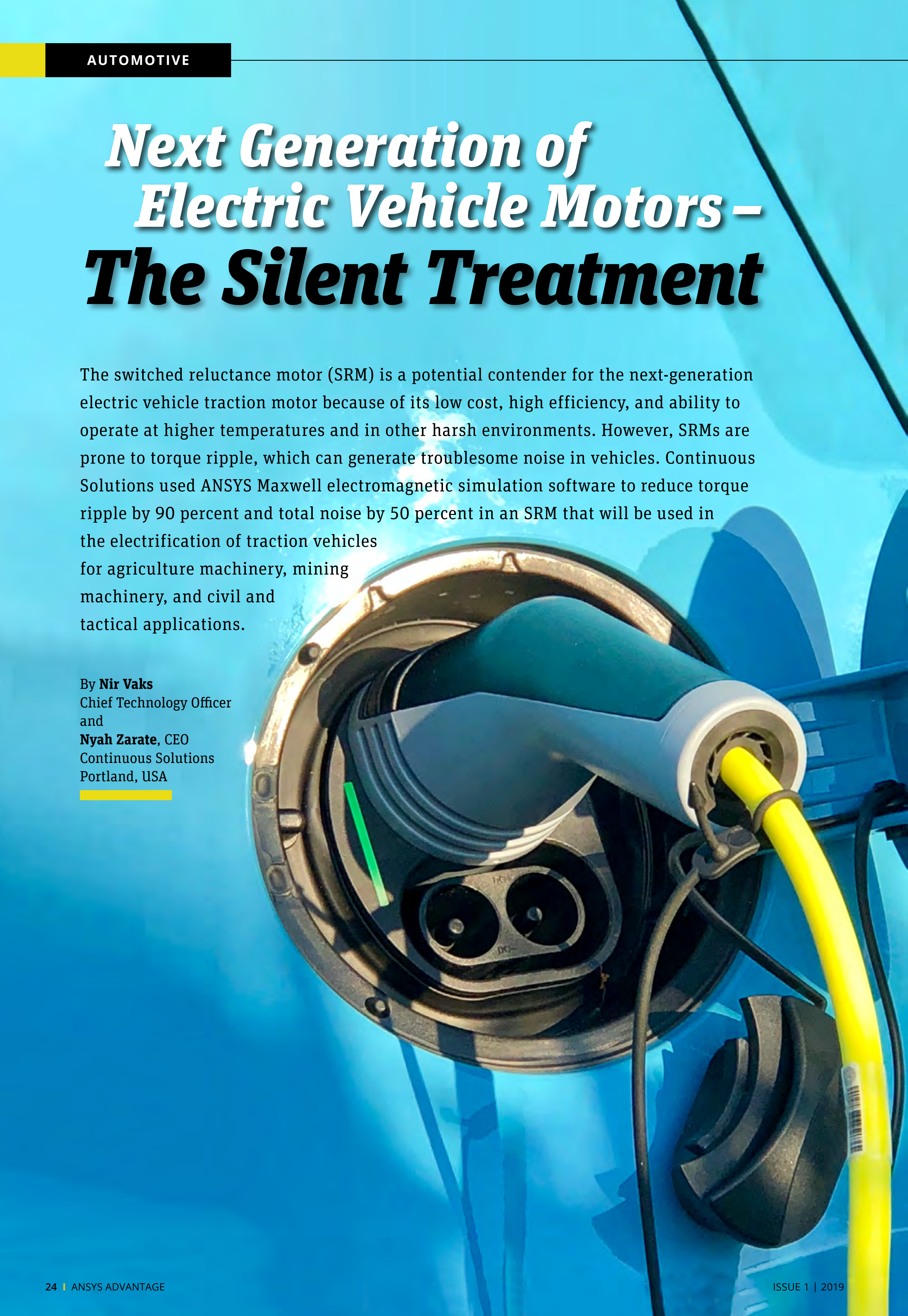
Next Generation of Electric Vehicle Motors – The Silent Treatment



The switched reluctance motor (SRM) is a potential contender for the next-generation electric vehicle traction motor because of its low cost, high efficiency, and ability to operate at higher temperatures and in other harsh environments. However, SRMs are prone to torque ripple, which can generate troublesome noise in vehicles. Continuous Solutions used ANSYS Maxwell electromagnetic simulation software to reduce torque ripple by 90 percent and total noise by 50 percent in an SRM that will be used in the electrification of traction vehicles for agriculture machinery, mining machinery, and civil and tactical applications.

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The concept of a switched reluctance motor (SRM) has been around for 180 years, but until recently it has only occasionally been used in industrial applications because of the complex circuitry required to control it. Over the last decade or so, high-powered microcontroller integrated circuits and computationally intensive control strategies have made SRMs more viable. A remaining challenge is the tendency of the SRM to emit considerable noise during its operation. This noise is unacceptable in applications such as luxury passenger cars, tactical vehicles and other machines in harsh environments.

Leveraging the ANSYS Startup Program, Continuous Solutions engineers address these challenges by producing virtual prototypes of prospective SRM designs in ANSYS Maxwell electromagnetic field simulation software. They model their control algorithm in Simplorer, Maxwell's system simulation feature, and tune the algorithm to cancel out torque ripple, which substantially reduces the overall motor noise and vibration.

> ***"The new motor is 20 percent less expensive and operates at 50 percent higher temperatures than comparable permanent magnet motors."***

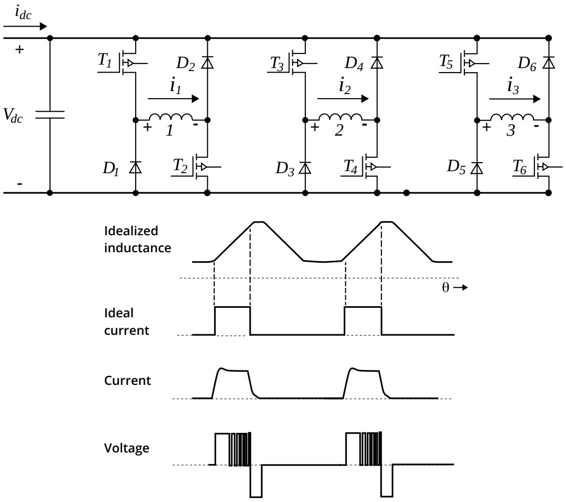
SRM BASICS

The SRM operates based on magnetic flux. Magnetic fields are analogous to electrical current and prefer to travel in the path of least magnetic resistance or flux. This explains why low-reluctance materials such as iron and steel have a strong tendency to align to a magnetic field. The SRM uses phased windings on its stator, and its rotor is made of a low-reluctance material with alternating zones of high and low reluctance. When power is applied to the stator windings, the rotor's magnetic reluctance generates a force that attempts to align the rotor pole — the low-reluctance peak — with the nearest stator pole. The SRM maintains rotation by switching the stator windings successively on and off so that the magnetic field of the stator causes the rotor to rotate.

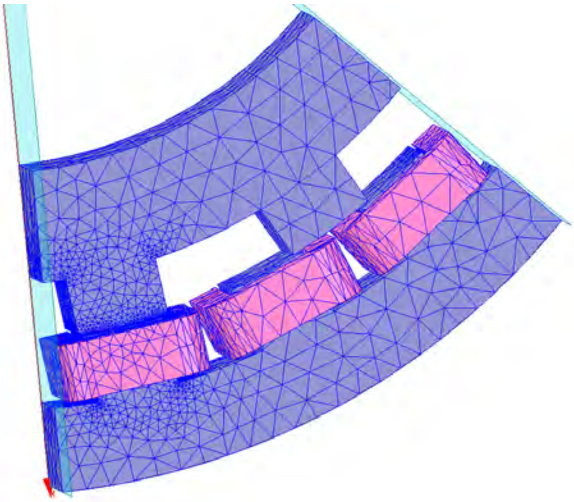
The rotor can be made from a solid block of steel or built up from thin steel stampings with notches for the magnetic poles. The elimination of permanent magnets and windings on the rotor makes the SRM considerably less expensive to produce than conventional permanent magnet electric motors. The rotor carries no current, so there is no need for a commutator and armature coils as in a DC motor, nor for a cast-metal squirrel cage as in an induction motor. Furthermore, the elimination of permanent magnets and rotor windings enables the SRM to operate at higher ambient temperatures — a valuable attribute in vehicle traction motors.

TORQUE RIPPLE CHALLENGE

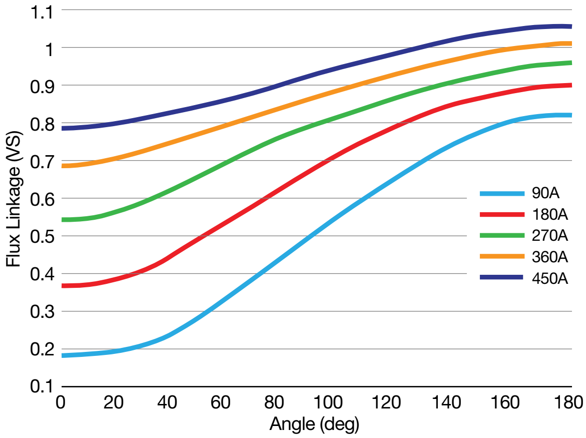
One of the greatest challenges in designing SRMs is that the inductance of each phase is proportional to the degree of alignment with the rotor poles. Excessive vibration and acoustic noise are generated



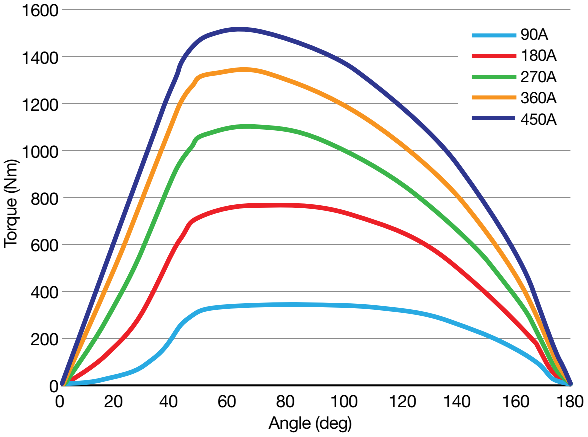
Asymmetric bridge converter circuit diagram (top) and resulting SRM waveforms



Model of SRM geometry in ANSYS Maxwell



ANSYS Maxwell results show flux linkage as a function of rotor position at various loads.



ANSYS Maxwell results show torque as a function of rotor position at various loads.

due to structural deformation and magnetic torque harmonics resulting from the stator–rotor interaction. Adding to this issue is the relative acute change in inductance as a function of rotor position and nonlinear control.

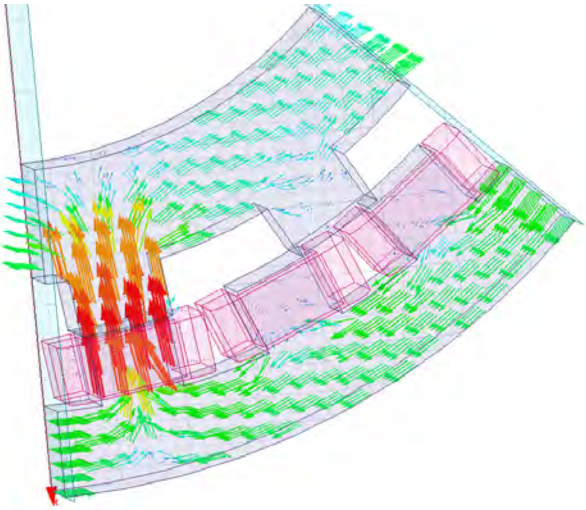
These interactions manifest as changes in torque known as torque ripple. Torque ripple can also be caused by mechanical issues such as imbalances in the rotor or stator. The result is vibrations that generate noise and can reduce the life of the motor.

In designing a new traction drive motor, Continuous Solutions' goal is to create a motor and drive that are less expensive and that can operate at higher temperatures than conventional permanent magnet motors while meeting efficiency, power density and noise targets equal to permanent magnet motors. Continuous Solutions engineers began by utilizing an in-house custom multi-objective 3D magnetic equivalent circuit (MEC) optimization program to speed the process of exploring the design space and identifying promising designs for further investigation. This program uses a genetic algorithm to explore various design parameters such as stator tooth height, excitation current and number of pole pairs, while iterating toward improvements in design objectives such as higher efficiency and lower mass.

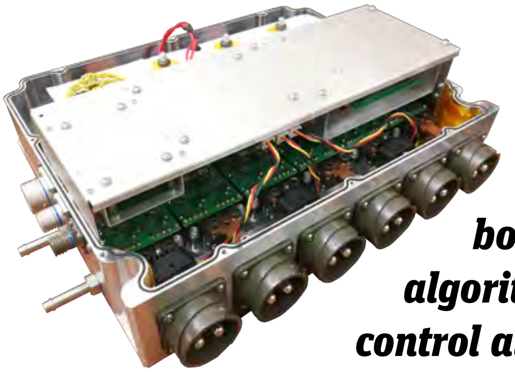
MODELING MOTOR DESIGNS

Continuous Solutions engineers developed detailed models of the promising design points identified by the optimization program in ANSYS Maxwell. They used ANSYS RMxprt, a template-based design tool, to quickly define the motor geometry. Rather than having to draw the components of the motor, they used the parametric design capabilities of RMxprt to define the SRM core. They entered the parameters of the core: the number of poles, and number and gauge of windings. They then created terminals and assigned excitations to the windings. The engineers then duplicated the windings along the Z-axis of the motor. Next, they defined the stator structure by specifying the number of poles, adding windings and assigning terminals to the windings. They defined the motor enclosure.

Engineers then transferred the 3D geometry along with motion and mechanical setup, core loss in stator and rotor steels, winding and source setup directly to Maxwell for detailed finite element analysis. Maxwell calculated performance data such as torque versus speed, power loss, flux in air gap, power factor and efficiency. Maxwell produced a torque report that showed the moving torque of the motor in newton-meters as a function of rotational angle. For a more detailed diagnostic view, they plotted magnetic flux over a cross section of the rotor and stator at key points in the time history where torque hit peaks or valleys. These plots showed that one of the main sources of noise was the stator being squeezed toward the rotor by



Magnetic flux plotted by ANSYS Maxwell on a cross section of rotor



Continuous Solutions 100kW SRM MILSPEC controller running Torque Ripple Mitigation technology

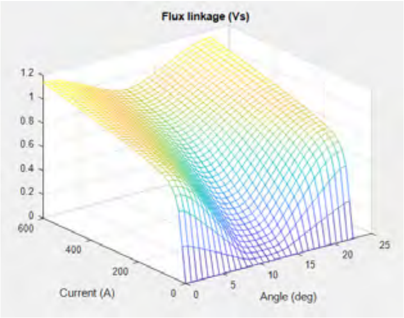
> ***“Engineers simultaneously improved both the motor design and the control algorithm until the integrated motor and control algorithm met all their objectives.”***

the attractive forces exerted by each pole pair as the stator is energized. One approach to this problem is to make the stator stronger, but this increases the cost and weight of the motor.

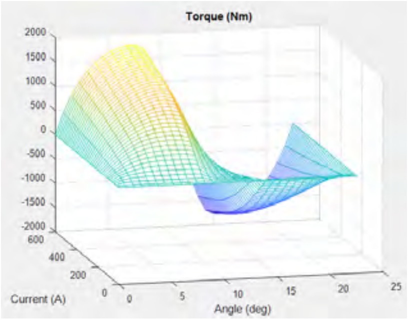
DESIGNING THE CONTROL ALGORITHM

Instead of seeking a mechanical solution, Continuous Solutions designed the control algorithm to inject current into normally inactive windings at precise times to cancel errant force vectors from the active wings. They designed the control algorithm in their in-house analytical tools and embedded it into a regular SRM inverter included in Simplorer. Then they connected the Simplorer inverter to the ANSYS Maxwell model of the motor and drove the motor with the control algorithm. The torque time history and magnetic flux plots guided Continuous Solutions engineers in smoothing out the torque ripples. Just as the motor is about to jerk to the left, the controller injects a signal to jerk to the right, canceling out the native motion and removing torque ripple wave. At the same time, engineers evaluated multiple design iterations in Maxwell to finalize the motor design. Over a series of iterations, engineers simultaneously improved both the motor design and the control algorithm until the integrated motor and control algorithm met all their objectives.

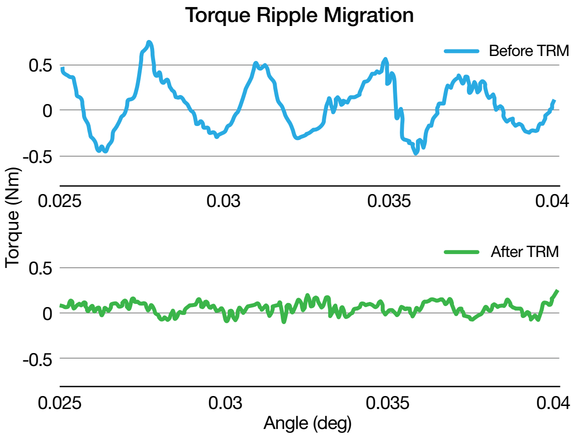
Continuous Solutions engineers proceeded to build and test a prototype of the new motor design, and its performance closely matched the simulation results. In addition, for mass manufacturing, Continuous Solutions has formed a strategic partnership with Nidec Motor Corporation to make this technology commercially available. The new motor is 20 to 50 percent less expensive and operates at 50 percent higher temperatures than comparable permanent magnet motors, while offering comparable efficiency, power density and noise performance.



3D map of produced flux linkage as a function of current load and rotor position



3D map of produced torque as a function of current load and rotor position



Reduction of torque ripple in SRM provided by Continuous Solutions Torque Ripple Mitigation controller