Electronic Design

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New Motor Designs Help EV Makers Kick the Rare-Earth Habit (Part 3)

This compact tutorial on the basics of synchronous reluctance motors reveals why they may be the big winner in the race to eliminate rare-earth materials from EVs.

Advanced electric motors can help give tomorrow's electric vehicles more range and performance while reducing or eliminating the need for rare-earth minerals found in the permanent-magnet synchronous motors (PMSMs) that have been widely used until now.[1]

Part 1 of this series explored several wound-rotor synchronous motor (WRSM) architectures and how they can be near-drop-in replacements for PMSM units. Part 2 examined the properties and application challenges of switched reluctance motors (SRMs), one of the most common types of so-called induction machines.

Part 3 looks at synchronous reluctance motors (SynRMs), another promising sub-species of induction-type machines *(Fig. 1)*. As with the other installments, we will introduce their operating principles, advantages, and disadvantages, as well as what it will take to turn them into a practical technology for powering next-generation EVs.

1. Able to reduce energy consumption up to 50% over commonly used induction motors, synchronous reluctance motors are expected to play an important role in next-generation EVs and other climate mitigating applications. (Credit: ABB)

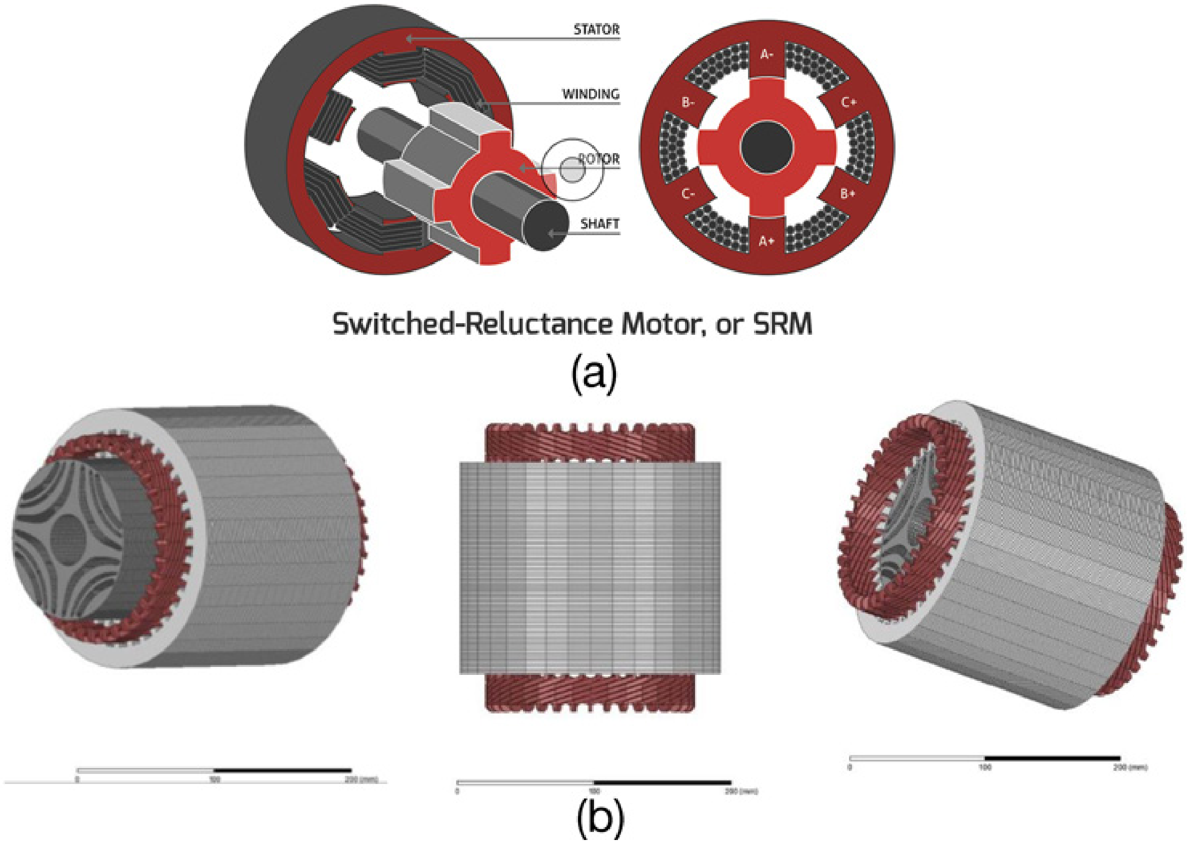
SynRMs vs. SRMs

Both SRMs and SynRMs generate torque by using a rotating magnetic field to induce non-permanent magnetic poles in a ferromagnetic rotor. Instead of windings or permanent magnets, the rotor, typically constructed from a stack of laminated iron sheets, is built to form regions of low reluctance that produce a magnetic field when exposed to the stator's rotating magnetic field.

As explained in Part 2, SRM rotors have "teeth" cut lengthwise around their circumference. They tend to be very magnetically permeable while the empty notches on either side of them are weakly permeable, forming "salient poles," i.e., areas of increased magnetic flux density *(Fig. 2a)*.[2]

While SRMs are rugged, inexpensive, and relatively efficient, they have several disadvantages. Many arise from the fact that their stator electromagnets must be driven by a trapezoidal unipolar (DC) waveform that switches between 0 V and the desired drive voltage.

In addition to their non-ideal torque/speed characteristics and requiring a more complex driver circuit, the trapezoidal wave's sharp transitions produce significant amounts of "torque ripple." These high-frequency variations in its output torque are caused by the interaction between the



2. A structural comparison is made between a switched reluctance motor (a) and a synchronous reluctance motor (b). (Credits: (a) Charged, (b) Electronics)

spatial harmonics of magnetomotive force (MMF) and the rotor geometry.

While certain techniques can reduce the noise and vibration produced by an SRM, it's very challenging to drop them to levels that would be acceptable for use in an EV.

SynRMs address some of these issues by using a different rotor structure that can be efficiently driven by a sinusoidal waveform. Instead of the discrete external teeth found in SRMs, most SynRMs' poles are multilayer structures within the rotor. Consisting of alternating layers of iron (flux guides) and air gaps (flux barriers), they shape the salience of each pole in relation to its proximity to the stator *(Fig. 2b)*.

When an alternating current is passed through the SynRM's stator, it creates a rotating magnetic field that causes the rotor to try to position itself in order to minimize the reluctance (magnetic resistance) in the magnetic circuit.[3] As we shall see, the shape and number of these internal gaps greatly affects the motor's performance.

SynRM Advantages

SynRMs offer several advantages over SRMs, including the fact that they produce less torque ripple and can be driven by a relatively simple variable-frequency sinusoidal motor-drive circuit. They can also be driven in a very efficient manner across a wide speed range—in some cases, close to zero RPM. And, unlike regular induction motors, the SynRM rotor has no induced current and thus no losses, making it extremely efficient.

On the other hand, classical SynRMs tend to have relatively low torque densities, and they still produce undesirable levels of torque ripple. Fortunately, these issues can be mitigated with careful attention to the design of the rotor and, to some extent, the stator.

In general, increasing the number poles tends to reduce torque ripple, although the incremental improvement decreases as the number of poles grows. However, the higher the number of poles, the more difficult it becomes to form effective flux barriers within the smaller radial section of the rotor. As a result, most motors use rotors with four to six poles; eight poles are considered the practical limit for most applications.

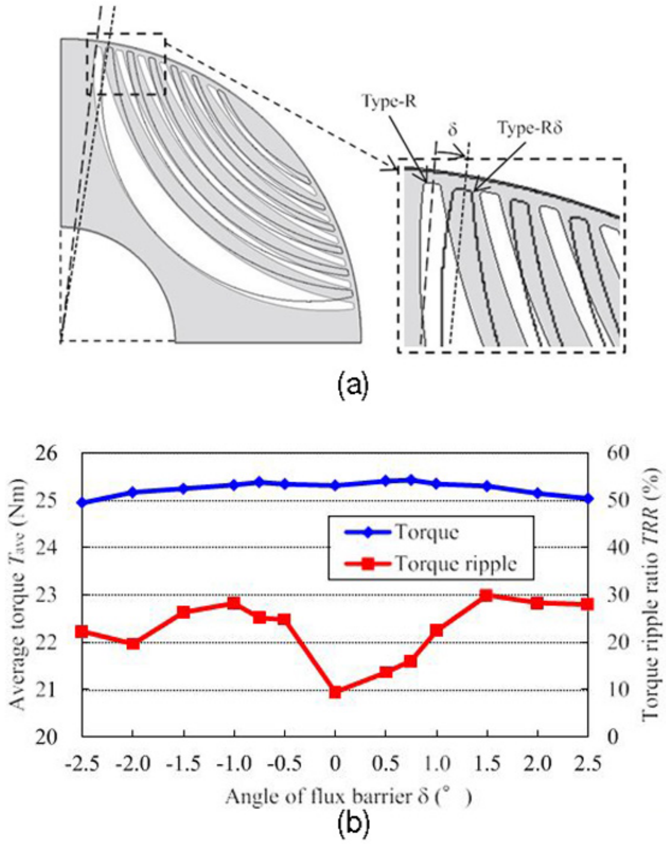
Likewise increasing the number of flux barriers within each rotor pole can be used to reduce torque ripple. These designs typically employ three to five barriers, with carefully chosen shapes that shape the magnetic flux to minimize harmonics and enable smooth transitions between stator windings.

Until recently, most flux barriers were either circular slots or segmented in some manner.[4] These two shapes provided good performance and efficiency for many applications, but they weren't ideal for use in high-power automotive motors *(Fig. 3)*.

New Software Enhances Rotor and Stator Design

The emergence of highly accurate magnetic and mechanical simulation and analysis software has made many new approaches to rotor and stator design possible, particularly the development of new flux gap shapes.[4] These new tools enable designers to experiment with "fluid," asymmetrical, and other unconventional air-gap shapes to create their desired tradeoffs between power density, efficiency, and torque ripple.[5] For example, it's possible to create a series of layered flux gaps, each with a different tip angle *(Fig. 4)*.

Research has demonstrated that adjusting the tip angles independently allows the characteristics of the flux-gap structures to be optimized for the desired combination of torque, torque ripple, and other characteristics.[6] Some studies show that using flux barriers with full asymmetric flux-barrier tips can reduce torque ripple by as much as 50% without significant degradation to the motor's average torque.



4. Advanced design and modeling techniques enable the creation of asymmetric flux barriers that are optimized to produce the best torque characteristics and the lowest torque ripple (a). A plot showing average torque and torque ripple versus flux barrier angle (Ie = 16.4 A, α = 55°) (b). (Credits: IEEE IEMDC; Electronics 2022, issue 11, references 4 & 5)

3. A SynRM Rotor with segmented flux barriers (a) is compared with those having circular flux barriers (b). (Credit: Wiley)

Additional improvements can be gained by using drive electronics that intelligently shape the stator drive waveform. Although this is beyond the scope of this article, several articles on the topic are cited in the references section below.[7, 8]

References

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