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By combining the lightness of an air-core motor with the high torque density of an axial-flux machine, the Infinitum motor is well suited for building ventilation and HVAC systems. The absence of a stator core allows us to put two identical rotors facing each other on either side of the stator, with each rotor carrying powerful permanent magnets. Electric motors consume a little over half of the world's electricity today. Caterpillar Venture Capital has invested in Infinitum Electric to develop a new line of alternators that are one-third the size and weight of existing models and quieter and more efficient as well. We estimate that if every motor in the world were replaced by an Infinitum Electric motor, it would reduce carbon emissions by 860 million tonnes per year. This article appears in the April 2022 print issue as "This Axial-Flux Motor With a PCB Stator Is Ripe for an Electrified World." The motor also has an air core—that is, there is no iron to mediate the magnetic flux and nothing in between the motor's magnetic parts but thin air. This arrangement creates a constant magnetic flux. In a typical electric motor, both the stator and rotor are made of ferromagnetic materials. Our motor generates as much power as a traditional alternating-current induction motor but has half the weight and size, makes a fraction of the noise, and emits at least 25 percent less carbon. Our company is working with a leading automotive supplier to develop an oil-cooled motor for a long-range hybrid vehicle. This advantage, together with other efficiencies, is why its noise averages about 5 decibels lower than that of conventional motors. Here's why that happens: A magnetic flux produces a force that at first points in the same direction the rotor is moving in; then, as the rotor turns, the alignment of the rotor poles changes in relation to the stator slots until the force points in the opposite direction. With oil cooling, we have realized a threefold increase in power density over our own air-cooled motor, bringing the power density into the 8 kilowatt/kilogram to 12 kW/kg range. At Infinitum Electric, we did away with those copper windings and instead use photolithographic techniques to etch thin copper traces interleaved with epoxy-glass laminate, which insulates each coil from neighboring coils. But there is no such alternating magnetic force in the Infinitum motor. The Infinitum Electric motor is what's known as an axial-flux motor, a design in which the stator's electromagnetic wiring stands parallel to a disk-shaped rotor containing permanent magnets. When a multiphase voltage system is applied to a motor that has a separate winding for each phase, the circulation of several currents generates a magnetic field that rotates in space. What's more, PCBs are manufactured by an automated process, which means they're much more uniform and reliable than hand-wound machines. There is thus very little magnetic energy available to smooth out the variations in the voltage supplied to the motor by the VFD. Our air-core motor can thus operate at a high efficiency over loads ranging from 25 percent to 100 percent of the rated power. Fast-forward to today. To remedy this deficiency, we added another element: an integrated variable frequency drive that is fine-tuned to operate with a low-impedance motor. We instead have each layer carry only one electrical phase, and we minimize the number of connections between layers. It is now finding applications in HVAC, manufacturing, heavy industry, and electric vehicles. Still, their pioneering achievements demonstrated the feasibility of PCB stators. Electric vehicles are another big market for this new motor. Our motor generates as much power as a traditional AC induction motor but has half the weight and size, makes a fraction of the noise, and emits at least 25 percent less carbon. That may not seem like much of a reduction, but this component of motor noise tends to be at a particularly bothersome pitch. The motor's software can also be updated in this fashion. Some 800 million motors are now sold annually worldwide, according to the market research group Imarc, a number that has been increasing by 10 percent each year. Heat pumps, which heat and cool in one system, are another application in which the motor can save energy, ease installation, and reduce noise. This radial force does nothing useful, and it aggravates noise and vibration, because the slots in the stator—needed to accommodate the copper coils—generate pulses. View PDFVolume 2, Issue 1, January 2021, Pages 65-81 Rights and content The layered components of an Infinitum Electric axial-flux motor are shown here, in exploded form.INFINITUM ELECTRIC This saving of energy is critically important. Software may be eating the world, but electricity is increasingly what makes the world go round. Connecting the coils in series is appropriate for three-phase industrial applications and next-generation electric vehicles. The alternator market is estimated at \$17 billion a year and growing. Put all these things together and the result is an air-core axial-flux permanent-magnet motor. It was one of the smoothest-running high-power generators ever built. Skipping the iron core also means the magnets on the rotors face a constant reluctance and a constant magnetic field as the rotor turns. The interaction of this rotating field and the field produced by rotor magnets is what turns the rotor. A complex manufacturing process was needed to build the stator, the copper windings were bulky, and the coil support structure was intricate. This alternating force produces torque ripples, which can cause metal fatigue in the motor and in the machinery that it is driving. Here's how it works. As in other axial-flux motors, that flux is parallel to the axis of rotation, rather than radial. Eliminating the iron core and minimizing copper together save 50 to 65 percent of the weight and 50 to 67 percent of the volume of the motor, when compared to an equivalent conventional iron-core motor. An electrical phase is an alternating voltage that forms a sinusoidal wave that is shifted in time relative to the voltage in another phase. That's particularly useful now that the pandemic has put a priority on purifying indoor air. In the past, attempts to build such a motor faced serious practical obstacles. My company, Infinitum Electric, of Austin, Texas, has developed a PCB stator motor that fits a wide variety of purposes. The various phases are synchronized so that the sum of the currents is always zero. We made them even more reliable by simplifying their topology, which has to do with the motor's phases. Our VFD uses high-efficiency silicon carbide MOSFETs, which reduce losses and contribute to overall system efficiency. That arrangement provides a continuous path for the electric current and reduces the risk of electrical failures. We're also working with companies that specialize in material handling, such as forklifts, conveyor systems, and the mixing equipment that's used to make food and beverages. As a result, the air gap was so wide that only a substantial magnet mass could create the necessary magnetic flux. And conveniently, the copper and the laminate expand and contract similarly as the temperature rises and falls, avoiding stress that might otherwise slowly pull the components apart. Once electric currents are applied and rotating magnetic fields are established, these fields produce two forces: one that produces useful torque and causes the rotor to rotate, and another that pulls the rotor radially towards the stator. A short path for magnetic flux is made possible by sandwiching rotors (gray) with magnets (red and blue) around a thinly printed circuit board stator (green). Despite the benefits of the PCB stator, people were slow to embrace the design because of a few misconceptions. Transportation, construction, and HVAC together account for about 60 percent of all U.S. greenhouse gas emissions; more efficient electric motors will help cut emissions in these sectors. Connecting in parallel is better for low-voltage applications, such as in an auxiliary EV motor. According to recent tests conducted by the U.S. General Services Administration and the U.S. Department of Energy, Infinitum Electric motors could save up to US \$8 million annually if deployed in the GSA's HVAC plants. But in 2011, CORE Outdoor Power developed a leaf blower and a weed trimmer, both of which used a PCB stator and yet were rugged as well as quiet. The VFD also controls the speed and torque as required by the application. As motors become ubiquitous, even small improvements in efficiency have the power to make a big difference for our planet today and over the next century. But in 2012 Boulder Wind Power put a PCB stator in a 12-meter-diameter direct-drive generator for a wind turbine that output 3 megawatts of power and just over 2 million newton meters of torque. The thinness of the PCB furnishes a high surface-to-volume ratio, which makes for more efficient cooling, thus allowing us to push two to three times as much current for a given amount of copper. Previous PCB stators mixed the copper traces from different phases in the same layer, which created the potential for short circuits. Another advantage of the new layout is the freedom it gives designers to connect coils either in series or in parallel. When alternating current flows through, it makes the rotor spin. Such remote monitoring offers a variety of ways to conserve energy, manage performance, and predict when maintenance may be needed. EVs are projected to make up 31 percent of the global fleet by 2050, according to the U.S. Energy Information Administration. This arrangement eliminates eddy-current losses in the magnets and the rotors, which therefore can be made of standard, unlaminated, low-carbon steel plates. First, there was the mistaken belief that PCBs were good only for delicate applications. That makes the oil-cooled version suitable for use in electric aviation, another promising market. Oil cooling works much more efficiently in our design than in a conventional motor because the coolant can be readily applied to the entire surface of the PCB. Neither company endured. Electric motors are making serious inroads into cars, trains, and aircraft, as well as industrial equipment and heating, ventilating, and air-conditioning systems. That's the equivalent of eliminating the emissions from 200 million cars annually. Removing the iron core eliminates loss due to the cyclical magnetization and demagnetization of the iron, while also avoiding energy-wasting eddy currents in the metal. Like other permanent-magnet motors, our axial-flux motor requires a variable frequency drive to smoothly start and accelerate the motor to the desired speed. The VFD also monitors performance, and the results can be reported via the cloud, if the user wishes. Because the magnetic air gap is narrow, we need only a small magnet, which is why we can wring a lot of power from a given mass and volume. The cooling can be done by blowing air over fins on the outside of the motor and across the electronic compartments. Boulder Wind Power ran out of funding before it could secure commercial contracts. CORE Outdoor Power couldn't compete in a crowded market where there were cheaper options. However, the air-core design gives the motor exceptionally low impedance (typically just 5 to 7 percent as much as in a conventional iron-core motor), because air cannot contain as much magnetic energy as iron can. Second, there was a sense that PCB stators could be used only for low-power machines.

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