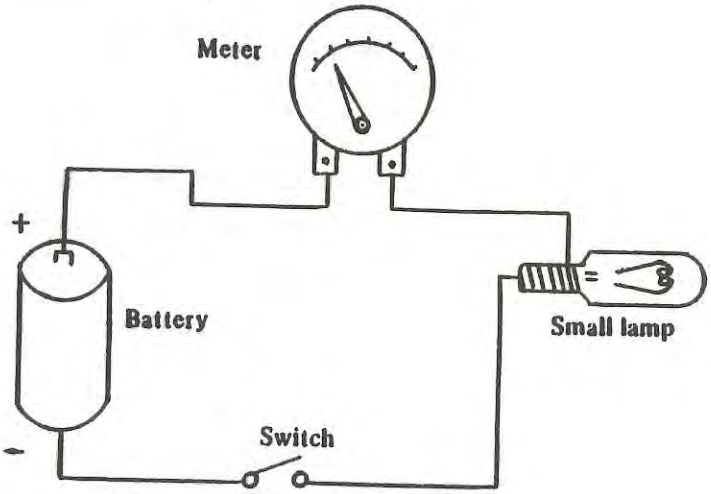
The above formula means that, the resistance of a conductor is in direct proportion to its length, and is inversely proportional to its sectional area.

(4) Units of electric current, voltage and resistance

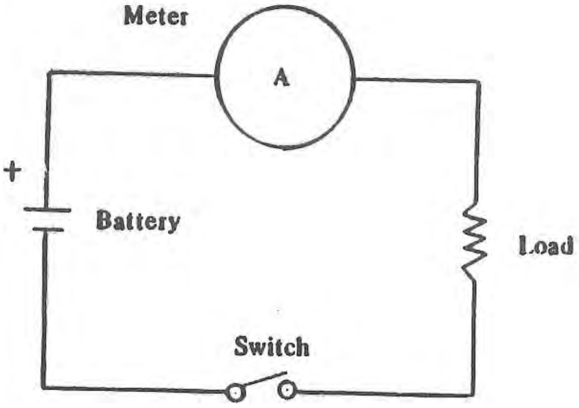
Current	Electric current is measured in amperes, milliamperes, and microamperes. This indicates the amount of electricity. (1A = 1,000mA, 1mA = 1,000μA)
Voltage	This is measured in volts and kilo-volts. Volt is the unit of electrical pressure difference existing between two points in a circuit. (1kV = 1,000V = 10^3V, 1MV = 1,000,000 = 10^6V)
Resistance	Resistance is measured in ohms, kilo-ohms and megohms. The symbol is Ω

1.4 Electric circuit

(1) "Load" is an appliance which emits light, heat or mechanical force by using electric energy supplied by a power source. In Fig. 1-5 "load" is a small lamp.



(a) Battery-lamp



(b) Schematic of (a)

Fig.1-5 Electric circuit

(2) Ohm's law

The relationship between voltage, current and resistance can be expressed mathematically by means of the following formula;

$$\text{Current} = \frac{\text{Voltage}}{\text{Resistance}} \quad \text{or } I = \frac{E}{R}$$

I = Amperes
E = Volts
R = Ohms

This formula means that the greater the voltage is, the greater will be the current; and greater the resistance, the smaller the current. Ohm's law formula can be transposed as follows;

$$E = 1 \times R \quad \text{and} \quad R = \frac{E}{1}$$

By using the Ohm's law formulas, the value of any one of the three electrical quantities in a circuit can be found if the values of the other two quantities are known.

When solving any Ohm's law problem, it is helpful to use the formula with the unknown quantity to the left of the equal sign.

Example

Suppose that a 2.5V lamp must be powered by a 12V battery; what resistance is required to reduce the voltage so that the lamp will operate correctly? The circuit is shown in Fig. 1-6.

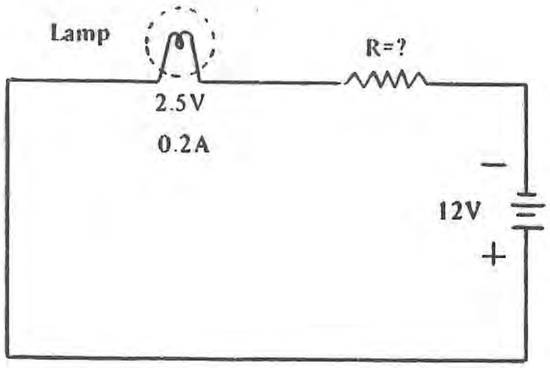


Fig.1-6

Figure. 1-6 is a circuit for the operation of a 2.5V lamp from a 12V battery using a resistor to provide the necessary drop in voltage. The correct value for R is 47.5Ω.

The information printed on the lamp will show that it is designed for 2.5V operation, and when this voltage is applied a current of 0.2A will pass. It is easy to calculate that resistance of the lamp:

$$R = \frac{E}{I} = \frac{2.5}{0.2} = 12.5 \text{ ohms}$$

Since the battery is 12V and the lamp requires 2.5V, it will be necessary to drop 9.5V in the resistor R. (see Fig. 1-6). In this case, 0.2A will flow in the resistor, the lamp and the wire.

$$\therefore R = \frac{9.5}{0.2} = 47.5\Omega$$

A 47.5 Ω resistor would therefore provide the required drop of 9.5V. Alternatively, we may consider the circuit as a whole. With a potential difference of 12V, 0.2A will flow when the total resistance is 60Ω, Since the resistance of the lamp is 12.5Ω, the resistance of the resistor R must be 47.5Ω.

(3) Kirchhoff's Laws

Two rules or laws known as Kirchhoffs laws are important in solving complicated electric circuits. Where the rules of series and parallel circuits cannot be applied, more general methods of analysis becomes necessary. These methods include the application of Kirchhoff's laws. Any circuit can be solved by Kirchhoff's laws, because they do not depend on series or parallel connections.

a) Kirchhoff's current law (first law)

The current flowing into any junction of an electric circuit is equal to the current flowing out of that junction (Fig. 1-7).

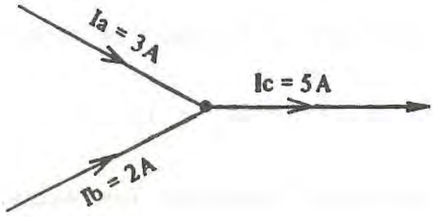


Fig.1-7

b) Kirchhoff's voltage law (second law)

The sum of the battery or generator voltages around any closed circuit is equal to the sum of the voltage drops in resistances around the same circuit. (Fig. 1-8).

Example

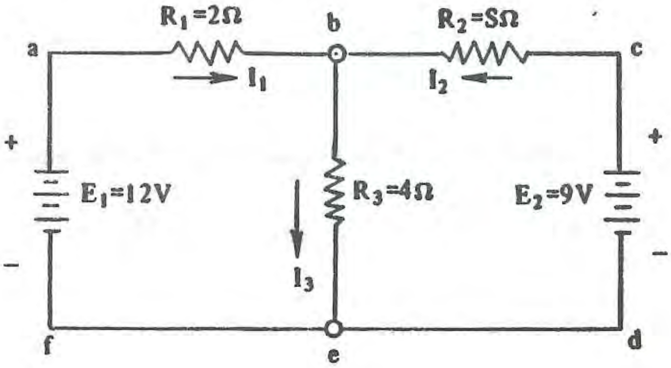


Fig.1-8

Using Kirchhoff's first law at the point b,

$$I_1 + I_2 = I_3$$

Using Kirchhoff's second law around circuit f a b e

$$2I_1 + 4I_3 = 12$$

Using Kirchhoff's second law around circuit d c b e

$$8I_2 + 4I_3 = 9$$

The above three equations have three unknown currents I_1, I_2 and I_3 and their value may be found by solving the three simultaneous equations.

Since $I_1 = I_3 - I_2$, the second equation may be written as

$$2I_3 - 2I_2 + 4I_3 = 12 \rightarrow -2I_2 + 6I_3 = 12$$

Multiply both sides by 4 and add to the third equation.

$$(8I_2 + 4I_3 = 9) - (8I_2 + 24I_3 = 48) \rightarrow (28I_3 = 57)$$

$$\therefore\ I_3 = \frac{57}{28}\text{ A}$$

Substitut this value into third equation

$$8I_2 + \frac{57}{7} = 9 \qquad 8I_2 = 9 - \frac{57}{7} = \frac{6}{7}$$

$$\therefore\ I_2 = \frac{6}{56}\text{ A}$$

Substitut I_2 and I_3 into first equation

$$I_1 = I_3 - I_2 = \frac{57}{28} - \frac{6}{56} = \frac{114-6}{56} = \frac{27}{14}\text{ A}$$

(4) Connection of resistance in D.C. circuit

a) Series connection

The total resistance in a series is equal to the sum of all resistances, as illustrated in Fig. 1-9.

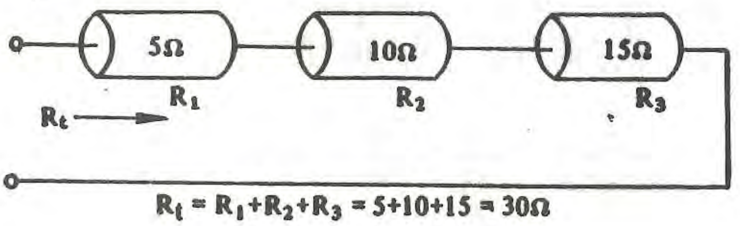
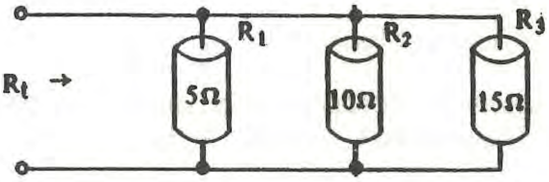


Fig.1-9 Series connection

b) Parallel connection

In case of parallel connection, the value of total resistance is reciprocal to the sum of reciprocal values of all resistances, as shown in Fig. 1-10. The total resistance is always less than the value of the lowest individual resistance.



$$R_t = \frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}} = \frac{1}{\frac{1}{5}+\frac{1}{10}+\frac{1}{15}}$$

$$= \frac{1}{\frac{6+3+2}{30}} = \frac{1}{\frac{11}{30}} = \frac{30}{11} = 2.72$$

Fig.1-10 Parallel connection

c) Compound connection

This is a combination of a series connection and a parallel connection, as illustrated in Fig. 1-11.

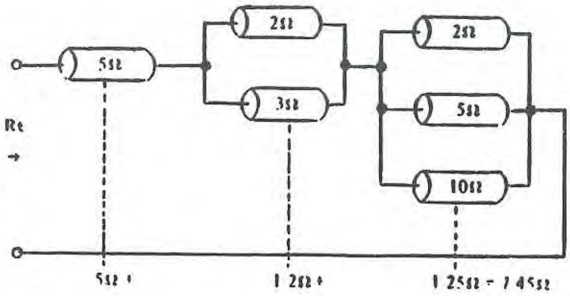


Fig.1-11 Compound connection

1.5 Magnetism

(1) The nature of magnet

We know that when we rub a magnet in the sand of the seashore, the iron sand particles are attracted on both ends of the magnet (Fig. 1-12).

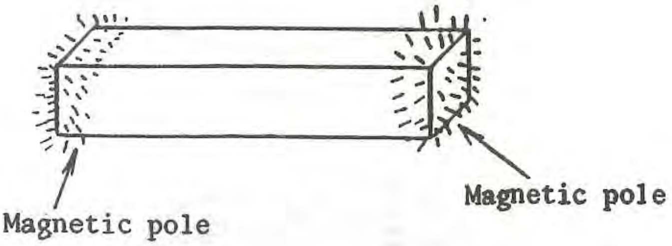


Fig.1-12 Bar magnet

There is a kind of force which attracts iron to both sides of the magnet. We know today that a magnet can attract not only pieces of iron, but certain other metals, such as nickel and cobalt, although with less force.

Substances that can be attracted by a magnet are called magnetic, and the ability of a magnet to attract magnetic substances is called magnetism.

(2) Magnetic field and magnetic lines of force

We call the space in which magnetic action is effective 'magnetic field', and it is imagined that there exists something which is the origin of magnetic action.

Note that the magnetic lines of force, like the electric lines of force, are imaginary. Nevertheless, the field acts as though the lines of force were present. It would seem that these lines try to follow the shortest distance from pole to pole, at the same time repeling each other.

If we place two unlike poles near each other, as in Fig. 1-13(a), the line of force acts from the north pole to the south pole. Since these lines of force tend to shorten, the two magnets are pulled to each other. If, on the other hand, we place two like poles near each other, as in Fig. 1-13(b), the lines of force tend to repel each other and the two magnets are pushed apart.

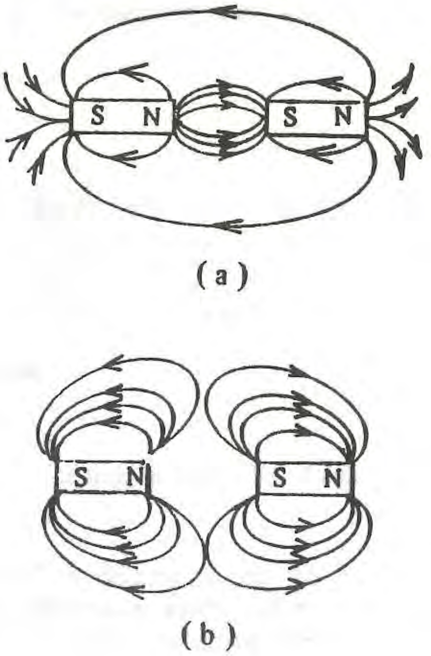


Fig.1-13 Magnet and magnetic lines of force

We can summarize the nature of magnet or magnetic lines of force as follows:

i) Magnet attracts iron.

ii) There are two poles (NS) in a magnet.

iii) Like poles repel each other.

iv) Unlike poles attract each other.

v) Magnetic lines of force act from north to south.

vi) Magnetic lines of force tend to shorten like rubber, and the same directional magnetic line of force repel each other.

2. Effects of Electric Current

2.1 Thermal effect

When mechanical energy is applied to a machine, it meets a kind of resistance called friction. Mechanical power is lost overcoming this friction. However, it is not really lost since it shows up as heat at the point or points of friction. It has merely been changed from mechanical energy to heat energy. Similarly, when electrical energy is applied to a conductor, the resulting current flow must overcome resistance of the conductor. Electrical power is not really lost, but is converted to heat in the conductor. That is, the electrical energy has been changes to heat energy. You will recall that the electrical power consumed by a circuit is equal to the product of the current and electromotive force. Thus:

$$P \text{ (in watts)} = E \text{ (in volts)} \times I \text{ (in amperes)}$$

Since, by Ohm's law, $E = I \times R$, by substituting for E in the first equation its equivalent $(I \times R)$, we may indicate the power equation on tems of current (I) and resistance (R).

Thus:

$$P = E \times I = (I \times R) \times I = I_2 \times R$$

Similarly, since $I = \frac{E}{R}$, we may indicate the power equation in terms of electromotive force (E) and resistance (R). Thus:

$$P = E \times I = E \times \frac{E}{R} = \frac{E_2}{R}$$

If we wish to determine the power consumed or lost as current flows through a resistor, we may multiply the square of that current by the resistance of the resistor. Still another method is to divide the square of the voltage drop by the resistance. Both these methods produce the same result. Since the voltage of a circuit usually is kept at a constant value, the two variables generally are the resistance of the resistor and the current flowing thorugh it. Hence the power loss most frequently is expressed in terms of $I_2 \times R$. Since this power produces heat, the heating effect of an electric current is often called the I_2 R loss. Suppose that the electric current (I) A flows in the resister (R) for (t) seconds, the quantity of heat energy is shown as follows;

$$H = I^2Rt \text{ .... unit: joule}$$

This relationship, expressing the power loss in t seconds is called Joule's.law. This principle is used for lamps, heaters, fuses etc. The unit of joule can be replaced to the unit of calorie as follows;

$$I\ (Cal) = 4.186\ (j) = 4.2\ (j)$$

That is, $I\ (j) = 0.24\ (Cal)$

Thus, $j = 0.24 \times I^2 \times R \times t$

2.2 Luminous effect

As you know, the electrons of an atom move in distinct orbits around the nucleus. If heat energy is applied to the atom, some of its electrons may acquire sufficient energy to jump from their normal orbit to the one farther removed from the nucleus. An atom in this state is said to be 'excited'. Since this is an unstable state, these electrons soon fall back to their normal orbits. As they do so, they release the excess energy they had acquired in the form of light energy. Thus if a substance such as a metal wire, for example, is heated sufficiently, some of it atoms may become excited and emit light as they return to their normal states.

You now know that as a current flows through a conductor, heat is produced as a result of the I_2R loss. If the current and resistance are large enough, the heat so produced may be great enough to make the conductor emit light. This is the principle of incandesent lamp, invented by Thomas A. Edison in 1879. To provide for a high enough resistance, Edison used a wire, or filament, made of carbon. However, if this filament is heated until it emits light - that is, to incandescence - it burns up in the air, which supports combustion. Therefore, Edison sealed the carbon filament in a glass bulb from which he pumped out the air.

2.3 Chemical effect

As shown in Fig. 2-1, if two metal plates (called electrodes) are set at opposite ends of the solution and a source of electromotive force is connected to these plates so that one becomes a positive electrode and the other a negative electrode, an electric field is created between these two electrodes. Since opposite charges attract, the negative chlorine ion is attracted to the positive electrode and the positive sodium ion is attracted to the negative electrode. Upon reaching the positive electrode, the chlorine ion surrenders its extra electron to the electrode and becomes a neutral chlorine atom. As the sodium ion reaches the negative electrode, it obtains an electron from the electrode and becomes a neutral sodium atom.

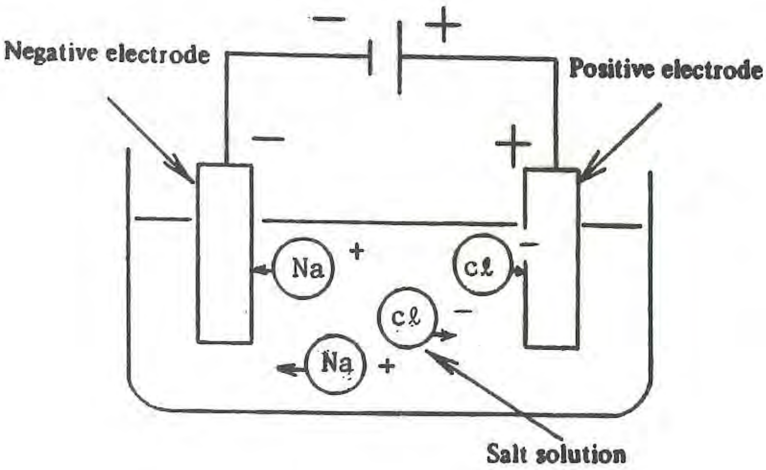


Fig. 2-1

The effect of the electromotive force, then, is to cause a movement of negative ions through the solution toward the positive electrode and an equal number of positive ions toward the negative electrode. This movement of charged particles constitutes an electric current and in this way the electric current flows through a liquid.

Such a solution which is a good conductor, is called an electrolyte. If the electric current flows into poles, chemical action will occur. Electric plating and electric polishing, electric refining, etc., are an application of chemical effect of electric current.

2.4 Magnetic effect

In 1819 Hans Christian Oersted, a Danish physicist, brought a small compass near a wire that was carrying an electric current. He noticed that the compass was deflected. When he turned the current off, the compass assumed its original position.

The deflection of the compass while current was flowing through the wire indicated that it was being acted upon by an external magnetic field. Where did this magnetic field come from? Not from the copper wire, which we know is non-magnetic, it could only come from the electric current flowing through the wire. When the electric current flows through an electric cable, the magnetic lines of force (magnetic field) occur arround it. The direction of magnetic field is determined easily by a simple method as shown in Fig. 2-2.

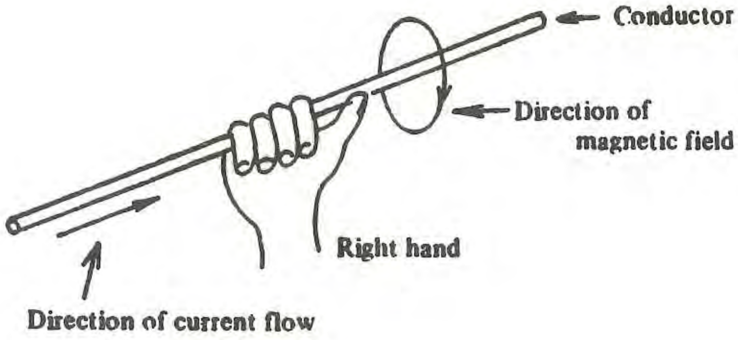


Fig. 2-2

If the conductor is grasped in right hand with the extended thumb pointing in the direction of the current flow, the other fingers then circle the conductor in the direction of the magnetic lines of force.

Suppose we bend the current-carrying conductor into a loop. The magnetic field then would appear as illustrated in Fig. 2-3. If we add more loops, each loop adds its magnetic field, thus producing a greater overall magnetic effect. The resulting magnetic field would appear as shown in Fig. 2-4.

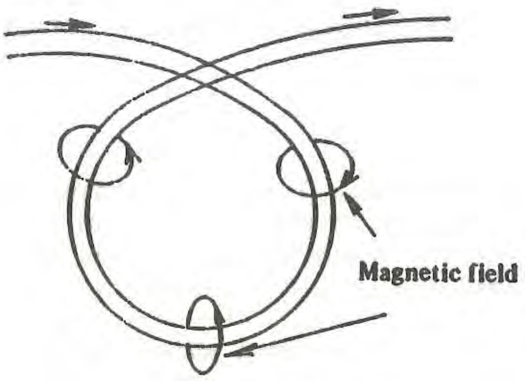


Fig. 2-3

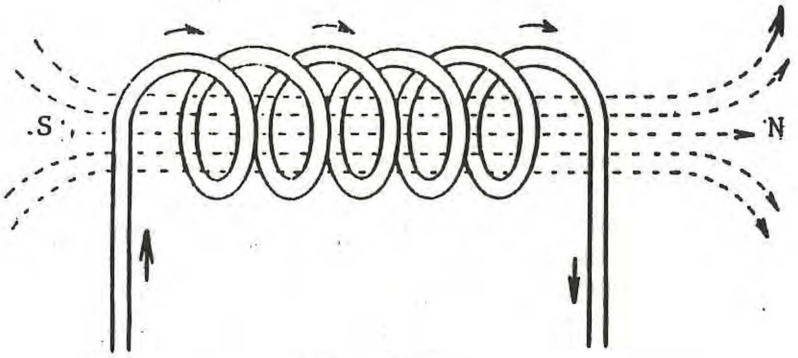


Fig. 2-4

Note that the coil becomes a temporary magnet with a set of north and south poles. The greater the number of loops, the stronger the magnetic field will be. The polarity of the magnet formed by the coil may be determined by grasping it in the right hand so that the fingers follow around the coil in the direction of the electric current. The extended thumb then will point towards the north pole (Fig. 2-5).

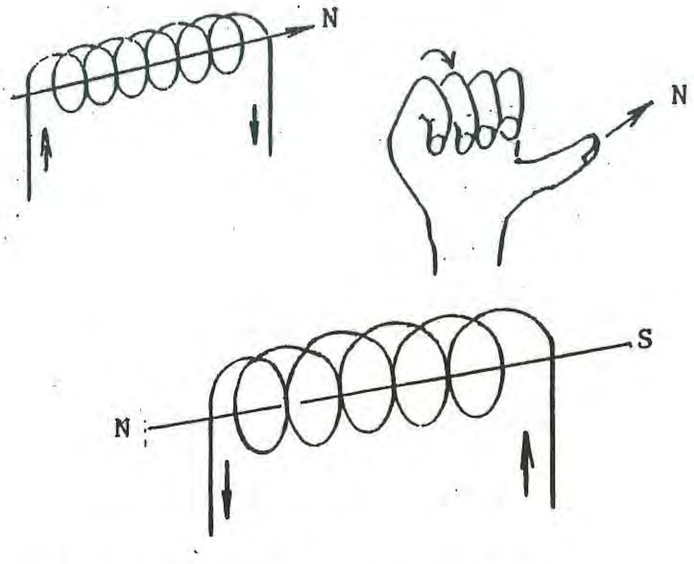


Fig.2-5 Direction of magnetic field

The strength of magnetic field can be increased by winding the coil on a core of magnetic material. Then the magnetism of the core is added to that of the coil.

3. Direct Current Electricity

3.1 Current carriers

If an electron is removed from a neutral atom, the atom becomes a positively charged ion. If an electron is added, the neutral atom becomes a negatively charged ion. In the space between any two charged particles there exists a stress, or field of force. We call this field of force the electric, or electrostatic field. Particles bearing like charges tend to repel one another, whereas particles bearing unlike charges tend to attract one another. The movement of charged particles arising from the presence of this field is called the electric current.

Moving particles that carry an electrical charge are called current carriers.

There are three types of carriers. In solid conductors, such as a copper wire, as an electron escapes from its parent nucleus the remaining positive ion is held in place. It is only the free electron that is able to move about.

Hence the current carriers of such a conductor consist of electrons, which are particles carrying a negative electrical charge.

In liquids and gases the charged ion, too, are free to move. Thus we have a second type of carrier, the ion. In semiconductors, such as germanium or silicon, we encounter a third type of carrier, which we shall study later.

3.2 Electromotive force

The electromotive force creates the electric pressure that causes a flow of current through a conductor. Another name for this force is voltage.

The unit of measurement of electromotive force, or voltage, is called the volt.

Where the volt is too large a unit, we may use the millivolt ($\frac{1}{1,000}$ of a volt) or microvolt ($\frac{1}{1,000,000}$ of a volt).

Where the volt is too small a unit, we may use the kilovolt (1,000 volts). Letter E stands for voltage.

3.3 Electric power and electric energy

When voltage is applied to a circuit with electric light, motor, electric heater etc., the current flows through the circuit and some work is done. The total of the work is called electric energy. The amount of work done is called electric power.

These relations can be expressed by means of the following formula;

Power = Current x Voltage or $P = I \times E$

The unit of electric power is Watt. The unit of horsepower is often used as the unit of electric power of motor. The relationship between both power is as follows;

$$1\ \text{HP} = 746\ \text{W}$$

Electric energy is expressed by means of the following formula;

$H = P \times T$

H; Electric energy
P; Electric power
T; Time (Second)

3.4 Condenser

(1) What is a condenser

As shown in Fig. 3-1, if the insulated parallel conducting plates A and B are connected to the positive and negative terminals of a battery, the positive terminal of the applied potential will attract some of the free electrons from electrode A and the negative terminal will repel electrons to electrode B.

Hence, the battery, or source of potential, has withdrawn electrons from electrode A and transferred them to electrode B. Thus plate A has become positively charged, since negative charges have been withdrawn from it and plate B has become negatively charged. That is, electrical charge is stored in two electrodes. An electric component that can store electric charge is called "condenser" or "capacitor".

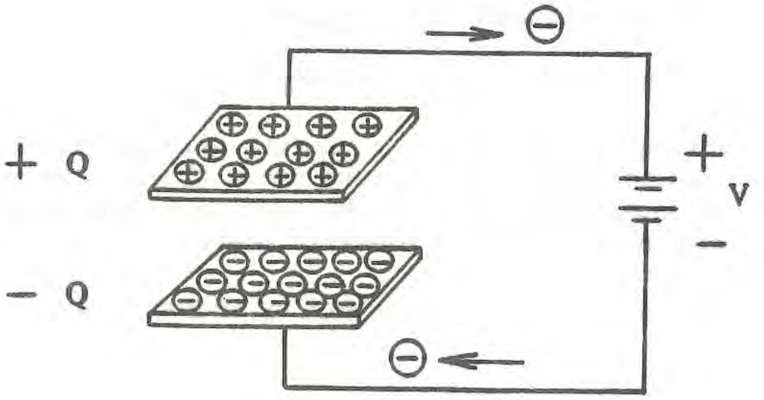


Fig.3-1 Transfer of electrons in capacitor plates

(2) Capacitance

The electrical charge stored in a condenser is:

a) proportional to the applied voltage

b) proportional to the plate area

c) inversely proportional to the distance between plate.

The property of a capacitor to store electrical energy in this way is called capacitance, or electrostatic capacity, the symbol for which is C.

(3) Unit of capacitance

The unit of capacitance is the farad, abbriviated F. farad can be defined as being the capacitance present when one coulomb of electrical quantity is stored in the electrostatic field of the capacitor or circuit as one volt is applied. The farad is generally too large a unit for ordinary purposes.

Accordingly, we have the microfarad (abbreviated μf) which is one-millionth (10^{-6}) of a farad. Where even the microfarad is too large as a unit we may use the picofarad(μf). Which is one millionth (10^{-6}) of a microfarad.

So far, we have been discussing capacitance in direct current terms. When considering AC circuit we must take a somewhat different point of view. The fomula of capacitance is as follows:

$$C = \frac{Q}{V} \text{ (F)}$$

C:	capacitance	(F)
Q:	electrical quantity	(C)
V:	applied voltage	(V)

(4) Condenser and insulator

If a slab of glass or hard rubber or some other good dielectric is inserted between the plates so as to fill completely the intervening space, the capacitance of the condenser will be increased.

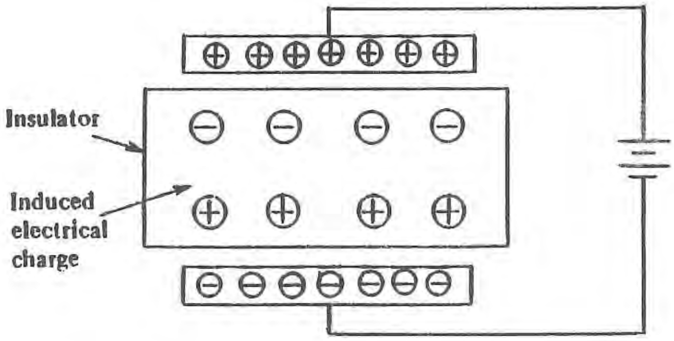


Fig.3-2 Condenser with insulator

This phenomenon is considered as the increase of electrical charge. As shown in Fig. 3-2, when some voltage is applied to the plates with an insulator between them, electric field occurs between two plates. Electrostatic induction which is due to the action of electric field induces positive charge and negative charge on the insulator. The polarity of these charges is reverse to that of the charge on the plate. Hence, it is considered that electric charge is neutralized and the voltage drops. But as constant voltage is applied to the plate, voltage does not drop.

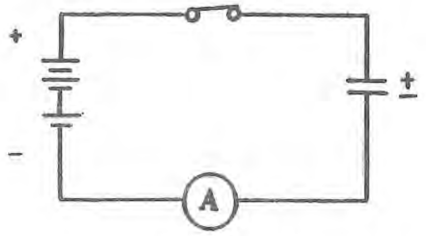
To a condenser with an insulator, the same quantity of electrical charge which on the insulator is supplied to plates by a battery. This means that as more electrical charge is stored in the plates, capacitance increases:

$$\frac{C'}{C} = \frac{\frac{Q'}{V}}{\frac{Q}{V}} = \frac{Q'}{Q}$$

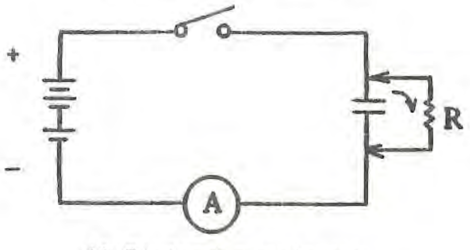
The ratio C'/C or Q'/Q is called relative capacitivity; or dielectric constant, of the dielectric between the plates.

(5) Charging and discharging a condenser

The performance of a condenser when connected in an electric circuit is shown in Fig. 3-3(a): there are two conducting plates connected to a battery through switch S and meter A., the plates being separated by a dielectric.



a) Charging condenser



b) Discharging condenser

Fig.3-3 Charging and discharging condenser

If the switch S is closed, the meter will deflect momentarily and then come back to zero. This indicates that, when the switch is closed, a quantity of electricity passed through the meter but that the current ceases almost immediately. The current flows for a time only sufficient to charge the condenser. After the condenser has become fully charged, the current ceases because the e, m, f, of the condenser is equal to that of the battery. Storing the electrical charge in a condenser is called "charging".

When the switch is opened, the electrical charge remains in the condenser. If charging voltage is high, to it is dangerous touch this condenser by hand. Hence, as shown in Fig. 3-3(b), when the switch is opened, connect a low resistor to both terminals of the condenser. Then the current flows through the resistor and the electrical charge on the condenser is converted to heat in the resistor. That is, the electrical charge comes back to zero and voltage to oV. To lose the electrical charge in the condenser is called "discharging".

3.5 Condensers in DC Circuit

(1) Parallel connection

If we connect condensers in parallel (Fig. 3-4) they act as though we were adding to the areas of their plates. Accordingly, the total capacitance increases. Thus, for condensers connected in parallel, the following formula applies:

$$C = C_1 + C_2 + C_3$$

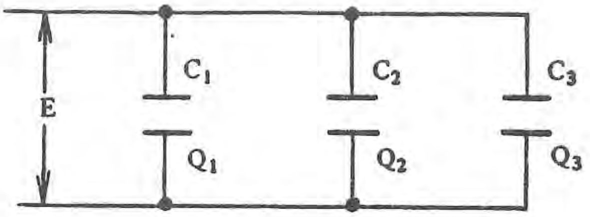


Fig.3-4 Condensers in parallel

Let the common voltage across the condenser be E and the total resulting charge Q.

Then, $Q = CE \ (C = \frac{Q}{E})$

and $Q_1 = C_1E, \ Q_2 = C_2E, \ Q_3 = C_3E$

The total charge,

$$Q = Q_1 + Q_2 + Q_3 = CE$$

$$CE = C_1E + C_2E + C_3E = (C_1 + C_2 + C_3)\ E$$

Therefore, $C = C_1 + C_2 + C_3$

That is, if condensers are connected in parallel, the resulting capacitance is the sum of the individual capacitances.

(2) Series connection

If we connect condensers in series, they act as though we were adding to the thickness of the dielectric. Accordingly, the total capacitance decreases. Thus for condensers connected in series, the following formula applies:

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

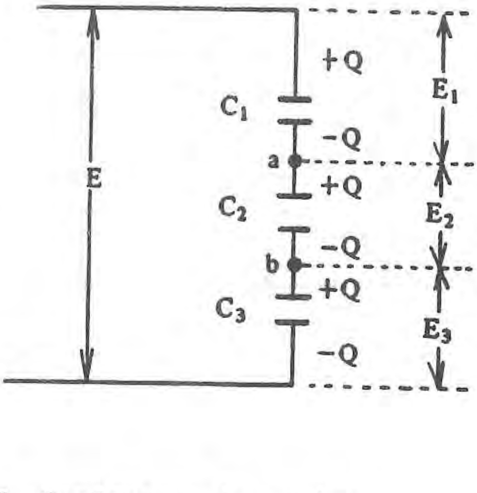


Fig.3-5 Condensers in series

This arrangement of condensers is shown in Fig. 3-5. Let E_1, E_2, E_3 be the potential differences across the condenser C_1, C_2, C_3.

After the voltage E is applied to the system, there will be +Q units of charge on the positive plate of C_1, and by the low of electrostatic induction, -Q units must be induced on the negative plate of C_1.

Now consider the region a, which consists of the negative plate of C_1, the positive plate of C_2, and the lead connecting them. Before the voltage E is applied to the system of condensers, no charge exists in the region a. After the application of the voltage, the net charge in this region must be zero, since perfect insulation is assumed and no charge can enter or leave the region.

Therefore, +Q units must come into existence in order that the net charge in the region a may remain zero (+Q) + (-Q). The same reasoning holds for the region b, between C_2 and C_3. Therefore, each of the three condensers in voltage E_1, E_2, E_3.

$$E_1 = \frac{Q}{C_1} \qquad E_2 = \frac{Q}{C_2} \qquad E_3 = \frac{Q}{C_3}$$

The sum of three condenser voltages must equal line voltage.

$$E_1 + E_2 + E_3 = E$$

$$E = \frac{Q}{C} = \frac{Q}{C_1} = \frac{Q}{C_2} = \frac{Q}{C_3}$$

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

That is, the reciprocal of the equivalent capacitance of a number of condensers in series is equal to the sum of the reciprocals of the capacitance of the individual condensers

4. Alternating Current Electricity

4.1 Single-phase Alternating Current

(1) Electromagnetic induction

In the circuit connecting the terminals of a zero-center galvanometer and a coil of about 50 turns of wire

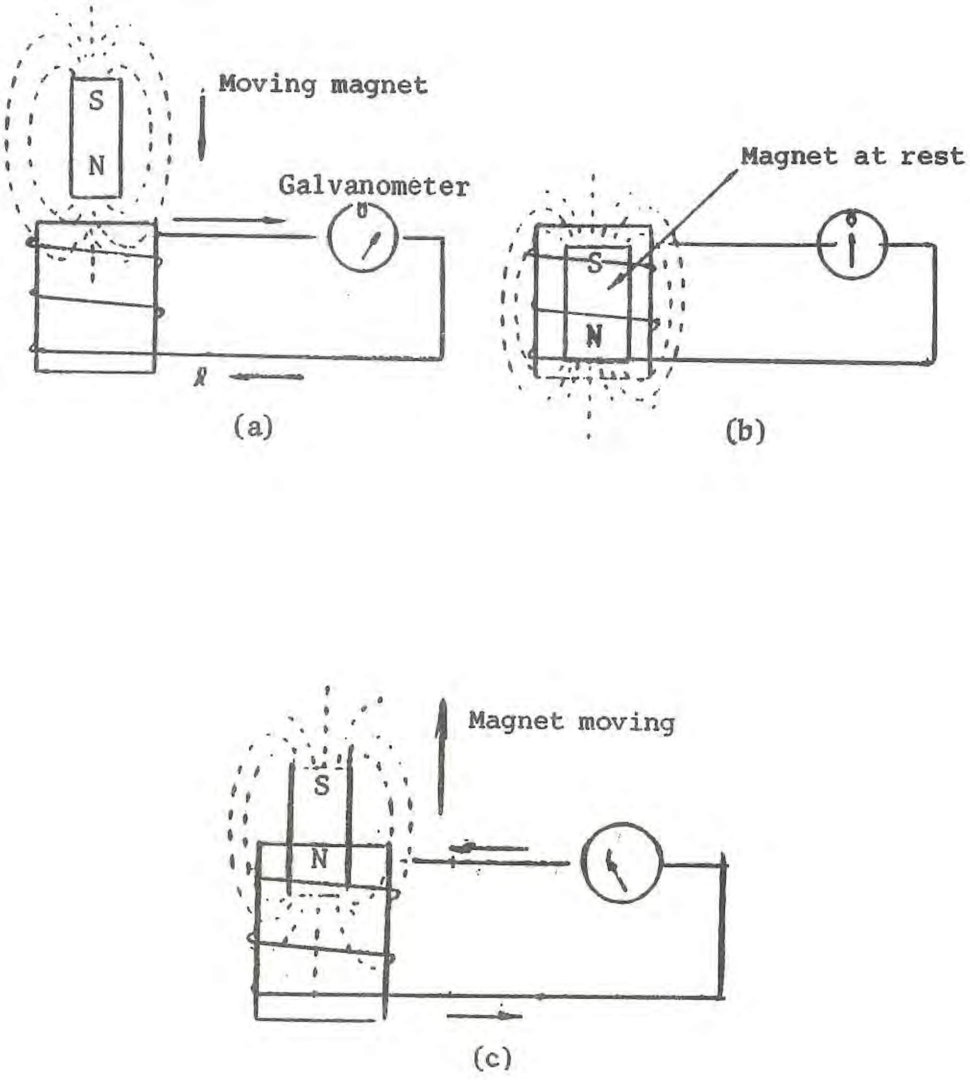


Fig. 4-1

wound in the shape of a cylinder, when the north end of a permanent magnet plunges into the centre of the coil as shown in Fig. 4-1(a), you will observe that the pointer is deflected to the right, showing that an electric current was set flowing for a moment in the coil and the galvanometer. When the magnet comes to rest inside the coil as shown in Fig. 4-1(b), the pointer swings back to zero, showing that the current has ceased. Now, when you move the magnet out of the coil as shown in Fig. 4-1(c), the pointer swings to the left, showing that once more an electric current is set flowing, but this time in the opposite direction. The same effect may be obtained if the magnet is held stationary and the coil moved. As the magnet is moved into or out of the coil, this magnetic field cuts across the wire of the coil. When a conductor cuts through a magnetic field, an electromotive force is set up between the ends of the conductor.

An electromotive force set up in a conductor in this way is called the induced electromotive force. The current set flowing as a result is an induced current.

The voltage induced by magnetic flux cutting the turns of a coil depends upon the number of turns and how fast the flux moves across the conductor. Either the flux or the conductor can move. Specifically, the amount of induced voltage is determined by the following three factors:

a) Amount of flux

The more magnetic lines of force cut across the conductor, the higher the amount of induced voltage.

b) Number of turns

The more turns in a coil, the higher the induced voltage as the total e is the sum of all the individual voltages induced in each turn in series.

c) Time rate of cutting

The faster the flux cuts a conductor, the higher the induced voltage. Then more lines of force cut the conductor within a specific period of time. These factors are or fundamental importance in many applications because any conductor with current will have voltage in it by a change in current and its associated magnetic flux.

The amount of induced voltage can be calculated according to Faraday's law of induction;

$$e \text{ (Volts)} = -N \frac{d\phi \text{ (webers)}}{dt \text{ (seconds)}} = \frac{d\psi}{dt}$$

$$\psi = N\phi \text{ (wb)}$$

Where e is the induced voltage, N: is the number of coil turns.

$\frac{d\phi}{dt}$ = specifies how fast the flux cuts across the conductor

with $\frac{d\phi}{dt}$ in webers per second, the induced voltage e is in volt units.

(2) Alternating-voltage generator

We can define A.C. voltage as one that continuously varies in magnitude and penodically reverses in polarity.

Figure 4-2 shows how such a voltage wave form is produced by a rotary generator, as the conductor loop rotates through the magnetic field to generate the induced voltage across its open terminals. In (a) the loop is shown in its horizontal starting position. When the loop rotates counterclockwise, the two long conductors of the loop move vertically up or down through the plane but parallel to the vertical flux lines. In this position, motion of the loop does not induce a voltage, because the conductors are not cutting across the flux.

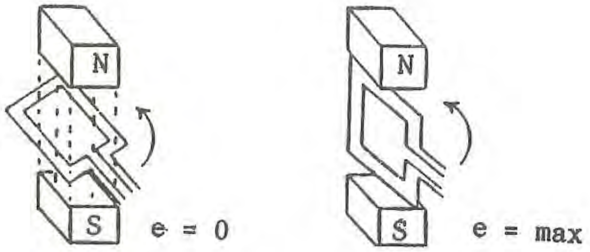


Fig.4-2 Loop rotating in magnetic field to produce alternating induced voltage

When the loop rotates through the upright position in (b), however, the conductor cuts across the flux, producing maximum induced voltage. The shorter connecting parts in the loop do not have any appreciable voltage induced in them.

Each of the longer conductors has opposite polarity of induced voltage because the one at the top is moving to the left while the bottom conductor is moving to the right. The amount of voltage varies from 0 to maximum as the loop moves from a flat position to an upright, where it can cut across the flux. Also the polarity at the terminals of the loop reverses as the motion of each conductor reverses during each half-revolution.

If the loop rotates at the speed of 50 revolutions per second, the A-C voltage will have the frequency of 50 cycles per second.

(3) The definition of alternating current

In case of alternating current (A.C.), the voltage is continually rising, falling, then becoming negative, rising and again falling, at regular intervals (Fig. 4-3).

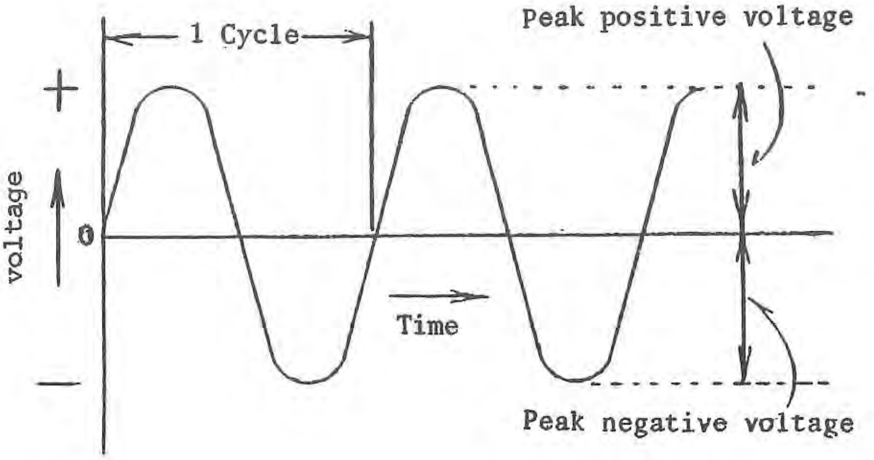


Fig.4-3 Form of alternating current

The current therefore flows first in one direction and then the other. Such a wave can be divided into identical sections, called a cycle

The frequency of alternating currents is measured in cycles per second, kilocycles per second or megacycles per second.

1 kc = 1,000 c
1 Mc = 1,000 kc
1 Gc = 1,000 Mc

The unit of frequency is called hertz, abbreviated Hz.

Let us consider again the alternating-voltage generator. One complete revolution of the loop around the circle is a cycle.

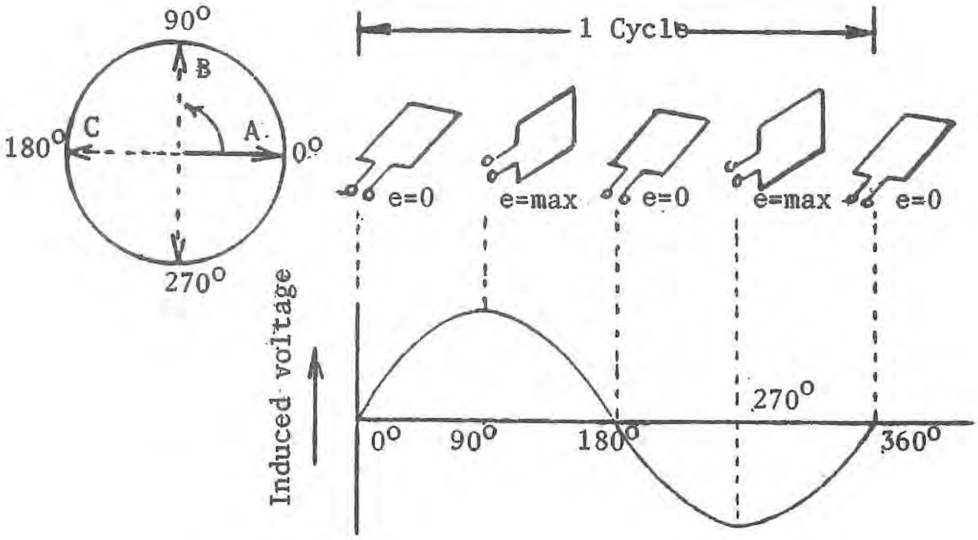


Fig. 4-4 One cycle of sine wave alternating voltage generated by the loop

In Fig. 4-4 the generator loop is shown in its position at each quarter-turn during one complete cycle. The corresponding wave of induced voltage also goes through one cycle.

(4) Voltage and current values for a sine wave

Since an alternating sine wave of voltage or current has many instantaneous values through the cycle, it is convenient to define specific magnitudes for comparing one wave with another.

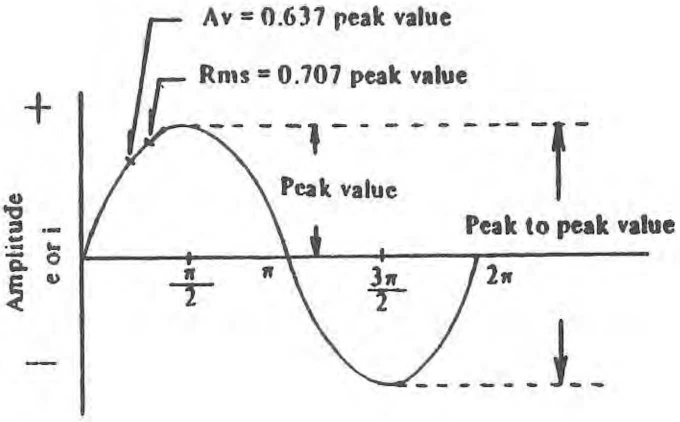


Fig.4-5 A.C. values for a sine wave of voltage or current

The peak, average, or root-mean-square (rms) value can be specified as shown in Fig. 4-5. These values can be used for either current or voltage.

Peak Value:- One characteristic commonly used is peak value, which is the maximum value Em or Im. The peak value applies to either the positive or the negative peak. In order to include both peak amplitude, the peak-to-peak value may be specified.

Average Value:- This value is an arithmetical average of all the values in a sine wave for one alternation or half-cycle. The half-cycle is used for the average because over a full cycle the average value is zero. This average equals 0.637. Since the peak value of the sine is 1 and the average equals 0.637, then

Average value = 0.637 × peak value

Root-mean-square or effective value:- The most common method of specifying the amount of a sine wave of voltage or current is by stating its value at 45°, which is 70.7 percent of the peak. This is its root-mean-square value, abbreviated rms. Therefore,

$$\text{rms value} = 0.707 \times \text{peak value}$$

It is often necessary to convert from rms to peak value. This can be done by transposing the above equation, as follows:

$$\text{peak value} = \frac{1}{0.707} \times \text{rms value} = 1{,}414 \times \text{rms value}$$

Peak-to-peak value which is double the peak value is as follows:

$$\text{peak-to-peak value} = 2.828 \times \text{rms value}$$

(5) Period

The amount of time for one cycle is the period. The symbol is T for time with a frequency of 50 cps. as an example, the time for one cycle is $\frac{1}{50}$ S. Therefore, the period is $\frac{1}{50}$ S in this case.

The frequency and period are reciprocal to each other.

$$T_{(s)} = \frac{1}{f(c)} \quad \text{or} \quad f_{(c)} = \frac{1}{T_{(s)}}$$

The second is the basic unit.

1 millisecond = 1 ms = 1×10^{-3} s
1 microsecond = 1 µs = 1×10^{-6} s
1 nanosecond = 1 ns = 1×10^{-9} s

For higher frequencies and shorter periods, smaller units of time are convenient.

(6) Nonsinusoidal A.C. wave forms

The sine wave is the basic wave form for A.C. variations. This wave form is produced by a rotary generator, as the output is proportional to the angle of rotation.

In many electronic applications, however other wave shapes are also important, for example, the saw tooth wave and the square wave. Any wave shape that is not a sine wave is called a nonsinusoidal wave. With nonsinusoidal wave forms, for either voltage or current there are important differences and similarities to consider. Note the following comparisons with sine waves.

(i) In all cases, the cycle is measured between two points having the same amplitude and varying in the same direction. The period is the time for one cycle (Fig. 4-6).

(ii) Peak amplitude is measured from the zero axis to the maximum positive or negative value. However, peak-to-peak is better for measuring non-sinusoidal waveshapes because they can have unsymetrical peaks.

(iii) The rms value of 0.707 maximum applies to sine waves.

(iv) Phase angles apply only to sine waves as angular measure is used only for sine waves.

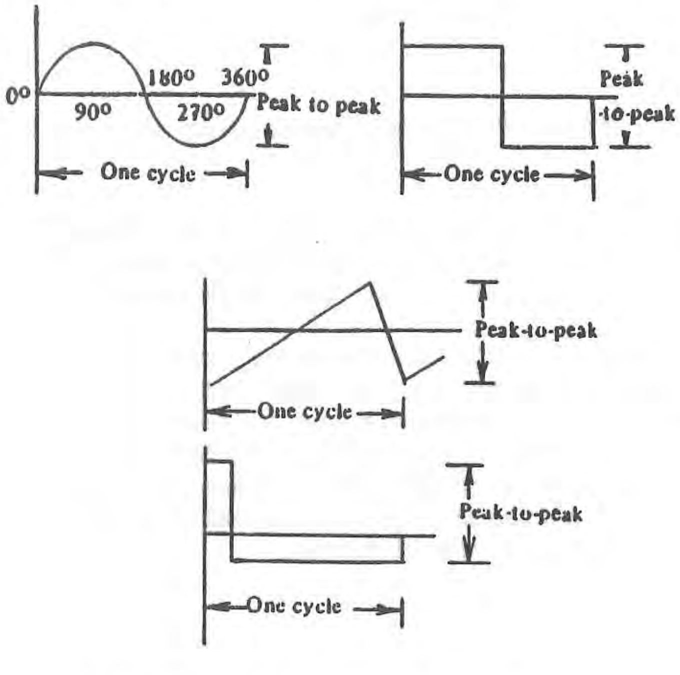


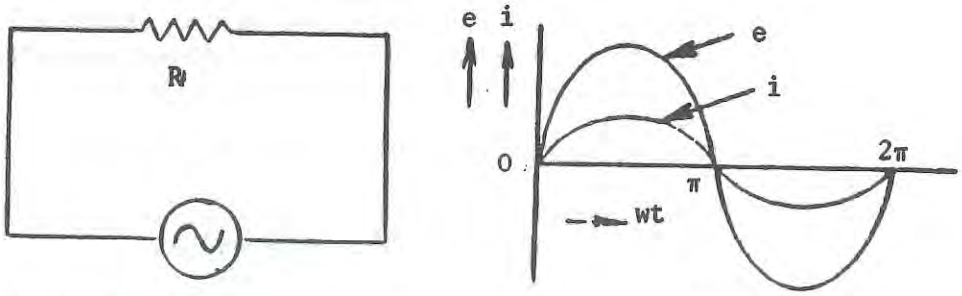
Fig.4-6 Cycle measurement

When we consider a repetitive nonsinusoidal waveform such as a 100 cycle square wave, its fundamental rate of repetition is 100 cycles. Exact multiples of the fundamental frequency are called harmonic frequencies. The second harmonic is 200 cycles, the third harmonic is 300 cycles, etc. Harmonics are useful in analyzing distorted sine waves or nonsinusoidal waveforms. Such waveforms consist of a pure sine wave at the fundamental frequency plus harmonic frequency components.

4.2 Phase difference in A.C. circuit

(1) Circuit containing only resistance

An A.C. circuit has an A.C. voltage source. This voltage connected across an external load resistance produces alternating current of the same waveform, frequency and phase as the applied voltage.



(a) A.C. voltage source (b)

Fig.4-7 Circuit containing only resistor

The amount of current equals E by Ohm's law. When E is an rms value, I is also an R rms value. For any instantaneous value of E during the cycle, the value of I is for the corresponding instant of time.

In an A.C. circuit with only resistance, the current variations i are in phase with the applied voltage e, as shown in Fig. 4-7. This in-phase relation between e and i means that such an A.C. circuit can be analyzed by the same methods used for D.C. circuit, since there is no phase angle to consider. However, when A.C. circuits have inductance and capacitance, there is usually a 90° phase angle that must be included in the calculations.

(2) Circuit containing only inductance

(a) Induction by alternating current

Inductance is the ability of a conductor to produce induced voltage when the current varies. Induced voltage is the result of flux cutting across a conductor, produced by physical motion of either the magnetic field or the conductor. When the current in a conductor varies in amplitude, however, the variations of current and its associated magnetic field are equivalent to motion of the flux. As the current increases in value, the magnetic field expands outward from the conductor. When the current decreases, the field collapses with changes of current, the flux is effectively in motion. Therefore, a varying current can produce induced voltage with the need for motion of the conductor.

It is important to note that induction by a varying current results from the change in current, not the current value itself.

(b) Self-inductance

The ability of a conductor to induce voltage in itself when the current changes is its self-inductance or simply inductance. The symbol for inductance is L, for linkages of the magnetic flux, and its unit is the henry (H).

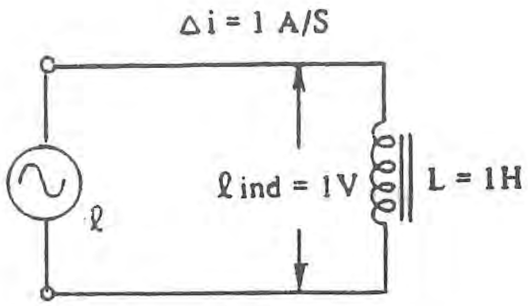
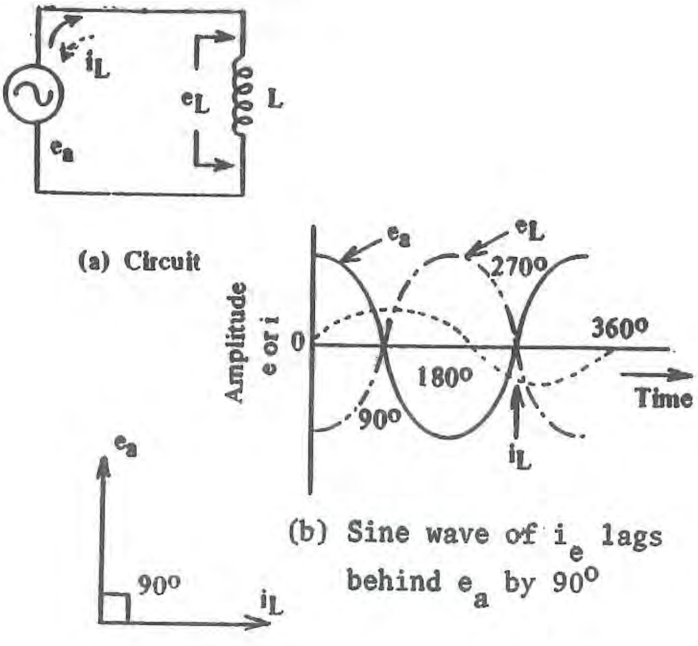


Fig. 4-8 Shows the definition of 1 H

One henry is the amount of inductance that allows one volt to be induced when the current changes at the rate of one ampere per second (Fig. 4-8).

(c) Circuit containing inductance

With sine-wave variations of current producing an inducing voltage, the current lags its applied voltage by exactly 90°, as shown in Fig. 4-9. The inductive circuit in (a) has the current and voltage waveshapes shown in (b).



(a) Circuit

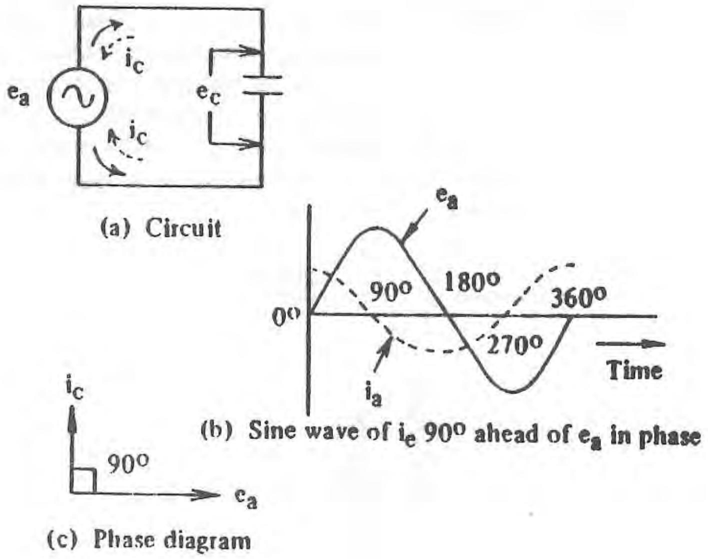
(b) Sine wave of i_e lags behind e_a by 90°

(c) Phase diagram

Fig. 4-9 Current in an inductance lags 90° in time behind the applied voltage

The phasor in (c) shows a 90° phase angle between i_L and e_a. Therefore, we can say that i_L lags behind e_s by 90°. Or e_a leads i_L by 90°. This 90° phase relation between i_L and e_a is true in any sine wave A.C. circuit. The 90° phase angle results because e_L depends on the rate of change of i_L.

(3) Circuit containing only capacitance



(a) Circuit

(b) Sine wave of i_e 90° ahead of e_a in phase

(c) Phase diagram

Fig. 4-10 Capacitive current i_c leads e_a by 90°

For a sine wave of applied voltage, the capacitor provides a cycle of alternating charge and discharge current, as shown in Fig.4-10. In (b), the waveshape of this charge and discharge current I_c is compared with the voltage e_a. Note that the instantaneous value of I_c is zero when e_a is at its maximum value. At either its positive or negative peak, e_a is not changing. For one instant at both peaks, therefore, the voltage must have a static value before changing direction. Then e is not changing and C is not charging or discharging. The result is zero current at this time. Also note that i_c is maximum when e_a is zero. Therefore, i_c and e_a are 90° out of phase. The phasors in Fig. 4-9 show i_c leading e_a by the counterclockwise angle of 90°. The 90° phase angle results because i_c depends on the rate of change of e_a.

4.3 Coil

(1) Mutual inductance

When the current in an inductor changes, the varying flux can cut across any other inductor nearby producing induced voltage in both inductors.

In Fig. 4-11 the coil L_1 is connected to a generator that produces varying current in the coil. The coil L_2 is not connected to L_1, but the coils are linked by a magnetic field. A varying current in L_1 therefore induces voltage across L_1 and across L_2. When the induced voltage produces current in L_2, its varying magnetic field induces voltage in L_1. The two coils L_1 and L_2 have mutual inductance, therefore because current in one can induce voltage in the other. The unit of mutual inductance is Henry and the symbol is L_M. Two coils have a mutual inductance of one henry when a current change of 1 A per second in one coil induces IV in the other coil.

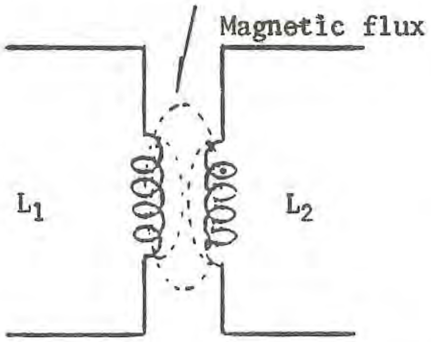


Fig. 4-11 Mutual inductance L_M between two coils L_1 and L_2 linked by magnetic flux

(2) Coefficient of coupling

The fraction of total flux from one coil linking another coil is the coefficient of coupling K, between the two coils

$$K = \frac{\text{flux linkages between } L_1 \text{ and } L_2}{\text{flux produced by } L_1}$$

There is no unit for K, as it is just a ratio of two values of magnetic flux. The value of K is generally stated as a decimal number, such as 0.5, rather than percentage.

The mutual inductance increases with higher values for the primary and secondary inductances and tighter coupling.

$$L_M = K\sqrt{L_1 \times L_2} \quad \text{henrys}$$

Where L_1 and L_2 are the self-inductance values of the two coils, K is the coefficient of coupling and L_M is the mutual inductance linking L_1 and L_2.

(3) Energy in magnetic field of inductance

Magnetic flux associated with current in an inductance has electrical energy supplied by the voltage source producing the current. The energy is stored in the field, since it can do the work of producing induced voltage when the flux moves.

The amount of electrical energy stored is

$$\text{Energy} = \quad = \tfrac{1}{2} LI^2 \text{ joules}$$

L : henry

I : ampere

(4) Inductance in series or parallel

The total inductance of coils connected in series is the sum of the individual inductance values, as for series resistance.

Since the series coils have the same current, the total induced voltage is a result of the total number of turns.

Therefore in series,

$$L_T = L_1 + L_2 + L_3 + \ldots\ldots\ldots\ldots$$

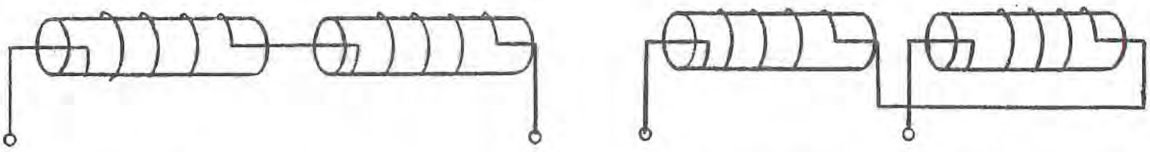
With coils connected in parallel, the total inductance is expressed by the following equation:

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots\ldots\ldots\ldots$$

The total inductance of two coils that connected in series and have mutual inductance:

The mutual inductance L_M is plus, increasing the total inductance, when the coils are series-aiding or minus when they are series-opposing to reduce the total inductance (Fig. 4-12):

$$L_T = L_1 + L_2 \pm 2L_M$$



(a) $L_T = L_1 + L_2 + 2L_M$

(b) $L_T = L_1 + L_2 - 2L_M$

Fig. 4-12

(5) A method of determining mutual inductance

First, the total inductance is measured for the series aiding connection. Let this be L_{Ta}. Then the connection to one coil is reversed to measure the total inductance for the series-opposing coils.

Let this be L_{Tb}. Then

$$L_M = \frac{L_{Ta} - L_{Tb}}{4}$$

When the mutual inductance is known, the coefficient of coupling K can be calculated from the fact that $L_M = \sqrt{L_1 L_2}$

4.4 Three-phase Alternating Current

(1) What is three-phase alternating current?

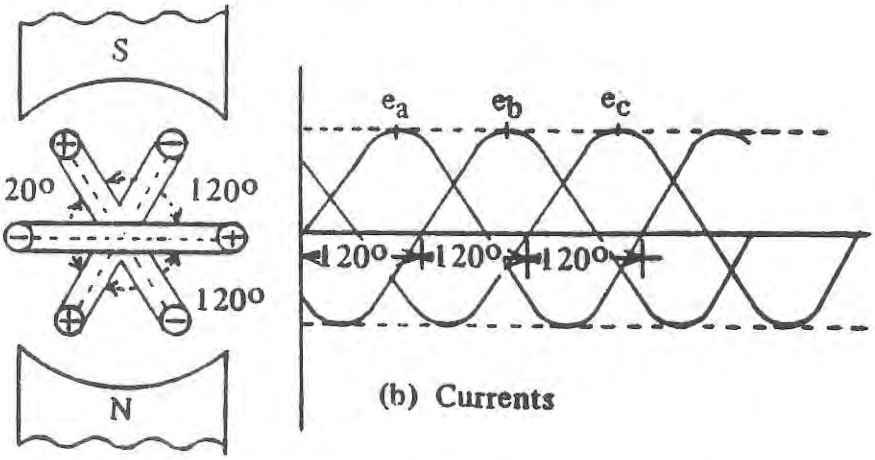
We have studied the alternating current which has an electromotive force as power source and is connected to the load by two wires. We called this single-phase alternating current. Electric power source which is used in our homes is single-phase alternating current. There is another system which has three electromotive forces as power source and can send the power by three electric wires. This system is called a three-phase alternating current.

In the three-phase alternating current, the relation between the three pairs of electromotive force is as follows:

(a) Frequency is equal.
(b) Amplitude of emf is equal.
(c) Phases of emf differ by 120°.

(2) The generation of three-phase alternating current

The generation of three-phase emrs by simple coils rotating in a bipolar magnetic field is shown in Fig. 4-13.



(b) Currents

(a) Generation of 3-phase emf

Fig. 4-13 The principles of three-phase generator

Three simple coils A,B,C fastened rigidly together 120° apart, rotate in a counterclockwise direction. The current can be conducted from each of the three coils to the external circuit by means of a pair of slip rings.

The emf induced in coil A is zero and is increasing in a positive direction. The emf induced in coil B is approaching its maximum negative value. The emf induced in coil C has passed its maximum positive value. In (b) are shown three emf waves e_a, e_b, e_c induced in the coils A,B,C. It will be noted that when the condition the emf in coil A is 0 and increasing positively; that in coil B is negative and approaching its negative maximum value; that in coil C is positive and decreasing in value. The three values of emf thus correspond to the positions of the coils. The emf e_b lags behind emf e_a by 120°, and emf e_c lags behind emf e_a by 240°, corresponding to the angles between the coil A and B and A and C.

4.5 Characteristics of Alternating Current

(1) Inductive reactance X_L

When alternating current flows in an inductance L, the amount of current is much less than the resistance alone would allow. This additional opposition to alternating current, resulting from the self-induced voltage across an inductance, is its inductive reactance X_L. The X_L is an opposition to current and, therefore, is measured in ohm. The amount of X_L equals $2\pi f_L$, where f is in cycles (hertz) and L in henrys.

(2) Capacitive reactance X_C

When a condenser charges and discharges with varying voltage applied, alternating current can flow. Although there cannot by any current through the dielectric of the condenser, its charge and discharge produces current in the circuit connected to the condenser.

This ability of a condenser to allow alternating current to flow with the voltage applied is specified by the capacitive reactance X_C. The amount of X_C is $\frac{-1}{2\pi fc}$

where f is in cycles (hertz) and C in farads. The X_C is measured in ohms.

(3) Impedance

The current flowing in the circuit as shown in Fig. 4-14 is as follows:

$$I = \frac{E}{\sqrt{R^2+(2\pi f_L - \frac{1}{2\pi f_C})^2}} = \frac{E}{\sqrt{R^2+(X_L - X_C)^2}} = \frac{E}{Z}$$

$$Z = \sqrt{R^2+ (X_L - X_C)^2}$$

Z is called impedance

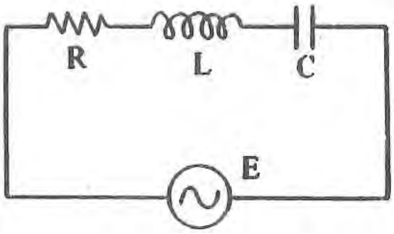


Fig. 4-14 R.L.C. circuit

(4) Resonance

Inductive reactance increases as the frequency is increased but capacitive reactance decreases with higher frequencies. Because of these opposite characteristics, for any LC Combination there must be a frequency at which X_L equals X_C. This case of equal and opposite reactance is called resonance, and A.C. circuit is then a resonant circuit.

The frequency at which the opposite reactances are equal is the resonant frequency. This frequency can be calculated as $fr = \frac{1}{2\pi\sqrt{LC}}$ where L is the inductance in henrys, C is the capacitance in farads and fr is the resonant frequency in cycles (hertz), that makes $X_L = X_C$.

(5) Power and power factor

In an A.C. circuit with reactance, the current I supplied by the source either leads or lags behind the source voltage E. Then the product EI is not the real power produced by the source. The real power, however, can always be calculated as I^2 R, where R is the total resistive component of a circuit, because current and voltage have the same phase in a resistance. To find the corresponding value of power as EI, this product must be multiplied by the cosine of the phase angle θ. Then

$$\text{Real power} = I^2R$$

or

$$\text{Real power} = EI \cos \theta_0$$

Where E and I are in rms values, to calculate the real power, in watts. Multiplying EI by the cosine of the phase angle provides the resistive component for real power equal to I^2R.

When E and I are out of phase because of reactance, the product of E × I is called apparent power. The unit is voltamperes instead of watts, since the watt is reserved for real power.

Real power can be considered as resistive power, which is dissipated as heat.

A reactance does not dissipate power but stores energy in the electric or magnetic field.

Because it indicates the resistive component, Cos θ is the power factor of the circuit, converting the EI product to real power.

For series circuits:

$$\text{Power factor} \quad = \quad \cos\theta = \frac{R}{Z}$$

For paralled circuits:

$$\text{Power factor} \quad = \quad \cos\theta = \frac{I_R}{I_T}$$

$$\text{Real power} \quad = \quad I^2R = 4 \times 100 = 400 \text{ W}$$

$$\text{Real power} \quad = \quad EI \cos\theta = 400 \times 2 \times 0.5 = 400$$

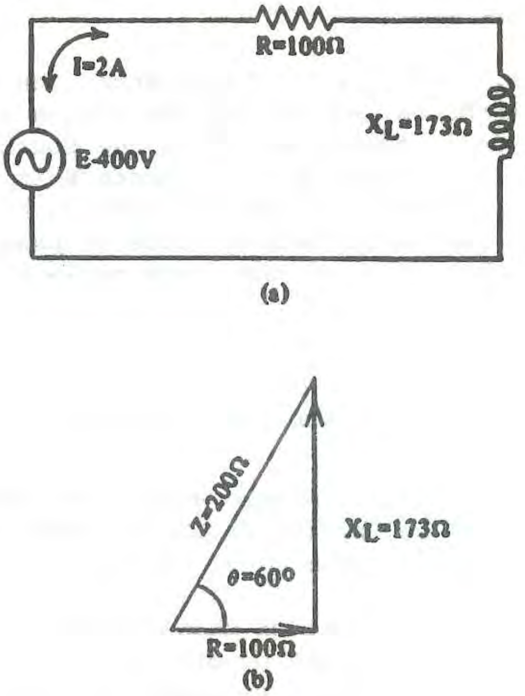


Fig. 4-15

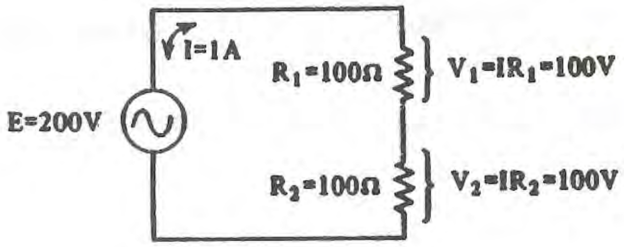
Either formula can be used for calculating the real power, whichever is more convenient.

4.6 Alternating current circuit

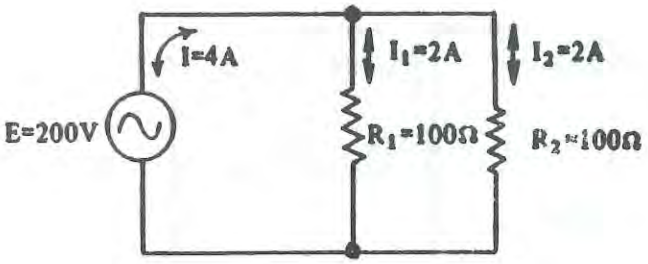
This unit shows how to analyze sine-wave A.C. circuit that has R X and X_C. How do we combine these three types of ohms of opposition, how much current flows, and what is the phase angle?

(1) A.C. circuits with resistance but no reactance

In both (a) and (b) in Fig. 4-16, all voltages and currents throughout the resistive circuit are in the same phase as the applied voltage because there is no reactance to cause a lead or lag in either current or voltage.



(a) Series resistance



(b) Parallel resistance

Fig.4-16 A.C. circuits with resistance but no reactance

(2) Circuits with inductive reactance alone

The circuits with X_L in Fig. 4-17 and 4-18 correspond to the series and parallel circuits in Fig. 1 with the ohms of X_L equal to the R values. Since applied voltage is the same, the values of current correspond because ohms of X_L are just as effective as ohms of R in limiting the current or producing a votlage drop. Although X_L is a phase quantity with a 90° phase angle, all the ohms of opposition are the same kind of reactance in this example.

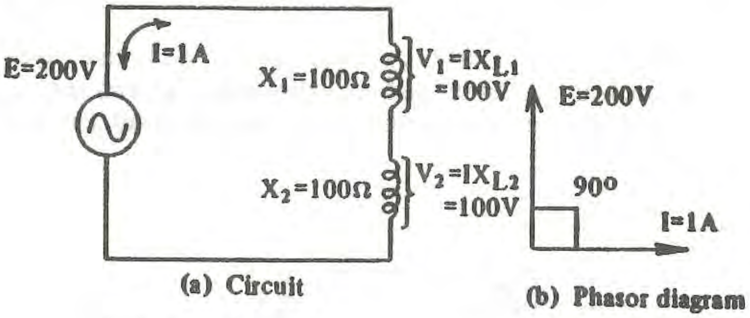


Fig. 4-17 Series circuit with X_L alone

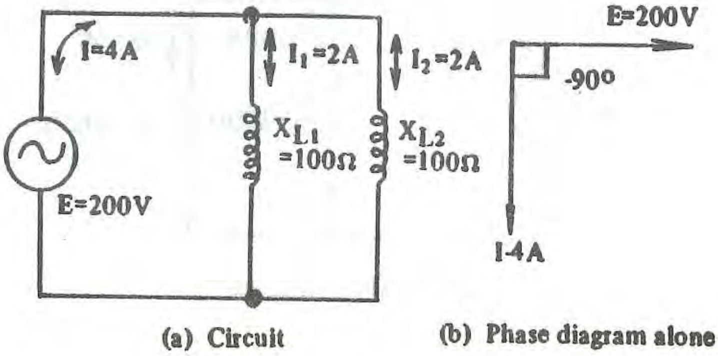
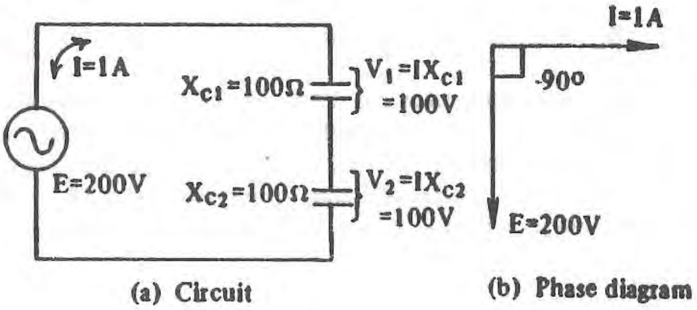


Fig.4-18 Parallel circuit with X_L

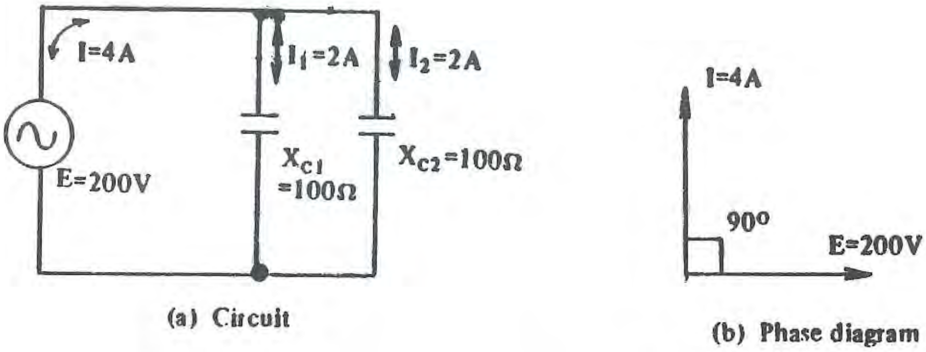
(3) Circuits with capacitive reactance alone

The circuit with X_C in place of X_L is shown in Fig. 4-19 and Fig. 4-20. Since there is no R or X_L, the series ohms of X_C can be combined directly. Also parallel I_C currents can be added.



(a) Circuit (b) Phase diagram

Fig. 4-19 Series Circuit with X_C alone



(a) Circuit (b) Phase diagram

Fig.4-20 Parallel circuit with X_C alone

(4) Opposite reactances cancel

In a circuit with both X_L and X_C, the opposite phase angles enable one to cancel the effect of the other. For X_L and X_C in series, the net reactance is the difference between the two series reactances, resulting in less reactance than either one. In parallel circuits, the I_L and I_C branch currents cancel. The net line current then is the difference between the two branch currents, resulting in less total line current than either branch current.

a) X_L and X_C in series

In the example in Fig. 4-21, the series combination of a 60 Ω X_L and a 40 Ω X_C in (a) and (b) is equivalent to the net reactance of the 20 Ω X_L shown in (c). Then with 20 Ω as the net reactance across the 240 V source, the current is 12A. This current lags behind the applied voltage E by 90° because the net reactance is inductive.

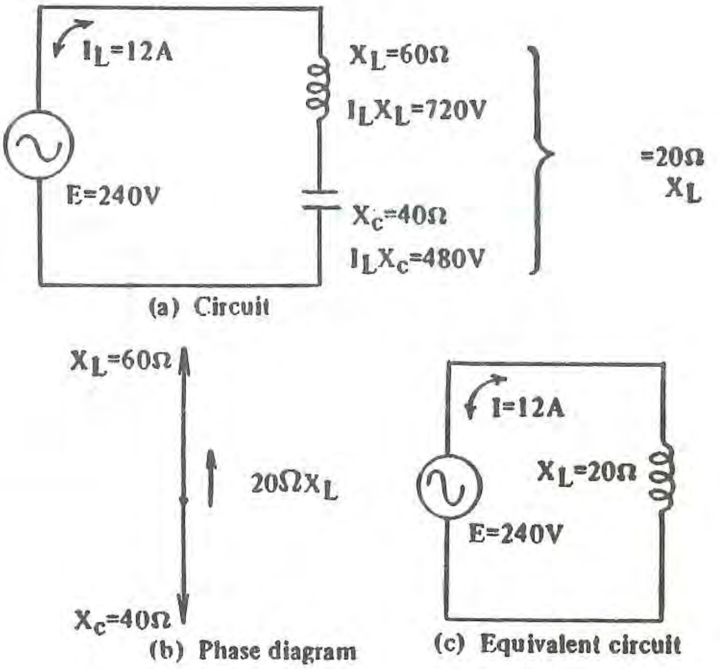
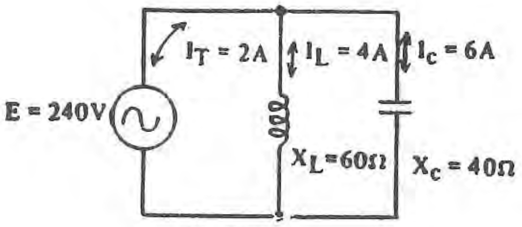


Fig.4-21 Series circuit with X_L and X_C

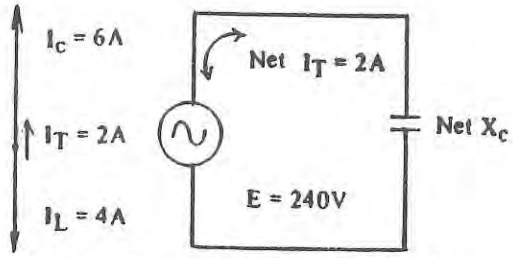
b) X_L and X_C in parallel

In Fig. 4-22, the 60 Ω X_L and 40 X_C are in parallel across the 240V source. Then the 60 Ω X_L branch current I_L is 4A and the 40 Ω X_C branch current I_C is 6A. The X_C branch has more current because it is smaller than X_L.

In terms of phase angle, I_L lags behind the parallel voltage E by 90° while I_C leads the same voltage by 90°. Therefore, the opposite reactive branch currents are 180° out of phase and cancel each other. The net line current then is the difference between 6A for I_C and 4A for I_L which equals the value of 2A. The resultant current leads E by 90° because it is capacitive current.



(a) Circuit

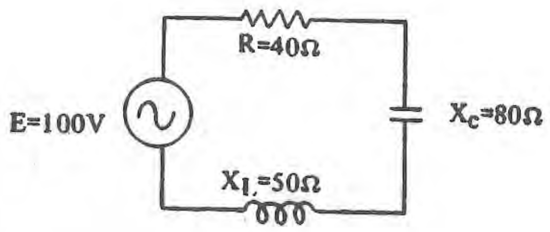


(b) Phase diagram (c) Equivalent circuit

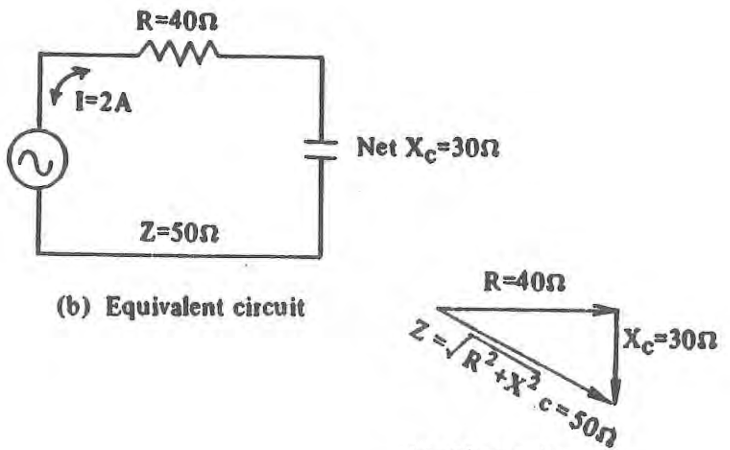
Fig. 4-22 Parallel circuit with X and X

(5) Series reactance and resistance

In this case, the resistive and reactive effects must be combined by phasors. For a series circuit, the ohms of opposition are added to find Z. First add all the series resistances for one total R. Also combine all the series reactances, adding the same kind but subtracting opposites. The results is one net reactance, indicated X, which may be either capacitive or inductive, depending on which kind of reactance is larger. Then the total R and net X can be added by phasors to find the ohm of opposition for the entire series circuit. (Fig. 4-23). (Magnitude of Z)



(a) RX_L X_c in series



(b) Equivalent circuit

(c) Phasor diagram

Fig.4-23 Impedance Z of series circuit with R, X_L and X_C

After the total R and net reactance X are found, they can be combined by the formula

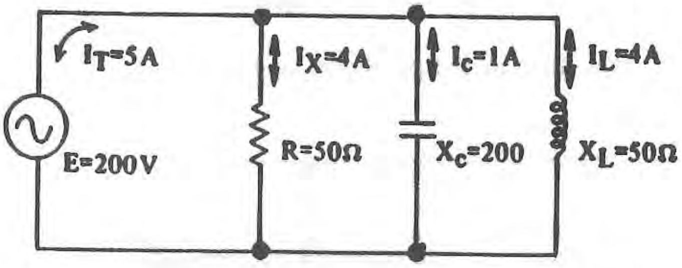
$$Z = \sqrt{R^2 + X^2}$$

The circuit's total impedance Z is the phasor sum of series resistance and reactance. Whether the net X is at + 90° for X_L or 90° for X_C does not matter in calculating the magnitude of Z.

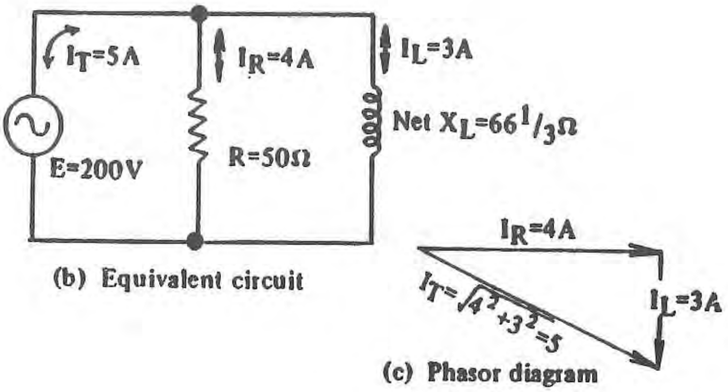
(6) Parallel reactance and resistance

With parallel circuits, the branch currents for resistance and reactance are added by phasors (Fig. 4-24). Then the total line current is found by the formula

$$I_T = \sqrt{I^2R + I^2X}$$



(a) R X_L and X_c in parallel

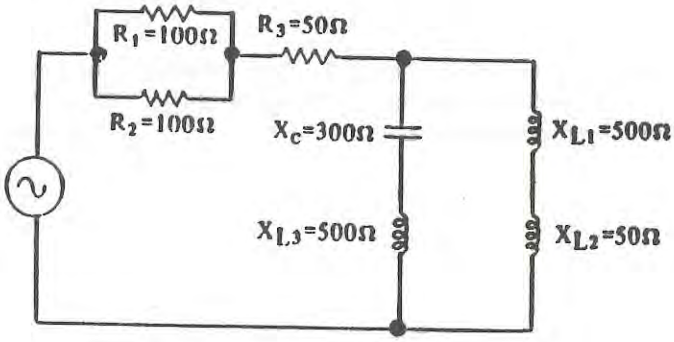


(b) Equivalent circuit

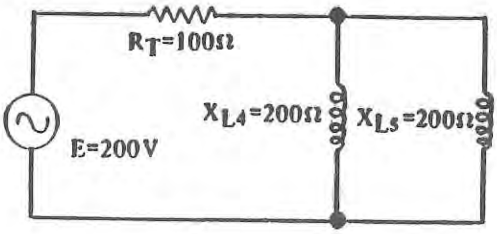
(c) Phasor diagram

Fig. 4-24 Total line current I_T of parallel circuit with R, X_L and X_c

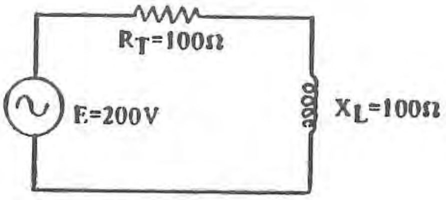
(7) Series parallel reactance and resistance



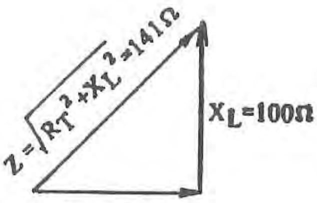
(a) Series parallel circuit with R, X_L and X_C



(b) Equivalent circuit



(c) Equivalent circuit



(d) Phasor diagram

Fig. 4-25 Series-parallel circuit with reactance and resistance

Figure 4-25 shows how a series parallel circuit can be reduced to a series circuit with just one reactance and one resistance. The phasor diagram for the equivalent circuit in (d) shows the total impedance Z of 141 Ω for a 100 Ω R in series with a 100 Ω X_L with 100 Ω impedance across the applied E of 100V, the current in the generator is 0.7A. The phase angle 0 is 45° for this circuit.

4.7 Complex numbers for A.C. circuit

Complex numbers form a numerical system that includes the phase angle of a quantity, with its magnitude. Therefore, complex numbers are useful in A.C. circuits, when the reactance of X_L or X_C makes it necessary to consider phase.

(1) Positive and negative numbers

In their more general form, numbers have both quantity and phase angle. In Fig. 4-26 positive and negative numbers are shown as corresponding to the phase angles of 0° and 180° respectively.

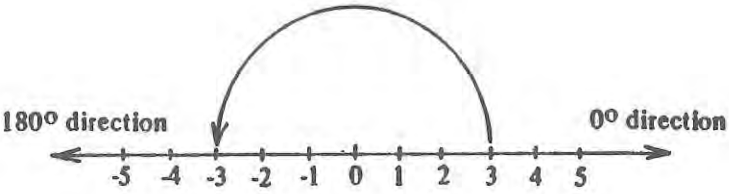


Fig. 4-26 Positive and negative numbers

For example, the numbers 1, 2 and 3 represents units along the line of zero phase angle. The + sign is often omitted, as it is assumed unless indicated otherwise.

In the opposite direction, negative numbers correspond to 180°. Or this phase angle corresponds to the factor of -1. The angle of rotation is the operator for the number.

(2) The *j* operator

The operator for a number can be any angle between 0° and 360°. Since the angle of 90° is important in A.C. circuits, the factor *j* is used to indicate 90°.

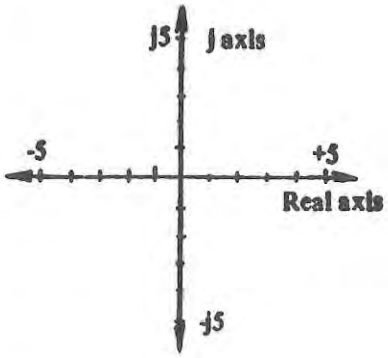


Fig. 4-27 The *j* axis at 90° from real axis

The number 5 means five units at 0°, the number -5 is at 180°, while *j* 5 indicates the 90° angle. The *j* is usually written before the numbers The reason is that the *j* sign is a 90° operator, just as the + sign is 0° operator and the - sign is a 180° operator. Any quantity at right angles to the zero axis, therefore, 90° counterclockwise, is on the + *j* axis. In mathematics, numbers on the horizontal axis are real numbers, including positive and negative values. Numbers on the *j* axis are called imaginary numbers. (Fig. 4-27).

More features of the *j* operator are shown in Fig. 4-28.

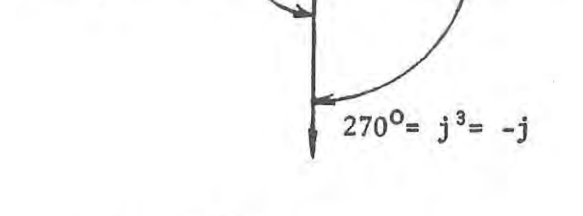


Fig. 4-28 The *j* operator

The angle of 180° corresponds to the j operation of 90° repeated twice. This angular rotation is indicated by the factor j^2 Since j^2 means 180°, which corresponds to the factor of -1, we can say that j^2 is the same as -1. Furthermore, the angle of 270° is the same as -90°, which corresponds to the operator $-j$. These characteristics of j operator are summarized as follows:

0° = 1 as a factor
90° = j as a factor
180° = j^2 as a factor = -1
270° = $j^3 = j^2 \times j$ = $-1 \times j = j$
360° = same as 0°

(3) Definition of a complex number

The combination of a real and imaginary term is a complex number. Usually, the real number is written first. As a example $4 + j^3$ is a complex number including 4 units on the real axis added to 3 units 90° out of phase on the j axis. The name complex number just means that its terms must be as phasors

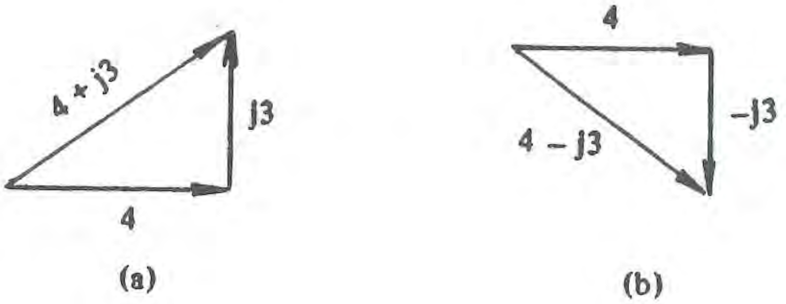


Fig. 4-29 Phasors corresponding to real terms and j terms, in rectangular coordinates

(4) How complex numbers are applied to A.C. circuit

The application are just a question of using a real term for 0 + j for 90°, and $-j$ for -90° to denote the phase angle.

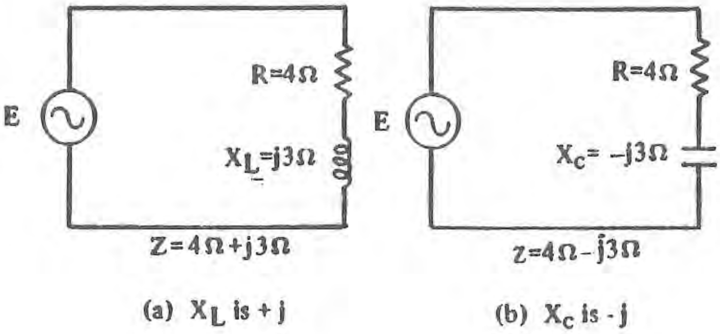


Fig. 4-30 Rectangular form of complex numbers for impedance

0° or a real number without any *j* operator is used for resistance R. For instance 4 Ω of R is stated just as 4 Ω. 90° or + *j* is used for inductive reactance X_L. For instance, a 3 Ω X_L is *j* 3 Ω -90° or -j is used for capacitive reactance X_C. For instance, a 3 Ω X_C is -j 3 Ω.

(5) Magnitude and angle of a complex number

In electrical terms a complex impedance (3 + j4) means 3 Ω of resistance and 4 Ω inductive reactance with a leading phase angle of 90°. The magnitude of the combined Z is the result out equal to $\sqrt{9+16} = \sqrt{25} = 5$.

The phase angle of the resultant is the angle whose tangent is 4/3. This angle $\theta = \tan^{-1} 4/3$.

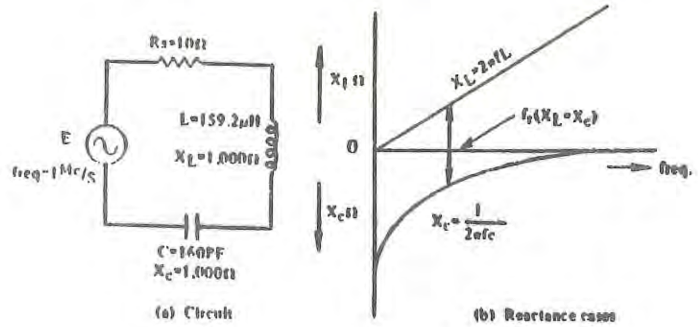
4.8 Resonance

The most common application of resonance in RF circuit is called tuning. In this use, the LC circuit provides maximum voltage output at the resonant frequency, compared with the amount of output at any other frequency, either below or above resonance.

All examples of tuning in radio and television are application of resonance.

(1) Series resonance

In a series A.C. circuit, inductive reactance leads by 90°, compared with the 0 reference angle of the resistance, while capacitive reactance lags by 90°. Therefore, X_L. amd X_C are 180° out of phase, and the opposite reactance cancel each other completely when they are equal.



(a) Circuit

(b) Reactance cases

Fig. 4-31 Series resonance

Figure 4-31 shows X_L and X_C equal, resulting in a net reactance of 0. The only opposition to current is the coil resistance R_g. With 0 reactance and just low value of series resistance, the generator voltage produces the greatest amount of current in the series LC circuit at the resonant frequency. The series resistance should be as small as possible for a sharp increase in current at resonance.

(2) Parallel resonance

Figure 4-32 shows L and C in parallel.

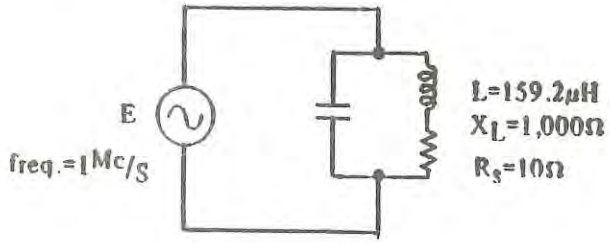


Fig. 4-32 Parallel resonance

When X_L equals X_C, the reactive branch currents are equal and opposite at resonance. Then they cancel each other to produce minimum current in the main line. Since line current is minimum, the impedence is maximum. These relation are based on R_S being very small, compared with X_L at resonance. In this case, the branch currents are practically equal when X_L and X_C are equal.

(3) Summary

a) Main characteristics for a series-resonant circuit:

- i) The current I is maximum at the resonant frequency.
- ii) I is in phase with the generator voltage or the phase angle of the circuit is 0.
- iii) The voltage is maximum across either L or C alone.
- iv) The impedance is minimum at f_r equal only to the low R_S.

b) Main characteristics for a parallel resonant circuit:

- i) The line current I_T is minimum at the resonant frequency.
- ii) I_T is in phase with the generator voltage E or the phase angle of the circuit is 0.
- iii) The impedance Z_T equal to $\frac{E}{I_T}$ is maximum at f_r because of the minimum I_T.

(4) Q magnitication factor of resonant circuit

The quantity of the resonant circuit, in sharpness of resonance, is indicated by the factor Q. In general, the higher the ratio of the reactance at resonance to the series resistance, the higher is the Q and the sharper the resonance effect.

4.1 Q of series circuit

In a series resonant circuit we can calculate Q from the following formula:

$$Q = \frac{X_L}{R_S}$$

where Q is the figure of merit,

X_L is the inductive reactance at the resonant frequency

R_S is the resistance in series with X_L

Q is a numerical factor without any units, because it is a ratio of reactance to resistance and the ohms cancel.

The Q of the resonant circuit can be considered a magnitication factor that determines how much the voltage across L or C increases by the resonant rise of current in a series circuit. Specially, the voltage out at series resonance is Q times the generator voltage.

$$V_L = V_C = Q \times E \text{ (generator)}$$

The fundamental nature of Q for a series resonant circuit is seen from the fact that the Q can be determined experimentally by measuring the Q rise in voltage across either L or C and comparing this voltage with the generator voltage E.

As a formula

$$Q = \frac{E \text{ out}}{E \text{ in}}$$

Where E out is the A.C. voltage measured across the coil or condenser and E in is the generator voltage.

4.2 Q of parallel circuit

In a parallel resonant circuit (Fig. 4-33), where R_S is very small compared with X_L, the Q also equals $\frac{X_L}{R_S}$.

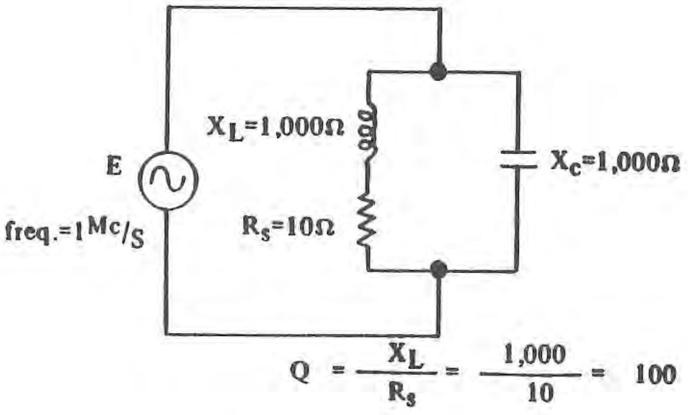


Fig. 4-33 Q of a parallel resonant circuit

For parallel resonance, the Q magnification factor determines by how much the impedance across the parallel LC circuit is increased because of the minimum line current. Specially, the impedance across the parallel resonant circuit is Q times the inductive reactance at the resonant frequency.

$$Z_T = Q \times X_L$$

5. Application of Electricity

5.1 Battery

(1) Introduction

An electric battery is a combination of two or more electro-chemical cells. A cell is either not rechargeable (primary cell) or is rechargeable (secondary cell). Cells and batteries store energy in chemical form in such a way that they can produce electric energy.

Whenever a direct current or voltage is required, a cell or battery can be used as the power supply.

(2) Primary cells

a) The principle

Almost any two dissimilar metals or conductors immersed in a diluted acid or alkaline solution will produce a difference of a potential between them. Figure 5-1 shows a primary cell in which a copper plate and a zinc plate are placed in dilute of sulfric acid solution.

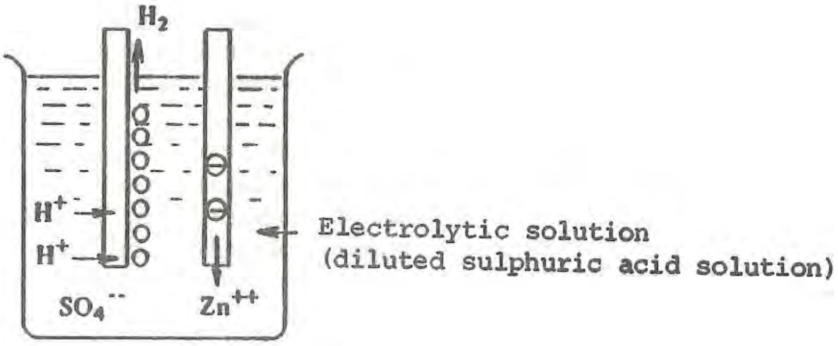


Fig.5-1 Primary cell

When the zinc plate is placed in the acid solution, the zince startes to dissolve. That is, zinc atoms startes to leave the plate and enter the solution. As each zinc atom leaves the plate, however, it leaves behind two electrons. Thus, the zinc atom becomes a positive Zinc ion (Zn^{++}). And the zinc plate, because of the electrons left behind, become negatively charged.

$$Zn \rightarrow Zn^{++} + 2e^-$$

The positive Zinc ions repel the positive hydrogen ions in the solution toward the copper plate. As each positive hydrogen ion reaches the copper plate, it seizes an electron from the plate and becomes in this way a hydrogen atom, bubbles off into the air. The copper plate, having lost electrons, becomes positively charged.

Thus, a difference of potential electromotive force: e.m.f is created between the zinc and the copper plate.

$$2H^+ + 2e^- \rightarrow H_2\uparrow$$

An interesting thing about the cell (called a voltaic cell in honor of its inventor), is the fact that its electromotive force does not depend upon its size. Its voltage depends, mainly, upon the chemical action and this in turn depends upon the materials of the plates (electrodes) and upon the substance used for the electrolyte. In the cell that was explained, described above the e.m.f. is about 1 V.

There are a number of disadvantages to the voltaic cell. When the external circuit is completed, some of these hydrogen bubbles that occur around the copper plate tend to cling to the positive plate, forming a sheath completely surrounding it. After a short time, the action of the cell ceases, owing to the insulating action of the hydrogen bubbles which prevent any new hydrogen ions from reaching the positive plate. We call this effect polarization.

Lec Lanche, a French scientist, using a plate, overcame the effect of polarization by placing the positive carbon plate in a porous cup containing manganese dioxide (MnO_2). The hydrogen atoms combined chemically with the manganese dioxide and thus could not form the insulating sheath around the plate. The manganese dioxide is called a depolarizer.

b) Dry cell

Another disadvantage of the voltaic cell is that the electrolyte is a liquid. Because of the possibility of spilling the electrolyte, the dry cell was developed. In this cell the electrolyte is a paste, instead of a liquid, and thus cannot be spilled readily.

i) Carbon-zinc cell

The cheapest and most easily available, primary cells in use today are of the carbon-zinc type shown in Fig. 5-2. A zinc can is used as the negative plate and as a container for the cell. A carbon rod in the center of the cell is the positive plate. The space between the zinc shell and carbon rod is filled with a paste containing sal ammoniac ($NH_4\ C\ell$) which is used as an electrolyte. In addition to the electrolyte, this paste contains manganese dioxide ($Mn\ O_2$), which is used as a depolarizer, and some material, such as sawdust, which is used as a filler. The top is sealed with a cap made of metal, pitch or sealing wax to prevent the paste from coming out. Immediately below this cap is an air space in which the gases formed by the cell may collect. The entire cell is enclosed in a cardboard case.

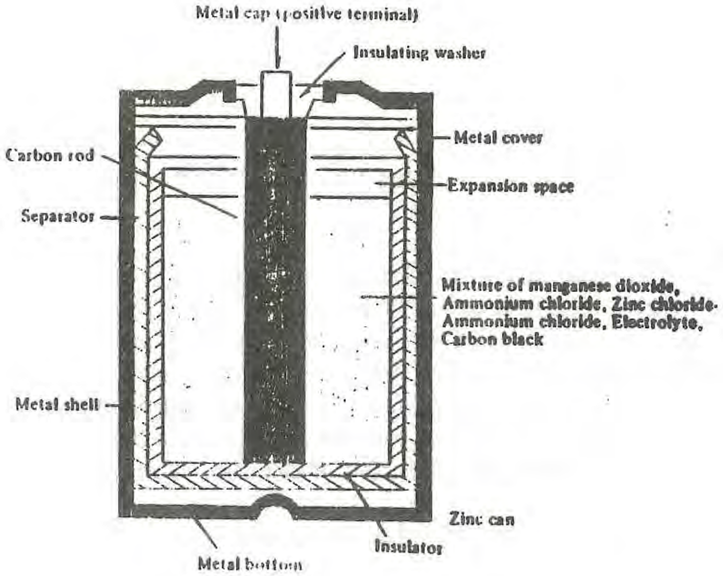


Fig.5-2 The carbon-zinc dry cell

ii) The alkaline-manganese cell

Another type of primary cell is the alkaline-manganese cell.

The positive element is manganese dioxide, which also acts as a depolarizer. The negative element is zinc. The electrolyte is a paste of potassium hydroxide. The whole is sealed in a steel can for protection. Its normal voltage is approximately 1.5V. The alkaline-manganese cell is better suited for heavy current drain and for long continuous action.

The alkaline-manganese cell is used to supply electric power to a great many devices such as toys, portable radio and television sets, and photographic equipment.

iii) Mercury cell

The third type of primary cell is the mercury cell. The positive element and depolarizer is mercuric oxide mixed with a small amount of graphite. The negative element is an amalgam of zinc and mercury. The electrolyte is a paste of potassium hydroxide mixed with zinc oxide. Its action, too, is somewhat similar to that of the carbon-zinc cell. It has the longest life of the three cells, and its chief advantage is that it's voltage remains fairly constant for the duration in use. It's normal voltage is approximately 1.3V and is somewhat lower than others. But it is the most expensive of the three.

Its constant voltage makes the cell suitable for a large variety of electronic instruments and other devices.

(3) Secondary cell

Secondary cell is also called storage cell. The electrical energy fed into the storage cell is changed into chemical energy which is stored in the cell.

A storage cell of this kind has an e.m.f. of about 2 volts. The voltage does not depend upon the size of the plates. But the amount of electrical energy which can be stored depends upon the area of the plates. In practice, a cell may consist of a number of plates which are sandwitched together with insulators (called separators) of wood or other material separating the positive and negative plates. All the negative plates are connected together and the same for the positive plates.

a) The lead-acid storage cell

The secondary cell in most general use has a lead dioxide(sometimes called lead peroxide) positive plate, a pure sponge lead negative plate and an electrolyte of diluted sulfuric acid. A group of these cells in series forms a lead-acid battery.

The chemical action that takes place internally can be represented by the following chemical formula.

(Positive plate side)

$$SO_4^{--} + 2H_2O \xrightleftharpoons[\text{discharging}]{\text{charging}} H_2SO_4 + 2O + 2H + 2e^-$$

$$P_bSO_4 + 2O + 2H \xrightleftharpoons[\text{discharging}]{\text{charging}} P_bO_2 + H_2SO_4$$

Accordingly:

$$P_bSO_4 + 2H_2O + SO_4^{--} \xrightleftharpoons[\text{discharging}]{\text{charging}} P_bO_2 + 2H_2SO_4 + 2e^-$$

(Negative plate side)

$$2H^+ + 2e^- \xrightleftharpoons[\text{discharging}]{\text{charging}} 2H$$

$$2P_bSo_4 + 2H \xrightleftharpoons[\text{discharging}]{\text{charging}} P_b + H_2SO_4$$

Accordingly:

$$P_bSO_4 + 2H^+ + 2c^- \quad \begin{matrix}\text{charging}\\ \text{discharging}\end{matrix} \quad P_b + H_2SO_4$$

b) Alkali storage cell

The American inventor, Thomas A. Edison, invented another type of storage cell. This is called the Edison storage cell. The Edison cell produces an e.m.f. of approximately 1.2V when fully charged and falls to 0.9V when discharged.

Waldemar Junger, a Swede, developed another type of storage cell - the nickel-cadmium storage cell.

The average operating voltage for a fully charged nickel-cadmium cell is approximately 1.2 volts.

The nickel-cadmium storage battery combines the best features of both the Edison and the lead-acid types. It is strong and has a very long active life.

(4) Discharging the battery

The voltage of a charged cell (lead-acid storage cell) is usually 2.1 volts, but it becomes 2.0 volts as soon as it begins discharging. After that, the voltage drops slowly to 1.8 volts. After that, voltage will decrease quickly, as shown in Fig. 5-3.

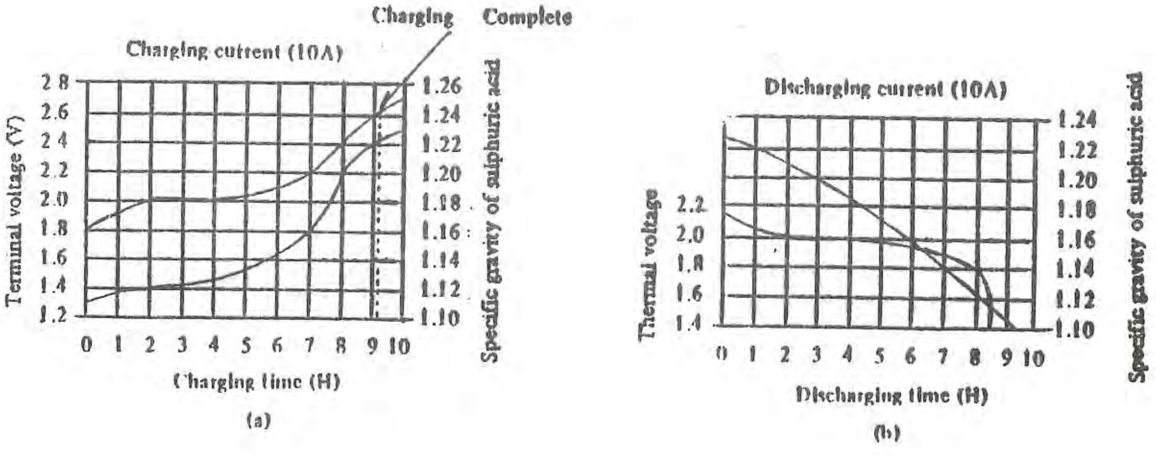


Fig. 5-3 The characteristics of charging and discharging batteries

(5) Capacity of a battery

The capacity of a battery is the amount of current which can flow until the stop point of discharge. This capacity is given in ampere-hours.

If, for example, a battery can deliver 20 amperes of current for 5 hours, it has an ampere-hour capacity of 5 × 20 or 100 ampere-hours.

(6) Charging the battery

The storage battery is a D.C. device. When it runs down and must be recharged, the recharging current must come from a D.C. source, such as D.C. generator or charger. If only A.C. is available, it must be rectified to a direct current before being applied to the battery.

During the charging period the positive terminal of the source must be connected the positive post of the battery and the negative terminal of the source to the negative post.

When the battery is charged, the specific gravity of electrolyte and voltage will rise as the following table:

(specific gravity)	(voltage)	(condition of charge)
1.130	1.75	Discharged
1.160	1.80	Very little useful capacity
1.190	1.85	1/4 charge
1.220	2.00	1/2 charge
1.250	2.10	3/4 charge
1.280	2.20	Full charge

When the specific gravity and voltage reach maximum and will not go higher, the battery is fully charged.

(7) Hydrometer

Specific gravity is measured with a hydrometer. Hydrometers in general use are of the syringe type, (Fig. 5-4) with a compressible rubber bulb at the top, a glass barrel, and a rubber hose at the bottom of the barrel. A thin calibrated hollow glass float with a weighted bottom is inside the barrel.

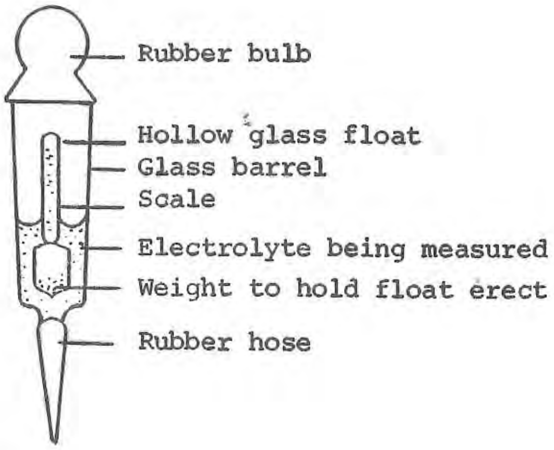
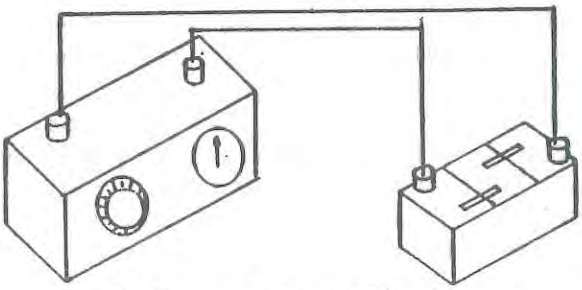
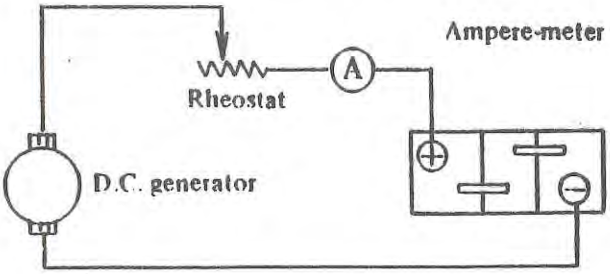


Fig.5-4 Hydrometer

(8) How a battery charger is connected to a battery



(a) Charging connection by charger



(b) Charging connection by D.C. generator

Fig.5-5 Charging a battery

There are a number of methods for charging a storage battery (Fig. 5-5). A D.C. generator is connected in series with a rheostat, ampere-meter and the battery to be charged. The generator and the battery are in opposition. Thus, if current is to be fed to the battery, the voltage of the generator must be high enough to overcome the opposing e.m.f. of the battery, its internal resistance, and the resistance of the rheostat and amperemeter.

(9) Maintaining the lead-acid battery

There are several important points regarding the maintenance of the lead acid battery. If the maintenance of the storage battery is insufficient, its life will be shortened.

a) Do not overcharge a battery. This will weaken the electrolyte and may cause damage to the battery plates.

b) Never allow a battery to remain in a discharged condition for a long time. If necessary to store for a year or more, batteries should be fully charged, the electrolyte removed, the cell flushed with clean water, and then filled with distilled water.

c) The specific gravity of the electrolyte solution in a lead acid battery which is fully charged (in the end of charging battery) ranges commonly from 1.22 - 1.23 and the one of the battery which is discharged (in the beginning of charging battery) is usually 1.12 - 1.14. Then, pay attention to the specific gravity of the electrolyte solution of the battery, which is in charging operation.

d) Maintain proper electrolyte level, and use only distilled water to replace lost water. Use only chemically pure sulfuric acid (diluted) if it should become necessary to add new electrolyte.

e) Keep flames and sparks away from a charging or recently charged battery. The mixture of hydrogen and oxygen gases given off during charge is highly explosive.

f) Be careful when using a hydrometer. Avoid spilling drops of acid electrolyte.

g) The connection at the terminal of a battery should be kept tight at all times.

h) Test-operate the battery at least once a month if possible.

i) Never allow electrolyte to heat. Keep it less than 40°C.

j) Keep the tops of the cells clean and free from moisture to prevent leakage across the surface of the cell top and to prevent dust and dirt from falling into the electrolyte.

k) Provide adequate ventilation while charging, since the gas given off is highly explosive and contains some acid vapor.

l) When removing caps, do not turn them over or place them on an unclean surface. This will prevent the transportation of foreign materials into the cells when the caps are replaced.

(10) Battery connection

a) Series connection

As illustrated in Fig. 5-6(a), if three batteries are connected in series, that is, with the positive terminal of one to the negative terminal of the other, the voltage of each battery is added to that of others.

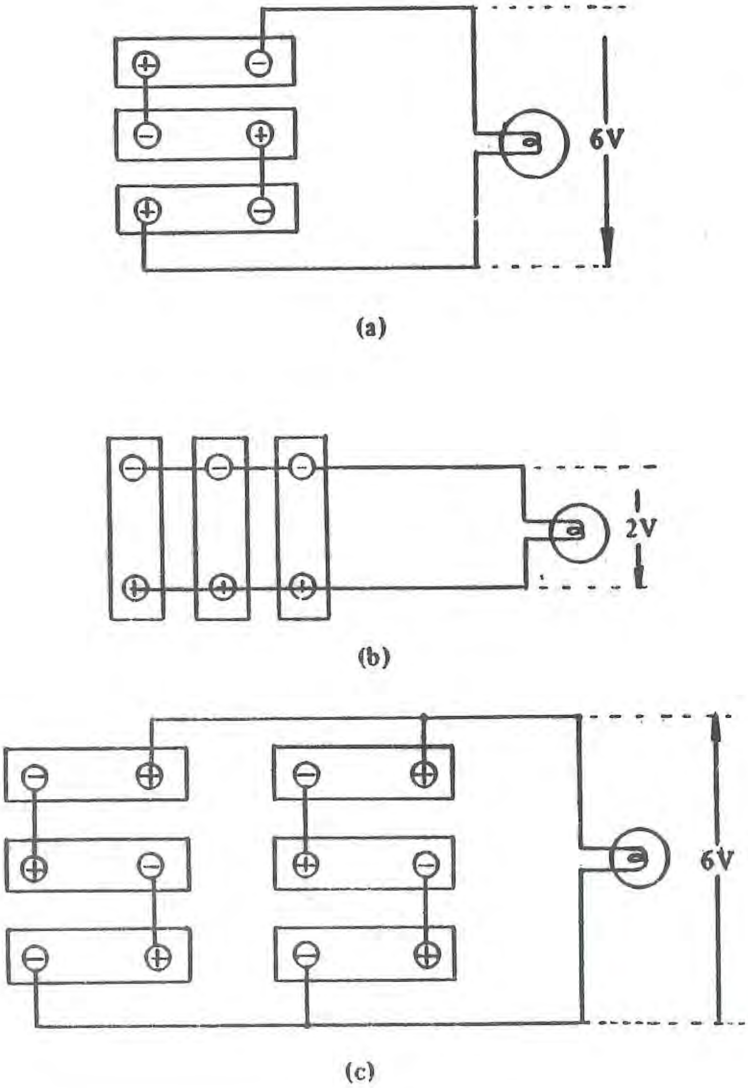
Series connection is to obtain a voltage higher than that produced by a single cell.

b) Parallel connection

As shown in Fig. 5-6(b), cells are connected in parallel to get a value of current greater than that which can be delivered by a single cell.

c) Compound connection

If we want to obtain both higher voltage and greater current, the batteries are connected in mixed connection series and in parallel, as shown in Fig. 5-6(c).



(a)

(b)

(c)

Fig. 5-6

5.2 Transformer

(1) Introduction

The transformer is a very important piece of equipment in our electrical systems. It is the device which has made possible the present-day large-scale developments in the efficient generation, transmission, and utilization of electrical power. It makes possible the efficient conversion of electrical energy at one voltage to electrical energy at any other voltage which is most suitable for that particular part of the system. Ordinarily, a transformer is used for changing the value of the voltage or current of the system, but sometimes it is used merely to insulate two circuits from each other while still permitting an interchange of energy between them or to match the impedance of a load to its source so as to obtain maximum power transfer.

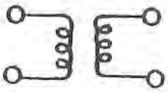
In the most general sense a transformer is any device which converts through electromagnetic means electrical energy from one circuit into electrical energy in another circuit. This electrical-energy conversion takes place whenever two A.C. electric circuits are in proximity to each other through the phenomenon of mutual inductance. Any change in the current of one of the circuits will tend to induce a voltage in the other circuits. The amount of energy converted, however, will be small unless the two circuits are closely coupled so that a large portion of the flux produced by current in one circuit will link with the other circuit. Therefore, the term transformer is used only for a construction that consists of two or more coils which are fairly closely coupled.

(2) Basic principles

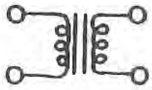
We already know that when an electric current flows through a coil of wire, it sets up a magnetic field around this coil. When this magnetic field cuts across a conductor, it sets up an electrical pressure, or voltage, which in turn sets a current flowing, if there is path through which it can flow. In the transformer, we have two stationary coils. We call one the primary, and the other secondary. We pass a fluctuating direct current or an alternating current through the primary coil. This current causes the magnetic field around the primary to fluctuate in step with it. This fluctuating magnetic field, cutting across the turns of the secondary coil, sets up an alternating electrical pressure that, in turn, causes an alternating current to flow in the secondary. This alternating current corresponds in form to the fluctuation direct current or the alternating current in the primary.

The windings are wound either one over the other or side by side on a common core. For low-frequency current (up to about 15,000 c/s) a core built up of iron strips is generally used. A magnetic field prefers to pass through iron rather than through air. Thus practically all the magnetic field is concentrated in the iron core. Since this core passes through both primary and secondary coils, very little of the magnetic field is lost to the outside and a very efficient transformer is produced. For radio frequencies (that is, frequencies above about 15,000 c/s), iron-core transformers are not employed because of the high loss of energy in the iron core at these frequencies. Accordingly, air-core transformers are usually employed for radio frequencies. Since the magnetic field is not concentrated in the core, such transformers are less efficient than the iron-core type.

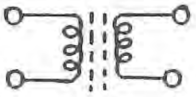
Some receivers use transformers with a special powdered-iron core for high-frequency currents. Such transformers are more efficient than the air-core type, without introducing high losses entailed by the use of the regular iron core. In electrical circuit, the symbol for the air-core transformer is



The symbol for the iron-core transformer is



and the symbol for the powdered iron-core transformer is



(3) Types of transformer

Transformers range in size from large power transformer for converting the energy of whole power stations to voltages suitable for transmission over large distance, to every small items, such as intervalve transformers used in portable radio sets, which are scarcely larger than postage stamps.

They may be classified according to frequency into groups:

a) Power frequency	50 c/s - 60 c/s
b) Audio frequency	50 c/s - 20 Kc/s
c) Radio frequency	20 Kc/s and above
d) Pulse transformer	

Again, according to the mode of operation, we have a classification:

1) Voltage transformers, in which the voltage applied to one winding is approximately constant under normal operating conditions and the transformer maintains a nearly constant voltage-ratio irrespective of load changes.

2) Current transformers, in which one winding is in series with a current source and the purpose of the transformer is to maintain a nearly constant ratio of the currents in its windings.

Alternatively, the classification can be made according to the purpose:

a) Power transformers
b) Distribution transformers
c) Testing transformers
d) Instrument transformers
    i) Voltage transformer
    ii) Current transformer.

(4) Transformer construction

Two general types of construction are used by manufacturers. They are known as

a) Core-type construction, and
b) Shell-type construction.

In the core type the magnetic core is built of laminations to form a rectangular frame, and the windings are arranged concentrically with each other on cylinders around the sides known as the legs or limbs of the core. With the shell type, two windings are flat circular or rectangular coils interleaved with each other.

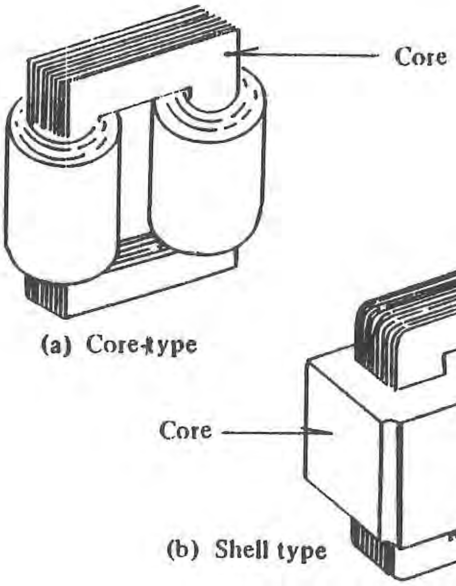


Fig. 5-7 Types of transformer

The core is usually divided and built around the coils on either side. Shell and core type construction are compared in a simple sketch in Fig. 5-7. In the core type the impression in created that the coils have been wound around the core, whereas with the shell type that the core has been built around the coils. Most of the larger transformers are of the core type.

(5) E.m.f. equation of a transformer

Suppose the maximum value of the flux to be ϕm webers and the frequency to be f c/s. From Fig. 5-8 it is seen that the flux has to change from + ϕm to - ϕm in half a cycle, namely in $\frac{\frac{1}{2}f}{2f}$ second.

Average rate of change of flux

$$= 2\,\phi m / \frac{\frac{1}{2}f}{2f} = 4f\phi m \text{ Webers/second.}$$

and average e.m.f. induced/turn = $4f\phi m$ volts

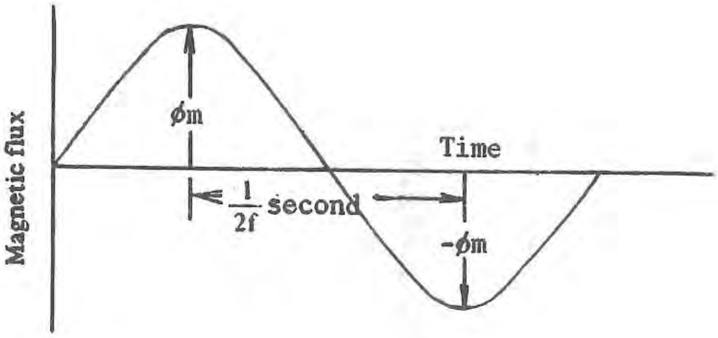


Fig. 5-8 Wave form of flux variation

But for a sinusoidal wave the r.m.s or effective value is 1.11 times the average value,

$\therefore$ r.m.s Value of e.m.f induce/turn

$= 1.11 \times 4f\phi m$

Hence, r.m.s. value of e.m.f. induced in primary E_1 = 4.44 $N_1 f\phi m$ volts and r.m.s. value of e.m.f. induced in secondary E_2 = 4.44 N_2 $f\phi m$ volts.

(6) Special transformer

a) Autotransformer

In principle and in general construction, the autotransformer does not differ from the conventional two-winding transformer thus far considered, but it does differ from it in the way in which the primary and secondary are interrelated. In the conventional transformer, the primary and secondary are completely insulated from each other but are magnetically linked by a common core. In the autotransformer, the two windings, primary and secondary, are both electrically and magnetically interconnected; in fact, a part of the single continuous winding is common to both primary and secondary (Fig. 5-9).

The autotransformer may be constructed in either of two ways. In one arrangement, there is a single continuous winding with taps brought out at convenient points determined by the desired secondary voltages; in the other arrangement, there are two or more distinct coils which are electrically connected to form a continuous winding.

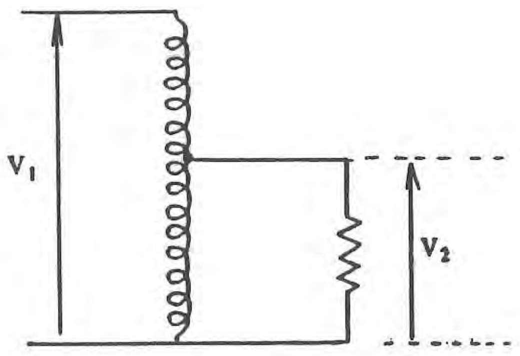


Fig. 5-9 Autotransformer

(b) Three-phase transformation

The three-phase transformation may be obtained by the use of three identical single-phase transformers. Both the three primeries and the three secondaries may be connected in either Y or Δ. The four possible correct connections are shown in Fig. 5-10. The ratio of transformation for the line voltages will be the same as the ratio of transformation of the transformers only when the same type of interconnection is used on both primary and secondary sides. The relative polarities of the transformers must be known so that the proper interconnections may be made for either the Y or Δ connections.

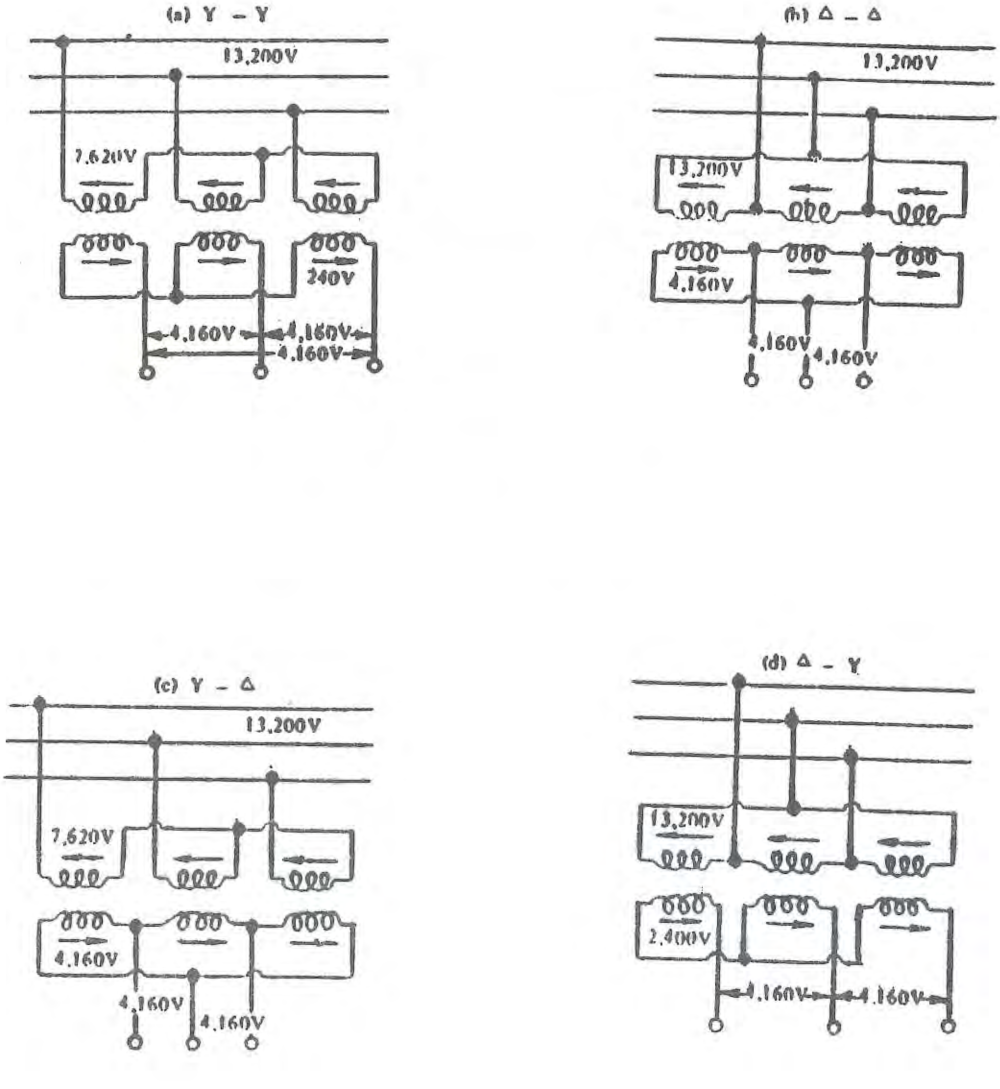


Fig.5-10 Three-phase connection of single-phase transformers

5.3 Measurement of Electricity

(1) Introduction

It is extremely important to have instruments by which we may measure directly the quantity of certain factors, such as current, voltage and resistance.

Such instruments are called meters. Their common purpose is to supply information concerning some variable quantities.

(2) The basic D.C. meter

a) The principle of the basic meter

A meter is really a small electric moter which has a moving pointer. The meter works on the principle of magnetic attraction and repulsion. According to this principle, the like poles repel each other and the unlike poles attract each other.

In Fig. 5-11(a), if the bar magnet is allowed to turn freely, it turns until its north-pole is as colse as possible to the south pole of the horseshoe magnet and its south pole is as close as possible to the north pole of the horseshoe magnet.

If the bar magnet is replaced by the coil of wire as shown in (b), it makes a meter. Whenever an electric current flows through this coil of wire as shown in(c), it acts as a magnet. The streng of this wire coil magnet depends on the size, number of turns in the coil and the amount of electric current flowing through the coil. The greater the current flow in the coil, the stronger the magnetic force of the coil magnet.

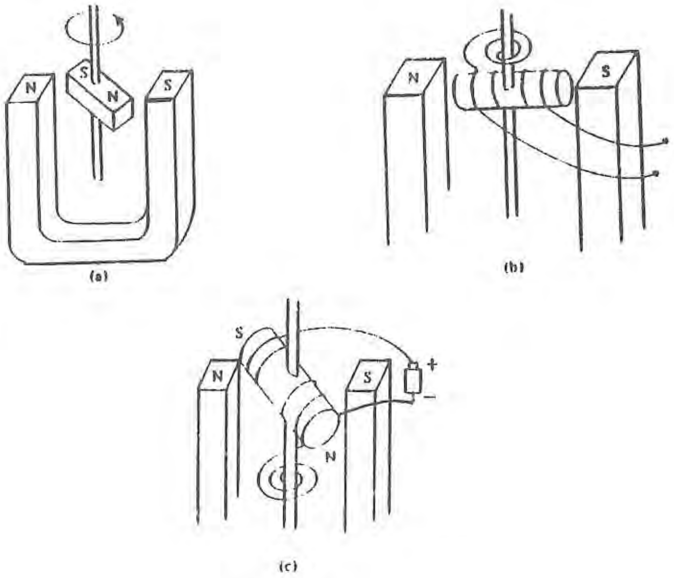


Fig. 5-11

If there is no current flow in the coil, it will have no magnetic strength and the coil will turn to a position where there will be no tension on the spring. If the electric current flows through the coil, the coil becomes a magnet and then the coil turns until the magnetic turning force which is balanced by the force due to tension in the spring.

b) Measurement of current

In the measurement of current, there are two important facts to remember.

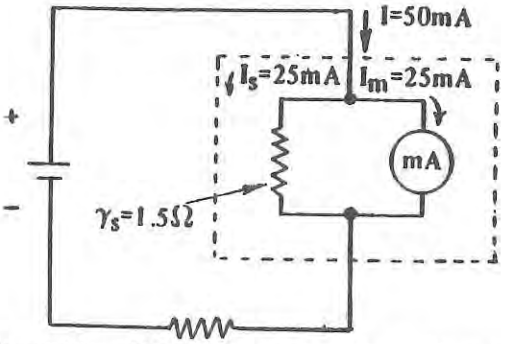
1) The current meter must be in series in the circuit where the current is to measured. The amount of deflection depends on the current passing through the meter. In a series circuit, the current is the same through all series components. Therefore, the current to be measured must be made to flow through the meter as a series component in the circuit.

2) A D.C. meter must be connected in the correct polarity for the meter to read up scale. Reversed polarity makes the meter read down scale, forcing the pointer against the stop at the left, which can break down the pointer.

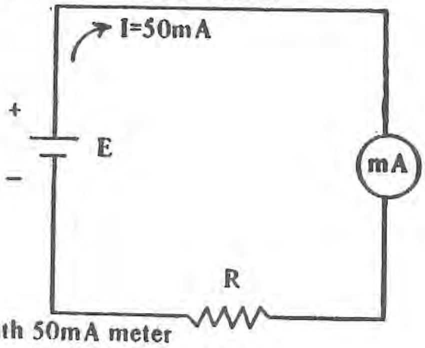
In general, a current meter should have low resistance, compared with the R of the circuit, so that the current is the same with or without the meter.

c) Meter shunts

A meter shunt is a precision resistor connected a cross the meter for the purpose of shunting, or by passing a specific fraction of the circuits current around the meter. The combination, then,provides a current meter with an extended range. The shunts are usually inside the meter case.



(a) Schematic diagram of a meter shunt



(b) Circuit with 50mA meter

Fig.5-12 Effect of shunt

In general, the shunt resistance for any range can be calculated with Ohm's law from the formula

$$\gamma_s = \frac{Vm}{I_s} \quad \text{............} \quad (1)$$

γ_s is the resistance and I_s is the current V_m is equal to $I_m \times \gamma_m$

The complete procedure for using the formula (1) is as follows.

(i) Find V_m. Calculate this for full-scale deflection as $I_m \times \gamma_m$

(ii) Find I_s. $I_s = I_b - I_m$.

(iii) Divide V_m by I_s to find R_s.

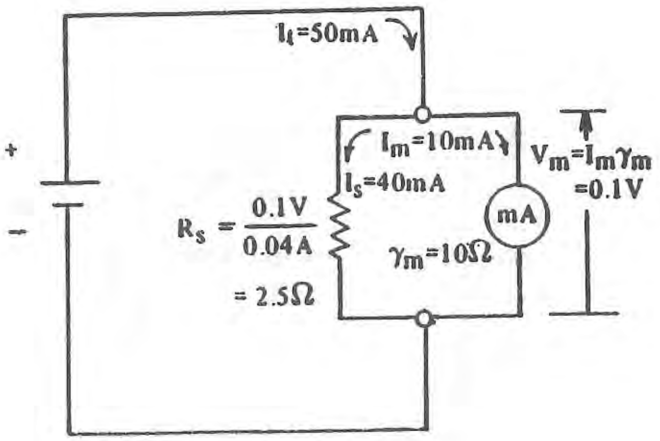


Fig.5-13 Calculating the resistance of a meter shunt

This means that if we want to extend the reading scale of a meter to η times, the shunt resistance can be calculated from the following formula.

$$\eta = 1 + \frac{\gamma_a}{\gamma_s} \quad \ldots\ldots. \ (2)$$

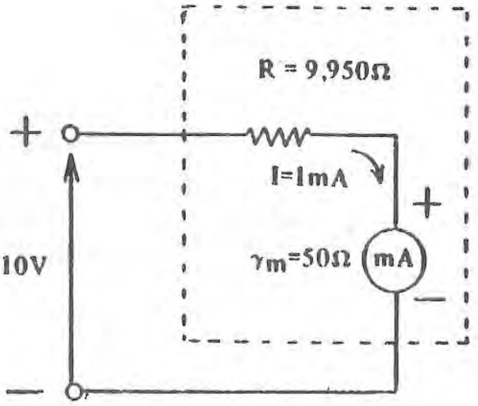
where η : magnification factor

γ_a : internal resistance of a meter

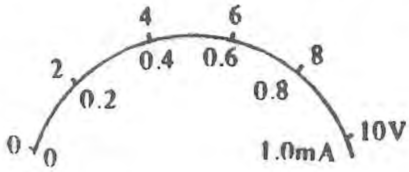
γ_s : shunt resistance

d) Measurement of voltage

Although a meter responds only to current in the moving coil, it is commonly used for measuring voltage by the addition of a high resistance in series with the meter. The series resistance must be much higher than the coil resistance in order to limit the current through the coil. The combination of the meter with its added series resistance then forms a volt meter. The series resistor, called a multiplier, is usually connected inside the voltmeter case (Fig. 5-14)



(a) Diagram showing effect of multiplier



(b) 10V scale and the corresponding 1mA scale

Fig.5-14 Effect of multiplier

Since a voltmeter has high resistance, it must be connected in parallel to measure the voltage across two points in a circuit. The circuit is not opened to connect the voltmeter in parallel. The correct polarity must be observed in using a D.C. voltmeter. Connect the positive voltmeter lead to the positive side of the potential difference being measured, and the negative lead to the negative side.

e) Multiplier resistance

The resistance of a multiplier can be calculated from the following formula.

$$R = \frac{\text{full scale E}}{\text{full scale I}} - \gamma_m$$

where R: multiplier resistance

γ_m: internal resistance of a meter

We can also extend the full scale of a voltmeter by using a high resistor in series with the voltmeter.

The high resistance can be calculated from the following formula

$$\frac{R_S + R_V}{R_V} = \eta \quad .... \quad (4)$$

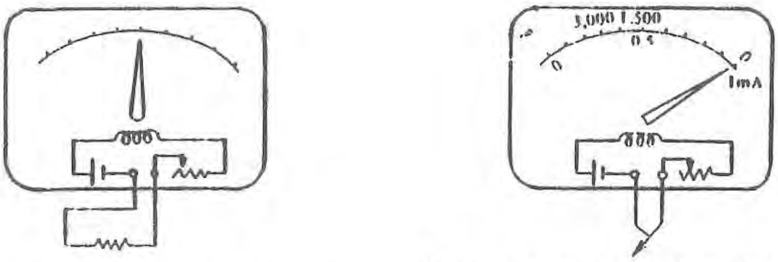
where η : magnification factor

R_V : internal resistance of a meter

R_S : the resistance of the high resistor

f) Measurement of resistance

The measurement of resistance is based upon current flowing through the circuit to be checked and on the voltage drop across the circuit produced by that current. If the current and voltage drop are known, the resistance can be calculated from Ohm's law. If the voltage is known and remains constant, we can calibrate the ammeter to read resistance directly. We call the recalibrated ammeter with its voltage supply an ohmmeter. In an ohmmeter, a dry cell is used as a source of energy. In Fig. 5-15, a 1.5 volt dry cell is connected in series with an ammeter having a full-scale current of 0.001 ampere and a 1,500 ohms resistance.



(a) When the test probes are shorted

(b) When an unknown resistor is connected

Fig.5-15 Basic ohmmeter circuit

When the test probes of the meter are touched together, the pointer moves all the way to the right side of the meter scale. This takes place because

$$I = \frac{E}{R} = \frac{1.5V}{1,500} = 0.001A$$

When the test probes are not connected to a circuit, there is no resistance to be measured. As a result, the right side of the scale must be marked zero.

Notice that this is opposite to the marking upon the scale of an ammeter or voltmeter. When the ohmmeter is connected to a circuit having a resistance of 1,500 ohms, it's pointer moves half way on the meter scale. The total resistance of the meter and the external circuit is now 3,000 ohms and

$$I = \frac{1.5V}{3,000\Omega} = 0.0005 \text{ A}$$

To obtain an accurate reading, the meter should always be zeroed before use.

When using an ohmmeter, always make sure that the power to the circuit being tested is turned off.

g) The multimeter

For general purpose and service type measurements, it is general practice to combine the functions of the D.C. voltmeter, the ohmmeter and the milliammeter into a single multipurpose instrument, commonly known as a VOM, or multimeter.

(3) The basic meter in A.C. measurement

a) The basic principle of A.C. meter

The moving-coil type of meter will not read if used in an A.C. circuit because the average value of an alternating current is zero. An A.C. meter must produce deflection of the meter pointer up-scale regardless of polarity.

The deflection is accomplished by one of the following methods for A.C. meters.

i) Thermal type

In this method, the heating effect of the current, which is independent of polarity, is used to provide meter deflection.

ii) Electromagnetic type

In this method, the relative magnetic polarity is maintained constant although the current reverse.

iii) Rectifier type

The rectifier changes the A.C. input to D.C. output for the meter.

All A.C. meters have scales calibrated in rms values, unless noted otherwise on the meter.

b) Rectifier method

The basic D.C. meter also finds use in A.C. measurements, when a rectifier is added to the measuring circuit.

Many types of rectifiers can be used, but the copper-oxide instrument rectifier type is usual in the common rectifier type meter. Other types of rectifiers, such as the semiconductor diodes and vacuum-tube diode, are in use. Figure 5-16 shows a meter rectifier circuit.

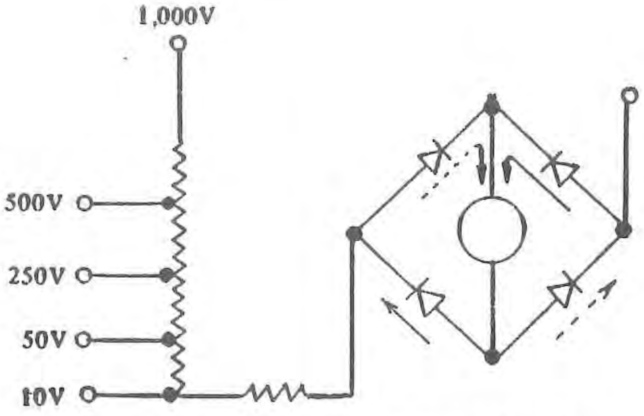


Fig.5-16 A rectifier type voltmeter

c) Themocouple type meters

This type of meter uses the thermocouple principle to supply a very sensitive D.C. meter. A diagrammatic sketch is shown in Fig. 5-17.

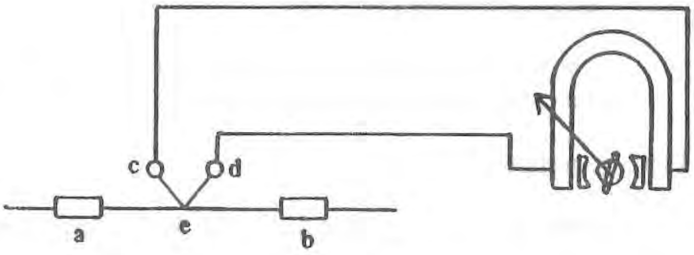


Fig.5-17 Thermocouple type of meter

The current to be measured flows from a to b, heating up the resistance wire. The themocouple has its hot junction at e and the cold junction at c and d. Since this meter depends only the heating effect, it is particularly adapted to current measurements at high frequencies.

PART TWO: BASIC ELECTRONICS

6. Vacuum Tube

6.1 Behavior of electrons

(1) Electrons in matter

As you know, all matter is composed of atoms, which consist of a neucleus and electrons. The electrons are placed under restraint of the proton in the neucleus in normal conditions and they revolve around the neucleus in an orderly way.

Some substances, when they are heated, release electrons which then fly off in the space. This phenomenon is called electron emission and is important for understanding of electron tube.

(2) Thermal electron emission

When a piece of metal is heated, thermal energy is given to the electrons and the temperature of the metal increases. The motion of electrons become more and more violent and finally some electrons leave the piece of metal. Such electrons are called thermal electrons and this phenomenon is called thermal electron emission (see Fig. 6-1). Metals differ widely with regard to thermal electron emission.

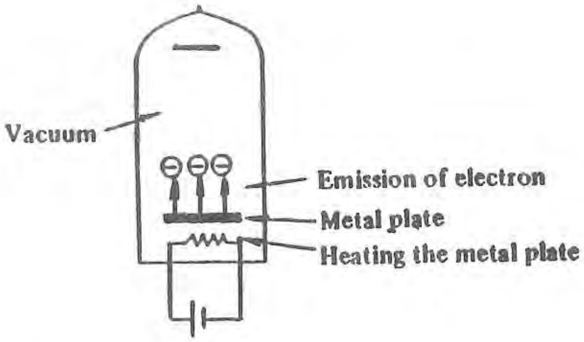


Fig.6-1 Thermal electron emission

6.2 Diode

(1) The structure of diode

A diode has two electrodes: a cathode and an anode plate, as shown in Fig. 6-2. Note the schematic symbol. The heater is not counted as an electrode because it is merely an incandescent filament to heat the cathode electrically. The plate surrounds the cathode. Therefore, electrons emitted from the surface of the cathode sleeve can be attracted to the metal anode to provide plate current. The plate is usually made of iron, nickel. or molybdenum.

The two types are illustrated schematically in Fig. 6-2. In(a), the filament-cathode is heated directly by electrical current, serving as an incandescent filament that produces themonic emission. In(b), the cathode is heated indirectly by a separate heater. The directly heated type is usually called a filament, while the filament for the indirectly heated cathode is called a heater.

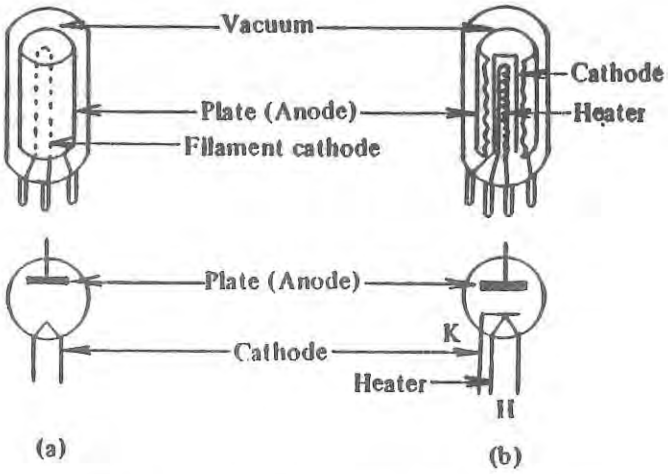
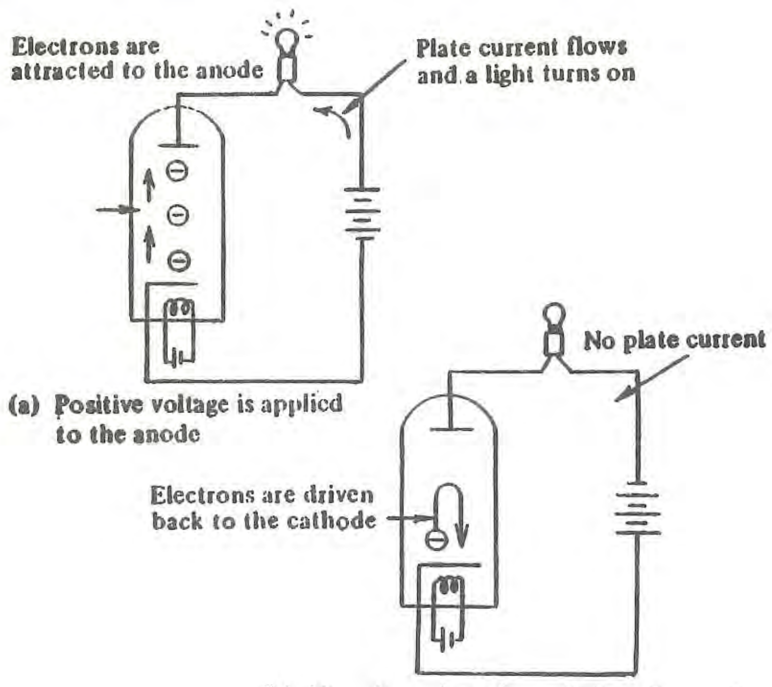


Fig.6-2 Structure and symbol of diode

(2) Operation of diode

Let on electric lamp and a battery connect to diode as shown in Fig. 6-3. In(a), as the positive terminal of a battery is connected to the anode, positive electrical charges are stored on the anode. Therefore, thermal electrons which are emitted from heated cathode will be attracted to the positive electrical charges and will neutralize the positive electrical charges on the anode. On the other hand, electrons are supplied to the cathode from a battery.



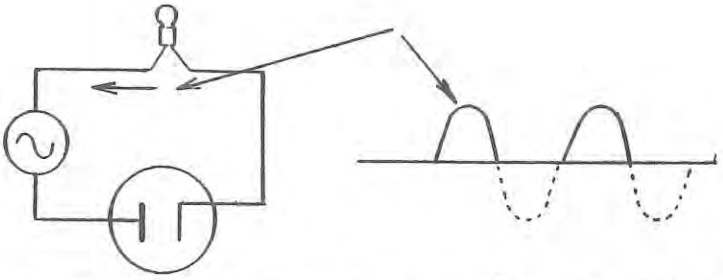
(a) Positive voltage is applied to the anode

(b) Negative voltage is applied to the anode

Fig.6-3 The operation of diode

Therefore,thermal electrons are continuously emitted and the positive electrical charges are continuously supplied to the anode. This movement of the thermal electrons and the positive electrical charges between cathode and anode constitutes an electric current which flows in the direction of the arrow. As a result, the electric lamp turns on. We call this current plate current. But in(b), as nagative voltage is applied to the anode, thermal electrons cannot be attracted to the anode. Therefore, as electric current does not flow, the electric lamp does not turn on.

As stated above, diode has a characteristic that the plate current flows when the positive voltage is applied to the anode. It keeps a constant direction of the current. That is, the operation of diode is to let the current pass in one-way direction.



(a) How to connect the circuit (b) The current waveform

Fig.6-4 A.C. to D.C.

Hence, if an alternating voltage is applied to the anode, current will flow only in the positive half cycles, and it will consist of a succession of pulses, always in the same direction. The tube therefore functions as a rectifier, in that an alternating voltage applied to the tube produces a unidirectional current (Fig.6-4).

Wide use is made of this characteristic to obtain direct voltages and current from an A.C. source for supplying radio equipment and amplifiers.

(3) Diode characteristic

As already explained, the movement of electrons between cathode and anode constitutes an electric current flow. The magnitude of the current depends on the number of electrons passing a given point per second, and this in turn is a function of a cathode temperature and anode-cathode potential.

The relation may be investigated by use of a diode in the circuit, as in Fig. 6-5. If the heater current is held constant at a value I_{f1} thus maintaining constant cathode temperature and the anode voltage E_b is increased from 0, the anode current I_b will increase in the manner shown by curve (a) of Fig. 6-6. If the heater current is increased to a new value I_{f2}, thereby raising the cathode temperature, curve (b) of the figure results. The two curves coincide at smaller anode voltage and each becomes horizontal in the upper region, but at different anode current values. In these horizontal regions the anode current is said to be 'temperature limited'; the effect is due to the

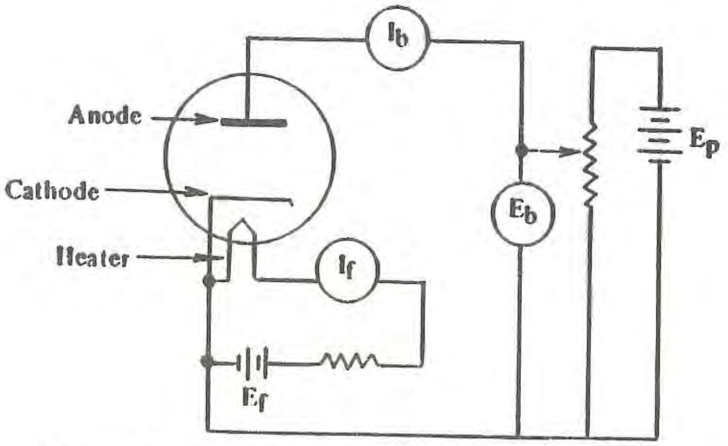


Fig.6-5 Circuit for obtaining diode characteristic

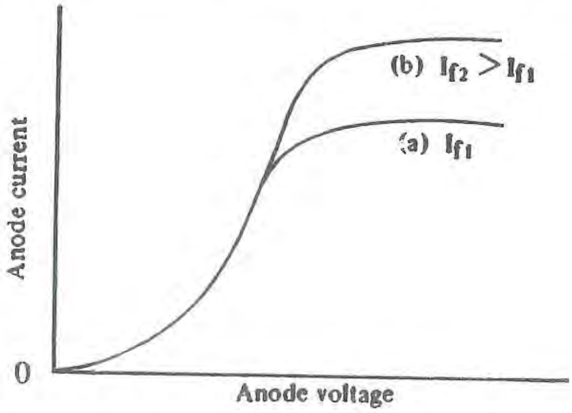


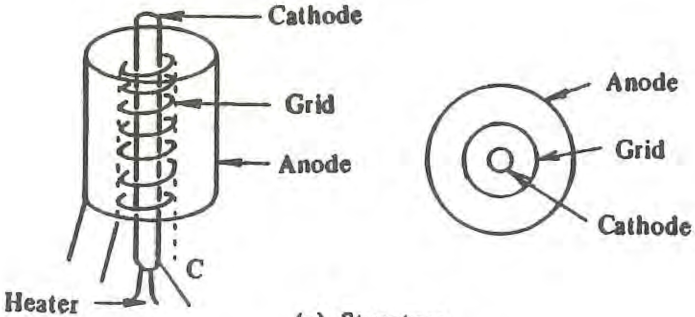
Fig.6-6 Effect of temperature limitation on diode current

fact that all the electrons which the cathode is able to emit at this temperature are reaching the anode, and consequently the current can increase no further. If, however, the cathode temperature is raised by increasing the heater current, more electrons are emitted and the temperature limited value of current is increased.

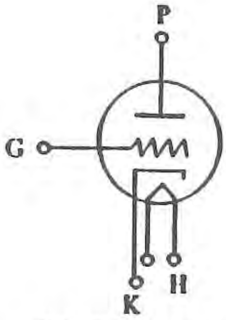
6.3 Triode

(1) The structure of triode

A triode is a tube which contains a third element, the grid, located between cathode and anode.



(a) Structure



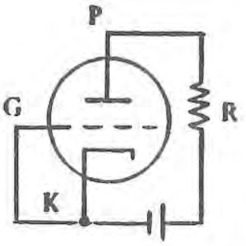
(b) Circuit symbol

Fig. 6-7

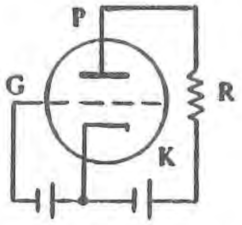
The grid usually takes the form of a helix or spiral of fine wire, so that electrons may pass freely throught it. Since the grid is nearer to the cathode, the potential of the grid has greater effect in controlling electron flow than does the anode potential.

(2) The operation of triode

As shown in Fig. 1-8(a), if positive voltage is applied to the anode in connecting between the cathode and the grid, thermal electrons emitted from the cathode will reach the anode without its movement being affected by the grid. In this case the operation is the same as that of the diode.



(a) When connecting the grid and the cathode



(b) When negative potential is applied to the grid

Fig.6-8 The operation of grid

But as shown in Fig. 6-8(b), if the grid is made negative to the cathode, its repelling effect will partly nullify the attractive effect of the positive anode potential on the electrons at the cathode and the anode current will be less than if the grid were not present. The grid may be made sufficiently negative to repell all the electrons and stop or cut off the anode current. Variation of grid potential will cause a similar variation in the value of anode current and thus the grid is able to control the anode current.

(3) Triode characteristics

The effect of grid and anode potentials on the plate current can be studied by means of Fig. 6-9. In this set up, if the anode potential is held constant and the grid potential varied, the characteristic curve is shown in Fig. 6-9.

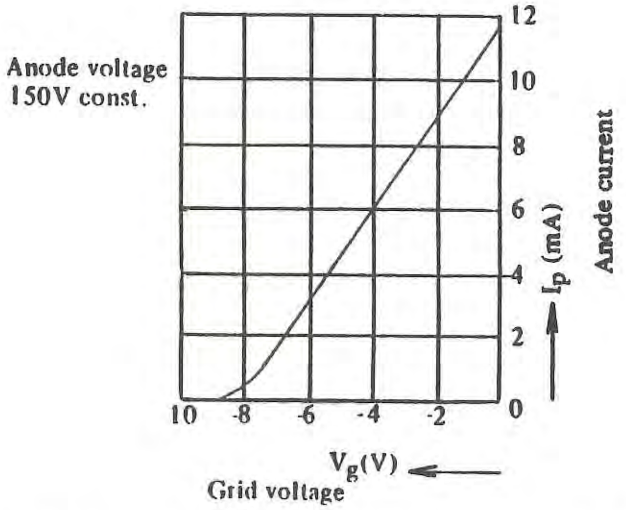


Fig.6-9 Grid-anode characteristics of triode

Such a curve, showing the relationship between the anode current and the grid potential for constant value of anode voltage is known as the grid-anode family or the transfer characteristic of the tube.

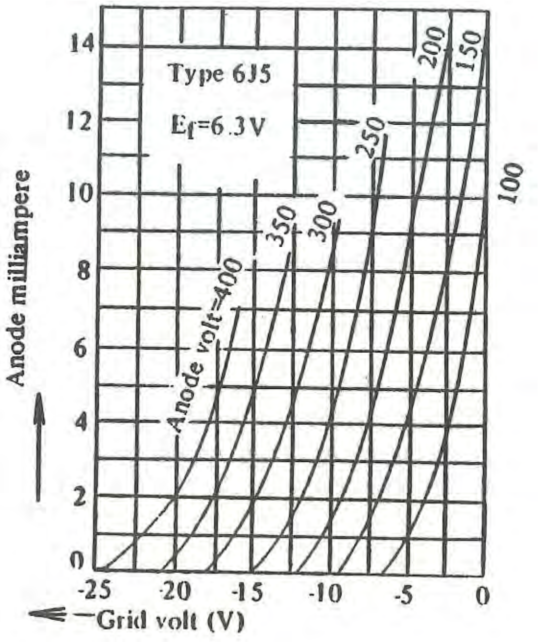


Fig.6-10 Grid-anode characteristics of a typical triode

Figure 6-10 shows the anode current plotted as a function of grid voltage for various constant values of anode voltage.

It may be noted that the curves tend to be nearly straight lines in the upper portions, and that the curves for various anode potentials are nearly parallel. It will be shown later that these properties are important where tube is to be used as amplifier, and where it is desirable to keep the distortion of the amplified signal as small as possible.

(4) Tube parameters

Three important ratios are performance coefficients helpful in analyzing and predicting tube operation. These ratios or parameters are the amplification factor, the transconductance or mutual conductance, and the internal A.C. plate resistance.

(a) The amplification factor symbolized by the Greek letter μ is defined as the ratio of plate (anode) voltage change to grid voltage change when the plate current is maintained constant.

It is a measure of the relative effectiveness of the grid as compared with the plate in controlling flow of plate current. In Fig. 6-11 the plate currents at A and B are the same and by the above definition

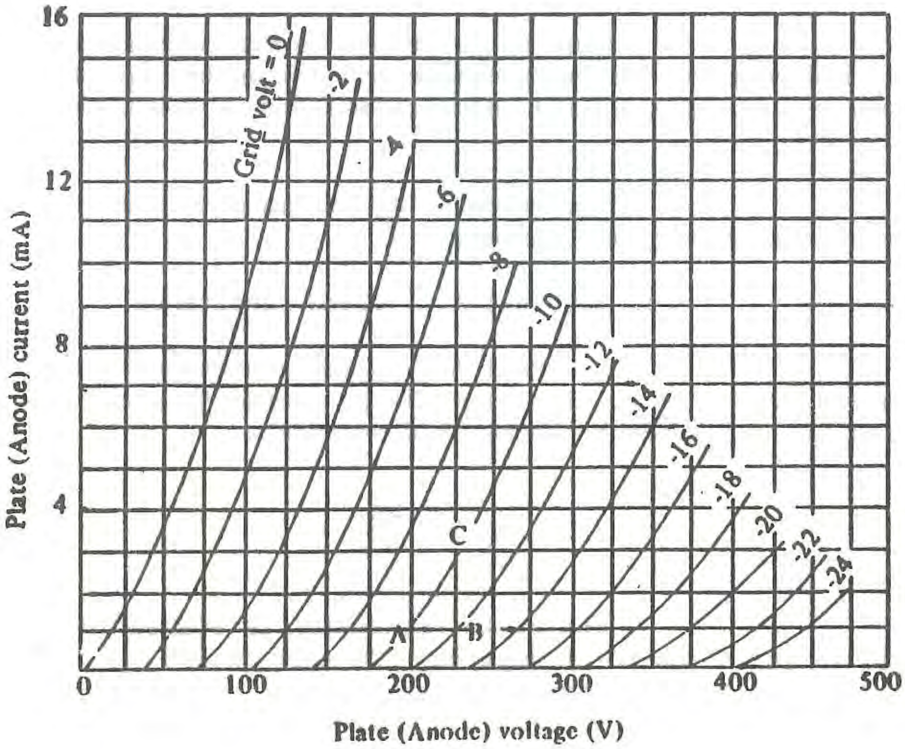


Fig.6-11 Plate characteristics of triode

$$\mu = \frac{AB}{\Delta\ell_c}$$

where $\Delta\ell_c$ represents the difference between the grid potentials of the two curves through A and B. In triodes, μ ranges in value from 2 to 100 with most tubes included in the range 10 to 40. For most triodes, the amplification factor is almost constant for all operating conditions, except at very low plate currents.

(b) Mutual conductance

(Grid-plate transconductance)

Mutual conductance symbolized by g_m is defined as the ratio of plate-current change to grid-voltage change producing it, when plate voltage is held constant. It is a measure of effectiveness of the grid in controlling the anode current. In Fig. 6-11,

$$g_m = \frac{BC}{\Delta\ell_c}$$

When BC is stated in microamperes: the value of g_m is in microamperes per volt change and its units are microhms ($\mu\mho$) For tubes in current use, its value ranges from a few hundred to above 40,000.

The value of g_m varies considerably, depending largely on the value plate current.

(c) Internal A.C. plate resistance

Internal A.C. plate resistance symbolized by γ_p is given by the ratio of plate-voltage change to plate-current change producing it, grid voltage being held constant.

$$\gamma_p = \frac{AB}{BC}$$

The plate resistance is stated in ohms, AB is measured in volts and BC in amperes. In most triode γ_p ranges in value between 300 and 100,000 ohms. By manipulation of the above three definitions it can be seem that the following relationship exists between the three tube coefficients.

$$\mu = g_m\gamma_p$$

It is thus sufficient to specify any pair of these quantities, since the third may be computed from them.

(5) The load line

A graphical construction may be employed to find the output current and voltage values for any operating condition. This method is illustrated in Fig. 1-12(b) which consists of the plate family of curves of the tube in the circuit of Fig. 6-12(a) and a superimposed load line.

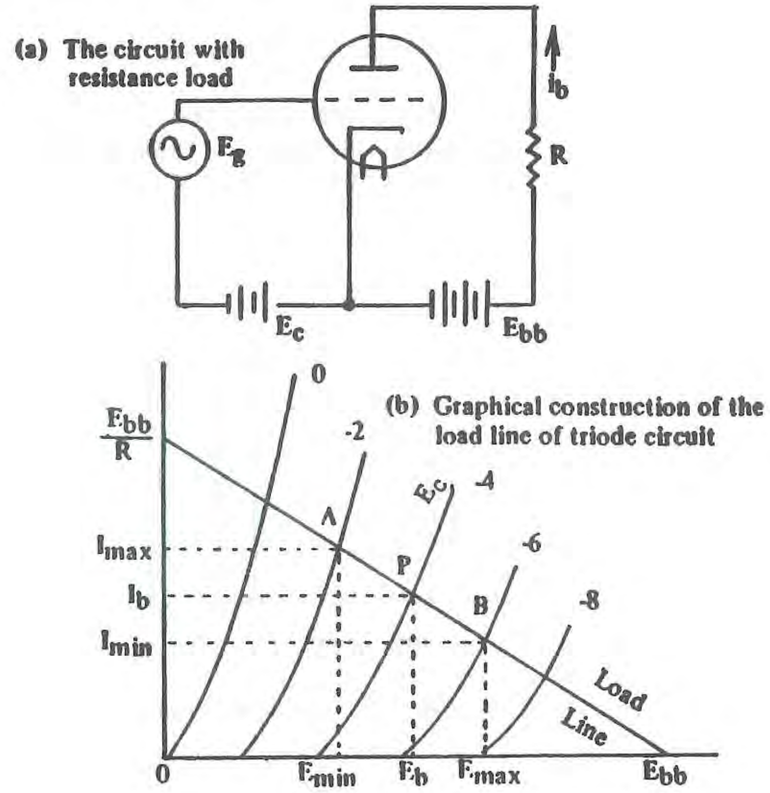


Fig. 6-12

The load line is a graph of the equation

$$\ell_b = E_{bb} - Ri_b$$

representing the voltage appearing in the plate circuit of Fig. 6-12(a). Any point on the line represents a possible combination of plate voltage and plate current, when $i_b = 0$, $e_b = E_{bb}$. The load line therefore intercepts the horizontal axis at this scale value. Similarly, the vertical intercept occurs at

$$i_b = \frac{E_{bb}}{R}$$

The load line is most readily drawn by use of these two points and is straight because R is a constant resistance.

(6) The equivalent circuit of a vacuum tube

Another method of determining the A.C. output of a vacuum tube is by means of the equivalent circuit. This is shown in Fig. 1-13 and corresponds to the practical circuit of Fig. 6-12(a).

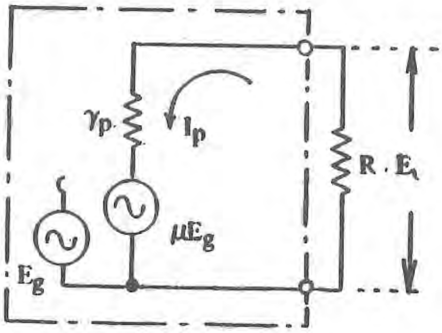


Fig.6-13 Equivalent circuit corresponding to Fig.6-12

The equivalent circuit leads to the same values of current and voltage in the load resistor R as the A.C. components of these quantities in the practical circuit.

The voltage gain of the circuit of Fig. 1-12 is defined as the ratio of the output A.C. voltage E_o between cathode and anode to the applied signal voltage on the grid. This voltage amplification will now be computed by use of the equivalent circuit.

Since γ_p and R form a simple series circuit, the A.C. current is given by

$$I_p = \frac{\mu E_g}{\gamma_p + R}$$

This current in R produces a voltage drop E_o.

$$E_o = -I_p R = \frac{-\mu E_g R}{\gamma_p + R}$$

Therefore, the voltage gain A is

$$A = \frac{E_0}{E_g} = \frac{-\mu R}{\gamma_p + R}$$

The negative sign indicates that E_o and E_g are opposite in phase.

6.4 Tetrode

(1) Construction and operation

This construction is similar to the triode, with cathode, control grid and plate, but there is an additional electrode called the screen grid between the control grid and plate.

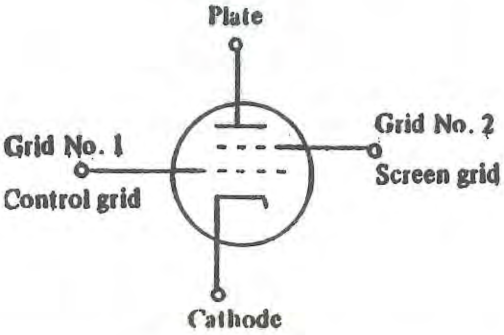


Fig.6-14 Schematic symbol of tetrode

As shown in Fig. 6-14, the control grid is No.1, placed close to cathode so that it still functions to control the space charge. The screen grid is grid No.2, closer to the plate. It is not used to control the plate current but has steady positive D.C. voltage to help accelerate electrons to be collected by the plate.

The path for plate current 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. Since the screen grid is positive, it will collect some electrons. These provide screen grid current that returns to the cathode through the screen-grid circuit. The screen-grid current is waste current, however, since it is not used in the output circuit. The plate current is the desired current that flows across the plate load resistor. Although the screen grid has some waste current, it is only a small part of the total electrons flowing through the tube. Most of electrons can go through the spaces in the screen grid, attracted by the higher positive potential of the plate.

(2) Secondary emission

Metals have the property of releasing electrons when the surface is bombarded by incident electrons. No heat energy is necessary. The requirement is high positive voltage to provide a strong accelerating field so that the incident electrons can strike at high velocity. The electrons released are then called secondary electrons and the process is secondary emission.

In vacuum tube, the metal plate is bombarded by the electrons emitter from the cathode. Therefore, the plate has secondary emission. In a diode or triode, though, the secondary electrons are no problem, because any secondary electrons near the plate are promptly collected by the positive plate. In a tetrode, however, the screen grid can attract secondary electrons emitted from the plate when the plate voltage drops below screen grid voltage. This effect reduces the plate current. For this reason, tetrodes are not commonly used in amplifier circuits. Generally, when a screen-grid tube is desired for an amplifier, a pentode is used.

6.5 Pentode

As shown in Fig. 6-15, the pentode has the same kind of construction as a tetrode but with the addition of a suppressor grid in the space between the screen grid and the plate.

Note that the first grid is the control grid, grid No.2 is the screen grid and grid No.3 is the suppressor grid. The suppressor grid is not used for input or output signal but has a fixed potential, usually equal to the cathode voltage. In most pentodes, the suppressor is connected internally to the cathode. When the suppressor has its own external pin connection, it is connected to either the cathode pin or chassis ground. Since the suppressor is close to the plate but has the cathode potential that is negative with respect to the plate, any

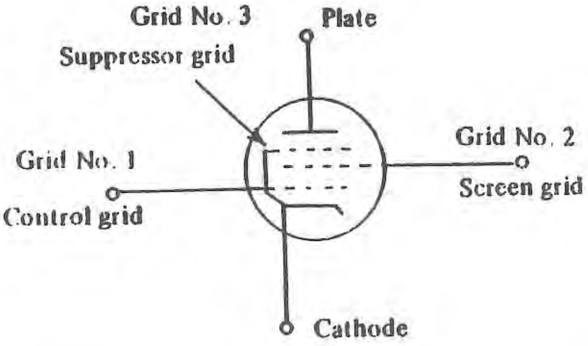


Fig.6-15 Schematic symbol of pentode

secondary electrons emitted are repelled back to the plate. The plate can still attract electrons from the cathode, however, to provide plate current. Inside the tube, the electrons released by themionic emission from the cathode flow through the spaces between wires in the control grid, screen grid and suppressor grid. The positive potential on the plate provides an accelerating field that is able to accelerate electrons from the space charge and through the grids to be collected by the plate.

6.6 Special Tube

(1) Cathode ray tube

As shown in Fig. 1-16, the cathode ray tube, or CRT, consists of an electron gun, deflection plates and a fluorescent screen inside the evacuated glass envelope. Although the cathode, control-grid and anode electrodes are constructed as cylinders, their function is the same as in conventional vacuum tubes. The cathode is heated to emit electrons, and the control grid controls the flow of electrons attracted by the positive potential of the anodes. High voltages are used on the order of 2 to 80 KV for the last anode. The inside surface of the front glass face plate is coated with a fluorescent material that emits light when bombarded by electrons. Green and white are two common colors of illumination that can be produced by the screen, depending on its chemical composition.

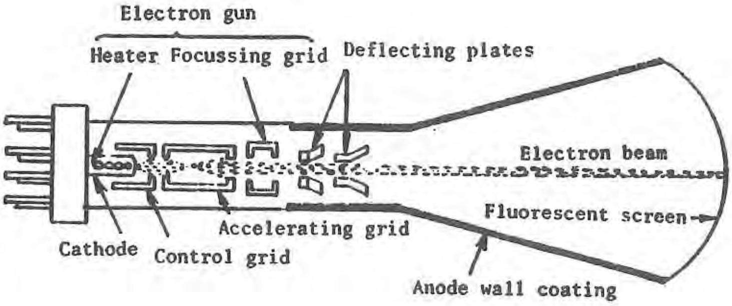


Fig.6-16 Cathode ray tube using electrostatic deflection and focusing

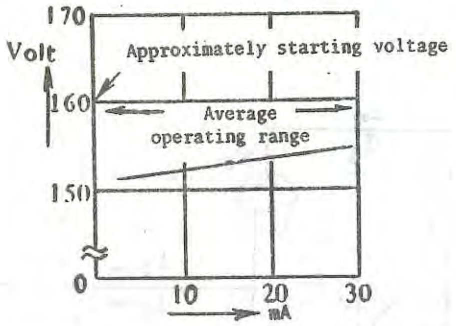
When the electron beam hits the screen, it produces a spot of light visible through the glass. In order to deflect the electron beam and move the position of the light spot on the screen, deflection voltage can be applied to the deflection plates. A pair of horizontal deflection plates provides the potential difference needed to move the electron beam left or right. Similarly, the pair of vertical deflection plates can move the beam up or down.

There is another type of CRT in which deflection is produced by horizontal and vertical magnetic fields set up by currents flowing in the deflecting coils X and Y.

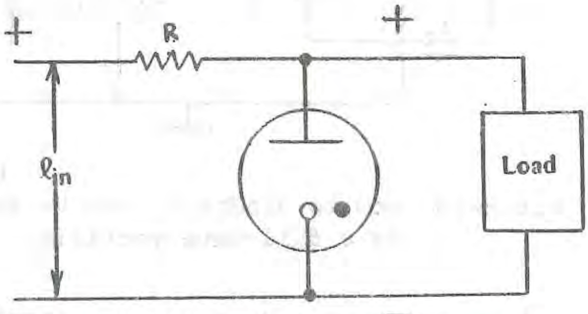
(2) Voltage regulators

If a small amount of some gas is introduced in a diode, the properties of the tube are markedly changed. When the voltage across the tube exceeds a critical ionizing potential the atoms are broken up into positive and negative ions. The presence of massive, slow-moving positive ions within the tube tends to minimize the negative space charge and very large currents can flow with low-voltage drops.

Cold-cathode gas diodes are widely used for voltage regulation. These tubes are designed to have fixed voltage drops of 55-150 volts (depending upon the gas employed). The tube current is one of the widely used types and can be varied from 5 to 30 m A with little change in voltage drops.



(a) Average characteristics of a voltage regulator tube



(b) A simple voltage regulator circuit

Fig.6-17 Regulator

Typical characteristics of such a tube are shown in Fig. 6-17(a) and a simple voltage regulator circuit in (b). Note that the tube is nonconducting until the gas is ionized by an initial overvoltage. Once the gas is ionized the voltage across the tube falls to its rated value if the circuit is properly arranged. If the tube is connected in the circuit of Fig. 1-17(b) the tube starts to conduct when the input voltage e exceeds the 160V starting voltage. The output voltage quickly drops to around 150 volts.

6.7 Application

(1) Full-wave rectifier

As shown in Fig. 1-18, the full-wave rectifier uses both alternations of the A.C. input to produce rectifiered D.C. output.

Therefore, the full-wave circuit can supply more D.C. power output than the equivalent half-wave circuit. Two diodes are necessary for the full wave circuit. One diode conducts for one alternation while the other rests. On the next alternation, conditions reverse, and the other diode conducts. The A.C. input supplies equal and opposite voltage for the two diodes.

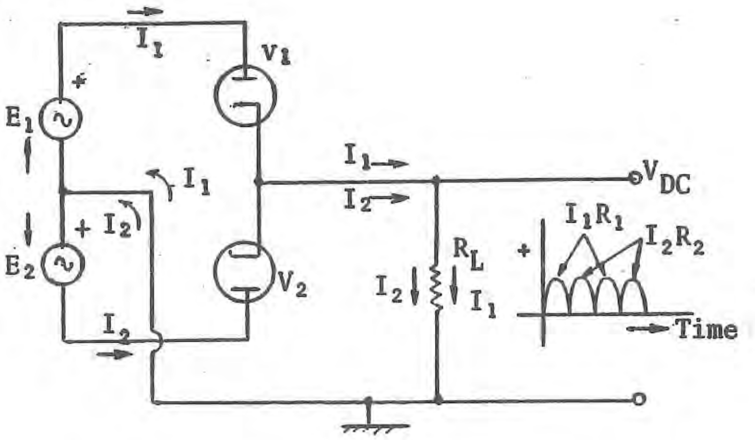


Fig.6-18 How to diodes V_1 and V_2 are used as a full-wave rectifier

Although the diodes conduct on opposite half-cycles, notice that for both cases the plate current for either tube flows in the same direction through R_L in returning to cathode. Therefore, the rectified output has one fixed polarity to provide D.C. output voltage.

The ripple frequency is double the frequency of the A.C. input voltage, since each half-cycle produces a fluctuation of D.C. output voltage.

(2) Power supply with full wave rectifier

The rectifier circuit often has the function of providing D.C. output voltage to be used as B^{++} voltage for the plate supply.

In this application, the rectifier circuit is called a power supply.

As shown in Fig. 6-19, the power transformer T steps up the A.C. input voltage to provide the desired amount of B⁺ output voltage. The high voltage secondary L_2 is center-tapped for equal and opposite A.C. input voltage to the two diodes.

The rectifier tube changes the A.C. input to D.C. output. However, a filter is needed to provide a steady D.C. voltage.

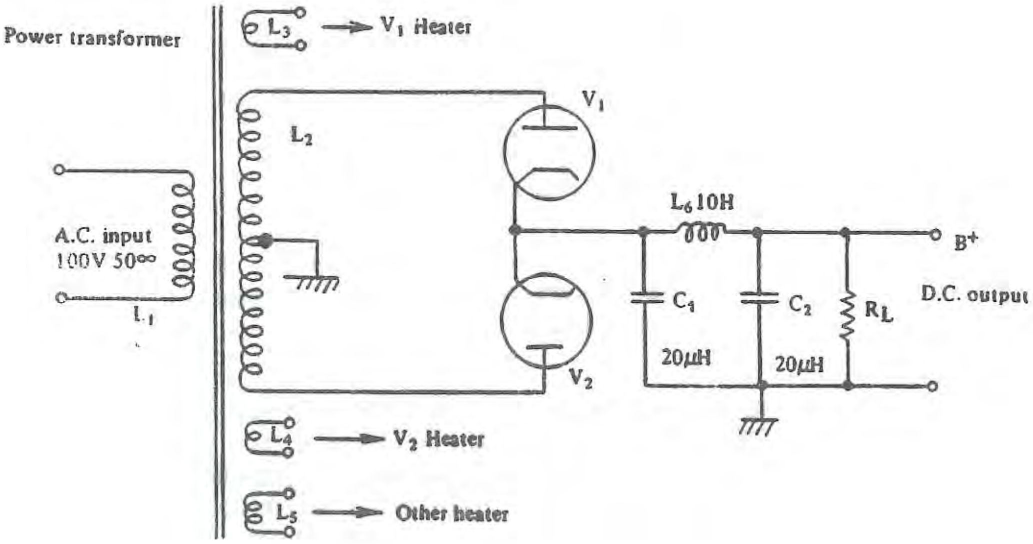


Fig.6-19 Circuit of full wave power supply for B^+ output voltage

This is the function of the π type low-pass filter with C_1 L_6 and C_2 to filter out the 100 c/s A.C. ripple. The result is a steady D.C. voltage for the B^+ output that supplies plate voltage to the amplifiers.

(3) Amplification of small alternating voltage

An important function of electron tube circuits in radio system is that of increasing the amplitude of small alternating voltages. It is often necessary to pass the signal through a number of amplifier stages in order to achieve the required amplification.

Figure 6-20 shows the basic circuit arrangement of a linear alternating voltage amplifier.

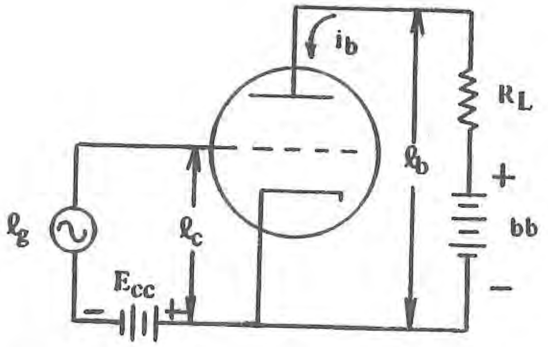


Fig.6-20 Basic circuit arrangement of a triode alternating voltage amplifier

The input voltage eg is applied between the grid and the cathode in series with a source of D.C. voltage E_{cc}. The amplified output is derived from an alternating voltage component established across the plate load resistance R_L. The D.C. grid voltage, called the grid bias, is included in order to maintain the grid negative for all instantaneous values of input voltage. The magnitude of E_{cc} is commonly chosen to be approximately half the cut-off voltage and the amplitudes of the grid-voltage variations around this point are ordinarily limited to values that maintain the operation within the linear region of the characteristic curves.

(4) Equivalent circuit of a linear voltage amplifeir

When an amplifier tube is operated linearly, the tube coefficients μ, g_m and γ_p may be assumed constant and evaluations of i_p and ℓ_p for given values of ℓ_g are usually made by an analytical method involving these coefficients. The tube circuit is replaced by an A.C. equivalent circuit whose constants are determined by the input voltage, the load impedance and the tube coefficients. The desired quantities are then evaluated by conventional methods of A.C. circuit analysis

Figure 1-21 shows a triode voltage amplifier, together with an equivalent representation of its circuit. The amplifier is of the same type previously considered, except that a general load impedance Z_L is employed in place of an assumed resistive load.

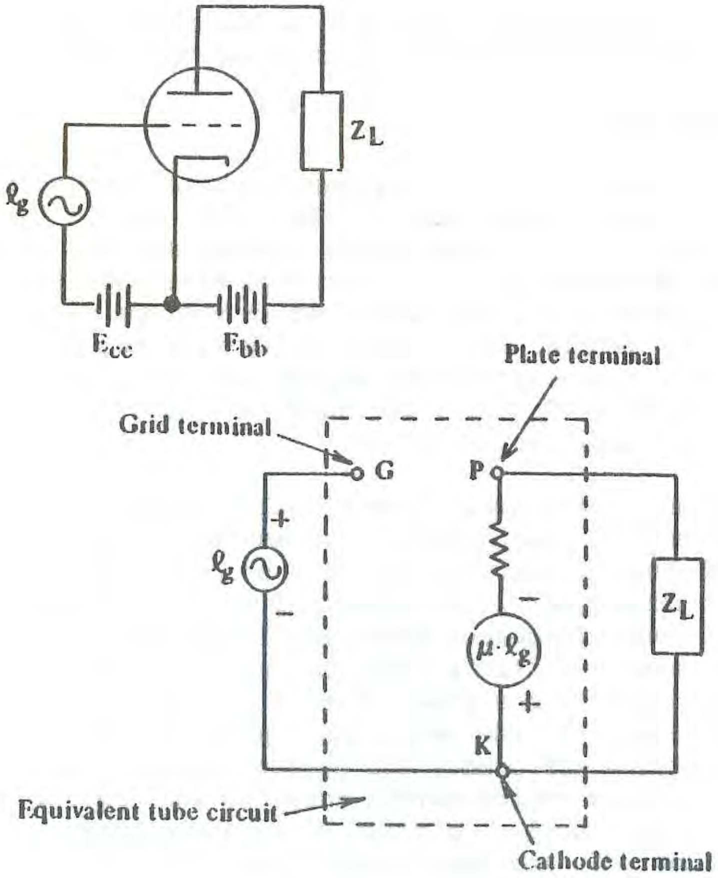


Fig.6-21 An equivalent circuit for a triode voltage amplifier

Appropriate relations for evaluating the alternating plate voltage E_p for a given value of E_g can be readily derived from the equivalent circuit.

Thus.

$$I_p = \frac{\mu E_g}{\gamma_p + Z_L}$$

and

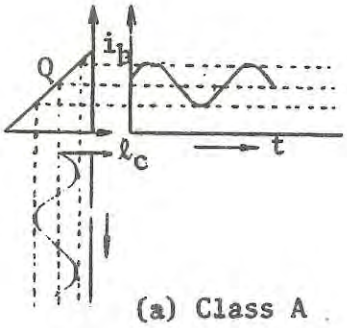
$$E_p = I_p Z_L = \frac{\mu E_g Z_L}{\gamma_p + Z_L}$$

The voltage amplification A is the ratio of the output to the input alternating voltage and is given by the relation.

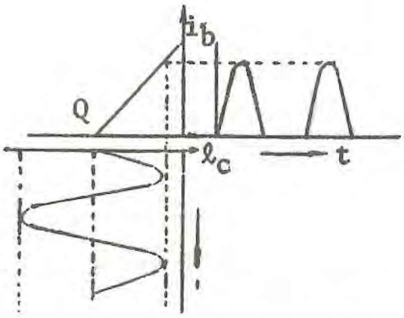
(5) Power amplifier

The operation of a power amplifier is characterized by the conversion of energy drawn from the plate D.C. supply into A.C. power under the control of an alternating voltage applied to the input terminals. Although the basic circuit arrangements used in power amplifier may be the same as those employed in voltage amplifiers, the specific design features are appropriately selected to provide a desired set of power characteristics, the amount of voltage gain being of secondary importance. Triodes, penthodes and beam power tubes find application in power amplifier circuits.

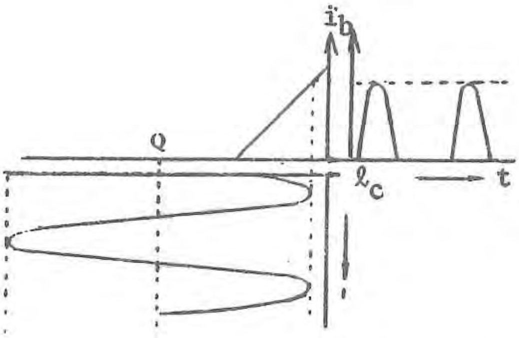
A number of general operational techniques find application in power amplifiers. The operating region may be confined to the linear portion of dynamic curve by use of a properly adjusted input voltage. Such an arrangement, corresponding to class A operation, is often employed in audio frequency power amplifiers where it is desired that the plate-current variations linearly reproduce the signal variations. However, the efficiency of the power conversion and the amount of useful output power are relatively low under this operating condition. To increase the conversion efficiency and output capabilities of power amplifier, the operating region may be extended well beyond the linear portion of the dynamic curve. In class B operation, the tube is biased approximately to cut off, and the current flows only during the positive half of the signal cycle. In class C operation, the plate-current wave form represents a very distorted version of the input-signal wave form. The use of this method is, therefore, confined to application in which the large harmonic components of the plate current may be reduced or eliminated by appropriate circuit connections. One technique for reducing distortion components involves the use of a parallel tuned load circuit resonant at the signal frequency. Thus, class B and C operation are widely used in R-F tuned power amplifiers. The distortion components may also be reduced in both tuned and untuned circuits by a push-pull tube arrangement, wherein signal voltages of equal instantaneous amplitudes but of opposite polarity are applied to the grid of two identical tubes.



(a) Class A



(b) Class B

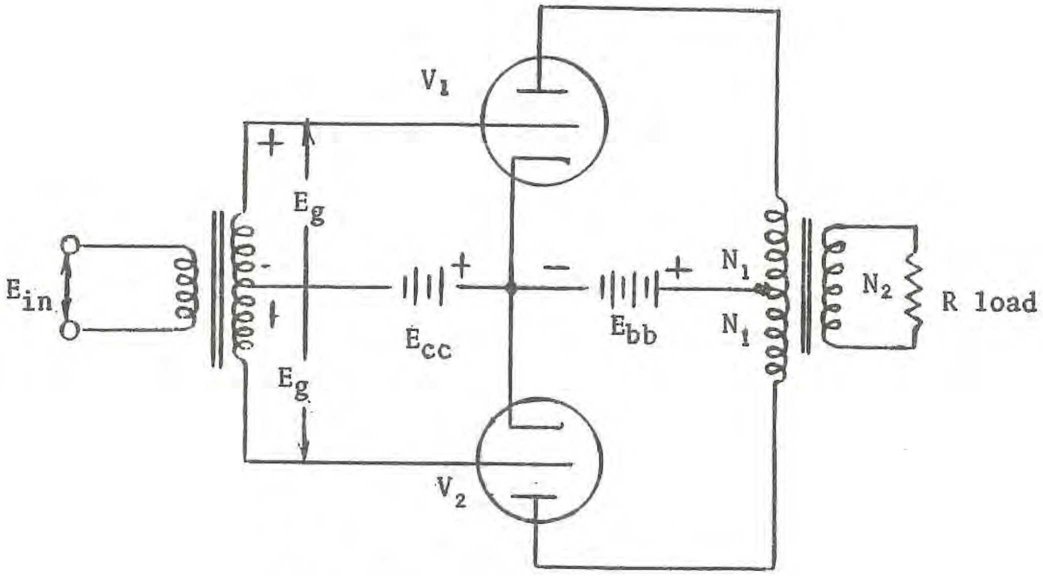


(c) Class C

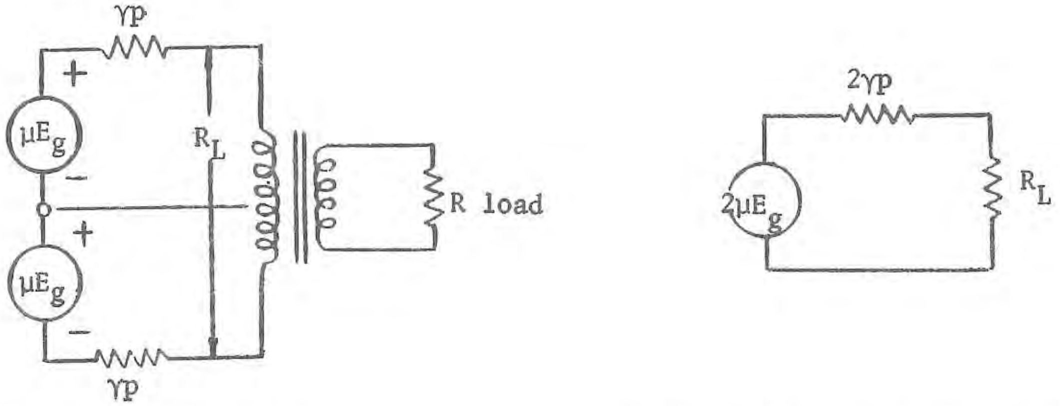
Fig.6-22 Amplifier classification in terms of the position of the Q point

(6) Push-pull amplifiers

Power amplifier circuits that employ a pair of tubes connected in a push-pull arrangement find a wide application as a means of securing a desired amount of A.C. power with a minimum amount of wave form distortion. Figure 6-23(a) shows a typical push-pull circuit.



(a) Push-pull amplifier circuit



(b) Equivalent circuit

(c) Final equivalent circuit

6.23 Push-pull amplifer circuit

The grids of two tubes having identical characteristics are connected to the opposite ends of the center-tapped secondary winding of an input transformer. The two plates are connected to the opposite ends of the center-tapped primary winding of an output transformer. When the grid voltage of one tube is increased in the positive direction, the grid if the other tube is simultaneously made more negative by a corresponding amount. Therefore, as the alternating input voltage produces plate-current variations in the two tubes, an increase in the current flowing from the center tap through one half of the output transformer primary is accompanied by a corresponding decrease in the current flowing from the center tap through the other half of the primary winding. The two varying currents, 180° out of phase and flowing in opposite directions through the primary winding, induce in-phase voltage in the secondary which combined to form the circuit output. If the tubes are linearly operated, the equivalent circuit shown in Fig. 6-23(b) may be used to represent the amplifier. The circuit representation may then be further amplified as shown in Fig. 6-23(c). The value of R_L is given by the equation.

$$R_L = [\frac{2N_1}{N_2}]^2 R_{load}$$

where N_2 is the number of turns in the secondary and N_1 is the number of turns in each half of the primary of the output transformer. The current in the equivalent circuit is seen to be equal to

$$1_p = \frac{2\mu E_g}{2\gamma_p + R_L} = \frac{\mu E_g}{\gamma p + \frac{R_L}{2}}$$

The power delivered to the load is

$$P = 1_p{}^2 RL = [\frac{\mu E_g}{\gamma p + \frac{R_L}{2}}]^2 R_L = 2 [\frac{\mu E_g}{\gamma p + \frac{R_L}{2}}]^2 \frac{R_L}{2}$$

It is seen that the output power is twice the power that would be obtained from each tube if it were working into an effective load resistance.

7. Semiconductors

7.1 Nature of semiconductors

(1) Atomic structure

An atom consists of a nucleus carrying a positive charge surrounded by one or more electrons revolving around the nucleus. Electrons which are moving in orbits close to the nucleus are subject to relatively strong forces of attraction towards the protons of the nucleus, whereas those in the outer orbits are acted upon by progressively smaller forces, and the electrons in the outmost orbit can be easily detached from their atoms to become carriers of negative charges.

Among semiconductors, the materials with which we are principally concerned are germanium and silicon. These materials, possess a crystalline structure, i.e. the atoms are arranged in an orderly manner. In both germanium and silicon, each atom has four electrons orbiting in the outmost shell and is therefore said to have a valency of four.

(2) Characteristics of semiconductors

In the case of a silicon atom (Si), the neucleus consists of 14 protons and 14 neutrons and when the atom is neutral, the neucleus is surrounded by 14 electrons, one or more of which may be detached from the atom. The electrons are distributed in rings of 2, 8, and 4. Si atoms do not usually gain or lose the valence electrons but share them with neighboring atoms to achieve a stable configuration with 8 electrons. This union of atoms sharing the valence electrons is called a covalent bond. These covalent bonds serve to keep the atoms together in crystal formation and are so strong that at absolute zero temperature, i.e.-273°C, there are no free electrons. Consequently, at that temperature, pure germanium and silicon behave as perfect insulators. At normal atmospheric temperature, some of the covalent bonds are broken, i.e. some of valence electrons break away from their atoms. We can assume that pure germanium and silicon are perfect insulators and that the properties utilized in semiconductor rectifiers are produced by controlled amounts of impurities introduced into pure germanium and silicon crystals.

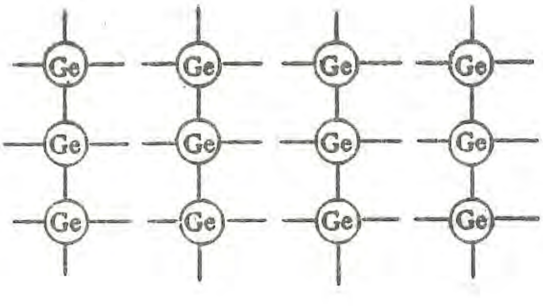


Fig.7.1 Crystal lattice structure of pure germanium, illustrating covalent bonds between Ge atoms

(3) *n*-type and *p*-type doping

The semiconductors germanium (Ge) and silicon (Si) have more resistance than metal conductors but much less resistance than insulators. However, the conductivity of semiconductors can be increased by adding elements, a process called doping. The purpose of doping is to inject free charges that can easily be moved by an applied voltage. These added charge carriers can be either negative or positive. When electrons are added, the doped semi-conductor is negative or *n*-type; a deficiency of electrons makes the material *p*-type.

(a) Free electron charges in *n*-type semiconductor

The doping elements arsenic, antimony and phosphorus have a valence of 5. For each of these atoms there are five electrons in the outermost ring. In a covalent bond with Ge or Si atoms having four valence electrons, each impurity atom provides an extra electron. As shown in Fig. 7-2, where the crystal lattice of Ge atoms includes one arsenic atom, four of the five valence electrons of the impurity element become part of the covalent bond structure. However, the extra electron can be considered a free charge because it is not needed for a covalent bond.

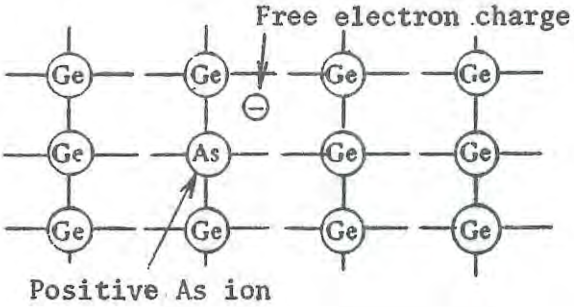


Fig.7-2 Crystal lattice structure of Germanium (GE) doped with arsenic (As)

(b) Free hole charges in *p*-type semiconductor

The doping elements aluminum, boron and gallium have a valence of 3. For each of these atoms there are three electrons in the outermost ring. In a covalent bond with Ge or Si atoms, there are seven electrons instead of eight for each bond with an impurity element. The one missing electron in such a covalent bond can be considered as a free positive charge called a hole charge. Figure 7-3 shows a hole charge in the crystal lattice of doped gemanium.

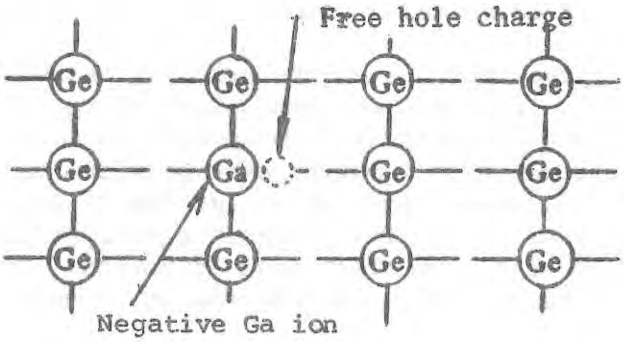


Fig.7-3 Crystal lattice structure of germanium (Ge) doped with gallium (Ga)

(4) Hole current

A hole has the same amount of positive charge as a proton, equal to an electron but with opposite polarity. However, a hole charge is not a proton. The proton is a fixed charge in the nucleus that is not free to move. A hole is a positive charge outside the nucleus, present only in semiconductors because of unfilled covalent bonds.

The idea of hole charges moving to provide hole current is illustrated in Fig. 7-4. In (a), along the top row, a hole charge is shown at point 1. Suppose that a valence electron from the filled bond at point 2 moves to point 1. As shown in (b), the bond at point 1 becomes filled and there is a hole charge at point 2. Similarly, an electron can move from point 3 to point 2 to fill this bond. With the sequence, the hole charge is moving from point 1 to point 5 to provide hole current, from left to right here. To produce this hole current, voltage could be applied across the semiconductor with the positive terminal at point 1. In general, the direction of hole current is the same as conventional current, opposite from the electron flow.

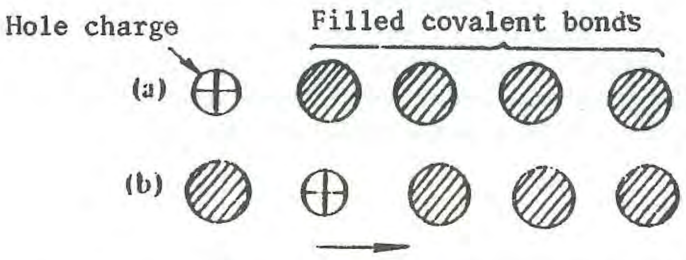


Fig.7-4 Hole charge moving to provide hole current

7.2 The *pn* junction

Let us consider a crystal, one half of which is doped with *p*-type impurity and the other half with *n*-type impurity. The *p*-type semiconductor has mobile holes and the same number of fixed negative ions. Similarly the *n*-type semiconductor has mobile electrons and the same number of fixed positive ions. Hence each region is initially neutral. Owing to their random movements, some of the holes will diffuse across the boundary into the *n*-type semiconductor and some of the free electrons will similarly diffuse into the *p*-type semiconductor, as shown in Fig. 7-5(a).

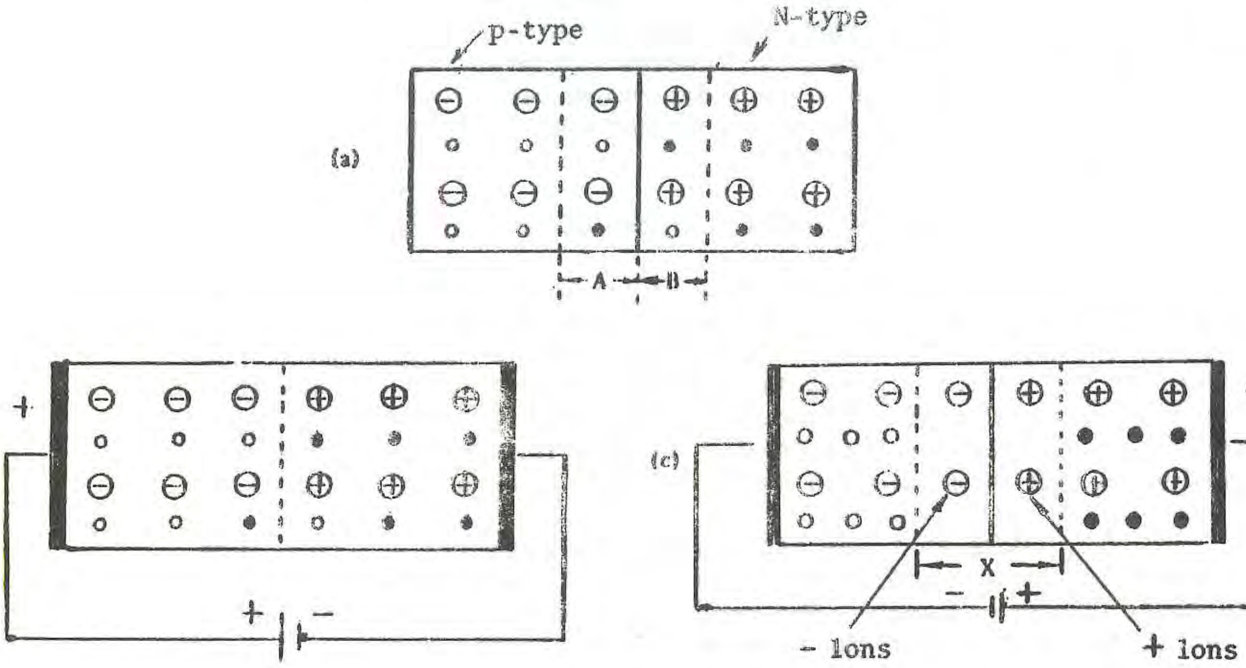


Fig.7-5 P-n junction (junction diode)

Consequently region A acquires an excess negative charge which repels any more electrons trying to migrate from the *n*-type into the *p*-type into semiconductor. Similarly, region B acquires a surplus of positive charge which prevents any further migration of holes across the boundary. These positive and negative charges are concentrated near the junction, and thus form a potential barrier between two regions.

(1) Forward bias

As shown in Fig. 7-5(b), when external voltage is applied across the junction, the direction of the electric field in the semiconductor is such as to produce a drift of holes towards the right in the *p*-type semiconductor and of free electrons towards the left in the *n*-type semiconductor. In the region of the junction, free electrons and holes combine. For each combination, an electron is liberated from a covalent bond in the region near positive plate and enters that plate, thereby creating a new hole which moves through the *p*-type material towards the junction. Simultaneously, an electron enters the *n*-region from the negative plate and moves through the *n*-type semiconductor towards the junction. The current in the diode is therefore due to hole-flow in the *p*-region, electron-flow in the *n*-region and a combination of the two in the vicinity of the junction.

(2) Reverse bias

When the polarity of the applied voltage is reversed, as shown in Fig. 7-5(c), the holes are attracted towards the negative electrode and the free electrons towards the positive electrode. This leaves a region x known as a depletion layer (the potential barrier) in which there are no holes or free electrons. Consequently the junction behaves as an insulator.

(3) The internal barrier potential

This potential barrier is only a few tenths of a volt. However, it keeps the *p* and *n* majority charges separate so that they are not neutralized on contact between *p* and *n* semiconductors. The effect of the internal potential can be overcome by 0.3 V across a Ge junction or 0.7 for Si. These are approximate values for a temperature of 25°C. The barrier voltage (V_b) is what makes the junction useful because V_b can be controlled by an external source.

Note that the ion charges are negative at the *p* face of the junction and positive at the *n* face. This is polarity of the majority charge carriers. The negative side of V_b prevents free electrons from entering the *p* materials, while the positive side of V_b prevents the hole charges from entering the *n* materials. The ions are anchored in position because the ions are charged atoms, which are practically immobile in the solid semiconductor, compared with free charge carriers.

(4) Static characteristic of a junction diode

Figure 7-6 shows the effects of forward and reverse voltages for Ge and Si.

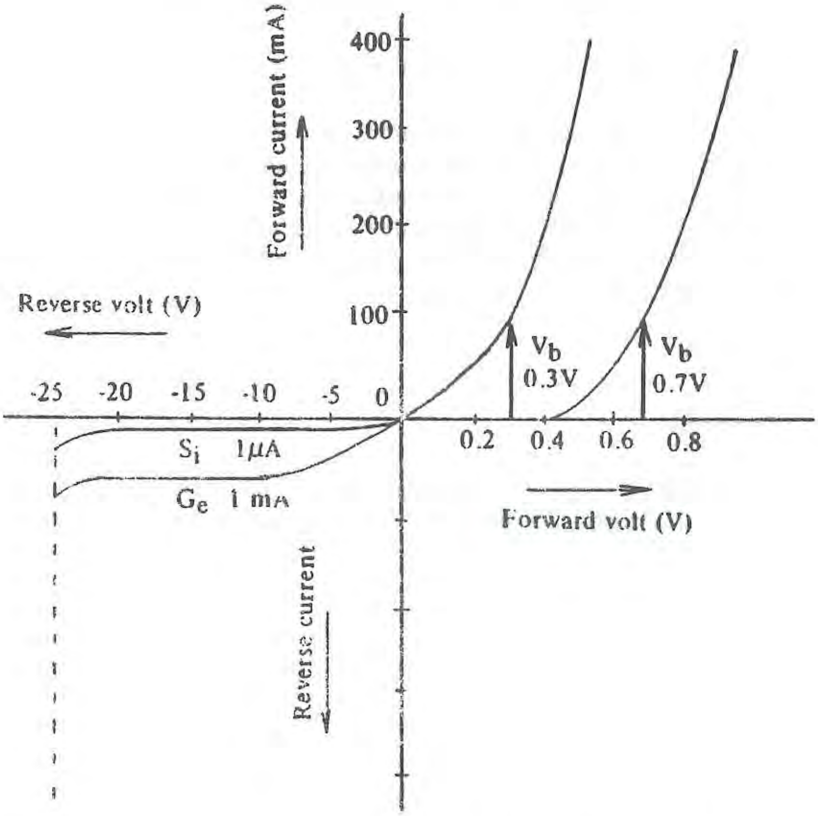


Fig.7-6 Static characteristics of Ge and Si junction

(a) Forward current

In the forward direction, when the applied voltage approaches V_b, then forward current can flow as the barrier potential is reduced.

At the value of V_b and for higher applied voltages, the forward current increases sharply.

(b) Reverse current

With reverse voltage, very little current flows, as shown in Fig. 7-6. The separate curves indicate typical values of 1 mA for Ge and 1 μ A for Si. This current is called reverse saturation current because it does not increase with more reverse voltage, up to the breakdown point.

The symbol is Ico, indicating a small cut-off current. This current increases with temperature.

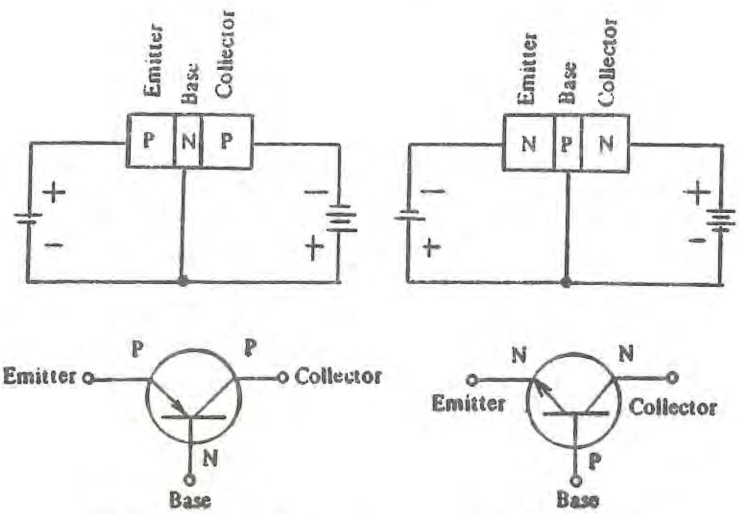
(c) Forward and reverse resistance

In the forward direction, Ge and Si junctions are practically a short circuit. This forward resistance may be 100Ω to less than 1Ω. In the reverse direction, the resistance of the junction is very high. Typical values of Ge junctions are 50 kΩ to 1 MΩ for the reverse resistance. Si junction has practically infinite resistance in the reverse direction.

7.3 Transistors

(1) General

As shown in Fig. 7-7, the transistor consists of a *pn* junction and a *np* junction, formed by having either a *p* or an *n* semiconductor.



(a) *PNP* transistor (b) *NPN* transistor

Fig.7-7 Transistors

The idea is to have the first section supply charges to be collected by the third section through the middle section. The electrode that supplies charges is the emitter; the electrode on the opposite side to collect the charges is the collector.

The base is in the middle to form two junctions.

(a) Emitter

The emitter-base junction is always biased in the forward direction. As shown in Fig. 7-7(a), the *p*-emitter supplies hole charges to its junction with the base. This direction is indicated by the emitter arrow for forward hole current. The arrow pointed into the base shows a *pn* junction. For the *npn* transistor in (b), the emitter supplies electron charges to the base. Therefore, the symbol for the *n*-emitter shows the arrow out from the base.

In the schematic symbols for transistors, only the emitter has an arrow to show which electrode is the emitter.

Most *npn* transistors are silicon, while most *pnp* transistors are germanium, but only because of the production methods.

(b) Collector

The function of the collector is to remove charges from junction with the base. In Fig. 7-7(a), the *pnp* transistor has a *p* collector receiving hole charges that flow in its output circuit. For the *npn* transistor in (b) the *n* collector receives electrons. The collector-base junction always has reverse voltage.

(c) Base

The base in the middle separates the emitter and collector. The base-emitter junction is forward-biased, allowing low resistance for the emitter circuit. The base-collector junction is reverse-biased, however, providing high resistance in the collector circuit. The final requirement in producing transistor action is to have the collector current controlled by the emitter-base circuit.

(d) Collector current

The base is much thinner than the emitter and collector, as shown in the alloy-junction type of transistor construction in Fig. 7-8

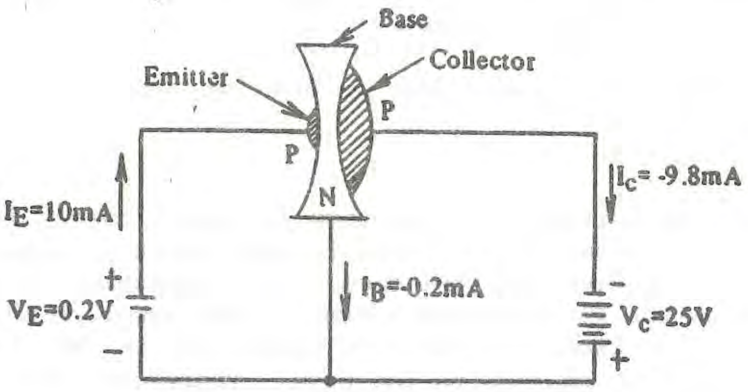


Fig.7-8 Electrode current of transistor (I_B, I_C and I_E)

Consider the current for the *pnp* transistor in Fig. 7-8. The *p* emitter supplies hole charges to the *n* base. Here the holes are minority charges. Because of light doping in the base, very few of the hole charges can recombine with electrons. Any recombination of charges in the base provides the very small base to emitter current. However, almost all the hole charges concentrated in the base at the base-emitter junction are moved by diffusion to the base-collector junction. At the *p*-collector, it has reverse voltage of negative polarity. For hole charges moving from the base, the negative voltage at the collector attracts the positive holes. As a result, the charges diffused from the emitter side of the base move into the collector to form a drift current of hole charges in the collector circuit.

The result is that practically all the current supplied by the emitter circuit becomes reverse current in the collector circuit.

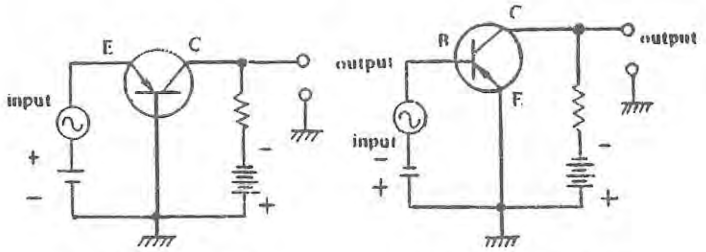
$$I_E = I_C + I_B$$

This formula states that the collector and base currents must add to equal the emitter current, which is the source.

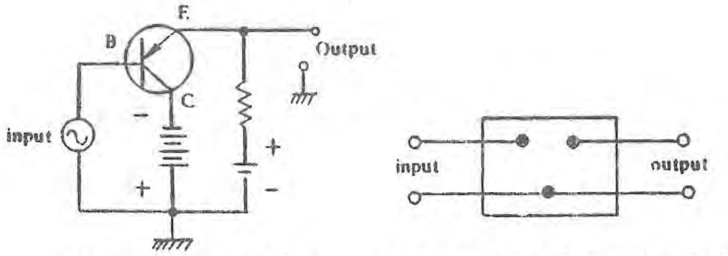
For most transistors, I_C is about 20 to 100 times more than I_B. The negative sign for the values of I_B and I_C in Fig.7-8 is used only to indicate direction.

(2) Characteristics of transistors

Since the transistor has only the three electrodes, one must be common to two pairs of terminals for input and output. Therefore, the three possibilities for amplifier circuit are: common base (CB), common emitter (CE), and common collector (CC). These three circuit arrangements are shown in Fig. 7-9 for *pnp* transistors. The circuits are the same for *npn* transistors but all polarities are reversed.



(a) Common base (CB) (b) Common emitter (CE)



(c) Common collector (CC) (d) The general case of common terminal

Fig.7-7 Amplifier circuits arrangements
for *pnp* transistor

(a) Static characteristics for a common-base circuit

Figure 7-10 shows an arrangement for determining the static characteristics of a *npn* transistor used in a common base circuit.

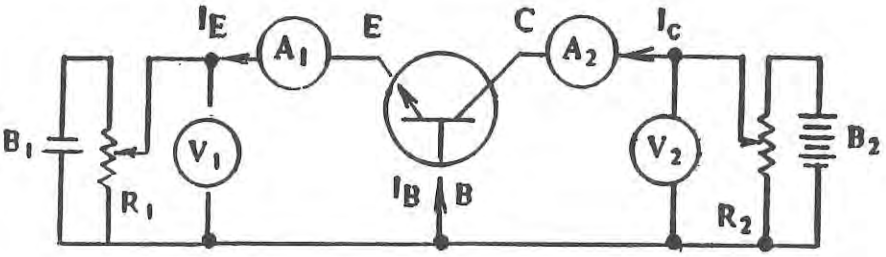
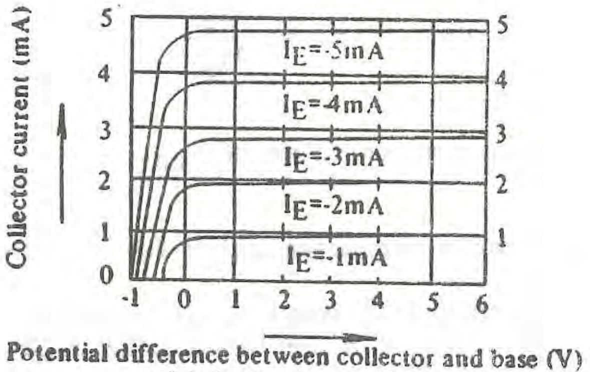
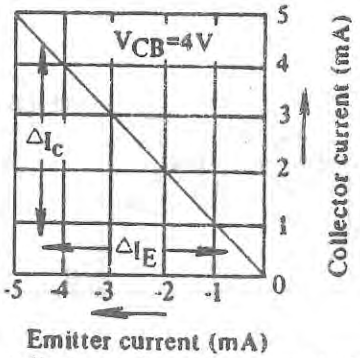


Fig.7-10 Determination of static characteristics for a common base *npn* transistor circuit

The procedure is to maintain the value of the emitter current, indicated by A_1, at a constant value, say 1 mA, by means of the slide resistor R_1 and note the readings on A_2 for various values of the collector-base voltage given by voltmeter V_2. The test is repeated for various values of the emitter current and the results are plotted as in Fig. 7-11.



(a) Static characteristics



(b) Relationship between collector and emitter currents for a given collector-base voltage.

Fig.7-11 Static characteristics for a common-base *npn* transistor circuit

From Fig. 7-11, it will be seen that for positive values of collector-base voltage, the collector current remains almost constant. Also, for a given collector-base voltage, the collector current is practically proportional to the emitter current. This relationship is shown in (b).

The ratio of the change, ΔI_C, of the collector current to the change, ΔI_E, of the emitter current, for a given collector-base voltage, is termed the current amplification factor for a common-base circuit and is represented by the symbol α.

That is,

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

for a given value of V_{CB}.

(b) Static characteristics for a common-emitter circuit

Figure 7-12 shows an arrangement for determining the static characteristics of a *npn* transistor used in a common-emitter circuit.

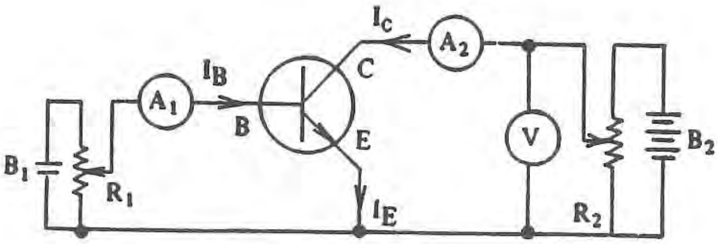


Fig.7-12 Determination of static characteristics for a common-emitter *npn* transistor circuit

The procedure is to maintain the base current, I_B, through a microammeter A_1, at a constant value, say 25 μA, and note the collector current, I_C, for various values of the collector-emitter voltage V_{CE}, the test being repeated for several values of the base current. The results are plotted as shown in Fig. 7-13.

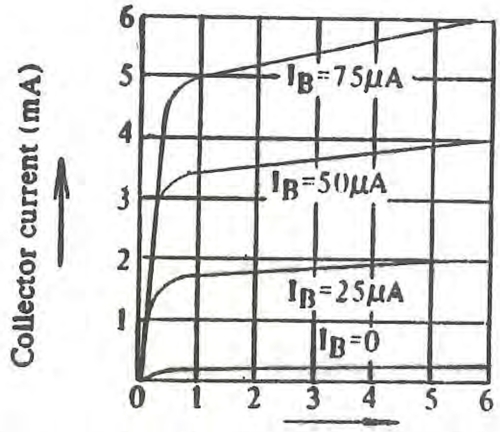
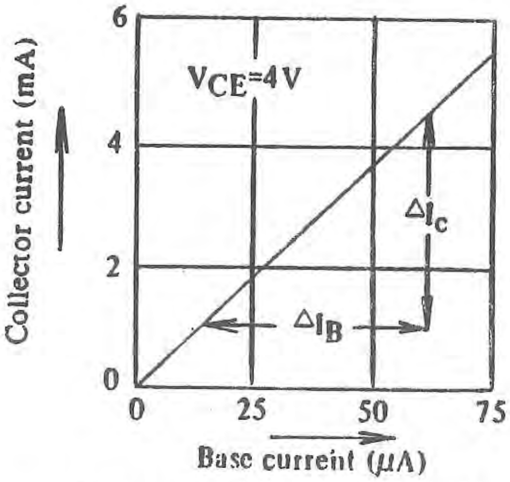


Fig.7-12 Determination of static characteristics for a common-emitter *npn* transistor circuit



(b) Relationship between collector and base currents for a given collector emitter voltage

Fig.7-13 Static characteristics for a common-emitter *npn* transistor circuit

For a given voltage between collector and emitter, the relationship between the collector and base current is practically linear as shown in (b). The ratio of the change, ΔI_C, of the collector cirremt tp tje cjamge. ΔI_B, of the base current, for a given collector-emitter voltage, is termed *the current amplification factor* for a common-emitter circuit and is represented by the symbol β.

That is,

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

for a given value of V_{CE}

(c) Relationship between α and β

From Fig. 7-10 and Fig. 7-11, it is seen that:

$$I_E = I_C + I_B$$

$$\Delta I_E = \Delta I_C + \Delta I_B$$

and,

$$\alpha = \frac{\Delta I_C}{\Delta I_E} = \frac{\Delta I_C}{(\Delta I_C + \Delta I_B)}$$

$$\frac{1}{\alpha} = 1 + \frac{\Delta I_B}{\Delta I_C} = 1 + \frac{1}{\beta} = \frac{1 + \beta}{\beta}$$

Hence,

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

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

Thus, if

$$\alpha = 0.98, \quad \beta = \frac{0.98}{0.02} = 49$$

and, if

$$\alpha = 0.99, \quad \beta = \frac{0.99}{0.01} = 99$$

i.e. a small variation in α corresponds to a large variation in β.

(d) Load line for a transistor

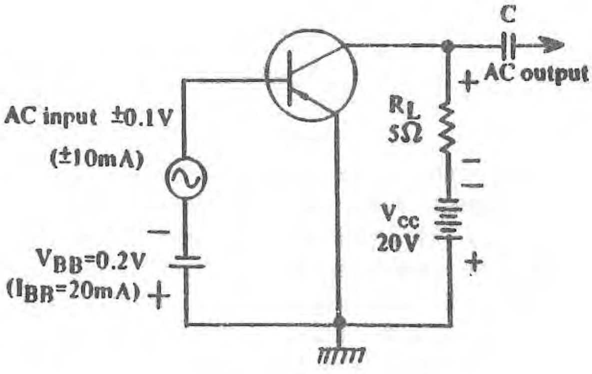
The static characteristics show electrode voltage and currents for the transistor itself, without a load in the output circuit. Actually an external load impedance is necessary to provide amplified output voltage. A typical circuit is shown in Fig. 7-14 with a 5 Ω R_L. Although the transistor is nonlinear, R_L has a linear voltampere characteristic. To see the effect of R_L on the collector voltage and current, the straight-line characteristic of R_L is superimposed on the collector characteristic curves, as in (b).

This graphical analysis with the load line of R_L can be used to determine specific values. The details of the load line intercepts with the collector characteristics are shown separately in (c).

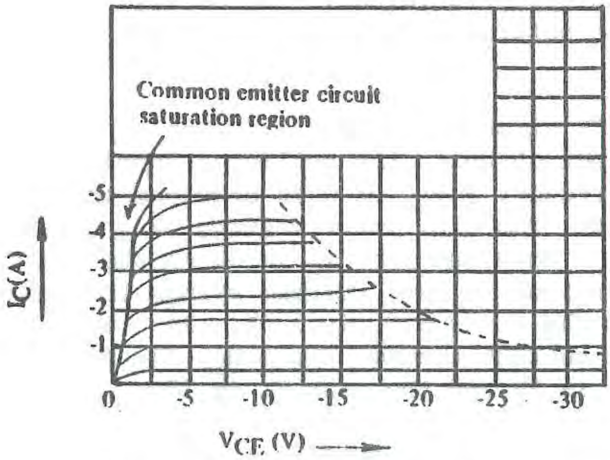
The CE circuit in Fig. 7-14 uses a *pnp* Ge power transistor. In the output circuit, the collector supply voltage V_{CC} is 20V. In the input circuit, a V_{BB} of 0.2V provides the forward bias for a 20 mA base current. The A.C. input voltage of ± 0.1V swings the base current ± 10mA. Then the peak I_B is 30 mA and the minimum I_B is 10mA. These variations in base current swings the collect current. The peak I_C is 3.4A and the minimum Z_C is 1.0A. As a result of the variations of collector current through the 5 R_L, the collector voltage varies. The minimum V_C is 3V and the peak V_C is 15V.

All values of collector current and voltage with a specified R_L are on the load line of R_L. To draw the load line, we need only the values of R_L and the supply voltage V_{CC} equal to 20 V on the horizontal axis where I_C is 0. This is one operating point because collector voltage equals V_{CC}. The opposite point is at the extreme value of collector current where V_C would be 0 with the voltage drop across R_L equal to the supply voltage.

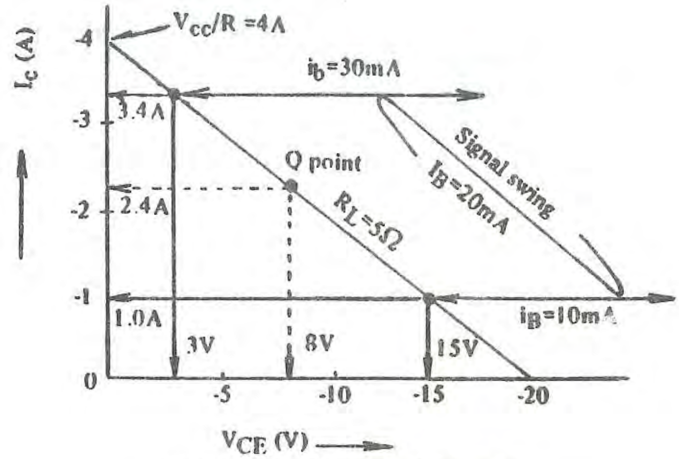
This end of the load line is at $I_C = \dfrac{V_{CC}}{R_L}$ on vertical axis where V_C is 0.



(a) CE circuit



(b) Construction of load line for 5Ω R_L on collector characteristics



(c) Details of load line intersepts

Fig.7-14 Load line analysis

This point is 4A. The straight line drawn between 4A on the vertical axis and 20V on the horizontal axis is the load line for the 5Ω R_L with 20V supply.

Where the load line intersects the collector curve for the base bias current of 20 mA in this example is the Q point. This point specifies static D.C. values without any A.C. signal input. The operating point of 20 mA for I_B is chosen here because it is a middle value between saturation and cut off of the collector current.

With input signal to the base, the A.C. drive change the base current up to the peak of 30 mA and down to the minimum of 10 mA. These values of i_B are two curves up and down from the Q point of 20 mA. The intersects with the load line are shown in Fig.7-14(c).

7.4 Application of semiconductors

(1) Diode rectifier circuit

The volt ampere characteristic of a *pn* junction shows it is a one way conductor. Therefore, the *pn* combination provides a simple, efficient diode rectifier.

The standard symbol for a semiconductor diode is an arrow and bar showing the direction of hole current. Therefore the arrow is the *p* side and the bar is the *n* side. Positive voltage applied to the *p* arrow makes the diode conduct, as this side is the anode, while the *n* bar is the cathode. The arrow and bar are generally marked on the diode. If not, a dot or band at one end indicates the cathode side.

(a) Half-wave rectifeir

In Fig. 7-15 the A.C. input voltage E is applied to the diode in series with the output load resistor R.

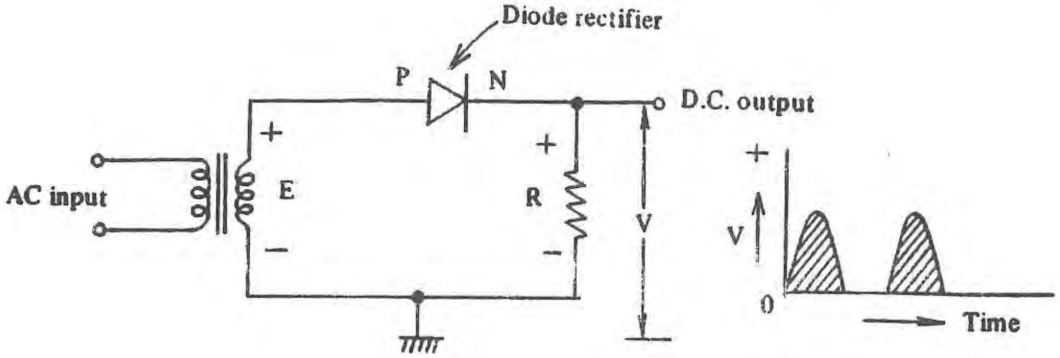


Fig.7-15 Half-wave rectifier circuit using semiconductor diodes

For the positive half cycles of A.C. input the *p* side of the diode is positive. This is the polarity for forward current. Then the diode conducts. E can then produce current through R, providing fluctuating D.C. voltage output V across R. On the negative half-cycle of A.C. input, the *p* side of the diode is negative. This polarity provides reverse voltage and the diode cannot conduct. Then there is no output across R. We can consider the diode as a one-way switch. Although not a steady D.C. value, the fluctuating output V is a D.C. voltage because it has only one polarity. The fluctuating components is the A.C. ripple in the D.C. output. A filter is used to reduce the amplitude of A.C. ripple.

(b) Full-wave rectifier

In Fig. 2-16, both alternation of the A.C. input produce D.C. output. Two diodes are necessary. D_1 conducts for one alternation when its anode is driven positive, while D_2 rests as its anode is negative. On the next alternation, the A.C. input voltage reverses in polarity and D_2 conducts without D_1. The A.C. input supplies equal and opposite voltages, usually with a center-tapped secondary winding in the power transformer.

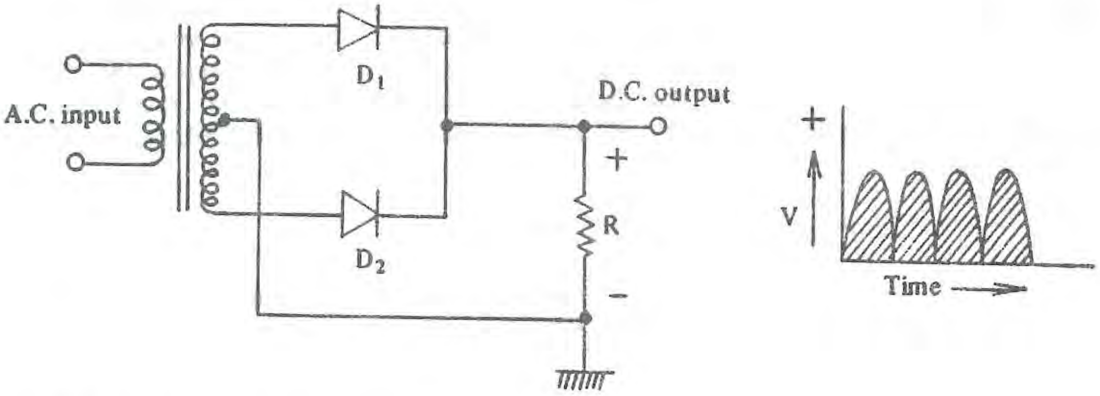


Fig.7-16 Full-wave rectifier circuit using semiconductor diodes

The ripple frequency for the full-wave rectifier is double the frequency of the A.C. input, as each half-cycle produces a fluctuation of D.C. output voltage.

(c) Rectifiers application

In addition to their use as power rectifiers, diodes are also used for detector circuits. For the audio detector in radio receivers, the A.C. input is modulated RF signal. This A.C. signal input must be rectified to filter out the RF variations and extract the audio modulation. Generally, a detector circuit has only one diode as a half-wave rectifier.

(2) Methods of forward bias

In the common-emitter circuit, the forward bias voltage for the base has the same polarity as the reverse collector voltage. Therefore, the base bias is generally taken from the collector output circuit. A series resistor or a voltage divider can be used to drop the voltage to the much lower values needed for forward bias. Three typical bias circuits are shown in Figs. 7-17, 7-18 and 7-19.

(a) Fixed base bias from V_{CC}

In Fig. 7-17, the base bias is provided by the resistor R_B connected directly to the collector supply voltage V_{CC}. The value of RB for a specified bias can be calculated as:

$$R_B = \frac{V_{RB}}{I_B} = \frac{V_{CC} - V_B}{I_B}$$

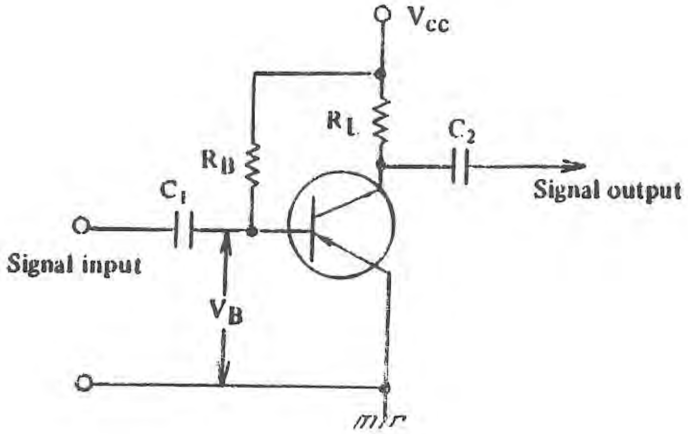


Fig.7-7 Fixed bias for base provided by R_B

Note that V_B is the base bias while V_{RB} is the I_R drop across R_B. Also V_{RB} is the difference between V_{CC} and V_B because the series voltage drops of V_B and V_{RB} must be add to equal the supply voltage, for either negative or positive V_{CC}.

(b) Base bias from V_C

In Fig. 7-18, R_B is connected to the collector voltage V_C, instead of the supply voltage V_{CC}. Then V_{RB} and R_B must be calculated from V_C.

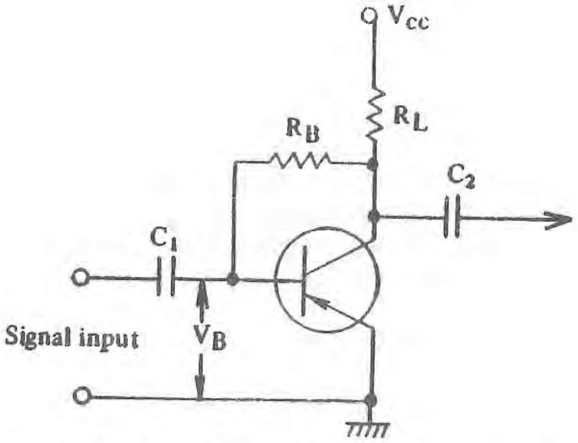


Fig.7-18 Base bias provided by R_B as voltage dropping resistor from the collector voltage V_C

(c) Self-bias in the emitter circuit

In Fig. 7-19, the emitter voltage V_E of 0.8V results from the voltage drop I_ER_E. This voltage is self-biased because V_E depends on the emitter current. However, note that V_E is positive at the N emitter, which is opposite from the polarity for forward bias. Therefore, a voltage divider in base circuit in base circuit is used to provide the required forward voltage. Here the R_1, R_2 divider supplies 1.4V positive at the base, in the forward polarity. The net bias voltage between base and emitter then is V_{BE}, equal to $1.4 - 0.8 = 0.6V$.

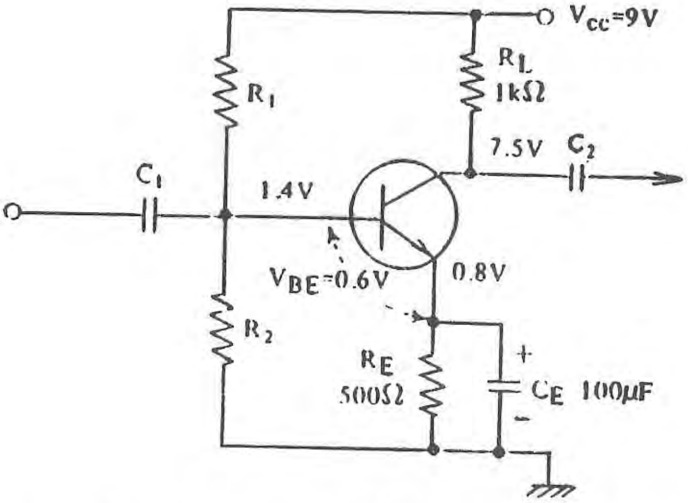


Fig.7-19 Typical audio amplifier circuit with self-bias in emitted circuit and base bias provided by the R_1, P_2 voltage divider

(3) Push-pull amplifier class B

In a similar manner to push-pull class B operation of vacuum tubes, Fig. 7-20 shows push-pull operation of the transistor.

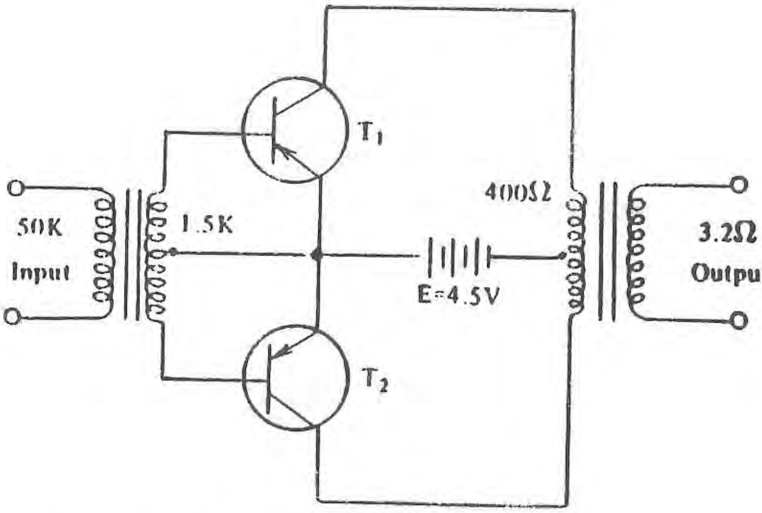


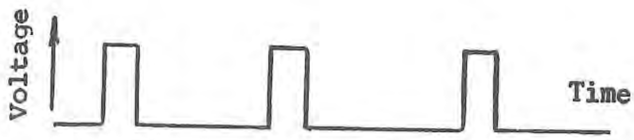
Fig.7-20 Push-pull amplifier (class B)

The bases of the two transistors are fed from a double signal source, in this case a transformer, that has both an in-phase and out-of-phase component of the applied signal. The signal applied to the base of one transistor is 180° out of phase with the signal applied to the base of the other transistor. As the transistors are zero biased, they conduct on only one-half the input cycle wave form. One transister at a time will conduct because of the phase difference, and both feed a common load. As with the vacuum tube amplifiers, the push-pull circuit is characterized by a high efficiency output and a cancellation of even order harmonic distortion within the stage.

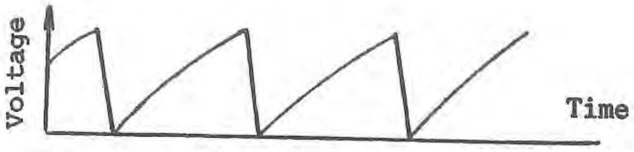
8. Pulse

8.1 General

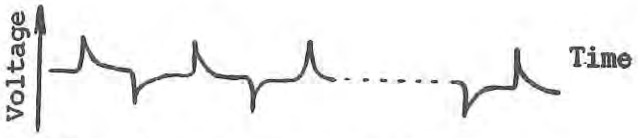
In many of the more recently developed radio transmission services, systematic use is made of electrical impulses having nonsinusoidal wave shapes of various specific forms. Some of these wave shapes are illustrated in Fig. 8-1.



(a) Periodic rectangular voltage pulses



(b) Saw-tooth wave



(c) Periodic trigger pulses

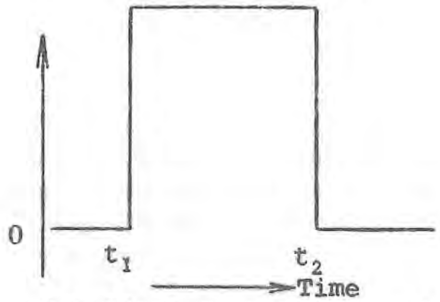
Fig.8-1 Various nonsinusoidal waves used in certain radio navigation equipment

These wave shapes are used extensively in radio navigation equipment and fishing electronic equipment. Consequently, such system include circuits designed to generate, shape and amplify nonsinusoidal voltages of special wave form.

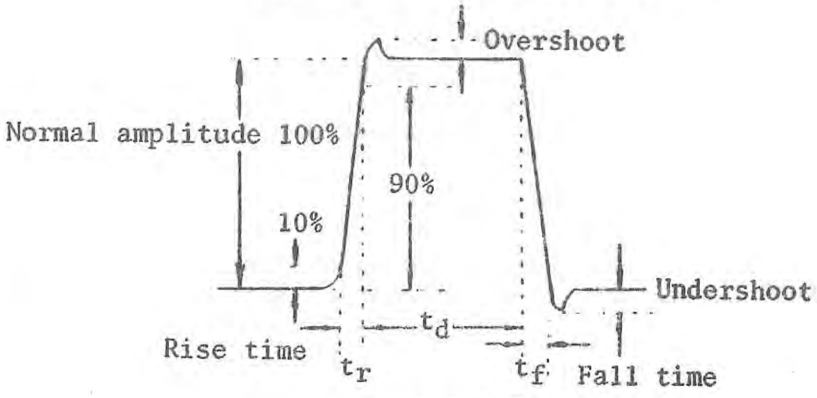
(1) Definitions

A pulse may be defined as a brief flow of voltage or current. It may be recurrent, but it is not cyclic except in the sense of being a highly distorted wave form.

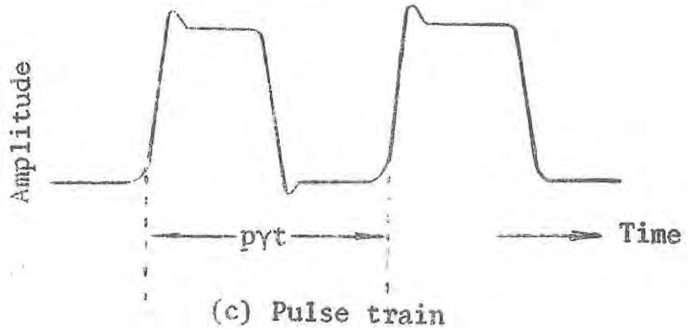
An ideal rectangular pulse is shown in Fig. 8-2. At time t_1, the voltage or current rises instantly from zero to maximum value. It remains at this value until time t_2, and then instantly returns to zero.



(a) Ideal rectangular pulse



(b) Modified pulse



(c) Pulse train

Fig.8-2 A rectangular pulse

In practical circuits, lumped or distributed inductance, capacitance and resistance always exist. As a result, such instantaneous changes as shown in Fig. 8-2(a) cannot occur.

A finite period of time must elapse before the voltage rises to a normal value or drops to zero.

This causes a modification of the ideal rectangular pulse, and it may assume the form shown in Fig. 8-2(b).

The time required for the pulse to increase from 10 to 90 percent of normal amplitude is called the *rise time* and is indicated by the letter symbol t_r.

The time required for the pulse to decrease from 90 to 10 percent of normal amplitude is called the *fall time* and is indicated by the letter symbol t_f.

The time interval between the end of rise time and the beginning of fall time is called the *duration* and is indicated by the letter symbol t_d. In some pulse generation, the initial amplitude rise exceeds the correct value and as shown in(b), a pipe called an *overshoot* is produced on the waveform. They may also be a corresponding undershoot when the amplitude suddenly falls. When pulses occur at regular intervals, as shown in Fig.3-2(c), the time between a point on one pulse and the corresponding point on an adjacent pulse is called the *pulse repetition time* abbreviated P γ t. A series of successive pulses is called *a pulse train*. The number of pulses that occur per second in a pulse train is called the *pulse repetition frequency*, abbreviated P γ f, or pulse repetition rate, abbreviated P γ r.

(2) A step voltage wave-form

A step voltage wave-form is defined as one which maintains a value of zero for all the time before to and then rises instantaneously to a value of E after t_o.

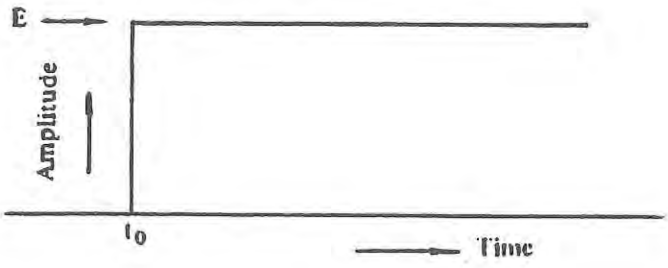


Fig.8-3 Step voltage

Such a waveform is shown in Fig. 8-3. An ideal rectangular pulse, such as that shown in Fig. 8-2(a), is actually the sum of two step voltages. This may be demonstrated by Fig. 8-4. The first step voltage, termed +E, occurs at time to and continues for the duration of the pulse. The second step voltage, termed -E, begins at the end of the pulse duration, time t_d, and continues until another pulse is applied. The resulting ideal pulse and the two step voltages are shown in Figs 8-4(a),(b) and (c) respectively.

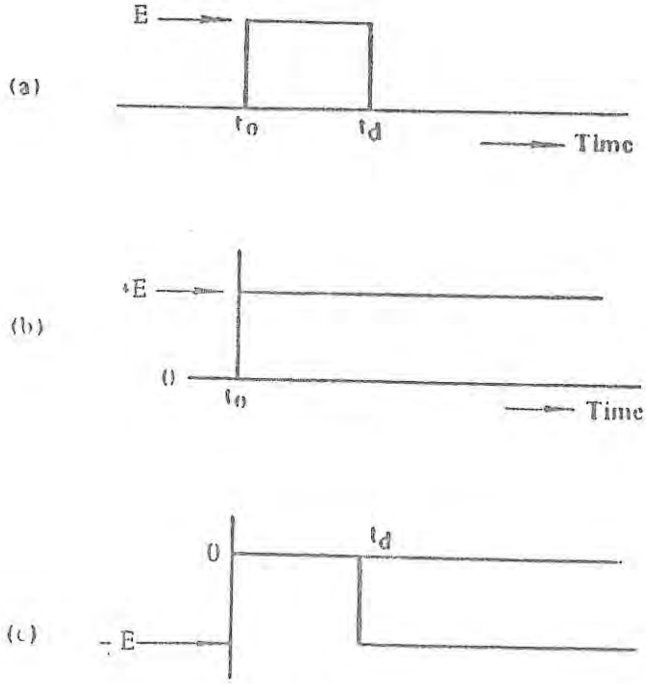


Fig. 8-4

(3) General considerations

In some applications, certain pulse characteristics can be changed without seriously affecting the transmission of intelligence. In a telegraph system, for example, rise and fall time may be altered within certain limitations without serious affecting the transmitted intelligence. The only requirement is the operator's ability to distinguish between dots and dashes. The capability with which a circuit passes a given wave form depends on its response characteristics. Familiarity with the response characteristics of various networks is the required foundation for understanding pulse-type circuits.

8.2 Pulse generating circuit

Pulse generation circuits are devided into two general classifications: passive (pulse-shaping) and active (self-oscilating).

In pulse generators of the passive type, a sine-wave oscillator is used as the basic generator. The output of this oscillator is then passed through pulse shaping circuits to obtain the desired wave form.

Active pulse generators are circuits which generate a pulse wave form directly and most of the active pulse generators use the relaxation principle. This method consists of building up energy in a capacitor and then, when a certain level of voltage is reached, discharging the capacitor. The multivibrator is the most common type of relaxation oscillator.

(1) Definitions

Multivibrator (MV)

A type of relaxation oscillator consisting of a two-stage resistance-coupled amplifier with the output of each stage regeneratively coupled to the other. In operation, the plate or collector current of one stage is at a maximum when the plate or collector current of the other is cut off. At regular intervals, or when properly triggered, switching from one state to the other occurs.

Astable MV:

A multivibrator in which neither stage is at a stabel state and the stage are switched from one state to the other at regular actuating voltage.

Bistable MV:

A multivibrator in which one stage remains stable in one state, with either stage conducting and the other cut off, until a triggering pulse is applied to initiate the switching action to reverse the stability condition.

Monostable MV:

A multivibrator which maintains current in one stage until it is triggered, at which time the other stage is made to conduct for a predetermined length of time and is then automatically switched back to its original state.

(2) Astable MV

(a) Vacuum tube astable MV

The circuit diagram of a vacuum-tube astable (free-running) MV is shown in Fig. 8-5.

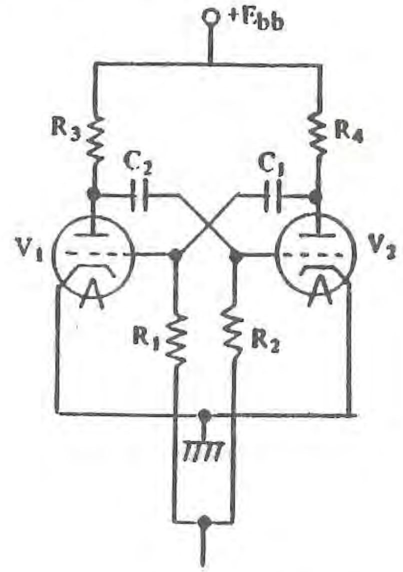


Fig.8-5 Vocuum tube as table MV

It is a simple R-C amplifier with the plate of each tube capacitively coupled to the grid of the other. Because there is a 180° phase reversal in signal between the grid and plate circuits of each tube, the feedback through the capacitor is regenerative. Any phase shift introduced by the R-C components is negligible and for practical purpose is disregarded.

(b) Transistor astable MV

A transistor astable multivibrator is shown in Fig. 3-6. The circuit is a simple R-C coupled common-emitter amplifier with the output of each transistor coupled to the input of the other. Because the common-emitter configuration provides signal inversion, the feedback is regenerative.

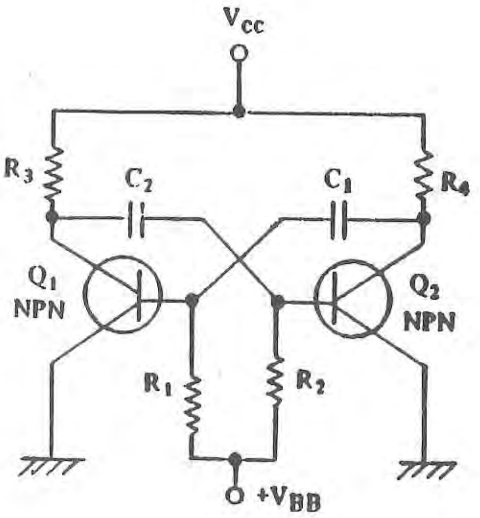
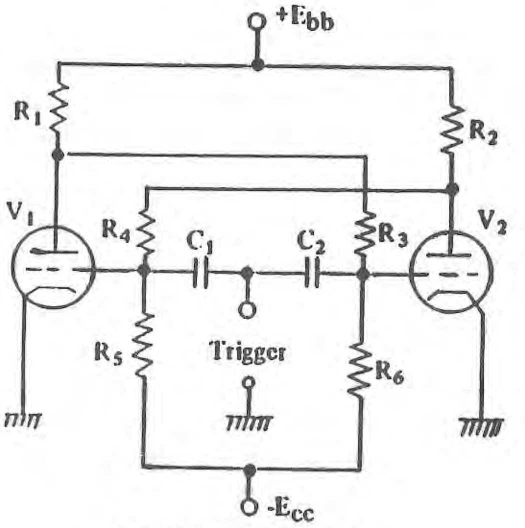


Fig.8-6 Transistor astable MV

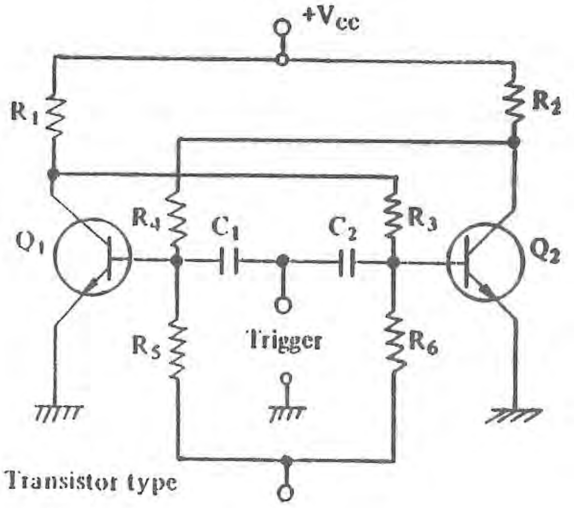
(3) Bistable MV

In the bistable multivibrator, an output pulse is obtained only if a driving (triggering) pulse is applied to the input. A full cycle of output is produced for every two triggering pulses properly applied and of correct polarity and amplitude.

The basic circuit, known as the Eccles - Jordan trigger circuit after its inventors, is shown in Fig. 8-7(a) and (b).



(a) Vacuum-tube type



(b) Transistor type

Fig.8-7 Bistable MV

Resistance coupling is used between the plates and grids of two tubes in(a) and between the collectors and bases of the transistors in (b). The circuit has two stable states or conditions of balance: one when V_1 or Q_1 is conducting and V_2 or Q_2 is cut off and the other when V_2 or Q_2 is conducting and V_1 or Q_1 is cut off. The circuit remains in one or the other of these stable states. There is no action to cause any of the electrode potentials to change while the circuit is in either steady state condition.

The nonconducting stage is caused to conduct by the proper application of a triggering pulse. A rapid reversal then occurs from one steady state to the other. Because of this rapid reversal, the circuit is also refered to by various other names such as the flip-flop, flip-flip, and flop-over.

The names regenerators, binary counter, locking circuit and frequency divider have also been used in connection with this circuit.

(4) Monostable MV

A monostable multivibrator is named for its self-restoring action: it is a multivibrator with only one permanently stable state. A correctly applied triggering pulse may produce a reversal of the stable state, but the circuit returns spontaneously to its original permanently stable condition. The temporary-stable state exists for only a finite period of time. Each time a triggering pulse is applied, the circuit first switches to the quasi-steady condition, and then, after a finite period of time, reverts to its original permanently stable condition where it remains until another pulse is applied.

Other names commonly used to describe the same circuit are *one-shot, driven* and *triggered* multivibrator. The circuit of a vacuum-tube monostabe MV is shown in Fig. 8-8 and that of a transistor monostable MV is shown in Fig. 8-9.

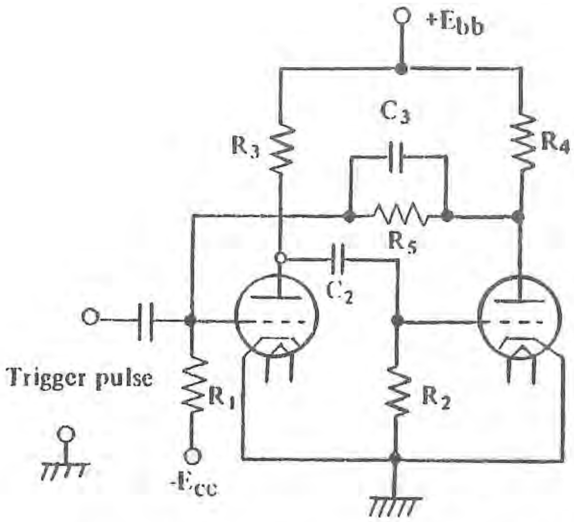


Fig.8-8 A vacuum-tube monostable MV

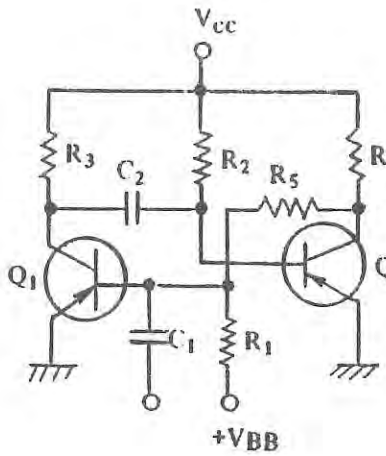


Fig.8-9 A transistor monostable MV

8.3 Pulse shaping circuit

(1) Shaping

Unwanted portions of waveforms may be clipped off or eliminated in another form of diode circuit, shown in Fig. 3-10.

If it is found desirable to eliminate all positive portions of the applied wave above a certain level E, the circuit of (a) may be used. As soon as the input exceeds E the diode has a positive anode and conducts, recording or shorting the output down to the fixed value of E. When the wave swings negative the diode opends, allowing the input wave to be passed to the output.

Resistance R should be large with respect to the diode forward resistance, and crystal diodes are preferred. Reversal of the series voltage allows the wave to be clipped at negative levels as in (b). Use of two diodes and two voltages allows a wave to be clipped on both halves, and if this is carried out at a low point on a sine wave the result is a fair approximation to a square wave.

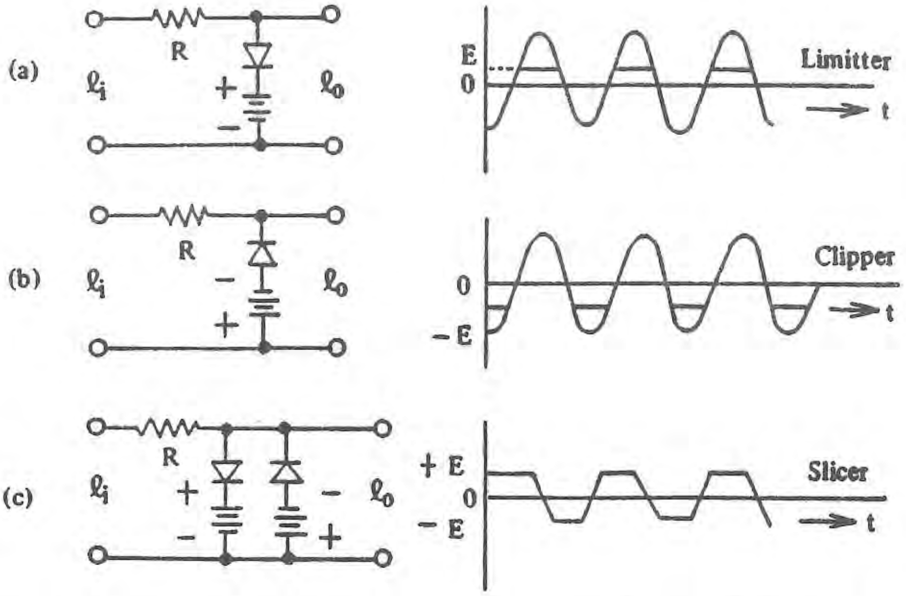


Fig.8-10 Circuits for clipping at levels other than zero

(2) Clamping circuit

It may be desired to insert a D.C. component or a zero axis into a wave at a particular level, after the wave has passed through an RC amplifier and lost its own D.C. axis. This operation can be performed by either a vacuum tube or a crystal diode in circuits such as in Fig. 3-11. The diode should have an internal forward resistance which is small with respect to R, and the condition is most easily met with crystals.

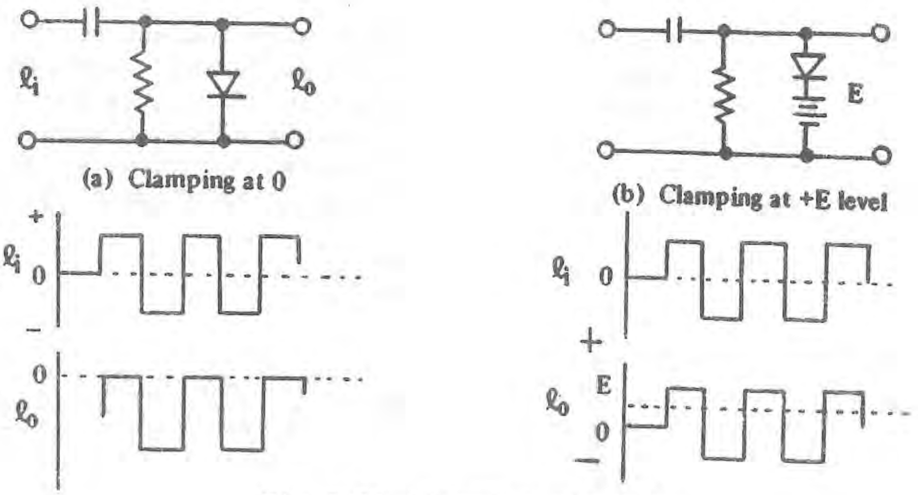


Fig.8-11 Clamping circuits

(3) Simple pulse-forming circuits.

The simple circuit of Fig. 3-12 is available for producing an output which is proportional to the rate of change or slope of an input wave. This operation is illustrated in Fig. 3-13(a) and (b), where a saw-tooth wave form is distorted by such a rate of change circuit as produce a rectangular set of pulses, positive where the input has an upward slope, negative where the input has a downward slope.

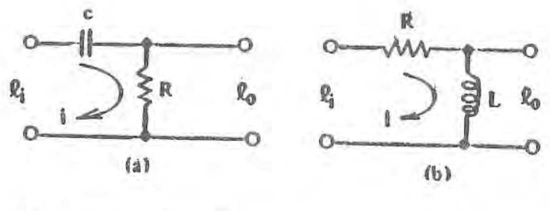


Fig.8-12 Networks for producing an input proportional to the rate of change of e_i

This action is further demonstrated in Fig. 8-13,(c) and (d), where a square wave is applied to the circuit and sharp pulses obtained only at the instants of rise and drop. Theoretically the heights of these pulses should be infinite because the slope of the square waves is infinite, but circuit limitations, including the fact that no voltage can ever rise at infinite speed in a practical circuit of R, L or C, causes the response to be more accurately represented by Fig. 8-14.

Such circuits are frequently employed to sort out waveforms having a given slope, or to reshape distorted pulses, usually in connection with tubes or transistors.

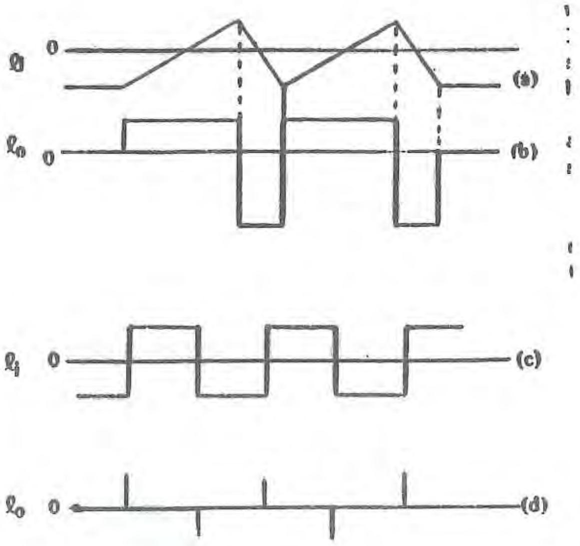


Fig.8-13 Effect of the circuit of Fig.8-12

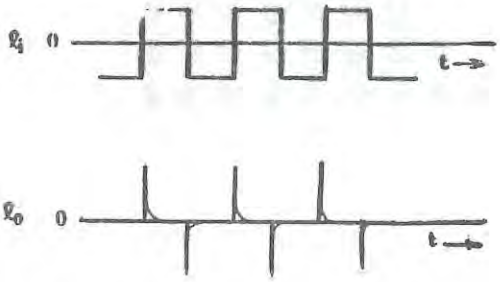


Fig.8-14 Actual performance of a circuit of the form of Fig. 3-12(b)

9. Digital Conception

9.1 General

Digital information processing requires special electronic components. Diodes and transistors can be used as switches in gates and flip-flops.

The efficient design of digital circuits also requires a special numbering system and a special algebra.

9.2 Binary number system

When we hear the word "number", most of us immediately, think of the familiar decimal number system with its ten digits: 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9. The 10 basic symbols arose because we have 10 figures.

The most familiar number system is the decimal system, whose digits are symbolized in Table 1.

Table-1 The decimal digits

Pebbles	Symbol
None	0
●	1
●●	2
●●●	3
●●●●	4
●●●●●	5
●●●●●●	6
●●●●●●●	7
●●●●●●●●	8
●●●●●●●●●	9

In the table are 10 basic symbols or digits: 0 through 9. Each of these symbols stands for a certain number of pebbles.

Other symbols could just as easily be used. For instance, instead of 0, 1, 2, 3, ... 9, we can use A. B. C. D......... J.

The use of 10 digits, 0 through 9, is really unnecessary. After all, since a number system is only a code, we can use any number of code symbols we want. A binary number system is a code that uses only two basic symbols. These digits can be any two distinct characters like A and B and the customary 0 and 1.

Table 2 shows the symbols of the binary number system.

Table-2 The binary digits

Pebbles	Symbol
None	0
●	1

What can we use for ● ● , ● ● ● and so on? After we reach 9 in the decimal number system, we form combination of decimal digits to get 10, 11, 12 etc. In the other words, the next decimal number after 9 is obtained by using the second digit followed by the first to get 10. The decimal number after 10 is obtained by using the second digit followed by second to get 11 and so forth.

In the binary system we use the same approach. After we reach 1, we have run out of binary digits. To represent ● ● , we merely use the second binary digits followed by the first to get 10. To present ● ● ● , we use 11. Thus, we count in binary as follows:

0, 1, 10, 11, 100. To avoid confusion with decimal numbers, it helps to read these binary numbers as zero, one, one-zero, one-one and one-zero-zero.

9.3 Number conversion

a) Binary to decimal conversion

In a binary number, each position to the right or left of the "binary point" corresponds to a power of 2, and each power of two has a decimal equivalent.

To convert a binary number to its decimal equivalent, add the decimal equivalents of each position occupied by a 1.

b) Decimal-to-binary conversion

A decimal number can be converted into its binary equivalent by the inverse process, i.e., by expressing the decimal number as a sum of powers of 2.

To convert a decimal integer to its binary equivalent, progressively divide the decimal number by 2, noting the remainders, the remainders taken in reverse order form the binary equivalent.

To convert a decimal fraction to its binary equivalent, progressively multiply the fraction by 2, removing and noting the carries; the carries taken in forward order from the binary equivalent.

c) Binary arithmetic

In addition, we add column by column, carrying where necessary into higher position columns.

In subtraction, we subtract column by column, borrowing where necessary from higher position columns.

In subtracting a larger number from a smaller, we can subtract the smaller from the larger and change the sign just as we do with decimals.

In multiplication, we obtain partial products using the binary multiplication table ($0 \times 0 = 0$, $0 \times 1 = 0$, $1 \times 0 = 0$, $1 \times 1 = 1$) and then add the partial products.

In division, we perform repeated subtractions just as in long division of decimals.

9.4 Boolean Algebra

Boolean algebra, which permits only two values or states for a variable, is well suited for the study of electrical switching circuits. The two permitted values of a variable are usually taken as 0 and 1, which may represent open and closed conditions of switches or false and true when applied to logical statements.

a) The OR gate

In digital electronics a gate is a circuit with one output and two or more input channels; an output signal occurs only for certain combination of input signals. The first kind of gate that we study is the OR gate. In the OR gate an output occurs when there is a signal in any of the input channels.

Figure 9-1 shows a two-input OR gate where a and b are the inputs and x is the output.

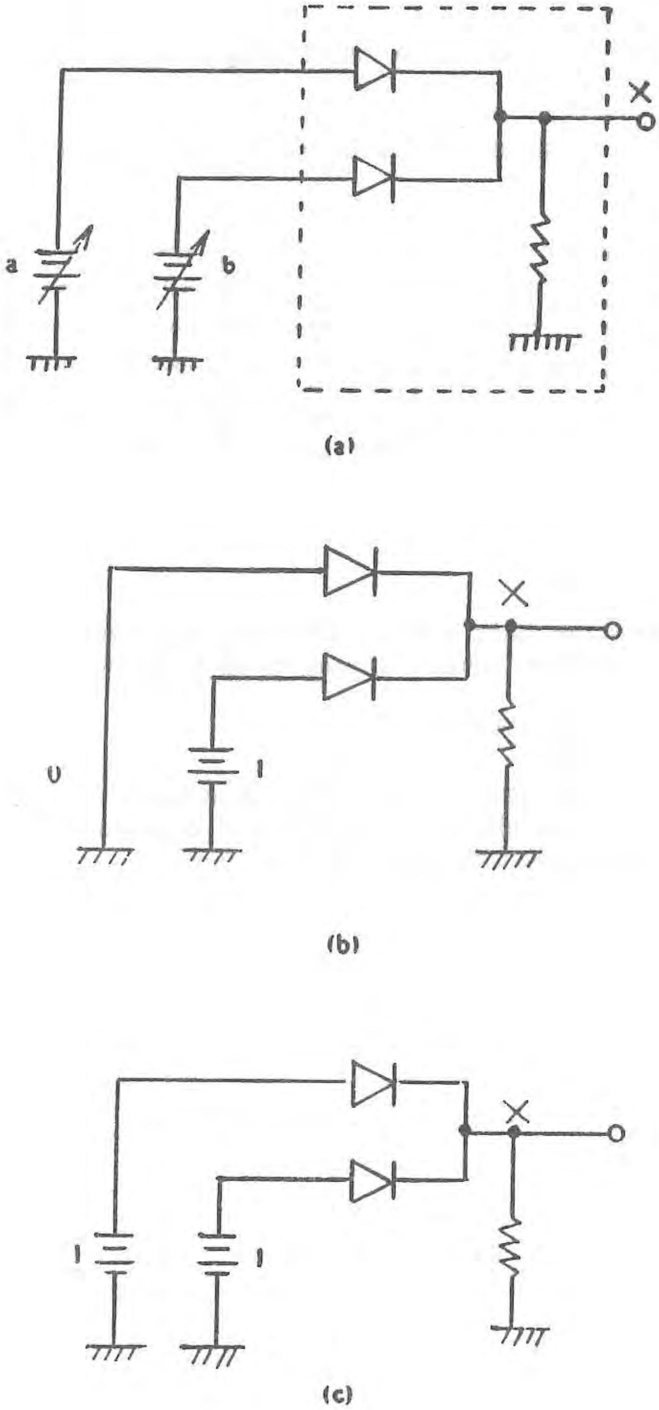


Fig.9-1 OR gate

For the moment, let us analyse this OR gate by restricting the input voltages to either 0 or 1 volt. There are only four possible cases to analyse.

Table 3 lists the input-output conditions of an OR gate.

Table-3 The OR gate truth table

a	b	x
0	0	0
0	1	1
1	0	1
1	1	1

Examine this table carefully and memorize the following: the OR gate has output 1 when either a or b or both are 1.

b) The AND gate

The AND gate is another basic kind of digital circuit. It has an output only when all inputs are present. As an example, consider the two-input AND gate of Fig. 9-2.

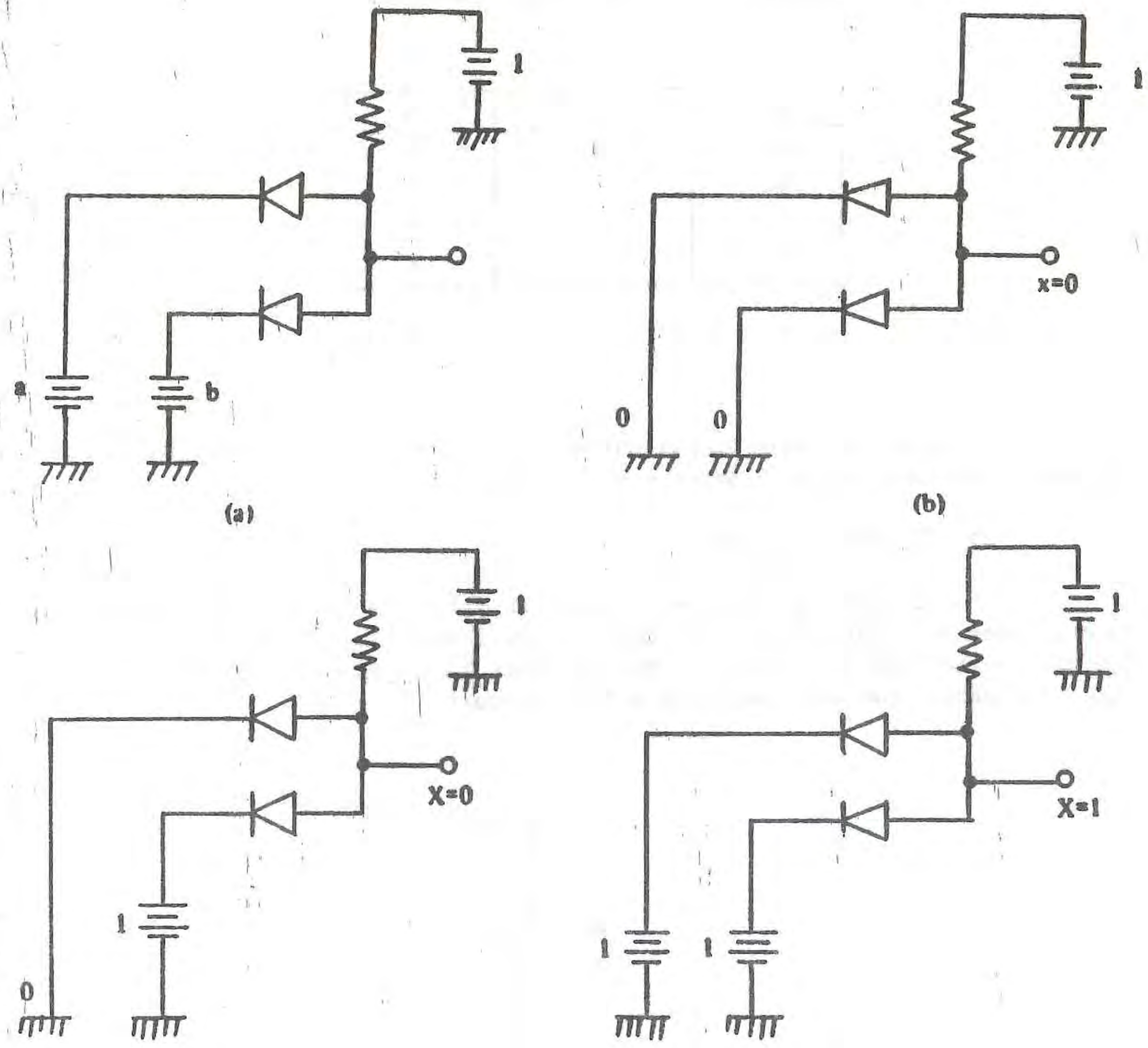


Fig.9-2 AND gate

Again, let us restrict all voltages to either 0 or 1 volt. There are four cases to analyse.

Table-4 The AND gate truth table

a	b	x
0	0	0
0	1	0
1	0	0
1	1	1

Examine this table carefully and memorize the following: the AND gate has output 1 when a and b are 1.

c) The NOT circuit

Another of the basic digital circuits is the NOT circuit, also called a complementary circuit or an inverter. This circuit has one input and one output. All it does is invert the input signal. Fig. 9-3 shows one way to build a NOT circuit.

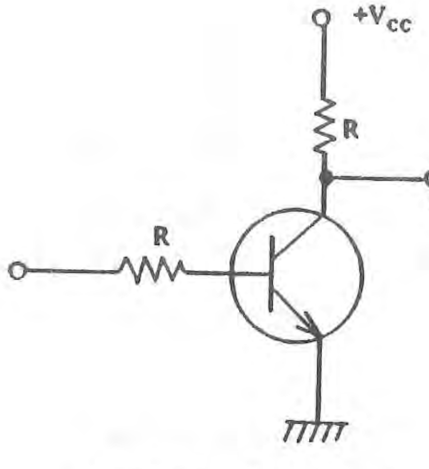


Fig.9-3 The NOT circuit

When the input voltage is high enough, the transistor saturates; therefore, the output is low. On the other hand, when the input voltage is low enough, the transistor cut off, and the output voltage is high.

Table-5 The truth table of the NOT circuit

Input	Output
0	1
1	0

We call this circuit a NOT circuit because the output is not the same as the input.

d) Schematic symbols

i) OR gate

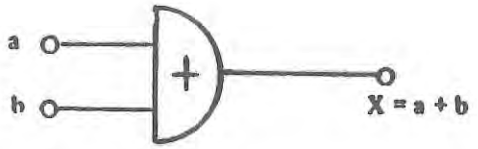


Fig.9.4 OR gate symbol

As shown in Fig. 9-4, we have symbolized a two input OR gate with a and b inputs and x output. In Boolean algebra the + sign symbolizes the action of an OR gate. In other words, we may think of the OR gate as an adding device that combines a with b to give a result x. In Boolean algebra when we write X = a + b we mean that a and b are to combined in the same way that an OR gate combines a and b. To remind us of this, we should read the expression.

X = a + B as X equals a or b

The + sign does not stand for ordinary addition: it **stands** for OR addition whose rules are given by the OR truth table. (Table-3).

ii) AND gate

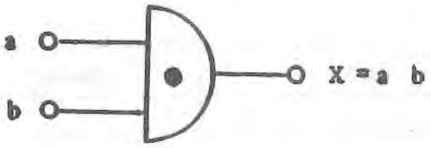


Fig.9-5 AND gate symbol

The multiplication sign has a new meaning in Boolean algebra. We think of an AND gate as a device that combines a and b to give a result of X. In Boolean algebra when we write

$$X = a \cdot b$$

or simply

$$X = ab$$

we mean that a and b are to be combined in the same way that an AND gate combines a with b to give an X output.

Even though the dot does not mean multiplication in the ordinary sense, the result of AND multiplication are exactly the same as for ordinary multiplication. Figure 4-5 shows the block-diagram symbol that we will use for the AND gate.

iii) The NOT circuit

Fig.9-6 NOT circuit symbol

In Boolean algebra the expression means that we are to change a in the same way that a NOT circuit changes a. We read the expression $X = \bar{a}$ as X equals NOT a.

The bar over a simply means that we change or complement the quantity to the alternate digit.

iv) NOR gate and NAND gate

Among DeMorgan's important contributions to logic are these two theorems:

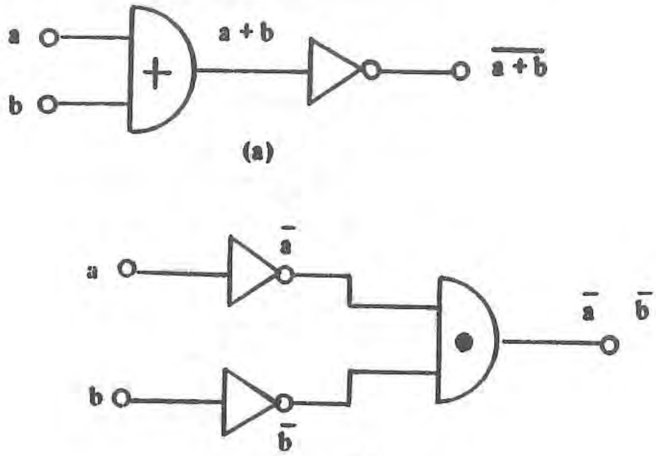
$$\overline{a + b} = \bar{a} \cdot \bar{b}$$

$$\overline{a \cdot b} = \overline{a + b}$$

The first equation says that the complement of a sum equals the product of the compelments.

The second equation says that the complement of a product equals the sum of the complements. The physical meaning of the first theorem is important. $\overline{a + b}$ represents a logic system in which a NOT circuit follows an OR gate (Fig. 4-7(a)).

Also, $a \cdot b$ describes a logic system in which the outputs of two NOT circuits are used as the inputs to an AND gate (Fig. 9-7(b)).



(a)

(b)

Fig.9-7 DeMorgan's first theorem

DeMorgan's theorem tells us that these two systems are interchangeable. In Fig. 4-7(a) a NOT follows an OR gate; we call this particular combination a NOR-OR or simply a NOR gate.

Table 6

a	b	$\overline{a+b}$
0	0	1
0	1	0
1	0	0
1	1	0

Table 7

a	b	$\bar{a}\cdot\bar{b}$
0	0	1
0	1	0
1	0	0
1	1	0

The second DeMorgan theorem is

$$\overline{a\cdot b} = \bar{a} + \bar{b}$$

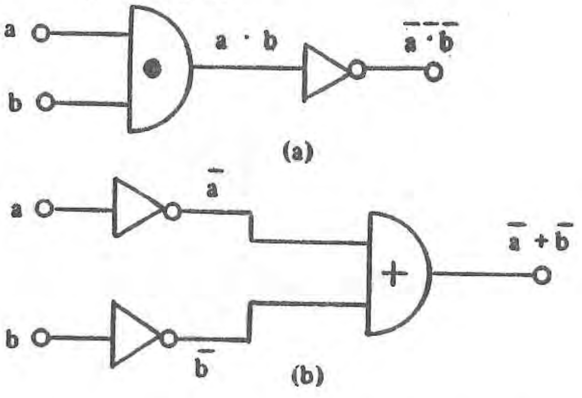


Fig.9-8 DeMorgan's second theorem

Tables 8 and 9 give the truth tables for each expression. Note that the truth tables are identical.

Table 8

a	b	$\overline{a \cdot b}$
0	0	1
0	1	1
1	0	1
1	1	0

Table 9

a	b	$\bar{a} + \bar{b}$
0	0	1
0	1	1
1	0	1
1	1	0

Therefore, the expressions are equivalent and the digital systems represented by a · b and a + b are interchangeable. Figure 8 shows these digital circuits. In Figure 8(a), a NOT follows and AND gate; we call this particular combination a NOT-AND gate, or simply a NAND gate.

We will simply abbreviate the NAND-gate symbol as shown in Fig. 9-9.

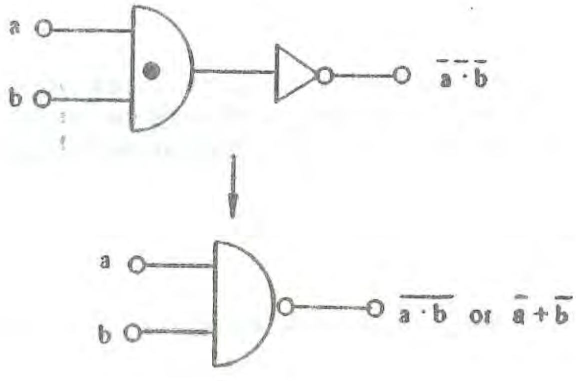


Fig.9-9 NAND gate symbol

9.5 Outline of digital circuits

a) The exclusive OR gate

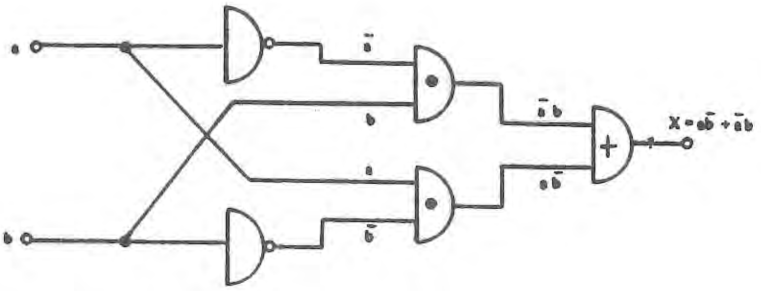


Fig.9-10 Exclusive-OR gate

Figure 9-10 shows an exclusive-OR gate. It has two inputs and one output. Each input goes into a NAND-gate inverter; the output of the NAND gates are $\bar{a}$ and $\bar{b}$. The final output is

$$X = \overline{ab + ab}$$

These result are summarized in Table 10.

Table-10 Exclusive-OR truth table

a	b	X
0	0	0
0	1	1
1	0	1
1	1	0

The exclusive OR gate gives us a new kind of function to work with. We will use the symbol $\oplus$ to stand for this function. That is, when we want to describe an exclusive-OR gate, we can write

$$X = a \oplus b$$

Read this as X equals a or b but not both.

b) The Half-adder

The half-adder adds two binary digits at a time. Fig.9-11 shows how to make a half-adder.

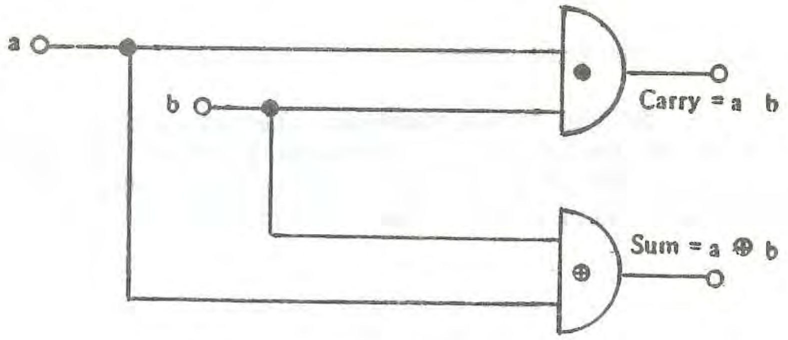


Fig.9-11 Half-adder

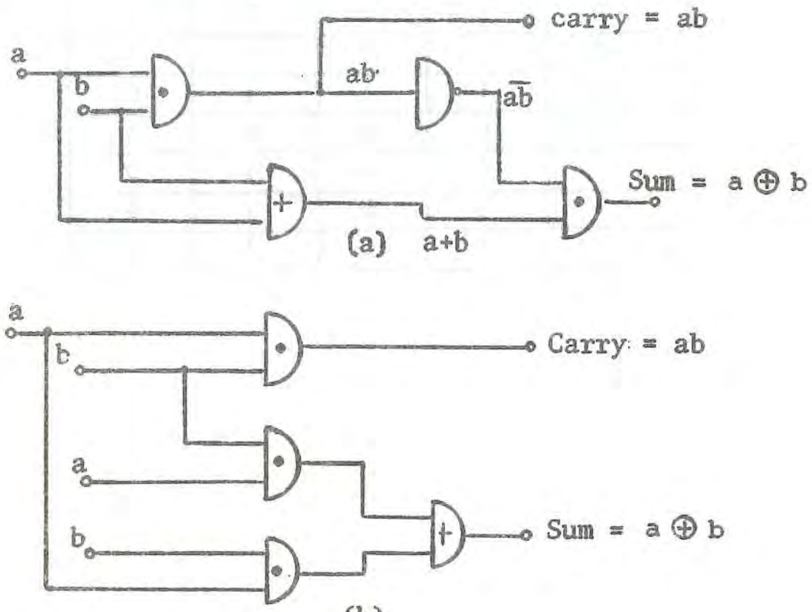
We can summarize these results in Table 11.

Table-11 Half-adder truth table

a	b	Carry	Sum
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

Figure 9-12 shows another way to build a half-adder.

There are many ways to build half-adders. The important thing to remember is that the half-adder adds two binary digits.



(a)

(b)

Fig.9-12 Other froms of half-adder

c) The full-adder

To add binary numbers electronically, we need a circuit that can handle three digits at a time. By connecting two half-adders and an OR gate, we get a full-adder, which is a circuit that can add three digits at a time.

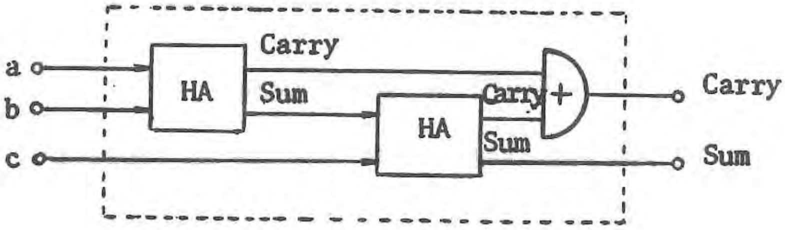


Fig.9-13 Full-adder

Fig. 9-13 shows a full-adder.

Table 11 shows the truth table of the full-adder.

Table-11 Full-adder truth table

a	b	c	Carry	Sum
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

Remember the key idea of the full-adder: it adds three binary digits at a time. Figure 9-14 shows how we can use full-adders to give us the sum of binary numbers with more than one bit.

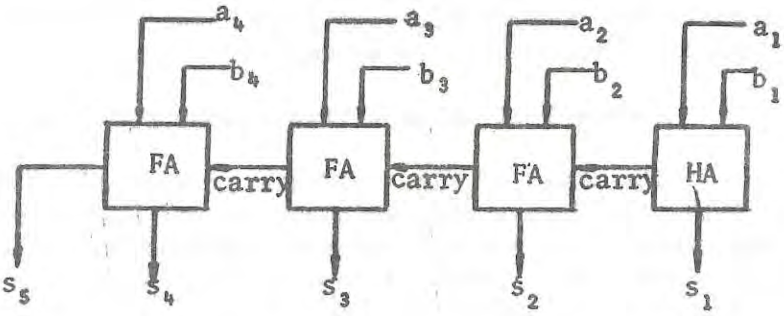


Fig.9-14 Parallel binary adder

Figure 15 shows a system that subtracts b_4 b_3 b_2 b_1 from a_4 a_3 a_2 a_1

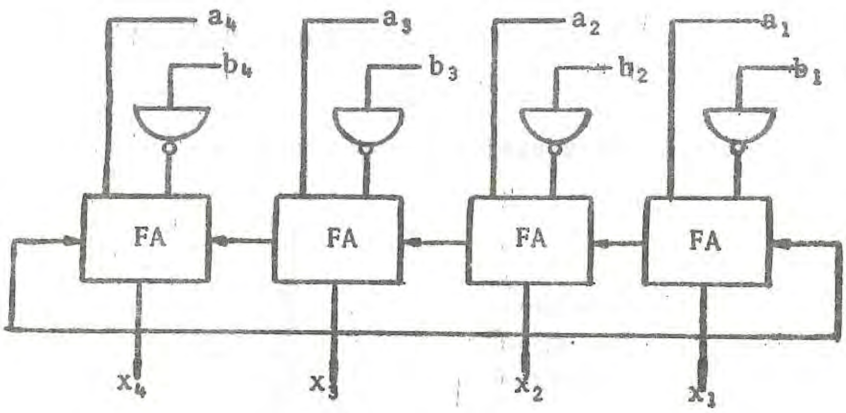


Fig.9-15 Parallel binary subtractor

9.6 Logic Systems

We can make logic systems using a variety of parts-like diodes and resistors or diodes and transistors or resistors and transistors.

a) Direct-coupled transistor logic (DCTL)

Direct-coupled transistor logic uses circuits in which input signals are coupled directly into bases and output signals are taken directly from collectors or emitters.

Figure 9-16 shows a three input DCTL NOR gate.

The gates of Fig. 9-17 are an example of DTL circuits. In Fig. 9-17, the diodes and resistors in the base circuit form an OR gate; the transistor is a NOT circuit; therefore, we have a NOT-OR or simply a NOR gate. When all the inputs are low, the base shuts off, so that X goes high. When any input is high, the base turns on, so that X goes low.

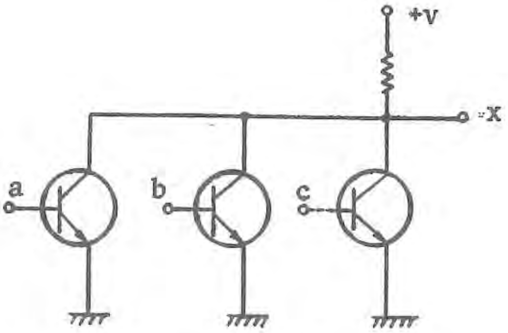


Fig.9-16 A three input DCTL NOR gate

b) Diode-transistor logic (DTL)

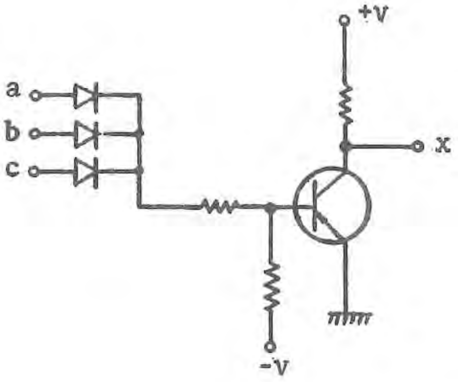


Fig.9-17 Example of DTL logic

c) The T flip-flop

A flip-flop is a multivibrator whose output can be either a low voltage or a high voltage, a_0 or a_1. This output stays low or high until the circuit is driven by an input called a trigger.

The T flip-flop is one type of flip-flop. It will change from low to high voltage, or vice versa, each time that a trigger drives it. There are many ways to build T flip-flop. Figure 9-18 shows an example of T flip-flop circuit.

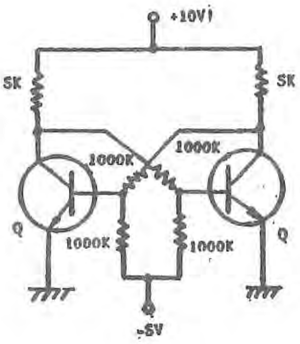


Fig.9-18 Example of T flip-flop

In this circuit on transistor saturates while the other cuts off.