A quest for energy efficiency has fostered development of switched-reluctance motors that are inherently simple and can supply variable speeds.

The switch to SWITCHED RELUCTANCE

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Resources

Emerson Motor Technologies, *emersonmotors.com* **Circle 621**

Short tutorial on SR motors by **Freescale Semiconductor**, *tinyrul.com/5gg8p5*

Rocky Mountain Technologies Inc., SR motor basics, *tinyrul.com/5vgckn*

Key Points

Switched-reluctance motors are candidates for high-performance variable-speed drive applications.

They are getting attention for uses that demand energy efficiency because of their relatively flat efficiency curve that can hit 90% over a broad range of operating conditions.

They can be more efficient than induction motors and work at variable speeds. They are also inherently simple. For a time, they powered **Maytag** Neptune washing machines.

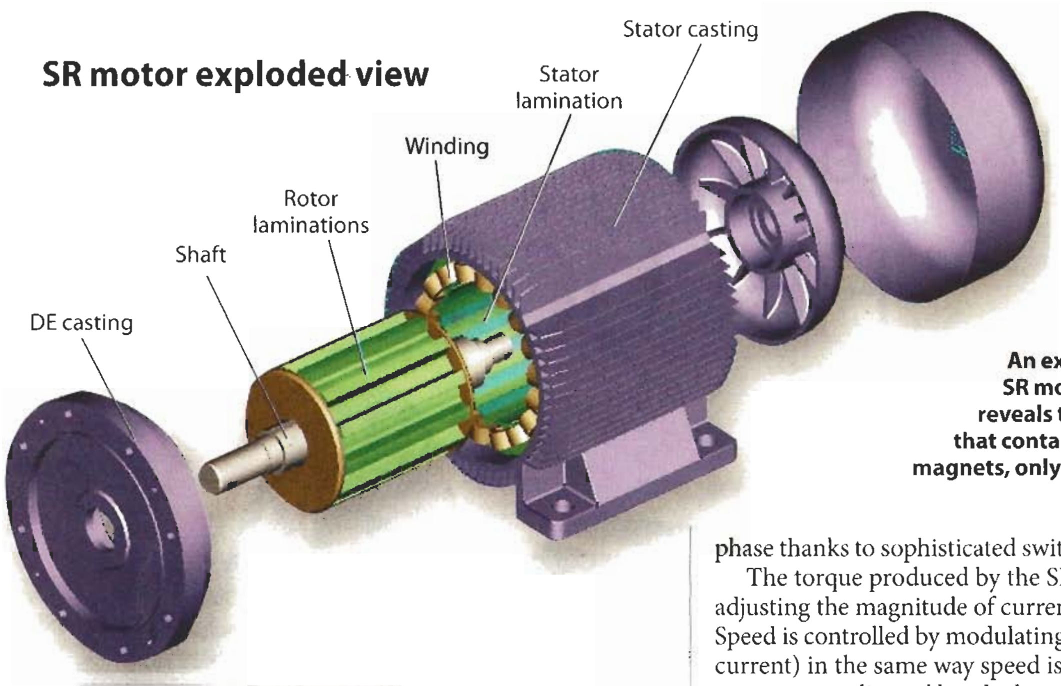
Switched-reluctance (SR) motors were developed in the 1800s but, apart from a few embedded-drive applications, they have not been widely applied. Their optimum operation depends on relatively sophisticated switching control, something not economical until the advent of compact but powerful solid-state power devices and ICs. Now, with a new emphasis on energy efficiency, switched-reluctance motors may be ready to take a more prominent role in appliances, industrial equipment, and even off-road gear.

A switched-reluctance motor works in a way that is somewhat analogous with a stepper motor. An SR-motor rotor consists of laminated-steel protuberances. It carries no windings, magnets, or other features. The protuberances are strongly magnetically permeable. Areas surrounding them are weakly permeable by virtue of slots cut into them.

SR-torque production resembles that of stepmotors because coils in the stator serve as electromagnets that attract the nearest rotor poles. One important difference between an SR motor and a stepper is that a stepper operates open loop. The rotor follows the magnetic field of the stator, but there is a possibility the two could get out of sync. On the other hand, an SR motor does not operate open loop but rather monitors its rotor position. Stator coils get energized in synchronism with the rotor and only when it is advantageous to do so. Moreover, the motor is configured so the phases overlap. Thus torque transfers smoothly from phase to

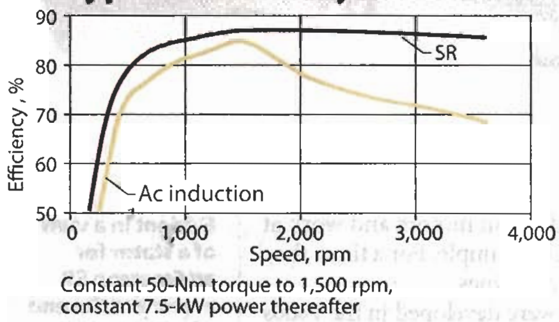
Evident in a view of a stator for an Emerson SR motor are the end windings which are more compact than those of induction motors. The difference arises because SR stator windings loop over only one set of laminations. As a result, SR motors can have flat aspect ratios. The rotor, left, is laminated steel and contains no magnets or windings.

SR motor exploded view



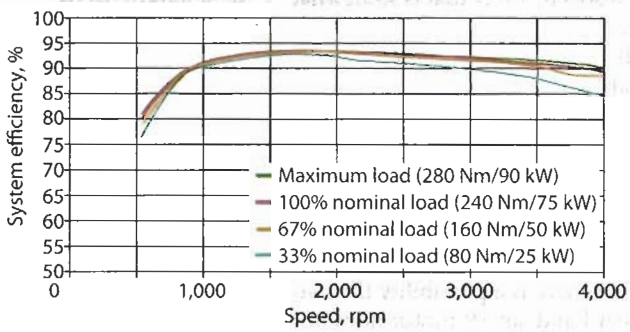
An exploded view of an SR motor from Emerson reveals the rotor structure that contains no windings or magnets, only steel laminations.

Typical efficiency at 7.5 kW



A comparison of operating efficiency for an Emerson SR motor and an equivalent ac-induction motor shows the high, relatively flat efficiency that SR motors can demonstrate at medium speeds and above.

Measured system efficiency versus speed



At moderate to high loads, SR motor efficiency remains relatively flat as evident from this plot by Emerson of an L75SR mk.2 compressor motor.

phase thanks to sophisticated switching.

The torque produced by the SR motor is controlled by adjusting the magnitude of current in the electromagnets. Speed is controlled by modulating the torque (via winding current) in the same way speed is controlled via armature current in traditional brush-dc motors and drives.

And SR motors can be engineered for power rather than for step accuracy as is the case with stepper motors. For example, **Emerson Motor Technologies** says it has routinely fielded SR motors in the 100 and 200-hp range, sizes not practical with steppers.

SR motors also have advantages in motion-control applications. An SR motor can produce 100% torque at stall indefinitely. This is because there is no heat produced in the rotor at stall. Rotor bearings stay cool as well. Only the stator coils experience a temperature rise, and they can be cooled via fins on the stator housing or other conventional means.

SR-stator windings are also simpler than those on induction or permanent-magnet ac motors: Each slot in the stator contains windings for only one phase. A winding that emerges from the stator slots need only loop back around one slot, rather than around multiple slots as on induction motors. This keeps down the volume of end windings and minimizes the risk of a phase-to-phase insulation failure.

Emerson, which has an SR-motor line dubbed SR Drives, points out this construction minimizes the energy lost on coil overhangs at the slot ends, since magnetic fields generated at the end of the slot do not contribute to doing work. A smaller end-winding area also keeps down the length of the motor and the amount of heat to be dissipated. Emerson says the result can sometimes be an SR motor one or two frame sizes smaller than an equivalent induction motor.

A point to note about SR motors concerns their reliance on position feedback from the rotor to operate. The rotor encoder can have a resolution that is relatively coarse compared to a transducer used on a motion-control application. The encoder feedback serves only to switch phases on and off, so it need only have the same number of

SR motor applications include high-power uses such as 45, 75, and 120-kW variable-speed screw compressors (above) from CompAir UK Ltd., and off-road equipment such as the LeTourneau L1350 loader which uses an Emerson B40 300-kW SR motor to drive each of its four wheels.

pulses-per-revolution as the rotor has poles. Simple low-cost, low-resolution Hall-effect devices are sufficient.

Alternatively, it is possible to run the motors in a sensorless scheme. This method uses electronics to detect changes in the phase inductance as the rotor moves past. The inductance changes by factors of 5:1 or more as the rotor moves from a fully aligned to fully misaligned position with respect to the phase windings.

Misconceptions

Emerson engineers say there is a misconception that SR motors tend to step when operated at low speeds. In reality, they say, torque production is relatively continuous, so there is no stepping behavior. They also say the energy efficiency of SR motors is at least as good as the best ac machines operating at their sweet spot. Engineers point out that the energy efficiency of ac motors drops dramatically when they operate at less than 50% load or when used in the field-weakening range at higher speeds. In contrast, complete SR systems (including all motor and inverter losses) can have an efficiency of well over 90% under a wide span of load conditions.

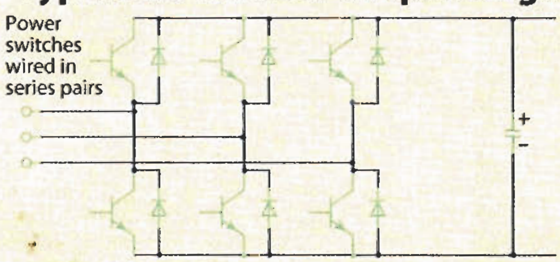
There is no fundamental high-speed limit for SR motors. Emerson says it has run some units at 70 krpm and is evaluating operation at 100 krpm for certain small machines. High speeds are constrained only by the bearing system and the yield strength of the rotor steel. Moreover, SR motors generate no back-EMF so there is no need to put energy into field weakening at high speeds, as is the case with permanent-magnet drives.

Drive electronics for SR motors resemble those for conventional variable-speed drives to a degree. Ordinary six-switch inverters for VFDs and SR motor drivers both contain an identical number of power switches (usually IGBTs) and diodes.

However, the SR drive has efficiency advantages compared to VFD drives that use relatively high PWM frequencies to synthesize sinusoidal ac waveforms and thus keep down harmonic content. Switching losses can be appreciable in these VFDs, thus the inverters tend to run hotter.

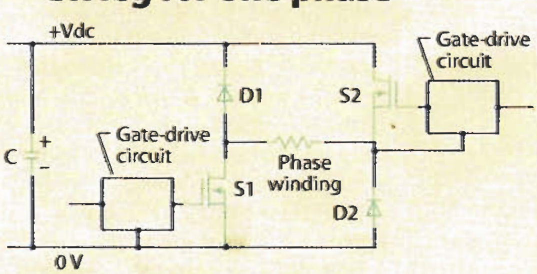
It is interesting to compare the operation of 12 or

Typical ac-inverter output stage



A drive circuit for a modern SR motor has the same number of power semiconductors as an inverter for an ordinary variable-frequency drive. However, the SR drive switches at a lower frequency because it need not synthesize a sinusoidal waveform. This minimizes energy losses and allows use of power semiconductors having lower power ratings than in an equivalent ac drive. The SR drive output configuration also eliminates the risk of shoot-through faults that can happen in inverters because the power switches are not wired in series.

SR leg for one phase



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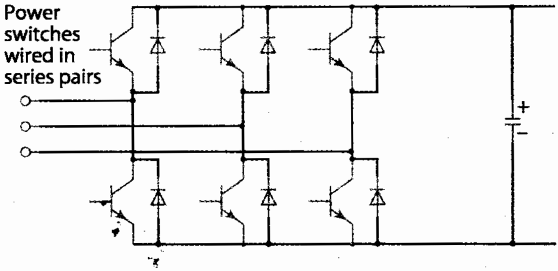

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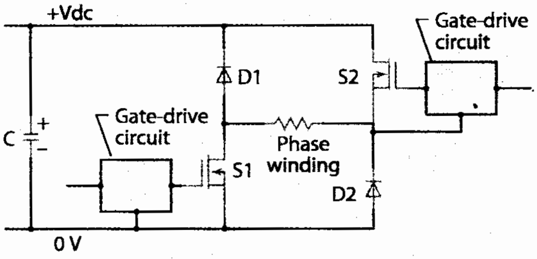

18-switch VFDs with the drive for a typical eight-pole SR motor. Here switching takes place at eight times the physical rotation speed of the motor. Thus for a 3,600-rpm motor, switching frequency per phase is 480 Hz, about 10 times slower than for the equivalent inverter. Switching losses are 10 times lower as well. Emerson says all in all, power loss in an SR inverter can be as much as half compared with an inverter for an ac motor.

Another common misconception is that SR motors cannot serve as generators because they have no rotor magnets. Actually these motors can become generators by altering the timing of phase excitation — that is, switch on the electromagnets when the stator and rotor poles are separating, rather than when they are approaching. Switching on a stator pole when it aligns with the rotor puts a magnetic field through the rotor. The mechanical load does work on this magnetic field as it pulls the magnetized poles apart. That action increases the stored energy in the magnetic field. This energy then returns to the power supply when the IGBTs controlling the phase winding turn off.

Efficiency concerns

Torque production in an SR motor is proportional to the amount of current put into the windings. Torque production is also unaffected by motor speed, unlike the case in ac motors where, in the field-weakening region, rotor current increasingly lags behind the rotating field as motor speed rises.

SR-torque density can easily exceed that of ac motors. But SR motors do have a somewhat lower torque density than permanent-magnet ac motors. PM motors operating at their design sweet spot can have a high-torque output per unit of stator current because the magnetic field has already been "paid for" by inclusion of permanent magnets. (In other words, no stator current is necessary to magnetize the motor.)

There are trade-offs, however, because efficiency falls off faster at light loads for a PM motor than for SR motors. And there is a loss of efficiency with PM motors at speeds high enough to necessitate use of field weakening to prevent the back-EMF from exceeding the power supply voltage. Applying a current to temporarily weaken the magnets causes losses in the windings and commensurate losses in efficiency. Loss of control under field weakening conditions in a PM machine is dangerous, too, because the back-EMF then exceeds the power supply voltage resulting in uncontrolled generating and, consequently, high currents. **MD**

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