Handbook of
Electric Motors and Electromagnetic Coils

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Electric Motor

Electric motors

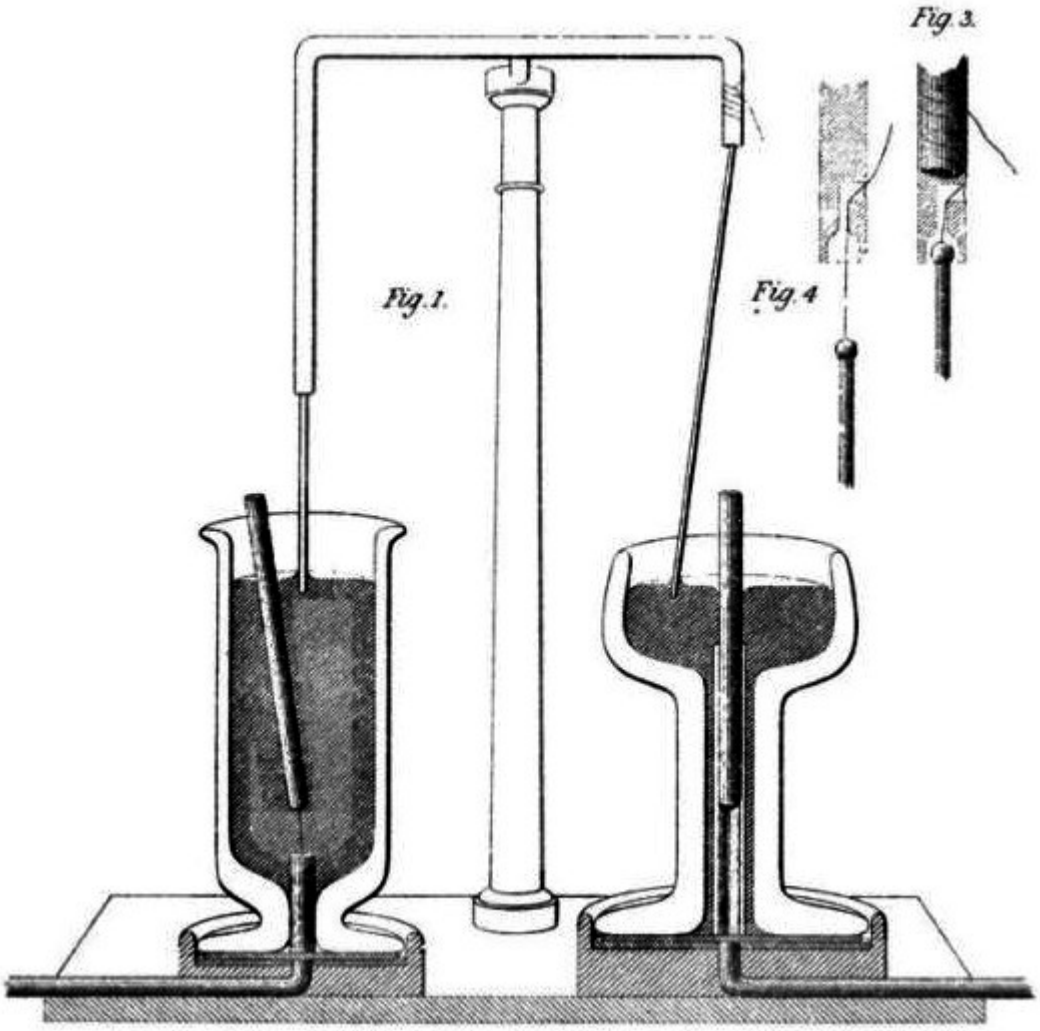
An **electric motor** converts electrical energy into mechanical energy. Most electric motors operate through interacting magnetic fields and current-carrying conductors to generate force, although electrostatic motors use electrostatic forces. The reverse process, producing electrical energy from mechanical 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.

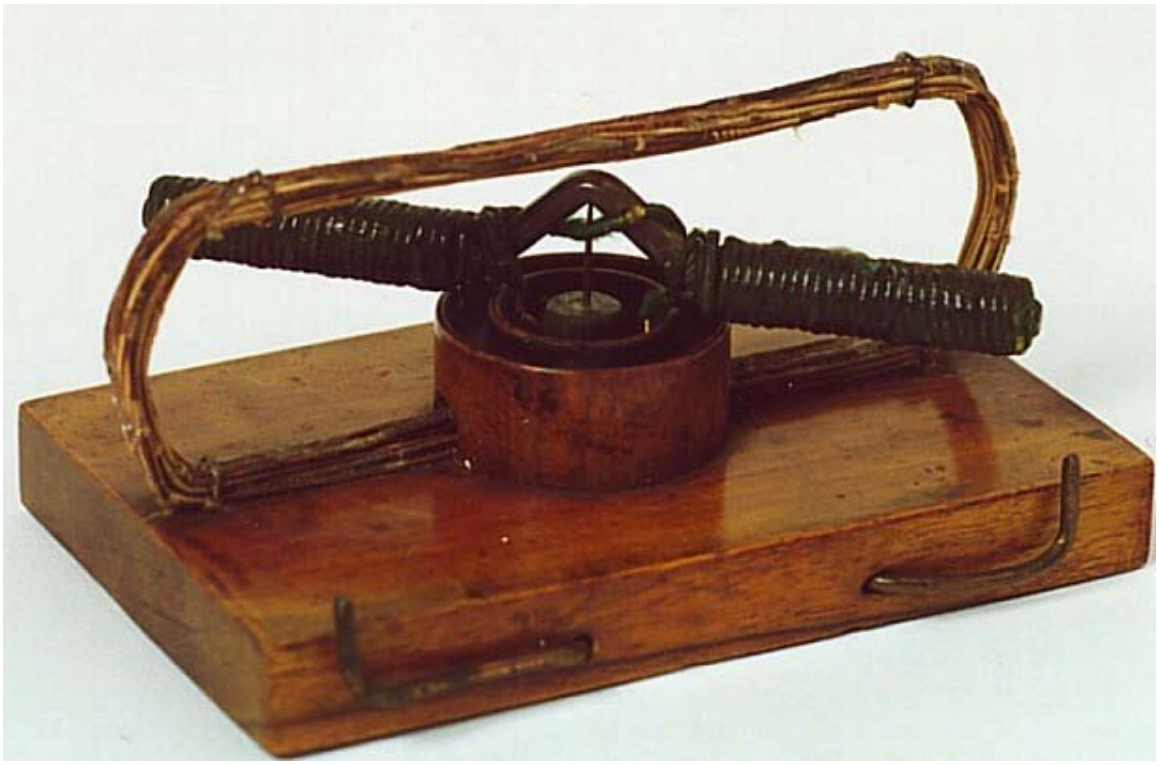
History and development



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.

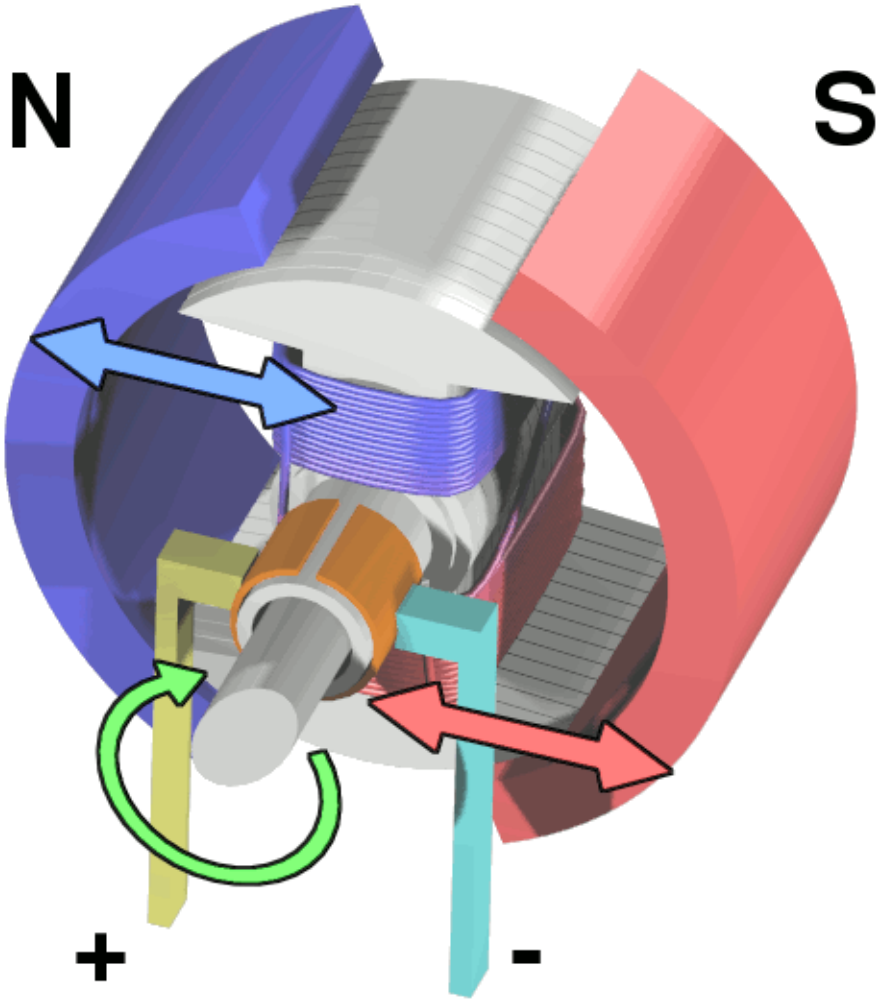
Permanent-magnet motors

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 commuation 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

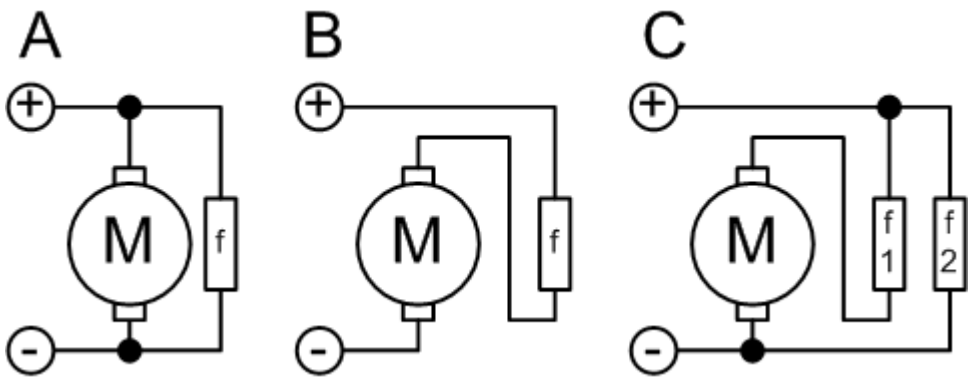


Workings of a brushed electric motor

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.

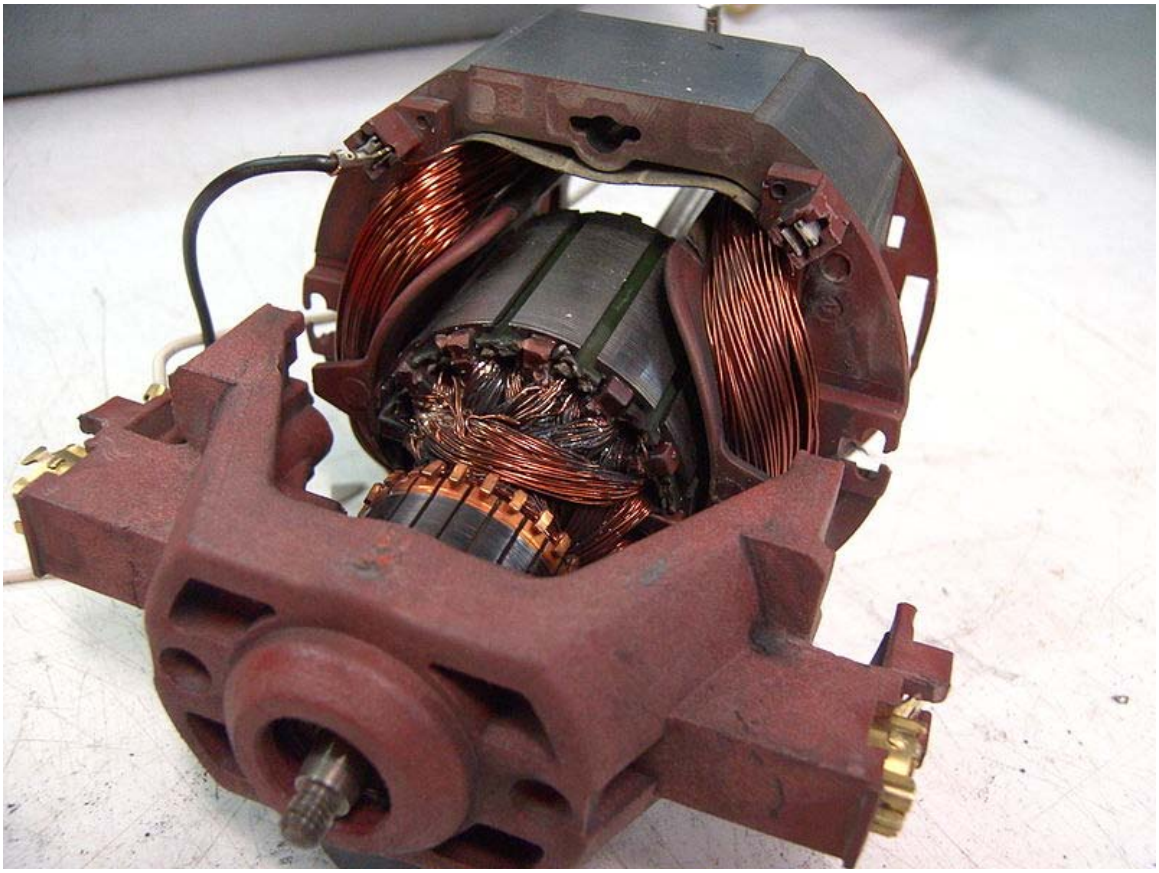
The printed armature (originally formed on a printed circuit board) in a printed armature motor is made from punched copper sheets that are laminated together using advanced composites to form a thin rigid disc. The printed armature has a unique construction, in the brushed motor world, in that it does 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	
Brushed DC	Simple speed control	Maintenance (brushes) Medium lifespan Costly commutator and brushes	Steel mills 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 η 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 ω 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:

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

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
μ is the permeability of the core
ω 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.

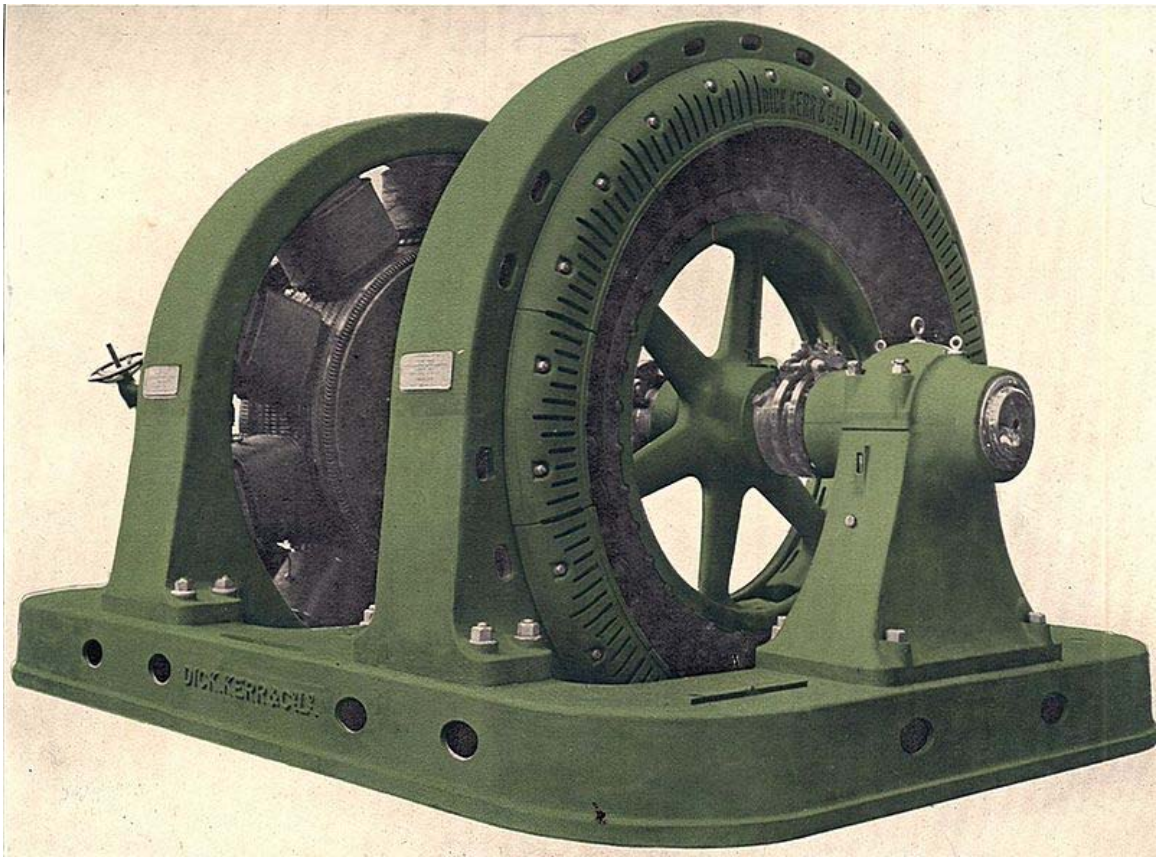
Electric motors are replacing hydraulic cylinders in airplanes and military equipment.

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.

Chapter 2

Synchronous Motor



A synchronous motor-generator set for AC to DC conversion.

A classic **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 rotating magnetic field which drives it. Another way of saying this is that it does not rely on slip under usual operating conditions and as a result, produces torque at synchronous speed. Contrast this with an induction motor, which must slip in order to produce torque. They operate synchronously with line frequency. As with squirrel-cage induction motors, speed is determined by the number of pairs of poles and the line frequency. Synchronous motors are available in sub-fractional **self-excited** sizes to high-horsepower **direct-**

current excited industrial sizes. In the fractional horsepower range, most synchronous motors are used where precise constant speed is required. In high-horsepower industrial sizes, the synchronous motor provides two important functions. First, it is a highly efficient means of converting ac energy to work. Second, it can operate at leading or unity power factor and thereby provide power-factor correction.

There are two major types of synchronous motors: **non-excited and direct-current excited**, which have no self-starting capability to reach synchronism without extra excitation means, such as electronic control or induction. But with recent advances in independent brushless excitation control of the rotor winding set that eliminates reliance on *slip* for operation, the **brushless wound-rotor doubly-fed electric machine** is the third type of synchronous motor with all the theoretical qualities of the synchronous motor and the wound-rotor doubly-fed motor combined, such as power factor correction, highest power density, highest potential torque density, low cost electronic controller, highest efficiency, etc.

Non-excited motors are manufactured in **permanent magnet**, **reluctance** and **hysteresis** designs. Reluctance and hysterisis designs employ a self-starting circuit and require no external excitation supply. Permanent magnet designs require electronic control for practical operation.

Reluctance designs have ratings that range from sub-fractional to about 30 hp. Sub-fractional horsepower motors have low torque, and are generally used for instrumentation applications. Moderate torque, integral horsepower motors use squirrel- cage construction with toothed rotors. When used with an adjustable frequency power supply, all motors in the drive system can be controlled at exactly the same speed. The power supply frequency determines motor operating speed.

Hysteresis motors are manufactured in sub-fractional horsepower ratings, primarily as servomotors and timing motors. More expensive than the reluctance type, hysteresis motors are used where precise constant speed is required.

DC-excited motors — Made in sizes larger than 1 hp, these motors require direct current supplied through slip rings for excitation. The direct current can be supplied from a separate source or from a dc generator directly connected to the motor shaft

Slip rings and brushes are used to conduct current to the rotor. The rotor poles connect to each other and move at the same speed - hence the name synchronous motor.

Synchronous motors fall under the category of synchronous machines which also includes the alternator (synchronous generator). These machines are commonly used in analog electric clocks, timers and other devices where correct time is required.

The "synchronous speed" of a synchronous motor is determined by the following formula:

$$v = \frac{120 \times f}{n}$$

where *v* is the speed of the rotor (in rpm), *f* is the frequency of the AC supply (in Hz) and *n* is the number of magnetic poles. Different from all other synchronous motors, the synchronous **brushless wound-rotor doubly-fed electric machine** operates from sub-synchronous to super-synchronous speeds or twice synchronous speed.

Parts

A synchronous motor is composed of the following parts:

- The stator is the outer shell of the motor, which carries the armature winding. This winding is spatially distributed for poly-phase AC current. This armature creates a rotating magnetic field inside the motor.
- The rotor is the rotating portion of the motor. It carries field winding, which may be supplied by a DC source. On excitation, this field winding behaves as a permanent magnet.Some machines use permanent magnets in the rotor.
- The slip rings on the rotor, to supply the DC to the field winding.
- The stator frame contains and supports the other parts and may include bearing housings.

Large machines may include additional parts for cooling the machine, supporting the rotor, lubricating and cooling the bearings, and various protection and measurement devices.

Operation

The operation of a synchronous motor is simple to imagine. The armature winding, when excited by a poly-phase (usually 3-phase) supply, creates a rotating magnetic field inside the motor. The field winding, which acts as a permanent magnet, simply locks in with the rotating magnetic field and rotates along with it. During operation, as the field locks in with the rotating magnetic field, the motor is said to be in synchronization.

Once the motor is in operation, the speed of the motor is dependent only on the supply frequency. When the motor load is increased beyond the break down load, the motor falls out of synchronization i.e., the applied load is large enough to pull out the field winding from following the rotating magnetic field. The motor immediately stalls after it falls out of synchronization.

Starting methods

Synchronous motors are not self-starting motors. This property is due to the inertia of the rotor. When the power supply is switched on, the armature winding and field windings are excited. Instantaneously, the armature winding creates a rotating magnetic field, which revolves at the designated motor speed. The rotor, due to inertia, will not follow

the revolving magnetic field. In practice, the rotor should be rotated by some other means near to the motor's synchronous speed to overcome the inertia. Once the rotor nears the synchronous speed, the field winding is excited, and the motor pulls into synchronization.

The following techniques are employed to start a synchronous motor:

- A separate motor (called pony motor) is used to drive the rotor before it locks in into synchronization.
- The field winding is shunted or induction motor like arrangements are made so that the synchronous motor starts as an induction motor and locks in to synchronization once it reaches speeds near its synchronous speed.
- Reducing the input electrical frequency to get the motor starting slowly, Variable-frequency drives can be used here which have Rectifier-Inverter circuits or Cycloconverter circuits.

Special Properties

Synchronous motors show some interesting properties, which finds applications in power factor correction. The synchronous motor can be run at lagging, unity or leading power factor. The control is with the field excitation, as described below:

- When the field excitation voltage is decreased, the motor runs in lagging power factor. The power factor by which the motor lags varies directly with the drop in excitation voltage. This condition is called under-excitation.
- When the field excitation voltage is made equal to the rated voltage, the motor runs at unity power factor.
- When the field excitation voltage is increased above the rated voltage, the motor runs at leading power factor. And the power factor by which the motor leads varies directly with the increase in field excitation voltage. This condition is called over-excitation.
- The most basic property of synchro motor is that it can be use both as a capacitor or inductor. Hence in turn it improves the power factor of system.

The leading power factor operation of synchronous motor finds application in power factor correction. Normally, all the loads connected to the power supply grid run in lagging power factor, which increases reactive power consumption in the grid, thus contributing to additional losses. In such cases, a synchronous motor with no load is connected to the grid and is run over-excited, so that the leading power factor created by synchronous motor compensates the existing lagging power factor in the grid and the overall power factor is brought close to 1 (unity power factor). If unity power factor is maintained in a grid, reactive power losses diminish to zero, increasing the efficiency of the grid. This operation of synchronous motor in over-excited mode to correct the power factor is sometimes called as Synchronous condenser.

Uses

- Synchronous motors find applications in all industrial applications where constant speed is necessary.
- Improving the power factor as Synchronous condensers.
- Low power applications include positioning machines, where high precision is required, and robot actuators.
- Mains synchronous motors are used for electric clocks.
- Record player turntables

Advantages

Synchronous motors have the following advantages over non-synchronous motors:

- Speed is independent of the load, provided an adequate field current is applied.
- Accurate control in speed and position using open loop controls, eg. stepper motors.
- They will hold their position when a DC current is applied to both the stator and the rotor windings.
- Their power factor can be adjusted to unity by using a proper field current relative to the load. Also, a "capacitive" power factor, (current phase leads voltage phase), can be obtained by increasing this current slightly, which can help achieve a better power factor correction for the whole installation.
- Their construction allows for increased electrical efficiency when a low speed is required (as in ball mills and similar apparatus).
- They run either at the synchronous speed or they do not run at all.

Examples

- brushless DC electric motor.
- stepper motor.
- Three-phase AC synchronous motors.
- Switched reluctance motor.
- Synchronous brushless wound-rotor doubly-fed electric machine.

Chapter 3

AC Motor

An **AC motor** is an electric motor driven by an alternating current. It commonly consists of two basic parts, an outside stationary stator having coils supplied with alternating current to produce a rotating magnetic field, and an inside rotor attached to the output shaft that is given a torque by the rotating field. Where speed stability is important, some AC motors (such as some Papst motors) have the stator on the inside and the rotor on the outside to optimize inertia and cooling.

There are two main types of AC motors, depending on the type of rotor used. The first type is the induction motor, which only runs slightly slower or faster than the supply frequency. The magnetic field on the rotor of this motor is created by an induced current. The second type is the synchronous motor, which does not rely on induction and as a result, can rotate exactly at the supply frequency or a sub-multiple of the supply frequency. The magnetic field on the rotor is either generated by current delivered through slip rings or by a permanent magnet. Other types of motors include eddy current motors, and also AC/DC mechanically-commutated machines in which speed is dependent on voltage and winding connection.

History

In 1882 Nikola Tesla identified the rotating magnetic induction field principle used in alternators and pioneered the use of this rotating and inducting electromagnetic field force to generate torque in rotating machines. He exploited this principle in the design of a poly-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.

Introduction of Tesla's motor in 1888 initiated what is sometimes referred to as the *Second Industrial Revolution*, making possible both the efficient generation and long distance distribution of electrical energy using the alternating current transmission system, also of Tesla's invention (1888). Before widespread use of Tesla's principle of poly-phase induction for rotating machines, all motors operated by continually passing a conductor through a stationary magnetic field (as in homopolar motor).

Initially Tesla suggested that the commutators from a machine could be removed and the device could operate on a rotary field of electromagnetic force. Professor Poeschel, his

teacher, stated that would be akin to building a perpetual motion machine. This was because Tesla's teacher had only understood one half of Tesla's ideas. Professor Poeschel had realized that the induced rotating magnetic field would start the rotor of the motor spinning, but he did not see that the counter electromotive force generated would gradually bring the machine to a stop. Tesla would later obtain 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.

Squirrel-cage rotors

Most common AC motors use the squirrel cage rotor, which will be found in virtually all domestic and light industrial alternating current motors. The squirrel cage refers to the rotating exercise cage for pet animals. The motor takes its name from the shape of its rotor "windings"- a ring at either end of the rotor, with bars connecting the rings running the length of the rotor. It is typically cast aluminum or copper poured between the iron laminates of the rotor, and usually only the end rings will be visible. The vast majority of the rotor currents will flow through the bars rather than the higher-resistance and usually varnished laminates. Very low voltages at very high currents are typical in the bars and end rings; high efficiency motors will often use cast copper to reduce the resistance in the rotor.

In operation, the squirrel cage motor may be viewed as a transformer with a rotating secondary. When the rotor is not rotating in sync with the magnetic field, large rotor currents are induced; the large rotor currents magnetize the rotor and interact with the stator's magnetic fields to bring the rotor almost into synchronization with the stator's field. An unloaded squirrel cage motor at rated no-load speed will consume electrical power only to maintain rotor speed against friction and resistance losses. As the mechanical load increases, so will the electrical load - the electrical load is inherently related to the mechanical load. This is similar to a transformer, where the primary's electrical load is related to the secondary's electrical load.

This is why a squirrel cage blower motor may cause household lights to dim upon starting, but does not dim the lights on startup when its fan belt (and therefore mechanical load) is removed. Furthermore, a stalled squirrel cage motor (overloaded or with a jammed shaft) will consume current limited only by circuit resistance as it attempts to start. Unless something else limits the current (or cuts it off completely) overheating and destruction of the winding insulation is the likely outcome.

To prevent the currents induced in the squirrel cage from superimposing itself back onto the supply, the squirrel cage is generally constructed with a prime number of bars, or at least a small multiple of a prime number (rarely more than 2). There is an optimum number of bars in any design, and increasing the number of bars beyond that point merely serves to increase the losses of the motor particularly when starting.

Virtually every washing machine, dishwasher, standalone fan, record player, etc. uses some variant of a squirrel cage motor.

Calecon Effect

If the rotor of a squirrel cage motor runs at the true synchronous speed, the flux in the rotor at any given place on the rotor would not change, and no current would be created in the squirrel cage. For this reason, ordinary squirrel-cage motors run at some tens of rpm slower than synchronous speed, even at no load. Because the rotating field (or equivalent pulsating field) actually or effectively rotates faster than the rotor, it could be said to *slip* past the surface of the rotor. The difference between synchronous speed and actual speed is called **slip**, and loading the motor increases the amount of slip as the motor slows down slightly.

Two-phase AC servo motors

A typical two-phase AC servo-motor has a squirrel cage rotor and a field consisting of two windings:

1. a constant-voltage (AC) main winding.
2. a control-voltage (AC) winding in quadrature (i.e., 90 degrees phase shifted) with the main winding so as to produce a rotating magnetic field. Reversing phase makes the motor reverse.

An AC servo amplifier, a linear power amplifier, feeds the control winding. The electrical resistance of the rotor is made high intentionally so that the speed/torque curve is fairly linear. Two-phase servo motors are inherently high-speed, low-torque devices, heavily geared down to drive the load.

Single-phase AC induction motors

Three-phase motors produce a rotating magnetic field. However, when only single-phase power is available, the rotating magnetic field must be produced using other means. Several methods are commonly used:

Shaded-pole motor

A common single-phase motor is the shaded-pole motor and is used in devices requiring low starting torque, such as electric fans or the drain pump of washing machines and dishwashers or in other small household appliances. In this motor, small single-turn copper "shading coils" create the moving magnetic field. Part of each pole is encircled by a copper coil or strap; the induced current in the strap opposes the change of flux through the coil. This causes a time lag in the flux passing through the shading coil, so that the maximum field intensity moves across the pole face on each cycle. This produces a low level rotating magnetic field which is large enough to turn both the rotor and its attached

load. As the rotor picks up speed the torque builds up to its full level as the principal magnetic field is rotating relative to the rotating rotor.

A **reversible shaded-pole motor** was made by Barber-Colman several decades ago. It had a single field coil, and two principal poles, each split halfway to create two pairs of poles. Each of these four "half-poles" carried a coil, and the coils of diagonally-opposite half-poles were connected to a pair of terminals. One terminal of each pair was common, so only three terminals were needed in all.

The motor would not start with the terminals open; connecting the common to one other made the motor run one way, and connecting common to the other made it run the other way. These motors were used in industrial and scientific devices.

An unusual, **adjustable-speed**, low-torque shaded-pole motor could be found in traffic-light and advertising-lighting controllers. The pole faces were parallel and relatively close to each other, with the disc centred between them, something like the disc in a watthour meter. Each pole face was split, and had a shading coil on one part; the shading coils were on the parts that faced each other. Both shading coils were probably closer to the main coil; they could have both been farther away, without affecting the operating principle, just the direction of rotation.

Applying AC to the coil created a field that progressed in the gap between the poles. The plane of the stator core was approximately tangential to an imaginary circle on the disc, so the travelling magnetic field dragged the disc and made it rotate.

The stator was mounted on a pivot so it could be positioned for the desired speed and then clamped in position. Keeping in mind that the effective speed of the travelling magnetic field in the gap was constant, placing the poles nearer to the centre of the disc made it run relatively faster, and toward the edge, slower.

It is possible that these motors are still in use in some older installations.

Split-phase induction motor

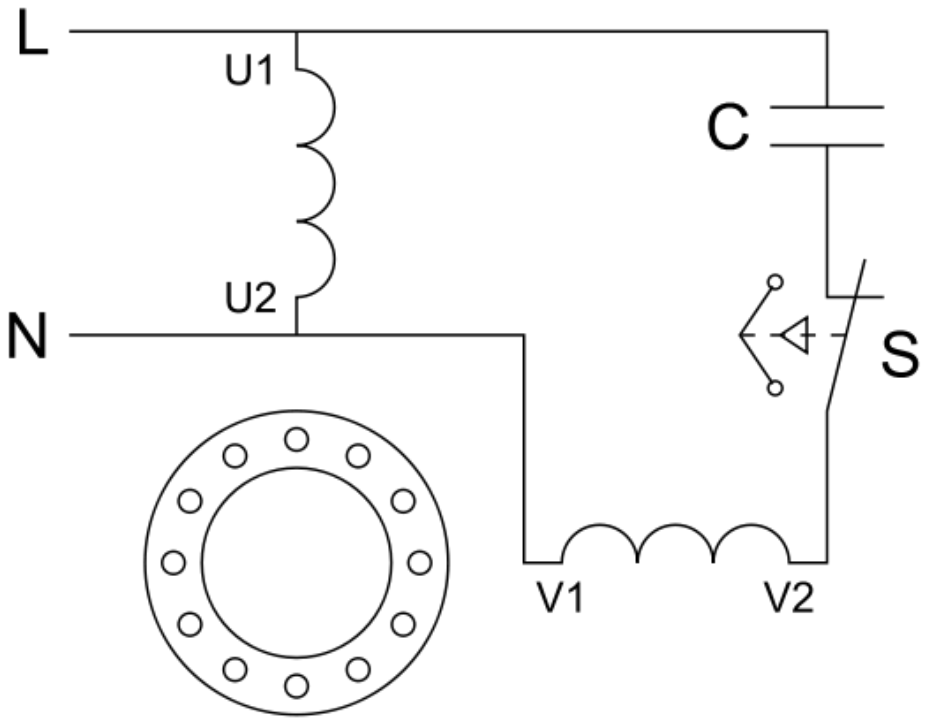
Another common single-phase AC motor is the *split-phase induction motor*, commonly used in major appliances such as washing machines and clothes dryers. Compared to the shaded pole motor, these motors can generally provide much greater starting torque by using a special startup winding in conjunction with a centrifugal switch.

In the split-phase motor, the startup winding is designed with a higher resistance than the running winding. This creates an LR circuit which slightly shifts the phase of the current in the startup winding. When the motor is starting, the startup winding is connected to the power source via a set of spring-loaded contacts pressed upon by the stationary centrifugal switch. The starting winding is wound with fewer turns of smaller wire than the main winding, so it has a lower inductance (L) and higher resistance (R). The lower L/R ratio creates a small phase shift, not more than about 30 degrees, between the flux

due to the main winding and the flux of the starting winding. The starting direction of rotation may be reversed simply by exchanging the connections of the startup winding relative to the running winding.

The phase of the magnetic field in this startup winding is shifted from the phase of the mains power, allowing the creation of a moving magnetic field which starts the motor. Once the motor reaches near design operating speed, the centrifugal switch activates, opening the contacts and disconnecting the startup winding from the power source. The motor then operates solely on the running winding. The starting winding must be disconnected since it would increase the losses in the motor.

Capacitor start motor



Schematic of a capacitor start motor.

A capacitor start motor is a split-phase induction motor with a starting capacitor inserted in series with the startup winding, creating an LC circuit which is capable of a much greater phase shift (and so, a much greater starting torque). The capacitor naturally adds expense to such motors.

Resistance start motor

A resistance start motor is a split-phase induction motor with a starter inserted in series with the startup winding, creating capacitance. This added starter provides assistance in the starting and initial direction of rotation.

Permanent-split capacitor motor

Another variation is the *permanent-split capacitor (PSC) motor* (also known as a capacitor start and run motor). This motor operates similarly to the capacitor-start motor described above, but there is no centrifugal starting switch, and what correspond to the start windings (second windings) are permanently connected to the power source (through a capacitor), along with the run windings. PSC motors are frequently used in air handlers, blowers, and fans (including ceiling fans) and other cases where a variable speed is desired.

A capacitor ranging from 3 to 25 microfarads is connected in series with the "start" windings and remains in the circuit during the run cycle. The "start" windings and run windings are identical in this motor, and reverse motion can be achieved by reversing the wiring of the 2 windings, with the capacitor connected to the other windings as "start" windings. By changing taps on the running winding but keeping the load constant, the motor can be made to run at different speeds. Also, provided all 6 winding connections are available separately, a 3 phase motor can be converted to a capacitor start and run motor by commoning two of the windings and connecting the third via a capacitor to act as a start winding.

Wound rotors

An alternate design, called the wound rotor, is used when variable speed is required. In this case, the rotor has the same number of poles as the stator and the windings are made of wire, connected to slip rings on the shaft. Carbon brushes connect the slip rings to an external controller such as a variable resistor that allows changing the motor's slip rate. In certain high-power variable speed wound-rotor drives, the slip-frequency energy is captured, rectified and returned to the power supply through an inverter. With bidirectionally controlled power, the wound-rotor becomes an active participant in the energy conversion process with the wound-rotor doubly-fed configuration showing twice the power density.

Compared to squirrel cage **rotors** and without considering brushless wound-rotor doubly-fed technology, wound rotor motors are expensive and require maintenance of the slip rings and brushes, but they were the standard form for variable speed control before the advent of compact power electronic devices. Transistorized inverters with variable-frequency drive can now be used for speed control, and wound rotor motors are becoming less common.

Several methods of starting a polyphase motor are used. Where the large inrush current and high starting torque can be permitted, the motor can be started across the line, by applying full line voltage to the terminals (direct-on-line, DOL). Where it is necessary to limit the starting inrush current (where the motor is large compared with the short-circuit capacity of the supply), reduced voltage starting using either series inductors, an autotransformer, thyristors, or other devices are used. A technique sometimes used is (star-delta, YΔ) starting, where the motor coils are initially connected in star for acceleration of the load, then switched to delta when the load is up to speed. This technique is more common in Europe than in North America. Transistorized drives can directly vary the applied voltage as required by the starting characteristics of the motor and load.

This type of motor is becoming more common in traction applications such as locomotives, where it is known as the asynchronous traction motor.

The speed of the AC motor is determined primarily by the frequency of the AC supply and the number of poles in the stator winding, according to the relation:

$$N_s = 120F / p$$

where

N_s = Synchronous speed, in revolutions per minute
F = AC power frequency
p = Number of poles per phase winding

Actual RPM for an induction motor will be less than this calculated synchronous speed by an amount known as *slip*, that increases with the torque produced. With no load, the speed will be very close to synchronous. When loaded, standard motors have between 2-3% slip, special motors may have up to 7% slip, and a class of motors known as *torque motors* are rated to operate at 100% slip (0 RPM/full stall).

The slip of the AC motor is calculated by:

$$S = (N_s - N_r) / N_s$$

where

N_r = Rotational speed, in revolutions per minute.
S = Normalised Slip, 0 to 1.

As an example, a typical four-pole motor running on 60 Hz might have a nameplate rating of 1725 RPM at full load, while its calculated speed is 1800 RPM.

The speed in this type of motor has traditionally been altered by having additional sets of coils or poles in the motor that can be switched on and off to change the speed of

magnetic field rotation. However, developments in power electronics mean that the frequency of the power supply can also now be varied to provide a smoother control of the motor speed.

Three-phase AC synchronous motors

If connections to the rotor coils of a three-phase motor are taken out on slip-rings and fed a separate field current to create a continuous magnetic field (or if the rotor consists of a permanent magnet), the result is called a synchronous motor because the rotor will rotate synchronously with the rotating magnetic field produced by the polyphase electrical supply.

The synchronous motor can also be used as an alternator.

Nowadays, synchronous motors are frequently driven by transistorized variable-frequency drives. This greatly eases the problem of starting the massive rotor of a large synchronous motor. They may also be started as induction motors using a squirrel-cage winding that shares the common rotor: once the motor reaches synchronous speed, no current is induced in the squirrel-cage winding so it has little effect on the synchronous operation of the motor, aside from stabilizing the motor speed on load changes.

Synchronous motors are occasionally used as traction motors; the TGV may be the best-known example of such use.

One use for this type of motor is its use in a power factor correction scheme. They are referred to as synchronous condensers. This exploits a feature of the machine where it consumes power at a leading power factor when its rotor is over excited. It thus appears to the supply to be a capacitor, and could thus be used to correct the lagging power factor that is usually presented to the electric supply by inductive loads. The excitation is adjusted until a near unity power factor is obtained (often automatically). Machines used for this purpose are easily identified as they have no shaft extensions. Synchronous motors are valued in any case because their power factor is much better than that of induction motors, making them preferred for very high power applications.

Some of the largest AC motors are pumped-storage hydroelectricity generators that are operated as synchronous motors to pump water to a reservoir at a higher elevation for later use to generate electricity using the same machinery. Six 350-megawatt generators are installed in the Bath County Pumped Storage Station in Virginia, USA. When pumping, each unit can produce 563,400 horsepower (420 megawatts).

Universal motors and series wound motors

AC motors can also have brushes. The universal motor is widely used in small home appliances and power tools.

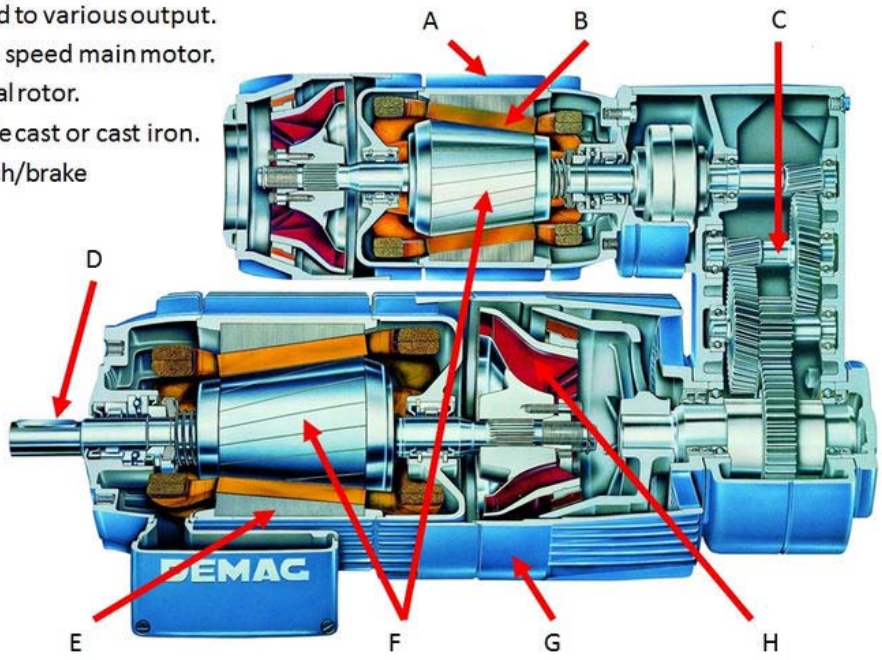
Repulsion motor

Repulsion motors are wound-rotor single-phase AC motors that are similar to universal motors. In a repulsion motor, the armature brushes are shorted together rather than connected in series with the field. By transformer action, the stator induces currents in the rotor, which create torque by repulsion instead of attraction as in other motors. Several types of repulsion motors have been manufactured, but the *repulsion-start induction-run* (RS-IR) motor has been used most frequently. The RS-IR motor has a centrifugal switch that shorts all segments of the commutator so that the motor operates as an induction motor once it has been accelerated to full speed. Some of these motors also lift the brushes out of contact with the commutator once the commutator is shorted. RS-IR motors have been used to provide high starting torque per ampere under conditions of cold operating temperatures and poor source voltage regulation. Few repulsion motors of any type are sold as of 2005.

Other types of motors

AC Motor with sliding rotor

A. Creep speed virtually independent of load
B. Single or two speed micro motor.
C. Intermediate gear unit.
D. Can be mated to various output.
E. Single or two speed main motor.
F. Sliding conical rotor.
G. Aluminum die cast or cast iron.
H. Integral clutch/brake



Demag AC Motor with sliding rotors-Rvancopp

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.

The high starting torque and low inertia of the conical rotor brake motor has proven to be ideal for the demands of high cycle dynamic drives in applications since the motor was invented designed, and introduced over 50 years ago by a company named Demag Cranes & Components Corp. This type of motor configuration was first introduced in the USA in 1963 by this company.

Single-speed or two speed motors that are designed for coupling to gear motor system gearboxes. Conical rotor brake motors are also used to power micro speed drives.

Motors of this type can also be found on overhead crane and hoist (device)The micro speed unit combines two motors and an intermediate gear reducer. These are used for applications where extreme mechanical positioning accuracy and high cycling capability are needed. The micro speed unit combines a “main” conical rotor brake motor for rapid speed and a “micro” conical rotor brake motor for slow or positioning speed. The intermediate gearbox allows a range of ratios, and motors of different speeds can be combined to produce high ratios between high and low speed.

Single-phase AC synchronous motors

Small single-phase AC motors can also be designed with magnetized rotors.

If a conventional squirrel-cage rotor has flats ground on it to create salient poles and increase reluctance, it will start conventionally, but will run synchronously, although it can provide only a modest torque at synchronous speed. This is known as a reluctance motor.

Because inertia makes it difficult to instantly accelerate the rotor from stopped to synchronous speed, these motors normally require some sort of special feature to get started. Some include a squirrel-cage structure to bring the rotor close to synchronous speed. Various other designs use a small induction motor (which may share the same field coils and rotor as the synchronous motor) or a very light rotor with a one-way mechanism (to ensure that the rotor starts in the "forward" direction). In the latter instance, applying AC power creates chaotic (or seemingly chaotic) jumping movement back and forth; such a motor will always start, but lacking the anti-reversal mechanism, the direction it runs is unpredictable. The Hammond organ tone generator used a non-self-starting synchronous motor (until comparatively recently), and had an auxiliary conventional shaded-pole starting motor. A spring-loaded auxiliary manual starting switch connected power to this second motor for a few seconds.

Hysteresis synchronous motors

These motors are relatively costly, and are used where exact speed (assuming an exact-frequency AC source) as well as rotation with a very small amount of fast variations in speed (called 'flutter" in audio recordings) is essential. Applications included tape recorder capstan drives (the motor shaft could be the capstan). Their distinguishing feature is their rotor, which is a smooth cylinder of a magnetic alloy that stays magnetized, but can be demagnetized fairly easily as well as re-magnetized with poles in a new location. Hysteresis refers to how the magnetic flux in the metal lags behind the external magnetizing force; for instance, to demagnetize such a material, one could apply a magnetizing field of opposite polarity to that which originally magnetized the material.

These motors have a stator like those of capacitor-run squirrel-cage induction motors. On startup, when slip decreases sufficiently, the rotor becomes magnetized by the stator's field, and the poles stay in place. The motor then runs at synchronous speed as if the rotor were a permanent magnet. When stopped and re-started, the poles are likely to form at different locations.

For a given design, torque at synchronous speed is only relatively modest, and the motor can run at below synchronous speed.

Electronically commutated motors

Such motors have an external rotor with a cup-shaped housing and a radially magnetized permanent magnet connected in the cup-shaped housing. An interior stator is positioned in the cup-shaped housing. The interior stator has a laminated core having grooves. Windings are provided within the grooves. The windings have first end turns proximal to a bottom of the cup-shaped housing and second end turns positioned distal to the bottom. The first and second end turns electrically connect the windings to one another. The permanent magnet has an end face rom the bottom of the cup-shaped housing. At least one galvano-magnetic rotor position sensor is arranged opposite the end face of the permanent magnet so as to be located within a magnetic leakage of the permanent magnet and within a magnetic leakage of the interior stator. The at least one rotor position sensor is designed to control current within at least a portion of the windings. A magnetic leakage flux concentrator is arranged at the interior stator at the second end turns at a side of the second end turns facing away from the laminated core and positioned at least within an angular area of the interior stator in which the at (?-someone got distracted)

ECM motors are increasingly being found in forced-air furnaces and HVAC systems to save on electricity costs as modern HVAC systems are running their fans for longer periods of time (duty cycle). The cost of using ECM motors in HVAC systems is higher, but the major benefit is the motor efficiency is much higher that other motor types at reduced speeds and partial loads.

Watthour-meter motors

These are essentially two-phase induction motors with permanent magnets that retard rotor speed, so that their speed is accurately proportional to the power passing through the meter. The rotor is an aluminium-alloy disc, and currents induced into it react with the field from the stator.

The stator is composed of three coils that are arranged facing the disc surface, with the magnetic circuit completed by a C-shaped core of permeable iron. One phase of the motor is produced by a coil with many turns located above the disc surface. This upper coil has a relatively high inductance, and is connected in parallel with the load. The magnetic field produced in this coil lags the applied (line/mains) voltage by almost 90 degrees. The other phase of the motor is produced by a pair of coils with very few turns of heavy-gauge wire, and hence quite-low inductance. These coils, located on the underside of the disc surface, are wired in series with the load, and produce magnetic fields in-phase with the load current.

Because the two lower coils are wound anti-parallel, and are each located equidistant from the upper coil, an azimuthally traveling magnetic flux is created across the disc surface. This traveling flux exerts an average torque on the disc proportional to the product of the power factor; RMS current, and voltage. It follows that the rotation of the magnetically-braked disc is in effect an analogue integration the real RMS power delivered to the load. The mechanical dial on the meter then simply reads off a numerical value proportional to the total number of revolutions of the disc, and thus the total energy delivered to the load.

Slow-speed synchronous timing motors

Representative are low-torque synchronous motors with a multi-pole hollow cylindrical magnet (internal poles) surrounding the stator structure. An aluminum cup supports the magnet. The stator has one coil, coaxial with the shaft. At each end of the coil are a pair of circular plates with rectangular teeth on their edges, formed so they are parallel with the shaft. They are the stator poles. One of the pair of discs distributes the coil's flux directly, while the other receives flux that has passed through a common shading coil. The poles are rather narrow, and between the poles leading from one end of the coil are an identical set leading from the other end. In all, this creates a repeating sequence of four poles, unshaded alternating with shaded, that creates a circumferential traveling field to which the rotor's magnetic poles rapidly synchronize. Some stepping motors have a similar structure.

Chapter 4

DC Motor and Brushed DC Electric Motor

DC motor

A **DC motor** is an electric motor that runs on direct current (DC) electricity.

Brushed

The brushed DC electric motor generates torque directly from DC power supplied to the motor by using internal commutation, stationary permanent magnets, and rotating electrical magnets. Like all electric motors or generators, torque is produced by the principle of Lorentz force, which states that any current-carrying conductor placed within an external magnetic field experiences a torque or force known as Lorentz force. Advantages of a brushed DC motor include low initial cost, high reliability, and simple control of motor speed. Disadvantages are high maintenance and low life-span for high intensity uses. Maintenance involves regularly replacing the brushes and springs which carry the electric current, as well as cleaning or replacing the commutator. These components are necessary for transferring electrical power from outside the motor to the spinning wire windings of the rotor inside the motor.

Synchronous

Synchronous DC motors, such as the brushless DC motor and the stepper motor, require external commutation to generate torque. They lock up if driven directly by DC power. However, BLDC motors are more similar to a synchronous ac motor.

Brushless

Brushless DC motors use a rotating permanent magnet in the rotor, and stationary electrical magnets on the motor housing. A motor controller converts DC to AC. This design is simpler than that of brushed motors because it eliminates the complication of transferring power from outside the motor to the spinning rotor. Advantages of brushless motors include long life span, little or no maintenance, and high efficiency. Disadvantages include high initial cost, and more complicated motor speed controllers.

Uncommutated

Other types of DC motors require no commutation.

- Homopolar motor – A homopolar motor has a magnetic field along the axis of rotation and an electric current that at some point is not parallel to the magnetic field. The name homopolar refers to the absence of polarity change.

Homopolar motors necessarily have a single-turn coil, which limits them to very low voltages. This has restricted the practical application of this type of motor.

- Ball bearing motor – A ball bearing motor is an unusual electric motor that consists of two ball bearing-type bearings, with the inner races mounted on a common conductive shaft, and the outer races connected to a high current, low voltage power supply. An alternative construction fits the outer races inside a metal tube, while the inner races are mounted on a shaft with a non-conductive section (e.g. two sleeves on an insulating rod). This method has the advantage that the tube will act as a flywheel. The direction of rotation is determined by the initial spin which is usually required to get it going.

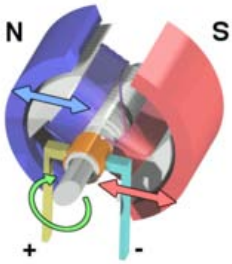
Brushed DC electric motor

A **brushed DC motor** is an internally commutated electric motor designed to be run from a DC power source.

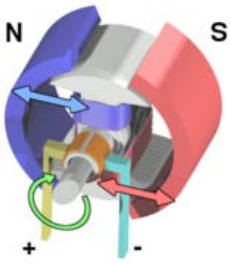
Simple two-pole DC motor

The following graphics illustrate a simple, two-pole, brushed, DC motor.

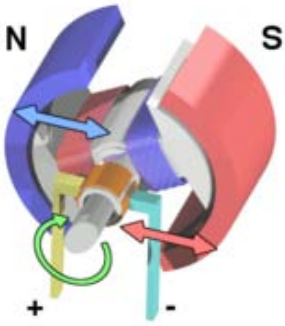
DC Motor Rotation



A simple DC electric motor. When the coil is powered, a magnetic field is generated around the armature. The left side of the armature is pushed away from the left magnet and drawn toward the right, causing rotation.



The armature continues to rotate.



When the armature becomes horizontally aligned, the commutator reverses the direction of current through the coil, reversing the magnetic field. The process then repeats.

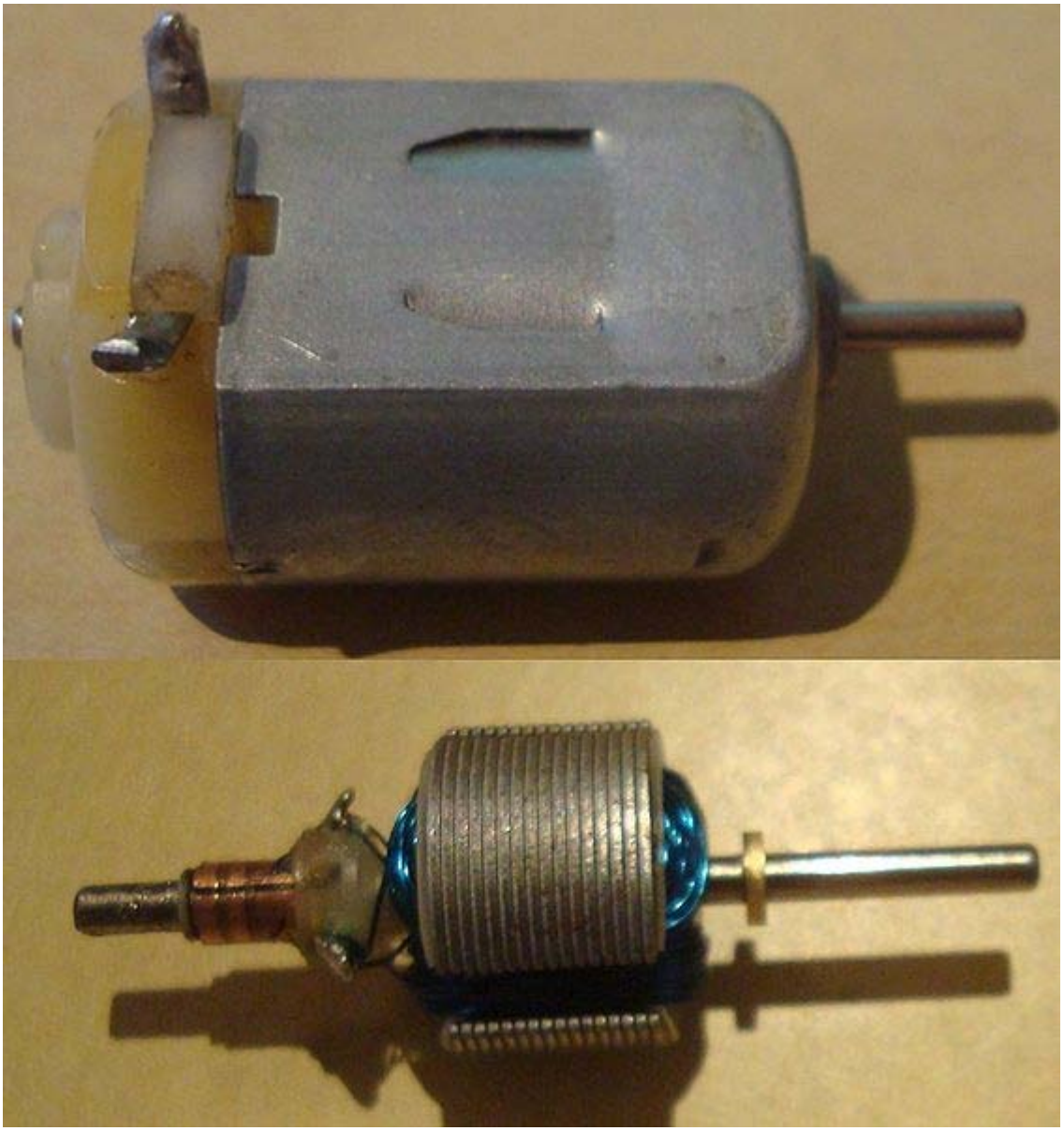
Electric motors of various sizes

When a current passes through the coil wound around a soft iron core, the side of the positive pole is acted upon by an upwards force, while the other side is acted upon by a

downward force. According to Fleming's left hand rule, the forces cause a turning effect on the coil, making it rotate. To make the motor rotate in a constant direction, "direct current" commutators make the current reverse in direction every half a cycle (in a two-pole motor) thus causing the motor to continue to rotate in the same direction.

A problem with the motor shown above is that when the plane of the coil is parallel to the magnetic field—i.e. when the rotor poles are 90 degrees from the stator poles—the torque is zero. In the pictures above, this occurs when the core of the coil is horizontal—the position it is just about to reach in the last picture on the right. The motor would not be able to start in this position. However, once it was started, it would continue to rotate through this position by inertia.

There is a second problem with this simple pole design. At the zero-torque position, both commutator brushes are touching (bridging) both commutator plates, resulting in a short-circuit. The power leads are shorted together through the commutator plates, and the coil is also short-circuited through both brushes (the coil is shorted twice, once through each brush independently). Note that this problem is independent of the non-starting problem above; even if there were a high current in the coil at this position, there would still be zero torque. The problem here is that this short uselessly consumes power without producing any motion (nor even any coil current.) In a low-current battery-powered demonstration this short-circuiting is generally not considered harmful. (Here, low-current means that the battery is intrinsically limited to low current and will not overheat if loaded with a short circuit; this is usually the case for an AA alkaline cell but not the case for batteries like the Li-ion cells used in many laptop batteries in this first decade of the 21st century.) However, if a two-pole motor were designed to do actual work with several hundred watts of power output, this shorting could result in severe commutator overheating, brush damage, and potential welding of the brushes—if they were metallic—to the commutator. Carbon brushes, which are often used, would not weld. In any case, a short like this is very wasteful, drains batteries rapidly and, at a minimum, requires power supply components to be designed to much higher standards than would be needed just to run the motor without the shorting.



The inside of an electric DC motor.

One simple solution is to put a gap between the commutator plates which is wider than the ends of the brushes. This increases the zero-torque range of angular positions but eliminates the shorting problem; if the motor is started spinning by an outside force it will continue spinning. With this modification, it can also be effectively turned off simply by stalling (stopping) it in a position in the zero-torque (i.e. commutator non-contacting) angle range. This design is sometimes seen in homebuilt hobby motors, e.g. for science fairs and such designs can be found in some published science project books. A clear downside of this simple solution is that the motor now coasts through a substantial arc of rotation twice per revolution and the torque is pulsed. This may work for electric fans or to keep a flywheel spinning but there are many applications, even where starting and stopping are not necessary, for which it is completely inadequate, such as driving the

capstan of a tape transport, or any instance where to speed up and slow down often and quickly is a requirement. Another disadvantage is that, since the coils have a measure of self inductance, current flowing in them cannot suddenly stop. The current attempts to jump the opening gap between the commutator segment and the brush, causing arcing.

Even for fans and flywheels, the clear weaknesses remaining in this design—especially that it is not self-starting from all positions—make it impractical for working use, especially considering the better alternatives that exist. Unlike the demonstration motor above, DC motors are commonly designed with more than two poles, are able to start from any position, and do not have any position where current can flow without producing electromotive power by passing through some coil. Many common small brushed DC motors used in toys and small consumer appliances, the simplest mass-produced DC motors to be found, have three-pole armatures. The brushes can now bridge two adjacent commutator segments without causing a short circuit. These three-pole armatures also have the advantage that current from the brushes either flows through two coils in series or through just one coil. Starting with the current in an individual coil at half its nominal value (as a result of flowing through two coils in series), it rises to its nominal value and then falls to half this value. The sequence then continues with current in the reverse direction. This results in a closer step-wise approximation to the ideal sinusoidal coil current, producing a more even torque than the two-pole motor where the current in each coil is closer to a square wave. Since current changes are half those of a comparable two-pole motor, arcing at the brushes is consequently less.

If the shaft of a DC motor is turned by an external force, the motor will act like a generator and produce an Electromotive force (EMF). During normal operation, the spinning of the motor produces a voltage, known as the counter-EMF (CEMF) or back EMF, because it opposes the applied voltage on the motor. The back EMF is the reason that the motor when free-running does not appear to have the same low electrical resistance as the wire contained in its winding. This is the same EMF that is produced when the motor is used as a generator (for example when an electrical load, such as a light bulb, is placed across the terminals of the motor and the motor shaft is driven with an external torque). Therefore, the total voltage drop across a motor consists of the CEMF voltage drop, and the parasitic voltage drop resulting from the internal resistance of the armature's windings. The current through a motor is given by the following equation:

$$I = \frac{V_{applied} - V_{cemf}}{R_{armature}}$$

The mechanical power produced by the motor is given by:

$$P = I \cdot V_{cemf}$$

As an unloaded DC motor spins, it generates a backwards-flowing electromotive force that resists the current being applied to the motor. The current through the motor drops as the rotational speed increases, and a free-spinning motor has very little current. It is only

when a load is applied to the motor that slows the rotor that the current draw through the motor increases.

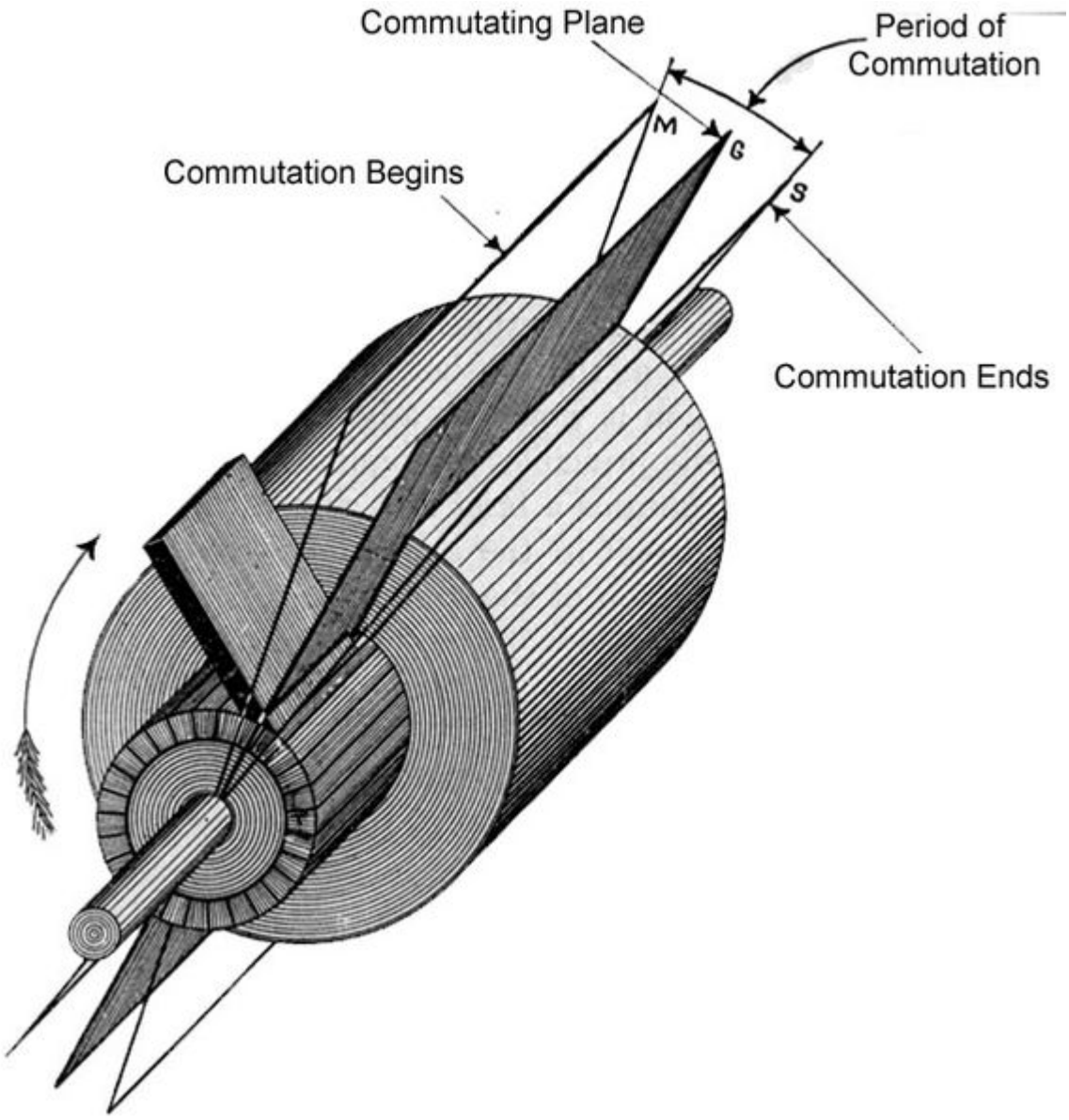
"In an experiment of this kind made on a motor with separately excited magnets, the following figures were obtained:

Revolutions per minute	0	50	100	160	180	195
Amperes	20	16.2	12.2	7.8	6.1	5.1

Apparently, if the motor had been helped on to run at 261.5 revolutions per minute, the current would have been reduced to zero. In the last result obtained, the current of 5.1 amperes was absorbed in driving the armature against its own friction at the speed of 195 revolutions per minute."

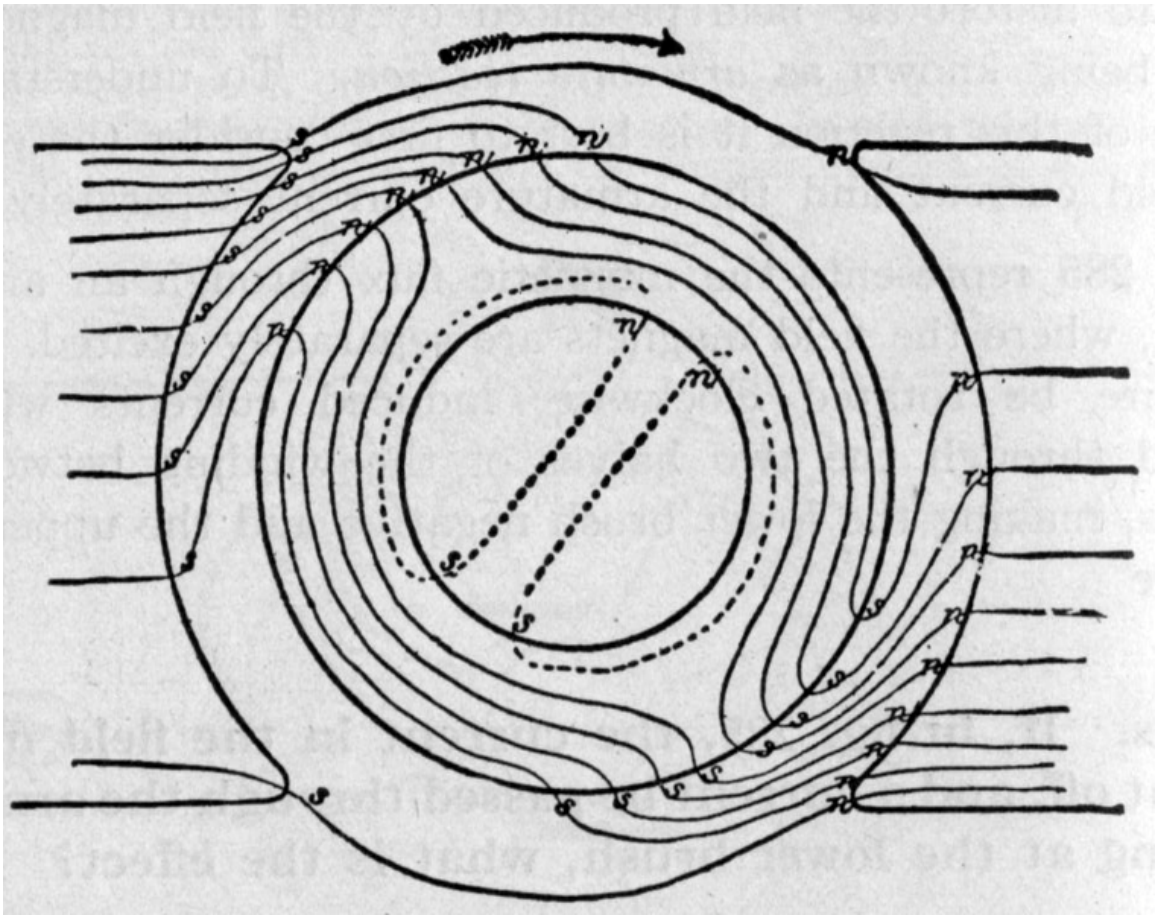
The commutating plane

In a dynamo, a plane through the centers of the contact areas where a pair of brushes touch the commutator and parallel to the axis of rotation of the armature is referred to as the *commutating plane*. In this diagram the commutating plane is shown for just one of the brushes, assuming the other brush made contact on the other side of the commutator with radial symmetry, 180 degrees from the brush shown.

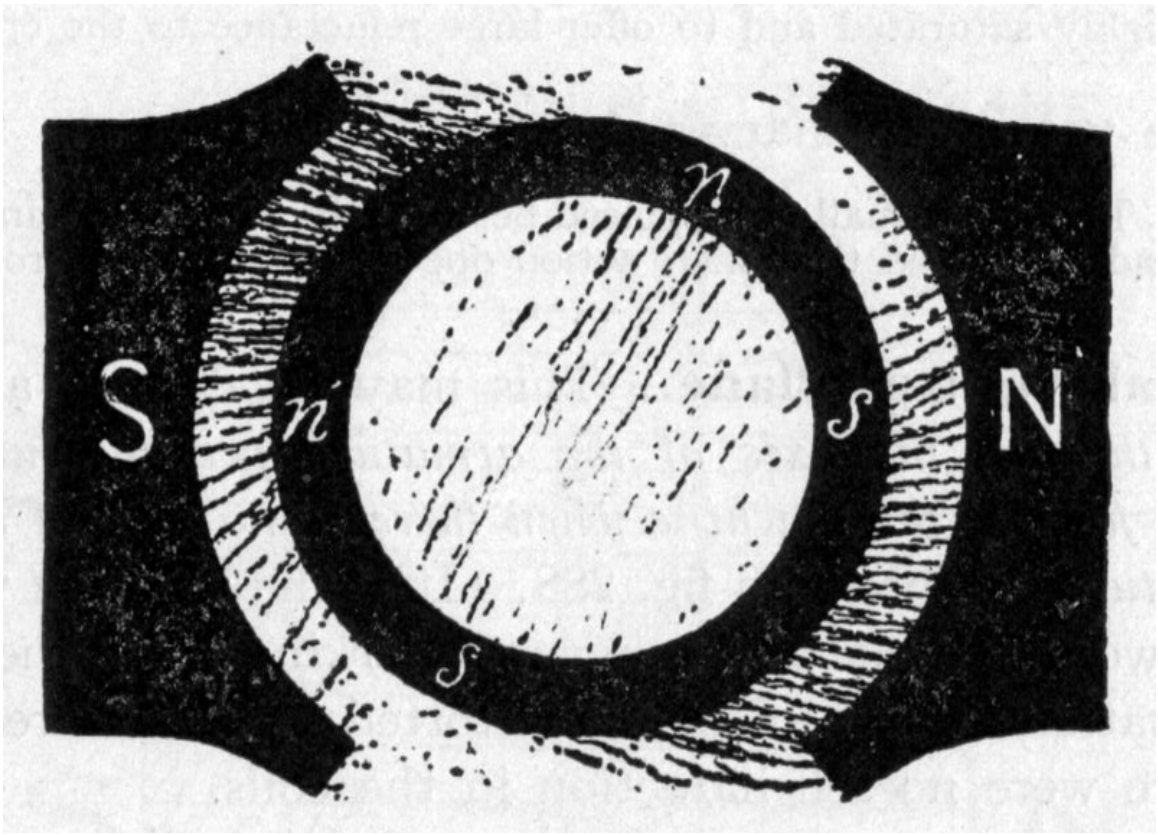


Compensation for stator field distortion

In a real dynamo, the field is never perfectly uniform. Instead, as the rotor spins it induces field effects which drag and distort the magnetic lines of the outer non-rotating stator.

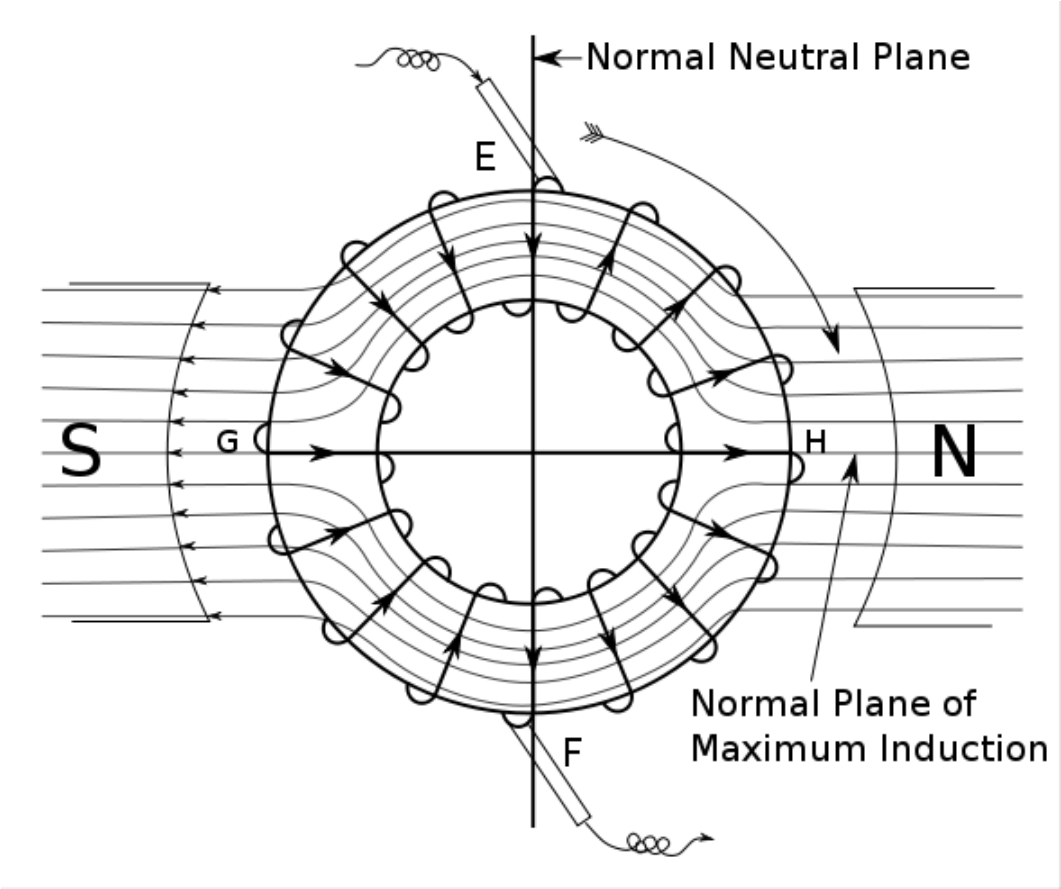


Exaggerated example of how the field is distorted by the rotor.

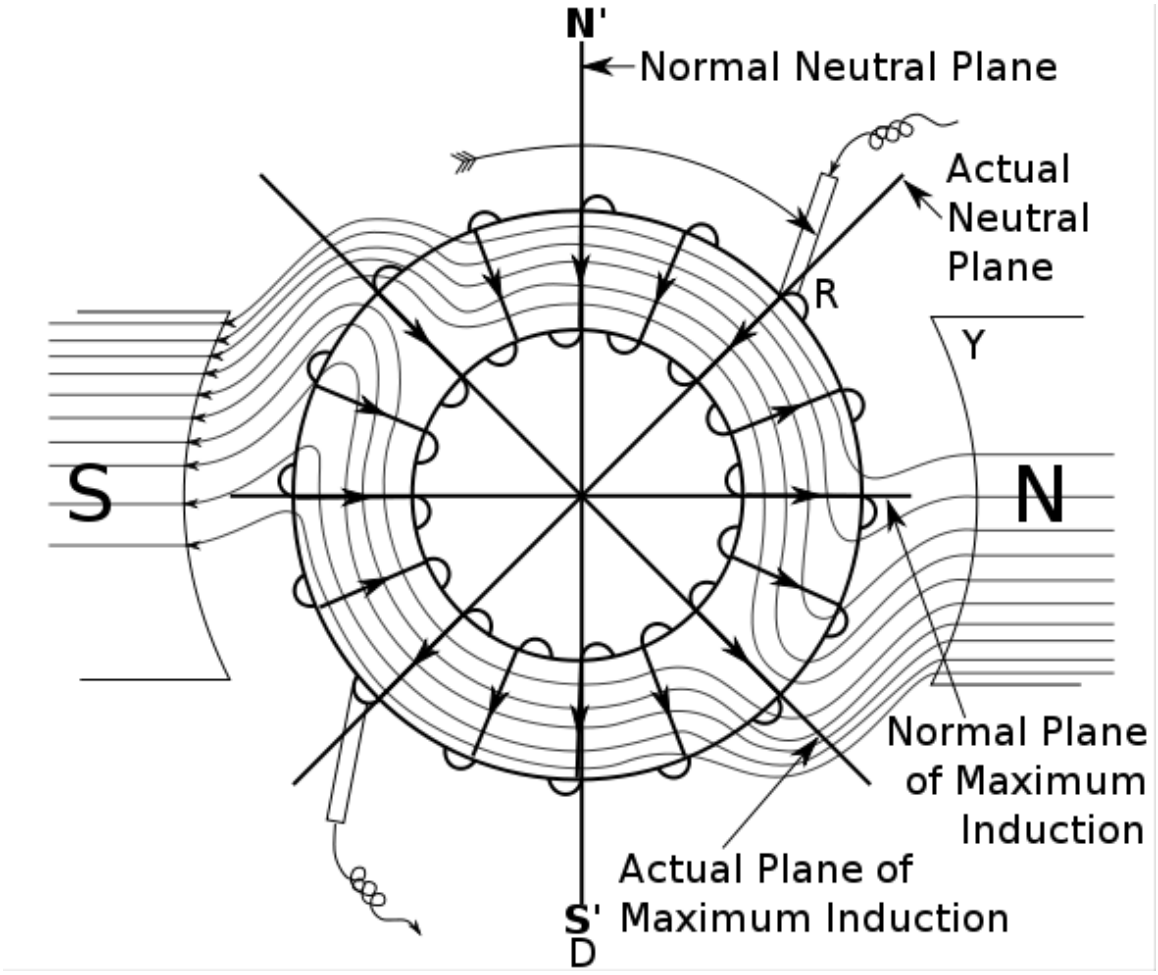


Iron filings show the distorted field across the rotor.

The faster the rotor spins, the further the degree of field distortion. Because the dynamo operates most efficiently with the rotor field at right angles the stator field, it is necessary to either retard or advance the brush position to put the rotor's field into the correct position to be at a right angle to the distorted field.



1. Centered position of the commutating plane if there were no field distortion effects.



Actual position of the commutating plane to compensate for field distortion.

These field effects are reversed when the direction of spin is reversed. It is therefore difficult to build an efficient reversible commutated dynamo, since for highest field strength it is necessary to move the brushes to the opposite side of the normal neutral plane.

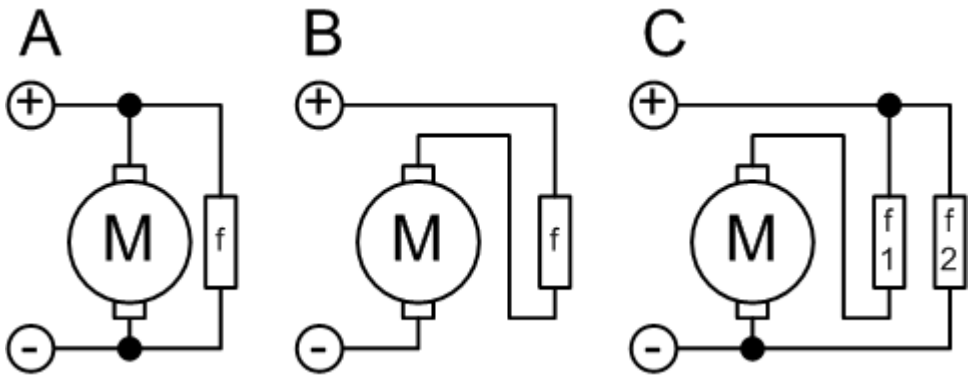
The effect can be considered to be somewhat similar to timing advance in an internal combustion engine. Generally a dynamo that has been designed to run at a certain fixed speed will have its brushes permanently fixed to align the field for highest efficiency at that speed.

Motor design variations

DC motors

DC motors are commonly constructed with wound rotors and either wound or permanent magnet stators.

Wound stators



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

The field coils have traditionally existed in four basic formats: separately-excited (sepex), series-wound, shunt-wound, and a combination of the latter two; compound-wound. In a series wound motor, the field coils are connected electrically in series with the armature coils (via the brushes). In a shunt wound motor, the field coils are connected in parallel, or "shunted" to the armature coils. In a separately-excited (sepex) motor the field coils are supplied from an independent source, such as a motor-generator and the field current is unaffected by changes in the armature current. The sepex system was sometimes used in DC traction motors to facilitate control of wheelslip.

Permanent-magnet motors

Permanent magnet types have some performance advantages over direct-current excited synchronous types, and have become predominant in fractional horsepower applications. They are smaller, lighter, more efficient and reliable than other singly-fed electric machines.

Originally all large industrial DC motors used wound field or rotor magnets. Permanent magnets have traditionally only been useful on small motors because it was difficult to find a material capable of retaining a high-strength field. Only recently have advances in materials technology allowed the creation of high-intensity permanent magnets, such as neodymium magnets, allowing the development of compact, high-power motors without the extra real-estate of field coils and excitation means. But as these high performance permanent magnets become more applied in electric motor or generator systems, other problems are realized.

Axial field motors

Traditionally, the field has been applied radially- in and away from the rotation axis of the motor. However some designs have the field flowing along the axis of the motor, with the rotor cutting the field lines as it rotates. This allows for much stronger magnetic fields, particularly if halbach arrays are employed. This, in turn, gives the motor's power at lower speeds. However, the focused flux density cannot rise about the limited residual flux density of the permanent magnet despite high coercivity and like all electric machine, the flux density of magnetic core saturation is the design constraint.

Speed control

Generally, the rotational speed of a DC motor is proportional to the voltage applied to it, and the torque is proportional to the current. Speed control can be achieved by variable battery tappings, variable supply voltage, resistors or electronic controls. The direction of a wound field DC motor can be changed by reversing either the field or armature connections but not both. This is commonly done with a special set of contactors (direction contactors).

The effective voltage can be varied by inserting a series resistor or by an electronically controlled switching device made of thyristors, transistors, or, formerly, mercury arc rectifiers.

In a circuit known as a chopper, the average voltage applied to the motor is varied by switching the supply voltage very rapidly. As the "on" to "off" ratio is varied to alter the average applied voltage, the speed of the motor varies. The percentage "on" time multiplied by the supply voltage gives the average voltage applied to the motor. Therefore, with a 100 V supply and a 25% "on" time, the average voltage at the motor will be 25 V. During the "off" time, the armature's inductance causes the current to continue through a diode called a "flyback diode", in parallel with the motor. At this point in the cycle, the supply current will be zero, and therefore the average motor current will always be higher than the supply current unless the percentage "on" time is 100%. At 100% "on" time, the supply and motor current are equal. The rapid switching wastes less energy than series resistors. This method is also called pulse-width modulation (PWM) and is often controlled by a microprocessor. An output filter is sometimes installed to smooth the average voltage applied to the motor and reduce motor noise.

Since the series-wound DC motor develops its highest torque at low speed, it is often used in traction applications such as electric locomotives, and trams. Another application is starter motors for petrol and small diesel engines. Series motors must never be used in applications where the drive can fail (such as belt drives). As the motor accelerates, the armature (and hence field) current reduces. The reduction in field causes the motor to speed up until it destroys itself. This can also be a problem with railway motors in the event of a loss of adhesion since, unless quickly brought under control, the motors can reach speeds far higher than they would do under normal circumstances. This can not only cause problems for the motors themselves and the gears, but due to the differential

speed between the rails and the wheels it can also cause serious damage to the rails and wheel treads as they heat and cool rapidly. Field weakening is used in some electronic controls to increase the top speed of an electric vehicle. The simplest form uses a contactor and field-weakening resistor; the electronic control monitors the motor current and switches the field weakening resistor into circuit when the motor current reduces below a preset value (this will be when the motor is at its full design speed). Once the resistor is in circuit, the motor will increase speed above its normal speed at its rated voltage. When motor current increases, the control will disconnect the resistor and low speed torque is made available.

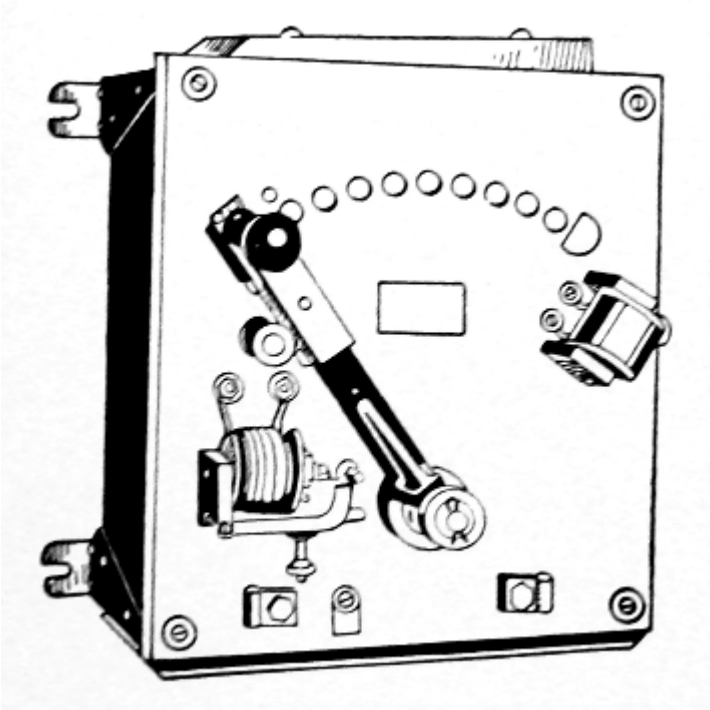
One interesting method of speed control of a DC motor is the Ward Leonard control. It is a method of controlling a DC motor (usually a shunt or compound wound) and was developed as a method of providing a speed-controlled motor from an AC supply, though it is not without its advantages in DC schemes. The AC supply is used to drive an AC motor, usually an induction motor that drives a DC generator or dynamo. The DC output from the armature is directly connected to the armature of the DC motor (sometimes but not always of identical construction). The shunt field windings of both DC machines are independently excited through variable resistors. Extremely good speed control from standstill to full speed, and consistent torque, can be obtained by varying the generator and/or motor field current. This method of control was the *de facto* method from its development until it was superseded by solid state thyristor systems. It found service in almost any environment where good speed control was required, from passenger lifts through to large mine pit head winding gear and even industrial process machinery and electric cranes. Its principal disadvantage was that three machines were required to implement a scheme (five in very large installations, as the DC machines were often duplicated and controlled by a tandem variable resistor). In many applications, the motor-generator set was often left permanently running, to avoid the delays that would otherwise be caused by starting it up as required. Although electronic (thyristor) controllers have replaced most small to medium Ward-Leonard systems, some very large ones (thousands of horsepower) remain in service. The field currents are much lower than the armature currents, allowing a moderate sized thyristor unit to control a much larger motor than it could control directly. For example, in one installation, a 300 amp thyristor unit controls the field of the generator. The generator output current is in excess of 15,000 amperes, which would be prohibitively expensive (and inefficient) to control directly with thyristors.

DC motor starters

The counter-emf aids the armature resistance to limit the current through the armature. When power is first applied to a motor, the armature does not rotate. At that instant the counter-emf is zero and the only factor limiting the armature current is the armature resistance. Usually the armature resistance of a motor is less than 1 Ω; therefore the current through the armature would be very large when the power is applied. This current can make an excessive voltage drop affecting other equipment in the circuit and even trip overload protective devices.

Therefore the need arises for an additional resistance in series with the armature to limit the current until the motor rotation can build up the counter-emf. As the motor rotation builds up, the resistance is gradually cut out.

Manual-starting rheostat



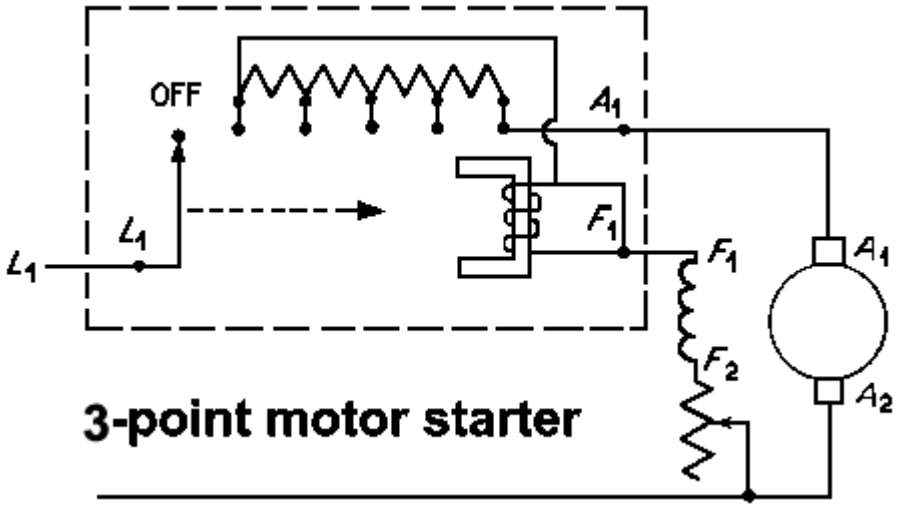
1917 DC motor manual starting rheostat with *no-voltage* and *overload* release features.

When electrical and DC motor technology was first developed, much of the equipment was constantly tended by an operator trained in the management of motor systems. The very first motor management systems were almost completely manual, with an attendant starting and stopping the motors, cleaning the equipment, repairing any mechanical failures, and so forth.

The first DC motor-starters were also completely manual, as shown in this image. Normally it took the operator about ten seconds to slowly advance the rheostat across the contacts to gradually increase input power up to operating speed. There were two different classes of these rheostats, one used for starting only, and one for starting and speed regulation. The starting rheostat was less expensive, but had smaller resistance elements that would burn out if required to run a motor at a constant reduced speed.

This starter includes a no-voltage magnetic holding feature, which causes the rheostat to spring to the off position if power is lost, so that the motor does not later attempt to restart in the full-voltage position. It also has overcurrent protection that trips the lever to the off position if excessive current over a set amount is detected.

Three-point starter



Three point starter

The incoming power is indicated as L1 and L2. The components within the broken lines form the three-point starter. As the name implies there are only three connections to the starter. The connections to the armature are indicated as A1 and A2. The ends of the field (excitement) coil are indicated as F1 and F2. In order to control the speed, a field rheostat is connected in series with the shunt field. One side of the line is connected to the arm of the starter (represented by an arrow in the diagram). The arm is spring-loaded so, it will return to the "Off" position when not held at any other position.

- On the first step of the arm, full line voltage is applied across the shunt field. Since the field rheostat is normally set to minimum resistance, the speed of the motor will not be excessive; additionally, the motor will develop a large starting torque.
- The starter also connects an electromagnet in series with the shunt field. It will hold the arm in position when the arm makes contact with the magnet.
- Meanwhile that voltage is applied to the shunt field, and the starting resistance limits the current to the armature.
- As the motor picks up speed counter-emf is built up; the arm is moved slowly to short.

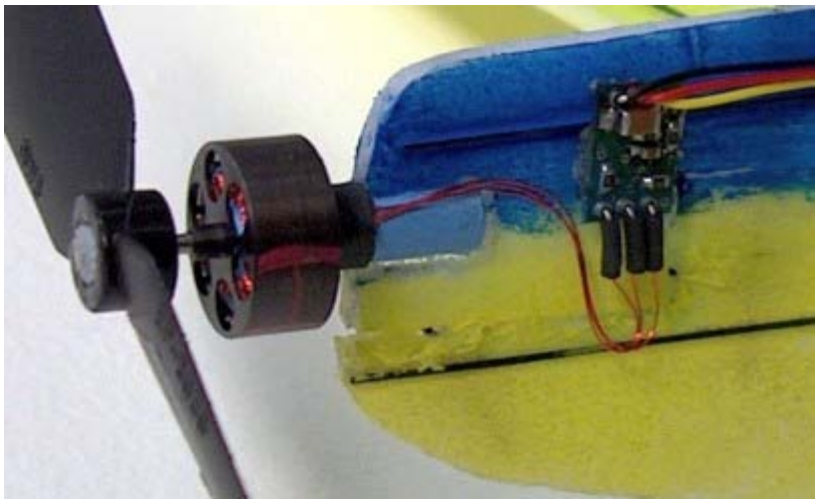
Four-point starter

The four-point starter eliminates the drawback of the three-point starter. In addition to the same three points that were in use with the three-point starter, the other side of the line, L1, is the fourth point brought to the starter when the arm is moved from the "Off" position. The coil of the holding magnet is connected across the line. The holding magnet and starting resistors function identical as in the three-point starter.

- The possibility of accidentally opening the field circuit is quite remote. The four-point starter provides the no-voltage protection to the motor. If the power fails, the motor is disconnected from the line.

Chapter 5

Brushless DC Electric Motor



A microprocessor-controlled BLDC motor powering a micro remote-controlled airplane. This external rotor motor weighs 5 grams, consumes approximately 11 watts (15 millihorsepower) and produces thrust of more than twice the weight of the plane.

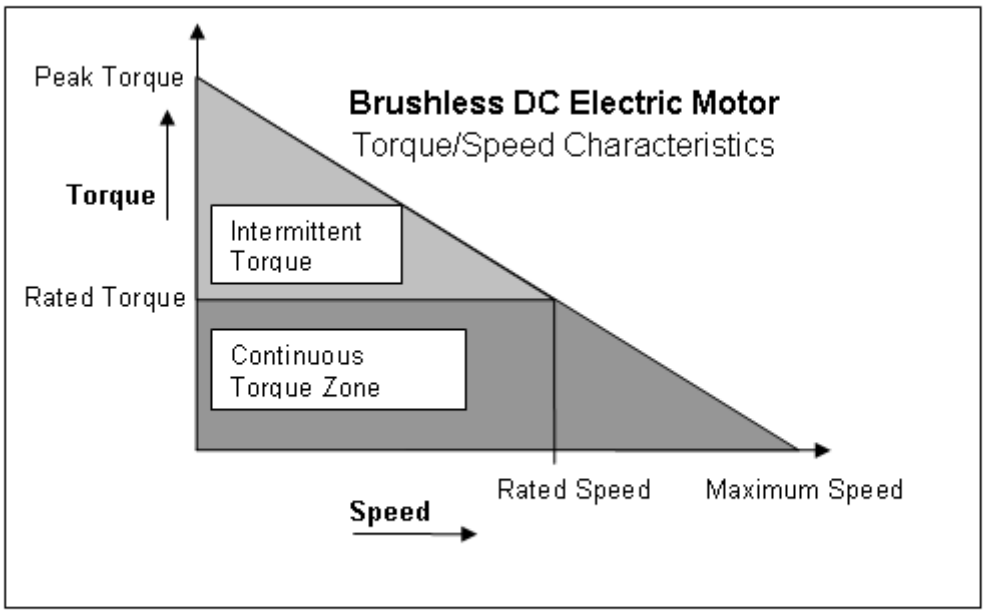
Brushless DC motors (**BLDC motors**, **BL motors**) also known as **electronically commutated motors** (ECMs, EC motors) are synchronous electric motors powered by direct-current (DC) electricity and having electronic commutation systems, rather than mechanical commutators and brushes. The current-to-torque and voltage-to-speed relationships of BLDC motors are linear.

BLDC motors may be described as stepper motors, with fixed permanent magnets and possibly more poles on the rotor than the stator, or reluctance motors. The latter may be without permanent magnets, just poles that are induced on the rotor then pulled into alignment by timed stator windings. However, the term *stepper motor* tends to be used for motors that are designed specifically to be operated in a mode where they are frequently stopped with the rotor in a defined angular position; this page describes more general BLDC motor principles, though there is overlap.

Brushless versus brushed DC motors

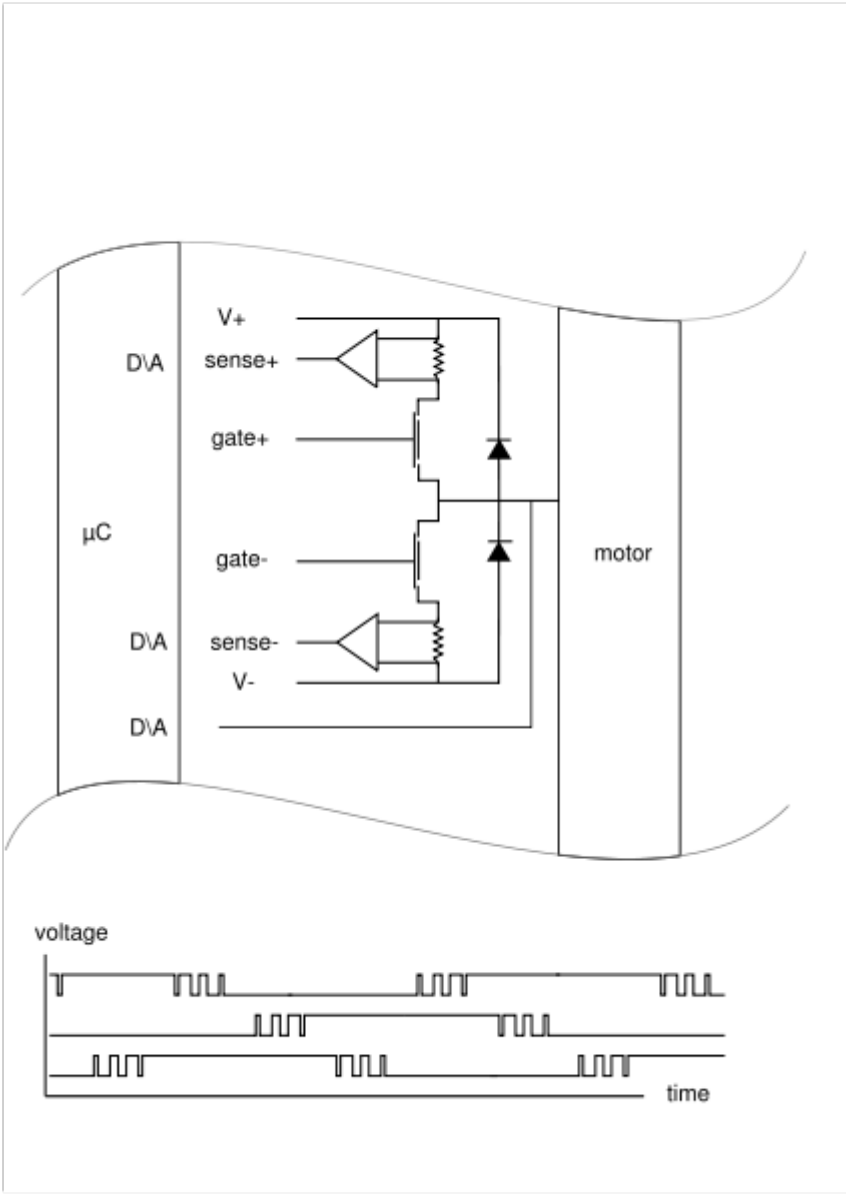
Brushed DC motors have been in commercial use since 1886. BLDC motors, however have only been commercially possible since 1962.

Limitations of brushed DC motors overcome by BLDC motors include lower efficiency and susceptibility of the commutator assembly to mechanical wear and consequent need for servicing, at the cost of potentially less rugged and more complex and expensive control electronics. BLDC motors develop maximum torque when stationary and have linearly decreasing torque with increasing speed as shown in the adjacent figure.



Brushless DC Electric Motor Torque-Speed Characteristics

A BLDC motor has permanent magnets which rotate and a fixed armature, eliminating the problems of connecting current to the moving armature. An electronic controller replaces the brush/commutator assembly of the brushed DC motor, which continually switches the phase to the windings to keep the motor turning. The controller performs similar timed power distribution by using a solid-state circuit rather than the brush/commutator system.



The interface circuitry between a digital controller and motor. The waveforms show multiple transitions between high and low voltage levels, approximations to a trapezoid or sinusoid which reduce harmonic losses. The circuit compensates for the induction of the windings, regulates power and monitors temperature.

BLDC motors offer several advantages over brushed DC motors, including more torque per weight and efficiency, reliability, reduced noise, longer lifetime (no brush and commutator erosion), elimination of ionizing sparks from the commutator, more power, and overall reduction of electromagnetic interference (EMI). With no windings on the rotor, they are not subjected to centrifugal forces, and because the windings are supported by the housing, they can be cooled by conduction, requiring no airflow inside the motor for cooling. This in turn means that the motor's internals can be entirely enclosed and protected from dirt or other foreign matter.

The maximum power that can be applied to a BLDC motor is exceptionally high, limited almost exclusively by heat, which can weaken the magnets. (Magnets demagnetize at high temperatures, the Curie point, and for neodymium-iron-boron magnets this temperature is lower than for other types.) A BLDC motor's main disadvantage is higher cost, which arises from two issues. First, BLDC motors require complex electronic speed controllers to run. Brushed DC motors can be regulated by a comparatively simple controller, such as a rheostat (variable resistor). However, this reduces efficiency because power is wasted in the rheostat. Second, some practical uses have not been well developed in the commercial sector. For example, in the Radio Control (RC) hobby, even commercial brushless motors are often hand-wound while brushed motors use armature coils which can be inexpensively machine-wound.

BLDC motors are often more efficient at converting electricity into mechanical power than brushed DC motors. This improvement is largely due to the absence of electrical and friction losses due to brushes. The enhanced efficiency is greatest in the no-load and low-load region of the motor's performance curve. Under high mechanical loads, BLDC motors and high-quality brushed motors are comparable in efficiency.

AC induction motors require induction of magnetic field in the rotor by the rotating field of the stator; this results in the magnetic and electric fields being out of phase. The phase difference requires greater current and current losses to achieve power. BLDC motors are microprocessor-controlled to keep the stator current in phase with the permanent magnets of the rotor, requiring less current for the same effect and therefore resulting in greater efficiency.

In general, manufacturers use brush-type DC motors when low system cost is a priority but brushless motors to fulfill requirements such as maintenance-free operation, high speeds, and operation in explosive environments where sparking could be hazardous.

Controller implementations

Because the controller must direct the rotor rotation, the controller requires some means of determining the rotor's orientation/position (relative to the stator coils.) Some designs use Hall effect sensors or a rotary encoder to directly measure the rotor's position. Others measure the back EMF in the undriven coils to infer the rotor position, eliminating the need for separate Hall effect sensors, and therefore are often called *sensorless* controllers. Like an AC motor, the voltage on the undriven coils is sinusoidal, but over an entire commutation the output appears trapezoidal because of the DC output of the controller.

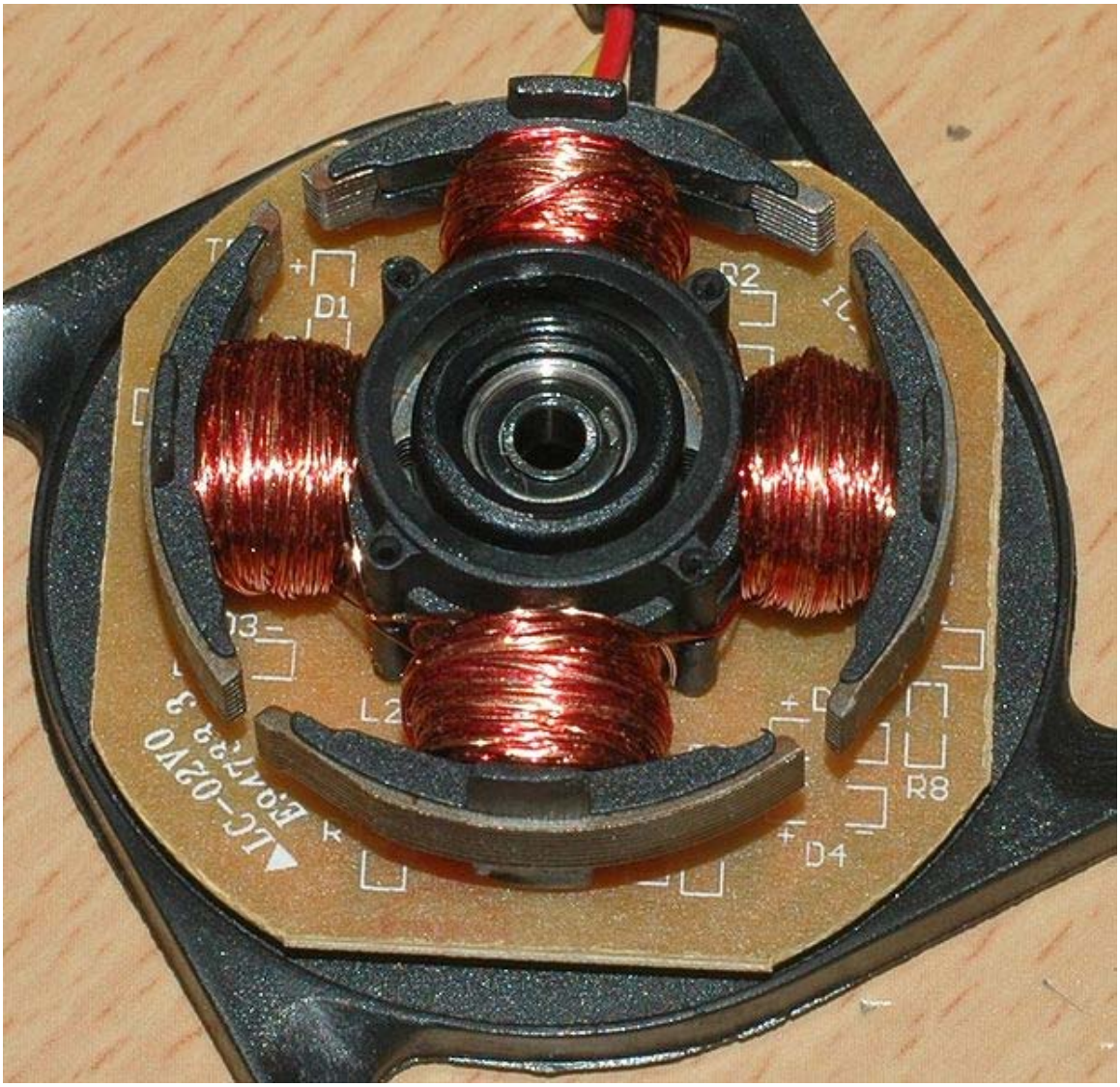
The controller contains 3 bi-directional drivers to drive high-current DC power, which are controlled by a logic circuit. Simple controllers employ comparators to determine when the output phase should be advanced, while more advanced controllers employ a microcontroller to manage acceleration, control speed and fine-tune efficiency.

Controllers that sense rotor position based on back-EMF have extra challenges in initiating motion because no back-EMF is produced when the rotor is stationary. This is

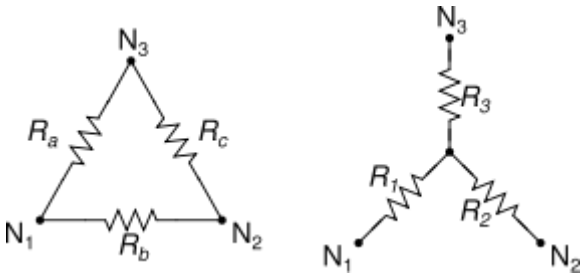
usually accomplished by beginning rotation from an arbitrary phase, and then skipping to the correct phase if it is found to be wrong. This can cause the motor to run briefly backwards, adding even more complexity to the startup sequence. Other sensorless controllers are capable of measuring winding saturation caused by the position of the magnets to infer the rotor position.

The controller unit is often referred to as an "ESC", meaning Electronic Speed Controller.

Variations in construction



The four poles on the stator of a two-phase BLDC motor. This is part of a computer cooling fan; the rotor has been removed.



Schematic for delta and wye winding styles. (This image does not illustrate the motor's inductive and generator-like properties)

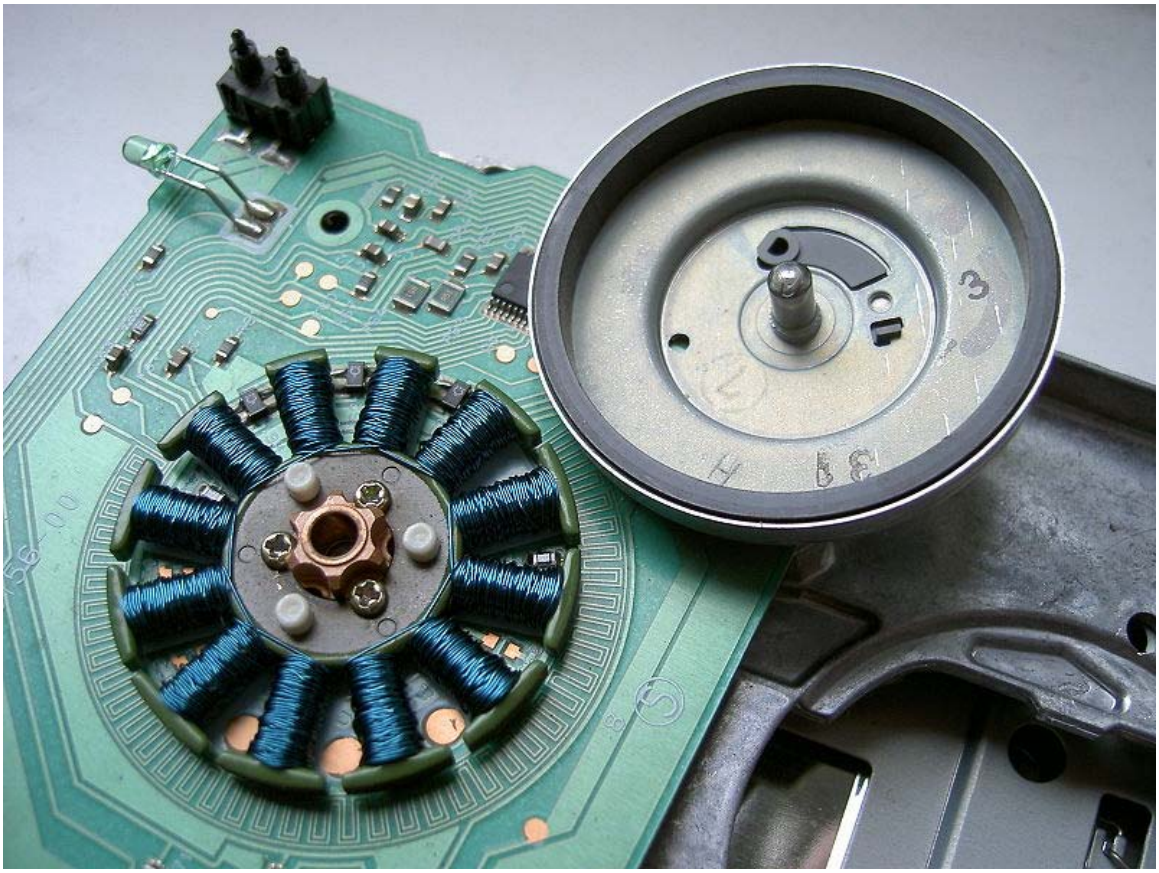
BLDC motors can be constructed in several different physical configurations: In the 'conventional' (also known as 'inrunner') configuration, the permanent magnets are part of the rotor. Three stator windings surround the rotor. In the 'outrunner' (or external-rotor) configuration, the radial-relationship between the coils and magnets is reversed; the stator coils form the center (core) of the motor, while the permanent magnets spin within an overhanging rotor which surrounds the core. The flat type, used where there are space or shape limitations, uses stator and rotor plates, mounted face to face. Outrunners typically have more poles, set up in triplets to maintain the three groups of windings, and have a higher torque at low RPMs. In all BLDC motors, the coils are stationary.

There are also two electrical configurations having to do with how the wires from the windings are connected to each other (not their physical shape or location). The delta configuration connects the three windings to each other (series circuits) in a triangle-like circuit, and power is applied at each of the connections. The wye ("Y"-shaped) configuration, sometimes called a star winding, connects all of the windings to a central point (parallel circuits) and power is applied to the remaining end of each winding.

A motor with windings in delta configuration gives low torque at low rpm, but can give higher top rpm. Wye configuration gives high torque at low rpm, but not as high top rpm.

Although efficiency is greatly affected by the motor's construction, the wye winding is normally more efficient. In delta-connected windings, half voltage is applied across the windings adjacent to the undriven lead (compared to the winding directly between the driven leads), increasing resistive losses. In addition, windings can allow high-frequency parasitic electrical currents to circulate entirely within the motor. A wye-connected winding does not contain a closed loop in which parasitic currents can flow, preventing such losses.

From a controller standpoint, the two styles of windings are treated exactly the same, although some less expensive controllers are designed to read voltage from the common center of the wye winding.



Spindle motor from a 3.5" floppy disk drive. The coils are copper wire coated with green film insulation. The rotor (upper right) has been removed and turned upside-down. The gray ring just inside its cup is a multi-pole permanent magnet.

AC and DC power supplies

It's helpful to consider three types of motors:

- Direct current (DC) motor: DC applied to both the stator and the rotor (via brushes and commutator), or else a permanent magnet stator. A BLDC motor has switched DC fed to the stator, and a permanent magnet rotor.
- Synchronous (or stepping) motor (AC): AC in one, DC in the other (i.e., rotor or stator). If it has a permanent-magnet rotor, it is much like a BLDC motor.
- Induction motor (AC): AC in both stator and rotor (mentioned for completeness).

Although BLDC motors are practically identical to permanent magnet AC motors, the controller implementation is what makes them DC. While AC motors feed sinusoidal current simultaneously to each of the legs (with an equal phase distribution), DC controllers only approximate this by feeding full positive and negative voltage to two of the legs at a time. The major advantage of this is that both the logic controllers and battery power sources also operate on DC, such as in computers and electric cars. In

addition, the approximated sine wave leaves one leg undriven at all times, allowing for back-EMF-based sensorless feedback.

Vector drives are DC controllers that take the extra step of converting back to AC for the motor; they are sophisticated inverters. The DC-to-AC conversion circuitry is usually expensive and less efficient, but these have the advantage of being able to run smoothly at very low speeds or completely stop (and provide torque) in a position not directly aligned with a pole. Motors used with a vector drive are typically called AC motors. When running at low speeds and under load, they don't cool themselves significantly; temperature rise has to be allowed for.

A motor can be optimized for AC (i.e. vector control) or it can be optimized for DC (i.e. block commutation). A motor which is optimized for block commutation will typically generate trapezoidal EMF. One can easily observe the shape of the EMF by connecting the motor wires (at least two of them) to an oscilloscope and then hand-cranking/spinning the shaft.

Another very important issue, at least for some applications like automotive vehicles, is the constant power speed ratio of a motor. The CPSR has direct impact on needed size of the inverter. Example: A motor with a high CPSR in a vehicle can deliver the desired power (e.g. 40 kW) from 3,000 rpm to 12,000 rpm, while using a 100 A inverter. A motor with low CPSR would need a 400 A inverter in order to do the same.

Stepping motors can also operate as AC synchronous motors (for instance, the Slo-Syn by Superior Electric), or the unusual battery-powered quartz-timed micropower clock that has a continuous-motion sweep second hand.

K_v rating

"K_v" is the motor velocity constant, measured in RPM per Volt (not to be confused with "kV," the abbreviation for "kilovolt") . The K_v rating of a brushless motor is the ratio of the motor's unloaded RPM to the peak (not RMS) voltage on the wires connected to the coils (the "back-EMF"). For example, a 5,700 K_v motor, supplied with 11.1 V, will run at a nominal 63,270 rpm (=5700 * 11.1).

By Lenz's law, a running motor will create a back-EMF proportional to the RPM. Once a motor is spinning so fast that the back-EMF is equal to the battery voltage (also called DC line voltage), then the motor has reached its "base speed". It is impossible for the ESCs to "speed up" that motor, even with no load, beyond the base speed without resorting to "field weakening". For some applications (e.g. automotive traction and high speed spindle motors) it is normal to exceed the base speed with a factor of 200 to 600%.

Applications

Consumer electronics

BLDC motors fulfill many functions originally performed by brushed DC motors, but cost and control complexity prevents BLDC motors from replacing brushed motors completely in lowest cost areas. Nevertheless, BLDC motors have come to dominate many applications particularly devices such as computer hard drives and CD/DVD players. Small cooling fans in electronic equipment are powered exclusively by BLDC motors.

They can be found in cordless power tools where the increased efficiency of the motor leads to longer periods of use before the battery needs to be charged.

Low speed, low power BLDC motors are used in direct-drive turntables for "analog" audio discs.

Transport

High power BLDC motors are found in electric vehicles and hybrid vehicles. These motors are essentially AC synchronous motors with permanent magnet rotors.

The Segway Scooter and Vectrix Maxi-Scooter use BLDC technology.

A number of electric bicycles use BLDC motors that are sometimes built into the wheel hub itself, with the stator fixed solidly to the axle and the magnets attached to and rotating with the wheel. The bicycle wheel hub is the motor. This type of electric bicycle also has a standard bicycle transmission with pedals, sprockets, and chain that can be pedaled along with, or without, the use of the motor as need arises.

Heating and ventilation

There is a trend in the HVAC and refrigeration industries to use BLDC motors instead of various types of AC motors. The most significant reason to switch to a BLDC motor is the dramatic reduction in power required to operate them versus a typical AC motor. While shaded-pole and permanent split capacitor motors once dominated as the fan motor of choice, many fans are now run using a BLDC motor. Some fans use BLDC motors also in order to increase overall system efficiency.

In addition to the BLDC motor's higher efficiency, certain HVAC systems (especially those featuring variable-speed and/or load modulation) use BLDC motors because the built-in microprocessor allows for programmability, better control over airflow, and serial communication.

Model engineering

BLDC motors are currently the most popular motor choice for model aircraft including helicopters. Their favorable power to weight ratios and large range of available sizes, from under 5 grams to large motors rated at thousands of watts, have revolutionized the market for electric-powered model flight.

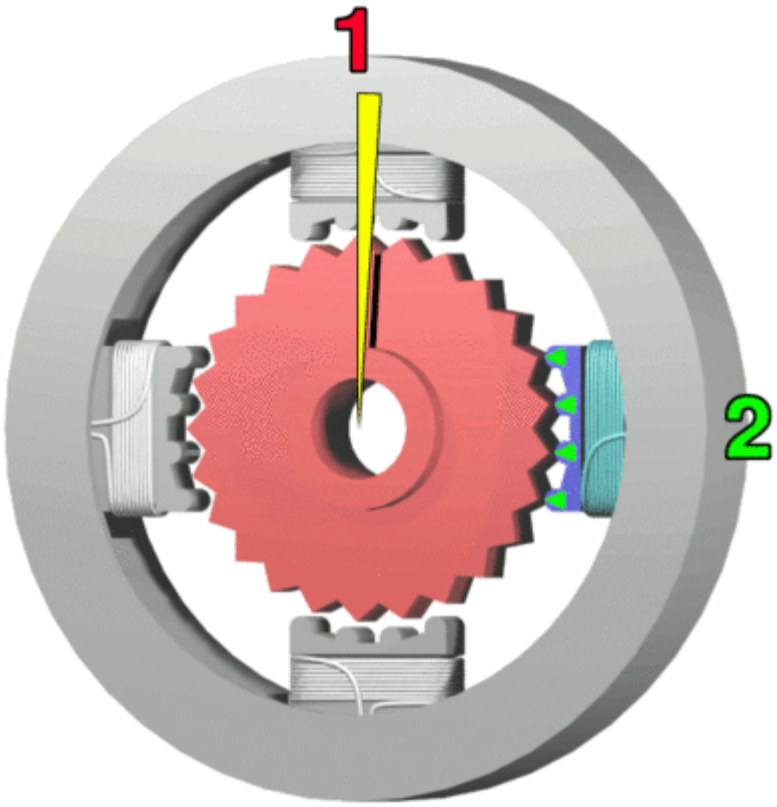
Their introduction has redefined performance in electric model aircraft and helicopters, displacing virtually all brushed electric motors. The large power to weight ratio of modern batteries and brushless motors allows models to ascend vertically, rather than climb gradually. The low noise and lack of mess compared to small glow fuel internal combustion engines that are used is another reason for their popularity.

Legal restrictions for the use of combustion engine driven model aircraft in some countries have also supported the shift to high-power electric systems.

Their popularity has also risen in the Radio Controlled Car, Buggy, and Truck scene, where sensor-type motors (with an extra six wires, connected to Hall effect sensors) allow the position of the rotor magnet to be detected. Brushless motors have been legal in RC Car Racing in accordance to ROAR (the American governing body for RC Car Racing), since 2006. Several RC Car Brushless motors, feature replaceable and upgradeable parts, such as sintered neodymium-iron-boron (rare earth magnets), ceramic bearings, and replaceable motor timing assemblies. These motors as a result are quickly rising to be the preferred motor type for electric on and off-road RC racers and recreational drivers alike, for their low maintenance, high running reliability and power efficiency (most Sensored motors have an efficiency rating of 80% or greater).

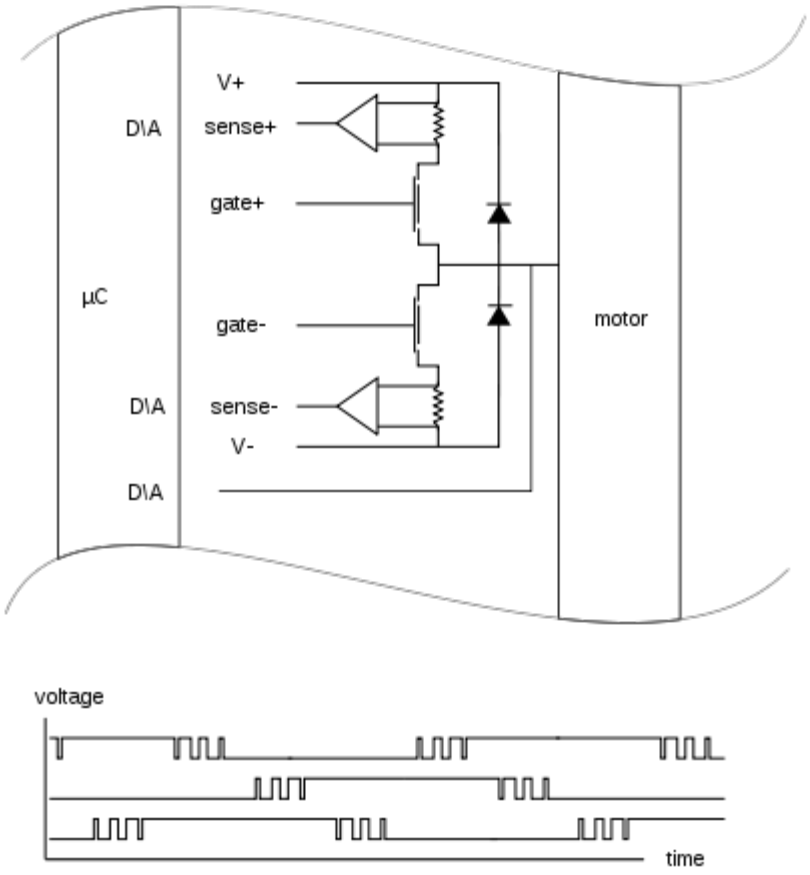
Chapter 6

Stepper Motor



Frame 1: The top electromagnet (1) is turned on, attracting the nearest tooth of a gear-shaped iron rotor.
With the teeth aligned to electromagnet (1), they will be slightly offset from electromagnet (2).
Frame 2: The top electromagnet (1) is turned off, and the right electromagnet (2) is energized, pulling the nearest teeth slightly to the right. This results in a rotation of 3.6° in this example.
Frame 3: The bottom electromagnet (3) is energized; another 3.6° rotation occurs.
Frame 4: The left electromagnet (4) is enabled, rotating again by 3.6°. When the top electromagnet (1) is again enabled, the teeth in the sprocket will have rotated by one

tooth position; since there are 25 teeth, it will take 100 steps to make a full rotation in this example.



Because of power requirements, induction of the windings, and temperature management, motors cannot be powered directly by most digital controllers. Some circuitry that can handle more power — a motor controller such as an H-bridge — must be inserted between digital controller and motor's windings. The above image shows the basic circuit of a motor controller that can also sense motor current. The circuitry to control one winding of a motor is shown; a stepper motor would use a circuit that could control four windings, and a normal DC motor would need circuitry to control two windings. All of this circuitry is typically incorporated in an integrated H-bridge chip.

A **stepper motor** (or **step motor**) is a brushless, synchronous electric motor that can divide a full rotation into a large number of steps. The motor's position can be controlled precisely without any feedback mechanism, as long as the motor is carefully sized to the application. Stepper motors are similar to switched reluctance motors (which are very large stepping motors with a reduced pole count, and generally are closed-loop commutated.)

Fundamentals of operation

Stepper motors operate differently from DC brush motors, which rotate when voltage is applied to their terminals. Stepper motors, on the other hand, effectively have multiple "toothed" electromagnets arranged around a central gear-shaped piece of iron. The electromagnets are energized by an external control circuit, such as a microcontroller. To make the motor shaft turn, first one electromagnet is given power, which makes the gear's teeth magnetically attracted to the electromagnet's teeth. When the gear's teeth are thus aligned to the first electromagnet, they are slightly offset from the next electromagnet. So when the next electromagnet is turned on and the first is turned off, the gear rotates slightly to align with the next one, and from there the process is repeated. Each of those slight rotations is called a "step", with an integer number of steps making a full rotation. In that way, the motor can be turned by a precise angle.

Stepper motor characteristics

1. Stepper motors are constant power devices.
2. As motor speed increases, torque decreases. (most motors exhibit maximum torque when stationary, however the torque of a motor when stationary 'holding torque' defines the ability of the motor to maintain a desired position while under external load).
3. The torque curve may be extended by using current limiting drivers and increasing the driving voltage (sometimes referred to as a 'chopper' circuit; there are several off the shelf driver chips capable of doing this in a simple manner).
4. Steppers exhibit more vibration than other motor types, as the discrete step tends to snap the rotor from one position to another (called a detent). The vibration makes stepper motors noisier than DC motors.
5. This vibration can become very bad at some speeds and can cause the motor to lose torque or lose direction. This is because the rotor is being held in a magnetic field which behaves like a spring. On each step the rotor overshoots and bounces back and forth, "ringing" at its resonant frequency. If the stepping frequency matches the resonant frequency then the ringing increases and the motor comes out of synchronism, resulting in positional error or a change in direction. At worst there is a total loss of control and holding torque so the motor is easily overcome by the load and spins almost freely.
6. The effect can be mitigated by accelerating quickly through the problem speeds range, physically damping (frictional damping) the system, or using a micro-stepping driver.

7. Motors with a greater number of phases also exhibit smoother operation than those with fewer phases (this can also be achieved through the use of a micro stepping drive)

Open-loop versus closed-loop commutation

Steppers are generally commutated open loop, i.e. the driver has no feedback on where the rotor actually is. Stepper motor systems must thus generally be over engineered, especially if the load inertia is high, or there is widely varying load, so that there is no possibility that the motor will lose steps. This has often caused the system designer to consider the trade-offs between a closely sized but expensive servomechanism system and an oversized but relatively cheap stepper.

A new development in stepper control is to incorporate a rotor position feedback (e.g. an encoder or resolver), so that the commutation can be made optimal for torque generation according to actual rotor position. This turns the stepper motor into a high pole count brushless servo motor, with exceptional low speed torque and position resolution. An advance on this technique is to normally run the motor in open loop mode, and only enter closed loop mode if the rotor position error becomes too large — this will allow the system to avoid hunting or oscillating, a common servo problem.

Types

There are three main types of stepper motors:

1. Permanent Magnet Stepper (can be subdivided in to 'tin-can' and 'hybrid', tin-can being a cheaper product, and hybrid with higher quality bearings, smaller step angle, higher power density)
2. Hybrid Synchronous Stepper
3. Variable Reluctance Stepper
4. Lavet type stepping motor

Permanent magnet motors use a permanent magnet (PM) in the rotor and operate on the attraction or repulsion between the rotor PM and the stator electromagnets. Variable reluctance (VR) motors have a plain iron rotor and operate based on the principle that minimum reluctance occurs with minimum gap, hence the rotor points are attracted toward the stator magnet poles. Hybrid stepper motors are named because they use a combination of PM and VR techniques to achieve maximum power in a small package size.

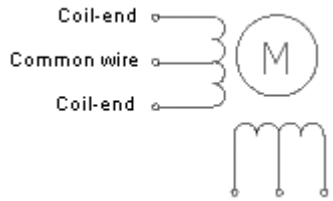
Two-phase stepper motors

There are two basic winding arrangements for the electromagnetic coils in a two phase stepper motor: bipolar and unipolar.

Unipolar motors

A unipolar stepper motor has two windings per phase, one for each direction of magnetic field. Since in this arrangement a magnetic pole can be reversed without switching the direction of current, the commutation circuit can be made very simple (e.g. a single transistor) for each winding. Typically, given a phase, one end of each winding is made common: giving three leads per phase and six leads for a typical two phase motor. Often, these two phase commons are internally joined, so the motor has only five leads.

A microcontroller or stepper motor controller can be used to activate the drive transistors in the right order, and this ease of operation makes unipolar motors popular with hobbyists; they are probably the cheapest way to get precise angular movements.



Unipolar stepper motor coils

(For the experimenter, one way to distinguish common wire from a coil-end wire is by measuring the resistance. Resistance between common wire and coil-end wire is always half of what it is between coil-end and coil-end wires. This is because there is twice the length of coil between the ends and only half from center (common wire) to the end.) A quick way to determine if the stepper motor is working is to short circuit every two pairs and try turning the shaft, whenever a higher than normal resistance is felt, it indicates that the circuit to the particular winding is closed and that the phase is working.

Bipolar motor

Bipolar motors have a single winding per phase. The current in a winding needs to be reversed in order to reverse a magnetic pole, so the driving circuit must be more complicated, typically with an H-bridge arrangement (however there are several off the shelf driver chips available to make this a simple affair). There are two leads per phase, none are common.

Static friction effects using an H-bridge have been observed with certain drive topologies.

Because windings are better utilized, they are more powerful than a unipolar motor of the same weight. This is due to the physical space occupied by the windings. A unipolar motor has twice the amount of wire in the same space, but only half used at any point in time, hence is 50% efficient (or approximately 70% of the torque output available). Though bipolar is more complicated to drive, the abundance of driver chip means this is much less difficult to achieve.

An 8-lead stepper is wound like a unipolar stepper, but the leads are not joined to common internally to the motor. This kind of motor can be wired in several configurations:

- Unipolar.
- Bipolar with series windings. This gives higher inductance but lower current per winding.
- Bipolar with parallel windings. This requires higher current but can perform better as the winding inductance is reduced.
- Bipolar with a single winding per phase. This method will run the motor on only half the available windings, which will reduce the available low speed torque but require less current.

Higher-phase count stepper motors

Multi-phase stepper motors with many phases tend to have much lower levels of vibration, although the cost of manufacture is higher. These motors tend to be called 'hybrid' and have more expensive machined parts, but also higher quality bearings. Though they are more expensive, they do have a higher power density and with the appropriate drive electronics are actually better suited to the application, however price is always an important factor. Computer printers may use hybrid designs.

Stepper motor drive circuits

Stepper motor performance is strongly dependent on the drive circuit. Torque curves may be extended to greater speeds if the stator poles can be reversed more quickly, the limiting factor being the winding inductance. To overcome the inductance and switch the windings quickly, one must increase the drive voltage. This leads further to the necessity of limiting the current that these high voltages may otherwise induce.

L/R drive circuits

L/R drive circuits are also referred to as constant voltage drives because a constant positive or negative voltage is applied to each winding to set the step positions. However, it is winding current, not voltage that applies torque to the stepper motor shaft. The current I in each winding is related to the applied voltage V by the winding inductance L and the winding resistance R. The resistance R determines the maximum current according to Ohm's law I=V/R. The inductance L determines the maximum rate of change of the current in the winding according to the formula for an Inductor dI/dt = V/L. Thus when controlled by an L/R drive, the maximum speed of a stepper motor is limited by its inductance since at some speed, the voltage U will be changing faster than the current I can keep up. In simple terms the rate of change of current is L X R (e.g. a 10mH inductance with 2 ohms resistance will take 20 ms to reach approx 2/3 of maximum torque or around 0.1 sec to reach 99% of max torque). To obtain high torque at high speeds requires a large drive voltage with a low resistance and low inductance. With an L/R drive it is possible to control a low voltage resistive motor with a higher voltage

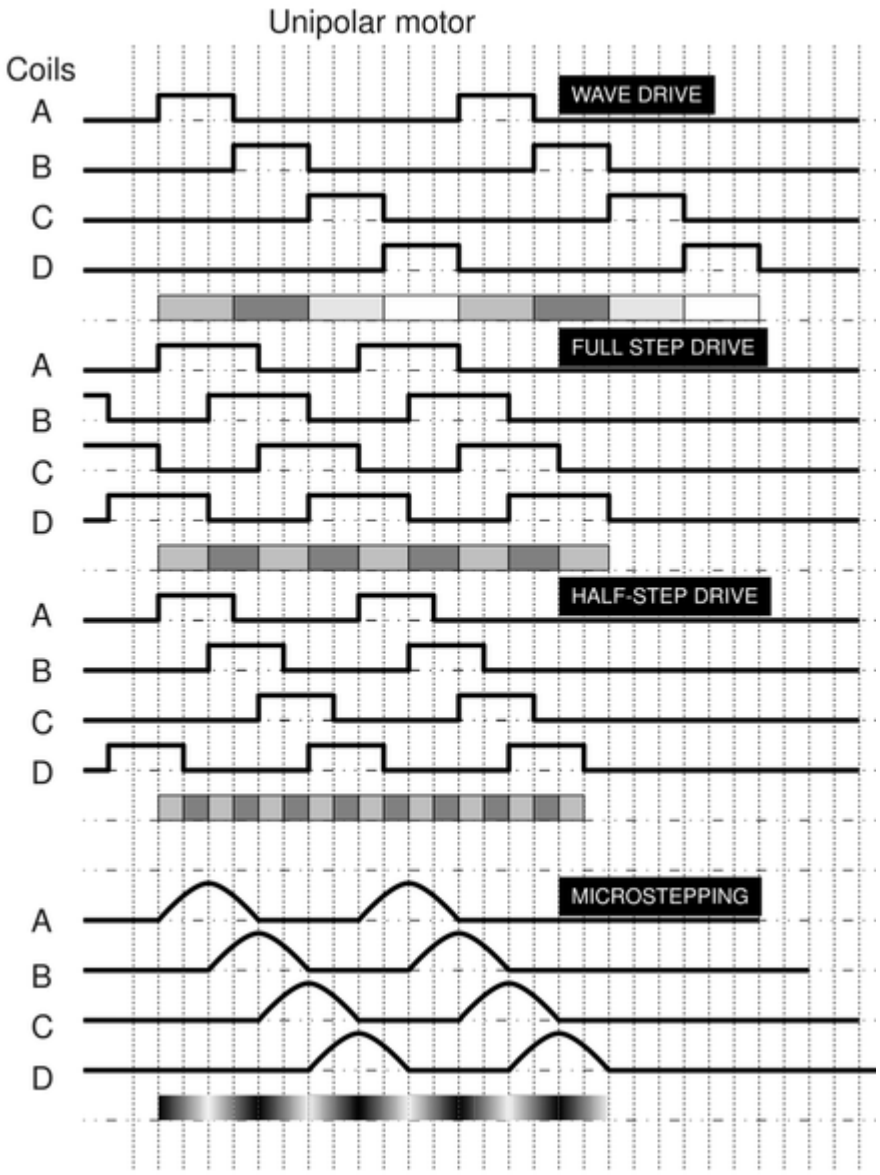
drive simply by adding an external resistor in series with each winding. This will waste power in the resistors, and generate heat. It is therefore considered a low performing option, albeit simple and cheap.

Chopper drive circuits

Chopper drive circuits are also referred to as constant current drives because they generate a somewhat constant current in each winding rather than applying a constant voltage. On each new step, a very high voltage is applied to the winding initially. This causes the current in the winding to rise quickly since dI/dt = V/L where V is very large. The current in each winding is monitored by the controller, usually by measuring the voltage across a small sense resistor in series with each winding. When the current exceeds a specified current limit, the voltage is turned off or "chopped", typically using power transistors. When the winding current drops below the specified limit, the voltage is turned on again. In this way, the current is held relatively constant for a particular step position. This requires additional electronics to sense winding currents, and control the switching, but it allows stepper motors to be driven with higher torque at higher speeds than L/R drives. Integrated electronics for this purpose are widely available.

Phase current waveforms

A stepper motor is a polyphase AC synchronous motor, and it is ideally driven by sinusoidal current. A full step waveform is a gross approximation of a sinusoid, and is the reason why the motor exhibits so much vibration. Various drive techniques have been developed to better approximate a sinusoidal drive waveform: these are half stepping and microstepping.



Different drive modes showing coil current on a 4-phase unipolar stepper motor

Wave drive

In this drive method only a single phase is activated at a time. It has the same number of steps as the full step drive, but the motor will have significantly less than rated torque. It is rarely used.

Full step drive (two phases on)

This is the usual method for full step driving the motor. Two phases are always on. The motor will have full rated torque.

Half stepping

When half stepping, the drive alternates between two phases on and a single phase on. This increases the angular resolution, but the motor also has less torque (approx 70%) at the half step position (where only a single phase is on). This may be mitigated by increasing the current in the active winding to compensate. The advantage of half stepping is that the drive electronics need not change to support it.

Microstepping

What is commonly referred to as microstepping is actually "sine cosine microstepping" in which the winding current approximates a sinusoidal AC waveform. Sine cosine microstepping is the most common form, but other waveforms are used . Regardless of the waveform used, as the microsteps become smaller, motor operation becomes more smooth, thereby greatly reducing resonance in any parts the motor may be connected to, as well as the motor itself. Resolution will be limited by the mechanical stiction, backlash, and other sources of error between the motor and the end device. Gear reducers may be used to increase resolution of positioning.

Step size repeatability is an important step motor feature and a fundamental reason for their use in positioning.

Example: many modern hybrid step motors are rated such that the travel of every full step (example 1.8 Degrees per full step or 200 full steps per revolution) will be within 3% or 5% of the travel of every other full step; as long as the motor is operated within its specified operating ranges. Several manufacturers show that their motors can easily maintain the 3% or 5% equality of step travel size as step size is reduced from full stepping down to 1/10 stepping. Then, as the microstepping divisor number grows, step size repeatability degrades. At large step size reductions it is possible to issue many microstep commands before any motion occurs at all and then the motion can be a "jump" to a new position.

Theory

A step motor can be viewed as a synchronous AC motor with the number of poles (on both rotor and stator) increased, taking care that they have no common denominator. Additionally, soft magnetic material with many teeth on the rotor and stator cheaply multiplies the number of poles (reluctance motor). Modern steppers are of hybrid design, having both permanent magnets and soft iron cores.

To achieve full rated torque, the coils in a stepper motor must reach their full rated current during each step. Winding inductance and reverse EMF generated by a moving rotor tend to resist changes in drive current, so that as the motor speeds up, less and less time is spent at full current — thus reducing motor torque. As speeds further increase, the current will not reach the rated value, and eventually the motor will cease to produce torque.

Pull-in torque

This is the measure of the torque produced by a stepper motor when it is operated without an acceleration state. At low speeds the stepper motor can synchronise itself with an applied step frequency, and this pull-in torque must overcome friction and inertia. It is important to make sure that the load on the motor is frictional rather than inertial as the friction reduces any unwanted oscillations.

Pull-out torque

The stepper motor pull-out torque is measured by accelerating the motor to the desired speed and then increasing the torque loading until the motor stalls or misses steps. This measurement is taken across a wide range of speeds and the results are used to generate the stepper motor's dynamic performance curve. As noted below this curve is affected by drive voltage, drive current and current switching techniques. A designer may include a safety factor between the rated torque and the estimated full load torque required for the application.

Detent torque

Synchronous electric motors using permanent magnets have a remnant position holding torque (called detent torque or cogging, and sometimes included in the specifications) when not driven electrically. Soft iron reluctance cores do not exhibit this behavior.

Stepper motor ratings and specifications

Stepper motors nameplates typically give only the winding current and occasionally the voltage and winding resistance. The rated voltage will produce the rated winding current at DC: but this is mostly a meaningless rating, as all modern drivers are current limiting and the drive voltages greatly exceed the motor rated voltage.

A stepper's low speed torque will vary directly with current. How quickly the torque falls off at faster speeds depends on the winding inductance and the drive circuitry it is attached to, especially the driving voltage.

Steppers should be sized according to published torque curve, which is specified by the manufacturer at particular drive voltages or using their own drive circuitry.

Applications

Computer-controlled stepper motors are one of the most versatile forms of positioning systems. They are typically digitally controlled as part of an open loop system, and are simpler and more rugged than closed loop servo systems.

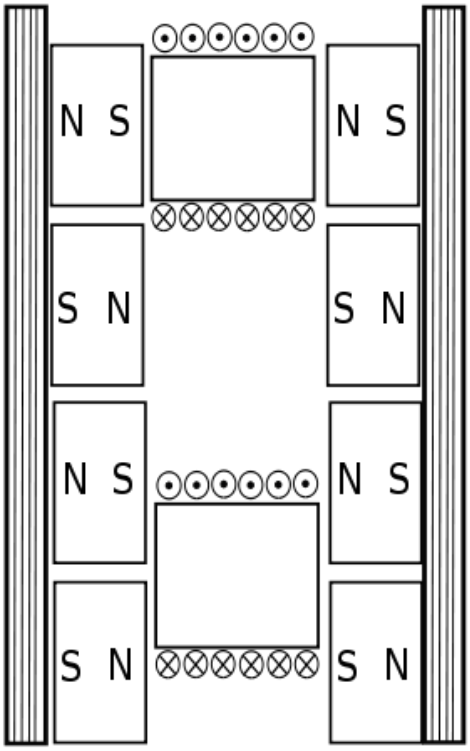
Industrial applications are in high speed pick and place equipment and multi-axis machine CNC machines often directly driving lead screws or ballscrews. In the field of

lasers and optics they are frequently used in precision positioning equipment such as linear actuators, linear stages, rotation stages, goniometers, and mirror mounts. Other uses are in packaging machinery, and positioning of valve pilot stages for fluid control systems.

Commercially, stepper motors are used in floppy disk drives, flatbed scanners, computer printers, plotters, slot machines, and many more devices.

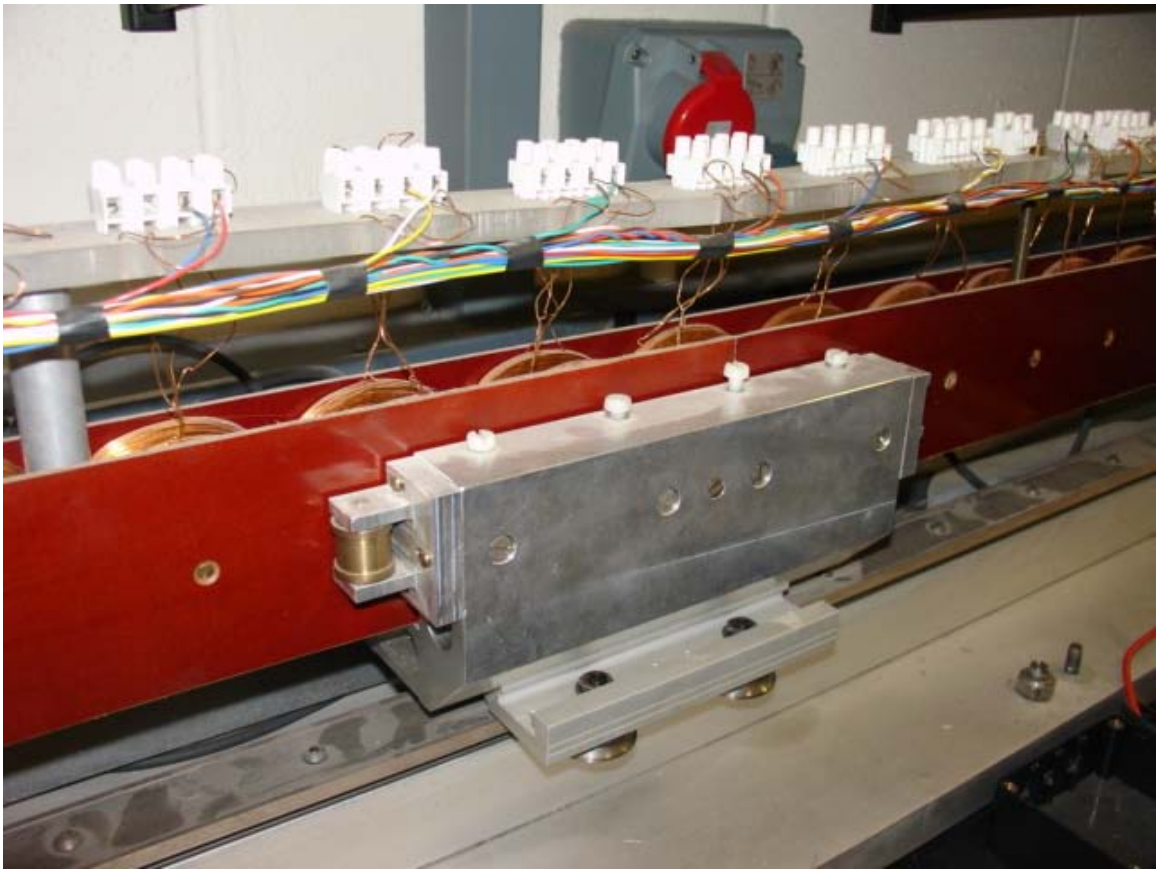
Chapter 7

Linear Motor



Free-body diagram of a U-channel linear motor. The view is perpendicular to the channel axis. The two coils at centre are mechanically connected, and are energized in "quadrature" (with a phase difference of 90° (π/2 radians)). If the bottom coil (as shown) leads in phase, then the motor will move downward (in the drawing), and vice versa. (Not to scale)

A linear motor for trains running Toei Oedo line



A prototype of linear motor with visible separate coils

A **linear motor** is an electric motor that has had its stator and rotor "unrolled" so that instead of producing a torque (rotation) it produces a linear force along its length. The most common mode of operation is as a Lorentz-type actuator, in which the applied force is linearly proportional to the current and the magnetic field (**F** = *q***v** × **B**).

Many designs have been put forward for linear motors, falling into two major categories, low-acceleration and high-acceleration linear motors. Low-acceleration linear motors are suitable for maglev trains and other ground-based transportation applications. High-acceleration linear motors are normally quite short, and are designed to accelerate an object up to a very high speed and then release it, like roller coasters. They are usually used for studies of hypervelocity collisions, as weapons, or as mass drivers for spacecraft propulsion. The high-acceleration motors are usually of the AC **linear induction motor** (LIM) design with an active three-phase winding on one side of the air-gap and a passive conductor plate on the other side. However, the direct current homopolar linear motor the railgun is another high acceleration linear motor design. The low-acceleration, high speed and high power motors are usually of the **linear synchronous motor** (LSM) design, with an active winding on one side of the air-gap and an array of alternate-pole magnets on the other side. These magnets can be permanent magnets or energized magnets. The Transrapid Shanghai motor is an LSM.

Low acceleration

The history of linear electric motors can be traced back at least as far as the 1840s, to the work of Charles Wheatstone at King's College in London, but Wheatstone's model was too inefficient to be practical. A feasible linear induction motor is described in the US patent 782312 (1905 - inventor Alfred Zehden of Frankfurt-am-Main), for driving trains or lifts. The German engineer Hermann Kemper built a working model in 1935. In the late 1940s, professor Eric Laithwaite of Imperial College in London developed the first full-size working model. In his design, and in most low-acceleration designs, the force is produced by a moving linear magnetic field acting on conductors in the field. Any conductor, be it a loop, a coil or simply a piece of plate metal, that is placed in this field will have eddy currents induced in it thus creating an opposing magnetic field, in accordance with Lenz's law. The two opposing fields will repel each other, thus forcing the conductor away from the stator and carrying it along in the direction of the moving magnetic field. He called the later versions of it magnetic river.

Because of these properties, linear motors are often used in maglev propulsion, as in the Japanese Linimo magnetic levitation train line near Nagoya. However, linear motors have been used independently of magnetic levitation, as in Bombardier's Advanced Rapid Transit systems worldwide and a number of modern Japanese subways, including Tokyo's Toei Oedo Line.

Similar technology is also used in some roller coasters with modifications but, at present, is still impractical on street running trams, although this, in theory, could be done by burying it in a slotted conduit.

ART trains propel themselves using an aluminium induction strip placed between the rails.

Outside of public transportation, vertical linear motors have been proposed as lifting mechanisms in deep mines, and the use of linear motors is growing in motion control applications. They are also often used on sliding doors, such as those of low floor trams such as the Citadis and the Eurotram. Dual axis linear motors also exist. These specialized devices have been used to provide direct *X*-*Y* motion for precision laser cutting of cloth and sheet metal, automated drafting, and cable forming. Mostly used linear motors are LIM (linear induction motor), LSM (linear synchronous motor). Linear DC motors are not used as it includes more cost and linear SRM suffers from poor thrust. So for long run in traction LIM is mostly preferred and for short run LSM is mostly preferred.

From concept to industrial use

In the 1980s, British engineer Hugh-Peter Kelly designed the first tubular linear motor by enclosing the permanent magnets in a sealed stainless steel cylinder. It was brought to market by linear motor manufacturer Linear Drives (now Copley Motion Systems). The patented permanent magnet arrangement induces a sinusoidal response in the coils that are enclosed in a square profile body. This allowed machine builders to use the new linear motors with standard sinusoidal servo drives commonly used in motion control.

Tubular linear motors

Tubular linear motors are more rugged than early flat-bed and U-channel linear motors allowing them to be used in dirty industrial environments such as food packaging and machine tools. The tubular construction protects the permanent magnets from the external environment and automatically balances attractive forces so that the motor is easier to integrate into machines. These motors operate at 5–9 m/s (15–30 ft/s) with high acceleration for dynamic motion control.

A new type of linear motor, called the ServoTube has allowed linear motors to be used in industrial environments by integrating the position sensing electronics into the motor body (called a forcer).

High acceleration

High-acceleration linear motors have been suggested for a number of uses. They have been considered for use as weapons, since current armour-piercing ammunition tends to consist of small rounds with very high kinetic energy, for which just such motors are suitable. Many amusement park roller coasters now use linear induction motors to propel the train at a high speed, as an alternative to using a lift hill. The United States Navy is also using linear induction motors in the Electromagnetic Aircraft Launch System that will replace traditional steam catapults on future aircraft carriers. They have also been suggested for use in spacecraft propulsion. In this context they are usually called mass drivers. The simplest way to use mass drivers for spacecraft propulsion would be to build a large mass driver that can accelerate cargo up to escape velocity.

High-acceleration linear motors are difficult to design for a number of reasons. They require large amounts of energy in very short periods of time. One rocket launcher design calls for 300 GJ for each launch in the space of less than a second. Normal electrical generators are not designed for this kind of load, but short-term electrical energy storage methods can be used. Capacitors are bulky and expensive but can supply large amounts of energy quickly. Homopolar generators can be used to convert the kinetic energy of a flywheel into electric energy very rapidly. High-acceleration linear motors also require very strong magnetic fields; in fact, the magnetic fields are often too strong to permit the use of superconductors. However, with careful design, this need not be a major problem.

Two different basic designs have been invented for high-acceleration linear motors: railguns and coilguns.

Usages of a linear motor for train propulsion

Usage with conventional rails

All applications are in rapid transit.

Guangzhou Metro L4 vehicle made by CSR Sifang Locomotive and Rolling Stock & Kawasaki Heavy Industries

Guangzhou Metro L5 vehicle made by CSR Sifang Locomotive and Rolling Stock and Kawasaki Heavy Industries

- Bombardier ART:
  - Airport Express in Beijing (opened 2008)
  - AirTrain JFK in New York (opened 2003)
  - Detroit People Mover in Detroit (opened 1987)
  - EverLine Rapid Transit System in Yongin (under construction)
  - Kelana Jaya Line in Kuala Lumpur (opened 1998)
  - Scarborough RT in Toronto (using UTDC's (predecessor) ICTS technology - opened 1985)
  - SkyTrain in Vancouver (Expo Line (using ITCS) opened 1985 and Millennium Line opened in 2002)
  - Beijing Subway Capital Airport Track (opened 2008)

- Several subways in Japan and China, built by Kawasaki Heavy Industries:
  - Limtrain in Saitama (short-lived demonstration track, 1988)
  - Nagahori Tsurumi-ryokuchi Line in Osaka (opened 1990)
  - Toei Ōedo Line in Tokyo (opened 2000)
  - Kaigan Line in Kobe (opened 2001)
  - Nanakuma Line in Fukuoka (opened 2005)
  - Imazatosuji Line in Osaka (opened 2006)

- Green Line in Yokohama (opened 2008)
- Tōzai Line in Sendai (under construction)
- Line 4 of Guangzhou Metro in Guangzhou, China (opened 2005).
- Line 5 of Guangzhou Metro in Guangzhou, China (open in December 2009).
- Line 6 of Guangzhou Metro in Guangzhou, China (under construction).

Both the Kawasaki trains and Bombardier's ART have the active part of the motor in the cars and use overhead wires (Japanese Subways) or a third rail (ART) to transfer power to the train.

Usage with monorails

- There is at least one known monorail system which is **not** magnetically levitated, but nonetheless uses linear motors. This is the Moscow Monorail. Originally, traditional motors and wheels were to be used. However, it was discovered during test runs that the proposed motors and wheels would fail to provide adequate traction under some conditions, for example, when ice appeared on the rail. Hence, wheels are still used, but the trains use linear motors to accelerate and slow down. This is possibly the only use of such a combination, due to the lack of such requirements for other train systems.

- The TELMAGV is a prototype of a monorail system that is also not magnetically levitated but uses linear motors.

Usage with magnetic levitation

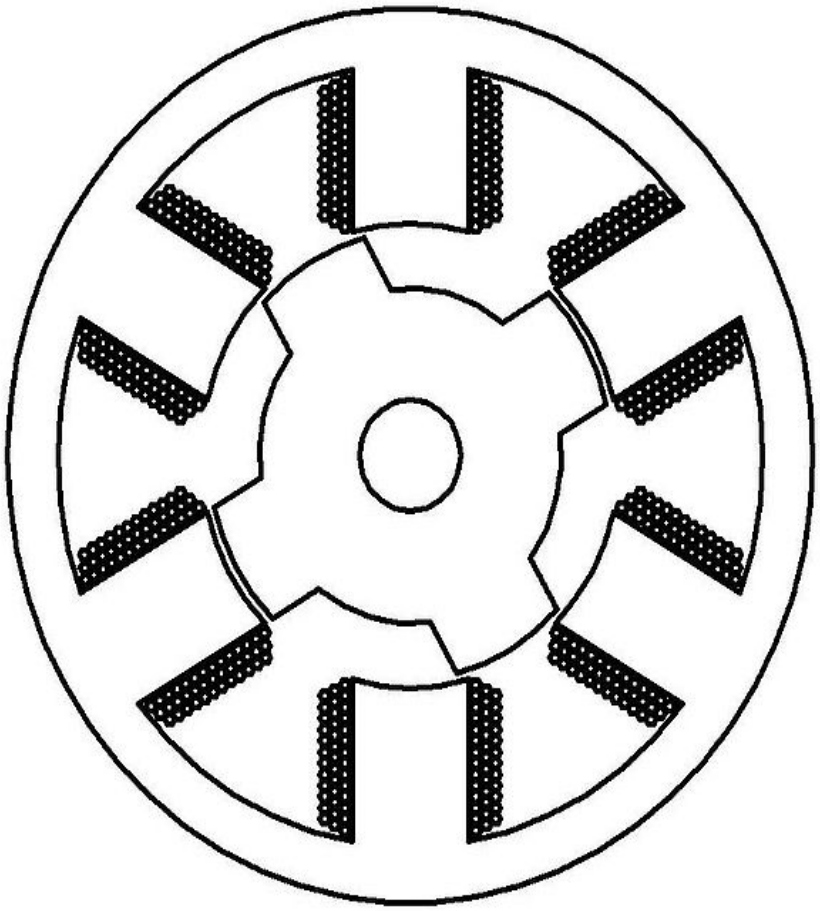
- High-speed trains:
  - Transrapid: first commercial use in Shanghai (opened in 2004)
  - JR-Maglev

- Rapid transit:
  - Birmingham Airport, UK (opened 1984, closed 1995)
  - M-Bahn in Berlin, Germany (opened in 1989, closed in 1991)
  - Daejeon EXPO, Korea (ran only 1993)
  - HSST: Linimo line in Aichi, Japan (opened 2005)

Chapter 8

Reluctance Motor and Piezoelectric Motor

Reluctance motor



Cross-section of switched reluctance machine with 6 stator and 4 rotor poles. Notice the concentrated windings on the stator poles.

A **reluctance motor** is a type of synchronous electric motor that induces non-permanent magnetic poles on the ferromagnetic rotor. Torque is generated through the phenomenon of magnetic reluctance.

A reluctance motor, in its various incarnations, may be known as a:

- Synchronous reluctance motor
- Variable reluctance motor
- Switched Reluctance Motor
- Variable reluctance stepping motor

Reluctance motors can have very high power density at low-cost, making them ideal for many applications. Disadvantages are high torque ripple when operated at low speed, and noise caused by torque ripple. Until recently, their use has been limited by the complexity inherent in both designing the motors and controlling them. These challenges are being overcome by advances in the theory, by the use of sophisticated computer design tools, and by the use of low-cost embedded systems for motor control. These control systems are typically based on microcontrollers using control algorithms and real-time computing to tailor drive waveforms according to rotor position and current or voltage feedback.

Design and operating fundamentals

The stator consists of multiple salient (i.e., projecting) electromagnet poles, similar to a wound field brushed DC motor. The rotor consists of soft magnetic material, such as laminated silicon steel, which has multiple projections acting as salient magnetic poles through magnetic reluctance. The number of rotor poles is typically less than the number of stator poles, which minimizes torque ripple and prevents the poles from all aligning simultaneously—a position which can not generate torque.

When a rotor pole is equidistant from the two adjacent stator poles, the rotor pole is said to be in the "fully unaligned position". This is the position of maximum magnetic reluctance for the rotor pole. In the "aligned position", two (or more) rotor poles are fully aligned with two (or more) stator poles, (which means the rotor poles completely face the stator poles) and is a position of minimum reluctance.

When a stator pole is energized, the rotor torque is in the direction that will reduce reluctance. Thus the nearest rotor pole is pulled from the unaligned position into alignment with the stator field (a position of less reluctance). (This is the same effect used by a solenoid, or when picking up ferromagnetic metal with a magnet.) In order to sustain rotation, the stator field must rotate in advance of the rotor poles, thus constantly "pulling" the rotor along. Some motor variants will run on 3-phase AC power. Most modern designs are of the **switched reluctance** type, because electronic commutation gives significant control advantages for motor starting, speed control, and smooth operation (low torque ripple).

Dual-rotor layouts provide more torque at lower price per volume or per mass.

The inductance of each phase winding in the motor will vary with position, because the reluctance also varies with position. This presents a control systems challenge.

Types of Reluctance motors

Synchronous reluctance

Synchronous reluctance motors do have an equal number of stator and rotor poles. The rotor saliency is arranged by introducing internal flux “barriers“ i.e. holes which direct the magnetic flux along the so called direct axis. Typical pole numbers are 4 and 6.

As the rotor is operating at synchronous speed and there are no current conducting parts in the rotor, the rotor losses are minimal compared to those of induction motor.

Once started at synchronous speed, the SynRM motor can operate with sinusoidal voltage, but the speed control requires an electronic frequency converter.

Switched reluctance or variable reluctance motor

The Switched Reluctance Motor (SRM) is a form of stepper motor that uses fewer poles. The SRM has the lowest construction cost of any industrial electric motor because of its simple structure. Common usages for an SRM include applications where the rotor must be held stationary for long periods and in potentially explosive environments such as mining because it lacks a mechanical commutator.

The phase windings in a SRM are electrically isolated from each other, resulting in higher fault tolerance compared to inverter driven AC induction motors. The optimal drive waveform is not a pure sinusoid, due to the non-linear torque relative to rotor displacement, and the highly position dependent inductance of the stator phase windings.

Applications

- SRM's are used in some washing machine designs.
- SRM's are commonly used in the control rod drive mechanisms of nuclear reactors.

Piezoelectric motor

A **piezoelectric motor** or **piezo motor** is a type of electric motor based upon the change in shape of a piezoelectric material when an electric field is applied. Piezoelectric motors make use of the converse piezoelectric effect whereby the material produces acoustic or ultrasonic vibrations in order to produce a linear or rotary motion. In one mechanism, the

elongation in a single plane is used to make a series stretches and position holds, similar to the way a caterpillar moves.

Current designs

Motors are made in both linear and rotary types.

Of these, one drive technique is to use piezoelectric ceramics to push a stator. Commonly known under the trademark names of *Inchworm* or *PiezoWalk* motors, these piezoelectric motors use three groups of crystals: two of which are **Locking** and one **Motive**, permanently connected to either the motor's casing or stator (not both) and sandwiched between the other two, which provides the motion. These piezoelectric motors are fundamentally stepping motors, with each step comprising either two or three actions, based on the locking type. Another mechanism employs the use of surface acoustic waves (SAW) to generate linear or rotational motion.

A second drive technique is illustrated by the trademark *Squiggle* motor, in which piezoelectric elements are bonded orthogonally to a nut and their ultrasonic vibrations rotate and translate a central lead screw. This is a direct drive mechanism.

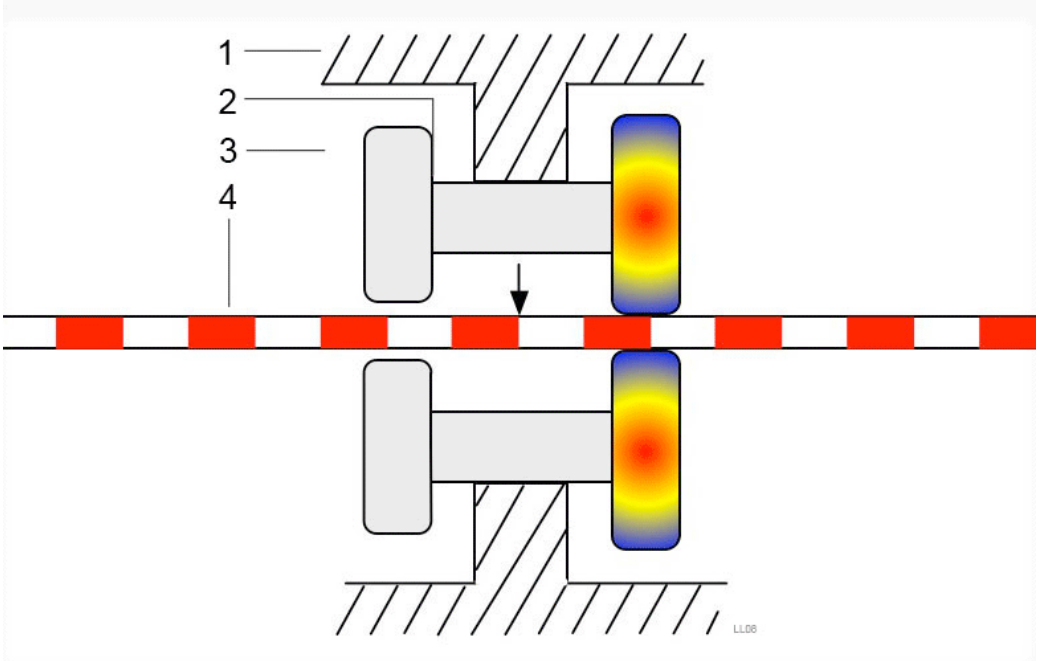
Locking mechanisms

The non-powered behaviour of the first type of piezoelectric motor is one of two options: **Normally Locked** or **Normally Free**. When no power is being applied to a Normally Locked motor, the spindle or carriage (for rotary or linear types, respectively) will not move under external force. For a Normally Free motor, the spindle or carriage will move freely under external force. However, if both locking groups are powered at rest, a Normally Free motor will resist external force without providing any motive force.

A combination of mechanical latches and crystals could be used, but this would restrict the maximum stepping rate of the motor.

The non-power behaviour of the second type of motor is locked, as the drive screw is locked by the threads on the nut. Thus it holds its position with the power off.

Stepping actions



Piezoelectric motor

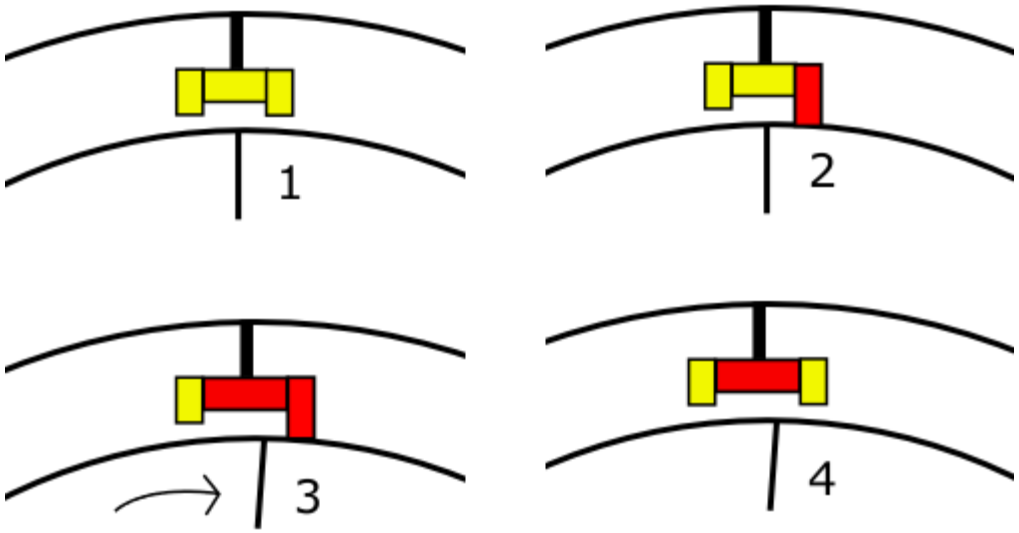


Fig. 1: Stepping stages of **Normally Free** motor

Regardless of locking type, stepping type piezoelectric motors — both linear and rotary — use the same mechanism to provide movement.

First, one group of *locking* crystals is activated — this gives one locked side and one unlocked side of the 'sandwich'.

Next, the *motive* crystal group is triggered and held — the expansion of this group moves the unlocked *locking* group along the motor path. This is the only stage where motor movement takes place.

Then the *locking* group triggered in stage one is released (in *Normally Locking* motors, the other is triggered). Then the *motive* group is released, retracting the 'trailing' *locking* group. Finally, both *locking* groups are returned to their default states.

Direct drive actions

The direct drive piezoelectric motor uses continuous ultrasonic vibrations to provide movement. A two-channel sinusoidal or square wave is applied to the piezoelectric elements at an ultrasonic frequency of 40 kHz to 200 kHz, matching the first bending resonant frequency of the threaded tube. This creates an orbital motion which drives the screw.

Speed and precision

The growth and forming of piezoelectric crystals is a well developed industry, yielding very uniform and consistent distortion for a given applied potential difference. This, combined with the minute scale of the distortions, gives the piezoelectric motor the ability to make very fine steps — manufacturers claim precision to the nanometer scale.

The high response rate and fast distortion of the crystals also allows the steps to be made at very high frequencies — upwards of 5 MHz. This gives a maximum linear speed of approximately 800 mm per second, or nearly 2.9 km/h.

Other designs

Single action

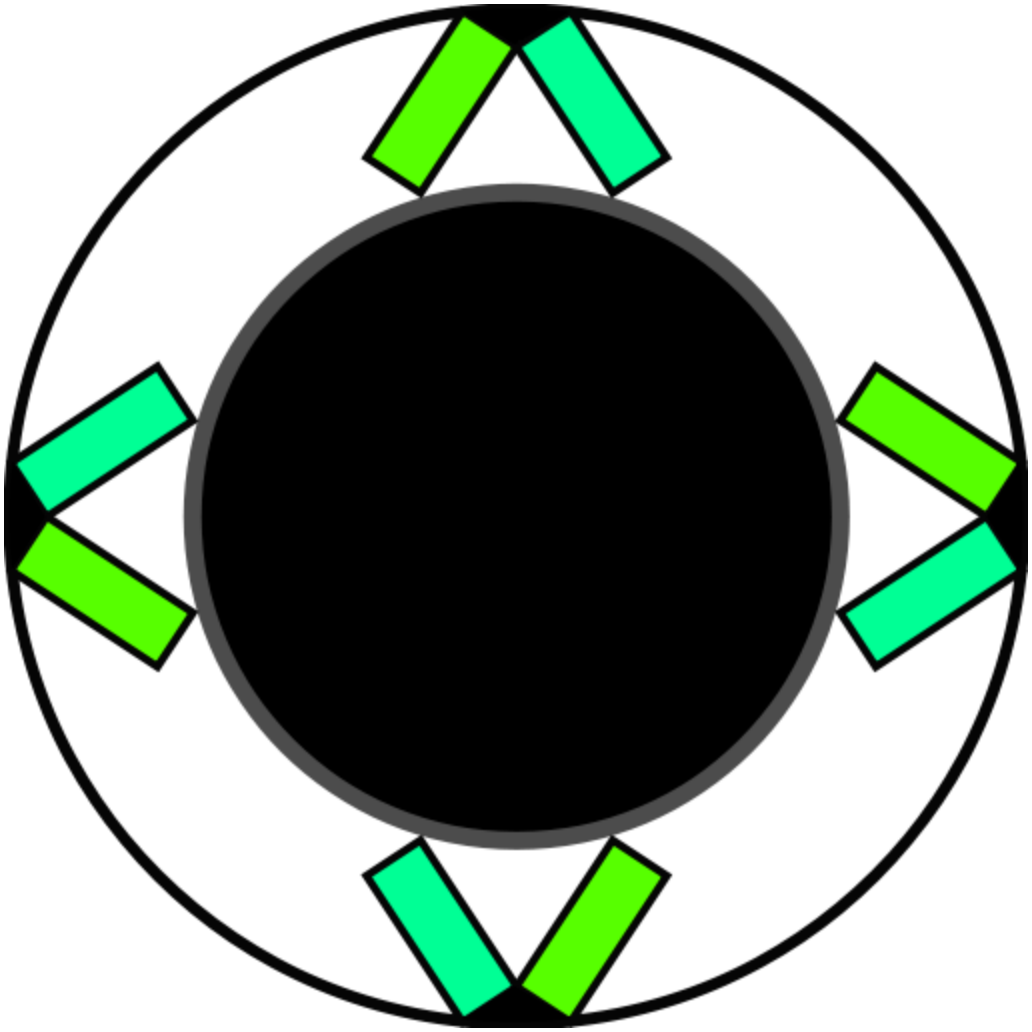


Fig. 2: Piezo ratchet stepping motor.

Very simple single-action stepping motors can be made with piezoelectric crystals. For example, with a hard and rigid rotor-spindle coated with a thin layer of a softer material (like a polyurethane rubber), a series of angled piezoelectric transducers can be arranged. (see Fig. 2). When one group of transducers is triggered, the rotor will be pushed around one step. This design is not capable of such small or precise steps as more complex designs, but can reach higher speeds and are cheaper to manufacture.

Patents

The first U.S. patent to disclose a vibrationally-driven motor may be "Method and Apparatus for Delivering Vibratory Energy" (U.S. Pat. No. 3,184,842, Maropis, 1965).

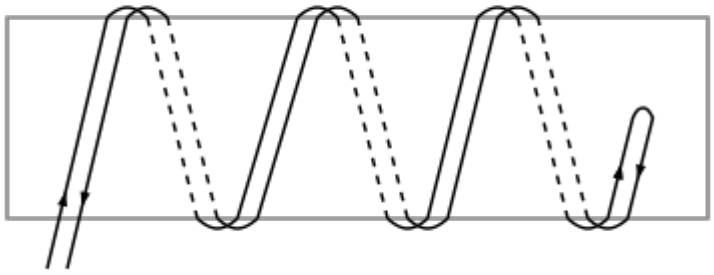
The Maropis patent describes a "vibratory apparatus wherein longitudinal vibrations in a resonant coupling element are converted to torsional vibrations in a toroid type resonant terminal element." Other important patents in the early development of this technology include:

- "Piezoelectric motor structures" (U.S. Pat. No. 4,019,073, Vishnevsky, et al., 1977)
- "Piezoelectrically driven torsional vibration motor" (U.S. Pat. No. 4,210,837, Vasiliev, et al., 1980)

Chapter 9

Bifilar Coil and Basket Winding

Bifilar Coil

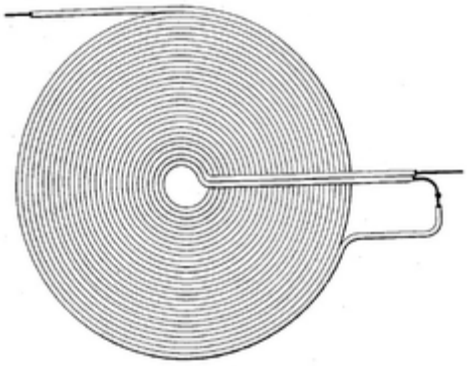


Non-inductive bifilar winding

A **bifilar coil** is an electromagnetic coil that contains two closely spaced, parallel windings. In engineering, the word *bifilar* describes wire which is made of two filaments or strands. It is commonly used to denote special types of winding wire for transformers. Wire can be purchased in bifilar form, usually as different colored enameled wire bonded together. For three strands, the term **trifilar coil** is used.

Description and applications

Bifilar coil configurations



Nikola Tesla's flat bifilar coil.

1. parallel-wound, series connected
2. parallel-wound, parallel connected
3. counter-wound (series)
4. counter-wound (parallel)

Some bifilars have adjacent coils in which the convolutions are arranged so that the potential difference is magnified (i.e., the current flows in same parallel direction). Others are wound so that the current flows in opposite directions. The magnetic field created by one winding is therefore equal and opposite to that created by the other, resulting in a net magnetic field of zero (i.e., neutralizing any negative effects in the coil). In electrical terms, this means that the self-inductance of the coil is zero.

The bifilar coil (more often called the *bifilar winding*) is used in modern electrical engineering as a means of constructing wire-wound resistors with negligible parasitic self-inductance.

A different type of bifilar coil is used in some relay windings and transformers used for a switched-mode power supply to suppress back-emf. In this case, the two wire coils are closely spaced and wound in parallel but are electrically isolated from each other. The primary coil is driven to operate the relay, and the secondary coil is short-circuited inside the case. When the current through the primary is interrupted, as happens when the relay is switched off, most of the magnetic energy is intercepted by the secondary coil which converts it to heat in its internal resistance. This is only one of several methods of absorbing the energy from the primary coil before it can damage the device (usually a vulnerable semiconductor) that drives the relay. The main disadvantage of this method is that it greatly increases the switching time of the relay.

When used in a switching transformer, one winding of the bifilar coil is used as a means of removing the energy stored in the stray magnetic flux which fails to link the *primary coil* to the *secondary coil* of the transformer. Because of their proximity, the wires of the bifilar coil both "see" the same stray magnetic flux. One wire is clamped to ground usually by a diode so that when the other "primary" wire of the bifilar coil no longer has a voltage applied across it by the switching transistor, the stray magnetic flux generates a current in the clamping coil with the primary side voltage appearing across it, causing an equal voltage to appear across the primary winding. If this clamping coil was not used, the stray magnetic flux would attempt to force a current to flow through the primary wire. Since the primary wire is switched off and the switching transistor is in a high resistance state, the high voltage which would appear on the semiconductor switching transistor would exceed its electrical breakdown or even damage it.

History

An early example of the bifilar coil can be seen in Nikola Tesla's United States patent 512,340 of 1894. Tesla explains that in some applications (which he does not specify) the self-inductance of a conventional coil is undesired and has to be neutralised by adding external capacitors. The bifilar coil in this configuration has increased self-capacitance, thereby saving the cost of the capacitors. It is notable that this is *not* the kind of bifilar winding used in non-inductive wirewound resistors where the windings are wired anti-series to null out self-inductance.

Basket Winding

Basket winding made with a Litz wire

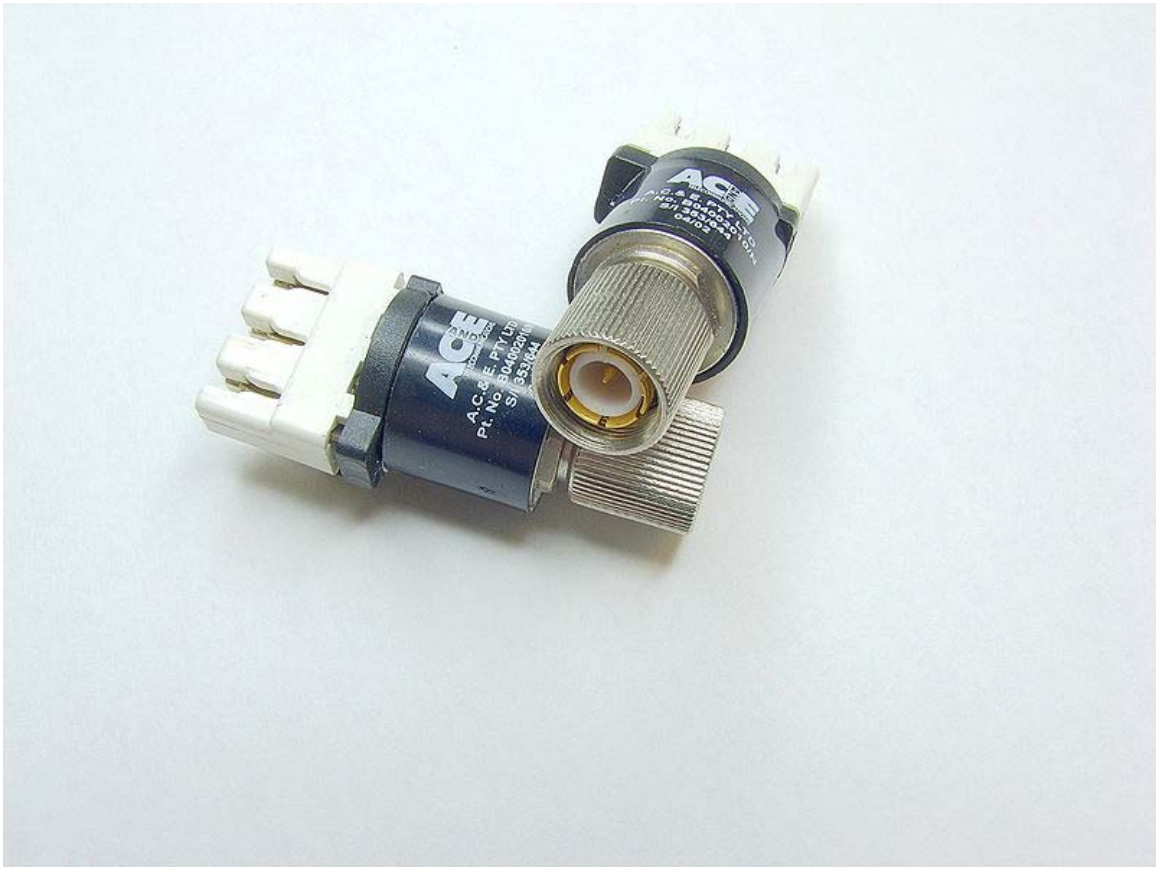
Basket winding is an electromagnetic coil wound in a special way, such that the wires in neighbouring layers cross each other at an angle as close to 90 degrees as possible. Such a winding results in low parasitic capacitance as compared with a regular winding with the same number of turns. However, the physical dimensions are greater which leads to higher leakage inductance.

Basket windings are used for high frequency coils, and are wound with a Litz wire, or a wire isolated with cotton or silk. The type of isolation is important also from mechanical

point of view during the winding, because a common enamelled magnet wire would not provide sufficient surface friction to hold the subsequent turns at the large angle.

Chapter 10

Balun



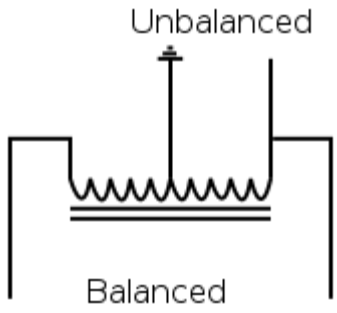
Pair of AC&E 120 Ohm twisted pair (Krone IDC) to 75 Ohm coaxial cable balun transformers. Actual length is about 3cm.

2 balun matching transformers

A **balun**, is a type of electrical transformer that can convert electrical signals that are balanced about ground (differential) to signals that are unbalanced (single-ended) and vice versa. They are also often used to connect lines of differing impedance. The origin of the word balun is **bal**(ance) + **un**(balance).

Baluns can take many forms and their presence is not always obvious. They always use electromagnetic coupling for their operation.

Types of balun

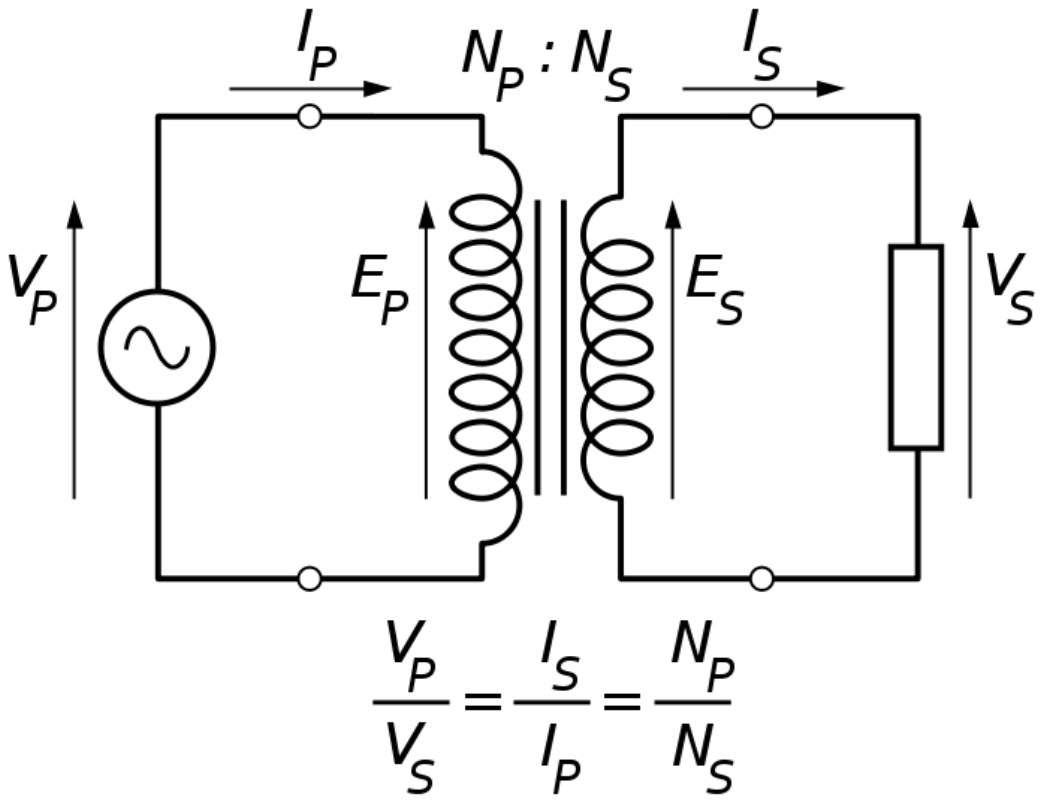


Autotransformer 4:1 wideband balun using two windings on a ferrite rod.

Autotransformer type

In an autotransformer, two coils on a ferrite rod can be used as a balun by winding the individual strands of enameled wire comprising the coil very tightly together. This winding can take one of two forms: either the two windings must be wound such that the two form a single layer where each turn is touching each of the adjacent turns of the other winding; or the two wires are twisted together before being wound into the coil.

The two windings are joined to become a single coil. The end of one of the windings on one side of the coil is connected to the end of the other winding on the other side of the coil. This point then becomes the ground for the unbalanced circuit. One of the remaining ends is connected to the ungrounded side of the unbalanced circuit, and one side of the balanced circuit. Finally, the other side of the balanced circuit is connected to the remaining end.



Isolated transformer

Classical transformer type

Isolated transformers have a real impedance at a resonance frequency where self-inductance and self-capacitance for each individual winding cancel themselves out.

Transmission-line transformer type

Baluns can be considered as simple forms of transmission line transformers.

A more complex (and subtle) type results when the transformer type (magnetic coupling) is combined with the transmission line type (electro-magnetic coupling). This is where whole transmission lines are used as windings, resulting in devices capable of very wideband operation. This whole class known generally as "Transmission Line Transformers" spawn their own huge variety. Very commonly, they use small ferrite cores in toroidal or "binocular" shapes. Something as simple as 10 turns of coaxial cable coiled up on a diameter about the size of a dinner plate makes an extremely effective choke balun for frequencies from about 10 MHz to beyond 30 MHz. The magnetic material may be "air", but it is a transmission line transformer.

Homemade 1:1 balun using a toroidal core and coaxial cable. This simple RF choke works as a balun by preventing signals passing along the outside of the braid. Such a device can be used to cure television interference by acting as a braid-breaker.

The Guanella transmission line transformer is often combined with a balun to act as an impedance matching transformer. Putting balancing aside a 1:4 transformer of this type consists of a 75 Ohm transmission line divided in parallel into two 150 Ohm cables, which are then combined in series for 300 Ohm. It is implemented as a specific wiring around the ferrite core of the balun.

Delay line type

A large class of baluns uses connected transmission lines of specific lengths, with no obvious "transformer" part. These are usually built for (narrow) frequency ranges where the lengths involved are some multiple of a quarter wavelength of the intended frequency in the transmission line medium. A common application is in making a coaxial

connection to a balanced antenna, and designs include many types involving coaxial loops and variously connected "stubs".

One easy way to make a balun is a one-half wavelength (λ/2) length of coaxial cable. The inner core of the cable is linked at each end to one of the balanced connections for a feeder or dipole. One of these terminals should be connected to the inner core of the coaxial feeder. All three braids should be connected together. This then forms a 4:1 balun which works at only one frequency.

Another narrow band design is to use a λ/4 length of metal pipe. The coaxial cable is placed inside the pipe; at one end the braid is wired to the pipe while at the other end no connection is made to the pipe. The balanced end of this balun is at the end where the pipe is wired to the braid. The λ/4 conductor acts as a transformer converting the infinite impedance at the unconnected end into a zero impedance at the end connected to the braid. Hence any current entering the balun through the connection, which goes to the braid at the end with the connection to the pipe, will flow into the pipe. This balun design is not good for low frequencies because of the long length of pipe that will be needed. An easy way to make such a balun is to paint the outside of the coax with conductive paint, then to connect this paint to the braid.

Balun alternatives

An RF choke can be used in place of a balun. If a coil is made using coaxial cable near to the feed point of a balanced antenna then the RF current that flows on the outer surface of the coaxial cable can be attenuated. One way of doing this would be to wrap a lossy material, such as ferrite around the coaxial cable;

Applications

A balun's function is generally to achieve compatibility between systems, and as such, finds extensive application in modern communications, particularly in realising frequency conversion mixers to make cellular phone and data transmission networks possible. They are also used to convert an E1 carrier signal from coaxial cable to UTP CAT-5 cable.

Radio and television

A 75-to-300 ohm balun built into the antenna plug.

In television, amateur radio, and other antenna installations and connections, baluns convert between 300 ohm ribbon cable or 450 ohm ladder line (balanced) and 75 Ω coaxial cable (unbalanced) or to directly connect a balanced antenna to (unbalanced) coax. To avoid EMC problems it is a good idea to connect a centre fed dipole antenna to coaxial cable via a balun. Match 300 Ω twin-lead cable to 75 Ω coaxial cable

In electronic communications, baluns convert Twinax cables to Category 5 cables, and back, or they convert between coaxial cable and ladder line.

In measuring the impedance or radiation pattern of a balanced antenna using a coaxial cable, it is important to place a balun between the cable and the antenna feed. Unbalanced currents that may otherwise flow on the cable will make the measured antenna impedance sensitive to the configuration of the feed cable, and the radiation pattern of small antennas may be distorted by radiation from the cable.

Baluns are present in radars, transmitters, satellites, in every telephone network, and probably in most wireless network modem/routers used in homes. It can be combined with transimpedance amplifiers to compose high-voltage amplifiers out of low-voltage components.

Video

While not as high as most RF applications, baseband video still uses frequencies up to several megahertz. Since this bandwidth is now well within range of modern twisted-pair cables, they are now being used to send video which would otherwise run over coaxial cable. Many better security cameras now have both a balanced UTP output and an unbalanced coaxial one via an internal balun, though any camera can be used with an external balun. A balun is also used on the video recorder end to convert back from the

100-ohm balanced to 75-ohm unbalanced. A balun of this type has a BNC connector with two screw terminals. VGA/DVI baluns are baluns with electronic circuitry used to connect VGA/DVI sources (laptop, DVD, etc.) to VGA/DVI display devices over long runs of CAT-5/CAT-6 cable. Runs over 130 m (400 ft) may lose quality due to attenuation and variations in the arrival time of each signal. A skew control and special low skew or skew free cable is used for runs over 130 m (400 ft).

Audio

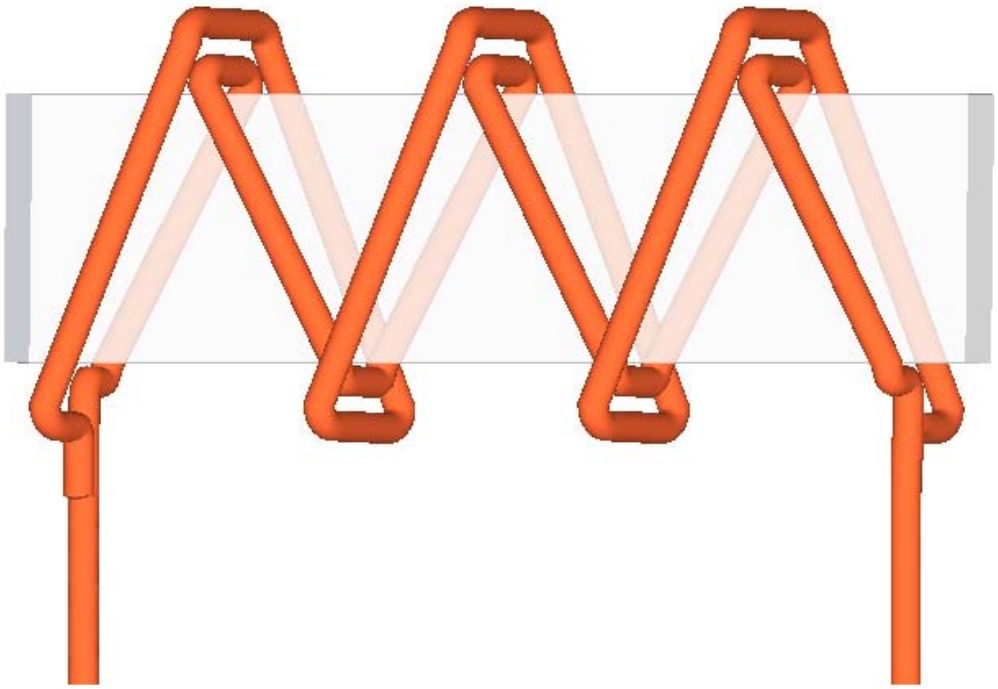
Three audio baluns (transformers).

In audio applications, baluns convert between high impedance unbalanced and low impedance balanced lines.

Except for the connections, the three devices in the image are electrically identical, but only the leftmost two can be used as baluns. The device on the left would normally be used to connect a high impedance source, such as a guitar, into a balanced microphone input, serving as a passive DI unit. The one in the centre is for connecting a low impedance balanced source, such as a microphone, into a guitar amplifier. The one at the right is not a balun, as it provides only impedance matching.

In power line communications, baluns are used in coupling signals onto a power line.

Ayrton-Perry Winding



Ayrton-Perry winding

Ayrton-Perry winding is a type of bifilar winding pattern used in winding wire on forms to make electronic components. Its advantage is that the resulting coil of wire has low values of parasitic inductance and parasitic capacitance. Ayrton-Perry windings of resistance wire are used to make wirewound RF resistors that are used at high frequencies, where inductance and capacitance are unwanted.

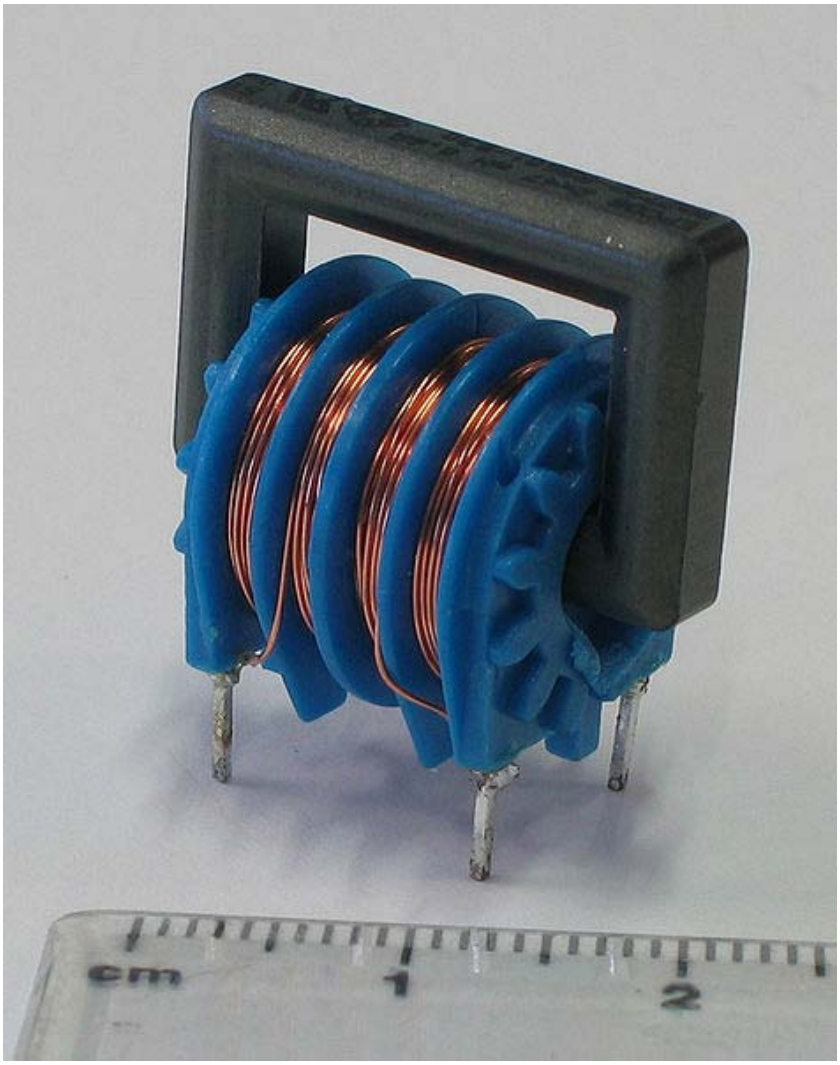
The winding is made of two separate wires wound in opposing directions along an insulating form and connected in parallel at the ends. Since there are the same number of turns of wire in either direction, the magnetic fields of the two wires cancel each other out, so the coil has little inductance. And since adjacent turns of the two wires are at approximately the same voltage, there is little parasitic capacitance between the turns.

One disadvantage is that because the two lengths of resistive wire are connected in parallel, four times the length of wire (twice the length for each coil) is needed to make a given resistance than if a single coil was used.

Chapter 11

Choke (Electronics) and Helmholtz Coil

Choke (Electronics)



A choke, with two 47mH windings and rated to handle 0.6A

A **choke** is an inductor designed to block (have a high reactance to) higher frequencies in an electrical circuit while passing signals of much lower frequency or direct current.

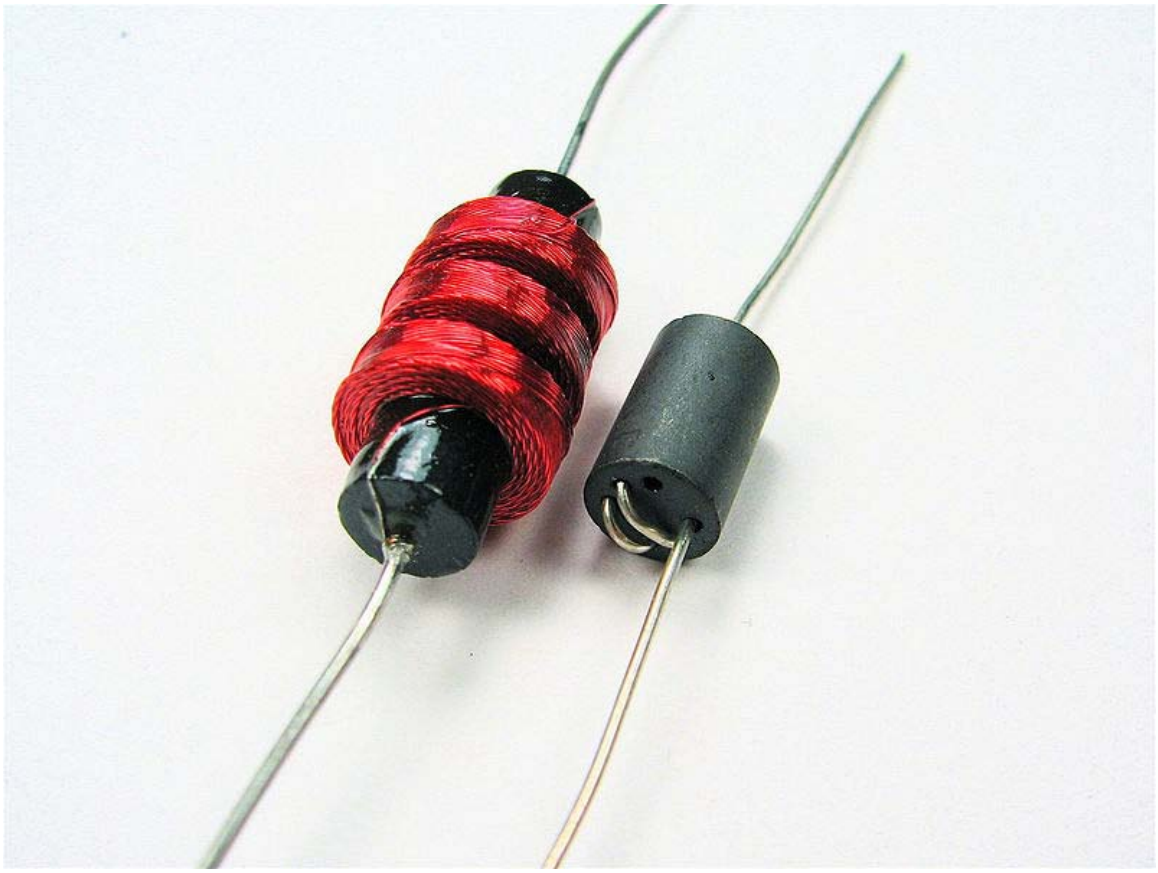
Description

Choke coils are inductances that isolate AC frequency currents from certain areas of a radio circuit. Chokes depend upon the property of self-inductance for their operation. They can be used to block alternating current while passing direct current (contrast with capacitor).

Common-mode choke

Common-mode choke coils are useful in a wide range of prevention of electromagnetic interference (EMI) and radio frequency interference (RFI) from power supply lines and for prevention of malfunctioning of electronic equipment. They pass differential currents (equal but opposite), while blocking common-mode currents.

Types and construction



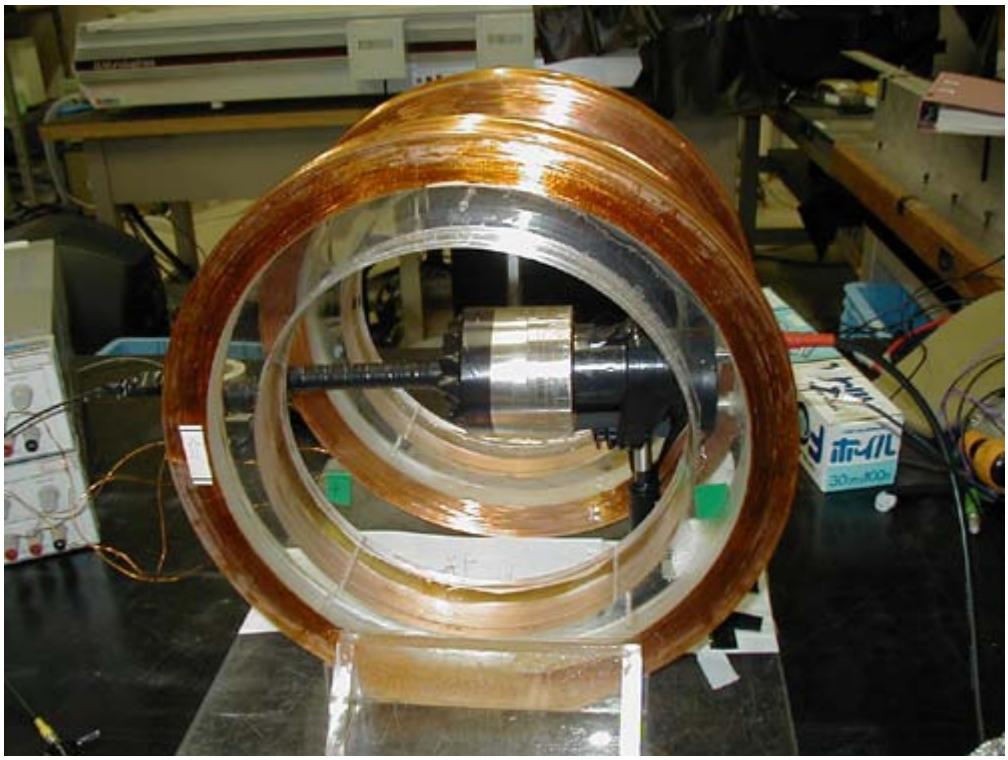
An MF or HF radio choke for tenths of an Ampere and several hundred Volts, and a ferrite bead VHF choke for several Amperes and tens of Volts.

Chokes used in radio circuits are divided into two classes – those designed to be used with audio frequencies, and the others to be used with radio frequencies. Audio frequency coils, usually called A.F. chokes, can have ferromagnetic iron cores to increase their inductance. Chokes for higher frequencies often have iron powder or ferrite cores. Chokes for even higher frequencies have non-magnetic cores and low inductance simulating the effects of an air-core.

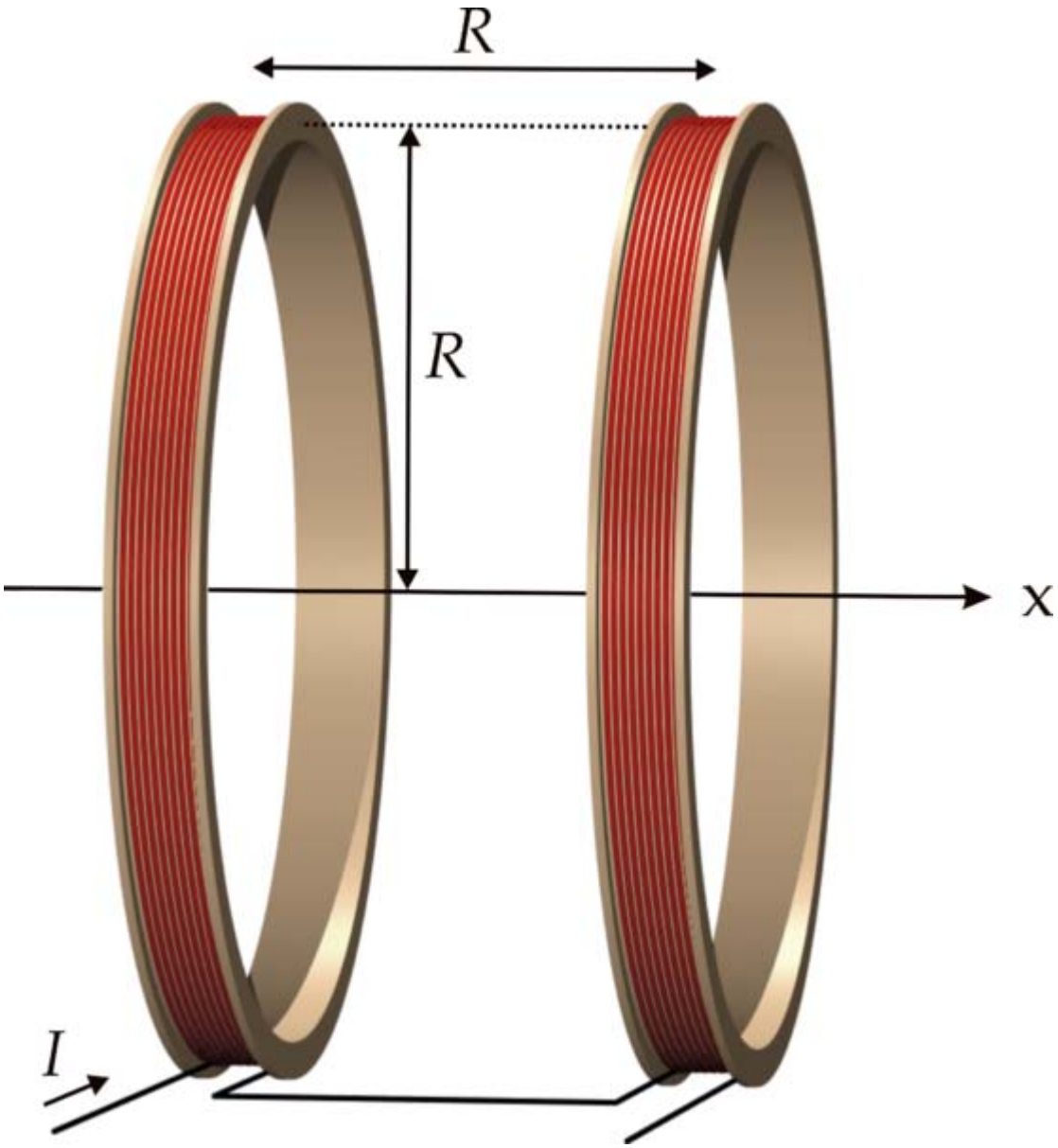
Solid-state chokes

Solid-state chokes (SSC) can manage higher currents than traditional chokes. They can help reduce the high frequency buzzing noises that occur when running under high electrical currents.

Helmholtz Coil



A Helmholtz coil



Helmholtz coil schematic drawing

A **Helmholtz coil** is a device for producing a region of nearly uniform magnetic field. It is named in honor of the German physicist Hermann von Helmholtz.

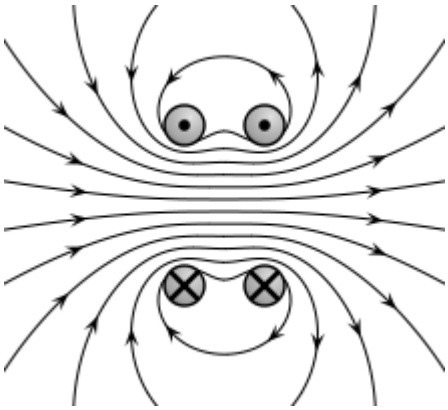
Description

A Helmholtz pair consists of two identical circular magnetic coils that are placed symmetrically one on each side of the experimental area along a common axis, and separated by a distance *h* equal to the radius *R* of the coil. Each coil carries an equal electrical current flowing in the same direction.

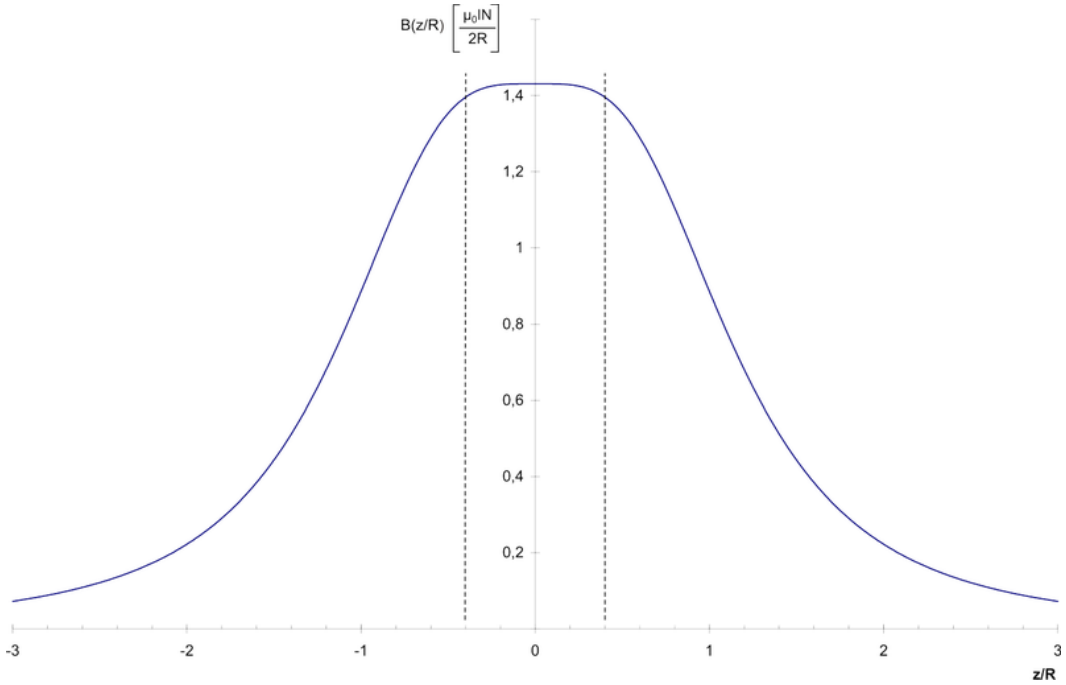
Setting $h = R$, which is what defines a Helmholtz pair, minimizes the nonuniformity of the field at the center of the coils, in the sense of setting $d^2B / dx^2 = 0$ (meaning that the first nonzero derivative is d^4B / dx^4 as explained below), but leaves about 6% variation in field strength between the center and the planes of the coils. A slightly larger value of h reduces the difference in field between the center and the planes of the coils, at the expense of worsening the field's uniformity in the region near the center, as measured by d^2B / dx^2.

In some applications, a Helmholtz coil is used to cancel out Earth's magnetic field, producing a region with a magnetic field intensity much closer to zero.

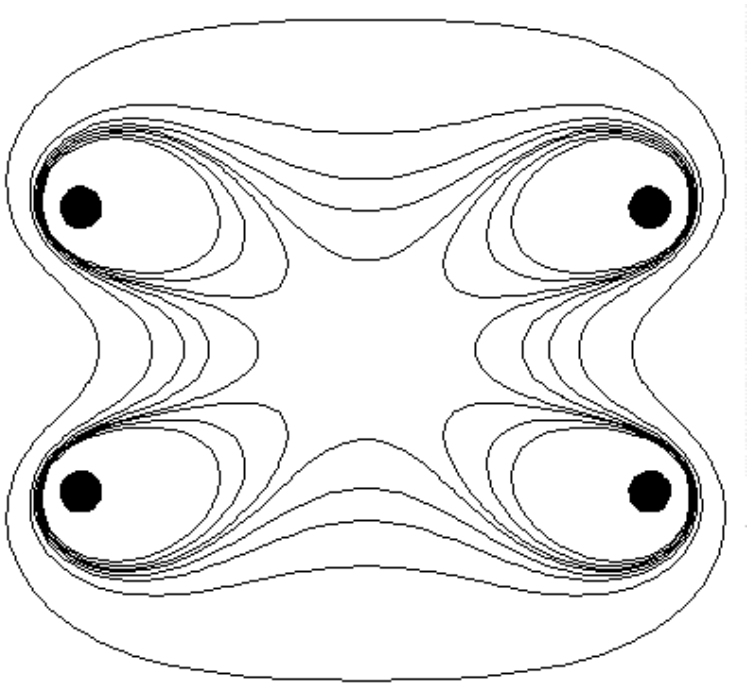
Mathematics



Magnetic field lines in a plane bisecting the current loops. Note the field is approximately uniform in between the coil pair. (In this picture the coils are placed one beside the other: the axis is horizontal)



Magnetic field induction along the axis crossing the center of coils; $z = 0$ is the point in the middle of distance between coils.



Contours showing the magnitude of the magnetic field near the coil pair. Inside the central 'octopus' the field is within 1% of its central value B_0. The five contours are for field magnitudes of $0.5B_0$, $0.8B_0$, $0.9B_0$, $0.95B_0$, and $0.99B_0$.

The calculation of the exact magnetic field at any point in space has mathematical complexities and involves the study of Bessel functions. Things are simpler along the axis of the coil-pair, and it is convenient to think about the Taylor series expansion of the field strength as a function of *x*, the distance from the central point of the coil-pair along the axis. By symmetry the odd order terms in the expansion are zero. By separating the coils so that charge $x = 0$ is an inflection point for each coil separately we can guarantee that the order x^2 term is also zero, and hence the leading non-uniform term is of order x^4. One can easily show that the inflection point for a simple coil is $R / 2$ from the coil center along the axis; hence the location of each coil at $x = \pm R/2$

A simple calculation gives the correct value of the field at the center point. If the radius is *R*, the number of turns in each coil is *n* and the current flowing through the coils is *I*, then the magnetic flux density, B at the midpoint between the coils will be given by

$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 n I}{R}$$

μ_0 is the permeability of free space ($1.26 \times 10^{-6}\ \mathrm{T \cdot m/A}$), and *R* is in meters.

Derivation

Start with the formula for the on-axis field due to a single wire loop (which is itself derived from the Biot-Savart law):

$$B = \frac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}}$$

Where:
μ_0= the permeability constant =
$4\pi \times 10^{-7}\ \mathrm{T \cdot m/A} = 1.26 \times 10^{-6}\ \mathrm{T \cdot m/A}$
I= coil current, in amperes
R= coil radius, in meters
x= coil distance, on axis, to point, in meters

However the coil consists of a number of wire loops, the total current in the coil is given by

nI= total current
Where:
n= number of wire loops in one coil

Adding this to the formula:

$$B = \frac{\mu_0 n I R^2}{2(R^2 + x^2)^{3/2}}$$

In a Helmholtz coil, a point halfway between the two loops has an x value equal to R/2, so let's perform that substitution:

$$B = \frac{\mu_0 n I R^2}{2(R^2 + (R/2)^2)^{3/2}}$$

There are also two coils instead of one, so let's multiply the formula by 2, then simplify the formula:

$$B = \frac{2\mu_0 n I R^2}{2(R^2 + (R/2)^2)^{3/2}}$$
$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 n I}{R}$$

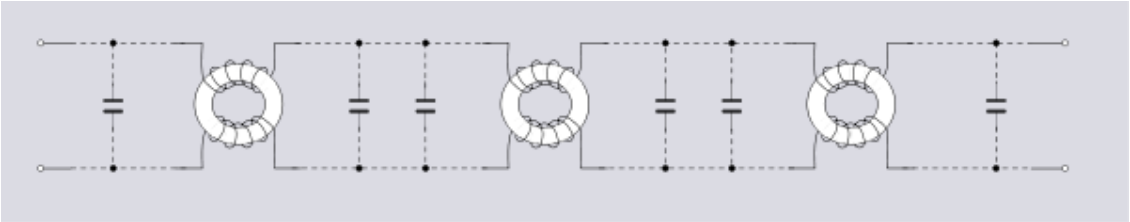
Chapter 12

Loading Coil

In electronics, a **loading coil** or **load coil** is a coil (inductor) that does not provide coupling to any other circuit, but is inserted in a circuit to increase its inductance. The need was discovered by Oliver Heaviside in studying the disappointing slow speed of the Transatlantic telegraph cable. He concluded additional inductance was required to prevent amplitude and time delay distortion of the transmitted signal. The mathematical condition for distortionless transmission is known as the Heaviside condition. Previous telegraph lines were overland or shorter, hence had less delay and the need for extra inductance was not so great. Submarine communications cables are particularly subject to the problem, but early 20th century ones using balanced pairs were often continuously loaded by iron tape rather than discretely by load coils.

Loading coils are archaically known as **Pupin coils** after Mihajlo Pupin (especially when used for the Heaviside condition), and the process of inserting them is sometimes called *pupinization*.

Applications



Schematic of a balanced loaded line. The capacitors are shown connected with dotted lines to indicate that the capacitance is actually distributed along the line rather than the discrete elements shown. The windings of the loading coil are wound such that the magnetic flux induced in the core is in the same direction for both windings.

Voice circuits

A common application of loading coils is to improve the voice-frequency amplitude response characteristics of the twisted balanced pairs in a telephone cable.

Loading coils inserted periodically in series with a pair of wires reduce the attenuation at the higher voice frequencies up to the cutoff frequency of the low-pass filter formed by the inductance of the coils (plus the distributed inductance of the wires) and the distributed capacitance between the wires. Above the cutoff frequency, attenuation increases rapidly. The shorter the interval between the coils, the higher the cut-off frequency.

It should be emphasised that the cutoff effect is an artifact of using lumped inductors. With loading methods using continuous distributed inductance there is no cutoff.

Without loading coils, the line response is dominated by the resistance and capacitance of the line with the attenuation gently increasing with frequency. With loading coils of exactly the right inductance, neither capacitance nor inductance dominate: the response is flat, waveforms are undistorted and the characteristic impedance is resistive up to the cutoff frequency. The coincidental formation of an audio frequency filter is also beneficial in that noise is reduced.

DSL

When loading coils are in place, signal attenuation remains low for signals within the passband of the transmission line but increases rapidly for frequencies above the audio cutoff frequency. Thus, if the pair is subsequently reused to support applications that require higher frequencies (such as analog or digital carrier systems or DSL), any loading coils that were present on the line must be removed or replaced with one which is transparent to DSL. Using coils with parallel capacitors will form a filter with the topology of an m-derived filter and a band of frequencies above the cut-off will also be passed.

If they are not removed, as when the subscriber is an extended distance (e.g. over 4 miles) from the Central Office, DSL can not be supported. This sometimes happens in dense, growing areas (subject to frequent national numbering scheme repartitioning) such as Southern California in the late 1990s and early 21st century.

Carrier systems

American early and middle 20th Century telephone cables had load coils at intervals of a mile (1.61 km), usually in coil cases holding many. The coils must be removed to pass high frequencies, but the coil cases provided convenient places for repeaters for digital T-carrier systems, which could carry 1.5 Mbit/s across that distance. Due to narrower streets and higher cost of copper, European cables had thinner wires and needed closer intervals. Intervals of a kilometer allowed European systems to carry 2 Mbit/s.

Radio antennae

A (mobile) radio antenna, shorter than a quarter wavelength for practical reasons, presents capacitive reactance to a transmission line. This can be canceled by inserting an

equal and opposite (inductive) reactance in series, by means of a loading coil typically at the base or center of the antenna. Consequently the antenna presents a resistance (desirable) to the transmission line.

Campbell equation

The Campbell equation is a relationship due to George Ashley Campbell for predicting the propagation constant of a loaded line. It is stated as;

$$\cosh(\gamma' d) = \cosh(\gamma d) + \frac{Z}{2Z_0}\sinh(\gamma d)$$

where,
γ is the propagation constant of the unloaded line
γ' is the propagation constant of the loaded line
d is the interval between coils on the loaded line
Z is the impedance of a loading coil and
Z_0 is the characteristic impedance of the unloaded line.

A more engineer friendly rule of thumb is that the approximate requirement for spacing loading coils is ten coils per wavelength of the maximum frequency being transmitted. This approximation can be arrived at by treating the loaded line as a constant k filter and applying image filter theory to it. From basic image filter theory the angular cutoff frequency and the characteristic impedance of a low-pass constant k filter are given by;

$$\omega_c = \frac{1}{\sqrt{L_{\frac{1}{2}} C_{\frac{1}{2}}}} \quad \text{and,} \quad Z_0 = \sqrt{\frac{L_{\frac{1}{2}}}{C_{\frac{1}{2}}}}$$

where $L_{\frac{1}{2}}$ and $C_{\frac{1}{2}}$ are the half section element values.

From these basic equations the necessary loading coil inductance and coil spacing can be found;

$$L = \frac{Z_0}{\omega_c} \quad \text{and,} \quad d = \frac{2}{\omega_c Z_0 C}$$

where C is the capacitance per unit length of the line.

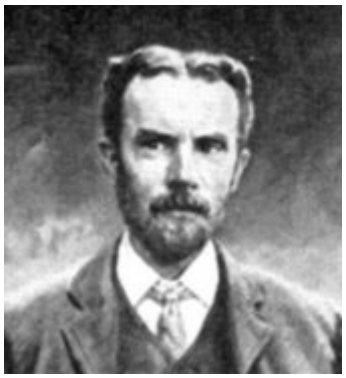
Expressing this in terms of number of coils per cutoff wavelength yields;

$$\frac{\lambda_c}{d} = \pi v Z_0 C$$

where *v* is the velocity of propagation of the cable in question.

History

Oliver Heaviside



Oliver Heaviside

The origin of the loading coil can be found in the work of Oliver Heaviside on the theory of transmission lines. Heaviside (1881) represented the line as a network of infinitesimally small circuit elements. By applying his operational calculus to the analysis of this network he discovered (1887) what has become known as the Heaviside condition. This is the condition that must be fulfilled in order for a transmission down a line to be free from distortion. The Heaviside condition is that the line series impedance, Z, must be proportional to the line shunt admittance, Y, at all frequencies. In terms of the primary line coefficients this is the condition;

$$\frac{R}{G} = \frac{L}{C}$$

where;
R is the series resistance of the line per unit length
L is the series self-inductance of the line per unit length
G is the shunt leakage conductance of the line insulator per unit length
C is the shunt capacitance between the line conductors per unit length

Heaviside was aware that this condition was not met in the practical telegraph cables in use in his day. In general, a real cable would have,

$$\frac{R}{G} \gg \frac{L}{C}$$

This is mainly due to the low value of leakage through the cable insulator, which is even more pronounced in modern cables which have better insulators than in Heaviside's day. In order to meet the condition, the choices are therefore to try and increase G or L or to decrease R or C. Decreasing R requires larger conductors. Copper was already in use in telegraph cables and this is the very best conductor available short of using silver.

Decreasing R means using more copper and a more expensive cable. Decreasing C would also mean a larger cable (although not necessarily more copper). Increasing G is highly undesirable, while it would reduce distortion, it would at the same time increase the signal loss. Heaviside considered, but rejected, this possibility which left him with the strategy of increasing L as the way to reduce distortion.

Heaviside immediately (1887) proposed several methods of increasing the inductance, including spacing the conductors further apart and loading the insulator with iron dust. Finally, Heaviside made the proposal (1893) to use discrete inductors at intervals along the line. However, he never succeeded in persuading the British GPO to take up the idea. Brittain attributes this to Heaviside's failure to provide engineering details on the size and spacing of the coils for particular cable parameters. Heaviside's eccentric character and setting himself apart from the establishment may also have played a part in their ignoring of him.

John Stone

John S. Stone worked for the American Telephone & Telegraph Company (AT&T) and was the first to attempt to apply Heaviside's ideas to real telecommunications. Stone's idea (1896) was to use a bimetallic iron-copper cable which he had patented. This cable of Stone's would increase the line inductance due to the iron content and had the potential to meet the Heaviside condition. However, Stone left the company in 1899 and the idea was never implemented.

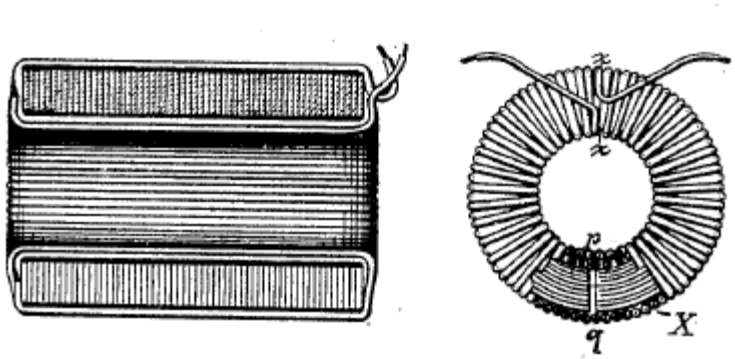
George Campbell

George Campbell was another AT&T engineer working for them in their Boston facility. Campbell was tasked with continuing the investigation into Stone's bimetallic cable, but soon abandoned this in favour of the loading coils idea. This was an independent discovery, Campbell being aware of Heaviside's work in discovering the Heaviside condition, but apparently not aware of Heaviside's suggestion of using loading coils to force a line to meet it. The motivation for the change of direction was Campbell's limited budget.

Campbell was struggling to set up a practical demonstration over a real telephone route with the budget he had been allocated. After considering that his artificial line simulators used lumped components rather than the distributed quantities found in a real line, he wondered if he could not insert the inductance with lumped components instead of using Stone's distributed line. When his calculations showed that the manholes on telephone routes were sufficiently close together to be able to insert the loading coils without the expense of either having to dig up the route or lay in new cables he changed to this new plan. The very first demonstration of loading coils on a telephone cable was on a 46-mile length of the so-called Pittsburgh cable (the test was actually in Boston, the cable had previously been used for testing in Pittsburgh) on September 6, 1899 carried out by Campbell himself and his assistant. The first telephone cable using loaded lines put into public service was between Jamaica Plain and West Newton in Boston on May 18, 1900.

Campbell's work on loading coils provided the theoretical basis for his subsequent work on filters which proved to be so important for frequency-division multiplexing. The cut-off phenomena of loading coils, an undesirable side-effect, can be exploited to produce a desirable filter frequency response.

Michael Pupin



Pupin's design of loading coil

Michael Pupin, inventor and Serbian immigrant to the USA, also played a part in the story of loading coils. Pupin filed a rival patent to the one of Campbell's. This patent of Pupin's dates from 1899. There is an earlier patent (1894, filed December 1893) which is sometimes cited as Pupin's loading coil patent but is, in fact, something different. The confusion is easy to understand, Pupin himself claims that he first thought of the idea of loading coils while climbing a mountain in 1894, although there is nothing from him published at that time.

Pupin's 1894 patent "loads" the line with capacitors rather than inductors, a scheme that has been criticised as being theoretically flawed and never put into practice. To add to the confusion, one variant of the capacitor scheme proposed by Pupin does indeed have coils. However, these are not intended to compensate the line in any way. They are there merely to restore DC continuity to the line so that it may be tested with regular equipment. Pupin states that the inductance is to be so large that it will block all AC signals above 50 Hz. Consequently, only the capacitor is adding any significant impedance to the line and "the coils will not exercise any material influence on the results before noted".

Legal battle

Heaviside never patented his idea; indeed, he took no commercial advantage of any of his work. Despite the legal disputes surrounding this invention, it is unquestionable that Campbell was the first to actually construct a telephone circuit using loading coils. There also can be little doubt that Heaviside was the first to publish and many would dispute Pupin's priority.

AT&T fought a legal battle with Pupin over his claim. Pupin was first to patent but Campbell had already conducted practical demonstrations before Pupin had even filed his patent (December 1899). Campbell's delay in filing was due to the slow internal machinations of AT&T.

However, AT&T foolishly deleted from Campbell's proposed patent application all the tables and graphs detailing the exact value of inductance that would be required before the patent was submitted. Since Pupin's patent contained a (less accurate) formula, AT&T was open to claims of incomplete disclosure. Fearing that there was a risk that the battle would end with the invention being declared unpatentable due to Heaviside's prior publication, they decided to desist from the challenge and buy an option on Pupin's patent for a yearly fee so that AT&T would control both patents. By January 1901 Pupin had been paid $200,000 and by 1917, when the AT&T monopoly ended and payments ceased, he had received a total of $455,000.

Benefit to AT&T

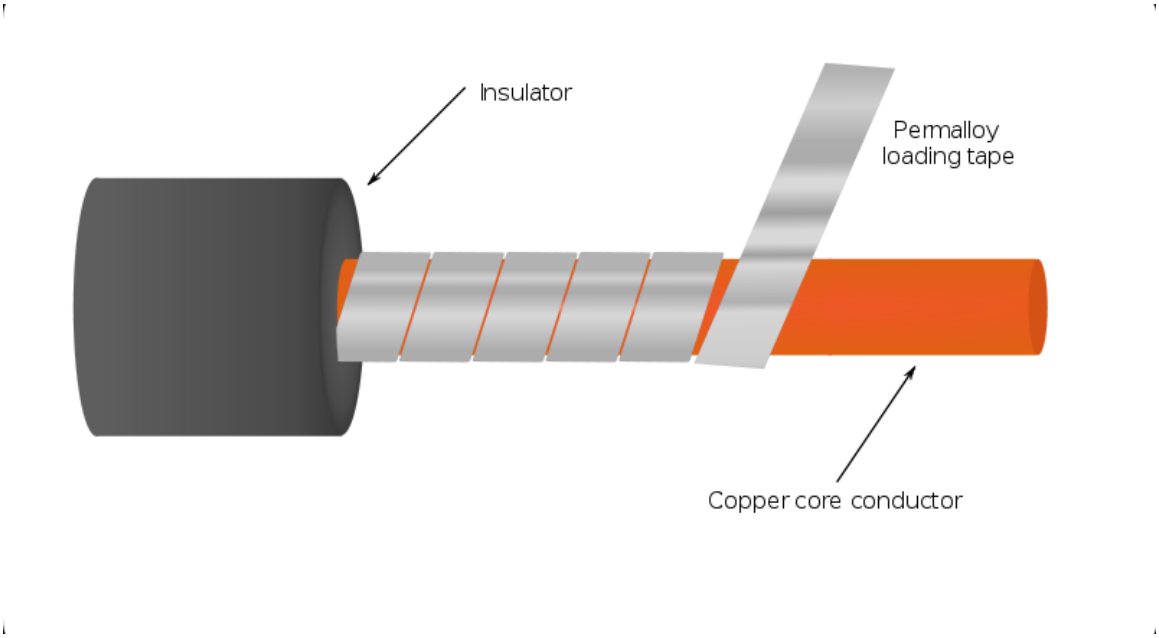
The invention was of enormous value to AT&T. Telephone cables could now be used to twice the distance previously possible, or alternatively, a cable of half the previous quality (and cost) could be used over the same distance. When considering whether to allow Campbell to go ahead with the demonstration, their engineers had estimated that they stood to save $700,000 in new installation costs in New York and New Jersey alone. It has been estimated that AT&T saved $100 million in the first quarter of the 20th century. Heaviside, who began it all, came away with nothing. He was offered a token payment but would not accept, wanting the credit for his work. He remarked ironically that if his prior publication had been admitted it would "interfere . . . with the flow of dollars in the proper direction . . .".

Krarup cable

Loading coils were not without their problems. For submarine cables where they were of most benefit, they were difficult to lay. The cable needed to be heavier and both this and the discontinuities in the profile where the coils occurred caused stresses in the cable during laying. Without great care, the cable might part and would be enormously expensive, possibly impossible, to fix. A second problem was that the material science of the time had difficulties sealing the joint between coil and cable against ingress of seawater. When this occurred, of course, the cable was ruined.

A Danish engineer, Carl Emil Krarup, invented a form of continuously loaded cable which solved these problems and the cable is named for him. Krarup cable has iron wires continuously wound around the central copper conductor with adjacent turns in contact with each other. This cable was the first use of continuous loading on any telecommunication cable. In 1902 Krarup both wrote his paper on this subject and saw the installation of the first cable between Helsingør (Denmark) and Helsingborg (Sweden).

Permalloy cable

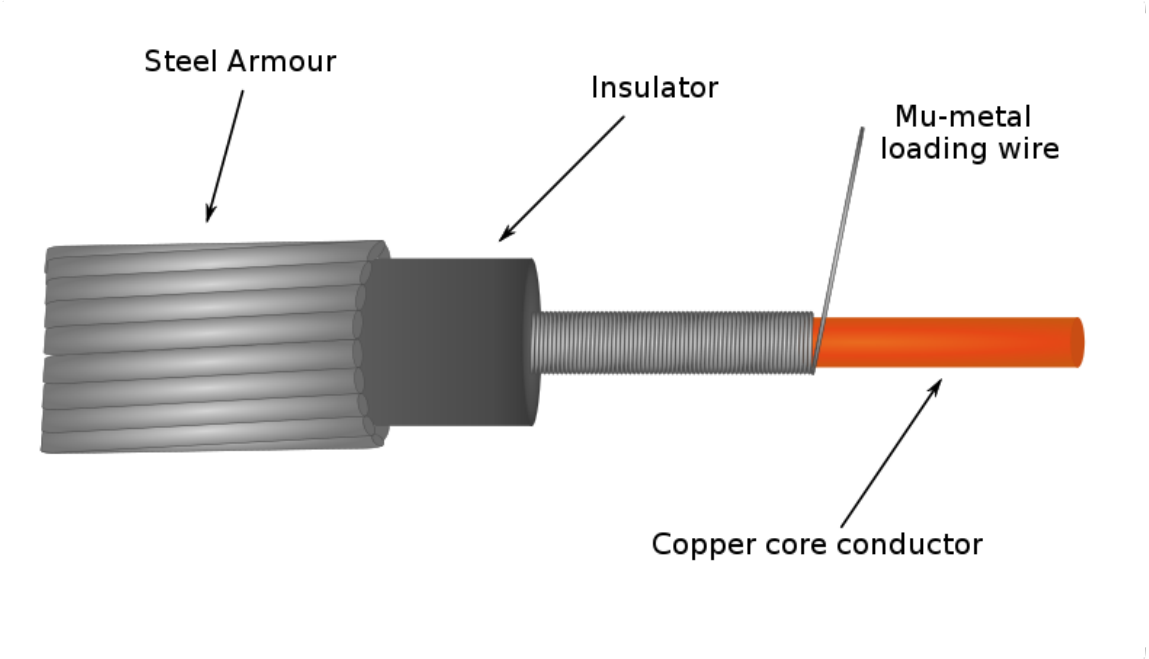


Permalloy cable construction

Even though Krarup cable added inductance to the line, it did not add enough to meet the Heaviside condition. AT&T searched for a better material with higher magnetic permeability. In 1914 Gustav Elmen discovered permalloy, a magnetic nickel-iron annealed alloy. Oliver E. Buckley, along with his colleagues at Bell Labs, H. D. Arnold and Elmen, c.1915 proposed a method of constructing submarine cable using permalloy tape wrapped around the copper conductors. This construction greatly improved the performance of the cable.

The cable was tested in a trial in Bermuda in 1923. The first permalloy cable to be put into service was between New York and Horta (Azores) in September 1924.

Mu-metal cable



Mu-metal cable construction

Mu-metal has similar magnetic properties to permalloy but the addition of copper to the alloy increases the ductility and allows the metal to be drawn into wire. Mu-metal cable is easier to construct than permalloy cable, the mu-metal being wound around the core copper conductor in much the same way as the iron wire in Krarup cable. A further advantage with mu-metal cable is that the construction lends itself to a variable loading profile whereby the loading is tapered towards the ends.

Mu-metal was invented (1923) by The Telegraph Construction and Maintenance Company Ltd., London, who made the cable, initially, for the Western Union Telegraph Co. Western Union were in competition with AT&T and the Western Electric Company who were using permalloy (the patent for permalloy was held by Western Electric).

Current practice

Loaded cable is no longer a useful technology for submarine communication cables, having first been superseded by co-axial cable using electrically powered in-line repeaters and then by fibre-optic cable. Manufacture of loaded cable declined in the 1930s and was then superseded by other technologies post-war. Loading coils can still be found in some telephone landlines today but new installations would use more modern technology.

Chapter 13

Low Tension Coil and Ignition Coil

Low Tension Coil

A **low tension coil** is an electrical device used to create a spark across the points of an ignitor on early 1900s gasoline engines, generally flywheel engines, hit and miss engines, and other engines of that era. In modern electronic terms, a low tension coil is simply a large inductor, an electrical device that stores energy for brief periods. The term "low tension" was the terminology of the day used to differentiate it from the term "high tension", and generally meant "low voltage" (tension) as opposed to "high voltage" (tension). High tension coils produce high voltages, generally meant to produce a spark across a spark plug.

Construction

A typical low tension coil (reproduction) used in the ignition system of an ignitor fired engine

A low tension coil consists of an iron core that has wire wrapped around it. The size of the iron core, the number of turns of wire, and the size of the wire determine the electrical properties of the coil. Terminals are provided to connect the coil into the ignition circuit. The wood ends are provided for mechanical stability, to provide for the terminal placement and to hold the wire on the coil over time. A cloth or tape covering is provided to protect the windings.

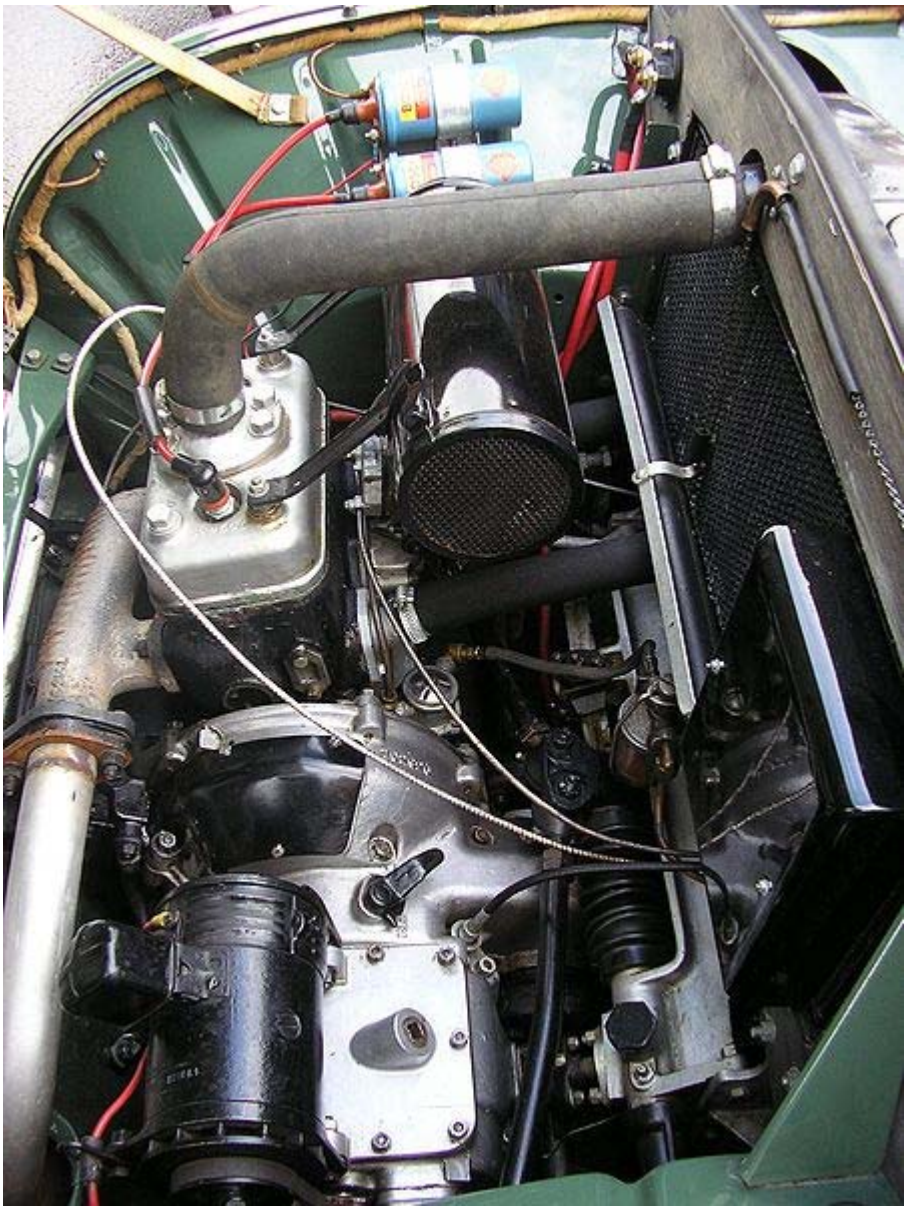
Use

A low tension coil for engine ignition is used in conjunction with a battery and an ignitor. The ignitor is no more than a set of contacts that reside inside the combustion chamber of the engine. A series circuit is made between the three components: battery connects to coil, second terminal on the coil connects to the ignitor, second terminal on the ignitor (usually connected electrically and mechanically to the engine itself) connects to the second terminal of the battery.

Theory of Operation

An inductor attempts to maintain a constant current flow through it. If the current in the circuit in which the inductor is connected goes down for some reason, the voltage developed across the inductor will go up in an attempt to try to maintain the constant current. When used with an ignitor ignition system in an engine, there is current flow when the ignitor contacts are closed. When the ignitor contacts are opened by the mechanical parts of the engine, current flow is interrupted. Because the low tension coil wants to maintain that current flow, the voltage across the coil rapidly goes up (usually to several hundred volts). When the voltage rises high enough, the voltage will jump the still very small gap of the ignitor contacts and create a spark which ignites the fuel mixture in the engine. Since there is a finite amount of energy stored in the coil, as soon as the spark jumps the gap the voltage across the coil collapses. As soon as the engine rotates and the ignitor contacts again close, current starts to flow through the coil and it again stores energy for the next cycle. A good description and moving gif of a low tension coil in operation can be found on Harrys Old Engines Ignition Page

Ignition Coil



Dual ignition coils (top of picture) on a Saab 92.

Bosch ignition coil

An **ignition coil** (also called a **spark coil**) is an induction coil in an automobile's ignition system which transforms the battery's 12 volts (6 volts in some older vehicles) to the thousands of volts (20 to 30 thousand volts or more) needed to spark the spark plugs. Some coils have an internal resistor to reduce the voltage and some rely on a resistor wire or an external resistor to reduce the voltage from the cars 12 volt wiring flowing into the coil. The wire which goes from the ignition coil to the distributor and the wires which go from the distributor to each of the spark plugs are called spark plug wires or high tension leads.

This specific form of the autotransformer, together with the contact breaker and a capacitor (still referred to in automobile parlance by its old name of "condensor"), converts low voltage from a battery into the high voltage required by spark plugs in an internal combustion engine.

Basic principles

When the contact breaker closes, it allows a current from the battery to build up in the primary winding of the ignition coil. (The current does not flow instantly because of the inductance of the coil.) Once the current has built up to its full level, the contact breaker opens. Since it has a capacitor connected across it, the primary winding and the capacitor form a tuned circuit, and as the stored energy oscillates between the inductor formed by the coil and the capacitor, the changing magnetic field in the core of the coil induces a much larger voltage in the secondary of the coil. More modern electronic ignition systems operate on exactly the same principle, but some rely on charging the capacitor to around 400 volts rather than charging the inductance of the coil.

Use in cars

In older vehicles a single (large) coil would serve all the spark plugs via the ignition distributor. Notable exceptions are the Saab 92, and the Wartburg 353 which have one ignition coil per cylinder.

Modern ignition systems

In modern systems, the distributor is omitted and ignition is instead electronically controlled. Much smaller coils are used with one coil for each spark plug or one coil serving two spark plugs (for example two coils in a four-cylinder engine, or three coils in a six-cylinder engine). A large ignition coil puts out about 20 kV, and a small one such as from a lawn mower puts out about 15 kV. These coils may be remotely mounted or they may be placed on top of the spark plug *(coil-on-plug* or *Direct Ignition)*. Where one coil serves two spark plugs (in two cylinders), it is through the "waste spark" system. In this arrangement the coil generates two sparks per cycle to both cylinders. The fuel in the cylinder that is nearing the end of its compression stroke is ignited, whereas the spark in its companion that is nearing the end of its exhaust stroke has no effect. The wasted spark system is more reliable than a single coil system with a distributor and cheaper than coil-on-plug.

Where coils are individually applied per cylinder, they may all be contained in a single molded block with multiple high-tension terminals. This is commonly called a coil-pack.

A bad coil pack may cause a slight or not so slight misfire, bad fuel economy, loss in power, and in some rare cases loss of braking performance and power steering problems.

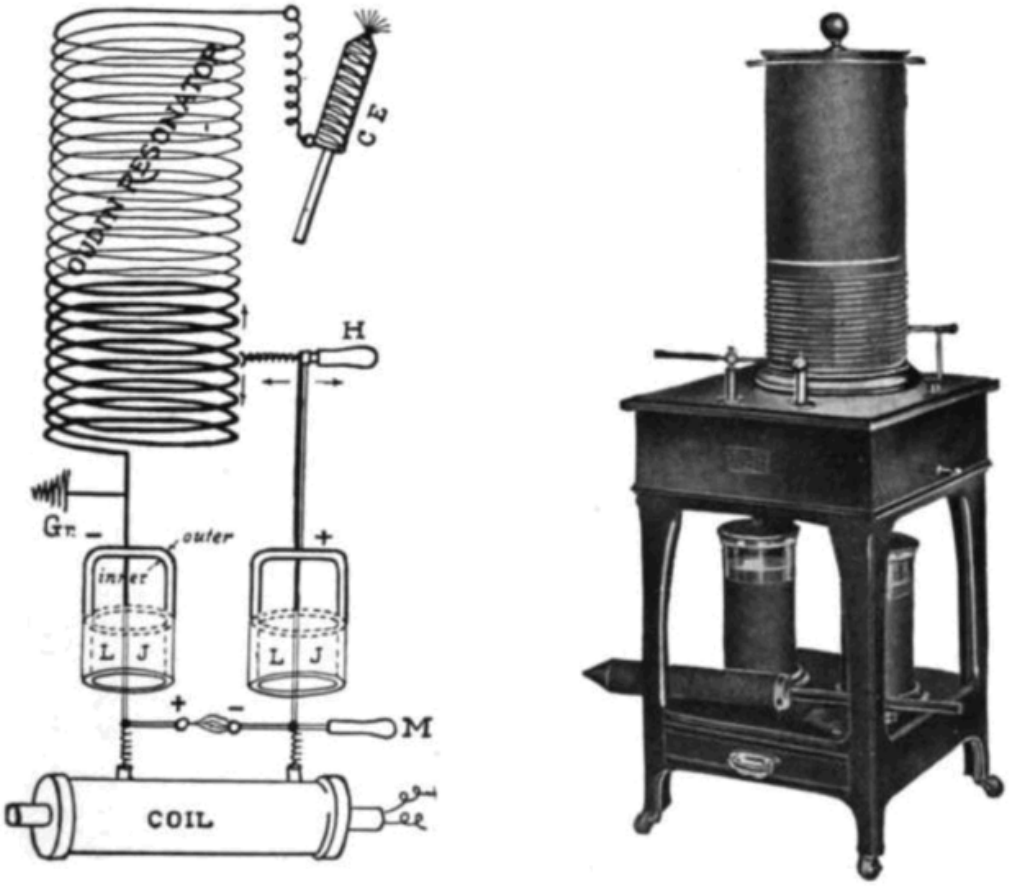
Tesla coil

The disruptive discharge Tesla coil is an early predecessor of the "ignition coil" in the ignition system as was invented in 1891. Tesla also gained U.S. Patent 609,250, "*Electrical Igniter for Gas Engines*", on August 16, 1898. The principles of the modern ignition coil used today is based on this design. A. Atwater Kent, in 1921, patented the modern form of the ignition coil.

Chapter 14

Oudin Coil, Polyphase Coil and Maxwell Coil

Oudin Coil



Oudin coil used for medical 'electrotherapy', 1907.

An **Oudin coil**, also called an **Oudin oscillator** or **Oudin resonator**, is a disruptive discharge coil wired as a transformer designed to produce high voltage arcs and discharges, similar to a Tesla coil. It was invented by French physician Paul Marie Oudin and physicist Jacques d'Arsonval around 1899.

The device is a high frequency current generator which uses the principles of resonant electrical circuits. It produces an antinode of high potential. The high-voltage, self-regenerative resonant transformer has the bottom ends of the primary and secondary coils connected together and to ground.

Oudin coils generate high voltages at high frequency, but produce lower currents than other disruptive discharge coils (such as the later version of the Tesla coil). The Oudin coil is modified for greater safety.

Polyphase Coil

Polyphase coils are electrical coils (phases) connected together in a polyphase system such as a generator or motor. In modern systems, the number of phases is usually three or a multiple of three. Each phase carries a sinusoidal alternating current whose phase is delayed relative to one of its neighbours and advanced relative to its other neighbour. The phase currents are separated in time evenly within each period of the alternating current. For example, in a three-phase system, the phases are separated from each other by one-third of the period.

Coil construction

Like all coils used in electrical machinery, polyphase coils (made from insulated conducting wire) are wound around ferromagnetic armatures with radial projections and maximum core-surface exposure to the magnetic field.

The windings are physically separated around the circumference of an electrical machine. The result of such an arrangement is a rotating magnetic field that is used to convert electrical power to rotary mechanical work, or vice versa.

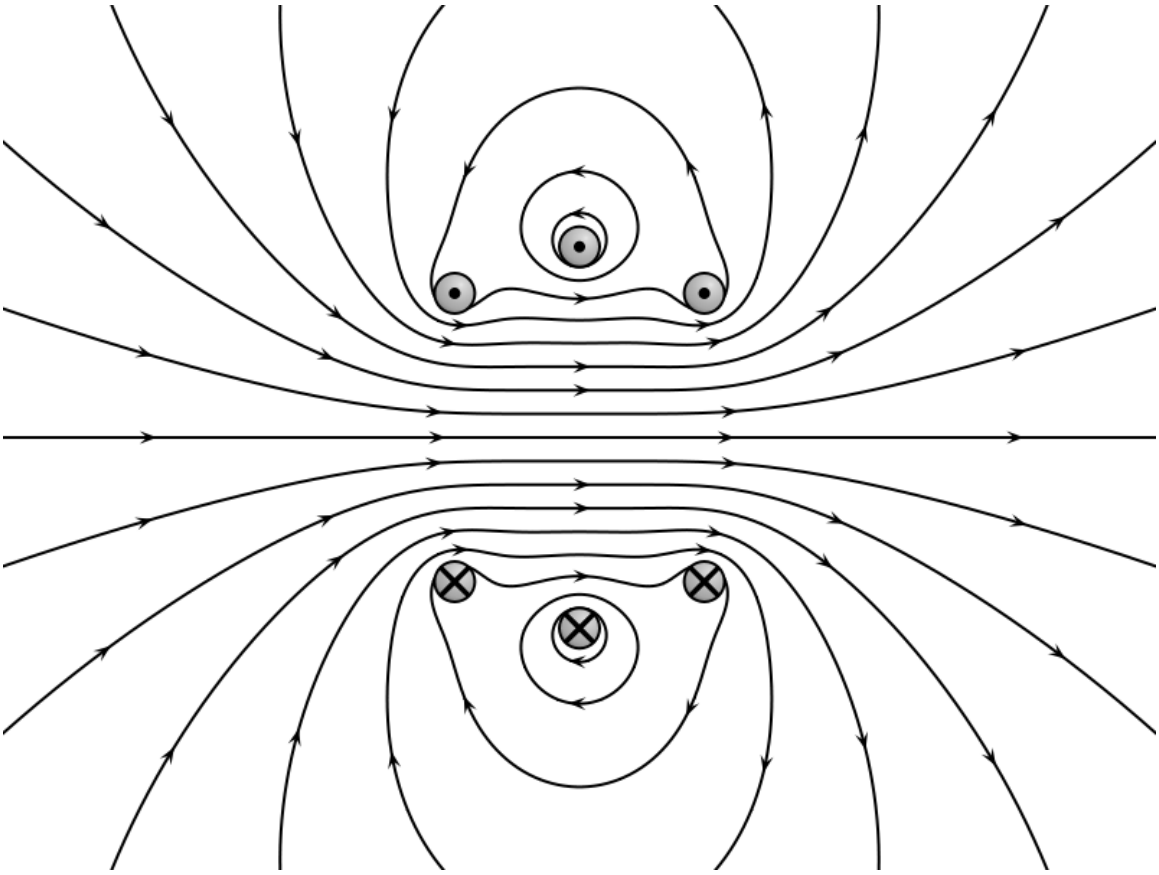
Polyphase motors and generators

Compared to single-phase motors and generators, polyphase motors are simpler, because they do not require external circuitry (using capacitors and inductors) to produce a starting torque. Polyphase machines can deliver constant power over each period of the alternating current, eliminating the pulsations found in a single-phase machine as the current passes through zero amplitude.

History

The use of polyphase coils in electrical power systems was pioneered by the engineers Nikola Tesla, Galileo Ferraris, and Michail Dolivo-Dobrovolsky.

Maxwell Coil



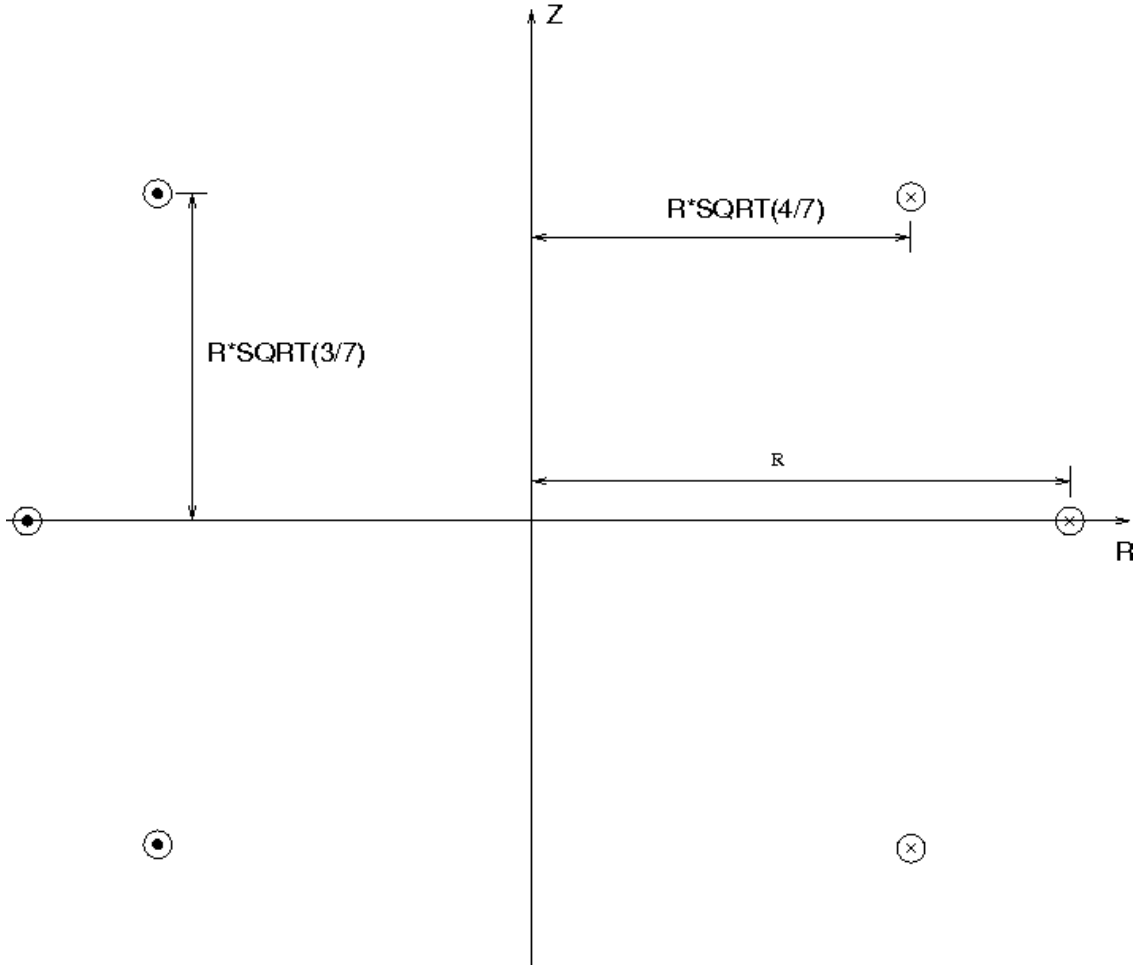
Magnetic field around a Maxwell coil

A **Maxwell coil** is a device for producing a large volume of almost constant (or constant-gradient) magnetic field.

Description

A constant-field Maxwell coil set consists of three coils oriented on the surface of a virtual sphere. According to Maxwell's original 1873 design each of the outer coils

should be of radius $\sqrt{\frac{4}{7}}R$ and distance $\sqrt{\frac{3}{7}}R$ from the plane of the central coil of radius *R*. The number of ampere-turns of each of the smaller coils should equal exactly $\frac{49}{64}$ of the middle coil.This arrangement removes variations in magnetic field, up to its 6th-order derivative with respect to position, near the centre of the virtual sphere.

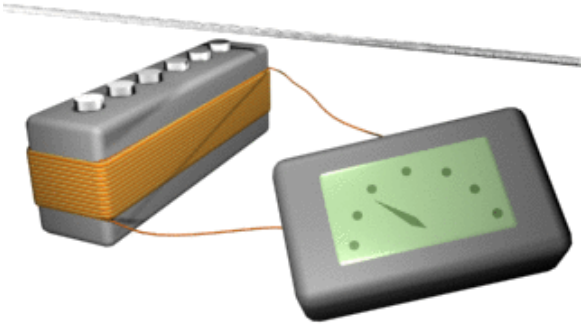


A gradient-field Maxwell coil is essentially the same geometry of the 3-coil configuration above, with the central coil removed to leave only the smaller two coils . If the current in one of the coils is reversed, a uniform-gradient magnetic field is produced near the centre of the two coils.

Chapter 15

Single Coil

This image shows three single coil pickups on a Stratocaster guitar. Left to right: bridge, middle and neck pickups.

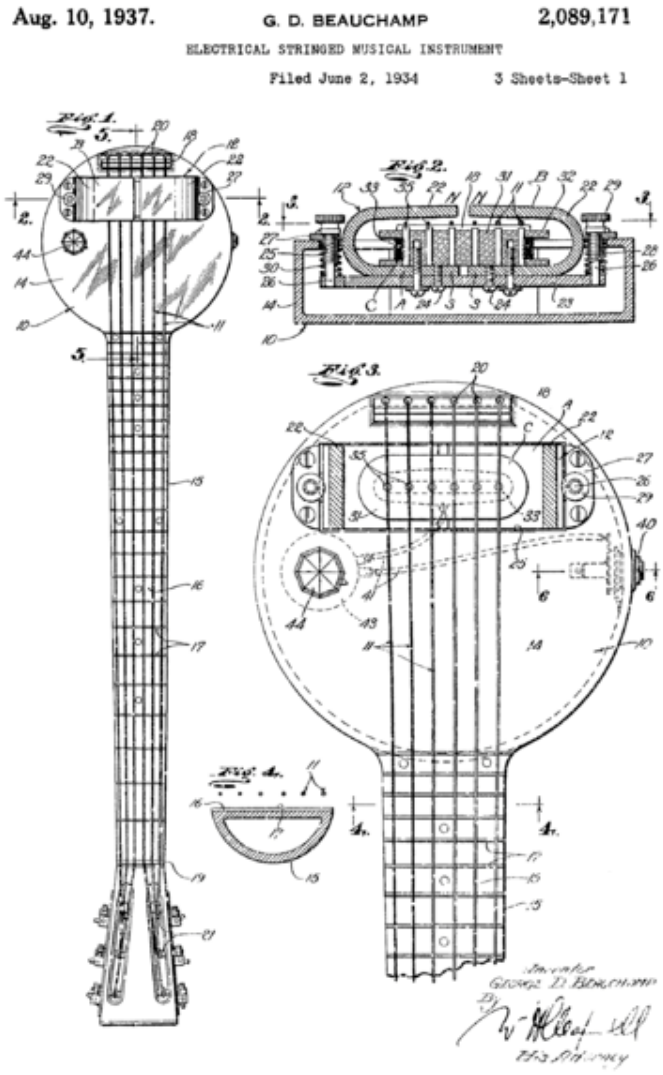


String effect on a single coil (electric guitar). The coil is connected to a multimeter that indicates the voltage changes when the string moves. This signal is normally sent to the amplifier.

A **single coil pickup** is a type of magnetic transducer, or pickup, for the electric guitar and the electric bass. It electromagnetically converts the vibration of the strings to an electric signal. Single coil pickups are one of the two most popular designs, along with dual-coil or "humbucking" pickups.

History

Beauchamp


Aug. 10, 1937. G. D. BEAUCHAMP 2,089,171

ELECTRICAL STRINGED MUSICAL INSTRUMENT

Filed June 2, 1934 3 Sheets-Sheet 1

Sketch of Rickenbacker "frying pan" lap steel guitar from 1934 patent application.

In the mid 1920s George Beauchamp, a Los Angeles, California guitarist, began experimentation with electric amplification of the guitar. Originally using a phonograph pickup assembly, Beauchamp began testing many different combinations of coils and magnets hoping to create the first electromagnetic guitar pickup. He wound his earliest

coils using a motor out of a washing machine, later on switching to a sewing machine motor, and eventually using single coiled magnets.

Beauchamp was backed in his efforts by Adolph Rickenbacker, an engineer and wealthy owner of a successful tool and die business. Beauchamp eventually produced the first successful single coil pickup. The pickup consisted of two massive "U" shaped magnets and one coil and was known as the "horseshoe pickup". The two horseshoe-shaped magnets surrounded the strings that passed over a single core plate (or blade) in the center of the coil.

Beauchamp outfitted the pickup in a custom built lap slide guitar. The production model based on this prototype became the Hawaiian Electro lap steel guitar, nicknamed the "Frying Pan" for its round, flat body.

In 1931 Beauchamp founded the Ro-Pat-In Company with Rickenbacker and his associates. Ro-Pat-In eventually became The Electro String Instrument Corporation and subsequently the Rickenbacker International Corporation. The company introduced its first "Electro-String Instruments" to the public in 1932.

Gibson

The Gibson Guitar Corporation introduced the "bar pickup" in 1935 for its new line of Hawaiian lap steel guitars. The pickup's basic construction is that of a metal blade inserted through the coil as a shared pole piece for all the strings. A pair of large flat magnets were fastened below the coil assembly.

In 1936 Gibson introduced the ES-150, its first electric Spanish styled guitar. The ES-150 was outfitted with the bar pickup. Jazz guitar innovator, Charlie Christian, began playing an ES-150 in the late 1930s with the Benny Goodman Orchestra. This caused the popularity of the electrified guitar to soar. Due to Christian’s close association with the ES-150 it began being referred to as the “Charlie Christian Model” and Gibson’s now famous bar pickup as the “Charlie Christian pickup” or “CC unit”.

Sound

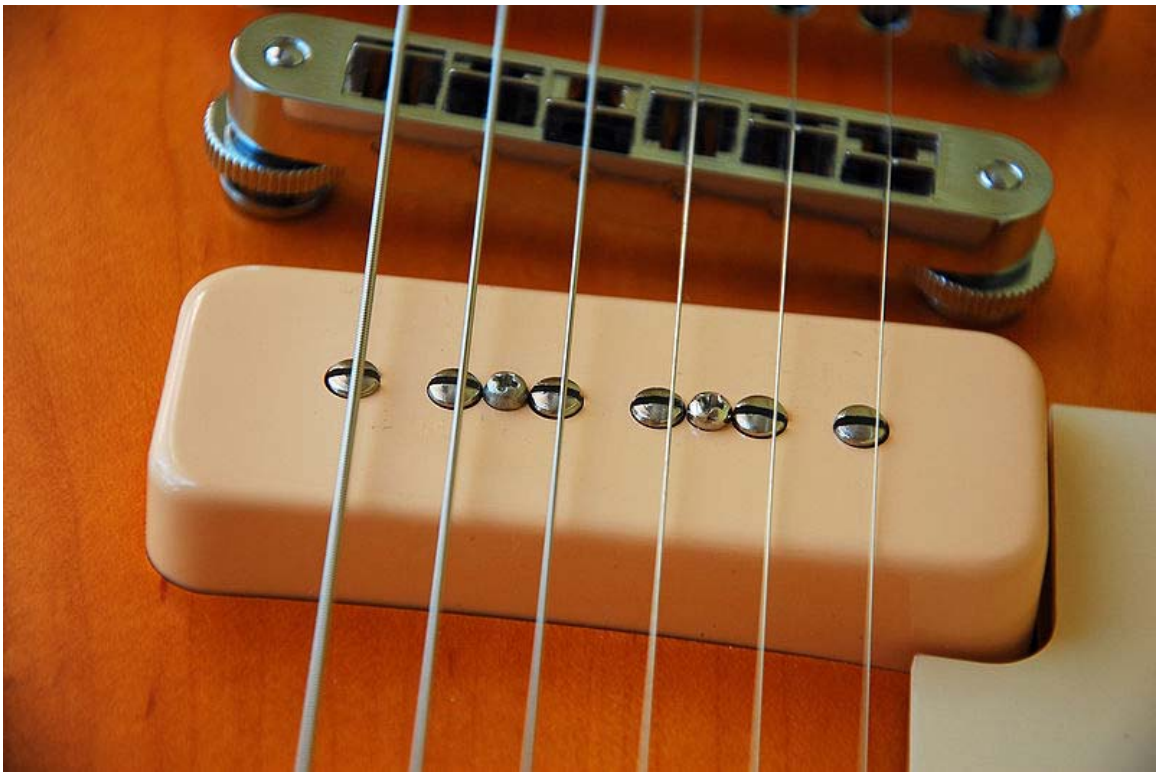
The sound of a single coil pickup can range from the strong, fat midrange sound of the Gibson P-90 to the bright and clear Fender Telecaster single-coil tone.

Common designs

Gibson P-90

The P-90 is a single-coil pickup designed by the Gibson Guitar Corporation. These pickups have a large, flat coil with adjustable steel screws as pole pieces, and a pair of flat alnico bar magnets lying under the coil bobbin. The adjustable pole pieces pick up the magnetism from the magnets. Moving the screw closer or further away from the magnet

determines signal strength, thus tone as well. There are two variations of P-90 pickup that differ mainly by mounting options:



Gibson P-90 soap bar

- **Soap bar** casing has true rectangular shape and the mounting screws are contained within the coil perimeter, positioned between the pole pieces, between strings 2-3 and 4-5, thus creating irregular and somewhat unusual pattern. Occasionally, they are mistaken for pole pieces; thus, the P-90 is sometimes erroneously said to have eight pole pieces. The "soap bar" nickname most probably comes from its predominantly rectangular shape and proportions resembling a bar of soap, and the fact that the first P-90s on the original Gibson Les Paul Model of 1952 were white.

P90 dog ear

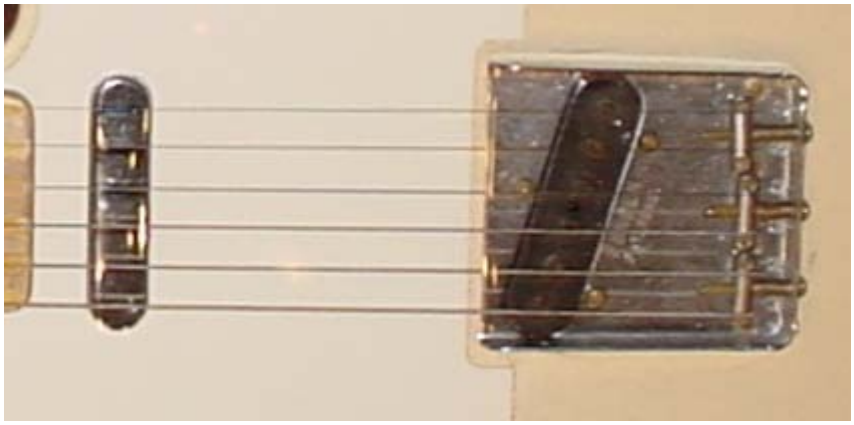
- **Dog ear** is a casing type with extensions at both sides of pickup that somewhat resemble dog's ears. These are extensions of the predominantly rectangular cover that encompass the outlying mounting screws. Dog-ear P-90 pickups were commonly mounted on Gibson's hollowbody guitars like the ES-330 and occasionally on solid body models like the Les Paul Junior. The same pickups were also available on Epiphone models (since Gibson was building Epiphone guitars in the 1950s) and the design is best remembered for its appearance on the hollow body Epiphone Casino of the mid to late 1960s.

The sound of a P-90 is somewhat brighter and more transparent than Gibson's later humbucker pickup, and every bit as crisp and snappy as Fender's single-coil pickups despite its high output and big sound.

Despite its tonal qualities the P-90 fell out of favor with Gibson in the early 1950s as a consequence of guitar players complaining about the amount of hum (noise) it put out. Gibson employee Seth Lover solved the hum problem by designing a hum-canceling pickup known as a humbucker, it was supposed to sound like a P-90 but in fact has quite a different sound. It nevertheless became Gibson's mainstay pickup from that point on. The P-90 likely did not become as popular for that reason, although many guitarists still prefer the tone of the P-90.

The hum problem proved extremely difficult to solve and despite numerous attempts by Gibson with their P-100, and the larger aftermarket pickup manufacturers with their stacked and sidewinders noiseless designs, hum-canceling P-90 pickups lost most of their favored tonal characteristics and generally did not gain acceptance among guitar players.

Telecaster design



Two pickups on a Telecaster

The Fender Telecaster features two single coils. The neck pickup produces a mellower sound, while the bridge pickup produces an extremely twangy, sharp tone with exaggerated treble response, because the bridge pickup is mounted on a steel plate. These design elements allow musicians to emulate steel guitar sounds, making it particularly appropriate for country music.

Pickups are selected with a three-position switch, and two wiring schemes exist:

- **Vintage**: 1) neck pickup with treble cutoff for a bassier sound; 2) neck pickup only; 3) bridge pickup only.
- **Modern**: 1) neck pickup only, with no treble cutoff; 2) neck and bridge; 3) bridge pickup only.

The Fender Esquire has a variation to the Vintage wiring scheme by using the scheme on a single pickup. This gives a treble cutoff in the first position, normal in the middle position, and a tone control cutoff in the third position.

Stratocaster design

Stratocaster pickups, viewed along the neck profile. Note that the poles are of different heights.

The traditional Stratocaster design guitar features three single coils. The guitarist can control which pickup or combination of pickups are selected with a lever switch. The pickup positions are usually referred to as the bridge, middle and neck pickups based on their proximity to those parts of the instrument.

Pickup position, number of coil winds, type of magnet wire, magnets and other factors shape the sound. A given pickup in the neck position will give louder, mellower and warmer sound, while an identical pickup in the bridge position will have lower output and produce a brighter, sharper sound. The reason the neck pickup has the most output is that the string's vibration has a higher amplitude at the neck position, being near the middle of the string length. Some manufacturers overwind the bridge pickup for more output to compensate for this difference.

The magnet poles have different heights. This is called a **magnet stagger** and is done to compensate for the different outputs of the string for two reasons. The first reason is that the fretboard has a radius (also called *camber*) of between 7 and 12 inches usually. Naturally the strings will follow the radius of the fretboard and so must the top surface of

the magnets, generally speaking. The second reason is that some strings have naturally higher output, the plain or non-wound G-string being the most significant and this calls for the corresponding magnet to be further compensated, resulting in an apparent odd looking stagger. Fender Strat pickups generally follow the traditional design and have the G string's magnet pole piece as tall as the D-string's, but this causes the G-string of modern string sets to be excessively loud and dominate all the other strings. This comes about because Stratocaster pickups were designed in the 1950s when string sets came with a wound G-string, but modern rock and blues players found it difficult to stretch or bend wound G-strings across the fretboard because of their inherently higher tension. In the 1970s, string manufacturers responded and introduced the now standard non-wound G-string which has lower tension and can be stretched more easily, but which produces much higher output. In order for the G-string to have the same output the corresponding magnet pole should have the greatest gap between the string and the magnet pole piece, thus different strings have magnets with differently compensated heights.

The first Stratocasters had a three-way pickup selector switch, selecting either the neck, middle or bridge pickup. Innovative guitarists found they could get an interesting sound by carefully positioning the selector switch lever between detented positions, where any two adjacent pickups would be on simultaneously. Some players wedged a plectrum between the pickguard and the selector switch to lock it in these positions. Later on, Fender introduced the now standard five-way selector switch, which uses additional detents between the original three positions to allow the combinations of any two adjacent pickups.

Modern Stratocasters have five-position pickup selector switch. Positions 1, 3 and 5 activate only one pickup (bridge, middle or neck respectively), while positions 2 and 4 activate a combination of two pickups (bridge and middle, or middle and neck, respectively). Some pickup sets have a reverse wound and reverse polarity middle pickup that when in combination with the normal bridge or neck pickups will cancel electromagnetic interference (noise/hum) which single coil pickups suffer badly from. The sonic effect of positions 2 and 4 is sometimes referred to as a "quack" or "notch positions", and some guitar notation includes directions to use these pickup combinations. One example is "Sultans of Swing" by Dire Straits which is played in position 2 (bridge and middle).

Noise problems

Fender Stratocaster and Telecaster pickups, being of the single-coil type, output a type of noise known as mains hum or 50Hz / 60Hz hum. Mains hum has its origin in wiring of a building and electrical apparatus/appliances such as transformers, electric motors and lighting. Hum is undesirable because it pollutes the musical notes being played on the instrument with its own sound of fixed unchanging frequency or pitch (usually 50 or 60 hertz) which is discordant with the musical sounds. To address this undesirable situation various attempts to eliminate mains hum signal from Fender single-coil pickups were made dating back to the early 1970s. DiMarzio, Seymour Duncan and EMG manufactured what are commonly known as stacked single coils which canceled mains

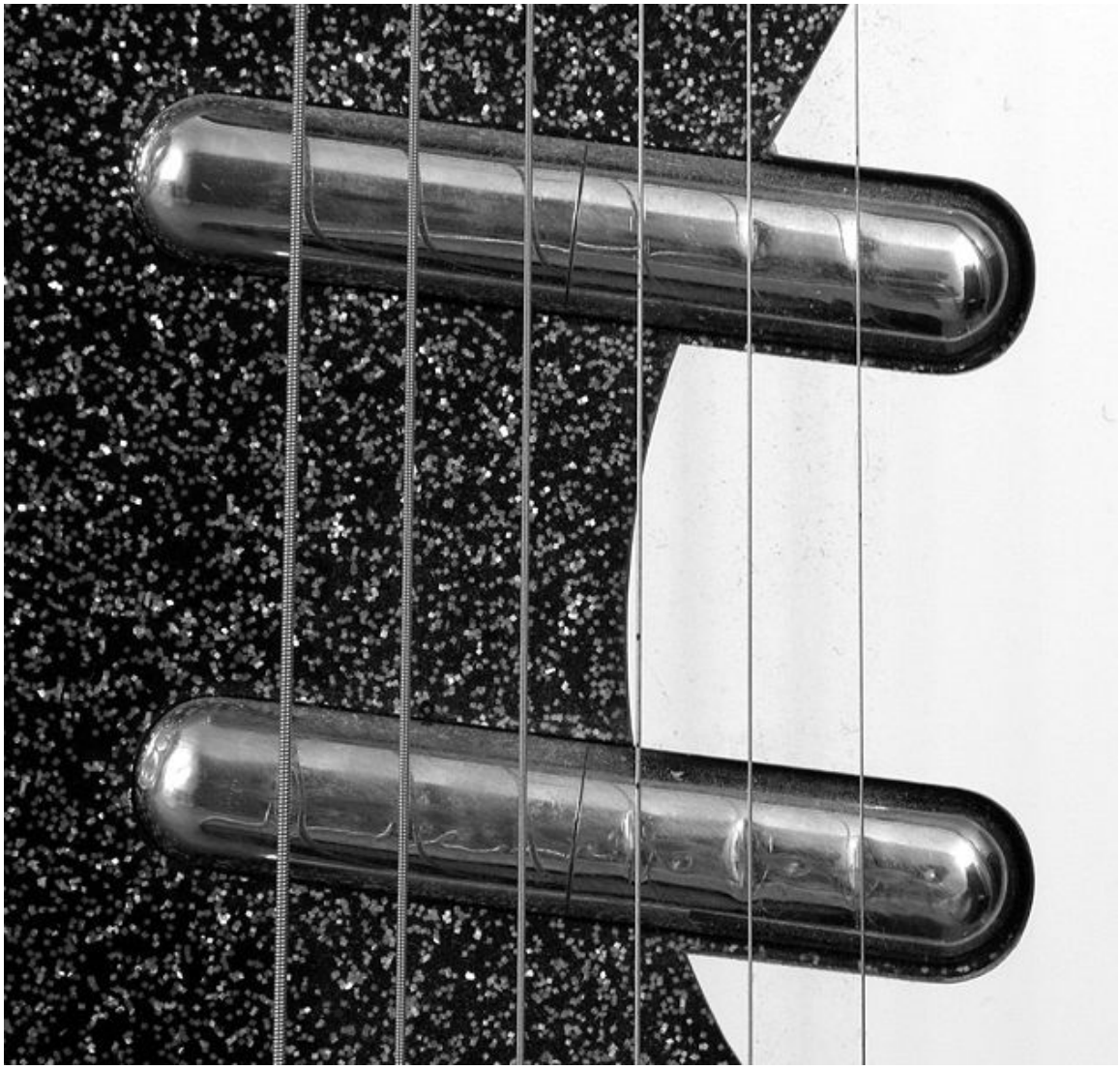
hum. Unfortunately these stacks also canceled string signal and had a detrimental effect on sound quality. EMG used active circuitry within the pickup to compensate for the losses caused by stacked coils by boosting and reshaping the damaged sound but this required an on-board battery with its attendant problems. The resultant sound was not authentic Fender trade mark sound but EMG pickups became popular for their own sound.

Actodyne General manufactured a low-noise design of single-coil pickup known as Lace Sensors, Don Lace being the inventor. The Lace Sensor pickup had a rubberized particle magnet and used ferrous shielding to reduce hum. Being the best at the time, Fender installed Lace Sensors on the Strat Plus model for many years as a solution to the mains hum problem. However the Lace Sensor was a stopgap solution because the sound was not authentic Fender trademark sound. Fender purists wanted the genuine sound of the original Fender pickups with Alnico rod magnets and Fender eventually discontinued Lace Sensors as their mainstay solution to mains hum circa 1998. Lace Sensors continue to be used by many guitar players regardless.

The search for an acceptable solution to mains hum gained new impetus around 1995 as guitar players became increasingly intolerant of degraded stacked single-coil sound. Fender was researching new techniques to solve the loss of tone around that time and eventually came out with their Vintage Noiseless design circa 1998.

Notable single-coil pickups

There are several well-known single-coil pickups that have a distinctive sound:



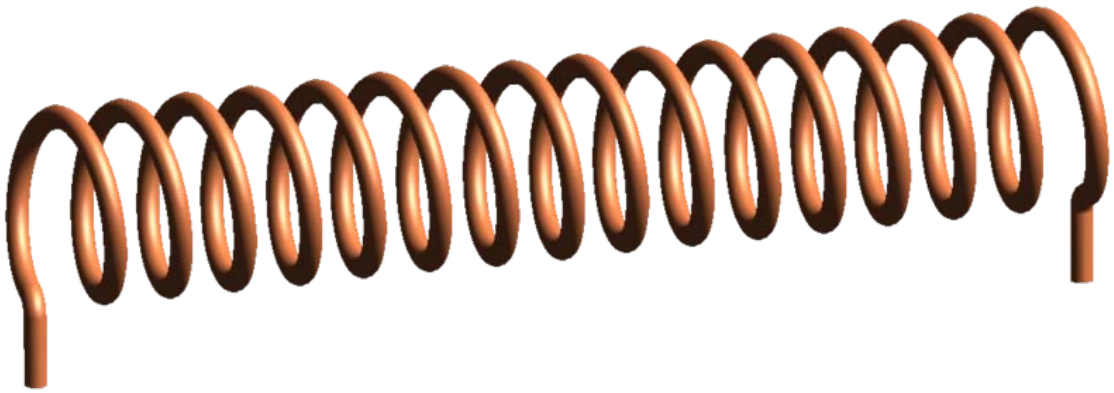
"Lipstick"-style single coil pickups on a Danelectro guitar

- Rickenbacker pickups (including the original 1930s "horseshoe" pickup as used in lap steel and solidbody upright basses, and later 6 string electric guitars, pedal steels, and electric bass guitars; also the "Toaster" and "Hi-Gain")
- Gibson bar pickup (1935) — later called the Charlie Christian pickup (1938)
- Gibson P-90 (1946)
- Fender Telecaster, Stratocaster, Jazzmaster, Jaguar, and other pickups
- Danelectro Lipstick
- Gretsch pickups (including the "HiLoTron")

- DeArmond pickups (found on various 50s and 60s guitars by various manufacturers including Gretsch, Guild, Epiphone, Martin, Kustom, Harmony, Regal, Premier, and others, but produced by the Rowe - DeArmond company of Toledo, Ohio; the trade name is now owned by Fender; single coil models including the 200 aka Dynasonic, 2K, and 2000, "mustache", various "gold foil" types, and many clip on, rail, or screw mount pickups designed for acoustic guitars and other instruments). The Fender "Tele-Sonic" featured large DeArmond single coils.
- Valco single coil pickups by Ralph Keller (1954) can be found in Airline, Supro, National, English Electronics, and a few Gretsch models of guitar from the 50's, 60's, and 70's. The majority of these pickups maintain the physical appearance of a larger, humbucking pickup. Early variations on the over-strings horseshoe pickup can be found on a number of similarly branded lapsteel guitars.
- Epiphone "New York" pickups
- Lace Sensor pickups (1987)

Chapter 16

Solenoid



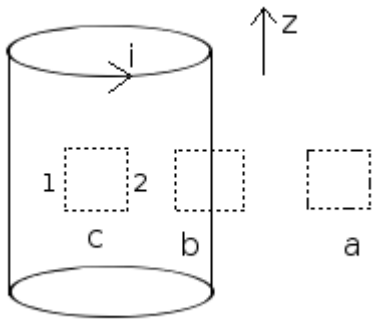
Solenoid

A **solenoid** is a coil wound into a tightly packed helix. In physics, the term **solenoid** refers to a long, thin loop of wire, often wrapped around a metallic core, which produces a magnetic field when an electric current is passed through it. Solenoids are important because they can create controlled magnetic fields and can be used as electromagnets. The term *solenoid* refers specifically to a magnet designed to produce a uniform magnetic field in a volume of space (where some experiment might be carried out).

In engineering, the term **solenoid** may also refer to a variety of transducer devices that convert energy into linear motion. The term is also often used to refer to a solenoid valve, which is an integrated device containing an electromechanical solenoid which actuates either a pneumatic or hydraulic valve, or a solenoid switch, which is a specific type of relay that internally uses an electromechanical solenoid to operate an electrical switch; for example, an automobile starter solenoid, or a linear solenoid, which is an electromechanical solenoid.

Magnetic field of a solenoid

Inside



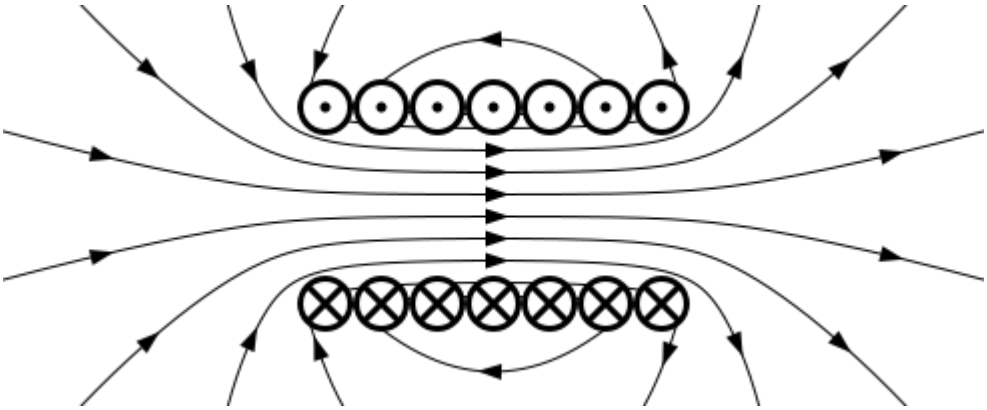
A solenoid with 3 Ampèrian loops: *a*, *b* and *c*.

In short: the magnetic field inside an infinitely long solenoid is homogeneous and its strength does not depend on the distance from the axis.

This is a derivation of the magnetic flux density around a solenoid that is long enough so that fringe effects can be ignored. In the diagram to the right, we immediately know that the flux density vector points in the positive *z* direction inside the solenoid, and in the negative *z* direction outside the solenoid. We see this by applying the right hand grip rule for the field around a wire. If we wrap our right hand around a wire with the thumb pointing in the direction of the current, the curl of the fingers shows how the field behaves. Since we are dealing with a long solenoid, all of the components of the magnetic field not pointing upwards cancel out by symmetry. Outside, a similar cancellation occurs, and the field is only pointing downwards.

Now consider the imaginary loop *c* that is located inside the solenoid. By Ampère's law, we know that the line integral of **B** (the magnetic flux density vector) around this loop is zero, since it encloses no electrical currents (it can be also assumed that the circuital electric field passing through the loop is constant under such conditions: a constant or constantly changing current through the solenoid). We have shown above that the field is pointing upwards inside the solenoid, so the horizontal portions of loop *c* doesn't contribute anything to the integral. Thus the integral of the up side 1 is equal to the integral of the down side 2. Since we can arbitrarily change the dimensions of the loop and get the same result, the only physical explanation is that the integrands are actually equal, that is, the magnetic field inside the solenoid is radially uniform. Note, though, that nothing prohibits it from varying longitudinally, which in fact it does.

Outside



Magnetic field created by a solenoid (cross-sectional view) described using field lines.

A similar argument can be applied to the loop *a* to conclude that the field outside the solenoid is radially uniform or constant. This last result, which holds strictly true only near the centre of the solenoid where the field lines are parallel to its length, is important inasmuch as it shows that the flux density outside is practically zero since the radii of the field outside the solenoid will tend to infinity.

An intuitive argument can also be used to show that the flux density outside the solenoid is actually zero. Magnetic field lines only exist as loops, they cannot diverge from or converge to a point like electric field lines can. The magnetic field lines follow the longitudinal path of the solenoid inside, so they must go in the opposite direction outside of the solenoid so that the lines can form a loop. However, the volume outside the solenoid is much greater than the volume inside, so the density of magnetic field lines outside is greatly reduced. Now recall that the field outside is constant. In order for the total number of field lines to be conserved, the field outside must go to zero as the solenoid gets longer.

Quantitative description

Now we can consider the imaginary loop *b*. Take the line integral of **B** around the loop, with the length of the loop *l*. The horizontal components vanish, and the field outside is practically zero, so Ampère's Law gives us:

$$Bl = \mu_0 Ni$$

where μ_0 is the magnetic constant, *N* the number of turns, *i* the current. From this we get:

$$B = \mu_0 \frac{Ni}{l}.$$

This equation is for a solenoid with no core. The inclusion of a ferromagnetic core, such as iron, increases the magnitude of the magnetic flux density in the solenoid. This is expressed by the formula

$$B = \mu_0 \mu_r \frac{Ni}{l} = \mu \frac{Ni}{l}$$

where μ_r is the relative permeability and μ ($\mu_0\mu_r$) the permeability of the material that the core is made of.

Inductance of a solenoid

As shown above, the magnetic flux density *B* within the coil is practically constant and is given by

$$B = \mu_0 \frac{Ni}{l}$$

where μ_0 is the magnetic constant, *N* the number of turns, *i* the current and *l* the length of the coil. Ignoring end effects, the total magnetic flux through the coil is obtained by multiplying the flux density *B* by the cross-section area *A*:

$$\Phi = \mu_0 \frac{NiA}{l},$$

When this is combined with the definition of inductance,

$$L = \frac{N\Phi}{i}$$

it follows that the inductance of a solenoid is given by:

$$L = \mu_0 \frac{N^2 A}{l}.$$

A table of inductance for short solenoids of various diameter to length ratios has been calculated by Dellinger, Whittmore, and Ould.

This, and the inductance of more complicated shapes, can be derived from Maxwell's equations. For rigid air-core coils, inductance is a function of coil geometry and number of turns, and is independent of current.

Similar analysis applies to a solenoid with a magnetic core, but only if the length of the coil is much greater than the product of the relative permeability of the magnetic core and the diameter. That limits the simple analysis to low-permeability cores, or extremely long

thin solenoids. The presence of a core can be taken into account in the above equations by replacing the magnetic constant μ_0 with μ or $\mu_0\mu_r$, where μ represents permeability and μ_r relative permeability. Note that since the permeability of ferromagnetic materials changes with applied magnetic flux, the inductance of a coil with a ferromagnetic core will generally vary with current.

Applications

Electromechanical solenoids

28. The Commercial Solenoid.—The solenoid is used in practice for tripping circuit breakers (Par. 237), for operating contactors in automatic motor starters (Par. 219), for operating voltage regulating devices (Par. 207), for arc lamp feeds (Chap. XIII, Vol. II), for operating valves, and for numerous other purposes. In practically all instances a soft iron (or steel) plunger or armature is necessary to obtain the tractive pull required of the solenoid. The operation of a solenoid and plunger is indicated in Fig. 30. The flux due to the solenoid produces magnetic poles on the plunger. The pole nearer the plunger will be of such sign that it will be urged along the lines of force, (see Par. 11) and in such a direction as to be drawn within the solenoid.

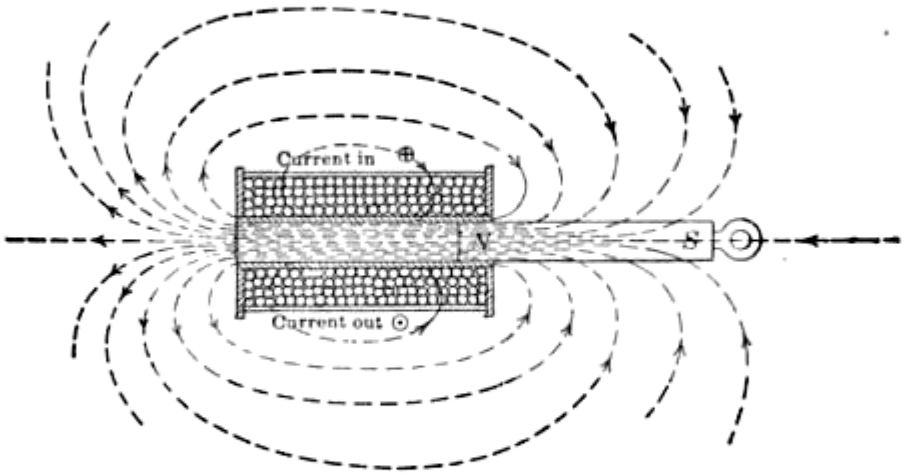


FIG. 30.—Simple solenoid and plunger.

A 1920 explanation of a commercial solenoid used as an electromechanical actuator

Electromechanical solenoids consist of an electromagnetically inductive coil, wound around a movable steel or iron slug (termed the armature). The coil is shaped such that the armature can be moved in and out of the center, altering the coil's inductance and thereby becoming an electromagnet. The armature is used to provide a mechanical force to some mechanism (such as controlling a pneumatic valve). Although typically weak over anything but very short distances, solenoids may be controlled directly by a controller circuit, and thus have very low reaction times.

The force applied to the armature is proportional to the change in inductance of the coil with respect to the change in position of the armature, and the current flowing through the coil. The force applied to the armature will always move the armature in a direction that increases the coil's inductance.

Electromechanical solenoids are commonly seen in electronic paintball markers, pinball machines, dot matrix printers and fuel injectors.

Rotary solenoid

The rotary solenoid is an electromechanical device used to rotate a ratcheting mechanism when power is applied. These were used in the 1950s for rotary snap-switch automation in electromechanical controls. Repeated actuation of the rotary solenoid advances the snap-switch forward one position. Two rotary actuators on opposite ends of the rotary snap-switch shaft, can advance or reverse the switch position.

The rotary solenoid has a similar appearance to a linear solenoid, except that the core is mounted in the center of a large flat disk, with two or three inclined grooves cut into the underside of the disk. These grooves align with slots on the solenoid body, with ball bearings in the grooves.

When the solenoid is activated, the core is drawn into the coil, and the disk rotates on the ball bearings in the grooves as it moves towards the coil body. When power is removed, a spring on the disk rotates it back to its starting position, also pulling the core out of the coil.

The rotary solenoid was invented in 1944 by George H. Leland, of Dayton, Ohio, to provide a more reliable and shock/vibration tolerant release mechanism for air-dropped bombs. Previously used linear (axial) solenoids were prone to inadvertent releases. U.S. Patent number 2,496,880 describes the electromagnet and inclined raceways that are the basis of the invention. Leland's engineer, Earl W. Kerman, was instrumental in developing a compatible bomb release shackle that incorporated the rotary solenoid. Bomb shackles of this type are found in a B-29 aircraft fuselage on display at the National Museum of the USAF in Dayton, Ohio.

Rotary voice coil

This is a rotational version of a solenoid. Typically the fixed magnet is on the outside, and the coil part moves in an arc controlled by the current flow through the coils. Rotary voice coils are widely employed in devices such as disk drives.

Pneumatic solenoid valves

A pneumatic solenoid valve is a switch for routing air to any pneumatic device, usually an actuator, allowing a relatively small signal to control a large device. It is also the interface between electronic controllers and pneumatic systems.

Hydraulic solenoid valves

Hydraulic solenoid valves are in general similar to pneumatic solenoid valves except that they control the flow of hydraulic fluid (oil), often at around 3000 psi (210 bar, 21 MPa, 21 MN/m^2). Hydraulic machinery uses solenoids to control the flow of oil to rams or actuators to (for instance) bend sheets of titanium in aerospace manufacturing. Solenoid-controlled valves are often used in irrigation systems, where a relatively weak solenoid opens and closes a small pilot valve, which in turn activates the main valve by applying fluid pressure to a piston or diaphragm that is mechanically coupled to the main valve. Solenoids are also in everyday household items such as washing machines to control the flow and amount of water into the drum.

Transmission solenoids control fluid flow through an automatic transmission and are typically installed in the transmission valve body.

Automobile starter solenoid

In a car or truck, the starter solenoid is part of an automobile starting system. The starter solenoid receives a large electric current from the car battery and a small electric current from the ignition switch. When the ignition switch is turned on (i.e. when the key is turned to start the car), the small electric current forces the starter solenoid to close a pair of heavy contacts, thus relaying the large electric current to the starter motor.

Starter solenoids can also be built into the starter itself, often visible on the outside of the starter. If a starter solenoid receives insufficient power from the battery, it will fail to start the motor, and may produce a rapid 'clicking' or 'clacking' sound. This can be caused by a low or dead battery, by corroded or loose connections in the cable, or by a broken or damaged positive (red) cable from the battery. Any of these will result in some power to the solenoid, but not enough to hold the heavy contacts closed, so the starter motor itself never spins, and the engine does not start.

Chapter 17

Tesla Coil

A **Tesla coil** is a type of resonant transformer circuit invented by Nikola Tesla around 1891. It is used to produce high voltage, low current, high frequency alternating current electricity, although Tesla coils produce higher current than the other source of high voltage discharges, electrostatic machines. Tesla experimented with a number of different configurations and they consist of two, or sometimes three, coupled resonant electric circuits. Tesla used these coils to conduct innovative experiments in electrical lighting, phosphorescence, x-ray generation, high frequency alternating current phenomena, electrotherapy, and the transmission of electrical energy without wires.

The early Tesla coil transformer design employs a medium- to high-voltage power source, one or more high voltage capacitor(s), and a spark gap to excite a multiple-layer primary inductor with periodic bursts of high frequency current. The multiple-layer Tesla coil transformer secondary is excited by resonant inductive coupling, the primary and secondary circuits both being *tuned* so they resonate at the same frequency (typically, between 25 kHz and 2 MHz). The later and higher-power coil design has a single-layer primary and secondary. These Tesla coils are often used by hobbyists and at venues such as science museums to produce long sparks.

Tesla coil circuits were used commercially in sparkgap radio transmitters for wireless telegraphy until the 1920s, and in electrotherapy and pseudomedical devices such as violet ray. Today their main use is entertainment and educational displays. Tesla coils are built by many high-voltage enthusiasts, research institutions, science museums and independent experimenters. Although electronic circuit controllers have been developed, Tesla's original spark gap design is less expensive and has proven extremely reliable.

History

Tesla's coil

The "American Electrician" gives a description of an early Tesla coil wherein a glass battery jar, 15 x 20 cm (6 x 8 in) is wound with 60 to 80 turns of AWG No. 18 B & S magnet wire (0.823 mm²). Into this is slipped a primary consisting of eight to ten turns of AWG No. 6 B & S wire (13.3 mm²) and the whole combination immersed in a vessel containing linseed or mineral oil. (Norrie, pg. 34-35)

Tesla Coil Theory

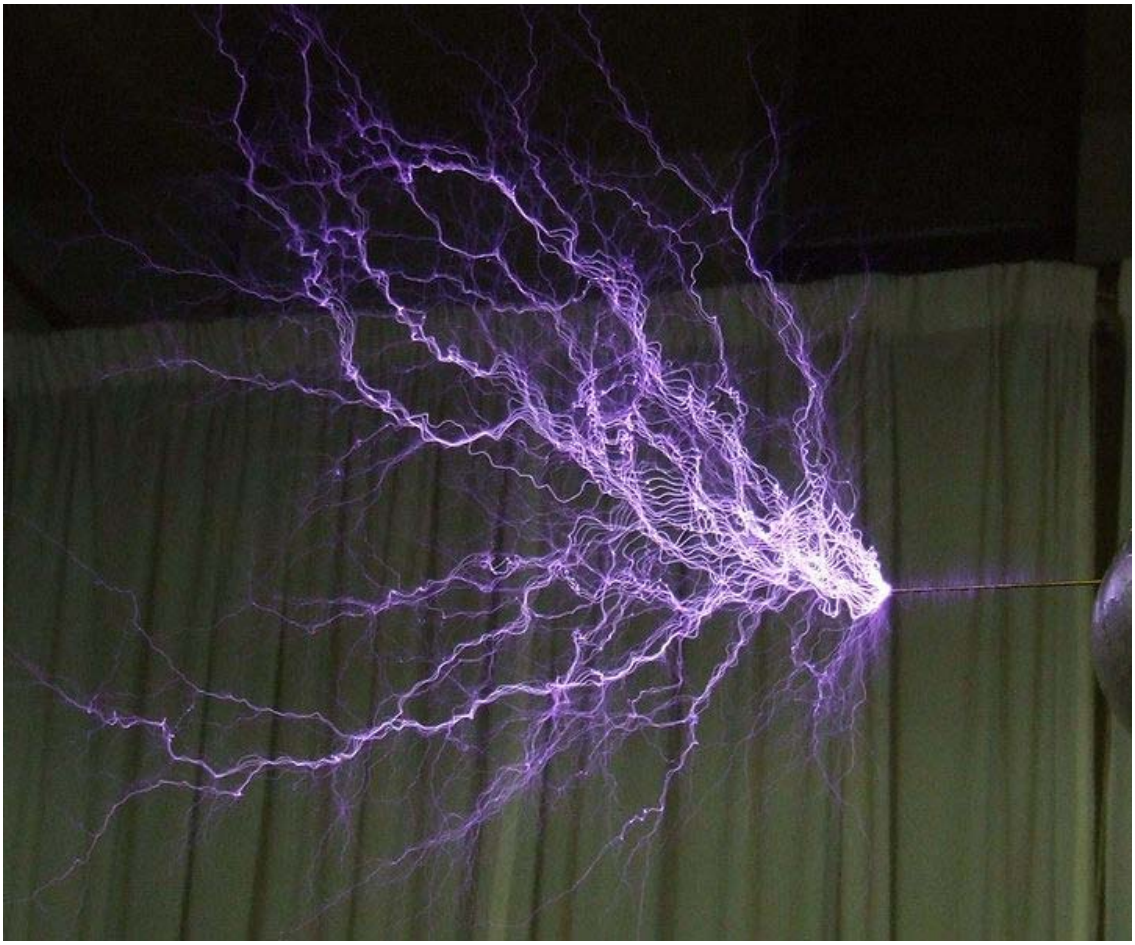
A Tesla coil transformer operates in a significantly different fashion than a conventional (i.e., iron core) transformer. In a conventional transformer, the windings are very tightly coupled, and voltage gain is determined by the ratio of the numbers of turns in the windings. This works well at normal voltages, however, at high voltages, the insulation between the two sets of windings is easily broken down, and this prevents iron cored transformers from running at extremely high voltages without damage.

With Tesla coils, unlike a conventional transformer, which may couple 97%+ of the magnetic fields between windings, a Tesla coil's windings are "loosely" coupled, with a large air gap, and thus the primary and secondary are typically sharing only 10–20% of their respective magnetic fields. Instead of a tight coupling, the coil transfers energy (via loose coupling) from one oscillating resonant circuit (the primary) to the other (the secondary) over a number of RF cycles.

As the primary energy transfers to the secondary, the secondary's output voltage increases until all of the available primary energy has been transferred to the secondary (less losses). Even with significant spark gap losses, a well designed Tesla coil can transfer over 85% of the energy initially stored in the primary capacitor to the secondary circuit. Thus the voltage gain of a Tesla coil can be significantly greater than a conventional transformer, since the air gap has a very high insulation.

With the loose coupling the voltage gain is instead proportional to the square root of the ratio of secondary and primary inductances.

Modern day Tesla coils



Electric discharge showing the lightning-like plasma filaments from a *Tesla coil*.

Modern high voltage enthusiasts usually build Tesla coils that are similar to some of Tesla's "later" air core designs. These typically consist of a primary tank circuit, a series LC (inductance-capacitance) circuit composed of a high voltage capacitor, spark gap and primary coil, and the secondary LC circuit, a series resonant circuit consisting of the secondary coil plus a terminal capacitance or "top load." In Tesla's more advanced design, the secondary LC circuit is composed of an air-core transformer secondary coil placed in series with a helical resonator. The helical coil is then connected to the terminal capacitance. Most modern coils use only a single helical coil comprising both the secondary and primary resonator. The terminal capacitance actually forms one 'plate' of a capacitor, the other 'plate' being the Earth (or "ground"). The primary LC circuit is tuned so that it resonates at the same frequency as the secondary LC circuit. The primary and secondary coils are magnetically coupled, creating a dual-tuned resonant air-core transformer. Earlier oil insulated Tesla coils needed large and long insulators at their high-voltage terminals to prevent discharge in air. Later version Tesla coils spread their electric fields over large distances to prevent high electrical stresses in the first place, thereby allowing operation in free air.

Tesla's 1902 design for his advanced magnifying transmitter used a top terminal consisting of a metal frame in the shape of a toroid, covered with hemispherical plates (constituting a very large conducting surface). The top terminal has relatively small capacitance, charged to as high a voltage as practicable. The outer surface of the elevated conductor is where the electrical charge chiefly accumulates. It has a large radius of curvature, or is composed of separate elements which, irrespective of their own radii of curvature, are arranged close to each other so that the outside ideal surface enveloping them has a large radius. This design allowed the terminal to support very high voltages without generating corona or sparks. Tesla, during his patent application process, described a variety of resonator terminals at the top of this later coil. Most Modern Tesla coils use simple toroids, typically fabricated from spun metal or flexible aluminum ducting, to control the high electrical field near the top of the secondary and to direct spark outward and away from the primary and secondary windings.

As pointed out above, more advanced Tesla coil transmitters involve a more tightly coupled air core resonance transformer network or "master oscillator" the output of which is then fed another resonator, sometimes called the "extra coil." The principle is that energy accumulates in the extra coil and the role of transformer secondary is played by the separate master oscillator secondary; the roles are not shared by a single secondary. In some modern three-coil Magnifying transmitter systems the extra coil is placed some distance from the transformer. Direct magnetic coupling to the upper secondary is not desirable, since the third coil is designed to be driven by injecting RF current directly into the bottom end.

This particular Tesla coil configuration consists of a secondary coil in close inductive relation with a primary, and one end of which is connected to a ground-plate, while its other end is led through a separate self-induction coil (whose connection should always be made at, or near, the geometrical center of that coil's circular aspect, in order to secure a symmetrical distribution of the current), and of a metallic cylinder carrying the current to the terminal. The primary coil may be excited by any desired source of high frequency current. The important requirement is that the primary and secondary sides must be tuned to the same resonant frequency to allow efficient transfer of energy between the primary and secondary resonant circuits. The conductor of the shaft to the terminal (topload) is in the form of a cylinder with smooth surface of a radius much larger than that of the spherical metal plates, and widens out at the bottom into a hood (which is slotted to avoid loss by eddy currents). The secondary coil is wound on a drum of insulating material, with its turns close together. When the effect of the small radius of curvature of the wire itself is overcome, the lower secondary coil behaves as a conductor of large radius of curvature, corresponding to that of the drum. The top of the extra coil may be extended up to the terminal U.S. Patent 1,119,732 and the bottom should be somewhat below the uppermost turn of the primary coil. This lessens the tendency of the charge to break out from the wire connecting both and to pass along the support.

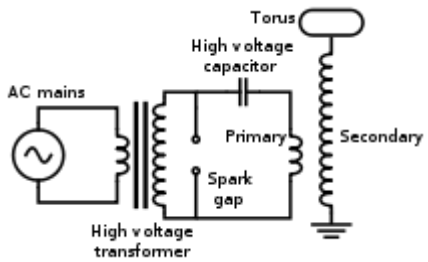
A sword-like discharge characteristic of a Vacuum Tube Tesla Coil. This particular coil was constructed by Xellers of the instructables community.

Modern day transistor or vacuum tube Tesla coils do not use a primary spark gap. Instead, the transistor(s) or vacuum tube(s) provide the switching or amplifying function necessary to generate RF power for the primary circuit. Solid-state Tesla coils use the lowest primary operating voltage, typically between 155 to 800 volts, and drive the primary winding using either a single, half-bridge, or full-bridge arrangement of bipolar transistors, MOSFETs or IGBTs to switch the primary current. Vacuum tube coils typically operate with plate voltages between 1500 and 6000 volts, while most spark gap coils operate with primary voltages of 6,000 to 25,000 volts. The primary winding of a traditional transistor Tesla coil is wound around only the bottom portion of the secondary (sometimes called the resonator). This helps to illustrate operation of the secondary as a pumped resonator. The primary *induces* alternating voltage into the bottommost portion of the secondary, providing regular "pushes" (similar to provided properly timed pushes to a playground swing). Additional energy is transferred from the primary to the secondary inductance and toploadcapacitance during each "push", and secondary output voltage builds (called *ring-up*). An electronic feedback circuit is usually used to adaptively synchronize the primary oscillator to the growing resonance in the secondary, and this is the only tuning consideration beyond the initial choice of a reasonable topload.

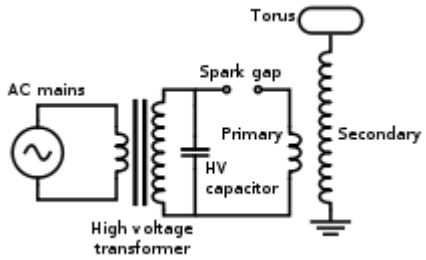
In a *dual resonant solid-state Tesla coil* (DRSSTC), the electronic switching of the solid-state Tesla coil is combined with the resonant primary circuit of a spark-gap Tesla coil. The resonant primary circuit is formed by connecting a capacitor in series with the primary winding of the coil, so that the combination forms a series tank circuit with a resonant frequency near that of the secondary circuit. Because of the additional resonant circuit, one manual and one adaptive tuning adjustment are necessary. Also, an interrupter is usually used to reduce the duty cycle of the switching bridge, in order to improve peak power capabilities; similarly, IGBTs are more popular in this application than bipolar transistors or MOSFETs, due to their superior power handling characteristics. Performance of a DRSSTC can be comparable to a medium power spark gap Tesla coil, and efficiency (as measured by spark length versus input power) can be significantly greater than a spark gap Tesla coil operating at the same input power.

Applications

Transmission



Typical Tesla Coil Schematic
This example circuit is designed to be driven by alternating currents. Here the spark gap shorts the high frequency across the first transformer. An inductance, not shown, protects the transformer. This design is favoured when a relatively fragile Neon Sign Transformer (NST) is used.



Alternate Tesla Coil Configuration
This circuit also driven by alternating currents. However, here the AC supply transformer must be capable of withstanding high voltages at high frequencies.

High voltage production

A large Tesla coil of more modern design often operates at very high peak power levels, up to many megawatts (millions of watts). It should therefore be adjusted and operated carefully, not only for efficiency and economy, but also for safety. If, due to improper tuning, the maximum voltage point occurs below the terminal, along the secondary coil, a discharge (spark) may break out and damage or destroy the coil wire, supports, or nearby objects.

Tesla experimented with these, and many other, circuit configurations. The Tesla coil primary winding, spark gap and tank capacitor are connected in series. In each circuit, the AC supply transformer charges the tank capacitor until its voltage is sufficient to break down the spark gap. The gap suddenly fires, allowing the charged tank capacitor to discharge into the primary winding. Once the gap fires, the electrical behavior of either circuit is identical. Experiments have shown that neither circuit offers any marked performance advantage over the other.

However, in the typical circuit (above), the spark gap's short circuiting action prevents high frequency oscillations from 'backing up' into the supply transformer. In the alternate circuit, high amplitude high frequency oscillations that appear across the capacitor also are applied to the supply transformer's winding. This can induce corona discharges between turns that weaken and eventually destroy the transformer's insulation. Experienced Tesla coil builders almost exclusively use the top circuit, often augmenting it with low pass filters (resistor and capacitor (RC) networks) between the supply transformer and spark gap to help protect the supply transformer. This is especially important when using transformers with fragile high voltage windings, such as Neon-sign transformers (NSTs). Regardless of which configuration is used, the HV transformer must be of a type that self-limits its secondary current by means of internal leakage inductance. A normal (low leakage inductance) high voltage transformer must use an external limiter (sometimes called a ballast) to limit current. NSTs are designed to have high leakage inductance to limit their short circuit current to a safe level.

Tuning precautions

The primary coil's resonant frequency should be tuned to that of the secondary, using low-power oscillations, then increasing the power until the apparatus has been brought under control. While tuning, a small projection (called a "breakout bump") is often added to the top terminal in order to stimulate corona and spark discharges (sometimes called streamers) into the surrounding air. Tuning can then be adjusted so as to achieve the longest streamers at a given power level, corresponding to a frequency match between the primary and secondary coil. Capacitive 'loading' by the streamers tends to lower the resonant frequency of a Tesla coil operating under full power. For a variety of technical reasons, toroids provide one of the most effective shapes for the top terminals of Tesla coils.

Air discharges

A small, later-type "*Tesla coil*" in operation. The output is giving 17-inch sparks. The diameter of the secondary is three inches. The power source is a 10000 V, 60 Hz current limited supply.

While generating discharges, electrical energy from the secondary and toroid is transferred to the surrounding air as electrical charge, heat, light, and sound. The electric currents that flow through these discharges are actually due to the rapid shifting of quantities of charge from one place (the top terminal) to other places (nearby regions of air). The process is similar to charging or discharging a capacitor. The current that arises from shifting charges within a capacitor is called a displacement current. Tesla coil discharges are formed as a result of displacement currents as pulses of electrical charge are rapidly transferred between the high voltage toroid and nearby regions within the air (called space charge regions). Although the space charge regions around the toroid are invisible, they play a profound role in the appearance and location of Tesla coil discharges.

When the spark gap fires, the charged capacitor discharges into the primary winding, causing the primary circuit to oscillate. The oscillating primary current creates a magnetic

field that couples to the secondary winding, transferring energy into the secondary side of the transformer and causing it to oscillate with the toroid capacitance. The energy transfer occurs over a number of cycles, and most of the energy that was originally in the primary side is transferred into the secondary side. The greater the magnetic coupling between windings, the shorter the time required to complete the energy transfer. As energy builds within the oscillating secondary circuit, the amplitude of the toroid's RF voltage rapidly increases, and the air surrounding the toroid begins to undergo dielectric breakdown, forming a corona discharge.

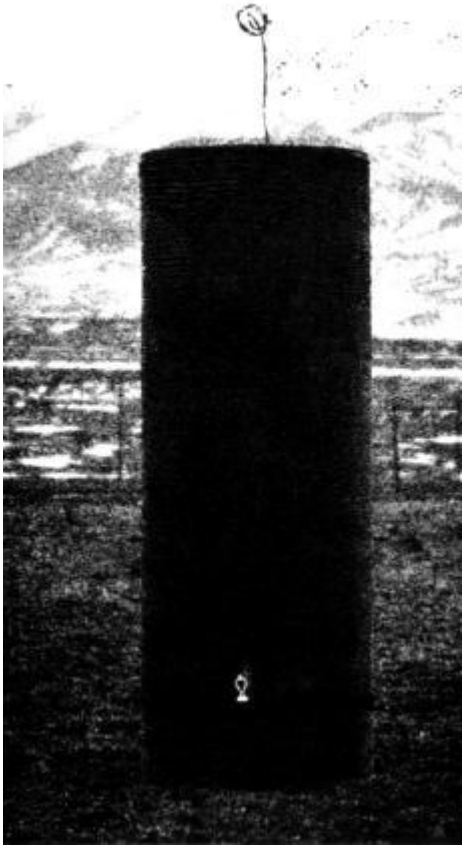
As the secondary coil's energy (and output voltage) continue to increase, larger pulses of displacement current further ionize and heat the air at the point of initial breakdown. This forms a very conductive "root" of hotter plasma, called a leader, that projects outward from the toroid. The plasma within the leader is considerably hotter than a corona discharge, and is considerably more conductive. In fact, it has properties that are similar to an electric arc. The leader tapers and branches into thousands of thinner, cooler, hairlike discharges (called streamers). The streamers look like a bluish 'haze' at the ends of the more luminous leaders, and it is the streamers that actually transfer charge between the leaders and toroid to nearby space charge regions. The displacement currents from countless streamers all feed into the leader, helping to keep it hot and electrically conductive.

The primary break rate of sparking Tesla coils is slow compared to the resonant frequency of the resonator-topload assembly. When the switch closes, energy is transferred from the primary LC circuit to the resonator where the voltage rings up over a short period of time up culminating in the electrical discharge. In a spark gap Tesla coil the primary-to-secondary energy transfer process happens repetitively at typical pulsing rates of 50–500 times per second, and previously formed leader channels don't get a chance to fully cool down between pulses. So, on successive pulses, newer discharges can build upon the hot pathways left by their predecessors. This causes incremental growth of the leader from one pulse to the next, lengthening the entire discharge on each successive pulse. Repetitive pulsing causes the discharges to grow until the average energy that's available from the Tesla coil during each pulse balances the average energy being lost in the discharges (mostly as heat). At this point, dynamic equilibrium is reached, and the discharges have reached their maximum length for the Tesla coil's output power level. The unique combination of a rising high voltage Radio Frequency envelope and repetitive pulsing seem to be ideally suited to creating long, branching discharges that are considerably longer than would be otherwise expected by output voltage considerations alone. High voltage discharges create filamentary multi-branched discharges which are purplish blue in colour. High energy discharges create thicker discharges with fewer branches, are pale and luminous, almost white, and are much longer than low energy discharges, because of increased ionisation. There will be a strong smell of ozone and nitrogen oxides in the area. The important factors for maximum discharge length appear to be voltage, energy, and still air of low to moderate humidity. However, even more than 100 years later after the first use of Tesla coils, there are many aspects of Tesla coil discharges and the energy transfer process that are still not completely understood.

Wireless transmission and reception

The Tesla coil can also be used for wireless transmission. In addition to the positioning of the elevated terminal well above the top turn of the helical resonator, another difference from the sparking Tesla coil is the primary break rate. The optimized Tesla coil transmitter is a continuous wave oscillator with a break rate equaling the operating frequency. The combination of a helical resonator with an elevated terminal is also used for wireless reception. The Tesla coil receiver is intended for receiving the non-radiating electromagnetic field energy produced by the Tesla coil transmitter. The Tesla coil receiver is also adaptable for exploiting the ubiquitous vertical voltage gradient in the Earth's atmosphere. Tesla built and used various devices for detecting electromagnetic field energy. His early wireless apparatus operated on the basis of Hertzian waves or ordinary radio waves, electromagnetic waves that propagate in space without involvement of a conducting guiding surface. During his work at Colorado Springs, Tesla believed he had established electrical resonance of the entire Earth using the Tesla coil transmitter at his "Experimental Station."

Tesla stated one of the requirements of the World Wireless System was the construction of resonant receivers. The related concepts and methods are part of his wireless transmission system (US1119732 — Apparatus for Transmitting Electrical Energy — 1902 January 18). Tesla made a proposal that there needed to be many more than thirty transmission-reception stations worldwide. In one form of receiving circuit the two input terminals are connected each to a mechanical pulse-width modulation device adapted to reverse polarity at predetermined intervals of time and charge a capacitor. This form of Tesla system receiver has means for commutating the current impulses in the charging circuit so as to render them suitable for charging the storage device, a device for closing the receiving-circuit, and means for causing the receiver to be operated by the energy accumulated.



Tesla coil in one experiment of many conducted in Colorado Springs. This is a grounded tuned coil in resonance with a nearby transmitter; Light is glowing near the bottom.

A Tesla coil used as a receiver is referred to as a *Tesla receiving transformer*. The Tesla coil receiver acts as a step-down transformer with high current output. The parameters of a Tesla coil transmitter are identically applicable to it being a receiver (*e.g.*., an antenna circuit), due to reciprocity. Impedance, generally though, is not applied in an obvious way; for electrical impedance, the impedance at the load (*e.g.*., where the power is consumed) is most critical and, for a Tesla coil receiver, this is at the point of utilization (such as at an induction motor) rather than at the receiving node. Complex impedance of an antenna is related to the electrical length of the antenna at the wavelength in use. Commonly, impedance is adjusted at the load with a tuner or a matching networks composed of inductors and capacitors.

A Tesla coil can receive electromagnetic impulses from atmospheric electricity and radiant energy, besides normal wireless transmissions. Radiant energy throws off with great velocity minute particles which are strongly electrified and other rays falling on the insulated-conductor connected to a condenser (i.e., a capacitor) can cause the condenser to indefinitely charge electrically. The helical resonator can be "shock excited" due to radiant energy disturbances not only at the fundamental wave at one-quarter wave-length but also is excited at its harmonics. Hertzian methods can be used to excite the Tesla coil

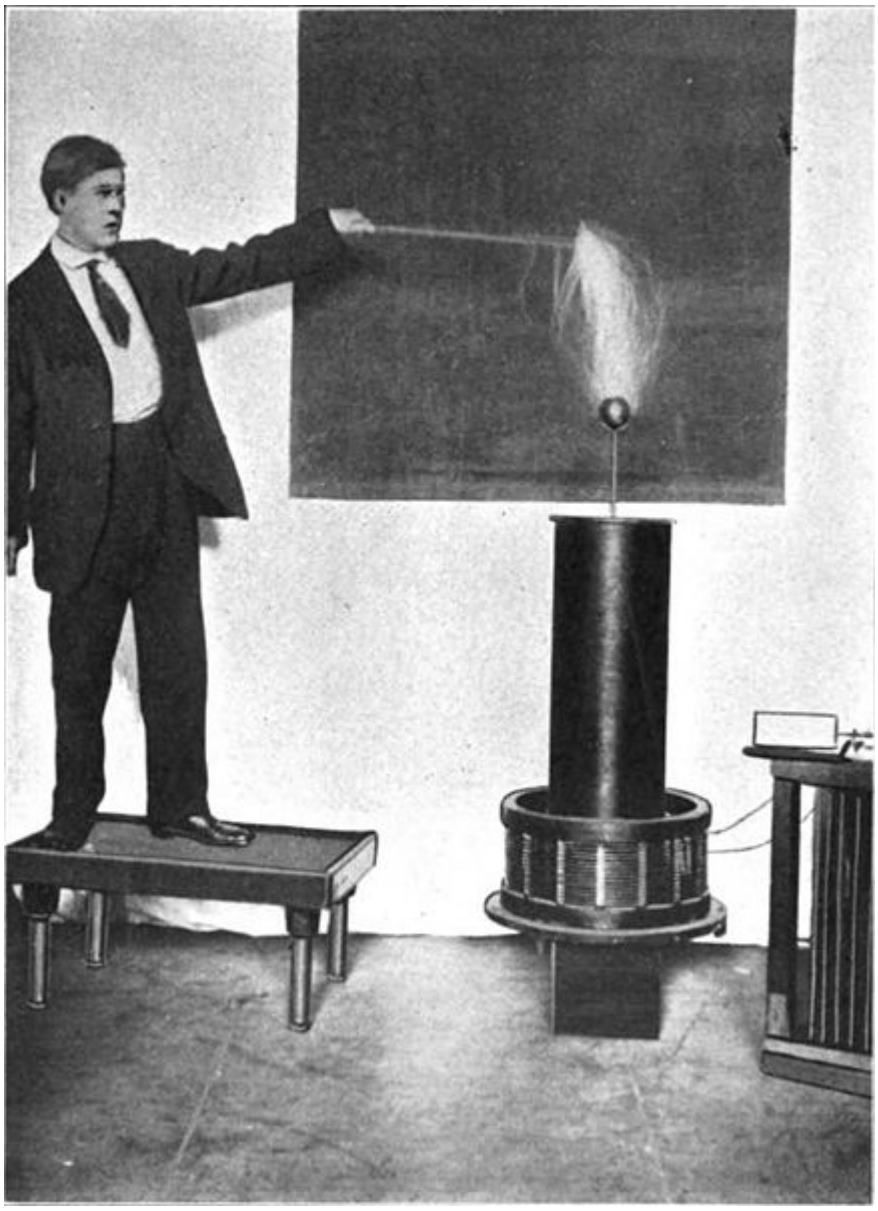
receiver with limitations that result in great disadvantages for utilization, though. The methods of ground conduction and the various induction methods can also be used to excite the Tesla coil receiver, but are again at a disadvantages for utilization. The charging-circuit can be adapted to be energized by the action of various other disturbances and effects at a distance. Arbitrary and intermittent oscillations that are propagated via conduction to the receiving resonator will charge the receiver's capacitor and utilize the potential energy to greater effect. Various radiations can be used to charge and discharge conductors, with the radiations considered electromagnetic vibrations of various wavelengths and ionizing potential. The Tesla receiver utilizes the effects or disturbances to charge a storage device with energy from an external source (natural or man-made) and controls the charging of said device by the actions of the effects or disturbances (during succeeding intervals of time determined by means of such effects and disturbances corresponding in succession and duration of the effects and disturbances). The stored energy can also be used to operate the receiving device. The accumulated energy can, for example, operate a transformer by discharging through a primary circuit at predetermined times which, from the secondary currents, operate the receiving device.

While Tesla coils can be used for these purposes, much of the public and media attention is directed away from transmission-reception applications of the Tesla coil since electrical spark discharges are fascinating to many people. Regardless of this fact, Tesla did suggest that this variation of the Tesla coil could utilize the phantom loop effect to form a circuit to induct energy from the Earth's magnetic field and other radiant energy sources (including, but not limited to, electrostatics). With regard to Tesla's statements on the harnessing of natural phenomena to obtain electric power, he stated:

Ere many generations pass, our machinery will be driven by a power obtainable at any point of the universe. — "Experiments with Alternate Currents of High Potential and High Frequency" (February 1892)

Tesla stated that the output power from these devices, attained from Hertzian methods of charging, was low, but alternative charging means are available. Tesla receivers, operated correctly, act as a step-down transformer with high current output. There are, to date, no commercial power generation entities or businesses that have utilized this technology to full effect. The power levels achieved by Tesla coil receivers have, thus far, been a fraction of the output power of the transmitters.

High frequency electrical safety



Student conducting Tesla coil streamers through his body, 1909

The 'skin effect'

The dangers of contact with high frequency electrical current are sometimes perceived as being less than at lower frequencies, because the subject usually doesn't feel pain or a 'shock'. This is often erroneously attributed to skin effect, a phenomenon that tends to inhibit alternating current from flowing inside conducting media. It was thought that in the body, Tesla currents travelled close to the skin surface, making them safer than lower

frequency electric currents. In fact, in the early 1900s a major use of Tesla coils was to apply high frequency current directly to the body in electrotherapy.

Although skin effect limits Tesla currents to the outer fraction of an inch in metal conductors, the 'skin depth' of human flesh at typical Tesla coil frequencies is still of the order of 60 inches (150 cm) or more. This means that high frequency currents will still preferentially flow through deeper, better conducting, portions of an experimenter's body such as the circulatory and nervous systems. The reason for the lack of pain is that a human being's nervous system does not sense the flow of potentially dangerous electrical currents above 15–20 kHz; essentially, in order for nerves to be activated, a significant number of ions must cross their membrane before the current (and hence voltage) reverses. Since the body no longer provides a warning 'shock', novices may touch the output streamers of small Tesla coils without feeling painful shocks. However, there is anecdotal evidence among Tesla coil experimenters that temporary tissue damage may still occur and be observed as muscle pain, joint pain, or tingling for hours or even days afterwards. This is believed to be caused by the damaging effects of internal current flow, and is especially common with continuous wave (CW), solid state or vacuum tube type Tesla coils. Some transformers can provide alternating current with such high frequencies that the skin depth becomes small enough for the voltage to be safe. Skin depth is inversely proportional to the root of the frequency, putting these frequencies in the megahertz range.

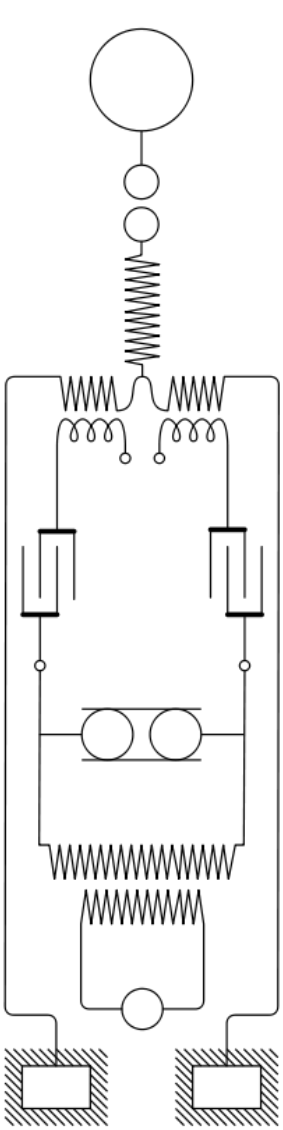
Large Tesla coils and magnifiers can deliver dangerous levels of high frequency current, and they can also develop significantly higher voltages (often 250,000–500,000 volts, or more). Because of the higher voltages, large systems can deliver higher energy, potentially lethal, repetitive high voltage capacitor discharges from their top terminals. Doubling the output voltage quadruples the electrostatic energy stored in a given top terminal capacitance. If an unwary experimenter accidentally places himself in path of the high voltage capacitor discharge to ground, the low current electric shock can cause involuntary spasms of major muscle groups and may induce life-threatening ventricular fibrillation and cardiac arrest. Even lower power vacuum tube or solid state Tesla coils can deliver RF currents that are capable of causing temporary internal tissue, nerve, or joint damage through Joule heating. In addition, an RF arc can carbonize flesh, causing a painful and dangerous bone-deep RF burn that may take months to heal. Because of these risks, knowledgeable experimenters avoid contact with streamers from all but the smallest systems. Professionals usually use other means of protection such as a Faraday cage or a chain mail suit to prevent dangerous currents from entering their body.

The most serious dangers associated with Tesla coil operation are associated with the primary circuit. It is the primary circuit that is capable of delivering a sufficient current at a significant voltage to stop the heart of a careless experimenter. Because these components are not the source of the trademark visual or auditory coil effects, they may easily be overlooked as the chief source of hazard. Should a high frequency arc strike the exposed primary coil while, at the same time, another arc has also been allowed to strike to a person, the ionized gas of the two arcs forms a circuit that may conduct lethal, low-frequency current from the primary into the person.

Further, great care should be taken when working on the primary section of a coil even when it has been disconnected from its power source for some time. The tank capacitors can remain charged for days with enough energy to deliver a fatal shock. Proper designs should always include 'bleeder resistors' to bleed off stored charge from the capacitors. In addition, a safety shorting operation should be performed on each capacitor before any internal work is performed.

Instances and devices

Magnifier Configurations



Classically driven configuration.

Later-type driven configuration. Pancake may be horizontal; lead to resonator is kept clear of it.

Tesla's Colorado Springs laboratory possessed one of the largest Tesla coils ever built, known as the "Magnifying Transmitter". The Magnifying Transmitter is somewhat different from classic 2-coil Tesla coils. A Magnifier uses a 2-coil 'driver' to excite the base of a third coil ('resonator') that is located some distance from the driver. The operating principles of both systems are similar. The world's largest currently existing 2-coil Tesla coil is a 130,000-watt unit, part of a 38-foot-tall (12 m) sculpture. It is owned by Alan Gibbs and currently resides in a private sculpture park at Kakanui Point near Auckland, New Zealand.

The Tesla coil is an early predecessor (along with the induction coil) of a more modern device called a flyback transformer, which provides the voltage needed to power the cathode ray tube used in some televisions and computer monitors. The disruptive discharge coil remains in common use as the *ignition coil* or *spark coil* in the ignition system of an internal combustion engine. These two devices do not use resonance to accumulate energy, however, which is the distinguishing feature of a Tesla coil. They do use inductive "kick", the forced, abrupt decay of the magnetic field, such that a voltage is provided by the coil at its primary terminals that is much greater than the voltage that was applied to establish the magnetic field, and it is this higher voltage that is then multiplied by the transformer turns ratio. Thus, they do store energy, and a Tesla resonator stores energy. A modern, low power variant of the Tesla coil is also used to power plasma globe sculptures and similar devices.

Scientists working with a glass vacuum line (e.g. chemists working with volatile substances in the gas phase, inside a system of glass tubes, taps and bulbs) test for the presence of tiny pin-holes in the apparatus (especially a newly blown piece of glassware) using a Tesla coil. When the system is evacuated and the discharging end of the coil moved over the glass, the discharge travels through any pin-hole immediately below it and thus illuminates the hole, indicating points that need to be annealed or re-blown before they can be used in an experiment.