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A Practical Primer On Motor Drives (Part 11): AC And DC Motor Types

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In the previous part in this series, the basic principles of motor operation were explained and the main categories of motors were introduced. This part 11 takes a closer look at the different motor types including ac induction motors, ac permanent magnet synchronous motors, and brushless and brushed dc motors. It also offers more details on universal motors, ac synchronous motors, and switched reluctance motors. Finally, this part concludes with some comments on servo motors and stepper motors, which are considered subclasses of other types discussed here.

AC Induction Motors (ACIMs)

Ac induction motors (ACIMs) consist of a stationary winding (stator) held inside a stator core, a rotating winding (rotor) connected to a shaft, a mechanical housing, and a bearing/support structure to properly locate the rotor inside the stator and permit rotation. This resembles the "generic" motor we described in part 10, but differs in that the rotor magnetic field is induced by the stator magnetic field and is not a supplied (i.e. generated) or permanent magnet field. The "cutaway" photograph in Fig. 1 of an ac induction motor shows the different parts.

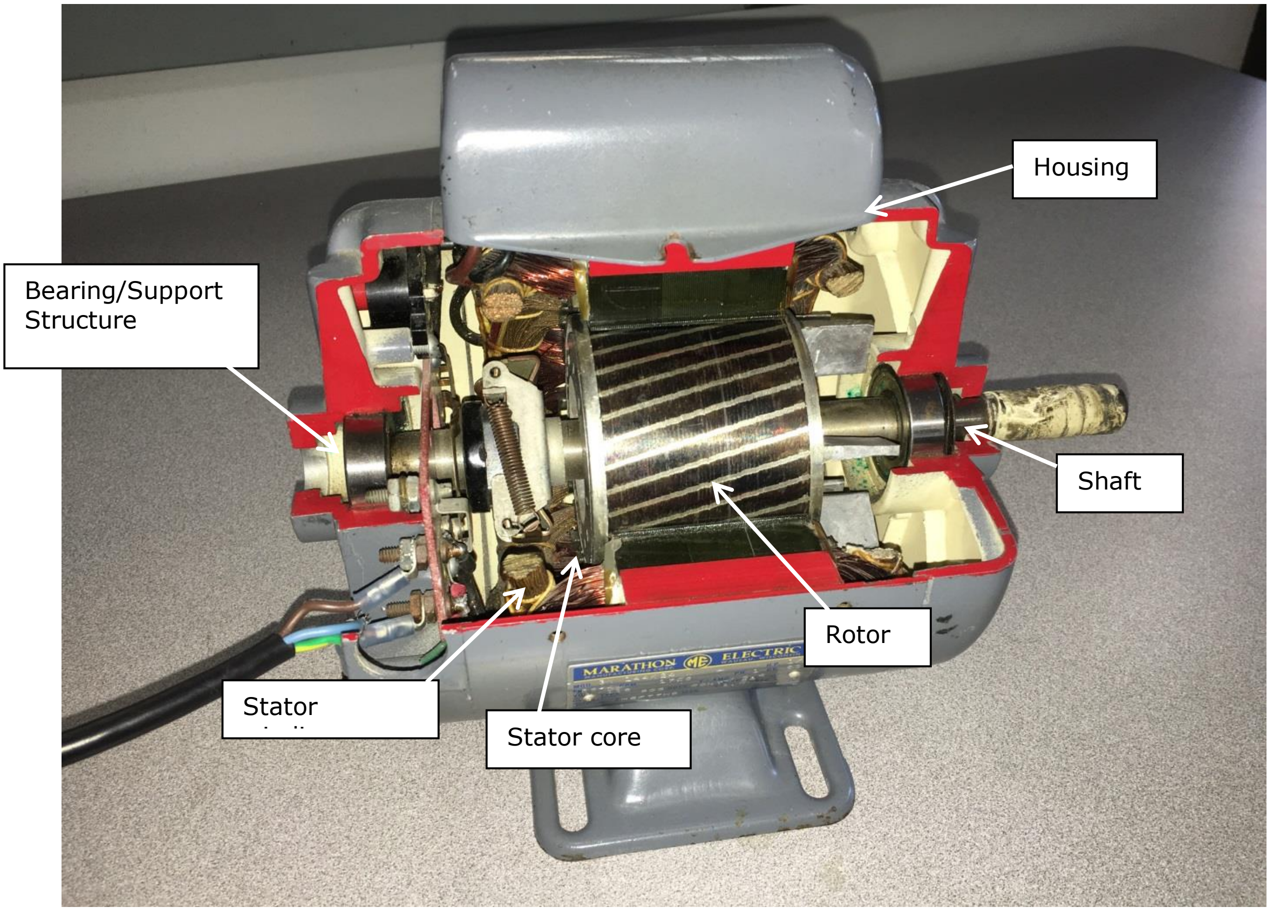

Fig. 1. In an ac induction motor, the rotor magnetic field is induced by the stator magnetic field rather than a supplied or permanent magnet field. Photograph courtesy of Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC), University of Wisconsin-Madison.

ACIMs have alternating voltage and current (ac) applied to the stator winding. Construction of the stator winding is such that the applied ac voltage rotates around the stator winding, which creates a rotating stator magnetic flux field. This rotating stator magnetic flux field induces a magnetic flux field in the rotor.

The two fields have opposing magnetic forces, which compels rotation of the rotor. Because the rotor magnetic field is "induced" by the stator magnetic field, these ac motors are termed "induction motors". Fig. 2 depicts how the single-phase stator and rotor magnetic flux fields produce rotation (the currents in the rotor conductor, shown in dark gray, are flowing into and out of the page in this example).

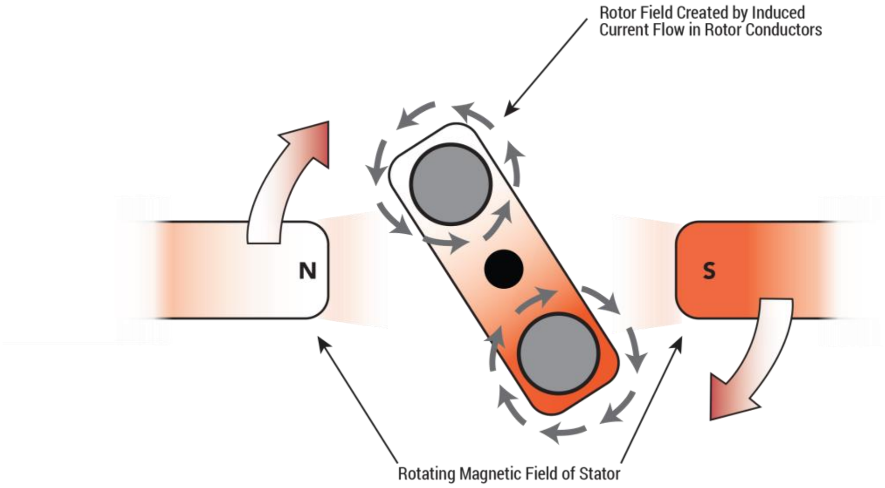

Fig. 2. The applied ac voltage rotates around the stator winding, creating a rotating stator magnetic flux field, which in turn induces a magnetic flux field in the rotor. The stator and rotor magnetic fields have the same polarity, which causes the stator and rotor to repel one another, and makes the rotor turn.

To induce rotor currents with the stator magnetic flux field, the stator magnetic flux field must rotate faster than the rotor's induced magnetic flux field. When the two magnetic flux field angular speeds match, the motor is in a no-load condition and the rotor shaft is rotating at its synchronous speed (100% of its rated speed), but it can generate no torque. Application of a load to the shaft causes the two magnetic flux field angular speeds to diverge and produce torque.

Essentially, the angular velocity of the rotor increases or decreases until it reaches the balance point at which the magnitudes of the stator and rotor currents and generated rotor torque balance the load applied at the shaft. We call the ratio between the rotor angular speed and stator magnetic flux angular speed "slip."

Slip, typically expressed in a percentage, is the difference between the synchronous (no-load) speed and the actual speed. Thus, an ACIM never operates at its rated (no-load, or 100%) speed, and is therefore sometimes called an ac asynchronous motor (ACAM).

One may show the relationship of torque to (rotor shaft) speed as a torque-speed curve, and there are optimal points on the curve where maximum torque occurs. The motor stator and rotor construction, and various other factors, determine the shape of the torque-speed curve. Different applications have different torque-to-speed needs. Fig. 3 shows a typical ACIM torque-speed curve.

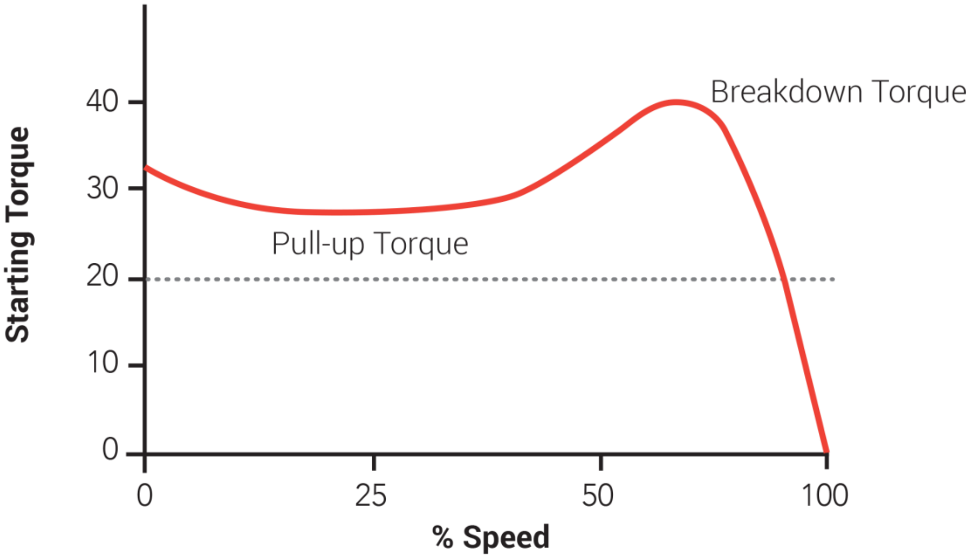

Fig. 3. A typical ACIM torque-speed curve. Looking at a torque-speed curve, users can determine whether torque-speed characteristics of a given ACIM meet their application needs.

ACIMs can be either single-phase or three-phase types and though their constructions may vary depending on the size of motor, their method of operation is always the same. In general, three-phase motors are more efficient, lend themselves to precision control, and are required for higher-power-output levels. At higher-power-output levels, three-phase motors are more cost-effective to manufacture and more reliable.

The principal advantage of an ACIM is that there is only one applied power source and no need for an expensive permanent magnet or separate dc power supply for the rotor. It is a simple design that can generate very high levels of power output. The construction is simpler and cost is lower than a permanent-magnet motor, and reliability is higher than a similar-sized dc (carbon-brushed) motor. When paired with a variable-frequency motor drive, speed and torque control capabilities are at least as good as the carbon-brushed dc motor.

Historically, control of ac induction motor speed or torque had been quite limited—a variable transformer (expensive and limited) provided input voltage adjustment, and output adjustment came by means of a valve (e.g., for a pump motor) or other mechanical device. Usually, motors were oversized and ran well below their rated power with no operator control of their speed or power (torque) output, leading to very inefficient operation. Modern variable-frequency motor drives overcame these limitations.

Single-Phase ACIM

Single-phase ACIMs are small motors that have a single alternating voltage phase applied to a single stator field winding. Because the single-phase stator magnetic flux field "alternates" and does not "rotate" around the stator, motor rotation could be in either direction at startup depending on the position of the rotor when the single-phase ac voltage is applied. Therefore, single-phase ACIMs often use a second "starting" winding that is 90° out of phase with the stator winding. For this reason, we sometimes describe single-phase ACIMs as two-phase motors.

This second winding ensures establishment of the stator rotating magnetic flux field in the correct direction at startup and that the motor shaft spins in the correct direction. Once the motor starts spinning, the second winding is electrically removed from the circuit. We often call these motors capacitor-start or split-phase motors. An example is depicted in Fig. 4. These motors are generally smaller, less expensive motors that often do not use any type of variable-frequency motor drive.

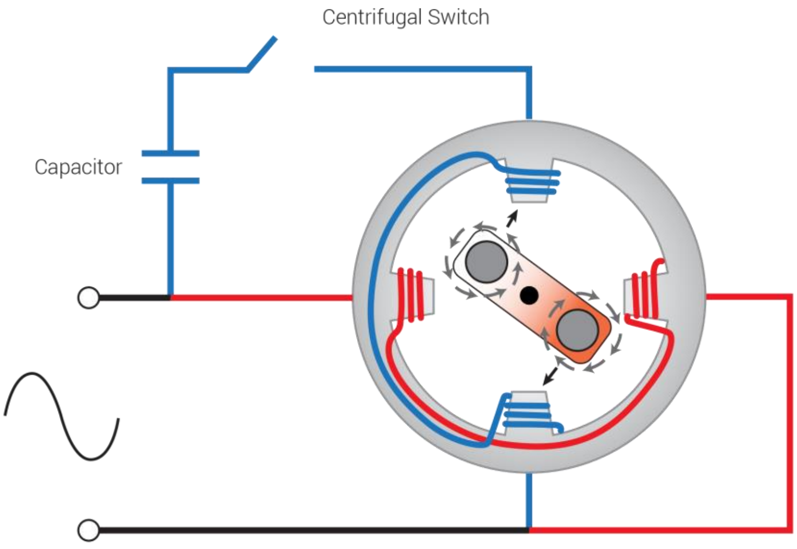

Fig. 4. A capacitor-start or split-phase motor employs a starting winding (blue) that is 90° out of phase with the stator winding to ensure that the rotor begins rotating in the desired direction. But after start-up, this second stator winding is disconnected.

These motors see application only for simple tasks (fans, blowers), and are limited to 120-/240-V inputs with a rating no more than ~1 hp or ~1 kW. Small ACIMs controlled by a motor drive may employ a motor drive with a single-phase ac input and a three-phase output driving a small three-phase ACIM.

Three-phase ACIM

Three-phase ACIMs range from small to large sizes and have a three-phase ac voltage applied to a three-phase stator field winding. Operation is identical to that of the single-phase ACIM except that the presence of a (naturally) rotating three-phase stator magnetic flux field makes construction and operation simpler and eliminates the need for a starting phase (a three-phase motor will predictably start in the defined direction.)

The three-phase stator winding creates a naturally rotating magnetic field, with the direction and rotational speed of the magnetic field related to the winding and pole construction of the stator. Three-phase motors are also more efficient than single-phase motors. See Fig. 5 for a graphical representation of the stator and rotor magnetic flux fields in a three-phase ac induction motor with a single-pole rotor.

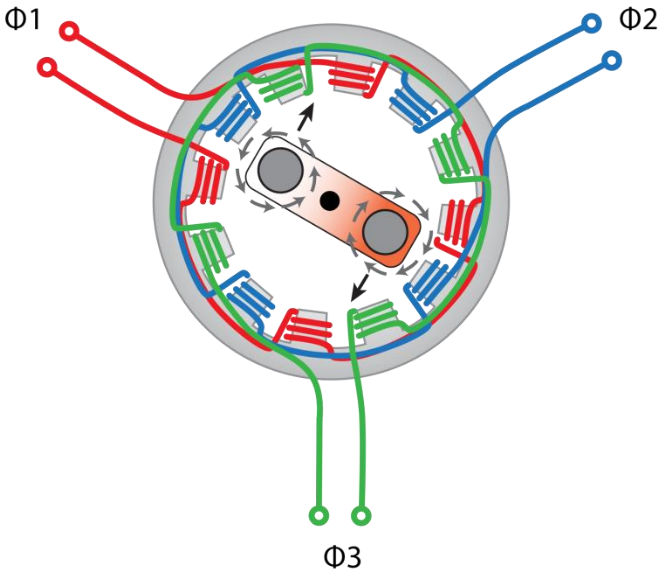

Fig. 5. In this three-phase ac induction motor with a single-pole rotor, the stator's rotating magnetic field induces a rotor magnetic flux field.

Three-phase ACIMs can range from <<1 hp (<750 W) to >1000 hp (>750 kW) with voltage ratings from a nominal 120 V to 14.4 kV. The majority of these motors are in the 600-V class (120 to 600 Vac) running on three-phase power with horsepower ratings <500 hp (375 kW). Three-phase ACIMs fall into several broad categories, as follows:

- Small induction—120 to 240 V, <1 hp (<750 W)
- Medium (low-voltage) induction—600-V class (380 V to 600 V) typically three-phase except in the lower power ratings, >1 hp (750 W) and up to 500 hp (375 kW)
- Large (medium- or high-voltage) induction—5-kV (2.4kV to 7.2 kV) and 15-kV class, three-phase ≥500 hp (375 kW).

AC Permanent-Magnet Synchronous Motors (PMSMs)

Ac permanent-magnet synchronous motors (PMSMs) have an ac three-phase stator but use a permanent magnet to generate a dc rotor flux field (Fig. 6.) Do not confuse PMSMs with an ac "wound-rotor" synchronous motor, a different (and much larger) motor type that uses a dc power supply to create a dc magnetic field in a wound coil rotor.

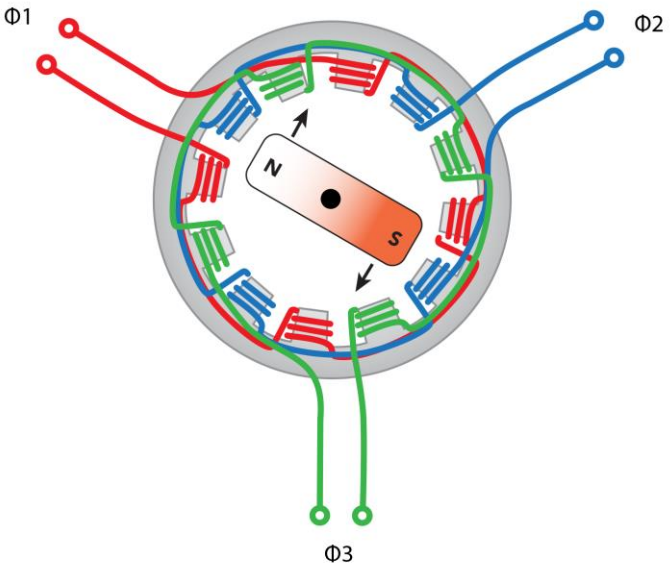

Fig. 6. In this three-phase PMSM motor with a single-pole rotor, the stator's rotating magnetic field interacts with the permanent magnet rotor field to create rotation of the rotor.

Typically, PMSMs are using some type of motor drive to supply pulse-width modulated (PWM) voltage to the stator. Power ratings can range from <<1 hp (1 kW) to 100 hp (75 kW). In general, these motors have very high power outputs for small size, especially if built with rare-earth permanent magnets (with very high magnetic flux densities.)

Some engineers refer to PMSM motors as "brushless DC" (BLDC), "brushless ac" (BLAC), or electronically commutated motors (ECMs.) In all these cases, the mechanical design is essentially the same—each contains a permanent magnet rotor, a stator coil, and an inverter circuit that inverts a dc source to create a three-phase PWM output (i.e., "electrical commutation.")

However, in general, most engineers would agree that a PMSM motor uses an electrical commutation scheme that applies three-phase voltage to all three windings at any given time, which results in a sinusoidal back-EMF voltage waveform on the stator winding. We know this as "sinewave modulation." This modulation scheme costs more but offers control performance with less audible noise and torque ripple than that described for brushless dc motors.

"Brushless" DC (BLDC) Motors

In reality, "brushless" dc (BLDC) motors are not dc motors at all—the term "brushless" seeks to distinguish them from a "brushed" (conventional carbon-brush) dc motor. Like PMSMs (described above), they utilize a three-phase electrically commutated ac stator winding with a permanent magnet rotor.

Many use the terms BLDC and PMSM interchangeably because the mechanical and electrical construction of the motor is largely the same for both types. However, in general, most engineers agree that a BLDC motor utilizes a six-step commutation scheme in which rotor position is actively sensed or calculated, and voltage is applied as a PWM waveform to only two of the three stator windings at one time with the switching of the winding voltages based on the sensed or calculated rotor position.

Because we apply voltage to only two of the three phases at any given time, the line-neutral back-EMF voltage waveform on each phase is trapezoidal in shape, not sinusoidal. Therefore, we know six-step commutation as "trapezoidal" control.

The nature of the applied voltage signal makes BLDC motors noisier during operation (audibly and electrically) than other designs, with higher torque ripple than PMSMs. However, they have reasonable cost and good torque characteristics. They often find use in lower-power applications (e.g., small appliances, power tools, etc.) where cost is a critical concern.

"Brushed" DC Motors

Conventional "brushed" dc motors include a field (stator) winding and an armature (rotor) winding. Connection of these two windings may be in series, parallel, or series/parallel. They may be energized from the same dc voltage supply, or the field (stator) winding may be separately excited from the armature (rotor) winding. Different applications require different torque vs. speed performance, or lower or higher levels of control capabilities. Thus, there is a variety of winding constructions and excitation choices.

In all constructions, a dc voltage applied to the field (stator) winding generates a stator magnetic flux field that interacts with the armature (rotor winding.) However, rotor rotation requires an alternating or rotating field (stator) magnetic flux field. That field comes from a commutator and carbon brush scheme that periodically reverses the voltage polarity applied to the rotor, which reverses the rotor magnetic field (Fig. 7.)

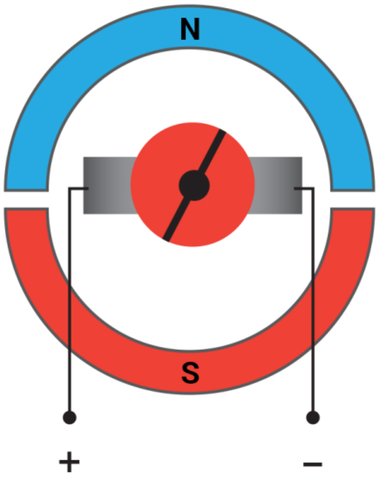

Fig. 7. In a brushed dc motor, a commutator and carbon brush scheme periodically reverses the voltage polarity applied to the rotor, which reverses the rotor magnetic field so that it opposes the stator magnetic field to produce rotation of the rotor.

In a dc motor, the field (stator) voltage and current control the (fixed direction) magnetic flux density seen by the rotor (armature.) By increasing or decreasing the field voltage (and therefore the field current), the field magnetic flux can be increased or decreased (thus controlling the speed.)

In a dc motor with a separately excited armature (rotor) magnetic flux field (i.e., not a series or shunt-wound design), the armature magnetic flux field can also be varied (thus controlling the torque.) The armature magnetic flux field is always (by definition) orthogonal to the field magnetic flux, so the motor is always operating at peak torque for a given armature magnetic flux field (i.e., applied armature voltage.)

Lower-power brushed dc motors use a permanent magnet to generate the field and armature magnetic flux fields. Higher-power brushed dc motors use an applied voltage to generate the field and armature magnetic flux fields.

The drawback of a brushed dc motor is the mechanical complexity, reliability, and cost. The mechanical commutator uses carbon brushes to "commutate" power through an insulated slip ring segment attached to the rotor. Carbon brushes wear over time and require replacement. Additionally, dc voltage is not widely available except from batteries in residential, commercial, or industrial locations, and, for a larger motor, must be supplied by an ac-dc converter, adding cost and complexity.

Despite the mechanical complexity and reliability issues of dc motors, they have very favorable control characteristics. Independent adjustment of voltage in field and armature windings provides independent and tight control of both speed and torque, a scheme often used in variable-speed applications. Such a scheme always produces peak torque for a given applied voltage, which is a highly desirable situation. Modern ac motor drives replicate these ideal control capabilities using vector field-oriented controls (FOCs) with the mechanically simpler and more-reliable ACIMs and PMSMs.

Today, the primary applications for brushed dc motors are as very small and/or low-cost motors used in throwaway devices such as children's toys, electric toothbrushes, or mobile phone vibrators.

Universal Motors

These motors combine characteristics of ACIMs and brushed dc motors. Given that they employ a carbon-brush commutation scheme, their original market advantage was to offer a better ac motor utilizing an additional dc field coil. With the pervasiveness of motor drives for control of ACIM, PMSM, and BLDC motors, universal motors are not seen as a viable alternative with 50-/60-Hz voltage inputs, and are not used with motor drives either. Therefore, their usage has declined considerably.

AC (Wound-Rotor) Synchronous Motors (ACSMs)

ACSMs utilize a three-phase (sinusoidal, utility-supplied) voltage to generate the rotating ac magnetic field in the stator and use a supplied dc voltage from a rectified ac supply (via slip-ring supply) to a rotor winding (Fig. 8) to generate a dc magnetic flux field. They are sometimes known simply as "synchronous motors."

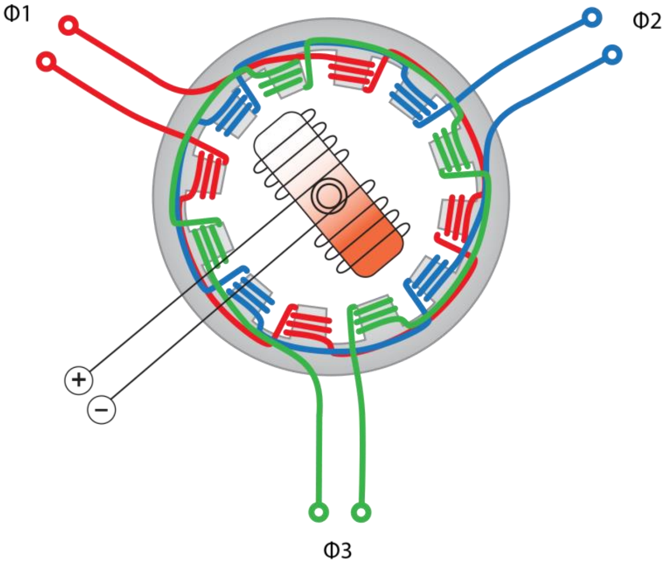

Fig. 8. An ac (wound-rotor) synchronous motor uses a three-phase sinusoidal voltage to generate the rotating ac magnetic field in the stator and uses a rectified ac supply (via slip-ring supply) to generate a supplied dc magnetic flux field in the rotor winding.

The rotor magnetic flux field rotates at the same rate as the applied ac magnetic flux field. Given a stable applied ac magnetic flux field (as would be supplied by the 50 or 60 Hz from a utility), the rotor spins at a constant, predictable speed related to the ac stator supply frequency and the number of stator and rotor pole pairs as long as the load is not beyond the design rating.

The speed is "synchronous" to some multiple of the input frequency up to the rated load of the motor. Unlike an ACIM, there is no slip angle between the stator and rotor magnetic flux fields. Additionally, ACSMs exhibit a power factor of 1.0, to the benefit of larger users of electricity who often pay a penalty to the utility for low power-factor operation. ACSMs are widely used in industrial processes due to their ability to run at a constant speed, despite significant load changes.

ACSMs are also built in small sizes using permanent magnets, but in general, references to an ac synchronous motor today mean a larger (>100 hp) ac motor with an applied dc rotor field run at a constant speed to supply a large industrial load. They do not benefit from use with a variable-frequency motor drive given their dedication to constant-speed operation.

Switched Reluctance Motors (SRMs)

Switched reluctance motors became possible with the advent of electronically commutated motor controls. An SRM is essentially a three- or four-phase stator and a rotor that has no magnetic field but possesses magnetizing properties (i.e., laminated steel.) As Fig. 9 illustrates, the SRM's rotor has no magnetic elements.

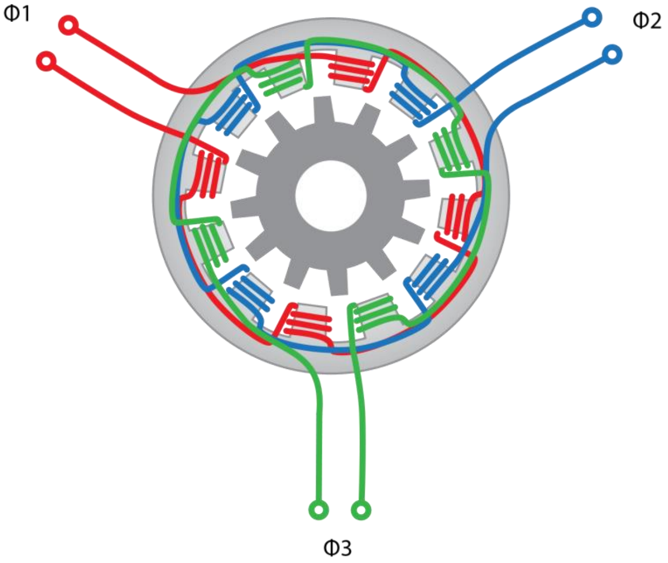

Fig. 9. A switched-reluctance motor employs a three- or four-phase stator (three phase is shown here) and a rotor capable of being magnetized by the stator's magnetic field. The misalignment of the rotor magnetic poles with the stator poles creates torque on the rotor.

As with BLDC motors, sensors determine rotor position but we apply voltage to only one phase at a time (perhaps two at a time during startup). Application of stator voltage creates a rotating magnetic field, and torque on the rotor comes from the misalignment of the rotor poles with the stator poles. The rotor magnetic flux field follows the path of least magnetic reluctance, hence the name.

SRMs can be very low in cost but have the highest noise and torque ripple of any electronically commutated motor. SRMs are possible only with the advent of motor drives, and there are significant cost savings and reliability improvements associated with their use. However, they carry significant drawbacks (high torque ripple, high noise) and they have not been widely commercialized.

Servomotors

Servomotors are a sub-class of various types of ACIMs or PMSMs that utilize rotary position sensors to allow movement and setting of an exact rotor position for an industrial application, such as machine tools, valve control, etc. Motors used in servo applications must have well-documented torque vs. speed characteristics, power, mechanical rotor inertia, etc.

Ac servomotors typically use permanent magnet rotors to minimize motor size and rotor mass. This avoids excessive rotor inertia when positioning the rotor/shaft (we use ACIMs where more power is required). Some type of rotor position feedback with known shaft position is required for detection and control of the exact rotor position.

Stepper Motors

Stepper motors contain a permanent-magnet rotor with a switchable stator coil operated much like a solenoid coil. By energizing the stator coil to a different pole, the rotor aligns with the stator coil magnetic flux field. As its name implies, a stepper motor does not rotate continuously but merely "steps" from one position to another based on the switching of the stator coil voltage.

Conclusion

Here in part 11, we have described the construction and operation of the major motor types. With this grounding in motor fundamentals, we are finally ready to begin a more in-depth discussion of the main topic of this series—motor drives. In the next part, we'll describe the operation of variable frequency drives. For a full list of topics that will be addressed in this series, see part 1.

About The Author

Kenneth Johnson is a director of marketing and product architect at Teledyne LeCroy. He began his career in the field of high voltage test and measurement at Hipotronics, with a focus on <69-kV electrical apparatus ac, dc and impulse testing with a particular focus on testing of transformers, induction motors and generators. In 2000, Ken joined Teledyne LeCroy as a product manager and has managed a wide range of oscilloscope, serial data protocol and probe products. He has three patents in the area of simultaneous physical layer and protocol analysis. His current focus is in the fields of power electronics and motor drive test solutions, and works primarily in a technical marketing role as a product architect for new solution sets in this area. Ken holds a B.S.E.E. from Rensselaer Polytechnic Institute.

For further reading on motor drives, see the How2Power Design Guide, locate the "Power Supply Function" category, and click on the "Motor drives" link.