Exclusive Technology Feature

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A Practical Primer On Motor Drives (Part 10): Motor Background

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The last two installments in this series reviewed power semiconductor devices and power conversion topologies, providing foundational knowledge for understanding how motor drives work and how they are designed. Equally important to understanding motor drives is a knowledge of how the load (i.e. the motor) works. In this part, we begin that discussion, providing an overview of the popular motor types and the basics of how motors work.

In general, all motors utilize a stator (also referred to as a field or stationary winding) and rotor (or rotating winding) connected to a drive shaft. The stator and rotor have opposing and constantly varying magnetic fields that create angular movement of the rotor. We use various electrical and mechanical constructions for motors depending on the application requirements (e.g., high torque, low speed, precision of movement, low cost, etc.). More than 99% of motors use either single-phase or three-phase windings—those that use more than three phases are found in niche applications where reliability through redundancy is critical (aircraft, military, space), though there is increasing interest in more than three-phase windings in commercial vehicle propulsion applications.

The predominant motors in use today are:

- Ac induction motors (ACIMs)
- Ac (wound-rotor) synchronous motors (ACSMs)
- (Brushed) dc motors
- Brushless dc (BLDC) motors
- Permanent-magnet synchronous motors (PMSMs).

Conventional “brushed” dc motors are mostly in use today in low-cost applications because more reliable variable-frequency (motor) drives and ac motors deliver greater benefits. We typically use ac synchronous motors in industrial applications requiring a fixed output speed. We often see use of ac induction motors, brushless dc motors, and permanent-magnet synchronous motors with drives. There are other types of motors not discussed here (e.g., “stepper” motors or servo motors) that are really special cases of PMSM or BLDC motors as well as other motor types in development that may or may not prove commercially viable.

Worldwide, motors consume ~45% of electrical energy. The largest motors have small unit volume but consume a far larger share of electrical energy. Therefore, there is intense focus on improving the efficiency of the largest motors, either through improvements in motor electromechanical design, use of advanced motor drives for higher efficiencies over a range of speeds and loads, or both.

Governments around the world have mandated increasingly strict efficiency standards for these motors, beginning in the United States in 1992 and followed in 1998 by the European Union. Essentially, these efficiency standards focus on the larger motors that consume the highest proportion of energy, and fall into four categories:

- Standard (low) efficiency (IEC IE1 level, or U.S. EPAct Below Standard Efficiency)
- High efficiency (IEC IE2 level, or U.S. NEMA Energy Efficiency/EPAct)
- Premium efficiency (IEC IE3 level, or U.S. NEMA Premium level)
- Super Premium efficiency (IEC IE4 level, or U.S. NEMA Super Premium level).

Small motors (less than one horsepower (hp) or equivalent to ~750 W) represent 90% of motors by unit volume, but only consume 9% of the total electricity used by all electric motors (see the reference.) These are single-phase or three-phase ac induction motors for general-purpose use; brushless dc (BLDC)/permanent-magnet synchronous motors (PMSMs) or electronically commutated motors (ECMs); and brushed dc motors used in appliances, small pumps, compressors, fans, etc. These motors do not meet efficiency standards, though their design may be very efficient (especially if powered from a battery).

Small motors may be paired with motor drives because there is some precision control-related capability that is very important to the proper operation of the motor in its intended use. One may only achieve such precise control with a drive. Examples of high-precision control include the servomotor in a disk drive, a brushless dc motor in a power tool, or the compressor or fan in a mini-split ductless heat pump.

Medium motors (greater than 1 hp/750 W but less than 500 hp/375 kW) represent ~9% of motors by unit volume but consume 68% of the electricity used by all motors. Most of these motors (around 85% market share) are three-phase ac induction motors used in industry, but brushed dc motors (declining share), and permanent-magnet motors (increasing share) are also available in this size range.

The efficiency standards described above are relevant to motors designed for standalone operation in this medium size range. When we integrate motors into a system in a manner precluding separate testing, they are exempt from these standards (i.e. the IEC IE2, IE3, and IE4 standard levels or the corresponding NEMA equivalents.) However, we even find many “exempt” motors in this class (e.g., a hybrid vehicle propulsion motor and drive) designed with high levels of efficiency.

Large motors (greater than 500 hp/375 kW) are 0.03% of motors by unit volume but consume about 23% of electricity used by all motors. These motors are three-phase ac induction motors and wound-rotor synchronous motors built-to-order for special-purpose industrial use. While not specifically covered by the efficiency requirements in the standards, the users of these motors are well aware of their high operating costs and efficiency does factor into initial purchase decisions.

Not counted in the totals above are the numerous small motors used in non-utility (grid) connected applications, such as servo-motor drives in hard disk drives, windshield wiper motors, etc.

Basic Motor Operation

All motors contain the same essential elements—a stationary winding, a rotating magnet, a shaft and other mechanical components.

The stationary winding (typically called the stator) creates a rotating magnetic field. This winding is physically contained in a magnetic “core” material to enhance the generated magnetic field and provide physical support when energized.

The rotating magnet (typically called the rotor) is alternatively repelled and attracted to the rotating magnetic field generated by the stator. The magnet could be either a permanent magnet, an induced magnetic field (as with an ac induction motor), or a generated magnetic field from a dc power supply (as with a wound-rotor synchronous ac motor).

The last two common elements are a shaft that attaches to the rotor to extract work and various other mechanical components.

We can think of the stator as two fixed permanent magnets arranged across from each other with opposing polarities so that a magnetic field is created between them. We can consider the rotor as another permanent magnet placed between the “stator magnets” and allowed to rotate around its center. If the “rotor magnet” is oriented such that its own magnetic field does not directly align with that of the stator magnets, then it will rotate until it does align, and then stop rotating. See the rotator and stator drawings in Fig. 1.

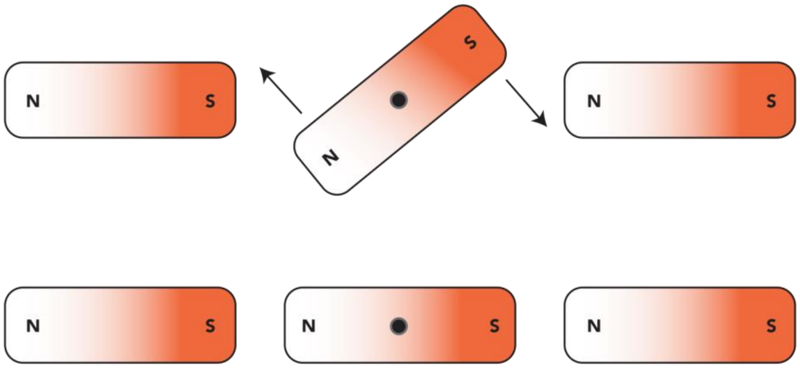

Fig. 1. Basic principle of motor operation. If the rotor magnet is oriented such that its polarities do not align with those of the stator magnets as shown in the top drawing, then the rotor will rotate until its magnet's polarities do align as shown in the lower drawing.

To reinitiate "rotor magnet" rotation, we would have to physically switch the polarity of the "stator magnets", which is impractical. However, it is practical to replace the permanent magnet "stator magnets" with electromagnets energized by an ac waveform that will automatically reverse the magnetic field at the ac frequency. Thus, the rotor magnet rotates as shown in the Fig. 2, with the top example at time t = 0 and the bottom example at arbitrary time t = 1.

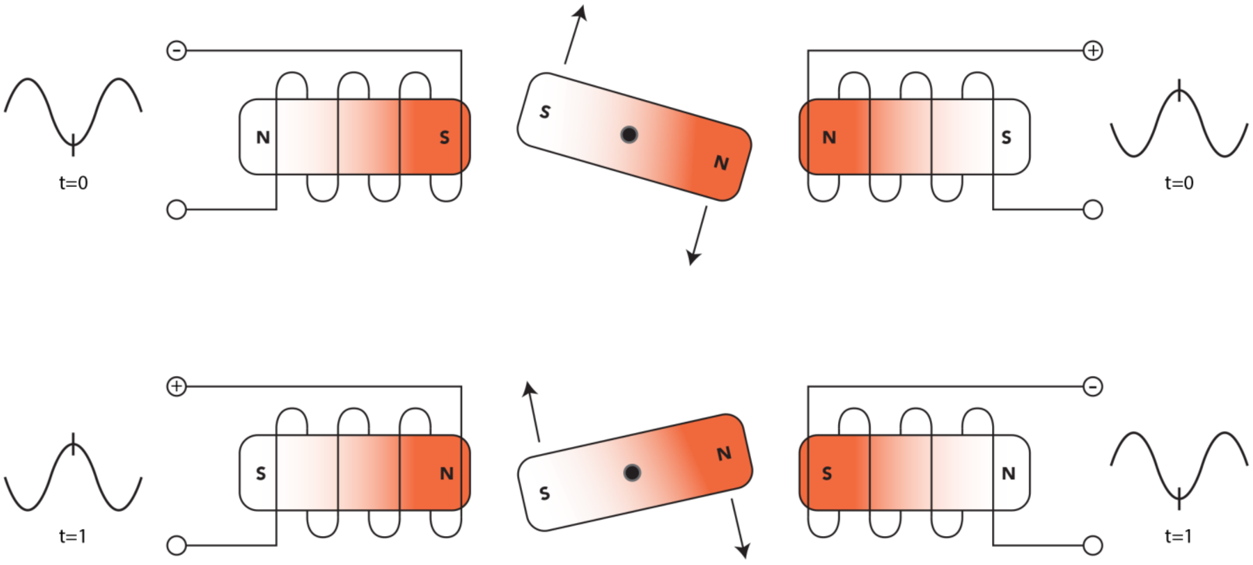

Fig. 2. If electromagnets energized by ac waveforms are used in the stators, the polarities of the stator magnets will contunually change, causing the rotor magnet to rotate continually.

By driving the stator electromagnets from a three-phase ac supply, we create three different magnetic fields, each 120° apart, which create a constantly rotating electromagnetic field (as the voltage and current vectors rotate). Fig. 3 illustrates a simplified situation of north and south polarities on the stator electromagnets, and not the actual vector magnitude, with the left example at time t = 0 and the right example at arbitrary time t = 1.

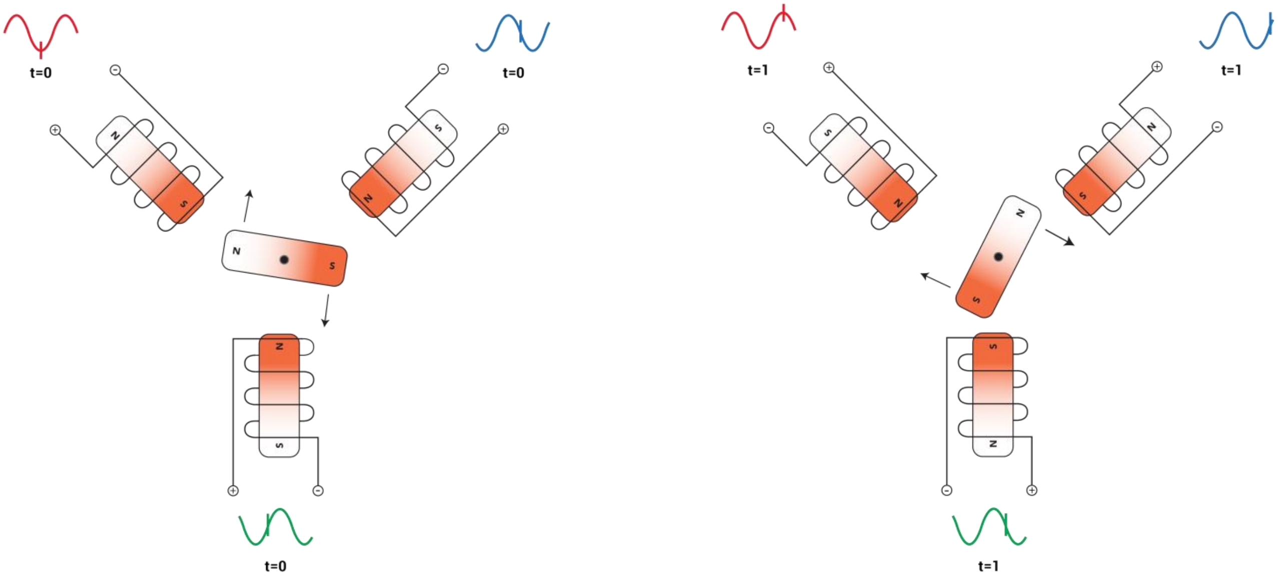

Fig. 3. Adding a third stator electromagnet, and driving the three electromagnets with a three-phase ac waveform, creates three magnetic fields that are physically 120 degrees apart.

Motor Stator Poles And Slots

The above simplified examples of basic motor operation showed one (single- or three-phase) rotating-stator magnetic field and one rotor magnetic pole. Such a motor would have considerable variation in the torque it could produce at the output shaft depending on the position of the rotor magnetic field relative to the stator magnetic field. Therefore, most motors have multiple sets of "slots" for the stator winding, and may have multiple magnetic "poles" on the rotor.

Stator Poles And Slots

To provide more magnetic field changes per rotor rotation, we may use "N" poles per phase in the stator winding. For example, a three-phase motor might have three poles, which would mean nine locations in the stator core for a winding. These locations are termed "slots" and there are often multiple slots per pole.

By definition, a three-phase motor has a minimum of three slots (one for each phase, which would be a single-pole stator). However, the actual number of slots could be much higher. We design motors for a certain number of stator slots (and poles) to optimize the motor cost and characteristics for its intended application.

Fig. 4 below shows an example of a three-phase motor that has four poles (per phase) and one slot in the stator core per pole, making 12 slots to hold the stator windings.

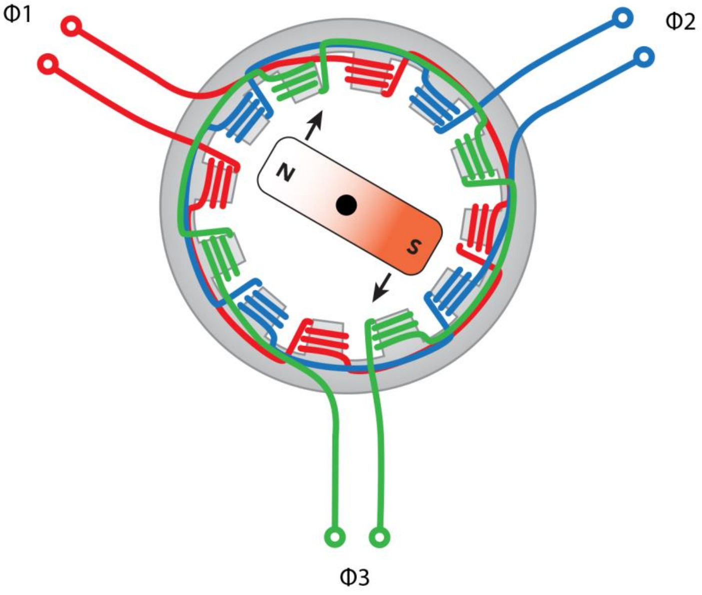

Fig. 4. A three-phase motor with four poles (per phase) has twelve "slots" for stator core windings .

The photo in Fig. 5 shows the stator for an ac induction electric motor. This three-phase motor contains a large number of stator slots, which appears to be 39 by count) in the stator core (where insertion of the stator windings takes place). This is certainly far more slots than the number of poles in the stator winding, and is likely a 13-pole stator.

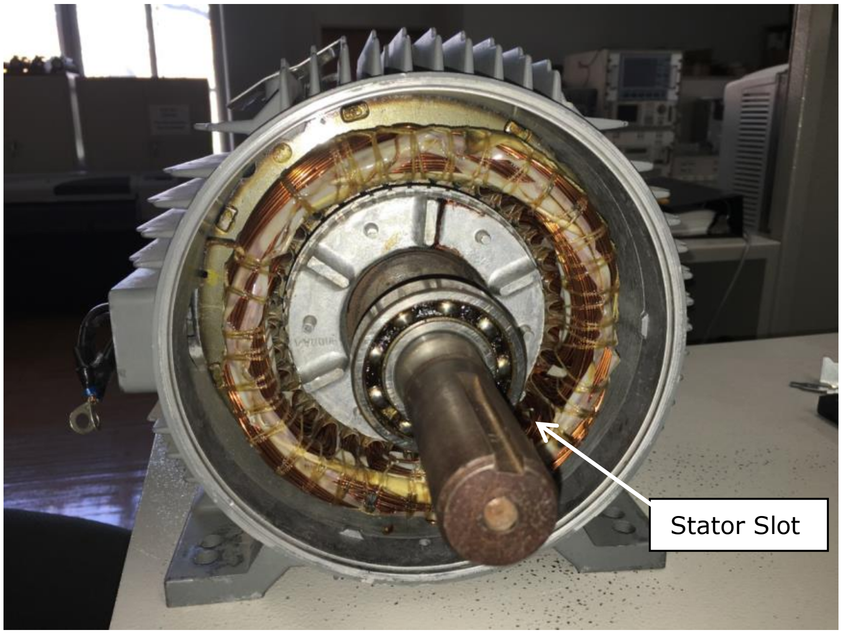

Fig. 5. Stator of a three-phase ac induction motor. This motor has what appears to be 39 stator slots. Photograph courtesy of Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC), University of Wisconsin-Madison.

Rotor Pole Pairs

A rotor "pole" is either a north or south magnetic field on the rotor magnet. We know these as "pole pairs" (a set of one north and one south magnetic field).

The previous examples in Fig. 4 showed a motor with a single rotor pole pair. Fig. 6 shows the same example but with a two pole-pair rotor (and again, with four stator poles and a three-phase stator.)

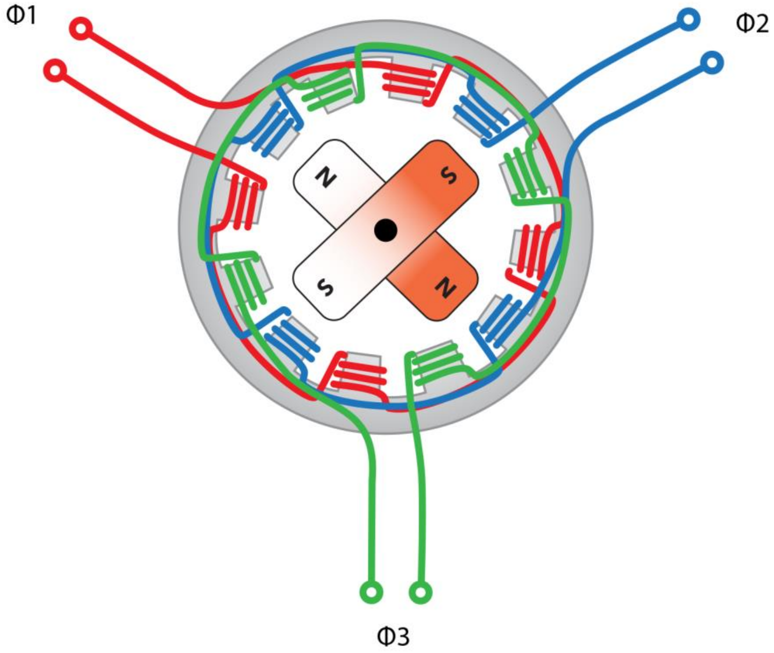

Fig. 6. A three-phase motor with four poles (per phase) as in Fig. 4 but with a two pole-pair rotor.

As with stator poles, motor engineers design for a given number of rotor pole pairs to optimize the motor cost and characteristics for its intended application.

Motor Operating Quadrants

Motors have a variety of application requirements and are designed and controlled so as to behave in specific ways per the application requirements. A motor shaft can rotate and provide torque in either a clockwise or counter-clockwise direction, and it can supply torque to generate power ("motoring") or resist the torque applied to it (i.e., "generating") in either direction as well.

The ability to control applied speed and torque in both directions is important for more complex control applications. Additionally, the ability to brake the motor with applied electrical force (instead of a mechanical brake) or re-generate power while braking is attractive for some applications (e.g., elevators, industrial process control, or vehicle propulsion).

One may describe the two rotational directions (clockwise and counterclockwise) and two torque applications (motoring and generating) in a four-quadrant operating mode diagram (Fig. 7.)

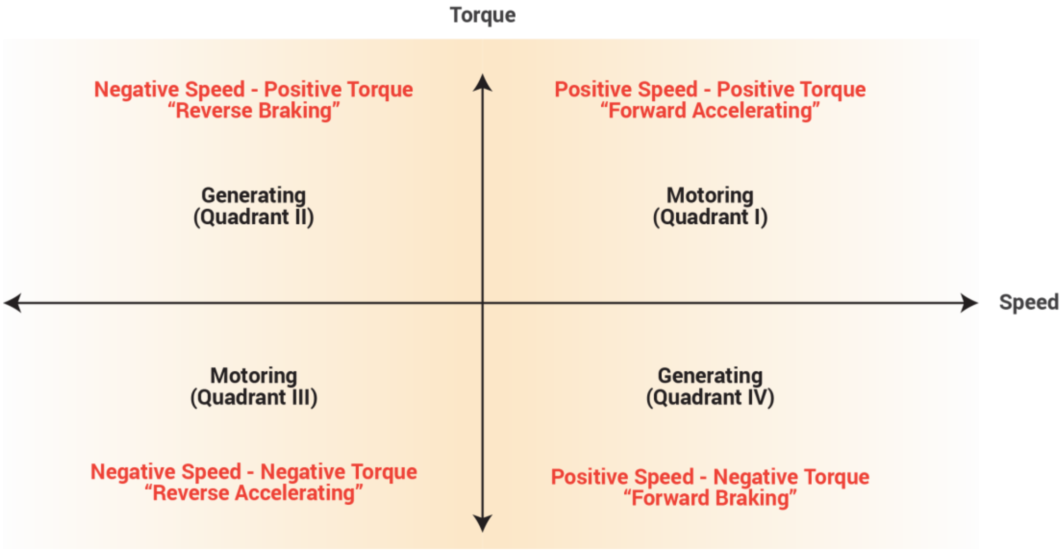

Fig. 7. The four quadrants of motor operation.

Straightforward applications, such as small fan or blower motors, operate only in a single direction and provide torque output (motoring) only with no need for electrical braking (i.e., quadrant 1 operation). A power drill motor might operate in both forward and reverse directions, but with no braking (i.e., quadrants 1 and 3 only). Vehicle propulsion motors would operate in all four quadrants to provide forward and reverse operation with regenerative braking.

To operate a motor in either direction without requiring a re-connection of supply leads to the stator needing an H-bridge (single-phase) or cascaded H-bridge (three-phase) power conversion and control system. We know such systems as "drives," and they electronically control switching for complex operation in multiple operating quadrants.

The most complex four-quadrant operations require use of more complex drive-control architectures and algorithms (e.g., vector field-oriented control, or vector FOC). Such applications call for more informative sensors and more complex control architectures to detect rotation direction and absolute rotor shaft (and therefore rotor magnetic field) position, such as quadrature encoder interfaces (QEIs) or resolvers.

Conclusion

In this part, we have reviewed the basic principles of motor operation. In part 11, we'll look at how these principles are applied in the different types of motors. For a full list of topics that will be addressed in this series, see part 1.

Reference

"EuP Lot 30: Electric Motors and Drives, Task 1: Product Definition, Standards and Legislation," ENER/C3/413-2010, by Anibal de Almeida, Hugh Falkner, João Fong, and Keeran Jugdoyal, June 2012 draft, see page 5 for statistics on motor energy usage.

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.