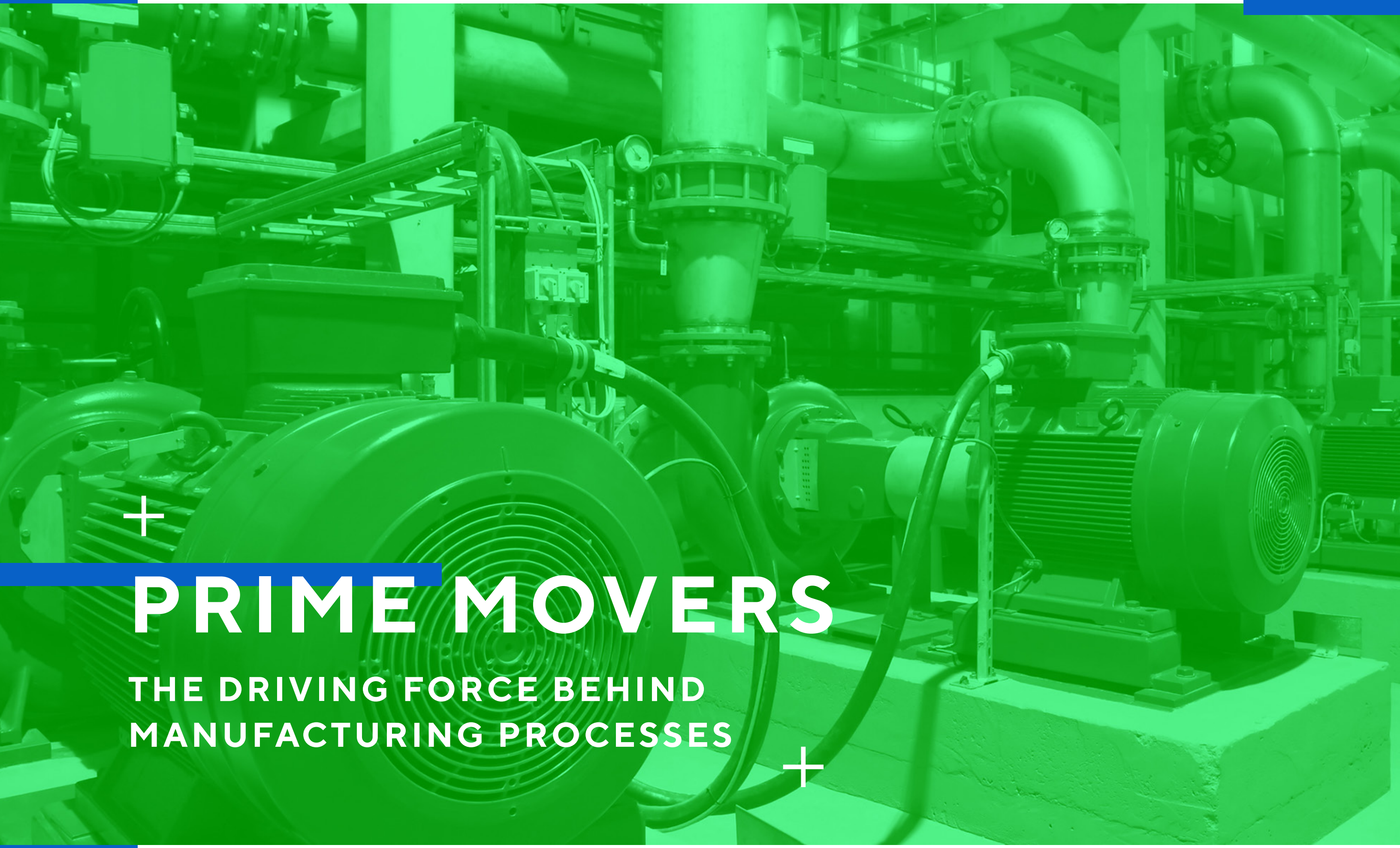

PRIME MOVERS

THE DRIVING FORCE BEHIND MANUFACTURING PROCESSES

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WHAT IS A PRIME MOVER?

All motors and engines are considered to be prime movers, the originating source of movement. While a motor converts applied energy to torque (rotational force), an *engine* usually converts raw material to reciprocating force, and then the crankshaft converts it to torque. The distinctions are often blurred in general discussion; however, it is important to understand how specific equipment operates in order to design the best possible Reliability Program. The goal of this white paper is to describe the various types of electric motors/engines and their principles of operation, common uses, and advantages/disadvantages.

HOW ELECTRIC MOTORS WORK

ELECTRICITY AND MAGNETISM

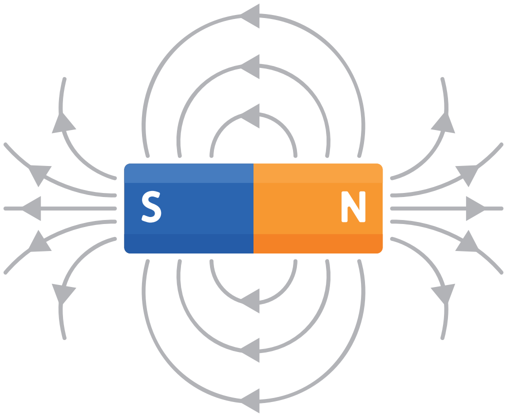

Figure 1: Magnetic Field (Source: iStock)

Let's start with the basics. Electrical force and magnetism are what make electric motors work. As shown in the below diagram of a magnetic field, magnetic lines of force exit the magnetic object from the North Pole and enter at the South Pole, creating a surrounding *field*. The lines of force do not actually move in the directions indicated; they are more of a *slope* that affects the movement of other things. They influence nearby objects, based on the strength and density of the lines within the magnetic field. If the near object is also magnetized, like poles will push against each other, and unlike poles will be attracted to each other. **The density and strength of lines of force are dependent on the materials from which the object is made.**

When an electrically conductive material (a wire) is placed within a strong enough electrical or magnetic field (near a magnetic source), the dipoles (electron-proton pairs) align with the magnetic field, and then they just sit there. But if the conductor is moved within the field, or into and out of the field, an opposing voltage is induced into the conductive material. If sufficient voltage is induced and the circuit is completed (a way in and a way out), current is generated in the conductor. This is caused by the unpaired electrons (-) moving toward the south-attracting or North (+) side. But this can only occur electrically when either the conductor moves or the magnetic field changes. **A motor or generator operates because field changes result in magnetic attraction and repulsion.**

In short, a magnetic or electrical field develops lines of force that cause opposing lines of force to develop in specific materials where they intersect. These lines of force cause a magnetic field to develop in an intersecting object, resulting in a voltage. **Current flow cannot occur unless there is a way in and a way out.**

The forces developed by a single wire passing through the magnetic field will usually be very small. Several things are done to increase these resultant forces to a useful level. The force (strength of the originating magnet) can be increased, the number of lines of force can be increased, the number of wires on the receiving side can be increased, or the number of times we move the wire through the field can be increased. To increase the strength of the originating magnet, we use an electromagnet. When electric current passes through certain materials, it results in a field of magnetism around the object. **The field shape and strength depend on the shape and type of material, as well as the amount of current passing through it.**

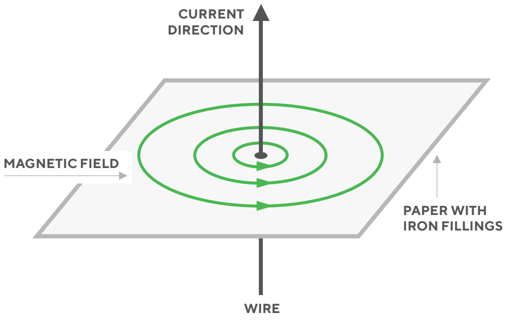

Figure 2: Electrical Current Direction (Source: iStock)

There are differing opinions about the direction of flow in electrical circuits. Some insist that flow is from positive to negative, others believe it flows from negative to positive. Suffice it to say that if a voltage source of any polarity is applied to a circuit, with the other end of the circuit connected to either an opposite polarity or a neutral/ground, the current will flow instantaneously. All calculations and designs will work either way if the chosen polarity scheme is constantly used throughout. For clarity, however, it is best to refer to pole IDs as positive or negative poles, rather than north or south.

The shape of the field around a single wire is circular and perpendicular to the direction of current flow (positive to negative). The field direction can be found by pointing your right thumb in the direction of flow and curling your fingers. The lines of force (flux) point in the direction that your fingers are pointing. Again, a single wire seldom produces useful field strength.

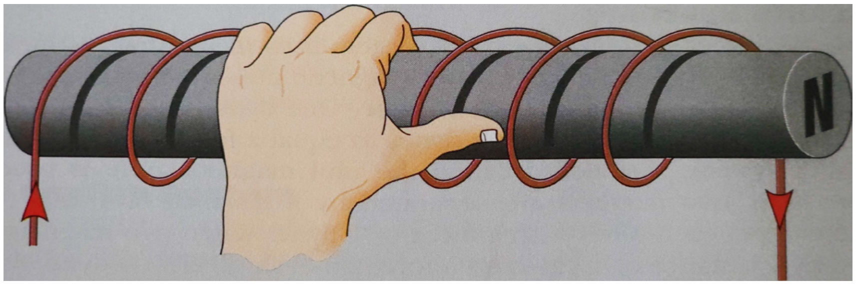

Figure 3: The left-hand rule can be used to determine the polarity of an electromagnet.
(Source: Delmar's Standard Textbook of Electricity, 2nd Edition, page 84)

If the wire is taken and coiled up before turning on the current, the lines of force where the coils are in proximity interact with each other and combine to form an overall much stronger field through the center of the coil. The polarity of this field can be found the same way, by curling the fingers of your right hand in the direction of the current flow around the coil. Your thumb will point toward the negative or south pole of the resultant magnetic field. The field strength can be further strengthened by using a core material that gathers or funnels the flux lines, increasing the flux density. Of course, increasing the applied voltage will also mean increased current and, therefore, a stronger magnet.

On the receiving, or induced, field side, we can place several wires (same shape and size) through the field at the same path and speed. If we connect these wires at each end, we get twice the current induced. Again, this effect can be accomplished by coiling the wire into the desired direction and shape and moving the entire coil through the field. The induced magnetic field will be opposite in polarity to the causative or supplied field. The difference in polarity is due to the nature of magnetism (opposites attract, likes repel, and induced charges are opposite in polarity from the inducing charge). If, by the time a magnetic pole reaches the attracting pole, the original attracting pole has changed polarity, the magnet that is free to move would then be repelled and be attracted by another attracting pole.

OPERATING PRINCIPLES

All motors, whether AC or DC, run because of magnetic fields that continually 'chase' themselves around in a circle. The exact physical construction depends on several factors, such as the amount of torque needed, the available electrical supply, speed requirements, etc. The magnetic field of either the rotor or stator is continually changing, causing attraction or repulsion in a circular pattern. This means that to achieve the rotating effect, there must be two electric fields that interact with each other. Different types of motors accomplish this in different ways, with different effects on the outcome and different uses.

DC VS. AC MOTORS

DC (Direct Current) Motors

DC motors were the first and most widely used since they could be powered by early direct-current lighting power distribution systems. This lightweight, universal motor can operate on direct current, making it ideal for portable power tools, appliances, and even toys. Larger DC motors are used in the propulsion of electric vehicles, elevators, and hoists, or in drives for steel rolling mills. A DC motor's speed can be controlled over a wide range, using either a variable supply voltage or by changing the strength of current in its field windings.

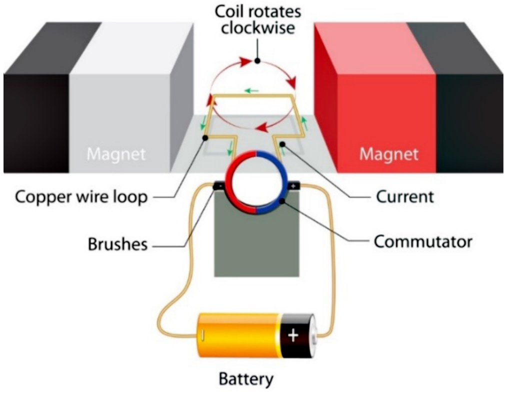

Figure 4: . A simple electric motor. (Source: iStock)

DC motors can also operate directly from rechargeable batteries, providing the impetus for the first electric vehicles and today's more advanced hybrid cars and fully electric cars, as well as driving a host of cordless tools. The advent of power electronics has made the replacement of DC motors with AC motors possible in many applications, in which the voltage is adjusted by 'chopping' the DC current into on-and-off cycles that have an effective lower voltage.

The basic construction of a DC motor contains a current-carrying armature, which is connected to the supply end through commutator segments and brushes. The armature is placed in between the north and south poles of a permanent magnet or an electromagnet, as shown in the diagram above.

The battery creates an 'N' pole on the left and an 'S' pole on the right rotor segment. As the rotor turns, the torque (F) carries it through the perpendicular angles since the commutator segments also rotate, switching polarity. This causes the rotor poles to switch polarity and become attracted to the next position in rotation.

Basically, DC motor speed is controlled by inserting resistance into the rotor circuit; thereby, controlling the rotor current, which determines torque and speed.

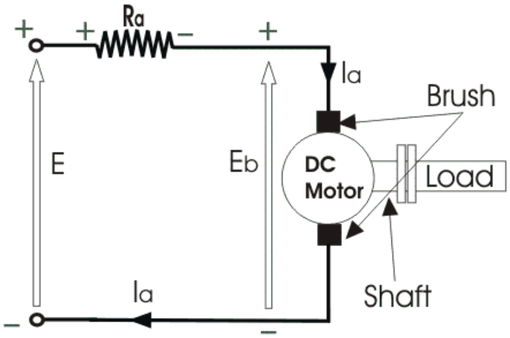

Figure 5: Detailed description of a DC motor. E is the supply voltage, Eb is the back EMF produced, and Ia and Ra are the armature current and armature resistance, respectively. The back EMF produced balances the supply voltage.
(Source: www.electrical4u.com/dc-motor-or-direct-current-motor)

Different numbers of stator and armature fields, as well as how they are connected, also provide different inherent speed/torque regulation characteristics, allowing the speed of a DC motor to be controlled by simply changing the voltage applied to the armature.

The sequence of turning a specific coil on or off dictates what direction the electromagnetic fields are pointed in. By turning coils on and off in sequence, a rotating magnetic field can be created. These rotating magnetic fields interact with the magnetic fields of the magnets (permanent or electromagnets) in the stationary part of the motor (stator) to create a force on the armature that causes it to rotate. In some DC motor designs, the stator fields use electromagnets to create their magnetic fields, which allow greater control over the motor. At high power levels, DC motors are almost always cooled using forced air.

There are three types of electrical connections between the stator (field) and rotor (armature) in DC electric motors: 1) series, 2) shunt/parallel, and 3) compound (various blends of series and shunt/parallel). Each connection type has its unique speed/torque characteristics appropriate for different loading torque profiles or signatures.

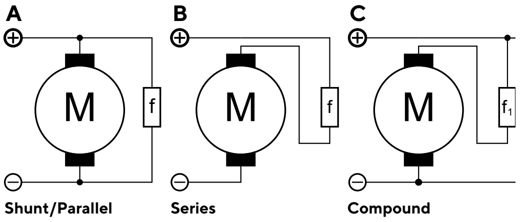

Figure 6: Electrical connection types in DC motors.
(Source: en.wikipedia.org/wiki/File:Serie_Shunt_Coumpound.svg)

A. Shunt connection

A shunt DC motor connects the armature and field windings in shunt, or parallel, with a common DC power source. This type of motor has good speed regulation, even as the load varies, but does not have the starting torque of a series DC motor. It is typically used for industrial, adjustable speed applications (such as machine tools), winding/unwinding machines, and tensioners.

B. Series connection

A series DC motor connects the armature and field windings in series with a common DC power source. The motor speed varies as a non-linear function of load torque and armature current; current is common to both the stator and rotor yielding current squared (I2) behavior. A series motor has very high starting torque and is commonly used for starting high inertia loads, such as trains, elevators, or hoists. This speed/torque characteristic is useful in applications such as dragline excavators, where the digging tool moves rapidly when unloaded but slowly when carrying a heavy load.

A series motor should never be started at no load. With no mechanical load on the series motor, the current is low, the counter-EMF produced by the field winding is weak, and so the armature must turn faster to produce sufficient counter-EMF to balance the supply voltage. The motor can be damaged by overspeed. This is called a 'runaway' condition.

The series-wound DC motor develops its highest torque at low speed; therefore, it is often used in traction applications, such as electric locomotives and trams. For many years, the DC motor was the mainstay of electric traction drives on both electric and diesel-electric locomotives, streetcars/trams, and diesel-electric drilling rigs. The introduction of DC motors and an electrical grid system to run machinery starting in the 1870s marked the beginning of a new 2nd Industrial Revolution.

Some series DC motors, called 'universal' motors, can also be used on alternating current. Battery power tools commonly have universal motors. Since the armature voltage and the field direction reverse at the same time, torque continues to be produced in the same direction. However, they run at a lower speed with lower torque on AC supply when compared to DC due to reactance voltage drop in AC, which is not present in DC. Since the speed is not related to the line frequency, universal motors can develop higher-than-synchronous speeds, making them lighter than induction motors of the same rated mechanical output. This is a valuable characteristic of handheld power tools.

Universal motors designed for commercial utility are usually of small capacity, not more than about 1 kW output. However, much larger universal motors are used for electric locomotives, fed by special low-frequency traction power networks to avoid problems with commutation under heavy and varying loads.

C. **Compound connection**
A series DC motor connects the armature and field windings in series with a common DC power source. The motor speed varies as a non-linear function of load torque and armature current; current is common to both the stator and rotor yielding current squared (I2) behavior. A series motor has very high starting torque and is commonly used for starting high inertia loads, such as trains, elevators, or hoists. This speed/torque characteristic is useful in applications such as dragline excavators, where the digging tool moves rapidly when unloaded but slowly when carrying a heavy load.

AC (ALTERNATING CURRENT) MOTORS

AC motors include many motor configurations and various types, such as single-phase and multi-phase. For this discussion, multi-phase means supplied with 3-phase power; however, 2-phase and 6-phase motors also exist. While most of these motors are typically either AC single- or multi-phase, there is a universal type that uses both AC single-phase and direct current (DC).

The two main classes of AC motors are induction and synchronous.

Induction motor (or asynchronous motor) – relies on a small difference in speed between the stator rotating magnetic field and the rotor shaft speed, called 'slip,' to induce rotor current in the rotor AC winding. Thus, the induction motor cannot produce torque near synchronous speed, where induction (or slip) is irrelevant or ceases to exist.

Synchronous motor – uses either permanent magnets, salient poles (projecting magnetic poles), or an independently excited rotor winding. The synchronous motor produces its rated torque at exactly synchronous speed. The brushless, wound-rotor, doubly fed synchronous motor system has an independently excited rotor winding that does not rely on the principles of slip induction of current. It functions exactly at the supply frequency, or at some fraction/multiple of the supply frequency.

Other types of motors include eddy current motors and AC/DC mechanically commutated machines, in which speed is dependent on voltage and winding connection.

When an AC source is supplied to the stator winding, flux is generated in the coil due to flow of current in the coil. The rotor winding is arranged in such a way that windings are short-circuited in the rotor itself. The flux from the stator will cut the coil in the rotor and since the rotor coils are short-circuited, current will start flowing in the coil of the rotor. When current flows, another flux is generated in the rotor. Now there are two flux fields, one is stator flux and another is rotor flux, and the rotor flux will lag with respect to the stator flux; thus, creating an offset. Due to this, the rotor will feel a torque that causes it to rotate in the direction of the rotating magnetic flux. So, the speed of the rotor depends on the AC supply frequency, and the speed can be controlled by varying either the frequency or the number of poles in the stator. This is the working principle of an induction motor of either single or three phases. A 3-phase induction motor is self-starting; a single-phase induction motor is not self-starting.

A 3-phase system has three alternating current supply phases with 120° timing difference. The fields induced in the rotor are opposite in polarity to the supplied field in the stator. The rotating magnetic field has a repeating phase difference, which will cause the rotor to feel a flux offset and develop torque. This causes it to move (rotate). If we consider three phases A, B, and C, when phase A is magnetized, the rotor will move towards the phase A winding; in the next moment, phase A reverses polarity; phase B will get magnetized, and it will attract the rotor; and this repeats with phase C. So, the rotor will continue to rotate.

There are two construction types of 3-phase rotors: squirrel cage and slip ring.

SQUIRREL CAGE:

A squirrel cage consists of metal bars mounted between shorting rings. A wound rotor is coils of wire laid into rotor slots to form poles, possibly with internal connections brought out to slip rings. Of the rotor images depicted below, A and B are wound rotors, while C is a cage rotor. Both A and B show a wound rotor with external connections to slip rings (right end) and a commutator (far end), respectively. Cage rotor bars are often skewed to prevent rotor lock.

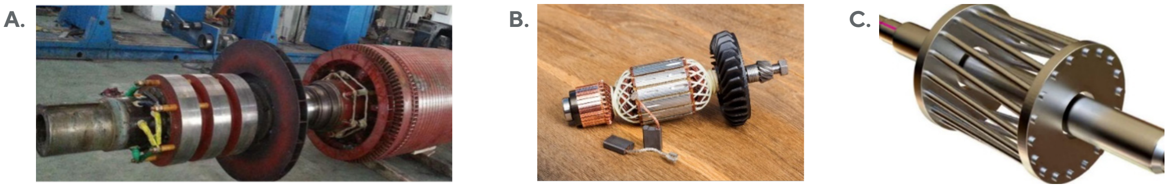

Figure 7: Wound vs. cage rotors. (Source: iStock)

Compared to cage rotors, wound rotor motors are expensive and require maintenance of the slip rings, commutators, brushes, and air passages; but they were the standard form for AC 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.

This motor is also called an ‘asynchronous’ motor because it runs at a speed less than its synchronous speed. Synchronous speed is the speed of rotation of the magnetic field in a rotary machine, and it depends on the frequency and number of poles in the stator. An induction motor always runs at a speed less than synchronous because the rotating magnetic field that is produced in the stator will generate flux in the rotor to make the rotor rotate. But due to the lagging of flux in the rotor relative to the stator, the rotor will never reach its rotating magnetic field speed (i.e. the synchronous speed).

A single-phase motor is not self-starting. A standard AC supply is a sinusoidal wave and produces a pulsating magnetic field in the uniformly distributed stator winding. On startup, the fields counter each other, and no torque is developed. To develop torque, one of the flux fields must be rotating or changing to provide a flux offset. When powered by a single phase, if the rotor is made to rotate in either direction by an applied force, it will start to turn. Therefore, several ways to electrically start a single-phase motor have been developed. One design splits the stator winding into two sections, physically offset from each other; the main winding and an auxiliary winding, with a capacitor in series with the auxiliary winding. This will make a timing difference when current is supplied to both coils. With the timing difference, the rotor will generate a flux offset, resulting in starting torque and rotation.

There are several other types of single-phase designs to get the motor started:
- Split phase (described above)
- Capacitor start
- Capacitor start capacitor run
- Shaded pole

The half-round protrusions on the motors pictured below are casings for capacitors. The box on top of the third picture encases both capacitor and power terminals. The start method should be shown on a 1-Ph motor nameplate and recorded in the Specifications sheet.


1.
2.
3.

Figure 8: Motor casings for capacitors. (Source: Photos provided by Allied Reliability)

A single-phase power system is widely used instead of a 3-phase system for domestic and commercial office/utility purposes – less so in industry. More economical for low power applications, single-phase motors are simple in construction and cost, reliable, and relatively easy to maintain. Due to these advantages, the single-phase motor is used in vacuum cleaners, fans, washing machines, centrifugal pumps, blowers, small toys, etc. The single-phase AC motors are further classified in the diagram below.

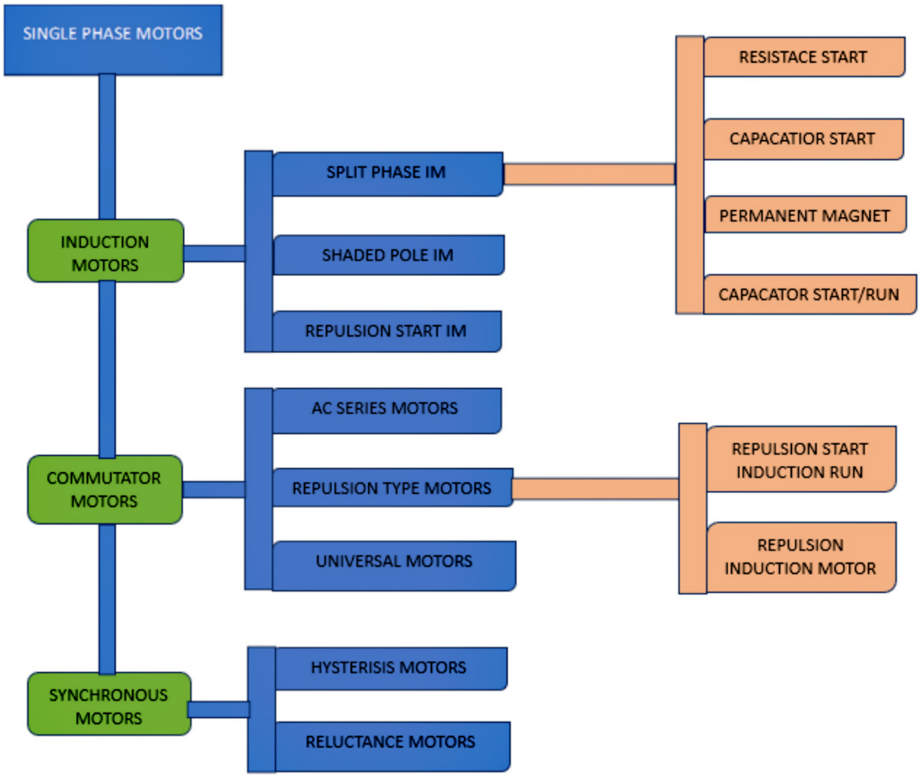

Figure 9: Motor classifications (Source: Diagram drawn by this author)

Some single-phase motors have commutators and brushes to provide the second flux current to the rotor. This is sometimes referred to as 'excitation.' This type of motor will have connections on one end of the casing, enclosing spring-mounted brush holders, and brush inspection or replacement must be included in any maintenance program. Induction, synchronous, and repulsion motors are also available in multi-phase design.

INDUCTION MOTORS

Three-phase Induction motors have been called the 'workhorse of industry.' In addition to being the most common type of motor, the operating principles can be used as a basis for many other types. They operate on the simplest and most basic principles, with very little deviation. An induction motor may be either single-phase or multi-phase, and is always AC.

Advantages and disadvantages of induction motors

There are several advantages of induction motors that contribute to their wide usage. Motor efficiency is defined as the percentage use of input power, and typical induction motors have high efficiency, up to 97%. Control and direction change are also simple. The direction of rotation of a 3-phase induction motor can easily be changed by changing the sequence of the 3-phase supply. In a single-phase motor, the direction can be reversed by reversing the capacitor terminals in the winding. These can both be easily accomplished in the starter circuit wiring. Other advantages are less armature reaction, no brush sparking because of the absence of commutators and brushes, rugged industrial construction, economical to purchase and install, ready availability, and ease of maintenance. A final advantage is the ability to brake the motor by plugging (reversing the applied source), or by using dynamic or regenerative braking. It is also fairly easy to control the speed in steps by:

- Reconfiguring the number of poles at the starter
- Inserting resistance into the rotor circuit of a wound rotor (rotor current affects slip, slip affects speed)

Note: The recent development of variable frequency drives has greatly simplified AC speed control, making these motors 'old school.'

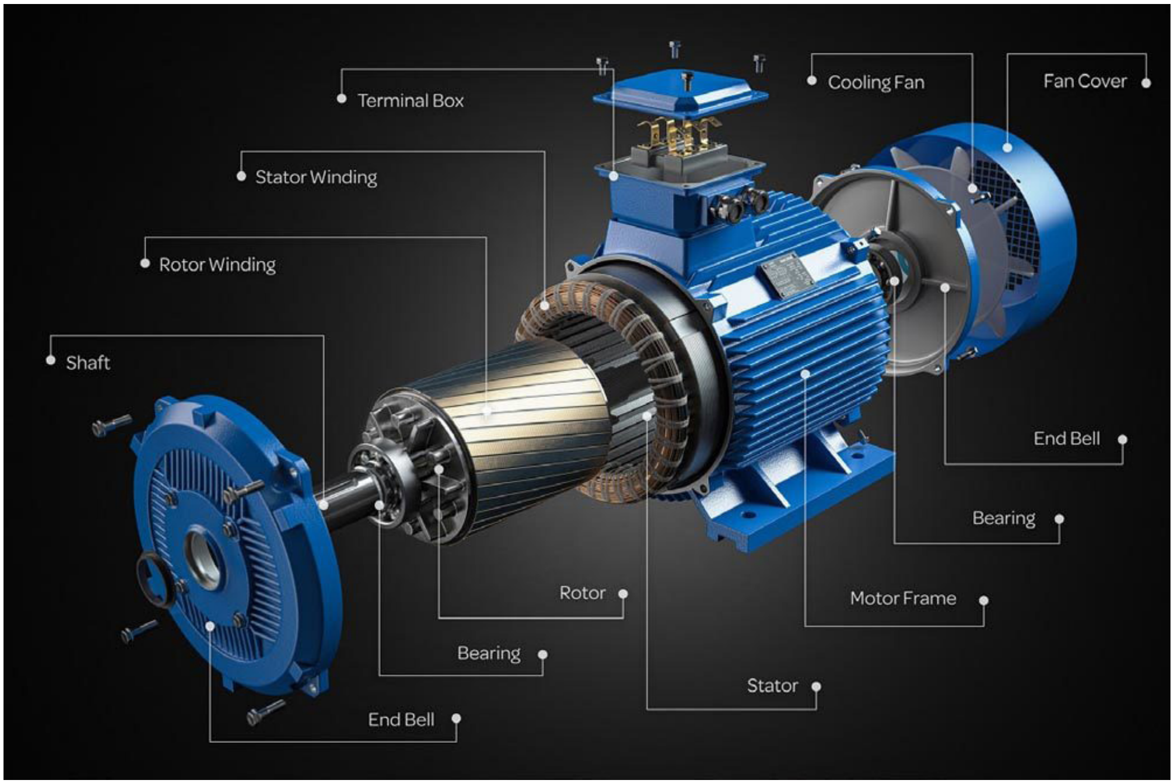

Figure 10: Cut-away view of wound rotor motor with no slip rings (Source: iStock)

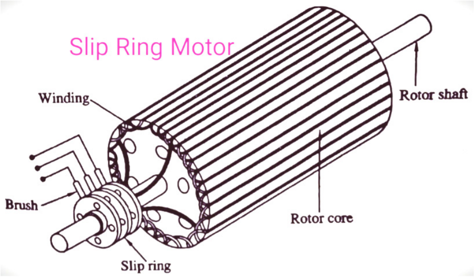

Figure 11: . Cut-away view of wound rotor motor with slip rings. (Source: www.intechopen.com/chapters/73820)

The main disadvantage of induction motors is that the speed varies with the mechanical load (slip increases). This effect is mitigated by careful sizing of the motor to the expected load. The speed can never exceed the design speed (when supplied as designed), but installation of a motor adequate to all mechanical requirements can reduce the occurrences where the motor tries to stall or slip.

SYNCHRONOUS MOTORS

Synchronous motors are used in timing applications, such as in synchronized clocks, timers in appliances, tape recorders, and precision servomechanisms in which the motor must operate at a precise speed. Speed accuracy is that of the power line frequency, which is carefully controlled in large, interconnected grid systems. They range from sub-fractional, self-excited sizes to high-horsepower industrial sizes.

- In the *fractional horsepower* range, most synchronous motors are used where precise, constant speed is required. These machines are commonly used in analog electric clocks, timers, and other devices where the correct time 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 a leading or unity power factor and, thereby, provide power-factor correction.

As previously discussed, when a 3-phase electric conductor is placed in certain geometrical positions (at an angle from one another), an electrical field is generated. If an electromagnet is present in this rotating magnetic field, the electromagnet is magnetically locked with the rotating magnetic field and rotates at the same speed as the rotating field.

In synchronous motors, the speed of the rotor is the same as the rotating magnetic field. It is basically a fixed-speed motor because it has only one speed, which is a synchronous speed, and therefore has no intermediate speed. In other words, it's in *sync* with the supply frequency.

Synchronous speed is given by **SS in rpm = 120 X f in cycles per sec ÷ P**

Where:

f = supply frequency

P = no. of pole-pairs

120 = constant showing # seconds per minute (60) X # peaks per cycle (2); thus, representing # power peaks per minute (1 negative, 1 positive). This allows the equation to be balanced with UOMs canceling.

You may also encounter non-excited synchronous motors, where the rotor is made of steel. At synchronous speed, it rotates in step with the rotating magnetic field of the stator, so it has an almost-constant magnetic field through it. The external stator field magnetizes the rotor, inducing the magnetic poles needed to turn it. The rotor is made of a high-retentivity material, such as cobalt steel. These motors are manufactured in permanent magnet, reluctance, and hysteresis designs (to be described later).

The stator is connected to a 3-phase AC supply and the rotor to a DC supply.

Characteristics

- Above a certain small size, synchronous motors are inherently not self-starting because they do not develop enough starting torque to overcome static inertia.
- They require some external means to bring their speed close to synchronous speed before they are synchronized.
- The speed of operation is in sync with the supply frequency and, hence, for constant supply frequency they behave as a constant speed motor irrespective of load condition.
- This motor has the unique characteristic of operating electrically under any power factor, either lagging or leading. This makes it useful in electrical power factor improvement.
- It can stall if, while running, counter torque (mechanical load) is increased beyond the maximum torque that the machine can develop.

Methods of starting synchronous motors

MOTOR STARTING WITH AN EXTERNAL PRIME MOVER:

Synchronous motors can be mechanically coupled with another motor. It could be either a 3-phase induction motor or a DC shunt motor. DC excitation to the synchronous motor is not fed initially. It is rotated and brought to speed very close to its synchronous speed, then DC excitation is applied. Once magnetic locking takes place, supply to the starting motor is cut off.

DAMPER WINDING:

In this case, the synchronous motor is of the salient pole type, with an additional winding placed in the rotor pole face. When the rotor is at an initial standstill, the relative speed between the damper winding and rotating air gap flux causes an induced emf, which produces the required starting torque. As rotation approaches synchronous speed, emf and torque are reduced. When the magnetic lock is achieved, torque reduces to zero. So, this synchronous motor is first run as a 3-phase induction motor using additional winding and finally, it is synchronized with the frequency.

POLYPHASE WOUND ROTOR MOTORS

The term 'wound rotor' is used in two ways. It can refer to the construction of a motor rotor (coils of wires placed in slots in the rotor), or it can refer to a subclass of AC induction motors that were used for many years when variable speed control was 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 a controller, such as a variable resistor, which 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, 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 in general use, although more common in traction applications, such as locomotives where, when used with a reduced voltage starter, it is known as an 'asynchronous traction' motor.

Methods of starting polyphase wound rotors

ACROSS-THE-LINE START:

Where a large inrush current and high starting torque are permitted, the motor can be started across the line, by applying full line voltage to the terminals.

REDUCED VOLTAGE START:

When it is necessary to limit the starting inrush current (where the motor is large compared with the short-circuit capacity of the supply), the motor is started at a reduced voltage – using either series inductors, an autotransformer, thyristors, or other devices.

STAR-DELTA START:

With the star-delta (YΔ) technique, the motor coils are initially connected in a 'star' configuration for acceleration of the load, then switched to a 'delta' configuration when the load is up to speed. This reduces the start torque due to opposing flux effects in the rotor windings, thus, reducing the speed profile. This technique is more common in Europe than in North America but can still be found in some applications.

Note: Transistorized drives can directly vary the applied voltage and/or frequency as required, thus, controlling/gradually increasing both torque and speed.

SERVOMOTOR SYSTEMS (USUALLY 2-PHASE)

A typical AC servomotor has a squirrel cage rotor and a magnetic field consisting of two windings:

1. Constant-voltage (AC) main winding
2. Control-voltage (AC) winding in quadrature (90 degrees phase shifted) with the main winding, which produces a rotating magnetic field. Reversing the 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 servomotors are inherently high-speed, low-torque devices heavily geared down to drive the load.

A servomotor is a closed-loop servomechanism that uses position feedback to control its motion and final position. The input to its control is a signal (either analogue or digital) representing the position commanded for the output shaft.

The motor is paired with some type of encoder to provide position and speed feedback. In the simplest case, only the position is measured. The measured position of the output is compared to the command position, the external input to the controller. If the output position differs from that required, an error signal is generated, which then causes the motor to rotate in either direction, as needed to bring the output shaft to the appropriate position. As the positions approach, the error signal reduces to zero and the motor stops.

The very simplest servomotors use position-only sensing via a potentiometer and bang-bang control of their motor (the motor rotates at full speed or is stopped). This type of servomotor is not widely used in industrial motion control, but it forms the basis of the simple and cheap servos used for radio-controlled models.

More sophisticated servomotors use optical rotary encoders to measure the speed of the output shaft and a variable-speed drive to control the motor speed. Both enhancements, usually in combination with a PID control algorithm, allow the servomotor to be brought to its commanded position more quickly and more precisely, with less overshooting.

Servomotors vs. stepper motors

A servomotor consumes power as it rotates to the commanded position, after which it rests. Stepper motors continue to consume power to lock in and hold the commanded position.

Servomotors are generally used as a high-performance alternative to the stepper motor. Stepper motors have some inherent ability to control position, as they have built-in output steps. This often allows them to be used as an open-loop position control, without any feedback encoder, as their drive signal specifies the number of steps of movement to rotate; but for this, the controller needs to know the position of the stepper motor on power up. Therefore, on first power up, the controller must activate the stepper motor and turn it to a known position, e.g. until it activates an end limit switch. This can be observed when switching on an inkjet printer – the controller will move the ink jet carrier to the extreme left and right to establish the end positions. A servomotor will immediately turn to whatever angle the controller instructs it to, regardless of the initial position at power up.

The lack of feedback of a stepper motor limits its performance, as it can only drive a load that is well within its capacity; otherwise, missed steps under load may lead to positioning errors, and the system may have to be restarted or recalibrated. The encoder and controller of a servomotor are an additional cost, but they optimize the performance of the overall system (for speed, power, and accuracy) relative to the capacity of the basic motor. With larger systems, where a powerful motor represents an increasing proportion of the system cost, servomotors have the advantage.

Closed-loop stepper motors have gained more popularity in recent years. They act like servomotors, but some differences in their software control allow smooth motion. The top three manufacturers of closed-loop stepper motor systems employ magnetic encoders as their feedback device of choice due to low cost and resistance to vibration. The main benefit of a closed-loop stepper motor is the cost-to-performance ratio. There is also no need to tune the PID controller on a closed-loop stepper system.

Many applications, such as laser cutting machines, may be offered in two ranges: the low-priced range using stepper motors and the high-performance range using servomotors.

Encoders

The first servomotors were developed with synchro's as their encoders. Much of the technology for these systems was developed for radar and anti-aircraft artillery during World War II. They have also been used for remote antenna positioning.

Simple servomotors may use resistive potentiometers as their position encoder. These are only used at the very simplest and cheapest level and are in close competition with stepper motors. They suffer from wear and electrical noise in the potentiometer track. Although it would be possible to electrically differentiate their position signal to obtain a speed signal, PID controllers that can make use of such a speed signal generally warrant a more precise encoder.

Modern servomotors use 'rotary' encoders, either absolute or incremental. Absolute encoders can determine their position at power-on but are more complicated and expensive. Incremental encoders are simpler, cheaper, and work at faster speeds. Incremental systems, like stepper motors, often combine their inherent ability to measure intervals of rotation with a simple zero-position sensor to set their position at startup.

Instead of servomotors, sometimes a motor with a separate, external linear encoder is used. These motor + linear encoder systems avoid inaccuracies in the drivetrain between the motor and linear carriage, but their design is made more complicated as they are no longer a pre-packaged, factory-made system.

Servo motor types

The type of motor is not critical to a servomotor and different types may be used. At the simplest, brushed, permanent magnet DC motors are used due to their simplicity and low cost. Small industrial servomotors are typically electronically commutated, brushless motors. For large industrial servomotors, AC induction motors are typically used, often with variable frequency drives to allow control of their speed. For ultimate performance in a compact package, brushless AC motors with permanent magnet fields are used, effectively large versions of brushless DC electric motors.

Drive modules for servomotors are a standard industrial component. Their design is a branch of power electronics, accepting a single direction and pulse count (rotation distance) as input. Most modern servomotors are designed and supplied around a dedicated controller module from the same manufacturer. They may also include over-temperature monitoring, over-torque, and stall detection features. It is difficult to produce the overall controller as an off-the-shelf module, so these are often custom-designed as part of the main controller. Integrated servomotors are designed to include the motor, driver, encoder, and associated electronics into a single package.

PERMANENT MAGNET MOTORS

A permanent magnet motor is a type of electric motor that uses permanent magnets rather than windings in the rotor. An AC permanent magnet motor is essentially a synchronous machine that rotates at a fraction or multiple of the line frequency supplied to the stator. However, a permanent magnet motor generates a steady magnetic field instead of the short-circuit current found on AC induction motors. They are more efficient but also more likely to overheat than induction motors.

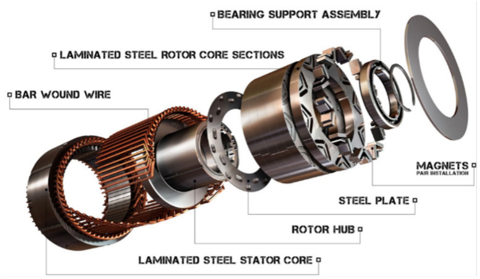

Figure 12: Cut-away view of a permanent magnet motor. (Source: https://www.energy.gov/sites/default/files/2019/06/f64/mat165_grant_2019_o_5.12_8.41pm_jl.pdf, Slide 3)

Permanent magnet motors have been used as gearless elevator motors since 2000. This type of motor is also used in some electric vehicles, machine tools, and other production machinery and material handling robots. They can be seen in the operation of CNC machine spindles, worktable rotation, ways, and part articulation, in both rotary and linear applications of controlled motion. Other uses include chip conveyors, hydraulic manifolds, oil reservoirs, coolant pumps, plastics and rubber molding and extrusion, papermaking, packaging, textiles, ceramic, glass, woodworking, and many other motion control applications.

Advantages and disadvantages

Advantages include compact size with high torque density and less weight, higher continuous torque over a wider range of speeds, lower rotor inertia, higher operational efficiencies with less rotor heating due to lack of magnetizing current, low torque ripple effect, good power factor, and a wide range of drive utilization or application possibilities. Permanent magnet synchronous torque motors typically have 30%-60% higher torque capacity and 30% better torque utilization with faster acceleration and deceleration compared to asynchronous induction-type motors. In the higher power ranges today, these motors are also showing a significantly longer use life, owing to the higher degree of rotor tension compensation. In other words, it reduces backlash (hysteresis) and more rapidly achieves precise position, whether under load or not. From the magnetic perspective, this condition derives from the combination of a larger air gap and smaller radial magnetic forces, with lower inertia moments and high short-term overload capacity while maintaining the desired torque.

Disadvantages include escalating costs, limited speed ranges in field applications, and degradation due to counter voltage created by the magnets in some applications, along with locked rotor overload possibilities.

Characteristics

- A permanent magnet synchronous motor (PMSM) uses permanent magnets embedded in the steel rotor to create a constant magnetic field.
- The stator carries windings connected to an AC supply to produce a rotating magnetic field.
- At synchronous speed, the rotor poles lock to the rotating magnetic field.
- Permanent magnet synchronous motors are like brushless DC motors.
- Because of the constant magnetic field in the rotor, they cannot use induction windings for startup. These motors require a variable-frequency power source to start.
- The main difference between a permanent magnet synchronous motor and an asynchronous motor is the rotor.
- Some studies indicate that NdFeB permanent magnet synchronous motors are around 2 percent more efficient than the highest-efficiency (IE3) asynchronous motors – using the same stator laminations and similar variable-frequency speed controllers.

RELUCTANCE MOTORS

Reluctance motors have a rotor consisting of a solid steel casting with salient (projecting, toothed) poles. Typically, there are fewer rotor than stator poles to minimize torque ripple and to prevent the poles from all aligning simultaneously – a position that cannot generate torque. The size of the air gap in the magnetic circuit, and thus the reluctance, is minimal when the poles are aligned with the (rotating) magnetic field of the stator and increases with the angle between them. This creates a torque pulling the rotor into alignment with the nearest pole of the stator field. At synchronous speed, the rotor is locked to the rotating stator field. This cannot start the motor, so the rotor poles usually have squirrel-cage windings embedded in them to provide torque below synchronous speed. The machine starts as an induction motor until it approaches synchronous speed, at which time the rotor pulls in and locks to the rotating stator field.

Reluctance motor designs have ratings that range from fractional horsepower (a few watts) to about 22 kW. Very small reluctance 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 the motor's operating speed.

Switched reluctance motors

In a switched reluctance motor (SRM), power is delivered to windings in the stator (case) rather than the rotor. This greatly simplifies mechanical design as power does not have to be delivered to a moving part, but it complicates the electrical design as some sort of switching system needs to be used to deliver power to the different windings. With modern electronic devices, precisely timed switching is not a problem, and the SRM is a popular design for modern stepper motors. Its main drawback is torque ripple.

An alternate use of the same mechanical design is the SRM as a generator when driven mechanically, and the load is switched to the coils in sequence to synchronize the current flow with the rotation. Such generators can be run at much higher speeds than conventional types since the armature can be made as one piece of monetizable material, a simple slotted cylinder. In this case, the abbreviation 'SRM' is extended to mean switched reluctance machine, although a switched reluctance generator (SRG) is also used. If configured as both motor and generator, it can be used for starting the prime mover to eliminate a dedicated starter motor. Once the prime mover is up to speed, the SRM connections are switched to Generator mode.

HYSTERESIS MOTORS

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

A *hysteresis* motor is a synchronous motor with a uniform air gap without DC excitation. It operates both with single and 3-phase power. The torque is produced due to hysteresis and eddy current induced in the rotor by the action of the rotating flux of the stator windings.

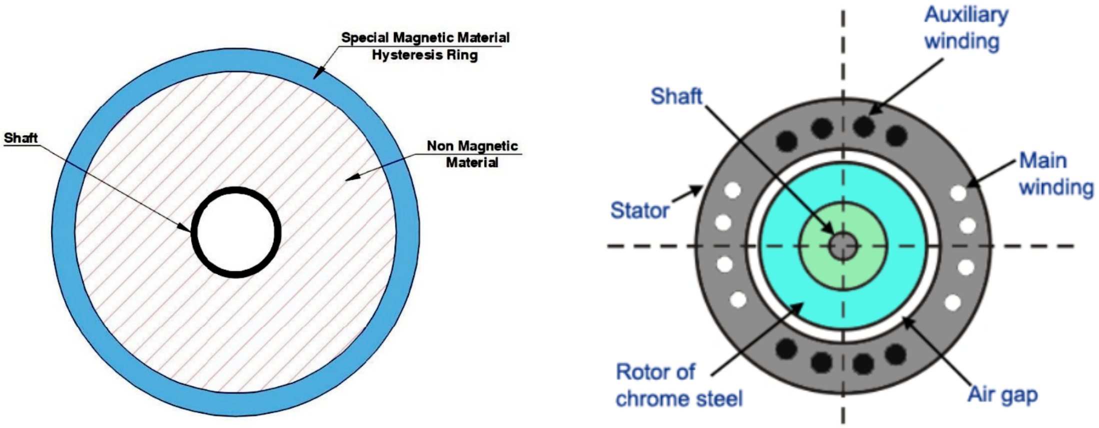

Figure 13: Hysteresis motor diagram (left) and cut-away (right) (Source: www.electrical4u.com/hysteresis-motor)

These motors have a solid, smooth, cylindrical rotor cast of a high coercivity magnetically hard cobalt steel. This material has a wide hysteresis loop (high coercivity), meaning once it is magnetized in a given direction, it requires a large reverse magnetic field to reverse the magnetization. The rotating stator field causes each small volume of the rotor to experience a reversing magnetic field. Because of hysteresis, the phase of the magnetization lags behind the phase of the applied field. This results in the axis of the magnetic field induced in the rotor to lag behind the axis of the stator field by a constant angle, producing a torque as the rotor tries to catch up with the stator field. As the rotor runs below synchronous speed, each particle of the rotor experiences a reversing magnetic field at the slip frequency, which drives it around its hysteresis loop, causing the rotor field to lag and create torque. There is a 2-pole, low reluctance bar structure in the rotor. As the rotor approaches synchronous speed and slip goes to zero, this magnetizes and aligns with the stator field, causing the rotor to lock to the rotating stator field.

Advantages

A major advantage of the hysteresis motor is that because the degree of lag is independent of speed, it develops constant torque from startup to synchronous speed. Therefore, it is self-starting and does not need an induction winding to start it, although many designs do have a squirrel-cage conductive winding structure embedded in the rotor to provide extra torque at startup.

STEPPER MOTORS

A stepper motor (a.k.a. step motor or stepping motor) divides a full rotation into several equal steps. The motor's position can then be commanded to move and hold at one of these steps without any feedback sensor (an open-loop controller) if the motor is carefully sized to the application with respect to torque and speed. These are sometimes referred to as 'chopper' motors because they chop a single rotation into discrete steps. Switched reluctance motors are actually very large stepping motors with a reduced pole count, and they ae generally closed-loop commutated. The stepper motor converts a series of input pulses (typically square wave pulses) into a precisely defined increment in the shaft position. Each pulse moves the shaft through a fixed angle.

Stepper motors effectively have multiple toothed electromagnets arranged around a central gear-shaped piece of iron. The electromagnets are energized by an external driver circuit or a microcontroller. To make the motor shaft turn, first, one electromagnet is given power, which magnetically attracts the gear's teeth. When the gear's teeth are 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. From there, the process is repeated. Each of those rotations is called a 'step' with an integer number of steps making a full rotation. This allows the motor to be turned by a precise angle.

There are three main types of stepper motors: 1) permanent magnet stepper, 2) hybrid synchronous stepper, and 3) variable reluctance stepper.

1. **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.
2. **Hybrid synchronous stepper motors** combine features of both synchronous and stepper motors for demanding applications with precise position, speed, and torque control. They are used mainly in industrial robotics and CNC machines.
3. **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.

Two-phase stepper motors

There are two basic winding arrangements for the electromagnetic coils in a 2-phase stepper motor: bipolar and unipolar.

UNIPOLAR WINDING ARRANGEMENT:

A unipolar stepper motor has one winding with a center tap per phase. Each section of windings is switched on for each direction of the magnetic field. In this arrangement, a magnetic pole can be reversed without switching the direction of current, so the commutation circuit can be made very simple (e.g. a single transistor) for each winding. Typically, in a given phase, the center tap of each winding is made common: with 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 micro-controller or stepper motor controller can be used to activate the drive transistors in the right order. This ease of operation makes unipolar motors popular with hobbyists. They are also probably the cheapest way to get precise angular movements.

BIPOLAR WINDING ARRANGEMENT:

A bipolar stepping motor has a single winding per phase. The current in a winding needs to be reversed 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 have been observed when using an H-bridge with certain drive setups. Dithering the stepper signal at a higher frequency than the motor can respond to will reduce this vibration.

Because windings are better utilized, bipolar motors 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, making it 50%

efficient (or approximately 70% of the torque output available). Though a bipolar stepper motor is more complicated to drive, the abundance of driver chips 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 inside the motor. This kind of motor can be wired in several configurations:

- Unipolar
- Bipolar with series windings – produces higher inductance but lower current per winding
- Bipolar with parallel windings – requires higher current but can perform better, as the winding inductance is reduced
- Bipolar with a single winding per phase – runs the motor on only half the available windings, which reduces the available low-speed torque but requires less current

Higher-phase count stepper motors

Multi-phase stepper motors with many phases tend to have much lower levels of vibration. While they are more expensive, they do have a higher power density and, with the appropriate drive electronics, are often better suited to the application.

LINEAR MOTORS

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. However, linear motors are not necessarily straight. Characteristically, a linear motor's active section has ends, whereas more conventional motors are arranged as a continuous loop.

The most common mode of operation is as an actuator, in which the applied force is linearly proportional to the current and the magnetic field. 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 rather short and are designed to accelerate an object to a very high speed.

High-acceleration linear motors are typically used in studies of hypervelocity collisions, as weapons, or as mass drivers for spacecraft propulsion. They are usually of the AC linear induction motor (LIM) design, with an active 3-phase winding on one side of the air gap and a passive conductor plate on the other side. The direct current homopolar linear motor 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 airgap and an array of alternate-pole magnets on the other side. These magnets can be permanent magnets or energized magnets. The Shanghai Trans rapid motor is an LSM example.

There are four types of linear motors:

1. Synchronous
2. Induction
3. Homopolar
4. Piezo electric

Synchronous linear motors

In this design, the rate of movement of the magnetic field is controlled, usually electronically, to track the motion of the rotor. For cost reasons, synchronous linear motors rarely use commutators, so the rotor often contains permanent magnets or soft iron. Examples include coil guns and the motors used on some maglev systems, as well as many other linear motors.

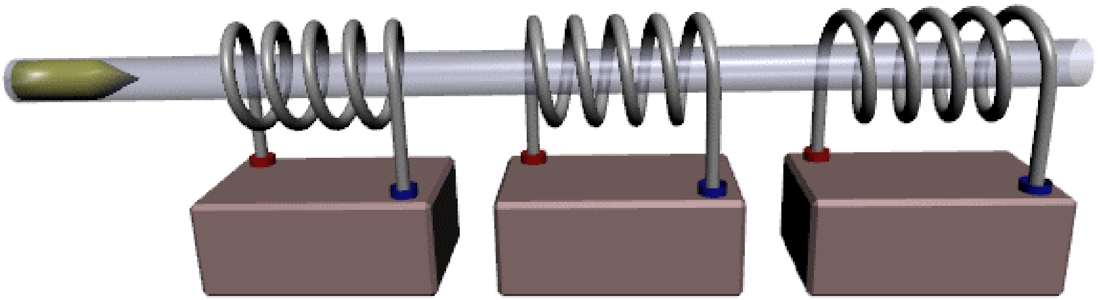

Figure 14: Graphic representation of a multistage coil gun with three coils, a barrel, and a ferromagnetic projectile (animated). (Source: https://commons.wikimedia.org/wiki/Category:Coilguns)

COIL GUN, OR GAUSS RIFLE:

This is a type of projectile accelerator consisting of one or more coils used as electromagnets in the configuration of a linear motor that accelerates a ferromagnetic or conducting projectile to high velocity. In almost all coil gun configurations, the coils and the gun barrel are arranged on a common axis. It is not a rifle, as the barrel is not rifled. The name 'Gauss' refers to Carl Friedrich, who formulated mathematical descriptions of the magnetic effect used by magnetic accelerators.

Coil guns generally consist of one or more coils arranged along a barrel, so the path of the accelerating projectile lies along the central axis of the coils. The coils are switched on and off in a precisely timed sequence, causing the projectile to be accelerated quickly along the barrel via magnetic forces. Coil guns are distinct from railguns, as the direction of acceleration in a railgun is at right angles to the central axis of the current loop formed by the conducting rails. In addition, railguns usually require the use of sliding contacts to pass a large current through the projectile, but coil guns do not necessarily require sliding contacts. While some simple coil gun concepts can use ferromagnetic projectiles, or even permanent magnet projectiles, most designs for high velocities incorporate a coupled coil as part of the projectile.

MAGLEV (DISAMBIGUATION):

A maglev (derived from magnetic levitation) is a transport method that uses magnetic levitation to move vehicles without contacting the ground. With maglev, a vehicle travels along a guideway using magnets to create both lift and propulsion, thereby reducing friction by a great extent and allowing very high speeds. Maglev technology includes no moving parts.

Maglev trains move more smoothly and more quietly than wheeled mass transit systems. The power needed for levitation is typically not a large percentage of its overall energy consumption; most goes to overcome drag, as with other high-speed transport. Maglev trains hold the speed record for trains. Compared to conventional trains, differences in construction affect the economics of maglev trains, making them much more efficient. For high-speed trains with wheels, wear and tear from wheel friction on rails accelerates equipment wear and prevents high speeds.

Conversely, maglev systems have been much more expensive to construct, offsetting lower maintenance costs.

The linear motor was naturally suited to use with maglev systems, as well. In the early 1970s, Laithwaite discovered a new arrangement of magnets, the 'magnetic river.' This enabled a single linear motor to produce both lift and forward thrust and allowed a maglev system to be built with a single set of magnets. Working at the British Rail Research Division in Derby, along with teams at several civil engineering firms, the 'transverse-flux' system was developed into a working system.

Linear induction motor

In a typical 3-phase linear induction motor, the rotor can be a looped conductor, a squirrel cage, a wound rotor, or an aluminum plate on top. As depicted below, the 'primary' core (grey) has grooves, and the windings are laid into them on top of each other. An aluminum plate above (not shown) serves as a 'secondary' core and will move relative to the primary if a 3-phase AC is applied.

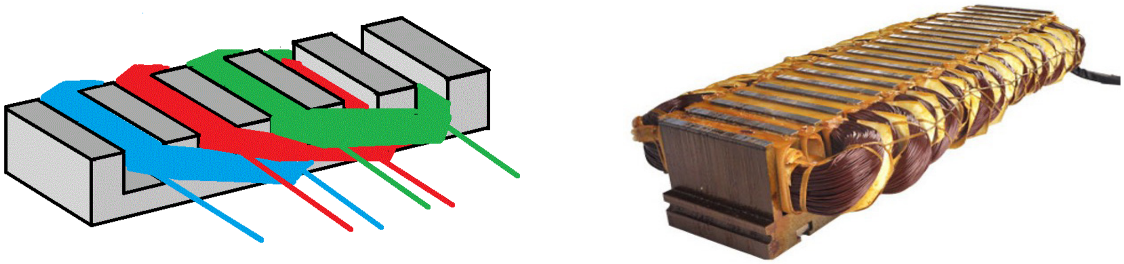

Figure 15: Stator (field) coil wraps in a linear induction motor (Source: https://en.wikipedia.org/wiki/Linear_induction_motor)

In this design, 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, which is placed in this field will have eddy currents induced in it, creating an opposing magnetic field in accordance with Lenz's law. The two opposing fields will repel each other, creating motion as the magnetic field sweeps along the length.

Inverter rated motors

Effects of VFDs on induction motors

The non-sinusoidal varying output of pulse width modulated variable frequency drives (VFDs) has several effects, including increased motor losses, inadequate ventilation at lower speeds, increased dielectric stresses on motor windings, magnetic noise, and shaft currents. These effects can combine to damage a motor's insulation and severely shorten its useful operating life.

High switching rates of modern power semiconductors lead to rapid changes in voltage in relatively short periods of time (dV/dt, quantified in units of volts per microsecond). Steep-fronted waves with large dV/dt or very fast rise times lead to voltage overshoots and other power supply problems.

When the motor impedance is greater than the impedance of the conductor cable between the motor and the drive, the voltage waveform will reflect at the motor terminals. This creates a standing wave. Longer motor cables favor higher amplitude standing waves. Voltage spikes have occurred with peak values as high as 2,150 volts (V) in a 480-V system operating at 10% overvoltage. These high spikes can lead to insulation breakdown, which results in phase-to-phase or turn-to-turn short circuits, and subsequently overcurrent drive sensor trips.

Preventive measures can be taken to avoid motor failures caused by voltage spikes. These include using power conditioning equipment (such as dV/dt filters or load reactors) and restricting the distance or cable length between the drive and the motor. Some drive installers also specify oversized motors or the use of high-temperature resistance Class H insulation.

Inverter-duty motor designs

Most motor manufacturers offer general purpose, 3-phase premium efficiency motors that feature 'inverter-friendly' insulation systems. These inverter-ready motors are suitable for use with variable torque loads over a wide speed range. In contrast, inverter-duty motors are wound with voltage spike-resistant insulation systems. Some use inverter-grade magnet wire to minimize the adverse effects of waveforms produced.

General purpose motors have been around for many years. They are the workhorse of almost every industry. An inverter-duty motor is a much newer concept that became necessary as motors began to be driven by VFDs (inverters or AC drives). An inverter-duty motor can withstand the higher voltage spikes produced by all VFDs (amplified at longer cable lengths) and can run at very slow speeds without overheating. This performance comes at a cost, i.e. inverter-duty motors can be much more expensive than general purpose motors. Since certain inverter rated motors have limitations, manufacturer specifications should be scrutinized when selecting these motors.

The effect and solutions of carrier frequencies

The voltage chopping that occurs in the drive sends high-voltage spikes (at the DC bus level) down the wire to the motor. If the system contains long cabling, there are instances where a reflected wave occurs at the motor. The reflected wave can effectively double the voltage on the wire, leading to premature failure of the motor insulation. Long cable lengths between the motor and drive increase the harmful effects of the reflected wave, as do high chopping frequencies (listed in drive manuals as 'carrier frequencies'). Line reactors, 1:1 transformers placed at the output of the drive, can help reduce the voltage spikes going from the drive to the motor. Line reactors are used in many instances when the motor is located far from the drive.

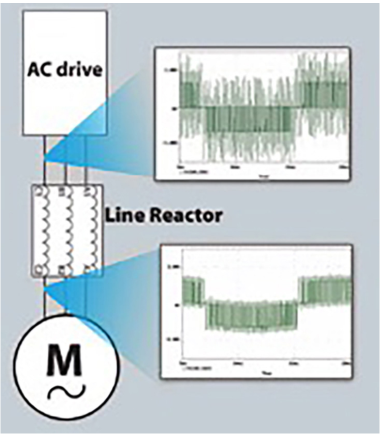

Figure 16: AC drive using a line reactor to reduce the voltage spikes. (Source: automationdirect.com/products)

SUMMARY

There is a great deal of information here, but it still only scratches the surface of fully understanding electric motors. Please do not panic. There is no need to memorize all of this, or even keep all the special configurations in mind. We simply wanted to give you an overview of the wide range of motor types – how they operate, their uses, and the differences you may encounter, even if rarely. Regardless of the type, all motors must be proactively maintained to keep them up and running as the critical prime movers of all manufacturing facility processes.

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