Short Flux Paths Cool SR Motors

Departure from traditional rotor/stator design makes a new motor that boosts efficiency, simplifies drive requirements, and cuts cost.

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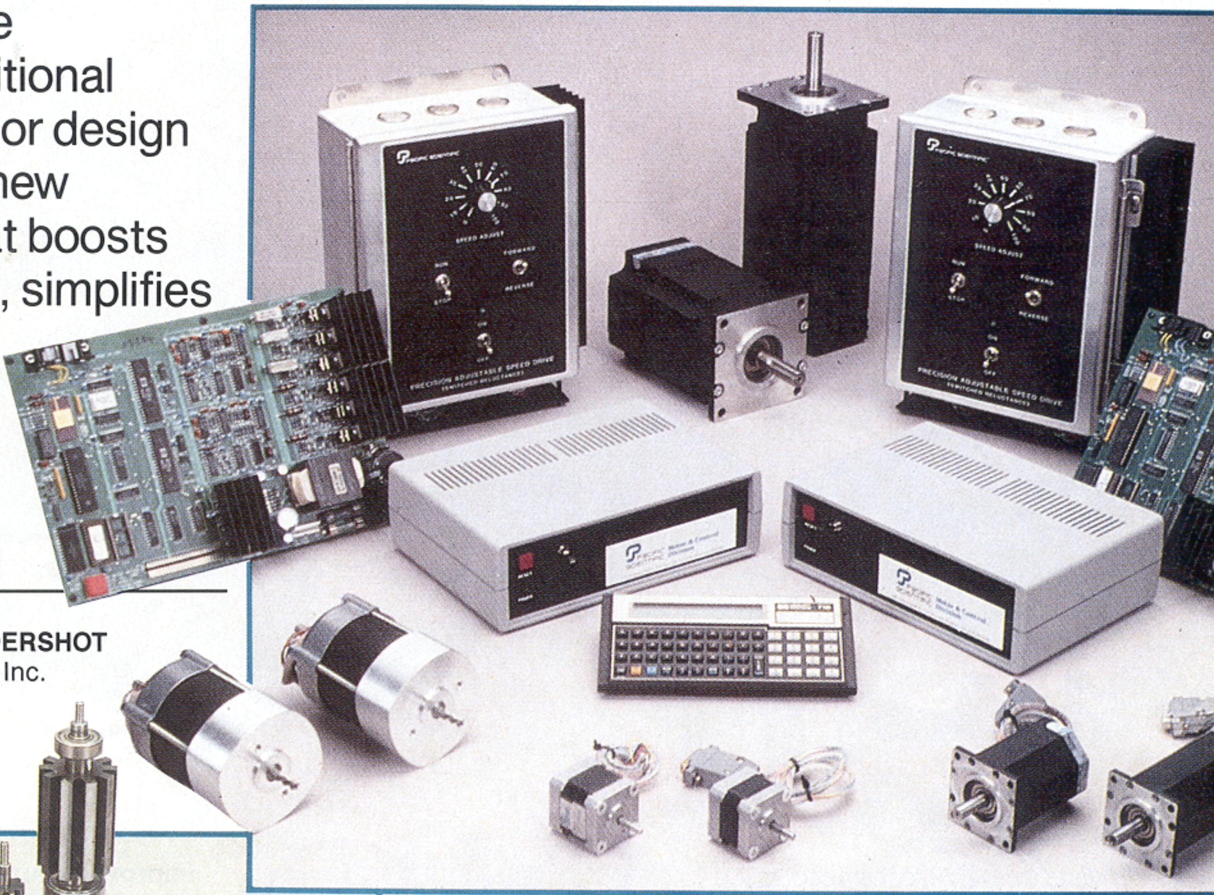
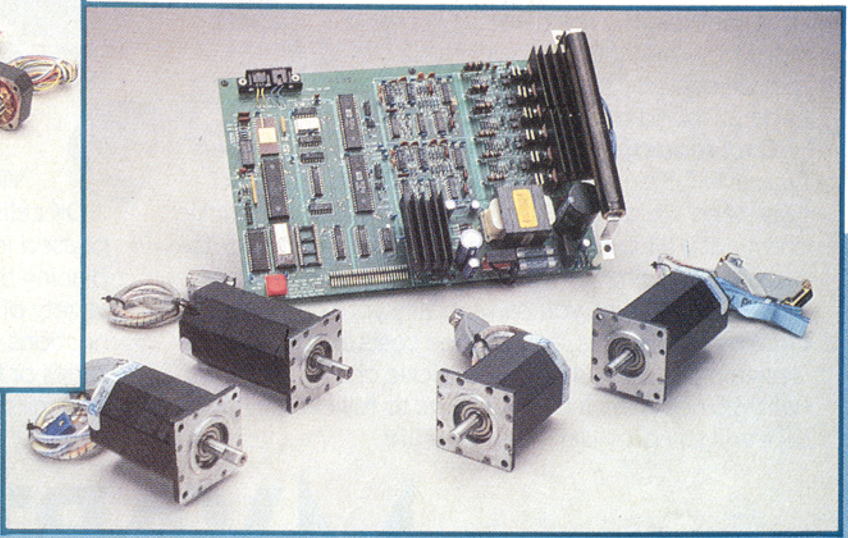




Switched-reluctance (SR) motors are brushless dc motors without magnets. They are more important to motion-control engineers today than in previous years for two reasons. First, low-cost solid-state drive components allow efficient control of SR motors in traditional variable-speed drives. Second, higher efficiencies, higher torques, and lower noise motors are produced by new design methods, including computer modeling, reducing time to production.

Conventional SR dc motors are similar to variable-reluctance (VR) motors, such as stepping types. But the most distinguishing quality of SR motors is the lack of either permanent magnets or wound coils for the rotor. SR motors also are brushless, with unexcited and magnetically permeable rotors. Rotor poles are attracted to electromagnetically energized stator poles, forcing the rotor to advance to a position of minimum reluctance or minimum resistance to the magnetic-flux flow.

The variable-reluctance characteristic observed in both VR stepping and SR motors is caused by the continuously changing air gap between stators and rotors as the shaft rotates. The methods used to commutate the motors determine their maximum speed and torque ripple.

Stepping motors, for example,

REFINED DESIGN WITH COMPUTER SIMULATION

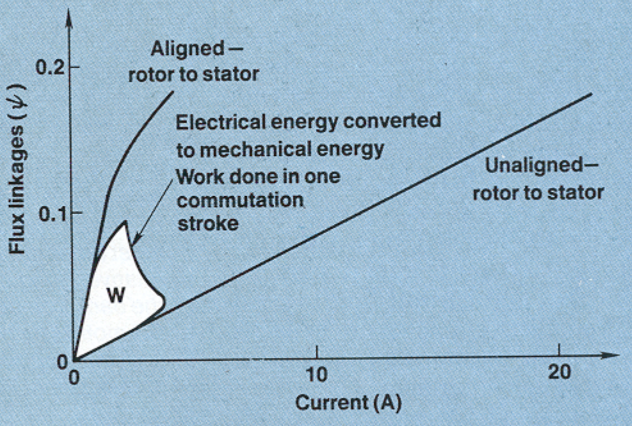
The salient-pole design of SR motors offers several important benefits that would ordinarily encourage engineers to use them in new equipment. But commercialization of such motors was slow because designers had trouble figuring out ways to control changes in air gap and pole permeance during motoring.

However, the computational capability of two computer-aided design (CAD) programs for personal computers significantly reduces traditional trial-and-error motor design time.

The first program is Magneto, by Integrated Engineering Software Inc., Winnipeg, Manitoba. It is a magnetic solver based on the boundary-element method (BEM) that simulates magnetic-circuit geometry such as pole shapes and lamination designs. Static models are analyzed to find an optimum balance between copper, iron, and lamination-pole geometry, and generate maximum torque and power from a given frame size. Compared to finite-element (FE) magnetic solvers, BEM solvers integrate, rather than differentiate elements. This results in a faster solution with a computer that does not need large memory capacity.

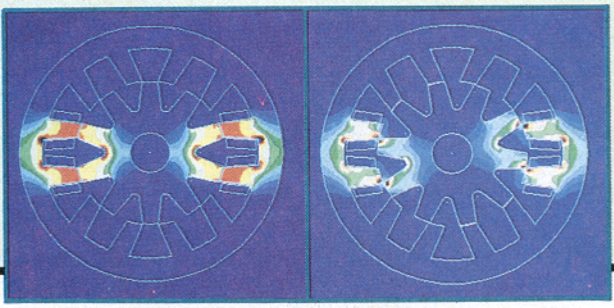
A dynamic computer simulation program called PC-SRD, (written by professor T. Miller, et al, at the University of Glasgow, Scotland) is used to optimize application-specific aspects of new SR motor designs. PC-SRD provides a performance analysis of motor designs based on size, stack length, number of turns, and voltage applied. Rpm is selected as an input variable to determine the torque, output power, efficiency, resistance, inductance and motor losses. Power transistors used for drive electronics also are sized in the simulation.

Scientific Pacific has used PC-SRD to optimize commutation angles, polarity relationships, number of phases, pole pairs per phase, and other aspects of motor designs.



Continuous changes in air gap and pole permeance as the rotor turns, make the SR motors difficult to design. But new computer-aided design (CAD) tools are changing that scenario. Performance characteristics are generated in a dynamic computer simulation and displayed on the monitor as tables, curves, and geometric shapes. They help the designer fine tune the motor design and predict its behavior when installed in a system.

SR motors do not need permanent magnets, rotor coils, or commutators to create torque. As a result, SR motors made by Pacific Scientific are relatively simple and inexpensive. The low-speed, high-torque qualities of SR motors make them well suited for applications that depend on precision-controlled direct drives. On the other hand, SR motors and drives also are known for their high-speed capability.



Magnetic-flux distribution of an SR motor using a magnetic solver called Magneto by Integrated Engineering Software. When the stator and rotor poles are aligned (left), zero flux and torque result. Maximum torque is produced with the stator and rotor poles offset (right).

simply receive a series of pulses that advance the rotor a fixed number of degrees per pulse (1.8° for a 200-step motor), typically without regard to the rotor's absolute position. SR motors, on the other hand, are commutated like brushless dc motors — commutation depends on rotor position not clock pulses.

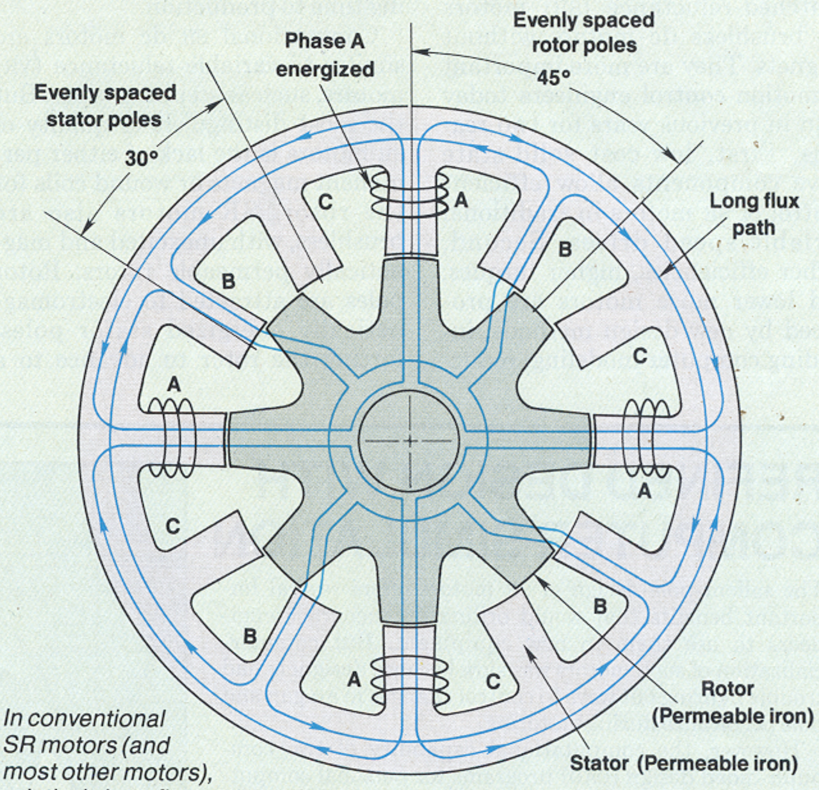
With the availability of new, inexpensive power MOSFETs and insulated-gate bipolar transistors (IGBTs), SR motors are now being used more frequently in new variable-speed drives. These semiconductors enable SR motor-control systems to operate at efficiencies up to 85% or more. These efficiencies are similar to inverter-driven ac motors and permanent-magnet (PM) motors. National Semiconductor Corp. has released preliminary specifications for an integrated circuit to control SR motors. IC functions include phase-switching outputs to drive power MOSFETs (with phase advance firing for high speed), pulse-width-modulated (PWM) phase outputs for closed-loop speed control, braking, and current limiting. Additional custom chips are expected to appear as more SR motors are used in new equipment.

Compared to ac induction, dc, and brushless dc motors presently used in many variable-speed drives, SR motors cost less to manufacture for two reasons. Passive SR rotors do not use permanent magnets nor excited copper windings, and no brushes or slip rings are needed. SR motors also use simple and inexpensive drive circuitry. And dedicated SR digital-control ICs are now available that further reduce discrete component count and simplify control design.

SR motors dissipate heat well and are inherently rugged. With no rotor windings, permanent magnets, or commutators, SR motors have lower inertia and higher operating speeds than comparable ac or PM dc motors. Also, SR motors' copper losses are lower than other motor types because of very short stator end windings.

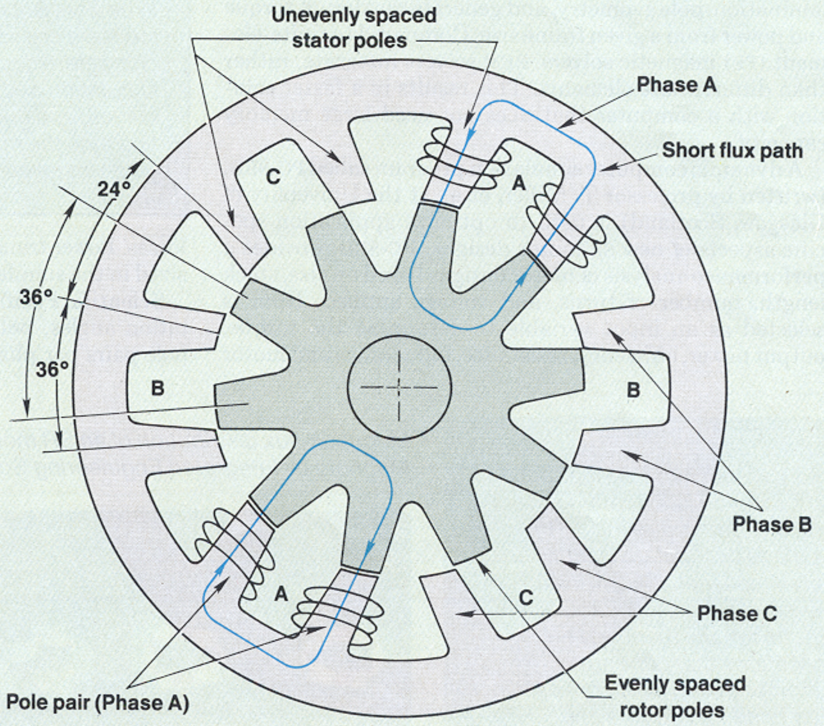
However, the efficiency of all motors has been limited mostly by hysteresis, and eddy-current losses, especially at speeds exceeding 5,000 rpm. All motors are plagued by hysteresis and eddy-current

Typical three-phase SR motor design

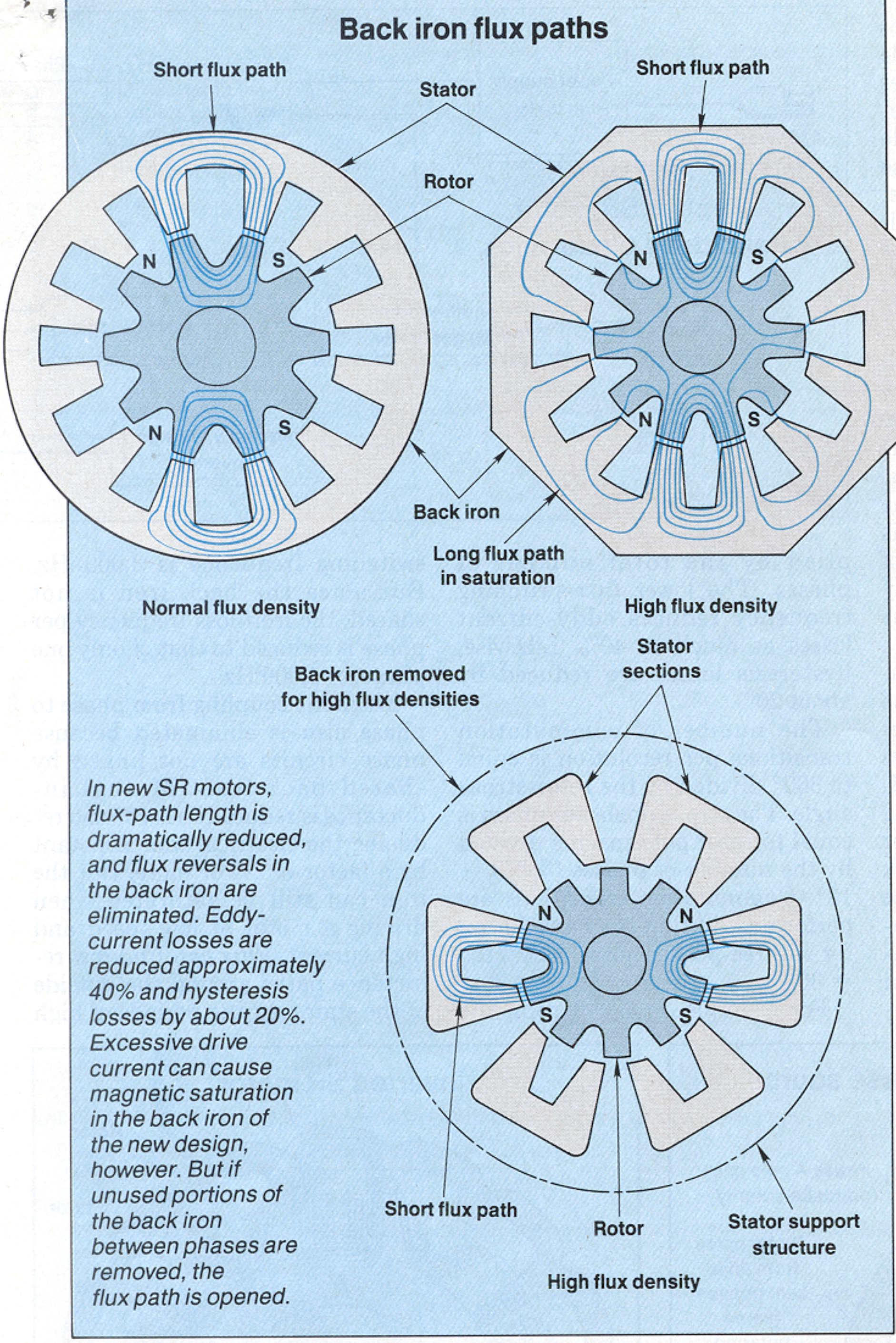


In conventional SR motors (and most other motors), relatively long flux paths through the back iron cause significant hysteresis and eddy-current losses. But SR motors, in general, have many benefits, such as low manufacturing cost, high speed, low inertia, low-copper loss, rugged design, and excellent heat dissipation.

New three-phase SR motor design



Pacific Scientific's SR motor excites poles in adjacent pairs to form a primary magnetic circuit. This substantially reduces the amount of back iron in the flux path and results in lower iron losses.



In new SR motors, flux-path length is dramatically reduced, and flux reversals in the back iron are eliminated. Eddy-current losses are reduced approximately 40% and hysteresis losses by about 20%. Excessive drive current can cause magnetic saturation in the back iron of the new design, however. But if unused portions of the back iron between phases are removed, the flux path is opened.

losses in the stator and in the rotor back iron. Also in conventional designs, all portions of the back iron are affected. Despite newer laminated, magnetically permeable, steel stator and rotor construction, iron losses still are significant.

Hysteresis losses result in the back iron when positive-to-negative currents are created by phase switching. Eddy-current losses are related to flux-switching frequency, which is the cyclic building and collapsing of magnetic fields in the stator. Hystersis losses vary as the first order of frequency, and eddy-current losses vary as the second order. Overall iron loss frequency is expressed as

$$f_l = (n_s)(n_p)(\text{rpm})/60$$

where n_s = number of times a phase current is switched, n_p = number of phases, and rpm = motor speed.

Hysteresis-loss magnitude is determined by flux-reversal frequency created when the directions of flux flow in overlapping magnetic circuits are opposed. Though stator poles do not typically undergo flux reversals, segments of the back iron have flux reversals during each phase-switching period. Rotor poles have one or more flux reversals per revolution, depending on the number of poles and phases.

Because flux paths for each phase share the entire back-iron area of the stator, a conventional SR motor's flux-switching frequency equals the commutation frequency of each phase multiplied by the number of phases energizing the motor. For a three-phase motor the flux-switching frequency in the back iron is equal to three times the commutation frequency per phase and causes high eddy-current losses. Linked phase circuits in the shared back iron also produce mutual induction that adversely increases motor-time constants.

Long flux paths through the rotor and around the outside of the stator subject the entire back iron to eddy-current and hysteresis losses that cause motor heating at high speeds.

Improved designs

New salient-pole motor designs increase efficiency over a range of speeds from several hundred to 30,000 rpm or more. They maintain SR motor advantages, but improve speed and efficiency by better lamination design.

These new patented motors have evenly spaced rotor poles and unevenly spaced stator poles. Windings are wrapped in directions that energize stator poles as pairs of adjacent poles having opposite polarities, creating a magnetic circuit path between each of the pole pairs.

The angle between poles in each wound, pole pair, measured in mechanical degrees, must be equal to the angle between rotor poles. This permits the pole pairs on the stator to align with poles on the rotor. A low-reluctance flux path is then created between poles in the pairs.

However, the angle between adjacent pole pairs always must be greater or less than the pole-pair angle. This ensures that torque is generated at the rotor. For example, a conventional, three-phase SR motor has 12 stator poles, equally spaced by 30°. The rotor has 8 poles with 45° spacing. By comparison, an equivalent motor of the new design also has 12 stator poles, but 10 rotor poles. The rotor poles are equally spaced at a 36° angle (360°/10 = 36°). The stator poles are arranged as six pairs corresponding to the 36° rotor-pole spacing to achieve a wound-phase angle equal to the rotor angle. These poles use 216° of the available 360° stator arc (6 × 36° = 216°). The remaining 144° determines the spacing between pole pairs (144°/6 = 24°).

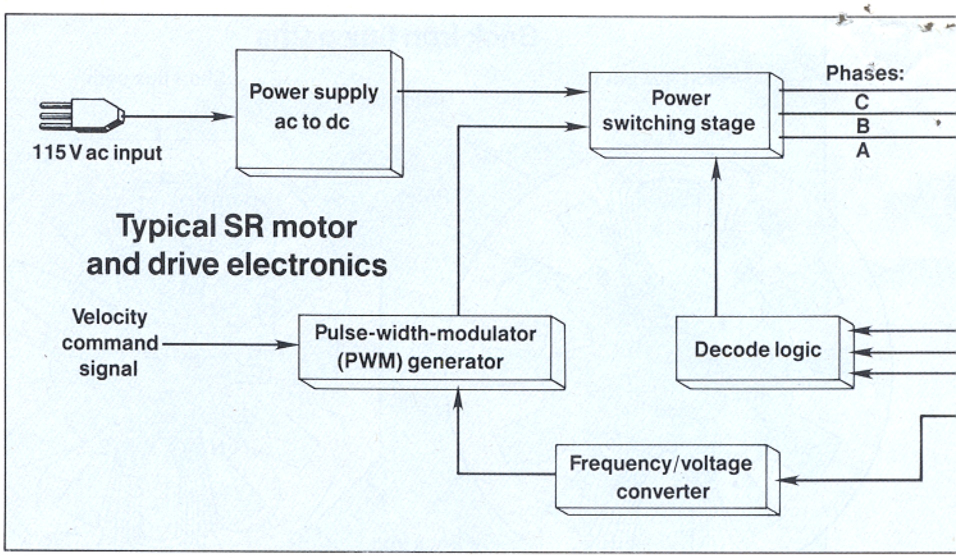
Both poles of a pair are excited together to assure that the primary magnetic circuit is formed only through the back-iron area of the stator that bridges the two poles. As a result, flux reversals in the stator iron are eliminated. This shorter path reduces the amount of included iron and proportionally reduces the losses compared to the conventional flux path.

In addition, energizing only adjacent stator poles minimizes the amount of back iron in the magnetic path, greatly reducing losses caused by the collapsing and building of a magnetic field. By avoiding energizing schemes that link stator pole pairs, each area of the back iron has flux flow for only one phase. The back-iron flux-switching frequency is reduced to the frequency of each phase, rather than the frequency of each phase multiplied by the total number of phases. The lower flux-switching frequency reduces eddy-current losses as much as 40%. Likewise, hysteresis losses are reduced by about 20%.

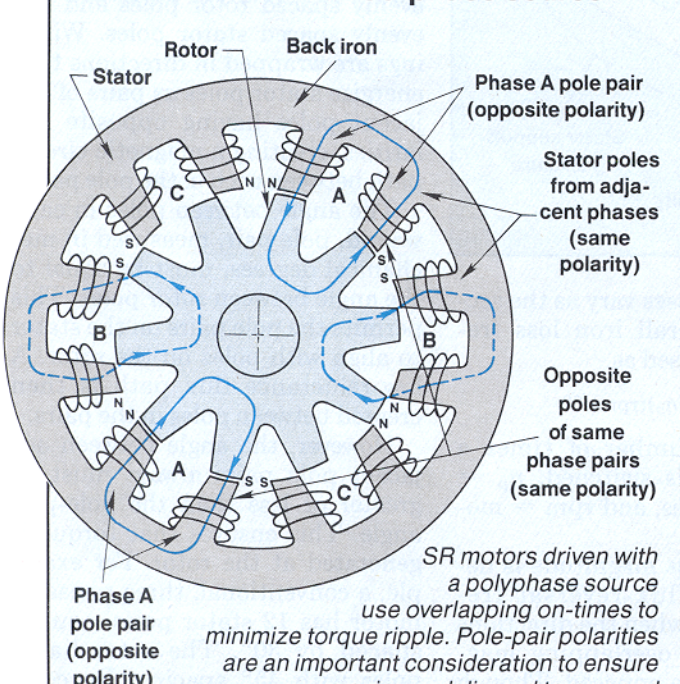
The number of commutation transitions per revolution is equal to 360° divided by the rotor-stroke angle. The stroke angle per phase is equal to rotor pole spacing divided by the number of phases (36°/3 = 12°. Commutation transitions are performed 30 times per revolution for a three-phase motor (360°/12° = 30).

For example, at 6,000 rpm, the switching frequency is 3,000 Hz. But since the back iron is not shared, the iron-loss frequency per phase is reduced to that of only one phase, or 1,000 Hz.

Magnetic coupling from phase to phase also is eliminated because phase circuits are not linked by shared back iron. Mutual inductance is reduced to zero, also reducing the electrical time constant by a factor of 2½ or more. But the iron can still be saturated when driving a motor at low speed and high current. Flux can find low reluctance paths around the outside of the stator during periods of high

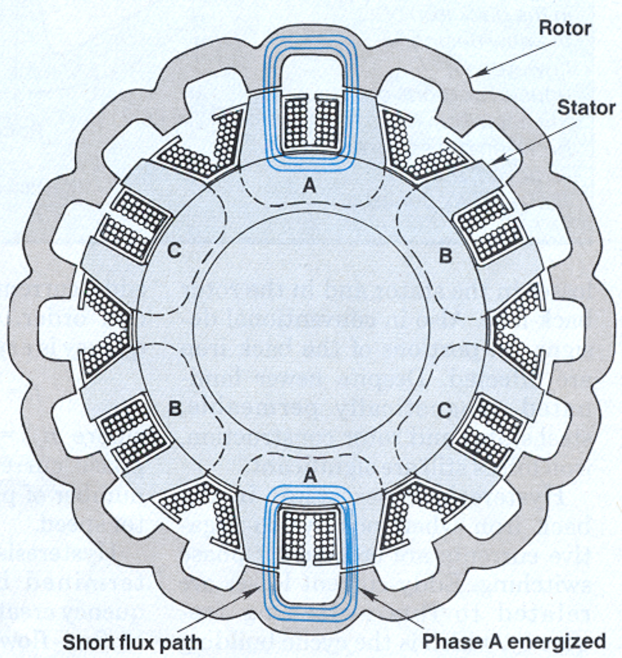


SR motor with three-phase source

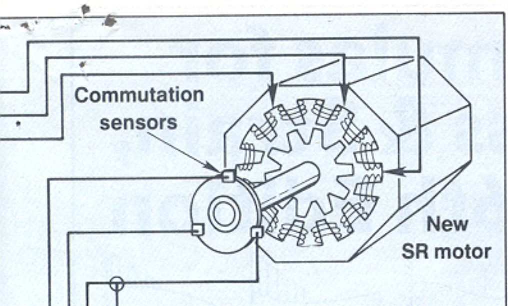


SR motors driven with a polyphase source use overlapping on-times to minimize torque ripple. Pole-pair polarities are an important consideration to ensure maximum delivered torque and minimum torque ripple.

Inverted SR motor



An inverted motor of newer SR designs features a wound stator and salient-pole rotor. Potential applications include combination starter motor and generator for automotive and aerospace markets.



The SR motor's salient-pole design results in simple, low-cost drive electronics. Controls are commercially available for both variable-speed and servo SR motor applications, and new custom ICs for control are emerging.

flux density, seeking an unsaturated portion of the circuit. The result is some sharing of back iron. To alleviate this problem, the unused segments of back iron between the phase pole pairs are simply removed.

Simpler controllers

Drive topology for the new salient-pole SR motors is simpler than for most other motors since they can be unipolar. The polarity of magnetic flux is not a consideration because permanent magnets are not used. Pole-pair polarity is determined only by the stator windings. Rotor position for phase switching is handled by Hall-effect devices, optical switches, optical encoders, or resolvers. Self-commutation schemes that require no added sensor also are under development.

These SR motors may be energized by a polyphase source, with one or more phases on at a given time. A hybrid scheme, in which the motor is driven by a different number of phases at different times, can be implemented by overlapping the on times of each phase to minimize torque ripple.

When an SR motor contains two pole pairs per phase, the magnetic polarity of the poles is important. To assure only two flux paths occur per phase, the polarity of the stator poles from adjacent phases must be the same (determined by winding direction of coils). The polarity of the poles in the same phase which are 180° apart must also be the same, otherwise four flux paths would result. ■