ELECTRIC POWER RESEARCH INSTITUTE

TECHNOLOGY INSIGHTS

A Report from EPRI's Innovation Scouts

MAGNETIC GEARBOXES FOR EXTREME-SCALE WIND TURBINES

THE TECHNOLOGY

Magnetic gears rely on field forces, rather than physical contact between driving and driven surfaces, to achieve high rotational speeds and ratios but at greatly reduced mass and size relative to mechanical gearboxes used in today's wind turbines.

THE VALUE

By reducing drive-train mass and size, magnetic gearing promises to alleviate constraints to future onshore and offshore wind turbines rated above 10 MW while also increasing efficiency, improving reliability, and reducing levelized cost of energy.

EPRI'S FOCUS

Through continued innovation scouting, EPRI is monitoring early-stage wind energy technologies and seeking promising concepts to advance through collaborative research, development, and demonstration projects.

TECHNOLOGY OVERVIEW

Larger turbines—beyond today's multi-megawatt (MW) onshore and offshore machines—are one of the most attractive options for reducing the cost of wind energy. Continued technology scale-up to achieve rated capacities of 10 MW and beyond requires novel concepts for overcoming the fundamental limitations of today's turbine designs and materials, including structural constraints on the mass of drive-train components.

Wind turbine transmissions, housed within the nacelle at the top of the tower, connect slow-turning rotor blades supported on a large main shaft with the faster-turning electric generator. Multi-stage mechanical gearboxes are commonly employed to convert slow, high-torque rotational power into the high-speed rotation required by conventional electromagnetic generators. The gearboxes are typically large, complex, and costly, and historically they have been prone to premature failure. The competing technology, embodied in direct-drive turbines, relies on massive and costly generators spinning at lower speeds but containing many more magnetic pole pairs. Hydraulic drive trains represent an emerging technology,[1] and a compressor-based system has been proposed for both transforming blade rotation into electricity and providing energy storage.[2]

Coupling a magnetic gearbox with a conventional generator represents a potential breakthrough technology for reducing the cost and mass of drive-train components in future turbines. Large magnetic gears are not commercially available, but the concept is proven at small scale. Paired magnetically coupled devices attached to the rotor render a mechanical ratio between the driving and driven components, with no physical contact between them. High rotational speeds are achieved without the need for multiple gears, numerous precision-engineered teeth, or continuous lubrication.

This *Technology Insights Brief* provides an overview of the technical basis, status, and potential of magnetic gearboxes for overcoming barriers to the development of future extreme-scale wind turbines.

BASIC SCIENCE

Conventional mechanical gearboxes include multiple stages to step up the slow rotation of large turbine blades to more than 1000 revolutions per minute, into the range where conventional generators operate for electricity production. Achieving high differentials with today's rotors necessitates large and heavy cogs with complex teething. Drive-train components are susceptible to materials degradation and failure under steady-state operation and especially under dynamic loading due to wind variability, where gusts impose unequal forces on blades and thus torque and bending on the rotor shaft. Components in physical contact—bearings and teeth—are particularly vulnerable to reduced lifetime and premature failure. Over the past two decades, improving gearbox reliability has been a major emphasis of wind energy research and development (R&D).[3]

The magnetic gearbox is a coupling system without contact between driving and driven components. This eliminates the potential for wear-related damage and failure. The basic technology of magnetic gears is known from the "Power-Transmitting Device" awarded US Patent 687,292 in 1901, "whereby power may be transmitted from one shaft to another by a means employing magnetic lines of force, and as a result the operation of the said device is noiseless, efficient, and easily controlled."[4] The concept has been developed further through patents issued from 1940 forward associated with magnetic gears and magnetic transmissions.[5-10]

In magnetic gears, rotating "cogs" act as magnets, with tightly controlled air gaps between them. Slower, higher-torque cogs have more magnetic poles. As poles alternate across the gap between elements, the gear ratio determines rotation or translational movement between input and output. A pure magnetic coupling has a gear ratio of unity. Magnetic gearboxes can achieve the very high ratios and rotational speeds required for wind power production from conventional generators. In addition, their capability to slip without damage under overload conditions mitigates an important failure mode.

For wind turbine applications, the three basic magnetic gear configurations shown in Figure 1 have been considered.[11,12] **Radial or cycloid magnetic gears** utilize concentric low- and high-speed rotors, separated by a bar stator and made up of alternate positive and negative magnet segments. The torque transmitted is a function of flux links between the larger outer ring and smaller inner ring. Gear ratio is defined by the pole number of driving over driven surfaces.

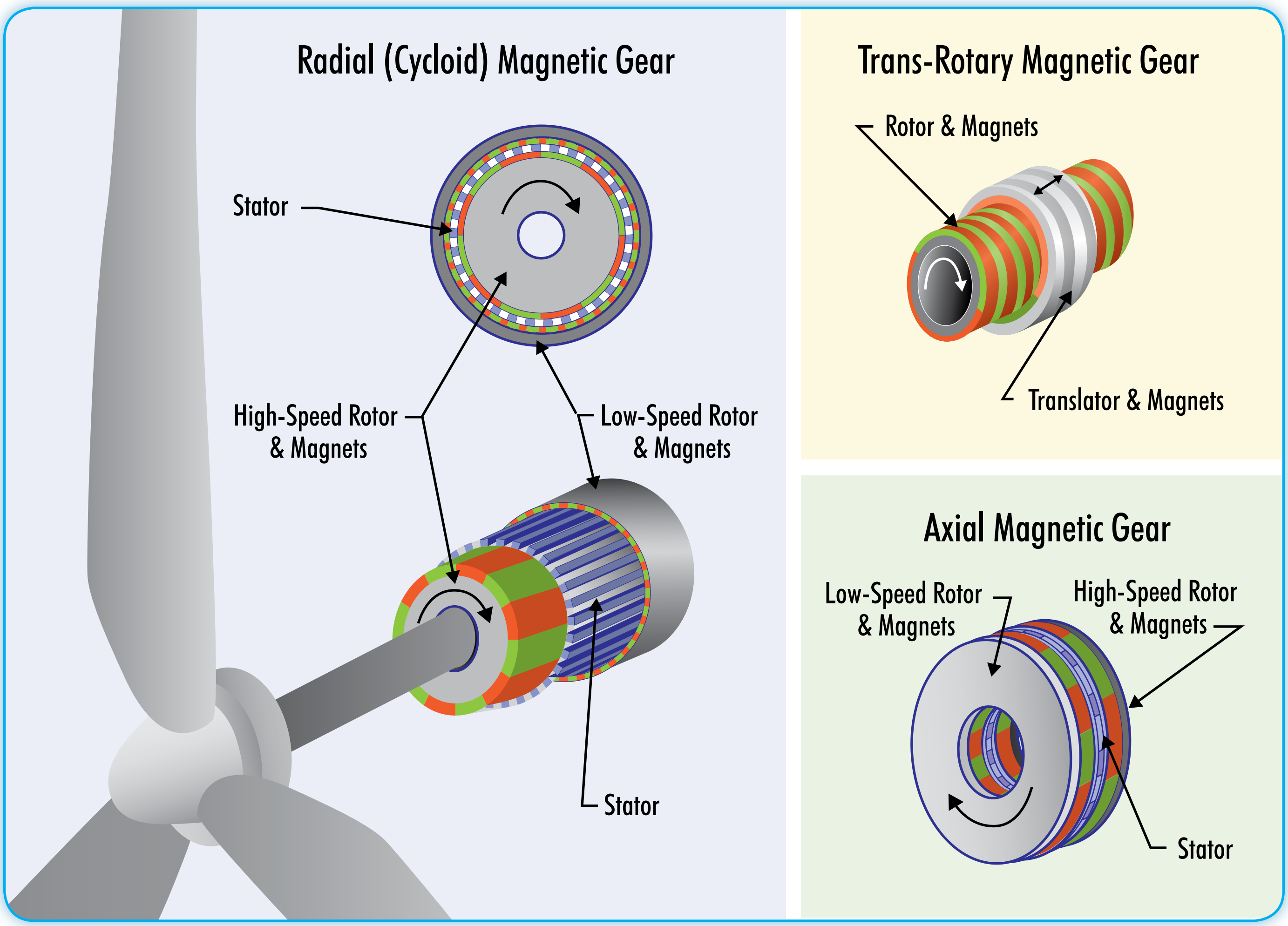

Figure 1 – Magnetic Gear Topologies for Wind Turbines

Trans-rotary gears use magnets in a helical arrangement, like that of screw threads. The number of poles, analogous to the number of starts in a threaded rod, is determined by magnet width and pitch. Helixes on the rotor and translator have the same pitch, and the latter slides over the former. The relationship between the rotor's angular speed and the translator's linear speed determines the gear ratio.

Axial gears consist of two disks containing alternate positive and negative magnets with a modulator disk in between and gear ratio defined by pole number. However, as the size of the magnetic areas become smaller, such as when packing in more pole pairs to achieve higher gear ratios or reduce disk sizing, radial-flux leakage creates a point of diminishing returns. Manufacturing challenges, plus huge axial forces on bearings at the main rotor shaft, represent barriers to further development of this configuration for wind turbine applications.

VALUE TO THE INDUSTRY

Magnetic gearbox technology could help eliminate barriers to the development of future onshore and offshore wind turbines with capacity of 10 MW and above by alleviating physical constraints to the continued upscaling of drive-train components. This innovation also is expected to reduce levelized cost of wind generation by improving gearbox efficiency and reliability.

As an alternative to multi-stage mechanical gearboxes, magnetic gearing can achieve the high differentials and rotation rates required by conventional electromagnetic generators but at greatly reduced mass. The size advantage also exists over direct-drive designs, which require ever-larger generators to transform low-speed torque into bulk power generation. Lighter and smaller magnetic gearboxes will help downsize nacelles, decreasing gravitational loading and thus enabling taller towers hosting larger rotors.

Magnetic gearing also promises performance advantages over conventional gearboxes, based largely on the lack of physical contact between driving and driven surfaces. Substantial reductions in friction losses will enable higher energy conversion efficiency—particularly at partial loads—as well as power generation at reduced wind speeds. Avoided contact and wear are expected to allow step-change improvements in gearbox reliability, both directly and through significant reductions in the vibrations and pulsations leading to additional damage and failure modes. Lubricant-free operation will further reduce maintenance requirements. Reduced noise levels may improve public acceptance.

The magnetic gearbox opens the prospect for massive wind turbines offering extended component lifetimes and low levelized cost of electricity. As an alternative to mechanical and hydraulic transmissions, the technology also appears suited for wave energy production, low-head hydro, boiler feedwater pump, and other power industry applications.

STATE OF THE TECHNOLOGY

On EPRI's technology readiness level (TRL) scale (Figure 2), heavy-duty magnetic gearing has achieved ~TRL4-5 through proof-of-concept testing and laboratory validation of a prototype cycloid gearbox designed and advanced by AMT, Inc., for ship propulsion under funding from the US Department of Energy (DOE) and US Office of Naval Research. The potential for significant performance advantages over conventional mechanical gearing has been demonstrated with a 10-kilowatt (kW) prototype. According to modeling by AMT, a magnetic gear coupled with a conventional generator and optimized for wind turbine applications could replace an electromechanical system eight times larger.[13]

Technology developers around the world are pursuing magnetic gearboxes. In Europe, under the MAGDRIVE research program, two magnetic gear prototypes were designed and tested. One is capable of operating at extremely low temperatures, under a vacuum—conditions experienced in space. The second is intended for ambient-temperature applications, from food processing to energy production.[14] A spin-off company, MAG SOAR, claims to have achieved a world-record gear ratio of 44:1 during 2016.[15] Other developers are touting early commercial products, generally for small-scale uses.

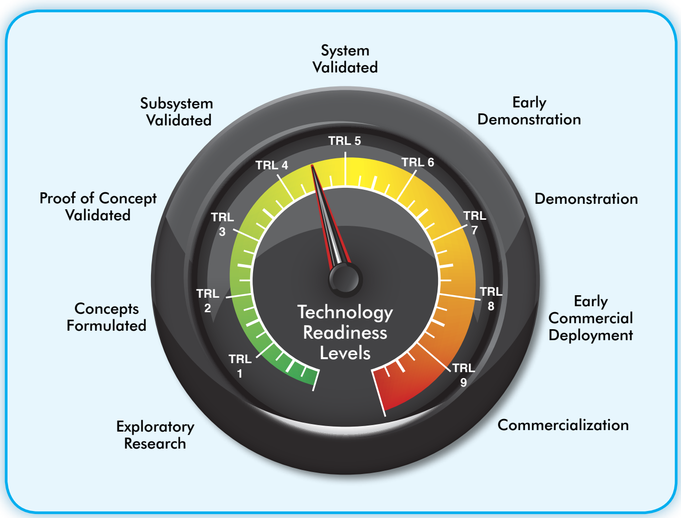

Figure 2 – Approximate Status of Heavy-Duty Magnetic Gears

No prototype horizontal-axis wind turbines with magnetic transmissions are known as of early 2017, but the application is under development. For example, researchers at the University of Setif-1 in Algeria developed and modeled a novel drive-train topology for future offshore turbines integrating a magnetic gear with a permanent magnet synchronous generator.[16] The Advanced Electrical Machines & Power Electronics Lab at Texas A&M University, one of the hotbeds of US research, has developed and tested sub-kW magnetic gear prototypes in axial, radial, and trans-rotary configurations and assessed their possible use in wind turbines.[11] Texas A&M researchers also are exploring ship propulsion, wave energy production, electric vehicle and bicycle drive, and other applications.[12]

Another leading US research group, previously centered at University of North Carolina at Charlotte (UNCC) and now at Portland State University, received 2014 funding from DOE and the US National Science Foundation focusing on early-stage development of magnetic gears for ocean and wind energy applications.[17,18] A prototype vertical-axis wind turbine with magnetic gearing has been demonstrated through a UNCC student design project, with a video posted on YouTube (https://www.youtube.com/watch?v=bsplGQiORWs).[19] Ongoing work builds on design, development, and testing of prototypes such as the one shown in Figure 3.[20] In 2015, DOE awarded funding to a public-private collaborative involving Georgia Tech focused on developing a magnetic gear platform for low-impact hydro drive trains.[21]

Challenges to commercialization of large magnetic transmissions for wind energy applications include material costs and manufacturing complexity, as well as system engineering. Significant R&D will be required to optimize gear design and integration with the main rotor shaft and generator, encompassing mechanical and electromagnetic interactions and turbine control strategies. Other components made of iron alloys may create interference, while magnetic bearings and additional innovations may allow for additional benefits.

NEXT STEPS & COLLABORATIVE OPPORTUNITIES

Magnetic gears integrated in extreme-scale onshore and offshore wind turbines are projected to achieve TRL8 in about eight to ten years. The next R&D milestone is to develop and test prototype magnetic gears integrated with wind turbine rotors and generators in the laboratory and then under field conditions to understand dynamic behavior and assess magnetic interactions with other components inside the nacelle.

Scale-up testing and refinement in the range of 100 to 250 kW will be required to define the best configurations for mechanical and magnetic coupling and to validate performance, efficiency, and reliability. This will help in refining estimates of future capital, operations, and maintenance costs, relative to other drive-train configurations for future wind turbines, as well as in identifying key sensitivities. Pilot testing at scales of 2 MW or greater will be needed to optimize full- and partial-load efficiencies and evaluate long-term reliability.

Through innovation scouting, EPRI has identified magnetic gearbox technology as a possible breakthrough enabling onshore and offshore turbines sized at 10 MW and higher, with competitive cost. EPRI is not engaged with any R&D groups at present but plans to monitor progress and explore possible funding opportunities. Pending the interest of utility and other members, potential roles include independent technical and economic assessment or active engagement in prototype testing and pilot demonstration to reduce the risk of early adopters.

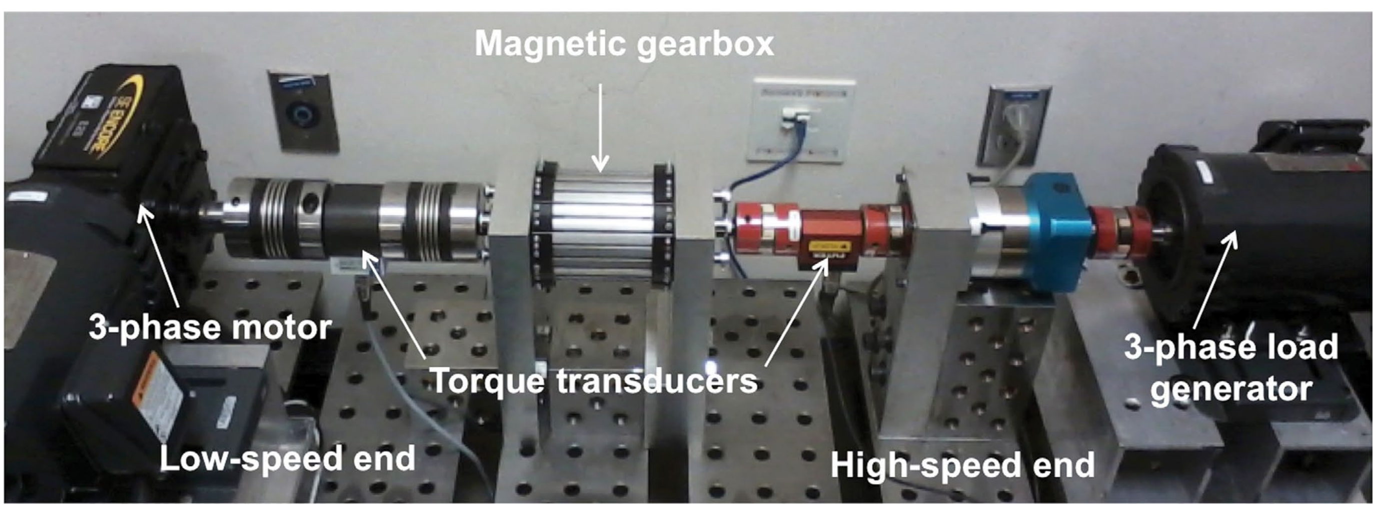

Figure 3 – Prototype Magnetic Gearbox With Ratio of 4.25:1 in Dynamometer Test Stand (Credit: Portland State University)

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