ELECTRICITY

& BASIC ELECTRICAL CIRCUITS

This publication is a non-mathematical explanation of electricity, electrical components and how electric circuits work. It is intended for students in schools and colleges requiring an understanding of this subject to assist them with other studies. It is a suitable introduction to the topic for students of the life and physical sciences.

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SOME PRELIMINARIES

The reader will be aware of the existence of static electricity associated with clothing and carpets made from artificial fibres and will have acquired some knowledge of magnetic fields while playing with magnets when a youngster. Historic man was also aware of the results obtained by stroking animal fur with various materials and that some stones (containing magnetite) would attract iron. Research into these natural phenomena has resulted in to-days electrical and electronics industries. Whatever your work you will, at some stage, make use of electrical products and will be handicapped without some knowledge of the properties of these natural forces. The following notes will provide this information.

Electricity in harness is apparent with, for example, the operation of an electric fire or motor and the generation of a picture on a TV screen. The fire is the result of a basic electric circuit and although a TV set is more complex it too consists of many simple circuits and it is simple circuits that are dealt with in this treatise.

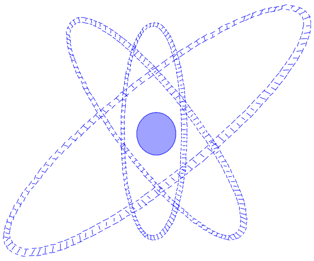
Electrical and magnetic circuits are usually associated with printed circuit boards and electric power cables but they also exist in other, perhaps unexpected, environments such as the human body. Students of the life sciences, as well as those studying the physical sciences, should therefore understand the basics of electrical circuits. The following notes should be read consecutively and will serve as an introduction to the subject.

When dealing with electricity vast measurement ranges are involved stretching from much smaller than a millionth of, to much greater than millions of some quantity or value. Some names you are likely to come across that are used to express multiples and sub-multiples of values or quantities are now listed.

Multiplication factor			Prefix	Symbol
One thousand million	1000000000	$= 10^{9}$	giga	G
One million	1000000	$= 10^{6}$	mega	M
One thousand	1000	$= 10^{3}$	kilo	k
One thousandth	0.001	$= 10^{-3}$	milli	m
One millionth	0.000001	$= 10^{-6}$	micro	µ
One thousand millionth	0.000000001	$= 10^{-9}$	nano	n
One million millionth	0.000000000001	$= 10^{-12}$	pico	p

Using the correct upper or lower case for the symbol is important.

CHARGE AND DISCHARGE



Consider first the simple picture of an atom visualised as a nucleus with orbiting electrons. There is no need here to ponder the make up of either the electron or the nucleus. The concept specifies that the electrons have a negative (—) electrical **charge** and the nucleus a positive (+) one. Opposites in life have the attribute of attracting each other and for this case of positive and negative charges the mutual attraction between them is called an **electric force**. In combination, the negative charges of the electrons and the positive charge of the nucleus cancel each other. Thus, to an outside observer an atom with its full complement of electrons is electrically neutral, i.e. it has no electric charge. Thus an item is "electrified" if it has gained or lost its normal number of electrons. Electrons figure highly in the next few paragraphs but because they are basic particles it is not possible to describe them in meaningful terms. However, using the idea of electrons as, or carrying, negative charges it is possible to describe the results obtained when they are encouraged to move from one atom or molecule to another.

Sparks, such as those sometimes generated while combing your hair, are caused by static electricity. The meaning of "static" electricity as opposed to "moving" electricity will become apparent shortly. When a spark occurs a discharge is said to have taken place, but a discharge cannot occur unless a charge is already present. How are these charges created? It is known that when two dissimilar materials have been in contact and are then isolated from each other, one of the materials will have a positive charge and the other a negative one. This phenomenon is known as tribo-electrification. Some combinations of materials will produce this effect more strongly than others. It seems that one of the materials acquires electrons at the expense of the other. The material that has gained a number of **free,** i.e. easily dislodged, electrons is said to be negatively charged. This is because, as mentioned earlier, electrons are regarded as representing negative charges, consequently the other material is then positively charged because it has lost some of its electrons. Atoms that are short of their normal complement of electrons are called positive ions. Such a situation can exist while combing your hair, with the comb and hair representing the two materials acquiring opposite charges.

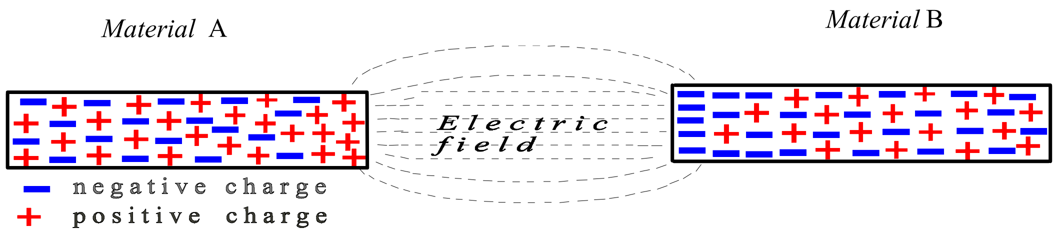


Fig 1. *Charges accumulate where the two materials separated. An attracting electric field then exists between the opposite charges.*

A spark occurs if electrons jump an air gap to a material that has a shortage of them. They do this because of the attractive electric force between the differently charged materials. Before a discharge takes place a charge represents static electricity and during a discharge that electricity is on the move and it is the electrons and not the much more massive positive ions that are able to jump the air gap. This movement of electrons is called an electric current and its unit of measurement is called the **ampere** usually shortened to **amp** (symbol **A**). For measurement purposes a particular size of charge must be given a name and it has been decided that an electrical charge (symbol **Q**) be measured in **coulombs** where 1 coulomb is 6.25x10^{18} electrons. If this number of electrons moves between any two points in one second the situation represents an electrical **current** (symbol **I**) of one amp, written as 1A. (The amp is not defined this way.) The range of electrical current met in everyday life is very large. Electrons jumping between comb and hair represent a few micro amps (symbol μ**A**) but a lightning discharge involves thousands of amps.

As free electrons accumulate to form a charge another phenomenon called **voltage** (symbol **V**) is created and as the charge increases so does this voltage. What is this voltage and where does it come from? It results from the work done, i.e. the energy that was used to move the electrons that now make up the charge. That energy is now stored in the charge as potential energy. Voltage is not a measurement of the amount of energy stored but it is proportional to it. The situation is analogous to pumping up a car tyre. Work has to be done, i.e. energy expended, to achieve that objective. As more air enters the tyre its air pressure increases. The measured increase can be quoted as being with respect to a vacuum or to local atmospheric pressure. A voltage measurement is also quoted as being relative to something. If charges are created while you comb your hair the comb will have so many volts with respect to your hair. Alternatively, your hair has a voltage with respect to your comb. Whichever way the situation is described, a voltage exists between hair and comb. Before a spark occurs this voltage is called a **potential difference** (symbol **pd**). This is analogous to the difference in air pressure between that inside an inflated tyre and that outside of it. This is not the same as the amount of **energy** stored in the inflated tyre. Once an electrical discharge has taken place the surplus electrons on one of the materials and the deficiency of them on the other no longer exists, therefore neither does the potential difference that was striving to restore the imbalance. An electrical discharge of the type we have been discussing is like a highly inflated tyre that suddenly bursts. The air inside the tyre returns to the surrounding atmosphere but, obviously, not to its original position in it. Similarly, following an electrical discharge, electrons do not return to the atoms or molecules they left.

As already stated, air pressure inside a vessel can be quoted as an absolute measurement, i.e. with respect to a vacuum, or relative to local atmospheric pressure, but the latter varies from day to day and from place to place. Similarly, voltage can be measured between two unique points but for general convenience it is usual to quote voltage measurements as being with respect to ground (earth) which is designated as being at 0 volts. Just as atmospheric pressure varies from place to place and with time, voltage differences that naturally exist between different parts of ground also vary with time. In the next diagram, Fig 2, **A** represents a negative charge and **C** a positive charge. The voltage associated with charge **A** is — 100V with respect to ground at point **B**. Charge **C** has +120V with respect to ground at point **D**. 1V exists between the ground points **B** and **D** therefore the voltage between points **A** and **D** is 101V and that between point **A** and **C** is 221V.

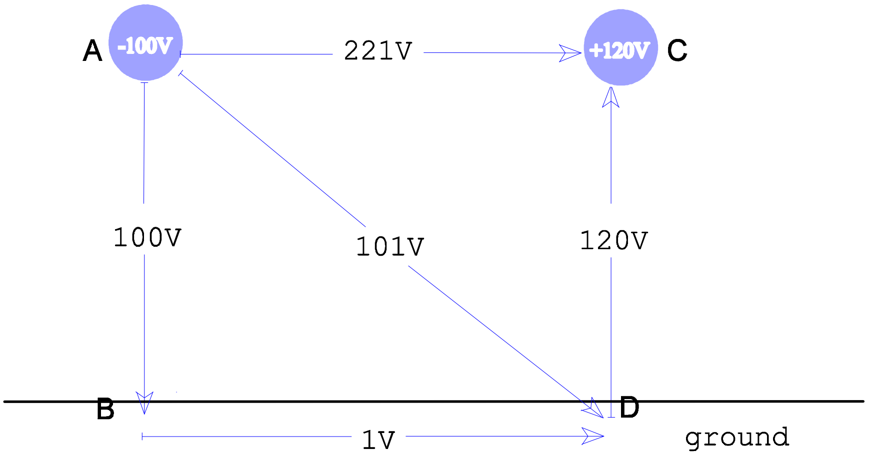


Fig 2. *An open arrow-head is used to denote a positive voltage measured with respect to its tail.*

Recapping: A potential difference, measured in volts, is created between two places when one of those places either has a surplus or a deficiency of electrons with respect to the other. The place with excess electrons has a negative charge and the place that has lost electrons has a positive charge. An electric tension of attraction, i.e. voltage, exists between these charges and this voltage wants to restore the imbalance to a neutral state. Charges of the same polarity would exhibit the opposite effect i.e. they would repel each other. A collection of free electrons is measured in coulombs and a concerted movement of electrons is called an electric current.

CAPACITANCE AND CAPACITORS

Returning to discussing a charge; evidently this cannot exist in isolation (except mathematically) because the voltage associated with it must be measured between two points. The relationship between a charge and this voltage can be written as:

$$Q = VC$$

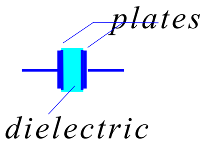
where C is something called **capacitance** that involves the charge's environment. It is convenient to replace the representation of a charge as the sphere used in the previous sketch with a symbol that embodies that environment and the points between which its voltage is measured. This symbol is two parallel plates with connecting wires. The combination is called a **capacitor**.

● = *connecting terminals; these are omitted in circuit diagrams.*

Referring to the hair combing situation where opposite charges form on the hair and comb, those two objects make a capacitor that holds the charge created during the combing process. On a grander scale, during thunder storm conditions charged clouds form huge capacitors that discharge between each other or to ground. Capacitance has units of **farads** (symbol **F**) but common working values are likely to be in micro farads, a million times smaller, that is 10^{-6}F (written as μ**F**). Values of capacitance 1000 times smaller still are called pica farads, i.e. 10^{-9}F (written as **pF**). Suppose that the value of a capacitor C is 0.1μF and the voltage V across it is 10V then from Q = VC (see above) the charge held by the capacitor is 1 micro coulomb. Since 1 coulomb represents approximately $6x10^{18}$ electrons this particular charge consists of about $6x10^{12}$ of them.

Capacitors used in electrical circuits are man made variants of those created by nature. They are designed to hold an electrical charge, but, as you would expect, the method used to create the charge is more sophisticated than the comb and hair technique. Such methods are considered a little later.

Since an electrical charge is a number of electrons temporally not tied to atoms and held in a suitable store, the larger that store the more electrons it can hold. If the parallel lines in the capacitor symbol represent parallel plates it is reasonable to suppose that the larger the area of those plates the larger the charge that can be held, and this turns out to be the case. These so called "plates" could be any shape, for example they could represent two parallel electrical conductors such as copper wire or nerve fibres. It is found that for given sized plates the closer they are the higher the value of capacitance. This value is also affected by the type of insulating material, called **dielectric**, that exists between those plates, thus the previous mention of a charge's environment.



CHARGING A CAPACITOR

Consider an empty capacitor that requires charging. In line with the previous discussion it is necessary to arrange for one of its plates to gain electrons at the expense of the other. Devices that can cause electrons to move in a particular direction and thus able to achieve this are: batteries, thermocouples, solar cells, driven electricity generators, etc. It is necessary to have an electrical path, such as a conducting wire, along which the electrons can easily move and the means to move them inserted into this path.

In the next diagram, Fig 3, the device chosen to move electrons is a battery. It moves them in one direction only and therefore is called a source of direct current (dc). The capacitor, battery, closed switch and conducting wire constitutes a closed loop called an electrical **circuit**. If the switch was open, i.e. off, there would be an **open circuit** and electrons could not flow. Closing the switch shown in the diagram allows the battery to force electrons to flow away from plate **A** of the capacitor towards plate **B** of the same capacitor. If the connections to the battery were reversed the electrons would be forced to move in the opposite direction.

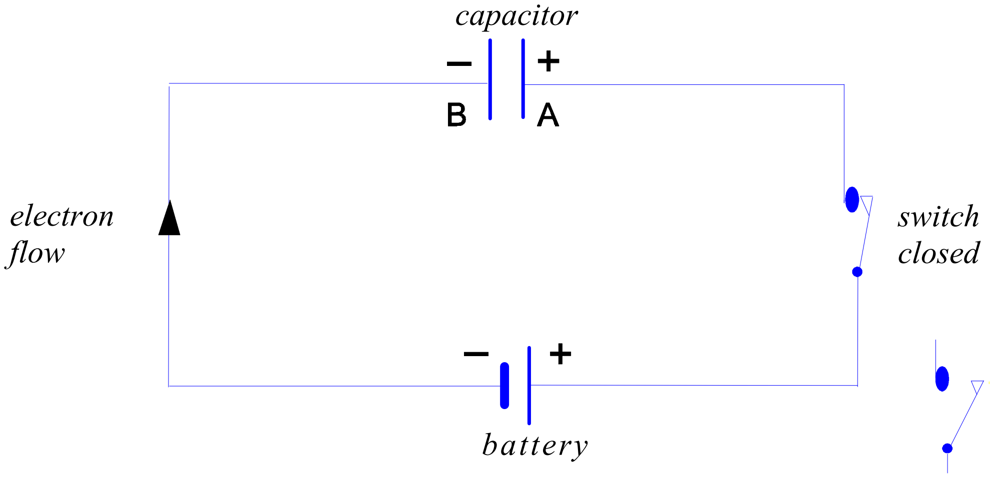


Fig 3. *Charging a capacitor.*

As long as the electrons continue to move, the capacitor continues to charge and the voltage across it to increase. Eventually the voltage across the capacitor plates closely approaches the voltage across the battery and because like charges repel each other the battery finds it increasingly difficult to continue the charging process. Thus it takes longer to increase the battery charge by a given amount towards the end of the charging process than it did at the start of it. This is demonstrated by the next graph, Fig 4. Eventually the two voltages become equal and charging ceases but if the battery voltage was increased the capacitor would increase its charge correspondingly until the battery and capacitor voltages became equal again. The charging rate for the capacitor is, like so many things in nature, exponential and the two voltages become identical after an infinite time interval. This is rather inconvenient for practical measurements therefore the capacitor is said to be fully charged when that charge becomes reasonably close to its final value. The time this takes depends on any obstacles put in the way of the electron movement and on the size of the capacitor.

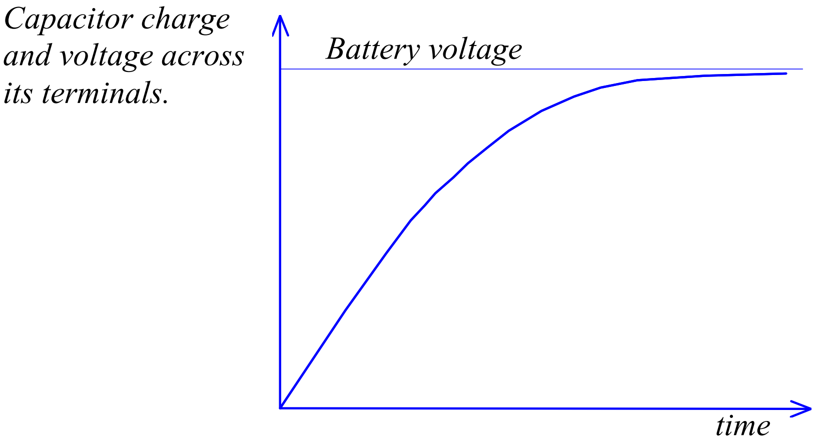


Fig 4. *The graph shows that as the capacitor charges the voltage across its terminals approach the battery voltage.*

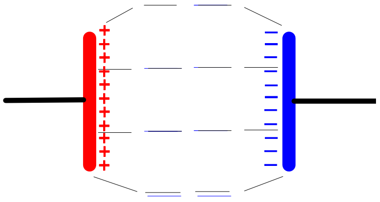
At one time it was assumed that electricity flowed from the positive terminal of a battery, through the circuit, to its negative terminal. It is now known that electron flow is, as already explained, in the opposite direction. Thus in Fig 3 the direction of current flow, based on convention, is in the opposite direction to that shown for the electron flow! Luckily, when circuit calculations based on circuit diagrams are made it does not matter if the direction of current flow is taken to be from negative to positive or from positive to negative. It is merely necessary to be consistent with the choice made throughout the calculations. What is important to remember is that electrons move from a negative to a positive potential.

If the battery shown is disconnected from the circuit once the capacitor had become charged by opening the switch there is no way for the free electrons to recombine with the plate they were encouraged to leave and the capacitor will remain with two equal and opposite charges on its plates, a voltage will be maintained between them and a quantity of electricity will have been stored. For this reason it is unwise to pick up a capacitor charged to a high voltage. Unfortunately you cannot tell if a capacitor is a charged just by looking at it.

In the case of the hair and comb situation the air dielectric between them broke down causing sparks. For our example with the battery and capacitor the latter can be assumed to have a dielectric that can withstand the battery voltage. Looked at another way, the battery voltage has been chosen so that it does not exceed the dielectric strength of the capacitor being used. In practice, a capacitor's dielectric will "leak" and some types of dielectric leak more easily than others. Thus with time these charges will tend to dissipate. Some of the electrons on the negative plate of the capacitor will return to the positive plate by migrating through the dielectric. Some will travel over the surface of the casing enclosing the capacitor and some of the electrons will combine with positive ions existing in the surrounding air.

LINES OF FORCE

At some time in the past the reader will very likely have played with, or have seen a demonstration of, the response of iron filings when placed in a magnetic field. They line up along "lines of force" and make manifest the existence of energy around the magnet. Energy is the capacity for doing work and in this case it has moved the filings into a pattern. It appears, then, that a magnet stores energy in its magnetic field or that the "field" is the energy. Magnets are not unique in having an associated energy field. A charged capacitor has an electric field, i.e. stored energy, existing between its charged plates that tries to pull those plates towards each other as if they are connected with taught elastic. This should be expected because one plate contains a positive charge and the other a negative charge and these unlike charges attract each other.

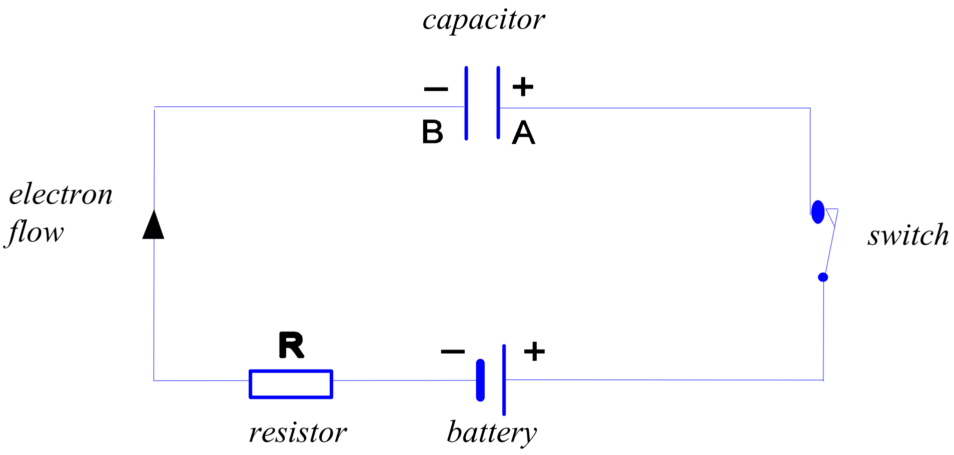


Electric field between plates.

A practical use for the energy existing between two charged plates of opposite polarity is exploited in the cathode ray tube (CRT) that is used, for example, in an oscilloscope. Charged horizontal and vertical deflection plates are used to position electrons onto a phosphorus screen to generate a trace. Each pair of plates constitutes a capacitor and electrons generated elsewhere in the CRT are forced to travel through the electric fields that exist between those plates. Those electrons are then attracted towards that part of the combined fields which at any instant is the most positive. Electrons can also be controlled with magnetic fields and complex displays such as TV pictures and radar displays use this method.

INTRODUCING RESISTANCE

To control the rate at which a capacitor is charged it is necessary to control the number of electrons that move during a given time. This does not mean altering the speed of the electrons, but how many of them are moved each second. Since electrons move more easily in some substances than in others, components can be manufactured from the types of material that impede their flow. Such components are called **resistors**. The materials they are made of have electrons more firmly attached to their constituent atoms than materials that are good electrical conductors. If a resistor (symbol **R**) is inserted into the circuit shown in Fig 3 the number of electrons moved in a given time will be reduced and the capacitor will take longer to charge to the battery voltage. The higher the value of the resistor the longer it will take for the capacitor to charge. This is shown in Fig 5.



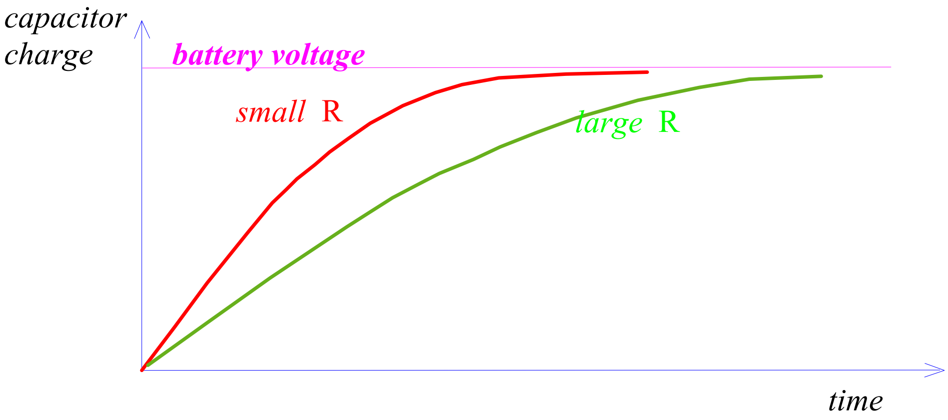
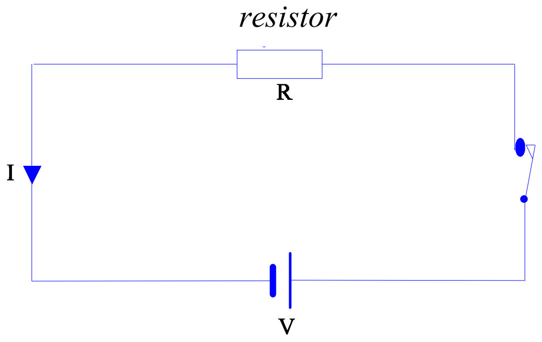


Fig 5. *The higher the resistor value* (R) *the longer the capacitor takes to charge, i.e. the longer it takes for a particular voltage to develop across its terminals.*

Resistor values are given in **ohms**, symbol Ω, and there is a relationship between ohms, volts and amps known as Ohm's law. The relevant formula is:

V=IR alternatively: **I=V/R** and **R=V/I**

This formula says: a current through a resistor will result in a voltage forming across that resistor and the amplitude of the voltage will be proportional to the current. Note that the resistor itself is not generating a voltage. Commonly used electrical items such as heaters and filament lamps are based on resistors that are designed to heat up when sufficient current flows through them. It does not matter in which direction current flows through a resistor in order to generate heat.



Alternative symbol for a resistor.

Fig 6. *Basic resistive circuit where* I = V/R. *By convention, current flow is represented as going in the opposite direction to electron flow.*

As an example, a 6 volt battery would cause 0.5 amp to flow through a resistor having a value of 12 ohms because I=V/R. This supposes that the battery was able to deliver that amount of current. Electric generators such as batteries are designed to provide a specified voltage while working over a specified current range.

Consider again the capacitor and resistor circuit in the previous diagram, fig 6, and let the battery voltage be called V_B, the voltage across the resistor v_R and the voltage across the capacitor v_C. Since the voltage applied across the circuit is the battery voltage the difference between the battery and capacitor voltages must represent the voltage across the resistor, i.e.

$$v_R = V_B - v_C.$$

Notice the use of upper and lower case symbols. It is conventional to use lower case letters to represent the instantaneous value of a quantity that is varying. Thus v_C and v_R represent values at a particular time t whereas the battery voltage V_B which is constant is represented in upper case. The current that flows through the battery and the resistor also flows into the capacitor - there is nowhere else for it to go. It has been pointed out that the voltage across a resistor is proportional to the current flowing through it, therefore the graph of the voltage across the resistor in the previous diagram is proportional to the current into, and therefore charging, the capacitor. Plots of voltage across the capacitor and current through the resistor as the capacitor charges, would result in complementary curves, thus:

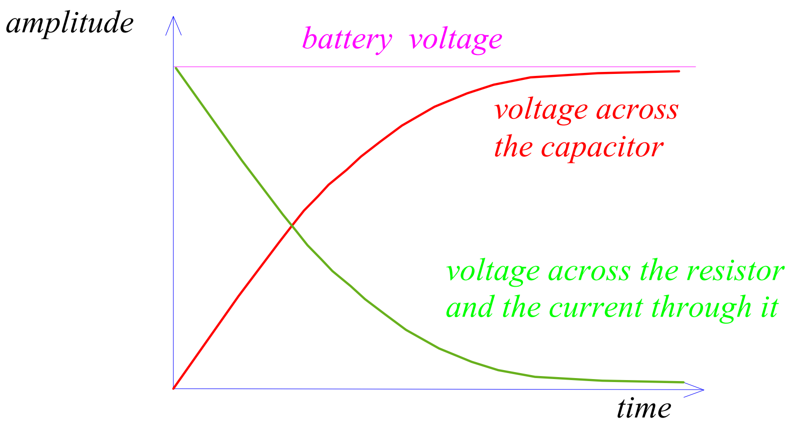


Fig 7. *When the capacitor is fully charged current ceases to flow.*

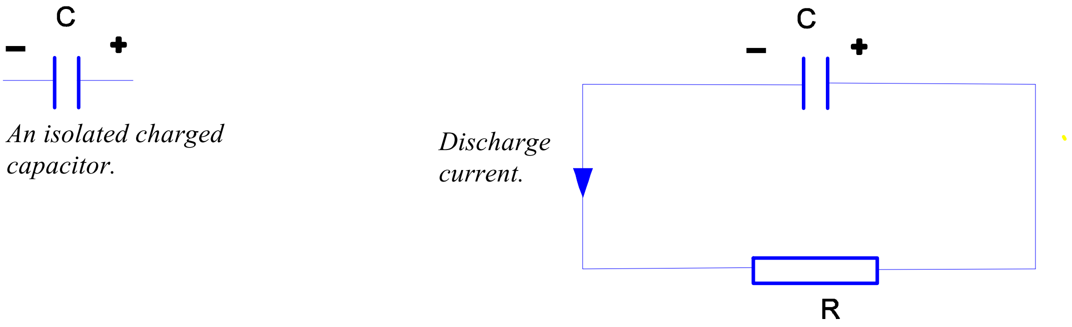
If no resistance was shown in the circuit diagram in Fig 6 it might be assumed that charging the capacitor would be an instantaneous act. However, no component is ideal and the capacitor, battery, and interconnecting conductors each have some resistance. These individual resistances are in series, i.e. the end of one of them is connected to the beginning of the next so that the same current flows through all of them. Their individual values can be added together and represented as an equivalent single resistor.

DISCHARGING A CAPACITOR

Most of the energy used to charge a capacitor will be stored in that capacitor. For the example we have been considering this energy originated from the battery that moved the electrons. During that process some losses will have been incurred. Although not obvious, these losses will have been in the form of heat generated as electrons collided with each other as they were forced through the circuit resistance.

A large capacitor can store a considerable amount of energy as demonstrated by the spark produced when short-circuiting the capacitor's terminals rapidly discharges this energy. Such procedure is not recommended because the resulting current flow could damage the capacitor. The stored energy can be dissipated in a gentler way by arranging for the discharge current to flow through a resistor. This is the opposite to that which takes place while charging and the voltage across the capacitor will decrease exponentially.

A capacitor's dielectric has the ability to "soak up" a charge after which it is reluctant to relinquish it therefore a momentary short circuit across a capacitors terminals does not "squeeze out" all of its charge. This allows the capacitor to regain some of its original charge after removal of that short. So beware of "discharged" high voltage capacitors. This characteristic is called dielectric absorption.



An isolated charged capacitor.

Fig 8. *Connecting a resistor in parallel (i.e. across) a charged capacitor will dissipate the charge*

THE RC TIME CONSTANT

The term **time constant** (symbol **T**) is commonly used when referring to electrical circuits and an explanation for it is appropriate at this stage. Where a circuit contains a resistor and capacitor connected in series the higher the value of resistance the smaller the charging (or discharging) current and therefore the longer it takes to charge (or discharge) a given sized capacitor. Similarly, the larger the value of the capacitor the longer it will take to charge (or discharge) for a given value of resistance. The product RC, where R is in ohms and C is in farads, is called the circuit's time constant and it has units of seconds. It is used as a guide to the response time of a circuit. It does not represent the time it takes to charge a capacitor but it does represent the time it would have taken if the start up rate of charge, which is approximately linear, had been maintained. This is demonstrated in the next diagram. It so happens that if a capacitor is charging towards a voltage V then at time T = RC the voltage across the capacitor has reached approximately 63% of its final value, i.e. 0.63V. When discharging, the voltage across the capacitor at time T is approximately 37% of its initial value, which was V.

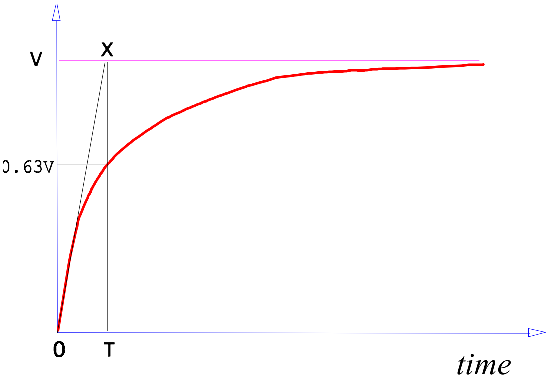


Fig 9a. *Capacitor charging. Initial charging gradient is* OX.

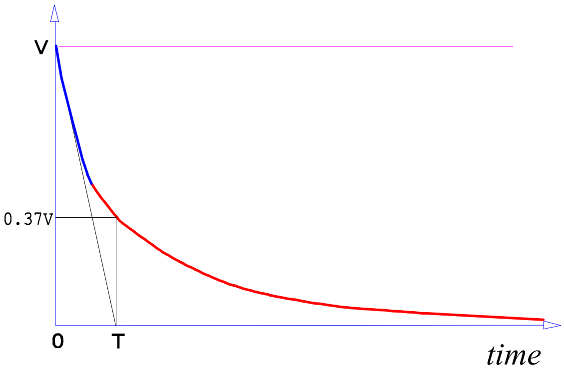


Fig 9b. *Capacitor discharging. Initial discharge gradient is* VT.

CURRENT THROUGH A CAPACITOR?

If current does not flow through a capacitor, and it does not unless its dielectric breaks down, how can the arrangements for charging a capacitor be considered a *circuit* for electrons and how do signals “pass through” a capacitor? The following discussion should remove any puzzling thoughts on the matter.

In the next diagram, Fig 10, the battery has been replaced with another type of generator that repeatedly displaces electrons first from plate A of the capacitor towards plate B and then reverses the procedure. This has the same effect as continuously reversing the battery connections in previous diagrams. The solid arrow-heads indicate the direction of electron flow.

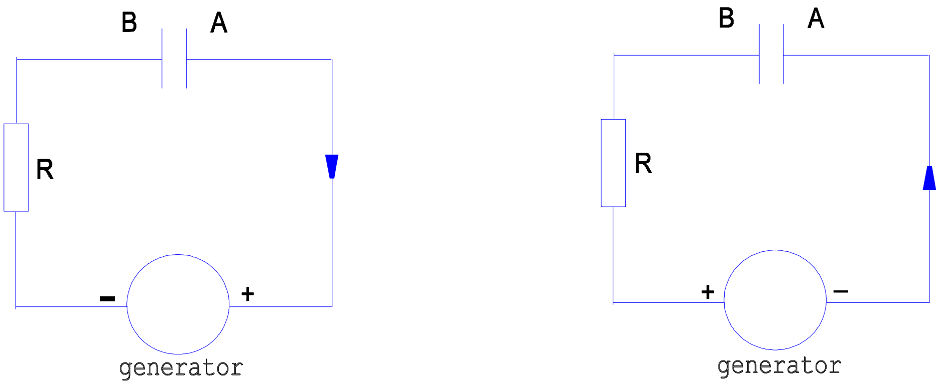


Fig 10. *In the left hand diagram electrons flow from plate A of the capacitor through the generator and resistor to plate B. Thus plate B becomes negative with respect to plate A. When the polarity of the generator is reversed electrons flow in the opposite direction and plate A becomes negative.*

If the generator shifts electrons in one direction until the capacitor is very close to full charge before it reverses polarity the voltage across the capacitor will appear as shown at **A** in Fig 11. However, if the generator reverses polarity before the capacitor can fully charge and discharge the capacitor voltage will appear as shown at **B**. The changes occur at points such as those labelled *.

Fig 11 - A

Generator voltage

Capacitor voltage

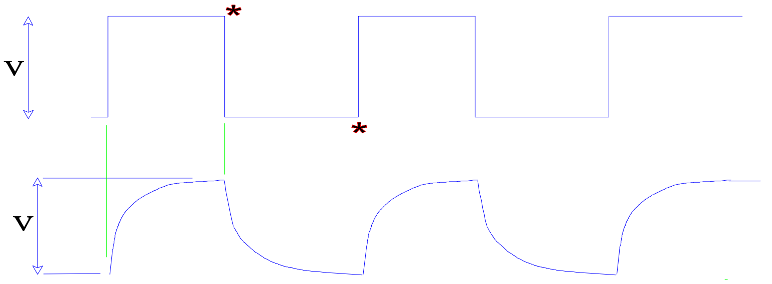
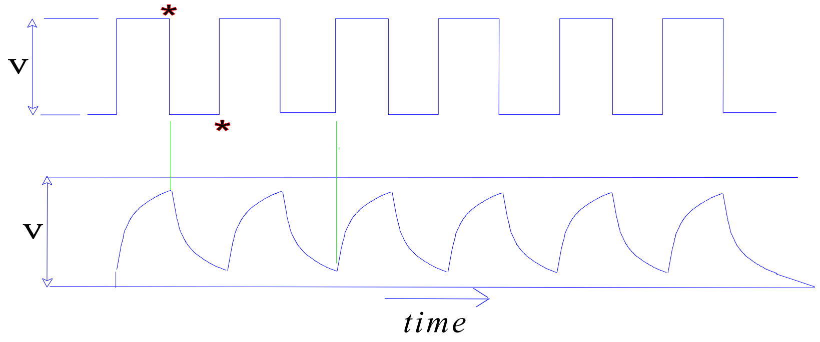


Fig 11 - B

Generator voltage

Capacitor voltage



Except for the times when the capacitor is fully charged and the generator is not changing direction, electrons flow around the circuit from one side of the capacitor to the other, i.e. in one direction or the other. This gives the illusion of a current path through the capacitor although only the voltage across it is changing. Although the generator voltage is rectangular the voltage across the capacitor is distorted from that shape. This is due to the capacitor charging characteristics explained on previous pages. Distortion would not have taken place if the only component in the circuit had been a resistor. Now consider the same circuit drawn in a slightly different form as given in Fig. 12.

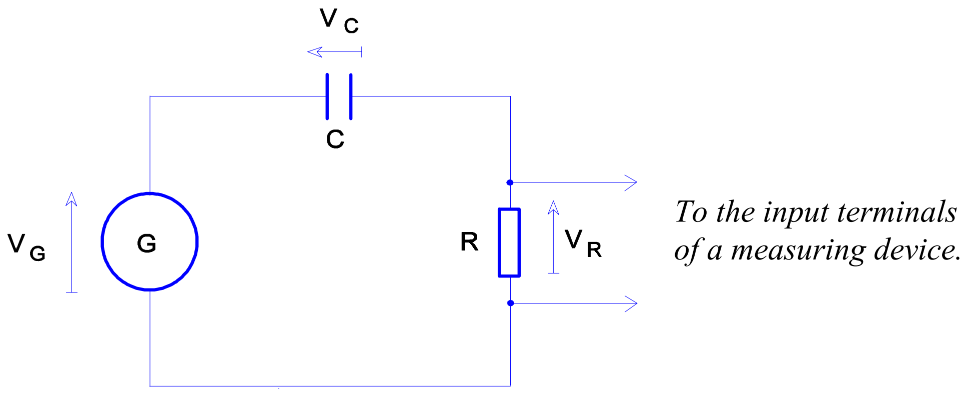


Fig 12. *Fig 10 drawn in a different form.*

As usual the open arrow-heads denote the positive voltage end of a component with respect to its other end and because the generator voltage is continuously changing they represent the situation at a particular time. The only source of voltage for the circuit shown is from the generator therefore the voltages $v_R + v_C$ must equal the generator voltage V_G. Let the generator G represents a signal source that could, for example, be a voltage produced from a transducer such as a video camera, or a voltage obtained from a pair of electrodes attached to a person - the range of possible signal sources is legion. As long as the signal voltage keeps changing, electrons will flow into and out of the capacitor and thus in one direction or the other through the resistor. This creates a voltage across the resistor that is proportional to the changing signal and this can be presented to the input terminals of a measuring instrument as shown. In the world of electronics this arrangement is called **capacitor coupling** and is often used where it is required to separate a changing signal from a fixed one. An example would be a signal superimposed upon a battery voltage.

CIRCUIT MAGNETISM

The discoveries to be outlined in the next few sections have led to the design of electric motors and generators, transformers and radio transmission, etc. They may also explain some undesired effects the novice will meet during laboratory experiments when using electronic apparatus.

It is a fact of life that whenever electrons, i.e. an electric current, flow through a conductor a magnetic field is created around the entire length of that conductor. The larger the current, i.e. the more electrons moving per second, the stronger that field will be and therefore the greater and further its influence.

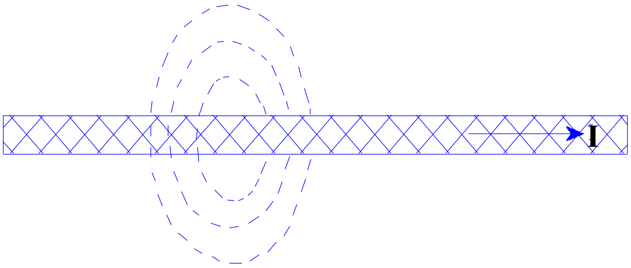


Fig 13. *The dashed lines represent the magnetic field around a current carrying conductor. This field extends along the entire length of the conductor.*

This electrical and magnetic association is called **electromagnetism** and the link was discovered by Oersted in 1820. Apparently the origin of this magnetic field is due to the uniform motion of electric charges, i.e. electrons, because the effect is not apparent with static electricity. An explanation for the observed characteristics of a permanent magnet could therefore be that enough electrons in a material have their trajectories uniformly aligned. Not all materials can maintain that electron configuration.

A magnetic field exists along the entire length of a conductor carrying current and when such a conductor is formed into a coil the associated magnetic field becomes concentrated within that coil. The resultant field is similar to that obtained with a bar magnet with the added advantage that if the direction of current through the coil is reversed the polarity of the magnetic field reverses, see the next diagram - Fig 14.

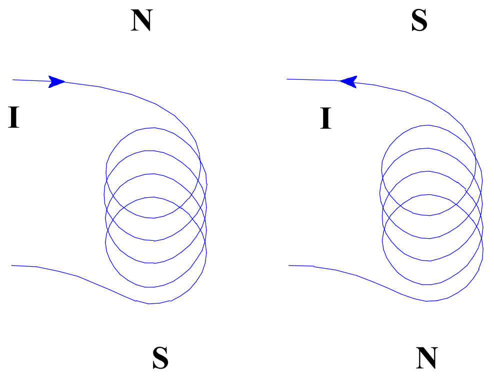


Fig 14. *The magnetic field reverses when the direction of current reverses.*

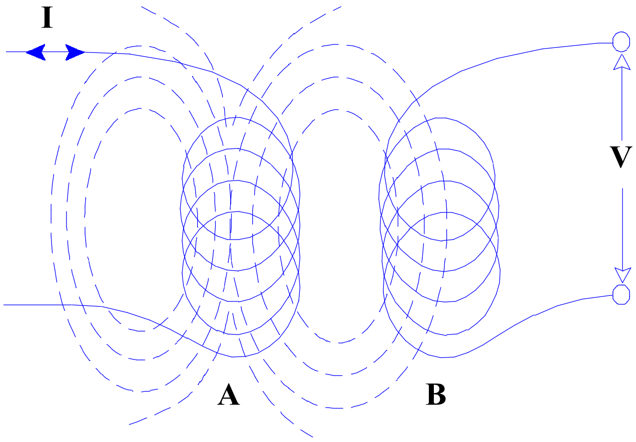
It may be remembered that the term north and south pole used for magnets originated from the use of a bar magnet in a compass. The end that points to the north is called the north seeking pole. This is shortened to north pole. Magnets formed by passing current through a coil resemble permanent magnets thus two such north or south poles repel while poles of opposite polarity attract each other. Also, if a coil is wound on an iron core the magnetic field concentrates, i.e. becomes stronger, within that core.

Coils used to shape a magnetic field for a particular application may differ considerably in outline to the spiral drawn in the previous diagram and coils designed to work at low frequencies will be bulky compared with those designed for radio frequencies. At a high enough frequency a single turn of a conductor can be very influential in a circuit. Each turn of a coil is insulated from every other turn. This is achieved by using wire coated with an insulating material. At radio frequencies where only a few turns are required air spaced turns may be used. If the insulation between two adjacent turns breaks down a **shorted turn** is created and this can cause the circuit to malfunction.

MAGNETIC INDUCTION

Ten years after Oersted's discovery, Faraday found that while the current in a coil is changing in amplitude an adjacent coil circuit will have a related current induced into it and if the adjacent coil is open circuit a voltage will be developed across its terminals. This is illustrated in Fig. 15.

Fig 15: *The changing current* **I** *through coil* **A** *creates a changing magnetic field that links with coil* **B**. *This will cause an induced voltage* **V** *across the open circuit terminals of coil* **B**. *If the ends of coil* **B** *are connected a current will flow through that coil.*



Experiment shows that the voltage **V** can be increased by either increasing the number of turns on the adjacent coil **B,** by increasing the value of current **I** or increasing the rate at which **I** changes. This circuit arrangement allows an applied current through a **primary** coil to produce a specific current through a **secondary** coil. One value of current is thus transformed into another value. The arrangement is therefore called a transformer. Similarly, a particular voltage applied across the primary coil can be transformed into another value across the terminals of the secondary coil. Note that there can be no energy gain because losses occur with the transforming process.

Faraday also discovered that a current was produced in a coil circuit if there was a change in a magnetic field along the axis of that coil. This can be demonstrated by moving a bar magnet in and out of a coil. The current is only produced while the magnet is moving, i.e. while the magnetic field around the magnet is “cutting” the turns of the coil. It makes no difference whether it is the magnet that moves while the coil remains stationary or if it is the other way around, it is the relative movement between the two that is important. The current is increased by using a stronger magnet or by moving the magnet faster.

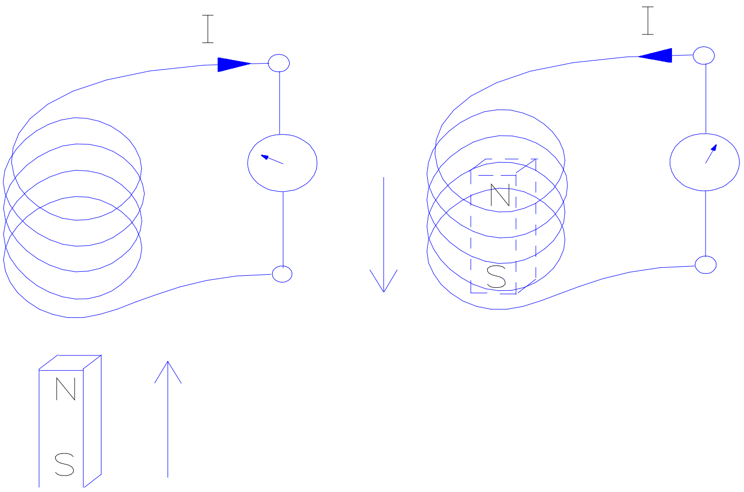


Fig 16. *The direction of current through the coil depends on the direction the magnet is moving. A stationary magnet does not generate current.*

Now some more name dropping, this time it is Lenz. He concluded that current induced into a coil is in such a direction that the magnetic field that accompanies that induced current opposes the magnetic field that is creating it. In other words, as a magnet’s north pole approaches the middle of a coil the current induced into that coil will be in a direction to create the coil’s north pole facing the oncoming north pole of the magnet. These north poles oppose each other and therefore work must be done to overcome this opposition. As the magnet is withdrawn the coil's current reverses direction, this changes what was the coil's north pole to a south pole. The latter now attracts the north pole of the departing magnet thus opposing its withdrawal. The work done, i.e. energy used, in moving the magnet has become electrical energy.

SELF INDUCTION

Current through a coil produces a magnetic field around that coil. While this current and its associated magnetic field are changing not only will current be induced into any adjacent circuit, the coil itself will be affected by the same mechanism and will produce a voltage of its own which is of opposite polarity to the voltage applied to it. This opposing voltage is referred to as a **self induced e.m.f.** or a **back e.m.f.** where e.m.f. stands for electro motive force. The effective voltage across the coil is therefore the applied voltage minus the self induced voltage. Consequently less current flows than would have done had it not been for this back e.m.f. Energy losses prevent the back e.m.f. being entirely successful in stopping current flow completely and eventually the applied voltage overcomes the opposition but this takes a finite time to happen as shown in Fig 17. Once the current reaches a constant steady value no back e.m.f. is generated; at that stage current is limited by resistance in the circuit.

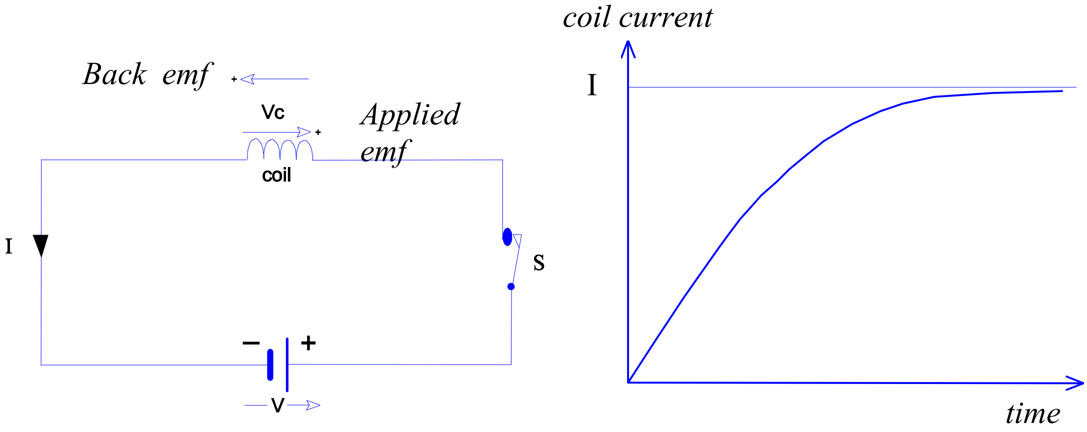


Fig 17. *When switch* S *is closed current increases to a maximum value of* I=V/R *where* R *is the circuit resistance which includes the coil's resistance. The voltage across the coil (Vc) is the battery voltage minus the back e.m.f.*

The situation just described applies to an air cored coil. An iron core will be relatively slow establishing its magnetic field because it takes time for the iron molecules to become aligned, consequently a back e.m.f. is not created immediately at switch-on and current is initially limited only by any resistance in the circuit. This results in a short but large current surge when the switch first closes. The switch used must be rated for this surge.

Consider now the opposite situation where a steady current through a coil is suddenly stopped. The existing magnetic field that was due to that current will start to collapse, this collapsing, i.e. changing, field will generate a voltage across the coil in which it is existing. This induced voltage has the opposite polarity to that created when the field was increasing. It now aids the current already flowing rather than trying to prevent it. When the circuit was switched on the opposite happened. Thus as the switch contacts open this added voltage enables the current to continue flowing between them thus creating an arc between those contacts. Eventually the distance between the switch contacts becomes too large for the electrons to jump and the arc stops. The same process generates the ignition spark in a petrol engine. (An electric spark is the colloquial name for arcing that is seen to last only a relatively short time.) The arcing problem is aggravated by switch contacts tending to bounce between open and closed states for several milliseconds while operating. This arcing damages the switch contacts.

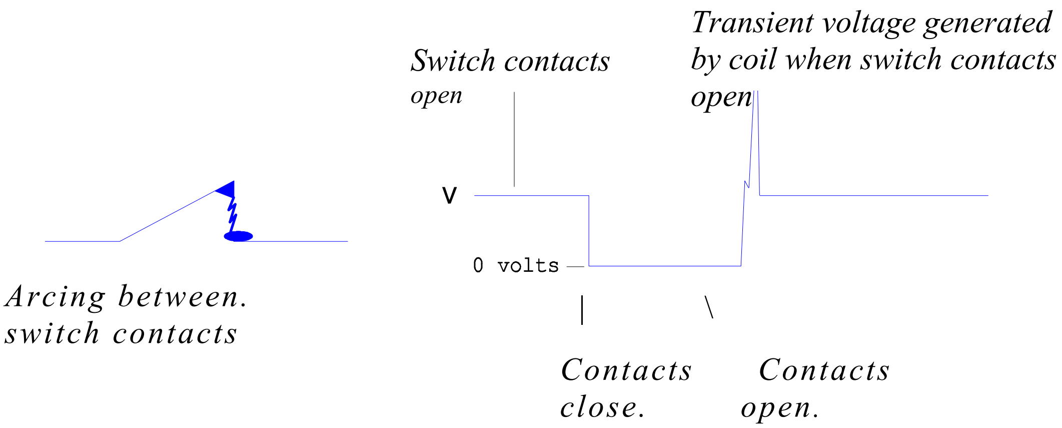


Fig 18. *Voltage across switch contacts in an inductive circuit.*

ATTRIBUTES OF A COIL

As already explained, an energised coil has a self induced e.m.f.. Such a component is said to be **inductive** or to possess **inductance** and is called an **inductor**. It is denoted by **L** and the amount of inductance it represents is measured in **henrys,** symbol **H**. Thus a coil will have an inductance of so many henrys. When a coil's magnetic field links to another coil the two coils are said to have **mutual inductance**, symbol **M**. This is in addition to their individual inductances.

Providing it with an iron core can increase the inductance of a coil. The actual core material is selected, or developed, to optimise the performance of the coil for a given application. Its effectiveness for the task is a measure of that materials **permeability,** symbol μ. The value of μ for a vacuum is unity. Some materials have a permeability of many thousand. Note that using an iron core also introduces non-linear characteristics into an inductive circuit. An air cored inductor known as a **solenoid** is used to operate a mechanism attached to an iron plunger that is attracted along the axis of the energised coil.

THE SNUBBER

The arcing that occurs while opening a switch in an inductive circuit will damage the switch contacts and radiate interference over a wide range of frequencies. Operating the contacts faster does not reduce arcing because the quicker the magnetic field collapses the higher the self induced e.m.f.. The situation can be controlled to some extent by arranging an alternative path for the arcing current. This is achieved by using a **snubber.** Most commonly this consists of a resistor and capacitor connected in series across the switch contacts. As the switch opens, the energy that would have formed the arc is then dissipated in the resistor of the alternative path. The values of the components used for the snubber depend upon the current and inductance to be switched.

THE L/R TIME CONSTANT

Resistance in series with an inductor limits the amount of current that could otherwise flow. Consequently the magnetic field associated with the current will also be reduced. In turn this means that a smaller self induced back e.m.f. will be generated allowing the current to attain its final steady value in a shorter time, see Fig 19.

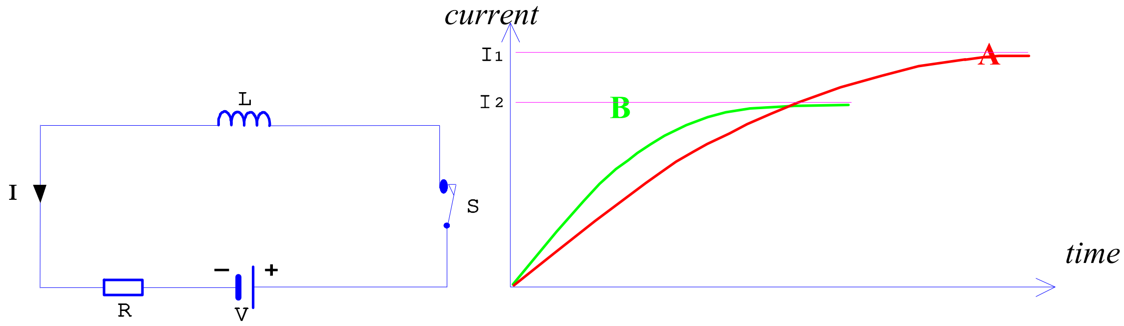


Fig 19. *The value of resistance* R *determines the circuit current at switch-on. For curve* B *the circuit has a higher value of* R *than for curve* A.

The inductor and resistor circuit has, like the resistor and capacitor combination, a time constant indicating the circuit's progress towards its final state as current starts to flow. It is expressed as:

$$T = L/R$$

where L is in henrys, R in ohms and T in seconds. Like the series RC circuit this defines the time to reach 63% of the circuits quiescent state while absorbing energy and 37% of that final state when expending it. If no additional resistance is present in an inductive circuit, the circuit resistance will come mainly from the wire making up the coil. If this has only a few turns that resistance will be small therefore after the back e.m.f. has had its effect a large steady current will flow. At high frequencies a characteristic called skin effect comes into play which increases the circuits resistance.

ANOTHER LOOK AT CURRENT

Recapping: uniform electron movement, ie a moving negative charge, is an electric current and this charge is measured in coulombs where 1 coulomb represents approximately 6 x 10^{18} electrons. The movement of that many electrons past a given point every second represents a current (I) of 1 ampere, 1 amp for short, and usually written as 1A. In electronics it is not unusual to be working with milliamps (mA), that is 10^{-3}A or with microamps (μA) i.e. 10^{-6}A, rather than amps. When large currents are required a large number of free electrons have to be available to be moved. Materials that qualify in this respect are the metals, in particular copper which is relatively inexpensive and has the required manufacturing qualities. The electrons in copper, as in other good electrical conductors, are rather restless. They are continuously careering about from molecule to molecule in a haphazard way. Their random movements negate a self generated current but can be encouraged, with the help of an electrical generator, to concentrate their restlessness in one direction and thus create a current. There are 8.28×10^{22} atoms in one cubic centimetre of copper and if at any given time each of those atoms is persuaded to allow just one of its electrons to shuffle along towards an adjacent cubic centimetre of copper, that would represent a current of:

number of atoms in 1cm^3 / number of electrons in 1 coulomb
i.e. $8.28 \times 10^{22} / 6.25 \times 10^{16}$ amps

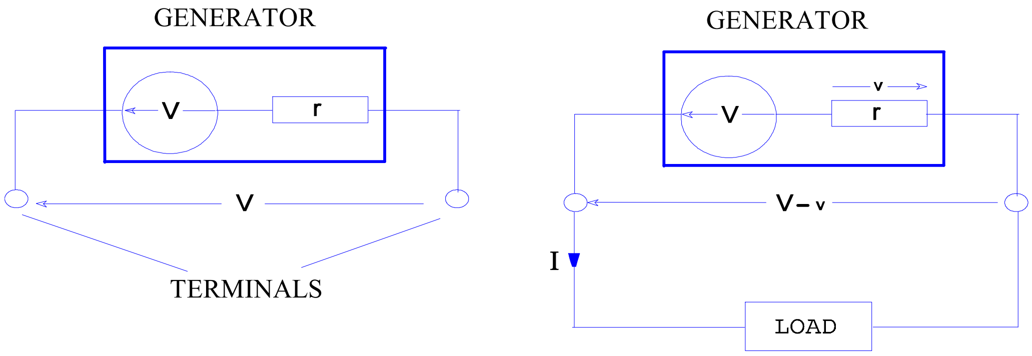
This is over 10,000A! It need not be the same electrons that enter and then exit that cubic centimetre of copper during that 1 second. They can stop along the way but others must continue the journey.
A current of 10,000A will be outside the experience of most readers some of which will be more interested in milliamps associated with chemical reactions but the same principles apply.

When a generator is inserted into a circuit its action is to repel electrons from one of its terminals and replace them with electrons entering its other terminal. These electrons are not "used up" as might be assumed from the expression "current consumption". Another misconception is to think of electrons moving round a circuit at the speed of light. An individual electron will not travel far before it collides with another electron atom or molecule. The instantaneous response witnessed at the end of a conductor is similar to that obtained when gently hitting a snooker ball into the end of a straight line of touching snooker balls. On impact the ball at the far end of the line moves smartly away but the other balls remain almost stationary. It is the energy contained in the cued ball that is transmitted along the line of near stationary balls. Similarly it is the effect of electrical energy in a circuit that we witness.

EMF AND VOLTAGE-DROP

Returning briefly to electric generators: whether they are massive mechanical devices involving moving magnetic fields or involve chemical reactions such as "batteries", they all produce a voltage called an **electromotive force** (symbol **e.m.f.**) that can move electrons around a circuit. This is not a different kind of voltage but a name given to the voltage across the generator terminals on open circuit, i.e. when no current is flowing. The distinction is important because all generators have some internal resistance across which a voltage will form when current flows and this **voltage drop**, as it is called, is not available for use outside that generator. On **load**, that is when a current is flowing, the voltage across a generator's terminals, called its **terminal voltage,** will be less than its e.m.f. by the amount lost across its own internal resistance. The situation is depicted in Fig. 19. Thus, the smaller a generator's internal resistance or the smaller the load current the less this internal voltage drop.

Similarly, even a good electrical conductor will have some resistance distributed along its length. Thus the passage of current through it will result in a voltage drop along its length resulting in less voltage being available across the load, see Fig. 20. Voltage drop along a length of cable can be an important consideration where large currents are involved. It can be reduced by making more electrons available and that is done by increasing the cross sectional area of the conductor.



Generator on open circuit. *Generator on load.*

Fig 19. V *represents the generators* e.m.f. *and* r *its internal resistance.*

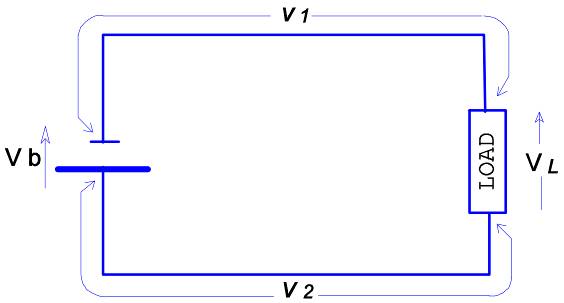


Fig 20. *The voltage (VL) across the load will be the battery voltage minus the voltage drops in the connecting leads, ie:*

$V_L = Vb - (v_1+v_2)$.

Another consideration when choosing the size of cable to use for large currents is the amount of heat generated in that cable due to its inherent resistance because this represents a potential fire hazard. This situation can exist in domestic premises where mains cables are thermally insulated by being placed, for example, under a carpet.

VARYING VOLTAGE AND CURRENT

Voltage or current signals being monitored for analysis will be varying with time, perhaps in a random way. Examples of the two types are shown in Fig. 21.

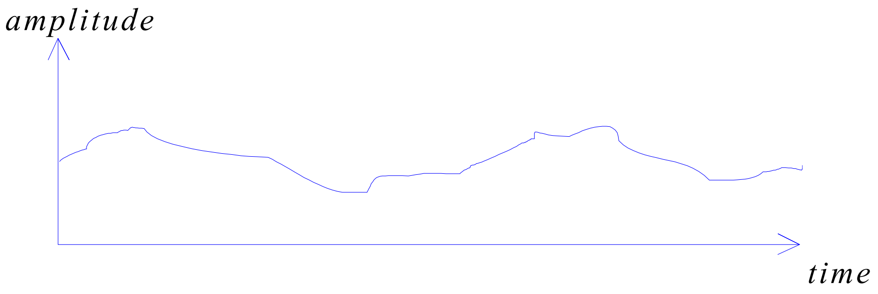


Fig 21a. *A signal with its amplitude varying randomly with time.*

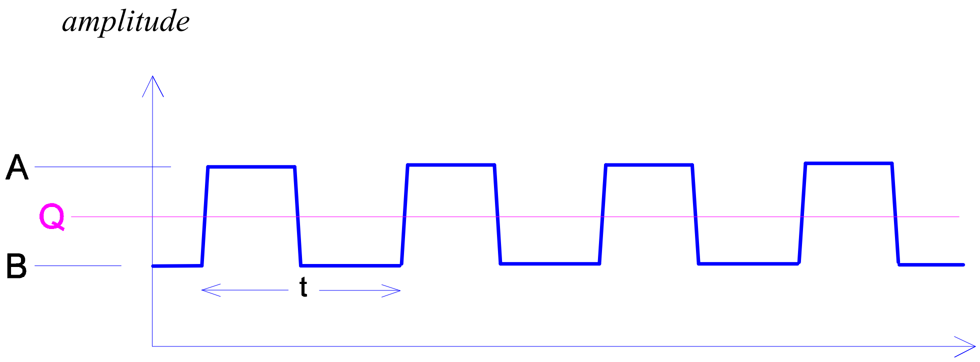


Fig 21b. A *waveform repeating its self over time.*

These **waveforms** would be seen with an oscilloscope. They may represent either voltage or current. Referring to the lower diagram let that part of the waveform above **Q** represents current flowing in one direction and that below **Q** current flowing in the opposite direction. The near vertical lines indicate the transition time between those two states. At points where the waveform crosses line **Q** the current is zero. The waveform repeats itself after a time **t** called the **period** of the waveform. For the case shown, current flows in either direction for an equal amount of time and is therefore called a square wave. Points along this waveform coinciding with line Q represent 0 volts and, by convention, points above that line are regarded as positive and those below it as negative. If the line Q represented a voltage other than zero then the waveform would be said to be “sitting on” that voltage.

Referring this waveform to the circuits in Fig 22: generator **G** pushes current through resistor **R** first in one direction, diagram (a) and then in the opposite direction, diagram (b). By using point **Q** on each diagram as a reference point, in diagram (a) **P** is positive with respect to **Q** but when the current is reversed, diagram (b), **P** becomes negative with respect to **Q**. Note that the use of ground as a reference is not relevant, the circuit could be existing in space.

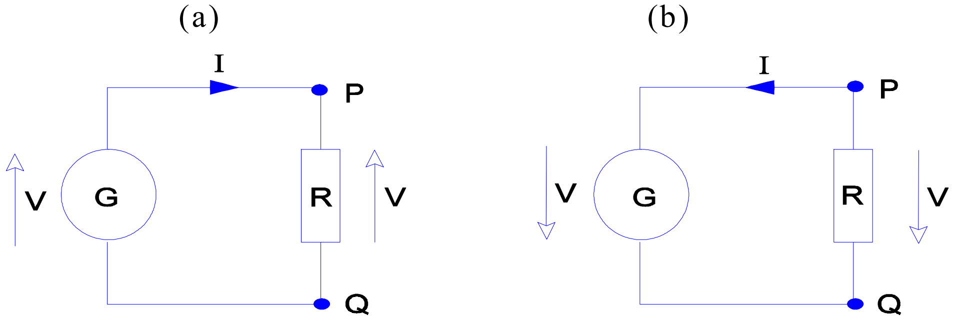


Fig 22. *Point P could equally well have been chosen as a reference point and if either Q or P was connected to ground then the voltage at the other point could be quoted as being with respect to ground.*

Any waveform shape can be generated. The electricity supply industry requires a continuously changing current for its transformers to work and uses a sinusoidal waveform i.e. sine wave also referred to as an alternating current (ac). This smoothly changing shape overcomes transient problems associated with waveforms that change suddenly.

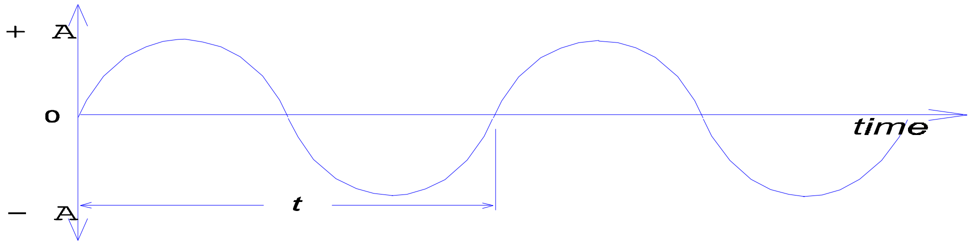
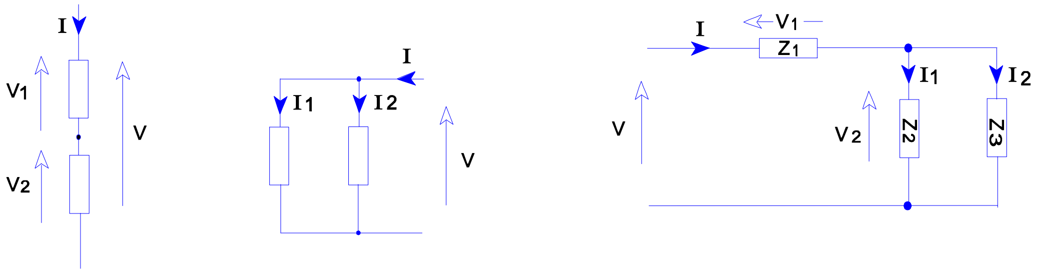


Fig 23. *Sine wave:* ***A*** *is the waveform's amplitude and* **t** *the time for one complete cycle, or period. 1Hz (one hertz) is one complete cycle of a sinusoidal waveform in one second. Thus a 50Hz supply completes 50 periods every second.*

MULTIPLE CIRCUITS AND COMPONENTS

A previous section explained how a changing current in one coil could introduce a current in an adjacent coil. In essence two circuits were involved. In all circumstances where a source of current can divide into two or more routes then more than one circuit exists. Circuit components can be connected in series or in parallel and in combinations of these arrangements. In the following diagrams the rectangles can represent resistors, capacitors, inductors or a combination of two or more of those component types. In the latter case the name given to the combination's influence on current flow is called **impedance**, symbol **Z.** Impedance is measured in ohms but unlike a pure resistance its value is frequency dependent. The influence of inductance and capacitance on current flow in a circuit is called **inductive reactance** (symbol $\mathbf{X_L}$) and **capacitive reactance** (symbol $\mathbf{X_C}$) respectively. The reactance of an inductance increases with the frequency of the current through it but the reactance of a capacitor is inversely proportional to the frequency of the voltage across its terminals.



Components in series.
$V = V_1 + V_2$

Components In parallel.
$I = I_1 + I_2$

Z_1 is in series with Z_2 and Z_3 which are connected in parallel.
$V = V_1 + V_2$ and $I = I_1 + I_2$.

Fig 24. *Common arrangements for circuit components.*

The total value of N resistors or inductors connected in **series** is:

$$R_T = R_1 + R_2 + \dots R_N$$

and

$$L_T = L_1 + L_2 + \dots L_N$$

but for capacitors it is obtained by solving, for C_T , the fraction:

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \dots \frac{1}{C_N}$$

C_T will be less than any individual value of C in the combination.

For **parallel** connections R_T and L_T are obtained from:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \dots\dots \frac{1}{R_N}$$

and

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \dots\dots \frac{1}{L_N}$$

while

$$C_T = C_1 + C_2 + \dots C_N$$

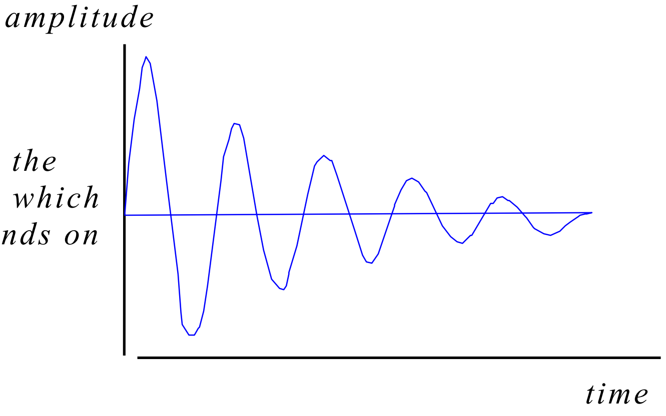
For the parallel case it is R_T and L_T that will be less than any of the individual values in the combination. For all the examples R is in ohms, L is in henrys and C is in farads. Note that C and L do not represent **reactance** the determination of which is beyond the scope of this monograph.

Let the right hand circuit in the previous diagram, Fig 24, depict something practical: Z1 could be the input impedance of a measuring probe and Z2 the impedance of a connecting cable between the probe and a monitoring device that has Z3 connected across its input terminals. It may be necessary to know, determine, or be aware of, the values of the components in the arrangement described to make a successful measurement and to make sense of what is being observed.

From the previous formulae it can be seen that when dealing with a number of components connected in parallel it may be useful to work directly with their inverse. In particular, this is the convention when dealing with radio frequencies. The inverse of resistance is called **conductance,** symbol **S**, and has units called **siemens**. Thus for the case of a resistor: S=1/R so that if R=8 ohms, S=0.125 siemens. Another name you will come across is **admittance**, this is the inverse of impedance and is denoted with Y, so that: Y = 1/Z.

There is a particular combination of reactance that is special: readers will be familiar with the sound of church bells each of which rings at a particular audio frequency when "energised" by being struck. The analogue of this in the electrical world occurs when inductors and capacitors coexist in the same circuit. They also **resonate** when "hit" with a pulse of electrical energy and the associated "ring" results in a damped oscillating current waveform as shown in Fig 25.

Fig 25. A damped electrical oscillation. Its frequency which depends on the vales of L and C. The rate at which its amplitude decreases depends on the value of R in the circuit.



ACTIVE AND PASSIVE

Resistors, capacitors and inductors are called **passive** electrical components. Electrical generators such as batteries and devices that can control electron streams are known as **active** components. A well-known example of the latter is the transistor. The processors used in digital computers are made up of thousands, sometimes millions, of transistors interconnected in a host of circuits but having an overall package size of only a few centimetres square. Such components are called integrated circuits. On a smaller scale are integrated circuits that provide distortion free amplification of signals. Such circuits are said to be **linear.** Circuits used in, but which are not exclusive to, digital computers are called **digital** circuits. In general, an electronic system will incorporate both types.

ENERGY AND POWER

The reader will be aware of energy where it is required to complete some manual task, but energy is required to effect all changes and this includes electrical and magnetic ones. Energy should not be confused with power therefore let us examine what is meant by those two names.

Electrical goods, e.g. hair dryers, light bulbs etc, have a **wattage** rating attached to them. This is the part's power rating and indicates the **rate** at which it uses energy. In other words:

power = energy / time or energy = power x time

Thus, the longer you use an electrical appliance the more energy not power that is being consumed. The unit of power is the **watt,** symbol **W**. This represents energy being used at the rate of 1 joule per second where **joule,** symbol **J,** is the unit of energy. Referring this to everyday life electricity is charged for by the amount of energy used, that is power x time where for practical reasons kilowatts, symbol **kW**, are used instead of watts and hours instead of seconds. These units are called kilowatt-hours, written as **kWh**. One kWh represents one unit on your electricity bill thus a one kW (1,000W) fire switched on continuously for 1 hour uses one unit of electricity. Since 1 watt is 1 joule per second it follows that the number of joules in 1kWh is:

1,000 watts x the number of seconds in an hour,
i.e. 1,000 x 60 x 60 joules,
that is 3,600,000 or 3.6×10^5 joules.

You may not be paying your electricity bills (yet) in which case the previous paragraph may fail to engage your full interest, however you could be concerned with calories. Dieticians express food values with kilocalories, which are the units referred to in the popular press as calories, and one kilocalorie is worth about 4185 joules. Knowing that about 3½kWh of energy will keep a person going for a day which would be the cheapest way of receiving that energy, from the electricity supply company or from a super market?
Another term used to denote energy is the **electron volt**. This is the amount of energy required to move an electron between two points having a potential difference of 1 volt. It turns out that 1 electron volt represents only 1.6×10^{-19}J.

ENERGY AND ELECTRICAL COMPONENTS

A resistor turns electrical energy from a primary source such as a battery into heat energy. The mass of the resistor may store heat for a while after the primary energy source has been disconnected but this is to do with the resistors bulk properties. Yet, charged capacitors and inductors carrying current have energy stored in their fields. The origin of this stored energy is the primary source from which energy was taken to build up those fields. The amount of stored energy involved can be calculated from the following:

For a capacitor	$J = \frac{1}{2}CV^2$ joules
For an inductor	$J = \frac{1}{2}LI^2$ joules

The following examples should clear up any doubts on the relationship between power and energy and provide a "feel" for the information that has been given. Consider a 1,000μF capacitor with 10V across its terminals. These are typical values for a low voltage power supply. The energy stored in the capacitor will be:

$$\begin{aligned} J &= \tfrac{1}{2}\,(1{,}000 \times 10^{-6} \times 10 \times 10) \\ &= 0.05 \text{ joules} \end{aligned}$$

This appears minuscule compared with the 3.6×10^6 joules associated with the 1kW fire mentioned earlier but that amount of energy was spread over an entire hour. It used just 1 joule of energy every millisecond. Suppose that the capacitor is discharged in one millisecond (1ms) which is relatively slow in electronic circuits, the power involved will be:

$$\begin{aligned} \text{power} &= \text{energy / time} \\ &= 0.05 / 0.001 \\ &= 50\text{W} \end{aligned}$$

If the discharge took place a thousand times faster, i.e. in 1μs, which is still not exceptionally fast in electronic circuit terms, the power involved becomes 50kW! This increase in power should be expected because, for example, if you have a car that cannot move fast enough for your requirements you would have to get a more powerful one. For competition racing it would also be designed for that purpose. Similarly, capacitors capable of providing large amounts of energy in a short period without self destructing during the process must also be designed for that application.

All electrical components and measuring devices have maximum ratings for voltage, current and wattage within which they must be operated. Ignoring these ratings will cause damage to components and result in unreliable measurement results.

MAKING MEASUREMENTS

As might be expected, a device for measuring voltage is called a **voltmeter** but one for measuring current is called an **ammeter**, (not ampmeter). A voltmeter is connected **across** the terminals of a circuit or device to measure the voltage between those two points. An ammeter is connected **into** a circuit to measure the current flowing in that circuit. It is also possible to make a non-invasive measurement of current via the magnetic field associated with it.

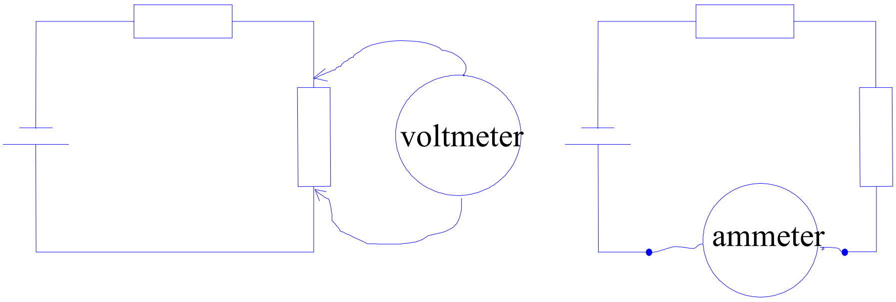
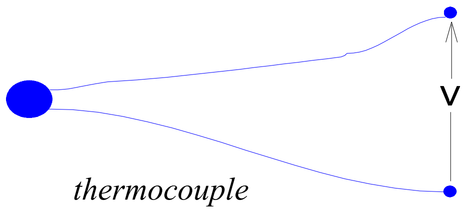


Fig 26. *A voltmeter is connected across a component or components, an ammeter is connected into a circuit.*

The ideal ammeter will not impede current flow, i.e. change it from that value that flows without its presence and an ideal voltmeter will not "load" a circuit, which means it will not allow current to flow through itself.

An ammeter must not be connected directly across the terminals of a generator, such as a car battery, to "see how much current there is in that battery". If you have followed the story so far you will know that a battery does not contain current but generates it. For the situation just conjectured the battery would probably produce sufficient current to damage the meter.

Electronic based scientific instrumentation actually measures voltage, current or an electromagnetic field although the output is calibrated in terms of something else such as temperature or pH. The source of the signal may be a transducer producing a voltage or current related to the subject being measured. Alternatively, a sensor may form part of a 4 terminal device, see Fig 27, that has a constant voltage or current applied to it. In this case the sensor changes its value, e.g. resistance, in sympathy with changes to the subject being measured. This results in a change in the output of the 4 terminal device. In some cases the electrical or magnetic signals of interest occur spontaneously in nature.



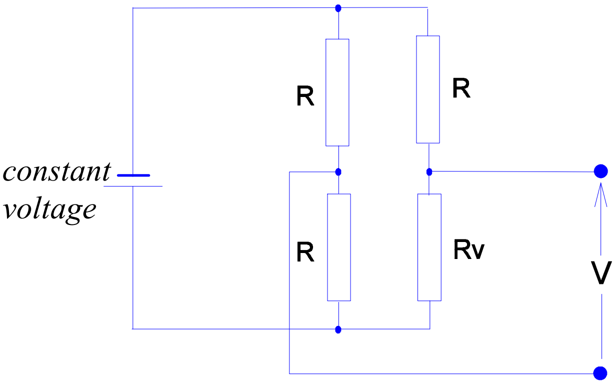


Fig 27. *For each case the voltage to be measured is* V. *The thermocouple produces its own voltage. In the case of the 4 terminal bridge circuit each* R *is fixed at a constant value and* Rv *(the sensor) is a variable that modulates the value of* V *in sympathy with what is being measured.*

What ever their source, signals usually require some sort of attention before they can be viewed, measured, recorded or used. This process is called **signal processing**. This usually entails operations such as enlarging, i.e. amplifying, the signal; reducing accompanying unwanted signals called **noise** with filters and then changing the signal into a digital representation that is suitable for a computer. The latter is called **analogue to digital** processing.

FINALY

These introductory notes to electricity and basic electrical circuits will have helped those who get involved with electronic apparatus but whose main subjects lay elsewhere. For such readers the sister publication Making Electrical Connections which deals with interconnecting electrical equipment may also be of interest. Alternatively, this monograph may have been used as a prologue to more serious study of the subject. In either case it is hoped that it has been helpful.