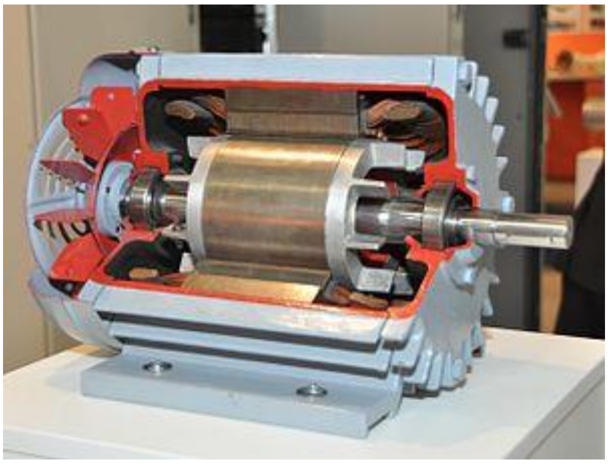
In normal motoring mode, most electric motors operate through the interaction between an electric motor's magnetic field and winding currents to generate force within the motor. In certain applications, such as in the transportation industry with traction motors, electric motors can operate in both motoring and generating or braking modes to also produce electrical energy from mechanical energy.

Found in applications as diverse as industrial fans, blowers and pumps, machine tools, household appliances, power tools, and disk drives, electric motors can be powered by direct current (DC) sources, such as from batteries, motor vehicles or rectifiers, or by alternating current (AC) sources, such as from the power grid, inverters or generators. Small motors may be found in electric watches. General-purpose motors with highly standardized dimensions and characteristics provide convenient mechanical power for industrial use. The largest of electric motors are used for ship propulsion, pipeline compression and pumped-storageapplications with ratings reaching 100 megawatts. Electric motors may be classified by electric power source type, internal construction, application, type of motion output, and so on.



Electric motors are used to produce linear or rotary force (torque), and should be distinguished from devices such as magnetic solenoids and loudspeakers that convert electricity into motion but do not generate usable mechanical powers, which are respectively referred to as actuators and transducers.

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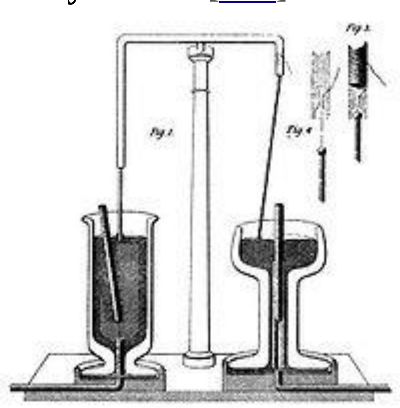
History[edit]

Main article: History of the electric motor

Early motors[edit]



Faraday's electromagnetic experiment, 1821[1]

Perhaps the first electric motors were simple electrostatic devices created by the Scottish monk Andrew Gordon in the 1740s.[2] The theoretical principle behind production of mechanical force by the interactions of an electric current and a magnetic field, Ampère's force law, was discovered later by André-Marie Ampère in 1820. The conversion of electrical energy into mechanical energy by 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 (PM) 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.[3] This motor is often demonstrated in physics experiments, brine substituting for toxic mercury. Though Barlow's wheel was an early refinement to this Faraday demonstration, these and similar homopolar motors were to remain unsuited to practical application until late in the century.

Jedlik's "electromagnetic self-rotor", 1827 (Museum of Applied Arts, Budapest). The historic motor still works perfectly today.[4]

In 1827, Hungarian physicist Ányos Jedlik started experimenting with electromagnetic coils. After Jedlik solved the technical problems of the continuous rotation with the invention of commutator, he called his early devices "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 DC 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.[5][6][7][8][9][10][11]

Success with DC motors[edit]

After many other more or less successful attempts with relatively weak rotating and reciprocating apparatus the German-speaking Prussian Moritz von Jacobi created the first real rotating electric motor in May 1834 that actually developed a remarkable mechanical output power. His motor set a world record which was improved only four years later in September 1838 by Jacobi himself. His second motor was powerful enough to drive a boat with 14 people across a wide river. It was not until 1839/40 that other developers worldwide managed to build motors of similar and later also of higher performance.

The first commutator DC electric motor capable of turning machinery was invented by the British scientist William Sturgeon in 1832.[12] Following Sturgeon's work, a commutator-type direct-current electric motor made with the intention of commercial use was built by the American inventor Thomas Davenport, which he patented in 1837. The motors ran at up to 600 revolutions per minute, and powered machine tools and a printing press.[13] Due to the high cost of primary battery power, the motors were commercially unsuccessful and Davenport went bankrupt. Several inventors followed Sturgeon in the development of DC motors but all encountered the same battery power cost issues. No electricity distribution had been developed at the time. Like Sturgeon's motor, there was no practical commercial market for these motors.[14]

In 1855, Jedlik built a device using similar principles to those used in his electromagnetic self-rotors that was capable of useful work.[5][11] He built a model electric vehicle that same year.[15]

The first commercially successful DC motors followed the invention by Zénobe Gramme who had in 1871 developed the anchor ring dynamo which solved the double-T armaturepulsating DC problem. In 1873, Gramme found that this dynamo could be used as a motor, which he demonstrated to great effect at exhibitions in Vienna and Philadelphia by connecting two such DC motors at a distance of up to 2 km away from each other, one as a generator.[16] (See also 1873 : l'expérience décisive [Decisive Workaround] .)

In 1886, Frank Julian Sprague invented the first practical DC motor, a non-sparking motor that maintained relatively 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 were 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. 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.[17] [a] 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.[18]

Application of electric motors revolutionized industry. Industrial processes were no longer limited by power transmission using line shafts, 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 stand for more than half of the electric energy consumption in the US.[19]

Emergence of AC motors[edit]

In 1824, the French physicist François Arago formulated the existence of rotating magnetic fields, termed Arago's rotations, which, by manually turning switches on and off, Walter Baily demonstrated in 1879 as in effect the first primitive induction motor.[20][21] [22][23] In the 1880s, many inventors were trying to develop workable AC motors[24] because AC's advantages in long distance high voltage transmission were counterbalanced by the inability to operate motors on AC. Practical rotating AC induction motors were independently invented by Galileo Ferraris and Nikola Tesla, a working motor model having been demonstrated by the former in 1885 and by the latter in 1887. In 1888, the *Royal Academy of Science of Turin*published Ferraris's research detailing the foundations of motor operation while however concluding that "the apparatus based on that principle could not be of any commercial importance as motor."[23][25][26][27][28][29][30][31][32][33][34][35][36] In 1888, Tesla presented his paper *A New System for Alternating Current Motors and Transformers* to the AIEE that described three patented two-phase four-stator-pole motor types: one with a four-pole rotor forming a non-self-starting reluctance motor, another with a wound rotor forming a self-starting induction motor, and the third a true synchronous motor with separately excited DC supply to rotor winding. One of the patents Tesla filed in 1887, however, also described a shorted-winding-rotor induction motor. George Westinghouse promptly bought Tesla's patents, employed Tesla to develop them, and assigned C. F. Scott to help Tesla, Tesla left for other pursuits in 1889.[23][30][33][34][35][36][37][38][39][40] [41][42][43][44] The constant speed AC induction motor was found not to be suitable for street cars[24] but Westinghouse engineers successfully adapted it to power a mining operation in Telluride, Colorado in 1891.[45][46][47]Steadfast in his promotion of three-phase development, Mikhail Dolivo-Dobrovolsky invented the three-phase cage-rotor induction motor in 1889 and the three-limb transformer in 1890. This type of motor is now used for the vast majority of commercial applications.[48][49]However, he claimed that Tesla's motor was not practical because of two-phase pulsations, which prompted him to persist in his three-phase work.[50] Although Westinghouse achieved its first practical induction motor in 1892 and developed a line of polyphase 60 hertz induction motors in 1893, these early Westinghouse motors were two-phase motors with wound rotors until B. G. Lamme developed a rotating bar winding rotor.[37] The General Electric Companybegan developing three-phase induction motors in 1891.[37] By 1896, General Electric and Westinghouse signed a cross-licensing agreement for the bar-winding-rotor design, later called the squirrel-cage rotor.[37] Induction motor improvements flowing from these inventions and innovations were such that a 100 horsepower (HP) induction motor currently has the same mounting dimensions as a 7.5 HP motor in 1897.[37]

Motor construction[edit]

Electric motor rotor (left) and stator (right)

Rotor[edit]

Main article: Rotor (electric)

In an electric motor the moving part is the rotor which turns the shaft to deliver the mechanical power. The rotor usually has conductors laid into it which carry currents that interact with the magnetic field of the stator to generate the forces that turn the shaft. However, some rotors carry permanent magnets, and the stator holds the conductors.

Stator[edit]

Main article: Stator

The stator is the stationary part of the motor’s electromagnetic circuit and usually consists of either windings or permanent magnets. The stator core is made up of many thin metal sheets, called laminations. Laminations are used to reduce energy losses that would result if a solid core were used.

Air gap[edit]

The distance between the rotor and stator is the air gap. The air gap has important effects, and is generally as small as possible, as a large gap has a strong negative effect on the performance of an electric motor. It is the main source of the low power factor at which motors operate. Air gap increases magnetizing current. For this purpose air gap should be small. Very small gaps may pose mechanical problems in addition to noise and losses.

Windings[edit]

Main article: Windings

Windings are wires that are laid in coils, usually wrapped around a laminated soft ironmagnetic core so as to form magnetic poles when energized with current.

Electric machines come in two basic magnet field pole configurations: *salient-pole* machine and *nonsalient-pole* machine. In the salient-pole machine the pole's magnetic field is produced by a winding wound around the pole below the pole face. In the *nonsalient-pole*, or distributed field, or round-rotor, machine, the winding is distributed in pole face slots.[51] Ashaded-pole motor has a winding around part of the pole that delays the phase of the magnetic field for that pole.

Some motors have conductors which consist of thicker metal, such as bars or sheets of metal, usually copper, although sometimes aluminum is used. These are usually powered byelectromagnetic induction.

Commutator[edit]

Main article: Commutator (electric)

A toy's small DC motor with its commutator

A commutator is a mechanism used to switch the input of most DC machines and certain AC machines consisting of slip ring segments insulated from each other and from the electric motor's shaft. The motor's armature current is supplied through the stationarybrushes in contact with the revolving commutator, which causes required current reversal and applies power to the machine in an optimal manner as therotor rotates from pole to pole.[52][53] In absence of such current reversal, the motor would brake to a stop. In light of significant advances in the past few decades due to improved technologies in electronic controller, sensorless control, induction motor, and permanent magnet motor fields, electromechanically commutated motors are increasingly being displaced by externally commutated induction and permanent-magnet motors.

Motor supply and control[edit]

Motor supply[edit]

A DC motor is usually supplied through slip ring commutator as described above. AC motors' commutation can be either slip ring commutator or externally commutated type, can be fixed-speed or variable-speed control type, and can be synchronous or asynchronous type.Universal motors can run on either AC or DC.

Motor control[edit]

Fixed-speed controlled AC motors are provided with direct-on-line or soft-start starters.

Variable speed controlled AC motors are provided with a range of different power inverter,variable-frequency drive or electronic commutator technologies.

The term electronic commutator is usually associated with self-commutated brushless DC motor and switched reluctance motor applications.

Major categories[edit]

Electric motors operate on three different physical principles: magnetic, electrostatic andpiezoelectric. By far the most common is magnetic.

In magnetic motors, magnetic fields are formed in both the rotor and the stator. The product between these two fields gives rise to a force, and thus a torque on the motor shaft. One, or both, of these fields must be made to change with the rotation of the motor. This is done by switching the poles on and off at the right time, or varying the strength of the pole.

The main types are DC motors and AC motors, the former increasingly being displaced by the latter.

AC electric motors are either asynchronous or synchronous.

Once started, a synchronous motor requires synchronism with the moving magnetic field's synchronous speed for all normal torque conditions.

In synchronous machines, the magnetic field must be provided by means other than induction such as from separately excited windings or permanent magnets.

A fractional horsepower (FHP) motor has a rating below about 1 horsepower (0.746 kW), or that is manufactured with a standard frame size smaller than a standard 1 HP motor. Many household and industrial motors are in the fractional horsepower class.

Type of Motor Commutation [54][55][56][57][58][59]				
Major Categories by Self-Commutated			**Externally Commutated**	
Mechanical-Commutator Motors		**Electronic-Commutator (EC) Motors**[59][b]	**Asynchronous Machines**	**Synchronous Machines**[2]
AC[60][c]	**DC**	**AC**[5, 6]	**AC**[6]	
*** Universal motor (AC commutator series motor[58] or AC/DC motor[57])[1]** *** Repulsion motor**	**Electrically excited DC motor:** *** Separately excited** *** Series** *** Shunt** *** Compound**	**With PM rotor:** *** BLDC motor** **With ferromagnetic rotor:** *** SRM**	**Three-phase motors:** *** SCIM[3, 8]** *** WRIM[4, 7, 8]** **AC motors:[10]** *** Capacitor** *** Resistance** *** Split** *** Shaded-pole**	**Three-phase motors:** *** WRSM** *** PMSM or BLAC motor[59]** **- IPMSM** **- SPMSM** *** Hybrid** **AC motors:[10]** *** Permanent-**

	PM DC motor			**split capacitor * Hysteresis * Stepper * SyRM * SyRM-PM hybrid**
Simple electronics	**Rectifier, linear transistor(s) or DC chopper**	**More elaborate electronics**	**Most elaborate electronics (VFD), when provided**	

Notes:

1. Rotation is independent of the frequency of the AC voltage.
2. Rotation is equal to synchronous speed (motor stator field speed).
3. In SCIM fixed-speed operation rotation is equal to slip speed (synchronous speed less slip).
4. In non-slip energy recovery systems WRIM is usually used for motor starting but can be used to vary load speed.
5. Variable-speed operation.
6. Whereas induction and synchronous motor drives are typically with either six-step or sinusoidal waveform output, BLDC motor drives are usually with trapezoidal current waveform; the behavior of both sinusoidal and trapezoidal PM machines is however identical in terms of their fundamental aspects.[61]
7. In variable-speed operation WRIM is used in slip energy recovery and double-fed induction machine applications.
8. A cage winding is a shorted-circuited squirrel-cage rotor, a wound winding is connected externally through slip rings.
9. Mostly single-phase with some three-phase.

Abbreviations:

- BLAC - Brushless AC
- BLDC - Brushless DC
- BLDM - Brushless DC motor
- EC - Electronic commutator
- PM - Permanent magnet
- IPMSM - Interior permanent magnet synchronous motor
- PMSM - Permanent magnet synchronous motor
- SPMSM - Surface permanent magnet synchronous motor

- SCIM - Squirrel-cage induction motor
- SRM - Switched reluctance motor
- SyRM - Synchronous reluctance motor
- VFD - Variable-frequency drive
- WRIM - Wound-rotor induction motor
- WRSM - Wound-rotor synchronous motor

Self-commutated motor[edit]

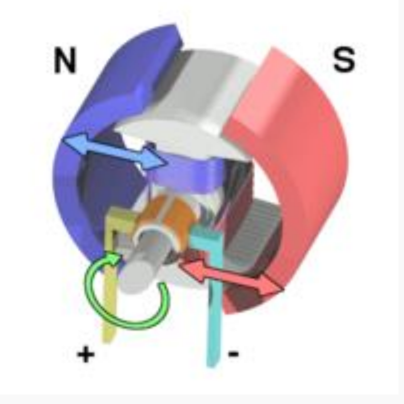
Brushed DC motor[edit]

Main article: DC motor

All self-commutated DC motors are by definition run on DC electric power. Most DC motors are small PM types. They contain a brushed internal mechanical commutation to reverse motor windings' current in synchronism with rotation.[62]

Electrically excited DC motor[edit]

Main article: Brushed DC electric motor



Workings of a brushed electric motor with a two-pole rotor and PM stator. ("N" and "S" designate polarities on the inside faces of the magnets; the outside faces have opposite polarities.)

A commutated DC motor has a set of rotating windings wound on an armature mounted on a rotating shaft. The shaft also carries the commutator, a long-lasting rotary electrical switch that periodically reverses the flow of current in the rotor windings as the shaft rotates. Thus, every brushed DC motor has AC flowing through its rotating windings. Current flows through one or more pairs of brushes that bear on the commutator; the brushes connect an external source of electric power to the rotating armature.

The rotating armature consists of one or more coils of wire wound around a laminated, magnetically "soft"ferromagnetic core. Current from the brushes flows through the commutator and one winding of the armature, making it a temporary magnet (anelectromagnet). The magnetic field produced by the armature interacts with a stationary magnetic field produced by either PMs or another winding a field coil, as part of the motor frame. The force between the two magnetic fields tends to rotate the motor shaft. The commutator switches power to the coils 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 as long as power is applied.

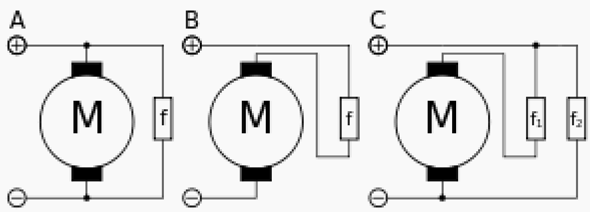
Many of the limitations of the classic commutator DC motor are due to the need for brushes to press against the commutator. This creates friction. Sparks are created by the brushes making and breaking circuits through the rotor coils as the brushes cross the insulating gaps between commutator sections. 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 generates electrical noise; sparking generates 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.

While most commutators are cylindrical, some are flat discs consisting of several segments (typically, at least three) mounted on an insulator.

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. (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.

DC machines are defined as follows:[63]

- Armature circuit - A winding where the load current is carried, such that can be either stationary or rotating part of motor or generator.
- Field circuit - A set of windings that produces a magnetic field so that the electromagnetic induction can take place in electric machines.
- Commutation: A mechanical technique in which rectification can be achieved, or from which DC can be derived, in DC machines.



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

There are five types of brushed DC motor:

- DC shunt-wound motor
- DC series-wound motor

- DC compound motor (two configurations):
    - Cumulative compound
    - Differentially compounded
- PM DC motor (not shown)
- Separately excited (not shown).

Permanent magnet DC motor[edit]

Main article: Permanent-magnet electric motor

A PM motor does not have a field winding on the stator frame, instead relying on PMs to provide the magnetic field against which the rotor field interacts to produce torque. Compensating windings in series with the armature may be used on large motors to improve commutation under load. Because this field is fixed, it cannot be adjusted for speed control. PM fields (stators) are convenient in miniature motors to eliminate the power consumption of the field winding. Most larger DC motors are of the "dynamo" type, which have stator windings. Historically, PMs could not be made to retain high flux if they were disassembled; field windings were more practical to obtain the needed amount of flux. However, large PMs are costly, as well as dangerous and difficult to assemble; this favors wound fields for large machines.

To minimize overall weight and size, miniature PM motors may use high energy magnets made with neodymium or other strategic elements; most such are neodymium-iron-boron alloy. With their higher flux density, electric machines with high-energy PMs are at least competitive with all optimally designed singly fed synchronous and induction electric machines. Miniature motors resemble the structure in the illustration, except that they have at least three rotor poles (to ensure starting, regardless of rotor position) and their outer housing is a steel tube that magnetically links the exteriors of the curved field magnets.

Electronic commutator (EC) motor[edit]

Brushless DC motor[edit]

Main article: Brushless DC electric motor

Some of the problems of the brushed DC motor are eliminated in the BLDC design. In this motor, the mechanical "rotating switch" or commutator is replaced by an external electronic switch synchronised to the rotor's position. BLDC motors are typically 85–90% efficient or more. Efficiency for a BLDC motor of up to 96.5% have been reported,[64] whereas DC motors with brushgear are typically 75–80% efficient.

The BLDC motor's characteristic trapezoidal back-emf waveform is derived partly from the stator windings being evenly distributed, and partly from the placement of the rotor's PMs. Also known as electronically commutated DC or inside out DC motors, the stator windings of trapezoidal BLDC motors can be with single-phase, two-phase or three-phase and use Hall effect sensors mounted on their windings for rotor position sensing and low cost closed-loop control of the electronic commutator.

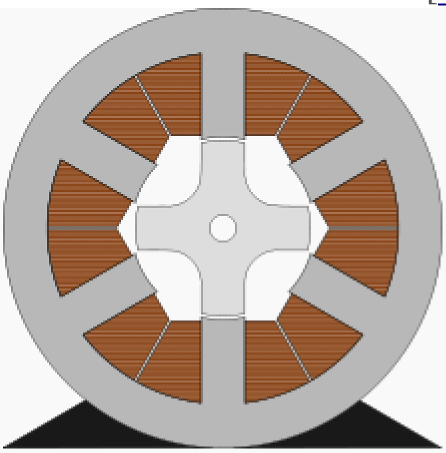
BLDC motors are commonly used where precise speed control is necessary, as in computer disk drives or in video cassette recorders, the spindles within CD, CD-

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 BLDC 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 BLDC 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 convenienttachometer signal for closed-loop control (servo-controlled) applications. In fans, the tachometer signal can be used to derive a "fan OK" signal as well as provide running speed feedback.
- The motor can be easily synchronized to an internal or external clock, leading to precise speed control.
- BLDC 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.
- BLDC motors are usually used in small equipment such as computers and are generally used in fans to get rid of unwanted heat.
- They are also acoustically very quiet motors which is an advantage if being used in equipment that is affected by vibrations.

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

Switched reluctance motor[edit]



6/4 pole switched reluctance motor

Main article: Switched reluctance motor

The SRM has no brushes or PMs, and the rotor has no electric currents. Instead, torque comes from a slight misalignment of poles on the rotor with poles on the stator. The rotor aligns itself with the magnetic field of the stator, while the stator field stator windings are sequentially energized to rotate the stator field.

The magnetic flux created by the field windings follows the path of least magnetic reluctance, meaning the flux will flow through poles of the rotor that are closest to the energized poles of the stator, thereby magnetizing those poles of the rotor and creating torque. As the rotor turns, different windings will be energized, keeping the rotor turning.

SRMs are now being used in some appliances.[65]

Universal AC-DC motor[edit]

Main article: Universal motor

Modern low-cost universal motor, from a vacuum cleaner. Field windings are dark copper-colored, toward the back, on both sides. The rotor's laminated core is gray metallic, with dark slots for winding the coils. The commutator (partly hidden) has become dark from use; it is toward the front. The large brown molded-plastic piece in the foreground supports the brush guides and brushes (both sides), as well as the front motor bearing.

A commutated electrically excited series or parallel wound motor is referred to as a universal motor because it can be designed to operate on both AC and DC power. A universal motor can operate well on AC because the current in both the field and the armature coils (and hence the resultant magnetic fields) will alternate (reverse polarity) in synchronism, and hence the resulting mechanical force will occur in a constant direction of rotation.

Operating at normal power line frequencies, universal motors are often found in a range less than1000 watts. Universal motors also formed 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 and they are now rarely used.

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. 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). Universal motors also lend themselves to electronic speed controland, as such, are an ideal choice for devices like 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.

Whereas SCIMs cannot turn a shaft faster than allowed by the power line frequency, universal motors can run at much higher speeds. This makes them useful for appliances such as blenders, vacuum cleaners, and hair dryers where high speed and light weight are 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 many similar miniature grinders exceed30,000 rpm.

Externally commutated AC machine[edit]

Main article: AC motor

The design of AC induction and synchronous motors is optimized for operation on single-phase or polyphase sinusoidal or quasi-sinusoidal waveform power such as supplied for fixed-speed application from the AC power grid or for variable-speed application from VFD controllers. An AC motor has two parts: a stationary stator having coils supplied with AC to produce a rotating magnetic field, and a rotor attached to the output shaft that is given a torque by the rotating field.

Induction motor[edit]

Main article: Induction motor

Cage and wound rotor induction motor[edit]

An induction motor is an asynchronous AC motor where power is transferred to the rotor by electromagnetic induction, much like transformer action. 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 Induction Motors and Wound Rotor Induction Motors. SCIMs have a heavy winding made up of solid bars, usually aluminum or copper, joined by rings at the ends of the rotor. When one considers only the bars and rings as a whole, they are much like an animal's rotating exercise cage, hence the name.

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 be in the outer parts of the rotor cage. As the motor accelerates, the slip frequency becomes lower, and more current is in the interior of the winding. By shaping the bars to change the resistance of the winding portions in the interior and outer parts of the cage, effectively a variable resistance is inserted in the rotor circuit. However, the majority of such motors have uniform bars.

In a WRIM, 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 through an inverter or separate motor-generator.

The WRIM 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.

Force and torque[edit]

The fundamental purpose of the vast majority of the world's electric motors is to electromagnetically induce relative movement in an air gap between a stator and rotor to produce useful torque or linear force.

According Lorentz force law the force of a winding conductor can be given simply by:

$$\mathbf{F} = I\boldsymbol{\ell} \times \mathbf{B}$$

or more generally, to handle conductors with any geometry:

$$\mathbf{F} = \mathbf{J} \times \mathbf{B}$$

The most general approaches to calculating the forces in motors use tensors.[79]

Power[edit]

Where rpm is shaft speed and T is torque, a motor's mechanical power output P_{em} is given by,[80]

in British units with T expressed in foot-pounds,

$$P_{em} = \frac{rpm \times T}{5252}$$ (horsepower), and,

in SI units with shaft angular speed expressed in radians per second, and T expressed in newton-meters,

$P_{em} = angularspeed \times T$ (watts).

For a linear motor, with force F expressed in newtons and velocity v expressed in meters per second,

$P_{em} = F \times v$ (watts).

In an asynchronous or induction motor, the relationship between motor speed and air gap power is, neglecting skin effect, given by the following:

$P_{airgap} = \frac{R_r}{s} * I_r^2$, where

R_r - rotor resistance

I_r^2 - square of current induced in the rotor

s - motor slip; ie, difference between synchronous speed and slip speed, which provides the relative movement needed for current induction in the rotor.

Goodness factor[edit]

Main article: Goodness factor

Professor Eric Laithwaite[82] proposed a metric to determine the 'goodness' of an electric motor:[83] $G = \frac{\omega}{resistance \times reluctance} = \frac{\omega\mu\sigma A_m A_e}{l_m l_e}$

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

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