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How Do Prime Step Motors Work?

A new step motor design boosts efficiency and reduces noise and vibration.

Prime-ratio hybrid step motors look and work exactly like the conventional hybrid versions. But the design of their stator-pole laminations improves motor efficiency while reducing noise and vibration.

Conventional stator laminations in hybrid step motors have five teeth per pole face. On the other hand, prime-ratio laminations have six teeth per pole face. As both prime and nonprime poles use the same 7.5° spacing between teeth, the prime-ratio pole is slightly larger than the nonprime version. As a result the open gap between the poles shrinks. The greater quantity of iron in the pole faces helps concentrate the stator magnetic field in the air gap between stator and rotor producing smoother operation with improved efficiency.

Most engineers are familiar with hybrid step motors. But inside the apparently simple mechanism rests a complex combination of laminations, coils, and magnets. Hybrid step motors combine the controllability of the variable reluctance motor with the higher torque of the permanent magnet or "canstack" motor.

While low cost is the most no-table feature of hybrid designs, better motor performance and efficiency are also important. New construction techniques now let motor designers use prime-ratio laminations that improve efficiency, lower audible noise, and reduce operating temperatures over standard hybrid step motors. The laminations also boost torque output without using expensive electronics.

Hybrid step motors today are refined versions of the original dynamoelectric machine patented by K.M. Feiertag in 1952. They differentiate themselves from standard electric motors by rotating in discrete amounts or steps rather than continuously. Typically, step motors are designed with 0.9, 1.8, or 3.6° full-step-angle increments. The full-step term is used because special driving methods such as half-stepping and microstepping rotate step-motors only a fraction of their full-step motion. The most common hybrid step motor in use today is the 1.8° model that requires 200 full steps to complete one revolution.

The "hybrid" term identifies a step motor using multitoothed stator poles and a permanent magnet located inside a multi-toothed rotor-cup assembly. Compared to nonhybrid versions, the hybrid design enhances the magnetic field on the surface of each rotor cup delivering higher torque.

Hybrid step motor construction consists of thin sheet-iron laminations layered one on top of another to form two stacks: a stator stack and a rotor stack. The stator stack performs double duty acting as both outer housing for the motor and forming the stator poles along its inner walls.

The rotor stacks form two cup-shape end pieces. The paired rotor cups are assembled with a permanent magnet axially aligned between them forming the rotor assembly. One rotor cup becomes the north pole of the magnet, while the other becomes the south pole.

Both rotor and stator stacks bear a slot pattern on their surface that resembles teeth on a gear. Rotor teeth possess a 7.2° pitch angle with each tooth and slot measuring 3.6°. This angle creates 50 teeth on the typical rotor. In addition, the teeth between each rotor cup are offset by the width of a tooth. The offset teeth force the magnetic field of the rotor cups into a longer, indirect path used to derive optimal energy from the rotor magnetic field. The intentional misalignment also prevents a loss of torque caused by the magnetic field shorting across the surface of the rotor from one polarity tooth directly to its opposite.

Copper magnet wire wraps around the stator poles forming electromagnetic coils. High-volume step motors use plastic-injected slot liners to insulate the coil of wire from the stator. Low-volume motors coat the stator with special insulating materials. The coating process is not as fast as the plastic lining, but saves the cost of an injection mold.

Motor torque is controlled by the interaction between the rotor and stator magnetic fields. The rotor field strength is fixed by the permanent magnet in the rotor. The number of wire turns per coil and the strength of the current flow through the wire determine the electromagnetic field strength of the stator. Smaller-gage wire means higher resistance and, thus, lower maximum current. Likewise, a high number of turns boost coil inductance, limiting the speed of current buildup in the coil. Wire size, the number of turns, and the diameter of the stator windings combine to determine coil resistance, inductance, and coil current — parameters that directly affect motor performance.

The number of teeth on a nonprime-ratio step motor is relative to a 7.2° pitch for each tooth. The face of the stator pole should be as wide as possible to direct as much flux as possible into the air gap. More flux in the air gap produces greater torque and less heat due to more efficient operation.

Conventional 1.8° hybrid step-motors contain five teeth per stator pole. Tooth width is proportional to the arc thickness of the pole face. The eight stator poles result in a total of 40 teeth. Openings between poles are used for winding magnet wire around the stators to create the magnetic coils. Slot openings must be wide enough to allow the magnet wire to pass through.

Prime ratio refers to the optimum number of teeth on the stator relative to the optimum number of teeth on the rotor. Hybrid step motors listed as prime ratio have one additional tooth per pole face. Shrinking the size of the opening between the poles makes room for the extra tooth. The tooth reduces the magnetic reluctance in the path of the stator magnetic field, putting more flux in the air gap between stator and rotor. The motor becomes more efficient at generating torque.

The number of teeth on the rotor assembly remains set at 50. By adding one tooth per pole, the total number of teeth on the stator increases from 40 teeth (eight poles five teeth/pole) to 48 teeth (eight poles six teeth/pole). So the ratio of stator teeth to rotor teeth with a prime-ratio hybrid step motor is 4.8:5 rather than the standard 4:5 of a nonprime-ratio model.

Greater tooth area puts more iron in the pole face. The stator-pole iron is approximately 16% wider in prime-ratio step motors than in nonprime versions. The wider tooth focuses more of the magnetic flux into the air gap between the rotor and stator. More effective flux use in the gap reduces flux saturation in the stator back iron minimizing eddy current losses. Benefits of more tooth area in prime ratio step motors include greater output torque with lower audible noise. Conversely, lower operating currents produce the same torque.

The motor operates cooler because of the better efficiency and larger surface area of the stator stack. Cooler running motors impart less heat to the equipment in which they operate. The equipment can, in turn, have tighter tolerances between mechanical components because of smaller mechanical expansion allowances. The better fit between parts limits vibration and noise.

Rotational smoothness improves with prime-ratio stator laminations because the smaller opening between poles reduces torque ripple. Efficiency is better at all speeds but is most visible when speeds are slow. Differences become obvious when prime and nonprime step motors are compared side to side. Cogging will be more apparent at slow speeds among nonprime-ratio motors because of the larger stator-pole opening and the smaller flux content in the air gap. Cogging in nonprime motors is also more apparent with lower rotor inertia.

The smooth, slow speeds produced by prime-ratio step-motors minimize amalgamation of materials when transferring sensitive medical samples or transporting chemicals. Prime ratio step motors used in laser marking, engraving, and cutting machines help lower system costs without sacrificing smoothness.

Hybrid step motors offer the ability to precisely position a load without using a closed-loop feedback device such as an encoder. Prime-ratio step motors attain smoothness at slow speeds without requiring a high-speed current-feedback loop to the controller. Compared to brushless servosystems, smooth motion is possible open loop with much less expense by eliminating the continual monitoring of the motor current.

How step motors operate

Step motors are open-loop devices that rely on the orientation of the rotor and stator teeth for rotation. Teeth on the stator poles and rotor-stack assembly require specific alignment for rotation to begin. Several force vectors created by magnetic flux work together to create rotary motion. In addition to flux vectors that emanate from the stator-pole face, there are also flux vectors between the stator's north-south pole pairs.

In a typical two-phase step motor, two pole pairs make up a phase for a total of eight poles. The phases are labeled A and B. When powered they create field-strengthening and weakening vectors that work in conjunction with air-gap vectors between stator-pole faces and rotor-cup teeth to rotate the motor in a given direction.

The poles of each phase alternate around the stator at 45° angles and reverse polarity between N and S pole every 90°. For example, if the A-phase stator poles reside at the 12, 3, 6, and 9 o'clock positions, the poles at 12 and 6 o'clock are north while those at 3 and 9 o'clock are south. The B-phase poles sit between the A-phase poles and follow the same N/S pattern.

The magnetic field of the rotor aligns with the magnetic field of the stator coils, locking the rotor in position. The motor rotates when current through one phase changes polarity. The direction of rotation is controlled by the order of phase reversals. As an example, if both phases start with a positive polarity, then reversing the A-phase first will step the motor in a clockwise direction. If the B-phase becomes negative first, the motor rotates one step counterclockwise. If the other phase then reverses polarity the motor keeps rotating in the same direction and continues to do so as long as the phases alternate reversing polarities.

A step motor "driver" controls the polarity and voltage supplied to the phases. Many drivers supply a voltage 4 or more higher than the operating voltage of the motor when the polarity is switched. The higher voltage helps overcome coil inductance by forcing a faster buildup of current through the coil, thus maximizing torque. A chopper circuit in the driver limits total current to the preset operating value for the motor. Drivers typically require a trigger pulse or "step command" to produce the change in polarity.

The stator and rotor teeth help concentrate the magnetic flux in the air gap between them. The strength of the flux vectors in the air gap, and thus motor torque, is directly proportional to the energy of the stator coil and the amount of tooth iron on the stator pole. Larger tooth surface areas in the air gap also boosts flux intensity and, ultimately, the amount of torque the motor generates. The result is improved mechanical time constants with faster motor acceleration.

The inside-out prime-ratio stepper

The inside-out step motor (IOS) construction places the rotor assembly to the outside while the stator remains in the middle. The unconventional design lends itself well to through-hole applications where pipes, wires, and conduits must pass through the centerline of the step motor.

A new patented design by Intelligent Motion Systems Inc. is the opposite of conventional hybrid step motor orientation. The inside-out stepper, or IOS, places the rotor assembly on the outside of the stator assembly, This orientation makes it possible to hollow out the core of the motor creating a "through hole," Such a feature invites innovative solutions for linear positioning, rotary, and gearbox systems.

The IOS delivers up to 1,200 lb of linear force at speeds <1 rps with repeatable accuracy to ±3 arc-min. In addition, the prime-ratio lamination architecture of the IOS42 augments motor torque and efficiency, reduces low-speed agitation, and significantly enhances smoothness of rotation.

Compared to traditional approaches, IOS motors let designers eliminate components to simplify mechanical designs, shrink footprints, and lower overall cost.