

# Electromagnetic Components



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## Chapter 1

# Capacitor



Modern capacitors, by a cm rule

**Type** Passive

**Invented** Ewald Georg von Kleist (October 1745)

**Electronic symbol**



A **capacitor** (formerly known as **condenser**) is a passive electronic component consisting of a pair of conductors separated by a dielectric (insulator). When there is a potential difference (voltage) across the conductors, a static electric field develops in the dielectric that stores energy and produces a mechanical force between the conductors. An ideal capacitor is characterized by a single constant value, capacitance, measured in farads. This is the ratio of the electric charge on each conductor to the potential difference between them.

Capacitors are widely used in electronic circuits for blocking direct current while allowing alternating current to pass, in filter networks, for smoothing the output of power supplies, in the resonant circuits that tune radios to particular frequencies and for many other purposes.



A typical electrolytic capacitor

The effect is greatest when there is a narrow separation between large areas of conductor, hence capacitor conductors are often called "plates", referring to an early means of construction. In practice the dielectric between the plates passes a small amount of leakage current and also has an electric field strength limit, resulting in a breakdown voltage, while the conductors and leads introduce an undesired inductance and resistance.

## ***History***



Battery of four Leyden jars in Museum Boerhaave, Leiden, the Netherlands.

In October 1745, Ewald Georg von Kleist of Pomerania in Germany found that charge could be stored by connecting a high voltage electrostatic generator by a wire to a volume of water in a hand-held glass jar. Von Kleist's hand and the water acted as conductors and the jar as a dielectric (although details of the mechanism were incorrectly identified at the time). Von Kleist found, after removing the generator, that touching the wire resulted in a painful spark. In a letter describing the experiment, he said "I would not take a second shock for the kingdom of France." The following year, the Dutch physicist Pieter van Musschenbroek invented a similar capacitor, which was named the Leyden jar, after the University of Leiden where he worked.

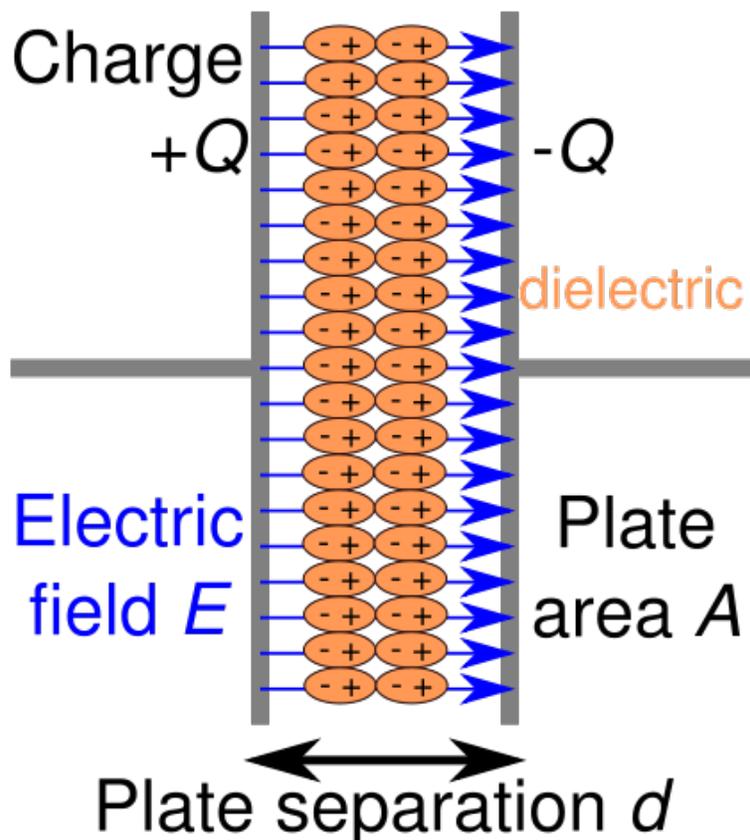
Daniel Gralath was the first to combine several jars in parallel into a "battery" to increase the charge storage capacity. Benjamin Franklin investigated the Leyden jar and "proved" that the charge was stored on the glass, not in the water as others had assumed. He also

adopted the term "battery", (denoting the increasing of power with a row of similar units as in a battery of cannon), subsequently applied to clusters of electrochemical cells. Leyden jars were later made by coating the inside and outside of jars with metal foil, leaving a space at the mouth to prevent arcing between the foils. The earliest unit of capacitance was the 'jar', equivalent to about 1 nanofarad.

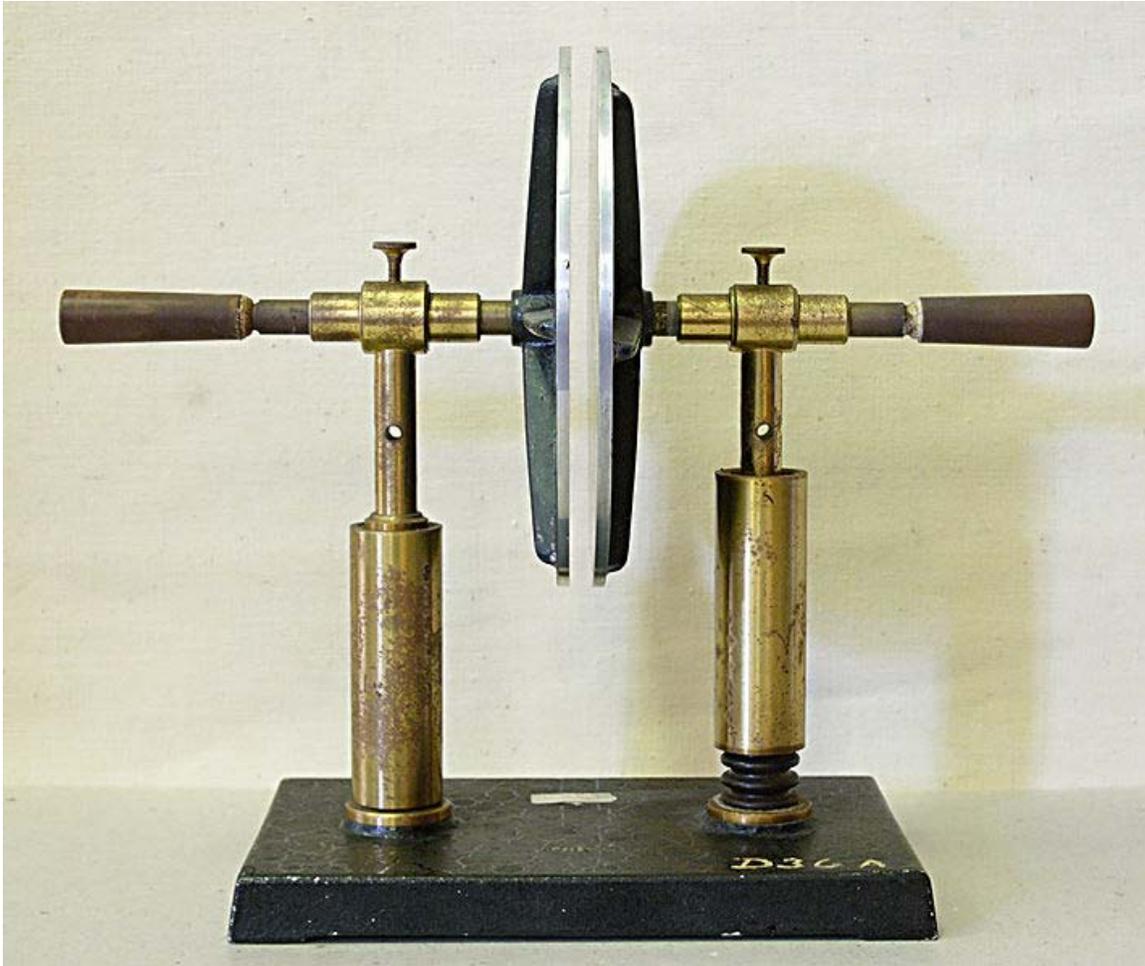
Leyden jars or more powerful devices employing flat glass plates alternating with foil conductors were used exclusively up until about 1900, when the invention of wireless (radio) created a demand for standard capacitors, and the steady move to higher frequencies required capacitors with lower inductance. A more compact construction began to be used of a flexible dielectric sheet such as oiled paper sandwiched between sheets of metal foil, rolled or folded into a small package.

Early capacitors were also known as *condensers*, a term that is still occasionally used today. The term was first used for this purpose by Alessandro Volta in 1782, with reference to the device's ability to store a higher density of electric charge than a normal isolated conductor.

### **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 called the dielectric medium though it may be a vacuum or 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.

The capacitor is a reasonably general model for electric fields within electric circuits. 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:

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

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

$$C = \frac{dq}{dv}$$

## Energy storage

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 given by:

$$W = \int_{q=0}^Q V dq = \int_{q=0}^Q \frac{q}{C} dq = \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} CV^2 = \frac{1}{2} VQ.$$

## 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,

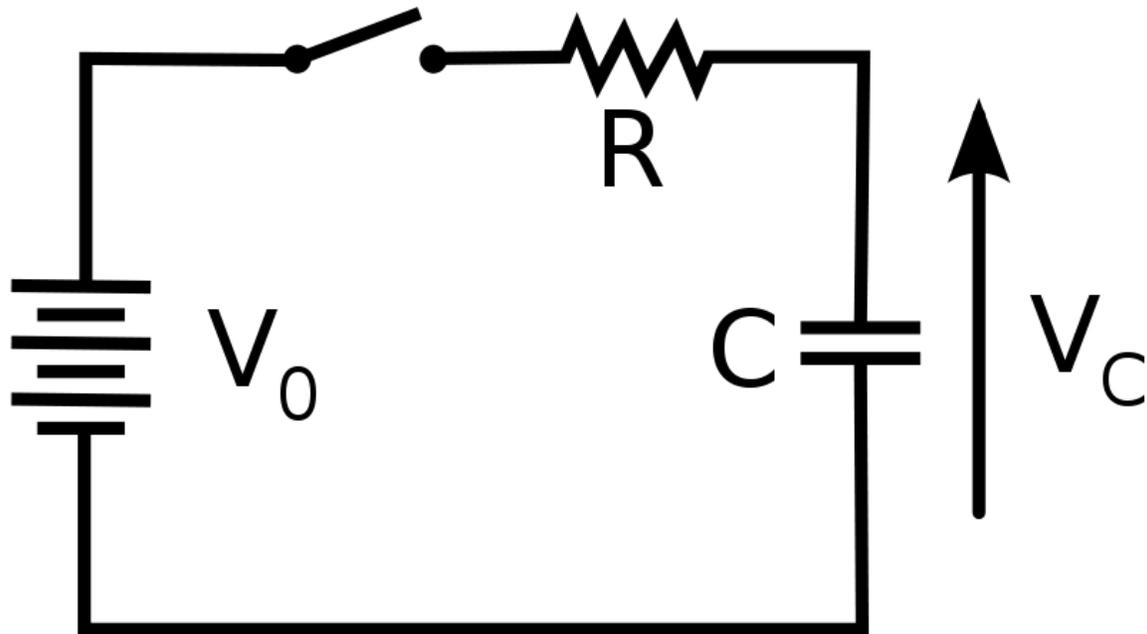
$$v(t) = \frac{q(t)}{C} = \frac{1}{C} \int_{t_0}^t i(\tau) d\tau + v(t_0)$$

Taking the derivative of this, and multiplying by  $C$ , yields the derivative form,

$$i(t) = \frac{dq(t)}{dt} = C \frac{dv(t)}{dt}$$

The dual of the capacitor is the inductor, which stores energy in the magnetic field rather than the 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

$$V_0 = v_{\text{resistor}}(t) + v_{\text{capacitor}}(t) = i(t)R + \frac{1}{C} \int_0^t i(\tau) d\tau.$$

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

$$RC \frac{di(t)}{dt} + i(t) = 0.$$

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, the differential equation yields

$$i(t) = \frac{V_0}{R} e^{-t/\tau_0}$$
$$v(t) = V_0 \left( 1 - e^{-t/\tau_0} \right),$$

where  $\tau_0 = RC$  is the *time constant* of the system.

As the capacitor reaches equilibrium with the source voltage, the voltage 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

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

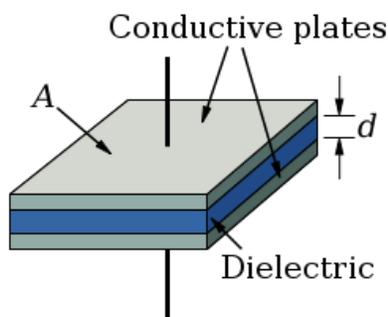
$$X = -\frac{1}{\omega C} = -\frac{1}{2\pi f C}$$
$$Z = \frac{1}{j\omega C} = -\frac{j}{\omega C} = -\frac{j}{2\pi f C}$$

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

Note that 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.

### Parallel plate model



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

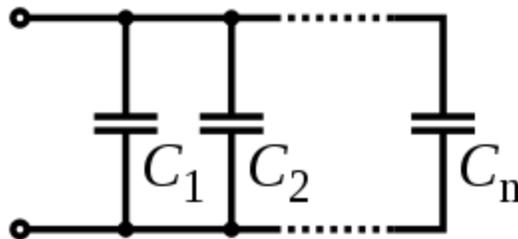
The simplest capacitor consists of two parallel conductive plates separated by a dielectric with permittivity  $\epsilon$  (such as air). The model may also be used to make qualitative predictions for other device geometries. The plates are considered to extend uniformly over an area  $A$  and a charge density  $\pm\rho = \pm Q/A$  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  $E = \rho/\epsilon$ . The voltage is defined as the line integral of the electric field between the plates

$$V = \int_0^d E dz = \int_0^d \frac{\rho}{\epsilon} dz = \frac{\rho d}{\epsilon} = \frac{Qd}{\epsilon A}.$$

Solving this for  $C = Q/V$  reveals that capacitance increases with area and decreases with separation

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

The capacitance is therefore greatest in devices made from materials with a high permittivity.



Several capacitors in parallel.

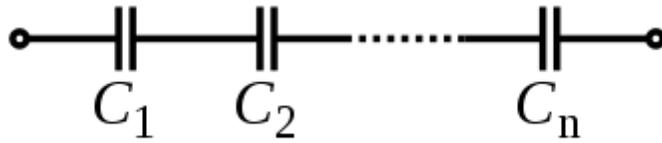
## Networks

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.

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

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. In such an application, several series connections may in turn be connected in parallel, forming a matrix. The goal is to maximize the energy storage utility of each capacitor without overloading it. Series connection is also used to adapt electrolytic capacitors for AC use.

### ***Non-ideal behaviour***

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.

### **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,

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

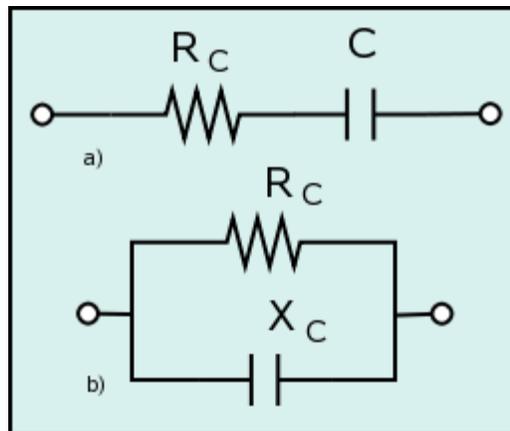
The maximum energy that can be stored safely in a capacitor is limited by the breakdown voltage. Due to the scaling of capacitance and breakdown voltage with dielectric

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 100V or so. As the voltage increases, the dielectric must be thicker, making high-voltage capacitors larger 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 will quickly "track" through the dielectric till it reaches the opposite plate and cause 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



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:

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

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).

## **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. Certain types of capacitors, such as electrolytic tantalum capacitors, usually have a rating for maximum ripple current (both in frequency and magnitude). This ripple current can cause damaging heat to be generated within the capacitor due to the current flow across resistive imperfections in the materials used within the capacitor, more commonly referred to as equivalent series resistance (ESR). For example electrolytic tantalum capacitors are limited by ripple current and generally have the highest ESR ratings in the capacitor family, while ceramic capacitors generally have no ripple current limitation and have some of the lowest ESR ratings.

## **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 and the 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.

Capacitors, especially ceramic capacitors, and older designs such as paper capacitors, can absorb sound waves resulting in a microphonic 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 microphonic 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.

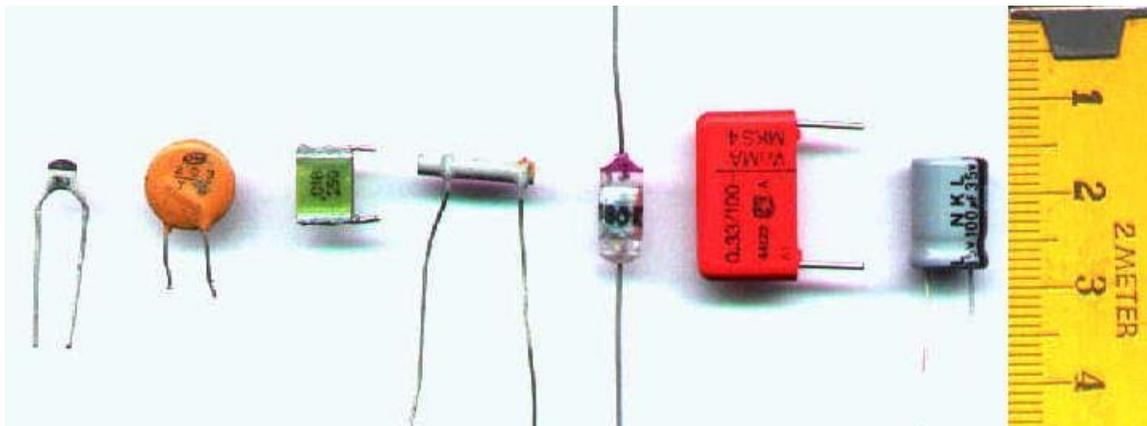
## **Capacitor types**

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**



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.

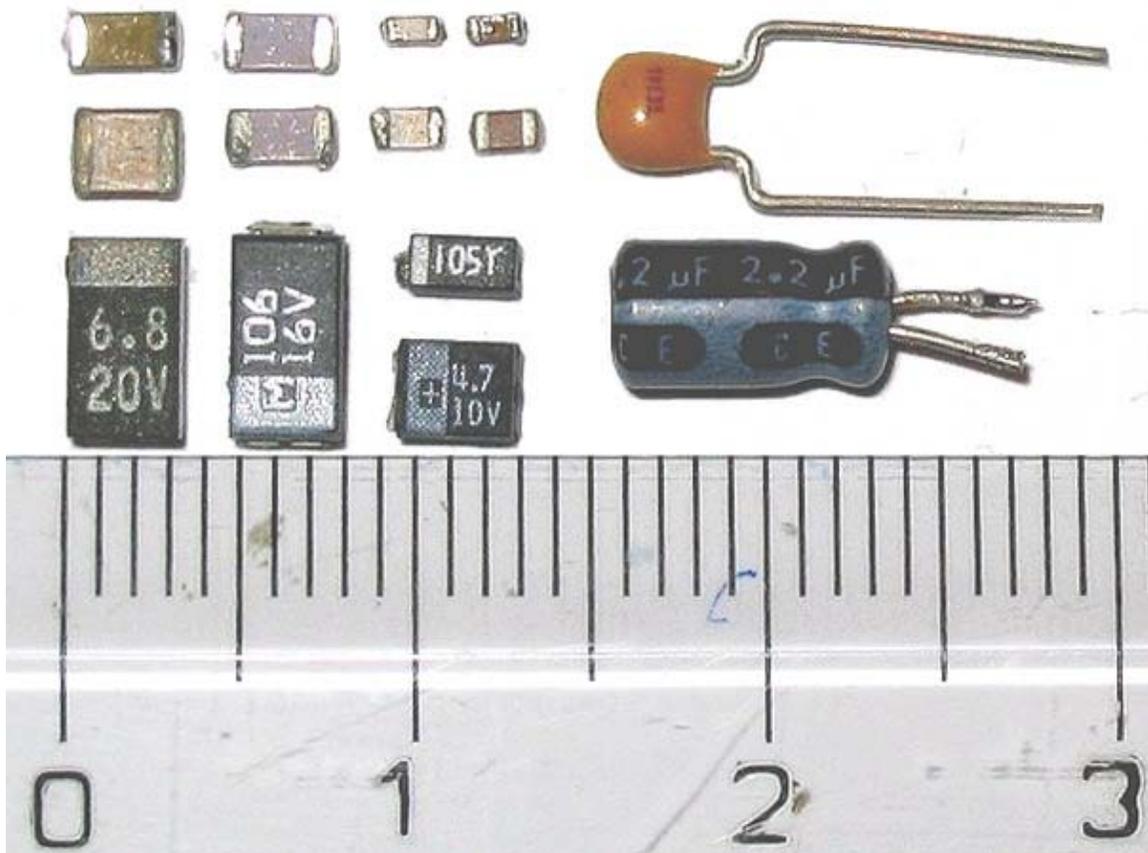
Several solid dielectrics are available, including paper, plastic, glass, mica and ceramic materials. Paper was used extensively in older devices and offers relatively high voltage performance. However, it is susceptible to water absorption, and has been largely replaced by plastic film capacitors. Plastics 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 supercapacitors 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 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. OS-CON (or OC-CON) capacitors are a polymerized organic semiconductor solid-electrolyte type that offer longer life at higher cost than standard electrolytic capacitors.

Several other types of capacitor are available for specialist applications. Supercapacitors store large amounts of energy. Supercapacitors 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



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.

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***

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  $\mu$ F**). 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  $XY \times 10^Z$  for the numbers XYZ) and the letter indicates the tolerance (J, K or M for  $\pm 5\%$ ,  $\pm 10\%$  and  $\pm 20\%$  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  $47 \times 10^3 \text{ pF} = 47 \text{ nF}$  ( $\pm 10\%$ ) with a working voltage of 330 V.

## Applications

Capacitors have many uses in electronic and electrical systems. They are so common that it is a rare electrical product that does not include at least one for some purpose.

### Energy storage

A capacitor can store electric energy when disconnected from its charging circuit, so it can be used like a temporary battery. 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, while capacitors using developing technologies could provide more than 2.52 kilojoules per kilogram.

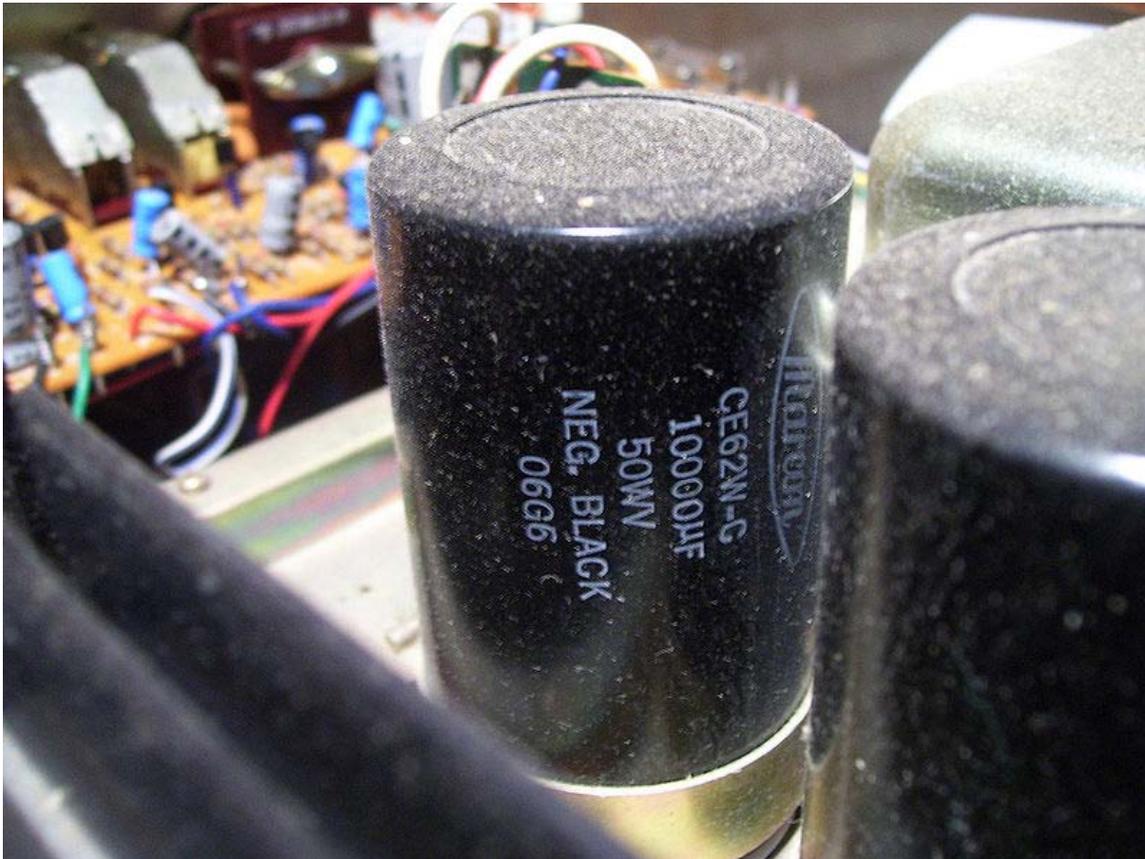
In car audio systems, large capacitors store energy for the amplifier to use on demand. Also for a flash tube a capacitor is used to hold the high voltage.

### 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



A 10,000 microfarad capacitor in a TRM-800 amplifier

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

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.

## **Supression and coupling**

### **Signal coupling**

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.

### **Noise filters and snubbers**

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 still radiate 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.

## 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 winding is used in series with a non-polarized *starting capacitor* to introduce a lag in the sinusoidal current through the starting winding. When the secondary winding is placed at an angle with respect to the primary 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.

There are also capacitor-run induction motors which 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

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 physical and/or electrical 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, e.g. as 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 theremin musical instrument by moving his 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.

## ***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. 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 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 capacitors are found in very old (pre 1975) fluorescent lamp ballasts, and other applications.

High-voltage 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 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.

## Chapter 2

# Transformer



Pole-mounted power distribution transformer with center-tapped secondary winding (note use of grounded conductor, right, as one leg of the primary feeder). It transforms the high voltage of the overhead distribution wires to the lower voltage used in house wiring.

A **transformer** is a static device that transfers electrical energy from one circuit to another through inductively coupled conductors—the transformer's coils. A varying current in the first or *primary* winding creates a varying magnetic flux in the transformer's core and thus a varying magnetic field through the *secondary* winding. This varying magnetic field induces a varying electromotive force (EMF) or "voltage" in the secondary winding. This effect is called mutual induction.

If a load is connected to the secondary, an electric current will flow in the secondary winding and electrical energy will be transferred from the primary circuit through the transformer to the load. In an ideal transformer, the induced voltage in the secondary winding ( $V_s$ ) is in proportion to the primary voltage ( $V_p$ ), and is given by the ratio of the number of turns in the secondary ( $N_s$ ) to the number of turns in the primary ( $N_p$ ) as follows:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

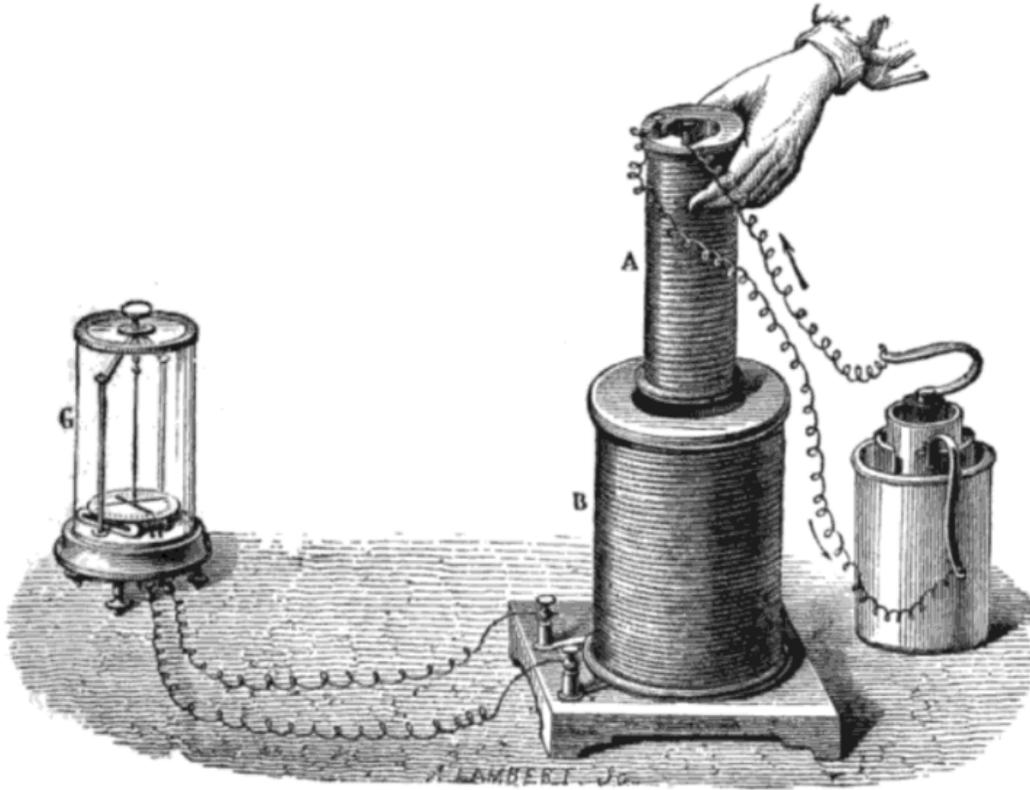
By appropriate selection of the ratio of turns, a transformer thus allows an alternating current (AC) voltage to be "stepped up" by making  $N_s$  greater than  $N_p$ , or "stepped down" by making  $N_s$  less than  $N_p$ .

In the vast majority of transformers, the windings are coils wound around a ferromagnetic core, air-core transformers being a notable exception.

Transformers range in size from a thumbnail-sized coupling transformer hidden inside a stage microphone to huge units weighing hundreds of tons used to interconnect portions of power grids. All operate with the same basic principles, although the range of designs is wide. While new technologies have eliminated the need for transformers in some electronic circuits, transformers are still found in nearly all electronic devices designed for household ("mains") voltage. Transformers are essential for high-voltage electric power transmission, which makes long-distance transmission economically practical.

## History

### Discovery



Faraday's experiment with induction between coils of wire

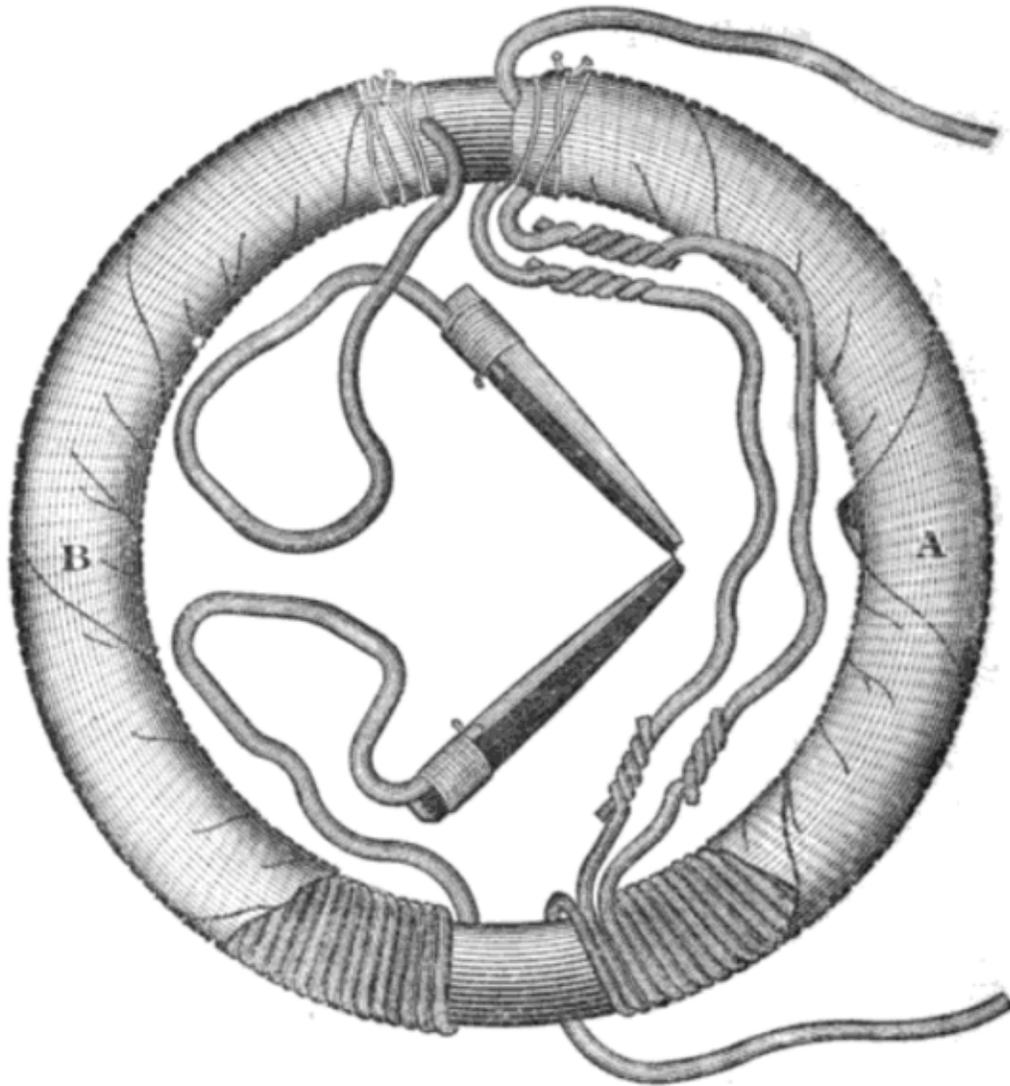
The phenomenon of electromagnetic induction was discovered independently by Michael Faraday and Joseph Henry in 1831. However, Faraday was the first to publish the results of his experiments and thus receive credit for the discovery. The relationship between electromotive force (EMF) or "voltage" and magnetic flux was formalized in an equation now referred to as "Faraday's law of induction":

$$|\mathcal{E}| = \left| \frac{d\Phi_B}{dt} \right|$$

where  $|\mathcal{E}|$  is the magnitude of the EMF in volts and  $\Phi_B$  is the magnetic flux through the circuit (in webers).

Faraday performed the first experiments on induction between coils of wire, including winding a pair of coils around an iron ring, thus creating the first toroidal closed-core transformer.

## Induction coils



Faraday's ring transformer

The first type of transformer to see wide use was the induction coil, invented by Rev. Nicholas Callan of Maynooth College, Ireland in 1836. He was one of the first researchers to realize that the more turns the secondary winding has in relation to the primary winding, the larger is the increase in EMF. Induction coils evolved from scientists' and inventors' efforts to get higher voltages from batteries. Since batteries produce direct current (DC) rather than alternating current (AC), induction coils relied upon vibrating electrical contacts that regularly interrupted the current in the primary to create the flux changes necessary for induction. Between the 1830s and the 1870s, efforts to build better induction coils, mostly by trial and error, slowly revealed the basic principles of transformers.

In 1876, Russian engineer Pavel Yablochkov invented a lighting system based on a set of induction coils where the primary windings were connected to a source of alternating current and the secondary windings could be connected to several "electric candles" (arc lamps) of his own design. The coils Yablochkov employed functioned essentially as transformers.

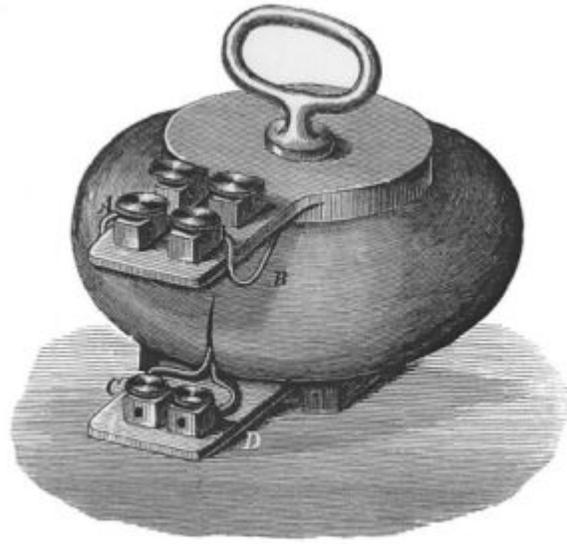
In 1878, the Ganz Company in Hungary began manufacturing equipment for electric lighting and, by 1883, had installed over fifty systems in Austria-Hungary. Their systems used alternating current exclusively and included those comprising both arc and incandescent lamps, along with generators and other equipment.

Lucien Gaulard and John Dixon Gibbs first exhibited a device with an open iron core called a "secondary generator" in London in 1882, then sold the idea to the Westinghouse company in the United States. They also exhibited the invention in Turin, Italy in 1884, where it was adopted for an electric lighting system. However, the efficiency of their open-core bipolar apparatus remained very low.

Induction coils with open magnetic circuits are inefficient for transfer of power to loads. Until about 1880, the paradigm for AC power transmission from a high voltage supply to a low voltage load was a series circuit. Open-core transformers with a ratio near 1:1 were connected with their primaries in series to allow use of a high voltage for transmission while presenting a low voltage to the lamps. The inherent flaw in this method was that turning off a single lamp affected the voltage supplied to all others on the same circuit. Many adjustable transformer designs were introduced to compensate for this problematic characteristic of the series circuit, including those employing methods of adjusting the core or bypassing the magnetic flux around part of a coil.

Efficient, practical transformer designs did not appear until the 1880s, but within a decade the transformer would be instrumental in the "War of Currents", and in seeing AC distribution systems triumph over their DC counterparts, a position in which they have remained dominant ever since.

## Closed-core lighting transformers

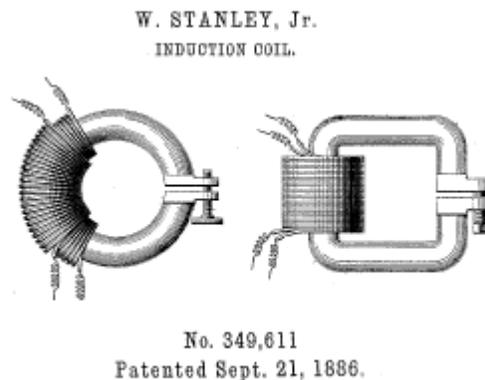


Drawing of Ganz Company's 1885 prototype. Capacity: 1400 VA, frequency: 40 Hz, voltage ratio: 120/72 V



Prototypes of the world's first high-efficiency transformers. They were built by the Z.B.D. team on 16th September 1884.

In the autumn of 1884, Ganz Company engineers Károly Zipernowsky, Ottó Bláthy and Miksa Déri had determined that open-core devices were impracticable, as they were incapable of reliably regulating voltage. In their joint patent application for the "Z.B.D." transformers, they described two designs with closed magnetic circuits: the "closed-core" and "shell-core" transformers. In the closed-core, the primary and secondary windings were wound around a closed iron ring; in the shell-core, the windings were passed *through* the iron core. In both designs, the magnetic flux linking the primary and secondary windings traveled almost entirely within the iron core, with no intentional path through air. The new Z.B.D. transformers reached 98 percent efficiency, which was 3.4 times higher than the open core bipolar devices of Gaulard and Gibbs. When they employed it in parallel connected electric distribution systems, closed-core transformers finally made it technically and economically feasible to provide electric power for lighting in homes, businesses and public spaces. Bláthy had suggested the use of closed-cores, Zipernowsky the use of shunt connections, and Déri had performed the experiments; Bláthy also discovered the transformer formula,  $V_s/V_p = N_s/N_p$ . The vast majority of transformers in use today rely on the basic principles discovered by the three engineers. They also reportedly popularized the word "transformer" to describe a device for altering the EMF of an electric current, although the term had already been in use by 1882. In 1886, the Ganz Company installed the world's first power station that used AC generators to power a parallel-connected common electrical network, the steam-powered Rome-Cerchi power plant.



#### Stanley's 1886 design for adjustable gap open-core induction coils

Although George Westinghouse had bought Gaulard and Gibbs' patents in 1885, the Edison Electric Light Company held an option on the U.S. rights for the Z.B.D. transformers, requiring Westinghouse to pursue alternative designs on the same principles. He assigned to William Stanley the task of developing a device for commercial use in United States. Stanley's first patented design was for induction coils with single cores of soft iron and adjustable gaps to regulate the EMF present in the secondary winding. This design was first used commercially in the U.S. in 1886. But Westinghouse soon had his team working on a design whose core comprised a stack of thin "E-shaped" iron plates, separated individually or in pairs by thin sheets of paper or other insulating material. Prewound copper coils could then be slid into place, and

straight iron plates laid in to create a closed magnetic circuit. Westinghouse applied for a patent for the new design in December 1886; it was granted in July 1887.

## Other early transformers

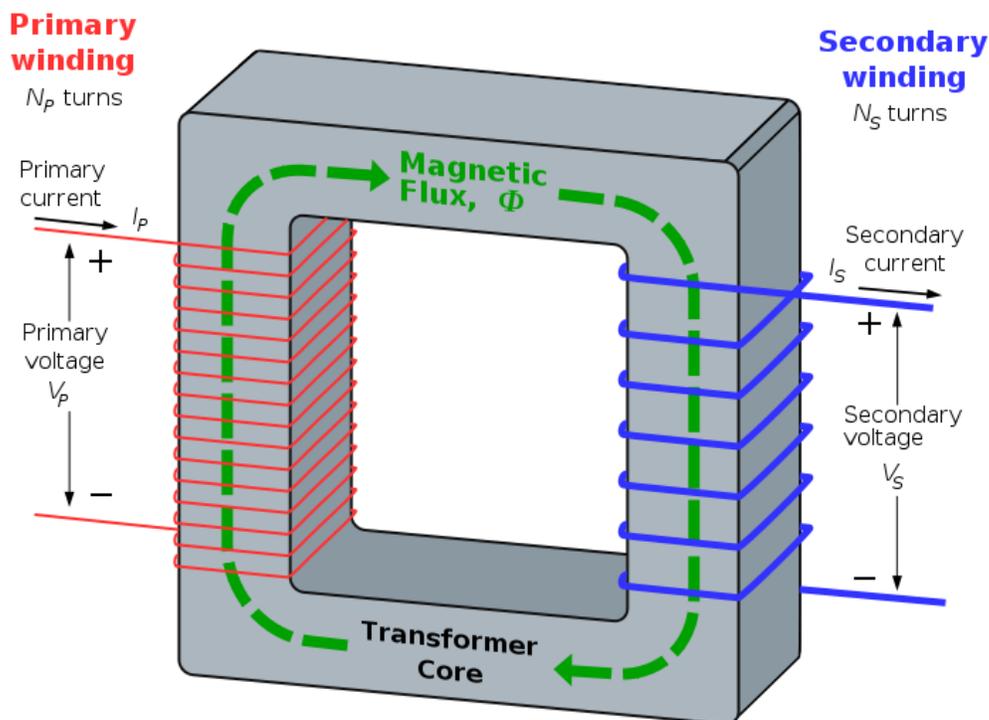
In 1889, Russian-born engineer Mikhail Dolivo-Dobrovolsky developed the first three-phase transformer at the Allgemeine Elektrizitäts-Gesellschaft ("General Electricity Company") in Germany.

In 1891, Nikola Tesla invented the Tesla coil, an air-cored, dual-tuned resonant transformer for generating very high voltages at high frequency.

Audio frequency transformers ("repeating coils") were used by early experimenters in the development of the telephone.

## Basic principles

The transformer is based on two principles: first, that an electric current can produce a magnetic field (electromagnetism), and, second that a changing magnetic field within a coil of wire induces a voltage across the ends of the coil (electromagnetic induction). Changing the current in the primary coil changes the magnetic flux that is developed. The changing magnetic flux induces a voltage in the secondary coil.



An ideal transformer

An ideal transformer is shown in the adjacent figure. Current passing through the primary coil creates a magnetic field. The primary and secondary coils are wrapped around a core of very high magnetic permeability, such as iron, so that most of the magnetic flux passes through both the primary and secondary coils.

## Induction law

The voltage induced across the secondary coil may be calculated from Faraday's law of induction, which states that:

$$V_s = N_s \frac{d\Phi}{dt},$$

where  $V_s$  is the instantaneous voltage,  $N_s$  is the number of turns in the secondary coil and  $\Phi$  is the magnetic flux through one turn of the coil. If the turns of the coil are oriented perpendicular to the magnetic field lines, the flux is the product of the magnetic flux density  $B$  and the area  $A$  through which it cuts. The area is constant, being equal to the cross-sectional area of the transformer core, whereas the magnetic field varies with time according to the excitation of the primary. Since the same magnetic flux passes through both the primary and secondary coils in an ideal transformer, the instantaneous voltage across the primary winding equals

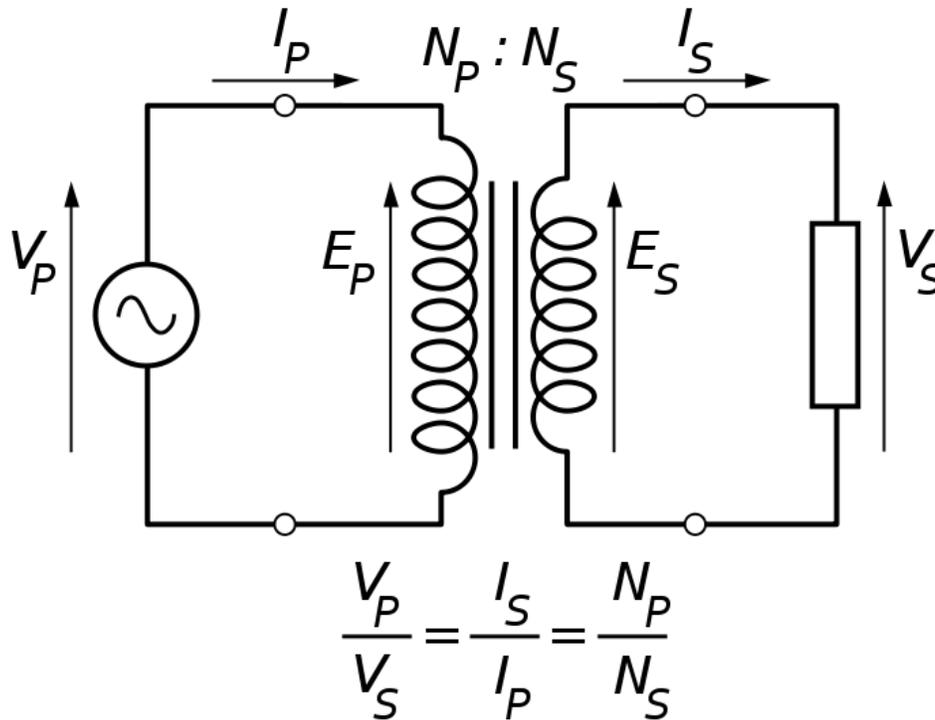
$$V_p = N_p \frac{d\Phi}{dt}.$$

Taking the ratio of the two equations for  $V_s$  and  $V_p$  gives the basic equation for stepping up or stepping down the voltage

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}.$$

$N_p/N_s$  is known as the *turns ratio*, and is the primary functional characteristic of any transformer. In the case of step-up transformers, this may sometimes be stated as the reciprocal,  $N_s/N_p$ . *Turns ratio* is commonly expressed as an irreducible fraction or ratio: for example, a transformer with primary and secondary windings of, respectively, 100 and 150 turns is said to have a turns ratio of 2:3 rather than 0.667 or 100:150.

## Ideal power equation



The ideal transformer as a circuit element

If the secondary coil is attached to a load that allows current to flow, electrical power is transmitted from the primary circuit to the secondary circuit. Ideally, the transformer is perfectly efficient; all the incoming energy is transformed from the primary circuit to the magnetic field and into the secondary circuit. If this condition is met, the incoming electric power must equal the outgoing power:

$$P_{\text{incoming}} = I_P V_P = P_{\text{outgoing}} = I_S V_S,$$

giving the ideal transformer equation

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} = \frac{I_P}{I_S}.$$

Transformers normally have high efficiency, so this formula is a reasonable approximation.

If the voltage is increased, then the current is decreased by the same factor. The impedance in one circuit is transformed by the *square* of the turns ratio. For example, if an impedance  $Z_s$  is attached across the terminals of the secondary coil, it appears to the

primary circuit to have an impedance of  $(N_p/N_s)^2 Z_s$ . This relationship is reciprocal, so that the impedance  $Z_p$  of the primary circuit appears to the secondary to be  $(N_s/N_p)^2 Z_p$ .

### **Detailed operation**

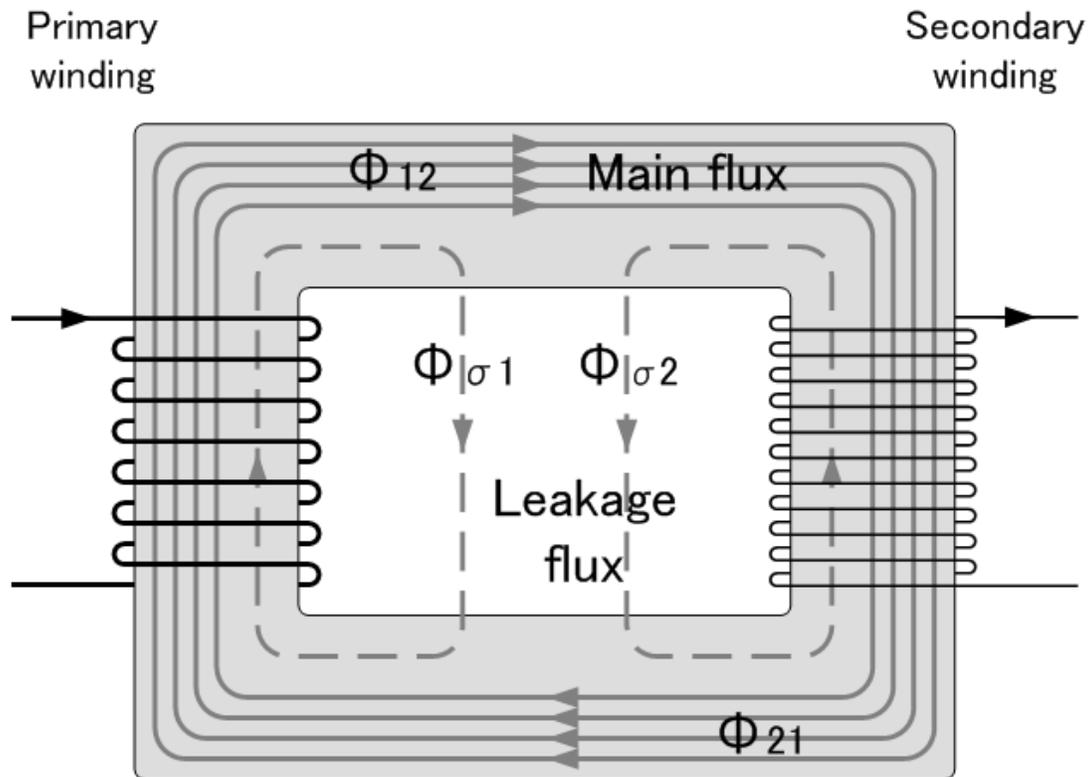
The simplified description above neglects several practical factors, in particular the primary current required to establish a magnetic field in the core, and the contribution to the field due to current in the secondary circuit.

Models of an ideal transformer typically assume a core of negligible reluctance with two windings of zero resistance. When a voltage is applied to the primary winding, a small current flows, driving flux around the magnetic circuit of the core. The current required to create the flux is termed the *magnetizing current*; since the ideal core has been assumed to have near-zero reluctance, the magnetizing current is negligible, although still required to create the magnetic field.

The changing magnetic field induces an electromotive force (EMF) across each winding. Since the ideal windings have no impedance, they have no associated voltage drop, and so the voltages  $V_p$  and  $V_s$  measured at the terminals of the transformer, are equal to the corresponding EMFs. The primary EMF, acting as it does in opposition to the primary voltage, is sometimes termed the "back EMF". This is due to Lenz's law which states that the induction of EMF would always be such that it will oppose development of any such change in magnetic field.

## Practical considerations

### Leakage flux



Leakage flux of a transformer

The ideal transformer model assumes that all flux generated by the primary winding links all the turns of every winding, including itself. In practice, some flux traverses paths that take it outside the windings. Such flux is termed *leakage flux*, and results in leakage inductance in series with the mutually coupled transformer windings. Leakage results in energy being alternately stored in and discharged from the magnetic fields with each cycle of the power supply. It is not directly a power loss, but results in inferior voltage regulation, causing the secondary voltage to fail to be directly proportional to the primary, particularly under heavy load. Transformers are therefore normally designed to have very low leakage inductance.

However, in some applications, leakage can be a desirable property, and long magnetic paths, air gaps, or magnetic bypass shunts may be deliberately introduced to a transformer's design to limit the short-circuit current it will supply. Leaky transformers may be used to supply loads that exhibit negative resistance, such as electric arcs, mercury vapor lamps, and neon signs; or for safely handling loads that become periodically short-circuited such as electric arc welders.

Air gaps are also used to keep a transformer from saturating, especially audio-frequency transformers in circuits that have a direct current flowing through the windings.

Leakage inductance is also helpful when transformers are operated in parallel. It can be shown that if the "per-unit" inductance of two transformers is the same (a typical value is 5%), they will automatically split power "correctly" (e.g. 500 kVA unit in parallel with 1,000 kVA unit, the larger one will carry twice the current).

## Effect of frequency

### Transformer universal EMF equation

If the flux in the core is purely sinusoidal, the relationship for either winding between its **rms voltage**  $E_{rms}$  of the winding, and the supply frequency  $f$ , number of turns  $N$ , core cross-sectional area  $a$  and peak magnetic flux density  $B$  is given by the universal EMF equation:

$$E_{rms} = \frac{2\pi f N a B_{peak}}{\sqrt{2}} \approx 4.44 f N a B$$

If the flux does not contain even harmonics the following equation can be used for **half-cycle average voltage**  $E_{avg}$  of any waveshape:

$$E_{avg} = 4 f N a B_{peak}$$

The time-derivative term in Faraday's Law shows that the flux in the core is the integral with respect to time of the applied voltage. Hypothetically an ideal transformer would work with direct-current excitation, with the core flux increasing linearly with time. In practice, the flux would rise to the point where magnetic saturation of the core occurs, causing a huge increase in the magnetizing current and overheating the transformer. All practical transformers must therefore operate with alternating (or pulsed) current.

The EMF of a transformer at a given flux density increases with frequency. By operating at higher frequencies, transformers can be physically more compact because a given core is able to transfer more power without reaching saturation and fewer turns are needed to achieve the same impedance. However, properties such as core loss and conductor skin effect also increase with frequency. Aircraft and military equipment employ 400 Hz power supplies which reduce core and winding weight. Conversely, frequencies used for some railway electrification systems were much lower (e.g. 16.7 Hz and 25 Hz) than normal utility frequencies (50 – 60 Hz) for historical reasons concerned mainly with the limitations of early electric traction motors. As such, the transformers used to step down the high over-head line voltages (e.g. 15 kV) are much heavier for the same power rating than those designed only for the higher frequencies.

Operation of a transformer at its designed voltage but at a higher frequency than intended will lead to reduced magnetizing current; at lower frequency, the magnetizing current

will increase. Operation of a transformer at other than its design frequency may require assessment of voltages, losses, and cooling to establish if safe operation is practical. For example, transformers may need to be equipped with "volts per hertz" over-excitation relays to protect the transformer from overvoltage at higher than rated frequency.

One example of state-of-the-art design is those transformers used for electric multiple unit high speed trains, particularly those required to operate across the borders of countries using different standards of electrification. The position of such transformers is restricted to being hung below the passenger compartment. They have to function at different frequencies (down to 16.7 Hz) and voltages (up to 25 kV) whilst handling the enhanced power requirements needed for operating the trains at high speed.

Knowledge of natural frequencies of transformer windings is of importance for the determination of the transient response of the windings to impulse and switching surge voltages.

## **Energy losses**

An ideal transformer would have no energy losses, and would be 100% efficient. In practical transformers energy is dissipated in the windings, core, and surrounding structures. Larger transformers are generally more efficient, and those rated for electricity distribution usually perform better than 98%.

Experimental transformers using superconducting windings achieve efficiencies of 99.85%. The increase in efficiency can save considerable energy, and hence money, in a large heavily-loaded transformer; the trade-off is in the additional initial and running cost of the superconducting design.

Losses in transformers (excluding associated circuitry) vary with load current, and may be expressed as "no-load" or "full-load" loss. Winding resistance dominates load losses, whereas hysteresis and eddy currents losses contribute to over 99% of the no-load loss. The no-load loss can be significant, so that even an idle transformer constitutes a drain on the electrical supply and a running cost; designing transformers for lower loss requires a larger core, good-quality silicon steel, or even amorphous steel, for the core, and thicker wire, increasing initial cost, so that there is a trade-off between initial cost and running cost.

Transformer losses are divided into losses in the windings, termed copper loss, and those in the magnetic circuit, termed iron loss. Losses in the transformer arise from:

### **Winding resistance**

Current flowing through the windings causes resistive heating of the conductors. At higher frequencies, skin effect and proximity effect create additional winding resistance and losses.

### **Hysteresis losses**

Each time the magnetic field is reversed, a small amount of energy is lost due to hysteresis within the core. For a given core material, the loss is proportional to the frequency, and is a function of the peak flux density to which it is subjected.

### **Eddy currents**

Ferromagnetic materials are also good conductors, and a core made from such a material also constitutes a single short-circuited turn throughout its entire length. Eddy currents therefore circulate within the core in a plane normal to the flux, and are responsible for resistive heating of the core material. The eddy current loss is a complex function of the square of supply frequency and inverse square of the material thickness. Eddy current losses can be reduced by making the core of a stack of plates electrically insulated from each other, rather than a solid block; all transformers operating at low frequencies use laminated or similar cores.

### **Magnetostriction**

Magnetic flux in a ferromagnetic material, such as the core, causes it to physically expand and contract slightly with each cycle of the magnetic field, an effect known as magnetostriction. This produces the buzzing sound commonly associated with transformers, and can cause losses due to frictional heating.

### **Mechanical losses**

In addition to magnetostriction, the alternating magnetic field causes fluctuating forces between the primary and secondary windings. These incite vibrations within nearby metalwork, adding to the buzzing noise, and consuming a small amount of power.

### **Stray losses**

Leakage inductance is by itself largely lossless, since energy supplied to its magnetic fields is returned to the supply with the next half-cycle. However, any leakage flux that intercepts nearby conductive materials such as the transformer's support structure will give rise to eddy currents and be converted to heat. There are also radiative losses due to the oscillating magnetic field, but these are usually small.

### **Dot convention**

It is common in transformer schematic symbols for there to be a dot at the end of each coil within a transformer, particularly for transformers with multiple primary and secondary windings. The dots indicate the direction of each winding relative to the others. Voltages at the dot end of each winding are in phase; current flowing into the dot end of a primary coil will result in current flowing out of the dot end of a secondary coil.

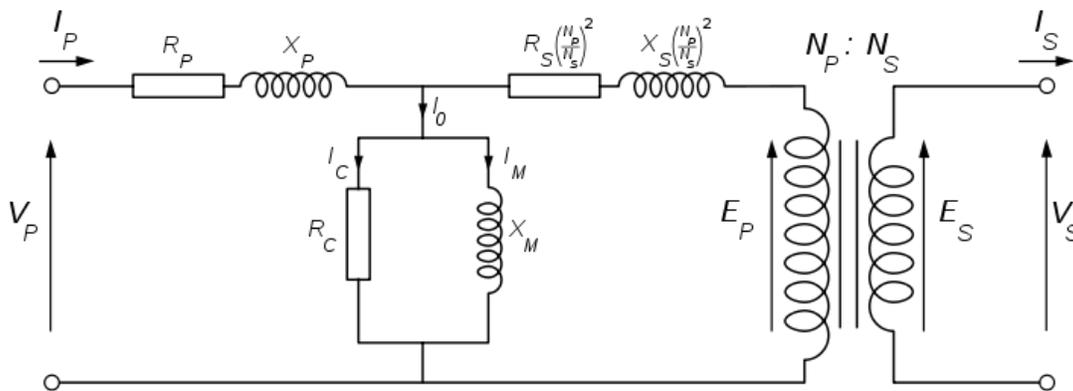
### ***Equivalent circuit***

The physical limitations of the practical transformer may be brought together as an equivalent circuit model (shown below) built around an ideal lossless transformer. Power loss in the windings is current-dependent and is represented as in-series resistances  $R_p$  and  $R_s$ . Flux leakage results in a fraction of the applied voltage dropped without contributing to the mutual coupling, and thus can be modeled as reactances of each leakage inductance  $X_p$  and  $X_s$  in series with the perfectly coupled region.

Iron losses are caused mostly by hysteresis and eddy current effects in the core, and are proportional to the square of the core flux for operation at a given frequency. Since the core flux is proportional to the applied voltage, the iron loss can be represented by a resistance  $R_C$  in parallel with the ideal transformer.

A core with finite permeability requires a magnetizing current  $I_m$  to maintain the mutual flux in the core. The magnetizing current is in phase with the flux; saturation effects cause the relationship between the two to be non-linear, but for simplicity this effect tends to be ignored in most circuit equivalents. With a sinusoidal supply, the core flux lags the induced EMF by  $90^\circ$  and this effect can be modeled as a magnetizing reactance (reactance of an effective inductance)  $X_m$  in parallel with the core loss component.  $R_C$  and  $X_m$  are sometimes together termed the *magnetizing branch* of the model. If the secondary winding is made open-circuit, the current  $I_0$  taken by the magnetizing branch represents the transformer's no-load current.

The secondary impedance  $R_s$  and  $X_s$  is frequently moved (or "referred") to the primary side after multiplying the components by the impedance scaling factor  $(N_p/N_s)^2$ .



Transformer equivalent circuit, with secondary impedances referred to the primary side

The resulting model is sometimes termed the "exact equivalent circuit", though it retains a number of approximations, such as an assumption of linearity. Analysis may be simplified by moving the magnetizing branch to the left of the primary impedance, an implicit assumption that the magnetizing current is low, and then summing primary and referred secondary impedances, resulting in so-called equivalent impedance.

The parameters of equivalent circuit of a transformer can be calculated from the results of two transformer tests: open-circuit test and short-circuit test.

## Types

A wide variety of transformer designs are used for different applications, though they share several common features. Important common transformer types include:

## Autotransformer



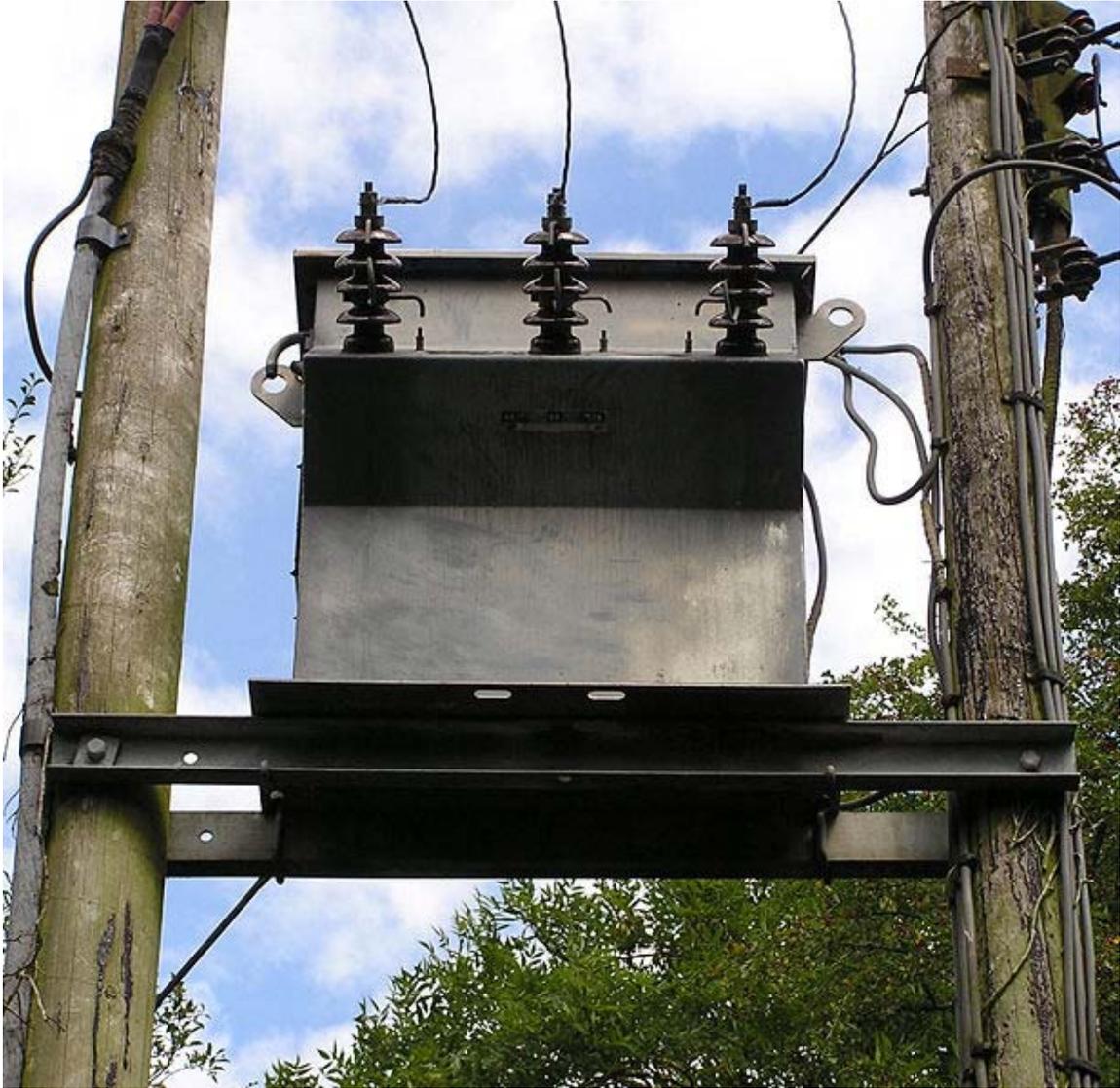
A variable autotransformer

In an autotransformer portions of the same winding act as both the primary and secondary. The winding has at least three taps where electrical connections are made. An autotransformer can be smaller, lighter and cheaper than a standard dual-winding transformer however the autotransformer does not provide electrical isolation.

Autotransformers are often used to step up or down between voltages in the 110-117-120 volt range and voltages in the 220-230-240 volt range, e.g., to output either 110 or 120V (with taps) from 230V input, allowing equipment from a 100 or 120V region to be used in a 230V region.

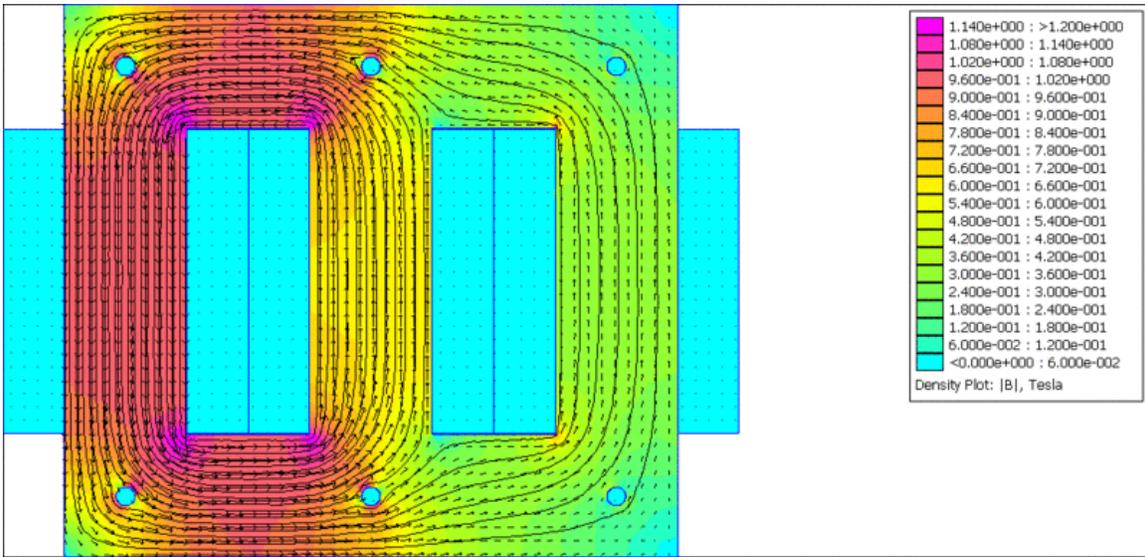
A variable autotransformer is made by exposing part of the winding coils and making the secondary connection through a sliding brush, giving a variable turns ratio. Such a device is often referred to by the trademark name *variac*.

## Polyphase transformers



Three-phase step-down transformer mounted between two utility poles

For three-phase supplies, a bank of three individual single-phase transformers can be used, or all three phases can be incorporated as a single three-phase transformer. In this case, the magnetic circuits are connected together, the core thus containing a three-phase flow of flux. A number of winding configurations are possible, giving rise to different attributes and phase shifts. One particular polyphase configuration is the zigzag transformer, used for grounding and in the suppression of harmonic currents.



Screenshot of a FEM simulation of the magnetic flux inside a three-phase power transformer.

## Leakage transformers



Leakage transformer

A leakage transformer, also called a stray-field transformer, has a significantly higher leakage inductance than other transformers, sometimes increased by a magnetic bypass or shunt in its core between primary and secondary, which is sometimes adjustable with a set screw. This provides a transformer with an inherent current limitation due to the loose coupling between its primary and the secondary windings. The output and input currents are low enough to prevent thermal overload under all load conditions—even if the secondary is shorted.

Leakage transformers are used for arc welding and high voltage discharge lamps (neon lights and cold cathode fluorescent lamps, which are series-connected up to 7.5 kV AC). It acts then both as a voltage transformer and as a magnetic ballast.

Other applications are short-circuit-proof extra-low voltage transformers for toys or doorbell installations.

## **Resonant transformers**

A resonant transformer is a kind of leakage transformer. It uses the leakage inductance of its secondary windings in combination with external capacitors, to create one or more resonant circuits. Resonant transformers such as the Tesla coil can generate very high voltages, and are able to provide much higher current than electrostatic high-voltage generation machines such as the Van de Graaff generator. One of the applications of the resonant transformer is for the CCFL inverter. Another application of the resonant transformer is to couple between stages of a superheterodyne receiver, where the selectivity of the receiver is provided by tuned transformers in the intermediate-frequency amplifiers.

## **Audio transformers**

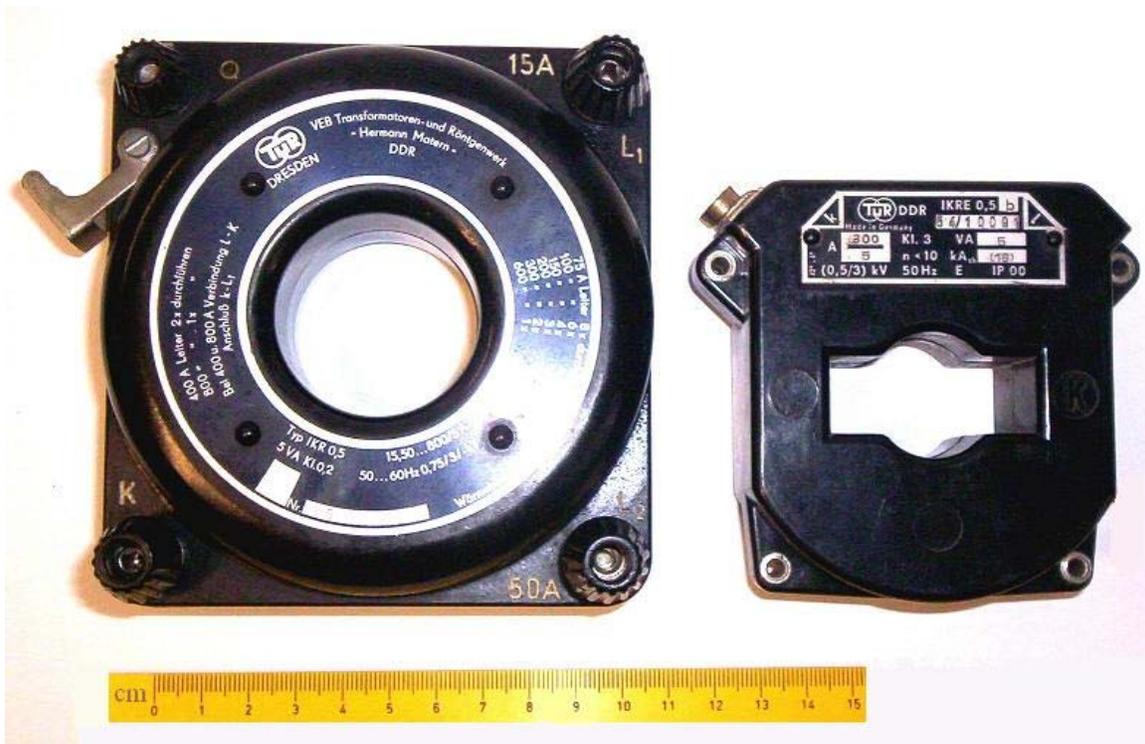
Audio transformers are those specifically designed for use in audio circuits. They can be used to block radio frequency interference or the DC component of an audio signal, to split or combine audio signals, or to provide impedance matching between high and low impedance circuits, such as between a high impedance tube (valve) amplifier output and a low impedance loudspeaker, or between a high impedance instrument output and the low impedance input of a mixing console.

Such transformers were originally designed to connect different telephone systems to one another while keeping their respective power supplies isolated, and are still commonly used to interconnect professional audio systems or system components.

Being magnetic devices, audio transformers are susceptible to external magnetic fields such as those generated by AC current-carrying conductors. "Hum" is a term commonly used to describe unwanted signals originating from the "mains" power supply (typically 50 or 60 Hz). Audio transformers used for low-level signals, such as those from microphones, often include shielding to protect against extraneous magnetically coupled signals.

## **Instrument transformers**

Instrument transformers are used for measuring voltage and current in electrical power systems, and for power system protection and control. Where a voltage or current is too large to be conveniently used by an instrument, it can be scaled down to a standardized, low value. Instrument transformers isolate measurement, protection and control circuitry from the high currents or voltages present on the circuits being measured or controlled.



Current transformers, designed for placing around conductors

A current transformer is a transformer designed to provide a current in its secondary coil proportional to the current flowing in its primary coil.

Voltage transformers (VTs), also referred to as "potential transformers" (PTs), are designed to have an accurately known transformation ratio in both magnitude and phase, over a range of measuring circuit impedances. A voltage transformer is intended to present a negligible load to the supply being measured. The low secondary voltage allows protective relay equipment and measuring instruments to be operated at a lower voltages.

Both current and voltage instrument transformers are designed to have predictable characteristics on overloads. Proper operation of over-current protective relays requires that current transformers provide a predictable transformation ratio even during a short-circuit.

## **Classification**

Transformers can be classified in many different ways; an incomplete list is:

- *By power capacity*: from a fraction of a volt-ampere (VA) to over a thousand MVA;
- *By frequency range*: power-, audio-, or radio frequency;
- *By voltage class*: from a few volts to hundreds of kilovolts;
- *By cooling type*: air-cooled, oil-filled, fan-cooled, or water-cooled;

- *By application:* such as power supply, impedance matching, output voltage and current stabilizer, or circuit isolation;
- *By purpose:* distribution, rectifier, arc furnace, amplifier output, etc.;
- *By winding turns ratio:* step-up, step-down, isolating with equal or near-equal ratio, variable, multiple windings.

## **Construction**

### **Cores**

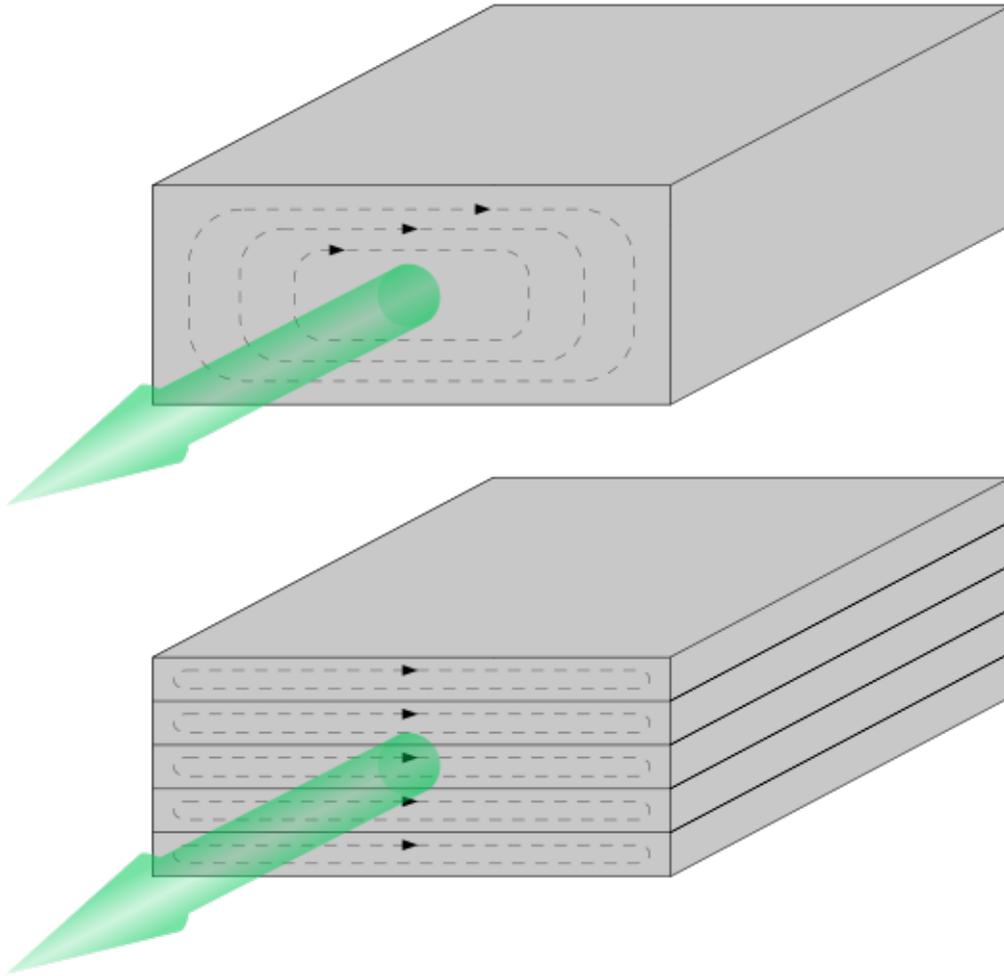


Laminated core transformer showing edge of laminations at top of photo

### **Laminated steel cores**

Transformers for use at power or audio frequencies typically have cores made of high permeability silicon steel. The steel has a permeability many times that of free space, and the core thus serves to greatly reduce the magnetizing current, and confine the flux to a path which closely couples the windings. Early transformer developers soon realized that cores constructed from solid iron resulted in prohibitive eddy-current losses, and their designs mitigated this effect with cores consisting of bundles of insulated iron wires. Later designs constructed the core by stacking layers of thin steel laminations, a principle that has remained in use. Each lamination is insulated from its neighbors by a thin non-conducting layer of insulation. The universal transformer equation indicates a minimum cross-sectional area for the core to avoid saturation.

The effect of laminations is to confine eddy currents to highly elliptical paths that enclose little flux, and so reduce their magnitude. Thinner laminations reduce losses, but are more laborious and expensive to construct. Thin laminations are generally used on high frequency transformers, with some types of very thin steel laminations able to operate up to 10 kHz.



Laminating the core greatly reduces eddy-current losses

One common design of laminated core is made from interleaved stacks of E-shaped steel sheets capped with I-shaped pieces, leading to its name of "E-I transformer". Such a design tends to exhibit more losses, but is very economical to manufacture. The cut-core or C-core type is made by winding a steel strip around a rectangular form and then bonding the layers together. It is then cut in two, forming two C shapes, and the core assembled by binding the two C halves together with a steel strap. They have the advantage that the flux is always oriented parallel to the metal grains, reducing reluctance.

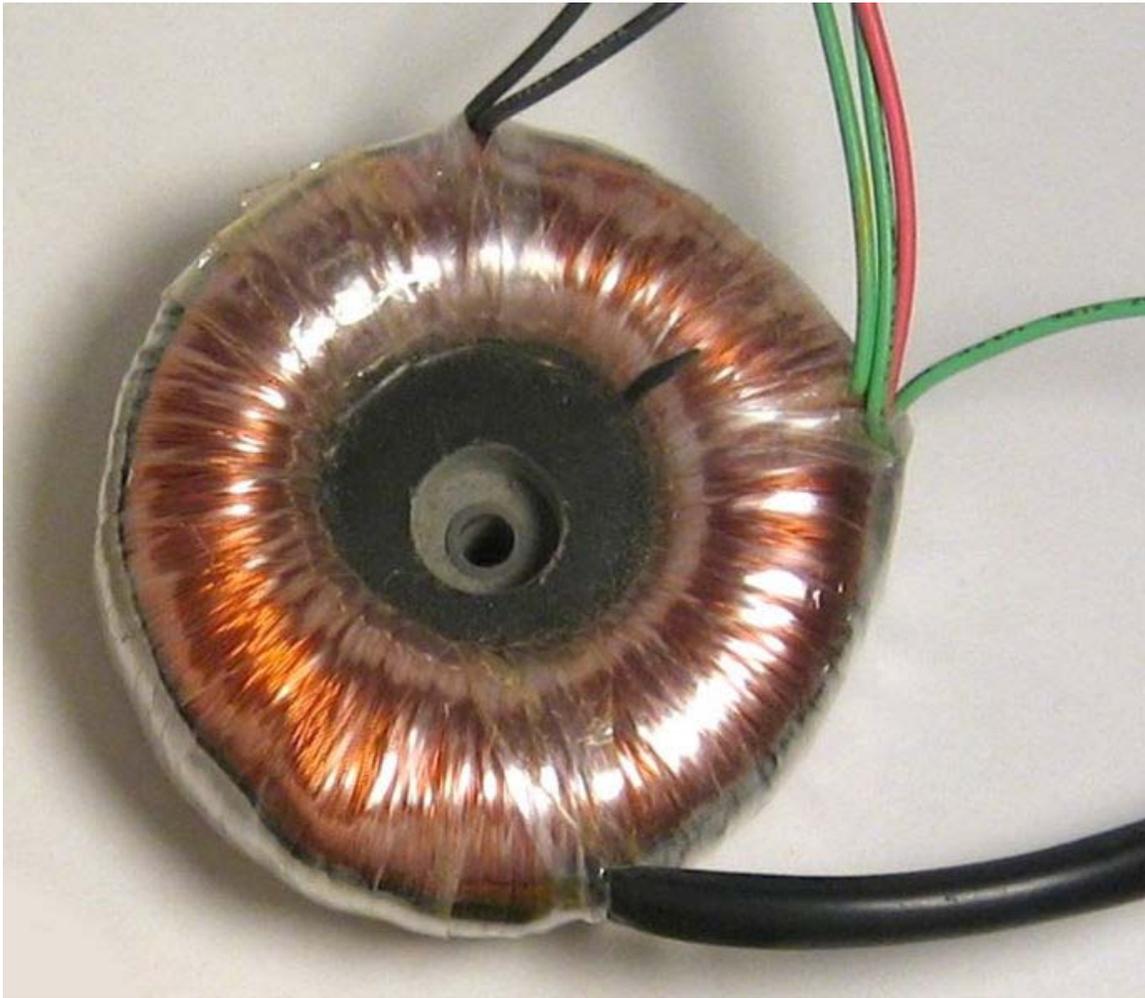
A steel core's remanence means that it retains a static magnetic field when power is removed. When power is then reapplied, the residual field will cause a high inrush current until the effect of the remaining magnetism is reduced, usually after a few cycles of the applied alternating current. Overcurrent protection devices such as fuses must be selected to allow this harmless inrush to pass. On transformers connected to long, overhead power transmission lines, induced currents due to geomagnetic disturbances during solar storms can cause saturation of the core and operation of transformer protection devices.

Distribution transformers can achieve low no-load losses by using cores made with low-loss high-permeability silicon steel or amorphous (non-crystalline) metal alloy. The higher initial cost of the core material is offset over the life of the transformer by its lower losses at light load.

### **Solid cores**

Powdered iron cores are used in circuits (such as switch-mode power supplies) that operate above main frequencies and up to a few tens of kilohertz. These materials combine high magnetic permeability with high bulk electrical resistivity. For frequencies extending beyond the VHF band, cores made from non-conductive magnetic ceramic materials called ferrites are common. Some radio-frequency transformers also have movable cores (sometimes called 'slugs') which allow adjustment of the coupling coefficient (and bandwidth) of tuned radio-frequency circuits.

## Toroidal cores



Small toroidal core transformer

Toroidal transformers are built around a ring-shaped core, which, depending on operating frequency, is made from a long strip of silicon steel or permalloy wound into a coil, powdered iron, or ferrite. A strip construction ensures that the grain boundaries are optimally aligned, improving the transformer's efficiency by reducing the core's reluctance. The closed ring shape eliminates air gaps inherent in the construction of an E-I core. The cross-section of the ring is usually square or rectangular, but more expensive cores with circular cross-sections are also available. The primary and secondary coils are often wound concentrically to cover the entire surface of the core. This minimizes the length of wire needed, and also provides screening to minimize the core's magnetic field from generating electromagnetic interference.

Toroidal transformers are more efficient than the cheaper laminated E-I types for a similar power level. Other advantages compared to E-I types, include smaller size (about half), lower weight (about half), less mechanical hum (making them superior in audio

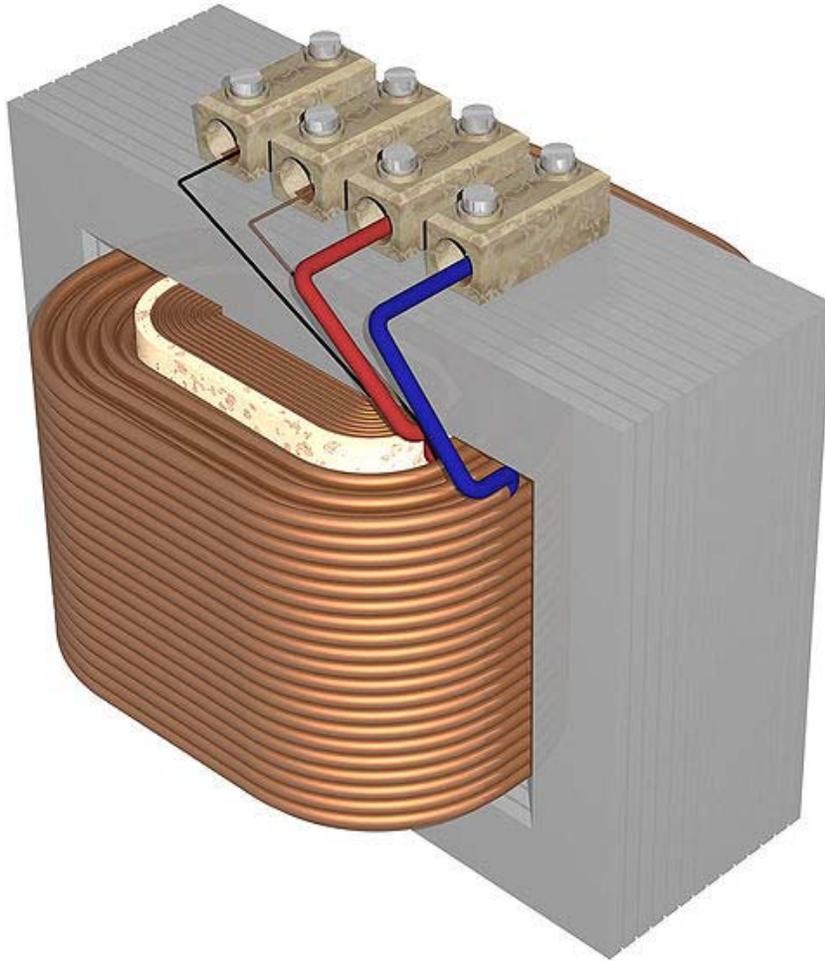
amplifiers), lower exterior magnetic field (about one tenth), low off-load losses (making them more efficient in standby circuits), single-bolt mounting, and greater choice of shapes. The main disadvantages are higher cost and limited power capacity. Because of the lack of a residual gap in the magnetic path, toroidal transformers also tend to exhibit higher inrush current, compared to laminated E-I types.

Ferrite toroidal cores are used at higher frequencies, typically between a few tens of kilohertz to hundreds of megahertz, to reduce losses, physical size, and weight of switch-mode power supplies. A drawback of toroidal transformer construction is the higher labor cost of winding. This is because it is necessary to pass the entire length of a coil winding through the core aperture each time a single turn is added to the coil. As a consequence, toroidal transformers are uncommon above ratings of a few kVA. Small distribution transformers may achieve some of the benefits of a toroidal core by splitting it and forcing it open, then inserting a bobbin containing primary and secondary windings.

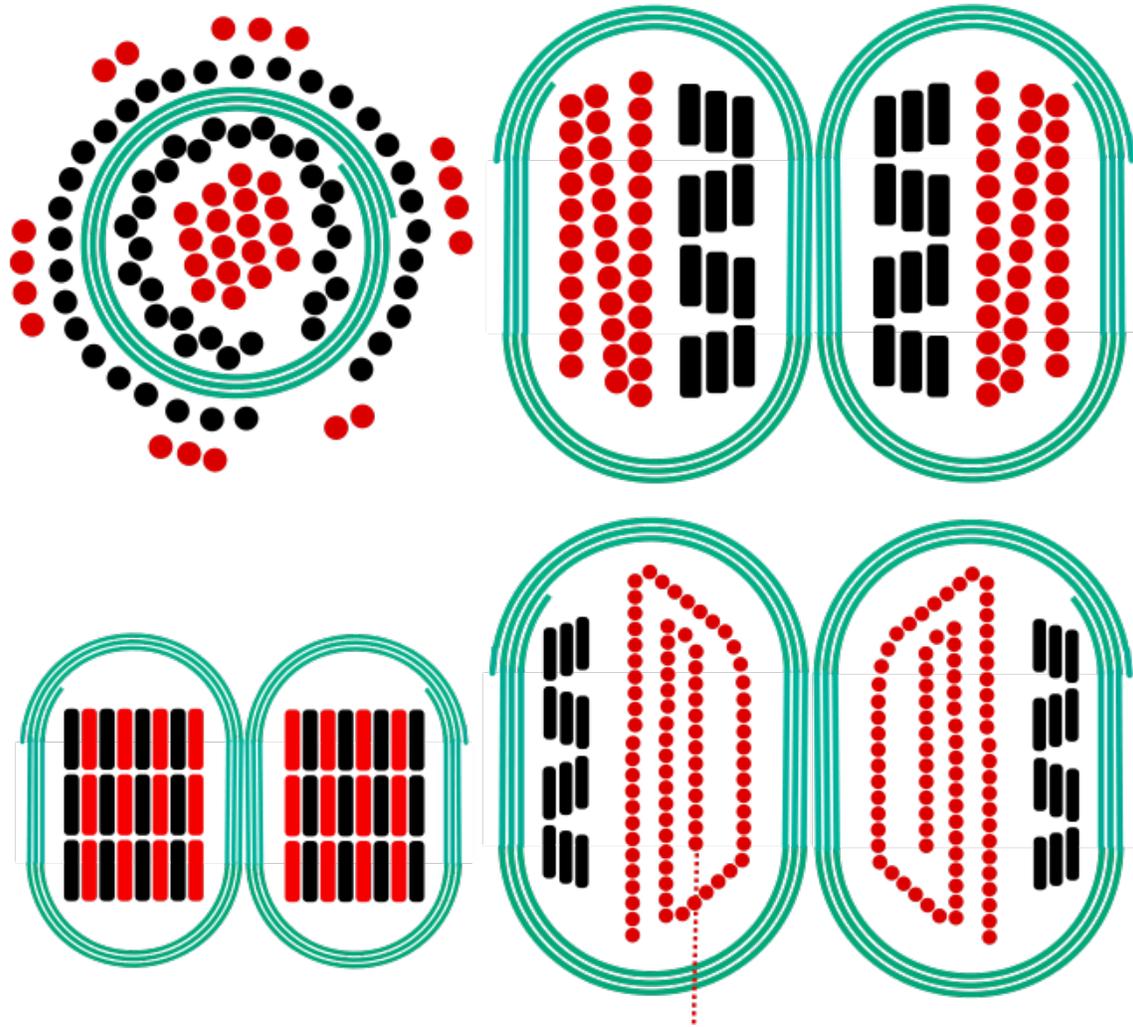
### **Air cores**

A physical core is not an absolute requisite and a functioning transformer can be produced simply by placing the windings near each other, an arrangement termed an "air-core" transformer. The air which comprises the magnetic circuit is essentially lossless, and so an air-core transformer eliminates loss due to hysteresis in the core material. The leakage inductance is inevitably high, resulting in very poor regulation, and so such designs are unsuitable for use in power distribution. They have however very high bandwidth, and are frequently employed in radio-frequency applications, for which a satisfactory coupling coefficient is maintained by carefully overlapping the primary and secondary windings. They're also used for resonant transformers such as Tesla coils where they can achieve reasonably low loss in spite of the high leakage inductance.

## Windings



Windings are usually arranged concentrically to minimize flux leakage.



Cut view through transformer windings. White: insulator. Green spiral: Grain oriented silicon steel. Black: Primary winding made of oxygen-free copper. Red: Secondary winding. Top left: Toroidal transformer. Right: C-core, but E-core would be similar. The black windings are made of film. Top: Equally low capacitance between all ends of both windings. Since most cores are at least moderately conductive they also need insulation. Bottom: Lowest capacitance for one end of the secondary winding needed for low-power high-voltage transformers. Bottom left: Reduction of leakage inductance would lead to increase of capacitance.

The conducting material used for the windings depends upon the application, but in all cases the individual turns must be electrically insulated from each other to ensure that the current travels throughout every turn. For small power and signal transformers, in which currents are low and the potential difference between adjacent turns is small, the coils are often wound from enamelled magnet wire, such as Formvar wire. Larger power transformers operating at high voltages may be wound with copper rectangular strip conductors insulated by oil-impregnated paper and blocks of pressboard.

High-frequency transformers operating in the tens to hundreds of kilohertz often have windings made of braided Litz wire to minimize the skin-effect and proximity effect losses. Large power transformers use multiple-stranded conductors as well, since even at low power frequencies non-uniform distribution of current would otherwise exist in high-current windings. Each strand is individually insulated, and the strands are arranged so that at certain points in the winding, or throughout the whole winding, each portion occupies different relative positions in the complete conductor. The transposition equalizes the current flowing in each strand of the conductor, and reduces eddy current losses in the winding itself. The stranded conductor is also more flexible than a solid conductor of similar size, aiding manufacture.

For signal transformers, the windings may be arranged in a way to minimize leakage inductance and stray capacitance to improve high-frequency response. This can be done by splitting up each coil into sections, and those sections placed in layers between the sections of the other winding. This is known as a stacked type or interleaved winding.

Both the primary and secondary windings on power transformers may have external connections, called taps, to intermediate points on the winding to allow selection of the voltage ratio. In distribution transformers the taps may be connected to an automatic on-load tap changer for voltage regulation of distribution circuits. Audio-frequency transformers, used for the distribution of audio to public address loudspeakers, have taps to allow adjustment of impedance to each speaker. A center-tapped transformer is often used in the output stage of an audio power amplifier in a push-pull circuit. Modulation transformers in AM transmitters are very similar.

Certain transformers have the windings protected by epoxy resin. By impregnating the transformer with epoxy under a vacuum, one can replace air spaces within the windings with epoxy, thus sealing the windings and helping to prevent the possible formation of corona and absorption of dirt or water. This produces transformers more suited to damp or dirty environments, but at increased manufacturing cost.

## Coolant



Cut-away view of three-phase oil-cooled transformer. The oil reservoir is visible at the top. Radiative fins aid the dissipation of heat.

High temperatures will damage the winding insulation. Small transformers do not generate significant heat and are cooled by air circulation and radiation of heat. Power transformers rated up to several hundred kVA can be adequately cooled by natural convective air-cooling, sometimes assisted by fans. In larger transformers, part of the design problem is removal of heat. Some power transformers are immersed in transformer oil that both cools and insulates the windings. The oil is a highly refined mineral oil that remains stable at transformer operating temperature. Indoor liquid-filled transformers are required by building regulations in many jurisdictions to use a non-flammable liquid, or to be located in fire-resistant rooms. Air-cooled dry transformers are

preferred for indoor applications even at capacity ratings where oil-cooled construction would be more economical, because their cost is offset by the reduced building construction cost.

The oil-filled tank often has radiators through which the oil circulates by natural convection; some large transformers employ forced circulation of the oil by electric pumps, aided by external fans or water-cooled heat exchangers. Oil-filled transformers undergo prolonged drying processes to ensure that the transformer is completely free of water vapor before the cooling oil is introduced. This helps prevent electrical breakdown under load. Oil-filled transformers may be equipped with Buchholz relays, which detect gas evolved during internal arcing and rapidly de-energize the transformer to avert catastrophic failure. Oil-filled transformers may fail, rupture, and burn, causing power outages and losses. Installations of oil-filled transformers usually includes fire protection measures such as walls, oil containment, and fire-suppression sprinkler systems.

Polychlorinated biphenyls have properties that once favored their use as a coolant, though concerns over their environmental persistence led to a widespread ban on their use. Today, non-toxic, stable silicone-based oils, or fluorinated hydrocarbons may be used where the expense of a fire-resistant liquid offsets additional building cost for a transformer vault. Before 1977, even transformers that were nominally filled only with mineral oils may also have been contaminated with polychlorinated biphenyls at 10-20 ppm. Since mineral oil and PCB fluid mix, maintenance equipment used for both PCB and oil-filled transformers could carry over small amounts of PCB, contaminating oil-filled transformers.

Some "dry" transformers (containing no liquid) are enclosed in sealed, pressurized tanks and cooled by nitrogen or sulfur hexafluoride gas.

Experimental power transformers in the 2 MVA range have been built with superconducting windings which eliminates the copper losses, but not the core steel loss. These are cooled by liquid nitrogen or helium.

## **Insulation drying**

Construction of oil-filled transformers requires that the insulation covering the windings be thoroughly dried before the oil is introduced. There are several different methods of drying. Common for all is that they are carried out in vacuum environment. The vacuum makes it difficult to transfer energy (heat) to the insulation. For this there are several different methods. The traditional drying is done by circulating hot air over the active part and cycle this with periods of vacuum (hot-air vacuum drying, HAV). More common for larger transformers is to use evaporated solvent which condenses on the colder active part. The benefit is that the entire process can be carried out at lower pressure and without influence of added oxygen. This process is commonly called vapour-phase drying (VPD).

For distribution transformers, which are smaller and have a smaller insulation weight, resistance heating can be used. This is a method where current is injected in the windings to heat the insulation. The benefit is that the heating can be controlled very well and it is energy efficient. The method is called low-frequency heating (LFH) since the current is injected at a much lower frequency than the nominal of the grid, which is normally 50 or 60 Hz. A lower frequency reduces the effect of the inductance in the transformer, so the voltage can be reduced.

## **Terminals**

Very small transformers will have wire leads connected directly to the ends of the coils, and brought out to the base of the unit for circuit connections. Larger transformers may have heavy bolted terminals, bus bars or high-voltage insulated bushings made of polymers or porcelain. A large bushing can be a complex structure since it must provide careful control of the electric field gradient without letting the transformer leak oil.

## **Applications**



Image of an electrical substation in Melbourne, Australia showing 3 of 5 220kV/66kV transformers, each with a capacity of 185MVA

A major application of transformers is to increase voltage before transmitting electrical energy over long distances through wires. Wires have resistance and so dissipate electrical energy at a rate proportional to the square of the current through the wire. By transforming electrical power to a high-voltage (and therefore low-current) form for transmission and back again afterward, transformers enable economical transmission of power over long distances. Consequently, transformers have shaped the electricity supply industry, permitting generation to be located remotely from points of demand. All but a tiny fraction of the world's electrical power has passed through a series of transformers by the time it reaches the consumer.

Transformers are also used extensively in electronic products to step down the supply voltage to a level suitable for the low voltage circuits they contain. The transformer also electrically isolates the end user from contact with the supply voltage.

Signal and audio transformers are used to couple stages of amplifiers and to match devices such as microphones and record players to the input of amplifiers. Audio transformers allowed telephone circuits to carry on a two-way conversation over a single pair of wires. A balun transformer converts a signal that is referenced to ground to a signal that has balanced voltages to ground, such as between external cables and internal circuits.

## Chapter 3

# Control Relay and Eddy Current Brake

## Control relay

A **control relay** is an electromechanical device which activates one or more switches according to the current through a coil not connected to the switches. The thyristor is a semiconductor device which carries out similar functions.

A relay is essentially an electromagnet with two possible states arranged so that when there is sufficient current the core of the relay's coil attracts a ferromagnetic armature which mechanically operates switches; a spring holds the armature away from the core when not actuated. The spring is designed to snap the contacts between two stable mechanical states; there should not be a range of coil current which allows the contacts to be in an intermediate state.

A relay allows circuits to be switched by electrical equipment: for example, a timer circuit with a relay could switch power at a preset time. For many years relays were the standard method of controlling industrial electronic systems. A number of relays could be used together to carry out complex functions (relay logic). The principle of relay logic is based on relays which energize and de-energize associated contacts. Relay logic is the predecessor of ladder logic, which is commonly used in Programmable logic controllers.

### **Operation**

When electric current passes through a coil, magnetic north and south poles are produced across the gap separating the coil and armature. The relay is actuated, or latched, when sufficient current through the coil makes the attractive force between the core and armature overcome the spring tension. The relay remains latched as long as at least a specific value of *holding current*, which can be lower than the actuating current, flows through the coil. When the current through the coil is reduced below this value, the magnetic attraction of the armature becomes too weak to hold it in the actuated position and the spring snaps it to the non-actuated position.

There are many considerations involved in the correct selection of a control relay for a particular application. These considerations include factors such as speed of operation, sensitivity, and hysteresis. Although typical control relays operate in the 5 ms to 20 ms range, relays with switching speeds as fast as 100 us are available. Reed relays which are actuated by low currents and switch fast are suitable for controlling small currents.

As for any switch, the current through the relay contacts (unrelated to the current through the coil) must not exceed a certain value to avoid damage. In the particular case of high-inductance circuits such as motors other issues must be addressed. When a power source is connected to an inductance, an input surge current which may be several times larger than the steady current exists. When the circuit is broken, the current cannot change instantaneously, which creates a potentially damaging spark across the separating contacts.

Consequently for relays which may be used to control inductive loads we must specify the maximum current that may flow through the relay contacts when it actuates, the *make rating*; the continuous rating; and the *break rating*. The make rating may be several times larger than the continuous rating, which is itself larger than the break rating.

### ***Derating factors***

#### **Type of load % of rated value**

Resistive	75
Inductive	35
Motor	20
Filament	10
Capacitive	75

Control relays should not be operated above rated temperature because of resulting increased degradation and fatigue. Common practice is to derate 20 degrees Celsius from the maximum rated temperature limit. Relays operating at rated load are also affected by their environment. Oil vapors may greatly decrease the contact tip life, and dust or dirt may cause the tips to burn before their normal life expectancy. Control relay life cycle varies from 50,000 to over one million cycles depending on the electrical loads of the contacts, duty cycle, application, and the extent to which the relay is derated. When a control relay is operating at its derated value, it is controlling a lower value of current than its maximum make and break ratings. This is often done to extend the operating life of the control relay. Table 1 lists the relay and switch derating factors for typical industrial control applications.

# Eddy current brake



An eddy current brake of a German ICE 3 in action.

An **eddy current brake**, like a conventional friction brake, is responsible for slowing an object, such as a train or a roller coaster. Unlike friction brakes, which apply pressure on two separate objects, eddy current brakes slow an object by creating eddy currents through electromagnetic induction which create resistance, and in turn either heat or electricity.

## ***Construction and operation***

### **Circular eddy current brake**



Circular eddy current brake on 700 Series Shinkansen

Electromagnetic brakes are similar to electrical motors; non-ferromagnetic metal discs (rotors) are connected to a rotating coil, and a magnetic field between the rotor and the coil creates a resistance used to generate electricity or heat. When electromagnets are used, control of the braking action is made possible by varying the strength of the magnetic field. A braking force is possible when electric current is passed through the electromagnets. The movement of the metal through the magnetic field of the electromagnets creates eddy currents in the discs. These eddy currents generate an

opposing magnetic field, which then resists the rotation of the discs, providing braking force. The net result is to convert the motion of the rotors into heat in the rotors.

Japanese Shinkansen trains had employed circular eddy current brake system on trailer cars since 100 Series Shinkansen. However, N700 Series Shinkansen abandoned eddy current brakes in favour of regenerative brakes since 14 of the 16 cars in the trainset used electric motors.

## **Linear eddy current brake**

The principle of the linear eddy current brake has been described by the French physicist Foucault, hence in French the eddy current brake is called the "frein à courants de Foucault".

The linear eddy current brake consists of a magnetic yoke with electrical coils positioned along the rail, which are being magnetized alternating as south and north magnetic poles. This magnet does not touch the rail, as with the magnetic brake, but is held at a constant small distance from the rail (approximately seven millimeters). It does not move along the rail, exerting only a vertical pull on the rail.

When the magnet is moved along the rail, it generates a non-stationary magnetic field in the head of the rail, which then generates electrical tension (Faraday's induction law), and causes eddy currents. These disturb the magnetic field in such a way that the magnetic force is diverted to the opposite of the direction of the movement, thus creating a horizontal force component, which works against the movement of the magnet.

The braking energy of the vehicle is converted in eddy current losses which lead to a warming of the rail. (The regular magnetic brake, in wide use in railways, exerts its braking force by friction with the rail, which also creates heat.)

The eddy current brake does not have any mechanical contact with the rail, and thus no wear, and creates no noise or odor. The eddy current brake is unusable at low speeds, but can be used at high speeds both for emergency braking and for regular braking.

The TSI (Technical Specifications for Interoperability) of the EU for trans-European high speed rail recommends that all newly built high speed lines should make the eddy current brake possible.



Eddy current brakes at the Intamin roller coaster *Goliath* in Walibi World (Netherlands)

The first train in commercial circulation to use such a braking is the ICE 3.

Modern roller coasters use this type of braking, but utilize permanent magnets instead of electromagnets, and require no electricity. However, their braking strength cannot be adjusted as easily as with an electromagnet.

## Chapter 4

# Electrical Steel

**Electrical steel**, also called **lamination steel**, **silicon electrical steel**, **silicon steel** or **transformer steel**, is specialty steel tailored to produce certain magnetic properties, such as a small hysteresis area (small energy dissipation per cycle, or low core loss) and high permeability.

The material is usually manufactured in the form of cold-rolled strips less than 2 mm thick. These strips are called laminations when stacked together to form a core. Once assembled, they form the laminated cores of transformers or the stator and rotor parts of electric motors. Laminations may be cut to their finished shape by a punch and die, or in smaller quantities may be cut by a laser, or by wire erosion.

### ***Metallurgy***

Electrical steel is an iron alloy which may have from zero to 6.5% silicon (Si:5Fe). Silicon significantly increases the electrical resistivity of the steel, which decreases the induced eddy currents and thus reduces the core loss. Manganese and aluminum can be added up to 0.5%.

Increasing the amount of silicon inhibits eddy currents and narrows the hysteresis loop of the material, thus lowering the core losses. However, the grain structure hardens and embrittles the metal, which adversely affects the workability of the material, especially when rolling it. When alloying, the concentration levels of carbon, sulfur, oxygen and nitrogen must be kept low, as these elements indicate the presence of carbides, sulfides, oxides and nitrides. These compounds, even in particles as small as one micrometer in diameter, increase hysteresis losses while also decreasing magnetic permeability. The presence of carbon has a more detrimental effect than sulfur or oxygen. Carbon also causes magnetic aging when it slowly leaves the solid solution and precipitates as carbides, thus resulting in an increase in power loss over time. For these reasons, the carbon level is kept to 0.005% or lower. The carbon level can be reduced by annealing the steel in a decarburizing atmosphere, such as hydrogen.

## ***Physical properties examples***

Melting point: ~1,500 °C (example for ~3.1% silicon content)

Density: 7,650 kg/m<sup>3</sup> (example for 3% silicon content)

Resistivity:  $47.2 \times 10^{-8}$  ( $\Omega \cdot m$ ) (example for 3% silicon content)

## ***Grain orientation***

There are two main types of electrical steel: grain-oriented and non-oriented.

**Grain-oriented** electrical steel usually has a silicon level of 3% (Si:11Fe). It is processed in such a way that the optimum properties are developed in the rolling direction, due to a tight control (proposed by Norman P. Goss) of the crystal orientation relative to the sheet. Due to the special orientation, the magnetic flux density is increased by 30% in the coil rolling direction, although its magnetic saturation is decreased by 5%. It is used for the cores of high-efficiency transformers, electric motor and generators. Cold Rolled Grain-oriented steel is often abbreviated to CRGO.

**Non-oriented** electrical steel usually has a silicon level of 2 to 3.5% and has similar magnetic properties in all directions, which makes it isotropic. It is less expensive and is used in applications where the direction of magnetic flux is changing, such as electric motors and generators. It is also used when efficiency is less important or when there is insufficient space to correctly orient components to take advantage of the anisotropic properties of grain-oriented electrical steel. Cold Rolled Non Grain-oriented steel is often abbreviated to CRNGO.

## ***Amorphous steel***

Transformers with amorphous steel cores can have core losses of one-third that of conventional steels. This material is a metallic glass prepared by pouring molten alloy steel onto a rotating cooled wheel, which cools the metal at a rate of about one megakelvin per second, so fast that crystals do not form. Amorphous steel has poorer mechanical properties and as of 2010 costs about twice as much as conventional steel, making it cost-effective only for some large distribution-type transformers.

## ***Lamination coatings***

Electrical steel is usually coated to increase electrical resistance between laminations, to provide resistance to corrosion or rust, and to act as a lubricant during die cutting. There are various coatings, organic and inorganic, and the coating used depends on the application of the steel. The type of coating selected depends on the heat treatment of the laminations, whether the finished lamination will be immersed in oil, and the working temperature of the finished apparatus. Very early practice was to insulate each lamination

with a layer of paper or a varnish coating, but this reduced the stacking factor of the core and limited the maximum temperature of the core.

### ***Magnetic properties***

The magnetic properties of electrical steel are dependent on heat treatment, as increasing the average crystal size decreases the hysteresis loss. Hysteresis loss is determined by a standard test and for common grades of electrical steel may range from about 2 to 10 watts per kilogram (1 to 5 watts per pound) at 60 Hz and 1.5 tesla magnetic field strength. Semi-processed electrical steels are delivered in a state that, after punching the final shape, a final heat treatment develops the desired 150-micrometer grain size. The fully processed steels are usually delivered with insulating coating, full heat treatment, and defined magnetic properties, for applications where the punching operation does not significantly degrade the material properties. Excessive bending, incorrect heat treatment, or even rough handling of core steel can adversely affect its magnetic properties and may also increase noise due to magnetostriction

Magnetic properties of electrical steels are tested using the internationally standardised Epstein frame method.

### ***Practical concerns***

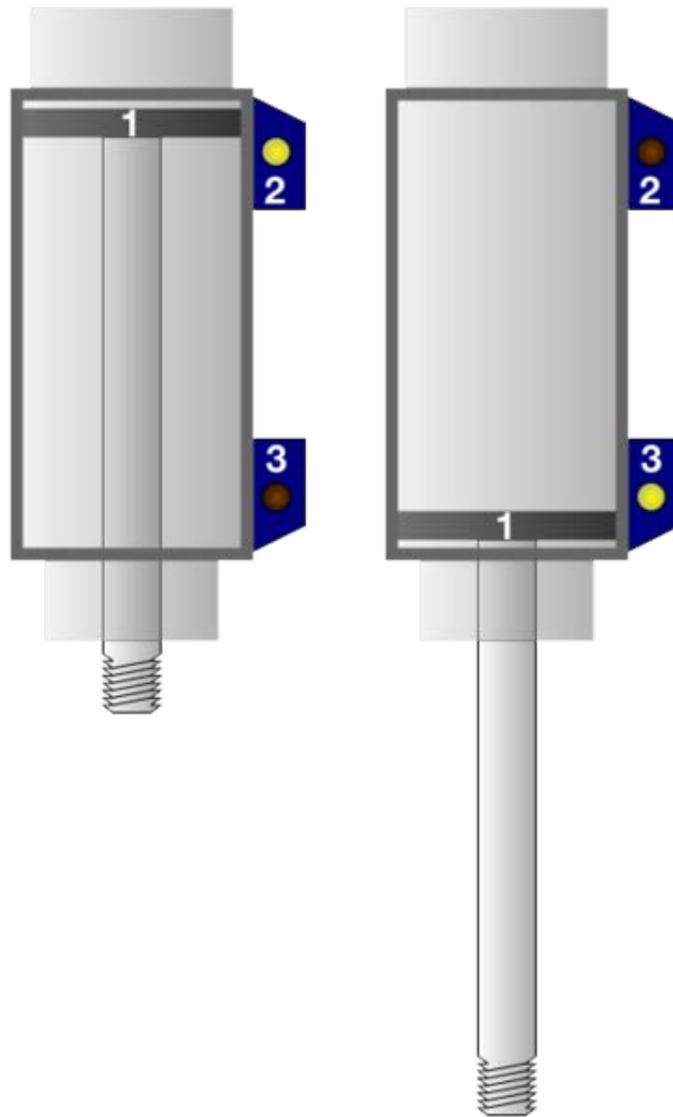
Core steel is much more costly than mild steel—in 1981 it was more than twice the cost per unit weight.

The size of magnetic domains in the sheet can be reduced by scribing the surface of the sheet with a laser, or mechanically. This greatly reduces the hysteresis losses in the assembled core.

## Chapter 5

# Hall Effect Sensor and Induction Loop

## Hall effect sensor



The magnetic piston (1) in this pneumatic cylinder will cause the Hall effect sensors (2 and 3) mounted on its outer wall to activate when it is fully retracted or extended.



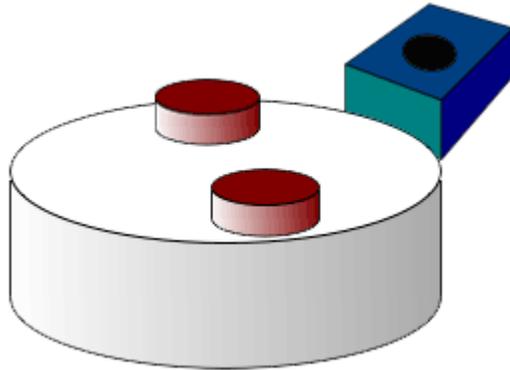
Clutch with Hall Effect sensor.

A **Hall effect sensor** is a transducer that varies its output voltage in response to changes in magnetic field. Hall sensors are used for proximity switching, positioning, speed detection, and current sensing applications.

In its simplest form, the sensor operates as an analogue transducer, directly returning a voltage. With a known magnetic field, its distance from the Hall plate can be determined. Using groups of sensors, the relative position of the magnet can be deduced.

Electricity carried through a conductor will produce a magnetic field that varies with current, and a Hall sensor can be used to measure the current without interrupting the circuit. Typically, the sensor is integrated with a wound core or permanent magnet that surrounds the conductor to be measured.

Frequently, a Hall sensor is combined with circuitry that allows the device to act in a digital (on/off) mode, and may be called a switch in this configuration. Commonly seen in industrial applications such as the pictured pneumatic cylinder, they are also used in consumer equipment; for example some computer printers use them to detect missing paper and open covers. When high reliability is required, they are used in keyboards.



Hall sensors are commonly used to time the speed of wheels and shafts, such as for internal combustion engine ignition timing, tachometers and anti-lock braking systems. They are used in brushless DC electric motors to detect the position of the permanent magnet. In the pictured wheel with two equally spaced magnets, the voltage from the sensor will peak twice for each revolution. This arrangement is commonly used to regulate the speed of disc drives.

### ***Hall probe***

A hall probe contains an indium compound crystal such as indium antimonide, mounted on an aluminum backing plate, and encapsulated in the probe head. The plane of the crystal is perpendicular to the probe handle. Connecting leads from the crystal are brought down through the handle to the circuit box.

When the Hall Probe is held so that the magnetic field lines are passing at right angles through the sensor of the probe, the meter gives a reading of the value of magnetic flux density (B). A current is passed through the crystal which, when placed in a magnetic field has a "Hall Effect" voltage developed across it. The Hall Effect is seen when a conductor is passed through a uniform magnetic field. The natural electron drift of the charge carriers causes the magnetic field to apply a Lorentz force (the force exerted on a charged particle in an electromagnetic field) to these charge carriers. The result is what is seen as a charge separation, with a build up of either positive or negative charges on the bottom or on the top of the plate. The crystal measures 5 mm square. The probe handle, being made of a non-ferrous material, has no disturbing effect on the field.

A Hall Probe is enough to measure the Earth's magnetic field. It must be held so that the Earth's field lines are passing directly through it. It is then rotated quickly so the field lines pass through the sensor in the opposite direction. The change in the flux density reading is double the Earth's magnetic flux density. A hall probe must first be calibrated against a known value of magnetic field strength. For a solenoid the hall probe is placed in the center.

## ***Hall Effect Sensor Interface***

Hall effect sensor may require analog circuitry to be interfaced to microprocessors. These interfaces may include input diagnostics, fault protection for transient conditions and short/open circuit detection. It may also provide and monitor the current to the hall effect sensor itself. There are precision IC products available to handle these features.

## **Induction loop**

**Induction loop** is a term used to describe an electromagnetic communication- and detection system, relying on the fact that a moving magnet will induce an electrical current in a nearby conducting wire. Induction loops are used for transmission and reception of communication signals, or for detection of metal objects in metal detectors or vehicle presence indicators. A common modern use for induction loops is to provide hearing assistance to hearing-aid users.

## ***Implementation***



An example of the Inductance loop installed in the road for cars and bikes

The "aerial" system of an induction loop installation can consist of one or more loops of a conductive element.

In industrial applications this might be a large single- or multi-turn, loop, or a complex multi-lobed, phase coincident sub-loop design, most effectively mounted above the required reception area in industrial applications.

An audio induction loop might have one or more loops sometimes with a phase shift between them, and either near to or around the area in which a hearing aid user would be present. Many different configurations can be used depending on the application.

Such an induction loop receiver is classically a very small iron-cored inductor (telecoil), although Rediffusion demonstrated a prototype Hall-Effect system in its PLL FM system.

The system commonly uses an analogue power amplifier matched to the low impedance of the transmission loop. The transmission is normally direct rather than superimposed or modulated upon a carrier, though multi-channel systems have been implemented using modulation.

Vehicle detection (inductive) loops are used to count vehicles passing or arriving at a certain point, for instance approaching a traffic light, and in motorway traffic management. An insulated, electrically conducting loop is installed under the road. An electrical voltage is generated when a ferrous (containing iron or steel) body passes close to the wire/loop

### ***Other definitions***

A different sort of "induction loop" is applied to metal detectors, where a large coil, which forms part of a resonant circuit, is effectively "detuned" by the coil's proximity to a conductive object. The detected object may be metallic, (metal and cable detection) or conductive/capacitive (stud/cavity detection) Other configurations of this equipment use two or more receiving coils, and the detected object modifies the inductive coupling or alters the phase angle of the voltage induced in the receiving coils relative to the oscillator coil.

An increasingly common application is for providing hearing aid-compatible "assistive listening" telecoil. In this application a loop or series of loops is used to provide an audio frequency oscillating magnetic field in an area where a hearing aid user may be present. Many hearing aids contain a telecoil which allows the user to receive and hear the magnetic field and remove the normal audio signal provided from the hearing aid microphone site. These loops are often referred to as a hearing loop or Audio induction loop.

### **Modern day applications**

- vehicle detection (e.g. at traffic lights)
- car park Parking Guidance and Information systems
- metal detectors
- audio induction loops

## Historical applications

- An Anti-submarine indicator loop was a device used to detect submarines and surface vessels using specially designed submerged cables connected to a galvanometer.

## Chapter 6

# Magnetic Amplifier

The **magnetic amplifier** (colloquially known as a "mag amp") is an electromagnetic device for amplifying electrical signals. The magnetic amplifier was invented early in the 20th century, and was used as an alternative to vacuum tube amplifiers where robustness and high current capacity were required. World War II Germany perfected this type of amplifier, and it was used for instance in the V-2 rocket. The magnetic amplifier was most prominent in power control and low-frequency signal applications from 1947 to about 1957, when the transistor began to supplant it. The magnetic amplifier has now been largely superseded by the transistor-based amplifier, except in a few safety critical, high reliability or extremely demanding applications. Combinations of transistor and mag-amp techniques are still used.

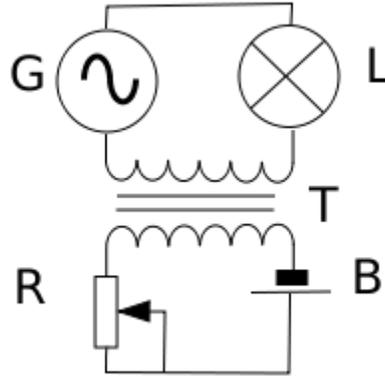
### ***Strengths***

The magnetic amplifier is a static device with no moving parts. It has no wear-out mechanism and has a good tolerance to mechanical shock and vibration. It requires no warm-up time. Multiple isolated signals may be summed by additional control windings on the magnetic cores. The windings of a magnetic amplifier have a higher tolerance to momentary overloads than comparable solid-state devices. The magnetic amplifier is also used as a transducer in applications such as current measurement and the flux gate compass

### ***Limitations***

The gain available from a single stage is limited and low compared to electronic amplifiers. Frequency response of a high gain amplifier is limited to about one-tenth the excitation frequency, although this is often mitigated by exciting magnetic amplifiers with currents at higher than utility frequency. Solid-state amplifiers can be more compact and efficient than magnetic amplifiers. The bias and feedback windings are not unilateral, and may couple energy back from the controlled circuit into the control circuit. This complicates the design of multistage amplifiers when compared with electronic devices.

## ***Principle of operation***



A saturable reactor, illustrating the principle of a magnetic amplifier

Visually a mag amp device may resemble a transformer but the operating principle is quite different from a transformer - essentially the mag amp is a saturable reactor. It makes use of magnetic saturation of the core, a non-linear property of a certain class of transformer cores. For controlled saturation characteristics the magnetic amplifier employs core materials that have been designed to have a specific B-H curve shape that is highly rectangular, in contrast to the slowly-tapering B-H curve of softly saturating core materials that are often used in normal transformers.

The typical magnetic amplifier consists of two physically separate but similar transformer magnetic cores, each of which has two windings - a control winding and an AC winding. A small DC current from a low impedance source is fed into the series-connected control windings. The AC windings may be connected either in series or in parallel, the configurations resulting in different types of mag amps. The amount of control current fed into the control winding sets the point in the AC winding waveform at which either core will saturate. In saturation, the AC winding on the saturated core will go from a high impedance state ("off") into a very low impedance state ("on") - that is, the control current controls at which voltage the mag amp switches "on".

A relatively small DC current on the control winding is able to control or switch large AC currents on the AC windings. This results in current amplification.

## ***Applications***

Magnetic amplifiers were important as modulation and control amplifiers in the early development of voice transmission by radio. A magnetic amplifier was used as voice modulator for a 2 kilowatt Alexanderson alternator, and magnetic amplifiers were used in the keying circuits of large high-frequency alternators used for radio communications. Magnetic amplifiers were also used to regulate the speed of Alexanderson alternators to maintain the accuracy of the transmitted radio frequency.

The ability to control large currents with small control power made magnetic amplifiers useful for control of lighting circuits, for stage lighting and for advertising signs. Saturable reactor amplifiers were used for control of power to industrial furnaces. Small magnetic amplifiers were used for radio tuning indicators, control of small motor and cooling fan speed, control of battery chargers.

Magnetic amplifiers were used extensively as the switching element in early switched-mode (SMPS) power supplies, as well as in lighting control. Semiconductor based solid-state switches have largely superseded them, though recently there has been some regained interest in using mag amps in compact and reliable switching power supplies. PC ATX power supplies often use mag amps for secondary side voltage regulation.

Magnetic amplifiers are still used in some arc welders.

Magnetic amplifier transformer cores designed specifically for switch mode power supplies are currently manufactured by several large electromagnetics companies, including Metglas and Mag-Inc.

Magnetic amplifiers can be used for measuring high DC-voltages without direct connection to the high voltage and are therefore still used in the HVDC-technique.

Magnetic amplifiers were used by locomotives to detect wheel slip, until replaced by Hall Effect current transducers. The cables from two traction motors passed through the core of the device. During normal operation the resultant flux was zero as both currents were the same and in opposite directions. However, the currents would differ during wheel slip, producing a resultant flux that acted as the Control winding, developing a voltage across a resistor in series with the AC winding which was sent to the wheel slip correction circuits.

## ***History***

### **Early development**

A voltage source and a series connected variable resistor may be regarded as a direct current signal source for a low resistance load such as the control coil of a saturable reactor which amplifies the signal. Thus, in principle, a saturable reactor is already an amplifier, although before 20th century they were used for simple tasks, such as controlling lighting and electrical machinery as early as 1885.

In the early 20th Century, the General Electric Company, under the direction of engineer E. F. W. Alexanderson, developed a system of transoceanic radio communications, using continuous wave transmission over great distances. Alexanderson drew upon the work of Nikola Tesla and Reginald Fessenden as the inspiration for his system.

The result of this work was the 2 kW Alexanderson alternator, which produced radio frequencies from 50 to 100 kHz and which critics had previously denounced as

impractical. Later, Guglielmo Marconi took a vested interest in the project and, in 1915, witnessed a demonstration of a new, 50 kW, 50 kHz alternator.

The experimental telegraphy and telephony demonstrations made during 1917 attracted the attention of the US Government, especially in light of partial failures in the transoceanic cable that snaked across the bottom of the Atlantic Ocean. The 50 kW alternator was commandeered by the US Navy and put into service in January 1918 and was used until 1920, when a 200 kW generator-alternator set was built and installed.

## **Usage in radio**

Magnetic amplifiers were used early on to control large, high-power alternators by turning them on and off for telegraphy or to vary the signal for voice modulation. However, the alternator's frequency limits were rather low to where a frequency multiplier had to be utilized to generate higher radio frequencies than the alternator was capable of producing. Even so, early magnetic amplifiers incorporating powdered-iron cores were incapable of producing radio frequencies above approximately 200 kHz. Other core materials, such as ferrite cores and oil-filled transformers, would have to be developed to allow the amplifier to produce higher frequencies.

## **Usage in aircraft**

Magnetic amplifiers were used in aircraft systems (avionics) before the advent of high reliability semiconductors. They were important in implementing early autoland systems and Concorde made use of the technology for the control of its engine air intakes before subsequent development of a replacement system using digital electronics.

## **Usage in computing**

Magnetic amplifiers were widely studied during the 1950s as a potential switching element for mainframe computers. Mag amps could be used to sum several inputs in a single core, which was very useful in the arithmetic logic unit (ALU). Custom tubes could do the same, but transistors could not, so the mag amp was able to combine the advantages of tubes and transistors in an era when the latter were expensive and unreliable.

However, that era was very short, lasting from the mid 1950s to about 1960, at which point new fabrication techniques were producing great improvements in transistors and dramatically lowering their price points. Only one large-scale mag amp machine was put into production, the UNIVAC Solid State, but a number of contemporary late-1950's/early-1960s computers made some use of the technology, like the Ferranti Orion.

## ***Misnomer uses***

In the 1970s, Robert Carver designed and produced several high quality high-powered audio amplifiers, calling them magnetic amplifiers. In fact, they were in most respects conventional audio amplifier designs with an unusual power supply circuit.

## Chapter 7

# Magnetic Cartridge



An Audio Technica AT-F3 MC cartridge

A **magnetic cartridge** is a transducer used for the playback of gramophone records on a turntable or phonograph. It converts mechanical vibrational energy from a stylus riding in a spiral record groove into an electrical signal that is subsequently amplified and then converted back to sound by a loudspeaker system.

## ***History***

The first electric pick-ups were developed in about 1925. They used a piezo-electric crystal of quartz, stimulated by a stylus made of sapphire or diamond. The magnetic cartridge is presently the most common form of sound pickup used and came into use in the 1950s, following the introduction of magnetic cutter heads around 1945 for mastering records.

## ***Types***

In high-fidelity systems, crystal and ceramic pickups have been replaced by the magnetic cartridge, using either a **moving magnet** or a **moving coil**.

Compared to the crystal and ceramic pickups, the magnetic cartridge gives improved playback fidelity and reduces record wear by tracking the groove with lighter pressure. Magnetic cartridges use much lower tracking forces and thus damage the record grooves less. They also have a lower output voltage than a crystal or ceramic pickup, in the range of only a few millivolts, thus requiring greater amplification.

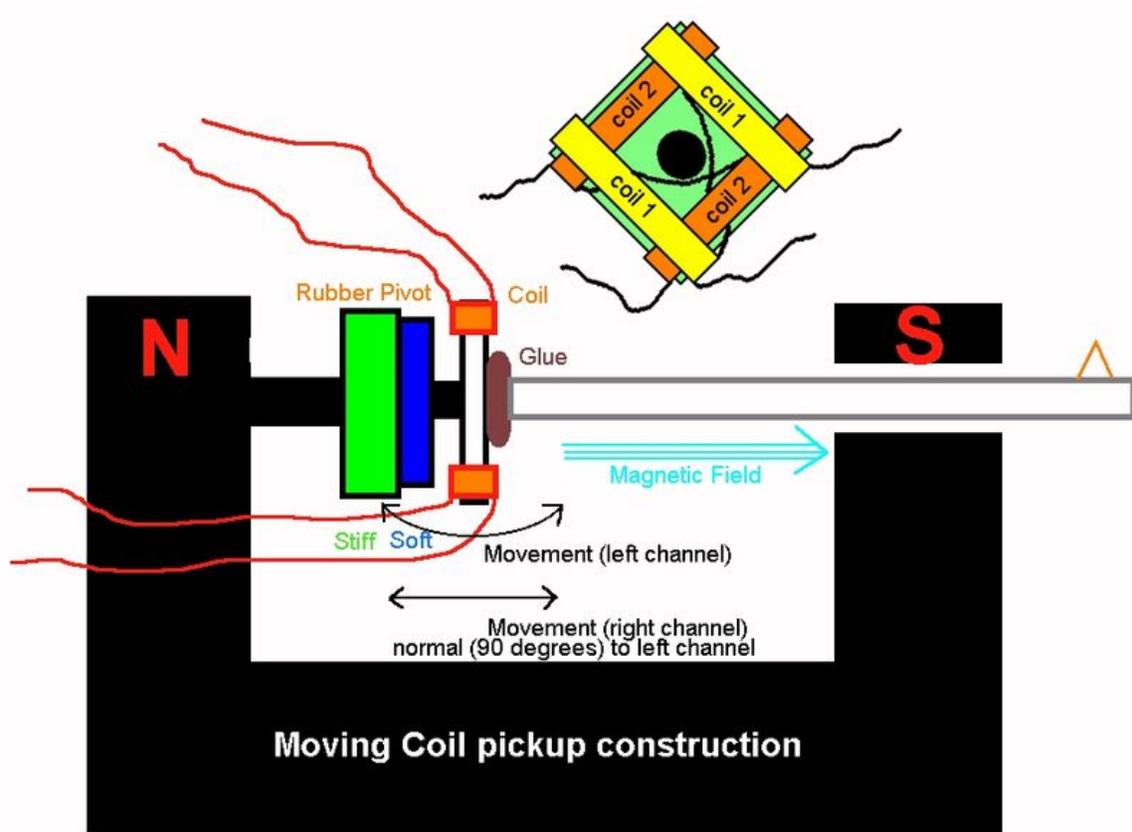
### **Moving Magnet (MM) cartridges**

In a moving magnet cartridge, the stylus cantilever carries a tiny permanent magnet, which is positioned between two sets of fixed coils (in a stereophonic cartridge), forming a tiny electromagnetic generator. As the magnet vibrates in response to the stylus following the record groove, it induces a tiny current in the coils.

Because the magnet is small and has little mass, and is not coupled mechanically to the generator (as in a ceramic cartridge), a properly adjusted stylus follows the groove more faithfully while requiring less tracking force (the downward pressure on the stylus).

There is a sub-category. Moving iron and induced magnet types (ADC being a well known example) which have the magnet fixed and move a piece of iron or other ferrous alloy in the field of the magnet to produce the signal within the fixed coils.

## Moving Coil (MC) cartridges



The MC design is again a tiny electromagnetic generator, but (unlike an MM design) with the magnet and coils reversed: the coils are attached to the stylus, and move within the field of a permanent magnet. The coils are tiny and made from very fine wire, so are even lighter than the small magnet used in an MM cartridge, thus improving the tracking ability of the cartridge. This can give extended frequency response as well as greater fidelity.

A disadvantage however is that moving-coil cartridges generate an even lower voltage signal than a moving-magnet type cartridge. This is because the moving coil cannot be large enough (it would be too heavy) to generate equivalent voltage levels. The resulting signal is only a few hundred microvolts, and thus more easily swamped by noise, induced hum, etc. Thus it is more challenging to design a preamplifier with the extremely low noise inputs needed for moving-coil cartridge, therefore a "step up transformer" is sometimes used instead.

Moving coil cartridges are extremely small precision instruments and are therefore generally expensive, but are frequently preferred by audiophiles due to their better performance.

## **Moving Micro Cross (MMC) cartridges**

The MMC design was invented and patented by Bang & Olufsen. Since it often uses a special mounting, it can be mostly found in Bang & Olufsen turntables (which also cannot use another type of cartridge). Apart from being produced for the Bang & Olufsen mounting system, the SP12 and SP14 were also available in standard 1/2" mount.

The MMC cartridge is a *moving iron* design. Magnets and coils are stationary while the *micro cross* moves with the stylus, thereby varying the distances between the arms of the cross and the magnets. The design obviously offers more freedom concerning magnet and coil mass (compared to MC and MM cartridges). For example, the MMC20 (presented in 1978) uses four coils wound around the magnetic cores with 1200 turns each. Minimizing the moving mass also reduces the unavoidable wear on the records.

It is also claimed that the MMC design allows for superior channel separation, since each channel's movements appear on a separate axis.

## **Moving Magnet vs. Moving Coil debate**

Moving magnet cartridges are more commonly found at the 'lower-end' of the market, while the 'higher-end' tends to be dominated by moving coil designs. The debate as to whether MM or MC designs can ultimately produce the better sound is often heated and subjective. The distinction between the two is often blurred by cost and design considerations - i.e. can an MC cartridge requiring another step-up amplification outperform well made MM cartridges that need simpler front-end stages? Every now and then a design comes along to re-open this debate. A good example being the Linn K9 (now discontinued) - regarded by some as one of the better MM designs and competitive with MC alternatives costing more. Amongst others, Grace, ADC and Grado also manufactured notably good designs.

## **"Decca" Cartridges (aka "Moving Iron")**

The Decca phono cartridges were a unique design, with fixed magnets and coils. The stylus shaft was composed of the diamond tip, a short piece of soft iron, and an L-shaped cantilever made of non-magnetic steel. Since the iron was placed very close to the tip (within 1 mm), the motions of the tip could be tracked very accurately. Decca engineers called this "positive scanning". Vertical and lateral compliance was controlled by the shape and thickness of the cantilever. Decca cartridges had a reputation for being very musical; however early versions required more tracking force than competitive designs - making record wear a concern.

## ***Stereo reproduction***

One reason that magnetic cartridges superseded the crystal pick-up was the relative ease with which it could be made to reproduce stereo recordings, which were introduced in 1958. In a stereo recording, the two channels are arranged to drive the record cutter head

at an angle of 45° to the vertical, effectively encoding each channel in the left and right V-shaped walls of the record groove. This system worked well, since it provided full compatibility with a monaural pick-up, so stereo records could be played on older mono equipment. To reproduce the stereo signal, the cartridge simply arranges pairs of coils at 45° to complement the cutting process. With careful design, the coils can be shielded from each other electrically and mechanically such that stereo separation is maximised.

## **Comparison with crystal technology**

Piezoelectric crystal or ceramic pickups had a few clear advantages. They were much easier and cheaper to make and were more robust than the delicate magnetic pickup. In addition, the output voltage from a crystal pickup is relatively large, requiring less amplification, which helped improve the signal-to-noise ratio. However, the signal from a crystal is not an accurate reproduction of the recording, as there is a lot of distortion introduced. The stylus is coupled to the crystal in a fairly rigid manner, which is also not as good at following rapid changes in the record grooves, so frequency response also suffers. This requires a greater tracking force, which in turn wears the records out faster. (This has earned cheap portable record players, the nickname "portable grinding wheel", in some circles.)

By contrast, since the magnetic cartridge is not mechanically coupled, the stylus and lever arm weight can be made exceedingly small. This gives extended frequency response and low distortion. The distortion is further minimised by the fact that there is more inherent linearity in the induction principle than there is in the piezo-electric one. Since the lighter stylus requires very low tracking forces, it requires a more sophisticated counterweighted arm, but reduces record wear.

The output from the magnetic cartridge is only a few millivolts compared to several tenths of a volt from a crystal or ceramic pickup. This requires an additional preamplifier stage. Careful design and shielding in the signal cables and amplifier is needed to prevent unwanted noise (shot noise or EMI). The magnetic induction principle also naturally leads to a linearly rising response with increasing frequency, and this needs to be compensated for to give correct (flat) frequency reproduction. Conversely, the very low bass frequencies are not efficiently picked up, so a strong bass boost is needed. This can amplify unwanted low frequency noise such as that from the turntable motor and drive mechanism itself (rumble). Crystal pickups do not suffer from these drawbacks and give a much better bass performance, so they may be preferred in some applications (such as DJ-ing), where robustness and good bass are favoured over highest fidelity reproduction. The moving coil pickups tend to have an even lower level of output, and so usually require a step-up transformer or very special preamplifiers to bring these signals up to the level of input that a standard amplifier requires. These special preamplifiers must have very low noise indeed (some have even been cryogenically cooled), and hence tend to be expensive. Many audiophiles claim that the benefits are worthwhile. There are higher output moving coil pickup cartridges that can be used directly into a normal moving magnet input, but these are in the minority.

The bass boost and high frequency rolloff can be conveniently incorporated into the preamplifier which implements the RIAA equalization curve, a noise reduction technique used on all modern records.

The magnetic nature of the modern pickup means it must be shielded from external fields, especially from the loudspeakers of the same system, or unpleasant and possibly damaging feedback can occur. For this reason, the cartridge itself has a shield, usually of mu-metal, to help screen out unwanted fields.

## ***The stylus***

The stylus, or "needle", is a crucial part of the record player (or 'phonograph' or 'gramophone', both terms now archaic), as it is the one part of the system that actually contacts the recorded disc and transfers its vibrations to the rest of the system. It is the part which also suffers the greatest wear. There are two desired qualities in a stylus: first, that it faithfully follows the contours of the recorded groove and transfers the vibration to the system, and second, that it does not damage the recorded disc.

## **History of materials**

Early phonograph styli in mechanical players were steel, or even fibre, needles, usually with a shank about 1/8" (3 mm) in diameter, ground to a sharp point. These were easily replaceable by the user, as they had a very limited life and wore out fairly rapidly with use. Extensive play tended to wear records out as well as needles.

When the electronic phonograph was introduced, styli were included as part of the pickup cartridge.

In early times, wear of cylinders and glass styli was problematic. By 1908, sapphire styli were being attached to the rice paper diaphragms, and in 1912 Edison began to use the diamond stylus. Typical low cost crystal cartridges of the 1950s tracked at 5-8 grams of force and used replaceable osmium tipped steel styli called *needles*, which styli might last only five to ten plays before needing replacement. To help make the stylus last longer, sapphire styli for 78 rpm records or diamond styli for 33 1/3 rpm LPs were re-introduced. A 78 rpm stylus typically has a 3 mil (0.08 mm) diameter while a stylus for 33 1/3 rpm *microgroove* LP discs has a 1 mil (0.03 mm) diameter tip to fit the narrower groove. Sapphire might be good for 40 or 50 hours while a diamond would last at least ten times that long. Typically, these early cartridges were of the "flip-over" type; the cartridge had a stylus on either side, one for 78 rpm discs, the other for 33 and 45 rpm ("microgroove") records. The entire cartridge could be rotated 180° by means of a knob or lever at the end of the tonearm to use the desired stylus.

Later, starting in the 1960s, most manufacturers settled on diamond-tipped styli for all cartridges. Magnetic cartridges lowered tracking forces to 1-2 grams, and with the obsolescence of 78's, diamond became the standard stylus material. Moving magnet

cartridges often have replaceable styli; most moving coil cartridges do not offer user-replaceable styli, although some manufacturers offer a trade-in or a re-tipping service.

Magnetic cartridge manufacturers usually provide a specialized range of styli for DJ use. More rugged conical styli are required due to the frequent reversals of direction involved in scratching and back-cueing.

## **Stylus shape**

The physical shape of the stylus has a bearing on its performance. The most obvious shape is the spherical stylus (also known as "conical"), where the tip of the stylus is ground to a hemisphere for playing monophonic recordings or for rugged use. However, this shape is unable to faithfully track all possible variations in a record groove. Better quality LP styli use an elliptical or "line contact" shape, arranged with its 0.02 mm (0.0007 inch) long axis across the record groove. The short axis may be from 0.005 to 0.01 mm (.0002 to .0004 inch) depending on the particular design. This shape followed the undulations of the groove better than spherical styli because they more closely resembled the triangular cutter used to create the groove.

In later years, bi-radial styli appeared where, in the perpendicular axis, the tip of the stylus was ground to a smaller radius than the main body. The result was a stylus that rode slightly lower in the groove and even more closely matched the shape of the triangular cutter than the elliptical design. There were several variations on the basic bi-radial design depending on the manufacturer who produced them.

## **Cantilevers**

The cantilever is the arm that connects the stylus to the magnet or pickup coils. Most cartridges have cantilevers made from aluminium or boron; some very expensive models have ruby, diamond, beryllium or carbon fiber cantilevers chosen for their exceptional stiffness.

## Chapter 8

# Magnetic Core

A **magnetic core** is a piece of magnetic material with a high permeability used to confine and guide magnetic fields in electrical, electromechanical and magnetic devices such as electromagnets, transformers, electric motors, inductors and magnetic assemblies. It is made of ferromagnetic metal such as iron, or ferrimagnetic compounds such as ferrites. The high permeability, relative to the surrounding air, causes the magnetic field lines to be concentrated in the core material. The magnetic field is often created by a coil of wire around the core that carries a current. The presence of the core can increase the magnetic field of a coil by a factor of several thousand over what it would be without the core.

The use of a magnetic core can enormously concentrate the strength and increase the effect of magnetic fields produced by electric currents and permanent magnets. The properties of a device will depend crucially on the following factors:

- the geometry of the magnetic core.
- the amount of air gap in the magnetic circuit.
- the properties of the core material (especially permeability and hysteresis).
- the operating temperature of the core.
- whether the core is laminated to reduce eddy currents.

In many applications it is undesirable that the core itself retain magnetization and become magnetized by the external field. This property, called *hysteresis* can cause energy losses in applications such as transformers. Therefore 'soft' magnetic materials with low hysteresis, such as silicon steel, rather than the 'hard' magnetic materials used for magnets, are usually used in cores.

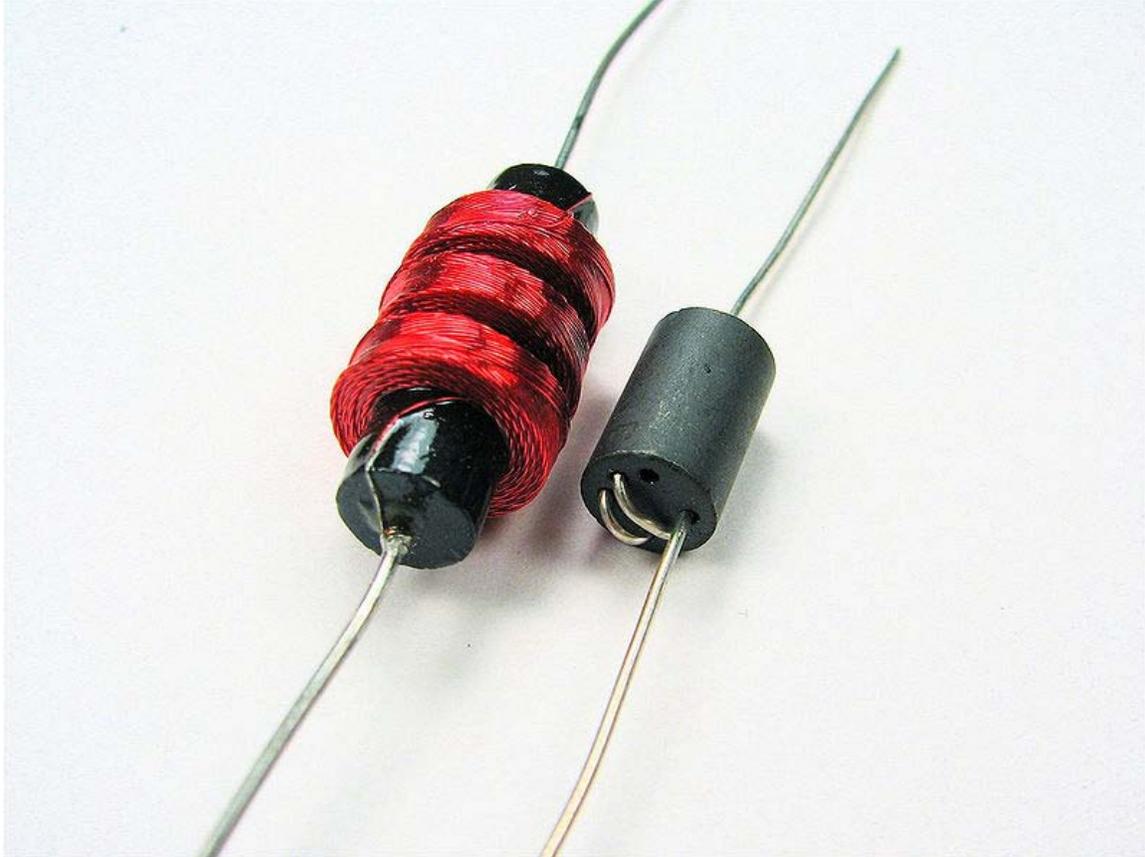
### ***Commonly used structures***

#### **Air core**

A coil not containing a magnetic core is called an air core coil. This includes coils wound on a plastic or ceramic form in addition to those made of stiff wire that are self-supporting and have air inside them. Air core coils have lower inductance than similarly

sized ferromagnetic core coils, but are used in radio frequency circuits to prevent energy losses called core losses that occur in magnetic cores. The absence of core losses permits a higher Q factor, so air core coils are used in high frequency resonant circuits.

### **Straight cylindrical rod**



On the left, a non-adjustable ferrite rod with connection wires glued to the ends. On the right, a molded ferrite rod with holes, with a single wire threaded through the holes.

Most commonly made of ferrite or a similar material, and used in radios especially for tuning an inductor. The rod sits in the middle of the coil and small adjustments of the rod's position will fine tune the inductance. Often the rod is threaded to allow adjustment with a screwdriver. In radio circuits, a blob of wax or resin is used once the inductor has been tuned to prevent the core from moving.

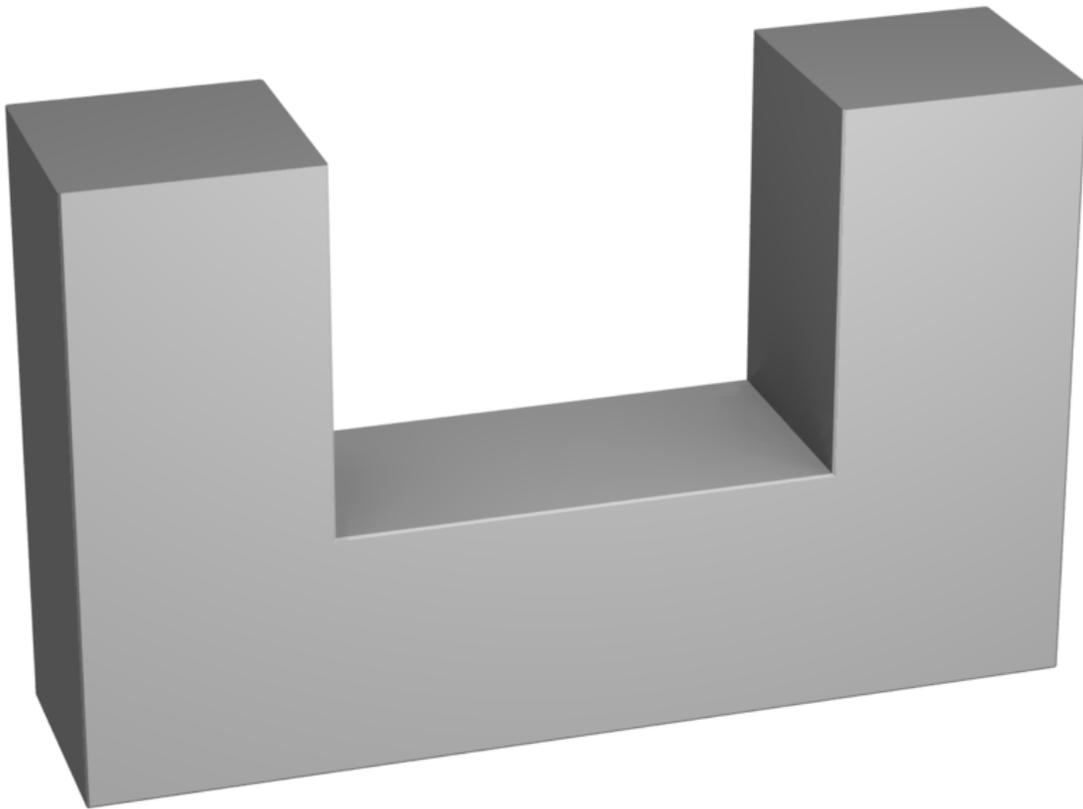
The presence of the high permeability core increases the inductance but the field must still spread into the air at the ends of the rod. The path through the air ensures that the inductor remains linear. In this type of inductor radiation occurs at the end of the rod and electromagnetic interference may be a problem in some circumstances.

## Single "I" core

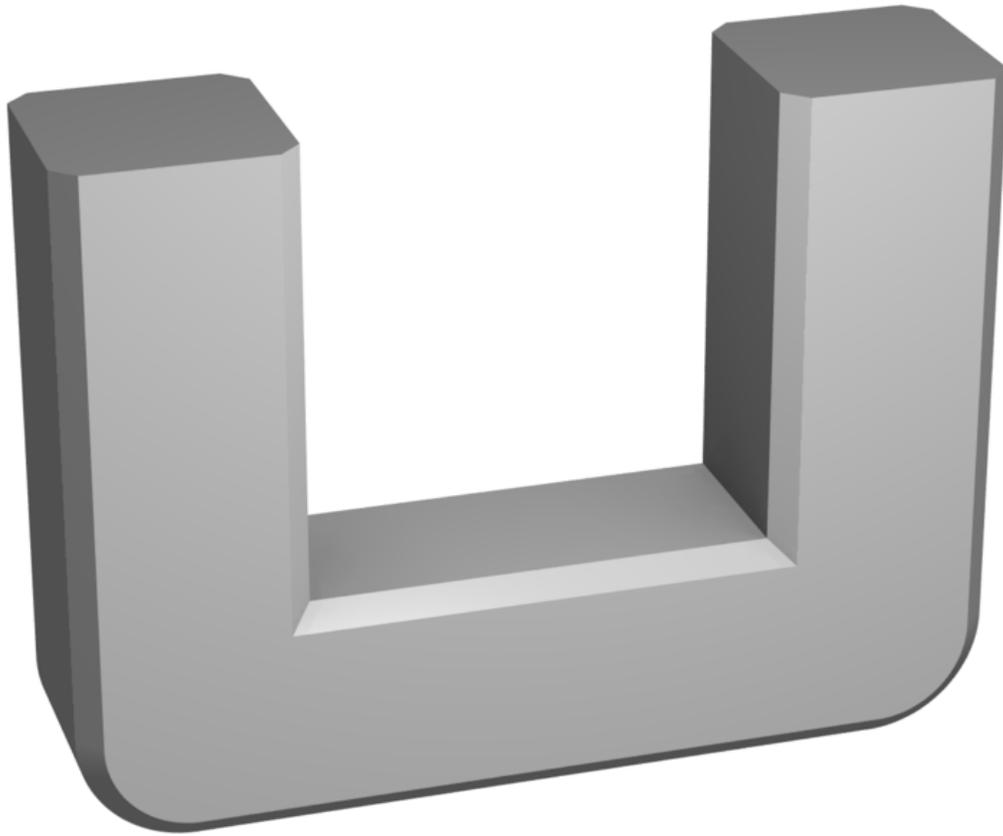
Like a cylindrical rod but square, rarely used on its own. This type of core is most likely to be found in car ignition coils.

## "C" or "U" core

*U and C-shaped cores are used with I or another C or U' core to make a square closed core, the simplest closed core shape. Windings may be put on one or both legs of the core.*



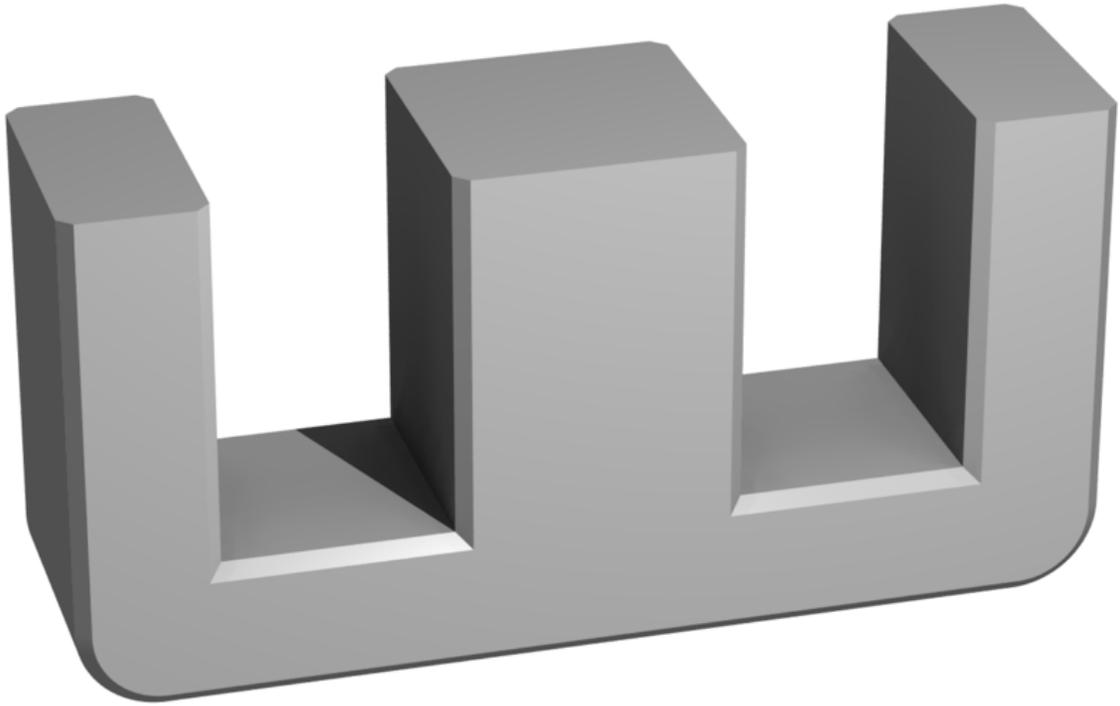
a U-shaped core, with sharp corners



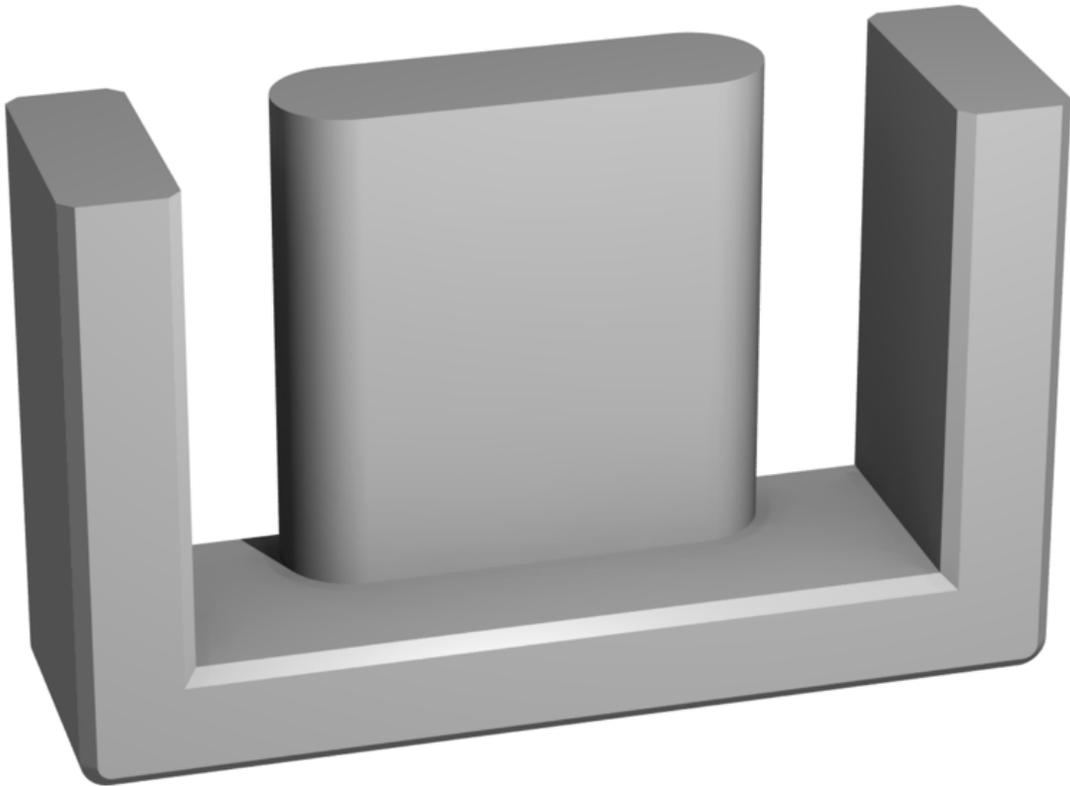
the C-shaped core, with rounded corners

### **"E" core**

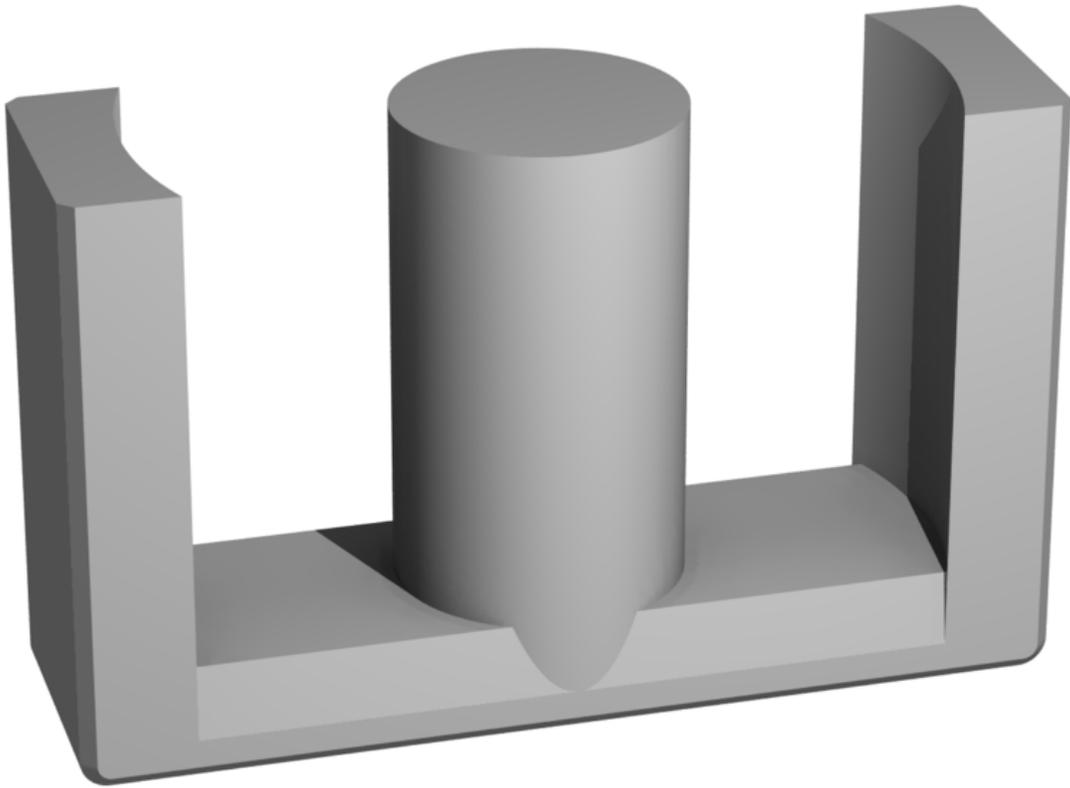
E-shaped core are more symmetric solutions to form a closed magnetic system. Most of the time, the electric circuit is wound around the center leg, whose section area is twice that of each individual outer leg.



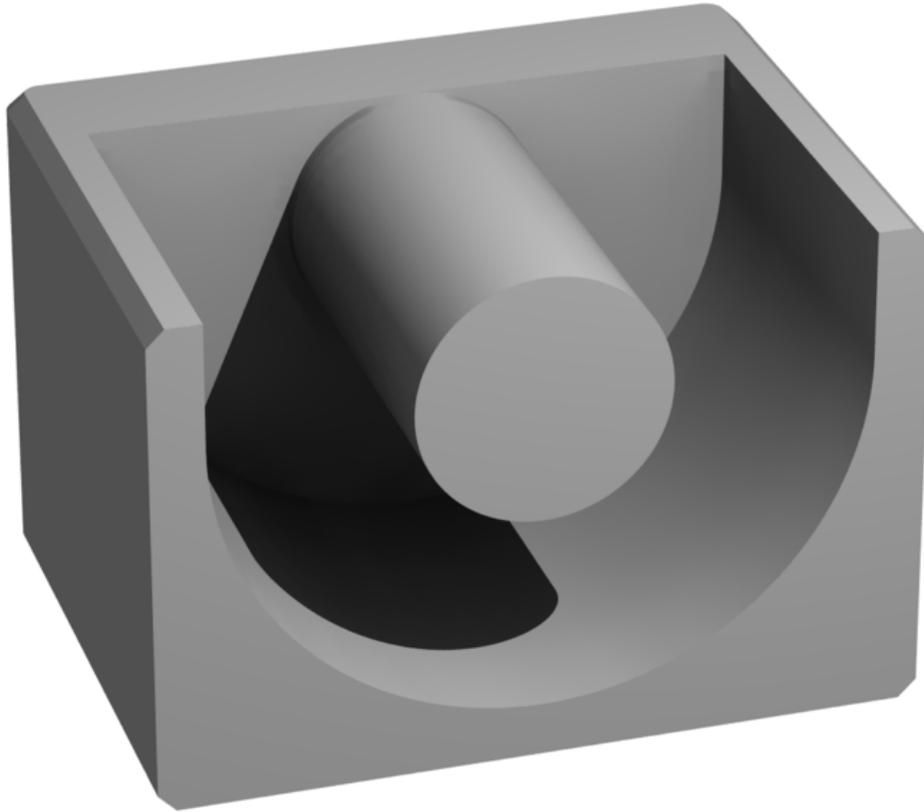
Classical *E* core



The *EFD'* core allows for construction of inductors or transformers with a lower profile



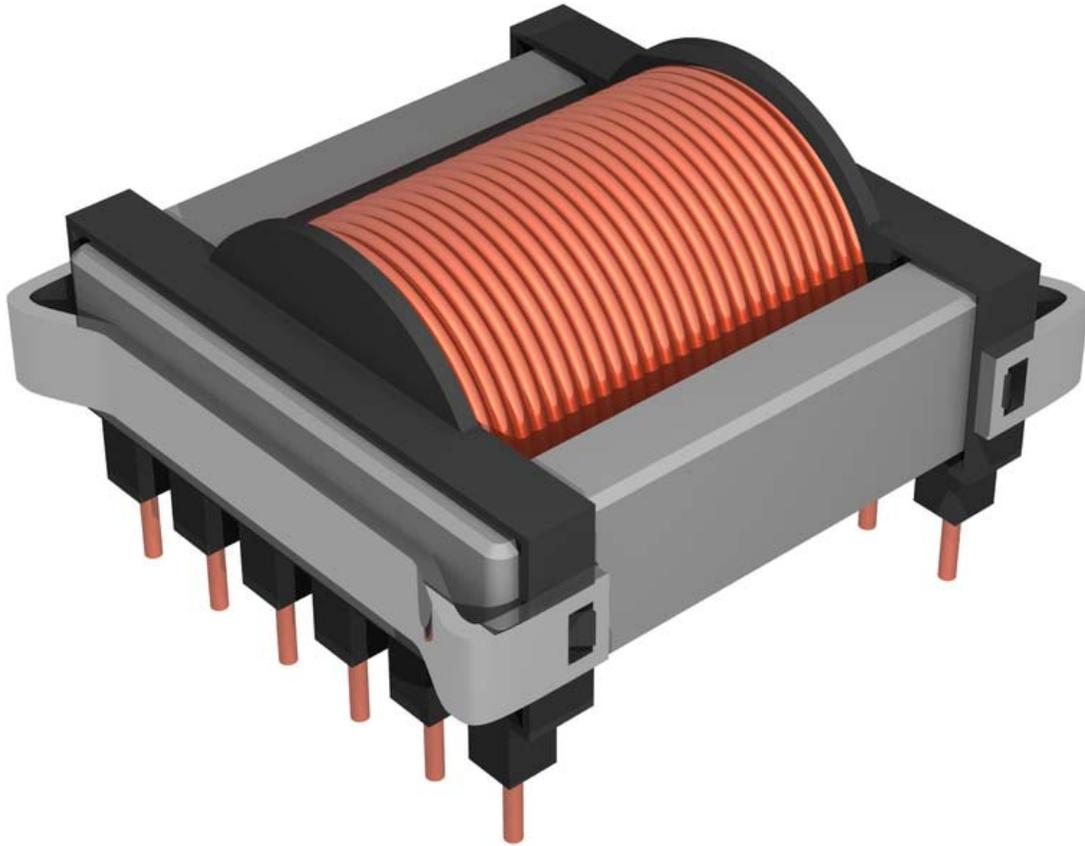
The *ER* core has a cylindrical central leg.



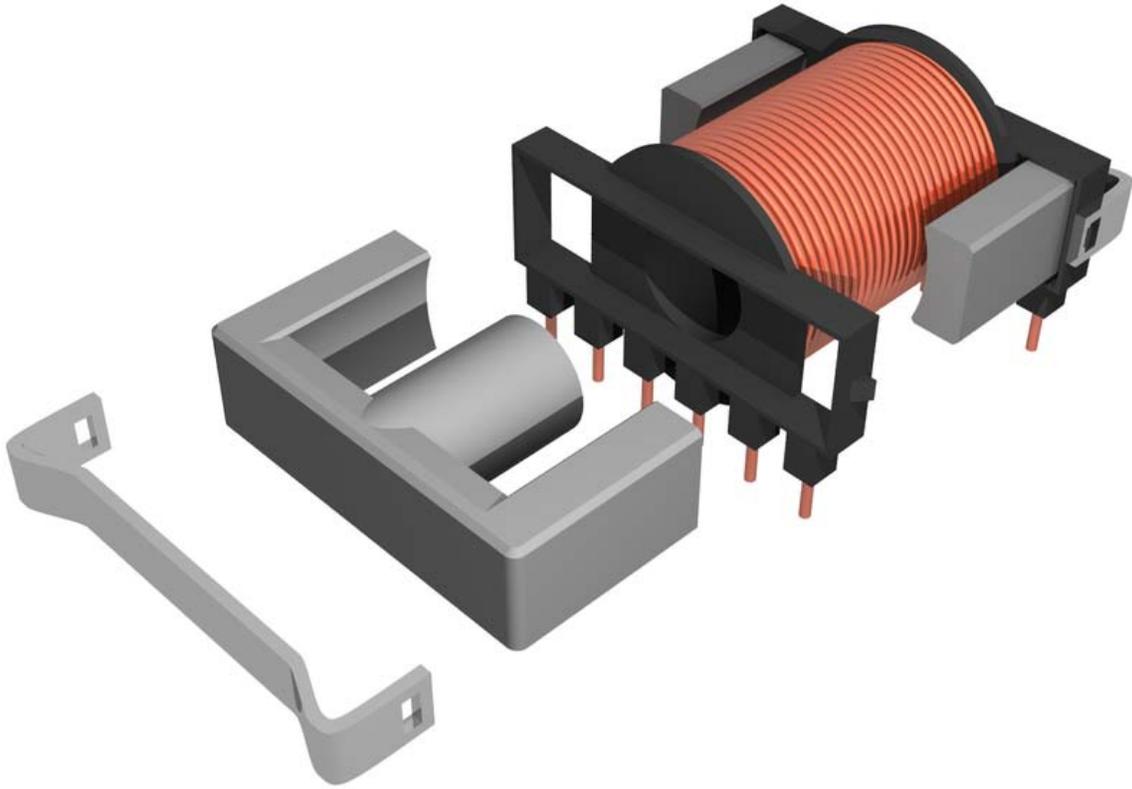
the *EP* core is halfway between a *E* and a *pot* core

### **"E" and "I" core**

Sheets of suitable iron stamped out in shapes like the (sans-serif) letters "E" and "I", are stacked with the "I" against the open end of the "E" to form a 3-legged structure. Coils can be wound around any leg, but usually the center leg is used. This type of core is much used for power transformers, autotransformers, and inductors.



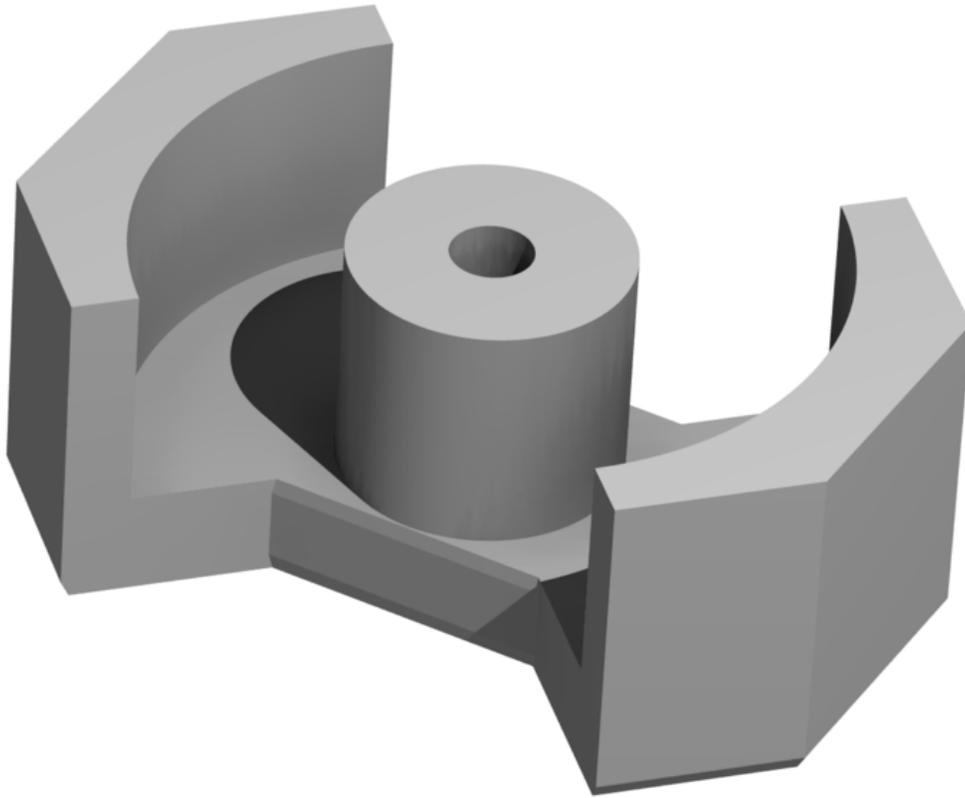
Construction of an inductor using two *ER* cores, a plastic bobbin and two clips. The bobbin has pins to be soldered to a printed circuit board.



Exploded view of the previous figure showing the structure

### **Pair of "E" cores**

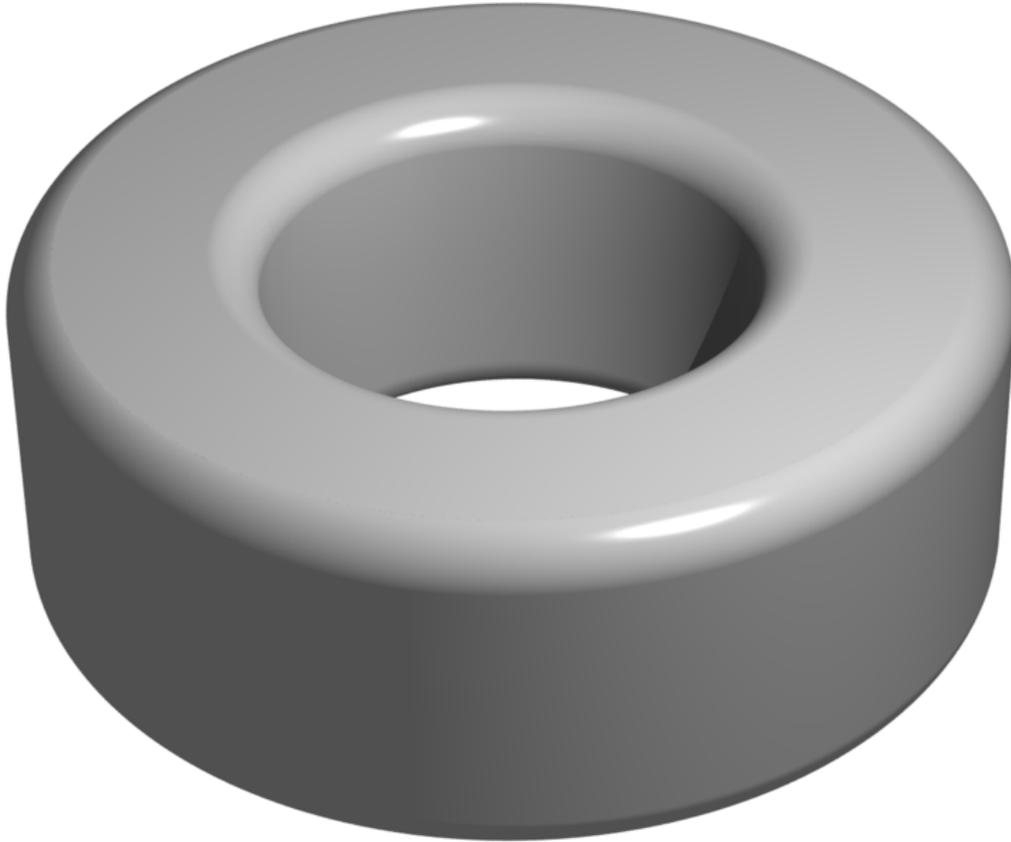
Again used for iron cores. Similar to using an "E" and "I" together, a pair of "E" cores will accommodate a larger coil former and can produce a larger inductor or transformer. If an air gap is required, the centre leg of the "E" is shortened so that the air gap sits in the middle of the coil to minimise fringing and reduce electromagnetic interference.



a pot core of 'RM' type

### **Pot core**

Usually ferrite or similar. This is used for inductors and transformers. The shape of a pot core is round with an internal hollow that almost completely encloses the coil. Usually a pot core is made in two halves which fit together around a coil former (bobbin). This design of core has a shielding effect, preventing radiation and reducing electromagnetic interference.



A toroidal core

### **Toroidal core**

This design is based on a toroid (the same shape as a doughnut). The coil is wound through the hole in the torus and around the outside. An ideal coil is distributed evenly all around the circumference of the torus. The symmetry of this geometry creates a magnetic field of circular loops inside the core, and the lack of sharp bends will constrain virtually all of the field to the core material. This not only makes a highly efficient transformer, but also reduces the electromagnetic interference radiated by the coil.

It is popular for applications where the desirable features are: high specific power per mass and volume, low mains hum, and minimal electromagnetic interference. One such application is the power supply for a hi-fi audio amplifier. The main drawback that limits their use for general purpose applications, is the inherent difficulty of winding wire through the center of a torus.

Unlike a split core (a core made of two elements, like a pair of  $E$  cores), specialized machinery is required for automated winding of a toroidal core. Toroids have less audible noise, such as mains hum, because the magnetic forces do not exert bending moment on the core. The core is only in compression or tension, and the circular shape is more stable mechanically.

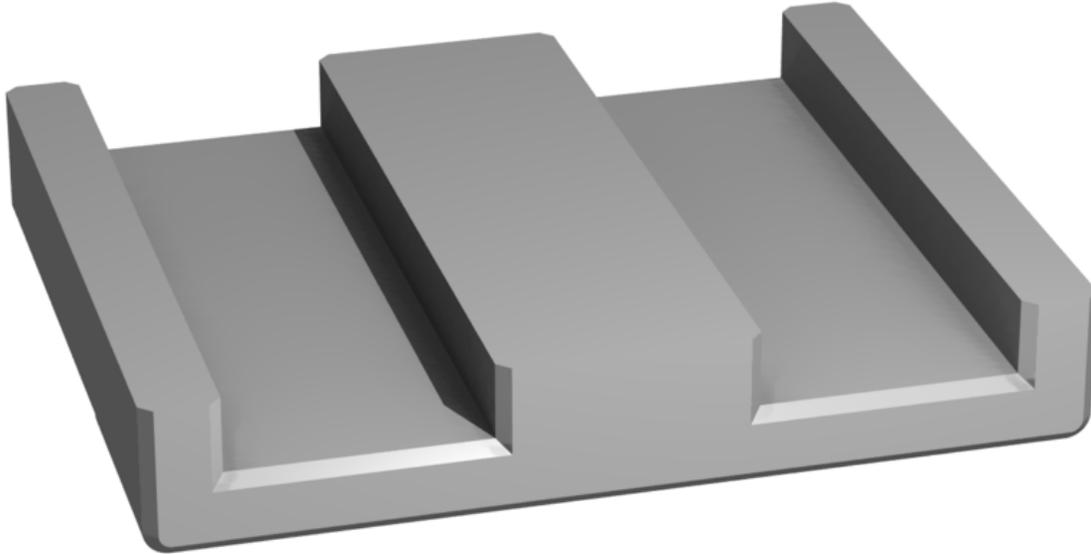
## Ring or bead



A ferrite ring on a computer data cable.

The ring is essentially identical in shape and performance to the toroid, except that inductors commonly pass only through the center of the core, without wrapping around the core multiple times.

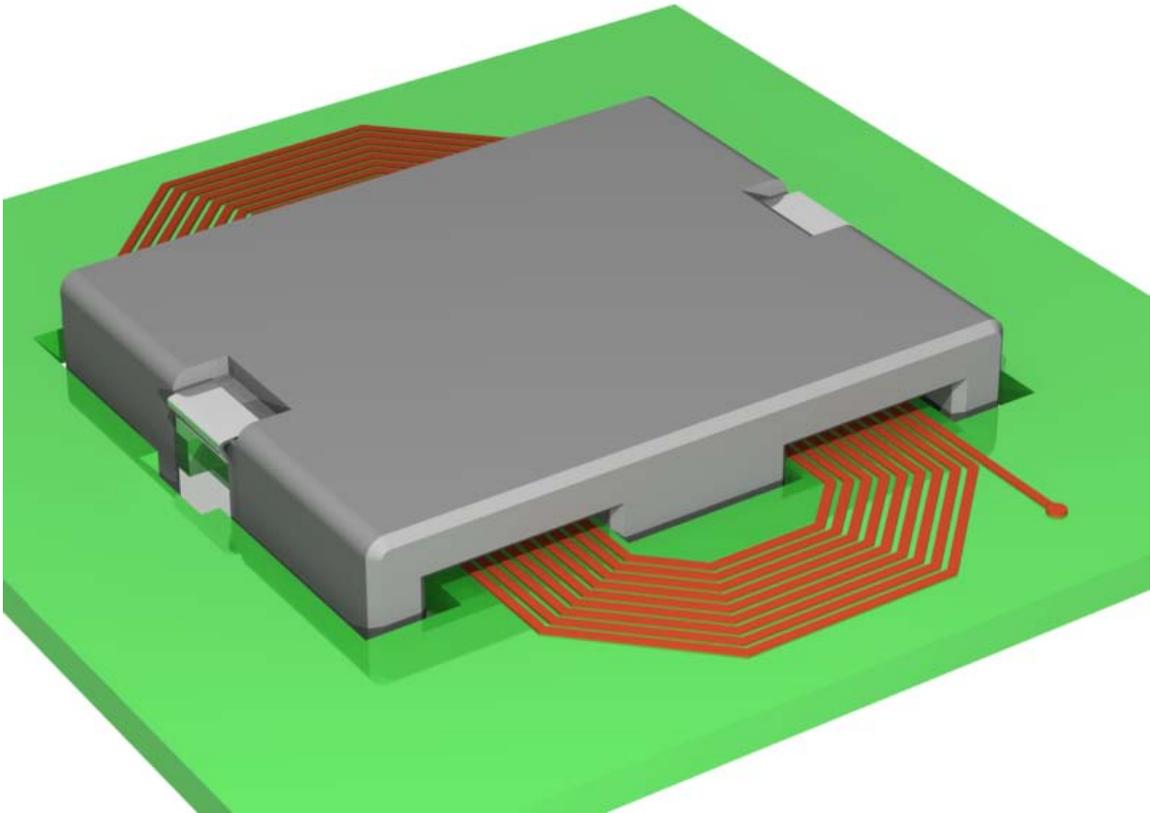
The ring core may also be composed of two separate C-shaped hemispheres secured together within a plastic shell, permitting it to be placed on finished cables with large connectors already installed, that would prevent threading the cable through the small inner diameter of a solid ring.



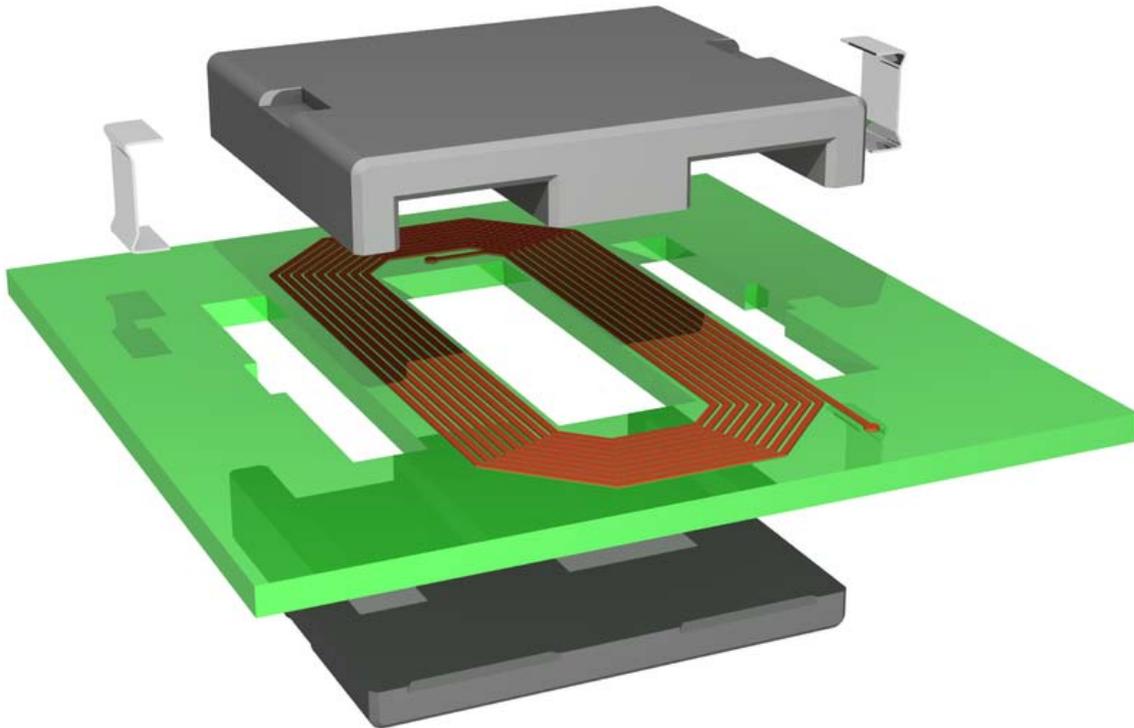
A planar 'E' core

### **Planar core**

A planar core consists of two flat pieces of magnetic material, one above and one below the coil. It is typically used with a flat coil that is part of a printed circuit board. This design is excellent for mass production and allows a high power, small volume transformer to be constructed for low cost. It is not as ideal as either a **pot core** or **toroidal core** but costs less to produce.



A planar inductor



Exploded view that shows the spiral track made directly on the printed circuit board

### **Core loss**

In a transformer or inductor, some of the power that would ideally be transferred through the device is lost in the core, resulting in heat and sometimes noise. There are various reasons for such losses, the primary ones being:

#### **Hysteresis loss**

When the magnetic field through the core changes, the magnetization of the core material changes by expansion and contraction of the tiny magnetic domains it is composed of, due to movement of the domain walls. This is a lossy process, because the domain walls get "snagged" on defects in the crystal structure and then "snap" past them, dissipating energy as heat. This is called hysteresis loss. It can be seen in the graph of the  $B$  field versus the  $H$  field for the material, which has the form of a closed loop. The amount of energy lost in the material in one cycle of the applied field is proportional to the area inside the hysteresis loop. Hysteresis loss increases with higher frequencies as more cycles are undergone per unit time.

## **Eddy current loss**

The induction of eddy currents within the core causes a resistive loss. The higher the resistance of the core material the lower the loss. Lamination of the core material can reduce eddy current loss, and also making the core of a nonconductive magnetic material like ferrite.

## ***Magnetic core materials***

Having no magnetically active core material (an "air core") provides very low inductance in most situations, so a wide range of high-permeability materials are used to concentrate the field. Most high-permeability material are ferromagnetic or ferrimagnetic.

## **Soft iron**

"Soft" iron is used in magnetic assemblies, electromagnets and in some electric motors; and it can create a concentrated field that is as much as 50,000 times more intense than an air core.

Iron is desirable to make magnetic cores, as it can withstand high levels of magnetic field without saturating (up to 2.16 teslas at ambient temperature.)

It is also used because, unlike "hard" iron, it does not remain magnetised when the field is removed, which is often important in applications where the magnetic field is required to be repeatedly switched.

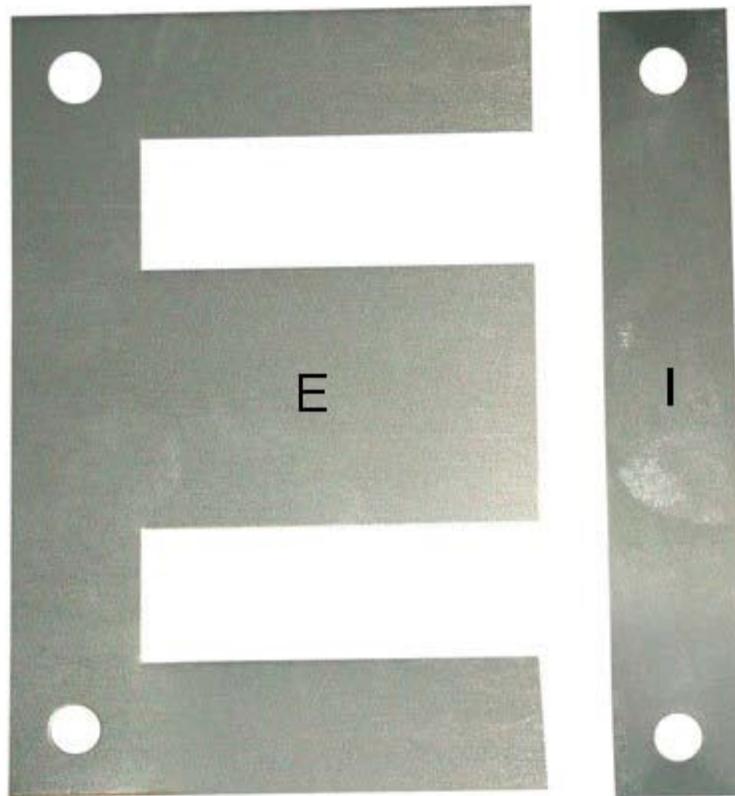
Unfortunately, due to the electrical conductivity of the metal, at AC frequencies a bulk block or rod of soft iron can often suffer from large eddy currents circulating within it that waste energy and cause undesirable heating of the iron.

## **Laminated silicon steel**

Because iron is a relatively good conductor, it cannot be used in bulk form with a rapidly changing field, such as in a transformer, as intense eddy currents would appear due to the magnetic field, resulting in huge losses (this is used in induction heating).

Two techniques are commonly used together to increase the resistivity of iron: lamination and alloying of the iron with silicon.

## Lamination



**Typical EI Lamination Pair**

Typical EI Lamination.

Laminated magnetic cores are made of thin, insulated iron sheets. Using this technique, the magnetic core is equivalent to many individual magnetic circuits, each one receiving only a small fraction of the magnetic flux (because their section is a fraction of the whole core section). Furthermore, these circuits have a resistance that is higher than that of a non-laminated core, also because of their reduced section. From this, it can be seen that the thinner the laminations, the lower the eddy currents.

### **Silicon alloying**

A small addition of silicon to iron (around 3%) results in a dramatic increase of the resistivity, up to four times higher. Further increase in silicon concentration impairs the steel's mechanical properties, causing difficulties for rolling due to brittleness.

Among the two types of silicon steel, grain-oriented (GO) and grain non-oriented (GNO), GO is most desirable for magnetic cores. It is anisotropic, offering better magnetic properties than GNO in one direction. As the magnetic field in inductor and transformer cores is static (compared to that in electric motors), it is possible to use GO steel in the preferred orientation.

## **Carbonyl iron**

Powdered cores made of carbonyl iron, a highly pure iron, have high stability of parameters across a wide range of temperatures and magnetic flux levels, with excellent Q factors between 50 kHz and 200 MHz. Carbonyl iron powders are basically constituted of micrometer-size spheres of iron coated in a thin layer of electrical insulation. This is equivalent to a microscopic laminated magnetic circuit, hence reducing the eddy currents, particularly at very high frequencies.

A popular application of carbonyl iron-based magnetic cores is in high-frequency and broadband inductors and transformers.

## **Iron powder**

Powdered cores made of hydrogen reduced iron have higher permeability but lower Q. They are used mostly for electromagnetic interference filters and low-frequency chokes, mainly in switched-mode power supplies.

## **Ferrite**

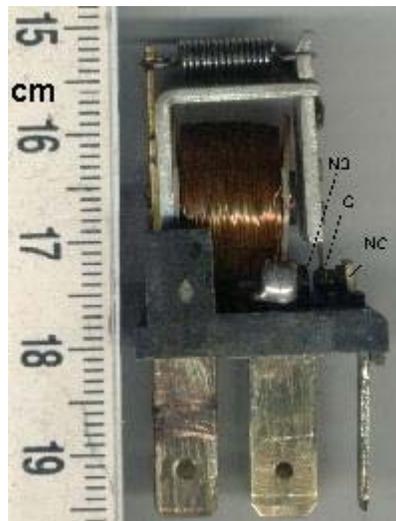
Ferrite ceramics are used for high-frequency applications. The ferrite materials can be engineered with a wide range of parameters.

## **Vitreous Metal**

Amorphous metal is a variety of alloys that are non crystalline or glassy. These are being used to create high efficiency transformers. The materials can be highly responsive to magnetic fields for low hysteresis losses and they can also have lower conductivity to reduce eddy current losses. China is currently making wide spread industrial and power grid usage of these transformers for new installations.

## Chapter 9

# Relay

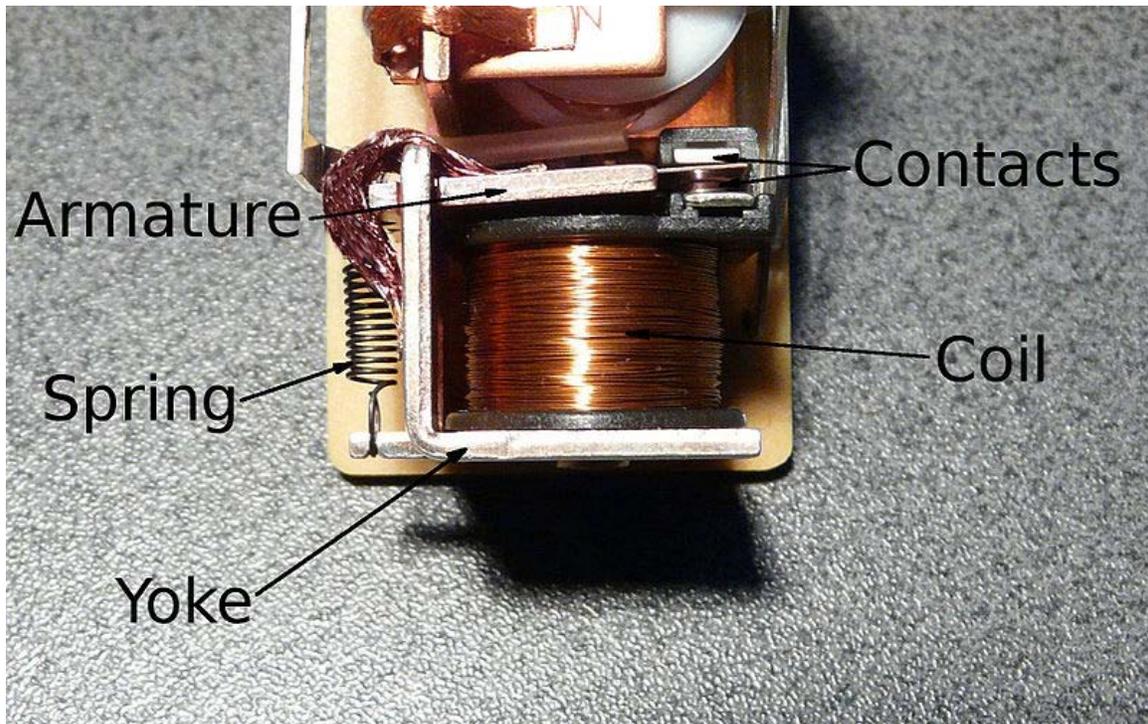


Automotive-style miniature relay, dust cover is taken off

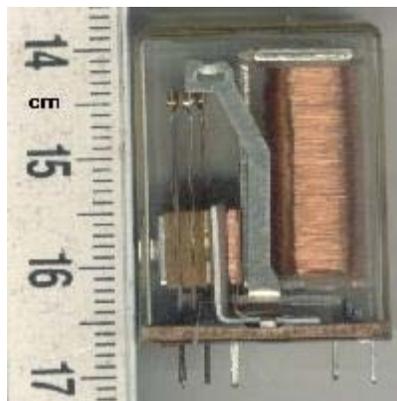
A **relay** is an electrically operated switch. Many relays use an electromagnet to operate a switching mechanism mechanically, but other operating principles are also used. Relays are used where it is necessary to control a circuit by a low-power signal (with complete electrical isolation between control and controlled circuits), or where several circuits must be controlled by one signal. The first relays were used in long distance telegraph circuits, repeating the signal coming in from one circuit and re-transmitting it to another. Relays were used extensively in telephone exchanges and early computers to perform logical operations.

A type of relay that can handle the high power required to directly drive an electric motor is called a contactor. Solid-state relays control power circuits with no moving parts, instead using a semiconductor device to perform switching. Relays with calibrated operating characteristics and sometimes multiple operating coils are used to protect electrical circuits from overload or faults; in modern electric power systems these functions are performed by digital instruments still called "protective relays".

### ***Basic design and operation***



Simple electromechanical relay



Small relay as used in electronics

A simple electromagnetic relay consists of a coil of wire surrounding a soft iron core, an iron yoke which provides a low reluctance path for magnetic flux, a movable iron armature, and one or more sets of contacts (there are two in the relay pictured). The armature is hinged to the yoke and mechanically linked to one or more sets of moving contacts. It is held in place by a spring so that when the relay is de-energized there is an air gap in the magnetic circuit. In this condition, one of the two sets of contacts in the relay pictured is closed, and the other set is open. Other relays may have more or fewer sets of contacts depending on their function. The relay in the picture also has a wire

connecting the armature to the yoke. This ensures continuity of the circuit between the moving contacts on the armature, and the circuit track on the printed circuit board (PCB) via the yoke, which is soldered to the PCB.

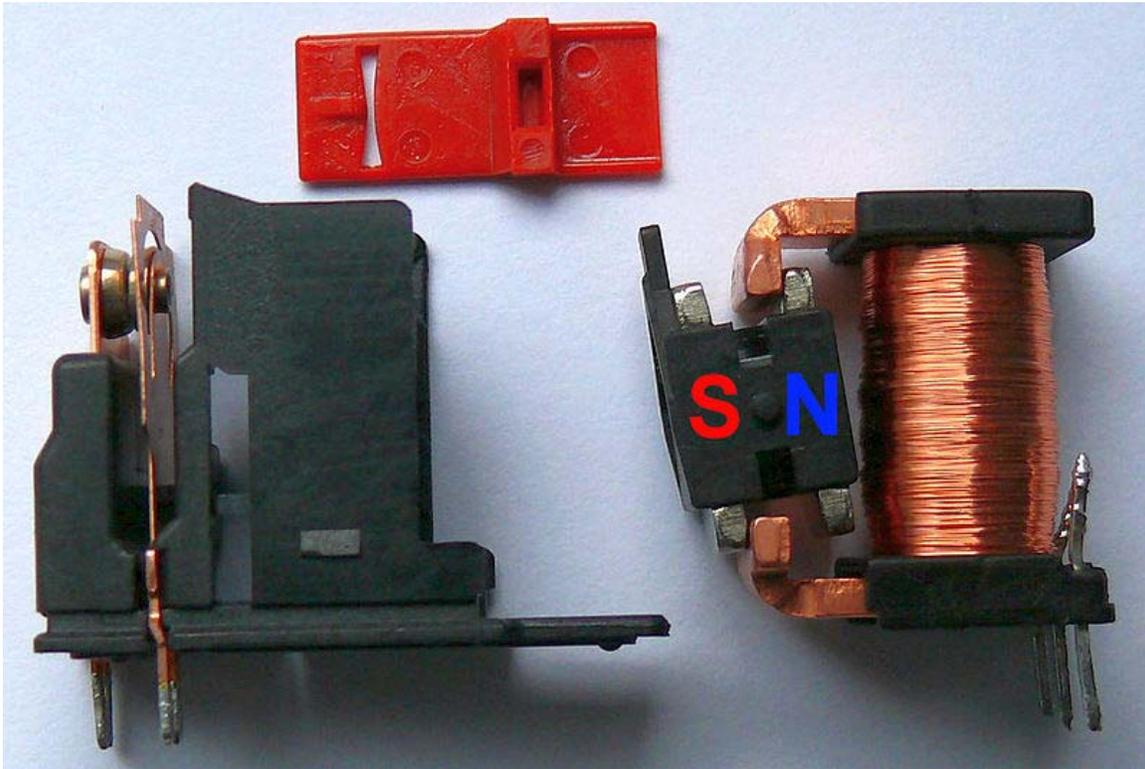
When an electric current is passed through the coil it generates a magnetic field that attracts the armature, and the consequent movement of the movable contact(s) either makes or breaks (depending upon construction) a connection with a fixed contact. If the set of contacts was closed when the relay was de-energized, then the movement opens the contacts and breaks the connection, and vice versa if the contacts were open. When the current to the coil is switched off, the armature is returned by a force, approximately half as strong as the magnetic force, to its relaxed position. Usually this force is provided by a spring, but gravity is also used commonly in industrial motor starters. Most relays are manufactured to operate quickly. In a low-voltage application this reduces noise; in a high voltage or current application it reduces arcing.

When the coil is energized with direct current, a diode is often placed across the coil to dissipate the energy from the collapsing magnetic field at deactivation, which would otherwise generate a voltage spike dangerous to semiconductor circuit components. Some automotive relays include a diode inside the relay case. Alternatively, a contact protection network consisting of a capacitor and resistor in series (snubber circuit) may absorb the surge. If the coil is designed to be energized with alternating current (AC), a small copper "shading ring" can be crimped to the end of the solenoid, creating a small out-of-phase current which increases the minimum pull on the armature during the AC cycle.

A solid-state relay uses a thyristor or other solid-state switching device, activated by the control signal, to switch the controlled load, instead of a solenoid. An optocoupler (a light-emitting diode (LED) coupled with a photo transistor) can be used to isolate control and controlled circuits.

## Types

### Latching relay



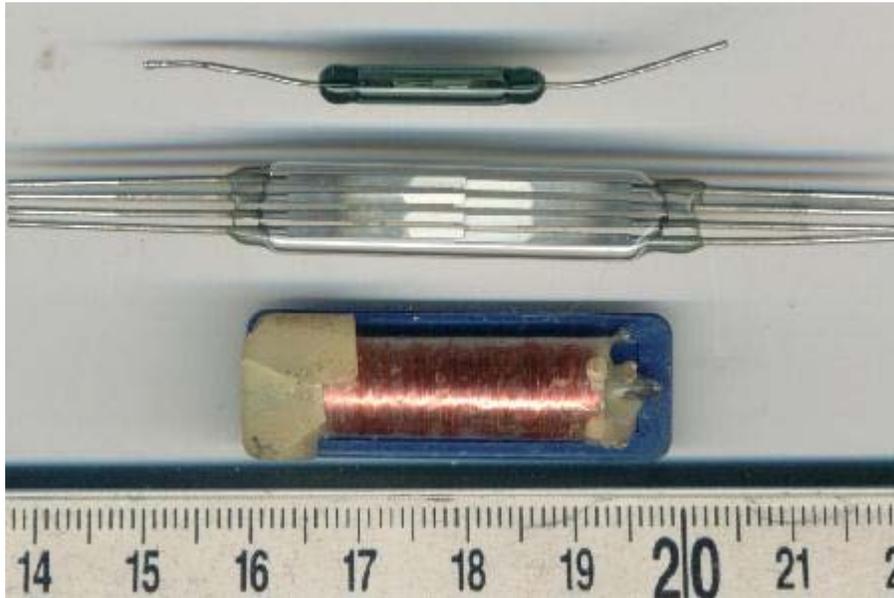
Latching relay with permanent magnet

A *latching relay* has two relaxed states (bistable). These are also called "impulse", "keep", or "stay" relays. When the current is switched off, the relay remains in its last state. This is achieved with a solenoid operating a ratchet and cam mechanism, or by having two opposing coils with an over-center spring or permanent magnet to hold the armature and contacts in position while the coil is relaxed, or with a remanent core. In the ratchet and cam example, the first pulse to the coil turns the relay on and the second pulse turns it off. In the two coil example, a pulse to one coil turns the relay on and a pulse to the opposite coil turns the relay off. This type of relay has the advantage that one coil consumes power only for an instant, while it is being switched, and the relay contacts retain this setting across a power outage. A remanent core latching relay requires a current pulse of opposite polarity to make it change state.

### Reed relay

A **reed relay** is a reed switch enclosed in a solenoid. The switch has a set of contacts inside an evacuated or inert gas-filled glass tube which protects the contacts against atmospheric corrosion; the contacts are made of magnetic material that makes them move under the influence of the field of the enclosing solenoid. Reed relays can switch faster

than larger relays, require only little power from the control circuit, but have low switching current and voltage ratings.



Top, middle: reed switches, bottom: reed relay

### **Mercury-wetted relay**

A **mercury-wetted reed relay** is a form of reed relay in which the contacts are wetted with mercury. Such relays are used to switch low-voltage signals (one volt or less) where the mercury reduces the contact resistance and associated voltage drop, for low-current signals where surface contamination may make for a poor contact, or for high-speed applications where the mercury eliminates contact bounce. Mercury wetted relays are position-sensitive and must be mounted vertically to work properly. Because of the toxicity and expense of liquid mercury, these relays are now rarely used.

### **Polarized relay**

A **polarized relay** placed the armature between the poles of a permanent magnet to increase sensitivity. Polarized relays were used in middle 20th Century telephone exchanges to detect faint pulses and correct telegraphic distortion. The poles were on screws, so a technician could first adjust them for maximum sensitivity and then apply a bias spring to set the critical current that would operate the relay.

### **Machine tool relay**

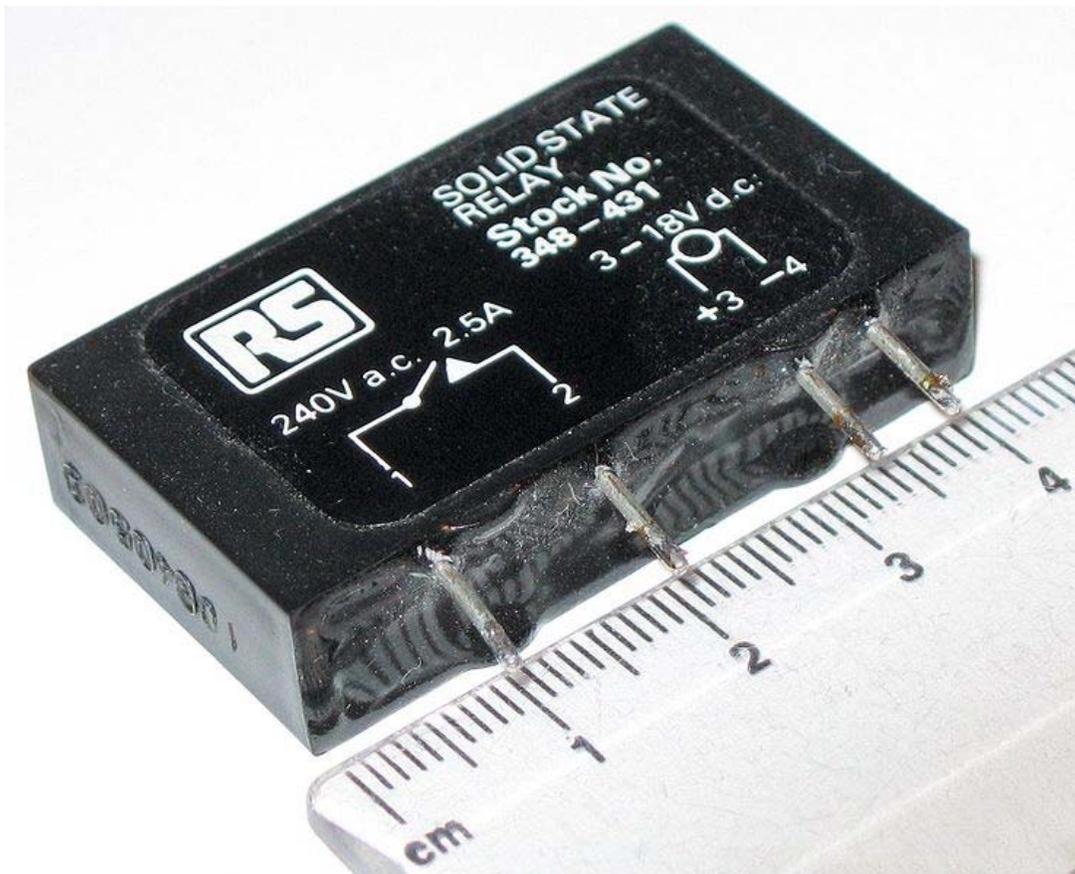
A **machine tool relay** is a type standardized for industrial control of machine tools, transfer machines, and other sequential control. They are characterized by a large number of contacts (sometimes extendable in the field) which are easily converted from normally-open to normally-closed status, easily replaceable coils, and a form factor that

allows compactly installing many relays in a control panel. Although such relays once were the backbone of automation in such industries as automobile assembly, the programmable logic controller (PLC) mostly displaced the machine tool relay from sequential control applications.

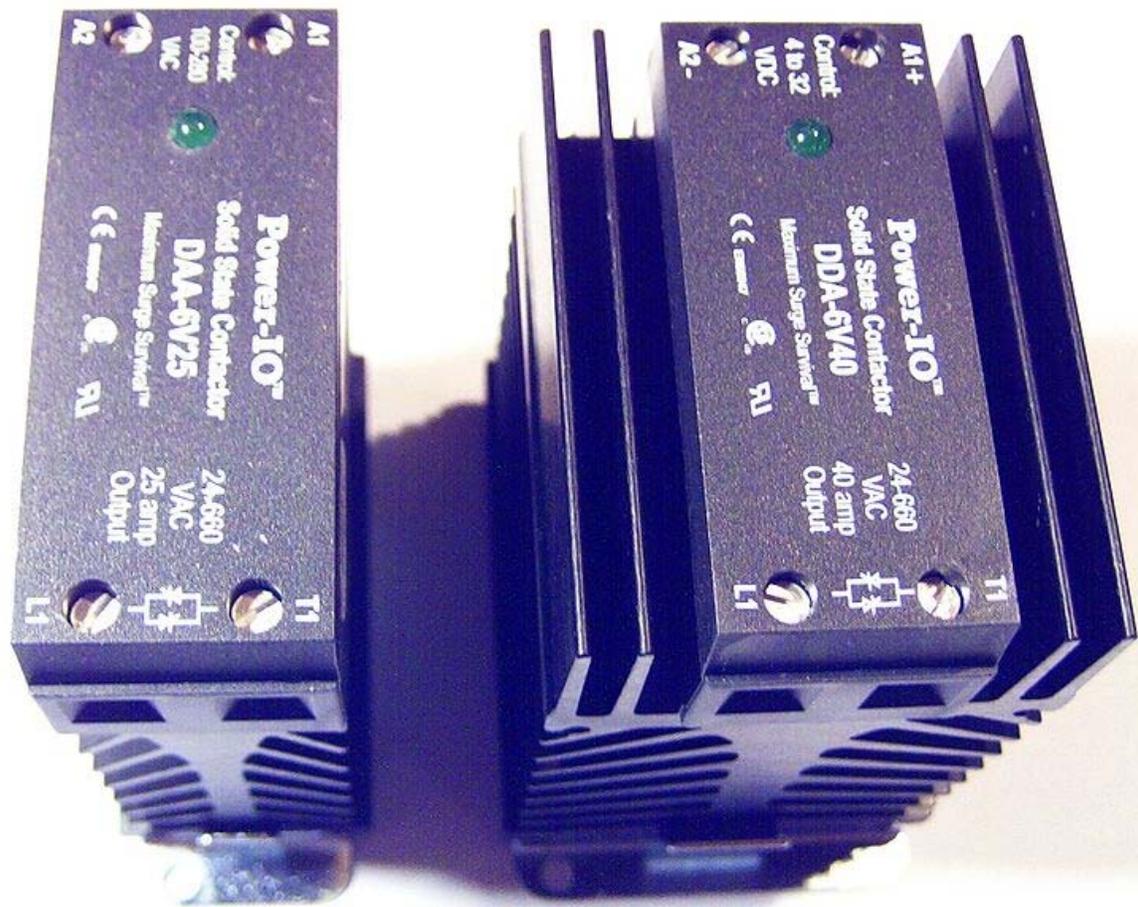
### Contactor relay

A **contactor** is a very heavy-duty relay used for switching electric motors and lighting loads, although contactors are not generally called relays. Continuous current ratings for common contactors range from 10 amps to several hundred amps. High-current contacts are made with alloys containing silver. The unavoidable arcing causes the contacts to oxidize; however, silver oxide is still a good conductor. Such devices are often used for motor starters. A motor starter is a contactor with overload protection devices attached. The overload sensing devices are a form of heat operated relay where a coil heats a bi-metal strip, or where a solder pot melts, releasing a spring to operate auxiliary contacts. These auxiliary contacts are in series with the coil. If the overload senses excess current in the load, the coil is de-energized. Contactor relays can be extremely loud to operate, making them unfit for use where noise is a chief concern.

### Solid-state relay



Solid state relay, which has no moving parts



25 A or 40 A solid state contactors

A **solid state relay (SSR)** is a solid state electronic component that provides a similar function to an electromechanical relay but does not have any moving components, increasing long-term reliability. With early SSR's, the tradeoff came from the fact that every transistor has a small voltage drop across it. This voltage drop limited the amount of current a given SSR could handle. As transistors improved, higher current SSR's, able to handle 100 to 1,200 Amperes, have become commercially available. Compared to electromagnetic relays, they may be falsely triggered by transients.

### **Solid state contactor relay**

A **solid state contactor** is a heavy-duty solid state relay, including the necessary heat sink, used for switching electric heaters, small electric motors and lighting loads; where frequent on/off cycles are required. There are no moving parts to wear out and there is no contact bounce due to vibration. They are activated by AC control signals or DC control signals from Programmable logic controller (PLCs), PCs, Transistor-transistor logic (TTL) sources, or other microprocessor and microcontroller controls.

## **Buchholz relay**

A **Buchholz relay** is a safety device sensing the accumulation of gas in large oil-filled transformers, which will alarm on slow accumulation of gas or shut down the transformer if gas is produced rapidly in the transformer oil.

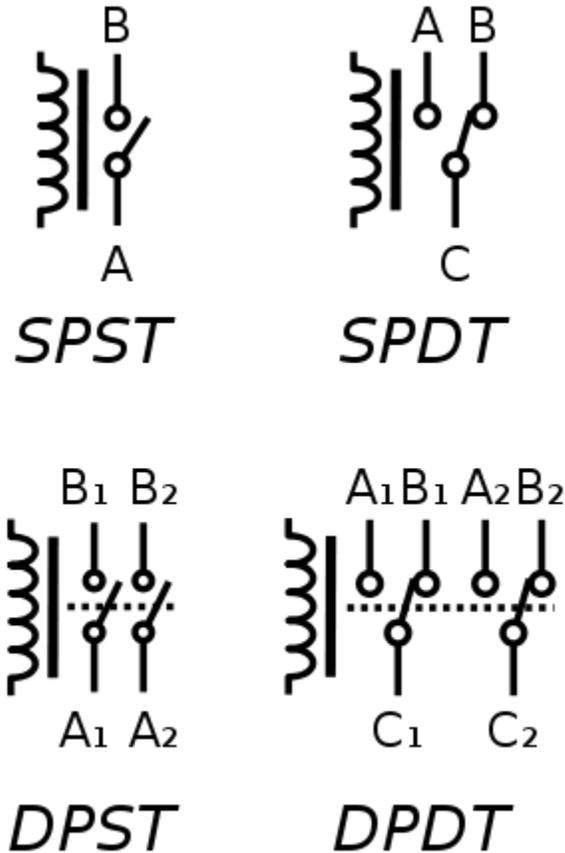
## **Forced-guided contacts relay**

A **forced-guided contacts relay** has relay contacts that are mechanically linked together, so that when the relay coil is energized or de-energized, all of the linked contacts move together. If one set of contacts in the relay becomes immobilized, no other contact of the same relay will be able to move. The function of forced-guided contacts is to enable the safety circuit to check the status of the relay. Forced-guided contacts are also known as "positive-guided contacts", "captive contacts", "locked contacts", or "safety relays".

## **Overload protection relay**

Electric motors need overcurrent protection to prevent damage from over-loading the motor, or to protect against short circuits in connecting cables or internal faults in the motor windings. One type of electric motor overload protection relay is operated by a heating element in series with the electric motor. The heat generated by the motor current heats a bimetallic strip or melts solder, releasing a spring to operate contacts. Where the overload relay is exposed to the same environment as the motor, a useful though crude compensation for motor ambient temperature is provided.

## ***Pole and throw***



Circuit symbols of relays. (C denotes the common terminal in SPDT and DPDT types.)

Since relays are switches, the terminology applied to switches is also applied to relays. A relay will switch one or more *poles*, each of whose contacts can be *thrown* by energizing the coil in one of three ways:

- Normally-open (**NO**) contacts connect the circuit when the relay is activated; the circuit is disconnected when the relay is inactive. It is also called a **Form A** contact or "make" contact. **NO** contacts can also be distinguished as "early-make" or **NOEM**, which means that the contacts will close before the button or switch is fully engaged.
- Normally-closed (**NC**) contacts disconnect the circuit when the relay is activated; the circuit is connected when the relay is inactive. It is also called a **Form B** contact or "break" contact. **NC** contacts can also be distinguished as "late-break" or **NCLB**, which means that the contacts will stay closed until the button or switch is fully disengaged.
- Change-over (**CO**), or double-throw (**DT**), contacts control two circuits: one normally-open contact and one normally-closed contact with a common terminal. It is also called a **Form C** contact or "transfer" contact ("break before make"). If

this type of contact utilizes a "make before break" functionality, then it is called a **Form D** contact.

The following designations are commonly encountered:

- **SPST** – Single Pole Single Throw. These have two terminals which can be connected or disconnected. Including two for the coil, such a relay has four terminals in total. It is ambiguous whether the pole is normally open or normally closed. The terminology "SPNO" and "SPNC" is sometimes used to resolve the ambiguity.
- **SPDT** – Single Pole Double Throw. A common terminal connects to either of two others. Including two for the coil, such a relay has five terminals in total.
- **DPST** – Double Pole Single Throw. These have two pairs of terminals. Equivalent to two SPST switches or relays actuated by a single coil. Including two for the coil, such a relay has six terminals in total. The poles may be Form A or Form B (or one of each).
- **DPDT** – Double Pole Double Throw. These have two rows of change-over terminals. Equivalent to two SPDT switches or relays actuated by a single coil. Such a relay has eight terminals, including the coil.

The "S" or "D" may be replaced with a number, indicating multiple switches connected to a single actuator. For example 4PDT indicates a four pole double throw relay (with 14 terminals).

**EN 50005** are among applicable standards for relay terminal numbering; a typical EN 50005-compliant SPDT relay's terminals would be numbered 11, 12, 14, A1 and A2 for the C, NC, NO, and coil connections, respectively.

## ***Applications***

Relays are used to and for:

- Control a high-voltage circuit with a low-voltage signal, as in some types of modems or audio amplifiers,
- Control a high-current circuit with a low-current signal, as in the starter solenoid of an automobile,
- Detect and isolate faults on transmission and distribution lines by opening and closing circuit breakers (protection relays),



A DPDT AC coil relay with "ice cube" packaging

- Isolate the controlling circuit from the controlled circuit when the two are at different potentials, for example when controlling a mains-powered device from a low-voltage switch. The latter is often applied to control office lighting as the low voltage wires are easily installed in partitions, which may be often moved as needs change. They may also be controlled by room occupancy detectors in an effort to conserve energy,
- Logic functions. For example, the boolean AND function is realised by connecting normally open relay contacts in series, the OR function by connecting normally open contacts in parallel. The change-over or Form C contacts perform the XOR (exclusive or) function. Similar functions for NAND and NOR are accomplished using normally closed contacts. The Ladder programming language is often used for designing relay logic networks.
  - Early computing. Before vacuum tubes and transistors, relays were used as logical elements in digital computers.

- Safety-critical logic. Because relays are much more resistant than semiconductors to nuclear radiation, they are widely used in safety-critical logic, such as the control panels of radioactive waste-handling machinery.
- Time delay functions. Relays can be modified to delay opening or delay closing a set of contacts. A very short (a fraction of a second) delay would use a copper disk between the armature and moving blade assembly. Current flowing in the disk maintains magnetic field for a short time, lengthening release time. For a slightly longer (up to a minute) delay, a dashpot is used. A dashpot is a piston filled with fluid that is allowed to escape slowly. The time period can be varied by increasing or decreasing the flow rate. For longer time periods, a mechanical clockwork timer is installed.

### ***Relay application considerations***



A large relay with two coils and many sets of contacts, used in an old telephone switching system.



Several 30-contact relays in "Connector" circuits in mid 20th century 1XB switch and 5XB switch telephone exchanges; cover removed on one

Selection of an appropriate relay for a particular application requires evaluation of many different factors:

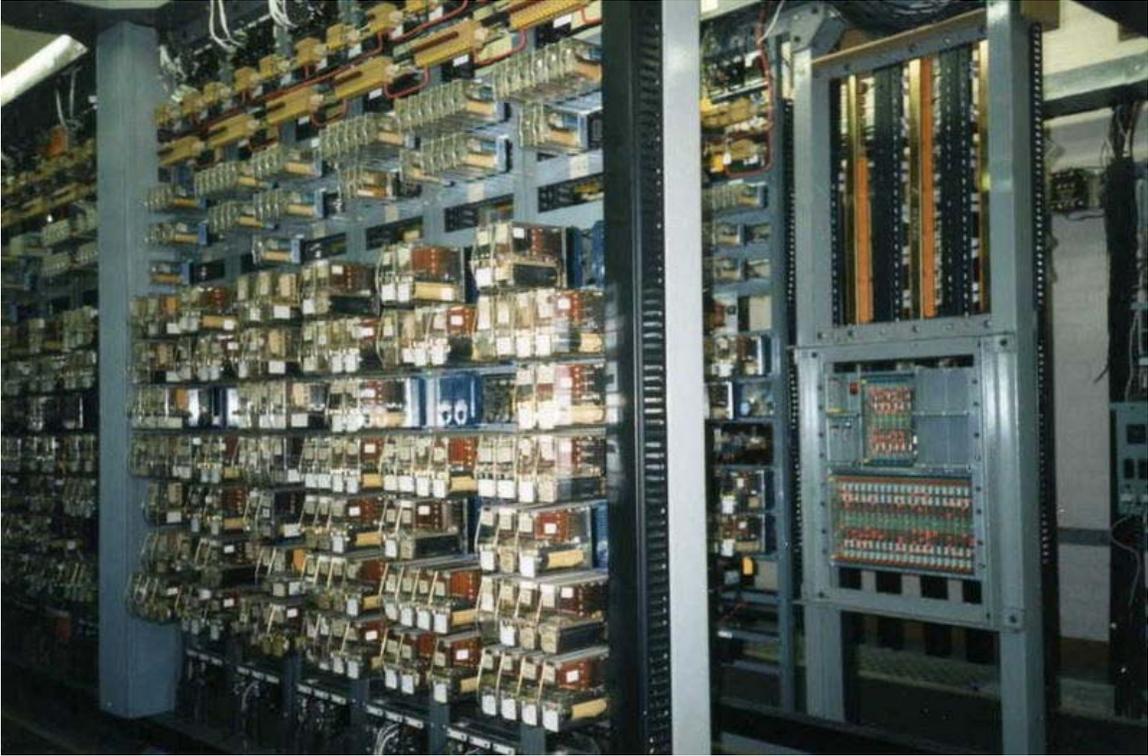
- Number and type of contacts – normally open, normally closed, (double-throw)
- Contact sequence – "Make before Break" or "Break before Make". For example, the old style telephone exchanges required Make-before-break so that the connection didn't get dropped while dialing the number.
- Rating of contacts – small relays switch a few amperes, large contactors are rated for up to 3000 amperes, alternating or direct current
- Voltage rating of contacts – typical control relays rated 300 VAC or 600 VAC, automotive types to 50 VDC, special high-voltage relays to about 15 000 V
- Coil voltage – machine-tool relays usually 24 VAC, 120 or 250 VAC, relays for switchgear may have 125 V or 250 VDC coils, "sensitive" relays operate on a few milliamperes

- Coil current
- Package/enclosure – open, touch-safe, double-voltage for isolation between circuits, explosion proof, outdoor, oil and splash resistant, washable for printed circuit board assembly
- Assembly – Some relays feature a sticker that keeps the enclosure sealed to allow PCB post soldering cleaning, which is removed once assembly is complete.
- Mounting – sockets, plug board, rail mount, panel mount, through-panel mount, enclosure for mounting on walls or equipment
- Switching time – where high speed is required
- "Dry" contacts – when switching very low level signals, special contact materials may be needed such as gold-plated contacts
- Contact protection – suppress arcing in very inductive circuits
- Coil protection – suppress the surge voltage produced when switching the coil current
- Isolation between coil circuit and contacts
- Aerospace or radiation-resistant testing, special quality assurance
- Expected mechanical loads due to acceleration – some relays used in aerospace applications are designed to function in shock loads of 50 g or more
- Accessories such as timers, auxiliary contacts, pilot lamps, test buttons
- Regulatory approvals
- Stray magnetic linkage between coils of adjacent relays on a printed circuit board.

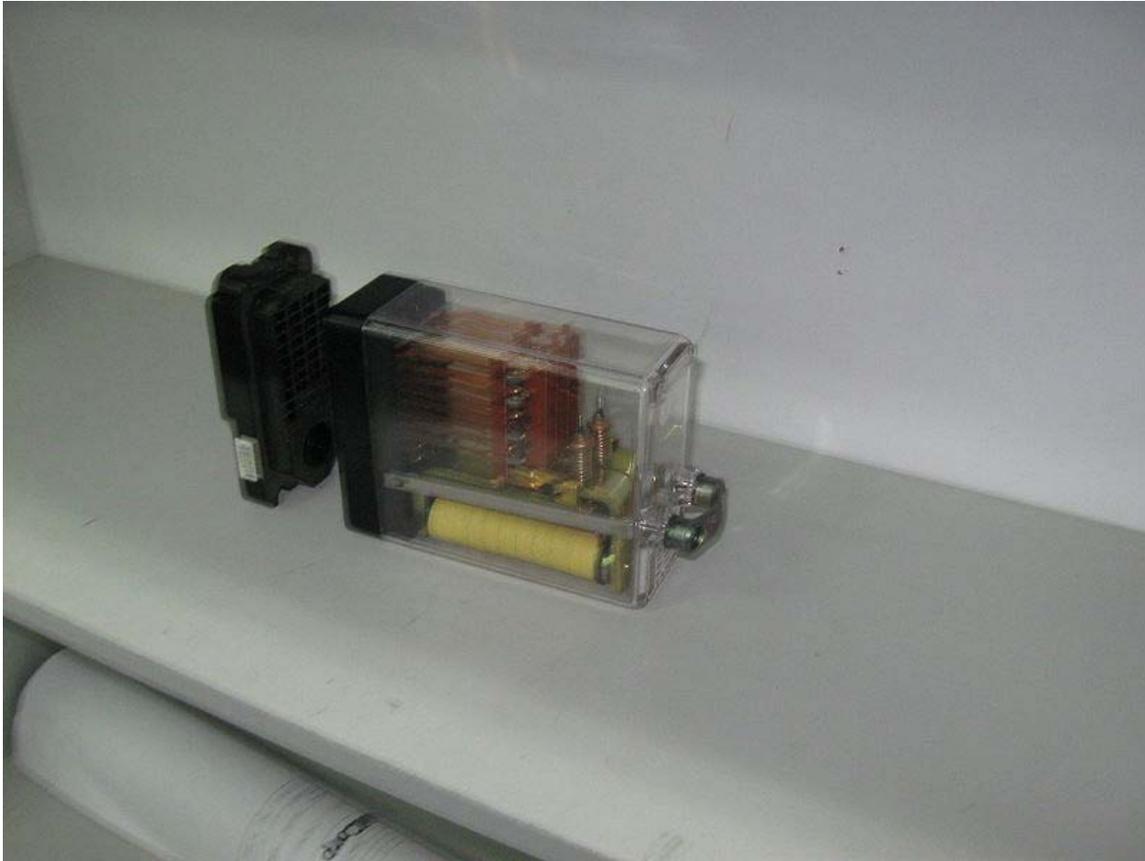
### ***Protective relays***

For protection of electrical apparatus and transmission lines, electromechanical relays with accurate operating characteristics were used to detect overload, short-circuits, and other faults. While many such relays remain in use, digital devices now provide equivalent protective functions.

## *Railway signalling*



Part of a relay interlocking using UK Q-style miniature plug-in relays.



UK Q-style signalling relay and base.

Railway signalling relays are very big and cumbersome compared to the mostly small voltages (less than 120 V) and currents (perhaps 100 mA) that they switch. Contacts are widely spaced to prevent dangerous flashovers and short circuits over a lifetime that may exceed fifty years. BR930 series plug-in relays are widely used on railways following British practice. These are 120 mm high, 180 mm deep and 56 mm wide and weigh about 1400 g, and can have up to 16 separate contacts, say 12 make and 4 break contacts.

Since rail signal circuits must be highly reliable, special techniques are used to detect and prevent failures in the relay system. To protect against false feeds, double switching relay contacts are often used on both the positive and negative side of a circuit, so that two false feeds are needed to cause a false signal. Not all relay circuits can be proved so there is reliance on construction features such as carbon to silver contacts to resist lightning induced contact welding and to provide AC immunity.

Opto-isolators are also used in some instances with railway signalling, especially where only a single contact is to be switched.

## Chapter 10

# Electric Motor



Electric motors

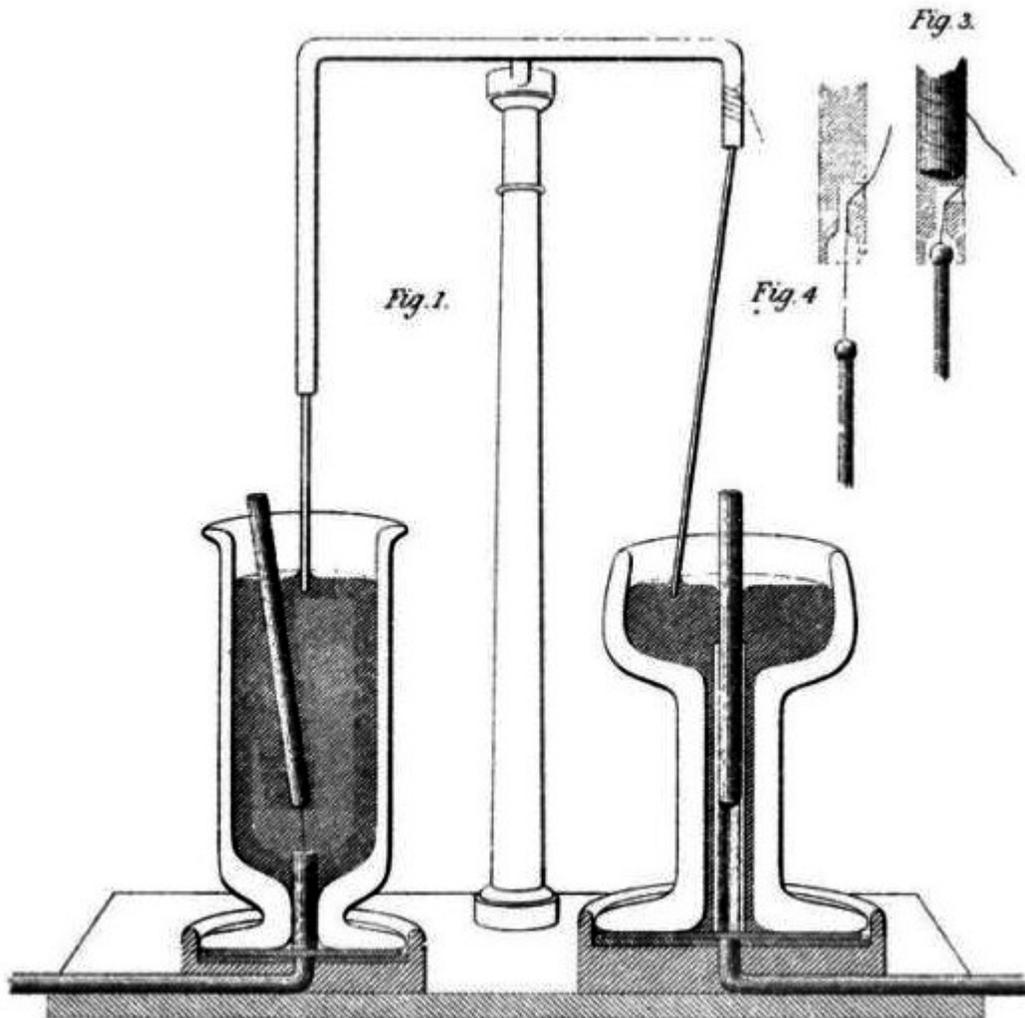
An **electric motor** converts electrical energy into mechanical energy. Most electric motors operate through interacting magnetic fields and current-carrying conductors to generate force, although electrostatic motors use electrostatic forces. The reverse process, producing electrical energy from mechanical energy, is done by generators such as an alternator or a dynamo. Many types of electric motors can be run as generators, and vice versa. For example a starter/generator for a gas turbine, or traction motors used on vehicles, often perform both tasks. Electric motors and generators are commonly referred to as electric machines.

Electric motors are found in applications as diverse as industrial fans, blowers and pumps, machine tools, household appliances, power tools, and disk drives. They may be powered by direct current (e.g., a battery powered portable device or motor vehicle), or by alternating current from a central electrical distribution grid. The smallest motors may be found in electric wristwatches. Medium-size motors of highly standardized dimensions and characteristics provide convenient mechanical power for industrial uses. The very largest electric motors are used for propulsion of ships, pipeline compressors, and water pumps with ratings in the millions of watts. Electric motors may be classified by the source of electric power, by their internal construction, by their application, or by the type of motion they give.

The physical principle of production of mechanical force by the interactions of an electric current and a magnetic field was known as early as 1821. Electric motors of increasing efficiency were constructed throughout the 19th century, but commercial exploitation of electric motors on a large scale required efficient electrical generators and electrical distribution networks.

Some devices, such as magnetic solenoids and loudspeakers, although they generate some mechanical power, are not generally referred to as electric motors, and are usually termed actuators and transducers, respectively.

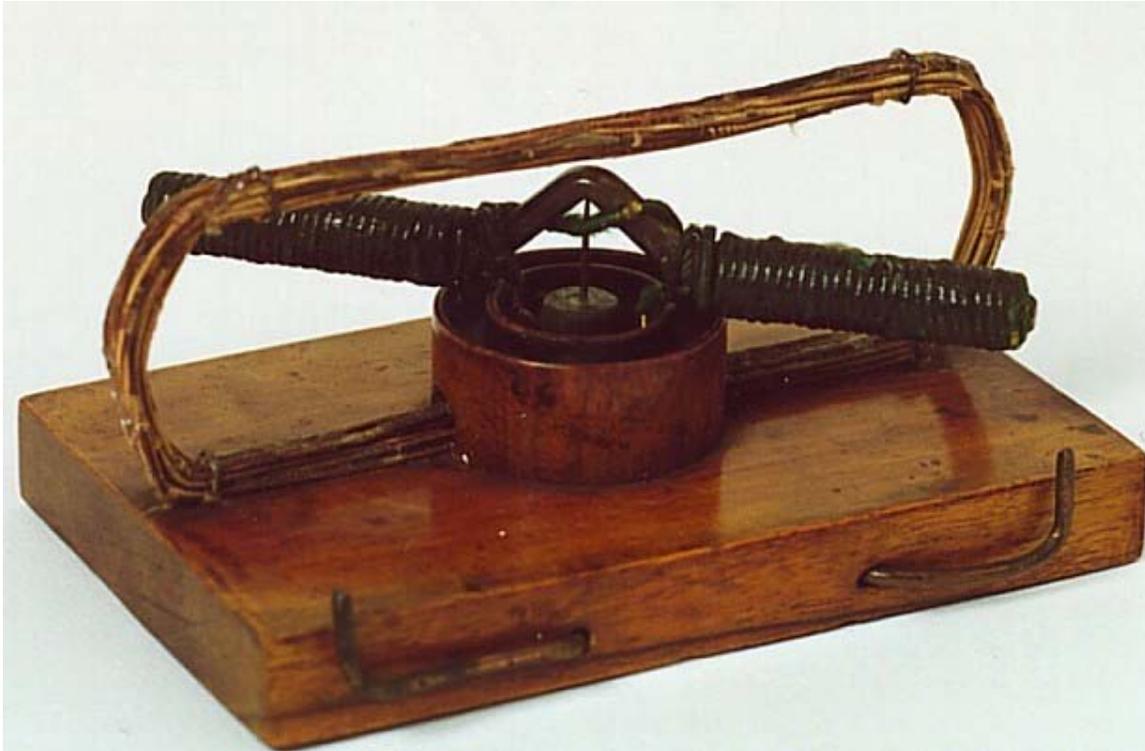
## ***History and development***



Faraday's electromagnetic experiment, 1821

### **Proof of principle**

The conversion of electrical energy into mechanical energy by an electromagnetic means was demonstrated by the British scientist Michael Faraday in 1821. A free-hanging wire was dipped into a pool of mercury, on which a permanent magnet was placed. When a current was passed through the wire, the wire rotated around the magnet, showing that the current gave rise to a close circular magnetic field around the wire. This motor is often demonstrated in school physics classes, but brine (salt water) is sometimes used in place of the toxic mercury. This is the simplest form of a class of devices called homopolar motors. A later refinement is the Barlow's wheel. These were demonstration devices only, unsuited to practical applications due to their primitive construction.



Jedlik's "electromagnetic self-rotor", 1827 (Museum of Applied Arts, Budapest. The historic motor still works perfectly today.)

In 1827, Hungarian physicist Ányos Jedlik started experimenting with devices he called "electromagnetic self-rotors". Although they were used only for instructional purposes, in 1828 Jedlik demonstrated the first device to contain the three main components of practical direct current motors: the stator, rotor and commutator. The device employed no permanent magnets, as the magnetic fields of both the stationary and revolving components were produced solely by the currents flowing through their windings.

### **The first electric motors**

The first commutator-type direct current electric motor capable of turning machinery was invented by the British scientist William Sturgeon in 1832. Following Sturgeon's work, a commutator-type direct-current electric motor made with the intention of commercial use was built by Americans Emily and Thomas Davenport and patented in 1837. Their motors ran at up to 600 revolutions per minute, and powered machine tools and a printing press. Due to the high cost of the zinc electrodes required by primary battery power, the motors were commercially unsuccessful and the Davenports went bankrupt. Several inventors followed Sturgeon in the development of DC motors but all encountered the same cost issues with primary battery power. No electricity distribution had been developed at the time. Like Sturgeon's motor, there was no practical commercial market for these motors.

In 1855 Jedlik built a device using similar principles to those used in his electromagnetic self-rotors that was capable of useful work. He built a model electric motor-propelled vehicle that same year. There is no evidence that this experimentation was communicated to the wider scientific world at that time, or that it influenced the development of electric motors in the following decades.

The modern DC motor was invented by accident in 1873, when Zénobe Gramme connected the dynamo he had invented to a second similar unit, driving it as a motor. The Gramme machine was the first electric motor that was successful in the industry.

In 1886 Frank Julian Sprague invented the first practical DC motor, a non-sparking motor capable of constant speed under variable loads. Other Sprague electric inventions about this time greatly improved grid electric distribution (prior work done while employed by Thomas Edison), allowed power from electric motors to be returned to the electric grid, provided for electric distribution to trolleys via overhead wires and the trolley pole, and provided controls systems for electric operations. This allowed Sprague to use electric motors to invent the first electric trolley system in 1887–88 in Richmond VA, the electric elevator and control system in 1892, and the electric subway with independently powered centrally controlled cars, which was first installed in 1892 in Chicago by the South Side Elevated Railway where it became popularly known as the "L". Sprague's motor and related inventions led to an explosion of interest and use in electric motors for industry, while almost simultaneously another great inventor was developing its primary competitor, which would become much more widespread.

In 1888 Nikola Tesla invented the first practicable AC motor and with it the polyphase power transmission system. Tesla continued his work on the AC motor in the years to follow at the Westinghouse company.

The development of electric motors of acceptable efficiency was delayed for several decades by failure to recognize the extreme importance of a relatively small air gap between rotor and stator. Efficient designs have a comparatively small air gap.

The St. Louis motor, long used in classrooms to illustrate motor principles, is extremely inefficient for the same reason, as well as appearing nothing like a modern motor. Photo of a traditional form of the St. Louis motor:

Application of electric motors revolutionized industry. Industrial processes were no longer limited by power transmission using shaft, belts, compressed air or hydraulic pressure. Instead every machine could be equipped with its own electric motor, providing easy control at the point of use, and improving power transmission efficiency. Electric motors applied in agriculture eliminated human and animal muscle power from such tasks as handling grain or pumping water. Household uses of electric motors reduced heavy labor in the home and made higher standards of convenience, comfort and safety possible. Today, electric motors consume more than half of all electric energy produced.

## ***Categorization of electric motors***

The classic division of electric motors has been that of Alternating Current (AC) types vs Direct Current (DC) types. This is more a *de facto* convention, rather than a rigid distinction. For example, many classic DC motors run on AC power, these motors being referred to as universal motors.

Rated output power is also used to categorize motors, those of less than 746 Watts, for example, are often referred to as fractional horsepower motors (FHP) in reference to the old imperial measurement.

The ongoing trend toward electronic control further muddles the distinction, as modern drivers have moved the commutator out of the motor shell. For this new breed of motor, driver circuits are relied upon to generate sinusoidal AC drive currents, or some approximation thereof. The two best examples are: the brushless DC motor and the stepping motor, both being poly-phase AC motors requiring external electronic control, although historically, stepping motors (such as for maritime and naval gyrocompass repeaters) were driven from DC switched by contacts.

Considering all rotating (or linear) electric motors require synchronism between a moving magnetic field and a moving current sheet for average torque production, there is a clearer distinction between an asynchronous motor and synchronous types. An asynchronous motor requires slip between the moving magnetic field and a winding set to induce current in the winding set by mutual inductance; the most ubiquitous example being the common AC induction motor which must slip to generate torque. In the synchronous types, induction (or slip) is not a requisite for magnetic field or current production (e.g. permanent magnet motors, synchronous brush-less wound-rotor doubly-fed electric machine).

### ***DC motors***

A DC motor is designed to run on DC electric power. Two examples of pure DC designs are Michael Faraday's homopolar motor (which is uncommon), and the ball bearing motor, which is (so far) a novelty. By far the most common DC motor types are the brushed and brushless types, which use internal and external commutation respectively to periodically reverse the current in the rotor windings.

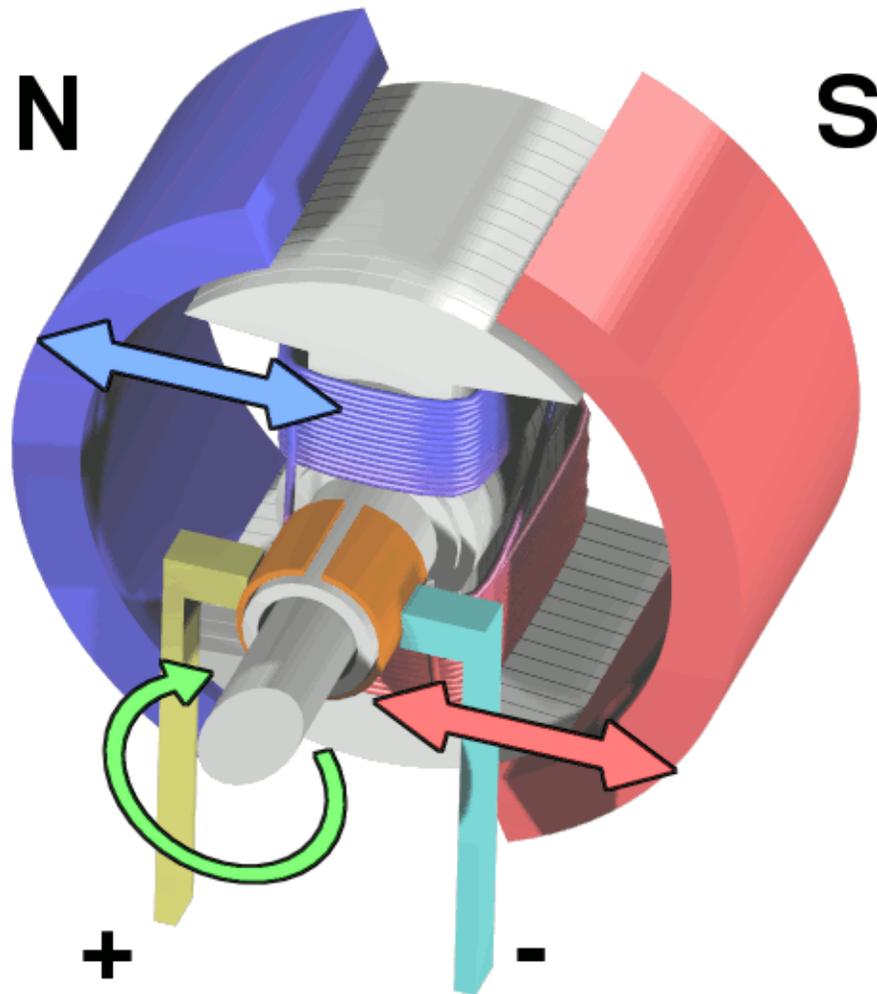
### ***Permanent-magnet motors***

A permanent-magnet motor does not have a field winding on the stator frame, instead relying on permanent magnets to provide the magnetic field against which the rotor field interacts to produce torque. Compensating windings in series with the armature may be used on large motors to improve commutation under load. Because this field is fixed, it cannot be adjusted for speed control. Permanent-magnet motors are convenient in miniature motors to eliminate the power consumption of the field winding. Most larger

DC motors are of the "dynamo" type, which requires current to flow in field windings to provide the stator magnetic field.

To minimize overall weight and size, miniature permanent-magnet motors may use high energy magnets made with neodymium or other strategic elements. With the higher flux density provided, electric machines with high energy permanent magnets are at least competitive with all optimally designed singly-fed synchronous and induction electric machines.

### Brushed DC motors



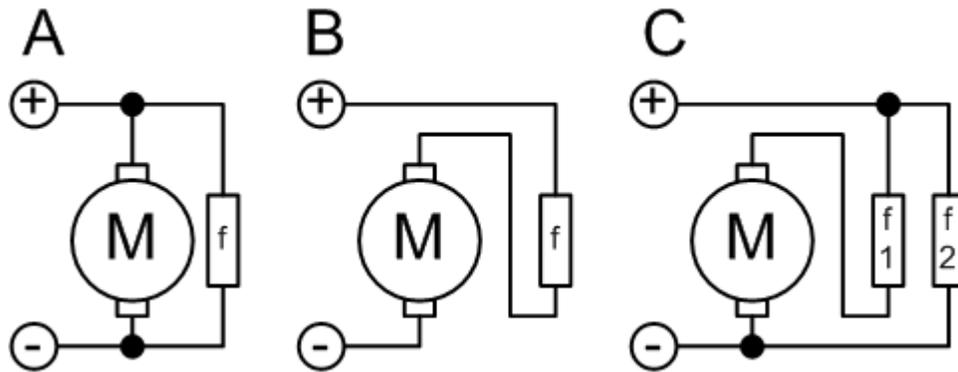
Workings of a brushed electric motor

DC motor design generates an oscillating current in a wound rotor, or armature, with a split ring commutator, and either a wound or permanent magnet stator. A rotor consists of

one or more coils of wire wound around a core on a shaft; an electrical power source is connected to the rotor coil through the commutator and its brushes, causing current to flow in it, producing electromagnetism. The commutator causes the current in the coils to be switched as the rotor turns, keeping the magnetic poles of the rotor from ever fully aligning with the magnetic poles of the stator field, so that the rotor never stops (like a compass needle does) but rather keeps rotating indefinitely (as long as power is applied and is sufficient for the motor to overcome the shaft torque load and internal losses due to friction, etc.)

Many of the limitations of the classic commutator DC motor are due to the need for brushes to press against the commutator. This creates friction. Sparks are created by the brushes making and breaking circuits through the rotor coils as the brushes cross the insulating gaps between commutator sections. Depending on the commutator design, this may include the brushes shorting together adjacent sections—and hence coil ends—momentarily while crossing the gaps. Furthermore, the inductance of the rotor coils causes the voltage across each to rise when its circuit is opened, increasing the sparking of the brushes. This sparking limits the maximum speed of the machine, as too-rapid sparking will overheat, erode, or even melt the commutator. The current density per unit area of the brushes, in combination with their resistivity, limits the output of the motor. The making and breaking of electric contact also causes electrical noise, and the sparks additionally cause RFI. Brushes eventually wear out and require replacement, and the commutator itself is subject to wear and maintenance (on larger motors) or replacement (on small motors). The commutator assembly on a large motor is a costly element, requiring precision assembly of many parts. On small motors, the commutator is usually permanently integrated into the rotor, so replacing it usually requires replacing the whole rotor.

Large brushes are desired for a larger brush contact area to maximize motor output, but small brushes are desired for low mass to maximize the speed at which the motor can run without the brushes excessively bouncing and sparking (comparable to the problem of "valve float" in internal combustion engines). (Small brushes are also desirable for lower cost.) Stiffer brush springs can also be used to make brushes of a given mass work at a higher speed, but at the cost of greater friction losses (lower efficiency) and accelerated brush and commutator wear. Therefore, DC motor brush design entails a trade-off between output power, speed, and efficiency/wear.



A: shunt  
 B: series  
 C: compound  
 f = field coil

There are five types of brushed DC motor:

- A. DC shunt-wound motor
- B. DC series-wound motor
- C. DC compound motor (two configurations):
  - Cumulative compound
  - Differentially compounded
- D. Permanent magnet DC motor (not shown)
- E. Separately excited (sepex) (not shown).

### Brushless DC motors

Some of the problems of the brushed DC motor are eliminated in the brushless design. In this motor, the mechanical "rotating switch" or commutator/brushgear assembly is replaced by an external electronic switch synchronised to the rotor's position. Brushless motors are typically 85–90% efficient or more (higher efficiency for a brushless electric motor of up to 96.5% were reported by researchers at the Tokai University in Japan in 2009), whereas DC motors with brushgear are typically 75–80% efficient.

Midway between ordinary DC motors and stepper motors lies the realm of the brushless DC motor. Built in a fashion very similar to stepper motors, these often use a permanent magnet external rotor, three phases of driving coils, one or more Hall effect sensors to sense the position of the rotor, and the associated drive electronics. The coils are activated, one phase after the other, by the drive electronics as cued by the signals from

either Hall effect sensors or from the back EMF (electromotive force) of the undriven coils. In effect, they act as three-phase synchronous motors containing their own variable-frequency drive electronics. A specialized class of brushless DC motor controllers utilize EMF feedback through the main phase connections instead of Hall effect sensors to determine position and velocity. These motors are used extensively in electric radio-controlled vehicles. When configured with the magnets on the outside, these are referred to by modelers as outrunner motors.

Brushless DC motors are commonly used where precise speed control is necessary, as in computer disk drives or in video cassette recorders, the spindles within CD, CD-ROM (etc.) drives, and mechanisms within office products such as fans, laser printers and photocopiers. They have several advantages over conventional motors:

- Compared to AC fans using shaded-pole motors, they are very efficient, running much cooler than the equivalent AC motors. This cool operation leads to much-improved life of the fan's bearings.
- Without a commutator to wear out, the life of a DC brushless motor can be significantly longer compared to a DC motor using brushes and a commutator. Commutation also tends to cause a great deal of electrical and RF noise; without a commutator or brushes, a brushless motor may be used in electrically sensitive devices like audio equipment or computers.
- The same Hall effect sensors that provide the commutation can also provide a convenient tachometer signal for closed-loop control (servo-controlled) applications. In fans, the tachometer signal can be used to derive a "fan OK" signal.
- The motor can be easily synchronized to an internal or external clock, leading to precise speed control.
- Brushless motors have no chance of sparking, unlike brushed motors, making them better suited to environments with volatile chemicals and fuels. Also, sparking generates ozone which can accumulate in poorly ventilated buildings risking harm to occupants' health.
- Brushless motors are usually used in small equipment such as computers and are generally used to get rid of unwanted heat.
- They are also very quiet motors which is an advantage if being used in equipment that is affected by vibrations.

Modern DC brushless motors range in power from a fraction of a watt to many kilowatts. Larger brushless motors up to about 100 kW rating are used in electric vehicles. They also find significant use in high-performance electric model aircraft.

### **Coreless or ironless DC motors**

Nothing in the principle of any of the motors described above requires that the iron (steel) portions of the rotor actually rotate. If the soft magnetic material of the rotor is made in the form of a cylinder, then (except for the effect of hysteresis) torque is exerted only on the windings of the electromagnets. Taking advantage of this fact is the **coreless or**

**ironless DC motor**, a specialized form of a brush or brushless DC motor. Optimized for rapid acceleration, these motors have a rotor that is constructed without any iron core. The rotor can take the form of a winding-filled cylinder, or a self-supporting structure comprising only the magnet wire and the bonding material. The rotor can fit inside the stator magnets; a magnetically soft stationary cylinder inside the rotor provides a return path for the stator magnetic flux. A second arrangement has the rotor winding basket surrounding the stator magnets. In that design, the rotor fits inside a magnetically soft cylinder that can serve as the housing for the motor, and likewise provides a return path for the flux.

Because the rotor is much lighter in weight (mass) than a conventional rotor formed from copper windings on steel laminations, the rotor can accelerate much more rapidly, often achieving a mechanical time constant under 1 ms. This is especially true if the windings use aluminum rather than the heavier copper. But because there is no metal mass in the rotor to act as a heat sink, even small coreless motors must often be cooled by forced air.

Related limited-travel actuators have no core and a bonded coil placed between the poles of high-flux thin permanent magnets. These are the fast head positioners for rigid-disk ("hard disk") drives.

### **Printed armature or pancake DC motors**

A rather unusual motor design the pancake/printed armature motor has the windings shaped as a disc running between arrays of high-flux magnets, arranged in a circle, facing the rotor and forming an axial air gap. This design is commonly known the pancake motor because of its extremely flat profile, although the technology has had many brand names since its inception, such as ServoDisc.

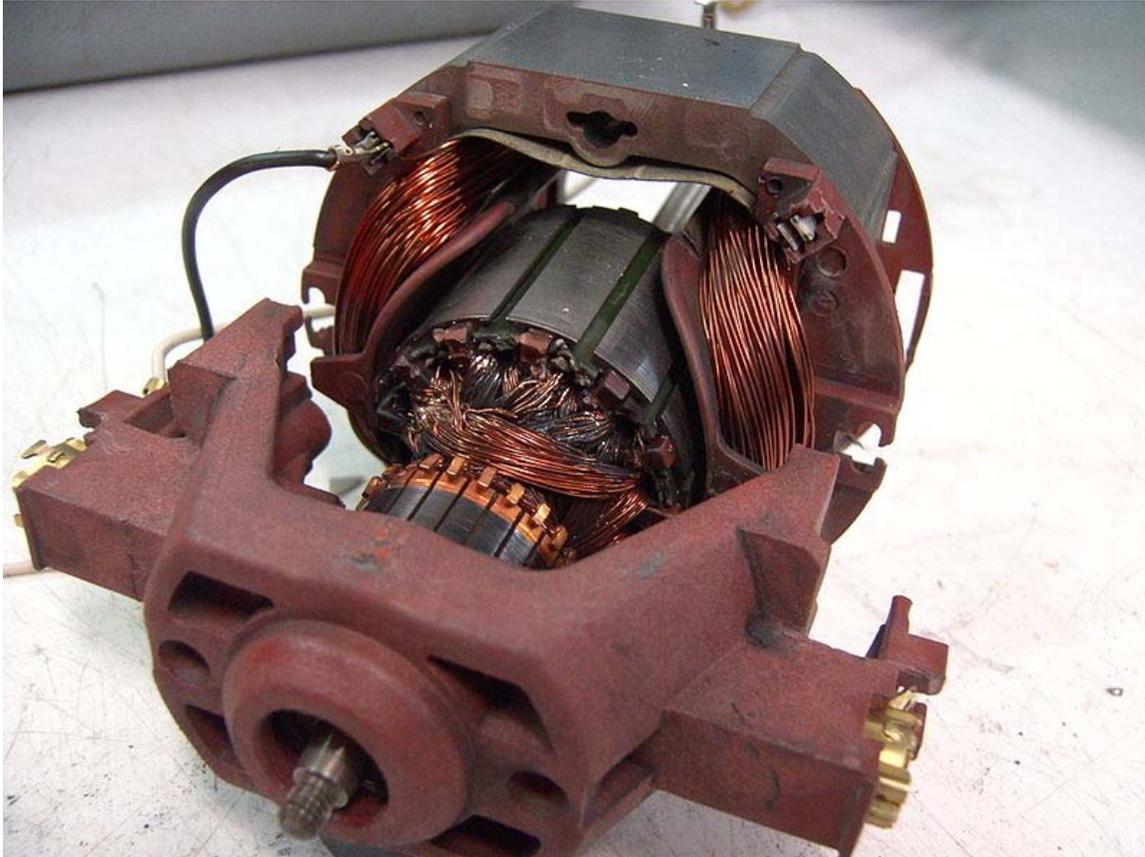
The printed armature (originally formed on a printed circuit board) in a printed armature motor is made from punched copper sheets that are laminated together using advanced composites to form a thin rigid disc. The printed armature has a unique construction, in the brushed motor world, in that it does not have a separate ring commutator. The brushes run directly on the armature surface making the whole design very compact.

An alternative manufacturing method is to use wound copper wire laid flat with a central conventional commutator, in a flower and petal shape. The windings are typically stabilized by being impregnated with electrical epoxy potting systems. These are filled epoxies that have moderate mixed viscosity and a long gel time. They are highlighted by low shrinkage and low exotherm, and are typically UL 1446 recognized as a potting compound for use up to 180°C (Class H) (UL File No. E 210549).

The unique advantage of ironless DC motors is that there is no cogging (vibration caused by attraction between the iron and the magnets) and parasitic eddy currents cannot form in the rotor as it is totally ironless. This can greatly improve efficiency, but variable-speed controllers must use a higher switching rate (>40 kHz) or direct current because of the decreased electromagnetic induction.

These motors were originally invented to drive the capstan(s) of magnetic tape drives, in the burgeoning computer industry. Pancake motors are still widely used in high-performance servo-controlled systems, humanoid robotic systems, industrial automation and medical devices. Due to the variety of constructions now available the technology is used in applications from high temperature military to low cost pump and basic servo applications.

### ***Universal motors***



Modern cheap universal motor, from a vacuum cleaner

A series-wound motor is referred to as a **universal motor** when it has been designed to operate on either AC or DC power. The ability to operate on AC is because the current in both the field and the armature (and hence the resultant magnetic fields) will alternate (reverse polarity) in synchronism, and hence the resulting mechanical force will occur in a constant direction.

Operating at normal power line frequencies, universal motors are often found in a range rarely larger than 1000 watt. Universal motors also form the basis of the traditional railway traction motor in electric railways. In this application, the use of AC to power a motor originally designed to run on DC would lead to efficiency losses due to eddy current heating of their magnetic components, particularly the motor field pole-pieces that, for DC, would have used solid (un-laminated) iron. Although the heating effects are

reduced by using laminated pole-pieces, as used for the cores of transformers and by the use of laminations of high permeability electrical steel, one solution available at start of the 20th century was for the motors to be operated from very low frequency AC supplies, with 25 and 16.7 Hz operation being common. Because they used universal motors, locomotives using this design were also commonly capable of operating from a third rail powered by DC.

An advantage of the universal motor is that AC supplies may be used on motors which have some characteristics more common in DC motors, specifically high starting torque and very compact design if high running speeds are used. The negative aspect is the maintenance and short life problems caused by the commutator. Such motors are used in devices such as food mixers and power tools which are used only intermittently, and often have high starting-torque demands. Continuous speed control of a universal motor running on AC is easily obtained by use of a thyristor circuit, while multiple taps on the field coil provide (imprecise) stepped speed control. Household blenders that advertise many speeds frequently combine a field coil with several taps and a diode that can be inserted in series with the motor (causing the motor to run on half-wave rectified AC).

Induction motors can't turn faster than allowed by the power line frequency. By contrast, universal motors generally run at high speeds, making them useful for appliances such as blenders, vacuum cleaners, and hair dryers where high speed and light weight is desirable. They are also commonly used in portable power tools, such as drills, sanders, circular and jig saws, where the motor's characteristics work well. Many vacuum cleaner and weed trimmer motors exceed 10,000 RPM, while Dremel and other similar miniature grinders will often exceed 30,000 RPM.

Universal motors also lend themselves to electronic speed control and, as such, are an ideal choice for domestic washing machines. The motor can be used to agitate the drum (both forwards and in reverse) by switching the field winding with respect to the armature. The motor can also be run up to the high speeds required for the spin cycle.

Motor damage may occur from overspeeding (running at an rotational speed in excess of design limits) if the unit is operated with no significant load. On larger motors, sudden loss of load is to be avoided, and the possibility of such an occurrence is incorporated into the motor's protection and control schemes. In some smaller applications, a fan blade attached to the shaft often acts as an artificial load to limit the motor speed to a safe level, as well as a means to circulate cooling airflow over the armature and field windings.

## ***AC motors***

In 1882, Nikola Tesla discovered the rotating magnetic field, and pioneered the use of a rotary field of force to operate machines. He exploited the principle to design a unique two-phase induction motor in 1883. In 1885, Galileo Ferraris independently researched the concept. In 1888, Ferraris published his research in a paper to the Royal Academy of Sciences in Turin.

Tesla had suggested that the commutators from a machine could be removed and the device could operate on a rotary field of force. Professor Poeschel, his teacher, stated that would be akin to building a perpetual motion machine. Tesla would later attain U.S. Patent 0,416,194, *Electric Motor* (December 1889), which resembles the motor seen in many of Tesla's photos. This classic alternating current electro-magnetic motor was an induction motor.

Michail Osipovich Dolivo-Dobrovolsky later invented a three-phase "cage-rotor" in 1890. This type of motor is now used for the vast majority of commercial applications.

An AC motor has two parts. A stationary stator having coils supplied with AC current to produce a rotating magnetic field, and a rotor attached to the output shaft that is given a torque by the rotating field.

### **AC Motor with sliding rotor**

Conical rotor brake motor incorporates the brake as an integral part of the conical sliding rotor. When the motor is at rest, a spring acts on the sliding rotor and forces the brake ring against the brake cap in the motor, holding the rotor stationary. When the motor is energized, its magnetic field generates both an axial and a radial component. The axial component overcomes the spring force, releasing the brake; while the radial component causes the rotor to turn. There is no additional brake control required.

### **Synchronous electric motor**

A synchronous electric motor is an AC motor distinguished by a rotor spinning with coils passing magnets at the same rate as the alternating current and resulting magnetic field which drives it. Another way of saying this is that it has zero slip under usual operating conditions. Contrast this with an induction motor, which must slip to produce torque. A synchronous motor is like an induction motor except the rotor is excited by a DC field. Slip rings and brushes are used to conduct current to rotor. The rotor poles connect to each other and move at the same speed hence the name synchronous motor.

### **Induction motor**

An induction motor is an asynchronous AC motor where power is transferred to the rotor by electromagnetic induction. An induction motor resembles a rotating transformer, because the stator (stationary part) is essentially the primary side of the transformer and the rotor (rotating part) is the secondary side. Polyphase induction motors are widely used in industry.

Induction motors may be further divided into squirrel-cage motors and wound-rotor motors. Squirrel-cage motors have a heavy winding made up of solid bars, usually aluminum or copper, joined by rings at the ends of the rotor. Currents induced into this winding provide the rotor magnetic field. The shape of the rotor bars determines the speed-torque characteristics. At low speeds, the current induced in the squirrel cage is

nearly at line frequency and tends to flow in the outer parts of the rotor cage. As the motor accelerates, the slip frequency becomes lower, and more current flows in the interior of the winding. By shaping the bars to change the resistance of the windings portions in the interior and outer parts of the cage, effectively a variable resistance is inserted in the rotor circuit.

In a wound-rotor motor, the rotor winding is made of many turns of insulated wire and is connected to slip rings on the motor shaft. An external resistor or other control devices can be connected in the rotor circuit. Resistors allow control of the motor speed, although significant power is dissipated in the external resistance. A converter can be fed from the rotor circuit and return the slip-frequency power that would otherwise be wasted back into the power system.

The wound-rotor induction motor is used primarily to start a high inertia load or a load that requires a very high starting torque across the full speed range. By correctly selecting the resistors used in the secondary resistance or slip ring starter, the motor is able to produce maximum torque at a relatively low supply current from zero speed to full speed. This type of motor also offers controllable speed.

Motor speed can be changed because the torque curve of the motor is effectively modified by the amount of resistance connected to the rotor circuit. Increasing the value of resistance will move the speed of maximum torque down. If the resistance connected to the rotor is increased beyond the point where the maximum torque occurs at zero speed, the torque will be further reduced.

When used with a load that has a torque curve that increases with speed, the motor will operate at the speed where the torque developed by the motor is equal to the load torque. Reducing the load will cause the motor to speed up, and increasing the load will cause the motor to slow down until the load and motor torque are equal. Operated in this manner, the slip losses are dissipated in the secondary resistors and can be very significant. The speed regulation and net efficiency is also very poor.

## **Doubly-fed electric motor**

Doubly-fed electric motors have two independent multiphase winding set, which contribute active (i.e., working) power to the energy conversion process, with at least one of the winding sets electronically controlled for variable speed operation. Two independent multiphase winding sets (i.e., dual armature) are the maximum provided in a single package without topology duplication. Doubly-fed electric motors are machines with an effective constant torque speed range that is twice synchronous speed for a given frequency of excitation. This is twice the constant torque speed range as singly-fed electric machines, which have only one active winding set.

A doubly-fed motor allows for a smaller electronic converter but the cost of the rotor winding and slip rings may offset the saving in the power electronics components. Difficulties with controlling speed near synchronous speed limit applications.

## Singly-fed electric motor

Most AC motors are singly-fed. Singly-fed electric motors have a single multiphase winding set that is connected to a power supply. Singly-fed electric machines may be either induction or synchronous. The active winding set can be electronically controlled. Singly-fed electric machines have an effective constant torque speed range up to synchronous speed for a given excitation frequency.

### Comparison of motor types

Comparison of motor types

Type	Advantages	Disadvantages	Typical Application	Typical Drive
AC polyphase induction squirrel-cage	Low cost, long life, high efficiency, large ratings available (to 1 MW or more), large number of standardized types	Starting inrush current can be high, speed control requires variable frequency source	Pumps, fans, blowers, conveyors, compressors	Poly-phase AC, variable frequency AC
Shaded-pole motor	Low cost Long life	Rotation slips from frequency Low starting torque Small ratings low efficiency	Fans, appliances, record players	Single phase AC
AC Induction (split-phase capacitor)	High power high starting torque	Rotation slips from frequency Starting switch required	Appliances Stationary Power Tools	Single phase AC
Universal motor	High starting torque, compact, high speed	Maintenance (brushes) lifespan Only small ratings economic	Drill, blender, vacuum cleaner, insulation blowers	Single phase AC or DC
AC Synchronous	Rotation in-sync with freq - hence no slip	More expensive	Industrial motors Clocks Audio turntables tape drives	Poly-phase AC
Stepper DC	Precision positioning High holding torque	High initial cost Requires a controller	Positioning in printers and floppy drives	DC
Brushless DC	Long lifespan	High initial cost	Hard drives	DC

	low maintenance High efficiency	Requires a controller	CD/DVD players electric vehicles Steel mills	
Brushed DC	Simple speed control	Maintenance (brushes) Medium lifespan Costly commutator and brushes	Paper making machines Treadmill exercisers automotive accessories	Direct DC or PWM
Pancake DC	Compact design Simple speed control	Medium cost Medium lifespan	Office Equip Fans/Pumps	Direct DC or PWM

### ***Servo motor***

A servomotor is used within a position-control or speed-control feedback control system. Servomotors are used in applications such as machine tools, pen plotters, and other control systems. Motors intended for use in a servomechanism must have well-documented characteristics for speed, torque, power. The dynamic response characteristics such as winding inductance and rotor inertia are also important; these factors limit the overall performance of the servomechanism loop. Large, powerful, but slow-responding servo loops may use conventional AC or DC motors and drive systems with position or speed feedback on the motor. As dynamic response requirements increase, more specialized motor designs such as coreless motors are used.

A servo system differs from some stepper motor applications in that the position feedback is continuous while the motor is running; a stepper system relies on the motor not to "miss steps" for short term accuracy, although a stepper system may include a "home" switch or other element to provide long-term stability of control.

### ***Electrostatic motor***

An electrostatic motor is based on the attraction and repulsion of electric charge. Usually, electrostatic motors are the dual of conventional coil-based motors. They typically require a high voltage power supply, although very small motors employ lower voltages. Conventional electric motors instead employ magnetic attraction and repulsion, and require high current at low voltages. In the 1750s, the first electrostatic motors were developed by Benjamin Franklin and Andrew Gordon. Today the electrostatic motor finds frequent use in micro-mechanical (MEMS) systems where their drive voltages are below 100 volts, and where moving, charged plates are far easier to fabricate than coils and iron cores. Also, the molecular machinery which runs living cells is often based on linear and rotary electrostatic motors.

## ***Torque motors***

A torque motor (also known as a limited torque motor) is a specialized form of induction motor which is capable of operating indefinitely while stalled, that is, with the rotor blocked from turning, without incurring damage. In this mode of operation, the motor will apply a steady torque to the load (hence the name).

A common application of a torque motor would be the supply- and take-up reel motors in a tape drive. In this application, driven from a low voltage, the characteristics of these motors allow a relatively constant light tension to be applied to the tape whether or not the capstan is feeding tape past the tape heads. Driven from a higher voltage, (and so delivering a higher torque), the torque motors can also achieve fast-forward and rewind operation without requiring any additional mechanics such as gears or clutches. In the computer gaming world, torque motors are used in force feedback steering wheels.

Another common application is the control of the throttle of an internal combustion engine in conjunction with an electronic governor. In this usage, the motor works against a return spring to move the throttle in accordance with the output of the governor. The latter monitors engine speed by counting electrical pulses from the ignition system or from a magnetic pickup and, depending on the speed, makes small adjustments to the amount of current applied to the motor. If the engine starts to slow down relative to the desired speed, the current will be increased, the motor will develop more torque, pulling against the return spring and opening the throttle. Should the engine run too fast, the governor will reduce the current being applied to the motor, causing the return spring to pull back and close the throttle.

## ***Stepper motors***

Closely related in design to three-phase AC synchronous motors are stepper motors, where an internal rotor containing permanent magnets or a magnetically soft rotor with salient poles is controlled by a set of external magnets that are switched electronically. A stepper motor may also be thought of as a cross between a DC electric motor and a rotary solenoid. As each coil is energized in turn, the rotor aligns itself with the magnetic field produced by the energized field winding. Unlike a synchronous motor, in its application, the stepper motor may not rotate continuously; instead, it "steps" — starts and then quickly stops again — from one position to the next as field windings are energized and de-energized in sequence. Depending on the sequence, the rotor may turn forwards or backwards, and it may change direction, stop, speed up or slow down arbitrarily at any time.

Simple stepper motor drivers entirely energize or entirely de-energize the field windings, leading the rotor to "cog" to a limited number of positions; more sophisticated drivers can proportionally control the power to the field windings, allowing the rotors to position between the cog points and thereby rotate extremely smoothly. This mode of operation is often called microstepping. Computer controlled stepper motors are one of the most

versatile forms of positioning systems, particularly when part of a digital servo-controlled system.

Stepper motors can be rotated to a specific angle in discrete steps with ease, and hence stepper motors are used for read/write head positioning in computer floppy diskette drives. They were used for the same purpose in pre-gigabyte era computer disk drives, where the precision and speed they offered was adequate for the correct positioning of the read/write head of a hard disk drive. As drive density increased, the precision and speed limitations of stepper motors made them obsolete for hard drives—the precision limitation made them unusable, and the speed limitation made them uncompetitive—thus newer hard disk drives use voice coil-based head actuator systems. (The term "voice coil" in this connection is historic; it refers to the structure in a typical (cone type) loudspeaker. This structure was used for a while to position the heads. Modern drives have a pivoted coil mount; the coil swings back and forth, something like a blade of a rotating fan. Nevertheless, like a voice coil, modern actuator coil conductors (the magnet wire) move perpendicular to the magnetic lines of force.)

Stepper motors were and still are often used in computer printers, optical scanners, and digital photocopiers to move the optical scanning element, the print head carriage (of dot matrix and inkjet printers), and the platen. Likewise, many computer plotters (which since the early 1990s have been replaced with large-format inkjet and laser printers) used rotary stepper motors for pen and platen movement; the typical alternatives here were either linear stepper motors or servomotors with complex closed-loop control systems.

So-called quartz analog wristwatches contain the smallest commonplace stepping motors; they have one coil, draw very little power, and have a permanent-magnet rotor. The same kind of motor drives battery-powered quartz clocks. Some of these watches, such as chronographs, contain more than one stepping motor.

Stepper motors were upscaled to be used in electric vehicles under the term SRM (Switched Reluctance Motor).

### ***Linear motors***

A linear motor is essentially an electric motor that has been "unrolled" so that, instead of producing a torque (rotation), it produces a straight-line force along its length by setting up a traveling electromagnetic field.

Linear motors are most commonly induction motors or stepper motors. You can find a linear motor in a maglev (Transrapid) train, where the train "flies" over the ground, and in many roller-coasters where the rapid motion of the motorless railcar is controlled by the rail. On a smaller scale, at least one letter-size (8.5" x 11") computer graphics X-Y pen plotter made by Hewlett-Packard (in the late 1970s to mid 1980's) used two linear stepper motors to move the pen along the two orthogonal axes.

## ***Nanotube nanomotor***

Researchers at University of California, Berkeley, recently developed rotational bearings based upon multiwall carbon nanotubes. By attaching a gold plate (with dimensions of the order of 100 nm) to the outer shell of a suspended multiwall carbon nanotube (like nested carbon cylinders), they are able to electrostatically rotate the outer shell relative to the inner core. These bearings are very robust; devices have been oscillated thousands of times with no indication of wear. These nanoelectromechanical systems (NEMS) are the next step in miniaturization and may find their way into commercial applications in the future.

## ***Spacecraft propulsive motors***

An **electrically powered spacecraft propulsion** system is any of a number of forms of electric motors which spacecraft can employ to gain mechanical energy in outer space. Most of these kinds of spacecraft propulsion work by electrically powering propellant to high speed, but electrodynamic tethers work by interacting with a planet's magnetosphere.

## ***Energy conversion by an electric motor***

Using mathematical models in terms of a magnetic dipole, Ribarič and Šušteršič consider how in the case of the synchronous motor and induction motor an external source is supplying electrical energy to the stator so as to maintain its revolving magnetic field; this energy is then transmitted by the revolving magnetic field to the magnetic dipole of the rotor; there it is converted into mechanical energy, and transmitted mechanically by the rotating shaft to an external user. On the other hand, in the case of a commutator motor, the external source delivers electrical energy directly to the rotor magnetic dipole for conversion into mechanical energy.

## ***Power***

The power output of a rotary electric motor is:

$$P = \frac{rpm \times T}{5252}$$

Where P is in horsepower, rpm is the shaft speed in revolutions per minute and T is the torque in foot pounds.

And for a linear motor:

$$P = F \times v$$

Where  $P$  is the power in watts, and  $F$  is in Newtons and  $v$  is the speed in metres per second.

## **Efficiency**

To calculate a motor's efficiency, the mechanical output power is divided by the electrical input power:

$$\eta = \frac{P_m}{P_e},$$

where  $\eta$  is energy conversion efficiency,  $P_e$  is electrical input power, and  $P_m$  is mechanical output power.

In simplest case  $P_e = VI$ , and  $P_m = T\omega$ , where  $V$  is input voltage,  $I$  is input current,  $T$  is output torque, and  $\omega$  is output angular velocity. It is possible to derive analytically the point of maximum efficiency. It is typically at less than 1/2 the stall torque.

## **Goodness factor**

Professor Eric Laithwaite proposed a metric to determine the 'goodness' of an electric motor:

$$G = \frac{\omega}{\text{resistance} \times \text{reluctance}} = \frac{\omega \mu \sigma A_m A_e}{l_m l_e}$$

Where:

- $G$  is the goodness factor (factors above 1 are likely to be efficient)
- $A_m, A_e$  are the cross sections of the magnetic and electric circuit
- $l_m, l_e$  are the lengths of the magnetic and electric circuits
- $\mu$  is the permeability of the core
- $\omega$  is the angular frequency the motor is driven at

From this he showed that the most efficient motors are likely to be relatively large. However, the equation only directly relates to non permanent magnet motors.

## **Torque capability of motor types**

When optimally designed within a given core saturation constraint and for a given active current (i.e., torque current), voltage, pole-pair number, excitation frequency (i.e., synchronous speed), and air-gap flux density, all categories of electric motors or generators will exhibit virtually the same maximum continuous shaft torque (i.e., operating torque) within a given air-gap area with winding slots and back-iron depth, which determines the physical size of electromagnetic core. Some applications require

bursts of torque beyond the maximum operating torque, such as short bursts of torque to accelerate an electric vehicle from standstill. Always limited by magnetic core saturation or safe operating temperature rise and voltage, the capacity for torque bursts beyond the maximum operating torque differs significantly between categories of electric motors or generators.

Capacity for bursts of torque should not be confused with field weakening capability inherent in fully electromagnetic electric machines (Permanent Magnet (PM) electric machine are excluded). Field weakening, which is not available with PM electric machines, allows an electric machine to operate beyond the designed frequency of excitation.

Electric machines without a transformer circuit topology, such as Field-Wound (i.e., electromagnet) or Permanent Magnet (PM) Synchronous electric machines cannot realize bursts of torque higher than the maximum designed torque without saturating the magnetic core and rendering any increase in current as useless. Furthermore, the permanent magnet assembly of PM synchronous electric machines can be irreparably damaged, if bursts of torque exceeding the maximum operating torque rating are attempted.

Electric machines with a transformer circuit topology, such as Induction (i.e., asynchronous) electric machines, Induction Doubly-Fed electric machines, and Induction or Synchronous Wound-Rotor Doubly-Fed (WRDF) electric machines, exhibit very high bursts of torque because the active current (i.e., Magneto-Motive-Force or the product of current and winding-turns) induced on either side of the transformer oppose each other and as a result, the active current contributes nothing to the transformer coupled magnetic core flux density, which would otherwise lead to core saturation.

Electric machines that rely on Induction or Asynchronous principles short-circuit one port of the transformer circuit and as a result, the reactive impedance of the transformer circuit becomes dominant as slip increases, which limits the magnitude of active (i.e., real) current. Still, bursts of torque that are two to three times higher than the maximum design torque are realizable.

The Synchronous WRDF electric machine is the only electric machine with a truly dual ported transformer circuit topology (i.e., both ports independently excited with no short-circuited port). The dual ported transformer circuit topology is known to be unstable and requires a multiphase slip-ring-brush assembly to propagate limited power to the rotor winding set. If a precision means were available to instantaneously control torque angle and slip for synchronous operation during motoring or generating while simultaneously providing brushless power to the rotor winding set, the active current of the Synchronous WRDF electric machine would be independent of the reactive impedance of the transformer circuit and bursts of torque significantly higher than the maximum operating torque and far beyond the practical capability of any other type of electric machine would be realizable. Torque bursts greater than eight times operating torque have been calculated.

## ***Continuous Torque Density***

The continuous torque density of conventional electric machines is determined by the size of the air-gap area and the back-iron depth, which are determined by the power rating of the armature winding set, the speed of the machine, and the achievable air-gap flux density before core saturation. Despite the high coercivity of neodymium or samarium-cobalt permanent magnets, continuous torque density is virtually the same amongst electric machines with optimally designed armature winding sets. Continuous torque density should never be confused with peak torque density, which comes with the manufacturer's chosen method of cooling, which is available to all, or period of operation before destruction by overheating of windings or even permanent magnet damage.

## ***Continuous Power Density***

The continuous power density is determined by the product of the continuous torque density and the constant torque speed range of the electric machine.

## ***Motor standards***

The following are major design and manufacturing standards covering electric motors:

- International Electrotechnical Commission: IEC 60034 Rotating Electrical Machines
- National Electrical Manufacturers Association (USA): NEMA MG 1 Motors and Generators
- Underwriters Laboratories (USA): UL 1004 - Standard for Electric Motors

## ***Uses***

Electric motors are used in many, if not most, modern machines. Obvious uses would be in rotating machines such as fans, turbines, drills, the wheels on electric cars, locomotives and conveyor belts. Also, in many vibrating or oscillating machines, an electric motor spins an irregular figure with more area on one side of the axle than the other, causing it to appear to be moving up and down.

Electric motors are also popular in robotics. They are used to turn the wheels of vehicular robots, and servo motors are used to turn arms and legs in humanoid robots. In flying robots, along with helicopters, a motor causes a propeller or wide, flat blades to spin and create lift force, allowing vertical motion.

Electric motors are replacing hydraulic cylinders in airplanes and military equipment.

In industrial and manufacturing businesses, electric motors are used to turn saws and blades in cutting and slicing processes, and to spin gears and mixers (the latter very common in food manufacturing). Linear motors are often used to push products into containers horizontally.

Many kitchen appliances also use electric motors. Food processors and grinders spin blades to chop and break up foods. Blenders use electric motors to mix liquids, and microwave ovens use motors to turn the tray food sits on. Toaster ovens also use electric motors to turn a conveyor to move food over heating elements.