Fundamentals of Radio and Electricity

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PHILIPS

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Fundamentals of Radio and Electricity

Introduction

It is possible to build and operate radio and electronic circuits simply by following the instructions, but the process becomes far more interesting and exciting if the fundamental principles are understood.

This section discusses these principles in sufficient detail to provide a good working knowledge for those who wish to take a more serious interest in electronics.

Atoms and electrons

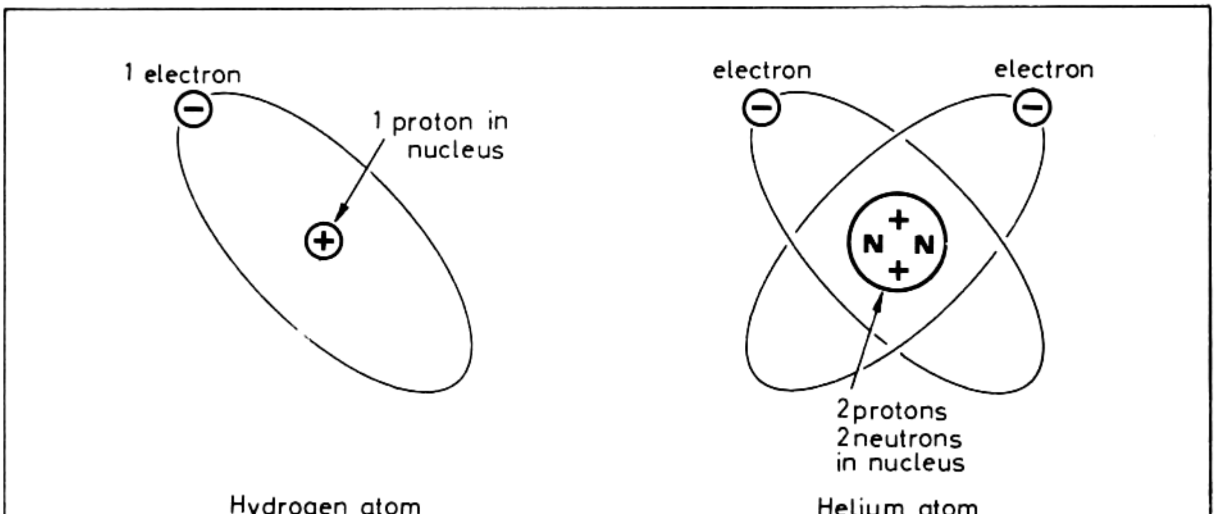
All matter is made up of 'molecules', the name given to the smallest part of an element or compound which can exist on its own and still display the characteristics of that element or compound.

Molecules are composed of still smaller particles called atoms. There are 102 different kinds of known atoms and these combine in various ways to make the molecules of substances we know. For example, two atoms of hydrogen and one of oxygen combine to form a molecule of water. A molecule of hydrogen is normally made up of two hydrogen atoms linked together, but in a strong electromagnetic field the gas dissociates into single atoms when it is known as 'monatomic' hydrogen.

Atoms are so small that they have never been seen but from their behaviour it is known that they are made up of a positively-charged relatively heavy core or 'nucleus', around which move a number of much lighter particles, each negatively charged, called electrons.

The make-up of the nucleus differs from one kind of atom to another and consists of a number of 'protons', each of which carries a positive charge (equal to that of the negative charge on the electron) and possibly a number of 'neutrons' which carry no charge. Atoms are normally electrically-neutral and hence the number of electrons moving around the nucleus is equal to the number of protons in the nucleus, so that the total negative charge of all the electrons exactly balances the total positive charge of all the protons.

The simplest form of atom is the hydrogen atom which has one proton and one electron. Helium has two protons and two neutrons in its nucleus, and two electrons. The copper atom is more complicated having 29 protons in its nucleus and 29 electrons in orbit. See diagram 1.



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The word 'atom' is derived from the Greek word *atomos*, meaning 'uncuttable' or indivisible. The ancient Greeks suggested that matter was composed of such fundamental, indestructible particles. It was not until 1912, however, that Rutherford first suggested the nuclear structure of the atom, following the discovery of the electron a few years earlier by J. J. Thompson. The modern basis of electricity is thus comparatively new and there is much still to be discovered. We now know enough, however, to realise that electricity is in everything around us.

Electric current

The atom is normally electrically neutral—that is, the positive electricity associated with the nucleus is exactly balanced by the total negative charge of its orbital electrons. These electrons revolve at different distances from the nucleus and in some cases the outer ones may be detached from their atoms. Should this happen the atom is no longer electrically-neutral; it is left with a net positive charge equal to the negative charge on the detached electron or electrons.

The ease with which electrons may be detached varies from substance to substance. In some materials electrons are easily detached and, if an electrical pressure (or voltage) is applied across a piece of such material, a drift of electrons will occur. This drift or flow of electrons is known as 'electric current'.

Conductors, insulators and semiconductors

Substances in which electrons are easily detached from their atoms are known as electrical 'conductors'. All metals fall into this category. Materials commonly used as conductors include silver, copper, aluminium, brass, mercury and carbon.

Substances in which the electrons are tightly held are known as 'insulators' because little or no current can flow through them. Typical insulators are mica, quartz, glass, plastics, air and oil.

In between the extremes of conductors and insulators are substances called semiconductors. Germanium and silicon are examples. By adding impurities to germanium and silicon they can be made to act as conductors in certain conditions and this is done in the manufacture of diodes and transistors. Other semiconductors, such as cadmium sulphide, are used for purposes such as the photocell.

Sources of electricity

In order to sustain an electric current through a conductor it is necessary to have some means of producing a continuous supply of electrons. This may be done by means of an electric generator which converts mechanical energy into electrical energy by moving conducting wires rapidly across a magnetic field, or by electro-chemical action as in a battery.

A battery may consist of a number of primary cells joined together in series to give the voltage required. The normal primary cell has an e.m.f. of 1½ volts and six are used in a 9-volt battery. In primary cells the chemicals are used up in time and a new battery is then required.

Another type of cell—called a 'secondary' cell, storage cell or accumulator—has a reversible chemical action and may be re-charged electrically and used almost indefinitely. This type is used in motor-car batteries. A secondary cell has an e.m.f. of about 2 volts and six are contained in a 12-volt car battery.

All sources of electricity provide a concentration of negatively-charged electrons at one point in the system, the negative pole, and an equal deficiency of them at the positive pole. If the negative and positive poles are joined together by a conductor the electrons, with their negative charges, will flow from the negative to the positive pole and this will constitute an electric current.

Positive and negative

Before the nature of electricity was so well understood it was accepted that positive current flowed from the positive terminal to the negative. This is termed 'conventional' current flow. Now we realise that current is in fact a flow of negative electrons from the negative to the positive pole. This is termed 'electron' current flow.

The terms negative and positive are purely arbitrary. It has been assumed that the datum from which negative and positive are measured is the potential of the earth we live on and this is taken as zero. A potential or voltage of one kind with respect to the earth is called positive and one of the opposite kind is called negative; if we had reversed our positive and negative it would have made no difference.

In general, in this manual, we refer to conventional current flow, from positive to negative.

Unit of quantity

As the charge on an electron is always the same, whatever type of atom it belongs to, this amount of charge could be used as the unit of quantity of electricity. It is however far too small to be of practical use and the unit adopted is the 'coulomb'. A coulomb is equal to $6{\cdot}281 \times 10^{18}$ electron charges—that is, it is over 6 million million million times as big as the electron charge. Q is used to represent quantity in terms of coulombs.

Unit of current

A current of one coulomb per second is called one *ampere* or *amp*. The symbol I is used to denote current flow.

A current unit of 1 amp is rather too high for use in electronics and milliamps (mA, or one thousandth of an amp) or micro-amps (μA; one millionth of an amp) are normally used.

The relationship between quantity and current is:

$$\underset{\text{(coulombs)}}{\text{Quantity}} = \underset{\text{(amps)}}{\text{Current}} \times \underset{\text{(secs)}}{\text{Time}}$$

$$\text{or} \quad Q = I \times t.$$

Unit of electrical pressure (e.m.f.)

The battery or other source of electron supply produces an 'electromotive force' (e.m.f.) which forces electrons to move along a conductor. This is comparable to the water pressure produced by a water tank in the roof; the higher it is, the greater the water pressure. The unit of electrical pressure is the *volt*.

Unit of electrical resistance

The resistance which a wire offers to the flow of electric current depends upon the nature of the material from which the wire is made (whether it is a good conductor or a bad conductor) and upon the cross-section of the wire and upon its length. This resistance is denoted by the symbol R and is measured in ohms. A circuit is said to have a resistance of one ohm if a current of one amp flows when the voltage across it is one volt.

A resistance of one ohm is small in comparison with the resistances normally used in electronics and the larger units kilohm (kΩ, or 1000 ohms) or the Megohm (MΩ; 1,000,000 ohms) are used.

Ohm's Law

It will be seen from the above that in a circuit there is a fixed relationship between volts, resistance and current. This is expressed in Ohm's Law which states:

$$\text{Current (in amps)} = \frac{\text{Volts (in volts)}}{\text{Resistance (in ohms)}}$$

$$\text{or} \qquad I = \frac{E}{R}$$

If two of these quantities are known the third can be calculated.

Thus, if a 1 kΩ resistor (or 1000 ohms) is connected across a 9-volt battery the current flowing through the resistor will be:

$$I = \frac{9}{1000} = {\cdot}009 \text{ amps}$$

$$= 9 \text{ milliamps.}$$

Electrical power

When a current flows through a resistor, it does work which is normally dissipated in the form of heat—for example, if the resistance is the filament of an electric bulb, it can be seen that the filament is raised to a white-heat temperature.

The unit of electrical power is the *watt* and the power dissipated in a circuit is:

$$W \text{ (watts)} = V \text{ (volts)} \times I \text{ (amperes).}$$

The power in Watts is the *rate* of working and 746 watts are equal to one horse-power. Thus, if the current through a transistor is 60 mA and the voltage between its collector and emitter is 0·2 volts the power dissipated in the transistor is:

$$W = 0{\cdot}2 \times \frac{60}{1000} = \frac{12}{1000} \text{ watts}$$
$$= 12 \text{ milliwatts.}$$

Resistors in series and parallel

Resistors may at times be joined in series or parallel as shown in diagram 2 (*a*) and (*b*).

In case (*a*), where the resistors are in series it is clear that the total resistance R is equal to the sum of the separate resistances. That is,

$$R = R1 + R2 + R3.$$

In the case of (*b*), where the resistors are in parallel it is clear that the voltage across the resistors R1, R2 and R3 is the same for each—say, E. The current through each resistor is therefore:

$$I_1 = \frac{E}{R1},\quad I_2 = \frac{E}{R2},\quad I_3 = \frac{E}{R3}$$

The total current I (total)

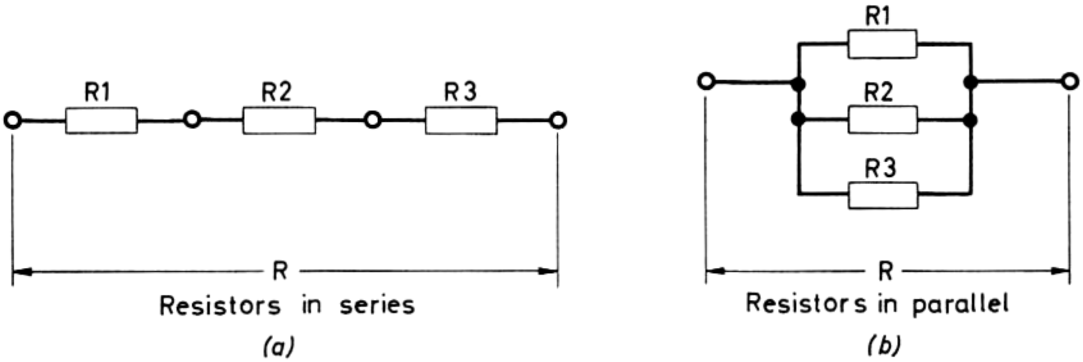
$$= I_1 + I_2 + I_3$$
$$= \frac{E}{R1} + \frac{E}{R2} + \frac{E}{R3}$$
$$= E\left(\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3}\right)$$

But I (total) $= \frac{E}{R}$ where R is the equivalent resistance of the circuit.

$$\text{Thus } \frac{E}{R} = E\left(\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3}\right)$$

$$\text{or } \frac{1}{R} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3}$$

That is, the reciprocal of the total resistance of a number of resistors in parallel is the sum of the reciprocals of the individual resistances.



Resistors in series
(*a*)

Resistors in parallel
(*b*)

2

Capacitors (condensers) and capacitance

Capacitors (or condensers) have the ability to store charges of electricity. They consist of two conducting plates separated by an insulating medium called a 'dialectric' (which may be air).

Diagram 3 shows two parallel conductor plates of area A separated by air at a distance *d*. They are connected to a battery of e.m.f. V volts.

When the battery is connected a (conventional) current flows momentarily from the battery to the positive plate. This current is the transfer of an electrical charge from the battery to the plate. As this transfer takes place the potential of the plate rises from its original level (say zero) to the voltage of the battery. When this voltage is reached the flow of current ceases and the capacitor is charged to a voltage V.

If the amount of charge which has flowed into the capacitor is Q coulombs (one coulomb equals one ampere flowing for one second), then the capacitance (or capacity) of the capacitor is $Q/V = C$ farads.

A capacitor is said to have a capacitance of one farad if a charge of one coulomb raises its potential by one volt. In practice smaller units are used. These are microfarads (μF, or one millionth of a farad) or picofarads (pF or μμF, equivalent to one millionth of a millionth of a farad).

In practical terms the capacitance may be calculated from the formula:

$$C = \frac{0{\cdot}0885\ KA}{d} \quad \text{pF}$$

where A is the area of overlap of the plates in square centimetres and *d* is the distance apart in centimetres. The same formula holds good if the dimensions are in inches provided 0·224 is substituted for 0·0885.

K is the dielectric constant of the material between the plates. It is 1 for air or a vacuum, 2·5 for paper, 7 for mica and may be up to 1,000 for certain ceramics. K is also known as the 'relative permittivity' or 'specific inductive capacity' of a material.

Thus capacitance is directly proportional to the area of the plates and the dielectric constant of the material between them, and is inversely proportional to the distance between the plates.

Electric field

When a capacitor is charged to a voltage V an electric field is established between the plates. The lines of electric force shown in the diagram indicate the nature and direction of the field. If a point charge (a unit positive charge) were introduced between the plates, it would be forced along the lines of force in the direction of the arrows. If the point charge were negative in character, it would travel in the opposite direction.

Whenever there is a potential an electric field is present. Voltage establishes an electric field just as current establishes a magnetic field around the wire it flows through. The electric and magnetic fields are constituent elements of radio waves and other forms of electromagnetic wave propagation (for example, light).

Capacitors in series and parallel

As the capacitance depends on the area of the plates, it would be expected that, when several capacitors are connected in parallel, the various capacitances would be added together (as would be the plate areas). This is in fact the case.

Thus, when capacitors are connected in parallel as shown in diagram 4 (*a*) the total capacitance is

$$C_T = C1 + C2 + C3$$

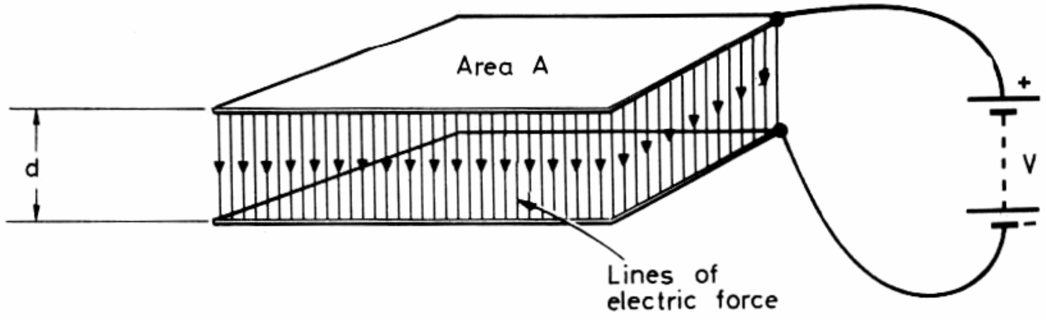
When they are connected in series as at (*b*) their total capacitance is given by:

$$\frac{1}{C_T} = \frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3}.$$

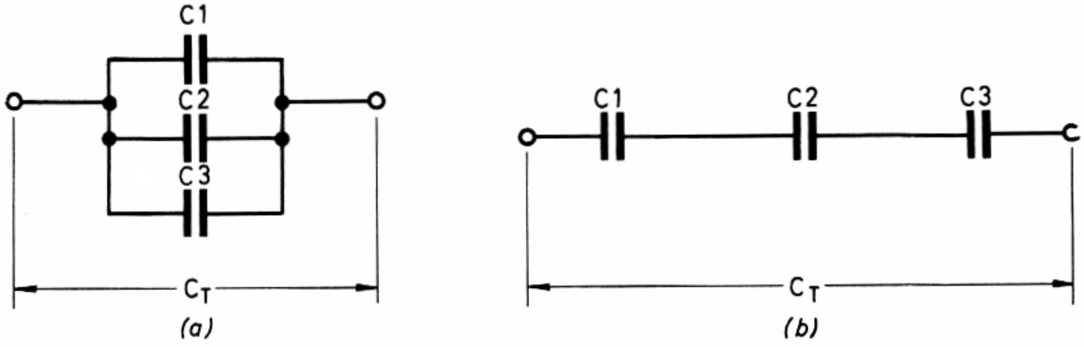
Charge and discharge of a capacitor (time constant)

If a capacitor C is connected to a battery via a resistor R as in 5 (*a*), a current will flow through R until the capacitor is charged up to the voltage V.

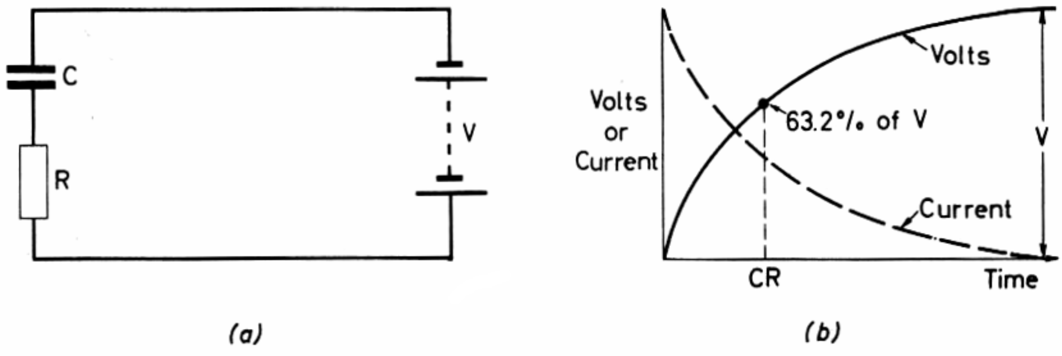
As the capacitor charges the voltage across it will rise as in diagram 5 (*b*). At any point in the charging process the voltage across R is the difference between the battery voltage and the voltage already built up in the capacitor. This difference is decreasing and so the rate of flow of current decreases as shown in 5 (*b*).


Area A
d
+
V
-
Lines of electric force

3


C1
C2
C3
C_T
(a)
C1
C2
C3
C_T
(b)

4

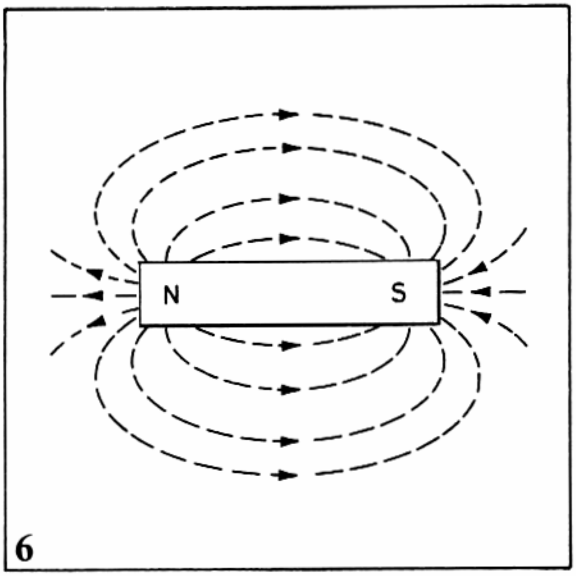

C
R
V
(a)
Volts or Current
Volts
63.2% of V
V
Current
CR
Time
(b)

5

The voltage on the capacitor will rise to 63·2% of its final value V (or to within 1/e of its final value, where e = 2·71828, the base of natural logarithms) in CR seconds, where C is in farads and R is in ohms.

This time is known as the *time constant* of the circuit.

If the battery is disconnected, the capacitor will retain its voltage (indefinitely in the case of the ideal capacitor). If the resistor R is now connected across the charged capacitor a current will flow through R until the capacitor is discharged. The voltage across the capacitor will fall by 63·2% in a time equal to the time constant CR.



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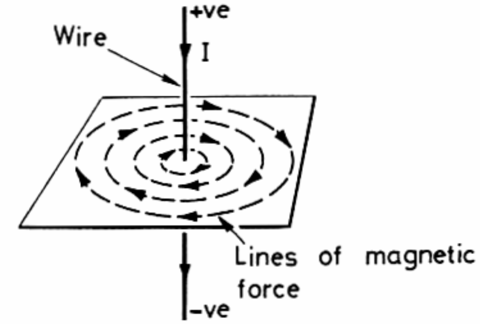

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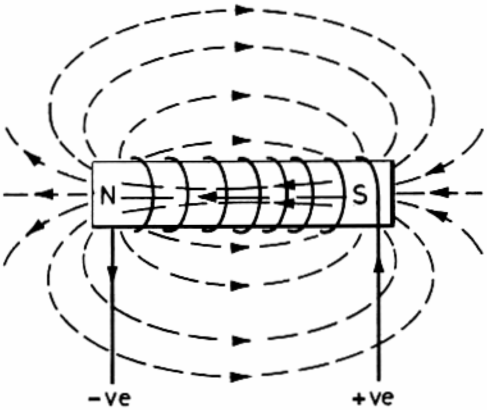

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Magnetism

The characteristics of an ordinary permanent bar magnet are well known. It will attract pieces of iron towards itself. If it is suspended on a piece of string so that it can swing in a horizontal plane, it will always come to rest with one end (the north-seeking end) pointing towards the north magnetic pole and the other end pointing towards the south magnetic pole. If two similar magnets are placed close together the north pole of one will attract the south pole but repel the north pole of the other.

The magnet behaves in this way because of the magnetic force it possesses. The field of this magnetic force may be seen by sprinkling iron filings on a stiff sheet of paper or card, placing the magnet underneath it, and then very gently tapping the paper. The lines of magnetic force will be mapped out by the positions in which the iron filings have settled (see diagram 6).

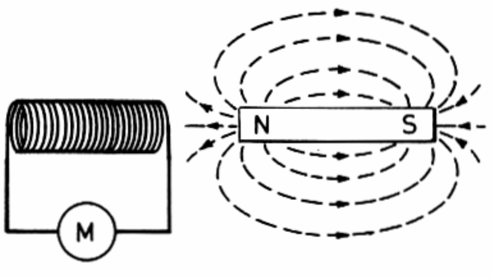
It is accepted that the lines of force run from the north-seeking pole N to the south pole S of the magnet as shown by the arrows in the diagram.

An electromagnet behaves in a similar way. A current of electricity flowing through a wire sets up a magnetic field around the wire. This again can be demonstrated with iron filings; see diagram 7.

In the diagram the wire passes vertically through the paper and the current passes downwards from positive to negative. The lines of magnetic force are concentric circles and the force acts in the direction of the arrows. This can be demonstrated with a small magnet. The direction of the magnetic field may be remembered by the following rule: Grip the wire in the right hand, thumb along the wire in the direction of current flow. The fingers then point in the direction of the magnetic field.

If the wire is now wound into a long coil or 'solenoid' it produces a magnetic field similar to that of a bar magnet. This is shown in diagram 8.

From the rule above it is clear that, with the current flowing through the coil in the direction indicated, the lines of magnetic force are concentrated in the core of the coil and follow an external course from the N pole to the S pole (shown by the arrows). If the direction of the current were reversed, the polarity and the direction of the field would also be reversed.



9

The strength of the magnetic field may be greatly increased if a soft iron core is introduced into the coil. The extent of the increase would depend on the nature or *permeability* of the core. The strength of the magnetic field produced by a solenoid is directly proportional to the current. It also depends on the number of turns in the coil, the cross-sectional area of the coil and the permeability of the core.

Just as permanent magnets attract or repel each other, so do electromagnets. There is similar interaction between an electromagnet and a permanent magnet. These characteristics are used in loudspeakers, earphones and microphones.

In the loudspeaker, the cone has attached to it a short light cylinder on which is wound the speech coil. The latter is situated so that it is free to move in and out with the loudspeaker cone in an annular space between the circular poles of a powerful permanent magnet. As the speech currents alternate through the speech coil, the coil and the loudspeaker cone are vibrated at the speech frequencies by the interaction between the field of the permanent magnet and the varying field set up by the speech coil.

In the earphone a circular magnetic disc or diaphragm is held in close attraction to, but just clear of, the poles of a permanent magnet. Around these poles are wound the speech coils of the earphone. When speech currents are fed through the coils they set up alternating magnetic fields which add to or subtract from the attraction of the permanent magnet on the diaphragm. The diaphragm either relaxes away from the permanent magnet or is drawn closer to it, and is thus vibrated at the speech frequencies.

A microphone works in the reverse way. When its diaphragm is vibrated by sound waves, the movement disturbs the existing magnetic fields and the changes set up corresponding electric currents in the coil windings.

Electromagnetic induction

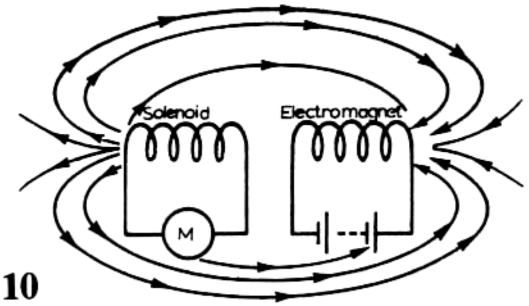
If a permanent magnet is pushed into a solenoid a current will flow momentarily in the wire. This may be seen if a sensitive meter is connected across the coil as shown in diagram 9.

As the magnet is pushed in the meter will deflect one way. As it is pulled out, it will deflect in the opposite direction. The faster the magnet is moved the greater will be the deflection.

When the magnet is moved into or out of the solenoid, the magnetic lines of force cut across the turns of the coil and induce a voltage and hence a current in them. The voltage is proportional to the *rate* of cutting of the lines of force and depends on the strength of the magnet and the size of the coil

This effect is known as *electromagnetic induction* and electrical generators are designed to utilise it.

If the permanent magnet in diagram 9 is replaced by an electromagnet as in diagram 10, the same effect will be produced. When the battery is switched on (equivalent to inserting the permanent magnet) the meter will deflect in one direction. When the battery is switched off (equivalent to withdrawing the permanent magnet) the deflection will be in the opposite sense.



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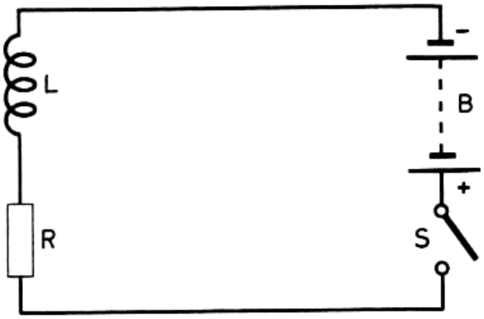


11

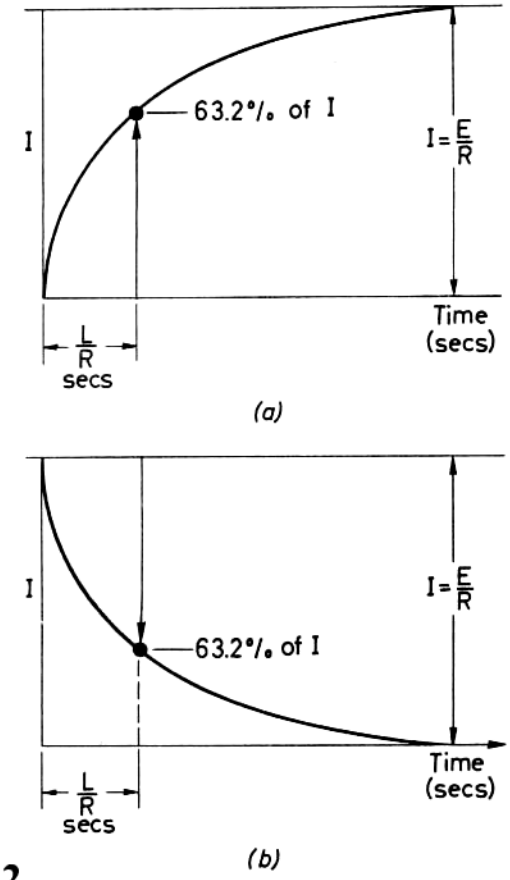
Self-inductance (inductance)

In the above case the electromagnet coil varied the magnetic field through the solenoid and produced a current in the solenoid.

Considering the solenoid alone, if there is a steady current flowing through it, a steady magnetic field will be established about it. If now the current through the solenoid is altered, the magnetic field will alter. This alteration will induce a current in the coil which will add to or subtract from the original current. The important factor is that this induced current will always tend to oppose any change. That is, if the original current is increasing, the induced current will be in the opposite direction and will try to decrease it. If the original current is decreasing, the induced current will be in the same direction to sustain it.

This effect is called self-induction and its magnitude depends upon the 'self-inductance' (or inductance) of the coil.

A coil is said to have an inductance of one *henry* (H) if one volt is induced across its terminals when the current through it is changing at the rate of one ampere per second.



12

The inductance depends on the number of turns in the coil, its cross-sectional area and the permeability of the core.

In practice the units millihenry (mH, or one thousandth of a henry) and microhenry (μH, or one millionth of a henry) are commonly used.

Inductances in series and parallel

By reasoning similar to that used in the case of resistors, it can be shown that for inductances in series:

$$L\ (\text{total}) = L1 + L2 + L3$$

For inductances in parallel:

$$\frac{1}{L\ (\text{total})} = \frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3}$$

Rise and fall of current in an inductive circuit (Time constant)

At this point it is useful to consider how current builds up or dies away in a circuit comprising an inductance.

There is always some resistance in a circuit. In diagram 11, it is R, in series with the inductance L, the battery B and the switch S. When switch S is closed current passes through R and the coil L back to the battery.

As the current rises the self-inductance of the coil tends to oppose the change. A self-induced voltage or e.m.f. is set up which tends to reduce the rate of increase of the current. This is known as a *back-e.m.f.* Eventually the current will reach a steady state ($I = E/R$) and the back-e.m.f. will become zero.

The way in which the current rises is shown in diagram 12 (*a*). It can be shown that the current rises to 63·2% (to *within* 1/e) of its final value in a time equal to L/R seconds (L being in henrys and R in ohms). This time, L/R is known as the *time constant* of the circuit.

If now the switch S is kept closed but the battery voltage is suddenly reduced to zero, the current will start to decrease towards zero but an e.m.f. will be induced in L tending to keep the current flowing. The current decreases as shown in diagram 12 (*b*) and will fall by 63·2% in a time equal to the time constant L/R.

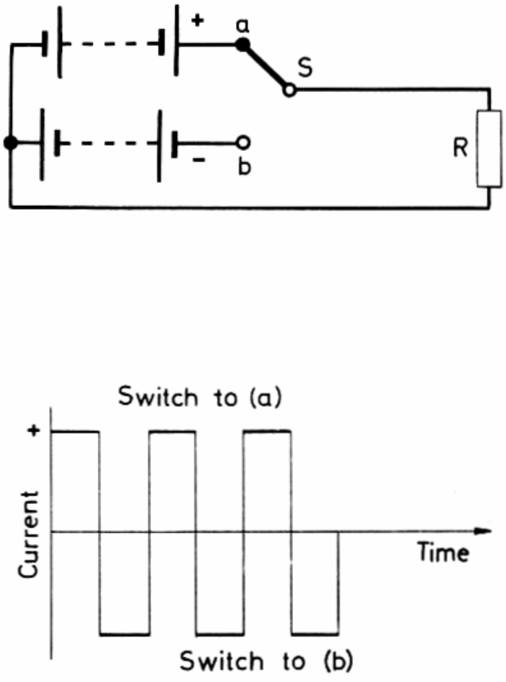
The way in which the current rises in an inductive circuit is exactly similar to the way in which the voltage rises in a capacitative circuit (time constant CR).

If an inductive circuit is broken rapidly a high voltage may be induced (since voltage is proportional to the rate of change of current). Precautions must be taken to prevent this damaging equipment. This high e.m.f. is used to advantage in induction coils and ignition coils in cars. It will be seen that inductance tends to oppose changes of current through it and this property is utilised in radio circuits.

Alternating current (a.c.)

Previous sections have been concerned mainly with *direct* current (d.c.)—that is, current, such as that from a battery, flowing in one direction through a circuit.

There is another important type of current flow called *alternating* current (a.c.), in which current flows backwards and forwards alternately through a circuit.



13

One form of alternating current could be produced through a resistor R by two similar batteries connected in opposite directions, see diagram 13. With switch S in position (*a*), the current through R would go one way and, with S in position (*b*), the current would go in the opposite direction. The graph in diagram 13 shows how the current would vary in time and with the reversals of the switch. The waveform is that of a 'square' wave, in which the current flows alternately at a steady value for equal times first in a positive then in a negative direction.

The most common a.c. waveform is the *sine-wave*, so called because the voltage or the current is proportional to the sine of an angle.

If R is a point moving anticlockwise in a circular path as in diagram 14 (*a*) the height of R above the horizontal, RH, varies as the angle θ varies (RH/RO = Sine θ). If RH is plotted against θ or time, a curve such as that shown at 14 (*b*) is obtained. This is a sine curve.

Note for future reference that as OR revolves its rate of revolution is defined as ω radians per second. As 2π radians equal 360° (one revolution or cycle), $\omega = 2\pi f$, where f is the frequency in Hertz (or, cycles or revolutions per second).

Electric generators usually consist of coils of wire rotating in a fixed magnetic field and these automatically produce a waveform of sinusoidal form. Oscillatory circuits used in radio transmitters and receivers also produce a waveform of sinusoidal form.

Characteristics of alternating current

An alternating current of sinusoidal waveform may be defined by three characteristics—its frequency, its amplitude and its phase.

In the diagram 15, one complete cycle of the waveform is represented by the section between A and B. This corresponds to one complete revolution of the radius OR in the earlier diagram. The 'frequency' is the number of complete cycles in one second and is measured in cycles per second (c/s) or *Hertz* (1 Hertz = 1 cycle per second). Electric power is generated at 50 Hz (60 Hz in the U.S.A. and Canada). Audio frequencies, which are audible as vibrations transmitted through air, have an extreme range of 16 Hz to 20,000 Hz. Radio and television frequencies range broadly from 100,000 Hz to 30,000,000,000 Hz (30 GHz).

The *amplitude* of an alternating current is the peak value (positive or negative) of volts or amps reached in the cycle (for example, point X in the diagram 15). The peak value is not however the most common way of defining alternating current. Instead a value is used equal to the d.c. value which would produce the same power or heating effect in a resistive load. This is the r.m.s. (root mean square) value which equals

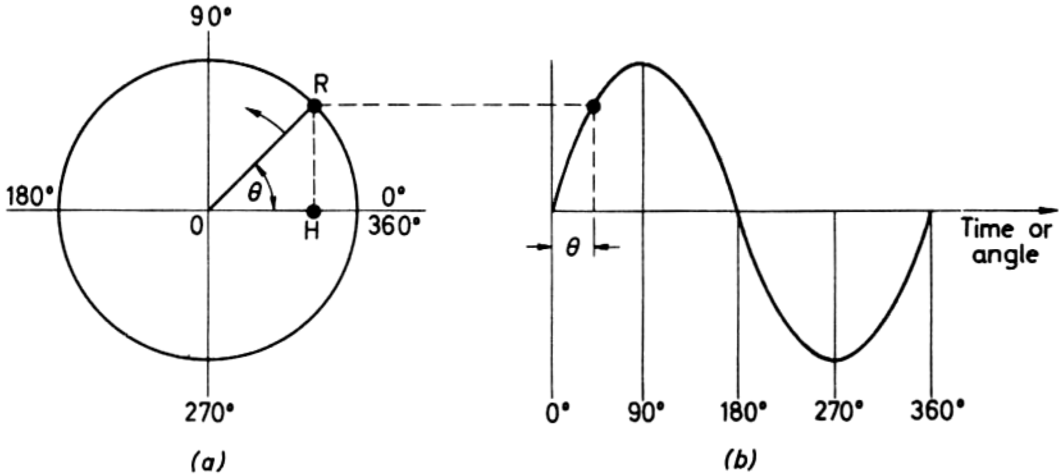
$$\frac{\text{peak value}}{\sqrt{2}} = \text{peak value} \times 0{\cdot}707.$$

Thus peak value = r.m.s. value $\times \sqrt{2} = 1{\cdot}414$ r.m.s. value. Thus an a.c. mains supply of 240 volts has a peak value of some 340 volts.

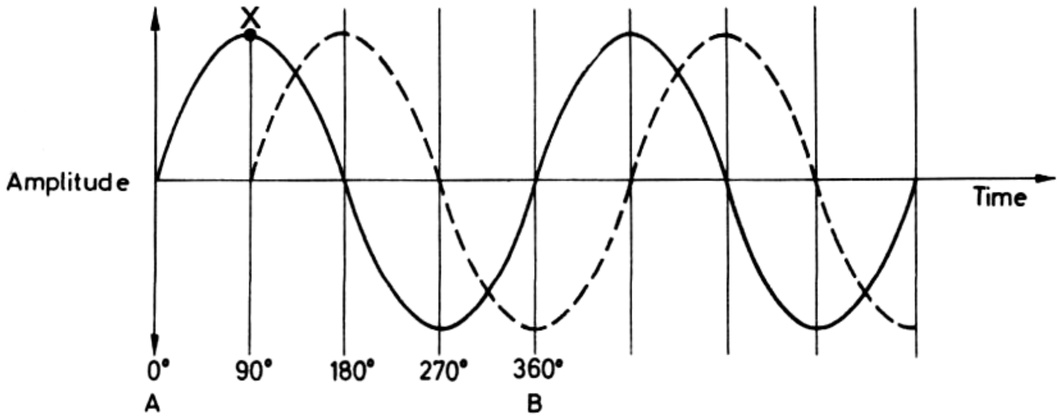
Although two alternating currents may be identical in regard to frequency and amplitude they may differ in phase. The diagram shows two such currents in which the one shown in dotted line lags behind the other by 90° or a $\frac{1}{4}$ of a cycle. By adding corresponding ordinates together these two curves could be combined to form a single sine wave (or current) with a phase midway between the two. If the two currents were completely in phase they would combine into a single current of double the amplitude. If they were exactly 180° out of phase the net result would be a current of zero amplitude, or no current. Phase is thus an important factor.

A.C. circuit containing resistance only

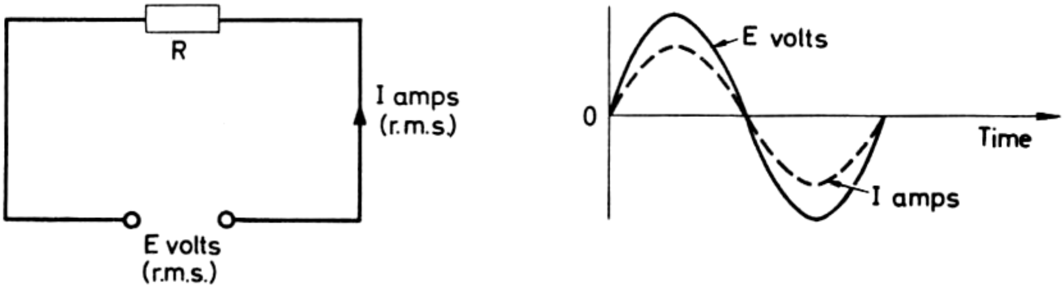
When an a.c. voltage is applied to a circuit containing resistance R only, as in diagram 16, Ohms law can be applied to find the value of the alternating current which will be set up through the resistance.


90°
R
180°
θ
0
H
0°
360°
270°
(a)
θ
Time or angle
0°
90°
180°
270°
360°
(b)

14


X
Amplitude
Time
0°
90°
180°
270°
360°
A
B

15


R
I amps
(r.m.s.)
E volts
(r.m.s.)
E volts
0
Time
I amps

16

The current will flow backwards and forwards through the resistance and at any instant its value will be:

$$I = \frac{E}{R}$$

and it will be *in phase* with the voltage as shown in the graph.

A.C. circuit containing capacitance only
When an alternating voltage is applied to a capacitor, as shown in diagram 17, the capacitor will be charged up first in one direction and then in the other as the supply voltage alternates.

In the conductors linking the capacitor with the supply, the current will flow backwards and forwards, charging up first one side of the capacitor and then the other. The current flow will be a maximum when the capacitor is uncharged—that is, when the applied voltage is zero but is changing most rapidly—and will be zero when the capacitor is fully charged—that is, when the applied voltage is at a maximum but is at the point of zero rate of change. The current will in fact follow a sine curve as shown in dotted line in diagram 17, and it will be seen that the current is 90° out of phase with the voltage and is in advance of it.

The magnitude of the current which flows will clearly depend on the capacity of the condenser C. The larger the capacity the larger will be the current needed to charge it up in the time available. The current will also depend upon the frequency of the applied voltage. If the frequency is increased the time of each charging and discharging period will be shortened and larger current flows will be needed to accomplish these operations in the shorter times.

Thus a capacitor offers an opposition to the passage of alternating current similar in a way to that offerred by a resistance but the effect is frequency dependent and there is a phase difference of 90° between voltage and current. This opposition is called the 'capacitive reactance' of the capacitor and is denoted by the symbol X_C.

$$X_C = 1/2\pi fC \text{ ohms}$$

where C is the capacitance in farads and f is the frequency in Hertz.

The current in a circuit containing capacitance only can be calculated by using Ohm's Law if reactance is substituted for the more normal resistance. Thus:

$$I = \frac{E}{X_C} = 2\pi fC \times E.$$

Summarising, for a capacitor, the current (*a*) leads the voltage by 90°; (*b*) is directly proportional to C, and (*c*) is directly proportional to f.

A.C. circuit containing inductance only
In diagram 18, an alternating voltage E is applied to a circuit containing inductance L only. It is assumed that the resistance is negligible. This voltage produces an alternating current I through the coil.

The current I is shown in dotted line. The current is changing continuously and the changes induce an e.m.f. in the coil which will always tend to oppose the change. The induced e.m.f. 'e' will be greatest when the rate of change of current is a maximum—that is, at the points A, C and E. It will be zero when the rate of change is zero as at points B and D, At A and E the current is increasing and therefore the induced e.m.f. will oppose and be negative. At C the current is decreasing and hence the induced e.m.f. will be positive. The broken line shows the induced e.m.f.

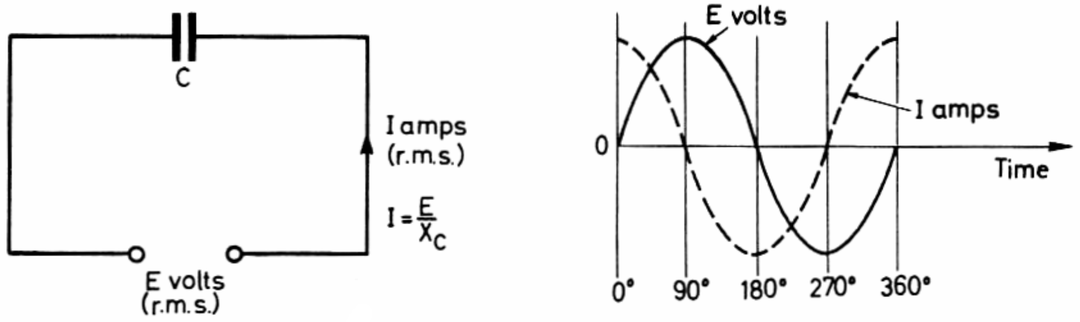
Reverting now to the original applied voltage E, this must always be equal and opposite to the induced voltage e (in fact slightly greater than e) if the current is to continue to be forced through the circuit. The applied voltage therefore must follow the full line in 18 (*b*).

It will thus be seen that in a purely inductive circuit the current lags behind the applied voltage by a phase angle of 90°.

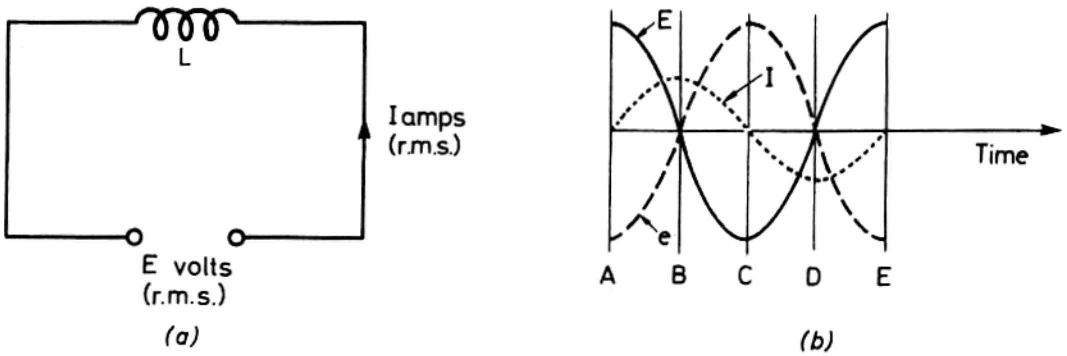
The opposition of an inductance to alternating current flow is called its *inductive reactance* and is denoted by X_L where

$$X_L = 2\pi fL \text{ ohms.}$$

(L is in henrys and f in Hertz.)



17



(a) *(b)*

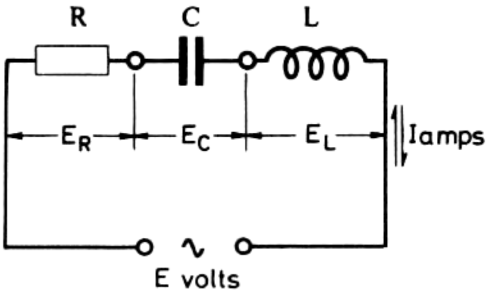
18

Using Ohm's Law with X_L substituted for R, the current through an inductance may be calculated as:

$$I = \frac{E}{X_L} = \frac{E}{2\pi f L} \text{ ohms.}$$

Thus, for an inductance, the current (*a*) lags the voltage by 90°, (*b*) is inversely proportional to L, and (*c*) is inversely proportional to f.

It will be noted that inductors and capacitors react to alternating current in exactly opposite ways and this fact has important applications in radio.



19

Impedance: a.c. circuit containing R, C and L

This type of circuit, as shown in diagram 19, is important in radio and has some interesting properties.

Resistance R, capacitance C and inductance L, oppose current flow in different ways so that their values cannot simply be added up to obtain the overall opposition. The current through R is in phase with the applied voltage and independent of frequency. The current through C increases with frequency and is 90° *ahead* of the voltage. The current through L decreases with frequency and is 90° *behind* the voltage.

The overall opposition is called the 'impedance' of the circuit and its symbol is Z. Hence:

$$I = E/Z$$

As R, C and L are in series the current through each must be the same. The voltages across each will vary, however, and these are shown in the diagram 19 as E_R, E_C and E_L.

The overall voltage at any time may be found, and thus Z may be found, by combining these separate voltages vectorally. A vector is a line which represents the magnitude of the voltage or another quantity by its length and the phase of the quantity by its direction (or angle). See diagram 20.

Thus, in the vector diagram 20 (*a*), E_R represents the voltage drop through R, in phase with the current I; E_C the voltage drop through C which leads the phase of the current by 90°; and E_L the voltage across L which lags 90° behind the current phase.

As E_L and E_C have exactly opposite phase effects the one may be subtracted directly from the other to give a combined vector $E_L - E_C$, as in vector diagram 20(*b*). This vector may now be combined with E_R to give a final overall resultant vector E. As the triangle is right angled,

$$E^2 = E_R{}^2 + (E_L - E_C)^2$$

Substituting $E_R = IR$; $E_L = IX_L = I.2\pi fC$; and $E_C = I.X_C = \frac{I}{2\pi fC}$ we get:

$$E^2 = I^2R^2 + I^2\left(2\pi fL - \frac{1}{2\pi fC}\right)^2$$

$$\text{or} \quad \frac{E^2}{I^2} = R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2$$

$$= Z^2\left(\text{since } I^2 = \frac{E^2}{Z^2};\ Z^2 = \frac{E^2}{I^2}\right)$$

Hence the overall impedance is:

$$Z = \sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}$$

Series resonant (acceptor) circuit

In the circuit in the preceding section in which R, C and L were in series the overall impedance Z was calculated. The current flowing in the circuit would thus be as follows:

$$I = \frac{E}{Z} = \frac{E}{\sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}}$$

As the reactance of the coil (2πfC) increases with frequency (f) and that of the capacitor 1/2πfC decreases with frequency, there must be some frequency at which the reactances of both are equal. At this point, the 'resonant' frequency of the circuit, when 2πfL = 1/2πfC, the reactances cancel out of the above equation and the current I becomes a maximum equal to E/R as shown in diagram 21.

Series resonant circuits are referred to as 'acceptor' circuits since at the resonant frequency the impedance is a minimum and they can therefore accept the maximum current.

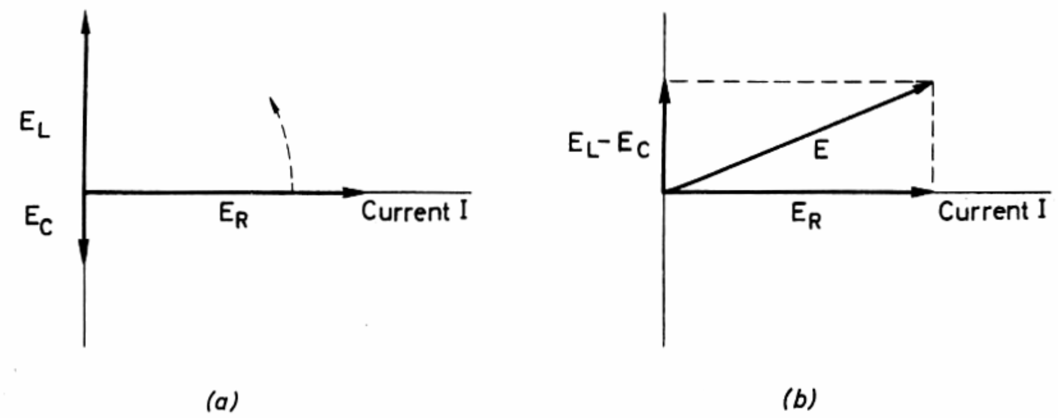
The resonant properties of this type of circuit can be used to pick out one particular frequency when many frequencies are present.

The resonant frequency of any series circuit may be found by equating the inductive and capacitive reactances thus:

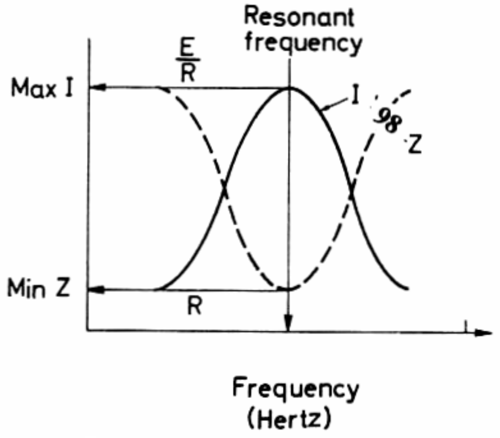
$$2\pi fL = \frac{1}{2\pi fC}$$

Whence $f = \frac{1}{2\pi\sqrt{LC}}$ (by rearrangement)
where L is in henrys, C in farads and f in Hertz.

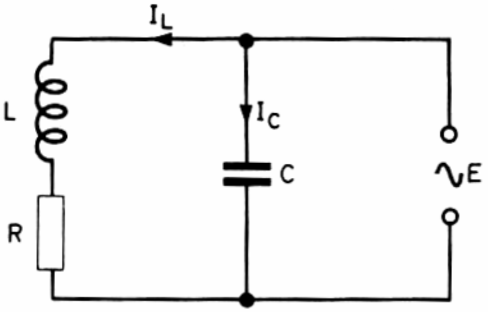
From this formula can be calculated the inductance of a coil needed to tune to a desired frequency, or over a band of frequencies, with a given capacitor.



20



21



22

Parallel resonant (rejector) circuit

A parallel resonant circuit is shown in diagram 22. The capacitor C is in parallel with the coil L. The coil must always have some inherent resistance and this is shown by resistor R in series with it.

In this circuit the voltage applied to C will be the same as that applied to the L and R arm. The current in the capacitor circuit will lead the applied voltage by 90° and its value will be

$$I_C = E \Big/ \frac{1}{2\pi fC} = E \times 2\pi fC.$$

In the inductor-resistor arm I_L will lag behind E but not quite by 90° owing to the presence of the resistor. The current I_L will be E/Z_L where $Z_L = \sqrt{R^2 + (2\pi fL)^2}$. As R is normally small compared with $2\pi fL$ we can say $I_L = E/2\pi fL$.

These currents may be plotted vectorally to obtain the overall resultant current I, as in diagram 23 (*a*). At some frequency (the resonant frequency) I_L will equal I_C and I will be at a minimum and almost in phase with E as in diagram 23 (*b*). When this happens,

$$E \times 2\pi fC = \frac{E}{2\pi fL}$$

or resonant frequency $f = \dfrac{1}{2\pi\sqrt{LC}}$

as for the series resonant circuit.

Parallel tuned circuits are called rejector circuits because they offer a high impedance and reject current at their resonant frequency. Because of these characteristics they are largely used for tuning circuits in radio. A resonance curve for a parallel resonant circuit is shown in diagram 24.

Transformers

In the section on electromagnetic induction it was stated that, if two coils are in proximity, a change of current in one will induce a voltage and current in the other. This effect is utilised in the transformer, a device which can transfer energy from one circuit to another without direct connection.

Diagram 25 shows a typical transformer, the lines between the two coils indicating a laminated iron core. The coil connected to the source of energy is usually called the *primary* coil and the other (or others, for there may be more than one) is called the *secondary*.

If the primary coil has N_P turns then the voltage across each turn of the primary is E_P/N_P. As the magnetic flux through the primary and secondary coils is for all practical purposes the same, each turn of the secondary will induce the same voltage E_P/N_P. Thus if there are N_S turns in the secondary coil the total voltage induced in the secondary will be:

$$N_S \times \frac{E_P}{N_P} = E_S$$

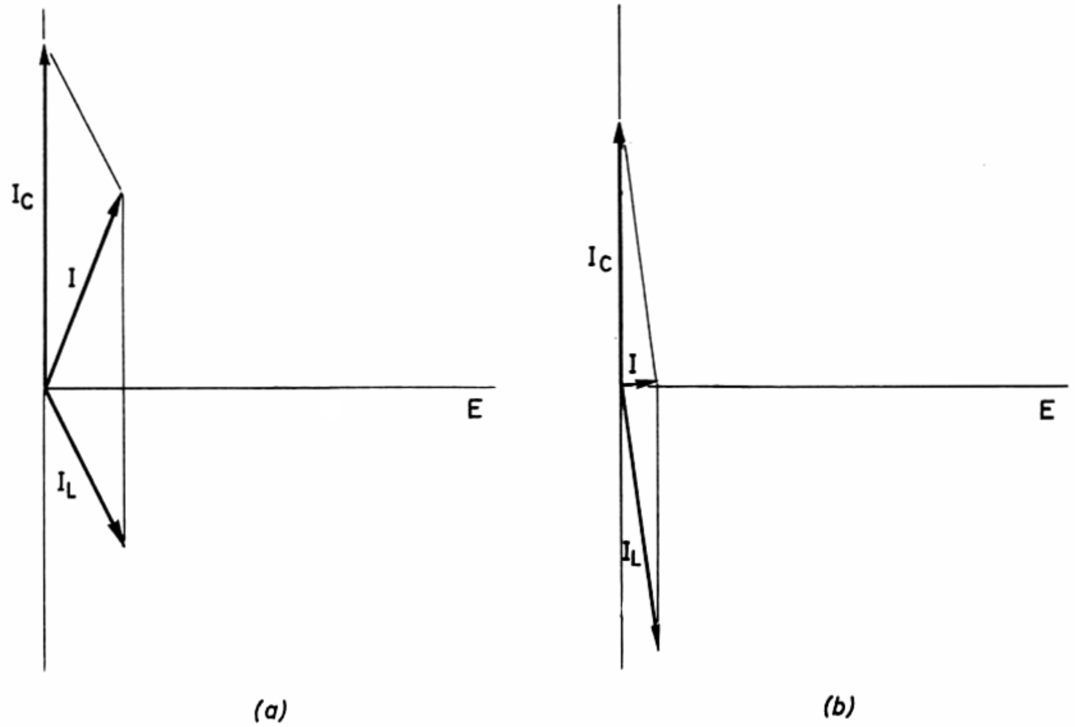
Thus $$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

That is, the *voltage* induced in the secondary is *proportional* to the 'turns ratio', N_S/N_P, of the transformer.

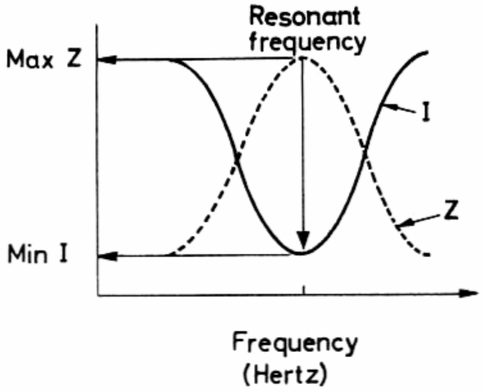
In an ideal transformer, the energy in the secondary ($E_S \times I_S$ volt-amps) is equal to that in the primary ($E_P \times I_P$), so that:

$$E_P.I_P = E_S.I_S.$$

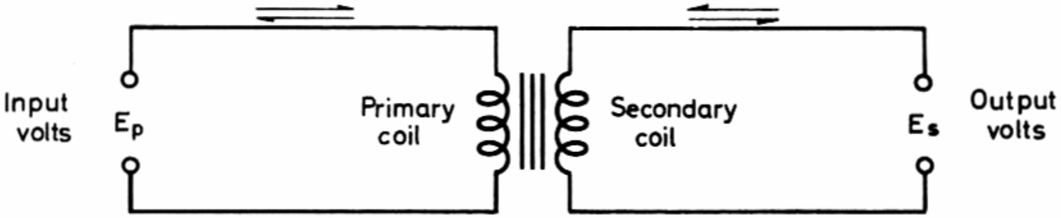
Thus $\dfrac{E_P}{E_S} = \dfrac{I_S}{I_P} = \dfrac{N_P}{N_S}$ (from above)


I_C
I
I_L
E
I_C
I
I_L
E
(a)
(b)

23


Resonant frequency
Max Z
I
Z
Min I
Frequency (Hertz)

24


Input volts
E_p
Primary coil
Secondary coil
E_s
Output volts

25

That is, the *current* induced in the secondary is *inversely* proportional to the turns ratio.

The impedance of an inductive circuit is given by Ohm's Law:

$$I = \frac{E}{Z} \text{ or } Z = \frac{E}{I}$$

Thus the impedance of the primary coil is $Z_P = E_P/I_P$ and of the secondary $Z_S = E_S/I_S$.

Hence: $$\frac{Z_S}{Z_P} = \frac{E_S}{I_S} \times \frac{I_P}{E_P}$$

$$= \frac{E_S}{E_P} \times \frac{I_P}{I_S} = \frac{N_S}{N_P} \times \frac{N_S}{N_P}$$

$$= \left(\frac{N_S}{N_P}\right)^2$$

Thus the ratio of the *impedance* of the coils of a transformer is proportional to the *square* of the turns ratio.

A transformer is a most useful device which can transform voltages or currents to required levels or match up impedances. Iron cores are used in mains voltage or audio transformers whilst in radio frequency transformers such as I.F. coils or aerial coils ferrite, iron dust or air cores are used to minimise losses. In the case of RF coils adjustable cores give a tuning facility.

Radio communications

The simple form of communication between people is by speech or sign. There has always been a need, however, to communicate at a distance. Hence the 'tom toms' in the jungle, the Indians' smoke signals, Morse flags and lamps, and the heliograph. With the advent of electricity, wires could carry electric messages over hundreds of miles, first by 'telegraphy' (stopping and starting the current) then by 'telephony', in which a steady current was varied by currents produced by a microphone, these variations being turned back into sound at the far end by an earphone or loudspeaker. With the discovery of 'wireless' or 'radio', it has now become possible to communicate over almost unlimited distances not only in terms of the world but through space itself.

Electromagnetic waves

The possibilities of communication by means of electromagnetic waves were first demonstrated by Hertz and Marconi.

If a conducting wire is suspended above the ground (for example, an 'aerial' wire) and is connected via a source of alternating current to the ground, we have in effect a capacitor as the ground itself is a conductor. The alternating current will charge first one side of this capacitor and then the other, and as this happens an electric field will be set up between the wire and the ground as already described in the section on capacitors. This field will wax and wane as the charge builds up and diminishes and it will reverse in direction in sympathy with the reversals of the alternating current.

The current flowing between the aerial and earth will at the same time set up a magnetic field around the wire and this will also change its direction in accordance with the reversals of the alternating current.

These two effects are inseparable from each other and combine to form an electromagnetic wave. Once the wave has been established, it radiates outwards from its source in all directions in the form of an ever-expanding sphere. A stone in a still pond sends out ripples of ever increasing radius and in a comparable way an electrical disturbance in an aerial sends out (in three dimensions) expanding spherical waves.

These spherical waves travel outwards at one speed, the speed of light (300 million metres, or seven times round the world, in one second).

The direction of the electric field is always at right angles to the direction of the magnetic field and both are at right angles to the direction in which the wave front is moving. At a distance from the transmitter a small area of the wave front would appear as a flat surface and the electric and magnetic lines of force would lie in the flat surface at right angles to each other.

Diagram 26 (*a*) illustrates a cross-section of a train of electromagnetic waves showing how the direction of the electric field alternates at the transmission frequency. Diagram 26 (*b*) shows how, in the plane of the wave front, the electric and magnetic fields are at right angles to each other and how both alternate in direction at the transmission frequency.

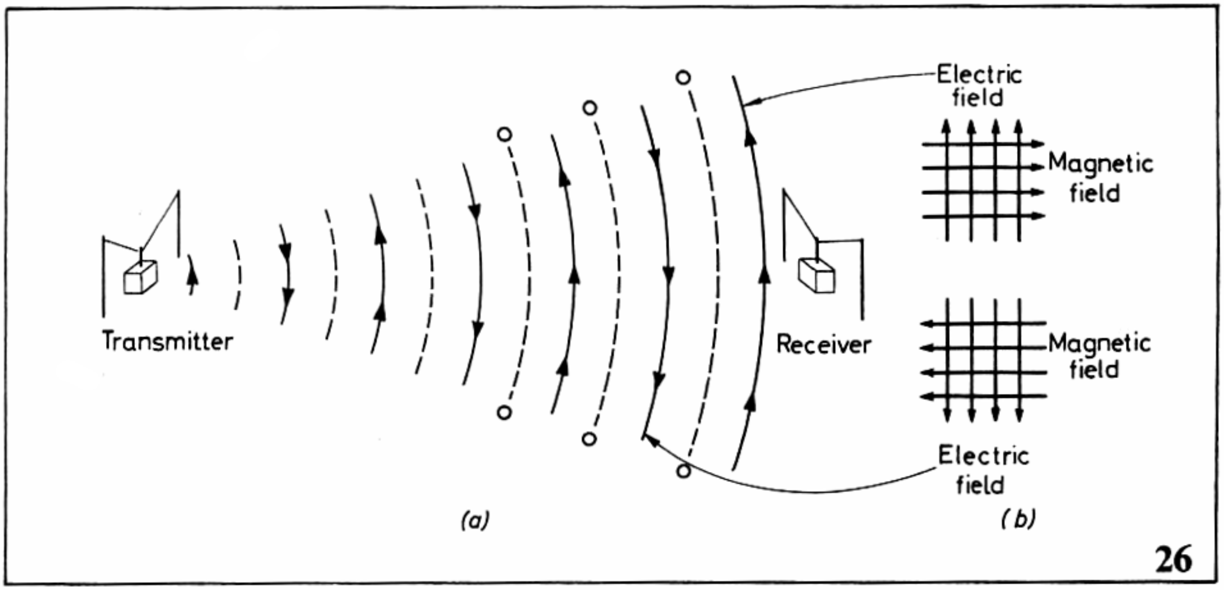
When the electromagnetic waves strike a conductor such as a receiving aerial wire the above process is exactly reversed and alternating currents are induced into the receiving aerial which correspond in all respects except strength with those fed into the transmitting aerial.

Frequency and wavelength

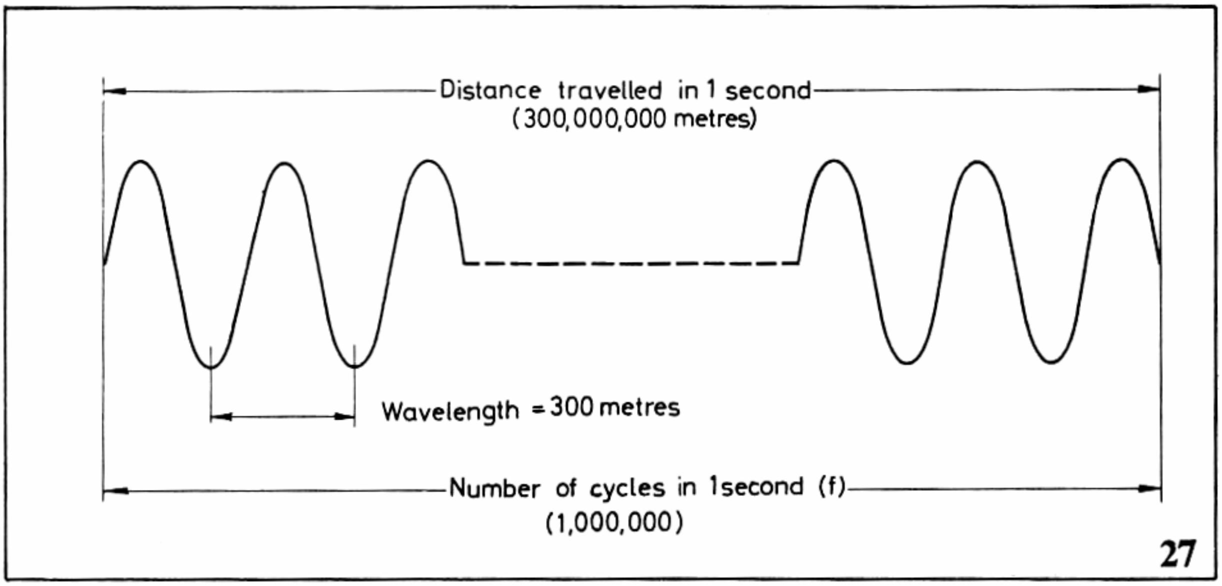
A radio wave may be defined by its frequency or its wavelength. The waves all travel at the speed of light and the relationship between the three is shown in diagram 27.

The wavelength is denoted by the symbol λ and

$$\lambda \text{ (metres)} = \frac{300{,}000{,}000}{\text{f (Hertz)}}$$



26



27

Carrier wave

A transmitter sends out a steady radio frequency signal called a *carrier* wave which is normally a sine wave as in diagram 28 (*a*).

This signal carries no information, but for morse signalling it can be broken by keying (that is, switching on and off) to produce the dots and dashes of the morse alphabet. This is shown in diagram 28 (*b*).

Modulation

For transmission of speech and music, the audio frequencies have to be imposed upon the carrier wave in some way and this process is called modulation. Modulation can be effected by varying the amplitude of the carrier wave or its frequency or its phase. The most commonly used type of modulation is amplitude modulation (A.M.), and this is shown in diagram 29.

The amplitude of the transmitter output is increased or decreased by the modulating signal and a modulated signal of varying amplitude is transmitted (see diagram 29).

De-modulation (detection or rectification)

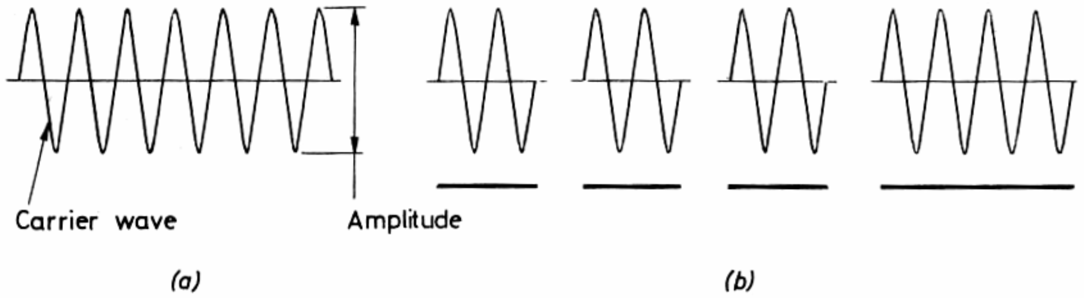
The modulated or 'chopped' carrier wave would not be audible in an earphone or loudspeaker because it alternates at a frequency which could not mechanically be followed by the diaphragm of an earphone or the cone of a loudspeaker and which in any case is beyond the range of hearing (16 Hz-20,000 Hz). The signal has to be 'de-modulated' or 'detected' and this is done by passing it through a diode which, as shown earlier, is a one-way device. The diode removes one half of the modulated (or 'chopped') carrier wave as shown in diagram 30.

The remaining half is direct or unidirectional current which is varying in amplitude at the audio frequency. The carrier frequency peaks may be averaged out by a capacitor to give the smooth d.c. variation shown in heavy line which is an exact reproduction of the modulating signal originally applied at the transmitter.

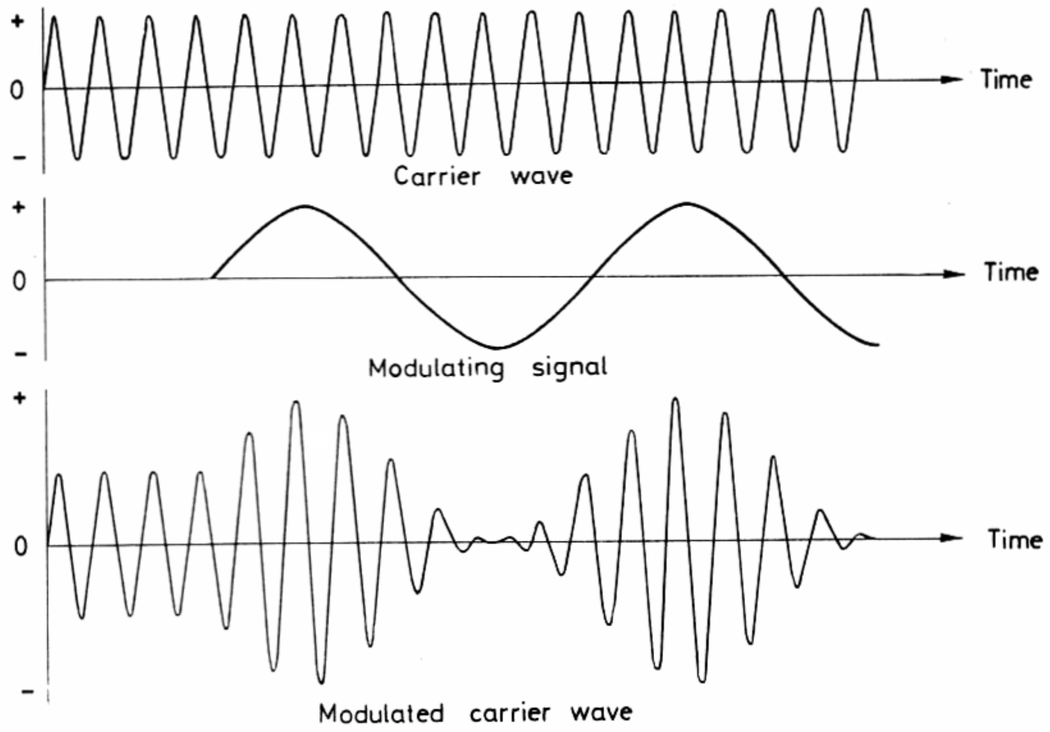
Diagram 31 shows the essential elements of a radio transmission and reception system.

Tuning

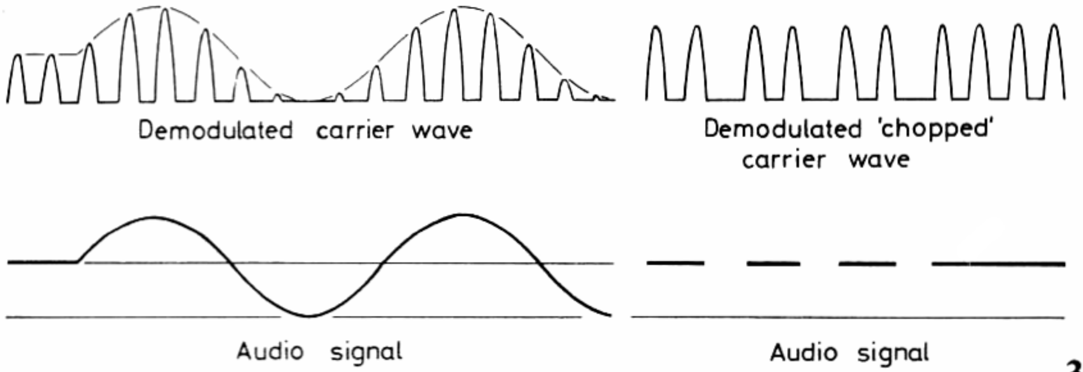
The ether is full of radio waves of all frequencies. Transmitter frequencies are allocated by international agreement so that mutual interference is avoided. The receiver can be 'tuned' in to the desired transmission by adjusting the inductance and capacity of the aerial circuit so that its 'resonant' frequency coincides with the carrier-wave frequency of the transmitter. This as already explained is when $f = 1/2\pi\sqrt{LC}$.



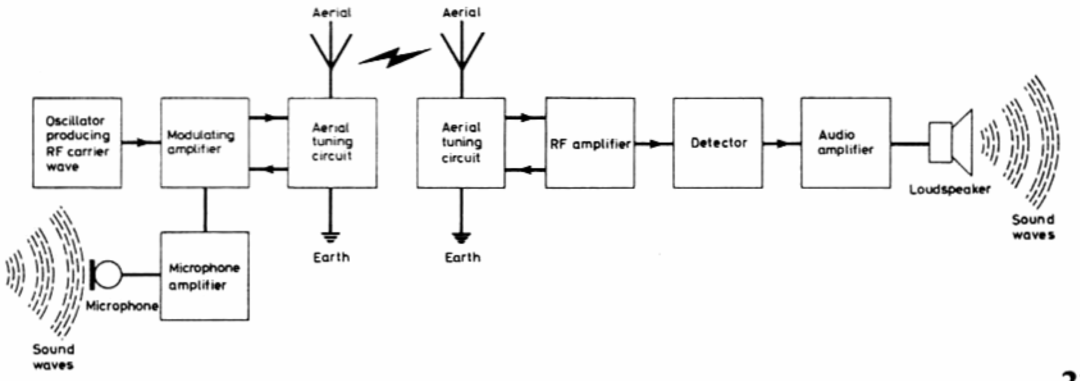
28


+
0
–
Time
Carrier wave
+
0
–
Time
Modulating signal
+
0
–
Time
Modulated carrier wave

29


Demodulated carrier wave
Demodulated 'chopped' carrier wave
Audio signal
Audio signal

30


Aerial
Aerial
Oscillator producing RF carrier wave
Modulating amplifier
Aerial tuning circuit
Aerial tuning circuit
RF amplifier
Detector
Audio amplifier
Loudspeaker
Sound waves
Earth
Earth
Microphone amplifier
Microphone
Sound waves

31

The electromagnetic spectrum

Radio waves cover only a small part of the electromagnetic spectrum which also embraces heat, light, gamma and cosmic rays. Radio waves have wavelengths ranging between roughly 3 kilometres and one centimetre. The frequency spectrum is shown in the table.