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News & Highlights

The Drive for Electric Motor Innovation

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Since 2018, Turntide Technologies' highly efficient electric motors—based on an updated version of an early 19th century design—have turned cooling fans in dairy barns across the United States; in addition, more than a dozen companies, including BMW and Amazon, have saved an estimated average of 64% on heating and cooling costs by retrofitting their rooftop heating, ventilation, and air conditioning (HVAC) systems with the company's "smart motor system" [1]. Now, as announced in June and July 2021 [1,2], the Sunnyvale, CA, USA-based company, backed by Bill Gates and Amazon, is shifting its focus to electric vehicles (EVs) after securing 225 million USD in funding and acquiring three startup firms—Hyperdrive Innovation, BorgWarner Gateshead, and Avid Technology—that make batteries, drivetrains, and EV controls, respectively.

For its electric motors (Fig. 1), Turntide started with a nearly two-century-old technology—the switch reluctance motor (SRM), invented by W.H. Taylor in 1838 [3]. The SRM is comparatively inexpensive to manufacture for two reasons. First, its simple rotor is made from a solid block of steel with notches for the poles. Second, the stator consists of evenly spaced solenoid-wound electromagnets. In contrast, the windings of a standard alternating current (AC) induction motor must conform to a complex pattern that fits into slots in the stator [3].

Until recently, the SRM had failed to gain wide acceptance because it was hard to control, resulting in considerable noise and vibration. Richard Hellinga, Turntide's chief technology officer, said the company's engineers have overcome these challenges by placing sensors in prototype motors to track the movements of the rotor. This allowed them to use a machine-learning algorithm to determine just the right times to switch the current on and off. The knowledge gained through that process has allowed them to devise a sensor-less SRM that minimizes vibration.

Although it has already lined up a handful of customers in the commercial vehicle and rail sectors, including Aston Martin and Hitachi Rail [2], Turntide faces stiff competition. As countries around the world seek to phase out gas-powered engines, companies around the globe are using artificial intelligence (AI)-assisted design and advances in materials and automation to reimagine the electric motor, with the goals of making it more efficient, less expensive to purchase and operate, and more environmentally friendly to manufacture.

Fig. 1. Turntide's EV motors will be based on their SRM shown here, currently used for industrial applications, such as barn cooling and HVAC. Credit: Turntide Technologies (public domain).

Electric motors run everything from HVAC systems to hard drives, escalators, and all manner of manufacturing equipment, accounting for more than 40% of global electricity consumption [4]. And demand for them will continue to grow into the 21st century, as evidenced by forecasts predicting that EVs will represent 10% of global passenger vehicle sales by 2025, 28% by 2030, and 58% by 2040 [5].

As manufacturers have moved to electrify vehicles, most research and development efforts have focused on the battery—traditionally the most expensive and range-limiting component. However, improving the efficiency of the motor itself could allow improvements in range and/or smaller—and lighter—battery packs.

All commercial EV motors made today are based on an AC, permanent magnet synchronous design, which consists of two primary parts: a housing, called a stator because it remains stationary, and a rotor, which spins, usually inside the stator but sometimes outside. Magnets attached to the rotor and stator repel or attract each other in sequence to generate spin and create torque. This simple setup has improved only incrementally since its initial design in the late 19th century. According to Hellinga, the primary

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reason for the longevity of this design has been ease of manufacturing.

"There are tons of factories that build these things," Hellinga said. "They are relatively inexpensive, but that price tag belies the fact that they consume a ton of energy, and the way supply chains are set up means that the people who make the motors are not the people who pay for the energy. And because that energy has become so expensive, we are now seeing a tremendous demand for innovation in motor technology."

While large auto manufacturers have remained mostly quiet about innovations in this area, smaller companies and startups have been more aggressive in promoting their efforts to reconceptualize the electric motor.

In one innovative approach, Magnax, a company headquartered in Kortrijk, Belgium, chose to rethink the electromagnetic interaction within its motor, thereby reducing its weight, size, and cost. Because air transports magnetic flux poorly, their design aimed to minimize the air gaps between rotor and stator teeth. While a traditional radial-flux machine puts the rotor inside the stator, Magnax's axial-flux machine flips that arrangement around. And it uses two rotors, one on either side of the stator to bracket it. In this configuration, the stator bears the electromagnetic teeth and does not function as the support—or yoke—for the rotor (Fig. 2) [6].

Eliminating the yoke—a steel cylinder comprising up to two-thirds of the stator's mass—saves a large amount of weight, which the company estimates can contribute to a 7% increase in an EV's range [6]. Doing away with the yoke also more than doubles the motor's power density compared with older yoked axial motors, and quadruples it compared with traditional internal combustion engines. Other advantages of the yokeless axial-flux design include the stator needing only about 60% of the copper and the rotor about 80% of the magnetic material compared with radial-flux motors of similar power and torque [6]. The company says it plans to begin producing 25 000 motors per year starting in 2022.

In another approach, Linear Labs (Dallas-Fort Worth, TX, USA) found a way to combine axial and radial flux designs in a single motor. Their "three-dimensional (3D) circumferential flux motor" comprises four rotors surrounding a stator. A central rotor spins inside a stator, while a second rotor spins outside the stator. Two additional rotors bookend the left and right ends of the stator, for a total of four sources of flux, with all torque generated in the direction of rotor motion. The result, the company claims, is a motor that at low revolutions per minute (RPM) produces two to three times the torque output of any other electric motor and remains twice as efficient throughout the torque and speed range compared to the average efficiency of standard motors [7]. Also,

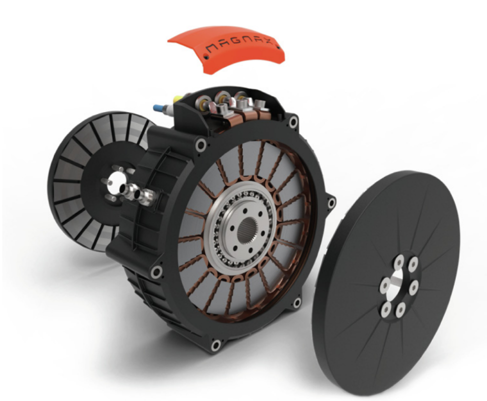

Fig. 2. Magnax's axial-flux electric motor has two rotors bracketing the central stator, eliminating the need for a yoke, and reducing the stator's weight by two-thirds, thereby increasing the motor's power density. Credit: Magnax (public domain).

because it can work efficiently at low RPM, Linear Labs' motor requires no reduction gear box—a device that takes the 10 000 or so RPM from a drive motor and reduces the speed at the wheels while multiplying torque—leading to decreases in vehicle weight and cost. The company says it has begun mass production and plans to manufacture 100 000 of its motors by the end of 2021 [8].

Other manufacturers have designed motors that completely do away with a common feature of most current electric motors: permanent magnets. These magnets, derived from rare earth materials, create their own continuous magnetic fields, thereby yielding high torque density. However, rare earths are expensive, with the period between June 2020 and August 2021 seeing a doubling in the price of neodymium, one of the more commonly used rare earths in electric motors [9]. Also, rare earths mostly come from one country, China, raising single-source concerns, as experienced in 2011 when prices increased seven-fold following China's warning that it might cut supplies during a dispute with Japan [9]. In addition, mining rare earths produces toxic chemicals associated with environmental concerns [10].

Even with these issues, some experts see permanent magnets remaining widely used. "Frankly, I do not currently see a trend away from permanent magnet machines," said Martin Doppelbauer, professor of hybrid EVs at the Karlsruhe Institute of Technology in Germany. "Most everyone uses them because they have the highest power density and best performance. That said, I do see that most manufacturers are developing alternatives to permanent magnet machines, and they have them in their drawers in case they need them when the prices of rare earth materials start rising again."

Ayman EL-Refaie, a professor of electrical and computer engineering at Marquette University in Milwaukee, WI, USA, is working with General Motors to develop drivetrains free of rare earth materials. Although he sees a potential need for motors built without rare earth magnets, there are difficulties involved in doing so. "When you try to remove these magnets, there are challenges," he said. "The size of the machine increases to make up for the lost power and there is the risk of permanent demagnetization with other grades of magnets that do not contain rare earths."

Yet another approach to alternative electric motor design forgoes using permanent magnets to turn the rotor, using electromagnetic force alone. But designs that place copper windings in the rotor need to transmit electricity to a moving target, and the contact points can wear out over time. One company attempting to overcome this challenge is Stuttgart, Germany-based Mahle. The auto parts company has built a motor free of both rare earths and physical contact. Power beamed wirelessly into the rotor energizes the windings to produce the electromagnetic field (Fig. 3). The company expects to begin mass production of its motor for passenger vehicles in 2023 or 2024 [11]. Other startups designing EV motors that do not rely on permanent magnets include Powdermet (Euclid, OH, USA) [12] and Turntide [13], while automotive stalwarts Nissan, BMW, Toyota, and Volkswagen are also investigating motor designs that minimize the use of permanent magnets [14].

Rather than focusing on building more powerful and efficient motors for central drivetrains, some companies, including Nidec (Kyoto, Japan) and Protean (Farnham, UK) are exploring engineering that places smaller motors right in the wheels, a move that would optimize weight distribution in an EV, eliminate the need for a motor compartment, increase efficiency by minimizing losses in transmission of torque, and increase maneuverability [15]. Nidec claims just one of its in-wheel motors can achieve a peak power output of 100 kW—equivalent to a 1.8 L gas engine—while weighing just 32 kg and fitting inside a 50 cm wheel [16], while Protean says each of its in-wheel motors delivers 80 kW at a weight of 36 kg [17].

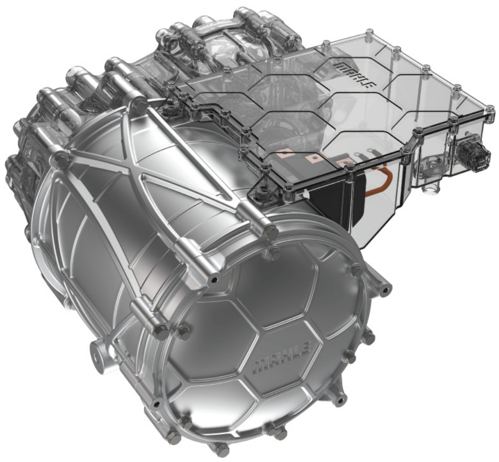

Fig. 3. In Mahle's permanent magnet-free electric motor, power beamed wirelessly into the rotor energizes the windings, turning the rotor by electromagnetic force alone. Such contact-less induction saves wear and tear. The design also makes the rotor's magnetism tunable, allowing high efficiency through the range of operating speeds. Credit: Mahle (public domain).

Outside of radical changes in design, Doppelbauer sees the most vital innovations to the electric motor sector coming in production, particularly with the copper windings inside the stator. "There is a lot of handwork in motor production, and there are several processes where quality control is an issue," he said. "With windings, for example, we have the potential danger that there may be a defect in the insulation that would potentially lead to reduced lifetime and eventual failure of the motor."

Replacing conventional round windings with hairpin windings that have a rectangular cross section allows for higher thermal stresses and optimizes the use of space inside the stator to ensure higher torque and sustained output. Automation of the bending process is also simpler than with round winding, facilitating mass production. "The disadvantage of hairpin windings is that you need a very high level of automation, so there are a lot of upfront costs to set up production," Doppelbauer said, adding that Porsche has been particularly successful in automating this process for the motors in its Taycan EV (Fig. 4).

Another production-related innovation Doppelbauer points to involves cooling, which traditionally means running water through a pipe coiled around the stator housing. Companies such as Equipmake (Norwich, UK) are exploring additive manufacturing to increase the surface area inside the motor and therefore reduce the need for cooling [15].

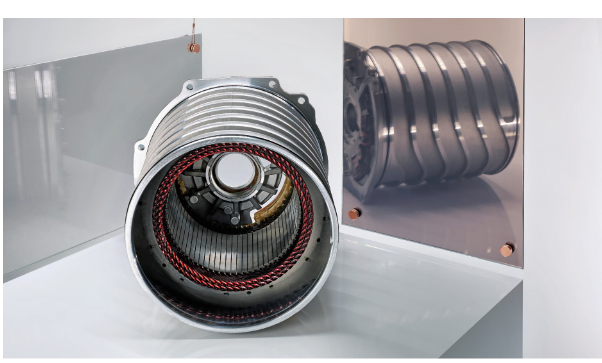

Fig. 4. For its Taycan EV, Porsche has developed an automated process for manufacturing electric motors with hairpin wire windings, rather than round ones. These windings allow for higher thermal stresses and optimize space in the stator to ensure higher torque. Credit: Porsche (public domain).

Regardless of whether innovation comes from optimizing in-production designs or redesigning from scratch, EL-Refaie said manufacturers need to take a long-term approach. "Some companies historically think shorter term, enacting changes in incremental steps," EL-Refaie said. "However, when you try to come up with radically different motor designs or develop new materials or manufacturing processes, you really need to be forward looking and open to taking some technical swings for success in this competitive field."

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