STUDY MATERIAL

ELECTRICAL TECHNOLOGY

(819)

CLASS – XI

(2018-19)

UNIT-1
CURRENT ELECTRICITY

1.1 Electricity as a source of energy

INTRODUCTION

Sources of electricity are everywhere in the world. Worldwide, there is a range of energy resources available to generate electricity. These energy resources fall into two main categories, often called renewable and non-renewable energy resources. Each of these resources can be used as a source to generate electricity, which is a very useful way of transferring energy from one place to another such as to the home or to industry.

Non-renewable sources of energy can be divided into two types: fossil fuels and nuclear fuel.

Fossil fuels

Sources of electricity include fossil fuels are found within the rocks of the Earth's surface. They are called fossil fuels because they are thought to have been formed many millions of years ago by geological processes acting on dead animals and plants, just like fossils.

Coal, oil and natural gas are fossil fuels. Because they took millions of years to form, once they are used up they cannot be replaced.

Oil and natural gas

Sources of electricity include oil and gas are chemicals made from molecules containing just carbon and hydrogen. All living things are made of complex molecules of long strings of carbon atoms. Connected to these carbon atoms are others such as hydrogen and oxygen. A simple molecule, called methane (CH4), is the main component of natural gas.

Crude oil (oil obtained from the ground) is a sticky, gooey black stuff. It contains many different molecules, but all are made of carbon and hydrogen atoms.

How were they formed?

Gas and oil were formed from the remains of small sea creatures and plants that died and fell to the bottom of seas. Over many millions of years, layers of mud or other sediments built up on top of these dead animals and plants. The pressure from these layers and heat from below the Earth's crust gradually changed the once-living material into oil and natural gas.

Over time, the layers of rocks in the Earth's crust move and may become squashed and folded. Gas and oil may move through porous rocks and may even come to the surface. In some places, pockets of oil and gas can be found, because non-porous rocks have trapped them.

Natural gas and crude oil can be found in many places around the world, such as the Middle East (about 70 per cent of the world's known resources of oil), the USA and under the North Sea off the coast of the UK.

When gas and oil burn they produce mainly carbon dioxide and water, releasing the energy they contain. Crude oil is a mixture of different chemicals and is usually separated out into fuels such as petrol, paraffin, kerosene and heavy fuel oils.

The oil-based fuels provide less energy per kilogram than natural gas. Both oil and natural gas produce carbon dioxide, which is a greenhouse gas.

How long will they last?

Oil and gas are non-renewable: they will not last forever. New sources of oil and gas are constantly being sought. It is thought that the current resources under the North Sea will last about another 20 years and the world resources will last for about 70 years.

Estimates vary, however, because we do not know where all the resources are and we do know how quickly we will use them. It is thought that with new discoveries these fossil fuels will last well into the next century.

Advantages

These sources of energy are relatively cheap and most are easy to get and can be used to generate electricity.

Disadvantages

When these fuels are burned they produce the gas carbon dioxide, which is a greenhouse gas and is a major contributor to global warming. Transporting oil around the world can produce oil slicks, pollute beaches and harm wildlife.

Coal

Sources of electricity can include coal, which mainly consists of carbon atoms that come from plant material from ancient swamp forests. It is a black solid that is reasonably soft. You can scratch it with a fingernail. It is not as soft as charcoal, however, and is quite strong. It can be carved into shapes. There are different types of coal. Some contain impurities such as sulphur that pollute the atmosphere further when they burn, contributing to acid rain.

How was it formed?

Millions of years ago, trees and other plants grew rapidly in a tropical climate, and when they died they fell into swamps. The water in the swamps prevented the plant material from decaying completely and peat was formed.

As time passed, layer upon layer of peat built up. The pressure from these layers and heat from below the Earth's crust gradually changed the material into coal.

Coal can be found in parts of the world that were once covered with swampy forests, such as the UK about 250 million years ago. There are large deposits in China, USA, Europe and Russia. South Africa also has relatively large deposits.

When coal burns it produces mainly carbon dioxide, some carbon monoxide and soot (which is unburned carbon). Many coals when burned produce smoky flames.

Their energy content weight for weight is not as great as oil. When coal burns it produces more carbon dioxide than oil.

How long will the supply of coal last?

The world has relatively large reserves of coal, more so than oil and gas. Estimates vary, but suggestions are that supplies will last well into the next century.

Advantages

Coal is relatively cheap, with large deposits left that are reasonably easy to obtain, some coal being close to the surface. It is relatively easy to transport because it is a solid.

Disadvantages

Some sources of coal are deep below the ground, as in the UK. They can be difficult, costly and dangerous to mine.

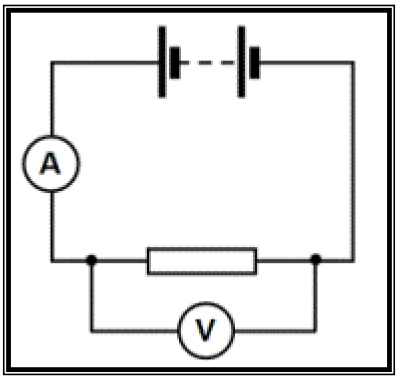
Burning coal without first purifying it contributes to global warming, as well as to the production of smog (smoke and fog), which is harmful to health. It is a finite resource and will eventually run out.

1.2 Definition of Resistance, Voltage, Current, Power, Energy and their units

Resistance- Resistance is the opposition that a substance offers to the flow of electric current. It is represented by the uppercase letter R. The standard unit of resistance is the ohm, sometimes written out as a word, and sometimes symbolized by the uppercase Greek letter omega. When an electric current of one ampere passes through a component across which a potential difference (voltage) of one volt exists, then the resistance of that component is one ohm.

In general, when the applied voltage is held constant, the current in a direct-current (DC) electrical circuit is inversely proportional to the resistance. If the resistance is doubled, the current is cut in half; if the resistance is halved, the current is doubled. This rule also holds true for most low-frequency alternating-current (AC) systems, such as household utility circuits. In some AC circuits, especially at high frequencies, the situation is more complex, because some components in these systems can store and release energy, as well as dissipating or converting it.

The electrical resistance per unit length, area, or volume of a substance is known as resistivity. Resistivity figures are often specified for copper and aluminum wire, in ohms per kilometer.



Opposition to AC, but not to DC, is a property known as reactance. In an AC circuit, the resistance and reactance combine vectorially to yield impedance.

VOLTAGE- Voltage, also called *electromotive force*, is a quantitative expression of the potential difference in charge between two points in an electrical field. The greater the voltage, the greater the flow of electrical current (that is, the quantity of charge carriers that pass a fixed point per unit of time) through a conducting or semiconducting medium for a given resistance to the flow. Voltage is symbolized by an uppercase italic letter *V* or *E*. The standard unit is the volt, symbolized by a non-italic uppercase letter V. One volt will drive one coulomb (6.24×10^{18}) charge carriers, such as electrons, through a resistance of oneohm in one second.

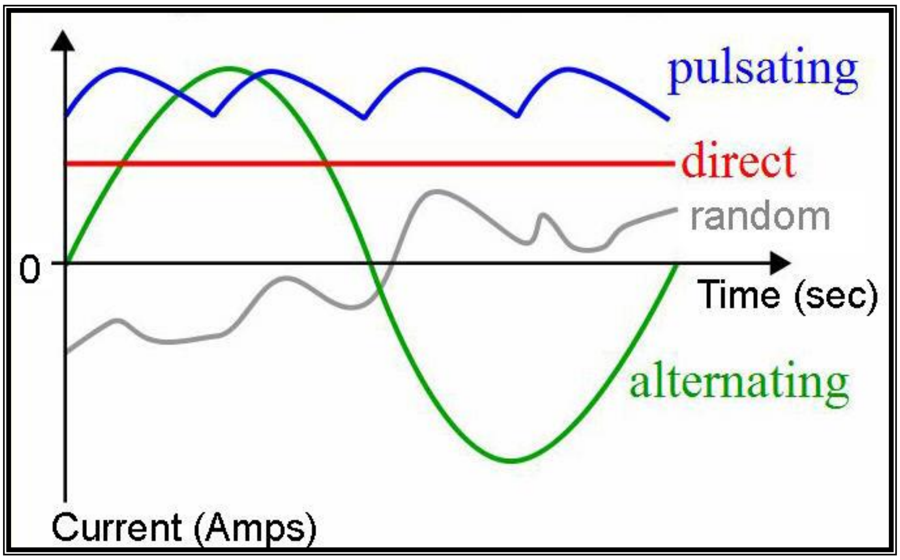
Voltage can be direct or alternating. A direct voltage maintains the same polarity at all times. In an alternating voltage, the polarity reverses direction periodically. The number of complete cycles per second is the frequency, which is measured in hertz (one cycle per second), kilohertz, megahertz, gigahertz, or terahertz. An example of direct voltage is the potential difference between the terminals of an electrochemical cell. Alternating voltage exists between the terminals of a common utility outlet.

A voltage produces an electrostatic field, even if no charge carriers move (that is, no current flows). As the voltage increases between two points separated by a specific distance, the electrostatic field becomes more intense. As the separation increases between two points having a given voltage with respect to each other, the electrostatic flux density diminishes in the region between them.

CURRENT- Current is a flow of electrical charge carriers, usually electrons or electron-deficient atoms. The common symbol for current is the uppercase letter I. The standard unit is the ampere, symbolized by A. One ampere of current represents one coulomb of electrical charge (6.24 x 10^{18} charge carriers) moving past a specific point in one second. Physicists consider current to flow from relatively positive points to relatively negative points; this is called conventional current or Franklin current. Electrons, the most common charge carriers, are negatively charged. They flow from relatively negative points to relatively positive points.

Electric current can be either direct or alternating. Direct current (DC) flows in the same direction at all points in time, although the instantaneous magnitude of the current might vary. In an alternating current (AC), the flow of charge carriers reverses direction periodically. The number of complete AC cycles per second is the frequency, which is measured in hertz. An example of pure DC is the current produced by an electrochemical cell. The output of a power-supply rectifier, prior to filtering, is an example of pulsating DC. The output of common utility outlets is AC.

Current per unit cross-sectional area is known as *current density*. It is expressed in amperes per square meter, amperes per square centimeter, or amperes per square millimeter. Current density can also be expressed in amperes per circular mil. In general, the greater the current in a conductor, the higher the current density. However, in some situations, current density varies in different parts of an electrical conductor. A classic example is the so-called *skin effect*, in which current density is high near the outer surface of a conductor, and low near the center. This effect occurs with alternating currents at high frequencies. Another example is the current inside an active electronic component such as a field-effect transistor (FET).



An electric current always produces a magnetic field. The stronger the current, the more intense the magnetic field. A pulsating DC, or an AC, characteristically produces an electromagnetic field. This is the principle by which wireless signal propagation occurs.

POWER- Electrical power is the rate at which electrical energy is converted to another form, such as motion, heat, or an electromagnetic field. The common symbol for power is the uppercase letter P. The standard unit is the watt,symbolized by W. In utility circuits, the kilowatt (kW) is often specified instead;1 kW = 1000 W.

One watt is the power resulting from an energy dissipation, conversion, or storage process equivalent to one joule per second. When expressed in watts, power is sometimes called*wattage*. The wattage in a direct current (DC) circuit is equal to the product of the voltage in volts and the current in amperes. This rule also holds for low-frequency alternating current (AC) circuits in which energy is neither stored nor released. At high AC frequencies, in which energy is stored and released (as well as dissipated or converted), the expression for power is more complex.

In a DC circuit, a source of E volts, delivering$I$amperes, produces P watts according to the formula:

$$P = EI$$

When a current of I amperes passes through a resistance of Rohms, then the power in watts dissipated or converted by that component is given by:

$$P = I^2R$$

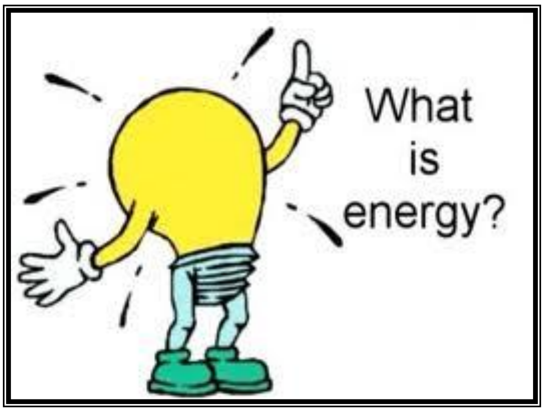
When a potential difference of E volts appears across a component having a resistance of Rohms, then the power in watts dissipated or converted by that component is given by:

$$P = E^2/R$$

In a DC circuit, power is a scalar (one-dimensional) quantity. In the general AC case, the determination of power requires two dimensions, because AC power is a vector quantity. Assuming there is no reactance (opposition to AC but not to DC) in an AC circuit, the power can be calculated according to the above formulas for DC, using root-mean-square values for the alternating current and voltage. If reactance exists, some power is alternately stored and released by the system. This is called apparent power or reactive power. The resistance dissipates power as heat or converts it to some other tangible form; this is called true power. The vector combination of reactance and resistance is known as impedance.

ENERGY- Energy is the capacity of a physical system to do work. The common symbol for energy is the uppercase letter *E*. The standard unit is the joule, symbolized by J. One joule (1 J) is the energy resulting from the equivalent of one newton (1 N) of force acting over one meter (1 m) of displacement. There are two main forms of energy, called potential energy and kinetic energy.

Potential energy, sometimes symbolized *U*, is energy stored in a system. A stationary object in a gravitational field, or a stationary charged particle in an electric field, has potential energy.



Kinetic energy is observable as motion of an object, particle, or set of particles. Examples include the falling of an object in a gravitational field, the motion of a charged particle in an electric field, and the rapid motion of atoms or molecules when an object is at a temperature above zero Kelvin.

Matter is equivalent to energy in the sense that the two are related by the Einstein equation:

$$E = mc^2$$

where *E* is the energy in joules, *m* is the mass in kilograms, and *c* is the speed of light, equal to approximately 2.99792×10^8 meters per second.

In electrical circuits, energy is a measure of power expended over time. In this sense, one joule (1 J) is equivalent to one watt (1 W) dissipated or radiated for one second (1 s). A common unit of energy in electric utilities is the kilowatt-hour (kWh), which is the equivalent of one kilowatt (kW) dissipated or expended for one hour (1 h). Because 1 kW = 1000 W and 1 h = 3600 s, 1 kWh = 3.6×10^6 J.

Heat energy is occasionally specified in British thermal units (Btu) by nonscientists, where 1 Btu is approximately equal to 1055 J. The heating or cooling capability of a climate-control system may be quoted in Btu, but this is technically a misuse of the term. In this sense, the system manufacturer or vendor is actually referring to Btu per hour (Btu/h), a measure of heating or cooling power.

1.3 Units of Resistance, Voltage, Current, Power, Energy

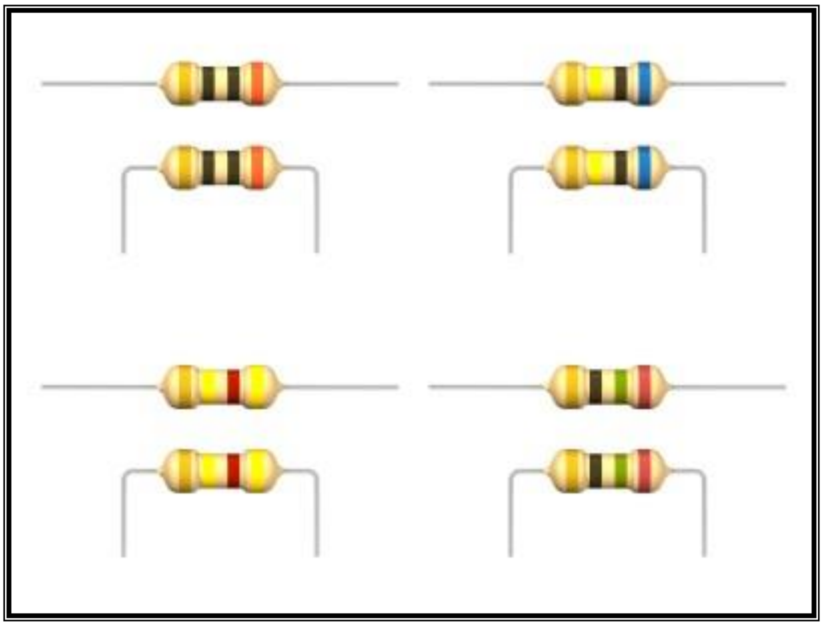
An electric circuit is formed when a conductive path is created to allow free electrons to continuously move. This continuous movement of free electrons through the conductors of a circuit is called a *current*, and it is often referred to in terms of "flow," just like the flow of a liquid through a hollow pipe.

The force motivating electrons to "flow" in a circuit is called *voltage*. Voltage is a specific measure of potential energy that is always relative between two points. When we speak of a certain amount of voltage being present in a circuit, we are referring to the measurement of how much *potential* energy exists to move electrons from one particular point in that circuit to another particular point. Without reference to *two* particular points, the term "voltage" has no meaning.

Quantity	Symbol	Unit of Measurement	Unit Abbreviation
Current	I	Ampere ("Amp")	A
Voltage	E *or* V	Volt	V
Resistance	R	Ohm	Ω

RELATION BETWEEN ELECTRICAL, MECHANICAL AND THERMAL UNITS

ELECTRIC UNIT :- An electrical unit is any unit of measurement that is used to describe a property found in electric circuits. Examples of some of the most common types of electrical unit include acoulomb, which is used for measuring charge; an ampere, which is used for measuring electrical current; and a volt, which is used to measure voltage. Electric units provide an absolute measurement of the state of a particular circuit at any one time, which is essential for building and maintaining electrical circuits.



The unit of voltage — the volt — is probably one of the most important electrical units. It is also sometimes known as the unit of electromotive force. This second name provides a clue as to what voltage actually is — a force that acts on electrons in a circuit and pushes them in a certain direction. The volt is also the electrical unit for potential difference which is a similar quantity.

Current is the flow of electrons around an electrical circuit. The electrical unit of current is the ampere, which describes the amount of charge flowing per second. For this reason the ampere can also be described as coulombs per second. At a basic level the current is a measurement of how many electrons are passing a certain point every second. This is due to the fact that each electron has a specific charge.

Aside from voltage and current the third basic electrical property is resistance and this has the unit of ohms. Electrical resistance describes the strength of opposition to the flow of electrons round a particular circuit. Although specially made resistors are used to increase the resistance in a circuit and hence reduce current any component has an inherent resistance. Even wires have a small but real resistance which increases with temperature.

Other electrical units include the watt, which is a measure of electrical power, and farad, which is a measure of capacitance. The joule is a standard unit in physics for energy although it can also be applied to electrical energy flowing round a circuit. A joule, however, is a relatively small unit, which is why kilowatt-hours — a more practical measurement of energy — is commonly used in many situations.

The coulomb is considered to be the standard electrical unit as it's a measurement of charge. It can also be considered as the amount of electricity transferred through a circuit in one second by a certain current. Equations linking these standard properties of an electrical circuit allow for detailed predictions of how electricity will behave in a certain situation.

MECHANICAL UNIT :-

In the typical fashion of working almost exclusively in SI units as part of an effort to remove the engineering profession from outdated unitary systems, this text will present all problems in SI. The table below should cover all the units use throughout the text.

Parameter	**SI**
Mass	kg
Angle	rad
Acceleration	$\frac{\mathrm{m}}{\mathrm{s}^2}$

Length	m
Force	N
Spring constant	$\frac{N}{m}$
Torsional Spring constant	$\frac{Nm}{rad}$
Damping constant	$\frac{Nsec}{m}$
Mass moment of inertia	kgm^2

THERMAL UNIT:- (often denoted *k*, *λ*, or *κ*) is the property of a material to conduct heat. It is evaluated primarily in terms of Fourier's Law for heat conduction.

Heat transfer occurs at a higher rate across materials of high thermal conductivity than across materials of low thermal conductivity. Correspondingly materials of high thermal conductivity are widely used in heat sink applications and materials of low thermal conductivity are used as thermal insulation. Thermal conductivity of materials is temperature dependent. The reciprocal of thermal conductivity is called thermal resistivity.

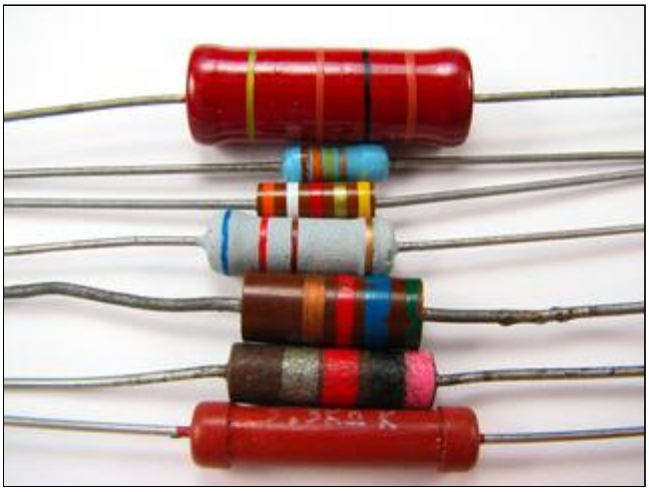
In SI units, thermal conductivity is measured in watts per meter kelvin (W/(m·K)). The dimension of thermal conductivity is $M^1L^1T^{-3}\Theta^{-1}$. These variables are (M)mass, (L)length, (T)time, and temperature. In Imperial units, thermal conductivity is measured in BTU/(hr·ft·°F).[note 1][1]

RELATION BETWEEN ELECTRICAL, MECHANICAL AND THERMAL UNITS

It is important to establish the relationship between the practical units for the measurement of mechanical power, energy and heat and unit used for the measurement of electric power, energy and heat .

FACTORS AFFECTING RESISTANCE OF A CONDUCTOR

Materials conduct electricity because their atoms and molecules have loosely-bound electrons. If you apply a voltage to the material, it pushes the loose electrons and electrical current flows. An electrical conductor has resistance because this flow is not perfect; some materials, such as silver and copper, conduct better than others, including rubber and glass. Shape, temperature and other factors affect electrical resistance.



Temperature

Electricity flows best when the atoms in a conductor remain still. Because heat makes atoms vibrate, it increases resistance. Generally, the hotter an object becomes, the more resistance it has. For some materials, such as silicon, this rule works backwards to an extent; for a certain range of temperatures, heat reduces resistance.

Materials

Materials with tightly-bound electrons, such as plastic and wood, make poor electrical conductors and have high resistance. Scientists do not consider these materials conductors at all; instead they call them "insulators." Among conductors, carbon and silicon have high resistance. The resistance of metals such as copper and nickel is much lower.

Size and Shape

Thin and small conductors have higher resistance than large, thick ones --- much as a narrow pipe resists the flow of a liquid more than a large-diameter pipe. Conductors for powerful, high-current industrial machines are much larger than those for low-power consumer electronics. The filament in an incandescent light bulb is a very fine wire designed to produce heat through high electrical resistance.

Current

Ideally, the amount of current does not affect the resistance in a material. In reality, however, materials become warm with increasing electrical currents, driving up resistance. Scientists call this resistance "non-ohmic." Electronic components called "resistors" have a constant resistance for a range of currents, though these, too become hot when forced to carry excessive current.

TEMPERATURE COEFFICIENT OF RESISTANCE

Resistance: Temperature Coefficient

Since the electrical resistance of a conductor such as a copper wire is dependent upon collisional proccesses within the wire, the resistance could be expected to increase with temperature since there will be more collisions. An intuitive approach to temperature dependence leads one to expect a fractional change in resistance which is proportional to the temperature change:

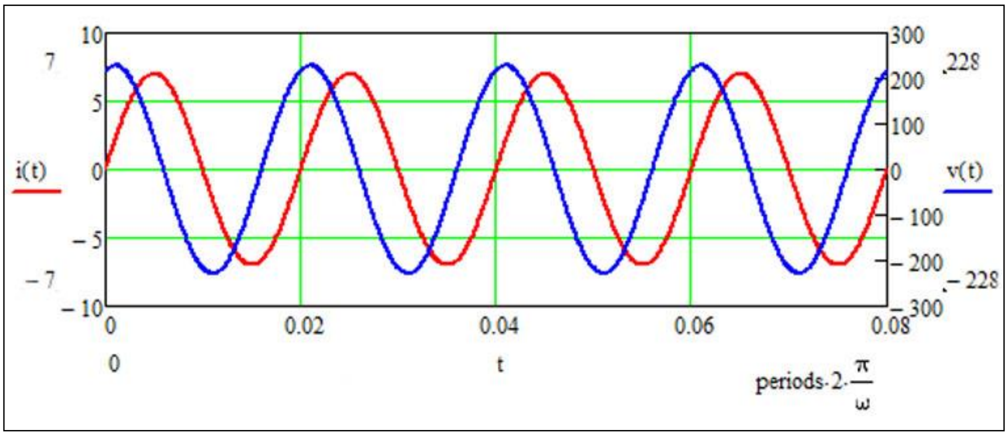
$$\frac{\Delta R}{R_0} = \alpha \Delta T \qquad \alpha = \text{temperature coefficient of resistance.}$$

Or, expressed in terms of the resistance at some standard temperature from a reference table:

$$\frac{R-R_0}{R_0} = \alpha(T-T_0) \quad \text{or} \quad R = R_0[1 + \alpha(T-T_0)]$$

DIFFERENCE BETWEEN AC AND DC VOLTAGE AND CURRENT

Alternating current (AC) and direct current (DC) are notable for inspiring the name of an iconic metal band, but they also happen to sit right at the center of the modern world as we know it. AC and DC are different types of voltage or current used for the conduction and transmission of electrical energy.



Electrical current is the flow of charged particles, or specifically in the case of AC and DC, the flow of electrons. According to Karl K. Berggren, professor of electrical engineering at MIT, the fundamental difference between AC and DC is the direction of flow. DC is constant and moves in one direction. "A simple way to visualize the difference is that, when graphed, a DC current looks like a flat line, whereas the flow of AC on a graph makes a sinusoid or wave-like pattern," says Berggren. "This is because AC changes over time in an oscillating repetition—the up curve indicates the current flowing in a positive direction and the down curve signifies the alternate cycle where the current moves in a negative direction. This back and forth is what gives AC its name."

Leaving aside lines and graphs for a moment, Berggren offers another way to distinguish between AC and DC by looking at how they work in the devices we use. The lamp next to your bed, for example, uses AC. This is because the source of the current came from far away, and the wave-like motion of the current makes it an efficient traveler. If you happen to be a read-by-flashlight kind of person, you are a consumer of DC power. A typical battery has negative and positive terminals, and the electrical charge (it's those electrons) moves in one direction from one to the other at a steady rate (the straight line on the graph).

Interestingly, if you're reading this on a laptop, you are actually using both kinds of current. The nozzle-shaped plug that goes into your computer delivers a direct current to the computer's battery, but it receives that charge from an AC plug that goes into the wall. The awkward little block that's in between the wall plug and your computer is a power adapter that transforms AC to DC.

Berggren explains that AC became popular in the late 19th century because of its ability to efficiently distribute power at low voltages. Initially, power is conducted at very high voltages. In order to get these high voltages down to the low voltages necessary to power, say, a household light bulb, it's necessary to transform the current. A transformer, which is basically two loops of wire, gets AC down from hundreds of thousands of volts to distributions of reasonable voltages (in the hundreds) to power most day to day electronics. The ability to transform voltages from AC meant that it was possible to transmit power much more efficiently across the country.

According to Berggren, there's a funny history of rivalry between AC and DC. In the later 19th century, there was a giant war between Edison and Westinghouse over AC and DC. Edison had patents in place that made him invested in the widespread use of DC. He set out to convince the world that DC was superior for the transmission and distribution of power. He resorted to crazy demonstrations like killing large animals with AC in an attempt to prove its terrible dangers. For a time, he was successful and most municipalities utilized local power plants with DC supply. However, getting power to less populated, rural communities all over the country with DC proved very inefficient, so Westinghouse ultimately won out and AC became the dominant power source.

UNIT- 2
D.C. CIRCUITS

2.1 OHM'S LAW

Ohm's Law deals with the relationship between voltage and current in an ideal conductor. This relationship states that:

The potential difference (voltage) across an ideal conductor is proportional to the current through it.

The constant of proportionality is called the "resistance", **R**.

Ohm's Law is given by:

V = I R

where V is the potential difference between two points which include a **resistance** R. I is the current flowing through the resistance. For biological work, it is often preferable to use the **conductance**, g = 1/R; In this form Ohm's Law is:

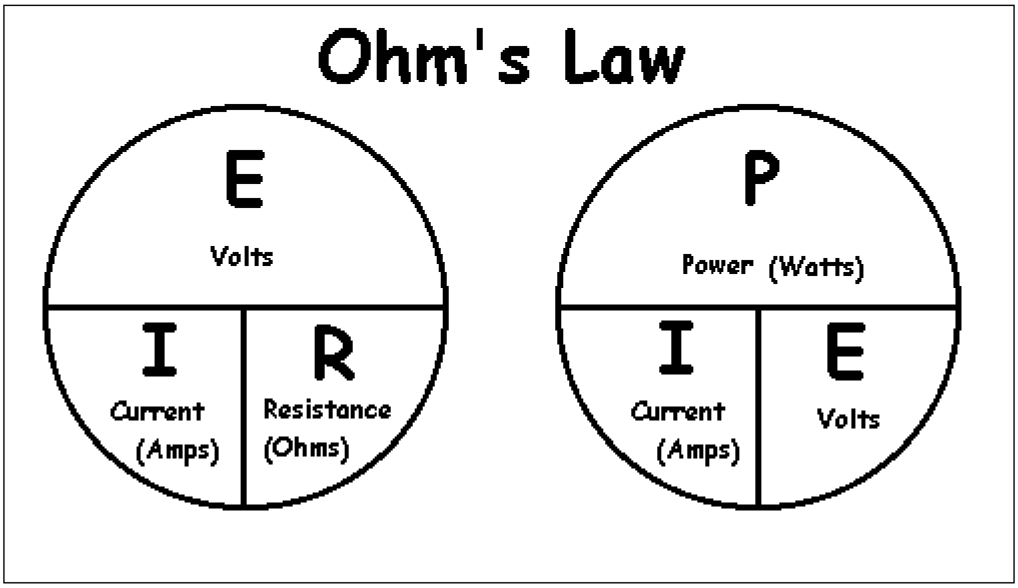
I = g V

Material that obeys Ohm's Law is called "**ohmic"** or "**linear"** because the potential difference across it varies linearly with the current.

Ohm's Law can be used to solve simple circuits. A complete circuit is one which is a closed loop. It contains at least one source of voltage (thus providing an increase of potential energy), and at least one potential drop i.e., a place where potential energy decreases. The sum of the voltages around a complete circuit is zero.

An increase of potential energy in a circuit causes a charge to move from a lower to a higher potential (ie. voltage). Note the difference between potential energy and potential.

Because of the electrostatic force, which tries to move a positive charge from a higher to a lower potential, there must be another 'force' to move charge from a lower potential to a higher inside the battery. This so-called force is called the **electromotive force**, or **emf**. The SI unit for the emf is a volt (and thus this is not really a force, despite its name). We will use a script E, the symbol $\mathcal{E}$, to represent the emf.



A decrease of potential energy can occur by various means. For example, heat lost in a circuit due to some electrical resistance could be one source of energy drop.

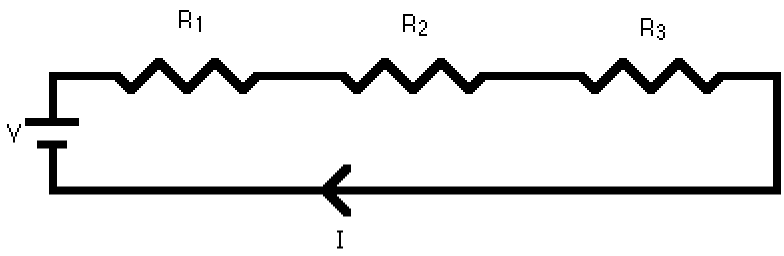
Because energy is conserved, the potential difference across an emf must be equal to the potential difference across the rest of the circuit. That is, Ohm's Law will be satisfied .

2.2 SERIES — PARALLEL RESISTANCE CIRCUITS

Series circuits

A series circuit is a circuit in which resistors are arranged in a chain, so the current has only one path to take. The current is the same through each resistor. The total resistance of the circuit is found by simply adding up the resistance values of the individual resistors:

equivalent resistance of resistors in series : $R = R_1 + R_2 + R_3 + \ldots$



A series circuit is shown in the diagram above. The current flows through each resistor in turn. If the values of the three resistors are:

$R_1 = 8\ \Omega$, $R_2 = 8\ \Omega$, and $R_3 = 4\ \Omega$, the total resistance is $8 + 8 + 4 = 20\ \Omega$.

With a 10 V battery, by V = I R the total current in the circuit is:

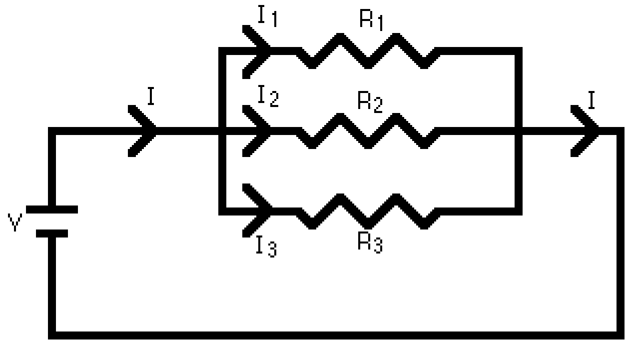
I = V / R = 10 / 20 = 0.5 A. The current through each resistor would be 0.5 A.

Parallel circuits

A parallel circuit is a circuit in which the resistors are arranged with their heads connected together, and their tails connected together. The current in a parallel circuit breaks up, with some flowing along each parallel branch and re-combining when the branches meet again. The voltage across each resistor in parallel is the same.

The total resistance of a set of resistors in parallel is found by adding up the reciprocals of the resistance values, and then taking the reciprocal of the total:

equivalent resistance of resistors in parallel: $1 / R = 1 / R_1 + 1 / R_2 + 1 / R_3 + ...$



A parallel circuit is shown in the diagram above. In this case the current supplied by the battery splits up, and the amount going through each resistor depends on the resistance. If the values of the three resistors are:

$R_1 = 8\ \Omega$, $R_2 = 8\ \Omega$, and $R_3 = 4\ \Omega$, the total resistance is found by:

$1 / R = 1 / 8 + 1 / 8 + 1 / 4 = 1 / 2$. This gives $R = 2\ \Omega$.

With a 10 V battery, by V = I R the total current in the circuit is: I = V / R = 10 / 2 = 5 A.

The individual currents can also be found using I = V / R. The voltage across each resistor is 10 V, so:

I_1 = 10 / 8 = 1.25 A
I_2 = 10 / 8 = 1.25 A
I_3=10 / 4 = 2.5 A

Note that the currents add together to 5A, the total current.

A parallel resistor short-cut

If the resistors in parallel are identical, it can be very easy to work out the equivalent resistance. In this case the equivalent resistance of N identical resistors is the resistance of one resistor divided by N, the number of resistors. So, two 40-ohm resistors in parallel are equivalent to one 20-ohm resistor; five 50-ohm resistors in parallel are equivalent to one 10-ohm resistor, etc.

When calculating the equivalent resistance of a set of parallel resistors, people often forget to flip the 1/R upside down, putting 1/5 of an ohm instead of 5 ohms, for instance. Here's a way to check your answer. If you have two or more resistors in parallel, look for the one with the smallest resistance. The equivalent resistance will always be between the smallest resistance divided by the number of resistors, and the smallest resistance. Here's an example.

You have three resistors in parallel, with values 6 ohms, 9 ohms, and 18 ohms. The smallest resistance is 6 ohms, so the equivalent resistance must be between 2 ohms and 6 ohms (2 = 6 /3, where 3 is the number of resistors).

Doing the calculation gives 1/6 + 1/12 + 1/18 = 6/18. Flipping this upside down gives 18/6 = 3 ohms, which is certainly between 2 and 6.

Circuits with series and parallel components

Many circuits have a combination of series and parallel resistors. Generally, the total resistance in a circuit like this is found by reducing the different series and parallel combinations step-by-step to end up with a single equivalent resistance for the circuit.

This allows the current to be determined easily. The current flowing through each resistor can then be found by undoing the reduction process.

General rules for doing the reduction process include:

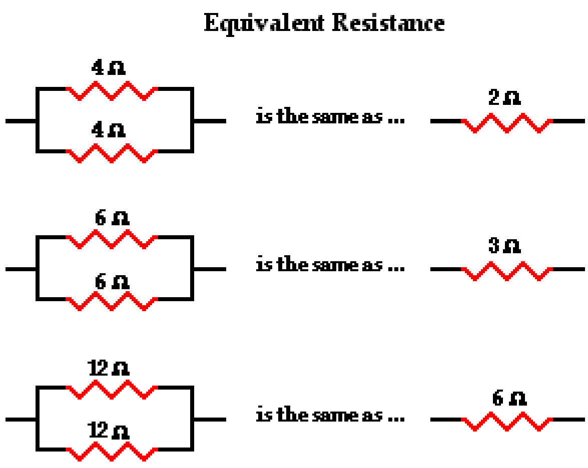
1. Two (or more) resistors with their heads directly connected together and their tails directly connected together are in parallel, and they can be reduced to one resistor using the equivalent resistance equation for resistors in parallel.
2. Two resistors connected together so that the tail of one is connected to the head of the next, with no other path for the current to take along the line connecting them, are in series and can be reduced to one equivalent resistor.

Finally, remember that for resistors in series, the current is the same for each resistor, and for resistors in parallel, the voltage is the same for each one.

2.3 CALCULATION OF EQUIVALENT RESISTANCE

Analysis of Combination Circuits

The basic strategy for the analysis of combination circuits involves using the meaning of equivalent resistance for parallel branches to transform the combination circuit into a series circuit. Once transformed into a series circuit, the analysis can be conducted in the usual manner. Previously in Lesson 4, the method for determining the equivalent resistance of parallel are equal, then the total or equivalent resistance of those branches is equal to the resistance of one branch divided by the number of branches.



This method is consistent with the formula

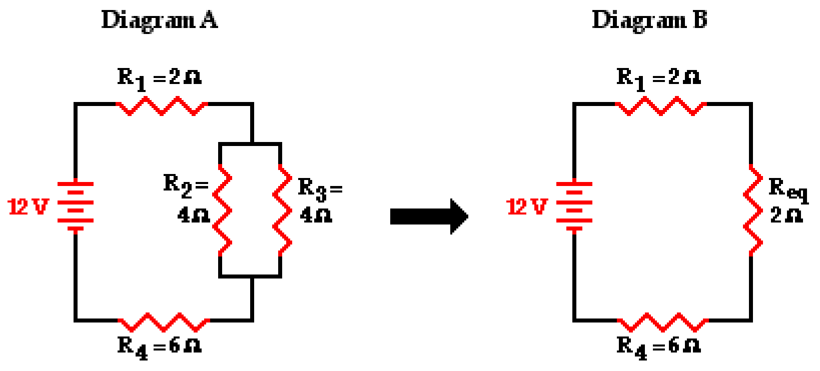
$1 / R_{eq} = 1 / R_1 + 1 / R_2 + 1 / R_3 + ...$

where R_1, R_2, and R_3 are the resistance values of the individual resistors that are connected in parallel. If the two or more resistors found in the parallel branches do not have equal resistance, then the above formula must be used. An example of this method was presented in a previous section of Lesson 4.

By applying one's understanding of the equivalent resistance of parallel branches to a combination circuit, the combination circuit can be transformed into a series circuit. Then an understanding of the equivalent resistance of a series circuit can be used to determine the total resistance of the circuit. Consider the following diagrams below. Diagram A represents a combination circuit with resistors R_2 and R_3 placed in parallel branches. Two 4-Ω resistors in parallel is equivalent to a resistance of 2 Ω. Thus, the two branches can be replaced by a single resistor with a resistance of 2 Ω. This is shown in Diagram B. Now that all resistors are in series, the formula for the total resistance of series resistors can be used to determine the total resistance of this circuit: The formula for series resistance is

$R_{tot} = R_1 + R_2 + R_3 + ...$

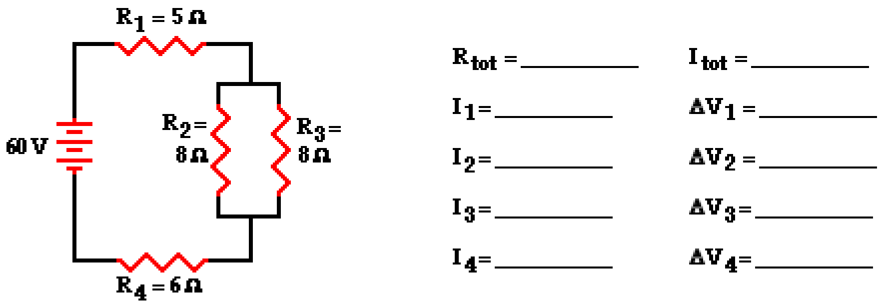
So in Diagram B, the total resistance of the circuit is 10 Ω.



Once the total resistance of the circuit is determined, the analysis continues using Ohm's law and voltage and resistance values to determine current values at various locations. The entire method is illustrated below with two examples.

Example 1:

The first example is the easiest case - the resistors placed in parallel have the same resistance. The goal of the analysis is to determine the current in and the voltage drop across each resistor.



As discussed above, the first step is to simplify the circuit by replacing the two parallel resistors with a single resistor that has an equivalent resistance. Two 8 Ω resistors in series is equivalent to a single 4 Ω resistor. Thus, the two branch resistors (R_2 and R_3) can be replaced by a single resistor with a resistance of 4 Ω. This 4 Ω resistor is in series with R_1 and R_4. Thus, the total resistance is

$R_{tot} = R_1 + 4\ \Omega + R_4 = 5\ \Omega + 4\ \Omega + 6\ \Omega$

$\mathbf{R_{tot} = 15\ \Omega}$

Now the Ohm's law equation ($\Delta V = I \bullet R$) can be used to determine the total current in the circuit. In doing so, the total resistance and the total voltage (or battery voltage) will have to be used.

$I_{tot} = \Delta V_{tot} / R_{tot} = (60\ V) / (15\ \Omega)$

$\mathbf{I_{tot} = 4\ Amp}$

The 4 Amp current calculation represents the current at the battery location. Yet, resistors $R_1$and R_4 are in series and the current in series-connected resistors is everywhere the same. Thus,

$I_{tot} = \mathbf{I_1 = I_4 = 4\ Amp}$

For parallel branches, the sum of the current in each individual branch is equal to the current outside the branches. Thus, $I_2 + I_3$ must equal 4 Amp. There are an infinite number of possible values of I_2 and I_3 that satisfy this equation. Since the resistance values are equal, the current values in these two resistors are also equal. Therefore, the current in resistors 2 and 3 are both equal to 2 Amp.

$I_2 = I_3 = 2$ Amp

Now that the current at each individual resistor location is known, the Ohm's law equation ($\Delta V = I \cdot R$) can be used to determine the voltage drop across each resistor. These calculations are shown below.

$\Delta V_1 = I_1 \cdot R_1 = (4 \text{ Amp}) \cdot (5\ \Omega)$

$\Delta V_1 = 20$ V

$\Delta V_2 = I_2 \cdot R_2 = (2 \text{ Amp}) \cdot (8\ \Omega)$

$\Delta V_2 = 16$ V

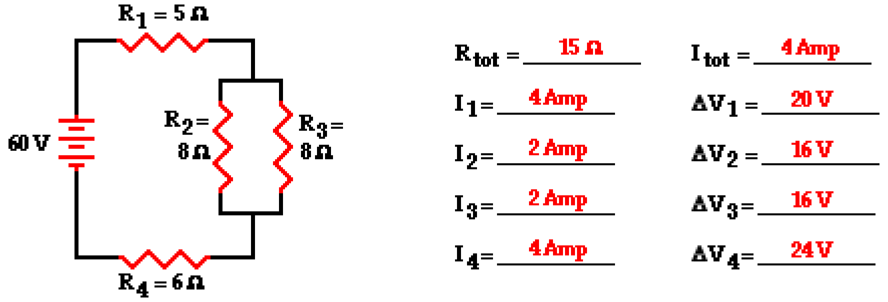
$\Delta V_3 = I_3 \cdot R_3 = (2 \text{ Amp}) \cdot (8\ \Omega)$

$\Delta V_3 = 16$ V

$\Delta V_4 = I_4 \cdot R_4 = (4 \text{ Amp}) \cdot (6\ \Omega)$

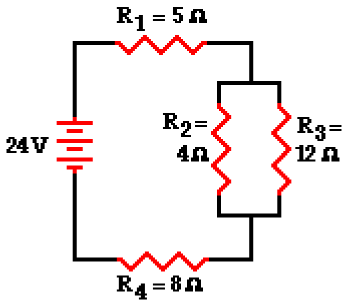
$\Delta V_4 = 24$ V

The analysis is now complete and the results are summarized in the diagram below.



Example 2:

The second example is the more difficult case - the resistors placed in parallel have a different resistance value. The goal of the analysis is the same - to determine the current in and the voltage drop across each resistor.



R_{tot} = ________	I_{tot} = ________
I_1 = ________	ΔV_1 = ________
I_2 = ________	ΔV_2 = ________
I_3 = ________	ΔV_3 = ________
I_4 = ________	ΔV_4 = ________

As discussed above, the first step is to simplify the circuit by replacing the two parallel resistors with a single resistor with an equivalent resistance. The equivalent resistance of a 4-Ω and 12-Ω resistor placed in parallel can be determined using the usual formula for equivalent resistance of parallel branches:

$1 / R_{eq} = 1 / R_1 + 1 / R_2 + 1 / R_3 ...$

$1 / R_{eq} = 1 / (4\ \Omega) + 1 / (12\ \Omega)$

$1 / R_{eq} = 0.333\ \Omega^{-1}$

$R_{eq} = 1 / (0.333\ \Omega^{-1})$

$R_{eq} = 3.00\ \Omega$

Based on this calculation, it can be said that the two branch resistors (R_2 and R_3) can be replaced by a single resistor with a resistance of 3 Ω. This 3 Ω resistor is in series with R_1 and R_4. Thus, the total resistance is

$R_{tot} = R_1 + 3\ \Omega + R_4 = 5\ \Omega + 3\ \Omega + 8\ \Omega$

R_{tot} = 16 Ω

Now the Ohm's law equation ($\Delta V = I \bullet R$) can be used to determine the total current in the circuit. In doing so, the total resistance and the total voltage (or battery voltage) will have to be used.

$I_{tot} = \Delta V_{tot} / R_{tot} = (24\ V) / (16\ \Omega)$

I_{tot} = 1.5 Amp

The 1.5 Amp current calculation represents the current at the battery location. Yet, resistors R_1 and R_4 are in series and the current in series-connected resistors is everywhere the same. Thus,

I_{tot} = $\mathbf{I_1 = I_4 = 1.5}$ **Amp**

For parallel branches, the sum of the current in each individual branch is equal to the current outside the branches. Thus, $I_2 + I_3$ must equal 1.5 Amp. There are an infinite possibilities of $I_2$and I_3 values that satisfy this equation. In the previous example, the two resistors in parallel had the identical resistance; thus the current was distributed equally among the two branches. In this example, the unequal current in the two resistors complicates the analysis. The branch with the least resistance will have the greatest current. Determining the amount of current will demand that we use the Ohm's law equation. But to use it, the voltage drop across the branches must first be known. So the direction that the solution takes in this example will be slightly different than that of the simpler case illustrated in the previous example.

To determine the voltage drop across the parallel branches, the voltage drop across the two series-connected resistors (R_1 and R_4) must first be determined. The Ohm's law equation ($\Delta V = I \bullet R$) can be used to determine the voltage drop across each resistor. These calculations are shown below.

$\Delta V_1 = I_1 \bullet R_1 = (1.5 \text{ Amp}) \bullet (5\ \Omega)$

$\mathbf{\Delta V_1 = 7.5\ V}$

$\Delta V_4 = I_4 \bullet R_4 = (1.5 \text{ Amp}) \bullet (8\ \Omega)$

$\mathbf{\Delta V_4 = 12\ V}$

This circuit is powered by a 24-volt source. Thus, the cumulative voltage drop of a charge traversing a loop about the circuit is 24 volts. There will be a 19.5 V drop (7.5 V + 12 V) resulting from passage through the two series-connected resistors (R_1 and R_4). The voltage drop across the branches must be 4.5 volts to make up the difference between the 24 volt total and the 19.5-volt drop across R_1 and R_4. Thus,

$\mathbf{\Delta V_2 = \Delta V_3 = 4.5\ V}$

Knowing the voltage drop across the parallel-connected resistors (R_1 and R_4) allows one to use the Ohm's law equation ($\Delta V = I \bullet R$) to determine the current in the two branches.

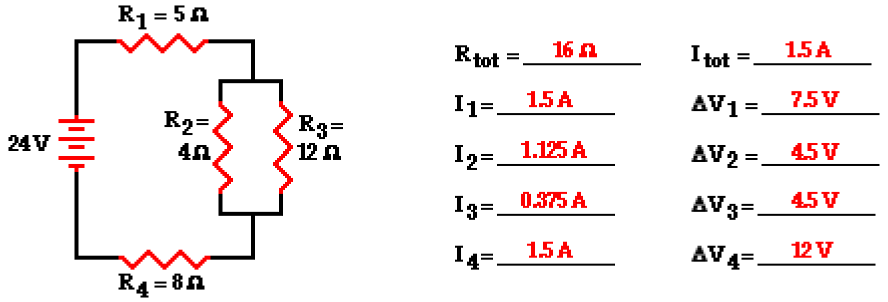
$I_2 = \Delta V_2 / R_2 = (4.5\ V) / (4\ \Omega)$

I_2 = 1.125 A

$I_3 = \Delta V_3 / R_3 = (4.5\ V) / (12\ \Omega)$

I_3 = 0.375 A

The analysis is now complete and the results are summarized in the diagram below.



Developing a Strategy

The two examples above illustrate an effective concept-centered strategy for analyzing combination circuits. Such analyses are often conducted in order to solve a physics problem for a specified unknown. In such situations, the unknown typically varies from problem to problem. In one problem, the resistor values may be given and the current in all the branches are the unknown. In another problem, the current in the battery and a few resistor values may be stated and the unknown quantity becomes the resistance of one of the resistors. Different problem situations will obviously require slight alterations in the approaches. Nonetheless, every problem-solving approach will utilize the same principles utilized in approaching the two example problems above.

The following suggestions for approaching combination circuit problems are offered to the beginning student:

- If a schematic diagram is not provided, take the time to construct one. Use schematic symbols such as those shown in the example above.
- When approaching a problem involving a combination circuit, take the time to organize yourself, writing down known values and equating them with a symbol such as I_{tot}, I_1, R_3, ΔV_2, etc. The organization scheme used in the two examples above is an effective starting point.

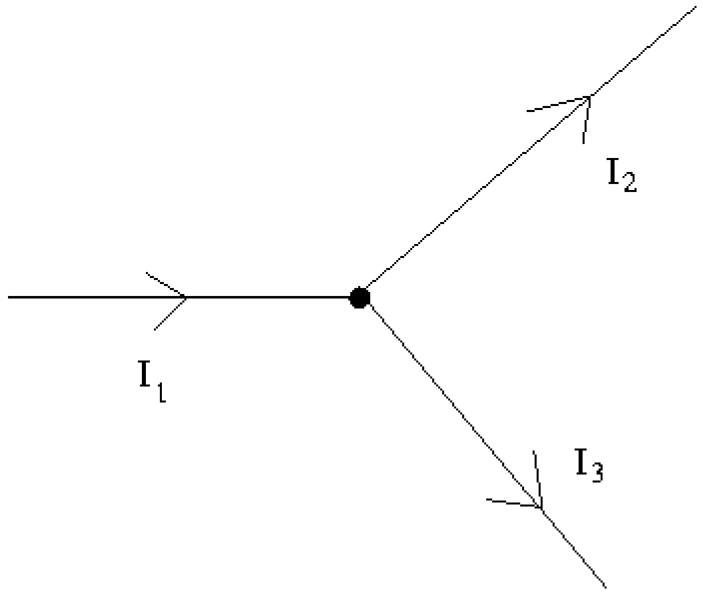
- Know and use the appropriate formulae for the equivalent resistance of series-connected and parallel-connected resistors. Use of the wrong formulae will guarantee failure.
- Transform a combination circuit into a strictly series circuit by replacing (in your mind) the parallel section with a single resistor having a resistance value equal to the equivalent resistance of the parallel section.
- Use the Ohm's law equation ($\Delta V = I \bullet R$) often and appropriately. Most answers will be determined using this equation. When using it, it is important to substitute the appropriate values into the equation. For instance, if calculating I_2, it is important to substitute the $\Delta V_2$and the R_2 values into the equation.

2.4 KIRCHHOFF S LAWS AND THEIR APPLICATIONS

Although useful to be able to reduce series and parallel resistors in a circuit when they occur, circuits in general are not composed exclusively of such combinations. For such cases there are a powerful set of relations called Kirchhoff's laws which enable one to analyze arbitrary circuits. There are two such laws:

- The 1st law or the *junction rule*: for a given junction or node in a circuit, the sum of the currents entering equals the sum of the currents leaving. This law is a statement of charge conservation. For example,

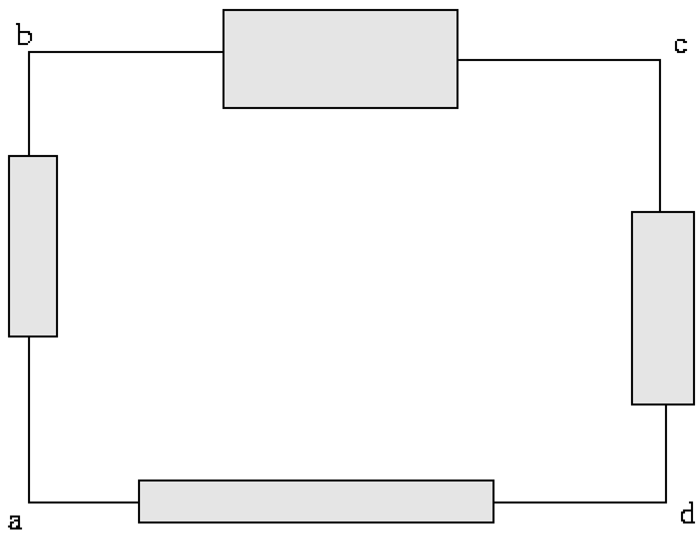
Figure 17.6: Illustration of Kirchhoff's junction rule



The junction rule tells us $I_1 = I_2 + I_3$.

- The 2nd law or the *loop rule*: around any closed loop in a circuit, the sum of the potential differences across all elements is zero. This law is a statement of energy conservation, in that any charge that starts and ends up at the same point with the same velocity must have gained as much energy as it lost. For example, in Fig. 17.7,

Figure 17.7: Illustration of Kirchhoff's loop rule



Where the boxes denote a circuit element, the loop rule tells us $0 = (V_b - V_a) + (V_c - V_b) + (V_d - V_c) + (V_d - V_a)$.

The second law entails certain sign conventions for potential differences across circuit elements. For batteries and resistors, these conventions are summarized in Fig. 17.8. Note that in these conventions the current always flows from a high to a low potential.

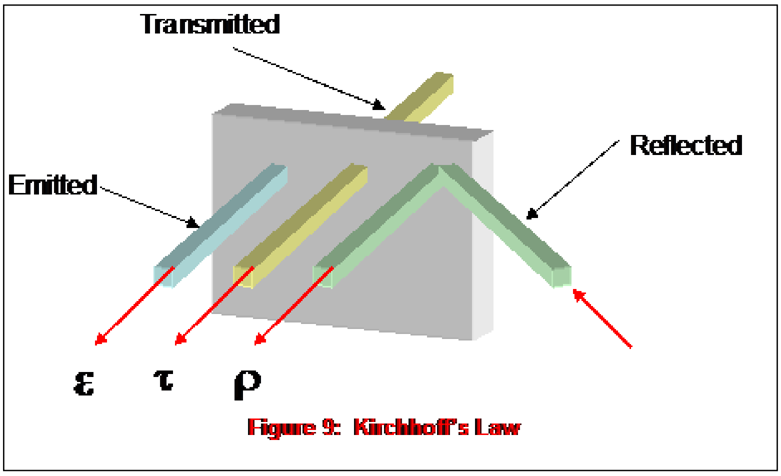
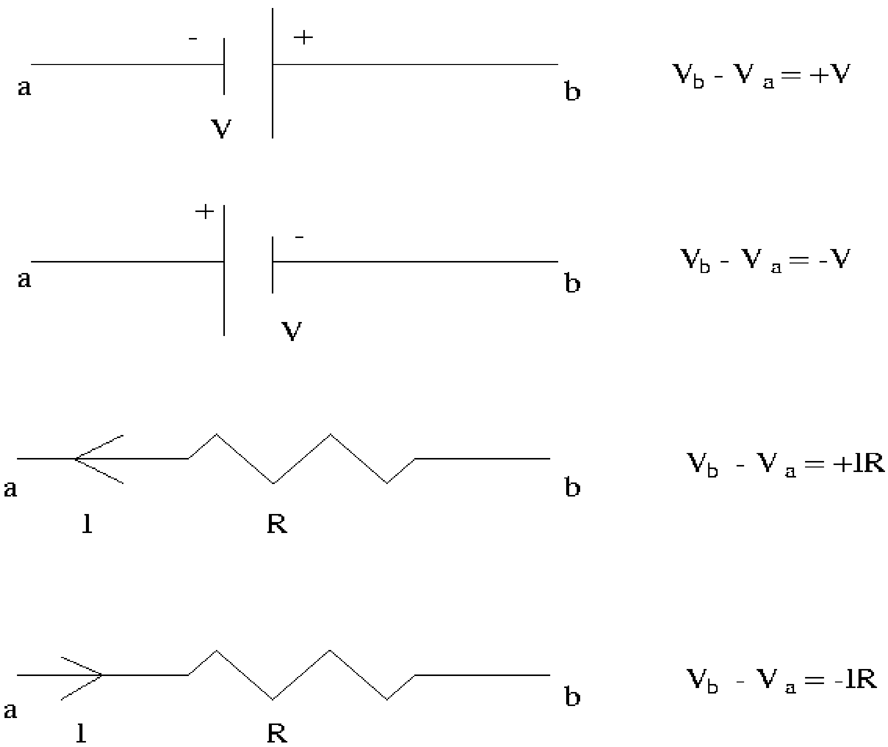


Figure 9: Kirchhoff's Law

Figure 17.8: Sign conventions for Kirchhoff's loop rule



In analyzing circuits using Kirchhoff's laws, it is helpful to keep in mind the following guidelines.

1.Draw the circuit and assign labels to the known and unknown quantities, including currents in each branch. You must assign directions to currents; don't worry if you guess incorrectly the direction of a particular unknown current, as the answer resulting from the analysis in this case will simply come out negative, but with the right magnitude.

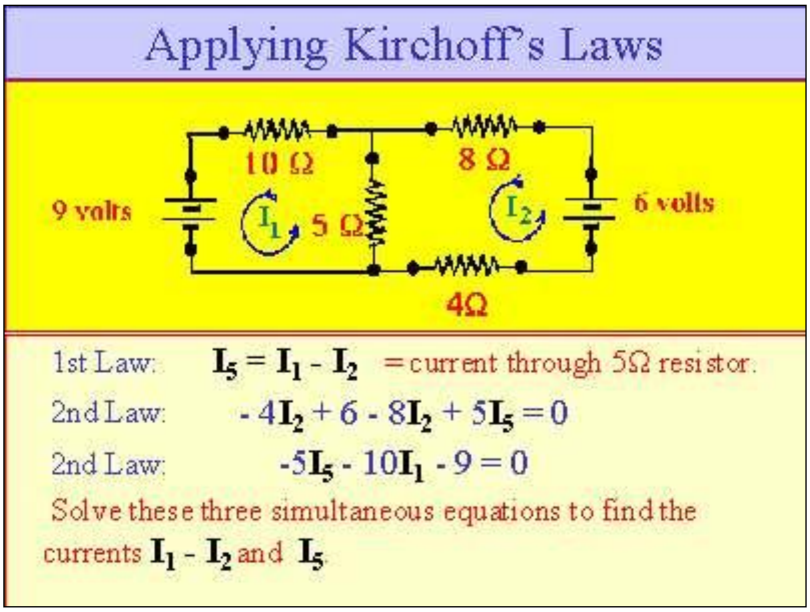
2. Apply the junction rule to as many junctions in the circuit as possible to obtain the maximum number of independent relations.

3. Apply the loop rule to as many loops in the circuit as necessary in order to solve for the unknowns. Note that if one has *n* unknowns in a circuit one will need *n* independent equations. In general there will be more loops present in a circuit than one needs to solve for all the unknowns; the relations resulting from these ``extra'' loops can be used as a consistency check on your final answers.

4. Solve the resulting set of simultaneous equations for the unknown quantities. Proficiency in analyzing circuits with Kirchhoff's laws, particularly with regard to the sign conventions and with solving simultaneous equations, comes with practice.

APPLICATION OF KIRCHHOFF'S LAWS

I. Kirchhoff's Laws are applications of two fundamental conservation laws: the Law of Conservation of Energy, and the Law of Conservation of Charge.



II. At any junction in an electric circuit, the total current flowing into the junction is the same as the total current leaving the junction. (Kirchhoff's Current Law, or Kirchhoff's First Law).

III. The algebraic sum of the potential differences in a complete circuit must be zero. (Kirchhoff's Voltage Law, or Kirchhoff's Second Law) .

IV. Kirchhoff's Laws are useful in understanding the transfer of energy through an electric circuit. They are also valuable in analyzing electric circuits.

UNIT-3

ELECTRIC CELLS

3.1 Primary cell

A **primary cell** is a battery that is designed to be used once and discarded, and not recharged with electricity and reused like a secondary cell (rechargeable battery). In general, the electrochemical reaction occurring in the cell is not reversible, rendering the cell unrechargeable. As a primary cell is used, chemical reactions in the battery use up the chemicals that generate the power; when they are gone, the battery stops producing electricity and is useless. In contrast, in a secondary cell, the reaction can be reversed by running a current into the cell with a battery charger to recharge it, regenerating the chemical reactants. Primary cells are made in a range of standard sizes to power small household appliances.

A **secondary cell** or battery is one that can be electrically recharged after use to their original pre-discharge condition, by passing current through the circuit in the opposite direction to the current during discharge. The following graphic evidences the recharging process.

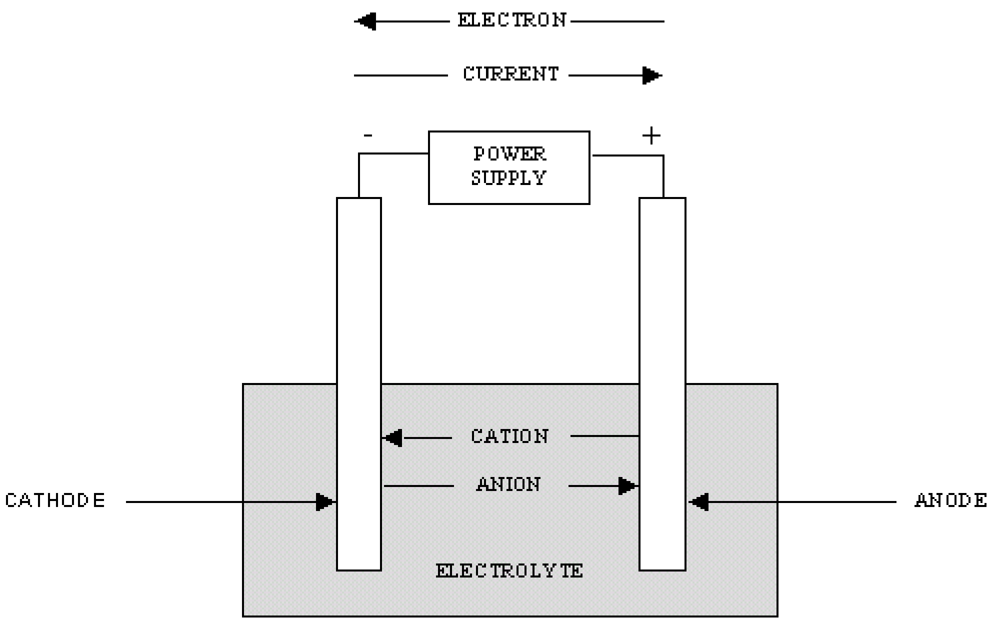


Figure 3: Recharging a Cell

Secondary batteries fall into two sub-categories depending on their intended applications.

- Cells that are utilized as energy storage devices, delivering energy on demand. Such cells are typically connected to primary power sources so as to be fully charged on demand. Examples of these type of secondary cells include emergency no-fail and standby power sources, aircraft systems and stationary energy storage systems for *load-leveling*.

- Cells that are essentially utilized as primary cells, but are recharged after use rather than being discarded. Examples of these types of secondary cells primarily include portable consumer electronics and electric vehicles.

Primary vs. Secondary – A Comparison

The following table summarizes the ***pros*** and cons of primary and secondary batteries.

Primary	***Secondary***
Lower initial cost. Higher life-cycle cost ($/kWh). ***Disposable***. ***Disposable.*** ***Replacement readily available***. ***Typically lighter and smaller; thus traditionally more suited for portable applications***. ***Longer service per charge and good charge***	Higher initial cost. ***Lower life-cycle cost ($/kWh) if charging in convenient and inexpensive.*** Regular maintenance required. Periodic recharging required. Replacements while available, are not produced in the same sheer numbers as primary batteries. May need to be pre-ordered. Traditionally less suited for portable applications, although recent advances in Lithium battery technology have lead to the development of smaller/lighter secondary batteries. Relative to primary battery systems, traditional

retention.	secondary batteries (particularly aqueous secondary batteries) exhibit inferior charge retention.
Not ideally suited for heavy load/*high discharge rate*performance.	***Superior high discharge rate performance at heavy loads***
Not ideally suited for load-leveling, emergency backup,*hybrid battery*, and high cost military applications.	***Ideally suited for load-leveling, emergency backup, hybrid battery and high cost military applications***
Traditionally limited to specific applications.	***The overall inherent versatility of secondary battery systems allows its use and continuing research for a large spectrum of applications.***

A third battery category is commonly referred to as the **reserve** cell. What differentiates the reserve cell from primary and secondary cells in the fact that a key component of the cell is separated from the remaining components, until just prior to activation. The component most often isolated is the electrolyte. This battery structure is commonly observed in thermal batteries, whereby the electrolyte remains inactive in a solid state until the melting point of the electrolyte is reached, allowing for ionic conduction, thus activating the battery. Reserve batteries effectively eliminate the possibility of self-discharge and minimize chemical deterioration. Most reserve batteries are used only once and then discarded. Reserve batteries are used in timing, temperature and pressure sensitive detonation devices in missiles, torpedoes, and other weapon systems.

Reserve cells are typically classified into the following 4 categories.

- Water activated batteries.
- Electrolyte activated batteries.
- Gas activated batteries.
- Heat activated batteries.

The **fuel cell** represents the fourth category of batteries. Fuel cells are similar to batteries except for the fact that that all active materials are not an integral part of the device (as in a battery). In fuel cells, active materials are fed into batteries from an outside source. The fuel cell differs from a battery in that it possesses the capability to produce electrical energy as long as active materials are fed to the electrodes, but stop operating in the absence of such materials. A well-known application of fuel cells has been in cryogenic fuels used in space vehicles. Use of fuel cell technology for terrestrial applications has been slow to develop, although recent advances have generated a revitalized interest in a variety of systems with applications such as utility power, load-leveling, on-site generators and electric vehicles.

WET CELL

Wet cell, sometimes called flooded, are made from a glass or plastic container filled with sulfuric acid in which lead plates are submerged. They were the first rechargeable batteries, invented in 1859, but are still in common use today in automobiles, trucks, RVs, motorized wheelchairs, golf carts and emergency power backup systems in household and industrial applications. The main concern for wet cell batteries in all applications is leaking sulfuric acid, as it is a dangerous corrosive that can damage what it contacts and can burn human tissue.

DRY CELL

Although there are many types of dry cell that do not contain liquid that can be spilled, the main competitors with wet cell batteries are gel cells and absorbent glass mat (AGM) batteries. The main difference is that the sulfuric acid is not in liquid from, and therefore leaking is much less of a hazard. The smaller types of dry cell batteries, such as alkaline or nickel-cadmium, usually cannot be manufactured in sizes or prices that could compete with the wet cells. So the decision is really between a wet cell, a gel cell or absorbent glass mat.

3.2 SERIES AND PARALLEL CONNECTIONS OF CELLS

Components of an electrical circuit or electronic circuit can be connected in many different ways. The two simplest of these are called **series** and **parallel** and occur very frequently. Components connected in series are connected along a single path, so the same current flows through all of the components. Components connected in parallel are connected so the same voltage is applied to each component.

A circuit composed solely of components connected in series is known as a **series circuit**; likewise, one connected completely in parallel is known as a **parallel circuit**.

In a series circuit, the current through each of the components is the same, and the voltage across the circuit is the sum of the voltages across each component.[1] In a parallel circuit, the voltage across each of the components is the same, and the total current is the sum of the currents through each component.

As an example, consider a very simple circuit consisting of four light bulbs and one 6 V battery. If a wire joins the battery to one bulb, to the next bulb, to the next bulb, to the next bulb, then back to the battery, in one continuous loop, the bulbs are said to be in series. If each bulb is wired to the battery in a separate loop, the bulbs are said to be in parallel. If the four light bulbs are connected in series, there is same current through all of them, and the voltage drop is 1.5 V across each bulb, which may not be sufficient to make them glow. If the light bulbs are connected in parallel, the currents through the light bulbs combine to form the current in the battery, while the voltage drop is 6.0 V across each bulb and they all glow.

In a series circuit, every device must function for the circuit to be complete. One bulb burning out in a series circuit breaks the circuit. In parallel circuits, each light has its own circuit, so all but one light could be burned out, and the last one will still function.

Series circuits are sometimes called *current*-coupled or daisy chain-coupled. The current in a series circuit goes through every component in the circuit. Therefore, all of the components in a series connection carry the same current. There is only one path in a series circuit in which the current can flow.

A series circuit's main disadvantage or advantage, depending on its intended role in a product's overall design, is that because there is only one path in which its current can flow, opening or breaking a series circuit at any point causes the entire circuit to "open" or stop operating. For example, if even one of the light bulbs in an older-style string of Christmas tree lights burns out or is removed, the entire string becomes inoperable until the bulb is replaced.

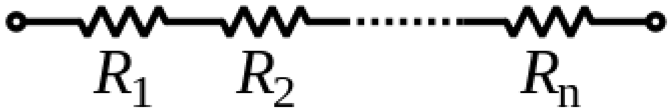
Current

$$I = I_1 = I_2 = \ldots = I_n$$

In a series circuit the current is the same for all elements.

Resistors

The total resistance of resistors in series is equal to the sum of their individual resistances:



$$R_{\text{total}} = R_1 + R_2 + \cdots + R_n$$

Electrical conductance presents a reciprocal quantity to resistance. Total conductance of a series circuits of pure resistors, therefore, can be calculated from the following expression:

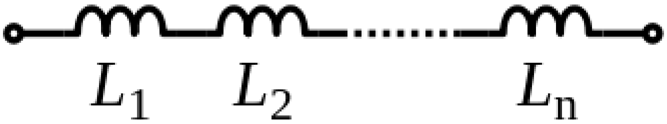
$$\frac{1}{G_{\text{total}}} = \frac{1}{G_1} + \frac{1}{G_2} + \cdots + \frac{1}{G_n}.$$

For a special case of two resistors in series, the total conductance is equal to:

$$G_{total} = \frac{G_1 G_2}{G_1 + G_2}.$$

Inductors

Inductors follow the same law, in that the total inductance of non-coupled inductors in series is equal to the sum of their individual inductances:



$$L_{\text{total}} = L_1 + L_2 + \cdots + L_n$$

However, in some situations it is difficult to prevent adjacent inductors from influencing each other, as the magnetic field of one device couples with the windings of its neighbours. This influence is defined by the mutual inductance M. For example, if two inductors are in series, there are two possible equivalent inductances depending on how the magnetic fields of both inductors influence each other.

When there are more than two inductors, the mutual inductance between each of them and the way the coils influence each other complicates the calculation. For a larger number of coils the total combined inductance is given by the sum of all mutual inductances between the various coils including the mutual inductance of each given coil with itself, which we term self-inductance or simply inductance. For three coils, there are six mutual inductances M_{12}, M_{13}, M_{23} and M_{21}, M_{31} and M_{32}. There are also the three self-inductances of the three coils: M_{11}, M_{22} and M_{33}.

Therefore

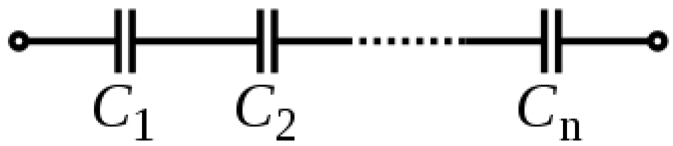
$$L_{\mathrm{total}} = (M_{11} + M_{22} + M_{33}) + (M_{12} + M_{13} + M_{23}) + (M_{21} + M_{31} + M_{32})$$

By reciprocity M_{ij} = M_{ji} so that the last two groups can be combined. The first three terms represent the sum of the self-inductances of the various coils. The formula is easily extended to any number of series coils with mutual coupling. The method can be used to find the self-inductance of large coils of wire of any cross-sectional shape by computing the sum of the mutual inductance of each turn of wire in the coil with every other turn since in such a coil all turns are in series.

Capacitors

See also Capacitor networks

Capacitors follow the same law using the reciprocals. The total capacitance of capacitors in series is equal to the reciprocal of the sum of the reciprocals of their individual capacitances:



$$\frac{1}{C_{\mathrm{total}}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n}.$$

Switches

Two or more switches in series form a logical AND; the circuit only carries current if all switches are 'on'. See AND gate.

Cells and batteries

A battery is a collection of electrochemical cells. If the cells are connected in series, the voltage of the battery will be the sum of the cell voltages. For example, a 12 volt car batterycontains six 2-volt cells connected in series. Some vehicles, such as trucks, have two 12 volt batteries in series to feed the 24 volt system.

Parallel circuits

If two or more components are connected in parallel they have the same potential difference (voltage) across their ends. The potential differences across the components are the same in magnitude, and they also have identical polarities. The same voltage is applicable to all circuit components connected in parallel. The total current is the sum of the currents through the individual components, in accordance with Kirchhoff's current law.

Voltage

In a parallel circuit the voltage is the same for all elements.

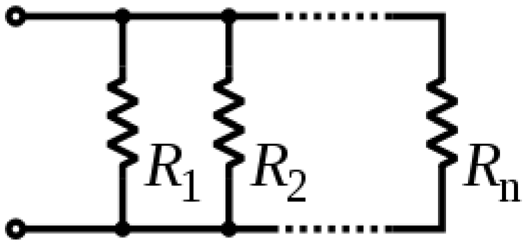
$$V = V_1 = V_2 = \ldots = V_n$$

Resistors

The current in each individual resistor is found by Ohm's law. Factoring out the voltage gives

$$I_{\text{total}} = V\left(\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}\right).$$

To find the total resistance of all components, add the reciprocals of the resistances R_i of each component and take the reciprocal of the sum. Total resistance will always be less than the value of the smallest resistance:



$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}.$$

For only two resistors, the unreciprocated expression is reasonably simple:

$$R_{\text{total}} = \frac{R_1 R_2}{R_1 + R_2}.$$

This sometimes goes by the mnemonic "product over sum".

For *N* equal resistors in parallel, the reciprocal sum expression simplifies to:

$$\frac{1}{R_{\text{total}}} = \frac{1}{R} \times N.$$

and therefore to:

$$R_{\text{total}} = \frac{R}{N}.$$

To find the current in a component with resistance R_i, use Ohm's law again:

$$I_i = \frac{V}{R_i}.$$

The components divide the current according to their reciprocal resistances, so, in the case of two resistors,

$$\frac{I_1}{I_2} = \frac{R_2}{R_1}.$$

An old term for devices connected in parallel is *multiple*, such as a multiple connection for arc lamps.

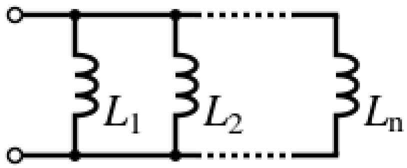
Since electrical conductance G is reciprocal to resistance, the expression for total conductance of a parallel circuit of resistors reads:

$$G_{\text{total}} = G_1 + G_2 + \cdots + G_n.$$

The relations for total conductance and resistance stand in a complementary relationship: the expression for a series connection of resistances is the same as for parallel connection of conductances, and vice versa.

Inductors

Inductors follow the same law, in that the total inductance of non-coupled inductors in parallel is equal to the reciprocal of the sum of the reciprocals of their individual inductances:



$$\frac{1}{L_{\text{total}}} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots + \frac{1}{L_n}.$$

If the inductors are situated in each other's magnetic fields, this approach is invalid due to mutual inductance. If the mutual inductance between two coils in parallel is M, the equivalent inductor is:

$$\frac{1}{L_{\text{total}}} = \frac{L_1 + L_2 - 2M}{L_1 L_2 - M^2}$$

If $L_1 = L_2$

$$L_{total} = \frac{L + M}{2}$$

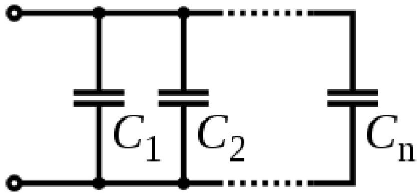
The sign of M depends on how the magnetic fields influence each other. For two equal tightly coupled coils the total inductance is close to that of each single coil. If the polarity of one coil is reversed so that M is negative, then the parallel inductance is nearly zero or the combination is almost non-inductive. It is assumed in the "tightly coupled" case M is very nearly equal to L. However, if the inductances are not equal and the coils are tightly coupled there can be near short circuit conditions and high circulating currents for both positive and negative values of M, which can cause problems.

More than three inductors becomes more complex and the mutual inductance of each inductor on each other inductor and their influence on each other must be considered. For three coils, there are three mutual inductances M_{12}, M_{13} and M_{23}. This is best handled by matrix methods and summing the terms of the inverse of the L matrix (3 by 3 in this case).

The pertinent equations are of the form: $v_i = \sum_j L_{i,j} \frac{di_j}{dt}$

Capacitors

The total capacitance of capacitors in parallel is equal to the sum of their individual capacitances:



$$C_{\text{total}} = C_1 + C_2 + \cdots + C_n.$$

The working voltage of a parallel combination of capacitors is always limited by the smallest working voltage of an individual capacitor.

Switches

Two or more switches in parallel form a logical OR; the circuit carries current if at least one switch is 'on'. See OR gate.

Cells and batteries

If the cells of a battery are connected in parallel, the battery voltage will be the same as the cell voltage but the current supplied by each cell will be a fraction of the total current. For example, if a battery contains four cells connected in parallel and delivers a current of 1 ampere, the current supplied by each cell will be 0.25 ampere. Parallel-connected batteries were widely used to power the valve filaments in portable radios but they are now rare. Some solar electric systems have batteries in parallel to increase the storage capacity; a close approximation of total amp-hours is the sum of all batteries in parallel.

Combining conductances

From Kirchhoff's circuit laws we can deduce the rules for combining conductances. For two conductances G_1 and G_2 in parallel the voltage across them is the same and from Kirchhoff's Current Law the total current is

$$I_{Eq} = I_1 + I_2.$$

Substituting Ohm's law for conductances gives

$$G_{Eq}V = G_1V + G_2V$$

and the equivalent conductance will be,

$$G_{Eq} = G_1 + G_2.$$

For two conductances G_1 and G_2 in series the current through them will be the same and Kirchhoff's Voltage Law tells us that the voltage across them is the sum of the voltages across each conductance, that is,

$$V_{Eq} = V_1 + V_2.$$

Substituting Ohm's law for conductance then gives,

$$\frac{I}{G_{Eq}} = \frac{I}{G_1} + \frac{I}{G_2}$$

which in turn gives the formula for the equivalent conductance,

$$\frac{1}{G_{Eq}} = \frac{1}{G_1} + \frac{1}{G_2}.$$

This equation can be rearranged slightly, though this is a special case that will only rearrange like this for two components.

$$G_{Eq} = \frac{G_1G_2}{G_1 + G_2}.$$

Notation

The value of two components in parallel is often represented in equations by two vertical lines "||", borrowing the parallel lines notation from geometry.[4][5]

$$R_{\rm eq} = R_1 \| R_2 = \frac{R_1R_2}{R_1 + R_2}$$

This simplifies expressions that would otherwise become complicated by expansion of the terms. For instance, the expression $R_1 \| R_2 \| R_3$ refers to 3 resistors in parallel, while the expanded expression is $\frac{R_1 R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3}$

LEAD ACID CELL

The lead–acid battery was invented in 1859 by French physicist Gaston Planté and is the oldest type of rechargeable battery. Despite having a very low energy-to-weight ratio and a low energy-to-volume ratio, its ability to supply high surge currents means that the cells have a relatively large power-to-weight ratio. These features, along with their low cost, makes it attractive for use in motor vehicles to provide the high current required by automobile starter motors.

As they are inexpensive compared to newer technologies, lead-acid batteries are widely used even when surge current is not important and other designs could provide higher energy densities. Large-format lead-acid designs are widely used for storage in backup power supplies in cell phone towers, high-availability settings like hospitals, and stand-alone power systems. For these roles, modified versions of the standard cell may be used to improve storage times and reduce maintenance requirements. Gel-cells and absorbed glass-mat batteries are common in these roles, collectively known as VRLA (valve-regulated lead-acid) batteries.

3.3 Discharging and recharging of cells

A **rechargeable battery**, **storage battery**, or **accumulator** is a type of electrical battery. It comprises one or more electrochemical cells, and is a type of energy accumulator used for electrochemical energy storage. It is technically known as a **secondary cell** because its electrochemical reactions are electrically reversible. Rechargeable batteries come in many different shapes and sizes, ranging from button cells to megawatt systems connected to stabilize an electrical distribution network. Several different combinations of chemicals are commonly used, including: lead–acid, nickel cadmium (NiCd), nickel metal hydride (NiMH), lithium ion (Li-ion), and lithium ion polymer (Li-ion polymer).

Rechargeable batteries have a lower total cost of use and environmental impact than disposable batteries. Some rechargeable battery types are available in the same sizes as common consumer disposable types. Rechargeable batteries have a higher initial cost but can be recharged inexpensively and reused many times

Usage and applications

Rechargeable batteries are used for automobile starters, portable consumer devices, light vehicles (such as motorized wheelchairs, golf carts, electric bicycles, and electric forklifts), tools, and uninterruptible power supplies. Emerging applications in hybrid electric vehicles andelectric vehicles are driving the technology to reduce cost and weight and increase lifetime.[1]

Traditional rechargeable batteries have to be charged before their first use; newer low self-discharge NiMH batteries hold their charge for many months, and are typically charged at the factory to about 70% of their rated capacity before shipping.

Grid energy storage applications use rechargeable batteries for load leveling, where they store electric energy for use during peak load periods, and for renewable energy uses, such as storing power generated from photovoltaic arrays during the day to be used at night. By charging batteries during periods of low demand and returning energy to the grid during periods of high electrical demand, load-leveling helps eliminate the need for expensive peaking power plants and helps amortize the cost of generators over more hours of operation.

The US National Electrical Manufacturers Association has estimated that US demand for rechargeable batteries is growing twice as fast as demand for nonrechargeables.[2]

Rechargeable batteries are used for mobile phones, laptops, mobile power tools like cordless screwdrivers. They are used as electric vehicle battery for example in electric cars, electric motorcycles and scooters, electric buses, electric trucks. In most submarines they are used to drive under water. In diesel-electric transmission they are used in ships, in locomotives and huge trucks. They are also used in distributed electricity generation and stand-alone power systems

Charging and discharging

During charging, the positive active material is oxidized, producing electrons, and the negative material is reduced, consuming electrons. These electrons constitute the current flow in the external circuit. The electrolyte may serve as a simple buffer for internal ion flow between the electrodes, as in lithium-ion and nickel-cadmium cells, or it may be an active participant in the electrochemical reaction, as in lead–acid cells.

The energy used to charge rechargeable batteries usually comes from a battery charger using AC mains electricity, although some are equipped to use a vehicle's 12-volt DC power outlet. Regardless, to store energy in a secondary cell, it has to be connected to a DC voltage source. The negative terminal of the cell has to be connected to the negative terminal of the voltage source and the positive terminal of the voltage source with the positive terminal of the battery. Further, the voltage output of the source must be higher than that of the battery, but not *much* higher: the greater the difference between the power source and the battery's voltage capacity, the faster the charging process, but also the greater the risk of overcharging and damaging the battery.

Chargers take from a few minutes to several hours to charge a battery. Slow "dumb" chargers without voltage or temperature-sensing capabilities will charge at a low rate, typically taking 14 hours or more to reach a full charge. Rapid chargers can typically charge cells in two to five hours, depending on the model, with the fastest taking as little as fifteen minutes. Fast chargers must have multiple ways of detecting when a cell reaches full charge (change in terminal voltage, temperature, etc.) to stop charging before harmful overcharging or overheating occurs. The fastest chargers often incorporate cooling fans to keep the cells from overheating.

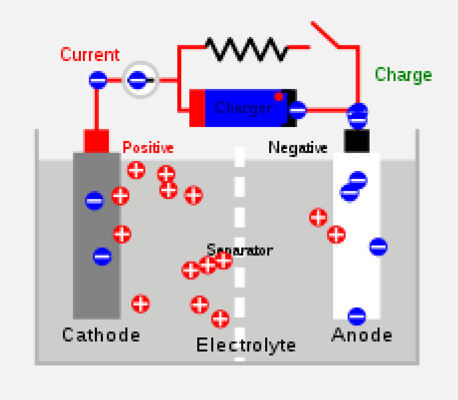


Diagram of the charging of a secondary cell battery.

Battery charging and discharging rates are often discussed by referencing a "C" rate of current. The C rate is that which would theoretically fully charge or discharge the battery in one hour. For example, trickle charging might be performed at C/20 (or a "20 hour" rate), while typical charging and discharging may occur at C/2 (two hours for full capacity). The available capacity of electrochemical cells varies depending on the discharge rate. Some energy is lost in the internal resistance of cell components (plates, electrolyte, interconnections), and the rate of discharge is limited by the speed at which chemicals in the cell can move about. For lead-acid cells, the relationship between time and discharge rate is described by Peukert's law; a lead-acid cell that can no longer sustain a usable terminal voltage at a high current may still have usable capacity, if discharged at a much lower rate. Data sheets for rechargeable cells often list the discharge capacity on 8-hour or 20-hour or other stated time; cells for uninterruptible power supply systems may be rated at 15 minute discharge.

Battery manufacturers' technical notes often refer to VPC; this is volts per cell, and refers to the individual secondary cells that make up the battery. (This is typically in reference to 12-volt lead-acid batteries.) For example, to charge a 12 V battery (containing 6 cells of 2 V each) at 2.3 VPC requires a voltage of 13.8 V across the battery's terminals.

Non-rechargeable alkaline and zinc–carbon cells output 1.5V when new, but this voltage drops with use. Most NiMH AA and AAA cells are rated at 1.2 V, but have a flatter discharge curve than alkalines and can usually be used in equipment designed to use alkaline batteries.

Damage from cell reversal

Subjecting a discharged cell to a current in the direction which tends to discharge it further, rather than charge it, is called reverse charging. Generally, pushing current through a discharged cell in this way causes undesirable and irreversible chemical reactions to occur, resulting in permanent damage to the cell. Reverse charging can occur under a number of circumstances, the two most common being:

- When a battery or cell is connected to a charging circuit the wrong way around.
- When a battery made of several cells connected in series is deeply discharged.

In the latter case, the problem occurs due to the different cells in a battery having slightly different capacities. When one cell reaches discharge level ahead of the rest, the remaining cells will force the current through the discharged cell. This is known as "cell reversal". Many battery-operated devices have a low-voltage cutoff that prevents deep discharges from occurring that might cause cell reversal.

Cell reversal can occur to a weakly charged cell even before it is fully discharged. If the battery drain current is high enough, the cell's internal resistance can create a resistive voltage drop that is greater than the cell's forward emf. This results in the reversal of the cell's polarity while the current is flowing. The higher the required discharge rate of a battery, the better matched the cells should be, both in the type of cell and state of charge, in order to reduce the chances of cell reversal.

In some situations, such as when correcting Ni-Cad batteries that have been previously overcharged, it may be desirable to fully discharge a battery. To avoid damage from the cell reversal effect, it is necessary to access each cell separately: each cell is individually discharged by connecting a load clip across the terminals of each cell, thereby avoiding cell reversal.

Damage during storage in fully discharged state

If a multi-cell battery is fully discharged, it will often be damaged due to the cell reversal effect mentioned above. It is possible however to fully discharge a battery without causing cell reversal—either by discharging each cell separately, or by allowing each cell's internal leakage to dissipate its charge over time.

Even if a cell is brought to a fully discharged state without reversal, however, damage may occur over time simply due to remaining in the discharged state. An example of this is the sulfation that occurs in lead-acid batteries that are left sitting on a shelf for long periods. For this reason it is often recommended to charge a battery that is intended to remain in storage, and to maintain its charge level by periodically recharging it. Since damage may also occur if the battery is overcharged, the optimal level of charge during storage is typically around 30% to 70%.

Depth of discharge

Depth of discharge (DOD) is normally stated as a percentage of the nominal ampere-hour capacity; 0% DOD means no discharge. Seeing as the usable capacity of a battery system depends on the rate of discharge and the allowable voltage at the end of discharge, the depth of discharge must be qualified to show the way it is to be measured. Due to variations during manufacture and aging, the DOD for complete discharge can change over time or number of charge cycles. Generally a rechargeable battery system will tolerate more charge/discharge cycles if the DOD is lower on each cycle.

Active components

The active components in a secondary cell are the chemicals that make up the positive and negative active materials, and the electrolyte. The positive and negative are made up of different materials, with the positive exhibiting a reduction potential and the negative having an oxidation potential. The sum of these potentials is the standard cell potential or voltage.

In primary cells the positive and negative electrodes are known as the cathode and anode, respectively. Although this convention is sometimes carried through to rechargeable systems — especially with lithium-ion cells, because of their origins in primary lithium cells — this practice can lead to confusion. In rechargeable cells the positive electrode is the cathode on discharge and the anode on charge, and vice versa for the negative electrode.

3.3 COMMON CHARGING METHODS

Charging Schemes

The charger has three key functions

- Getting the charge into the battery (Charging)
- Optimising the charging rate (Stabilising)
- Knowing when to stop (Terminating)

The charging scheme is a combination of the charging and termination methods.

Charge Termination

Once a battery is fully charged, the charging current has to be dissipated somehow. The result is the generation of heat and gasses both of which are bad for batteries. The essence of good charging is to be able to detect when the reconstitution of the active chemicals is complete and to stop the charging process before any damage is done while at all times maintaining the cell temperature within its safe limits. Detecting this cut off point and terminating the charge is critical in preserving battery life. In the simplest of chargers this is when a predetermined upper voltage limit, often called the **termination voltage** has been reached. This is particularly important with fast chargers where the danger of overcharging is greater.

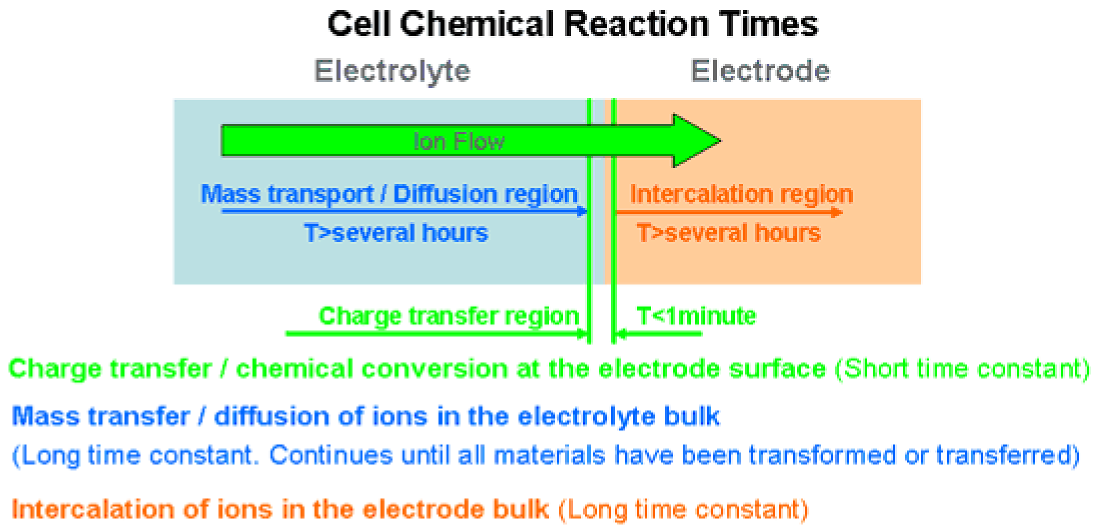
Safe Charging

If for any reason there is a risk of over charging the battery, either from errors in determining the cut off point or from abuse this will normally be accompanied by a rise in temperature. Internal fault conditions within the battery or high ambient temperatures can also take a battery beyond its safe operating temperature limits. Elevated temperatures hasten the death of batteries and monitoring the cell temperature is a good way of detecting signs of trouble from a variety of causes. The temperature signal, or a resettable fuse, can be used to turn off or disconnect the charger when danger signs appear to avoid damaging the battery. This simple additional safety precaution is particularly important for high power batteries where the consequences of failure can be both serious and expensive.

Charging Times

During fast charging it is possible to pump electrical energy into the battery faster than the chemical process can react to it, with damaging results.

The chemical action can not take place instantaneously and there will be a reaction gradient in the bulk of the electrolyte between the electrodes with the electrolyte nearest to the electrodes being converted or "charged" before the electrolyte further away. This is particularly noticeable in high capacity cells which contain a large volume of electrolyte.



There are in fact at least three key processes involved in the cell chemical conversions.

- One is the "charge transfer", which is the actual chemical reaction taking place at the interface of the electrode with the electrolyte and this proceeds relatively quickly.
- The second is the "mass transport" or "diffusion" process in which the materials transformed in the charge transfer process are moved on from the electrode surface, making way for further materials to reach the electrode to take part in the transformation process. This is a relatively slow process which continues until all the materials have been transformed.
- The charging process may also be subject to other significant effects whose reaction time should also be taken into account such as the "intercalation process" by which Lithium cells are charged in which Lithium ions are inserted into the crystal lattice of the host electrode. See also Lithium Plating due to excessive charging rates or charging at low temperatures.

All of these processes are also temperature dependent.

In addition there may be other parasitic or side effects such as passivation of the electrodes, crystal formation and gas build up, which all affect charging times and efficiencies, but these may be relatively minor or infrequent, or may occur only during conditions of abuse. They are therefore not considered here.

The battery charging process thus has at least three characteristic time constants associated with achieving complete conversion of the active chemicals which depend on both the chemicals employed and on the cell construction. The time constant associated with the charge transfer could be one minute or less, whereas the mass transport time constant can be as high as several hours or more in a large high capacity cell. This is one of the the reasons why cells can deliver or accept very high pulse currents, but much lower continuous currents.(Another major factor is the heat dissipation involved). These phenomena are non linear and apply to the discharging process as well as to charging. There is thus a limit to the charge acceptance rate of the cell. Continuing to pump energy into the cell faster than the chemicals can react to the charge can cause local overcharge conditions including polarisation, overheating as well as unwanted chemical reactions, near to the electrodes thus damaging the cell. Fast charging forces up the rate of chemical reaction in the cell (as does fast discharging) and it may be necessary to allow "rest periods" during the charging process for the chemical actions to propagate throughout the bulk of the chemical mass in the cell and to stabilise at progressive levels of charge.

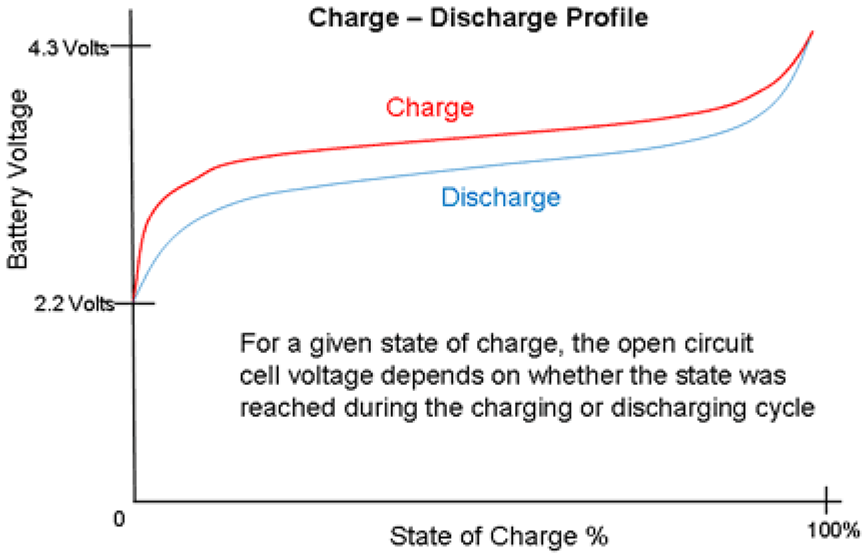
See also the affects of Chemical Changes and Charging Rate in the section on Battery Life.

A memorable though not quite equivalent phenomenon is the pouring of beer into a glass. Pouring very quickly results in a lot of froth and a small amount of beer at the bottom of the glass. Pouring slowly down the side of the glass or alternatively letting the beer settle till the froth disperses and then topping up allows the glass to be filled completely.

Hysteresis

The time constants and the phenomena mentioned above thus give rise to hysteresis in the battery. During charging the chemical reaction lags behind the application of the charging voltage and similarly, when a load is applied to the battery to discharge it, there is a delay before the full current can be delivered through the load. As with magnetic hysteresis, energy is lost during the charge discharge cycle due to the chemical hysteresis effect.

The diagram below shows the hystersis effect in a Lithium battery.



Allowing short settling or rest periods during the charge discharge processes to accommodate the chemical reaction times will tend to reduce but not eliminte the voltage difference due to hysteresis.

The true battery voltage at any state of charge (SOC) when the battery is in its "at rest" or quiecent condition will be somewhere between the charge and discharge curves. During charging the measured cell voltage during a rest period will migrate slowly downwards towards the quiescent condition as the chemical transformation in the cell stabilises. Similarlly during discharging, the measured cell voltage during a rest period will migrate upwards towards the quescent condition.

Fast charging also causes increased Joule heating of the cell because of the higher currents involved and the higher temperature in turn causes an increase in the rate of the chemical conversion processes.

The section on Discharge Rates shows how the effective cell capacity is affected by the discharge rates.

The section on Cell Construction describes how the cell designs can be optimised for fast charging.

Charge Efficiency

This refers to the properties of the battery itself and does not depend on the charger. It is the ratio (expressed as a percentage) between the energy removed from a battery during discharge compared with the energy used during charging to restore the original capacity. Also called the Coulombic Efficiency or Charge Acceptance.

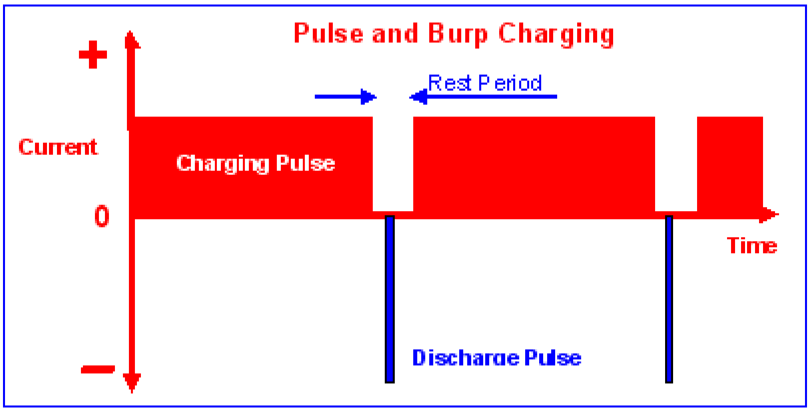
Charge acceptance and charge time are considerably influenced by temperature as noted above. Lower temperature increases charge time and reduces charge acceptance.

Note that at low temperatures the battery will not necessarily receive a full charge even though the terminal voltage may indicate full charge. See Factors Influencing State of Charge.

Basic Charging Methods

- **Constant Voltage** A constant voltage charger is basically a DC power supply which in its simplest form may consist of a step down transformer from the mains with a rectifier to provide the DC voltage to charge the battery. Such simple designs are often found in cheap car battery chargers. The lead-acid cells used for cars and backup power systems typically use constant voltage chargers. In addition, lithium-ion cells often use constant voltage systems, although these usually are more complex with added circuitry to protect both the batteries and the user safety.
- **Constant Current** Constant current chargers vary the voltage they apply to the battery to maintain a constant current flow, switching off when the voltage reaches the level of a full charge. This design is usually used for nickel-cadmium and nickel-metal hydride cells or batteries.

- **Taper Current** This is charging from a crude unregulated constant voltage source. It is not a controlled charge as in V Taper above. The current diminishes as the cell voltage (back emf) builds up. There is a serious danger of damaging the cells through overcharging. To avoid this the charging rate and duration should be limited. Suitable for SLA batteries only.
- **Pulsed charge** Pulsed chargers feed the charge current to the battery in pulses. The charging rate (based on the average current) can be precisely controlled by varying the width of the pulses, typically about one second. During the charging process, short rest periods of 20 to 30 milliseconds, between pulses allow the chemical actions in the battery to stabilise by equalising the reaction throughout the bulk of the electrode before recommencing the charge. This enables the chemical reaction to keep pace with the rate of inputting the electrical energy. It is also claimed that this method can reduce unwanted chemical reactions at the electrode surface such as gas formation, crystal growth and passivation. (See also Pulsed Charger below). If required, it is also possible to sample the open circuit voltage of the battery during the rest period.



The optimum current profile depends on the cell chemistry and construction.

- **Burp charging** Also called **Reflex** or **Negative Pulse Charging** Used in conjunction with pulse charging, it applies a very short discharge pulse, typically 2 to 3 times the charging current for 5 milliseconds, during the charging rest period to depolarise the cell. These pulses dislodge any gas bubbles which have built up on the electrodes during fast charging, speeding up the stabilisation process and hence the overall charging process. The release and diffusion of the gas bubbles is known as "burping". Controversial claims have been made for the improvements in both the charge rate and the battery lifetime as well as for the removal of dendrites made possible by this technique. The least that can be said is that "it does not damage the battery".

- **IUI Charging** This is a recently developed charging profile used for fast charging standard flooded lead acid batteries from particular manufacturers. It is not suitable for all lead acid batteries. Initially the battery is charged at a constant (I) rate until the cell voltage reaches a preset value - normally a voltage near to that at which gassing occurs. This first part of the charging cycle is known as the bulk charge phase. When the preset voltage has been reached, the charger switches into the constant voltage (U) phase and the current drawn by the battery will gradually drop until it reaches another preset level. This second part of the cycle completes the normal charging of the battery at a slowly diminishing rate. Finally the charger switches again into the constant current mode (I) and the voltage continues to rise up to a new higher preset limit when the charger is switched off. This last phase is used to equalise the charge on the individual cells in the battery to maximise battery life. See Cell Balancing.
- **Trickle charge** Trickle charging is designed to compensate for the self discharge of the battery. Continuous charge. Long term constant current charging for standby use. The charge rate varies according to the frequency of discharge. Not suitable for some battery chemistries, e.g. NiMH and Lithium, which are susceptible to damage from overcharging. In some applications the charger is designed to switch to trickle charging when the battery is fully charged.
- **Float charge**. The battery and the load are permanently connected in parallel across the DC charging source and held at a constant voltage below the battery's upper voltage limit. Used for emergency power back up systems. Mainly used with lead acid batteries.
- **Random charging** All of the above applications involve controlled charge of the battery, however there are many applications where the energy to charge the battery is only available, or is delivered, in some random, uncontrolled way. This applies to automotive applications where the energy depends on the engine speed which is continuously changing. The problem is more acute in EV and HEV applications which use regenerative braking since this generates large power spikes during braking which the battery must absorb. More benign applications are in solar panel installations which can only be charged when the sun is shining. These all require special techniques to limit the charging current or voltage to levels which the battery can tolerate.

Charging Rates

Batteries can be charged at different rates depending on the requirement. Typical rates are shown below:

- Slow Charge = Overnight or 14-16 hours charging at 0.1C rate
- Quick Charge = 3 to 6 Hours charging at 0.3C rate
- Fast Charge = Less than 1 hour charging at 1.0C rate

Slow charging

Slow charging can be carried out in relatively simple chargers and should not result in the battery overheating. When charging is complete batteries should be removed from the charger.

- Nicads are generally the most robust type with respect to overcharging and can be left on trickle charge for very long periods since their recombination process tends to keep the voltage down to a safe level. The constant recombination keeps internal cell pressure high, so the seals gradually leak. It also keeps the cell temperature above ambient, and higher temperatures shorten life. So life is still better if you take it off the charger.
- Lead acid batteries are slightly less robust but can tolerate a short duration trickle charge. Flooded batteries tend to use up their water, and SLAs tend to die early from grid corrosion. Lead-acids should either be left sitting, or float-charged (held at a constant voltage well below the gassing point).
- NiMH cells on the other hand will be damaged by prolonged trickle charge.
- Lithium ion cells however can not tolerate overcharging or overvoltage and the charge should be terminated immediately when the upper voltage limit is reached.

Fast / Quick Charging

As the charging rate increases, so do the dangers of overcharging or overheating the battery. Preventing the battery from overheating and terminating the charge when the battery reaches full charge become much more critical. Each cell chemistry has its own characteristic charging curve and battery chargers must be designed to detect the end of charge conditions for the specific chemistry involved. In addition, some form of Temperature Cut Off (TCO) or Thermal Fuse must be incorporated to prevent the battery from overheating during the charging process.

Fast charging and quick charging require more complex chargers. Since these chargers must be designed for specific cell chemistries, it is not normally possible to charge one cell type in a charger that was designed for another cell chemistry and damage is likely to occur. Universal chargers, able to charge all cell types, must have sensing devices to identify the cell type and apply the appropriate charging profile.

Note that for automotive batteries the charging time may be limited by the available power rather than the battery characteristics. Domestic 13 Amp ring main circuits can only deliver 3KW. Thus, assuming no efficiency loss in the charger, a ten hour charge will at maximum put 30 KWh of energy into the battery. Enough for about 100 miles. Compare this with filling a car with petrol.

It takes about 3 minutes to put enough chemical energy into the tank to provide 90 KWh of mechanical energy, sufficient to take the car 300 miles. To put 90 KWh of electrical energy into a battery in 3 minutes would be equivalent to a charging rate of 1.8 MegaWatts!!

Charge Termination Methods

The following chart summarises the charge termination methods for popular batteries. These are explained in the section below.

	Charge Termination Methods			
	SLA	Nicad	NiMH	Li-Ion
Slow Charge	Trickle OK	Tolerates Trickle	Timer	Voltage Limit
Fast Charge 1	Imin	NDV	dT/dt	Imin at Voltage Limit
Fast Charge 2	Delta TCO	dT/dt	dV/dt=0	
Back up Termination 1	Timer	TCO	TCO	TCO
Back up Termination 2	DeltaTCO	Timer	Timer	Timer

TCO = Temperature Cut Off

Delta TCO = Temperature rise above ambient

I min = Minimum current

Charge Control Methods

Many different charging and termination schemes have been developed for different chemistries and different applications. The most common ones are summarised below.

Controlled charging

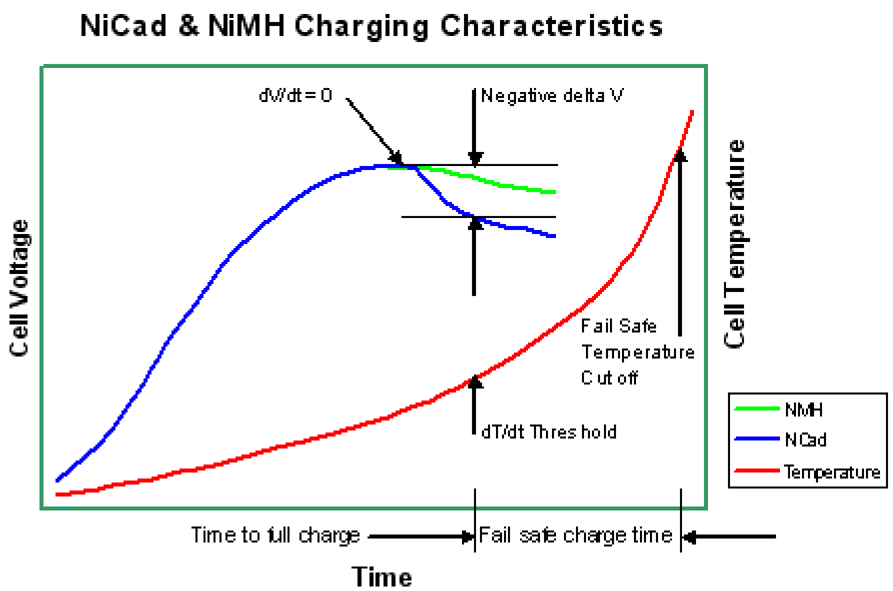
Regular (slow) charge

- **Semi constant current** Simple and economical. Most popular. Low current therefore does not generate heat but is slow, 5 to 15 hours typical. Charge rate 0.1C. Suitable for Nicads
- **Timer controlled** charge system Simple and economical. More reliable than semi-constant current. Uses IC timer. Charges at 0.2C rate for a predetermined period followed by trickle charge of 0.05C. Avoid constantly restarting timer by taking the battery in and out of the charger since this will compromise its effectiveness. The incorporation of an absolute temperature cut-off is recommended. Suitable for Nicad and NiMH batteries.

Fast charge (1 to 2 hours)

- **Negative delta V (NDV) Cut-off charge system**

  This is the most popular method for rapid charging for Nicads.

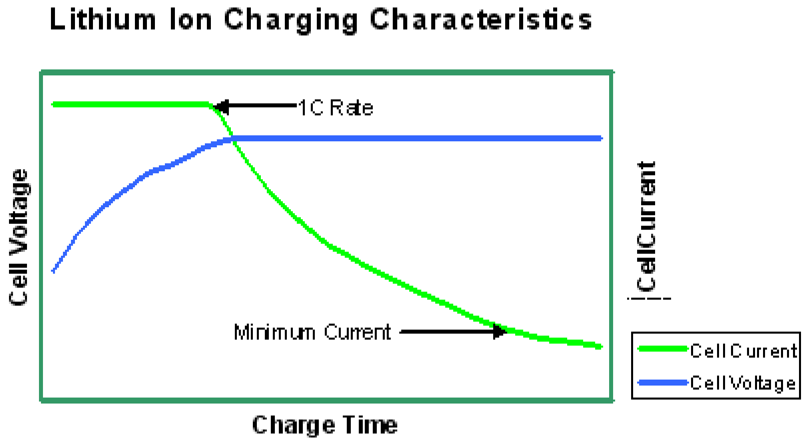


Batteries are charged at constant current of between 0.5 and 1.0 C rate. The battery voltage rises as charging progresses to a peak when fully charged then subsequently falls. This voltage drop, -delta V, is due to polarisation or oxygen build up inside the cell which starts to occur once the cell is fully charged. At this point the cell enters the overcharge danger zone and the temperature begins to rise rapidly since the chemical changes are complete and the excess electrical energy is converted into heat. The voltage drop occurs regardless of the discharge level or ambient temperature and it can therefore be detected and used to identify the peak and hence to cut off the charger when the battery has reached its full charge or switch to trickle charge.

This method is not suitable for charging currents less than 0.5 C since delta V becomes difficult to detect. False delta V can occur at the start of the charge with excessively discharged cells. This is overcome by using a timer to delay the detection of delta V sufficiently to avoid the problem. Lead acid batteries do not demonstrate a voltage drop on charge completion hence this charging method is not suitable for SLA batteries.

- **dT/dt Charge system** NiMH batteries do not demonstrate such a pronounced NDV voltage drop when they reach the end of the charging cycle as can be seen in the graph above and so the NDV cut off method is not reliable for ending the NiMH charge. Instead the charger senses the rate of increase of the cell temperature per unit time. When a predetermined rate is reached the rapid charge is stopped and the charge method is switched to trickle charge. This method is more expensive but avoids overcharge and gives longer life. Because extended trickle charging can damage a NiMH battery, the use of a timer to regulate the total charging time is recommended.

- **Constant-current Constant-voltage (CC/CV) controlled** charge system. Used for charging Lithium and some other batteries which may be vulnerable to damage if the upper voltage limit is exceeded. The manufacturers' specified constant current charging rate is the maximum charging rate which the battery can tolerate without damaging the battery. Special precautions are needed to maximise the charging rate and to ensure that the battery is fully charged while at the same time avoiding overcharging. For this reason it is recommended that the charging method switches to constant voltage before the cell voltage reaches its upper limit. Note that this implies that chargers for Lithium Ion cells must be capable of controlling both the charging current and the battery voltage.



In order to mainain the specified constant current charging rate, the charging voltage must increase in unison with the cell voltage to overcome the back EMF of the cell as it charges up. This occurs quite rapidly during the constant current mode until the cell upper voltage limit of the cell is reached, after which point the charging voltage is maintained at that level, known as the float level, during the constant voltage mode. During this constant voltage period, the current decreases to a trickle charge as the charge approaches completion. Cut off occurs when a predetermined minimum current point, which indicates a full charge, has been reached. See also Lithium Batteries - Charging and Battery Manufacturing - Formation.

Note 1: When **Fast Charging** rates are specified, they usually refer to the constant current mode. Depending on the cell chemistry this period could be between 60% and 80% of the time to full charge. These rates should not be extrapolated to estimate the time to fully charge the battery because the charging rate tails off quickly during the constant voltage period.

Note 2: Because it is not possible to charge Lithium batteries at the charging C rate specified by the manufacturers for the full duration of the charge, it is also not possible to estimate the time to charge a battery from empty simply by dividing the AmpHour capacity of the battery by the specified charging C rate, since the rate changes during the charging process. The following equation however gives a reasonable approximation of the time to fully charge an empty battery when the standard CC/CV charging method is used:

Charging time (hrs) = 1.3 * (Battery capacity in Ah) / (CC mode charging current)

- **Voltage controlled** charge system. Fast charging at rates between 0.5 and 1.0 C rate. The charger switched off or switched to trickle charge when predetermined voltage has been reached. Should be combined with temperature sensors in the battery to avoid overcharge or thermal runaway.
- **V- Taper controlled** charge system Similar to Voltage controlled system. Once a predetermined voltage has been reached the rapid charge current is progressively reduced by reducing the supply voltage then switched to trickle charge. Suitable for SLA batteries it allows higher charge level to be reached safely. (See also taper current below)
- **Failsafe timer**

  Limits the amount of charge current that can flow to double the cell capacity. For example for a 600mAh cell, limit the charge to a maximum of 1,200mAH. Last resort if cut off not achieved by other means.
- **Pre-charging**

  As a safety precaution with high capacity batteries a pre-charging stage is often used. The charging cycle is initiated with a low current. If there is no corresponding rise in the battery voltage it indicates that there is possibly a short circuit in the battery.
- **Intelligent Charging System**

  Intelligent charging systems integrate the control systems within the charger with the electronics within the battery to allow much finer control over the charging process. The benefits are faster and safer charging and battery longer cycle life. Such a system is described in the section on Battery Management Systems.

Note

Most chargers provided with consumer electronics devices such as mobile phones and laptop computers simply provide a fixed voltage source. The required voltage and current profile for charging the battery is provided (or should be provided) from electronic circuits, either within the device itself or within the battery pack, rather than by the charger. This allows flexibility in the choice of chargers and also serves to protect the device from potential damage from the use of inappropriate chargers.

Voltage Sensing

During charging, for simplicity, the battery voltage is usually measured across the charger leads. However for high current chargers, there can be a significant voltage drop along the charger leads, resulting in an underestimate of the true battery voltage and consequent undercharging of the battery if the battery voltage is used as the cut-off trigger. The solution is to measure the voltage using a separate pair of wires connected directly across the battery terminals. Since the voltmeter has a high internal impedance there will be minimal voltage drop in the voltmeter leads and the reading will be more accurate. This method is called a Kelvin Connection. See also DC Testing.

Charger Types

Chargers normally incorporate some form of voltage regulation to control the charging voltage applied to the battery. The choice of charger circuit technology is usually a price - performance trade off. Some examples follow:

- **Switch Mode Regulator (Switcher) -** Uses pulse width modulation to control the voltage. Low power dissipation over wide variations in input and battery voltage. More efficient than linear regulators but more complex.
  Needs a large passive LC (inductor and capacitor) output filter to smooth the pulsed waveform. Component size depends on curent handling capacity but can be reduced by using a higher switching frequency, typically 50 kHz to 500kHz., since the size of the required transformers, inductors and capacitors is inversely proportional to the operating frequency.
  Switching heavy currents gives rise to EMI and electrical noise.
- **Series Regulator (Linear) -** Less complex but more lossy - requiring a heat sink to dissipate the heat in the series, voltage dropping transistor which takes up the difference between the supply and the output voltage. All the load current passes through the regulating transistor which consequently must be a high power device. Because there is no switching, it delivers pure DC and doesn't need an output filter. For the same reason, the design doesn't suffer from the problem of radiated and conducted emissions and electrical noise. This makes it suitable for low noise wireless and radio applications.
  With fewer components they are also smaller.
- **Shunt Regulator -** Shunt regulators are common in photovoltaic (PV) systems since they are relatively cheap to build and simple to design. The charging current is controlled by a switch or transistor connected in parallel with the photovoltaic panel and the storage

battery. Overcharging of the battery is prevented by shorting (shunting) the PV output through the transistor when the voltage reaches a predetermined limit. If the battery voltage exceeds the PV supply voltage the shunt will also protect the PV panel from damage due to reverse voltage by discharging the battery through the shunt. Series regulators usually have better control and charge characteristics.

- **Buck Regulator** A switching regulator which incorporates a step down DC-DC converter. They have high efficiency and low heat losses. They can handle high output currents and generate less RF interference than a conventional switch mode regulator. A simple transformerless design with low switch stress and a small output filter.
- **Pulsed Charger**. Uses a series transistor which can also be switched. With low battery voltages the transistor remains on and conducts the source current directly to the battery. As the battery voltage approaches the desired regulation voltage the series transistor pulses the input current to maintain the desired voltage. Because it acts as a switch mode supply for part of the cycle it dissipates less heat and because it acts as a linear supply part of the time the output filters can be smaller. Pulsing allows the battery time to stabilise (recover) with low increments of charge at progressively high charge levels during charging. During rest periods the polarisation of the cell is lowered. This process permits faster charging than possible with one prolonged high level charge which could damage the battery since it does not permit gradual stabilisation of the active chemicals during charging. Pulse chargers usually need current limiting on the input source for safety reasons, adding to the cost.
- **Universal Serial Bus (USB) Charger**

  The USB specification was developed by a group of computer and peripheral device manufacturers to replace a plethora of proprietary mechanical and electrical interconnection standards for transferring data between computers and external devices. It included a two wire data connection, a ground (earth) line and a 5 Volt power line provided by the host device (the computer) which was available to power the external devices. An unintended use of the USB port has been to provide the 5 Volt source not only to power peripheral devices directly, but also to charge any batteries installed in these external devices. In this case the peripheral device itself must incorporate the necessary charge control circuitry to protect the battery. The original USB standard specified a a data rata of 1.5 Mbits/sec and a maximum charging current of 500mA.

  Power always flows from the host to the device, but data can flow in both directions. For this reason the USB host connector is mechanically different from the USB device connector and thus USB cables have different connectors at each end.

This prevents any 5 Volt connection from an external USB source from being applied to the host computer and thus from possibly damaging the host machine.

Subsequent upgrades increased the standard data rates to 5 Gigabits/sec and the available current to 900 mA. However the popularity of the USB connection has led to a lot of non standard variants paricularly the use of the USB connector to provide a pure power source without the associated data connection. In such cases the USB port may simply incorporate a voltage regulator to provide the 5 Volts from a 12 Volt automotive power rail or a rectifier and regulator to provide the 5 Volts DC from the 110 Volts or 240 Volts AC mains supply with output currents up to 2100 mA. In both cases the device accepting the power has to provide the necessary charge control. Mains powered USB power supplies, often known as "dumb" USB chargers, may be incorporated into the body of the mains plugs or into separate USB receptacles in wall mounted AC power socket outlets.

See more about USB connections in the section on battery Data Buses.

- **Inductive Charging**

  Inductive charging does not refer to the charging process of the battery itself. It refers to the design of the charger. Essentially the input side of charger, the part connected to the AC mains power, is constructed from a transformer which is split into two parts. The primary winding of the transformer is housed in a unit connected to the AC mains supply, while the secondary winding of the transformer is housed in the same sealed unit which contains the battery, along with the rest of the conventional charger electronics. This allows the battery to be charged without a physical connection to the mains and without exposing any contacts which could cause an electric shock to the user.

  A low power example is the electric toothbrush. The toothbrush and the charging base form the two-part transformer, with the primary induction coil contained in the base and the secondary induction coil and the electronics contained in the toothbrush. When the toothbrush is placed into the base, the complete transformer is created and the induced current in the secondary coil charges the battery. In use, the appliance is completely separated from the mains power and since the battery unit is contained in a sealed compartment the toothbrush can be safely immersed in water.

The technique is also used to charge medical battery implants.

A high power example is a charging system used for EVs. Similar to the toothbrush in concept but on a larger scale, it is also a non-contact system. An induction coil in the electric vehicle picks up current from an induction coil in the floor of the garage and charges the vehicle overnight. To optimise system efficiency, the air gap between the static coil and the pickup coil can be reduced by lowering the pickup coil during charging and the vehicle must be precisely placed over the charging unit.

A similar system has been used for electric buses which pick up current from induction coils embedded beneath each bus stop thus enabling the range of the bus to be extended or conversely, smaller batteries can be specified for the same itinerary. One other advantage of this system is that if the battery charge is constantly topped up, the depth of discharge can be minimised and this leads to a longer cycle life. As shown in the section on Battery Life, the cycle life increases exponentially as the depth of discharge is reduced.

A simpler and less expensive alternative to this opportunity charging is for the vehicle to make a conductive coupling with electric contacts on an overhead gantry at each bus stop.

Proposals have also been made to install a grid of inductive charging coils under the surface along the length of public roadways to allow vehicles to pick up charge as they drive along however no practical examples have yet been installed.

- **Electric Vehicle Charging Stations**

  For details about the specialised, high power chargers used for EVs, see the section about Electric Vehicle Charging Infrastructure.

Charger Power Sources

When specifying a charger it is also necessary to specify the source from which the charger derives its power, its availability and its voltage and power range. Efficiency losses in the charger should also be taken into account, particularly for high power chargers where the magnitude of the losses can be significant. Some examples are given below.

Controlled Charging

Easy to accommodate and manage.

- **AC Mains**

  Many portable low power chargers for small electrical appliances such as computers and mobile phones are required to operate in international markets. They therefore have auto sensing of the mains voltage and in special cases the mains frequency with automatic switching to the appropriate input circuit.

  Higher power applications may need special arrangements. Single phase mains power is typically limited to about 3 KW. Three phase power may be required for charging high capacity batteries (over 20 KWh capacity) such as those used in electric vehicles which may require charging rates of greater than 3 KW to achieve reasonable charging times.
- **Regulated DC Battery Supply**

  May be provided by special purpose installations such as mobile generating equipment for custom applications.
- **Special Chargers**

  Portable sources such as solar panels.

Opportunity Charging

Opportunity charging is charging the battery whenever power is available or between partial discharges rather than waiting for the battery to be completely discharged. It is used with batteries in cycle service, and in applications when energy is available only intermittently.

It can be subject to wide variations in energy availability and wide variations in power levels. Special control electronics are needed to protect the battery from overvoltage. By avoiding complete discharge of the battery, cycle life can be increased.

Availability affects the battery specification as well as the charger.

Typical applications are:-

- **Onboard vehicle chargers** (Alternators, Regenerative braking)
- **Inductive chargers** (on vehicle route stopping points)

- **Solar power**
- **Wind power**

Mechanical charging

This is only applicable to specific cell chemistries. It is nor a charger technology in the normal sense of the word. Mechanical charging is used in some high power batteries such as Flow Batteries and Zinc Air batteries. Zinc air batteries are recharged by replacing the zinc electrodes. Flow batteries can be recharged by replacing the electrolyte.

Mechanical charging can be carried out in minutes. This is much quicker than the the long charging time associated with the conventional reversible cell electrochemistry which could take several hours. Zinc air batteries have therefore been used to power electric buses to overcome the problem of excessive charging times.

Charger Performance

The battery type and the application in which it is used set performance requirements which the charger must meet.

- **Output Voltage Purity**

  The charger should deliver a clean regulated voltage output with tight limits on spikes, ripple, noise and radio frequency interference (RFI) all of which could cause problems for the battery or the circuits in which it is used.

For high power applications, the charging performance may be limited by the design of the charger.

- **Efficiency**

  When charging high power batteries, the energy loss in the charger can add significantly to the charging times and to the operating costs of the application. Typical charger efficiencies are around 90%, hence the need for efficient designs.
- **Inrush Current**

When a charger is initially switched on to an empty battery the inrush current could be considerably higher than the maximum specified charging current. The charger must therefore be dimensioned either to deliver or limit this current pulse.

- **Power Factor**

  This could also be an important consideration for high power chargers.

3.4 PREPARATION OF ELECTROLYTE

B.1 Composition of electrolyte

B.1.1 Depending on operating or testing conditions use electrolyte according to Table B.1.

Table B.1

Electrolyte type	**Operating conditions or testing conditions**	**Composition**
I	Putting into operation Replacement of electrolyte Determination of 80% rated capacity Operating of batteries at ambient temperature from plus 5 to plus 40 °C; test operation	Water solution of caustic soda with addition of (10±1) g/l lithium hydrate (LiOH). Density of electrolyte from 1,19 to 1,21 g/cm^3
II	Operating at ambient temperature from minus 15 to plus 35 °C; Carrying out of testing instead of electrolyte type I	Water solution of caustic potash with addition of (10±1) g/l lithium hydrate (LiOH). Density of electrolyte from 1,19 to 1,21 g/cm^3
III	Operation at ambient temperature below minus 15 °C; test operation of accumulators at temperature minus 45 °C	Water solution of caustic potash with density from 1,26 to 1,28 g/cm^3
Note: shown densities correspond to temperature of plus (25±10) °C.		

B.2 Materials for preparation of electrolyte

B.2.1 For preparation of electrolyte use materials with quality not lower than:

a. technical caustic soda grade PX the first quality sort or grade TP as per GOST 2263-79;

b. potassium hydroxide technical grade (caustic potash), extra or first quality sort according to GOST 9285-78;
c. lithium hydroxide technical grade according to GOST 8595-83;
d. distilled water according to GOST 6709-72 or condensate.

B.2.2 Store solid alkalis in hermetically closed alkali proof ware.

B.3 Approximate amount of the components for preparation of electrolyte:

- For preparation of electrolyte type I:

a) technical caustic soda grades PX and TP - 215 g;

b) lithium hydroxide ($LiOH \times H_2O$) - 20 g;

c) distilled water or condensate - 1000 g (1 l).

- For preparation of electrolyte type II:

a) caustic potash (solid) - 270 g;

b) lithium hydroxide ($LiOH \times H_2O$) - 20 g;

c) distilled water or condensate - 1000 g (1 l).

- For preparation of electrolyte type III:

a) caustic potash (solid) - 480 g;

b) distilled water or condensate - 1000 g (1 l).

B.4 ORDER OF ELECTROLYTE PREPARATION

B.4.1 Prepare electrolyte only in clean steel or cast-iron ware.

It is recommended to have steel tanks with two cocks: one cock located at the height not less than 100 mm from the bottom - for draining of clarified alkali, the other one located at the bottom - for removal of accumulated residue (mud).

B.4.2 Fill the tank with required amount of water, then load solid caustic soda PX or TP in small bits or caustic potash of the first quality sort (solid), mix to accelerate dissolution. Then, while intensively stirring, add lithium hydroxide to obtained solution (if necessary).

If caustic soda grade PX first quality sort or caustic potash (liquid) is used, dilute with water up to required density and add lithium hydroxide.

Carefully mix the solution until complete dissolution of lithium.

B.4.3 Cool down the prepared electrolyte to temperature plus (25±10) ^{0}C, to measure the density with the help of areometer.

If the density appears to lower than requested, add caustic soda or caustic potash; the density is higher than requested, add distilled water or condensate.

Let electrolyte to precipitate up to complete clarification (from 6 to 12 hours), then pour the clarified part to hermetically closable glass or steel reservoir.

3.5 CARE AND MAINTENANCE OF SECONDARY CELLS

The condition of charge of batteries (secondary cells) should be tested on a regular basis. GMDSS regulations stipulate that the voltage of any secondary batteries should be read and recorded each day and in the case of lead/acid batteries, the specific gravity of the electrolyte should be measured and recorded each month.

The crew should be aware of which equipment contains batteries (primary cells) and they should be checked regularly for leakage and must be replaced in accordance with the expiration dates given by the manufacturers. Spares should be carried on board.

REPLACING BATTERIES

Batteries have to be correctly connected into the circuit due to the terminals having either positive or negative polarity. Positive terminals should be connected to positive equipment connections and negative terminals should be connected to negative equipment connections.

Connecting the wrong way round is likely to damage both the battery and the equipment.

CHARGING BATTERIES (SECONDARY CELLS)

Batteries should be recharged according to the manufacturer's recommendations.

When charging batteries the correct polarity must be observed as well. When connecting a portable charger, the red or positive lead from the charger must go to the positive terminal and the black or negative lead from the charger must go to the negative terminal. Connecting the charger the wrong way round will damage the battery, it could even cause an explosion.

Recommendations on battery care and maintenance

- Batteries should be kept clean and dry.
- Batteries should be kept in a purpose designed battery box that will not allow battery content to pour out in any circumstances.

ONLY FOR SECONDARY CELLS:

- Battery bank should be adequately secured because batteries are heavy and may be dangerous to the crew and the vessel if they get loose in the event of a knockdown.
- Signs of corrosion on batteries and near them should be regulary checked.
- The top of the battery and the terminals should be kept clean. This will prevent stray currents flowing between the terminals and flattening the battery.
- The battery terminals could be protected from corrosion with a thin coat of petroleum jelly.
- The vessel's batteries are usually kept in the bilge where the weight is low down, but this makes them very vulnerable in case of flood or fire. This is an argument for having a dedicated radio battery higher up in the vessel where it is more protected.

ONLY FOR LEAD/ACID BATTERIES (SECONDARY CELLS):

- Lead/acid batteries should be kept in a purpose designed battery box that will allow the flammable hydrogen gas to escape but not allow sea water to get in.
- The electrolyte level should be regularly checked in lead/acid batteries. Only distilled water should be used when topping up the electrolyte otherwise impurities will be added which will drastically shorten the life of the battery.
- During the charging cycle of lead/acid batteries, when hydrogen gas is given off, the area should be ventilated well and crew must not smoke in the vicinity.
- Great care must be taken when handling the sulphuric acid electrolyte on lead/acid batteries. A sensible precaution would be to wear rubber gloves, old clothing and safety googles.

UNIT-4

HEATING AND LIGHTING EFFECTS OF CURRENT

4.1- **Joule's Law of electric heating and its domestic applications**

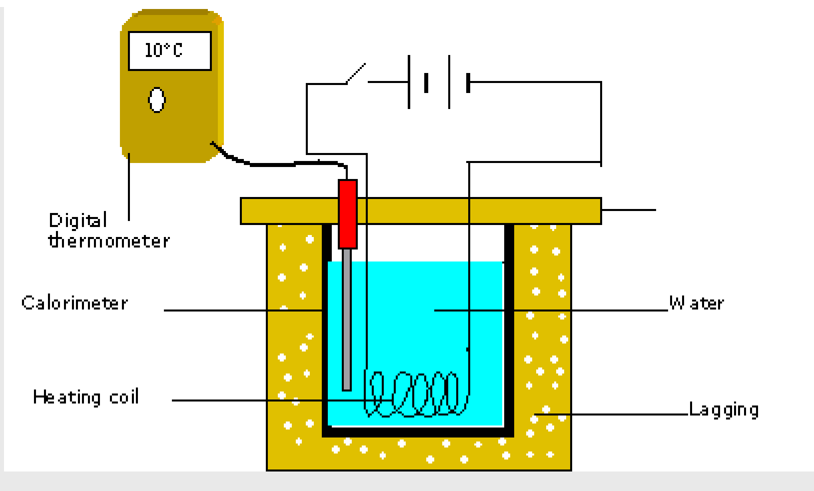
Electric current has three effects:

A. Heating
B. Chemical
C. Magnetic

A. Heating: $W = I^2Rt$

Heat is produced in current-carrying conductors, resulting in an increase in temperature of the conducting material. The heating is a result of the collisions between the moving free electrons and the relatively stationary atoms of the conductor material. As a result, heating increases rapidly with increase of current flow, since a greater rate of flow results in more collisions.

Use the following apparatus to demonstrate the heating effect of an electric current:



Everyday examples of heating effect of electricity

The heating effect of an electric current has many practical applications, e.g. in radiant electric fires, cookers, hairdryers, kettles, toasters, domestic irons, immersion heaters, etc.

Joule's Law

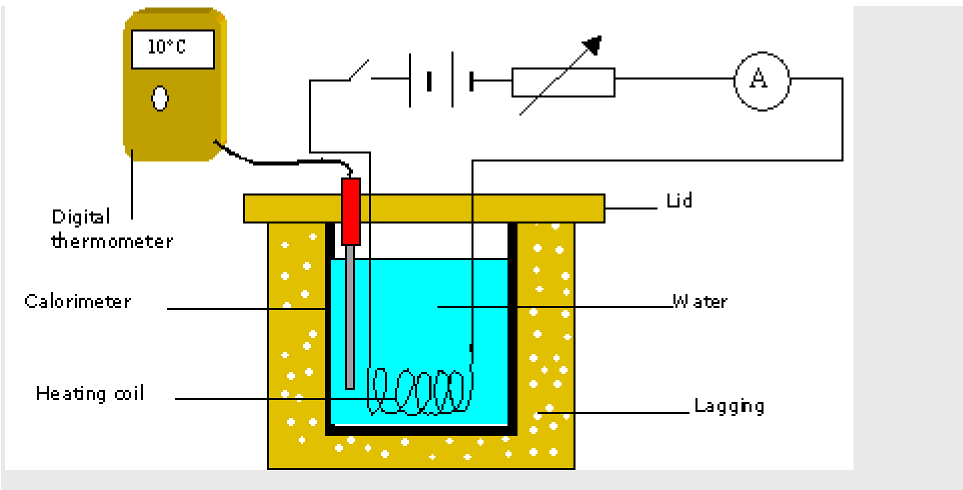
The rate at which heat is produced in a resistor is proportional to the square of the current flowing through it, if the resistance is constant.

$P \mu I^2$

Verification of Joule's Law (As $\Delta\theta \mu I^2$)

Apparatus

Lagged beaker or calorimeter with a lid, heating coil, battery or low-voltage power supply, rheostat, ammeter or multimeter, thermometer, stopwatch, balance.



Procedure

1. Put sufficient water in a calorimeter to cover the heating coil. Set up the circuit as shown.
2. Note the temperature.
3. Switch on the power and simultaneously start the stopwatch. Allow a current of 0.5 A

to flow for five minutes. Make sure the current stays constant throughout; adjust the rheostat if necessary.

4. Note the current, using the ammeter.
5. Note the time for which the current flowed.
6. Stir and note the highest temperature. Calculate the change in temperature $\Delta\theta$.
7. Repeat the above procedure for increasing values of current I, taking care not to exceed the current rating marked on the rheostat or the power supply. Take at least six readings.
8. Plot a graph of $\Delta\theta$ (Y-axis) against I^2 (X-axis).

Results

θ_1/° C	θ_2/° C	$\Delta\theta$/° C	I/A I^2/A^2

A straight-line graph through the origin verifies that $\Delta\theta$µ I^2 i.e. Joule's Law.

Note

The heat energy produced is the mass multiplied by specific heat capacity multiplied by rise in temperature:$\mathbf{Q = mc\Delta\theta}$

The energy liberated per second in the device is defined as the electrical power. This energy is $P = RI^2$.

Therefore $RI^2 = mc\Delta\theta\ /t$

$I^2 = (mc/Rt)\ \Delta\theta$.

As the mass, specific heat capacity, resistance and time are constant, $\Delta\theta$µ$\mathbf{I^2}$.

Hence **P µ $\mathbf{I^2}$** i.e. Joule's law.

You could do this experiment using a joulemeter to measure the power supplied, and an ammeter to measure the electric current. Then you could graph P **vs** I^2 directly.

Sample question

An electric kettle draws a current of 10 A when connected to the 230 V mains supply.
Calculate
(a) the power of the kettle
(b) the energy produced in 5 minutes
(c) the rise in temperature
if all the energy produced in 5 minutes is used to heat 2 kg of water.
(Specific heat capacity of water = 4200 J kg^{-1} K^{-1}.)

Solution
(a) P = IV
= 10 × 230
= 2300 W
= 2.3 kW.

(b) Energy produced in 5 minutes = Pt
= 2300 × 5 × 60
= 690 000 J
= 690 kJ.

(c) Energy produced = energy gained by water
690 000 = mcΔθ
= (2)(4200)(Δθ)
Δθ =**690000 / (** 2 x 4200)

= 82.1 K = Rise in temperature of the water

Practical Applications of Joule's Heating

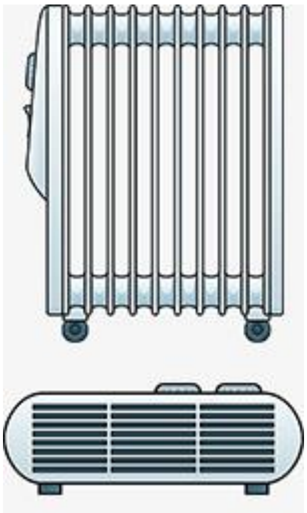
This heating is inevitable in any electrical circuit. Since the energy lost by the flowing charges ends up as disorderly thermal motion, the phrase 'ohmic dissipation' is also used to describe it. Often, this is an undesirable effect. For example, in electric circuits, the heat produced in a small region, can increase the temperature of the components so much that their properties change. Also to decrease ohmic losses, power transmission over long distances is effected at high voltage so that the current is reduced.

In many cases however, Joule heating is very useful. One common application is the fuse used in electric circuits. It is a short piece of metal, inserted in a circuit, which melts when excessive current flows through it and thus breaks the circuit. It thus protects appliances. The material of a fuse generally has a low melting point and high conductivity.

Familiar domestic applications are the electric iron, bread toaster, even electric kettle, heater, etc.

Electric heating is also used in producing light, as in an incandescent bulb. Here, the filament is made of a resistor that retains as much of the heat generated as possible. Then it can get very hot and emit light. It must not melt at the high temperature. Usually, tungsten is used for the bulb filament, as it has a high melting point ($6116^{o}F$) and is a strong metal. A small amount of the power used by the filament appears as radiated light, but most of it appears as heat.

4.2 ELECTRIC HEATING



Most electric heaters are relatively cheap to buy, but relatively expensive to run.

When are electric heaters a good option?

Electric heaters can be suitable for:

- smaller rooms that only get used occasionally, for short periods of time
- using instead of portable LPG heaters or open fires - electric heaters are much safer and cheaper to run if you have no other options e.g. in many rental houses.

The heating capacity of electric plug-in heaters is typically no more than 2.4 kW. This means in larger and/or poorly insulated rooms you may need to run more than one heater to reach comfortable and healthy temperatures. Only use one heater per power outlet to avoid overloading problems.

Are some electric heaters more efficient than others?

With the exception of heat pumps, all electric heaters are equally efficient. They convert all the electricity they consume into useful heat - so don't believe claims that any one type is more efficient than the other.

Different types of heaters for different heating needs

Different kinds of electric heaters, such as radiant, fan, convection and night store heaters, distribute heat differently. Choosing the right type of heater is important to get the full benefit of all of the heat you're paying for.

See the heater sizing calculator to work out how much heat you need.

Radiant heaters

The bar heater with glowing elements and a reflector is a radiant heater. These mainly heat objects and people rather than the air in a room. They are commonly available as either free-standing, wall or high-wall mounted models.

They can be useful:

- in rooms with high ceilings.
- in large rooms where you only need the heat in one area, or
- where you want to feel instant heat without waiting until the air in the room has warmed up, e.g. in large bathrooms (only use high wall mounted models here), while standing at the kitchen sink or for that quick early morning breakfast in a cold house.

Radiant heaters can be a fire risk if in close proximity to flammable materials and are dangerous to children. High-wall mounted models (available from electrical supply stores) can be installed out of reach from children and away from flammable materials.

There are more modern versions of the radiant heater, often called a panel, marble or stonestore heater, where the elements are behind, or inside a panel or other mass made of metal, brick, stone or something more expensive like marble. These heaters give a more even, lower temperature heat, but still cost the same to run for a set amount of heat. They are not any more efficient than any other type of electric heater.

Fan heaters

Fan heaters, sometimes also called ceramic heaters, can be noisy but distribute heated air around the room rather than letting it form a layer of hot air below the ceiling.

They are good for:

- boosting a convection heater while heating up a room by providing additional heating capacity and helping with better distributing heated air, so the room feels warm quicker.
- quick warmth in smaller rooms which require heating for very short periods of time, for instance in the kitchen or bathroom in the morning
- keeping children safe - high-wall mounted models can be installed out of reach from children for their and your home's safety.

Convection heaters

A convection heater mainly heats the air rather than surfaces. These include column heaters (oil and 'oil-free') and convection heaters with a heating element inside a casing which has grilles at the top and bottom to allow air to flow through.

These are a good choice for medium-sized rooms that require heating for longer periods of time, such as living rooms and bedrooms. They steadily warm the air by convection - the hot air rising and then slowly circulating around the room - and provide background warmth.

Some have a built-in fan to better mix the air while warming up a room to achieve a more even room temperature quicker.

Their surface temperatures are lower than radiant heaters, so they are somewhat safer, but they still get hot enough to burn skin.

Note that they can easily be tipped over unless fixed in place - the weight and sharp fins of oil column heaters can be particularly dangerous to children.

Panel heaters

Flat-panel heaters are often promoted as "eco" or cheap to run. They have very low heat output, which is usually insufficient to heat up a room to comfortable and healthy temperatures. So while they may cost less to run, they also produce very little heat. One advantage of low-wattage panel heaters is that they typically don't get hot enough for children or pets to burn themselves.

A higher wattage, thermostatically controlled heater is usually a better alternative to panel heaters as the higher heat capacity allows heating up a room quickly, then the thermostat can cycle the heater on and off to maintain a comfortable temperature without wasting energy unnecessarily.

Night store heaters

Night store heaters use mass like bricks to store heat from cheaper off-peak electricity at night and slowly release it during the day. They can be more economical than common electric heaters for houses that are occupied during the day, and where a cheaper night rate tariff for electricity is available.

However, if your house is empty during the day, these are not a good heating option for you as a lot of the heat will be released when it is not needed.

Electric under floor heating

Electric underfloor heating goes between the floorboard and any floor covering like carpet or thin timber flooring. Any covering that goes on top of the electric underfloor heating makes it harder for the heat to get into the room. It is very important that the floor is well insulated underneath, otherwise a lot of the heat you pay for will be lost downwards. Although electric under floor heating can heat large areas well, it can be expensive to run.

Features to look for

Thermostats: help maintain an even temperature for your comfort and conserve electricity. Some electric heaters have a temperature dial, but most don't and require a lot more trial and error until the desired thermostat setting is found.

Unfortunately the thermostats in most electric heaters aren't very accurate, resulting in large temperature fluctuations. The heater itself often interferes with the temperature sensor of it's own thermostat.

To work well the temperature sensor should be located as far away as possible from the heated parts of the heater, e.g. at the bottom of the heater where the unheated room air is drawn in. Also check whether the heater specifications provide any claimed thermostat accuracy.

If the thermostat of your heater doesn't work well, a separate plug-in thermostat that goes between the wall socket and your heater plug can be useful. You can buy them online, just search the internet for "plug-in thermostat". Alternatively you can get an electrician to install a separate, hard-wired room thermostat to control the heater. These are usually wall-mounted and, if installed correctly, will better sense the actual room temperature.

Timers: allow you to turn a heater on to warm up the kitchen half an hour before you get up, or to turn a heater off after you have gone to bed.

Fans: help a room warm up faster by distributing the air more evenly rather than letting heat build-up near the ceiling.

Thermal cutout: Some heaters have a built-in thermal cutout which turn the heater off if it overheats - this is an important safety feature to look for.

Tilt switch: Some portable heaters have a built-in tilt switch which turns the heater off if the heater overturns - another important safety feature to look for.

How much do they cost to run?

The page on calculating appliance running costs shows you how to calculate the running costs for your specific heaters. If your heater has a few different heat settings, then it will often say somewhere on the heater the Wattage of each setting. You need to know this to calculate the running costs.

Use your electric heaters wisely

Safety first. Risks associated with using electric heaters include electrocution, burns and fire. Always follow the manufacturer's instructions.

- **Only heat the areas you're using,** and only while you're using them.
- **Keep the heat in** by shutting doors and curtains.

- **Set the thermostat for healthy indoor temperatures.** World Health Organisation guidelines recommend at least 18˚C in any rooms you're using (or at least 20˚C if you have vulnerable people in the home, like children, the elderly or the ill), and at least 16˚C in bedrooms overnight.

4.3 LIGHTING EFFECT OF ELECTRIC CURRENT

Heating Effect of Electric Current

In the 19th century, James Joule studied a property, which says that "when an electric current flows through the filament of a bulb, it generates heat, and so the bulb becomes hot". This property is named the heating effect of electric current.

Compact Fluorescent Lamps (CFL's)

We use electric bulbs to obtain light. Due to the heating effect, some part of the energy received by the bulb is used up, and hence, some electricity is wasted. CFL's do not depend on the heating effect of electricity to produce light, since they do not use filaments. Using CFL's instead of ordinary bulbs minimises wastage of electricity. In CFL's, light is generated using two electrodes. The fluorescent coating inside each tube makes the light brighter.

We use every day many appliances that work on the property of the heating effect of electric current. For example, the electric room heater, electric roti maker, electric iron, toaster, hair dryer, electric stove, immersion water heater, food warmer, electric coffee maker, electric rice cooker and geyser work on the property of the heating effect of electric current.

Heating Elements

These appliances have coils of wire that produce heat, which are known as heating elements. As current flows through these electrical appliances, the coils of wire inside turn bright orange red in colour. This is because a huge amount of heat is produced. Different appliances have different types of heating elements. The type of heating element depends on the function of the appliance. Some appliances are required to produce more heat than others.

ISI Mark

You should purchase only appliances that bear an ISI mark. ISI stands for Indian Standards Institute. If an appliance bears the ISI mark, it means that it is safe and will not waste electrical energy. Moreover, it is a mark of quality.

Factors affecting production of heat

The factors that affect the production of heat in a wire through which an electric current is passing are the length and thickness of the wire, the duration of flow of current, and the material of the wire.

Electric Fuse

The electric fuse works on the principle of the heating effect of electric current. An electric fuse is a safety device to prevent damage to an electrical circuit when excessive current flows through it. It is made of a special material. As the current increases beyond a limit, the wire in the electric fuse melts and breaks off. The fuse is then said to have blown off. The circuit is broken and current stops flowing through it. Thus, a fuse prevents fires.

There are various types of fuses. Some fuses are used only in buildings, while others are used in appliances.

Reasons for Excessive Currenct

When all the appliances are connected to the same socket, these appliances draw more current, and so the load increases.

When the insulation on the wires is torn, two wires carrying current touch each other directly. This causes a spark, which leads to fire. This is termed as a SHORT CIRCUIT. If a fuse is not used, then overloading and short circuits result in fire.

Miniature Circuit Breakers (MCB)

Instead of fuses, MCBs are used nowadays because these are switches that turn off automatically when there is an overload or a short circuit. After solving the problem in the circuit, the switch can be turned back on, and then the current flows as usual.

4.4 FILAMENTS USED IN LAMPS, AND GASEOUS DISCHARGE LAMPS, THEIR WORKING AND APPLICATIONS.

A lamp is an energy converter. Although it may carry out secondary functions, its prime purpose is the transformation of electrical energy into visible electromagnetic radiation. There are many ways to create light. The standard method for creating general lighting is the conversion of electrical energy into light.

Types of Light

Incandescence

When solids and liquids are heated, they emit visible radiation at temperatures above 1,000 K; this is known as incandescence.

Such heating is the basis of light generation in filament lamps: an electrical current passes through a thin tungsten wire, whose temperature rises to around 2,500 to 3,200 K, depending upon the type of lamp and its application.

There is a limit to this method, which is described by Planck's Law for the performance of a black body radiator, according to which the spectral distribution of energy radiated increases with temperature. At about 3,600 K and above, there is a marked gain in emission of visible radiation, and the wavelength of maximum power shifts into the visible band. This temperature is close to the melting point of tungsten, which is used for the filament, so the practical temperature limit is around 2,700 K, above which filament evaporation becomes excessive. One result of these spectral shifts is that a large part of the radiation emitted is not given off as light but as heat in the infrared region. Filament lamps can thus be effective heating devices and are used in lamps designed for print drying, food preparation and animal rearing.

Electric discharge

Electrical discharge is a technique used in modern light sources for commerce and industry because of the more efficient production of light. Some lamp types combine the electrical discharge with photoluminescence.

An electric current passed through a gas will excite the atoms and molecules to emit radiation of a spectrum which is characteristic of the elements present. Two metals are commonly used, sodium and mercury, because their characteristics give useful radiations within the visible spectrum. Neither metal emits a continuous spectrum, and discharge lamps have selective spectra. Their colour rendering will never be identical to continuous spectra. Discharge lamps are often classed as high pressure or low pressure, although these terms are only relative, and a high-pressure sodium lamp operates at below one atmosphere.

Types of Luminescence

Photoluminescence occurs when radiation is absorbed by a solid and is then re-emitted at a different wavelength. When the re-emitted radiation is within the visible spectrum the process is called *fluorescence* or *phosphorescence*.

Electroluminescence occurs when light is generated by an electric current passed through certain solids, such as phosphor materials. It is used for self-illuminated signs and instrument panels but has not proved to be a practical light source for the lighting of buildings or exteriors.

Evolution of Electric Lamps

Although technological progress has enabled different lamps to be produced, the main factors influencing their development have been external market forces. For example, the production of filament lamps in use at the start of this century was possible only after the availability of good vacuum pumps and the drawing of tungsten wire. However, it was the large-scale generation and distribution of electricity to meet the demand for electric lighting that determined market growth. Electric lighting offered many advantages over gas- or oil-generated light, such as steady light that requires infrequent maintenance as well as the increased safety of having no exposed flame, and no local by-products of combustion.

During the period of recovery after the Second World War, the emphasis was on productivity. The fluorescent tubular lamp became the dominant light source because it made possible the shadow-free and comparatively heat-free lighting of factories and offices, allowing maximum use of the space. The light output and wattage requirements for a typical 1,500 mm fluorescent tubular lamp is given in table 1.

Table 1. Improved light output and wattage requirements of some typical 1,500 mm fluorescent tube lamps

Rating (W)	Diameter	Gas fill	Light output (lumens)

	(mm)		
80	38	argon	4,800
65	38	argon	4,900
58	25	krypton	5,100
50	25	argon	5,100 (high frequency gear)

By the 1970s oil prices rose and energy costs became a significant part of operating costs. Fluorescent lamps that produce the same amount of light with less electrical consumption were demanded by the market. Lamp design was refined in several ways. As the century closes there is a growing awareness of global environment issues. Better use of declining raw materials, recycling or safe disposal of products and the continuing concern over energy consumption (particularly energy generated from fossil fuels) are impacting on current lamp designs.

Performance Criteria

Performance criteria vary by application. In general, there is no particular hierarchy of importance of these criteria.

Light output: The lumen output of a lamp will determine its suitability in relation to the scale of the installation and the quantity of illumination required.

Colour appearance and colour rendering: Separate scales and numerical values apply to colour appearance and colour rendering. It is important to remember that the figures provide guidance only, and some are only approximations. Whenever possible, assessments of suitability should be made with actual lamps and with the colours or materials that apply to the situation.

Lamp life: Most lamps will require replacement several times during the life of the lighting installation, and designers should minimize the inconvenience to the occupants of odd failures and maintenance. Lamps are used in a wide variety of applications. The anticipated average life is often a compromise between cost and performance. For example, the lamp for a slide projector will have a life of a few hundred hours because the maximum light output is important to the quality of the image. By contrast, some roadway lighting lamps may be changed every two years, and this represents some 8,000 burning hours.

Further, lamp life is affected by operating conditions, and thus there is no simple figure that will apply in all conditions. Also, the effective lamp life may be determined by different failure modes. Physical failure such as filament or lamp rupture may be preceded by reduction in light output or changes in colour appearance. Lamp life is affected by external environmental conditions such as temperature, vibration, frequency of starting, supply voltage fluctuations, orientation and so on.

It should be noted that the average life quoted for a lamp type is the time for 50% failures from a batch of test lamps. This definition of life is not likely to be applicable to many commercial or industrial installations; thus practical lamp life is usually less than published values, which should be used for comparison only.

Efficiency: As a general rule the efficiency of a given type of lamp improves as the power rating increases, because most lamps have some fixed loss. However, different types of lamps have marked variation in efficiency. Lamps of the highest efficiency should be used, provided that the criteria of size, colour and lifetime are also met. Energy savings should not be at the expense of the visual comfort or the performance ability of the occupants. Some typical efficacies are given in table 2.

Table 2. Typical lamp efficacies

Lamp efficacies	
100 W filament lamp	14 lumens/watt
58 W fluorescent tube	89 lumens/watt
400 W high-pressure sodium	125 lumens/watt
131 W low-pressure sodium	198 lumens/watt

Main lamp types

Over the years, several nomenclature systems have been developed by national and international standards and registers.

In 1993, the International Electrotechnical Commission (IEC) published a new International Lamp Coding System (ILCOS) intended to replace existing national and regional coding systems. A list of some ILCOS short form codes for various lamps is given in table 3.

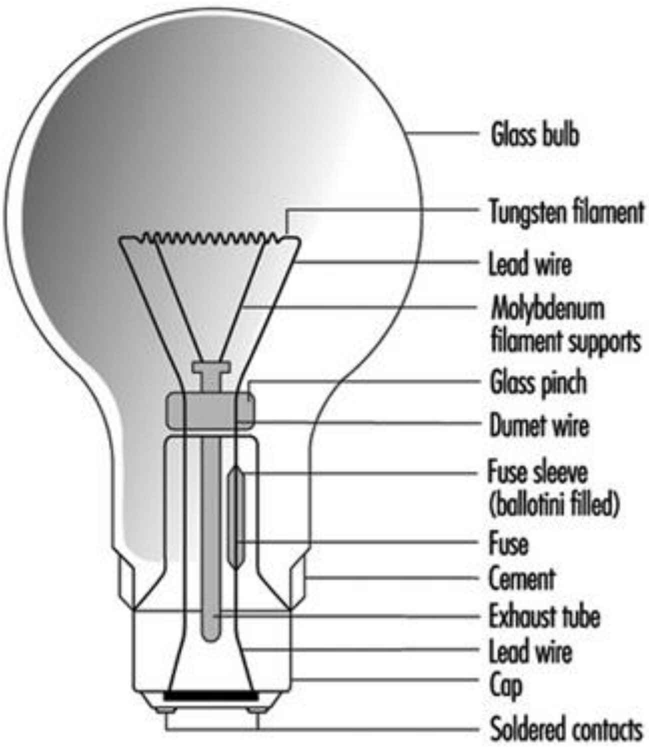
Table 3. International Lamp Coding System (ILCOS) short form coding system for some lamp types

Type (code)	Common ratings (watts)	Colour rendering	Colour temperature (K)	Life (hours)
Compact fluorescent lamps (FS)	5–55	good	2,700–5,000	5,000–10,000
High-pressure mercury lamps (QE)	80–750	fair	3,300–3,800	20,000
High-pressure sodium lamps (S-)	50–1,000	poor to good	2,000–2,500	6,000–24,000
Incandescent lamps (I)	5–500	good	2,700	1,000–3,000
Induction lamps (XF)	23–85	good	3,000–4,000	10,000–60,000
Low-pressure sodium lamps (LS)	26–180	monochromatic yellow colour	1,800	16,000
Low-voltage tungsten halogen lamps (HS)	12–100	good	3,000	2,000–5,000
Metal halide lamps (M-)	35–2,000	good to excellent	3,000–5,000	6,000–20,000
Tubular fluorescent lamps (FD)	4–100	fair to good	2,700–6,500	10,000–15,000
Tungsten halogen lamps (HS)	100–2,000	good	3,000	2,000–4,000

Incandescent lamps

These lamps use a tungsten filament in an inert gas or vacuum with a glass envelope. The inert gas suppresses tungsten evaporation and lessens the envelope blackening. There is a large variety of lamp shapes, which are largely decorative in appearance. The construction of a typical General Lighting Service (GLS) lamp is given in figure 1.

Figure 1. Construction of a GLS lamp



Incandescent lamps are also available with a wide range of colours and finishes. The ILCOS codes and some typical shapes include those shown in table 4.

Table 4. Common colours and shapes of incandescent lamps, with their ILCOS codes

Colour/Shape	**Code**
Clear	/C
Frosted	/F
White	/W
Red	/R
Blue	/B

Green	/G
Yellow	/Y
Pear shaped (GLS)	IA
Candle	IB
Conical	IC
Globular	IG
Mushroom	IM

Incandescent lamps are still popular for domestic lighting because of their low cost and compact size. However, for commercial and industrial lighting the low efficacy generates very high operating costs, so discharge lamps are the normal choice. A 100 W lamp has a typical efficacy of 14 lumens/watt compared with 96 lumens/watt for a 36 W fluorescent lamp.

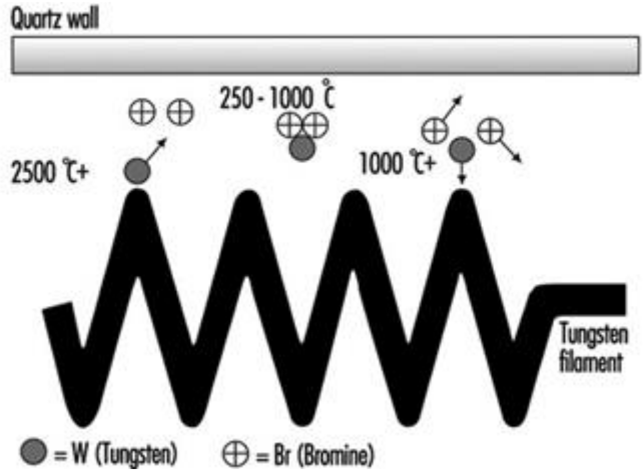
Incandescent lamps are simple to dim by reducing the supply voltage, and are still used where dimming is a desired control feature.

The tungsten filament is a compact light source, easily focused by reflectors or lenses. Incandescent lamps are useful for display lighting where directional control is needed.

Tungsten halogen lamps

These are similar to incandescent lamps and produce light in the same manner from a tungsten filament. However the bulb contains halogen gas (bromine or iodine) which is active in controlling tungsten evaporation. See figure 2.

Figure 2. The halogen cycle



Fundamental to the halogen cycle is a minimum bulb wall temperature of 250 °C to ensure that the tungsten halide remains in a gaseous state and does not condense on the bulb wall. This temperature means bulbs made from quartz in place of glass. With quartz it is possible to reduce the bulb size.

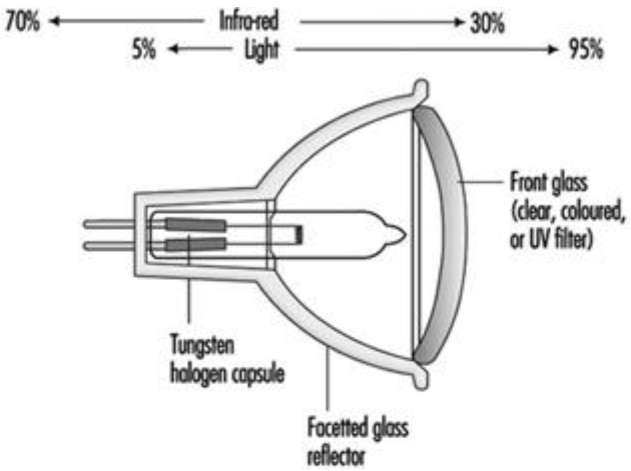
Most tungsten halogen lamps have an improved life over incandescent equivalents and the filament is at a higher temperature, creating more light and whiter colour.

Tungsten halogen lamps have become popular where small size and high performance are the main requirement. Typical examples are stage lighting, including film and TV, where directional control and dimming are common equirements.

Low-voltage tungsten halogen lamps

These were originally designed for slide and film projectors. At 12 V the filament for the same wattage as 230 V becomes smaller and thicker. This can be more efficiently focused, and the larger filament mass allows a higher operating temperature, increasing light output. The thick filament is more robust. These benefits were realized as being useful for the commercial display market, and even though it is necessary to have a step-down transformer, these lamps now dominate shop-window lighting. See figure 3.

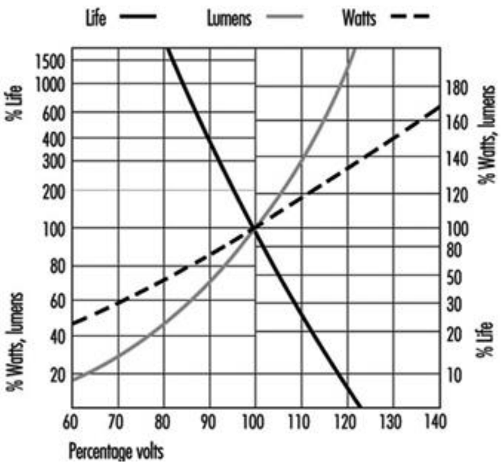
Figure 3. Low-voltage dichroic reflector lamp



Although users of film projectors want as much light as possible, too much heat damages the transparency medium. A special type of reflector has been developed, which reflects only the visible radiation, allowing infrared radiation (heat) to pass through the back of lamp. This feature is now part of many low-voltage reflector lamps for display lighting as well as projector equipment.

Voltage sensitivity: All filament lamps are sensitive to voltage variation, and light output and life are affected. The move to "harmonize" the supply voltage throughout Europe at 230 V is being achieved by widening the tolerances to which the generating authorities can operate. The move is towards ±10%, which is a voltage range of 207 to 253 V. Incandescent and tungsten halogen lamps cannot be operated sensibly over this range, so it will be necessary to match actual supply voltage to lamp ratings. See figure 4.

Figure 4. GLS filament lamps and supply voltage



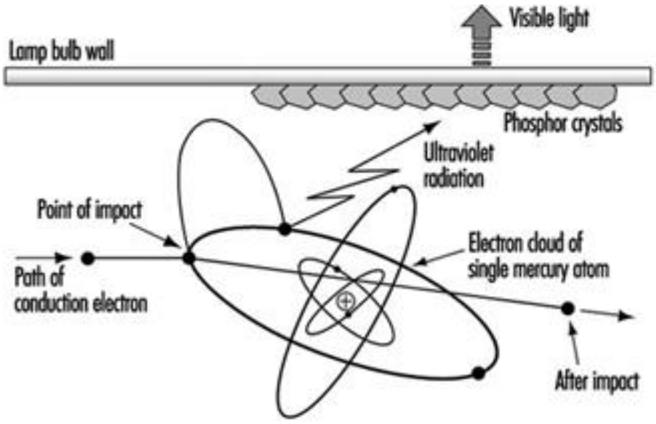
Discharge lamps will also be affected by this wide voltage variation, so the correct specification of control gear becomes important.

Tubular fluorescent lamps

These are low pressure mercury lamps and are available as “hot cathode” and “cold cathode” versions. The former is the conventional fluorescent tube for offices and factories; “hot cathode” relates to the starting of the lamp by pre-heating the electrodes to create sufficient ionization of the gas and mercury vapour to establish the discharge.

Cold cathode lamps are mainly used for signage and advertising. See figure 5.

Figure 5. Principle of fluorescent lamp



Fluorescent lamps require external control gear for starting and to control the lamp current. In addition to the small amount of mercury vapour, there is a starting gas (argon or krypton).

The low pressure of mercury generates a discharge of pale blue light. The major part of the radiation is in the UV region at 254 nm, a characteristic radiation frequency for mercury. Inside of the tube wall is a thin phosphor coating, which absorbs the UV and radiates the energy as visible light. The colour quality of the light is determined by the phosphor coating. A range of phosphors are available of varying colour appearance and colour rendering.

During the 1950s phosphors available offered a choice of reasonable efficacy (60 lumens/watt) with light deficient in reds and blues, or improved colour rendering from “deluxe” phosphors of lower efficiency (40 lumens/watt).

By the 1970s new, narrow-band phosphors had been developed. These separately radiated red, blue and green light but, combined, produced white light. Adjusting the proportions gave a range of different colour appearances, all with similar excellent colour rendering. These tri-phosphors are more efficient than the earlier types and represent the best economic lighting solution, even though the lamps are more expensive. Improved efficacy reduces operating and installation costs.

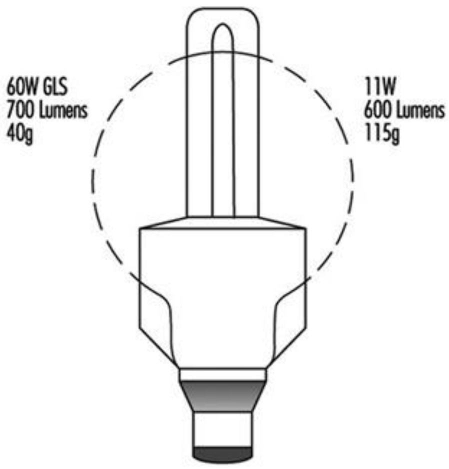
The tri-phosphor principle has been extended by multi-phosphor lamps where critical colour rendering is necessary, such as for art galleries and industrial colour matching.

The modern narrow-band phosphors are more durable, have better lumen maintenance, and increase lamp life.

Compact fluorescent lamps

The fluorescent tube is not a practical replacement for the incandescent lamp because of its linear shape. Small, narrow-bore tubes can be configured to approximately the same size as the incandescent lamp, but this imposes a much higher electrical loading on the phosphor material. The use of tri-phosphors is essential to achieve acceptable lamp life. See figure 6.

Figure 6. Four-leg compact fluorescent



All compact fluorescent lamps use tri-phosphors, so, when they are used together with linear fluorescent lamps, the latter should also be tri-phosphor to ensure colour consistency.

Some compact lamps include the operating control gear to form retro-fit devices for incandescent lamps. The range is increasing and enables easy upgrading of existing installations to more energy-efficient lighting. These integral units are not suitable for dimming where that was part of the original controls.

High-frequency electronic control gear: If the normal supply frequency of 50 or 60 Hz is increased to 30 kHz, there is a 10% gain in efficacy of fluorescent tubes. Electronic circuits can operate individual lamps at such frequencies. The electronic circuit is designed to provide the same light output as wire-wound control gear, from reduced lamp power. This offers compatibility of lumen package with the advantage that reduced lamp loading will increase lamp life significantly. Electronic control gear is capable of operating over a range of supply voltages.

There is no common standard for electronic control gear, and lamp performance may differ from the published information issued by the lamp makers.

The use of high-frequency electronic gear removes the normal problem of flicker, to which some occupants may be sensitive.

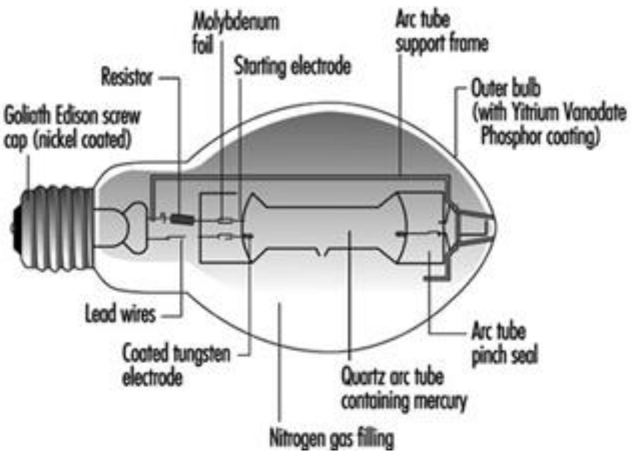
Induction lamps

Lamps using the principle of induction have recently appeared on the market. They are low-pressure mercury lamps with tri-phosphor coating and as light producers are similar to fluorescent lamps. The energy is transferred to the lamp by high-frequency radiation, at approximately 2.5 MHz from an antenna positioned centrally within the lamp. There is no physical connection between the lamp bulb and the coil. Without electrodes or other wire connections the construction of the discharge vessel is simpler and more durable. Lamp life is mainly determined by the reliability of the electronic components and the lumen maintenance of the phosphor coating.

High-pressure mercury lamps

High-pressure discharges are more compact and have higher electrical loads; therefore, they require quartz arc tubes to withstand the pressure and temperature. The arc tube is contained in an outer glass envelope with a nitrogen or argon-nitrogen atmosphere to reduce oxidation and arcing. The bulb effectively filters the UV radiation from the arc tube. See figure 7.

Figure 7. Mercury lamp construction



At high pressure, the mercury discharge is mainly blue and green radiation. To improve the colour a phosphor coating of the outer bulb adds red light. There are deluxe versions with an increased red content, which give higher light output and improved colour rendering.

All high-pressure discharge lamps take time to reach full output. The initial discharge is via the conducting gas fill, and the metal evaporates as the lamp temperature increases.

At the stable pressure the lamp will not immediately restart without special control gear. There is a delay while the lamp cools sufficiently and the pressure reduces, so that the normal supply voltage or ignitor circuit is adequate to re-establish the arc.

Discharge lamps have a negative resistance characteristic, and so the external control gear is necessary to control the current. There are losses due to these control gear components so the user should consider total watts when considering operating costs and electrical installation. There is an exception for high-pressure mercury lamps, and one type contains a tungsten filament which both acts as the current limiting device and adds warm colours to the blue/green discharge. This enables the direct replacement of incandescent lamps.

Although mercury lamps have a long life of about 20,000 hours, the light output will fall to about 55% of the initial output at the end of this period, and therefore the economic life can be shorter.

Metal halide lamps

The colour and light output of mercury discharge lamps can be improved by adding different metals to the mercury arc. For each lamp the dose is small, and for accurate application it is more convenient to handle the metals in powder form as halides. This breaks down as the lamp warms up and releases the metal.

A metal halide lamp can use a number of different metals, each of which give off a specific characteristic colour. These include:

- dysprosium—broad blue-green
- indium—narrow blue
- lithium—narrow red
- scandium—broad blue-green
- sodium—narrow yellow
- thallium—narrow green
- tin—broad orange-red

There is no standard mixture of metals, so metal halide lamps from different manufacturers may not be compatible in appearance or operating performance. For lamps with the lower wattage ratings, 35 to 150 W, there is closer physical and electrical compatibility with a common standard.

Metal halide lamps require control gear, but the lack of compatibility means that it is necessary to match each combination of lamp and gear to ensure correct starting and running conditions.

Low-pressure sodium lamps

The arc tube is similar in size to the fluorescent tube but is made of special ply glass with an inner sodium resistant coating. The arc tube is formed in a narrow “U” shape and is contained in an outer vacuum jacket to ensure thermal stability. During starting, the lamps have a strong red glow from the neon gas fill.

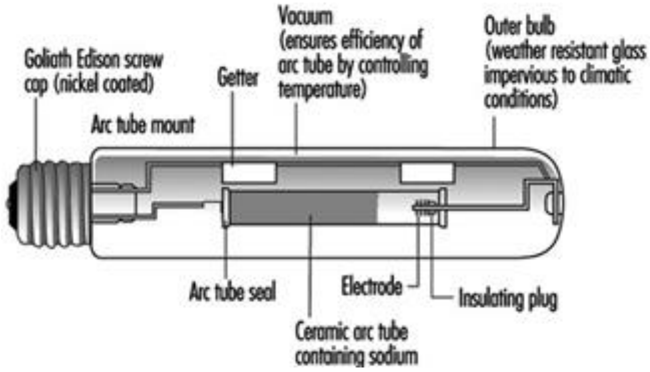
The characteristic radiation from low-pressure sodium vapour is a monochromatic yellow. This is close to the peak sensitivity of the human eye, and low-pressure sodium lamps are the most efficient lamps available at nearly 200 lumens/watt. However the applications are limited to where colour discrimination is of no visual importance, such as trunk roads and underpasses, and residential streets.

In many situations these lamps are being replaced by high-pressure sodium lamps. Their smaller size offers better optical control, particularly for roadway lighting where there is growing concern over excessive sky glow.

High-pressure sodium lamps

These lamps are similar to high-pressure mercury lamps but offer better efficacy (over 100 lumens/watt) and excellent lumen maintenance. The reactive nature of sodium requires the arc tube to be manufactured from translucent polycrystalline alumina, as glass or quartz are unsuitable. The outer glass bulb contains a vacuum to prevent arcing and oxidation. There is no UV radiation from the sodium discharge so phosphor coatings are of no value. Some bulbs are frosted or coated to diffuse the light source. See figure 8.

Figure 8. High-pressure sodium lamp construction



As the sodium pressure is increased, the radiation becomes a broad band around the yellow peak, and the appearance is golden white. However, as the pressure increases, the efficiency decreases. There are currently three separate types of high-pressure sodium lamps available, as shown in table 5.

Table 5. Types of high-pressure sodium lamp

Lamp type (code)	**Colour (K)**	**Efficacy (lumens/watt)**	**Life (hours)**
Standard	2,000	110	24,000
Deluxe	2,200	80	14,000
White (SON)	2,500	50	

Generally the standard lamps are used for exterior lighting, deluxe lamps for industrial interiors, and White SON for commercial/display applications.

Dimming of Discharge Lamps

The high-pressure lamps cannot be satisfactorily dimmed, as changing the lamp power changes the pressure and thus the fundamental characteristics of the lamp.

Fluorescent lamps can be dimmed using high-frequency supplies generated typically within the electronic control gear. The colour appearance remains very constant. In addition, the light output is approximately proportional to the lamp power, with consequent saving in electrical power when the light output is reduced. By integrating the light output from the lamp with the prevailing level of natural daylight, a near constant level of luminance can be provided in an interior.

UNIT- 5

CAPACITOR AND ITS CAPACITY

A **capacitor** (originally known as a **condenser**) is a passive two-terminal electrical component used to store energy electro-statically in an electric field. The forms of practical capacitors vary widely, but all contain at least two electrical conductors (plates) separated by a dielectric (i.e., insulator). The conductors can be thin films of metal, aluminum foil or disks, etc. The 'non conducting' dielectric acts to increase the capacitor's charge capacity. A dielectric can be glass, ceramic, plastic film, air, paper, mica, etc. Capacitors are widely used as parts of electrical circuits in many common electrical devices. Unlike a resistor, a capacitor does not dissipate energy. Instead, a capacitor stores energy in the form of an electrostatic field between its plates.

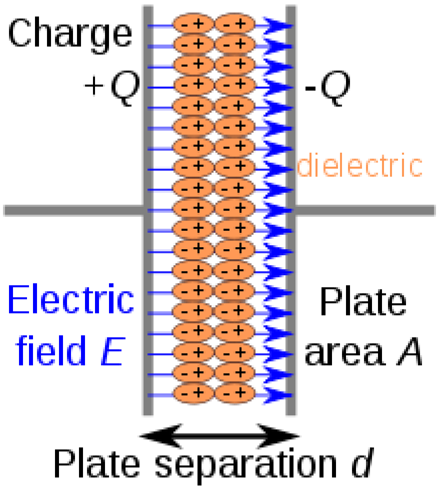
When there is a potential difference across the conductors (e.g., when a capacitor is attached across a battery), an electric field develops across the dielectric, causing positive charge (+Q) to collect on one plate and negative charge (-Q) to collect on the other plate. If a battery has been attached to a capacitor for a sufficient amount of time, no current can flow through the capacitor. However, if an accelerating or alternating voltage is applied across the leads of the capacitor, a displacement current can flow.

An ideal capacitor is characterized by a single constant value for its capacitance. Capacitance is expressed as the ratio of the electric charge (Q) on each conductor to the potential difference (V) between them. The SI unit of capacitance is the farad (F), which is equal to one coulomb per volt (1 C/V). Typical capacitance values range from about 1 pF (10^{-12} F) to about 1 mF (10^{-3} F).

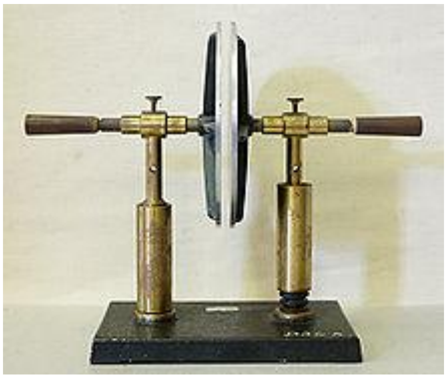
The capacitance is greater when there is a narrower separation between conductors and when the conductors have a larger surface area. In practice, the dielectric between the plates passes a small amount of leakage current and also has an electric field strength limit, known as the breakdown voltage. The conductors and leads introduce an undesired inductance and resistance.

Capacitors are widely used in electronic circuits for blocking direct current while allowing alternating current to pass. In analog filter networks, they smooth the output of power supplies. In resonant circuits they tune radiosto particular frequencies. In electric power transmission systems they stabilize voltage and power flow.

THEORY OF OPERATION



Charge separation in a parallel-plate capacitor causes an internal electric field. A dielectric (orange) reduces the field and increases the capacitance.



A simple demonstration of a parallel-plate capacitor

A capacitor consists of two conductors separated by a non-conductive region.[10] The non-conductive region is called the dielectric. In simpler terms, the dielectric is just an electrical insulator. Examples of dielectric media are glass, air, paper, vacuum, and even a semiconductor depletion region chemically identical to the conductors. A capacitor is assumed to be self-contained and isolated, with no net electric charge and no influence from any external electric field. The conductors thus hold equal and opposite charges on their facing surfaces, and the dielectric develops an electric field. In SI units, a capacitance of one farad means that one coulomb of charge on each conductor causes a voltage of one volt across the device.

An ideal capacitor is wholly characterized by a constant capacitance C, defined as the ratio of charge $\pm Q$ on each conductor to the voltage V between them:

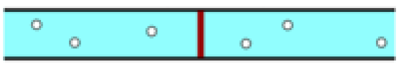
$$C = \frac{Q}{V}$$

Because the conductors (or plates) are close together, the opposite charges on the conductors attract one another due to their electric fields, allowing the capacitor to store more charge for a given voltage than if the conductors were separated, giving the capacitor a large capacitance.

Sometimes charge build-up affects the capacitor mechanically, causing its capacitance to vary. In this case, capacitance is defined in terms of incremental changes:

$$C = \frac{\mathrm{d}Q}{\mathrm{d}V}$$

Hydraulic analogy[edit]



In the hydraulic analogy, a capacitor is analogous to a rubber membrane sealed inside a pipe. This animation illustrates a membrane being repeatedly stretched and un-stretched by the flow of water, which is analogous to a capacitor being repeatedly charged and discharged by the flow of charge.

In the hydraulic analogy, charge carriers flowing through a wire are analogous to water flowing through a pipe. A capacitor is like a rubber membrane sealed inside a pipe. Water molecules cannot pass through the membrane, but some water can move by stretching the membrane. The analogy clarifies a few aspects of capacitors:

- *The current alters the charge on a capacitor*, just as the flow of water changes the position of the membrane. More specifically, the effect of an electric current is to increase the charge of one plate of the capacitor, and decrease the charge of the other plate by an equal amount. This is just as when water flow moves the rubber membrane, it increases the amount of water on one side of the membrane, and decreases the amount of water on the other side.
- *The more a capacitor is charged, the larger its voltage drop*; i.e., the more it "pushes back" against the charging current. This is analogous to the fact that the more a membrane is stretched, the more it pushes back on the water.
- *Charge can flow "through" a capacitor even though no individual electron can get from one side to the other.* This is analogous to the fact that water can flow through the pipe even though no water molecule can pass through the rubber membrane. Of course, the flow cannot continue in the same direction forever; the capacitor will experience dielectric breakdown, and analogously the membrane will eventually break.
- The *capacitance* describes how much charge can be stored on one plate of a capacitor for a given "push" (voltage drop). A very stretchy, flexible membrane corresponds to a higher capacitance than a stiff membrane.
- A charged-up capacitor is storing potential energy, analogously to a stretched membrane.

ENERGY OF ELECTRIC FIELD

Work must be done by an external influence to "move" charge between the conductors in a capacitor. When the external influence is removed, the charge separation persists in the electric field and energy is stored to be released when the charge is allowed to return to its equilibrium position. The work done in establishing the electric field, and hence the amount of energy stored, is

$$W = \int_0^Q V \mathrm{d}q = \int_0^Q \frac{q}{C} \mathrm{d}q = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}CV^2 = \frac{1}{2}VQ$$

Here Q is the charge stored in the capacitor, V is the voltage across the capacitor, and C is the capacitance.

In the case of a fluctuating voltage $V(t)$, the stored energy also fluctuates and hence power must flow into or out of the capacitor. This power can be found by taking the time derivative of the stored energy:

$$P = \frac{\mathrm{d}W}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2}CV^2\right) = CV(t)\frac{\mathrm{d}V}{\mathrm{d}t}$$

CURRENT–VOLTAGE RELATION

The current $I(t)$ through any component in an electric circuit is defined as the rate of flow of a charge $Q(t)$ passing through it, but actual charges—electrons—cannot pass through the dielectric layer of a capacitor. Rather, an electron accumulates on the negative plate for each one that leaves the positive plate, resulting in an electron depletion and consequent positive charge on one electrode that is equal and opposite to the accumulated negative charge on the other. Thus the charge on the electrodes is equal to the integral of the current as well as proportional to the voltage, as discussed above. As with any antiderivative, a constant of integration is added to represent the initial voltage $V(t_0)$. This is the integral form of the capacitor equation:

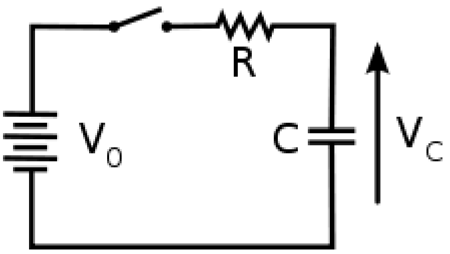
$$V(t) = \frac{Q(t)}{C} = \frac{1}{C}\int_{t_0}^{t} I(\tau)\mathrm{d}\tau + V(t_0)$$

Taking the derivative of this and multiplying by C yields the derivative form:

$$I(t) = \frac{\mathrm{d}Q(t)}{\mathrm{d}t} = C\frac{\mathrm{d}V(t)}{\mathrm{d}t}$$

The dual of the capacitor is the inductor, which stores energy in a magnetic field rather than an electric field. Its current-voltage relation is obtained by exchanging current and voltage in the capacitor equations and replacing C with the inductance L.

DC circuits



A simple resistor-capacitor circuit demonstrates charging of a capacitor.

A series circuit containing only a resistor, a capacitor, a switch and a constant DC source of voltage V_0 is known as a *charging circuit*. If the capacitor is initially uncharged while the switch is open, and the switch is closed at t_0, it follows from Kirchhoff's voltage law that

$$V_0 = v_{\text{resistor}}(t) + v_{\text{capacitor}}(t) = i(t)R + \frac{1}{C}\int_{t_0}^{t} i(\tau)\mathrm{d}\tau$$

Taking the derivative and multiplying by C, gives a first-order differential equation:

$$RC\frac{\mathrm{d}i(t)}{\mathrm{d}t} + i(t) = 0$$

At $t = 0$, the voltage across the capacitor is zero and the voltage across the resistor is V_0. The initial current is then $I(0) = V_0/R$. With this assumption, solving the differential equation yields

$$I(t) = \frac{V_0}{R}e^{-\frac{t}{\tau_0}}$$
$$V(t) = V_0\left(1 - e^{-\frac{t}{\tau_0}}\right)$$

where $\tau_0 = RC$ is the *time constant* of the system. As the capacitor reaches equilibrium with the source voltage, the voltages across the resistor and the current through the entire circuit decay exponentially. The case of *discharging* a charged capacitor likewise demonstrates exponential decay, but with the initial capacitor voltage replacing V_0 and the final voltage being zero.

AC circuits[edit]

See also: reactance (electronics) and electrical impedance § Deriving the device-specific impedances

Impedance, the vector sum of reactance and resistance, describes the phase difference and the ratio of amplitudes between sinusoidally varying voltage and sinusoidally varying current at a given frequency. Fourier analysis allows any signal to be constructed from a spectrum of frequencies, whence the circuit's reaction to the various frequencies may be found. The reactance and impedance of a capacitor are respectively

$$X = -\frac{1}{\omega C} = -\frac{1}{2\pi f C}$$
$$Z = \frac{1}{j\omega C} = -\frac{j}{\omega C} = -\frac{j}{2\pi f C}$$

where j is the imaginary unit and ω is the angular frequency of the sinusoidal signal. The $-j$ phase indicates that the AC voltage $V = ZI$ lags the AC current by 90°: the positive current phase corresponds to increasing voltage as the capacitor charges; zero current corresponds to instantaneous constant voltage, etc.

Impedance decreases with increasing capacitance and increasing frequency. This implies that a higher-frequency signal or a larger capacitor results in a lower voltage amplitude per current amplitude—an AC "short circuit" or AC coupling. Conversely, for very low frequencies, the reactance will be high, so that a capacitor is nearly an open circuit in AC analysis—those frequencies have been "filtered out".

Capacitors are different from resistors and inductors in that the impedance is *inversely* proportional to the defining characteristic; i.e., capacitance.

A capacitor connected to a sinusoidal voltage source will cause a displacement current to flow through it. In the case that the voltage source is $V_0\cos(\omega t)$, the displacement current can be expressed as:

$$I = C\frac{dV}{dt} = -\omega C V_0 \sin(\omega t)$$

At sin(ωt) = -1, the capacitor has a maximum (or peak) current whereby $I_0 = \omega C V_0$. The ratio of peak voltage to peak current is due to capacitive reactance (denoted X_C).

$$X_C = \frac{V_0}{I_0} = \frac{V_0}{\omega C V_0} = \frac{1}{\omega C}$$

X_C approaches zero as ω approaches infinity. If X_C approaches 0, the capacitor resembles a short wire that strongly passes current at high frequencies. X_C approaches infinity as ω approaches zero. If X_C approaches infinity, the capacitor resembles an open circuit that poorly passes low frequencies.

The current of the capacitor may be expressed in the form of cosines to better compare with the voltage of the source:

$$I = -I_0 \sin(\omega t) = I_0 \cos(\omega t + 90^\circ)$$

In this situation, the current is out of phase with the voltage by +π/2 radians or +90 degrees (i.e., the current will lead the voltage by 90°).

Laplace circuit analysis (s-domain)[edit]

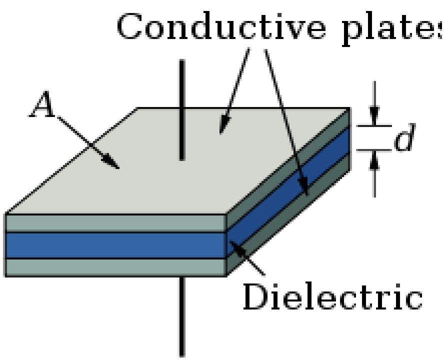
When using the Laplace transform in circuit analysis, the impedance of an ideal capacitor with no initial charge is represented in the *s* domain by:

$$Z(s) = \frac{1}{sC}$$

where

- *C* is the capacitance, and
- *s* is the complex frequency.

Parallel-plate model



Dielectric is placed between two conducting plates, each of area *A*and with a separation of *d*

The simplest capacitor consists of two parallel conductive plates separated by a dielectric (such as air) with permittivity ε . The model may also be used to make qualitative predictions for other device geometries. The plates are considered to extend uniformly over an area *A* and a charge density ±ρ = ±*Q*/*A* exists on their surface. Assuming that the width of the plates is much greater than their separation *d*, the electric field near the centre of the device will be uniform with the magnitude *E* = ρ/ε. The voltage is defined as the line integral of the electric field between the plates

$$V = \int_0^d E\,\mathrm{d}z = \int_0^d \frac{\rho}{\varepsilon}\,\mathrm{d}z = \frac{\rho d}{\varepsilon} = \frac{Qd}{\varepsilon A}$$

Solving this for *C* = *Q*/*V* reveals that capacitance increases with area of the plates, and decreases as separation between plates increases.

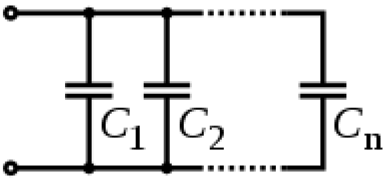
$$C = \frac{\varepsilon A}{d}$$

The capacitance is therefore greatest in devices made from materials with a high permittivity, large plate area, and small distance between plates.

A parallel plate capacitor can only store a finite amount of energy before dielectric breakdown occurs. The capacitor's dielectric material has a dielectric strength U_d which sets the capacitor's breakdown voltage at $V = V_{bd} = U_d d$. The maximum energy that the capacitor can store is therefore

$$E = \frac{1}{2}CV^2 = \frac{1}{2}\frac{\varepsilon A}{d}(U_d d)^2 = \frac{1}{2}\varepsilon A d U_d^2$$

We see that the maximum energy is a function of dielectric volume, permittivity, and dielectric strength per distance. So increasing the plate area while decreasing the separation between the plates while maintaining the same volume has no change on the amount of energy the capacitor can store. Care must be taken when increasing the plate separation so that the above assumption of the distance between plates being much smaller than the area of the plates is still valid for these equations to be accurate. In addition, these equations assume that the electric field is entirely concentrated in the dielectric between the plates. In reality there are fringing fields outside the dielectric, for example between the sides of the capacitor plates, which will increase the effective capacitance of the capacitor. This could be seen as a form of parasitic capacitance. For some simple capacitor geometries this additional capacitance term can be calculated analytically.[17] It becomes negligibly small when the ratio of plate area to separation is large.



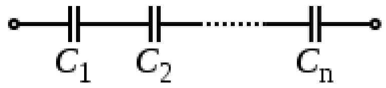
Several capacitors in parallel.

Networks

For capacitors in parallel

> Capacitors in a parallel configuration each have the same applied voltage. Their capacitances add up. Charge is apportioned among them by size. Using the schematic diagram to visualize parallel plates, it is apparent that each capacitor contributes to the total surface area.
>
> $$C_{eq} = C_1 + C_2 + \cdots + C_n$$

For capacitors in series



Several capacitors in series.

Connected in series, the schematic diagram reveals that the separation distance, not the plate area, adds up. The capacitors each store instantaneous charge build-up equal to that of every other capacitor in the series. The total voltage difference from end to end is apportioned to each capacitor according to the inverse of its capacitance. The entire series acts as a capacitor *smaller* than any of its components.

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n}$$

Capacitors are combined in series to achieve a higher working voltage, for example for smoothing a high voltage power supply. The voltage ratings, which are based on plate separation, add up, if capacitance and leakage currents for each capacitor are identical. In such an application, on occasion series strings are connected in parallel, forming a matrix. The goal is to maximize the energy storage of the network without overloading any capacitor. For high-energy storage with capacitors in series, some safety considerations must be applied to ensure one capacitor failing and leaking current will not apply too much voltage to the other series capacitors.

Series connection is also sometimes used to adapt polarized electrolytic capacitors for bipolar AC use. See electrolytic capacitor#Designing for reverse bias.

Voltage distribution in parallel-to-series networks.

To model the distribution of voltages from a single charged capacitor (A) connected in parallel to a chain of capacitors in series (B_n):

$$(volts)A_{\mathrm{eq}} = A\left(1 - \frac{1}{n+1}\right)$$
$$(volts)B_{1..\mathrm{n}} = \frac{A}{n}\left(1 - \frac{1}{n+1}\right)$$
$$A - B = 0$$

Note: This is only correct if all capacitance values are equal.

The power transferred in this arrangement is:

$$P = \frac{1}{R} \cdot \frac{1}{n+1} A_{\mathrm{volts}} \left(A_{\mathrm{farads}} + B_{\mathrm{farads}}\right)$$

Non-ideal behavior

Capacitors deviate from the ideal capacitor equation in a number of ways. Some of these, such as leakage current and parasitic effects are linear, or can be assumed to be linear, and can be dealt with by adding virtual components to the equivalent circuit of the capacitor. The usual methods of network analysis can then be applied. In other cases, such as with breakdown voltage, the effect is non-linear and normal (i.e., linear) network analysis cannot be used, the effect must be dealt with separately. There is yet another group, which may be linear but invalidate the assumption in the analysis that capacitance is a constant. Such an example is temperature dependence. Finally, combined parasitic effects such as inherent inductance, resistance, or dielectric losses can exhibit non-uniform behavior at variable frequencies of operation.

Breakdown voltage

Above a particular electric field, known as the dielectric strength E_{ds}, the dielectric in a capacitor becomes conductive. The voltage at which this occurs is called the breakdown voltage of the device, and is given by the product of the dielectric strength and the separation between the conductors,

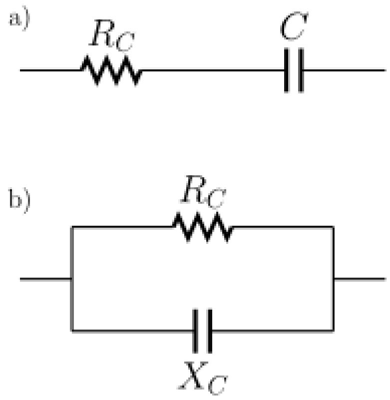
$$V_{\mathrm{bd}} = E_{\mathrm{ds}} d$$

The maximum energy that can be stored safely in a capacitor is limited by the breakdown voltage. Due to the scaling of capacitance and breakdown voltage with dielectric thickness, all capacitors made with a particular dielectric have approximately equal maximum energy density, to the extent that the dielectric dominates their volume.

For air dielectric capacitors the breakdown field strength is of the order 2 to 5 MV/m; for mica the breakdown is 100 to 300 MV/m, for oil 15 to 25 MV/m, and can be much less when other materials are used for the dielectric. The dielectric is used in very thin layers and so absolute breakdown voltage of capacitors is limited. Typical ratings for capacitors used for general electronics applications range from a few volts to 1 kV. As the voltage increases, the dielectric must be thicker, making high-voltage capacitors larger per capacitance than those rated for lower voltages. The breakdown voltage is critically affected by factors such as the geometry of the capacitor conductive parts; sharp edges or points increase the electric field strength at that point and can lead to a local breakdown. Once this starts to happen, the breakdown quickly tracks through the dielectric until it reaches the opposite plate, leaving carbon behind causing a short circuit.

The usual breakdown route is that the field strength becomes large enough to pull electrons in the dielectric from their atoms thus causing conduction. Other scenarios are possible, such as impurities in the dielectric, and, if the dielectric is of a crystalline nature, imperfections in the crystal structure can result in an avalanche breakdown as seen in semi-conductor devices. Breakdown voltage is also affected by pressure, humidity and temperature.

Equivalent circuit[edit]



Two different circuit models of a real capacitor

An ideal capacitor only stores and releases electrical energy, without dissipating any. In reality, all capacitors have imperfections within the capacitor's material that create resistance. This is specified as the *equivalent series resistance* or **ESR** of a component. This adds a real component to the impedance:

$$R_{\text{C}} = Z + R_{\text{ESR}} = \frac{1}{j\omega C} + R_{\text{ESR}}$$

As frequency approaches infinity, the capacitive impedance (or reactance) approaches zero and the ESR becomes significant. As the reactance becomes negligible, power dissipation approaches $P_{\text{RMS}} = V_{\text{RMS}}^2 / R_{\text{ESR}}$.

Similarly to ESR, the capacitor's leads add *equivalent series inductance* or **ESL** to the component. This is usually significant only at relatively high frequencies. As inductive reactance is positive and increases with frequency, above a certain frequency capacitance will be canceled by inductance. High-frequency engineering involves accounting for the inductance of all connections and components.

If the conductors are separated by a material with a small conductivity rather than a perfect dielectric, then a small leakage current flows directly between them. The capacitor therefore has a finite parallel resistance, and slowly discharges over time (time may vary greatly depending on the capacitor material and quality).

Q factor[edit]

The quality factor (or *Q*) of a capacitor is the ratio of its reactance to its resistance at a given frequency, and is a measure of its efficiency. The higher the Q factor of the capacitor, the closer it approaches the behavior of an ideal, lossless, capacitor.

The Q factor of a capacitor can be found through the following formula:

$$Q = \frac{X_C}{R_C} = \frac{1}{\omega C R_C}$$

Where:

- ω is frequency in radians per second,
- C is the capacitance,
- X_C is the capacitive reactance, and
- R_C is the series resistance of the capacitor.

Ripple current

Ripple current is the AC component of an applied source (often a switched-mode power supply) whose frequency may be constant or varying. Ripple current causes heat to be generated within the capacitor due to the dielectric losses caused by the changing field strength together with the current flow across the slightly resistive supply lines or the electrolyte in the capacitor. The equivalent series resistance (ESR) is the amount of internal series resistance one would add to a perfect capacitor to model this. Some types of capacitors, primarily tantalum and aluminum electrolytic capacitors, as well as some film capacitors have a specified rating value for maximum ripple current.

- Tantalum electrolytic capacitors with solid manganese dioxide electrolyte are limited by ripple current and generally have the highest ESR ratings in the capacitor family. Exceeding their ripple limits can lead to shorts and burning parts.
- Aluminium electrolytic capacitors, the most common type of electrolytic, suffer a shortening of life expectancy at higher ripple currents. If ripple current exceeds the rated value of the capacitor, it tends to result in explosive failure.
- Ceramic capacitors generally have no ripple current limitation and have some of the lowest ESR ratings.
- Film capacitors have very low ESR ratings but exceeding rated ripple current may cause degradation failures.

Capacitance instability

The capacitance of certain capacitors decreases as the component ages. In ceramic capacitors, this is caused by degradation of the dielectric. The type of dielectric, ambient operating and storage temperatures are the most significant aging factors, while the operating voltage has a smaller effect. The aging process may be reversed by heating the component above the Curie point. Aging is fastest near the beginning of life of the component, and the device stabilizes over time. Electrolytic capacitors age as the electrolyte evaporates. In contrast with ceramic capacitors, this occurs towards the end of life of the component.

Temperature dependence of capacitance is usually expressed in parts per million (ppm) per °C. It can usually be taken as a broadly linear function but can be noticeably non-linear at the temperature extremes. The temperature coefficient can be either positive or negative, sometimes even amongst different samples of the same type. In other words, the spread in the range of temperature coefficients can encompass zero. See the data sheet in the leakage current section above for an example.

Capacitors, especially ceramic capacitors, and older designs such as paper capacitors, can absorb sound waves resulting in a micro phonic effect. Vibration moves the plates, causing the capacitance to vary, in turn inducing AC current. Some dielectrics also generate piezoelectricity. The resulting interference is especially problematic in audio applications, potentially causing feedback or unintended recording. In the reverse micro phonic effect, the varying electric field between the capacitor plates exerts a physical force, moving them as a speaker. This can generate audible sound, but drains energy and stresses the dielectric and the electrolyte, if any.

Current and voltage reversal

Current reversal occurs when the current changes direction. Voltage reversal is the change of polarity in a circuit. Reversal is generally described as the percentage of the maximum rated voltage that reverses polarity. In DC circuits, this will usually be less than 100% (often in the range of 0 to 90%), whereas AC circuits experience 100% reversal.

In DC circuits and pulsed circuits, current and voltage reversal are affected by the damping of the system. Voltage reversal is encountered in RLC circuits that are under-damped. The current and voltage reverse direction, forming a harmonic oscillator between the inductance and capacitance. The current and voltage will tend to oscillate and may reverse direction several times, with each peak being lower than the previous, until the system reaches an equilibrium. This is often referred to as ringing. In comparison, critically damped or over-damped systems usually do not experience a voltage reversal. Reversal is also encountered in AC circuits, where the peak current will be equal in each direction.

For maximum life, capacitors usually need to be able to handle the maximum amount of reversal that a system will experience. An AC circuit will experience 100% voltage reversal, while under-damped DC circuits will experience less than 100%. Reversal creates excess electric fields in the dielectric, causes excess heating of both the dielectric and the conductors, and can dramatically shorten the life expectancy of the capacitor. Reversal ratings will often affect the design considerations for the capacitor, from the choice of dielectric materials and voltage ratings to the types of internal connections used.

Dielectric absorption[edit]

Capacitors made with some types of dielectric material show "dielectric absorption" or "soakage". On discharging a capacitor and disconnecting it, after a short time it may develop a voltage due to hysteresis in the dielectric. This effect can be objectionable in applications such as precision sample and hold circuits.

Leakage

Leakage is equivalent to a resistor in parallel with the capacitor. Constant exposure to heat can cause dielectric breakdown and excessive leakage, a problem often seen in older vacuum tube circuits, particularly where oiled paper and foil capacitors were used. In many vacuum tube circuits, interstage coupling capacitors are used to conduct a varying signal from the plate of one tube to the grid circuit of the next stage. A leaky capacitor can cause the grid circuit voltage to be raised from its normal bias setting, causing excessive current or signal distortion in the downstream tube. In power amplifiers this can cause the plates to glow red, or current limiting resistors to overheat, even fail. Similar considerations apply to component fabricated solid-state (transistor) amplifiers, but owing to lower heat production and the use of modern polyester dielectric barriers this once-common problem has become relatively rare.

Electrolytic failure from disuse[edit]

Electrolytic capacitors are *conditioned* when manufactured by applying a voltage sufficient to initiate the proper internal chemical state. This state is maintained by regular use of the equipment. If a system using electrolytic capacitors is unused for a long period of time it can lose its conditioning, and will generally fail with a short circuit when next operated, permanently damaging the capacitor. To prevent this in tube equipment, the voltage can be slowly brought up using a variable transformer (variac) on the mains, over a twenty or thirty minute interval. Transistor equipment is more problematic as such equipment *may* be sensitive to low voltage ("brownout") conditions, with excessive currents due to improper bias in some circuits.

Capacitor types[edit]

Practical capacitors are available commercially in many different forms. The type of internal dielectric, the structure of the plates and the device packaging all strongly affect the characteristics of the capacitor, and its applications.

Values available range from very low (picofarad range; while arbitrarily low values are in principle possible, stray (parasitic) capacitance in any circuit is the limiting factor) to about 5 kF supercapacitors.

Above approximately 1 microfarad electrolytic capacitors are usually used because of their small size and low cost compared with other technologies, unless their relatively poor stability, life and polarised nature make them unsuitable. Very high capacity supercapacitors use a porous carbon-based electrode material.

Dielectric materials[edit]

Capacitor materials. From left: multilayer ceramic, ceramic disc, multilayer polyester film, tubular ceramic, polystyrene, metalized polyester film, aluminum electrolytic. Major scale divisions are in centimetres.

Most types of capacitor include a dielectric spacer, which increases their capacitance. These dielectrics are most often insulators. However, low capacitance devices are available with a vacuum between their plates, which allows extremely high voltage operation and low losses. Variable capacitors with their plates open to the atmosphere were commonly used in radio tuning circuits. Later designs use polymer foil dielectric between the moving and stationary plates, with no significant air space between them.

In order to maximise the charge that a capacitor can hold, the dielectric material needs to have as high a permittivity as possible, while also having as high a breakdown voltage as possible.

Several solid dielectrics are available,

including paper, plastic, glass, mica and ceramic materials. Paper was used extensively in older devices and offers relatively high voltage performance. However, it is susceptible to water absorption, and has been largely replaced by plastic film capacitors. Plastics offer better stability and aging performance, which makes them useful in timer circuits, although they may be limited to low operating temperatures and frequencies. Ceramic capacitors are generally small, cheap and useful for high frequency applications, although their capacitance varies strongly with voltage and they age poorly. They are broadly categorized as class 1 dielectrics, which have predictable variation of capacitance with temperature or class 2 dielectrics, which can operate at higher voltage. Glass and mica capacitors are extremely reliable, stable and tolerant to high temperatures and voltages, but are too expensive for most mainstream applications. Electrolytic capacitors and super capacitors are used to store small and larger amounts of energy, respectively, ceramic capacitors are often used in resonators, and parasitic capacitance occurs in circuits wherever the simple conductor-insulator-conductor structure is formed unintentionally by the configuration of the circuit layout.

Electrolytic capacitors use an aluminum or tantalum plate with an oxide dielectric layer. The second electrode is a liquid electrolyte, connected to the circuit by another foil plate. Electrolytic capacitors offer very high capacitance but suffer from poor tolerances, high instability, gradual loss of capacitance especially when subjected to heat, and high leakage current. Poor quality capacitors may leak electrolyte, which is harmful to printed circuit boards. The conductivity of the electrolyte drops at low temperatures, which increases equivalent series resistance. While widely used for power-supply conditioning, poor high-frequency characteristics make them unsuitable for many applications. Electrolytic capacitors will self-degrade if unused for a period (around a year), and when full power is applied may short circuit, permanently damaging the capacitor and usually blowing a fuse or causing failure of rectifier diodes (for instance, in older equipment, arcing in rectifier tubes). They can be restored before use (and damage) by gradually applying the operating voltage, often done on antique vacuum tube equipment over a period of 30 minutes by using a variable transformer to supply AC power. Unfortunately, the use of this technique may be less satisfactory for some solid state equipment, which may be damaged by operation below its normal power range, requiring that the power supply first be isolated from the consuming circuits. Such remedies may not be applicable to modern high-frequency power supplies as these produce full output voltage even with reduced input.

Tantalum capacitors offer better frequency and temperature characteristics than aluminum, but higher dielectric absorption and leakage.

Polymer capacitors (OS-CON, OC-CON, KO, AO) use solid conductive polymer (or polymerized organic semiconductor) as electrolyte and offer longer life and lower ESR at higher cost than standard electrolytic capacitors.

A Feed through is a component that, while not serving as its main use, has capacitance and is used to conduct signals through a circuit board.

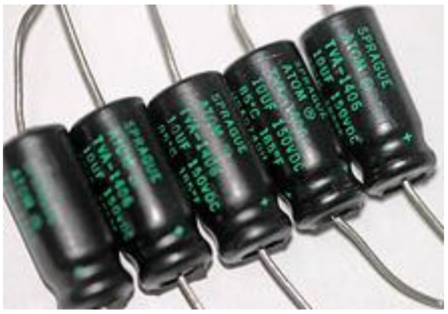
Several other types of capacitor are available for specialist applications. Super capacitors store large amounts of energy. Super capacitors made from carbon aerogel, carbon nanotubes, or highly porous electrode materials, offer extremely high capacitance (up to 5 kF as of 2010) and can be used in some applications instead of rechargeable batteries. Alternating current capacitors are specifically designed to work on line (mains) voltage AC power circuits. They are commonly used in electric motor circuits and are often designed to handle large currents, so they tend to be physically large. They are usually ruggedly packaged, often in metal cases that can be easily grounded/earthed. They also are designed with direct current breakdown voltages of at least five times the maximum AC voltage.

Structure[edit]

Capacitor packages: SMD ceramic at top left; SMD tantalum at bottom left; through-hole tantalum at top right; through-hole electrolytic at bottom right. Major scale divisions are cm.

The arrangement of plates and dielectric has many variations depending on the desired ratings of the capacitor. For small values of capacitance (microfarads and less), ceramic disks use metallic coatings, with wire leads bonded to the coating. Larger values can be made by multiple stacks of plates and disks. Larger value capacitors usually use a metal foil or metal film layer deposited on the surface of a dielectric film to make the plates, and a dielectric film of impregnated paper or plastic – these are rolled up to save space. To reduce the series resistance and inductance for long plates, the plates and dielectric are staggered so that connection is made at the common edge of the rolled-up plates, not at the ends of the foil or metalized film strips that comprise the plates.

The assembly is encased to prevent moisture entering the dielectric – early radio equipment used a cardboard tube sealed with wax. Modern paper or film dielectric capacitors are dipped in a hard thermoplastic. Large capacitors for high-voltage use may have the roll form compressed to fit into a rectangular metal case, with bolted terminals and bushings for connections. The dielectric in larger capacitors is often impregnated with a liquid to improve its properties.



Several axial-lead electrolytic capacitors

Capacitors may have their connecting leads arranged in many configurations, for example axially or radially. "Axial" means that the leads are on a common axis, typically the axis of the capacitor's cylindrical body – the leads extend from opposite ends. Radial leads might more accurately be referred to as tandem; they are rarely actually aligned along radii of the body's circle, so the term is inexact, although universal. The leads (until bent) are usually in planes parallel to that of the flat body of the capacitor, and extend in the same direction; they are often parallel as manufactured.

Small, cheap discoidal ceramic capacitors have existed since the 1930s, and remain in widespread use. Since the 1980s, surface mount packages for capacitors have been widely used. These packages are extremely small and lack connecting leads, allowing them to be soldered directly onto the surface of printed circuit boards. Surface mount components avoid undesirable high-frequency effects due to the leads and simplify automated assembly, although manual handling is made difficult due to their small size.

Mechanically controlled variable capacitors allow the plate spacing to be adjusted, for example by rotating or sliding a set of movable plates into alignment with a set of stationary plates. Low cost variable capacitors squeeze together alternating layers of aluminum and plastic with a screw. Electrical control of capacitance is achievable with varactors (or varicaps), which are reverse-biased semiconductor diodes whose depletion region width varies with applied voltage. They are used in phase-locked loops, amongst other applications.

Capacitor markings[edit]

Most capacitors have numbers printed on their bodies to indicate their electrical characteristics. Larger capacitors like electrolytics usually display the actual capacitance together with the unit (for example, **220 μF**). Smaller capacitors like ceramics, however, use a shorthand consisting of three numbers and a letter, where the numbers show the capacitance in pF (calculated as XY × 10^Z for the numbers XYZ) and the letter indicates the tolerance (J, K or M for ±5%, ±10% and ±20% respectively).

Additionally, the capacitor may show its working voltage, temperature and other relevant characteristics.

Example

A capacitor with the text **473K 330V** on its body has a capacitance of 47 × 10^3 pF = 47 nF (±10%) with a working voltage of 330 V. The working voltage of a capacitor is the highest voltage that can be applied across it without undue risk of breaking down the dielectric layer.

Applications

This mylar-film, oil-filled capacitor has very low inductance and low resistance, to provide the high-power (70 megawatt) and high speed (1.2 microsecond) discharge needed to operate a dye laser.

Energy storage

A capacitor can store electric energy when disconnected from its charging circuit, so it can be used like a temporary battery, or like other types of rechargeable energy storage system.[26] Capacitors are commonly used in electronic devices to maintain power supply while batteries are being changed. (This prevents loss of information in volatile memory.)

Conventional capacitors provide less than 360 joules per kilogram of energy density, whereas a conventional alkaline battery has a density of 590 kJ/kg.

In car audio systems, large capacitors store energy for the amplifier to use on demand. Also for a flash tube a capacitor is used to hold the high voltage.

PULSED POWER AND WEAPONS

Groups of large, specially constructed, low-inductance high-voltage capacitors (*capacitor banks*) are used to supply huge pulses of current for many pulsed power applications. These include electromagnetic forming, Marx generators, pulsed lasers (especially TEA lasers), pulse forming networks, radar, fusion research, and particle accelerators.

Large capacitor banks (reservoir) are used as energy sources for the exploding-bridgewire detonators or slapper detonators in nuclear weapons and other specialty weapons. Experimental work is under way using banks of capacitors as power sources for electromagnetic armour and electromagnetic railguns and coilguns.

Power conditioning[edit]

A 10 millifarad capacitor in an amplifier power supply

Reservoir capacitors are used in power supplies where they smooth the output of a full or half wave rectifier. They can also be used in charge pump circuits as the energy storage element in the generation of higher voltages than the input voltage.

Capacitors are connected in parallel with the power circuits of most electronic devices and larger systems (such as factories) to shunt away and conceal current fluctuations from the primary power source to provide a "clean" power supply for signal or control circuits. Audio equipment, for example, uses several capacitors in this way, to shunt away power line hum before it gets into the signal circuitry. The capacitors act as a local reserve for the DC power source, and bypass AC currents from the power supply. This is used in car audio applications, when a stiffening capacitor compensates for the inductance and resistance of the leads to the lead-acid car battery.

Power factor correction[edit]

A high-voltage capacitor bank used for power factor correction on a power transmission system.

In electric power distribution, capacitors are used for power factor correction. Such capacitors often come as three capacitors connected as a three phase load. Usually, the values of these capacitors are given not in farads but rather as a reactive power in volt-amperes reactive (var). The purpose is to counteract inductive loading from devices like electric motors and transmission lines to make the load appear to be mostly resistive. Individual motor or lamp loads may have capacitors for power factor correction, or larger sets of capacitors (usually with automatic switching devices) may be installed at a load center within a building or in a large utility substation.

Suppression and coupling

Signal coupling

Polyester film capacitors are frequently used as coupling capacitors.

Because capacitors pass AC but block DC signals (when charged up to the applied dc voltage), they are often used to separate the AC and DC components of a signal. This method is known as *AC coupling* or "capacitive coupling". Here, a large value of capacitance, whose value need not be accurately controlled, but whose reactance is small at the signal frequency, is employed.

Decoupling

A decoupling capacitor is a capacitor used to protect one part of a circuit from the effect of another, for instance to suppress noise or transients. Noise caused by other circuit elements is shunted through the capacitor, reducing the effect they have on the rest of the circuit. It is most commonly used between the power supply and ground. An alternative name is *bypass capacitor* as it is used to bypass the power supply or other high impedance component of a circuit.

Decoupling capacitors need not always be discrete components. Capacitors used in these applications may be built in to a printed circuit board, between the various layers. These are often referred to as embedded capacitors.[27] The layers in the board contributing to the capacitive properties also function as power and ground planes, and have a dielectric in between them, enabling them to operate as a parallel plate capacitor.

High-pass and low-pass filters

Noise suppression, spikes, and snubbers

Further information: High-pass filter and Low-pass filter

When an inductive circuit is opened, the current through the inductance collapses quickly, creating a large voltage across the open circuit of the switch or relay. If the inductance is large enough, the energy will generate a spark, causing the contact points to oxidize, deteriorate, or sometimes weld together, or destroying a solid-state switch. A snubber capacitor across the newly opened circuit creates a path for this impulse to bypass the contact points, thereby preserving their life; these were commonly found in contact breaker ignition systems, for instance. Similarly, in smaller scale circuits, the spark may not be enough to damage the switch but will stillradiate undesirable radio frequency interference (RFI), which a filter capacitor absorbs. Snubber capacitors are usually employed with a low-value resistor in series, to dissipate energy and minimize RFI. Such resistor-capacitor combinations are available in a single package.

Capacitors are also used in parallel to interrupt units of a high-voltage circuit breaker in order to equally distribute the voltage between these units. In this case they are called grading capacitors.

In schematic diagrams, a capacitor used primarily for DC charge storage is often drawn vertically in circuit diagrams with the lower, more negative, plate drawn as an arc. The straight plate indicates the positive terminal of the device, if it is polarized (see electrolytic capacitor).

Motor starters

In single phase squirrel cage motors, the primary winding within the motor housing is not capable of starting a rotational motion on the rotor, but is capable of sustaining one. To start the motor, a secondary "start" winding has a series non-polarized *starting capacitor* to introduce a lead in the sinusoidal current. When the secondary (start) winding is placed at an angle with respect to the primary (run) winding, a rotating electric field is created. The force of the rotational field is not constant, but is sufficient to start the rotor spinning. When the rotor comes close to operating speed, a centrifugal switch (or current-sensitive relay in series with the main winding) disconnects the capacitor. The start capacitor is typically mounted to the side of the motor housing. These are called capacitor-start motors, that have relatively high starting torque. Typically they can have up-to four times as much starting torque than a split-phase motor and are used on applications such as compressors, pressure washers and any small device requiring high starting torques.

Capacitor-run induction motors have a permanently connected phase-shifting capacitor in series with a second winding. The motor is much like a two-phase induction motor.

Motor-starting capacitors are typically non-polarized electrolytic types, while running capacitors are conventional paper or plastic film dielectric types.

Signal processing

The energy stored in a capacitor can be used to represent information, either in binary form, as in DRAMs, or in analogue form, as in analog sampled filters and CCDs. Capacitors can be used in analog circuits as components of integrators or more complex filters and in negative feedback loop stabilization. Signal processing circuits also use capacitors to integrate a current signal.

Tuned circuits

Capacitors and inductors are applied together in tuned circuits to select information in particular frequency bands. For example, radio receivers rely on variable capacitors to tune the station frequency. Speakers use passive analog crossovers, and analog equalizers use capacitors to select different audio bands.

The resonant frequency *f* of a tuned circuit is a function of the inductance (*L*) and capacitance (*C*) in series, and is given by:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where *L* is in henries and *C* is in farads.

Sensing[edit]

Main article: capacitive sensing

Main article: Capacitive displacement sensor

Most capacitors are designed to maintain a fixed physical structure. However, various factors can change the structure of the capacitor, and the resulting change in capacitance can be used to sense those factors.

Changing the dielectric:

> The effects of varying the characteristics of the **dielectric** can be used for sensing purposes. Capacitors with an exposed and porous dielectric can be used to measure humidity in air. Capacitors are used to accurately measure the fuel level in airplanes; as the fuel covers more of a pair of plates, the circuit capacitance increases.

Changing the distance between the plates:

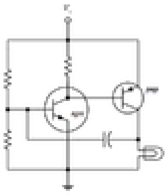
> Capacitors with a flexible plate can be used to measure strain or pressure. Industrial pressure transmitters used for process control use pressure-sensing diaphragms, which form a capacitor plate of an oscillator circuit. Capacitors are used as the sensor in condenser microphones, where one plate is moved by air pressure, relative to the fixed position of the other plate. Some accelerometers use MEMS capacitors etched on a chip to measure the magnitude and direction of the acceleration vector. They are used to detect changes in acceleration, in tilt sensors, or to detect free fall, as sensors triggering airbag deployment, and in many other applications. Some fingerprint

sensors use capacitors. Additionally, a user can adjust the pitch of a therem in musical instrument by moving their hand since this changes the effective capacitance between the user's hand and the antenna.

Changing the effective area of the plates:

Capacitive touch switches are now used on many consumer electronic products.

Oscillators



Example of a simple oscillator that requires a capacitor to function

A capacitor can possess spring-like qualities in an oscillator circuit. In the image example, a capacitor acts to influence the biasing voltage at the npn transistor's base. The resistance values of the voltage-divider resistors and the capacitance value of the capacitor together control the oscillatory frequency.

Hazards and safety

Capacitors may retain a charge long after power is removed from a circuit; this charge can cause dangerous or even potentially fatal shocks or damage connected equipment. For example, even a seemingly innocuous device such as a disposable camera flash unit powered by a 1.5 volt AA battery contains a capacitor which may be charged to over 300 volts. This is easily capable of delivering a shock. Service procedures for electronic devices usually include instructions to discharge large or high-voltage capacitors, for instance using a Brinkley stick. Capacitors may also have built-in discharge resistors to dissipate stored energy to a safe level within a few seconds after power is removed. High-voltage capacitors are stored with the terminals shorted, as protection from potentially dangerous voltages due to dielectric absorption.

Some old, large oil-filled paper or plastic film capacitors contain polychlorinated biphenyls (PCBs). It is known that waste PCBs can leak into groundwater under landfills. Capacitors containing PCB were labelled as containing "Askarel" and several other trade names. PCB-filled paper capacitors are found in very old (pre-1975) fluorescent lamp ballasts, and other applications.

Capacitors may catastrophically fail when subjected to voltages or currents beyond their rating, or as they reach their normal end of life. Dielectric or metal interconnection failures may create arcing that vaporizes the dielectric fluid, resulting in case bulging, rupture, or even an explosion. Capacitors used in RF or sustained high-current applications can overheat, especially in the center of the capacitor rolls. Capacitors used within high-energy capacitor banks can violently explode when a short in one capacitor causes sudden dumping of energy stored in the rest of the bank into the failing unit. High voltage vacuum capacitors can generate soft X-rays even during normal operation. Proper containment, fusing, and preventive maintenance can help to minimize these hazards.

High-voltage capacitors can benefit from a pre-charge to limit in-rush currents at power-up of high voltage direct current (HVDC) circuits. This will extend the life of the component and may mitigate high-voltage hazards.

- 

Swollen caps of electrolytic capacitors – special design of semi-cut caps prevents capacitors from bursting

- 

This high-energy capacitor from adefibrillator can deliver over 500 joules of energy. A resistor is connected between the terminals for safety, to allow the stored energy to be released.

5.2 CONCEPT OF CHARGING AND DISCHARGING OF CAPACITORS

CHARGING AND DISCHARGING A CAPACITOR

A Capacitor is a passive device that stores energy in its Electric Field and returns energy to the circuit whenever required. A Capacitor consists of two Conducting Plates separated by an Insulating Material or Dielectric. Figure 1 and Figure 2 are the basic structure and the schematic symbol of the Capacitor respectively.

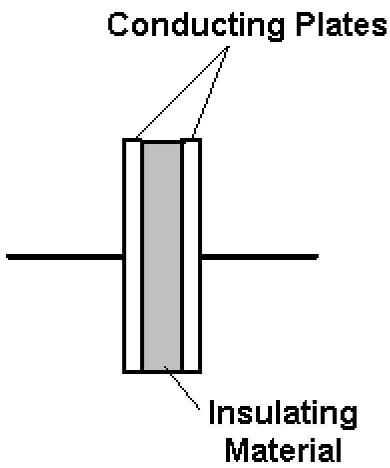


Figure 1: Basic structure of the Capacitor

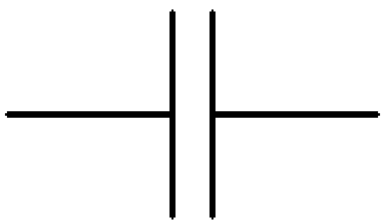


Figure 2: Schematic symbol of the Capacitor

When a Capacitor is connected to a circuit with Direct Current (DC) source, two processes, which are called “charging” and “discharging” the Capacitor, will happen in specific conditions.

In Figure 3, the Capacitor is connected to the DC Power Supply and Current flows through the circuit. Both Plates get the equal and opposite charges and an increasing Potential Difference, v_c, is created while the Capacitor is charging. Once the Voltage at the terminals of the Capacitor, v_c, is equal to the Power Supply Voltage, $v_c = V$, the Capacitor is fully charged and the Current stops flowing through the circuit, the Charging Phase is over.

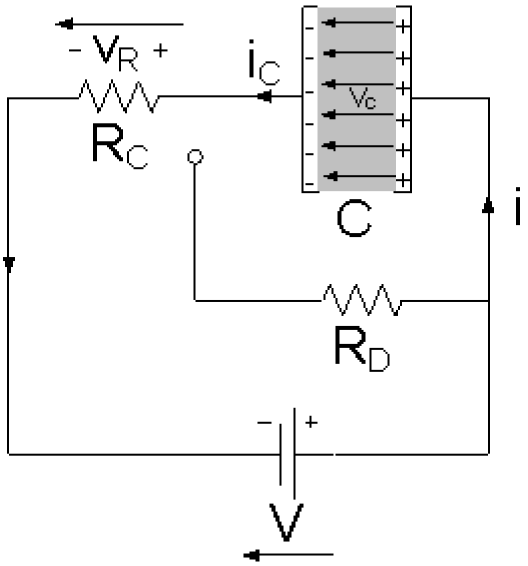


Figure 3: The Capacitor is Charging

A Capacitor is equivalent to an Open-Circuit to Direct Current, $R = \infty$, because once the Charging Phase has finished, no more Current flows through it. The Voltage v_c on a Capacitor cannot change abruptly.

When the Capacitor disconnected from the Power Supply, the Capacitor is discharging through the Resistor R_D and the Voltage between the Plates drops down gradually to zero, $v_c = 0$, Figure 4.

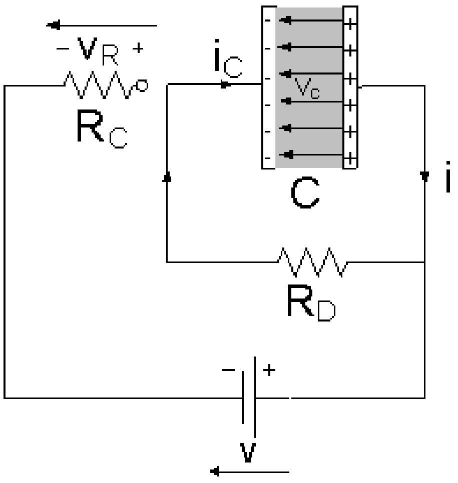


Figure 4: The Capacitor is Discharging

In Figures 3 and 4, the Resistances of R_C and R_D affect the charging rate and the discharging rate of the Capacitor respectively.

The product of Resistance R and Capacitance C is called the Time Constant τ, which characterizes the rate of charging and discharging of a Capacitor, Figure 5.

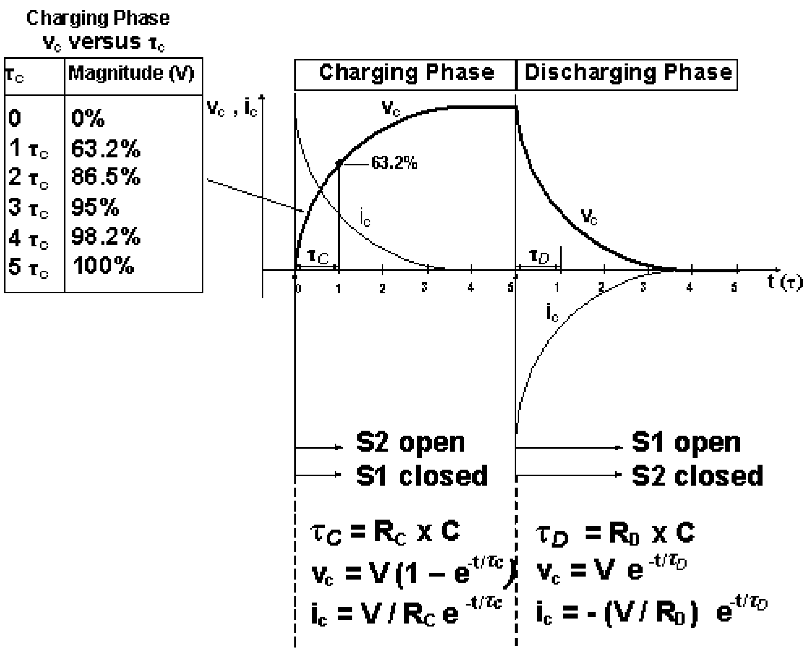


Figure 5: The Voltage v_c and the Current iC during the Charging Phase and Discharging Phase

The smaller the Resistance or the Capacitance, the smaller the Time Constant, the faster the charging and the discharging rate of the Capacitor, and vice versa.

Capacitors are found in almost all electronic circuits. They can be used as a fast battery. For example, a Capacitor is a storehouse of energy in photoflash unit that releases the energy quickly during short period of the flash.

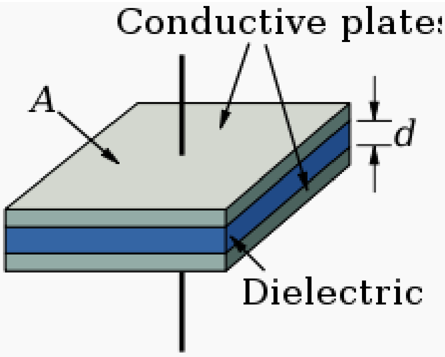
5.3 TYPES OF CAPACITORS AND THEIR USE IN CIRCUITS.

A **capacitor** (formerly known as a **condenser**) is a passive two-terminal electrical component that stores electric energy in an electric field. The forms, styles, and materials of practical capacitors vary widely, but all contain at least two electrical conductors (called "plates") separated by an insulating layer (called the dielectric). Capacitors are widely used as parts of electrical circuits in many common electrical devices.

Capacitors, together with resistors, inductors, and memristors, belong to the group of "passive components" used in electronic equipment. Although, in absolute figures, the most common capacitors are integrated capacitors (e.g. in DRAMs or flash memory structures), this article is concentrated on the various styles of capacitors as discrete components.

Small capacitors are used in electronic devices to couple signals between stages of amplifiers, as components of electric filters and tuned circuits, or as parts of power supply systems to smooth rectified current. Larger capacitors are used for energy storage in such applications as strobe lights, as parts of some types of electric motors, or for power factor correction in AC power distribution systems. Standard capacitors have a fixed value of capacitance, but adjustable capacitors are frequently used in tuned circuits. Different types are used depending on required capacitance, working voltage, current handling capacity, and other properties.

THEORY OF CONVENTIONAL CONSTRUCTION



A dielectric material is placed between two conducting plates (electrodes), each of area ***A*** and with a separation of ***d***.

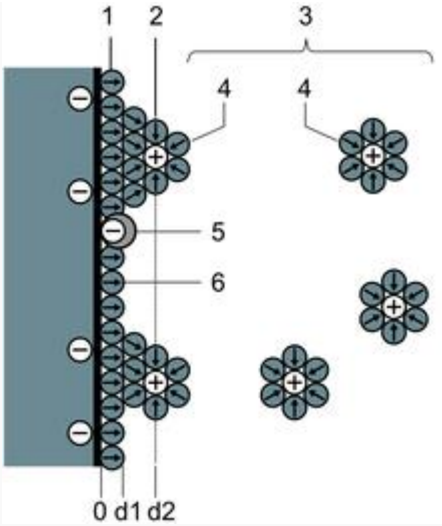
In a conventional capacitor, the electric energy is stored statically by charge separation, typically electrons, in an electric field between two electrode plates. The amount of charge stored per unit voltage is essentially a function of the size of the plates, the plate material's properties, the properties of the dielectric material placed between the plates, and the separation distance (i.e. dielectric thickness). The potential between the plates is limited by the properties of the dielectric material and the separation distance.

Nearly all conventional industrial capacitors except some special styles such as "feed-through capacitors", are constructed as "plate capacitors" even if their electrodes and the dielectric between are wound or rolled. The capacitance formula for plate capacitors is:

$$C = \frac{\varepsilon A}{d}.$$

The capacitance ***C*** increases with the area ***A*** of the plates and with the permittivity ***ε*** of the dielectric material and decreases with the plate separation distance ***d***. The capacitance is therefore greatest in devices made from materials with a high permittivity, large plate area, and small distance between plates.

Theory of electrochemical construction



Schematic of double layer capacitor.

1. IHP Inner Helmholtz Layer

2. OHP Outer Helmholtz Layer

3. Diffuse layer

4. Solvated ions

5. Specifically adsorptive ions (Pseudo capacitance)

6. Solvent molecule.

Another type – the electrochemical capacitor – makes use of two other storage principles to store electric energy. In contrast to ceramic, film, and electrolytic capacitors, super capacitors (also known as electrical double-layer capacitors (EDLC) or ultra capacitors) do not have a conventional dielectric. The capacitance value of an electrochemical capacitor is determined by two high-capacity storage principles. These principles are:

- electrostatic storage within Helmholtz double layers achieved on the phase interface between the surface of the electrodes and the electrolyte **(double-layer capacitance)**; and

- electrochemical storage achieved by a faradaic electron charge-transfer by specifically adsorpted ions with redox reactions**(pseudocapacitance)**. Unlike batteries, in these reactions, the ions simply cling to the atomic structure of an electrode without making or breaking chemical bonds, and no or negligibly small chemical modifications are involved in charge/discharge.

The ratio of the storage resulting from each principle can vary greatly, depending on electrode design and electrolyte composition. Pseudo capacitance can increase the capacitance value by as much as an order of magnitude over that of the double-layer by itself.[2]

Common capacitors and their names

Capacitors are divided into two mechanical groups: Fixed capacitors with fixed capacitance values and variable capacitors with variable (trimmer) or adjustable (tunable) capacitance values.

The most important group is the fixed capacitors. Many got their names from the dielectric. For a systematic classification these characteristics can't be used, because one of the oldest, the electrolytic capacitor, is named instead by its cathode construction. So the most-used names are simply historical.

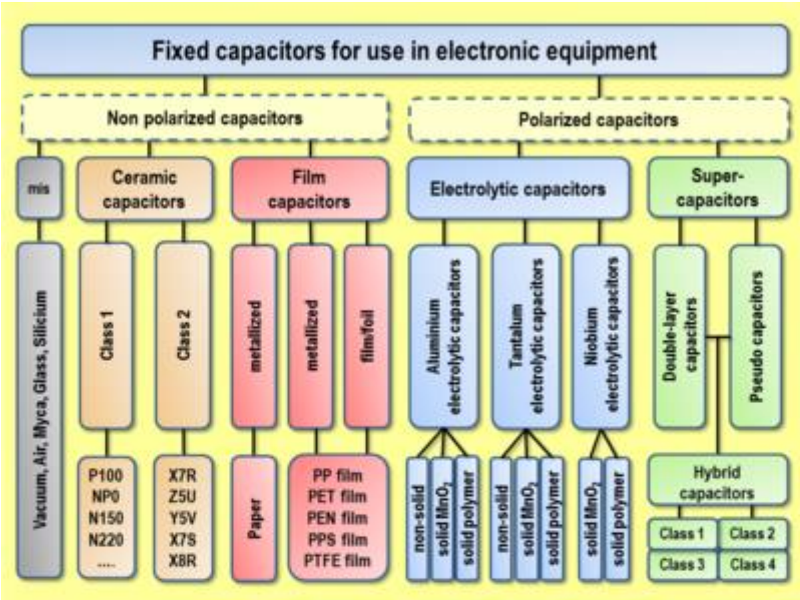
The most common kinds of capacitors are:

- **Ceramic capacitors** have a ceramic dielectric.
- **Film** and **paper capacitors** are named for their dielectrics.
- **Aluminum, tantalum** and **niobium electrolytic capacitors** are named after the material used as the anode and the construction of the cathode
- **Supercapacitor** is the family name for:
  - **Double-layer capacitors** were named for the physical phenomenon of the Helmholtz double-layer

- ○ **[Pseudocapacitors]** were named for their ability to store electric energy electro-chemically with reversible faradaic charge-transfer
  - ○ **Hybrid capacitors** combine double-layer and pseudocapacitors to increase power density

▪ Seldom-used **Silver mica, glass, silicon, air-gap and vacuum capacitors** were named for their dielectric.

Capacitors in each family have similar physical design features, but vary, for example, in the form of the terminals.



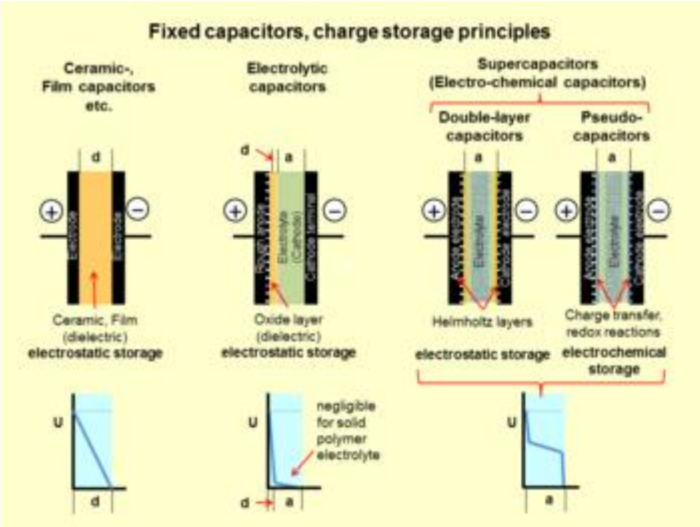
In addition to the above shown capacitor types, which derived their name from historical development, there are many individual capacitors that have been named based on their application. They include:

- Power capacitors, motor capacitors, DC-link capacitors, suppression capacitors, audio crossover capacitors, lighting ballast capacitors, snubber capacitors, coupling ,decoupling or bypassing capacitors.

Often, more than one capacitor family is employed for these applications, e.g. interference suppression can use ceramic capacitors or film capacitors.

Other kinds of capacitors are discussed in the #Special capacitors section.

Dielectrics



Principle charge storage of different capacitor types and their inherent voltage progression

The most common dielectrics are:

- Ceramics
- Plastic films
- Oxide layer on metal (Aluminum, Tantalum, Niobium)
- Natural materials like mica, glass, paper, air, vacuum

All of them store their electrical charge statically within an electric field between two (parallel) electrodes.

Beneath these conventional capacitors a family of electrochemical capacitors called Super capacitors was developed. Super capacitors don't have a conventional dielectric. They store their electrical charge statically in Helmholtz double-layers and faradaically at the surface of electrodes

- with static Double-layer capacitance in a double-layer capacitor and
- with pseudocapacitance (faradaic charge transfer) in a Pseudocapacitor
- or with both storage principles together in hybrid capacitors.

The most important material parameters of the different dielectrics used and the appr. Helmholtz-layer thickness are given in the table below.

Key parameters

Capacitor style	Dielectric	Permittivity at 1 kHz	Maximum/realized. dielectric strength V/µm	Minimum thickness of the dielectric µm
Ceramic capacitors, Class 1	paraelectric	12–40	< 100(?)	1
Ceramic capacitors, Class 2	ferroelectric	200–14,000	< 35	0.5
Film capacitors	Polypropylene (PP)	2.2	650/450	1.9 – 3.0
Film capacitors	Polyethylen terephthalate, Polyester (PET)	3.3	580/280	0.7–0.9
Film capacitors	Polyphenylene sulfide (PPS)	3.0	470/220	1.2
Film capacitors	Polyethylene naphthalate (PEN)	3.0	500/300	0.9–1.4
Film capacitors	Polytetrafluoroethylene (PTFE)	2.0	450(?)/250	5.5
Paper capacitors	Paper	3.5–5.5	60	5–10
Aluminium electrolytic capacitors	Aluminium oxide Al_2O_3	9,6[8]	710	< 0.01 (6.3 V) < 0.8 (450 V)
Tantalum electrolytic capacitors	Tantalum pentoxide Ta_2O_5	26[8]	625	< 0.01 (6.3 V) < 0.08 (40 V)

Niobium electrolytic capacitors	Niobium pentoxide, Nb_2O_5	42	455	< 0.01 (6.3 V) < 0.10 (40 V)
Supercapacitors Double-layer capacitors	Helmholtz double-layer	-	5000	< 0.001 (2.7 V)
Vacuum capacitors	Vacuum	1	40	-
Air gap capacitors	Air	1	3.3	-
Glass capacitors	Glass	5–10	450	-
Mica capacitors	Mica	5–8	118	4–50

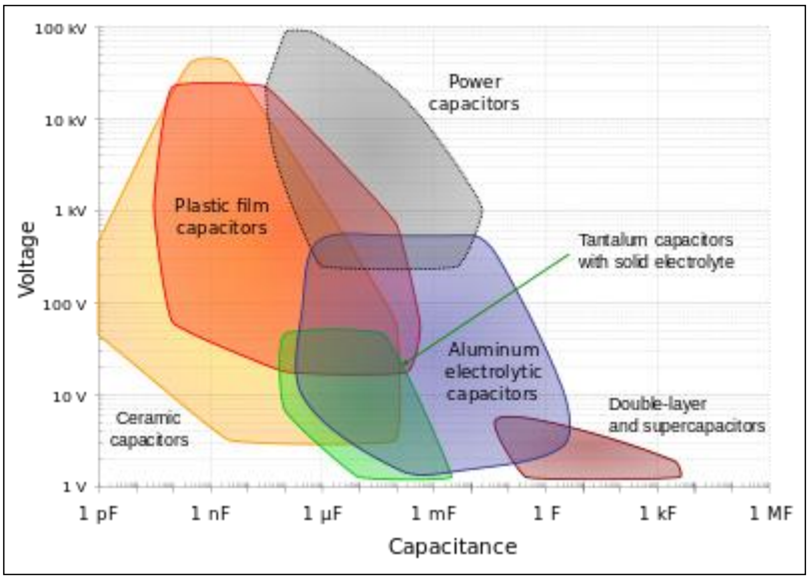
The capacitor's plate area can be adapted to the wanted capacitance value. The permittivity and the dielectric thickness are the determining parameter for capacitors. Ease of processing is also crucial. Thin, mechanically flexible sheets can be wrapped or stacked easily, yielding large designs with high capacitance values. Razor-thin metallized sintered ceramic layers covered with metallized electrodes however, offer the best conditions for the miniaturization of circuits with SMD styles.

A short view to the figures in the table above gives the explanation for some simple facts:

- **Supercapacitors** have the highest capacitance density because of its special charge storage principles
- **Electrolytic capacitors** have lesser capacitance density than supercapacitors but the highest capacitance density of conventional capacitors because its thin dielectric.
- **Ceramic capacitors** class 2 have much higher capacitance values in a given case than class 1 capacitors because of their much higher permittivity.

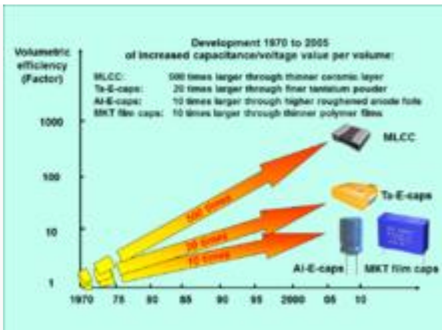
- **[Film capacitors](#)** with their different plastic film material do have a small spread in the dimensions for a given capacitance/voltage value of a film capacitor because the minimum dielectric film thickness differs between the different film materials.

Capacitance and voltage range



Capacitance ranges from picofarad to more than hundreds of farad. Voltage ratings can reach 100 kilovolts. In general, capacitance and voltage correlates with physical size and cost.

Miniaturization



Capacitor volumetric efficiency increased from 1970 to 2005 (click image to enlarge)

As in other areas of electronics, volumetric efficiency measures the performance of electronic function per unit volume. For capacitors, the volumetric efficiency is measured with the "CV product", calculated by multiplying the capacitance (C) by the maximum voltage rating (V), divided by the volume. From 1970 to 2005, volumetric efficiencies have improved dramatically.

Miniaturizing of capacitors

- 

Stacked paper capacitor (Block capacitor) from 1923 for noise decoupling (blocking) in telegraph lines

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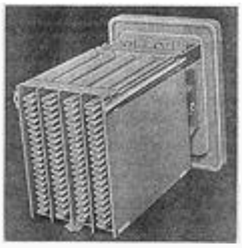
Wound metallized paper capacitor from the early 1930s in hardpaper case, capacitance value specified in "cm" in the cgs system; 5,000 cm corresponds to 28 nF

- 

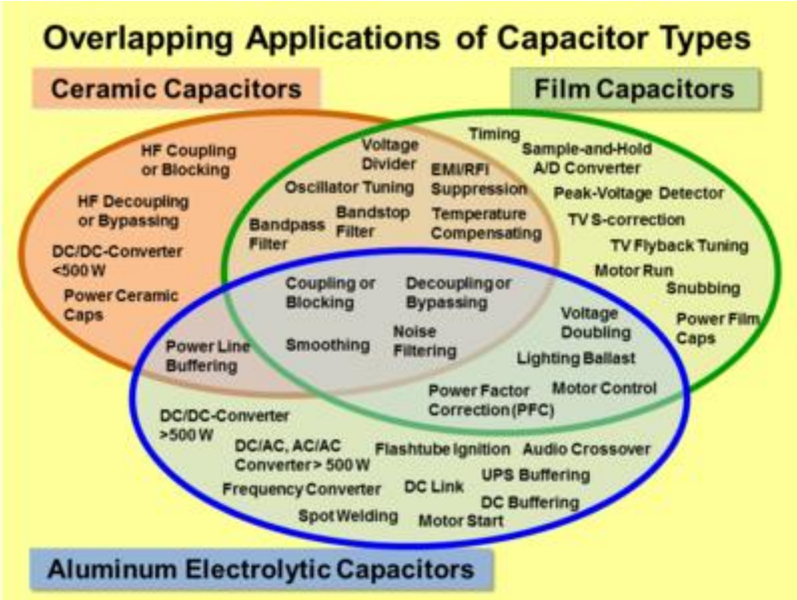
Folded wet aluminum electrolytic capacitor, Bell System 1929, view onto the folded anode, which was mounted in a squared housing (not shown) filled with liquid electrolyte

- 

Two 8 µF, 525 V wound wet aluminum electrolytic capacitors in paper housing sealed with tar out of a 1930s radio.

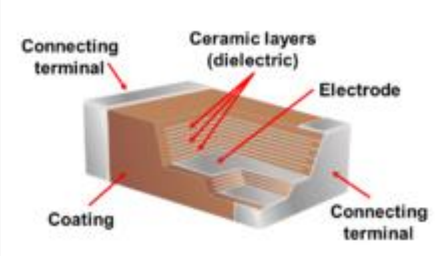
Overlapping range of applications

These individual capacitors can perform their application independent of their affiliation to an above shown capacitor type, so that an overlapping range of applications between the different capacitor types exists.



Types and styles

Ceramic capacitors



Construction of a **M**ulti-**L**ayer **C**eramic **C**apacitor (MLCC)

A **ceramic capacitor** is a non-polarized fixed capacitor made out of two or more alternating layers of ceramic and metal in which the ceramic material acts as the dielectric and the metal acts as the electrodes. The ceramic material is a mixture of finely ground granules ofparaelectric or ferroelectric materials, modified by mixed oxides that are necessary to achieve the capacitor's desired characteristics. The electrical behavior of the ceramic material is divided into two stability classes:

- Class 1 ceramic capacitors with high stability and low losses compensating the influence of temperature in resonant circuit application. Common EIA/IEC code abbreviations are C0G/NP0, P2G/N150, R2G/N220, U2J/N750 etc.
- Class 2 ceramic capacitors with high volumetric efficiency for buffer, by-pass and coupling applications Common EIA/IEC code abbreviations are: X7R/2XI, Z5U/E26, Y5V/2F4, X7S/2C1, etc.

The great plasticity of ceramic raw material works well for many special applications and enables an enormous diversity of styles, shapes and great dimensional spread of ceramic capacitors. The smallest discrete capacitor, for instance, is a "01005" chip capacitor with the dimension of only 0.4 mm × 0.2 mm.

The construction of ceramic multilayer capacitors with mostly alternating layers results in single capacitors connected in parallel. This configuration increases capacitance and decreases all losses and parasitic inductances. Ceramic capacitors are well-suited for high frequencies and high current pulse loads.

Because the thickness of the ceramic dielectric layer can be easily controlled and produced by the desired application voltage, ceramic capacitors are available with rated voltages up to the 30 kV range.

Some ceramic capacitors of special shapes and styles are used as capacitors for special applications, including RFI/EMI suppression capacitors for connection to supply mains, also known as safety capacitors, X2Y® capacitors for bypassing and decoupling applications, feed-through capacitors for noise suppression by low-pass filters and ceramic power capacitors for transmitters and HF applications.

- **Diverse styles of ceramic capacitors**

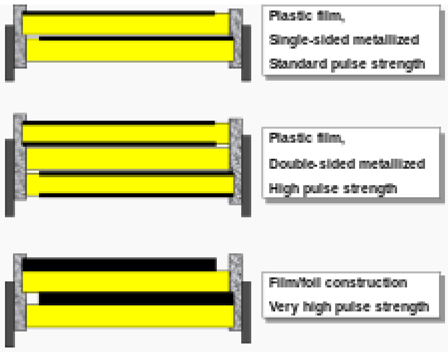
Multi-layer ceramic capacitors (MLCC chips) for SMD mounting

Ceramic X2Y® decoupling capacitors

Ceramic EMI suppression capacitors for connection to the supply mains (safety capacitor)

High voltage ceramic power capacitor

Film capacitors



Three examples of different film capacitor configurations for increasing surge current ratings

Film capacitors or plastic film capacitors are non-polarized capacitors with an insulating plastic film as the dielectric. The dielectric films are drawn to a thin layer, provided with metallic electrodes and wound into a cylindrical winding. The electrodes of film capacitors may be metallized aluminum or zinc, applied on one or both sides of the plastic film, resulting in metallized film capacitors or a separate metallic foil overlying the film, called film/foil capacitors.

Metallized film capacitors offer self-healing properties. Dielectric breakdowns or shorts between the electrodes do not destroy the component. The metallized construction makes it possible to produce wound capacitors with larger capacitance values (up to 100 µF and larger) in smaller cases than within film/foil construction.

Film/foil capacitors or metal foil capacitors use two plastic films as the dielectric. Each film is covered with a thin metal foil, mostly aluminium, to form the electrodes. The advantage of this construction is the ease of connecting the metal foil electrodes, along with excellent current pulse strength.

A key advantage of every film capacitor's internal construction is direct contact to the electrodes on both ends of the winding. This contact keeps all current paths very short. The design behaves like a large number of individual capacitors connected in parallel, thus reducing the internal ohmic losses (ESR) and ESL. The inherent geometry of film capacitor structure results in low ohmic losses and a low parasitic inductance, which makes them suitable for applications with high surge currents (snubbers) and for AC power applications, or for applications at higher frequencies.

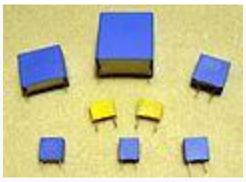
The plastic films used as the dielectric for film capacitors are Polypropylene (PP), Polyester (PET), Polyphenylene sulfide (PPS), Polyethylene naphthalate (PEN), andPolytetrafluoroethylene or Teflon (PTFE). Polypropylene film material with a market share of something about 50% and Polyester film with something about 40% are the most used film materials. The rest of something about 10% will be used by all other materials including PPS and paper with roughly 3%, each.

Characteristics of plastic film materials for film capacitors				
	Film material, abbreviated codes			
Film characteristics	**PET**	**PEN**	**PPS**	**PP**
Relative permittivity at 1 kHz	3.3	3.0	3.0	2.2
Minimum film thickness (µm)	0.7–0.9	0.9–1.4	1.2	2.4–3.0
Moisture absorption (%)	low	0.4	0.05	<0.1
Dielectric strength (V/µm)	580	500	470	650
Commercial realized voltage proof (V/µm)	280	300	220	400
DC voltage range (V)	50–1,000	16–250	16–100	40–2,000
Capacitance range	100 pF–22 µF	100 pF–1 µF	100 pF–0.47 µF	100 pF–10 µF

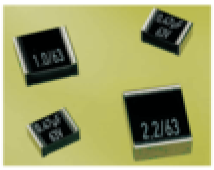
Application temperature range (°C)		−55 to +125 /+150	−55 to +150	−55 to +150	−55 to +105
ΔC/C versus temperature range (%)		±5	±5	±1.5	±2.5
Dissipation factor (•10^{-4})	at 1 kHz	50–200	42–80	2–15	0.5–5
	at 10 kHz	110–150	54–150	2.5–25	2–8
	at 100 kHz	170–300	120–300	12–60	2–25
	at 1 MHz	200–350	–	18–70	4–40
Time constant R_{Insul}•C (s)	at 25 °C	≥10,000	≥10,000	≥10,000	≥100,000
	at 85 °C	1,000	1,000	1,000	10,000
Dielectric absorption (%)		0.2–0.5	1–1.2	0.05–0.1	0.01–0.1
Specific capacitance (nF•V/mm^3)		400	250	140	50

Some film capacitors of special shapes and styles are used as capacitors for special applications, including RFI/EMI suppression capacitors for connection to the supply mains, also known as safety capacitors,[17] Snubber capacitors for very high surge currents,[18] Motor run capacitors, AC capacitors for motor-run applications[19]

High pulse current load is the most important feature of film capacitors so many of the available styles do have special terminations for high currents

- 

Radial style (single ended) for through-hole solder mounting on printed circuit boards

- 

SMD style for printed circuit board surface mounting, with metallized contacts on two opposite edges

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Radial style with heavy-duty solder terminals for snubber applications and high surge pulse loads

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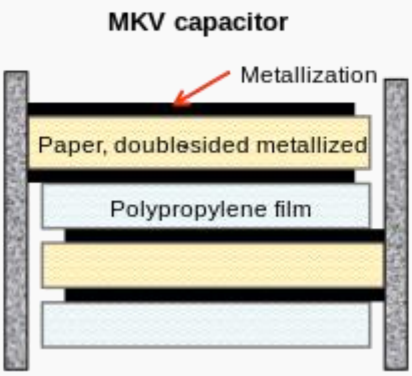
Heavy-duty snubber capacitor with screw terminals

Film power capacitors



MKV power capacitor, double-sided metallized paper (field-free mechanical carrier of the electrodes), polypropylene film (dielectric), windings impregnated with insulating oil

A related type is the power film capacitor. The materials and construction techniques used for large power film capacitors mostly are similar to those of ordinary film capacitors. However, capacitors with high to very high power ratings for applications in power systems and electrical installations are often classified separately, for historical reasons. The standardization of ordinary film capacitors is oriented on electrical and mechanical parameters. The standardization of power capacitors by contrast emphasizes the safety of personnel and equipment, as given by the local regulating authority.

As modern electronic equipment gained the capacity to handle power levels that were previously the exclusive domain of "electrical power" components, the distinction between the "electronic" and "electrical" power ratings blurred. Historically, the boundary between these two families was approximately at a reactive power of 200 volt-amps.

Film power capacitors mostly use polypropylene film as the dielectric. Other types include metallized paper capacitors (MP capacitors) and mixed dielectric film capacitors with polypropylene dielectrics. MP capacitors serve for cost applications and as field-free carrier electrodes (soggy foil capacitors) for high AC or high current pulse loads. Windings can be filled with an insulating oil or with epoxy resin to reduce air bubbles, thereby preventing short circuits.

They find use as converters to change voltage, current or frequency, to store or deliver abruptly electric energy or to improve the power factor. The rated voltage range of these capacitors is from approximately120 V AC (capacitive lighting ballasts) to 100 kV.[20]

Power film capacitors for applications in power systems, electrical installations and plants

- 

Power film capacitor for AC Power factor correction (PFC), packaged in a cylindrical metal can

- 

Power film capacitor in rectangular housing

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One of several energy storage power film capacitor banks, for magnetic field generation at the Hadron-Electron Ring Accelerator (HERA), located on theDESY site in Hamburg

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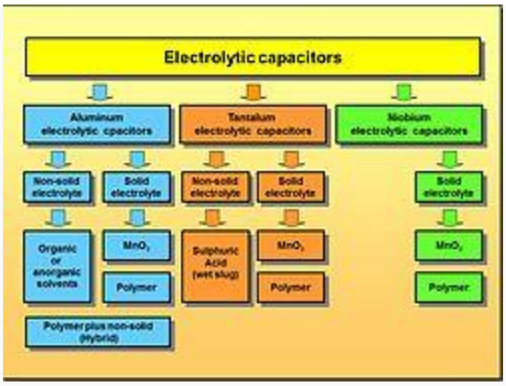
75MVAR substation capacitor bank at 150kV

Electrolytic capacitors



Electrolytic capacitors diversification

Electrolytic capacitors have a metallic anode covered with an oxidized layer used as dielectric. The second electrode is a non-solid (wet) or solid electrolyte. Electrolytic capacitors are polarized. Three families are available, categorized according to their dielectric.

- Aluminum electrolytic capacitors with aluminum oxide as dielectric
- Tantalum electrolytic capacitors with tantalum pentoxide as dielectric
- Niobium electrolytic capacitors with niobium pentoxide as dielectric.

The anode is highly roughened to increase the surface area. This and the relatively high permittivity of the oxide layer gives these capacitors very high capacitance per unit volume compared with film- or ceramic capacitors.

The permittivity of tantalum pentoxide is approximately three times higher than aluminium oxide, producing significantly smaller components. However, permittivity determines only the dimensions. Electrical parameters, especially conductivity, are established by the electrolyte's material and composition. Three general types of electrolytes are used:

- non solid (wet, liquid)—conductivity approximately 10 mS/cm and are the lowest cost
- solid manganese oxide—conductivity approximately 100 mS/cm offer high quality and stability
- solid conductive polymer (Polypyrrole)—conductivity approximately 10,000 mS/cm,[21] offer ESR values as low as <10 mΩ

Internal losses of electrolytic capacitors, prevailing used for decoupling and buffering applications, are determined by the kind of electrolyte.

Some important values of the different electrolytic capacitors

Anode material	Electrolyte	Capacitance range (μF)	Max. rated voltage at 85 °C (V)	Upper categorie temperature (°C)	Specific ripple current (mA/mm³) 1)
Aluminum (roughned foil)	non solid, e.g. Ethylene glycol, DMF, DMA, GBL	0.1–2,700,000	600	150	0.05–2.0
	solid, Manganese dioxide (MnO_2	0.1–1,500	40	175	0.5–2.5
	solid conductive polymere (e.g. Polypyrrole)	10–1,500	25	125	10–30
Tantalum	non solid	0.1–1,000	630	125	–

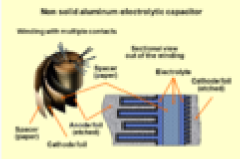
(roughned foil)	Sulfuric acid				
Tantalum (sintered)	non solid sulfuric acid	0.1–15,000	150	200	–
	solid Manganese dioxide (MnO_2	0.1–3,300	125	150	1.5–15
	solid conductive polymere (e.g. Polypyrrole)	10–1,500	35	125	10–30
Niobium (sintered)	solid Manganese dioxide (MnO_2	1–1,500	10	125	5–20
	solid conductive polymere (e.g. Polypyrrole)	2.2–1,000	25	105	10–30
[1)] Ripple current at 100 kHz and 85 °C / volumen (nominal dimensions)					

The large capacitance per unit volume of electrolytic capacitors make them valuable in relatively high-current and low-frequency electrical circuits, e.g. in power supply filters for decoupling unwanted AC components from DC power connections or as coupling capacitors in audio amplifiers, for passing or bypassing low-frequency signals and storing large amounts of energy. The relatively high capacitance value of an electrolytic capacitor combined with the very low ESR of the polymer electrolyte of polymer capacitors, especially in SMD styles, makes them a competitor to MLC chip capacitors in personal computer power supplies.

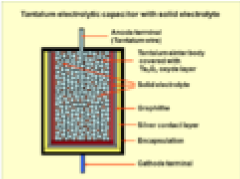
Bipolar aluminum electrolytic capacitors (also called Non-Polarized capacitors) contain two anodized aluminum foils, behaving like two capacitors connected in series opposition.

Electolytic capacitors for special applications include motor start capacitors,[22] flashlight capacitors[23] and audio frequency capacitors.[24]

Schematic representation

- 

Schematic representation of the structure of a wound aluminum electrolytic capacitor with non solid (liquid) electrolyte

- 

Schematic representation of the structure of a sintered tantalum electrolytic capacitor with solid electrolyte

Aluminum, tantalum and niobium electrolytic capacitors

- 

Axial, radial (single ended) anv V-chip styles of aluminum electrolytic capacitors

- 

Snap-in style of aluminum electrolytic capacitors for power applications

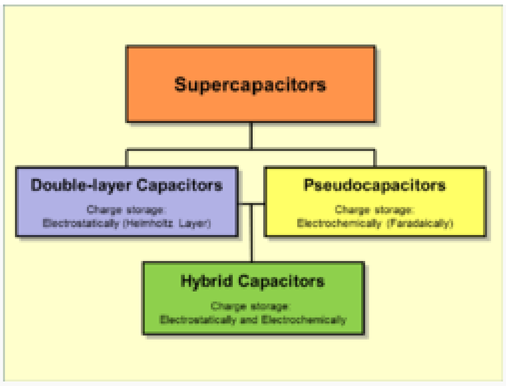
- 

SMD style for surface mounting of aluminum electrolytic capacitors with polymer electrolyte

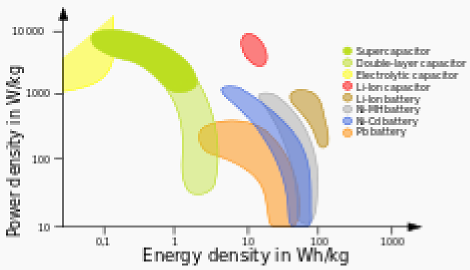
- 

Tantalum electrolytic chip capacitors for surface mounting

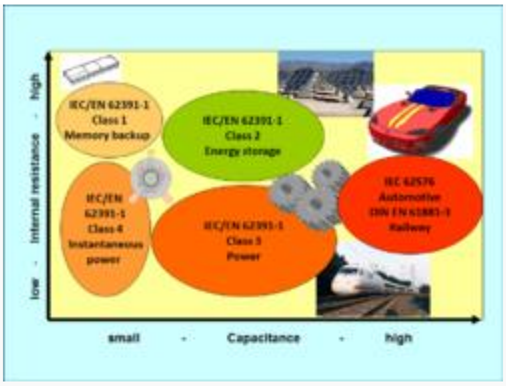
Super-capacitors



Hierarchical classification of supercapacitors and related types



Ragone chart showing power density vs. energy density of various capacitors and batteries



Classification of supercapacitors into classes regarding to IEC 62391-1, IEC 62567and DIN EN 61881-3 standards

Super-capacitors (SC), comprise a family of electrochemical capacitors. Super-capacitor, sometimes called **ultra-capacitor** is a generic term for electric double-layer capacitors (EDLC), pseudo-capacitors and hybrid capacitors. They don't have a conventional solid dielectric. The capacitance value of an electrochemical capacitor is determined by two storage principles, both of which contribute to the total capacitance of the capacitor:

- Double-layer capacitance – Storage is achieved by separation of charge in a Helmholtz double layer at the interface between the surface of a conductor and an electrolytic solution. The distance of separation of charge in a double-layer is on the order of a few Angstroms (0.3–0.8 nm). This storage is electrostatic in origin.
- Pseudo-capacitance – Storage is achieved by redox reactions, electrosorbtion or intercalation on the surface of the electrode or by specifically adsorpted ions that results in a reversible faradaic charge-transfer. The pseudo-capacitance is faradaic in origin.

The ratio of the storage resulting from each principle can vary greatly, depending on electrode design and electrolyte composition. Pseudocapacitance can increase the capacitance value by as much as an order of magnitude over that of the double-layer by itself.[25]

Super-capacitors are divided into three families, based on the design of the electrodes:

- **Double-layer capacitors** – with carbon electrodes or derivates with much higher static double-layer capacitance than the faradaic pseudo-capacitance
- **Pseudocapacitors** – with electrodes out of metal oxides or conducting polymers with a high amount of faradaic pseudo-capacitance
- **Hybrid capacitors** – capacitors with special and asymmetric electrodes that exhibit both significant double-layer capacitance and pseudo-capacitance, such as lithium-ion capacitors

Super-capacitors bridge the gap between conventional capacitors and rechargeable batteries. They have the highest available capacitance values per unit volume and the greatest energy density of all capacitors. They support up to 12,000 Farads/1.2 Volt,[29]with capacitance values up to 10,000 times that of electrolytic capacitors.[25] While existing super-capacitors have energy densities that are approximately 10% of a conventional battery, their power density is generally 10 to 100 times greater. Power density is defined as the product of energy density, multiplied by the speed at which the energy is delivered to the load. The greater power density results in much shorter charge/discharge cycles than a battery is capable, and a greater tolerance for numerous charge/discharge cycles. This makes them well-suited for parallel connection with batteries, and may improve battery performance in terms of power density.

Within electrochemical capacitors, the electrolyte is the conductive connection between the two electrodes, distinguishing them from electrolytic capacitors, in which the electrolyte only forms the cathode, the second electrode.

Super-capacitors are polarized and must operate with correct polarity. Polarity is controlled by design with asymmetric electrodes, or, for symmetric electrodes, by a potential applied during the manufacturing process.

Super-capacitors support a broad spectrum of applications for power and energy requirements, including:

- Low supply current during longer times for memory backup in (SRAMs) in electronic equipment
- Power electronics that require very short, high current, as in the KERS system in Formula 1 cars
- Recovery of braking energy for vehicles such as buses and trains

Super-capacitors are rarely interchangeable, especially those with higher energy densities. IEC standard 62391-1 *Fixed electric double layer capacitors for use in electronic equipment* identifies four application classes:

- Class 1, Memory backup, discharge current in mA = 1 • C (F)
- Class 2, Energy storage, discharge current in mA = 0.4 • C (F) • V (V)
- Class 3, Power, discharge current in mA = 4 • C (F) • V (V)
- Class 4, Instantaneous power, discharge current in mA = 40 • C (F) • V (V)

Exceptional for electronic components like capacitors are the manifold different trade or series names used for supercapacitors like: *APowerCap, BestCap, BoostCap, CAP-XX, DLCAP, EneCapTen, EVerCAP, DynaCap, Faradcap, GreenCap, Goldcap, HY-CAP, Kapton capacitor, Super capacitor, SuperCap, PAS Capacitor, PowerStor, PseudoCap, Ultracapacitor* making it difficult for users to classify these capacitors.

Double-layer, Lithium-Ion and supercapacitors

- 

Double-layer capacitor with 1 F at 5.5 V for data buffering

- 

Radial (single ended) style of lithium ion capacitors for high energy density

Class X and Class Y capacitors

Many safety regulations mandate that Class X or Class Y capacitors must be used whenever a "fail-to-short-circuit" could put humans in danger, to guarantee galvanic isolation even when the capacitor fails.

Lightning strikes and other sources cause high voltage surges in mains power. Safety capacitors protect humans and devices from high voltage surges by shunting the surge energy to ground.[30]

In particular, safety regulations mandate a particular arrangement of Class X and Class Y mains filtering capacitors. [31]

In principle, any dielectric could be used to build Class X and Class Y capacitors; perhaps by including an internal fuse to improve safety.[32][33][34][35] In practice, capacitors that meet Class X and Class Y specifications are typically ceramic RFI/EMI suppression capacitors or plastic film RFI/EMI suppression capacitors.

Miscellaneous capacitors

Beneath the above described capacitors covering more or less nearly the total market of discrete capacitors some new developments or very special capacitor types as well as older types can be found in electronics.

Integrated capacitors

- Integrated capacitors—in integrated circuits, nano-scale capacitors can be formed by appropriate patterns of metallization on an isolating substrate. They may be packaged in multiple capacitor arrays with no other semi-conductive parts as discrete components.[36]
- Glass capacitors—First Leyden jar capacitor was made of glass, As of 2012 glass capacitors were in use as SMD version for applications requiring ultra-reliable and ultra-stable service.

Power capacitors

- Vacuum capacitors—used in high power RF transmitters
- SF_6 gas filled capacitors—used as capacitance standard in measuring bridge circuits

Special capacitors

- Printed circuit boards—metal conductive areas in different layers of a multi-layer printed circuit board can act as a highly stable capacitor. It is common industry practice to fill unused areas of one PCB layer with the ground conductor and another layer with the power conductor, forming a large distributed capacitor between the layers.

- Wire—2 pieces of insulated wire twisted together. Capacitance values usually range from 3 pF to 15 pF. Used in homemade VHF circuits for oscillation feedback.

Specialized devices such as built-in capacitors with metal conductive areas in different layers of a multi-layer printed circuit board and kludges such as twisting together two pieces of insulated wire also exist.

Capacitors made by twisting 2 pieces of insulated wire together are called gimmick capacitors. Gimmick capacitors were used in commercial and amateur radio receivers.

Obsolete capacitors

- Mica capacitors—the first capacitors with stable frequency behavior and low losses, used for military radio applications during World War II
- Air-gap capacitors—used by the first spark-gap transmitters

- **Miscellaneous capacitors**

Some 1nF × 500VDC rated silver mica capacitors

Vacuum capacitor with uranium glass encapsulation

Variable capacitors

Variable capacitors may have their capacitance changed by mechanical motion. Generally two versions of variable capacitors has to be to distinguished

- Tuning capacitor – variable capacitor for intentionally and repeatedly tuning an oscillator circuit in a radio or another tuned circuit

- Trimmer capacitor – small variable capacitor usually for one-time oscillator circuit internal adjustment

Variable capacitors include capacitors that use a mechanical construction to change the distance between the plates, or the amount of plate surface area which overlaps. They mostly use air as dielectric medium.

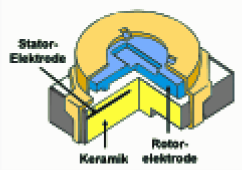
Semi-conductive variable capacitance diodes are not capacitors in the sense of passive components but can change their capacitance as a function of the applied reverse bias voltage and are used like a variable capacitor. They have replaced much of the tuning and trimmer capacitors.

- **Variable capacitors**

Air gap tuning capacitor

Vacuum tuning capacitor

Trimmer capacitor for through hole mounting

- 

Trimmer capacitor for surface mounting

Comparison of types[edit]

Features and applications as well as disadvantages of capacitors

Capacitor type	**Dielectric**	**Features/applications**	**Disadvantages**
Ceramic capacitors			
Ceramic Class 1 capacitors	paraelectric ceramic mixture of Titanium dioxide modified by additives	Predictable linear and low capacitance change with operating temperature Excellent high frequency characteristics with low losses. For temperature compensation inresonant circuit application. Available in voltages up to 15,000 V	Low permittivity ceramic, capacitors with low volumetric efficiency, larger dimensions than Class 2 capacitors
Ceramic Class 2 capacitors	ferroelectric ceramic mixture of barium titanate and suitable additives	High permittivity, high volumetric efficiency, smaller dimensions than Class 1 capacitors. For buffer, by-pass and coupling applications. Available in voltages up to 50,000 V.	Lower stability and higher losses than Class 1. Capacitance changes with change in applied voltage, with frequency and with aging effects. Slightlymicrophonic

Film capacitors			
Metallized film capacitors	PP, PET, PEN, PPS, (PTFE)	Metallized film capacitors are significantly smaller in size than film/foil versions and have self-healing properties.	Thin metallized electrodes limit the maximum current car rying capability respectively the maximum possible pulse voltage.
Film/foil film capacitors	PP, PET, PTFE	Film/foil film capacitors have the highest surge ratings/pulse voltage, respectively. Peak currents are higher than for metallized types.	No self-healing properties: internal short may be disabling. Larger dimensions than metallized alternative.
Polypropylene (PP) film capacitors	Polypropylene (Treofan®)	Most popular film capacitor dielectric. Predictable linear and low capacitance change with operating temperature. Suitable for applications in Class-1 frequency-determining circuits and precision analog applications. Very narrow capacitances. Extremely low dissipation factor. Low moisture absorption, therefore suitable for "naked" designs with no coating. High insulation resistance. Usable in high power applications such as snubber or IGBT. Used also in AC power applications,	Maximum operating temperature of 105 °C. Relatively low permittivity of 2.2. PP film capacitors tend to be larger than other film capacitors. More susceptible to damage from transient over-voltages or voltage reversals than oil-impregnated MKV-capacitors for pulsed powerapplications.

		such as in motors or power factor correction. Very low dielectric losses. High frequency and high power applications such as induction heating. Widely used for safety/EMI suppression, including connection to power supply mains.	
Polyester (PET) film (Mylar) capacitors	Polyethylene terephthalate,Polyester(Hostaphan®, Mylar®)	Smaller in size than functionally comparable polypropylene film capacitors. Low moisture absorption. Have almost completely replaced metallized paper and polystyrene film for most DC applications. Mainly used for general purpose applications or semi-critical circuits with operating temperatures up to 125 °C. Operating voltages up to 60,000 V DC.	Usable at low (AC power) frequencies. Limited use in power electronics due to higher losses with increasing temperature and frequency.
Polyethylene naphthalate (PEN) film capacitors	Polyethylene naphthalate(Kaladex®)	Better stability at high temperatures than PET. More suitable for high temperature applications and for SMD packaging. Mainly used for non-critical filtering, coupling and decoupling, because temperature dependencies are not	Lower relative permittivity and lower dielectric strength imply larger dimensions for a given capacitance and rated voltage than PET.

		significant.	
Polyphenylene Sulfide (PPS) film capacitors	Polyphenylene (Torelina®)	Small temperature dependence over the entire temperature range and a narrow frequency dependence in a wide frequency range. Dissipation factor is quite small and stable. Operating emperatures up to 270 °C. Suitable for SMD. Tolerate increased reflow soldering temperatures for lead-free soldering mandated by theRoHS 2002/95/European Union directive	Above 100 °C, the dissipation factor increases, increasing component temperature, but can operate without degradation. Cost is usually higher than PP.
Polytetrafluoroethylene (PTFE) (Teflon film) capacitors	Polytetrafluoroethylene(Teflon®)	Lowest loss solid dielectric. Operating temperatures up to 250 °C. Extremely high insulation resistance. Good stability. Used in mission-critical applications.	Large size (due to low dielectric constant). Higher cost than other film capacitors.
Polycarbonate (PC) film capacitors	Polycarbonate	Almost completely replaced by PP	Limited manufacturers
Polystyrene (PS) film capacitors	Polystyrene (Styroflex)	Almost completely replaced by PET	Limited manufacturers
Polysulphone film capacitors	Polysulfone	Similar to polycarbonate. Withstand full voltage at	Only development, no series found (2012)

		comparatively higher temperatures.	
Polyamide film capacitors	Polyamide	Operating temperatures of up to 200 °C. High insulation resistance. Good stability. Low dissipation factor.	Only development, no series found (2012)
Polyimide film (Kapton) capacitors	Polyimide (Kapton)	Highest dielectric strength of any known plastic film dielectric.	Only development, no series found (2012)
Film-based power capacitors			
Metallized paper power capacitors	Paper impregnated with insulating oil or epoxy resin	Self-healing properties. Originally impregnated with wax, oil or epoxy. Oil-Kraft paper version used in certain high voltage applications. Mostly replaced by PP.	Large size. Highly hygroscopic, absorbingmoisture fro m the atmosphere despit e plastic enclosures and impregnates. Moisture increases dielectric losses and decreases insulation r esistance.
Paper film/foil power capacitors	Kraft paperimpregnated with oil	Paper covered with metal foils as electrodes. Low cost. Intermittent duty, high discharge applications.	Physically large and heavy. Significantly lower energy density than PP dielectric. Not self-healing. Potential catastrophic failure due to high stored energy.
PP dielectric, field-free paper power capacitors (MKV power capacitors)	Double-sided (field-free) metallized paper as electrode carrier. PP as dielectic, impregnated with insulating oil, epoxy resin or insulating gas	Self-healing. Very low losses. High insulation resistance. High inrush current strength. High thermal stability.	Physically larger than PP power capacitors.

		Heavy duty applications such as commutating with high reactive power, high frequencies and a high peak current load and other AC applications.	
Single- or double-sided metallized PP power capacitors	PP as dielectric, impregnated with insulating oil, epoxy resin or insulating gas	Highest capacitance per volume power capacitor. Self-healing. Broad range of applications such as general-purpose, AC capacitors, motor capacitors, smoothing or filtering, DC links, snubbing or clamping, damping AC, series resonant DC circuits, DC discharge, AC commutation, AC power factor correction.	critical for reliable high voltage operation and very high inrush current loads, limited heat resistance (105 °C)
PP film/foil power capacitors	Impregnated PP or insulating gas, insulating oil, epoxy resin or insulating gas	Highest inrush current strength	Larger than the PP metallized versions. Not self-healing.
Electrolytic capacitors			
Electrolytic capacitors with non solid (wet, liquid) electrolyte	Aluminum oxide Al_2O_3	Very large capacitance to volume ratio. Capacitance values up to 2,700,000 µF/6.3 V. Voltage up to 550 V. Lowest cost per capacitance/voltage values. Used where low losses and high	Polarized. Significant leakage. Relatively high ESR and ESL values, limiting high ripple current and high frequency applications. Lifetime calculation required because drying out phenomenon. Vent or burst when

		capacitance stability are not of major importance, especially for lower frequencies, such as by-pass, coupling, smoothing and buffer applications in power supplies and DC-links.	overloaded, overheated or connected wrong polarized. Water based electrolyte may vent at end-of-life, showing failures like "capacitor plague"
	Tantalum pentoxide Ta_2O_5	Wet tantalum electrolytic capacitors (wet slug)[42] Lowest leakage among electrolytics. Voltage up to 630 V (tantalum film) or 125 V (tantalum sinter body). Hermetically sealed. Stable and reliable. Military and space applications.	Polarized. Violent explosion when voltage, ripple current or slew rates are exceeded, or under reverse voltage. Expensive.
[Electrolytic capacitors with solid [Manganese dioxide]] electrolyte	Aluminum oxide Al 2O 3 Tantalum pentoxide Ta_2O_5, Niobium pentoxide Nb 2O 5	Tantalum and niobium with smaller dimensions for a given capacitance/voltage vs aluminum. Stable electrical parameters. Good long-term high temperature performance. Lower ESR lower than non-solid (wet) electrolytics.	Polarized. About 125 V. Low voltage and limited, transient, reverse or surge voltage tolerance. Possible combustion upon failure. ESR much higher than conductive polymer electrolytics. Manganese expected to be replaced by polymer.
Electrolytic capacitors with solid Polymerelectrolyte (Polymer	Aluminum oxide Al 2O 3, Tantalum pentoxide Ta_2O_5,	Greatly reduced ESR compared with manganese or non-solid (wet) elelectrolytics. Higher ripple current	Polarized. Highest leakage current among electrolytics. Higher prices than non-solid or manganese dioxide.

capacitors)	Niobium pentoxide Nb 2O 5	ratings. Extended operational life. Stable electrical parameters. Self-healing.[43] Used for smoothing and buffering in smaller power supplies especially in SMD.	Voltage limited to about 100 V. Explodes when voltage, current, or slew rates are exceeded or under reverse voltage.
Supercapacitors			
Supercapacitors Pseudocapacitors	Helmholtz double-layer plus faradaic pseudo-capacitance	Energy density typically tens to hundreds of times greater than conventional electrolytics. More comparable to batteries than to other capacitors. Large capacitance/volume ratio. Relatively low ESR. Thousands of farads. RAM memory backup. Temporary power during battery replacement. Rapidly absorbs/delivers much larger currents than batteries. Hundreds of thousands of charge/discharge cycles. Hybrid vehicles. Recuperation	Polarized. Low operating voltage per cell. (Stacked cells provide higher operating voltage.) Relatively high cost.
Hybrid capacitors Lithium ion capacitors (LIC)	Helmholtz double-layer plus faradaic pseudo-capacitance. Anode doped with lithium ions.	Higher operating voltage. Higher energy density than common EDLCs, but smaller than lithium ion batteries (LIB). No thermal runaway	Polarized. Low operating voltage per cell. (Stacked cells provide higher operating voltage.) Relatively high cost.

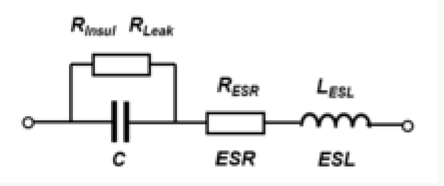
		reactions.	
Miscellaneous capacitors			
Air gap capacitors	Air	Low dielectric loss. Used for resonating HF circuits for high power HF welding.	Physically large. Relatively low capacitance.
Vacuum capacitors	Vacuum	Extremely low losses. Used for high voltage, high power RF applications, such as transmitters and induction heating. Self-healing if arc-over current is limited.	Very high cost. Fragile. Large. Relatively low capacitance.
SF 6-gas filled capacitors	SF 6 gas	High precision.[44] Extremely low losses. Very high stability. Up to 1600 kV rated voltage. Used as capacitance standard in measuring bridge circuits.	Very high cost
Metallized mica (Silver mica) capacitors	Mica	Very high stability. No aging. Low losses. Used for HF and low VHF RF circuits and as capacitance standard in measuring bridge circuits. Mostly replaced by Class 1 ceramic capacitors	Higher cost than class 1 ceramic capacitors
Glass capacitors	Glass	Better stability and frequency than silver mica. Ultra-reliable. Ultra-stable.	Higher cost than class 1 ceramic

		Resistant to nuclear radiation. Operating temperature: −75 °C to +200 °C and even short overexposure to +250 °C.[45]	
Integrated capacitors	oxide-nitride-oxide (ONO)	Thin (down to 100 µm). Smaller footprint than most MLCC. Low ESL. Very high stability up to 200 °C. High reliability	Customized production
Variable capacitors			
Air gap tuning capacitors	Air	Circular or various logarithmic cuts of the rotor electrode for different capacitance curves. Split rotor or stator cut for symmetric adjustment. Ball bearing axis for noise reduced adjustment. For high professional devices.	Large dimensions. High cost.
Vacuum tuning capacitors	Vacuum	Extremely low losses. Used for high voltage, high power RF applications, such as transmitters and induction heating. Self-healing if arc-over current is limited.	Very high cost. Fragile. Large dimensions.
SF_6 gas filled tuning capacitor	SF_6	Extremely low losses. Used for very high voltage high power RF applications.	Very high cost, fragile, large dimensions

Air gap trimmer capacitors	Air	Mostly replaced by semiconductive variable capacitance diodes	High cost
Ceramic trimmer capacitors	Class 1 ceramic	Linear and stable frequency behavior over wide temperature range	High cost

Electrical characteristics

Series-equivalent circuit



Series-equivalent circuit model of a capacitor

Discrete capacitors deviate from the ideal capacitor. An ideal capacitor only stores and releases electrical energy, with no dissipation. Capacitor components have losses and parasitic inductive parts. These imperfections in material and construction can have positive implications such as linear frequency and temperature behavior in class 1 ceramic capacitors. Conversely, negative implications include the non-linear, voltage-dependent capacitance in class 2 ceramic capacitors or the insufficient dielectric insulation of capacitors leading to leakage currents.

All properties can be defined and specified by a series equivalent circuit composed out of an idealized capacitance and additional electrical components which model all losses and inductive parameters of a capacitor. In this series-equivalent circuit the electrical characteristics are defined by:

- *C*, the capacitance of the capacitor

- R_{insul}, the insulation resistance of the dielectric, not to be confused with the insulation of the housing
- R_{leak}, the resistance representing the leakage current of the capacitor
- R_{ESR}, the equivalent series resistance which summarizes all ohmic losses of the capacitor, usually abbreviated as "ESR"
- L_{ESL}, the equivalent series inductance which is the effective self-inductance of the capacitor, usually abbreviated as "ESL".

Using a series equivalent circuit instead of a parallel equivalent circuit is specified by IEC/EN 60384-1.

Standard capacitance values and tolerances

The "rated capacitance" C_R or "nominal capacitance" C_N is the value for which the capacitor has been designed. Actual capacitance depends on the measured frequency and ambient temperature. Standard measuring conditions are a low-voltage AC measuring method at a temperature of 20 °C with frequencies of

- 100 kHz, 1 MHz (preferred) or 10 MHz for non-electrolytic capacitors with $C_R \leq 1$ nF:
- 1 kHz or 10 kHz for non-electrolytic capacitors with 1 nF < $C_R \leq 10$ µF
- 100/120 Hz for electrolytic capacitors
- 50/60 Hz or 100/120 Hz for non-electrolytic capacitors with $C_R > 10$ µF

For super-capacitors a voltage drop method is applied for measuring the capacitance value. .

Capacitors are available in geometrically increasing preferred values (E series standards) specified in IEC/EN 60063. According to the number of values per decade, these were called the E3, E6, E12, E24 etc. series. The range of units used to specify capacitor values has expanded to include everything from pico- (pF), nano- (nF) and microfarad (µF) to farad (F). Millifarad and kilofarad are uncommon.

The percentage of allowed deviation from the rated value is called tolerance. The actual capacitance value should be within its tolerance limits, or it is out of specification. IEC/EN 60062 specifies a letter code for each tolerance.

Tolerances of capacitors and their letter codes

E series	Tolerance			
	C_R > 10 pF	Letter code	C_R < 10 pF	Letter code
E 96	1%	F	0.1 pF	B
E 48	2%	G	0.25 pF	C
E 24	5%	J	0.5 pF	D
E 12	10%	K	1 pF	F
E 6	20%	M	2 pF	G
E3	−20/+50%	S	-	-
	−20/+80%	Z	-	-

The required tolerance is determined by the particular application. The narrow tolerances of E24 to E96 are used for high-quality circuits such as precision oscillators and timers. General applications such as non-critical filtering or coupling circuits employ E12 or E6. Electrolytic capacitors, which are often used for filtering and bypassing capacitors mostly have a tolerance range of ±20% and need to conform to E6 (or E3) series values.

Temperature dependence

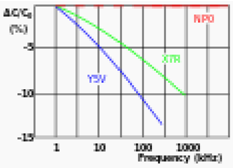
Capacitance typically varies with temperature. The different dielectrics express great differences in temperature sensitivity. The temperature coefficient is expressed in parts per million (ppm) per degree Celsius for class 1 ceramic capacitors or in % over the total temperature range for all others.

Temperature coefficients of some common capacitors

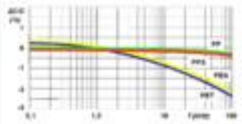
Type of capacitor, dielectric material	Temperature coefficient ΔC/C	Application temperature range
Ceramic capacitor class 1 paraelectric NP0	± 30 ppm/K (±0.5 %)	−55 to +125 °C
Ceramic capacitor class 2 ferroelectric X7R	±15 %	−55 to +125 °C
Ceramic capacitor class 2, ferroelectric Y5V	+22 % / −82 %	−30 to +85 °C
Film capacitor Polypropylene (PP)	±2.5 %	−55 to +85/105 °C
Film capacitor Polyethylen terephthalate, Polyester (PET)	+5 %	−55 to +125/150 °C
Film capacitor Polyphenylene sulfide (PPS)	±1.5 %	−55 to +150 °C
Film capacitor Polyethylene naphthalate (PEN)	±5 %	−40 to +125/150 °C
Film capacitor Polytetrafluoroethylene (PTFE)	?	−40 to +130 °C
Metallized paper capacitor (impregnated)	±10 %	−25 to +85 °C
Aluminum electrolytic capacitor Al_2O_3	±20 %	−40 to +85/105/125 °C
Tantalum electrolytic capacitor Ta_2O_5	±20 %	−40 to +125 °C

Frequency dependence

Most discrete capacitor types have more or less capacitance changes with increasing frequencies. The dielectric strength of class 2 ceramic and plastic film diminishes with rising frequency. Therefore their capacitance value decreases with increasing frequency. This phenomenon for ceramic class 2 and plastic film dielectrics is related to dielectric relaxation in which the time constant of the electrical dipoles is the reason for the frequency dependence of permittivity. The graphs below show typical frequency behavior of the capacitance for ceramic and film capacitors.

- **Frequency dependence of capacitance for ceramic and film capacitors**
  - 

Frequency dependence of capacitance for ceramic class 2 capacitors (NP0 class 1 for comparisation)

  - 

Frequency dependence of capacitance for film capacitors with different film materials

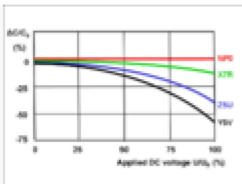
For electrolytic capacitors with non-solid electrolyte, mechanical motion of the ions occurs. Their movability is limited so that at higher frequencies not all areas of the roughened anode structure are covered with charge-carrying ions. As higher the anode structure is roughned as more the capacitance value decreases with increasing frequency. Low voltage types with highly roughened anodes display capacitance at 100 kHz approximately 10 to 20% of the value measured at 100 Hz.

Voltage dependence

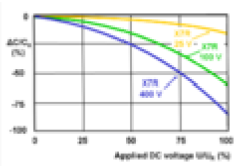
Capacitance may also change with applied voltage. This effect is more prevalent in class 2 ceramic capacitors. The permittivity of ferroelectric class 2 material depends on the applied voltage. Higher applied voltage lowers permittivity. The change of capacitance can drop to 80% of the value measured with the standardized measuring voltage of 0.5 or 1.0 V. This behavior is a small source of non-linearity in low-distortion filters and other analog applications. In audio applications this can be the reason for harmonic distortion.

Film capacitors and electrolytic capacitors have no significant voltage dependence.

- **Voltage dependence of capacitance for some different class 2 ceramic capacitors**

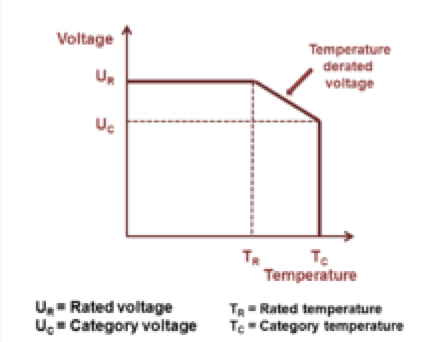


Simplified diagram of the change in capacitance as a function of the applied voltage for 25-V capacitors in different kind of ceramic grades



Simplified diagram of the change in capacitance as a function of applied voltage for X7R ceramics with different rated voltages

Rated and category voltage



Relation between rated and category temperature range and applied voltage

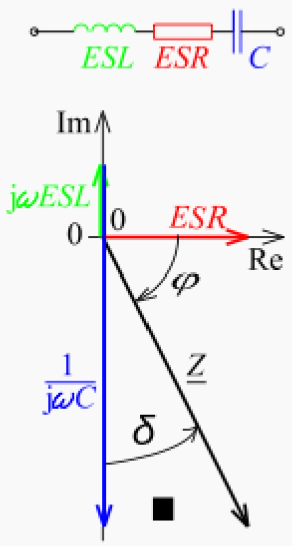
The voltage at which the dielectric becomes conductive is called the breakdown voltage, and is given by the product of the dielectric strength and the separation between the electrodes. The dielectric strength depends on temperature, frequency, shape of the electrodes, etc. Because a breakdown in a capacitor normally is a short circuit and destroys the component, the operating voltage is lower than the breakdown voltage. The operating voltage is specified such that the voltage may be applied continuously throughout the life of the capacitor.

In IEC/EN 60384-1 the allowed operating voltage is called "rated voltage" or "nominal voltage". The rated voltage (UR) is the maximum DC voltage or peak pulse voltage that may be applied continuously at any temperature within the rated temperature range.

The voltage proof of nearly all capacitors decreases with increasing temperature. For some applications it is important to use a higher temperature range. Lowering the voltage applied at a higher temperature maintains safety margins. For some capacitor types therefore the IEC standard specify a second "temperature derated voltage" for a higher temperature range, the "category voltage". The category voltage (UC) is the maximum DC voltage or peak pulse voltage that may be applied continuously to a capacitor at any temperature within the category temperature range.

The relation between both voltages and temperatures is given in the picture right.

Impedance



Simplified series-equivalent circuit of a capacitor for higher frequencies (above); vector diagram with electrical reactances X_{ESL} and X_C and resistance ESR and for illustration the impedance Z and dissipation factor tan δ

In general, a capacitor is seen as a storage component for electric energy. But this is only one capacitor function. A capacitor can also act as an ACresistor. In many cases the capacitor is used as a decoupling capacitor to filter or bypass undesired biased AC frequencies to the ground. Other applications use capacitors for capacitive coupling of AC signals; the dielectric is used only for blocking DC. For such applications the AC resistance is as important as the capacitance value.

The frequency dependent AC resistance is called impedance Z and is the complex ratio of the voltage to the current in an AC circuit. Impedance extends the concept of resistance to AC circuits and possesses both magnitude and phase at a particular frequency. This is unlike resistance, which has only magnitude.

$$Z = |Z|e^{j\theta}$$

The magnitude $|Z|$ represents the ratio of the voltage difference amplitude to the current amplitude, j is the imaginary unit, while the argument θ gives the phase difference between voltage and current.

In capacitor data sheets, only the impedance magnitude |Z| is specified, and simply written as "Z" so that the formula for the impedance can be written in Cartesian form

$$Z = R + jX$$

where the real part of impedance is the resistance R (for capacitors ESR) and the imaginary part is the reactance X.

As shown in a capacitor's series-equivalent circuit, the real component includes an ideal capacitor C, an inductance $L(ESL)$ and a resistor $R(ESR)$. The total reactance at the angular frequency ω therefore is given by the geometric (complex) addition of a capacitive reactance (Capacitance) $X_C = -\frac{1}{\omega C}$ and an inductive reactance (Inductance): $X_L = \omega L_{\mathrm{ESL}}$.

To calculate the impedance Z the resistance has to be added geometrically and then Z is given by

$Z = \sqrt{ESR^2 + (X_{\mathrm{C}} + (-X_{\mathrm{L}}))^2}$. The impedance is a measure of the capacitor's ability to pass alternating currents. In this sense the impedance can be used like Ohms law

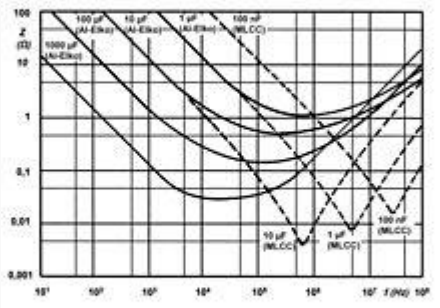
$$Z = \frac{\hat{u}}{\hat{\imath}} = \frac{U_{\mathrm{eff}}}{I_{\mathrm{eff}}}.$$

to calculate either the peak or the effective value of the current or the voltage.

In the special case of resonance, in which the both reactive resistances

$$X_C = -\frac{1}{\omega C} \text{ and } X_L = \omega L_{\mathrm{ESL}}$$

have the same value ($X_C = X_L$), then the impedance will only be determined by ESR.



Typical impedance curves for different capacitance values over frequency showing the typical form with a decreasing impedance values below resonance and increasing values above resonance. As higher the capacitance as lower the resonance.

The impedance specified in the datasheets often show typical curves for the different capacitance values. With increasing frequency as the impedance decreases down to a minimum. The lower the impedance, the more easily alternating currents can be passed through the capacitor. At the apex, the point of resonance, where XC has the same value than XL, the capacitor has the lowest impedance value. Here only the ESR determines the impedance. With frequencies above the resonance the impedance increases again due to the ESL of the capacitor. The capacitor becomes an inductance.

As shown in the graph, the higher capacitance values can fit the lower frequencies better while the lower capacitance values can fit better the higher frequencies.

Aluminum electrolytic capacitors have relatively good decoupling properties in the lower frequency range up to about 1 MHz due to their large capacitance values. This is the reason for using electrolytic capacitors in standard or switched-mode power supplies behind therectifier for smoothing application.

Ceramic and film capacitors are already out of their smaller capacitance values suitable for higher frequencies up to several 100 MHz. They also have significantly lower parasitic inductance, making them suitable for higher frequency applications, due to their construction with end-surface contacting of the electrodes. To increase the range of frequencies, often an electrolytic capacitor is connected in parallel with a ceramic or film capacitor.

Many new developments are targeted at reducing parasitic inductance (ESL). This increases the resonance frequency of the capacitor and, for example, can follow the constantly increasing switching speed of digital circuits. Miniaturization, especially in the SMD multilayer ceramic chip capacitors (MLCC), increases the resonance frequency. Parasitic inductance is further lowered by placing the electrodes on the longitudinal side of the chip instead of the lateral side. The "face-down" construction associated with multi-anode technology in tantalum electrolytic capacitors further reduced ESL. Capacitor families such as the so-called MOS capacitor or silicon capacitors offer solutions when capacitors at frequencies up to the GHz range are needed.

Inductance (ESL) and self-resonant frequency

ESL in industrial capacitors is mainly caused by the leads and internal connections used to connect the capacitor plates to the outside world. Large capacitors tend to have higher ESL than small ones because the distances to the plate are longer and every mm counts as an inductance.

For any discrete capacitor, there is a frequency above DC at which it ceases to behave as a pure capacitor. This frequency, where X_C is as high as X_L, is called the self-resonant frequency. The self-resonant frequency is the lowest frequency at which the impedance passes through a minimum. For any AC application the self-resonant frequency is the highest frequency at which capacitors can be used as a capacitive component.

This is critically important for decoupling high-speed logic circuits from the power supply. The decoupling capacitor supplies transient current to the chip. Without decouplers, the IC demands current faster than the connection to the power supply can supply it, as parts of the circuit rapidly switch on and off. To counter this potential problem, circuits frequently use multiple bypass capacitors—small (100 nF or less) capacitors rated for high frequencies, a large electrolytic capacitor rated for lower frequencies and occasionally, an intermediate value capacitor.

Ohmic losses, ESR, dissipation factor, and quality factor

The summarized losses in discrete capacitors are ohmic AC losses. DC losses are specified as "leakage current" or "insulating resistance" and are negligible for an AC specification. AC losses are non-linear, possibly depending on frequency, temperature, age or humidity. The losses result from two physical conditions:

- line losses including internal supply line resistances, the contact resistance of the electrode contact, line resistance of the electrodes, and in "wet" aluminum electrolytic capacitors and especially supercapacitors, the limited conductivity of liquid electrolytes and
- dielectric losses from dielectric polarization.

The largest share of these losses in larger capacitors is usually the frequency dependent ohmic dielectric losses. For smaller components, especially for wet electrolytic capacitors, conductivity of liquid electrolytes may exceed dielectric losses. To measure these losses, the measurement frequency must be set. Since commercially available components offer capacitance values cover 15 orders of magnitude, ranging from pF (10^{-12} F) to some 1000 F in supercapacitors, it is not possible to capture the entire range with only one frequency. IEC 60384-1 states that ohmic losses should be measured at the same frequency used to measure capacitance. These are:

- 100 kHz, 1 MHz (preferred) or 10 MHz for non-electrolytic capacitors with $C_R \leq 1$ nF:
- 1 kHz or 10 kHz for non-electrolytic capacitors with 1 nF < $C_R \leq 10$ µF
- 100/120 Hz for electrolytic capacitors
- 50/60 Hz or 100/120 Hz for non-electrolytic capacitors with $C_R >$ 10 µF

A capacitor's summarized resistive losses may be specified either as ESR, as a dissipation factor(DF, tan δ), or as quality factor (Q), depending on application requirements.

Capacitors with higher ripple current I_R loads, such as electrolytic capacitors, are specified with equivalent series resistance ESR. ESR can be shown as an ohmic part in the above vector diagram. ESR values are specified in datasheets per individual type.

The losses of film capacitors and some class 2 ceramic capacitors are mostly specified with the dissipation factor tan δ. These capacitors have smaller losses than electrolytic capacitors and mostly are used at higher frequencies up to some hundred MHz. However the numeric value of the dissipation factor, measured at the same frequency, is independent on the capacitance value and can be specified for a capacitor series with a range of capacitance. The dissipation factor is determined as the tangent of the reactance ($X_C - X_L$) and the ESR, and can be shown as the angle δ between imaginary and the impedance axis.

If the inductance ESL is small, the dissipation factor can be approximated as:

$$\tan\delta = ESR \cdot \omega C$$

Capacitors with very low losses, such as ceramic Class 1 and Class 2 capacitors, specify resistive losses with a quality factor (Q). Ceramic Class 1 capacitors are especially suitable for LC resonant circuits with frequencies up to the GHz range, and precise high and low pass filters. For an electrically resonant system, Q represents the effect ofelectrical resistance and characterizes a resonator's bandwidth B relative to its center or resonant frequency f_0. Q is defined as the reciprocal value of the dissipation factor.

$$Q = \frac{1}{tan\delta} = \frac{f_0}{B}$$

A high Q value is for resonant circuits a mark of the quality of the resonance.

Comparization of ohmic losses for different capacitor types for resonant circuits (Reference frequency 1 MHz)

Capacitor type	Capacitance (pF)	ESR at 100 kHz (mΩ)	ESR at 1 MHz (mΩ)	tan δ at 1 MHz (10^{-4})	Quality factor
Silicon capacitor[47]	560	400	—	2,5	4000

Mica capacitor[48]	1000	650	65	4	2500
Class 1 ceramic capacitor (NP0)[49]	1000	1600	160	10	1000

Limiting current loads

A capacitor can act as an AC resistor, coupling AC voltage and AC current between two points. Every AC current flow through a capacitor generates heat inside the capacitor body. These dissipation power loss P is caused by ESR and is the squared value of the effective (RMS) current I

$$P = I^2 \cdot ESR$$

The same power loss can be written with the dissipation factor $tan\delta$ as

$$P = \frac{U^2 \cdot tan\delta}{2\pi f \cdot C}$$

The internal generated heat has to be distributed to the ambient. The temperature of the capacitor, which is established on the balance between heat produced and distributed, shall not exceed the capacitors maximum specified temperature. Hence, the ESR or dissipation factor is a mark for the maximum power (AC load, ripple current, pulse load, etc.) a capacitor is specified for.

AC currents may be a:

- ripple current—an effective (RMS) AC current, coming from an AC voltage superimposed of an DC bias, a
- pulse current—an AC peak current, coming from an voltage peak, or an
- AC current—an effective (RMS) sinusoidal current

Ripple and AC currents mainly warms the capacitor body. By this currents internal generated temperature influences the breakdown voltage of the dielectric. Higher temperature lower the voltage proof of all capacitors. In wet electrolytic capacitors higher temperatures force the evaporation of electrolytes, shortening the life time of the capacitors. In film capacitors higher temperatures may shrink the plastic film changing the capacitor's properties.

Pulse currents, especially in metallized film capacitors, heat the contact areas between end spray (schoopage) and metallized electrodes. This may reduce the contact to the electrodes, heightening the dissipation factor.

For safe operation, the maximal temperature generated by any AC current flow through the capacitor is a limiting factor, which in turn limits AC load, ripple current, pulse load, etc.

Ripple current

A "ripple current" is the RMS value of a superimposed AC current of any frequency and any waveform of the current curve for continuous operation at a specified temperature. It arises mainly in power supplies (including switched-mode power supplies) after rectifying an AC voltage and flows as charge and discharge current through the decoupling or smoothing capacitor. The "rated ripple current" shall not exceed a temperature rise of 3, 5 or 10 °C, depending on the capacitor type, at the specified maximum ambient temperature.

Ripple current generates heat within the capacitor body due to the ESR of the capacitor. The ESR, composed out of the dielectric losses caused by the changing field strength in the dielectric and the losses resulting out of the slightly resistive supply lines or the electrolyte depends on frequency and temperature. For ceramic and film capacitors in generally ESR decreases with increasing temperatures but heighten with higher frequencies due to increasing dielectric losses. For electrolytic capacitors up to roughly 1 MHz ESR decreases with increasing frequencies and temperatures.

The types of capacitors used for power applications have a specified rated value for maximum ripple current. These are primarily aluminum electrolytic capacitors, and tantalum as well as some film capacitors and Class 2 ceramic capacitors.

Aluminium electrolytic capacitors, the most common type for power supplies, experience shorter life expectancy at higher ripple currents. Exceeding the limit tends to result in explosive failure.

Tantalum electrolytic capacitors with solid manganese dioxide electrolyte are also limited by ripple current. Exceeding their ripple limits tends to shorts and burning components.

For film and ceramic capacitors, normally specified with a loss factor tan δ, the ripple current limit is determined by temperature rise in the body of approximately 10 °C. Exceeding this limit may destroy the internal structure and cause shorts.

Pulse current

The rated pulse load for a certain capacitor is limited by the rated voltage, the pulse repetition frequency, temperature range and pulse rise time. The "pulse rise time" dv/dt, represents the steepest voltage gradient of the pulse (rise or fall time) and is expressed in volts per μs (V/μs).

The rated pulse rise time is also indirectly the maximum capacity of an applicable peak current I_P. The peak current is defined as:

$$I_p = C \cdot dv/dt$$

where: I_P is in A; C in μF; dv/dt in V/μs

The permissible pulse current capacity of a metallized film capacitor generally allows an internal temperature rise of 8 to 10 K.

In the case of metallized film capacitors, pulse load depends on the properties of the dielectric material, the thickness of the metallization and the capacitor's construction, especially the construction of the contact areas between the end spray and metallized electrodes. High peak currents may lead to selective overheating of local contacts between end spray and metallized electrodes which may destroy some of the contacts, leading to increasing ESR.

For metallized film capacitors, so-called pulse tests simulate the pulse load that might occur during an application, according to a standard specification. IEC 60384 part 1, specifies that the test circuit is charged and discharged intermittently. The test voltage corresponds to the rated DC voltage and the test comprises 10000 pulses with a repetition frequency of 1 Hz. The pulse stress capacity is the pulse rise time. The rated pulse rise time is specified as 1/10 of the test pulse rise time.

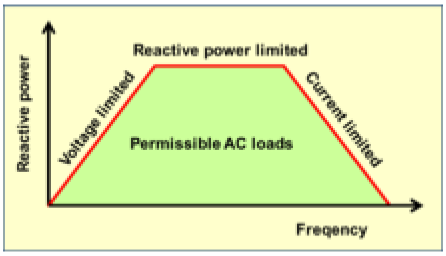
The pulse load must be calculated for each application. A general rule for calculating the power handling of film capacitors is not available because of vendor-related internal construction details. To prevent the capacitor from overheating the following operating parameters have to be considered:

- peak current per µF
- Pulse rise or fall time dv/dt in V/µs
- relative duration of charge and discharge periods (pulse shape)
- maximum pulse voltage (peak voltage)
- peak reverse voltage;
- Repetition frequency of the pulse
- Ambient temperature
- Heat dissipation (cooling)

Higher pulse rise times are permitted for pulse voltage lower than the rated voltage.

Examples for calculations of individual pulse loads are given by many manufactures, e.g. WIMA and Kemet.

AC current

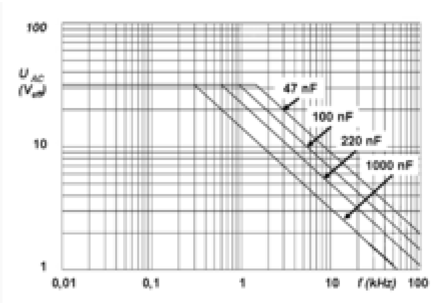


Limiting conditions for capacitors operating with AC loads

An AC load only can be applied to a non-polarized capacitor. Capacitors for AC applications are primarily film capacitors, metallized paper capacitors, ceramic capacitors and bipolar electrolytic capacitors.

The rated AC load for an AC capacitor is the maximum sinusoidal effective AC current (rms) which may be applied continuously to a capacitor within the specified temperature range. In the datasheets the AC load may be expressed as

- rated AC voltage at low frequencies,
- rated reactive power at intermediate frequencies,
- reduced AC voltage or rated AC current at high frequencies.



Typical rms AC voltage curves as a function of frequency, for 4 different capacitance values of a 63 V DC film capacitor series

The rated AC voltage for film capacitors is generally calculated so that an internal temperature rise of 8 to 10 °K is the allowed limit for safe operation. Because dielectric losses increase with increasing frequency, the specified AC voltage has to be derated at higher frequencies. Datasheets for film capacitors specify special curves for derating AC voltages at higher frequencies.

If film capacitors or ceramic capacitors only have a DC specification, the peak value of the AC voltage applied has to be lower than the specified DC voltage.

AC loads can occur in AC motor run capacitors, for voltage doubling, in snubbers, lighting ballast and for power factor correction PFC for phase shifting to improve transmission network stability and efficiency, which is one of the most important applications for large power capacitors. These mostly large PP film or metallized paper capacitors are limited by the rated reactive power VAr.

Bipolar electrolytic capacitors, to which an AC voltage may be applicable, are specified with a rated ripple current.

Insulation resistance and self-discharge constant

The resistance of the dielectric is finite, leading to some level of DC "leakage current" that causes a charged capacitor to lose charge over time. For ceramic and film capacitors, this resistance is called "insulation resistance R_{ins}". This resistance is represented by the resistor R_{ins} in parallel with the capacitor in the series-equivalent circuit of capacitors. Insulation resistance must not be confused with the outer isolation of the component with respect to the environment.

The time curve of self-discharge over insulation resistance with decreasing capacitor voltage follows the formula

$$u(t) = U_0 \cdot \mathrm{e}^{-t/\tau_s},$$

With stored DC voltage U_0 and self-discharge constant

$$\tau_s = R_{ins} \cdot C$$

Thus, after τ_s voltage U_0 drops to 37% of the initial value.

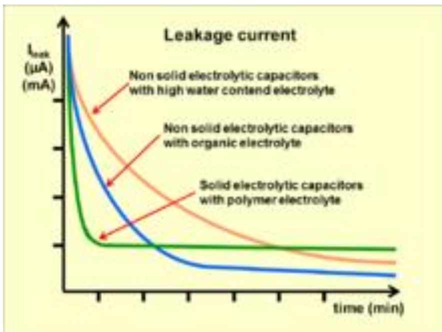
The self-discharge constant is an important parameter for the insulation of the dielectric between the electrodes of ceramic and film capacitors. For example, a capacitor can be used as the time-determining component for time relays or for storing a voltage value as in a sample and hold circuits or operational amplifiers.

Class 1 ceramic capacitors have an insulation resistance of at least 10 GΩ, while class 2 capacitors have at least 4 GΩ or a self-discharge constant of at least 100 s. Plastic film capacitors typically have an insulation resistance of 6 to 12 GΩ. This corresponds to capacitors in the uF range of a self-discharge constant of about 2000–4000 s.[52]

Insulation resistance respectively the self-discharge constant can be reduced if humidity penetrates into the winding. It is partially strongly temperature dependent and decreases with increasing temperature. Both decrease with increasing temperature.

In electrolytic capacitors, the insulation resistance is defined as leakage current.

Leakage current



The general leakage current behavior of electrolytic capacitors depend on the kind of electrolyte

For electrolytic capacitors the insulation resistance of the dielectric is termed "leakage current". This DC current is represented by the resistor R_{leak} in parallel with the capacitor in the series-equivalent circuit of electrolytic capacitors. This resistance between the terminals of a capacitor is also finite. R_{leak} is lower for electrolytics than for ceramic or film capacitors.

The leakage current includes all weak imperfections of the dielectric caused by unwanted chemical processes and mechanical damage. It is also the DC current that can pass through the dielectric after applying a voltage. It depends on the interval without voltage applied (storage time), the thermic stress from soldering, on voltage applied, on temperature of the capacitor, and on measuring time.

The leakage current drops in the first minutes after applying DC voltage. In this period the dielectric oxide layer can self-repair weaknesses by building up new layers. The time required depends generally on the electrolyte. Solid electrolytes drop faster than non-solid electrolytes but remain at a slightly higher level.

The leakage current in non-solid electrolytic capacitors as well as in manganese oxide solid tantalum capacitors decreases with voltage-connected time due to self-healing effects. Although electrolytics leakage current is higher than current flow over insulation resistance in ceramic or film capacitors, the self-discharge of modern non solid electrolytic capacitors takes several weeks.

A particular problem with electrolytic capacitors is storage time. Higher leakage current can be the result of longer storage times. These behaviors are limited to electrolytes with a high percentage of water. Organic solvents such as GBL do not have high leakage with longer storage times.

Leakage current is normally measured 2 or 5 minutes after applying rated voltage.

Microphonics

All ferroelectric materials exhibit piezoelectricity a piezoelectric effect. Because Class 2 ceramic capacitors use ferroelectric ceramics dielectric, these types of capacitors may have electrical effects called microphonics. Microphonics (microphony) describes how electronic components transform mechanical vibrations into an undesired electrical signal (noise).[53] The dielectric may absorb mechanical forces from shock or vibration by changing thickness and changing the electrode separation, affecting the capacitance, which in turn induces an AC current. The resulting interference is especially problematic in audio applications, potentially causing feedback or unintended recording.

In the reverse microphonic effect, varying the electric field between the capacitor plates exerts a physical force, turning them into an audio speaker. High current impulse loads or high ripple currents can generate audible sound from the capacitor itself, draining energy and stressing the dielectric.

Dielectric absorption (soakage)

Dielectric absorption occurs when a capacitor that has remained charged for a long time discharges only incompletely when briefly discharged. Although an ideal capacitor would reach zero volts after discharge, real capacitors develop a small voltage from time-delayed dipole discharging, a phenomenon that is also called dielectric relaxation, "soakage" or "battery action".

Values of dielectric absorption for some often used capacitors

Type of capacitor	Dielectric Absorption
Air and vacuum capacitors	Not measurable
Class-1 ceramic capacitors, NP0	0.6%
Class-2 ceramic capacitors, X7R	2.5%
Polypropylene film capacitors (PP)	0.05 to 0.1%
Polyester film capacitors (PET)	0.2 to 0.5%
Polyphenylene sulfide film capacitors (PPS)	0.05 to 0.1%
Polyethylene naphthalate film capacitors (PEN)	1.0 to 1.2%
Tantalum electrolytic capacitors with solid electrolyte	2 to 3%,[55] 10%[56]
Aluminium electrolytic capacitor with non solid electrolyte	10 to 15%
Double-layer capacitor or super capacitors	data not available

In many applications of capacitors dielectric absorption is not a problem but in some applications, such as long-time-constant integrators, sample-and-hold circuits, switched-capacitor analog-to-digital converters, and very low-distortion filters, it is important that the capacitor does not recover a residual charge after full discharge, and capacitors with low absorption are specified. The voltage at the terminals generated by the dielectric absorption may in some cases possibly cause problems in the function of an electronic circuit or can be a safety risk to personnel. In order to prevent shocks most very large capacitors are shipped with shorting wires that need to be removed before they are used.

Energy density

The capacitance value depends on the dielectric material (ε), the surface of the electrodes (A) and the distance (d) separating the electrodes and is given by the formula of a plate capacitor:

$$C \approx \frac{\varepsilon A}{d}$$

The separation of the electrodes and the voltage proof of the dielectric material defines the breakdown voltage of the capacitor. The breakdown voltage is proportional to the thickness of the dielectric.

Theoretically, given two capacitors with the same mechanical dimensions and dielectric, but one of them have half the thickness of the dielectric. With the same dimensions this one could place twice the parallel-plate area inside. This capacitor has theoretically 4 times the capacitance as the first capacitor but half of the voltage proof.

Since the energy density stored in a capacitor is given by:

$$E_{\text{stored}} = \frac{1}{2}CV^2,$$

thus a capacitor having a dielectric half as thick as another has 4 times higher capacitance but ½ voltage proof, yielding an equal maximum energy density.

Therefore, dielectric thickness does not affect energy density within a capacitor of fixed overall dimensions. Using a few thick layers of dielectric can support a high voltage, but low capacitance, while thin layers of dielectric produce a low breakdown voltage, but a higher capacitance.

This assumes that neither the electrode surfaces nor the permittivity of the dielectric change with the voltage proof. A simple comparison with two existing capacitor series can show whether reality matches theory. The comparison is easy, because the manufacturers use standardized case sizes or boxes for different capacitance/voltage values within a series.

Comparison of energy stored in capacitors with the same dimensions but with different rated voltages and capacitance values

Electrolytic capacitors NCC, KME series Ø D × H = 16.5 mm × 25 mm[59]		**Metallized PP film capacitors** KEMET; PHE 450 series W × H × L = 10.5 mm × 20.5 mm × 31.5 mm[60]	
Capacitance/Voltage	**Stored Energy**	**Capacitance/Voltage**	**Stored Energy**
4700 µF/10 V	**235 mW·s**	1.2 µF/250 V	**37.5 mW·s**
2200 µF/25 V	**688 mW·s**	0.68 µF/400 V	**54.4 mW·s**
220 µF/100 V	**1100 mW·s**	0.39 µF/630 V	**77.4 mW·s**
22 µF/400 V	**1760 mW·s**	0.27 µF/1000 V	**135 mW·s**

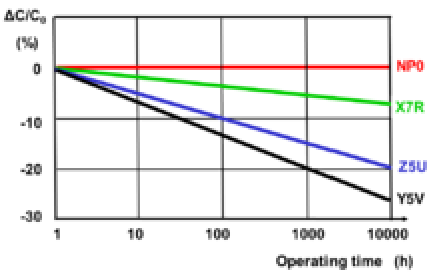
In reality modern capacitor series do not fit the theory. For electrolytic capacitors the sponge-like rough surface of the anode foil gets smoother with higher voltages, decreasing the surface area of the anode. But because the energy increases squared with the voltage, and the surface of the anode decreases lesser than the voltage proof, the energy density increases clearly. For film capacitors the permittivity changes with dielectric thickness and other mechanical parameters so that the deviation from the theory has other reasons.

Comparing the capacitors from the table with a supercapacitor, the highest energy density capacitor family. For this, the capacitor 25 F/2.3 V in dimensions D × H = 16 mm × 26 mm from Maxwell HC Series, compared with the electrolytic capacitor of approximately equal size in the table. This supercapacitor has roughly 5000 times higher capacitance than the 4700/10 electrolytic capacitor but ¼ of the voltage and has about 66,000 mWs (0.018 Wh) stored electrical energy,[62] approximately 100 times higher energy density (40 to 280 times) than the electrolytic capacitor.

Long time behavior, aging

Electrical parameters of capacitors may change over time during storage and application. The reasons for parameter changings are different, it may be a property of the dielectric, environmental influences, chemical processes or drying-out effects for non-solid materials.

Aging



Aging of different Class 2 ceramic capacitors compared with NP0-Class 1 ceramic capacitor

In ferroelectric Class 2 ceramic capacitors, capacitance decreases over time. This behavior is called "aging". This aging occurs in ferroelectric dielectrics, where domains of polarization in the dielectric contribute to the total polarization. Degradation of polarized domains in the dielectric decreases permittivity and therefore capacitance over time.[63][64] The aging follows a logarithmic law. This defines the decrease of capacitance as constant percentage for a time decade after the soldering recovery time at a defined temperature, for example, in the period from 1 to 10 hours at 20 °C. As the law is logarithmic, the percentage loss of capacitance will twice between 1 h and 100 h and 3 times between 1 h and 1,000 h and so on. Aging is fastest near the beginning, and the absolute capacitance value stabilizes over time.

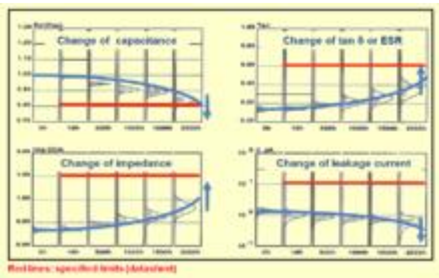
The rate of aging of Class 2 ceramic capacitors depends mainly on its materials. Generally, the higher the temperature dependence of the ceramic, the higher the aging percentage. The typical aging of X7R ceramic capacitors is about 2.5&nbs;% per decade.[65] The aging rate of Z5U ceramic capacitors is significantly higher and can be up to 7% per decade.

The aging process of Class 2 ceramic capacitors may be reversed by heating the component above the Curie point.

Class 1 ceramic capacitors and film capacitors do not have ferroelectric-related aging. Environmental influences such as higher temperature, high humidity and mechanical stress can, over a longer period, lead to a small irreversible change in the capacitance value sometimes called aging, too.

The change of capacitance for P 100 and N 470 Class 1 ceramic capacitors is lower than 1%, for capacitors with N 750 to N 1500 ceramics it is ≤ 2%. Film capacitors may lose capacitance due to self-healing processes or gain it due to humidity influences. Typical changes over 2 years at 40 °C are, for example, ±3 % for PE film capacitors and ±1 % PP film capacitors.

Life time

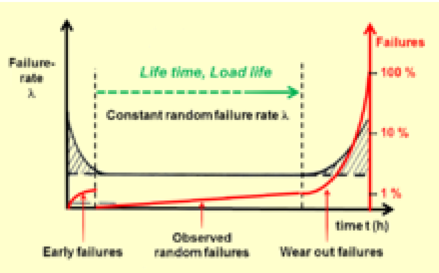


The electrical values of electrolytic capacitors with non-solid electrolyte changes over the time due to evaporation of electrolyte. Reaching specified limits of the parameters the capacitors will be count as "wear out failure".

Electrolytic capacitors with non-solid electrolyte age as the electrolyte evaporate. This evaporation depends on temperature and the current load the capacitors experience. Electrolyte escape influences capacitance and ESR. Capacitance decreases and the ESR increases over time. In contrast to ceramic, film and electrolytic capacitors with solid electrolytes, "wet" electrolytic capacitors reach a specified "end of life" reaching a specified maximum change of capacitance or ESR. End of life, "load life" or "lifetime" can be estimated either by formula or diagrams or roughly by a so-called "10-degree-law". A typical specification for an electrolytic capacitor states a lifetime of 2,000 hours at 85 °C, doubling for every 10 degrees lower temperature, achieving lifespan of approximately 15 years at room temperature.

Super-capacitors also experience electrolyte evaporation over time. Estimation is similar to wet electrolytic capacitors. Additional to temperature the voltage and current load influence the life time. Lower voltage than rated voltage and lower current loads as well as lower temperature extend the life time.

Failure rate



The life time (load life) of capacitors correspondents with the time of constant random failure rate shown in the bathtub curve. For electrolytic capacitors with non-solid electrolyte and super-capacitors ends this time with the beginning of wear out failures due to evaporation of electrolyte

Capacitors are reliable components with low failure rates, achieving life expectancies of decades under normal conditions. Most capacitors pass a test at the end of production similar to a "burn in", so that early failures are found during production, reducing the number of post-shipment failures.

Reliability for capacitors is usually specified in numbers of Failures In Time (FIT) during the period of constant random failures. FIT is the number of failures that can be expected in one billion (10^9) component-hours of operation at fixed working conditions (e.g. 1000 devices for 1 million hours, or 1 million devices for 1000 hours each, at 40 °C and 0.5 U_R). For other conditions of applied voltage, current load, temperature, mechanical influences and humidity the FIT can recalculated with terms standardized for industrial or military[contexts.

Additional information

Soldering

Capacitors may experience changes to electrical parameters due to environmental influences like soldering, mechanical stress factors (vibration, shock) and humidity. The greatest stress factor is soldering. The heat of the solder bath, especially for SMD capacitors, can cause ceramic capacitors to change contact resistance between terminals and electrodes; in film capacitors, the film may shrink, and in wet electrolytic capacitors the electrolyte may boil. A recovery period enables characteristics to stabilize after soldering; some types may require up to 24 hours. Some properties may change irreversibly by a few per cent from soldering.

Electrolytic behavior from storage or disuse

Electrolytic capacitors with non-solid electrolyte are "aged" during manufacturing by applying rated voltage at high temperature for a sufficient time to repair all cracks and weaknesses that may have occurred during production. Some electrolytes with a high water content react quite aggressively or even violently with unprotected aluminum. This leads to a "storage" or "disuse" problem of electrolytic capacitors manufactured before the 1980s. Chemical processes weaken the oxide layer when these capacitors are not used for too long. New electrolytes with "inhibitors" or "passivators" were developed during the 1980s to solve this problem. As of 2012 the standard storage time for electronic components of two years at room temperature substantiates (cased) by the oxidation of the terminals will be specified for electrolytic capacitors with non-solid electrolytes, too. Special series for 125 °C with organic solvents like GBL are specified up to 10 years storage time ensure without pre-condition the proper electrical behavior of the capacitors.

For antique radio equipment, "pre-conditioning" of older electrolytic capacitors may be recommended. This involves applying the operating voltage for some 10 minutes over a current limiting resistor to the terminals of the capacitor. Applying a voltage through a safety resistor repairs the oxide layers.

IEC/EN standards

The tests and requirements to be met by capacitors for use in electronic equipment for approval as standardized types are set out in the generic specification IEC/EN 60384-1 in the following sections.

Generic specification

IEC/EN 60384-1 - *Fixed capacitors for use in electronic equipment*

Ceramic capacitors

- IEC/EN 60384-8—*Fixed capacitors of ceramic dielectric, Class 1*
- IEC/EN 60384-9—*Fixed capacitors of ceramic dielectric, Class 2*

EC/EN 60384-21—*Fixed surface mount multilayer capacitors of ceramicdielectric, Class 1*

IEC/EN 60384-22—*Fixed surface mount multilayer capacitors of ceramic dielectric, Class 2*

Film capacitors

- IEC/EN 60384-2—*Fixed metallized polyethylene-terephthalate film dielectric d.c. capacitors*
- IEC/EN 60384-11—*Fixed polyethylene-terephthalate film dielectric metal foil d.c. capacitors*
- IEC/EN 60384-13—*Fixed polypropylene film dielectric metal foil d.c. capacitors*
- IEC/EN 60384-16—*Fixed metallized polypropylene film dielectric d.c. capacitors*
- IEC/EN 60384-17—*Fixed metallized polypropylene film dielectric a.c. and pulse*
- IEC/EN 60384-19—*Fixed metallized polyethylene-terephthalate film dielectric surface mount d.c. capacitors*
- IEC/EN 60384-20—*Fixed metalized polyphenylene sulfide film dielectric surface mount d.c. capacitors*
- IEC/EN 60384-23—*Fixed metallized polyethylene naphthalate film dielectric chip d.c. capacitors*

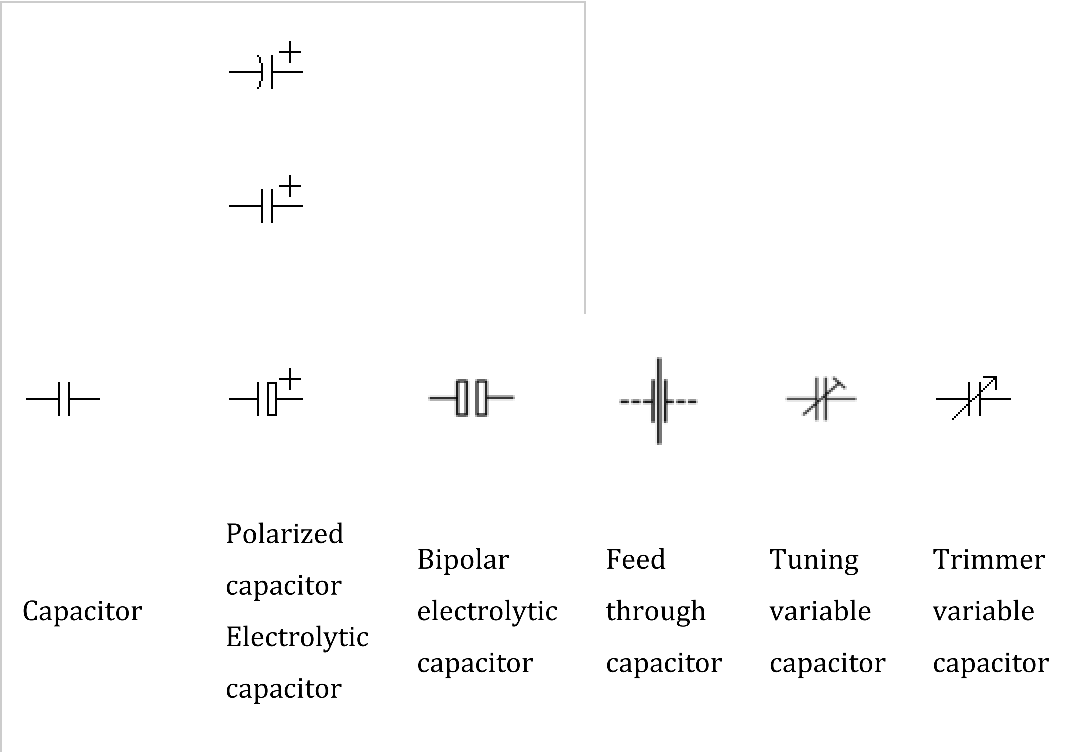
Electrolytic capacitors

- IEC/EN 60384-3—*Surface mount fixed tantalum electrolytic capacitors with manganese dioxide solid electro*lyte
- IEC/EN 60384-4—*Aluminium electrolytic capacitors with solid (MnO2) and non-solid electrolyte*
- IEC/EN 60384-15—*fixed tantalum capacitors with non-solid and solid electrolyte*
- IEC/EN 60384-18—*Fixed aluminium electrolytic surface mount capacitors with solid (MnO_2) and non-solid electrolyte*
- IEC/EN 60384-24—*Surface mount fixed tantalum electrolytic capacitors with conductive polymer solid electrolyte*
- IEC/EN 60384-25—*Surface mount fixed aluminium electrolytic capacitors with conductive polymer solid electrolyte*
- IEC/EN 60384-26-*Fixed aluminium electrolytic capacitors with conductive polymer solid electrolyte*

Supercapacitors

- IEC/EN 62391-1—*Fixed electric double-layer capacitors for use in electric and electronic equipment - Part 1: Generic specification*
- IEC/EN 62391-2—*Fixed electric double-layer capacitors for use in electronic equipment - Part 2: Sectional specification - Electric double-layer capacitors for power application*

Capacitor symbols



Capacitor symbols

Markings

Imprinted

Capacitors, like most other electronic components and if enough space is available, have imprinted markings to indicate manufacturer, type, electrical and thermal characteristics, and date of manufacture. If they are large enough the capacitor is marked with:

- manufacturer's name or trademark;
- manufacturer's type designation;

- polarity of the terminations (for polarized capacitors)
- rated capacitance;
- tolerance on rated capacitance
- rated voltage and nature of supply (AC or DC)
- climatic category or rated temperature;
- year and month (or week) of manufacture;
- certification marks of safety standards (for safety EMI/RFI suppression capacitors)

Polarized capacitors have polarity markings, usually "−" (minus) sign on the side of the negative electrode for electrolytic capacitors or a stripe or "+" (plus) sign, see #Polarity marking. Also, the negative lead for leaded "wet" e-caps is usually shorter.

Smaller capacitors use a shorthand notation. The most commonly used format is: XYZ J/K/M VOLTS V, where XYZ represents the capacitance (calculated as XY × 10^Z pF), the letters J, K or M indicate the tolerance (±5%, ±10% and ±20% respectively) and VOLTS V represents the working voltage.

Examples:

- 105K 330V implies a capacitance of 10 × 10^5 pF = 1 µF (K = ±10%) with a working voltage of 330 V.
- 473M 100V implies a capacitance of 47 × 10^3 pF = 47 nF (M = ±20%) with a working voltage of 100 V.

Capacitance, tolerance and date of manufacture can be indicated with a short code specified in IEC/EN 60062. Examples of short-marking of the rated capacitance (microfarads): µ47 = 0,47 µF, 4µ7 = 4,7 µF, 47µ = 47 µF

The date of manufacture is often printed in accordance with international standards.

- Version 1: coding with year/week numeral code, "1208" is "2012, week number 8".
- Version 2: coding with year code/month code. The year codes are: "R" = 2003, "S"= 2004, "T" = 2005, "U" = 2006, "V" = 2007, "W" = 2008, "X" = 2009, "A" = 2010, "B" = 2011, "C" = 2012, "D" = 2013, etc. Month codes are: "1" to "9" = Jan. to Sept., "O" = October, "N" = November, "D" = December. "X5" is then "2009, May"

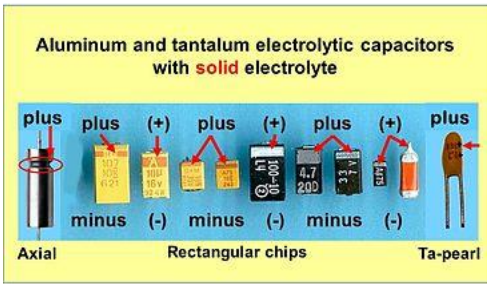
For very small capacitors like MLCC chips no marking is possible. Here only the traceability of the manufacturers can ensure the identification of a type.

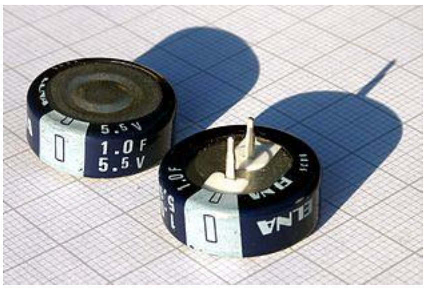
Colour coding

As of 2013 Capacitors do not use color coding.

Polarity marking

Polarity marking





Aluminum e-caps with non-solid electrolyte have a polarity marking at the cathode (minus) side. Aluminum, tantalum, and niobium e-caps with solid electrolyte have a polarity marking at the anode (plus) side. Super-capacitor are marked at the minus side.

Market segments

Discrete capacitors today are industrial products produced in very large quantities for use in electronic and in electrical equipment. Globally, the market for fixed capacitors was estimated at approximately US$18 billion in 2008 for 1,400 billion (1.4×10^{12}) pieces.[73] This market is dominated by ceramic capacitors with estimate of approximately one trillion (1×10^{12}) items per year.

Detailed estimated figures in value for the main capacitor families are:

- Ceramic capacitors—US$8.3 billion (46%);
- Aluminum electrolytic capacitors—US$ 3.9 billion (22%);
- Film capacitors and Paper capacitors—US$ 2.6 billion, (15%);
- Tantalum electrolytic capacitors—US$ 2.2 billion (12%);
- Super capacitors (Double-layer capacitors)—US$ 0.3 billion (2%); and
- Others like silver mica and vacuum capacitors—US$ 0.7 billion (3%).

All other capacitor types are negligible in terms of value and quantity compared with the above types.

5.4 SERIES AND PARALLEL CONNECTION OF CAPACITORS

Capacitors in Series and in Parallel

Capacitors are one of the standard components in electronic circuits. Moreover, complicated combinations of capacitors often occur in practical circuits. It is, therefore, useful to have a set of rules for finding the equivalent capacitance of some general arrangement of capacitors. It turns out that we can always find the equivalent capacitance by repeated application oftwo simple rules. These rules related to capacitors connected in series and in parallel.

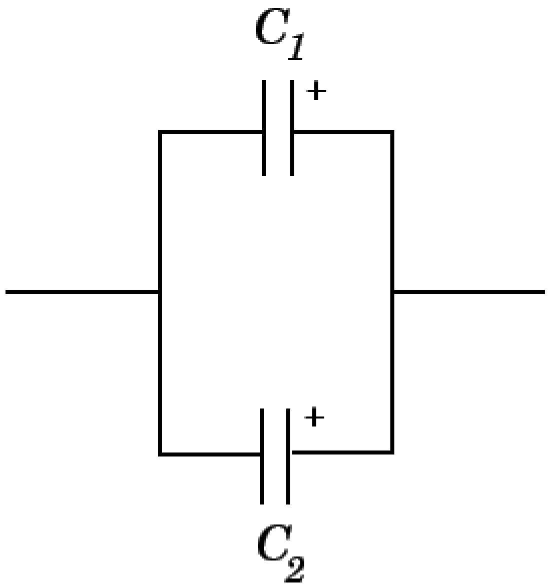


Figure 15: Two capacitors connected in parallel.

Consider two capacitors connected in parallel: i.e., with the positively charged plates connected to a common ``input'' wire, and the negatively charged plates attached to a common ``output'' wire--see Fig. 15. What is the equivalent capacitance between the input and output wires? In this case, the potential difference V across the two capacitors is the same, and is equal to the potential difference between the input and output wires. The total charge Q, however, stored in the two capacitors is divided between the capacitors, since it must distribute itself such that the voltage across the two is the same. Since the capacitors may have different capacitances, C_1 and C_2, the charges Q_1 and Q_2 may also be different. The equivalent capacitance C_{eq} of the pair of capacitors is simply the ratio Q/V, where $Q = Q_1 + Q_2$ is the total stored charge. It follows that

$$C_{eq} = \frac{Q}{V} = \frac{Q_1 + Q_2}{V} = \frac{Q_1}{V} + \frac{Q_2}{V}, \tag{113}$$

giving

$$C_{eq} = C_1 + C_2. \tag{114}$$

Here, we have made use of the fact that the voltage V is common to all three capacitors. Thus, the rule is:

The equivalent capacitance of two capacitors connected in parallel is the sum of the individual capacitances.

For N capacitors connected in parallel, Eq. (114) generalizes to $C_{eq} = \sum_{i=1}^{N} C_i$.

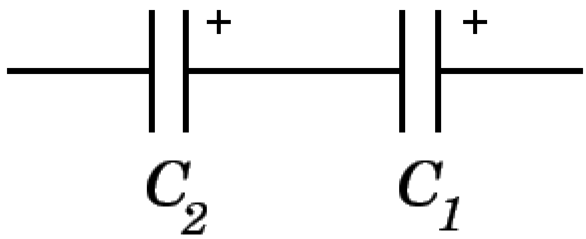


Figure 16: Two capacitors connected in series.

Consider two capacitors connected in series: i.e., in a line such that the positive plate of one is attached to the negative plate of the other--see Fig. 16. In fact, let us suppose that the positive plate of capacitor 1 is connected to the ``input'' wire, the negative plate of capacitor 1 is connected to the positive plate of capacitor 2, and the negative plate of capacitor 2 is connected to the ``output'' wire. What is the equivalent capacitance between the input and output wires? In this case, it is important to realize that the charge Q stored in the two capacitors is the same. This is most easily seen by considering the ``internal'' plates: i.e., the negative plate of capacitor 1, and the positive plate of capacitor 2. These plates are physically disconnected from the rest of the circuit, so the total charge on them must remain constant. Assuming, as seems reasonable, that these plates carry zero charge when zero potential difference is applied across the two capacitors, it follows that in the presence of a non-zero potential difference the charge $+Q$ on the positive plate of capacitor 2 must be balanced by an equal and opposite charge $-Q$ on the negative plate of capacitor 1. Since the negative plate of capacitor 1 carries a charge $-Q$, the positive plate must carry a charge $+Q$. Likewise, since the positive plate of capacitor 2 carries a charge $+Q$, the negative plate must carry a charge $-Q$. The net result is that both capacitors possess the same stored charge Q. The potential drops, V_1 and V_2, across the two capacitors are, in general, different. However, the sum of these drops equals the total potential drop V applied across the input and output wires: i.e., $V = V_1 + V_2$. The equivalent capacitance of the pair of capacitors is again $C_{eq} = Q/V$. Thus,

$$\frac{1}{C_{eq}} = \frac{V}{Q} = \frac{V_1 + V_2}{Q} = \frac{V_1}{Q} + \frac{V_2}{Q}, \tag{115}$$

giving

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2}. \tag{116}$$

Here, we have made use of the fact that the charge Q is common to all three capacitors. Hence, the rule is:

The reciprocal of the equivalent capacitance of two capacitors connected in series is the sum of the reciprocals of the individual capacitances.

For N capacitors connected in series, Eq. (116) generalizes to $1/C_{eq} = \sum_{i=1}^{N} (1/C_i)$.

5.5 ENERGY STORED IN A CAPACITOR

Let us consider charging an initially uncharged parallel plate capacitor by transferring a charge Q from one plate to the other, leaving the former plate with charge $-Q$ and the later with charge $+Q$. Of course, once we have transferred some charge, an electric field is set up between the plates which opposes any further charge transfer. In order to fully charge the capacitor, we must do work against this field, and this work becomes energy stored in the capacitor. Let us calculate this energy.

Suppose that the capacitor plates carry a charge q and that the potential difference between the plates is V. The work we do in transferring an *infinitesimal* amount of charge dq from the negative to the positive plate is simply

$$dW = V\,dq. \tag{117}$$

In order to evaluate the total work $W(Q)$ done in transferring the total charge Q from one plate to the other, we can divide this charge into many small increments dq, find the incremental work dW done in transferring this incremental charge, using the above formula, and then sum all of these works. The only complication is that the potential difference V between the plates is a function of the total transferred charge. In fact, $V(q) = q/C$, so

$$dW = \frac{q\,dq}{C}. \tag{118}$$

Integration yields

$$W(Q) = \int_0^Q \frac{q\,dq}{C} = \frac{Q^2}{2\,C}. \tag{119}$$

Note, again, that the work W done in charging the capacitor is the same as the energy stored in the capacitor. Since $C = Q/V$, we can write this stored energy in one of three equivalent forms:

$$W = \frac{Q^2}{2C} = \frac{C V^2}{2} = \frac{Q V}{2}. \tag{120}$$

These formulae are valid for any type of capacitor, since the arguments that we used to derive them do not depend on any special property of parallel plate capacitors.

Where is the energy in a parallel plate capacitor actually stored? Well, if we think about it, the only place it could be stored is in the electric field generated between the plates. This insight allows us to calculate the energy (or, rather, the energy density) of an electric field.

Consider a vacuum-filled parallel plate capacitor whose plates are of cross sectional area A, and are spaced a distance d apart. The electric field E between the plates is approximately uniform, and of magnitude σ/ϵ_0, where $\sigma = Q/A$, and Q is the charge stored on the plates. The electric field elsewhere is approximately zero. The potential difference between the plates is $V = E\,d$. Thus, the energy stored in the capacitor can be written

$$W = \frac{C V^2}{2} = \frac{\epsilon_0\,A\,E^2\,d^2}{2\,d} = \frac{\epsilon_0\,E^2\,Ad}{2}, \tag{121}$$

where use has been made of Eq. (108). Now, $A\,d$ is the volume of the field-filled region between the plates, so if the energy is stored in the electric field then the energy per unit volume, or *energy density*, of the field must be

$$w = \frac{\epsilon_0\,E^2}{2}. \tag{122}$$

It turns out that this result is quite general. Thus, we can calculate the energy content of any electric field by dividing space into little cubes, applying the above formula to find the energy content of each cube, and then summing the energies thus obtained to obtain the total energy.

It is easily demonstrated that the energy density in a dielectric medium is

$$w = \frac{\epsilon E^2}{2}, \tag{123}$$

where $\epsilon = K \epsilon_0$ is the permittivity of the medium. This energy density consists of two elements: the energy density $\epsilon_0 E^2/2$ held in the electric field, and the energy density $(K-1) \epsilon_0 E^2/2$ held in the dielectric medium (this represents the work done on the constituent molecules of the dielectric in order to polarize them).

UNIT- 6

ELECTROMAGNETIC EFFECTS

6.1 PERMANENT MAGNETS AND ELECTROMAGNETS

Permanent Magnets and Electromagnets: What are the Differences?

A permanent magnet is an object made from a material that is magnetized and creates its own persistent magnetic field. As the name suggests, a permanent magnet is 'permanent'. This means that it always has a magnetic field and will display a magnetic behavior at all times.

An electromagnet is made from a coil of wire which acts as a magnet when an electric current passes through it. Often an electromagnet is wrapped around a core of ferromagnetic material like steel, which enhances the magnetic field produced by the coil.

Permanent Magnet v. Electromagnet: Magnetic Properties

A permanent magnet's magnetic properties exist when the magnet is (magnetized). An electromagnetic magnet only displays magnetic properties when an electric current is applied to it. That is how you can differentiate between the two. The magnets that you have affixed to your refrigerator are permanent magnets, while electromagnets are the principle behind AC motors.

Permanent Magnet v. Electromagnet: Magnetic Strength

Permanent magnet strength depends upon the material used in its creation. The strength of an electromagnet can be adjusted by the amount of electric current allowed to flow into it. As a result, the same electromagnet can be adjusted for different strength levels.

Permanent Magnet v. Electromagnet: Loss of Magnetic Properties

If a permanent magnet loses its magnetic properties, as it does by heating to a (maximum) temperature, it will be rendered useless and its magnetic properties can be only recovered by re-magnetizing. Contrarily, an electromagnet loses its magnetic power every time an electric current is removed and becomes magnetic once again when the electric field is introduced.

Permanent Magnet v. Electromagnet: Advantages

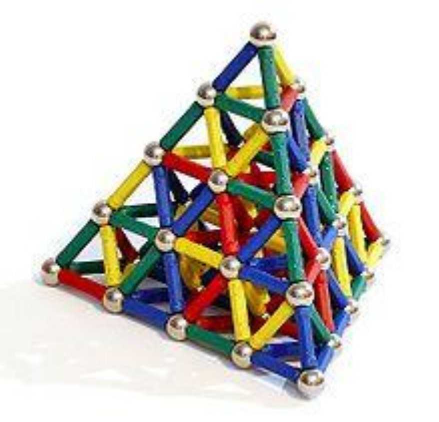
The main advantage of a permanent magnet over an electromagnet is that a permanent magnet does not require a continuous supply of electrical energy to maintain its magnetic field. However, an electromagnet's magnetic field can be rapidly manipulated over a wide range by controlling the amount of electric current supplied to the electromagnet.

USES

- Magnetic recording media: VHS tapes contain a reel of magnetic tape. The information that makes up the video and sound is encoded on the magnetic coating on the tape. Common audio cassettes also rely on magnetic tape. Similarly, in computers, floppy disks and hard disks record data on a thin magnetic coating.
- Credit, debit, and automatic teller machine cards: All of these cards have a magnetic strip on one side. This strip encodes the information to contact an individual's financial institution and connect with their account(s).
- Common televisions and computer monitors: TV and computer screens containing a cathode ray tube employ an electromagnet to guide electrons to the screen. Plasma screens and LCDs use different technologies.
- Speakers and microphones: Most speakers employ a permanent magnet and a current-carrying coil to convert electric energy (the signal) into mechanical energy (movement that creates the sound). The coil is wrapped around a bobbin attached to the speaker cone and carries the signal as changing current that interacts with the field of the permanent magnet. The voice coil feels a magnetic force and in response, moves the cone and pressurizes the neighboring air, thus generating sound. Dynamic microphones employ the same concept, but in reverse. A microphone has a diaphragm or membrane

attached to a coil of wire. The coil rests inside a specially shaped magnet. When sound vibrates the membrane, the coil is vibrated as well. As the coil moves through the magnetic field, a voltage is induced across the coil. This voltage drives a current in the wire that is characteristic of the original sound.

- Electric guitars use magnetic pickups to transduce the vibration of guitar strings into electric current that can then be amplified. This is different from the principle behind the speaker and dynamic microphone because the vibrations are sensed directly by the magnet, and a diaphragm is not employed. The Hammond organ used a similar principle, with rotating tone wheels instead of strings.
- Electric motors and generators: Some electric motors rely upon a combination of an electromagnet and a permanent magnet, and, much like loudspeakers, they convert electric energy into mechanical energy. A generator is the reverse: it converts mechanical energy into electric energy by moving a conductor through a magnetic field.
- Medicine: Hospitals use magnetic resonance imaging to spot problems in a patient's organs without invasive surgery.
- Chemistry: Chemists use nuclear magnetic resonance to characterize synthesized compounds.
- Chucks are used in the metalworking field to hold objects. Magnets are also used in other types of fastening devices, such as the magnetic base, the magnetic clamp and the refrigerator magnet.
- Compasses: A compass (or mariner's compass) is a magnetized pointer free to align itself with a magnetic field, most commonly Earth's magnetic field.
- Art: Vinyl magnet sheets may be attached to paintings, photographs, and other ornamental articles, allowing them to be attached to refrigerators and other metal surfaces. Objects and paint can be applied directly to the magnet surface to create collage pieces of art. Magnetic art is portable, inexpensive and easy to create. Vinyl magnetic art is not for the refrigerator anymore. Colorful metal magnetic boards, strips, doors, microwave ovens, dishwashers, cars, metal I beams, and any metal surface can be receptive of magnetic vinyl art. Being a relatively new media for art, the creative uses for this material is just beginning.
- Science projects: Many topic questions are based on magnets, including the repulsion of current-carrying wires, the effect of temperature, and motors involving magnets.



- Magnets have many uses in toys. M-tic uses magnetic rods connected to metal spheres for construction. Note the geodesic pyramid
- Toys: Given their ability to counteract the force of gravity at close range, magnets are often employed in children's toys, such as theMagnet Space Wheel and Levitron, to amusing effect.
- Refrigerator magnets are used to adorn kitchens, as a souvenir, or simply to hold a note or photo to the refrigerator door.
- Magnets can be used to make jewelry. Necklaces and bracelets can have a magnetic clasp, or may be constructed entirely from a linked series of magnets and ferrous beads.
- Magnets can pick up magnetic items (iron nails, staples, tacks, paper clips) that are either too small, too hard to reach, or too thin for fingers to hold. Some screwdrivers are magnetized for this purpose.
- Magnets can be used in scrap and salvage operations to separate magnetic metals (iron, cobalt, and nickel) from non-magnetic metals (aluminum, non-ferrous alloys, etc.). The same idea can be used in the so-called "magnet test", in which an auto body is inspected with a magnet to detect areas repaired using fiberglass or plastic putty.
- Magnetic levitation transport, or maglev, is a form of transportation that suspends, guides and propels vehicles (especially trains) through electromagnetic force. The maximum recorded speed of a maglev train is 581 kilometers per hour (361 mph).
- Magnets may be used to serve as a fail-safe device for some cable connections. For example, the power cords of some laptops are magnetic to prevent accidental damage to the port when tripped over. The MagSafe power connection to the Apple MacBook is one such example.

6.2 POLARITIES OF AN ELECTROMAGNET AND RULES FOR FINDING THEM.

There are some simple rules to help you find out which end of an electromagnet is north and which is south.

(a) Direction of the current round the ends of the coil of wire (Physicists call a straight coil of wire a solenoid).

Look at the ends of the coil from the outside; the direction of the current follows the direction of the letters N and S for north and south (see Figure 1).

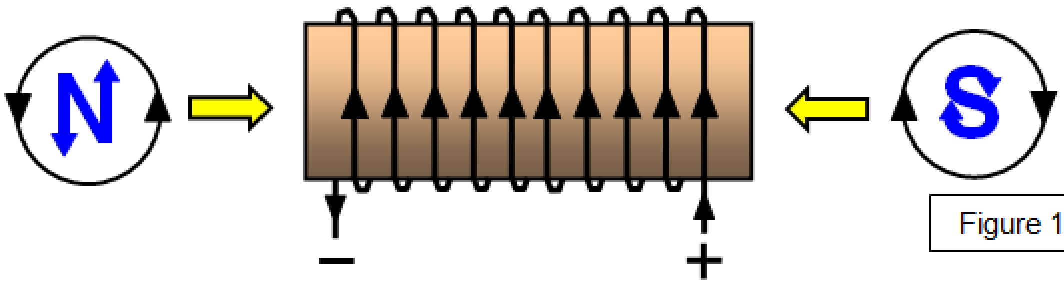


Figure 1

(b) the right hand grip rule

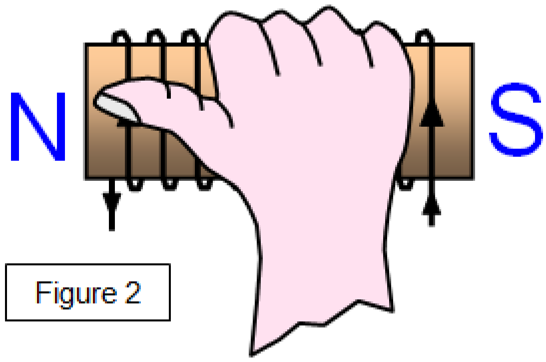


Figure 2

(i)for a solenoid

If you imagine gripping the solenoid with your right hand so that your fingers follow the direction of the current then your thumb will point towards the **NORTH** end of the electromagnet (see Figure 2).

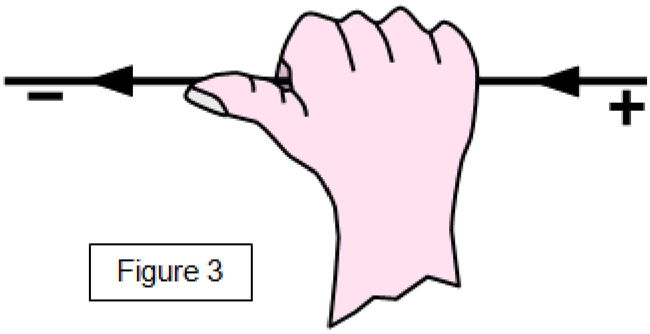
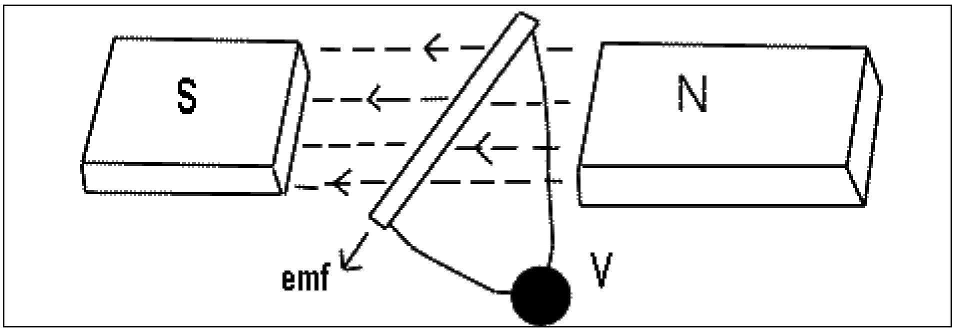


Figure 3

(ii) for a straight wire

If you imagine griping the wire with your right hand with your thumb in the direction of the current then your fingers will show the direction of the magnetic field round the wire pointing from **NORTH to SOUTH.**

6.3 FARADAY'S LAWS OF ELECTROMAGNETIC INDUCTION



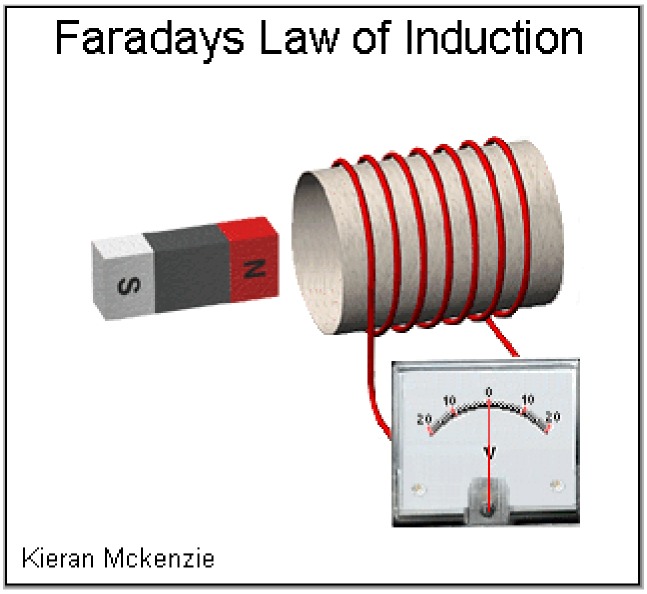
In 1831, Micheal Faraday formulated two laws on the bases of experiments. These laws are called Faraday's laws of electromagnetic induction.

FIRST LAW

First Law of Faraday's Electromagnetic Induction state that whenever a conductor are placed in a varying magnetic field emf are induced which is called induced emf, if the conductor circuit are closed current are also induced which is called induced current.

Or

Whenever a conductor is rotated in magnetic field emf is induced which are induced emf.



SECOND LAW

Second Law of Faraday's Electromagnetic Induction state that the induced emf is equal to the rate of change of flux linkages (flux linkages is the product of turns, n of the coil and the flux associated with it).

FARADAY'S LAW'S EXPLANATION

Let

Initial flux linkages = Nφ1

Final flux linkages = Nφ2

Change in flux linkages= Nφ2 – Nφ1

=N((φ2-φ1)

If (φ2-φ1)= φ

Then change in flux linkages=Nφ

Rate of change of flux linkages= Nφ/t wb/sec

Taking derivative of right hand side we get

Rate of change of flux linkages= $N d\varphi/dt$ wb/sec

Rut according to Faraday's laws of electromagnetic induction, the rate of change of flux linkages equal to the induced emf, hence we can write

$= N d\varphi/dt$ volt

Generally Faraday's laws is written as

$e = -N d\varphi/dt$ volt

Where negative sign represents the direction of the induced current in the conductor will be such that the magnetic field produced by it will oppose the verb cause produce it.

6.4 DYNAMICALLY INDUCED EMF AND STATICALLY INDUCED EMF

When emf is induced in a coil or conductor by virtue of movement of either the conductor or the magnetic field, the emf is called dynamically induced EMF as has been explained in section 1.11.

When EMF is induced in a stationary coil by changing its flux linkage due to change in current flow through the coil, such emf is called statically induced EMF.

If a coil carries a current, flux is established around the coil. If the current is changed quickly, the flux linkage by the coil will change as shown in Fig. 1.13 (a).

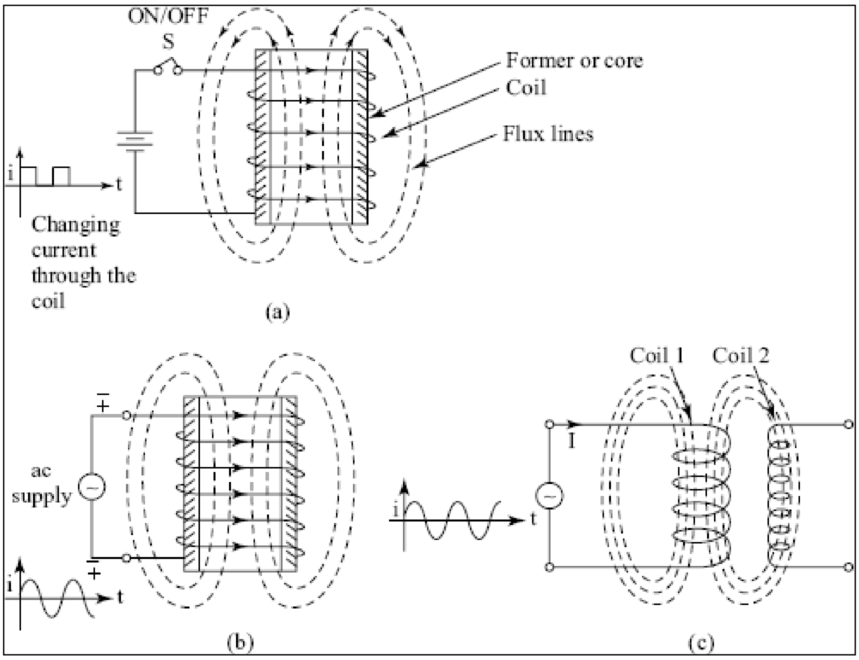


Figure 1.13 (a) Change in flux linkage in a coil due to switching ON and switching OFF of dc current; (b) change in flux linkage due to alternating current supply;(c) induced emf in coils 1 and 2 due to changing flux produced by alternating current flowing in coil 1

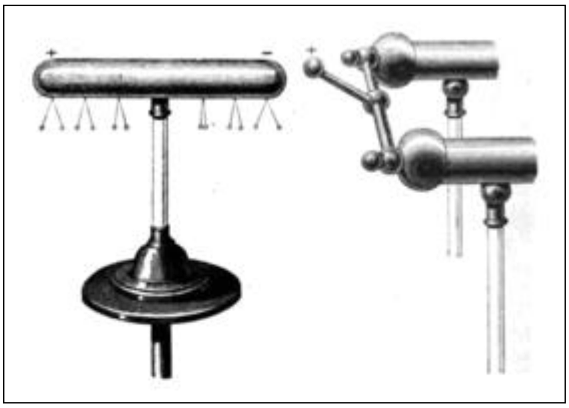
In Fig. 1.13 (a), a coil of certain number of turns is wound on a former, i.e., its core. Current is supplied from a battery by closing a switch S. If the switch is continuously turned on and off, flux linkage by the coil will change. The rate of change of the flux linkage will induce EMF in the coil.

A similar effect will be there if an ac supply is applied across the coil as shown in Fig. 1.13 (b). The direction of current in the coil is shown for the positive half cycle of the alternating current. The direction of current will change in every half cycle, and hence the direction of flux produced will change in every half cycle. The magnitude of current changes continuously since a sinusoidal current is flowing. This changing current will create a changing flux linkage, thereby inducing EMF in the coil in both the cases as shown in Fig. 1.13 (a) and (b). Note that in Fig. 1.13 (a), if the switch S is kept closed, a steady direct current, i.e., a constant current will flow through the coil.

This constant current will produce a constant flux. There will be no change in flux linkage by the coil with respect to time, and hence no EMF will be induced in the coil. Thus, the **necessary condition for the production of induced EMF is that there should be a change in flux linkage and not merely flux linkage by a coil.**

6.5 Static induction

Electrostatic induction is a redistribution of electrical charge in an object, caused by the influence of nearby charges. Induction was discovered by British scientist John Canton in 1753 and Swedish professor Johan Carl Wilcke in 1762. Electrostatic generators, such as the Wimshurst machine, the Van de Graaff generator and the electrophorus, use this principle. Due to induction, the electrostatic potential (voltage) is constant at any point throughout a conductor.[3] Induction is also responsible for the attraction of light nonconductive objects, such as balloons, paper or styrofoam scraps, to static electric charges. Electrostatic induction should not be confused with electromagnetic induction.



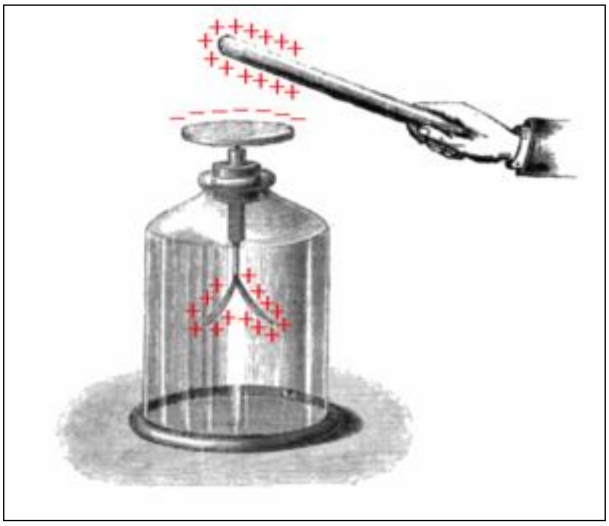
Demonstration of induction, in 1870s. The positive terminal of an electrostatic machine is placed near an uncharged brass cylinder, causing the left end to acquire a positive charge and the right to acquire a negative charge. The small pith ball electroscopeshanging from the bottom show that the charge is concentrated at the ends.

A normal uncharged piece of matter has equal numbers of positive and negative electric charges in each part of it, located close together, so no part of it has a net electric charge. The positive charges are the atoms' nucleiwhich are bound into the structure of matter and are not free to move. The negative charges are the atoms' electrons. In electrically conductive objects such as metals, some of the electrons are able to move freely about in the object.

When a charged object is brought near an uncharged, electrically conducting object, such as a piece of metal, the force of the nearby charge causes a separation of these charges. For example, if a positive charge is brought near the object (see picture at right), the electrons in the metal will be attracted toward it and move to the side of the object facing it. When the electrons move out of an area, they leave an unbalanced positive charge due to the nuclei. This results in a region of negative charge on the object nearest to the external charge, and a region of positive charge on the part away from it. These are called *induced charges*. If the external charge is negative, the polarity of the charged regions will be reversed.

Since this process is just a redistribution of the charges that were already in the object, it doesn't change the *total* charge on the object; it still has no net charge. This induction effect is reversible; if the nearby charge is removed, the attractions between the positive and negative internal charges cause them to intermingle again.

Charging an object by induction



Gold-leaf electroscope, showing induction, before the terminal is grounded.

However, the induction effect can also be used to put a net charge on an object. If, while it is close to the positive charge, the above object is momentarily connected through a conductive path to electrical ground, which is a large reservoir of both positive and negative charges, some of the negative charges in the ground will flow into the object, under the attraction of the nearby positive charge. When the contact with ground is broken, the object is left with a net negative charge.

This method can be demonstrated using a gold-leaf electroscope, which is an instrument for detecting electric charge. The electroscope is first discharged, and a charged object is then brought close to the instrument's top terminal. Induction causes a separation of the charges inside the electroscope's metal rod, so that the top terminal gains a net charge of opposite polarity to that of the object, while the gold leaves gain a charge of the same polarity. Since both leaves have the same charge, they repel each other and spread apart. The electroscope has not acquired a net charge: the charge within it has merely been redistributed, so if the charged object were to be moved away from the electroscope the leaves will come together again.

But if an electrical contact is now briefly made between the electroscope terminal and ground, for example by touching the terminal with a finger, this causes charge to flow from ground to the terminal, attracted by the charge on the object close to the terminal. This charge neutralizes the charge in the gold leaves, so the leaves come together again. The electroscope now contains a net charge opposite in polarity to that of the charged object. When the electrical contact to earth is broken, e.g. by lifting the finger, the extra charge that has just flowed into the electroscope cannot escape, and the instrument retains a net charge. The charge is held in the top of the electroscope terminal by the attraction of the inducing charge. But when the inducing charge is moved away, the charge is released and spreads throughout the electroscope terminal to the leaves, so the gold leaves move apart again.

The sign of the charge left on the electroscope after grounding is always opposite in sign to the external inducing charge. The two rules of induction are:

- If the object is not grounded, the nearby charge will induce *equal* and *opposite* charges in the object.
- If *any part* of the object is momentarily grounded while the inducing charge is near, a charge opposite in polarity to the inducing charge will be attracted from ground into the object, and it will be left with a charge*opposite* to the inducing charge.

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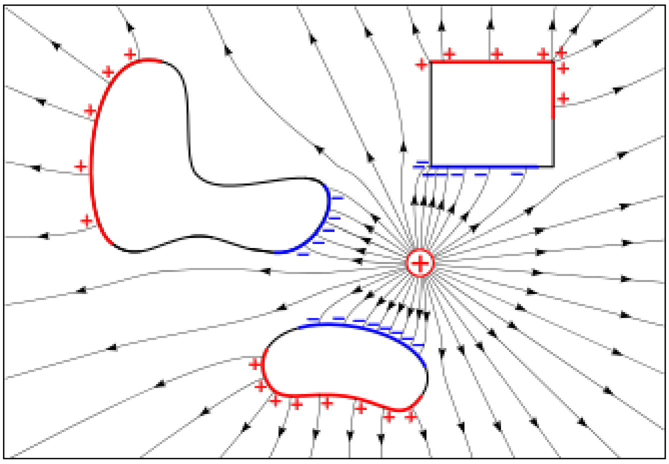
The electrostatic field inside a conductive object is zero



Surface charges induced in metal objects by a nearby charge. The electrostatic field *(lines with arrows)* of a nearby positive charge *(+)* causes the mobile charges in metal objects to separate. Negative charges *(blue)*are attracted and move to the surface of the object facing the external charge. Positive charges *(red)* are repelled and move to the surface facing away. These induced surface charges create an opposing electric field that exactly cancels the field of the external charge throughout the interior of the metal. Therefore electrostatic induction ensures that the electric field everywhere inside a conductive object is zero.

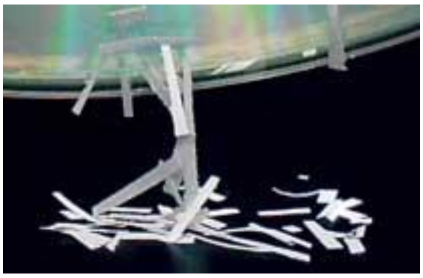
A remaining question is how large the induced charges are. The movement of charge is caused by the force exerted by the electric field of the external charged object. As the charges in the metal object continue to separate, the resulting positive and negative regions create their own electric field, which opposes the field of the external charge. This process continues until very quickly (within a fraction of a second) an equilibrium is reached in which the induced charges are exactly the right size to cancel the external electric field throughout the interior of the metal object. Then the remaining mobile charges (electrons) in the interior of the metal no longer feel a force and the net motion of the charges stops.

Induced charge resides on the surface

Since the mobile charges in the interior of a metal object are free to move in any direction, there can never be a static concentration of charge inside the metal; if there was, it would attract opposite polarity charge to neutralize it. Therefore in induction, the mobile charges move under the influence of the external charge until they reach the surface of the metal and collect there, where they are constrained from moving by the boundary.

This establishes the important principle that electrostatic charges on conductive objects reside on the surface of the object. External electric fields induce surface charges on metal objects that exactly cancel the field within.] Since the field is the gradient of the electrostatic potential, another way of saying this is that in electrostatics, the potential (voltage) throughout a conductive object is constant.

Induction in dielectric objects



A similar induction effect occurs in nonconductive (dielectric) objects, and is responsible for the attraction of small light nonconductive objects, like balloons, scraps of paper or Styrofoam, to static electric charges.[7][8][9][10] In nonconductors, the electrons are bound to atoms or molecules and are not free to move about the object as in conductors; however they can move a little within the molecules.

If a positive charge is brought near a nonconductive object, the electrons in each molecule are attracted toward it, and move to the side of the molecule facing the charge, while the positive nuclei are repelled and move slightly to the opposite side of the molecule. Since the negative charges are now closer to the external charge than the positive charges, their attraction is greater than the repulsion of the positive charges, resulting in a small net attraction of the molecule toward the charge. This is called polarization, and the polarized molecules are called dipoles. This effect is microscopic, but since there are so many molecules, it adds up to enough force to move a light object like Styrofoam. This is the principle of operation of a pith-ball electroscope.

6.6 ENERGY STORED IN AN INDUCTANCE.

Suppose that an inductor of inductance L is connected to a variable DC voltage supply. The supply is adjusted so as to increase the current i flowing through the inductor from zero to some final value I. As the current through the inductor is ramped up, an emf $\mathcal{E} = -L\, di/dt$ is generated, which acts to oppose the increase in the current. Clearly, work must be done against this emf by the voltage source in order to establish the current in the inductor. The work done by the voltage source during a time interval dt is

$$dW = P\, dt = -\mathcal{E}\, i\, dt = i\, L\, \frac{di}{dt}\, dt = L\, i\, di.$$

Here, $P = -\mathcal{E}\, i$ is the instantaneous rate at which the voltage source performs work. To find the total work W done in establishing the final current I in the inductor, we must integrate the above expression. Thus,

$$W = L \int_0^I i\, di,$$

giving

$$W = \frac{1}{2}\, L\, I^2.$$

This energy is actually stored in the magnetic field generated by the current flowing through the inductor. In a pure inductor, the energy is stored without loss, and is returned to the rest of the circuit when the current through the inductor is ramped down, and its associated magnetic field collapses.

Consider a simple solenoid. Equations can be combined to give

$$W = \frac{1}{2}\,L\,I^2 = \frac{\mu_0\,N^2\,A}{2\,l}\,\left(\frac{B\,l}{\mu_0\,N}\right)^2,$$

which reduces to

$$W = \frac{B^2}{2\,\mu_0}\,l\,A.$$

This represents the energy stored in the magnetic field of the solenoid. However, the volume of the field-filled core of the solenoid is $l\,A$, so the magnetic energy density (*i.e.*, the energy per unit volume) inside the solenoid is $w = W/(l\,A)$, or

$$w = \frac{B^2}{2\,\mu_0}.$$

It turns out that this result is quite general. Thus, we can calculate the energy content of any magnetic field by dividing space into little cubes (in each of which the magnetic field is approximately uniform), applying the above formula to find the energy content of each cube, and summing the energies thus obtained to find the total energy.

When electric and magnetic fields exist together in space, Eqs. As mentioned above can be combined to give an expression for the total energy stored in the combined fields per unit volume:

$$w = \frac{\epsilon_0\,E^2}{2} + \frac{B^2}{2\,\mu_0}.$$

The RL Circuit

Consider a circuit in which a battery of emf V is connected in series with an inductor of inductance L and a resistor of resistance R. For obvious reasons, this type of circuit is usually called an RL *circuit*. The resistance R includes the resistance of the wire loops of the inductor, in addition to any other resistances in the circuit.

In steady-state, the current I flowing around the the circuit has the magnitude

$$I = \frac{V}{R} \tag{254}$$

specified by Ohm's law. Note that, in a steady-state, or DC, circuit, zero back-emf is generated by the inductor, according to Eq. (243), so the inductor effectively disappears from the circuit. In fact, inductors have no effect whatsoever in DC circuits. They just act like pieces of conducting wire.

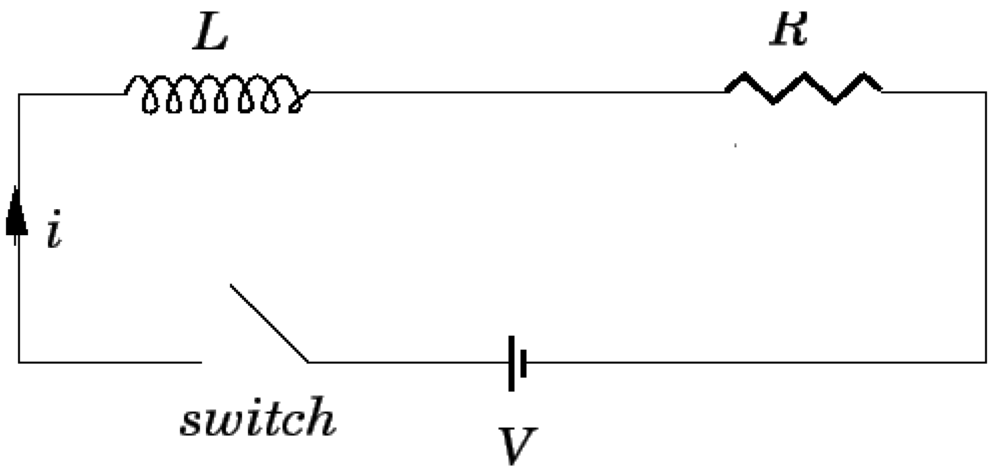


Figure 46: *An* RL *circuit with a switch.*

Let us now slightly modify our RL circuit by introducing a switch. The new circuit is shown in Fig. 46. Suppose that the switch is initially open, but is suddenly closed at $t = 0$. Obviously, we expect the instantaneous current i which flows around the circuit, once the switch is thrown, to eventually settle down to the steady-state value $I = V/R$. But, how long does this process take? Note that as the current flowing around the circuit is building up to its final value, a non-zero back-emf is generated in the inductor, according to Eq. (243). Thus, although the inductor does not affect the final steady-state value of the current flowing around the circuit, it certainly does affect how long after the switch is closed it takes for this final current to be established.

If the instantaneous current i flowing around the circuit changes by an amount di in a short time interval dt, then the emf generated in the inductor is given by [see Eq. (243)]

$$\mathcal{E} = -L\,\frac{di}{dt}. \tag{255}$$

Applying Ohm's law around the circuit, we obtain

$$V + \mathcal{E} = i\,R, \tag{256}$$

which yields

$$-L\,\frac{di}{dt} = i\,R - V. \tag{257}$$

Let

$$i' = i - I, \tag{258}$$

where $I = V/R$ is the steady-state current. Equation (257) can be rewritten

$$\frac{di'}{dt} = -i'\,\frac{R}{L}, \tag{259}$$

since $di' = di$ (because I is non-time-varying). At $t = 0$, just after the switch is closed, we expect the current i flowing around the circuit to be zero. It follows from Eq. (258) that

$$i'(t=0) = -I. \tag{260}$$

Integration of Eq. (259), subject to the initial condition (260), yields

$$i'(t) = -I\,\mathrm{e}^{-R\,t/L}. \tag{261}$$

Thus, it follows from Eq. (258) that

$$i(t) = I\,(1 - \mathrm{e}^{-R\,t/L}). \tag{262}$$

The above expression specifies the current i flowing around the circuit a time interval t after the switch is closed (at time $t = 0$). The variation of the current with time is sketched in Fig. 47. It can be seen that when the switch is closed the current i flowing in the circuit does not suddenly jump up to its final value, $I = V/R$. Instead, the current increases smoothly from zero, and gradually asymptotes to its final value. The current has risen to approximately 63% of its final value a time

$$\tau = \frac{L}{R} \tag{263}$$

after the switch is closed (since $\mathrm{e}^{-1} \simeq 0.37$). By the time $t = 5\,\tau$, the current has risen to more than 99% of its final value (since $\mathrm{e}^{-5} < 0.01$). Thus, $\tau = L/R$ is a good measure of how long after the switch is closed it takes for the current flowing in the circuit to attain its steady-state value. The quantity τ is termed the *time-constant* or, somewhat unimaginatively, the *L over R time*, of the circuit.

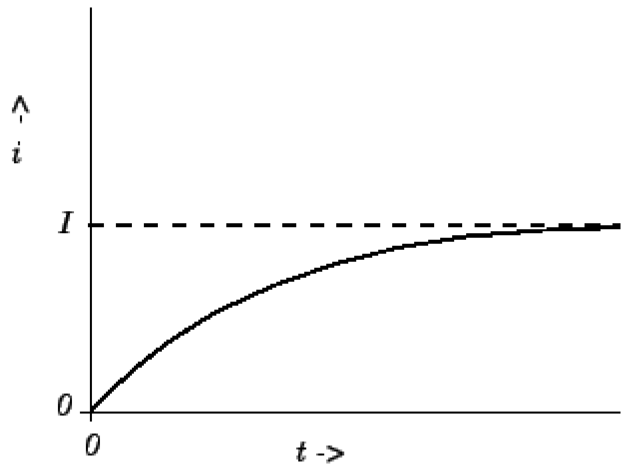


Figure 47: *Sketch of the current rise phase in an* RL *circuit switched on at* $t = 0$.

Suppose that the current flowing in the circuit discussed above has settled down to its steady-state value $I = V/R$. Consider what would happen if we were to suddenly (at $t = 0$, say) switch the battery out of the circuit, and replace it by a conducting wire. Obviously, we would expect the current to eventually decay away to zero, since there is no longer a steady emf in the circuit to maintain a steady current. But, how long does this process take?

Applying Ohm's law around the circuit, in the absence of the battery, we obtain

$$\mathcal{E} = i\,R, \tag{264}$$

where $\mathcal{E} = -L\,di/dt$ is the back-emf generated by the inductor, and i is the instantaneous current flowing around the circuit. The above equation reduces to

$$\frac{di}{dt} = -i\,\frac{R}{L}. \tag{265}$$

At $t = 0$, immediately after the battery is switched out of the circuit, we expect the current i flowing around the circuit to equal its steady-state value I, so that

$$i(t = 0) = I. \tag{266}$$

Integration of Eq. (265), subject to the boundary condition (266), yields

$$i(t) = I\,\mathrm{e}^{-Rt/L}. \tag{267}$$

According to the above formula, once the battery is switched out of the circuit, the current decays smoothly to zero. After one L/R time (*i.e.*, $t = L/R$), the current has decayed to 37% of its initial value. After five L/R times, the current has decayed to less than 1% of its initial value.

We can now appreciate the significance of self inductance. The back-emf generated in an inductor, as the current flowing through it tries to change, effectively prevents the current from rising (or falling) much faster than the L/R time of the circuit. This effect is sometimes advantageous, but is often a great nuisance. All circuits possess some self inductance, as well as some resistance, so all have a finite L/R time. This means that when we power up a DC circuit, the current does not jump up instantaneously to its steady-state value. Instead, the rise is spread out over the L/R time of the circuit. This is a good thing. If the current were to rise instantaneously then extremely large inductive electric fields would be generated by the sudden jump in the magnetic field, leading, inevitably, to breakdown and electric arcing. So, if there were no such thing as self inductance then every time we switched a DC electric circuit on or off there would be a big blue flash due to arcing between conductors. Self inductance can also be a bad thing. Suppose that we possess a fancy power supply, and wish to use it to send an electric signal down a wire. Of course, the wire will possess both resistance and inductance, and will, therefore, have some characteristic L/R time. Suppose that we try to send a square-wave signal down the wire. Since the current in the wire cannot rise or fall faster than the L/R time, the leading and trailing edges of the signal get smoothed out over an L/R time. The typical difference between the signal fed into the wire (upper trace) and that which comes out of the other end (lower trace) is illustrated in Fig. 48. Clearly, there is little point in us having a fancy power supply unless we also possess a low inductance wire, so that the signal from the power supply can be transmitted to some load device without serious distortion.

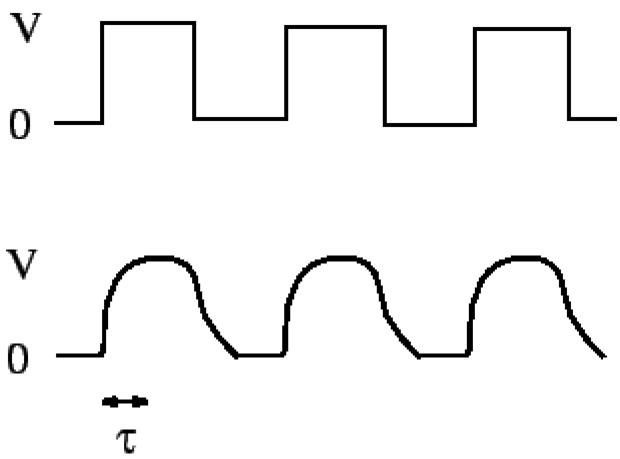


Figure 48: *Typical difference between the input wave-form (top) and the output wave-form (bottom) when a square-wave is sent down a line with finite* L/R *time,* τ *.*

6.7 TORQUE PRODUCED ON A CURRENT CARRYING COIL IN A MAGNETIC FIELD

Remember that when a current-carrying wire is placed in an external magnetic field then it will experience a magnetic force that can be calculated with the equation

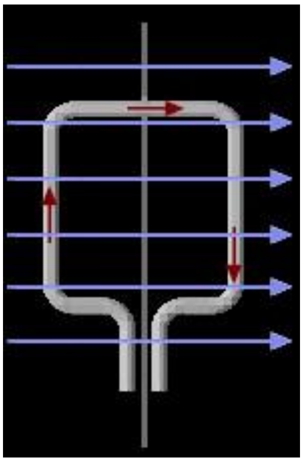
$$F = B_{\perp} I \ell$$

and obeys the right hand rule.

- thumb points in the direction of the current, I
- fingers point in the direction of the external magnetic field, B
- palm faces the direction of the force, F

This physlet by Walter Fendt illustrates this Lorentz force.

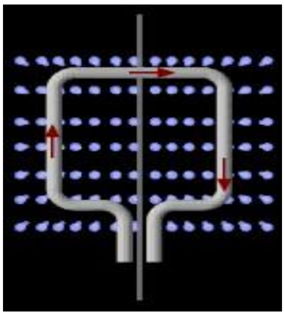
Example #1: Now let's place a freely-pivoting loop carrying a clockwise (red arrow) current in an external (+x) magnetic field.



i. as the current flows up the left side, it will experience a force in the -z direction.
ii. as the current flows across the top of the loop, no force is exerted since the current and the magnetic field are parallel.
iii. as the current flows down the right side, it will experience a force in the +z direction.

These forces will result in the right side of the loop rotating towards the reader.

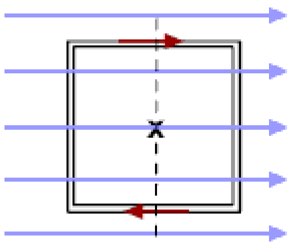
Example #2: Now let's place the same freely-pivoting loop carrying a clockwise (red arrow) current in an external (+z) magnetic field.



i. as the current flows up the left side, it will experience a force in the +x direction.
ii. as the current flows across the top of the loop, it will experience a force in the -y direction
iii. as the current flows down the right side, it will experience a force in the -x direction.

Since the lines of action of both forces along the vertical sides pass through the axis of rotation they will not produce a torque. Note that the line of action of the force along the top section of the loop runs parallel to the axis and consequently can also not produce a torque. **In this orientation, the coil will not rotate about the specified axis.**

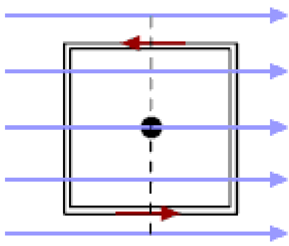
Every current-carrying coil has an **area vector**, **A**, that is oriented perpendicular to is cross-sectional area and points in the direction dictated by the right hand curl rule:



I circulates clockwise

A points in the -z direction

B points in the +x direction



I circulates counter-clockwise

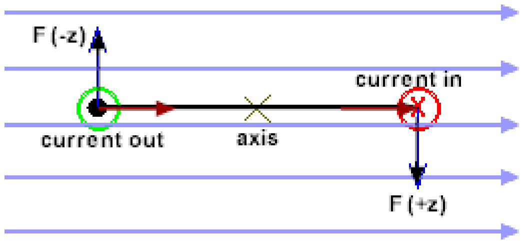
A points in the +z direction

B points in the +x direction

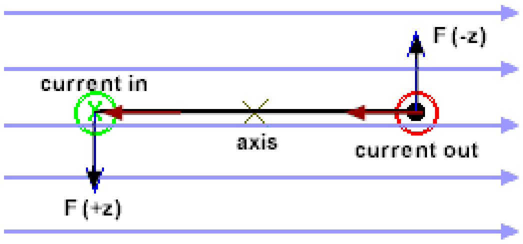
the right edge of the coil would rotate towards the reader

the right edge of the coil would rotate away from the reader

aerial view



aerial view

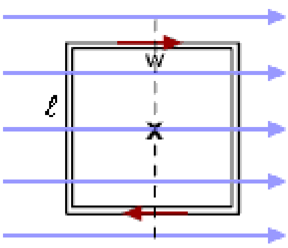


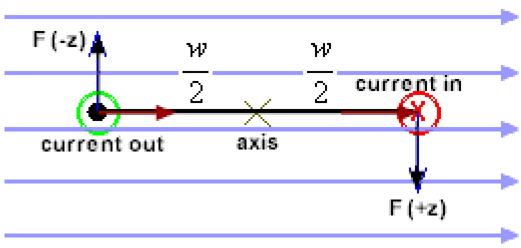
Take a moment and investigate the following physlet modeling the rotation of the current-carrying loop in a magnetic field by Dr. Scott at Lawrence Technological University in Southfield, Michigan. Notice how the direction/magnitude of the current, direction/magnitude of the magnetic field and the size of the angle between the magnetic moment (area vector) affect the loop's rotation.

When the area vector is at right angles to the magnetic field the torque is maximized. Conversely, when the area vector is parallel to the magnetic field no torque is produced as evidenced in our second introductory example.

So how do we calculate the magnitude of the torque on a current-carrying coil?

Returning to our initial example,





We see that the torque

$$\tau = r \times F$$
$$\tau = rF \sin \theta$$

can be calculated using the appropriate values for **r** and **F** as

$$\tau = 2\left(\frac{w}{2} F \sin \theta\right)$$
$$\tau = 2\left(\frac{w}{2} BI\ell \sin \theta\right)$$
$$\tau = BI\ell w \sin \theta$$
$$\tau = BIA \sin \theta$$

If there was more than one loop, the expression would be multiplied by the number of loops, N.

$$\tau = NBIA \sin \theta$$

The expression NIA is called the **magnetic moment** of the loop and it measured in Am^2. Although we have derived this equation for a rectangular loop, it can be used with any planar loop of any geometry - in particular, circular loops whose areas are $A = \pi r^2$.

6.8 DYNAMO

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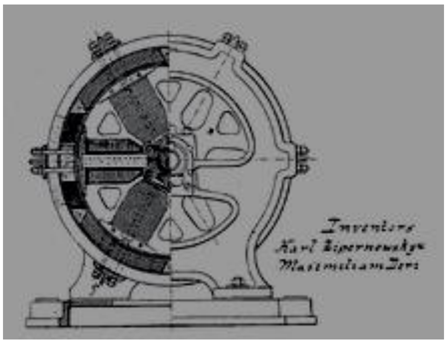


A **dynamo** is an electrical generator that produces direct current with the use of a commutator. Dynamos were the first electrical generators capable of delivering power for industry, and the foundation upon which many other later electric-power conversion devices were based, including the electric motor, the alternating-current alternator, and the rotary converter. Today, the simpler alternator dominates large scale power generation, for efficiency, reliability and cost reasons. A dynamo has the disadvantages of a mechanical commutator. Also, converting alternating to direct current using power rectification devices (vacuum tube or more recently solid state) is effective and usually economic.

The word dynamo (from the Greek word dynamis; meaning power) was originally another name for an electrical generator, and still has some regional usage as a replacement for the word generator. A small electrical generator built into the hub of a bicycle wheel to power lights is called a hub dynamo, although these are invariably AC devices,[citation needed] and are actually magnetos.

Description

The dynamo uses rotating coils of wire and magnetic fields to convert mechanical rotation into a pulsing direct electric current through Faraday's law of induction. A dynamo machine consists of a stationary structure, called the stator, which provides a constant magnetic field, and a set of rotating windings called the armature which turn within that field. The motion of the wire within the magnetic field causes the field to push on the electrons in the metal, creating an electric current in the wire. On small machines the constant magnetic field may be provided by one or more permanent magnets; larger machines have the constant magnetic field provided by one or more electromagnets, which are usually called field coils.

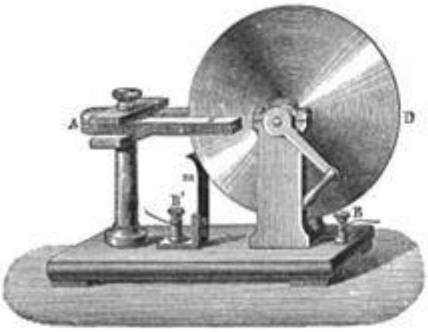
Commutation

The commutator is needed to produce direct current. When a loop of wire rotates in a magnetic field, the potential induced in it reverses with each half turn, generating an alternating current. However, in the early days of electric experimentation, alternating current generally had no known use. The few uses for electricity, such as electroplating, used direct current provided by messy liquid batteries. Dynamos were invented as a replacement for batteries. The commutator is essentially a rotary switch. It consists of a set of contacts mounted on the machine's shaft, combined with graphite-block stationary contacts, called "brushes", because the earliest such fixed contacts were metal brushes. The commutator reverses the connection of the windings to the external circuit when the potential reverses, so instead of alternating current, a pulsing direct current is produced.

Excitation

The earliest dynamos used permanent magnets to create the magnetic field. These were referred to as "magneto-electric machines" or magnetos.[1] However, researchers found that stronger magnetic fields, and so more power, could be produced by using electromagnets (field coils) on the stator.[2] These were called "dynamo-electric machines" or dynamos.[1] The field coils of the stator were originally separately excited by a separate, smaller, dynamo or magneto. An important development by Wilde and Siemens was the discovery that a dynamo could also bootstrap itself to be self-excited, using current generated by the dynamo itself. This allowed the growth of a much more powerful field, thus far greater output power.

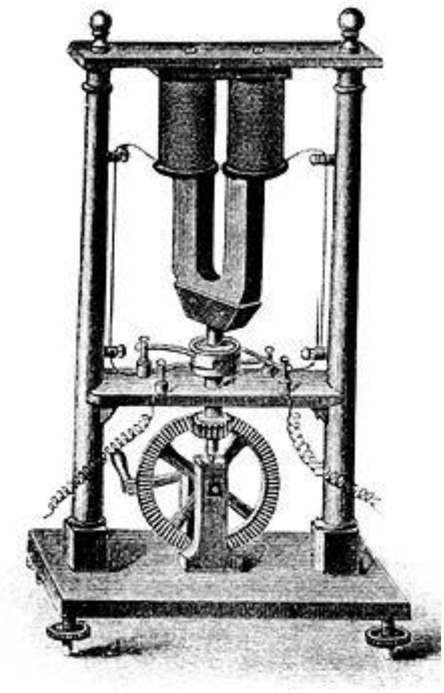
Historical milestones



FARADAY'S DISK

The first electric generator was invented by Michael Faraday in 1831, a copper disk that rotated between the poles of a magnet. This was not a dynamo because it did not use a commutator. However, Faraday's diskgenerated very low voltage because of its single current path through the magnetic field. Faraday and others found that higher, more useful voltages could be produced by winding multiple turns of wire into a coil. Wire windings can conveniently produce any voltage desired by changing the number of turns, so they have been a feature of all subsequent generator designs, requiring the invention of the commutator to produce direct current.

Jedlik's dynamo



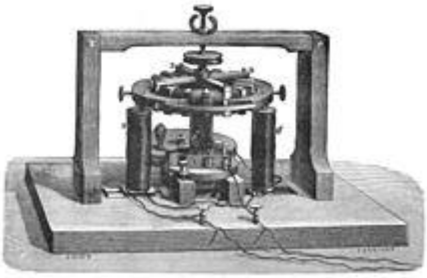
Pixii's dynamo. The commutator is located on the shaft below the spinning magnet.

In 1827, Hungarian Anyos Jedlik started experimenting with electromagnetic rotating devices which he called electromagnetic self-rotors. In the prototype of the single-pole electric starter, both the stationary and the revolving parts were electromagnetic. He formulated the concept of the dynamo about six years before Siemens and Wheatstone but did not patent it as he thought he was not the first to realize this. His dynamo used, instead of permanent magnets, two electromagnets placed opposite to each other to induce the magnetic field around the rotor. It was also the discovery of the principle of dynamo self-excitation.

Pixii's dynamo

The first dynamo based on Faraday's principles was built in 1832 by Hippolyte Pixii, a French instrument maker. It used a permanent magnet which was rotated by a crank. The spinning magnet was positioned so that its north and south poles passed by a piece of iron wrapped with insulated wire. Pixii found that the spinning magnet produced a pulse of current in the wire each time a pole passed the coil. However, the north and south poles of the magnet induced currents in opposite directions. To convert the alternating current to DC, Pixii invented a commutator, a split metal cylinder on the shaft, with two springy metal contacts that pressed against it.

Pacinotti dynamo



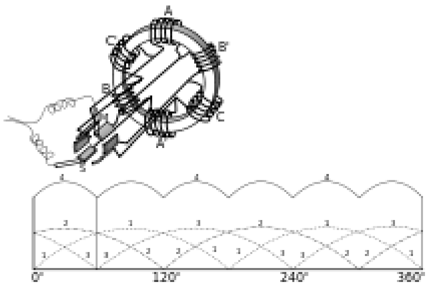
These early designs had a problem: the electric current they produced consisted of a series of "spikes" or pulses of current separated by none at all, resulting in a low average power output. As with electric motors of the period, the designers did not fully realize the seriously detrimental effects of large air gaps in the magnetic circuit. Antonio Pacinotti, an Italian physics professor, solved this problem around 1860 by replacing the spinning two-pole axial coil with a multi-pole toroidal one, which he created by wrapping an iron ring with a continuous winding, connected to the commutator at many equally spaced points around the ring; the commutator being divided into many segments. This meant that some part of the coil was continually passing by the magnets, smoothing out the current.

Siemens and Wheatstone dynamo (1867)

The first practical designs for a dynamo were announced independently and simultaneously by Dr. Werner Siemens and Charles Wheatstone. On January 17, 1867, Siemens announced to the Berlin academy a "dynamo-electric machine" (first use of the term) which employed self-powering electromagnetic field coils rather than permanent magnets to create the stator field.[6] On the same day that this invention was announced to the Royal Society Charles Wheatstone read a paper describing a similar design with the difference that in the Siemens design the stator electromagnets were in series with the rotor, but in Wheatstone's design they were in parallel.[7]The use of electromagnets rather than permanent magnets greatly increases the power output of a dynamo and enabled high power generation for the first time. This invention led directly to the first major industrial uses of electricity. For example, in the 1870s Siemens used electromagnetic dynamos to power electric arc furnaces for the production of metals and other materials.

Gramme ring dynamo

Small Gramme dynamo, around 1878



How Gramme dynamo works to produce a smooth output waveform.

Zénobe Gramme reinvented Pacinotti's design in 1871 when designing the first commercial power plants, which operated in Paris in the 1870s. Another advantage of Gramme's design was a better path for the magnetic flux, by filling the space occupied by the magnetic field with heavy iron cores and minimizing the air gaps between the stationary and rotating parts. The Gramme dynamo was the first machine to generate commercial quantities of power for industry. Further improvements were made on the Gramme ring, but the basic concept of a spinning endless loop of wire remains at the heart of all modern dynamos.

Brush dynamo

Charles F. Brush assembled his first dynamo in the summer of 1876 using a horse-drawn treadmill to power it. U.S. Patent #189997 "Improvement in Magneto-Electric Machines" was issued April 24, 1877. Brush started with the basic Gramme design where the wire on the sides and interior of the ring were outside the effective zone of the field and too much heat was retained. To improve upon this design, his ring armature was shaped like a disc rather than the cylinder shape of the Gramme armature. The field electromagnets were positioned on the sides of the armature disc rather than around the circumference. There were four electromagnets, two with north pole shoes and two with south pole shoes. The like poles opposed each other, one on each side of the disc armature. In 1881 one of The Brush Electric Company dynamos was reported to be; 89 inches long, 28 inches wide, and 36 inches in height, and weighs 4,800 pounds, and ran at a speed of about 700 revolutions per minute. It was believed to be the largest dynamo in the world at that time. Forty arc lights were fed by it, and it required 36 horse power.

Discovery of electric motor principles

While not originally designed for the purpose, it was discovered that a dynamo can act as an electric motor when supplied with direct current from a battery or another dynamo. At an industrial exhibition in Vienna in 1873, Gramme noticed that the shaft of his dynamo began to spin when its terminals were accidentally connected to another dynamo producing electricity. Although this wasn't the first demonstration of an electric motor, it was the first practical one. It was found that the same design features which make a dynamo efficient also make a motor efficient. The efficient Gramme design, with small magnetic air gaps and many coils of wire attached to a many-segmented commutator, also became the basis for the design of all practical DC motors.

Large dynamos producing direct current were problematic in situations where two or more dynamos are working together and one has an engine running at a lower power than the other. The dynamo with the stronger engine will tend to drive the weaker as if it were a motor, against the rotation of the weaker engine. Such reverse-driving could feed back into the driving engine of a dynamo and cause a dangerous out of control reverse-spinning condition in the lower-power dynamo. It was eventually determined that when several dynamos all feed the same power source all the dynamos must be locked into synchrony using a jackshaft interconnecting all engines and rotors to counter these imbalances.

Dynamo as commutated DC generator

After the discovery of the AC Generator and that alternating current can in fact be useful for something, the word dynamo became associated exclusively with the commutated DC electric generator, while an AC electrical generator using either slip rings or rotor magnets would become known as an alternator.

Rotary converter development

After dynamos and motors were found to allow easy conversion back and forth between mechanical or electrical power, they were combined in devices called rotary converters, rotating machines whose purpose was not to provide mechanical power to loads but to convert one type of electric current into another, for example DC into AC. They were multi-field single-rotor devices with two or more sets of rotating contacts (either commutators or sliprings, as required), one to provide power to one set of armature windings to turn the device, and one or more attached to other windings to produce the output current.

The rotary converter can directly convert, internally, any type of electric power into any other. This includes converting between direct current (DC) and alternating current (AC), three phase and single phase power, 25 Hz AC and 60 Hz AC, or many different output voltages at the same time. The size and mass of the rotor was made large so that the rotor would act as a flywheel to help smooth out any sudden surges or dropouts in the applied power.

The technology of rotary converters was replaced in the early 20th century by mercury-vapor rectifiers, which were smaller, did not produce vibration and noise, and required less maintenance. The same conversion tasks are now performed by solid state power semiconductor devices. Rotary converters were still used for the West Side IRT subway in Manhattan into the late 1960s, and possibly some years later. They were powered by 25 Hz AC, and provided DC at 600 volts for the trains.

Modern uses

Dynamos still have some uses in low power applications, particularly where low voltage DC is required, since an alternator with a semiconductor rectifier can be inefficient in these applications. Hand cranked dynamos are used in clockwork radios, hand powered flashlights, mobile phone rechargers, and other human powered equipment to recharge batteries.

UNIT-7

A.C CIRCUITS

WHAT IS AN ALTERNATING VOLTAGE?

Faraday's law of induction provides a basis for converting mechanical energy into electrical energy. The basic idea is to move a coil of wire relative to a magnetic field. This motion will generate a current in the wire. Such a device is called a *generator* and a conceptual drawing of this device is shown in figure 1.

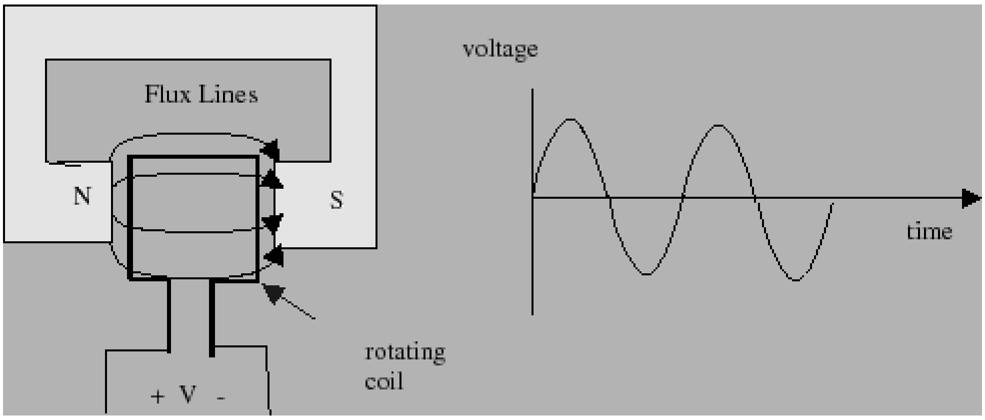


Figure 1: A generator and the voltage it generates

To make things simple, the coil is usually made to rotate within the field. As the coil rotates, it cuts through the flux lines, generating a voltage across the coil's terminals. When the face of the coil is parallel to the field, it cuts rapidly through the flux lines. But when the coil has turned 90 degrees and is perpendicular to the field lines, then the motion of the coil is tangential to the field and no voltage is produced. As the coil turns past this point, it cuts through the field in the opposite direction, generating a negative voltage. The end result of this chain of events is that the voltage produced by the generator varies as the cosine of the angle as shown below. This sinusoidal waveform is referred to as an *alternating* current or AC.

The equation for a waveform of this type is:

$$v(t) = A\cos(\omega t + \phi) \tag{1}$$

where A is the *amplitude*, ω is the *frequency*, and ϕ is the *phase*. Since $v(t)$ is a time-varying voltage signal, A has units of volts. The frequency has units of radians per second. Phase is measured in radians. We often measure frequency in a related unit of *cycles per second*. A cycle corresponds to 2π radians.

The sinusoidal waveform in equation 1 is a **periodic** waveform. A signal v is periodic if and only if there exists $T > 0$ such that $v(t) = v(t+T)$ for all t. To see if a sinusoidal waveform is periodic we therefore need to find T such that

$$A\cos(\omega t + \phi) = A\cos(\omega(t+T) + \phi) \tag{2}$$

In particular, we know that the cosine function repeats every 2π radians so we need to find T such that

$$A\cos(\omega(t+T) + \phi) = A\cos(\omega t + 2\pi + \phi) \tag{3}$$

Clearly this occurs if $\omega T = 2\pi$ or rather

$$T = \frac{2\pi}{\omega} \tag{4}$$

is the **fundamental period** of this sinusoidal function.

The *size* of a sine wave can be measured in a variety of ways. We may, for instance, use the waveform's amplitude (A) to specify the waveform's size. Another measure of "size" is the signal's **root mean square** or **rms**strength

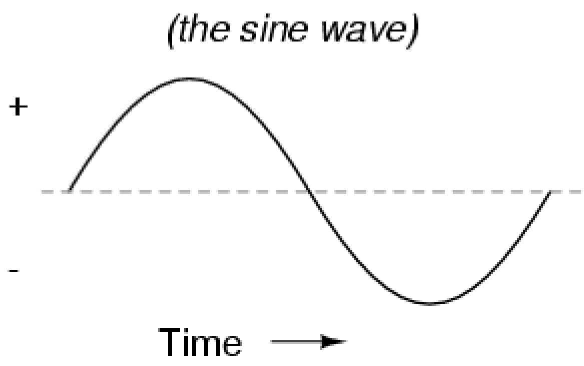
$$\text{RMS} = \left[\int_0^{\omega/2\pi} (A\cos(\omega t + \phi))^2 \, dt \right]^{1/2} \tag{5}$$

Since generators naturally produce sine waves, these waveforms play an important role in electrical engineering. It also turns out that sine waves also provide an efficient way of transporting electrical energy over a long distance. This is part of the reason why AC voltages are used in international power grids and, of course, this is why your wall socket provides a 120 volts (rms) AC voltage at 60 Hz.

In contrast to AC voltages, batteries provide a *direct current* or DC voltage. DC voltages are constant over time. In order to obtain DC voltages from an AC wall socket we're going to have to find some way of **regulating** the AC power source.

AC WAVEFORMS

When an alternator produces AC voltage, the voltage switches polarity over time, but does so in a very particular manner. When graphed over time, the "wave" traced by this voltage of alternating polarity from an alternator takes on a distinct shape, known as a *sine wave*: Figure below



Graph of AC voltage over time (the sine wave).

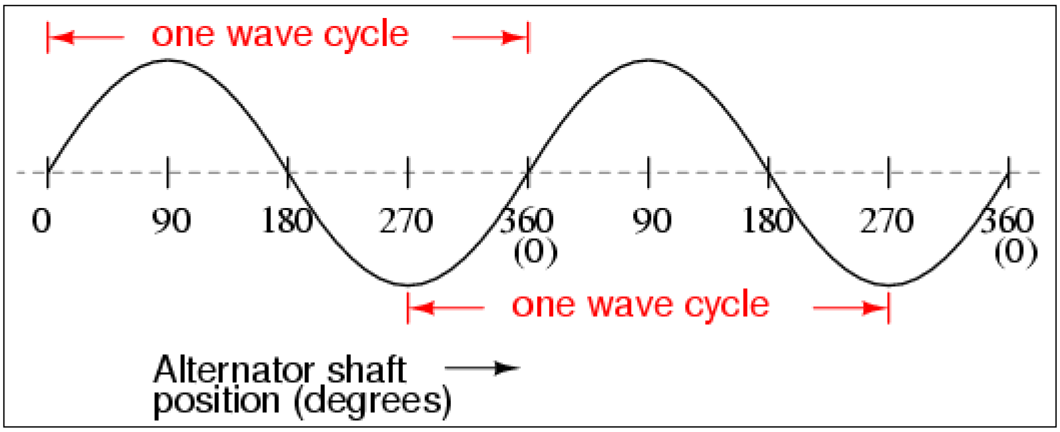
In the voltage plot from an electromechanical alternator, the change from one polarity to the other is a smooth one, the voltage level changing most rapidly at the zero ("crossover") point and most slowly at its peak. If we were to graph the trigonometric function of “sine” over a horizontal range of 0 to 360 degrees, we would find the exact same pattern as in Table below.

Trigonometric “sine” function.

Angle (°)	**sin(angle)**	**wave**	**Angle (°)**	**sin(angle)**	**wave**
0	0.0000	zero	180	0.0000	zero
15	0.2588	+	195	-0.2588	-
30	0.5000	+	210	-0.5000	-
45	0.7071	+	225	-0.7071	-
60	0.8660	+	240	-0.8660	-
75	0.9659	+	255	-0.9659	-
90	1.0000	+peak	270	-1.0000	-peak
105	0.9659	+	285	-0.9659	-
120	0.8660	+	300	-0.8660	-
135	0.7071	+	315	-0.7071	-
150	0.5000	+	330	-0.5000	-
165	0.2588	+	345	-0.2588	-
180	0.0000	zero	360	0.0000	zero

The reason why an electromechanical alternator outputs sine-wave AC is due to the physics of its operation. The voltage produced by the stationary coils by the motion of the rotating magnet is proportional to the rate at which the magnetic flux is changing perpendicular to the coils (Faraday's Law of Electromagnetic Induction). That rate is greatest when the magnet poles are closest to the coils, and least when the magnet poles are furthest away from the coils. Mathematically, the rate of magnetic flux change due to a rotating magnet follows that of a sine function, so the voltage produced by the coils follows that same function.

If we were to follow the changing voltage produced by a coil in an alternator from any point on the sine wave graph to that point when the wave shape begins to repeat itself, we would have marked exactly one *cycle* of that wave. This is most easily shown by spanning the distance between identical peaks, but may be measured between any corresponding points on the graph. The degree marks on the horizontal axis of the graph represent the domain of the trigonometric sine function, and also the angular position of our simple two-pole alternator shaft as it rotates: Figure below



Alternator voltage as function of shaft position (time).

Since the horizontal axis of this graph can mark the passage of time as well as shaft position in degrees, the dimension marked for one cycle is often measured in a unit of time, most often seconds or fractions of a second. When expressed as a measurement, this is often called the *period* of a wave. The period of a wave in degrees is *always* 360, but the amount of time one period occupies depends on the rate voltage oscillates back and forth.

A more popular measure for describing the alternating rate of an AC voltage or current wave than *period* is the rate of that back-and-forth oscillation. This is called *frequency*. The modern unit for frequency is the Hertz (abbreviated Hz), which represents the number of wave cycles completed during one second of time. In the United States of America, the standard power-line frequency is 60 Hz, meaning that the AC voltage oscillates at a rate of 60 complete back-and-forth cycles every second. In Europe, where the power system frequency is 50 Hz, the AC voltage only completes 50 cycles every second. A radio station transmitter broadcasting at a frequency of 100 MHz generates an AC voltage oscillating at a rate of 100 *million* cycles every second.

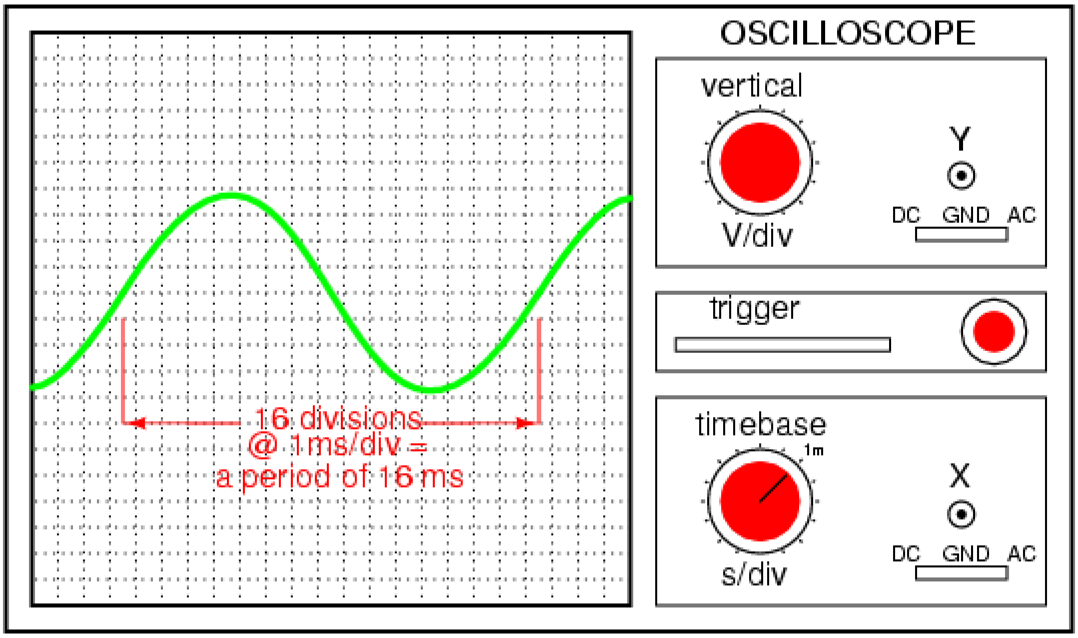
Prior to the canonization of the Hertz unit, frequency was simply expressed as "cycles per second." Older meters and electronic equipment often bore frequency units of "CPS" (Cycles Per

Second) instead of Hz. Many people believe the change from self-explanatory units like CPS to Hertz constitutes a step backward in clarity. A similar change occurred when the unit of "Celsius" replaced that of "Centigrade" for metric temperature measurement. The name Centigrade was based on a 100-count ("Centi-") scale ("-grade") representing the melting and boiling points of H_2O, respectively. The name Celsius, on the other hand, gives no hint as to the unit's origin or meaning.

Period and frequency are mathematical reciprocals of one another. That is to say, if a wave has a period of 10 seconds, its frequency will be 0.1 Hz, or 1/10 of a cycle per second:

$$\text{Frequency in Hertz} = \frac{1}{\text{Period in seconds}}$$

An instrument called an *oscilloscope*, Figure below, is used to display a changing voltage over time on a graphical screen. You may be familiar with the appearance of an *ECG* or *EKG* (electrocardiograph) machine, used by physicians to graph the oscillations of a patient's heart over time. The ECG is a special-purpose oscilloscope expressly designed for medical use. General-purpose oscilloscopes have the ability to display voltage from virtually any voltage source, plotted as a graph with time as the independent variable. The relationship between period and frequency is very useful to know when displaying an AC voltage or current waveform on an oscilloscope screen. By measuring the period of the wave on the horizontal axis of the oscilloscope screen and reciprocating that time value (in seconds), you can determine the frequency in Hertz.



$$\text{Frequency} = \frac{1}{\text{period}} = \frac{1}{16\text{ ms}} = 62.5\text{ Hz}$$

Time period of sinewave is shown on oscilloscope.

Voltage and current are by no means the only physical variables subject to variation over time. Much more common to our everyday experience is *sound*, which is nothing more than the alternating compression and decompression (pressure waves) of air molecules, interpreted by our ears as a physical sensation. Because alternating current is a wave phenomenon, it shares many of the properties of other wave phenomena, like sound. For this reason, sound (especially structured music) provides an excellent analogy for relating AC concepts.

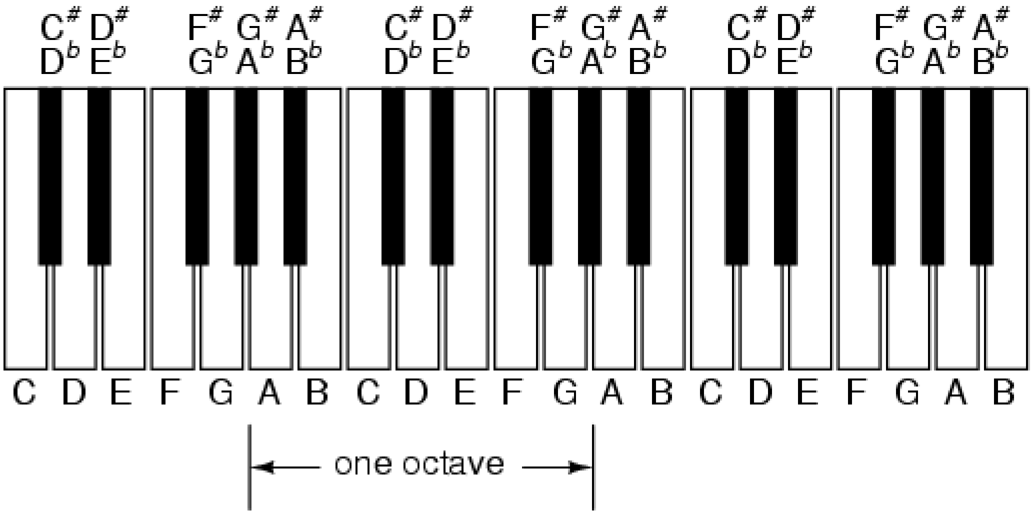
In musical terms, frequency is equivalent to *pitch*. Low-pitch notes such as those produced by a tuba or bassoon consist of air molecule vibrations that are relatively slow (low frequency). High-pitch notes such as those produced by a flute or whistle consist of the same type of vibrations in the air, only vibrating at a much faster rate (higher frequency). Figure below is a table showing the actual frequencies for a range of common musical notes.

Note	Musical designation	Frequency (in hertz)
A	A_1	220.00
A sharp (or B flat)	$A^{\#}$ or B^{b}	233.08
B	B_1	246.94
C (middle)	C	261.63
C sharp (or D flat)	$C^{\#}$ or D^{b}	277.18
D	D	293.66
D sharp (or E flat)	$D^{\#}$ or E^{b}	311.13
E	E	329.63
F	F	349.23
F sharp (or G flat)	$F^{\#}$ or G^{b}	369.99
G	G	392.00
G sharp (or A flat)	$G^{\#}$ or A^{b}	415.30
A	A	440.00
A sharp (or B flat)	$A^{\#}$ or B^{b}	466.16
B	B	493.88
C	C^1	523.25

The frequency in Hertz (Hz) is shown for various musical notes.

Astute observers will notice that all notes on the table bearing the same letter designation are related by a frequency ratio of 2:1. For example, the first frequency shown (designated with the letter "A") is 220 Hz. The next highest "A" note has a frequency of 440 Hz -- exactly twice as many sound wave cycles per second. The same 2:1 ratio holds true for the first A sharp (233.08 Hz) and the next A sharp (466.16 Hz), and for all note pairs found in the table.

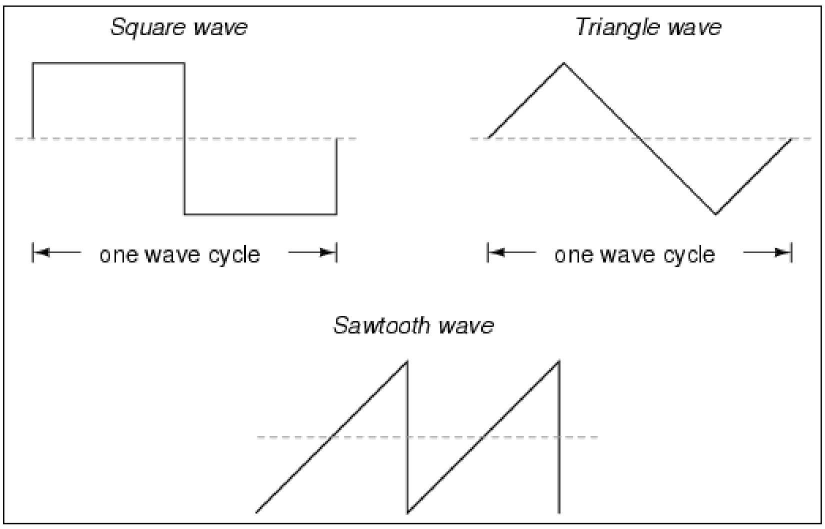
Audibly, two notes whose frequencies are exactly double each other sound remarkably similar. This similarity in sound is musically recognized, the shortest span on a musical scale separating such note pairs being called an *octave*. Following this rule, the next highest "A" note (one octave above 440 Hz) will be 880 Hz, the next lowest "A" (one octave below 220 Hz) will be 110 Hz. A view of a piano keyboard helps to put this scale into perspective: Figure below



An octave is shown on a musical keyboard.

As you can see, one octave is equal to *seven* white keys' worth of distance on a piano keyboard. The familiar musical mnemonic (doe-ray-mee-fah-so-lah-tee) -- yes, the same pattern immortalized in the whimsical Rodgers and Hammerstein song sung in The Sound of Music -- covers one octave from C to C.

While electromechanical alternators and many other physical phenomena naturally produce sine waves, this is not the only kind of alternating wave in existence. Other "waveforms" of AC are commonly produced within electronic circuitry. Here are but a few sample waveforms and their common designations in figure below



SOME COMMON WAVESHAPES (WAVEFORMS).

These waveforms are by no means the only kinds of waveforms in existence. They're simply a few that are common enough to have been given distinct names. Even in circuits that are supposed to manifest “pure” sine, square, triangle, or sawtooth voltage/current waveforms, the real-life result is often a distorted version of the intended waveshape. Some waveforms are so complex that they defy classification as a particular “type” (including waveforms associated with many kinds of musical instruments). Generally speaking, any waveshape bearing close resemblance to a perfect sine wave is termed*sinusoidal*, anything different being labeled as *non-sinusoidal*. Being that the waveform of an AC voltage or current is crucial to its impact in a circuit, we need to be aware of the fact that AC waves come in a variety of shapes.

REVIEW:

- AC produced by an electromechanical alternator follows the graphical shape of a sine wave.
- One *cycle* of a wave is one complete evolution of its shape until the point that it is ready to repeat itself.
- The *period* of a wave is the amount of time it takes to complete one cycle.
- *Frequency* is the number of complete cycles that a wave completes in a given amount of time. Usually measured in Hertz (Hz), 1 Hz being equal to one complete wave cycle per second.
- Frequency = 1/(period in seconds)

WHAT IS POWER FACTOR?

Power factor is the ratio between the KW (Kilo-Watts) and the KVA (Kilo-Volt Amperes) drawn by an electrical load where the KW is the actual load power and the KVA is the apparent load power. It is a measure of how effectively the current is being converted into useful work output and more particularly is a good indicator of the effect of the load current on the efficiency of the supply system.

All current flow will cause losses in the supply and distribution system. A load with a power factor of 1.0 result in the most efficient loading of the supply and a load with a power factor of 0.5 will result in much higher losses in the supply system.

A poor power factor can be the result of either a significant phase difference between the voltage and current at the load terminals, or it can be due to a high harmonic content or distorted/discontinuous current waveform.

Poor load current phase angle is generally the result of an inductive load such as an i nduction motor, power transformer, lighting ballasts, welder or induction furnace. A distorted current waveform can be the result of a rectifier, variable speed drive, switched mode power supply, discharge lighting or other electronic load.

A poor power factor due to an inductive load can be improved by the addition of power factor correction, but, a poor power factor due to a distorted current waveform requires an change in equipment design or expensive harmonic filters to gain an appreciable improvement.

Many inverters are quoted as having a power factor of better than 0.95 when in reality, the true power factor is between 0.5 and 0.75. The figure of 0.95 is based on the cosine of the angle between the voltage and current but does not take into account that the current waveform is discontinuous and therefore contributes to increased losses on the supply.

Power Factor Correction

Capacitive Power Factor correction is applied to circuits which include induction motors as a means of reducing the inductive component of the current and thereby reduce the losses in the supply. There should be no effect on the operation of the motor itself.

An induction motor draws current from the supply, that is made up of resistive components and inductive components.

The **resistive** components are:

1) Load current.
2) Loss current.

The **inductive** components are:

3) Leakage reactance.
4) Magnetizing current.

The current due to the leakage reactance is dependent on the total current drawn by the motor, but the magnetizing current is independent of the load on the motor.

The magnetizing current will typically be between 20% and 60% of the rated full load current of the motor. The magnetizing current is the current that establishes the flux in the iron and is very necessary if the motor is going to operate.

The magnetizing current does not actually contribute to the actual work output of the motor. It is the catalyst that allows the motor to work properly. The magnetizing current and the leakage reactance can be considered passenger components of current that will not affect the power drawn by the motor, but will contribute to the power dissipated in the supply and distribution system.

Take for example a motor with a current draw of 100 Amps and a power factor of 0.75 The resistive component of the current is 75 Amps and this is what the KWh meter measures. The higher current will result in an increase in the distribution losses of (100 x 100) /(75 x 75) = 1.777 or a 78% increase in the supply losses.

In the interest of reducing the losses in the distribution system, power factor correction is added to neutralize a portion of the magnetizing current of the motor.

Typically, the corrected power factor will be 0.92 - 0.95 Some power retailers offer incentives for operating with a power factor of better than 0.9, while others penalize consumers with a poor power factor. There are many ways that this is mete red, but the net result is that in order to reduce wasted energy in the distribution system, the consumer will be encouraged to apply power factor correction.

Power factor correction is achieved by the addition of capacitors in parallel with the connected motor circuits and can be applied at the starter, or applied at the switchboard or distribution panel. The resulting capacitive current is leading current and is used to cancel the lagging inductive current flowing from the supply.

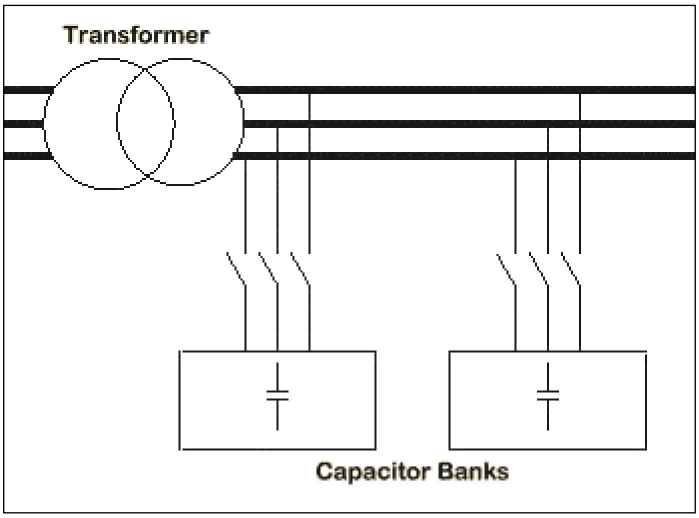
METHODS OF POWER FACTOR CORRECTION

Capacitors connected at each starter and controlled by each starter is known as *"Static Power Factor Correction"* while capacitors connected at a distribution board and controlled independently from the individual starters is known as *"Bulk Correction".*

BULK CORRECTION

The Power factor of the total current supplied to the distribution board is monitored by a controller which then switches capacitor banks In a fashion to maintain a power factor better than a preset limit. (Typically 0.95)

Ideally, the power factor should be as close to unity (Power factor of "1") as possible. There is no problem with bulk correction operating at unity.



STATIC CORRECTION

As a large proportion of the inductive or lagging current on the supply is due to the magnetizing current of induction motors, it is easy to correct each individual motor by connecting the correction capacitors to the motor starters.

With static correction, it is important that the capacitive current is less than the inductive magnetizing current of the induction motor.

In many installations employing static power factor correction, the correction capacitors are connected directly in parallel with the motor windings. When the motor is off-line, the capacitors are also off-line. When the motor is connected to the supply, the capacitors are also connected providing correction at all times that the motor is connected to the supply. This removes the requirement for any expensive power factor monitoring and control equipment.

In this situation, the capacitors remain connected to the motor terminals as the motor slows down. An induction motor, while connected to the supply, is driven by a rotating magnetic field in the stator which induces current into the rotor.

When the motor is disconnected from the supply, there is for a period of time, a magnetic field associated with the rotor. As the motor decelerates, it generates voltage out its terminals at a frequency which is related to it's speed.

The capacitors connected across the motor terminals, form a resonant circuit with the motor inductance.

If the motor is critically corrected, (corrected to a power factor of 1.0) the inductive reactance equals the capacitive reactance at the line frequency and therefore the resonant frequency is equal to the line frequency.

If the motor is over corrected, the resonant frequency will be below the line frequency.

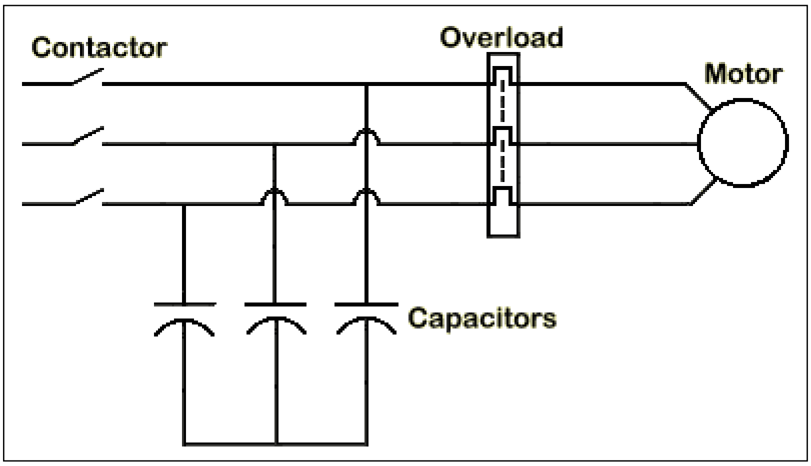
If the frequency of the voltage generated by the decelerating motor passes throu gh the resonant frequency of the corrected motor, there will be high currents and voltages around the motor/capacitor circuit. This can result in sever damage to the capacitors and motor. It is imperative that motors are never over corrected or critically corrected when static correction is employed.

Static power factor correction should provide capacitive current equal to 80% of the **magnetizing current**, which is essentially the open shaft current of the motor.

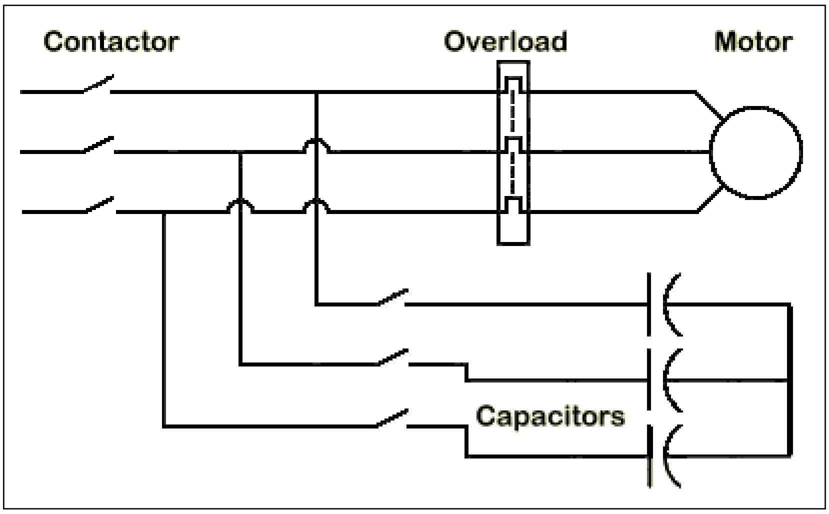
The magnetizing current for induction motors can vary considerably. Typically, magnetizing currents for large two pole machines can be as low as 20% of the rated current of the motor while smaller low speed motors can have a magnetizing current as high as 60% of the rated full load current of the motor.

It is not practical to use a "Standard table" for the correction of induction motors giving optimum correction on all motors. Tables result in under correction on most motors but can result in over correction in some cases. Where the open shaft current can not be measured, and the magnetizing current is not quoted, an approximate level for the maximum correction that can be applied can be calculated from the half load characteristics of the motor.

It is dangerous to base correction on the full load characteristics of the motor as in some cases, motors can exhibit a high leakage reactance and correction to 0.95 at full load will result in over correction under no load, or disconnected conditions.



Static correction is commonly applied by using one contactor to control both the motor and the capacitors. It is better practice to use two contactors, one for the motor and one for the capacitors. Where one contactor is employed, it should be up sized for the capacitive load. The use of a second contactor eliminates the problems of resonance between the motor and the capacitors.



Inverter

Static Power factor correction **must not be** used when the motor is controlled by a variable speed drive or inverter. The connection of capacitors to the output of an inverter can cause serious damage to the inverter and the capacitors due to the high frequency switched voltage on the output of the inverters.

The current drawn from the inverter has a poor power factor, particularly at low load, but the motor current is isolated from the supply by the inverter. The phase angle of the current drawn by the inverter from the supply is close to zero resulting in very low inductive current regardless of what the motor is doing. The inverter does not however, operate with a good power factor.

Many inverter manufacturers quote a cos Ø of better than 0.95 and this is generally true, however the current is non sinusoidal and the resultant harmonics cause a power factor (KW/KVA) of closer to 0.7 depending on the input design of the inverter. Inverters with input reactors and DC bus reac tors will exhibit a higher true power factor than those without.

The connection of capacitors close to the input of the inverter can also result in damage to the inverter. The capacitors tend to cause transients to be amplified, resulting in higher voltage impulses applied to the input circuits of the inverter, and the energy behind the impulses is much greater due to the energy storage of the capacitors.

It is recommended that capacitors should be at least 75 Meters away from inverter inputs to elevate the impedance between the inverter and capacitors and reduce the potential damage caused.

Switching capacitors, Automatic bank correction etc, will cause voltage transients and these transients can damage the input circuits of inverters. The energy is proportional to the amount of capacitance being switched. It is better to switch lots of small amounts of capacitance than few large amounts.

Solid State Soft Starter

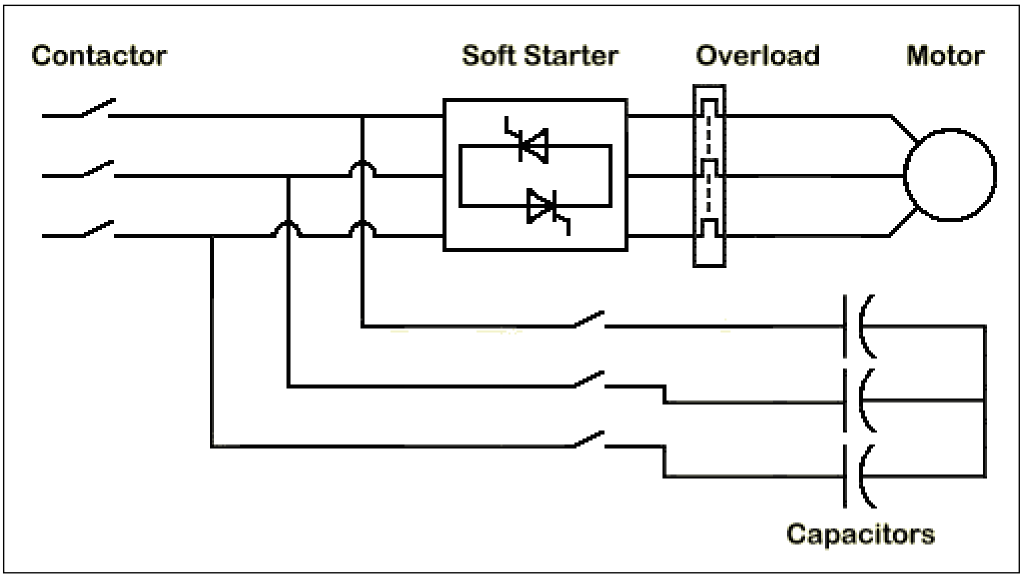
Static Power Factor correction capacitors **<u>must not</u>** be connected to the output of a solid state soft starter.

When a solid state soft starter is used, the capacitors must be controlled by a separate contactor, and switched in when the soft starter output voltage has reached line voltage. Many soft starters provide a *"top of ramp"* or *"bypass contactor control"* which can be used to control the power factor correction capacitors.

The connection of capacitors close to the input of the soft starter can also result in damage to the soft starter if an isolation contactor is not used. The capacitors tend to cause transients to be amplified, resulting in higher voltage impulses applied to the SCRs of the Soft Starter, and the energy behind the impulses is much greater due to the energy storage of the capacitors.

It is recommended that capacitors should be at least 50 Meters away from Soft starters to elevate the impedance between the inverter and capacitors and reduce the potential damage caused.

Switching capacitors, Automatic bank correction etc, will cause voltage transients and these transients can damage the SCRs of Soft Starters if they are in the Off state without an input contactor. The energy is proportional to the amount of capacitance being switched. It is better to switch lots of small amounts of capacitance than few large amounts.



Supply Harmonics

Harmonics on the supply cause a higher current to flow in the capacitors. This is because the impedance of the capacitors goes down as the frequency goes up. This increase in current flow through the capacitor will result in additional heating of the capacitor and reduce it's life

The harmonics are caused by many non linear loads, the most common in the industrial market today, are the variable speed controllers and switch-mode power supplies

Harmonic voltages can be reduced by the use of a harmonic compensator, which is essentially a large inverter that cancels out the harmonics. This is an expensive option.

Passive harmonic filters comprising resistors, inductors and capacitors can also be used to reduce harmonic voltages. This is also an expensive exercise.

In order to reduce the damage caused to the capacitors by the harmonic currents, it is becoming common today to install detuning reactors in series with the power factor correction capacitors. These reactors are designed to make the correction circuit inductive to the higher frequency harmonics. Typically, a reactor would be designed to create a resonant circuit with the capacitors above the third harmonic, but sometimes it is below. (Never tuned to a harmonic frequency!!)

Adding the inductance in series with the capacitors will reduce their effective capacitance at the supply frequency. Reducing the resonant or tuned frequency will reduce the the effective capacitance further.

The object is to make the circuit look as inductive as possible at the 5th harmonic and higher, but as capacitive as possible at the fundamental frequency. Detuning reactors will also reduce the chance of the tuned circuit formed by the capacitors and the inductive supply being resonant on a supply harmonic frequency, thereby reducing damage due to supply resonance amplifying harmonic voltages caused by non linear loads.

Supply Resonance

Capacitive Power factor correction connected to a supply caus es resonance between the supply and the capacitors.

If the fault current of the supply is very high, the effect of the resonance will be minimal, however in a rural installation where the supply is very inductive and can be a high impedance, the resonance can be very severe resulting in major damage to plant and equipment.

Voltage surges and transients of several times the supply voltage are not uncommon in rural areas with weak supplies, especially when the load on the supply is low.

As with any resonant system, a transient or sudden change in current will result in the resonant circuit ringing, generating a high voltage. The magnitude of the voltage is dependant on the 'Q' of the circuit which in turn is a function of the circuit loading. One of the problems with supply resonance is that the 'reaction' is often well remove from the 'stimulus' unlike a pure voltage drop problem due to an overloaded supply. This makes fault finding very difficult and often damaging surges and transients on the supply are treated as 'just one of those things'.

To minimize supply resonance problems, there are a few steps that can be taken, but they do need to be taken by all on the particular supply.

1) Minimize the amount of power factor correction, particularly when the load is light. The power factor correction minimizes losses in the supply. When the supply is lightly loaded, this is not such a problem.

2) Minimize switching transients. Eliminate open transition switching - usually associated with generator plants and alternative supply switching, and with some elect romechanical starters such as the star/delta starter.

3) Switch capacitors on to the supply in lots of small steps rather than a few large steps.

4) Switch capacitors on o the supply after the load has been applied and switch off the supply before or with the load removal.

Harmonic Power Factor correction is not applied to circuits that draw either discontinuous or distorted current waveforms

Most electronic equipment includes a means of creating a DC supply. This involves rectifying the AC voltage, causing harmonic currents. In some cases, these harmonic currents are insignificant relative to the total load current drawn, but in many installations, a large proportion of the current drawn is rich in harmonics.

If the total harmonic current is large enough, there will be a resultant distortion of the supply waveform which can interfere with the correct operation of other equipment. The addition of harmonic currents results in increased losses in the supply.

Power factor correction for distorted supplies can not be achieved by the addition of capacitors. The harmonics can be reduced by designing the equipment using active rectifiers, by the addition of passive filters (LCR) or by the addition of electronic power factor correction inverters which restore the waveform back to its undistorted state.

This is a specialist area requiring either major design changes, or specialized equipment to be used.

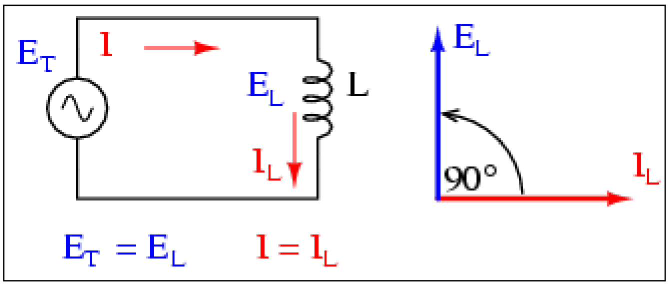
A.C. SERIES CIRCUITS WITH (I) RESISTANCE AND INDUCTANCE

Inductors do not behave the same as resistors. Whereas resistors simply oppose the flow of electrons through them (by dropping a voltage directly proportional to the current), inductors oppose *changes* in current through them, by dropping a voltage directly proportional to the *rate of change* of current. In accordance with *Lenz's Law*, this induced voltage is always of such a polarity as to try to maintain current at its present value. That is, if current is increasing in magnitude, the induced voltage will "push against" the electron flow; if current is decreasing, the polarity will reverse and "push with" the electron flow to oppose the decrease. This opposition to current change is called *reactance*, rather than resistance.

Expressed mathematically, the relationship between the voltage dropped across the inductor and rate of current change through the inductor is as such:

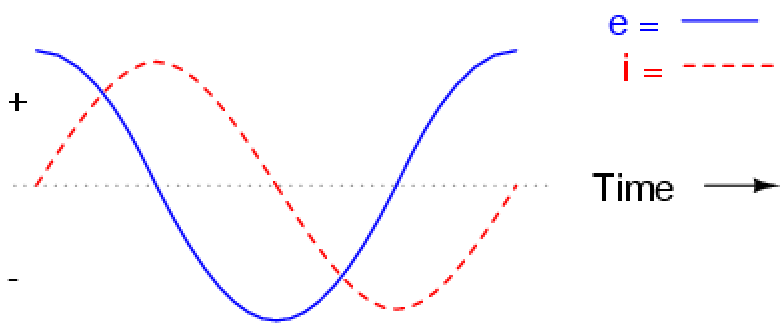
$$e = L\frac{di}{dt}$$

The expression *di/dt* is one from calculus, meaning the rate of change of instantaneous current (i) over time, in amps per second. The inductance (L) is in Henrys, and the instantaneous voltage (e), of course, is in volts. Sometimes you will find the rate of instantaneous voltage expressed as "v" instead of "e" (v = L di/dt), but it means the exact same thing. To show what happens with alternating current, let's analyze a simple inductor circuit: (Figure below)



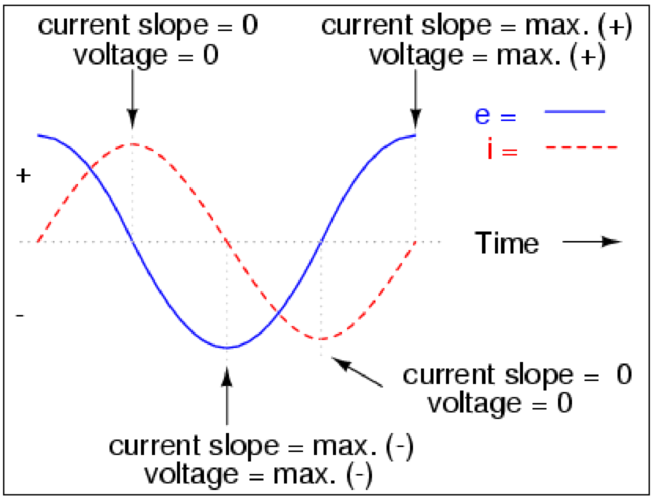
Pure inductive circuit: Inductor current lags inductor voltage by 90°.

If we were to plot the current and voltage for this very simple circuit, it would look something like this: (Figure below)



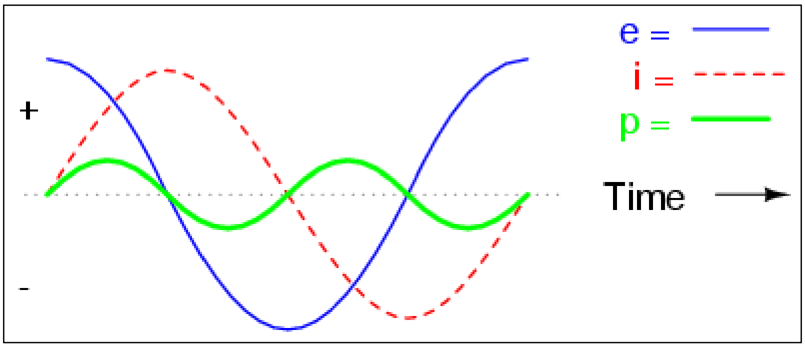
Pure inductive circuit, waveforms.

Remember, the voltage dropped across an inductor is a reaction against the *change* in current through it. Therefore, the instantaneous voltage is zero whenever the instantaneous current is at a peak (zero change, or level slope, on the current sine wave), and the instantaneous voltage is at a peak wherever the instantaneous current is at maximum change (the points of steepest slope on the current wave, where it crosses the zero line). This results in a voltage wave that is 90° out of phase with the current wave. Looking at the graph, the voltage wave seems to have a "head start" on the current wave; the voltage "leads" the current, and the current "lags" behind the voltage. (Figure below)



Current lags voltage by 90º in a pure inductive circuit.

Things get even more interesting when we plot the power for this circuit: (Figure below)



In a pure inductive circuit, instantaneous power may be positive or negative

Because instantaneous power is the product of the instantaneous voltage and the instantaneous current (p=ie), the power equals zero whenever the instantaneous current *or* voltage is zero. Whenever the instantaneous current and voltage are both positive (above the line), the power is positive. As with the resistor example, the power is also positive when the instantaneous current and voltage are both negative (below the line). However, because the current and voltage waves are 90º out of phase, there are times when one is positive while the other is negative, resulting in equally frequent occurrences of *negative instantaneous power*.

But what does *negative* power mean? It means that the inductor is releasing power back to the circuit, while a positive power means that it is absorbing power from the circuit. Since the positive and negative power cycles are equal in magnitude and duration over time, the inductor releases just as much power back to the circuit as it absorbs over the span of a complete cycle. What this means in a practical sense is that the reactance of an inductor dissipates a net energy of zero, quite unlike the resistance of a resistor, which dissipates energy in the form of heat. Mind you, this is for perfect inductors only, which have no wire resistance.

An inductor's opposition to change in current translates to an opposition to alternating current in general, which is by definition always changing in instantaneous magnitude and direction. This opposition to alternating current is similar to resistance, but different in that it always results in a phase shift between current and voltage, and it dissipates zero power. Because of the differences, it has a different name: *reactance*. Reactance to AC is expressed in ohms, just like resistance is, except that its mathematical symbol is X instead of R. To be specific, reactance associate with an inductor is usually symbolized by the capital letter X with a letter L as a subscript, like this: X_L.

Since inductors drop voltage in proportion to the rate of current change, they will drop more voltage for faster-changing currents, and less voltage for slower-changing currents. What this means is that reactance in ohms for any inductor is directly proportional to the frequency of the alternating current. The exact formula for determining reactance is as follows:

$$X_L = 2\pi f L$$

If we expose a 10 mH inductor to frequencies of 60, 120, and 2500 Hz, it will manifest the reactances in Table Figure below.

Reactance of a 10 mH inductor:

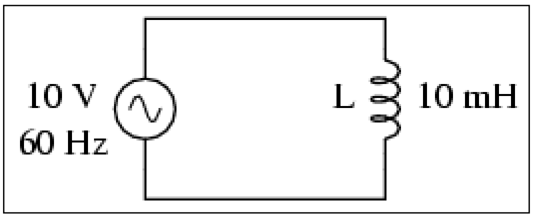
Frequency (Hertz)	**Reactance (Ohms)**
60	3.7699
120	7.5398
2500	157.0796

In the reactance equation, the term "2πf" (everything on the right-hand side except the L) has a special meaning unto itself. It is the number of radians per second that the alternating current is "rotating" at, if you imagine one cycle of AC to represent a full circle's rotation. A *radian* is a unit of angular measurement: there are 2π radians in one full circle, just as there are 360^o in a full circle. If the alternator producing the AC is a double-pole unit, it will produce one cycle for every full turn of shaft rotation, which is every 2π radians, or 360^o. If this constant of 2π is multiplied by frequency in Hertz (cycles per second), the result will be a figure in radians per second, known as the *angular velocity* of the AC system.

Angular velocity may be represented by the expression 2πf, or it may be represented by its own symbol, the lower-case Greek letter Omega, which appears similar to our Roman lower-case "w": ω. Thus, the reactance formula $X_L = 2\pi fL$ could also be written as $X_L = \omega L$.

It must be understood that this "angular velocity" is an expression of how rapidly the AC waveforms are cycling, a full cycle being equal to 2π radians. It is not necessarily representative of the actual shaft speed of the alternator producing the AC. If the alternator has more than two poles, the angular velocity will be a multiple of the shaft speed. For this reason, ω is sometimes expressed in units of *electrical* radians per second rather than (plain) radians per second, so as to distinguish it from mechanical motion.

Any way we express the angular velocity of the system, it is apparent that it is directly proportional to reactance in an inductor. As the frequency (or alternator shaft speed) is increased in an AC system, an inductor will offer greater opposition to the passage of current, and vice versa. Alternating current in a simple inductive circuit is equal to the voltage (in volts) divided by the inductive reactance (in ohms), just as either alternating or direct current in a simple resistive circuit is equal to the voltage (in volts) divided by the resistance (in ohms). An example circuit is shown here: (Figure <u>below</u>)



Inductive reactance

(inductive reactance of 10 mH inductor at 60 Hz)

$$X_L = 3.7699\ \Omega$$

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

$$I = \frac{10\ V}{3.7699\ \Omega}$$

$$I = 2.6526\ A$$

However, we need to keep in mind that voltage and current are not in phase here. As was shown earlier, the voltage has a phase shift of +90° with respect to the current. (Figure below) If we represent these phase angles of voltage and current mathematically in the form of complex numbers, we find that an inductor's opposition to current has a phase angle, too:

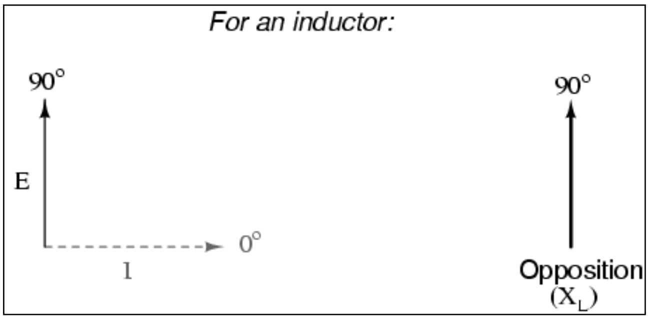
$$\text{Opposition} = \frac{\text{Voltage}}{\text{Current}}$$

$$\text{Opposition} = \frac{10 \text{ V} \angle 90^\circ}{2.6526 \text{ A} \angle 0^\circ}$$

$$\text{Opposition} = 3.7699 \ \Omega \angle 90^\circ$$

or

$$0 + j3.7699 \ \Omega$$



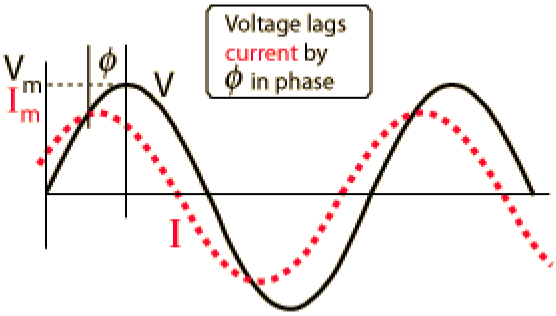
Current lags voltage by 90° in an inductor.

Mathematically, we say that the phase angle of an inductor's opposition to current is 90°, meaning that an inductor's opposition to current is a positive imaginary quantity. This phase angle of reactive opposition to current becomes critically important in circuit analysis, especially for complex AC circuits where reactance and resistance interact. It will prove beneficial to represent *any* component's opposition to current in terms of complex numbers rather than scalar quantities of resistance and reactance.

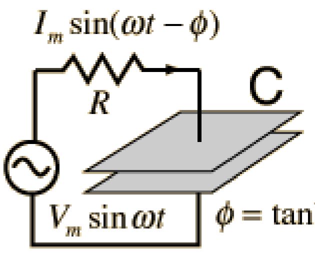
A.C. SERIES CIRCUITS WITH (II) RESISTANCE AND CAPACITANCE

RC Circuit

Impedance
$I = \frac{V}{Z}$ $Z = \sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}$
Calculate



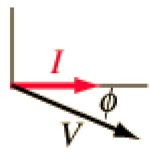
Examine
Capacitor
Resistor



Phase

$$\phi = \tan^{-1}\frac{-1/\omega C}{R}$$

$$I = \frac{I_m}{\sqrt{2}},\ V = \frac{V_m}{\sqrt{2}}$$

Contribution to complex impedance	Phasor diagram
$R - \frac{j}{\omega C}$	

You know that the voltage in a capacitive lags the current because the current must flow to build up the charge, and the voltage across the capacitor is proportional to that charge which is built up on the capacitor plates.

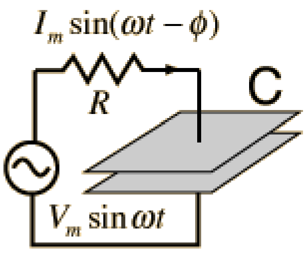
Index

Capacitance concepts

Inductance concepts

RC Impedance

The frequency dependent impedance of an RC series circuit.



$$Z = \sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}$$

at phase:

$$\phi = \tan^{-1}\frac{-1/\omega C}{R}$$

For C = [ ] x10^ [ ] F = [ ] μF = [ ] pF

at angular frequency ω = [ ] x10^ [ ] rad/s,

frequency = [ ] x10^ [ ] Hz = [ ] kHz = [ ] MHz

and resistance **R** = [ ] x10^ [ ] ohms = [ ] kohms = [ ] Megohms,

the impedance is

Z = [ ] x10^ [ ] ohms = [ ] kohms = [ ] Megohms

at phase ϕ = [ ] degrees.

Default values will be entered for unspecified parameters, but all component values can be changed. Click outside the box after entering data to initiate the calculation.

AC behavior of RC circuit

A.C. SERIES CIRCUITS WITH (II) RESISTANCE INDUCTANCE AND CAPACITANCE

Direct current (DC) circuits involve current flowing in one direction. In alternating current (AC) circuits, instead of a constant voltage supplied by a battery, the voltage oscillates in a sine wave pattern, varying with time as:

$$V = V_0 \sin \omega t$$

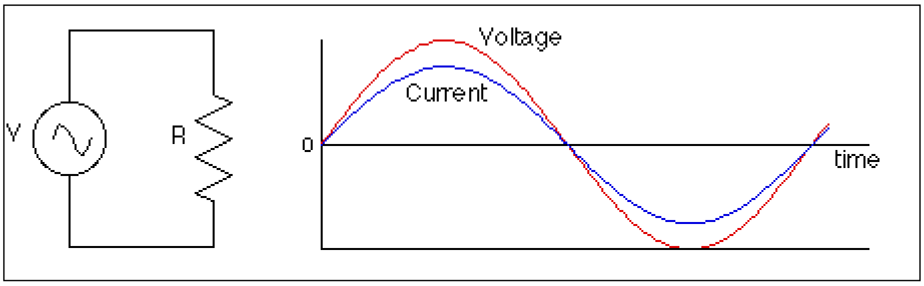
In a household circuit, the frequency is 60 Hz. The angular frequency is related to the frequency, f, by:

$$\omega = 2 \pi f$$

Vo represents the maximum voltage, which in a household circuit in North America is about 170 volts. We talk of a household voltage of 120 volts, though; this number is a kind of average value of the voltage. The particular averaging method used is something called root mean square (square the voltage to make everything positive, find the average, take the square root), or rms. Voltages and currents for AC circuits are generally expressed as rms values. For a sine wave, the relationship between the peak and the rms average is:

rms value = 0.707 peak value

Resistance in an AC circuit

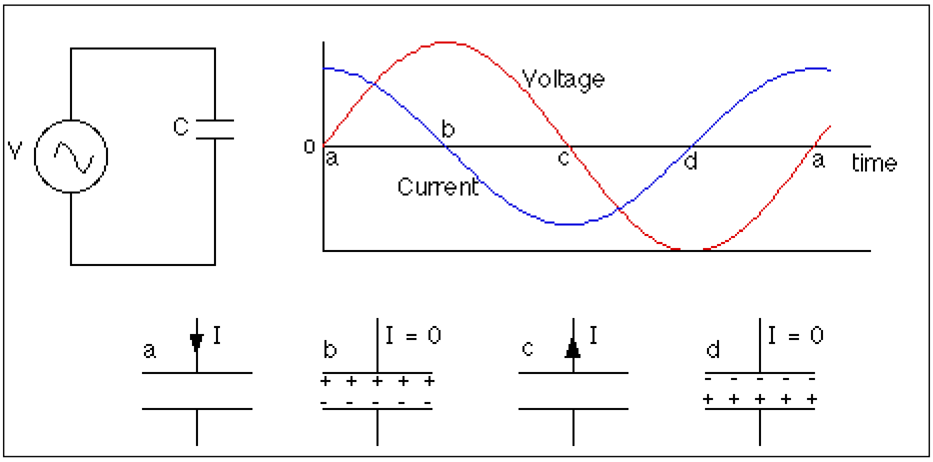


The relationship V = IR applies for resistors in an AC circuit, so

$$I = V / R = (V_0 / R) \sin(\omega t) = I_0 \sin(\omega t)$$

In AC circuits we'll talk a lot about the phase of the current relative to the voltage. In a circuit which only involves resistors, the current and voltage are in phase with each other, which means that the peak voltage is reached at the same instant as peak current. In circuits which have capacitors and inductors (coils) the phase relationships will be quite different.

Capacitance in an AC circuit



Consider now a circuit which has only a capacitor and an AC power source (such as a wall outlet). A capacitor is a device for storing charging. It turns out that there is a 90° phase difference between the current and voltage, with the current reaching its peak 90° (1/4 cycle) before the voltage reaches its peak. Put another way, the current leads the voltage by 90° in a purely capacitive circuit.

To understand why this is, we should review some of the relevant equations, including:

relationship between voltage and charge for a capacitor: $CV = Q$

relationship between current and the flow of charge : $I = \Delta Q / \Delta t$

The AC power supply produces an oscillating voltage. We should follow the circuit through one cycle of the voltage to figure out what happens to the current.

Step 1 - At point a (see diagram) the voltage is zero and the capacitor is uncharged. Initially, the voltage increases quickly. The voltage across the capacitor matches the power supply voltage, so the current is large to build up charge on the capacitor plates.

The closer the voltage gets to its peak, the slower it changes, meaning less current has to flow. When the voltage reaches a peak at point b, the capacitor is fully charged and the current is momentarily zero.

Step 2 - After reaching a peak, the voltage starts dropping. The capacitor must discharge now, so the current reverses direction. When the voltage passes through zero at point c, it's changing quite rapidly; to match this voltage the current must be large and negative.

Step 3 - Between points c and d, the voltage is negative. Charge builds up again on the capacitor plates, but the polarity is opposite to what it was in step one. Again the current is negative, and as the voltage reaches its negative peak at point d the current drops to zero.

Step 4 - After point d, the voltage heads toward zero and the capacitor must discharge. When the voltage reaches zero it's gone through a full cycle so it's back to point a again to repeat the cycle.

The larger the capacitance of the capacitor, the more charge has to flow to build up a particular voltage on the plates, and the higher the current will be. The higher the frequency of the voltage, the shorter the time available to change the voltage, so the larger the current has to be. The current, then, increases as the capacitance increases and as the frequency increases.

Usually this is thought of in terms of the effective resistance of the capacitor, which is known as the capacitive reactance, measured in ohms. There is an inverse relationship between current and resistance, so the capacitive reactance is inversely proportional to the capacitance and the frequency:

A capacitor in an AC circuit exhibits a kind of resistance called capacitive reactance, measured in ohms. This depends on the frequency of the AC voltage, and is given by:

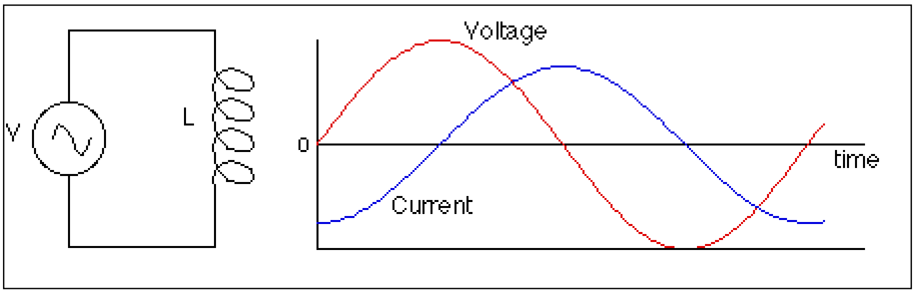
$$\text{capacitive reactance: } X_C = 1 / \omega C = 1 / 2\pi f C$$

We can use this like a resistance (because, really, it is a resistance) in an equation of the form V = IR to get the voltage across the capacitor:

$$V = I X_C$$

Note that V and I are generally the rms values of the voltage and current.

Inductance in an AC circuit



An inductor is simply a coil of wire (often wrapped around a piece of ferromagnet). If we now look at a circuit composed only of an inductor and an AC power source, we will again find that there is a 90° phase difference between the voltage and the current in the inductor. This time, however, the current lags the voltage by 90°, so it reaches its peak 1/4 cycle after the voltage peaks.

The reason for this has to do with the law of induction:

$$\varepsilon = -N \Delta\Phi / \Delta t \qquad \text{or} \quad \varepsilon = -L \Delta I / \Delta t$$

Applying Kirchoff's loop rule to the circuit above gives:

$$V - L \Delta I / \Delta t = 0 \qquad \text{so} \qquad V = L \Delta I / \Delta t$$

As the voltage from the power source increases from zero, the voltage on the inductor matches it. With the capacitor, the voltage came from the charge stored on the capacitor plates (or, equivalently, from the electric field between the plates). With the inductor, the voltage comes from changing the flux through the coil, or, equivalently, changing the current through the coil, which changes the magnetic field in the coil.

To produce a large positive voltage, a large increase in current is required. When the voltage passes through zero, the current should stop changing just for an instant. When the voltage is large and negative, the current should be decreasing quickly. These conditions can all be satisfied by having the current vary like a negative cosine wave, when the voltage follows a sine wave.

How does the current through the inductor depend on the frequency and the inductance? If the frequency is raised, there is less time to change the voltage. If the time interval is reduced, the change in current is also reduced, so the current is lower. The current is also reduced if the inductance is increased.

As with the capacitor, this is usually put in terms of the effective resistance of the inductor. This effective resistance is known as the inductive reactance. This is given by:

$$X_L = \omega L = 2\pi f L$$

where L is the inductance of the coil (this depends on the geometry of the coil and whether its got a ferromagnetic core). The unit of inductance is the henry.

As with capacitive reactance, the voltage across the inductor is given by:

$$V = IX_L$$

Where does the energy go?

One of the main differences between resistors, capacitors, and inductors in AC circuits is in what happens with the electrical energy. With resistors, power is simply dissipated as heat. In a capacitor, no energy is lost because the capacitor alternately stores charge and then gives it back again. In this case, energy is stored in the electric field between the capacitor plates. The amount of energy stored in a capacitor is given by:

$$\text{energy in a capacitor: Energy} = 1/2\ CV^2$$

In other words, there is energy associated with an electric field. In general, the energy density (energy per unit volume) in an electric field with no dielectric is:

$$\text{Energy density in an electric field} = 1/2\ \varepsilon_0\ E^2$$

With a dielectric, the energy density is multiplied by the dielectric constant.

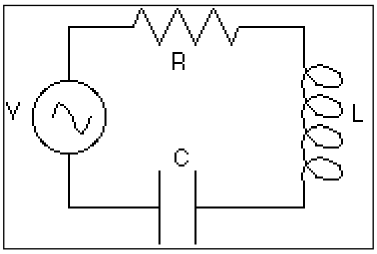
There is also no energy lost in an inductor, because energy is alternately stored in the magnetic field and then given back to the circuit. The energy stored in an inductor is:

$$\text{energy in an inductor: Energy} = 1/2\ LI^2$$

Again, there is energy associated with the magnetic field. The energy density in a magnetic field is:

$$\text{Energy density in a magnetic field} = B^2/(2\mu_0)$$

RLC Circuits



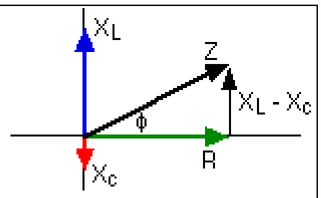
Consider what happens when resistors, capacitors, and inductors are combined in one circuit. If all three components are present, the circuit is known as an RLC circuit (or LRC). If only two components are present, it's either an RC circuit, an RL circuit, or an LC circuit.

The overall resistance to the flow of current in an RLC circuit is known as the impedance, symbolized by Z. The impedance is found by combining the resistance, the capacitive reactance, and the inductive reactance. Unlike a simple series circuit with resistors, however, where the resistances are directly added, in an RLC circuit the resistance and reactances are added as vectors.

This is because of the phase relationships. In a circuit with just a resistor, voltage and current are in phase. With only a capacitor, current is 90° ahead of the voltage, and with just an inductor the reverse is true, the voltage leads the current by 90°. When all three components are combined into one circuit, there has to be some compromise.

To figure out the overall effective resistance, as well as to determine the phase between the voltage and current, the impedance is calculated like this. The resistance R is drawn along the +x-axis of an x-y coordinate system. The inductive reactance is at 90° to this, and is drawn along the +y-axis. The capacitive reactance is also at 90° to the resistance, and is 180° different from the inductive reactance, so it's drawn along the -y-axis. The impedance, Z, is the sum of these vectors, and is given by:

$$Z = [R^2 + (X_L - X_C)^2]^{1/2}$$



The current and voltage in an RLC circuit are related by V = IZ. The phase relationship between the current and voltage can be found from the vector diagram: its the angle between the impedance, Z, and the resistance, R. The angle can be found from:

$$\tan\phi = (X_L - X_C) / R$$

If the angle is positive, the voltage leads the current by that angle. If the angle is negative, the voltage lags the currents.

The power dissipated in an RLC circuit is given by:

$$P = VI \cos\phi$$ $\cos\phi$ is known as the power factor in the circuit

Note that all of this power is lost in the resistor; the capacitor and inductor alternately store energy in electric and magnetic fields and then give that energy back to the circuit.

Q FACTOR OF R.L.C. SERIES CIRCUITS.

An **RLC circuit** (the letters R, L and C can be in other orders) is an electrical circuit consisting of a resistor, aninductor, and a capacitor, connected in series or in parallel. The RLC part of the name is due to those letters being the usual electrical symbols for resistance, inductance and capacitance respectively. The circuit forms a harmonic oscillator for current and will resonate in a similar way as an LC circuit will. The main difference that the presence of the resistor makes is that any oscillation induced in the circuit will die away over time if it is not kept going by a source. This effect of the resistor is called damping. The presence of the resistance also reduces the peak resonant frequency somewhat. Some resistance is unavoidable in real circuits, even if a resistor is not specifically included as a component. An ideal, pure LC circuit is an abstraction for the purpose of theory.

There are many applications for this circuit. They are used in many different types of oscillator circuits. Another important application is for tuning, such as in radio receivers ortelevision sets, where they are used to select a narrow range of frequencies from the ambient radio waves. In this role the circuit is often referred to as a tuned circuit. An RLC circuit can be used as a band-pass filter, band-stop filter, low-pass filter or high-pass filter. The tuning application, for instance, is an example of band-pass filtering. The RLC filter is described as a *second-order* circuit, meaning that any voltage or current in the circuit can be described by a second-order differential equation in circuit analysis.

The three circuit elements can be combined in a number of different topologies. All three elements in series or all three elements in parallel are the simplest in concept and the most straightforward to analyse. There are, however, other arrangements, some with practical importance in real circuits. One issue often encountered is the need to take into account inductor resistance. Inductors are typically constructed from coils of wire, the resistance of which is not usually desirable, but it often has a significant effect on the circuit.

An important property of this circuit is its ability to resonate at a specific frequency, the resonance frequency, f_0. Frequencies are measured in units of hertz. In this article, however, angular frequency, ω_0, is used which is more mathematically convenient. This is measured in radiansper second. They are related to each other by a simple proportion,

$$\omega_0 = 2\pi f_0$$

Resonance occurs because energy is stored in two different ways: in an electric field as the capacitor is charged and in a magnetic field as current flows through the inductor. Energy can be transferred from one to the other within the circuit and this can be oscillatory. A mechanical analogy is a weight suspended on a spring which will oscillate up and down when released. This is no passing metaphor; a weight on a spring is described by exactly the same second order differential equation as an RLC circuit and for all the properties of the one system there will be found an analogous property of the other. The mechanical property answering to the resistor in the circuit is friction in the spring/weight system. Friction will slowly bring any oscillation to a halt if there is no external force driving it. Likewise, the resistance in an RLC circuit will "damp" the oscillation, diminishing it with time if there is no driving AC power source in the circuit.

The resonance frequency is defined as the frequency at which the impedance of the circuit is at a minimum. Equivalently, it can be defined as the frequency at which the impedance is purely real (that is, purely resistive). This occurs because the impedances of the inductor and capacitor at resonance are equal but of opposite sign and cancel out. Circuits where L and C are in parallel rather than series actually have a maximum impedance rather than a minimum impedance. For this reason they are often described asantiresonators, it is still usual, however, to name the frequency at which this occurs as the resonance frequency.

Natural frequency

The resonance frequency is defined in terms of the impedance presented to a driving source. It is still possible for the circuit to carry on oscillating (for a time) after the driving source has been removed or it is subjected to a step in voltage (including a step down to zero). This is similar to the way that a tuning fork will carry on ringing after it has been struck, and the effect is often called ringing. This effect is the peak natural resonance frequency of the circuit and in general is not exactly the same as the driven resonance frequency, although the two will usually be quite close to each other. Various terms are used by different authors to distinguish the two, but resonance frequency unqualified usually means the driven resonance frequency. The driven frequency may be called the undamped resonance frequency or undamped natural frequency and the peak frequency may be called the damped resonance frequency or the damped natural frequency. The reason for this terminology is that the driven resonance frequency in a series or parallel resonant circuit has the value[1]

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

This is exactly the same as the resonance frequency of an LC circuit, that is, one with no resistor present. The resonant frequency for an RLC circuit is the same as a circuit in which there is no damping, hence undamped resonance frequency. The peak resonance frequency, on the other hand, depends on the value of the resistor and is described as the damped resonant frequency. A highly damped circuit will fail to resonate at all when not driven. A circuit with a value of resistor that causes it to be just on the edge of ringing is called critically damped. Either side of critically damped are described as underdamped (ringing happens) and over damped (ringing is suppressed).

Circuits with topologies more complex than straightforward series or parallel (some examples described later in the article) have a driven resonance frequency that deviates from $\omega_0 = \frac{1}{\sqrt{LC}}$ and for those the undamped resonance frequency, damped resonance frequency and driven resonance frequency can all be different.

Damping

Damping is caused by the resistance in the circuit. It determines whether or not the circuit will resonate naturally (that is, without a driving source). Circuits which will resonate in this way are described as under damped and those that will not are over damped. Damping attenuation (symbol α) is measured in nepers per second. However, the unit less damping factor (symbol ζ, zeta) is often a more useful measure, which is related to α by

$$\zeta = \frac{\alpha}{\omega_0}$$

The special case of $\zeta = 1$ is called critical damping and represents the case of a circuit that is just on the border of oscillation. It is the minimum damping that can be applied without causing oscillation.

Bandwidth

The resonance effect can be used for filtering, the rapid change in impedance near resonance can be used to pass or block signals close to the resonance frequency. Both band-pass and band-stop filters can be constructed and some filter circuits are shown later in the article. A key parameter in filter design is bandwidth. The bandwidth is measured between the 3dB-points, that is, the frequencies at which the power passed through the circuit has fallen to half the value passed at resonance. There are two of these half-power frequencies, one above, and one below the resonance frequency

$$\Delta\omega = \omega_2 - \omega_1$$

where $\Delta\omega$ is the bandwidth, ω_1 is the lower half-power frequency and ω_2 is the upper half-power frequency. The bandwidth is related to attenuation by,

$$\Delta\omega = 2\alpha$$

when the units are radians per second and nepers per second respectively[citation needed]. Other units may require a conversion factor. A more general measure of bandwidth is the fractional bandwidth, which expresses the bandwidth as a fraction of the resonance frequency and is given by

$$F_{\mathrm{b}} = \frac{\Delta\omega}{\omega_0}$$

The fractional bandwidth is also often stated as a percentage. The damping of filter circuits is adjusted to result in the required bandwidth. A narrow band filter, such as a notch filter, requires low damping. A wide band filter requires high damping.

Q factor

The Q factor is a widespread measure used to characterize resonators. It is defined as the peak energy stored in the circuit divided by the average energy dissipated in it per radian at resonance. Low Q circuits are therefore damped and lossy and high Q circuits are under damped. Q is related to bandwidth; low Q circuits are wide band and high Q circuits are narrow band. In fact, it happens that Q is the inverse of fractional bandwidth

$$Q = \frac{1}{F_b} = \frac{\omega_0}{\Delta\omega}$$

Q factor is directly proportional to selectivity, as Q factor depends inversely on bandwidth.

For a series resonant circuit, the Q factor can be calculated as follows:[2]

$$Q = \frac{1}{\omega_0 RC} = \frac{\omega_0 L}{R}$$

Scaled parameters

The parameters ζ, F_b, and Q are all scaled to ω_0. This means that circuits which have similar parameters share similar characteristics regardless of whether or not they are operating in the same frequency band.

The article next gives the analysis for the series RLC circuit in detail. Other configurations are not described in such detail, but the key differences from the series case are given. The general form of the differential equations given in the series circuit section are applicable to all second order circuits and can be used to describe the voltage or current in any element of each circuit.

Series RLC circuit

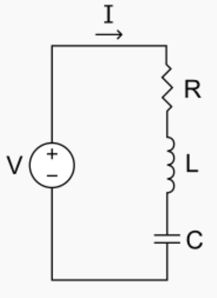


Figure 1: RLC series circuit

V – the voltage of the power source

I – the current in the circuit

R – the resistance of the resistor

L – the inductance of the inductor

C – the capacitance of the capacitor

In this circuit, the three components are all in series with the voltage source. The governing differential equation can be found by substituting intoKirchhoff's voltage law (KVL) the constitutive equation for each of the three elements. From KVL,

$$v_R + v_L + v_C = v(t)$$

where v_R, v_L, v_C are the voltages across R, L and C respectively and $v(t)$ is the time varying voltage from the source. Substituting in theconstitutive equations,

$$Ri(t) + L\frac{di}{dt} + \frac{1}{C}\int_{-\infty}^{\tau=t} i(\tau)\, d\tau = v(t)$$

For the case where the source is an unchanging voltage, differentiating and dividing by L leads to the second order differential equation:

$$\frac{d^2i(t)}{dt^2} + \frac{R}{L}\frac{di(t)}{dt} + \frac{1}{LC}i(t) = 0$$

This can usefully be expressed in a more generally applicable form:

$$\frac{d^2i(t)}{dt^2} + 2\alpha\frac{di(t)}{dt} + {\omega_0}^2 i(t) = 0$$

and ω_0 are both in units of angular frequency. α is called the *neper frequency*, or *attenuation*, and is a measure of how fast the transient response of the circuit will die away after the stimulus has been removed. Neper occurs in the name because the units can also be considered to be nepers per second, neper being a unit of attenuation. ω_0 is the angular resonance frequency.

For the case of the series RLC circuit these two parameters are given by:[4]

$$\alpha = \frac{R}{2L} \text{ and } \omega_0 = \frac{1}{\sqrt{LC}}$$

A useful parameter is the *damping factor*, ζ which is defined as the ratio of these two,

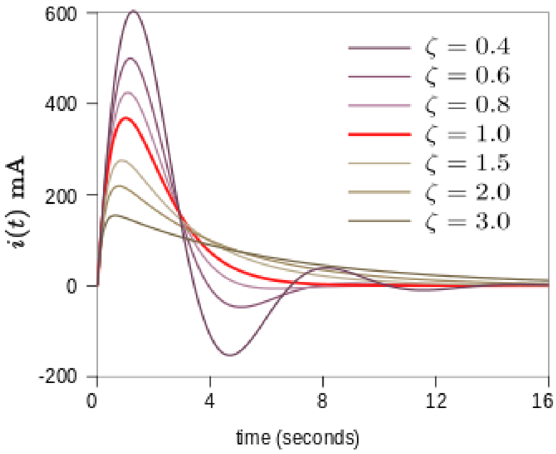
$$\zeta = \frac{\alpha}{\omega_0}$$

In the case of the series RLC circuit, the damping factor is given by,

$$\zeta = \frac{R}{2}\sqrt{\frac{C}{L}}$$

The value of the damping factor determines the type of transient that the circuit will exhibit.[5] Some authors do not use ζ and call α the damping factor.[6]

Transient response



Plot showing under-damped and over-damped responses of a series RLC circuit. The critical damping plot is the bold red curve. The plots are normalized for *L* = 1, *C* = 1 and $\omega_0 = 1$

The differential equation for the circuit solves in three different ways depending on the value of ζ. These are underdamped ($\zeta < 1$), overdamped ($\zeta > 1$) and critically damped ($\zeta = 1$). The differential equation has the characteristic equation,[7]

$$s^2 + 2\alpha s + {\omega_0}^2 = 0$$

The roots of the equation in *s* are,[7]

$$s_1 = -\alpha + \sqrt{\alpha^2 - {\omega_0}^2}$$

$$s_2 = -\alpha - \sqrt{\alpha^2 - {\omega_0}^2}$$

The general solution of the differential equation is an exponential in either root or a linear superposition of both,

$$i(t) = A_1 e^{s_1 t} + A_2 e^{s_2 t}$$

The coefficients A_1 and A_2 are determined by the boundary conditions of the specific problem being analysed. That is, they are set by the values of the currents and voltages in the circuit at the onset of the transient and the presumed value they will settle to after infinite time.[8]

Over damped response

The over damped response ($\zeta > 1$) is,

$$i(t) = A_1 e^{-\omega_0\left(\zeta + \sqrt{\zeta^2 - 1}\right)t} + A_2 e^{-\omega_0\left(\zeta - \sqrt{\zeta^2 - 1}\right)t}$$

The over damped response is a decay of the transient current without oscillation.[10]

Under damped response

The under damped response ($\zeta < 1$) is,[11]

$$i(t) = B_1 e^{-\alpha t} \cos(\omega_d t) + B_2 e^{-\alpha t} \sin(\omega_d t)$$

By applying standard trigonometric identities the two trigonometric functions may be expressed as a single sinusoid with phase shift,[12]

$$i(t) = B_3 e^{-\alpha t} \sin(\omega_d t + \varphi)$$

The under damped response is a decaying oscillation at frequency ω_d. The oscillation decays at a rate determined by the attenuation α. The exponential in α describes the envelope of the oscillation. B_1 and B_2 (or B_3 and the phase shift φ in the second form) are arbitrary constants determined by boundary conditions. The frequency ω_d is given by,

$$\omega_d = \sqrt{{\omega_0}^2 - \alpha^2} = \omega_0 \sqrt{1 - \zeta^2}$$

This is called the damped resonance frequency or the damped natural frequency. It is the frequency the circuit will naturally oscillate at if not driven by an external source. The resonance frequency, ω_0, which is the frequency at which the circuit will resonate when driven by an external oscillation, may often be referred to as the undamped resonance frequency to distinguish it.

Critically damped response

The critically damped response ($\zeta = 1$) is,[14]

$$i(t) = D_1 t e^{-\alpha t} + D_2 e^{-\alpha t}$$

The critically damped response represents the circuit response that decays in the fastest possible time without going into oscillation. This consideration is important in control systems where it is required to reach the desired state as quickly as possible without overshooting. D_1 and D_2 are arbitary constants determined by boundary conditions.

Laplace domain

The series RLC can be analyzed for both transient and steady AC state behavior using the Laplace transform.[16] If the voltage source above produces a waveform with Laplace-transformed $V(s)$ (where s is the complex frequency $s = \sigma + i\omega$), KVL can be applied in the Laplace domain:

$$V(s) = I(s)\left(R + Ls + \frac{1}{Cs}\right)$$

where $I(s)$ is the Laplace-transformed current through all components. Solving for $I(s)$:

$$I(s) = \frac{1}{R + Ls + \frac{1}{Cs}} V(s)$$

And rearranging, we have that

$$I(s) = \frac{s}{L\left(s^2 + \frac{R}{L}s + \frac{1}{LC}\right)} V(s)$$

Laplace admittance

Solving for the Laplace admittance $Y(s)$:

$$Y(s) = \frac{I(s)}{V(s)} = \frac{s}{L\left(s^2 + \frac{R}{L}s + \frac{1}{LC}\right)}$$

Simplifying using parameters α and ω_0 defined in the previous section, we have

$$Y(s) = \frac{I(s)}{V(s)} = \frac{s}{L\left(s^2 + 2\alpha s + {\omega_0}^2\right)}$$

Poles and zero

The zeros of $Y(s)$ are those values of s such that $Y(s) = 0$:

$$s = 0 \text{ and } |s| \rightarrow \infty$$

The poles of $Y(s)$ are those values of s such that $Y(s) \rightarrow \infty$. By the quadratic formula, we find

$$s = -\alpha \pm \sqrt{\alpha^2 - {\omega_0}^2}$$

The poles of $Y(s)$ are identical to the roots s_1 and s_2 of the characteristic polynomial of the differential equation in the section above.

*General solution**[edit]***

For an arbitrary $E(t)$, the solution obtained by inverse transform of $I(s)$ is:

$$I(t) = \frac{1}{L}\int_0^t E(t-\tau)e^{-\alpha\tau}\left(\cos\omega_d\tau - \frac{\alpha}{\omega_d}\sin\omega_d\tau\right)d\tau \text{ in the underdamped case } (\omega_0 > \alpha)$$

$$I(t) = \frac{1}{L}\int_0^t E(t-\tau)e^{-\alpha\tau}(1-\alpha\tau)\,d\tau \text{ in the critically damped case } (\omega_0 = \alpha)$$

$$I(t) = \frac{1}{L}\int_0^t E(t-\tau)e^{-\alpha\tau}\left(\cosh\omega_r\tau - \frac{\alpha}{\omega_r}\sinh\omega_r\tau\right)d\tau \text{ in the overdamped case } (\omega_0 < \alpha)$$

where $\omega_r = \sqrt{\alpha^2 - {\omega_0}^2}$, and cosh and sinh are the usual hyperbolic functions.

Sinusoidal steady state

Sinusoidal steady state is represented by letting $s = i\omega$

Taking the magnitude of the above equation with this substitution:

$$|Y(s = i\omega)| = \frac{1}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}.$$

and the current as a function of ω can be found from

$$|I(i\omega)| = |Y(i\omega)||V(i\omega)|.$$

There is a peak value of $|I(i\omega)|$. The value of ω at this peak is, in this particular case, equal to the undamped natural resonance frequency

$$\omega_0 = \frac{1}{\sqrt{LC}}.$$

UNIT- 8

SOLDERING AND BRAZING

8.1 Introduction

Soldering and brazing provide permanent joint to bond metal pieces. Soldering and brazing process lies somewhere in between fusion welding and solid state welding. These processes have some advantages over welding process. These can join the metal having poor weld ability, dissimilar metals; very less amount of heating is needed. The major disadvantage is joint made by soldering and brazing has low strength as compared to welded joint.

8.2 Soldering

It is a process in which two or more items are joined together by melting and putting a filler metal (solder) into the joint, the filler metal having a lower melting point than the adjoining metal. Unlike welding, soldering does not involve melting the work pieces. In brazing, the filler metal melts at a higher temperature, but the work piece metal does not melt.

8.2.1 PRINCIPLE OF SOLDERING

Soldering is very much similar to brazing and its principle is same as that of brazing. The major difference lies with the filler metal, the filler metal used in case of soldering should have the melting temperature lower than 450°C. The surfaces to be soldered must be pre-cleaned so that these are faces of oxides, oils, etc. An appropriate flux must be applied to the faying surfaces and then surfaces are heated. Filler metal called solder is added to the joint, which distributes between the closely fitted surfaces. Strength of soldered joint is much lesser than welded joint and less than a brazed joint.

8.2.2 TOOLS OF SOLDERING

Soldering Iron

Soldering can be done using soldering iron. It is inexpensive and portable. Soldering wire is required to solder

Wire Cutter

The wire cutter is a very handy little soldering tool. Use it to cut long component legs, or to strip the end of a wire.This is also called flush cutters, diagonal cutters, electronic snippers, clippers, etc

Soldering Stand

A soldering iron gets hot, so it’s important to place it in a safe way in between soldering. A soldering iron stand is very handy for this.

Wet Sponge

A wet sponge is very useful for cleaning the tip of the soldering iron. The tip is hot which means it will oxidize very fast and get dirty. A clean tip transfers heat faster and makes your soldering easier.A sponge is so cheap anyway, so you should always keep one together with your other soldering tools.

Tweezers

Tweezers are great. You can use them to keep components in their place and to avoid burning your fingers when soldering.

If you ever soldering surface mount components, these are very useful for placing small components.

8.3 DESOLDERING

The reverse process of soldering is desoldering. It is a process of removal of solder and components mounted on circuit boards for repair purpose. Sometimes you make a mistake or you need to replace a component in a circuit. This means you have to desolder to fix it. There are two tools used for desoldering

Solder sucker or desoldering pump:

The solder sucker, or solder pump, is a mechanical vacuum pump. It sucks the solder away from the solder joint. Just heat the solder joint to make the solder fluid, and then suck it off with the solder sucker. This tool is used when we need to remove a lot of solder at once.

Solder wick

The solder wick is another tool for removing solder. It's made up of copper threads that will absorb the solder from the solder joint.

8.4 PROCEDURE TO SOLDER COMPONENTS:

1. Place the soldering iron in its stand and plug it in.
2. Wait for the soldering iron to heat up. Adjust the temperature of the soldering station to 350^0 C (degrees Celsius)
3. Ensure the solder sponge is damp. A dry sponge will not clean the tip effectively, and one that is too wet will lower the temperature of the tip making for an ineffective solder joint.
4. Carefully wipe the tip on the damp sponge until clean. Continually wipe the tip while soldering a circuit board.
5. Moisten the sponge.
6. Wipe the tip of the iron on the damp sponge. This will clean the tip.
7. Bend the lead of component using plier sothat it can be inserted in the holes of Printed Circuit Board(PCB)
8. Insert the component to be soldered into the circuit board and bend the leads protruding from the bottom of the circuit board at an angle of approx 45^0
9. When ready, hold the soldering iron at a 45° angle, and heat both the lead and the pad simultaneously. Touch the solder wire in the space between the iron tip and the lead.
10. Keep the soldering iron tip still while moving the solder around the joint as it melts.
11. Remove the solder tip first and the solder wire next, (prevents spiking).
12. Allow to the joint to cool naturally and undisturbed, do not blow on the solder joint to cool it.
13. When you have completed all solder joints thoroughly clean your board, using Isopropyl Alcohol, and a bristle brush, to remove the flux residue and other contaminants.

8.5 BRAZING

Brazing is a metal-joining process in which two or more metal items are joined together by melting and flowing a filler metal into the joint, the filler metal having a lower melting point than the adjoining metal.

8.5.1 BRAZING MATERIALS

A variety of alloys are used as filler metals for brazing depending on the intended use or application method. In general, braze alloys are made up of 3 or more metals to form an alloy with the desired properties. The filler metal for a particular application is chosen based on its ability to: wet the base metals, withstand the service conditions required, and melt at a lower temperature than the base metals or at a very specific temperature.

Braze alloy is generally available as rod, ribbon, powder, paste, cream, wire and preforms (such as stamped washers). Depending on the application, the filler material can be pre-placed at the desired location or applied during the heating cycle. For manual brazing, wire and rod forms are generally used as they are the easiest to apply while heating. In the case of furnace brazing, alloy is usually placed beforehand since the process is usually highly automated.Some of the more common types of filler metals used are

- Aluminum-silicon
- Copper
- Copper-silver
- Copper-zinc (brass)
- Copper-tin (bronze)
- Gold-silver
- Nickel alloy
- Silver
- Amorphous brazing foil using nickel, iron, copper, silicon, boron, phosphorus, etc.

8.5.2 PRINCIPLE OF BRAZING

In case of brazing joining of metal pieces is done with the help of filler metal. Filler metal is melted and distributed by capillary action between the faying surfaces of the metallic parts being joined. In this case only filler metal melts. There is no melting of workpiece metal. The filler metal (brazing metal) should have the melting point more than 450°C. Its melting point should be lesser than the melting point of workpiece metal. The metallurgical bonding between work and filler metal and geometric constrictions imposed on the joint by the workpiece metal make the joint stronger than the filler metal out of which the joint has been formed.

8.5.3 PROCEDURE OF BRAZING

1. Ensure good fit and proper clearances.

Brazing uses capillary action to distribute molten filler metal between the surfaces of the base metals. So when you're brazing, maintain a clearance between the base metals to allow capillary action to work most effectively. Keep in mind that generally, as the clearance increases, joint strength decreases. Capillary action stops around 0.012 in. If you're joining two flat parts, you can rest one on top of the other.When you're planning your joint clearances, remember that brazed joints are made at brazing temperatures, not at room temperature. Take into account the coefficient of thermal expansion of the metals being joined, particularly with tubular assemblies in which dissimilar metals are joined.

2. Clean the metals.

Capillary action works properly only with clean metal surfaces. If they're coated with oil, grease, rust, scale, or dirt, you must remove these contaminants or they'll form a barrier between the base metal surfaces and the brazing materials.

3. Flux the parts.

Flux is a chemical compound applied to the joint surfaces before brazing. Its use, with a few exceptions, is essential in the atmospheric brazing process. This is because heating a metal surface accelerates oxide formation, the result of a chemical reaction between the hot metal and oxygen in the air. If you don't prevent these oxides from forming, they'll inhibit the brazing filler metal from wetting and bonding to the surfaces.

A coating of flux on the joint area shields the surfaces from the air, preventing oxide formation. It also dissolves and absorbs any oxides that form during heating or that were not removed completely in the cleaning process.

4. Assemble for brazing.

Once your parts are cleaned and fluxed, hold them in position for brazing. Be sure they remain in correct alignment during the heating and cooling cycles so that capillary action can do its job. If the shape and weight of the parts permit, the simplest way to hold them together is by gravity.

5.Braze the assembly.

The actual brazing involves heating the assembly to brazing temperature and flowing the filler metal through the joint. Be sure when you're heating an assembly to brazing temperature that you don't heat it to the base materials' melting point.

6. Clean the brazed joint.

After you braze the assembly, clean it. Because most brazing fluxes are corrosive, cleaning is essential. Cleaning usually is a two-step operation:

1. Remove the flux residues.
2. Remove any oxide scale formed during the brazing process by pickling.

8.6 TYPES OF SOLDER:

1. Soft soldering

It is a process for joining small intricate parts having low melting points which damages when soldering process is carried out at high temperature. It uses tin-lead alloy as filler material. The melting point of the filler material should be below 400 °C . It uses gas torch as the heat source.

2. Hard soldering

In this process, hard solder connects two pieces of metals by expanding into the pores of the work piece opened by high temperature. The filler material possess high temperature above 450 °C.It comprises of two parts namely silver soldering and brazing.

3. Silver soldering

It is a clean process useful for fabricating small fittings, doing odd repairs and making tools. It uses an alloy containing silver as filler material. Silver provides free flowing characteristics but silver solder is not good at gap filling hence, different fluxes are recommended for precised silver solder.

8.7 FLUX

The purpose of flux is to facilitate the soldering process. One of the obstacles to a successful solder joint is an impurity at the site of the joint, for example, dirt, oil or oxidation. The impurities can be removed by mechanical cleaning or by chemical means.

One of the earliest forms of flux was charcoal, which acts as a reducing agent and helps prevent oxidation during the soldering process.

TYPES OF SOLDERING FLUXES

Soldering fluxes can be classified as:

- Organic, and
- Inorganic

Organic Fluxes

Organic fluxes are either rosin or water soluble materials. Rosin used for fluxes are wood gum, and other rosin which are not water soluble. Organic fluxes are mostly used for electrical and electronic circuit making. These are chemically unstable at elevated temperature but non-corrosive at room temperature.

Inorganic Fluxes

Inorganic fluxes are consists of inorganic acids; mixture of metal chlorides (zinc and ammonium chlorides). These are used to achieve rapid and active fluxing where formations of oxide films are problems.

Fluxes should be removed after soldering either by washing with water or by chemical solvents. The main functions performed by fluxes are :

- remove oxide films and tarnish from base part surfaces,
- prevent oxidation during heating, and
- promote wetting of the faying

The fluxes should

- be molten at soldering temperature,
- be readily displaced by the molten solder during the process, and leave a residue that is non-corrosive and non-conductive.

8.8 Common Types of Soldering Defects

1. Pin Holes & Blow Holes on a Printed Circuit Board-Pin holes or blow holes are the same thing and caused by the printed board outgassing during soldering. Pin and blow hole formation during wave soldering is normally always associated with thickness of copper plating. The only way to eliminate the problem is improve the board quality with a minimum of 25um of copper plating in the through hole.

2. Bulbous Joint / Excess Fillet on a Printed Circuit Board-A solder joint on chip components that is over the height of the part with a convex meniscus is referred to as bulbous or excess fillet. It is caused during separation of the board from the solder wave and is more common in nitrogen soldering.

3. Cracked Joint on a Printed Circuit Board-Cracking of a solder joint on a plated through joint is uncommon. The joint fails due to expansion and contraction of the lead in the joint. It is not very common for failures to occur today due to the experience and pre testing conducted by many leading electronics companies.

4. Flux Residues on a Printed Circuit Board-Flux residues visible on the board are more common due to the reduction in the use of cleaning in the industry.

5. Incomplete Joints on a Printed Circuit Board-The incomplete solder fillet is often seen on single-sided boards after wave soldering. Incomplete solder fillets are caused by poor hole-to-lead ratio, steep conveyor angles, excessive wave temperature and contamination on the edge of the pads.

6. Solder Mask Discoloration on a Printed Circuit Board-Normally this is a cosmetic issue but should be investigated for the real cause. When running a thicker board it is probable that the soldering process or dwell times may have changed.

7. Solder Skips on a Printed Circuit Board-Unsoldered surface mount joints are referred to as solder skips where the termination does not have any solder. It is caused by incorrect chip wave height or gassing of the flux on the underside of the board.

8. Solder Flags on a Printed Circuit Board-Solder flags or spikes are due either to inconsistent flux application or poor control of solder drainage from the wave.If poor flux application is the cause, there will be other evidence on the surface of the board, like thin whiskers of solder similar to snail trails on a garden path.

8.9 COMPARISON OF SOLDERING AND BRAZING

Soldering and brazing are the most common joining process use in industries for joining same and different metal. Today we will learn about these processes and further we will compare soldering vs brazing. These all are joining processes but different process uses in different conditions. Soldering are used in electrical and electronics industries.

Advantages of soldering:
1. It require less heat.

1. Solder is good electric conductor so make a good electrical joint.

3. It does not require skilled labour.

Advantages of brazing:
1. It does not melt base metals.

2. Both similar and dissimilar metals can join.

3. It does not form internal stress due to uneven heating.

4. It can use in mass production.

5. Brazing produces a clean joint.

UNIT- 9

MEASURING INSTRUMENTS

Introduction

The instruments, which are used to measure any quantity are known as measuring instruments. This chapter covers mainly the **electronic instruments**, which are useful for measuring either electrical quantities or parameters.

Following are the most commonly used electronic instruments.

- Voltmeter
- Ammeter
- wattmeter
- Ohmmeter
- energymeter
- Multimeter

9.1 VOLTMETER and AMMETER

Voltmeter

As the name suggests, **voltmeter** is a measuring instrument which measures the voltage across any two points of an electric circuit. There are two types of voltmeters: DC voltmeter, and AC voltmeter.

DC voltmeter measures the DC voltage across any two points of an electric circuit, whereas AC voltmeter measures the AC voltage across any two points of an electric circuit.

Ammeter

As the name suggests, **ammeter** is a measuring instrument which measures the current flowing through any two points of an electric circuit. There are two types of ammeters: DC ammeter, and AC ammeter.

DC ammeter measures the DC current that flows through any two points of an electric circuit. Whereas, AC ammeter measures the AC current that flows through any two points of an electric circuit.

The ammeter and voltmeter are of two types

1. Moving Iron type
2. Moving coil type

9.1.1 MOVING IRON INTRUMENTS

Moving-iron **instruments** are generally used to measure alternating voltages and currents. In moving-iron instruments the movable system consists of one or more pieces of specially-

shaped soft iron, which are so pivoted as to be acted upon by the **magnetic field** produced by the current in coil.
There are two general types of moving-iron instruments namely:

1. **Repulsion** (or double iron) type (figure 9.1)
2. **Attraction** (or single-iron) type (figure 9.2)

The brief description of different components of a moving-iron instrument is given below:

- **Moving element:** a small piece of soft iron in the form of a vane or rod.
- **Coil:** to produce the magnetic field due to current flowing through it and also to magnetize the iron pieces.
- **In repulsion type**, a **fixed** vane or rod is also used and magnetized with the same polarity.
- **Control torque** is provided by spring or weight (gravity).
- **Damping torque** is normally pneumatic, the damping device consisting of an air chamber and a moving vane attached to the instrument spindle.
- **Deflecting torque** produces a movement on an aluminum pointer over a graduated scale.

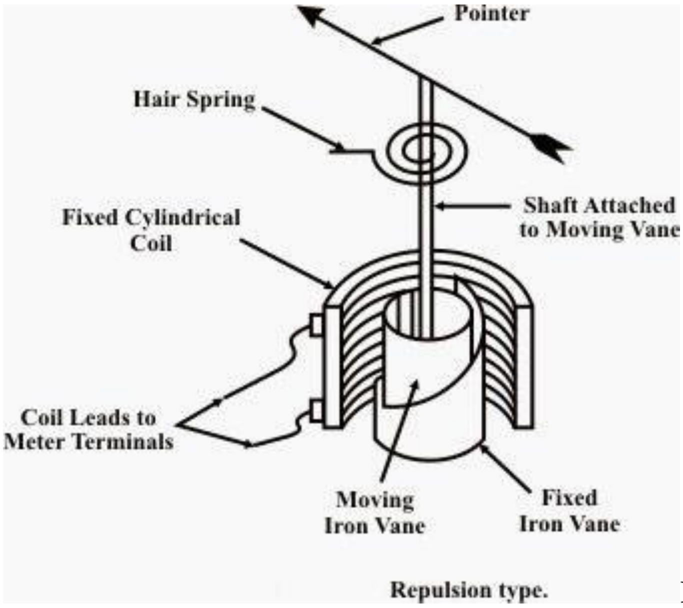
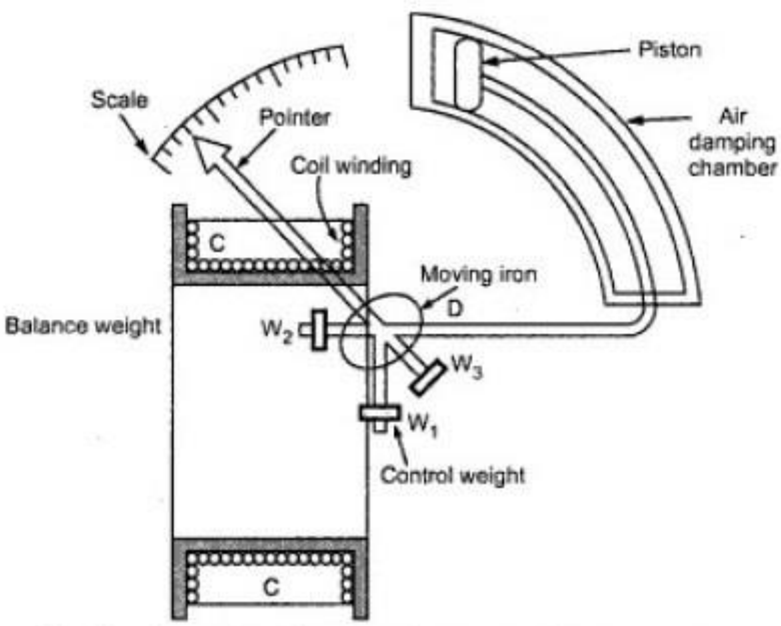


FIGURE 9.1



Moving iron attraction type instrument

Figure 9.2

Measurement of Electric Voltage and Current

- Moving iron instruments are used as Voltmeter and Ammeter only.
- Both can work on AC as well as on DC.

Ammeter

- Instrument used to measure current in the circuit.
- Always connected in series with the circuit and carries the current to be measured.
- This current flowing through the coil produces the desired deflecting torque.
- It should have low resistance as it is to be connected in series.

Voltmeter

- Instrument used to measure voltage between two points in a circuit.
- Always connected in parallel.
- Current flowing through the operating coil of the meter produces deflecting torque.
- It should have high resistance. Thus a high resistance of order of kilo ohms is connected in series with the coil of the instrument.

9.1.2 MOVING COIL INTRUMENT

When a current carrying conductor is placed in a magnetic field, it experiences a force and tends to move in the direction as per Fleming's left-hand rule.

Fleming left-hand rule:

If the first and the second finger and the thumb of the left hand are held so that they are at right angle to each other, then the thumb shows the direction of the force on the conductor, the first finger points towards the direction of the magnetic field and the second finger shows the direction of the current in the wire.

Construction

A coil of thin wire is mounted on an aluminum frame (spindle) positioned between the poles of a U shaped permanent magnet which is made up of magnetic alloys like alnico.

Refer to figure 9.3, the coil is pivoted on the jeweled bearing and thus the coil is free to rotate. The current is fed to the coil through spiral springs which are two in numbers. The coil which carries a current, which is to be measured, moves in a strong magnetic field produced by a permanent magnet and a pointer is attached to the spindle which shows the measured value.

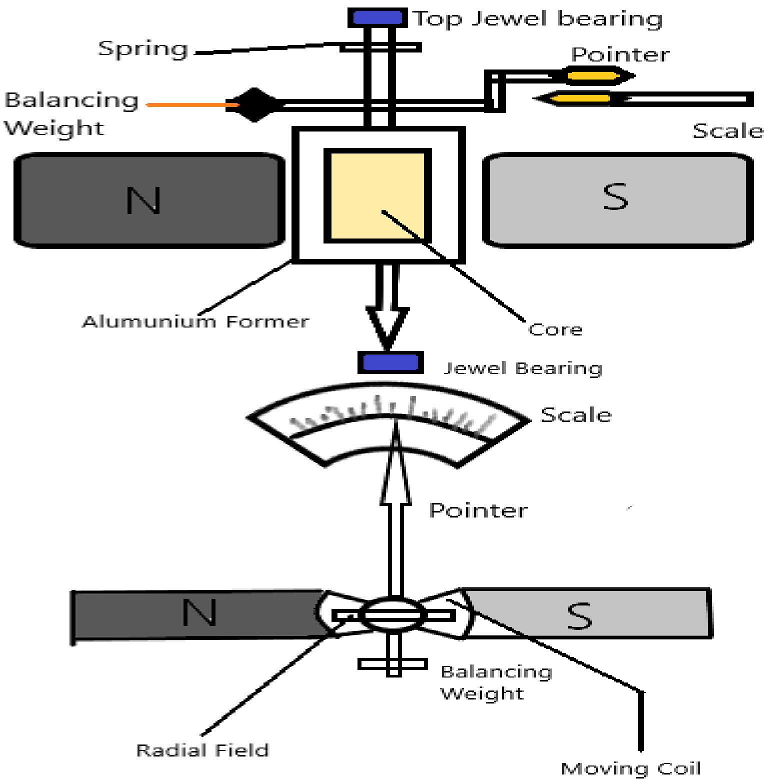


Figure 9.3

Working

When a current flow through the coil, it generates a magnetic field which is proportional to the current in case of an ammeter. The deflecting torque is produced by the electromagnetic action of the current in the coil and the magnetic field.

When the torques are balanced the moving coil will stop and its angular deflection represents the amount of electrical current to be measured against a fixed reference, called a scale. If the permanent magnet field is uniform and the spring linear, then the pointer deflection is also linear. The controlling torque is provided by two phosphorous bronze flat coiled helical springs. These springs serve as a flexible connection to the coil conductors.Damping is caused by the eddy current set up in the aluminum coil which prevents the oscillation of the coil.

Applications

The PMMC can be used as:

1) **Ammeter**:

When PMMC is used as an ammeter, except for a very small current range, the moving coil is connected across a suitable low resistance shunt, so that only small part of the main current flows through the coil.

The shunt consists of a number of thin plates made up of alloy metal, which is usually magnetic and has a low-temperature coefficient of resistance, fixed between two massive blocks of copper. A resistor of the same alloy is also placed in series with the coil to reduce errors due to temperature variation.

2) **Voltmeter**:

When PMMC is used as a voltmeter, the coil is connected in series with a high resistance. Rest of the function is same as above. The same moving coil can be used as an ammeter or voltmeter with an interchange of above arrangement

Advantages

- The PMMC consumes less power and has great accuracy.
- It has a uniformly divided scale and can cover an arc of 270 degrees.
- The PMMC has a high torque to weight ratio.
- It can be modified as ammeter or voltmeter with suitable resistance.
- It has efficient damping characteristics and is not affected by stray magnetic field.
- It produces no losses due to hysteresis.

Disadvantage

- The moving coil instrument can only be used on D.C supply as the reversal of current produces a reversal of torque on the coil.
- It's very delicate and sometimes uses AC circuit with a rectifier.
- It's costly as compared to moving coil iron instruments.
- It may show an error due to loss of magnetism of permanent magnet.

9.2 DYNAMOMETER TYPE WATTMETER

Dynamometer wattmeter is used for measuring the power. ***If two coils are connected such that, current proportional to the load voltage, flows through one coil and current proportional to the load current, flows through another coil, the meter can be calibrated directly in watts.*** This is true because the indication depends upon the product of the two magnetic fields. The strength of the magnetic fields depends upon the values of the current flowing through the coils.

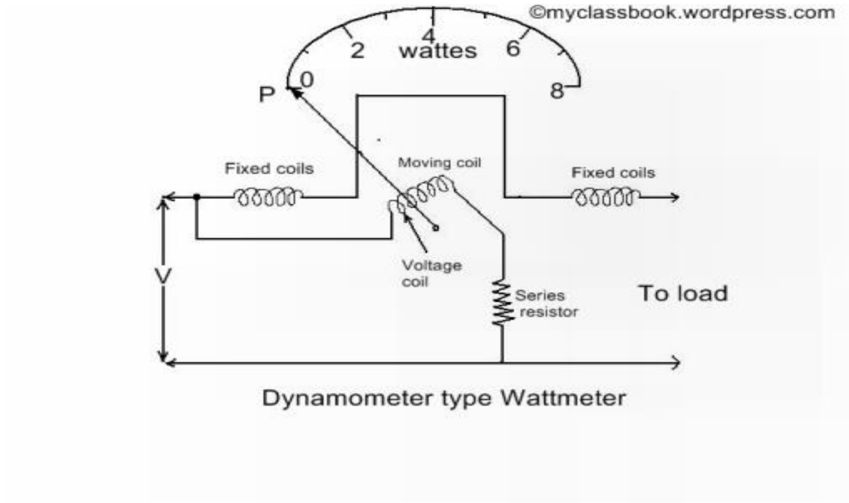


FIGURE 9.4

Working of Dynamometer Type Wattmeter:
Let us consider

- v=supply voltage
- i=load current and
- R=resistance of the moving coil circuit
- Current through fixed coils, i(f)=I
- Current through the moving coil, i(m)=v/R

Deflecting torque,

$$T_d \propto (i_f * i_m) \propto \frac{iv}{R}$$

- For a DC circuit, the deflecting torque is thus proportional to the power.
- For any circuit with fluctuating torque, the instantaneous torque is proportional to instantaneous power. In this case, due to the inertia of moving parts, the deflection will be proportional to the average power. For sinusoidal alternating quantities, the average power is VI COSθ where
- V = r.m.s. value of voltage,
- I = r.m.s. value of current, and
- θ = phase angle between V and I

Hence an electrodynamic instrument, when connected as shown in the figure, indicates the power, irrespective of the fact it is connected in an AC or DC circuit.

9.3 OHMMETER

An **ohmmeter** is an electrical instrument that measures electrical resistance, the opposition to an electric current. Micro-ohmmeters (microhmmeter or microohmmeter) make low resistance measurements. Megohmmeters (also a trademarked device Megger) measure large values of resistance. The unit of measurement for resistance is ohms (Ω).

Ohmmeter Working

In an Ohmmeter, the deflection of the needle is controlled by the amount of battery current. Before calculating the resistance of an unknown electrical circuit or resistor, first of all, the test leads of the Ohmmeter are shorted together.

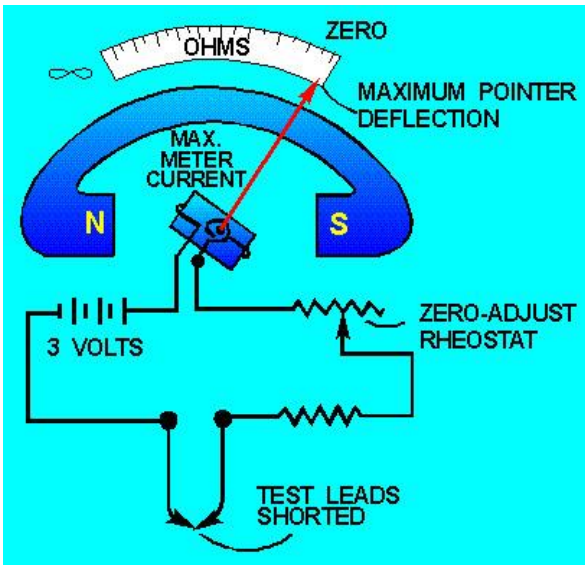


Figure 9.4

When the leads are shorted, the meter is adjusted for proper operation on the selected range and the needle drives back to the maximum position on the Ohms scale and the meter current is max. After using an Ohmmeter, the test leads should be removed. If the test leads remain connected to the Ohmmeter, then the battery of the meter gets discharged(Refer figure 9.4). When the rheostat is adjusted properly, with the test leads shorted, the needle of the meter comes to zero position, and this specifies a zero resistance between the test leads.

9.4 MEGGER

The device enable us to measure electrical leakage in wire, results are very reliable as we shall be passing electric current through device while we are testing. The equipment basically uses for verifying the electrical insulation level of any device such as motors, cables, generators, windings, etc. This is a very popular test being carried out since very long back. Not necessary it shows us exact area of electrical puncture but shows the amount of leakage current and level of moisture within electrical equipment/winding/system.

Figure 9.5

1. Digital Display :- A digital display to show IR value in digital form.
2. Wire Leads :- Two nos of wire leads for connecting **megger** with electrical external system to be tested.
3. Selection Switches :- Switches use to select electrical parameters ranges.
4. Indicators :- To indicates various parameters status i.e. On-Off. For Example Power, hold, Warning, etc.

Advantages of Electronic Type Megger

- Level of accuracy is very high.
- IR value is digital type, easy to read.
- One person can operate very easily.
- Works perfectly even at very congested space.
- Very handy and safe to use.

Disadvantages of Electronic Type Megger

- Require an external source of energy to energies i.e. Dry cell.
- Costlier in market.

9.5 INDUCTION TYPE ENERGY METER

The principle of working and construction of ***induction type meter*** is very simple and easy to understand that's why these are widely used in measuring energy in domestic as well as industrial world. In all induction meters we have two fluxes which are produced by two different alternating currents on a metallic disc. Due to alternating fluxes there is an induced emf, the emf produced at one point (as shown in the figure 9.6) interacts with the alternating current of the other side resulting in the production of torque.

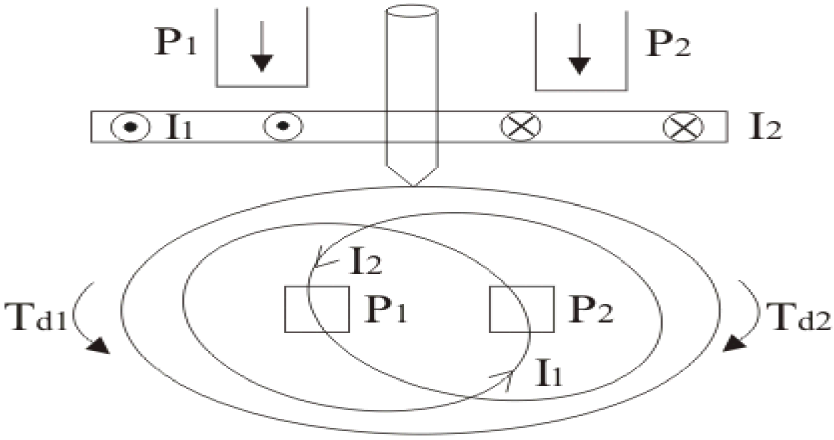


Figure 9.6

Similarly, the emf produced at the point two interacts with the alternating current at point one, resulting in the production of torque again but in opposite direction. Hence due to these two torques which are in different directions, the metallic disc moves.

This is basic principle of working of an **induction type meters**. Now let us derive the mathematical expression for deflecting torque. Let us take flux produced at point one be equal to F_1 and the flux and at point two be equal to F_2. Now the instantaneous values of these two flux can written as:

$$F_1 = F_{m1} sin\omega t, \quad F_2 = F_{m2} sin(\omega t - B)$$

Where, F_{m1} and F_{m2} are respectively the maximum values of fluxes F_1 and F_2, B is phase difference between two fluxes.

Construction of Induction type Energy Meter

The construction of the single phase energy meter is shown in the figure 9.7

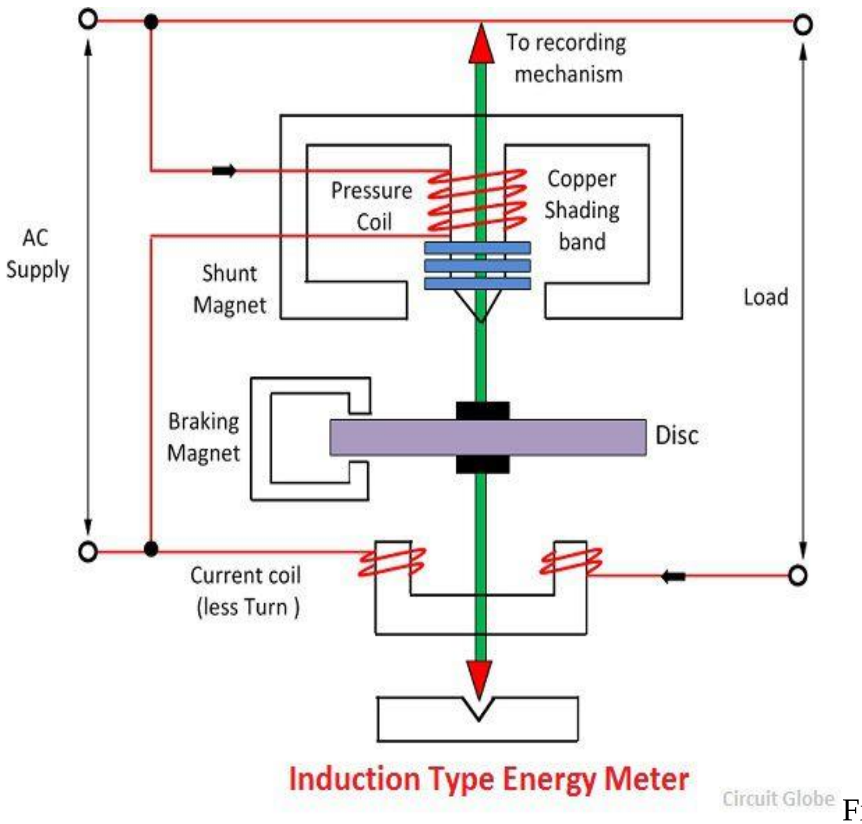


Figure 9.7

The energy meter has four main parts. They are the

1. Driving System
2. Moving System
3. Braking System
4. Registering System

The detail explanation of their parts is written below.

1. Driving System – The electromagnet is the main component of the driving system. It is the temporary magnet which is excited by the current flow through their coil. The core of the electromagnet is made up of silicon steel lamination. The driving system has two electromagnets. The upper one is called the shunt electromagnet, and the lower one is called series electromagnet.The series electromagnet is excited by the load current flow through the current coil. The coil of the shunt electromagnet is directly connected with the supply and hence carry the current proportional to the shunt voltage. This coil is called the pressure coil.The centre limb of the magnet has the copper band. These bands are adjustable. The main function of the copper band is to align the flux produced by the shunt magnet in such a way that it is exactly perpendicular to the supplied voltage.

2. Moving System – The moving system is the aluminium disc mounted on the shaft of the alloy. The disc is placed in the air gap of the two electromagnets. The eddy current is induced in the disc because of the change of the magnetic field. This eddy current is cut by the magnetic flux. The interaction of the flux and the disc induces the deflecting torque.

When the devices consume power, the aluminium disc starts rotating, and after some number of rotations, the disc displays the unit used by the load. The number of rotations of the disc is counted at particular interval of time. The disc measured the power consumption in kilowatt hours.

3. Braking system – The permanent magnet is used for reducing the rotation of the aluminium disc. The aluminium disc induces the eddy current because of their rotation. The eddy current cut the magnetic flux of the permanent magnet and hence produces the braking torque.

This braking torque opposes the movement of the disc, thus reduces their speed. The permanent magnet is adjustable due to which the braking torque is also adjusted by shifting the magnet to the other radial position.

4. Registration (Counting Mechanism) – The main function of the registration or counting mechanism is to record the number of rotations of the aluminium disc. Their rotation is directly proportional to the energy consumed by the loads in the kilowatt hour.

Working of the Energy Meter

The energy meter has the aluminium disc whose rotation determines the power consumption of the load. The disc is placed between the air gap of the series and shunt electromagnet. The shunt magnet has the pressure coil, and the series magnet has the current coil.

The pressure coil creates the magnetic field because of the supply voltage, and the current coil produces it because of the current.

The field induces by the voltage coil is lagging by 90º on the magnetic field of the current coil because of which eddy current induced in the disc. The interaction of the eddy current and the magnetic field causes torque, which exerts a force on the disc. Thus, the disc starts rotating.

The force on the disc is proportional to the current and voltage of the coil. The permanent magnet controls their rotation. The permanent magnet opposes the movement of the disc and equalises it on the power consumption. The cyclometer counts the rotation of the disc.

9.6 DIGITAL MULTIMETER

Digital multimeters or DMMs can measure a variety of different parameters within an electrical circuit. The basic DMMs can measure amps, volts and ohms, as the older analogue meters did, but with the ease of incorporating further functionality into an integrated circuit, many digital multimeters are able to make a number of other measurements as well.

It can be used to measure voltage, current, continuity etc. therefore it is named as multimeter.

Typical DMM controls and connections

The interfaces on the front of a digital multimeter are normally very straightforward. They consist of a number of items:

1. ***Display*** The display on a DMM is normally easy to see and read. Most have four digits, the first of which can often only be either a 0 or 1, and there will normally be a + / - indication as well. There may also be a few other smaller indicators such as AC / DC etc dependent upon the model of DMM
2. ***Main connections*** There will be some main connections for the probes to connect to. Although only two are needed at any one time, there may be three or four. Typically these may be:

    1. Common - for use with all measurements and this will take the negative or black lead and probe
    2. Volts, ohms, frequency - this connection is used for most measurements and will take the positive or red lead and probe.
    3. Amps and milliamps - this connection is used for the current measurements and will again take the red lead and probe.
    4. High current - there is often a separate connection for high current measurements. Care must be taken to use this rather than the low current connection if high levels of current are anticipated

    These are typical connections for a multimeter and each model of multimeter may have its own requirements and connections.

    Main switch There will usually be a single main rotary switch to select the type of measurement to be made and the range that is needed.

    Additional connections There may be additional connections for other measurements such as temperature where a thermocouple will need its own connections. Some meters are also able to measure the gain of transistors, and these will require separate connections on the meter.

    Additional buttons and switches There will be a few additional buttons and switches. The main one will obviously be the on/off button. Other functions including items such as peak hold may also be available

DMM operation

The operation of a DMM itself is normally very straightforward. With a knowledge of how to make voltage, current and resistance measurements (see the "Related Articles" on the left hand side of this page for further details) it is then a matter of putting the multimeter to use. If the meter is new then it will obviously be necessary to install a battery to power it. This is normally simple and straightforward and details can be found in the operating instructions for the DMM.

When using the meter it is possible to follow a number of simple steps:

1. Turn the meter on

2. Insert the probes into the correct connections - this is required because there may be a number of different connections that can be used.
3. Set switch to the correct measurement type and range for the measurement to be made. When selecting the range, ensure that the maximum range is above that anticipated. The range on the DMM can then be reduced as necessary. However by selecting a range that is too high, it prevents the meter being overloaded.
4. Optimise the range for the best reading. If possible enable all the leading digits to not read zero, and in this way the greatest number of significant digits can be read.
5. Once the reading is complete, it is a wise precaution to place the probes into the voltage measurement sockets and turn the range to maximum voltage. In this way if the meter is accidentally connected without thought for the range used, there is little chance of damage to the meter. This may not be true if it left set for a current reading, and the meter is accidentally connected across a high voltage point!

Working Principle of Digital Multimeter

As shown in block diagram, in a typical Digital multimeter the input signal i.e ac or dc voltage, current, resistance, temperature or any other parameter is converted to dc voltage within the range of the ADC. The analog to digital converter then converts the pre-scaled dc voltage into its equivalent digital numbers which will be displayed on the display unit. Sometimes, digital controller block is implemented with a microcontroller or a microprocessor manages the flow of information within the instrument.

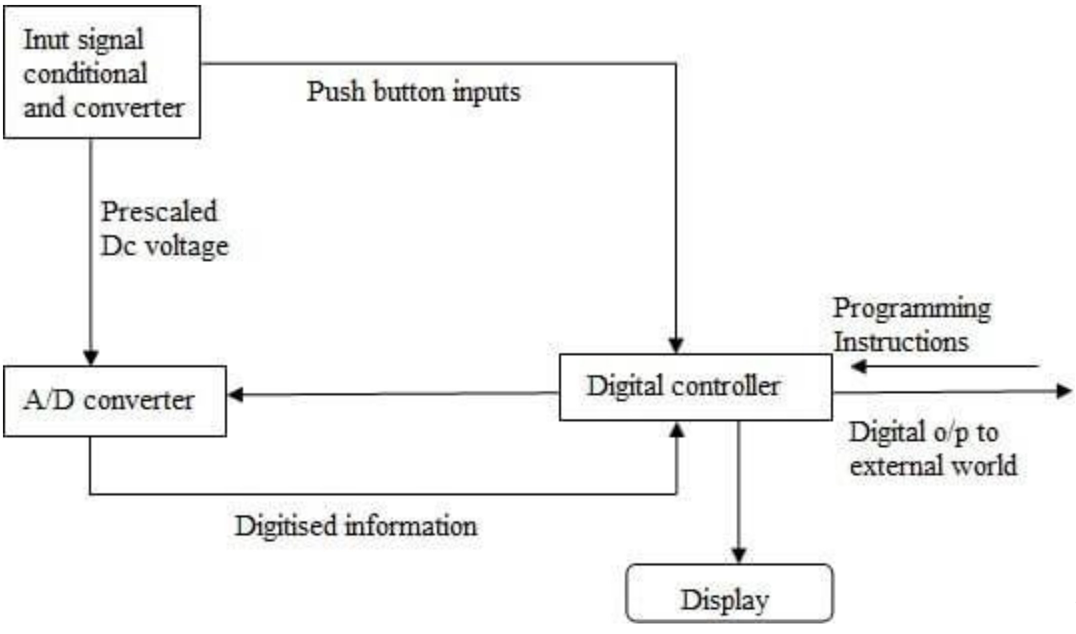


Figure 9.8

This block will coordinate all the internal functions as well as transferring information to external devices such as printers or personal computer. In the case of some hand held multimeter, some of or all of these blocks may be implemented in a VLSI circuit while A/D converter and display driver can be in the same IC.

UNIT- 10

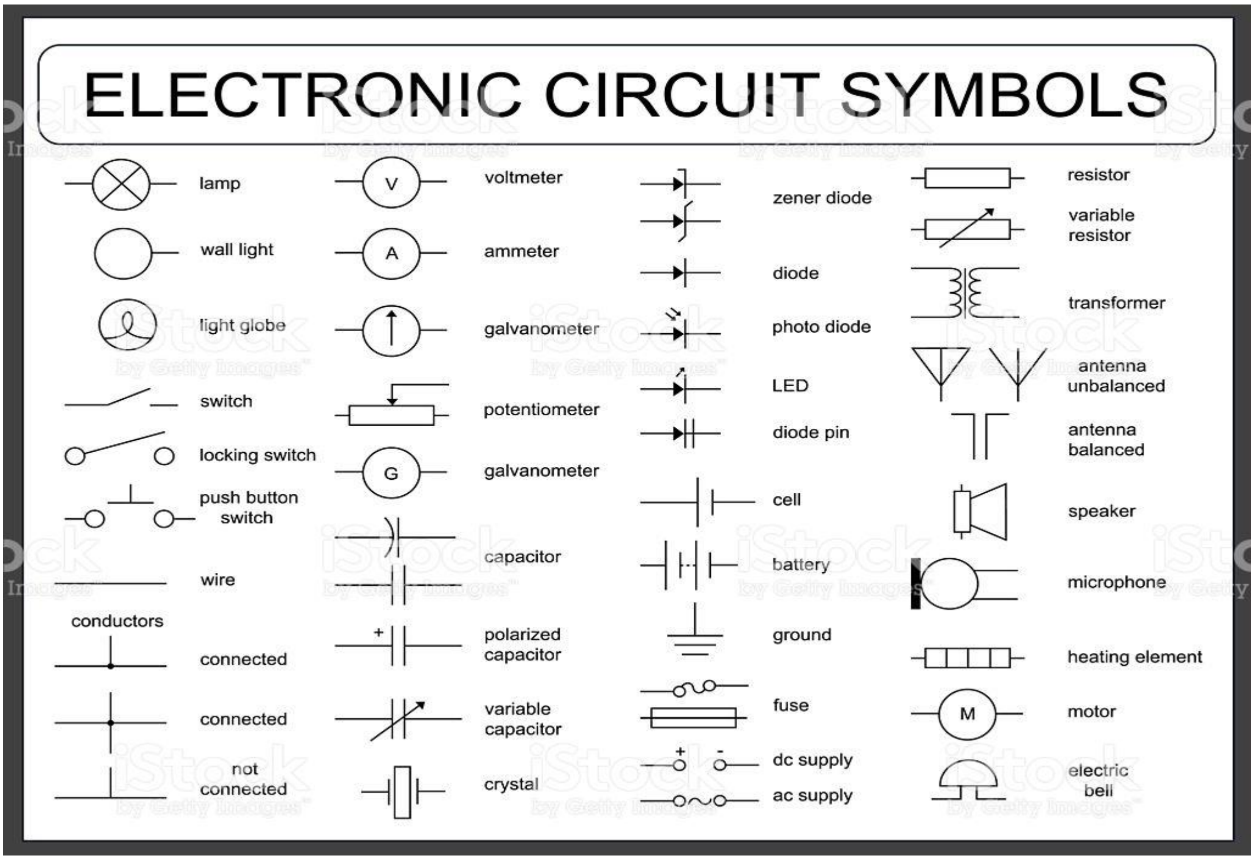
ELECTRICAL ENGINEERING DRAWING

Introduction

An **electrical drawing**, is a type of technical drawing that shows information about power, lighting, and communication for an engineering or architectural project. Any electrical working drawing consists of "lines, symbols, dimensions, and notations to accurately convey an engineering's design to the workers, who install the electrical system on the job

10.1 Wiring Diagram:

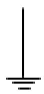
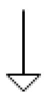
Most symbols used on a wiring diagram look like abstract versions of the real objects they represent. For example, a switch will be a break in the line with a line at an angle to the wire, much like a light switch you can flip on and off. A resistor will be represented with a series of squiggles symbolizing the restriction of current flow. An antenna is a straight line with three small lines branching off at its end, much like a real antenna

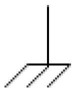
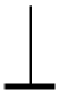
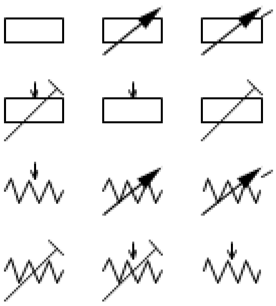


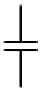
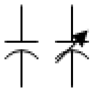
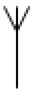
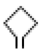
- Wire, conducts current
- Fuse, disconnect when current exceeds a certain amount

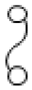
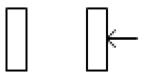
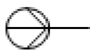
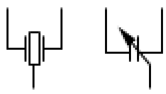
- Capacitor, used to store electric charge
- Toggle Switch, stops the flow of current when open
- Push Button Switch, momentarily allows current flow when button is pushed in, breaks current when released
- Battery, stores electric charge and generates a constant voltage
- Resistor, restricts current flow
- Ground wire, used for protection
- Circuit breaker, used to protect a circuit from an overload of current
- Inductor, a coil that generates a magnetic field
- Antenna, transmits and receives radio waves
- Surge protector, used to protect a circuit from a spike in voltage
- Lamp, generates light when current flows through
- Diode, allows current to flow in one direction indicated by an arrowhead or triangle on the wire
- Microphone, converts sound into electrical signal
- Electrical motor
- Transformer, changes AC voltage from high to low or vice versa

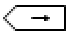
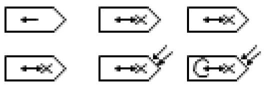
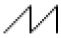
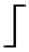
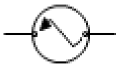
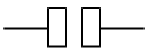
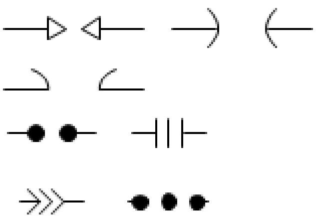
The following table lists some basic electrical symbols :

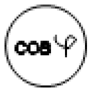
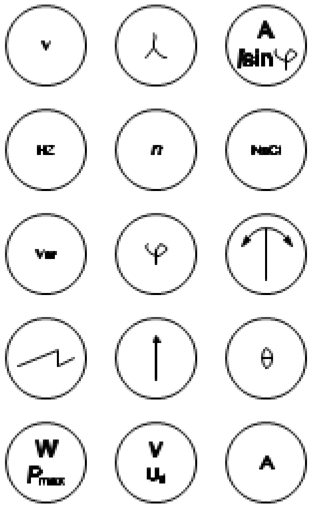
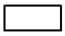
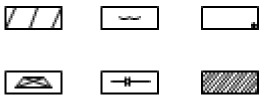
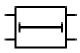
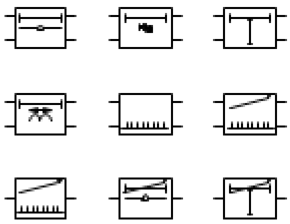
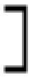
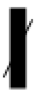
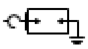
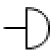
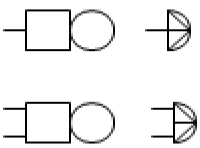
Name	**Electrical Symbol**	**Alternate Symbol**	**Function Description**
ground			A connection to earth. Used for zero potential reference and electrical shock protection.
equipotentiality			Equipotentiality is a symbol to identify parts that have the same voltage (i.e. same electrical potential i.e. equipotential). Since equipotential

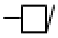
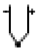
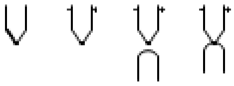
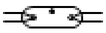
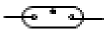
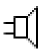
			surfaces all have the same voltage, you won't get shocked if you touch two such surfaces (unless of course you are also touching some OTHER part that has a different potential from the first two).
chassis			Connected to the chassis of the circuit.
battery			Supplies electrical energy. A battery is more than one cell. It generates constant voltage and represents a battery in an equipment package.
resister			A resistor restricts the flow of current, for example to limit the current passing through an LED. A resistor is used with a capacitor in a timing circuit.
attenuator			A box with input and control logic on

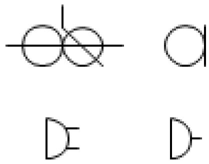
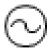
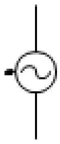
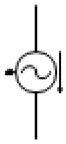
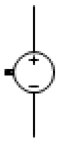
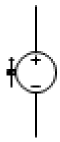
			one side, and output on the other.
capacitor			A capacitor stores electric charge. A capacitor is used with a resistor in a timing circuit. It can also be used as a filter, to block DC signals but pass AC signals.
accumulator			Accumulators are designed to increase or relieve pressure in the system.
antenna			A antenna is a radio antenna that can be made of a simple wire, with a center-fed driven element.
loop antenna			A loop antenna is a radio antenna consisting of a loop (or loops) of wire, tubing, or other electrical conductor with its ends connected to a balanced transmission line.
crystal			A crystal oscillator uses

			the mechanical resonance of a vibrating crystal of piezoelectric material to create an electrical signal with a very precise frequency.
circuit breaker			A circuit breaker is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit.
fuse			A type of sacrificial overcurrent protection device. Represents low voltage and power fuses.
ideal source			
generic component			
transducer			
inductor			A coil of wire which creates a magnetic field when current passes through it. It may have an iron core

			inside the coil. It can be used as a transducer converting electrical energy to mechanical energy by pulling on something. It is a passive two-terminal electrical component used to store energy in a magnetic field.
half inductor			
pickup head			
pulse			
saw tooth			
step function			
explosive squib			Explosive squib is often used on stage and film to trigger various special effects.
sensing link squib			
squib igniter			
surge protectors			Surge protectors protect your electronics from power surges in your electrical system.

instrument			For example, a voltmeter is an instrument used for measuring electrical potential difference between two points in an electric circuit. The wattmeter is an instrument for measuring the electric power in watts of any given circuit.
material			
delay element			Delay element provides a specified delay between actuation of the propellant-actuated devices.
permanent magnet			A permanent magnet is a material or object that produces a magnetic field.
magnet core			
ferrite core			
igniter plug			
bell			The electric bell is found in a normal house doorbell, and

buzzer			when activated it makes a ringing sound. An electrical buzzer is similar to the bell, but instead of a single tone or bell sound it makes a constant buzz noise.
thermal element			
thermocouple			
thermopile			
lamp			A transducer which converts electrical energy to light, which is used for a lamp providing illumination, for example a car headlamp or torch bulb.
fluorescent lamp			
speaker			A speaker can take digital input and turn it into analogue sound waves. One of the most important parts of a wide range of electrical products like TVs and telephones.

microphone			
oscillator			Produces a repetitive electronic signal, often a sine wave or a square wave.
AC source			Alternating Current, continually change direction.
DC source			Direct Current, always flow in one direction.

Unit-11

Electrical Wiring

Electrical wiring is the method of connecting various electrical accessories for distribution of electrical energy from main line (metre board) to home appliances. There are various types of wiring schemes such as

1. Cleat Wiring
2. Casing and Capping Wiring
3. CTS or TRS Wiring
4. Metal Sheathed Wiring
5. Conduit Wiring
6. Concealed Wiring

Cleat Wiring

This kind of wiring utilises ordinary VIR or PVC insulated wires. The wires are held on walls or ceilings with the help of porcelain, plastic or wooden cleats. It is a temporary wiring system. This type of wiring is not suitable for domestic use. It is simple and cheap wiring system. Fault finding and identifying are easier in this kind of wiring as wires are in open. Modification or addition of lines are easier. There are various disadvantages of this type of wiring. As wires are exposed to directly steam humidity, smoke, rain etc. may damage the cables and wire. This is not a reliable and sustainable wiring.

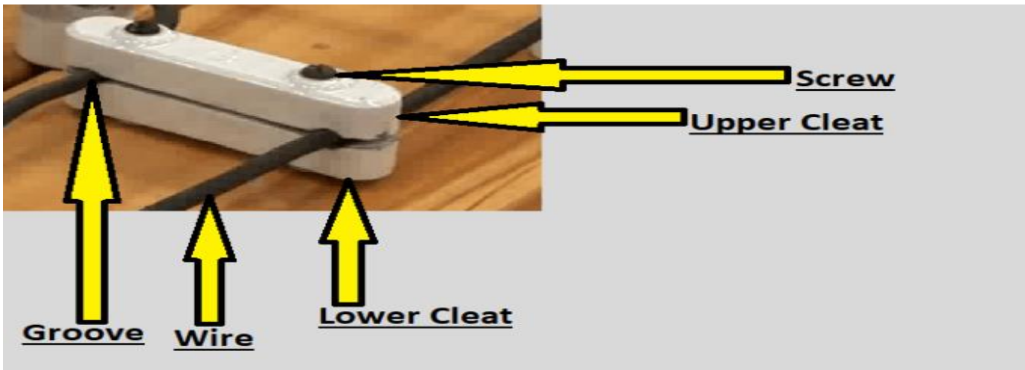


Fig.1 Cleat

Procedure

1. Put straight lines on wall with the help coloured thread marker.
2. Mark the points at equal interval of 1m.
3. Drill with help of drilling machine in marked holes.
4. Place rawal plugs in these holes.
5. Cleat is screwed in these holes but not too much screwed because of chance to damage of cable.
6. Extra cables are taken for holder switches.
7. After completion short circuit and insulation tests are performed.

Casing and Capping wiring

It is an old wiring system and was very popular wiring system in the past. In this system wooden or PVC material is used for casing as well as capping. The cables are of VIR or PVC or any other insulated material. This wiring system is economical as compared to sheathed and conduit wiring system. It is very reliable and can be customized easily. Due to capping and casing long lasting in field also. Repairing is easy if phase and neutral are taken separately. It is robust against the weather change. It is shock proof because of insulated casing and capping. There are few disadvantages of casing and capping wiring system. It is on high risk of fire because of the wooden or PVC material used for casing and capping. It is not so robust against humidity, alkalies and acidic condition. Repairing is costly and white ant can damage wooden part of the wiring system if casing and casing are of wooden material.

Fig.2 casing and caping

Procedure

1. Put straight lines on wall with the help coloured thread marker.
2. Mark the points at equal interval not so far from each other.
3. Drill with help of drilling machine in marked holes.
4. Put casing on the walls and screwed on the wall.
5. Extra cables are taken for holder switches.
6. After completion short circuit and insulation tests are performed.

CTS or TRSWiring

In this type of wiring the cables are hold on the wooden batten and are pinned with brass link pins. It is spaced at a distance of 10cm for horizontal run and 15cm for vertical run. The cables used for this kind of wiring are single core or double core or three core TRS cables. Mostly single core cables are preferred. The teak wood straight batten with at least a thickness of 10mm is used. It a simple, easy and economical wiring system. It looks good and repairing is also easy. It is a robust type of wiring. Less chance of leakage current and customization is easier.Not safe for external wear and tear. Heavey wires are not suitable for this kind of wiring.

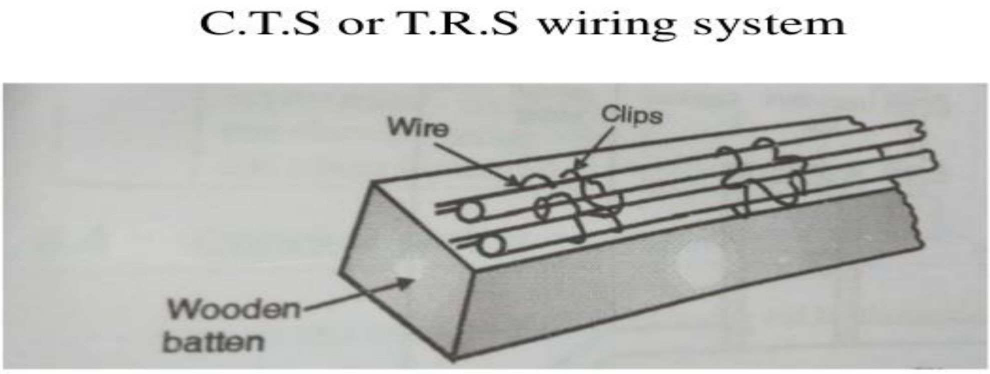


Fig.3

Procedure

1. Put straight lines on wall with the help coloured thread marker.
2. Mark the points at equal interval not so far from each other.
3. Drill with help of drilling machine in marked holes.
4. Put casing on the walls and screwed on the wall.
5. Clip the cable with the help of clips.
6. After completion short circuit and insulation tests are performed.

Metal Sheathed Wiring

This type of wiring contains conductors insulated with VIR and covered with an outer sheath of an alloy. This sheath gives protection against moisture, atmospheric corrosion and mechanical damage. All the metallic covering is grounded at the entry point and are continuous to avoid any kind of electrolytic action that can take place due to leakage current. And also give a passage to ground in case of any short circuiting. The wires are hold on wooden batten and fixing by using clips just like in TRS.

Procedure

1. Put straight lines on wall with the help coloured thread marker.
2. Mark the points at equal interval not so far from each other.
3. Drill with help of drilling machine in marked holes.
4. Put batten on the wall.
5. Metal sheathed wires are hold on batten with the help of clips.
6. After completion short circuit and insulation tests are performed.

Conduit and Concealed Wiring

This wiring can be classified into two groups one is surface conduit and another one is concealed conduit wiring. Surface conduit wiring is the wiring in which conduits are installed on roofs or walls. In this wiring conduit is put on wall with the help of holes on equal distance. Conduit can be of metallic and non-metallic. Metallic conduit can be further divided into two parts- class-A and class-B conduit. Class-A is small gauge whereas Class-B is of large gauge. If the conduit is inside the wall then the method is called concealed wiring. That is the wires are inside roofs and walls. Conduit should be continuous and connected to the ground in case of metallic conduit. The concealed wiring is most popular now these days. Conduit wiring is a professional way of wiring. Non-metallic conduit is made up of PVC and is used for tunnelling the cable inside. It is very safe and robust type of wiring, looking very good. Future customization is very easy and also repair and maintenance. It is robust against the weather change. No risk of electrical shock. Although it has many advantages but have few disadvantages like it is costly and difficult to find the fault.

Procedure

1. Put straight lines on wall with the help coloured thread marker.
2. Mark the points at equal interval not so far from each other.
3. Drill with help of drilling machine in marked holes.
4. Put conduit on the wall.
5. After completion short circuit and insulation tests are performed.

In case of concealed wiring the conduit are put inside the wall and roof at the time of construction according to design and the rest of the process is same as conduit wiring.

Factors of selection of a particular wiring system

There various factors which to be considered for wiring a building like type of wiring, position of fans or lamps or power point etc. The choice of wiring must be in such a way that it considers technical as well as economical aspect. Following factors are considered for the wiring system.

1. The cost of wiring.
2. The durability of the wiring system
3. The permanency of wiring system
4. The wiring should be customizable for future.
5. The wiring must be good looking
6. Mechanical protection must be considered during the wiring for future.
7. Taken consideration of safety especially short circuiting and fire.
8. Maintenance cost must be low.
9. Determination of load of the building to decide type of cable suitable for wiring.

Importance of switch, fuse and earthling

Switch is device which controls the flow of electron. Control is of binary typei.e either it allows the electron flow or it stop the electron flow completely. For an electrical appliance to on or off one must need a controlling device to start or stop the operation of the device. That purpose is fulfilled by the switch. With help of switches every logic is performed.

Fuses are generally used to protect the electrical devices from damage. Each fuse have a maximum current handling capability or current rating above that current the fuse wire is blown away and protect the whole system from damage.It also protects overheating from excess current. It is also protecting the human beings from electrical shock.

Earthing is grounding the astray currents in the circuit. It is very important to ground the electric wiring. It will give protection from electric overload. It helps to direct the current where we want. It stabilizes the voltage levels. Earth is the best conductor so current finds a path of less resistivity and goes into the ground and protect us from excessive current in the circuit. Overall it helps us to protect our appliances and us from excessive current that can causes danger in the form of fire or electric shock.

Types of fault their causes and remedy

There are various types of fault occur in an electric wiring. Different types of faults in an electric wiring can be categorized as follows:

1. High resistance joints
2. Discontinuity of wires
3. Faulty accessories
4. Short circuit currents
5. Overload currents

High resistance joints

This problem is due the loose joints of the conductor or wires. It can also results due to loose connections of wires with switches or sockets. It can causes high current and produces heat in the circuit which will results in disconnection or fire in the wiring. It can be removed b y avoiding the joints as much as possible. Joints must be tight and right. Screw of socket or switches must be screwed properly.

Discontinuity of wires

The high resistance circuit may be results in open circuiting of wires. In this case the current does not flow in the wire. It also occurs due to mechanical damage of wires. This problem mostly occurs in earthing because these wires are of weak in comparison to the phase. This problem can be removed by considering proper precautions in joints and avoiding the chance of mechanical damage by considering the factors of mechanical damage.

Faulty accessories

Due to ageing of accessories the springs, sockets, screws lose its temperament and can causes either open circuiting or short circuiting in the wiring. It can damage other devices or can causes the system open circuit that is no current in the circuit. It can be cured by changing those accessories and by replacing the aged accessories.

Short circuit currents
It can occur due to short circuiting of either live and neutral wires or live and earth wires. In this situation a very high currents flows in the wires and it can causes severe damages in the circuit as well as outside the circuit. It can be cured by replacing the faulty conductors in the wiring.

Overload currents
It is due to the excess load in the system from its designed load. A slight increase in load can be tolerated by the system. But in case of excessive loads the wires do not tolerate these loads and can be burnt out. It will results in either short circuiting or open circuiting in the wiring. Sometimes it also causes fire due to excessive heat produced due to large loads. This problem can be resolved by removing excessive loads from the circuits and by removing faulty wires as well as appliances from the system.

Types of earthing- Plate Earthing and Pipe Earthing
Plate Earthing
A plate of copper or galvanised iron is used for plate earthing. A copper plate of 60cmx60cmx3.18mm or galvanised iron plate of 60cmx60cmx6.35mm in dimensions are buried vertical in the ground. The depth of the plate must not be less than 3m and proper considering the moisture in the soil.

Pipe Earthing
In this type of earthing a galvanised steel pipe is placed vertically inside the ground. In general a pipe of 40mm diameter and 2.75m in lengths are taken for ordinary soil and will be of lager length for dry or rocky soils. The moisture of soil is decides the length of pipe.

Procedure of earthing
1. Dig in the ground depending upon the moisture, type and application of earthing.
2. For plate earthing put plate inside the ground and in case of pipe earthing put pipe inside the ground.
3. Tight the earth plate with the help of screws.
4. Take two earth wires and tight it properly.
5. Grease the joints to avoid corrosion.
6. Put all wires in a metallic pipe and must be taken above the ground.
7. Put charcoal and lime around the pipe or plate for maintaining proper moisture in the earthing.
8. Test the earthing through earth tester it must not be greater than 1ohm.

Applications
In general pipe earthing is used for electrical system whereas plate earthing is used for electronic system. Nowadays pipe earthing is used for both electrical and electronic appliances.

Distribution board system and methods to find number of circuits and circuit distribution

Distribution boards consists of circuit breaker and sub-main circuit breaker. The calculation of number circuits (breaker) can be carried out in two ways. The load estimation technique is used estimate the total load in a distribution board. Another is the calculation of current by summing load power.

Load estimation can be carried out by considering the load density and area. Load density varies from one place to another place. As for example for residential applications it is 4 to 8kVA for 100m^2 and for commercial applications such as shop it is 10kVA for 100m^2. Current can be calculated from the knowledge of load density, voltage and area. Taking safety factor for current 27% above the calculated current. Then we can consider standard value of the circuit breaker. Depending on the value of current the switch board can be designed for each place.

Loop in system for wiring connections

In this method of wiring each appliances are connected in parallel. In this arrangement of wiring connection each appliances can be controlled individually. For connection of light, switch, the feed conductor is looped in by bringing it to the terminal and carrying forward for next point. The connections of the circuit is in looped around till the last circuit is reached. The line conductor is looped either in switchbox and neutral are looped in switch box or appliances. It does not require junction box so it is economical. No joints are beneath the roofs and walls in this type of wiring system. It is easier to locate the fault in the wiring. It requires larger amount of wires for wiring because of looping. Looping is difficult through lamp holders and switches.

IE rules for wiring

IE stands for Indian electrical rules for wiring. For the protection of public the wiring at consumer premises must be according to the IE rule standard. Wiring must be carried out by licensed electrical contractor. The wire of wiring must be of Indian Standard Institution or equivalent. The contractor wiring completion test report must be submitted to the customer. As required by rule 45 of the Indian Electricity Rules, 1956, no electrical installation work (including additions, alterations, repairs and adjustments to existing installations), except such replacement of lamps, fans, fuses, switches, low voltage domestic appliances and fittings as in no way alter the capacity and the character of the installation, shall be carried out upon the premises on behalf of any consumer or owner for the purposes of supply of energy to such consumer or owner, except by an electrical contractor licensed by the in this behalf and under the direct supervision of a person holding a certificate of competency issued or recognised by the ... Any person committing a breach of rule 45 shall render himself liable to punishment under rule 139 of the said rules.

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