Proceedings of the 1st International Nuclear and Renewable Energy Conference (INREC10), Amman, Jordan, March 21-24, 2010

WIND TURBINE GEARBOX TECHNOLOGIES

Adam Ragheb[*] and Magdi Ragheb[**]

[*]Department of Aerospace Engineering
[**]Department of Nuclear, Plasma and Radiological Engineering
University of Illinois at Urbana-Champaign,
216 Talbot Laboratory,
104 South Wright Street,
Urbana, Illinois 61801, USA.
aragheb@illinois.edu, mragheb@illinois.edu

ABSTRACT

The reliability problems associated with transmission or gearbox equipped wind turbines and the existing solutions of using direct drive gearless turbines and torque-splitting, are reviewed. As alternative solutions we propose the Geared Turbofan Engine (GTF) technology, and magnetically-levitated bearings from the aerospace industry, and the consideration of Continuously Variable Transmissions (CVTs) from the automobile industry, and discuss their promise in addressing the gearbox problems currently encountered by existing wind turbine technology.

1. INTRODUCTION

Operational experience reveals that the gearboxes of modern electrical utility wind turbines at the MW level of rated power are their weakest-link-in-the-chain component. Small wind turbines at the kW level of rated power do not need the use of gearboxes since their rotors rotate at a speed that is significantly larger than utility level turbines and can be directly coupled to their electrical generators.

The typical design lifetime of a utility wind turbine is 20 years, but the gearboxes, which convert the rotor blades rotational speed of between 5 and 22 rpm to the generator-required rotational speed of around 1,000 to 1,600 rpm, commonly fail within an operational period of 5 years, and have to be replaced. That 20 year lifetime goal is itself a reduction from an earlier 30 year lifetime design goal.

2. EXPERIENCE WITH TURBINE TRANSMISSIONS

Among insurers, who joined the market in the 1990s, wind power is currently considered a risky sector. German industry giant Allianz was faced with around 1,000 damage claims in the year 2006 alone. Gearboxes had to be replaced in large numbers according to the German Insurance Association.

On average, an operator has to expect damage to his facility every four years, excluding malfunctions and uninsured breakdowns.

Many insurance companies now are writing maintenance agreements requiring wind producers to write the replacement of vulnerable components such as gearboxes every five years directly into their contracts. A gearbox replacement can cost up to 10 percent of the original construction cost, enough to cut deep into the projected profits.

Wind gusts lead to misalignment of the drive train and gradual failure of the gear components. This failure interval is disturbing, as it creates a significant increase in the capital and operating costs and downtime of a turbine, while greatly reducing its profitability and reliability. Existing gearboxes are a spinoff from marine technology used in shipbuilding. The gearboxes are massive components as shown in Figs. 1 and 2.

Figure 1. *View inside a Liberty wind turbine gearbox. Source: Liberty.*

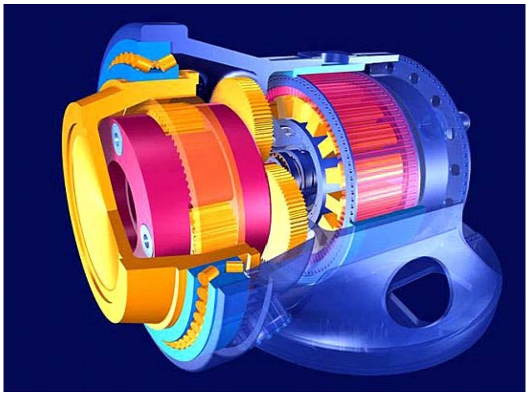

Figure 2. *Rotor bearings, gearbox and generator assembly of M5000 wind turbine. Source: Multibrid.*

In this work, we identify and shed light on current or on-the-horizon gearbox technologies in the wind industry and other industries in the hopes of disseminating the knowledge, design technologies, and lessons learned across the wind turbine industry and possibly avoiding costly duplication of research into reliable gearboxes. Highly reliable gearboxes currently exist, but there appears to be limited exchange of information between the aerospace propulsion industry and the wind turbine industry.

This work will review the current solutions to the gearbox problem through the direct drive approach, provide a background on turbofans from the aerospace industry and their technologies as a possible solution, and examine the benefits and disadvantages of using a Continuously Variable Transmission (CVT).

3. GEARLESS OR DIRECT DRIVE WIND TURBINES

Currently, Enercon GmbH of Aurich, Germany has presented a mass-produced solution to the low gearbox reliability. It has licensed the technology to Japan Steel Works (JSW) in Japan.

This solution is their direct drive wind turbine, which utilizes an annular multiple poles generator. This generator significantly reduces the number of moving components, lowering the amount of repair work and associated turbine downtime. In order to satisfy the service life requirements specified by Enercon, the copper winding of the stator component of the generator consists of individual insulation class F round copper wires that are bundled and insulated with varnish. This copper winding is then installed by hand, with Enercon suggesting that the continuous insulating materials have the opportunity to be fully tested. An image of Enercon's annular generators undergoing assembly is shown in Fig. 3, while the finished stator and rotor are shown in Fig. 4.

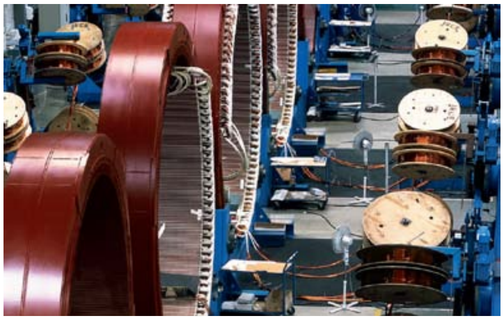

Figure 3. *Multipole annular generators under assembly. Source: Enercon.*

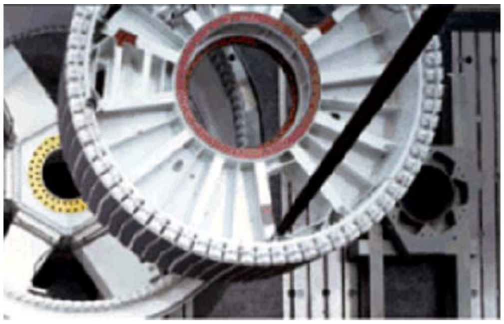

Figure 4. *Stator and rotor of E-70 wind turbine. Source: Enercon.*

In order to produce AC power at the required 50 and 60 Hz for Europe and the USA, respectively, a 4-pole generator would need to run at a nominal rotational speed of about 1,500 revolutions per minute (rpm), while a 6-pole generator would operate at a setting of around 1,000 rpm. As the number of poles increases, the rpm required to operate decreases linearly:

$$\omega_{generator} = 100\frac{f}{N} rpm \tag{1}$$

where ω is the rotational speed in rpm, f is the frequency in Hz, and N is the number of generator poles.

For the USA frequency of 60 Hz, Eqn. 1 yields:

$$\omega_{generator} = \frac{6,000}{N} rpm$$

This shows that an 8-pole generator would need to operate only at approximately 750 rpm, and a 200-pole generator at only 30 rpm to produce a 60 Hz electrical current.

The gearing ratio G for a transmission is defined as:

$$Gearing\ ratio: G = \frac{\omega_{generator}}{\omega_{rotor}} \tag{2}$$

where $\omega_{generator}$ is the rotational speed of the generator and ω_{rotor} is the rotational speed of the rotor, both in rpm.

A 4-pole generator operating at 1,500 rpm and rotor blades rotating at 20 rpm would require a transmission with a gearing ratio of 75, while a 200-pole generator operating at 30 rpm with rotor blades operating at 30 rpm yields a gearing ratio of 1, which negates the need for a gearbox

It is interesting to note that based on Fig. 5, the Enercon wind turbine appears to leave the weight of the rotors and blades unbalanced on the upwind side of the tower, while Fig. 6, which depicts a JSW turbine, appears to use the transformer and converter to counterbalance the blades and generator. These components are traditionally located on the ground.

Figure 5. *Multipole generator coupling to rotor hub and tower. Source: Enercon*

Figure 6. *Counterbalanced JSW J82 permanent magnet synchronous generator gearless wind turbine. Source: JSW.*

4. ANNULAR GENERATOR

The annular generator is of primary importance in the gearless system design of the E-70 wind turbine. It offers the advantages of totally avoiding the gearbox components, a lower wear caused by a slow machine rotation, low stress due to the high level of speed variability, the incorporation of yield optimized control and a high level of grid compatibility.

Combined with the rotor hub, it provides an almost frictionless flow of energy, while the gentle running of fewer moving components guarantees minimal material wear. Unlike conventional asynchronous generators, the annular generator is subjected to minimal mechanical wear, which makes it ideal for particularly heavy demands and a long service life.

The annular generator is a low speed synchronous generator with no direct grid coupling. The output voltage and frequency vary with the speed and are converted for output to the grid by a Direct Current (DC) link and inverter. This achieves a high degree of speed variability

The copper winding in the stator, the stationary part of the annular generator, uses a single layer basket winding that is produced using the insulation Class F to 155 °C. It consists of individual round wires that are gathered in bundles and insulated with varnish. The copper winding is done manually. In spite of increasing automation in other manufacturing areas, preference has been given to manual labor in this case since it ensures that the materials used are fully tested. A special processing method allows continuous windings to be produced. Each wire strand is continuous from start to finish.

Advantages of continuous winding include:

- Prevention of processing faults in the production of electrical connections
- Maintains the high quality copper wire insulating system
- Elimination of the contact resistance
- Elimination of weak points that are susceptible to corrosion and material fatigue

The magnetic field of the stator winding is excited by pole shoes. These are located on the disk rotor, the mobile part of the annular generator. Since the shape and position of the pole shoes have a decisive influence on the noise emission of the annular generator, Research and Development (R&D) has dedicated particular attention to this aspect. The result is an improved adaptation of the pole shoes to the slow rotation of the annular generator with no significant noise being generated.

5. MANUAL LABOR VERSUS AUTOMATION

It should be noted that outsourcing has two inherent problems. By outsourcing, proprietary technologies and/or processes are transferred to the receiving country, and it is only a temporary solution. As the wealth of the outsourcee country grows, its workers will demand ever-increasing wages and benefits. In addition to this, funds are exiting the outsourcing country to the outsourcee, and through the aforementioned technology transfer, outsourcing may inadvertently be creating a new competitor through the technology transfers.

Technology transfer is a significant disadvantage to outsourcing of manual labor, which is becoming ever-increasingly unaffordable in the industrialized nations.

For these reasons, it can be inferred that hand-wound electrical generators for wind turbines are not viable in the far-term and an automated winding process of annular generators must be given serious design and investment consideration.

6. GEARBOX DESIGN OPTIONS

The weakest link of a utility size wind turbine has been their gearbox. As turbine sizes increased, the design of gearboxes able to handle the torque generated by longer and heavier blades has become a problem. In addition, turbine loading is variable and hard to predict. Some gearboxes have failed in less than two years of operation.

Most of these failures have been attributed to the movement of the machine chassis, which causes misalignment of the gearbox with the generator shafts and leads to failure. Such failure occurs in the high speed rear gearing portion of the gearbox when the bearings become faulty. Regular turbine realignments can reduce the frequency of failure, but do not preclude their occurrence.

Manufacturers have made their turbines more reliable by improving the oil lubrication and filtration system in the gearbox so it can remove all particles larger than seven microns in size. If a particle of that size breaks free of the meshing gears, it can damage other gears and bearings.

Enercon in Germany, and Japan Steel Works under license, have increased the number of generator poles in their machines, eliminating the gearbox. Most electrical generators have 4 or 6 magnetic pole pairs in their windings and must use a gearbox. With the generator built with 50-100 pole pairs, the use of electronic control can eliminate the need for a gearbox.

The coupling of the blades directly to the generator in machines without a gearbox also eliminates the mechanical or tonal noise produced by conventional turbines.

7. TORQUE SPLITTING, DISTRIBUTED GEARING

A California based wind turbine manufacturer improved reliability by using distributed gearing using multiple paths and 4 generators to ensure continued turbine operation even if one of the generators fails. This unique approach splits the large amount of torque experienced by the gearboxes due to the blades, which in some cases are longer than the wing of a Boeing 747. Figure 7 illustrates this arrangement.

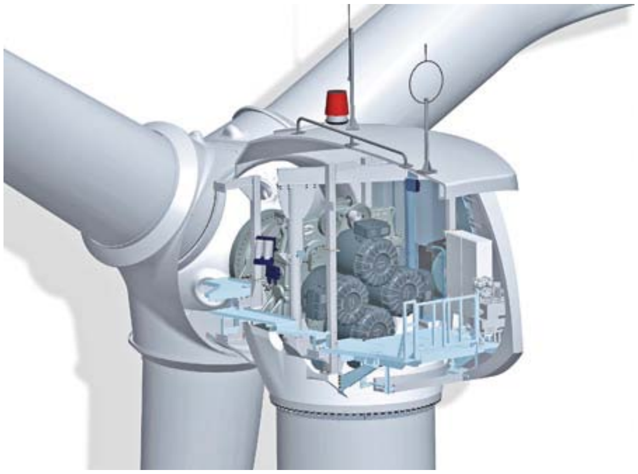

Figure 7. *Torque splitting between four electrical generators operated in parallel. Source: Clipper Wind Power Inc.*

This design however, encountered a problem with its 2.5 MW turbine, caused by poor quality control and an apparent design problem, affecting the company's financial performance. The 20 MW Steel Winds wind farm in upstate New York, using eight of the turbines, has been shut down because of a gearbox problem in the turbines. All eight turbines suffered from a manufacturing problem and repairing the problem required several months.

The Steel Winds project, on a former Bethlehem Steel site that is also a listed Superfund toxic waste site, was the first to use the 2.5 MW machines. The eight wind turbines rolled off the company's assembly line in Cedar Rapids, Iowa, in late 2006, and went into service at the site on Lake Erie in April 2007.

The operators of the project, UPC Wind and BQ Energy, first noticed the problems with the wind machines in August 2007. Upon inspection, engineers discovered that a tooth on one of the four gears in the box had broken. Inspections found the problem on all of the turbines on the site.

Similar turbines at projects in Iowa and Minnesota had the same problem and required repairs. SNL Financial, a trade news service, reported that 50 turbines required repair. The Steel Wind turbines were all under warranty, according to a UPC Wind official, so the manufacturer covered the costs of repair.

8. HISTORY OF THE DIRECT DRIVE APPROACH

During the past few years, the market share for direct drive wind turbines accounted for 13-15 percent of the total turbine market, with the number standing at 14 percent in 2007.

Enercon of Germany has dominated the direct drive wind turbine market since they introduced their first direct drive system in 1993, with their current product range offering turbines of rated power 100 kW to 6 MW and about 12,600 systems produced by 2009. Their flagship model is the E-126, which features a 12 meter diameter annular generator and a 127 meter blade diameter. Enercon has been effective in meeting its competition, as companies such as Jeumont Industrie, Seewind, and Heidelberg have all offered direct drive turbine concepts, but none have yet demonstrated a significant commercial impact.

Japan Steel Works (JSW) became involved in Wind Power Systems using its long experience in industrial machinery and energy technology. Initially, it delivered 30 sets of General Electric (GE) 1.5s wind turbines in Japan. Using the acquired operational experience, JSW adopted the technology of permanent magnet gearless synchronous generator wind turbines from Enercon in Germany and manufactures its own wind turbine including the rotor blades and the tower.

Lagerwey of the Netherlands offered a 750 kW family of turbines, but filed for bankruptcy in 2003 after fabricating only 200 units. Emergya Wind Technology purchased the Lagerwey technology and since 2004 has offered a 900 kW DirectWing 900*54 wind turbine, effectively having scaled up the Lagerway technology. The former leaders of Lagerwey produced one 2 MW direct drive prototype under the auspices of the Zephyros consortium, but sold it to Harokasan in Japan.

In July 2008, Siemens Energy embarked upon a 2-year testing program for a 3.6 MW rated power experimental direct drive turbine. This concept machine was installed near the coast of Ringkøbing, Denmark, with a second slightly different generator design installed by December 2008. Henrik Stiesdal commented that Siemens realizes that direct drive wind turbines may become competitive with their geared counterparts at the upper end of turbine sizes, and through these two test rigs hopes to determine if and at what level direct drive systems can be made competitive.

Despite the prior failings of competitors to Enercon in the direct drive market sector, there exists a high level of optimism and a growing level of interest. In addition to the efforts of Siemens Energy, a number of companies are currently attempting to gain a foothold in the direct drive sector. They are summarized below in Table 1.

Table 1. *Current Market Direct Drive Market Entrants.*

Country	Company	Turbine Rated Power (MW)
The Netherlands	DarWinD	4.7
Norway	ScanWind	3.5
Germany	Vensys	1.2, 1.5, 2.5
Spain	Mtorres	1.65
Italy	LeitWind	1.2, 1.5
South Korea	Unison	0.75

It should be noted that interest from coal-rich China indeed does exist, as Goldwind currently licenses production of Vensys wind turbines, and as of recent, owns 70 percent of the Vensys shares.

Currently, the direct drive generator design of choice is the Permanent Magnet (PM) type of generator. Benefits of PM generators include their compactness relative to external field excitation generators as well as the fact that it is widely held that this generator design exhibits a very high efficiency even when subjected to a partial load. Disadvantages of PM generators however include the inability to control the field strength and significantly more stringent manufacturing and tolerance requirements.

9. GEARED TURBOFAN TECHNOLOGY

Pratt and Whitney, the maker of jet engines powering aircraft such as the F-15 Eagle, 747 Jumbo Jet, and C-17 Globemaster, spent over 10 years of research and over $350 million in development costs to develop a Geared Turbo Fan Engine (GTF). In order to understand why this jet engine technology development has potential positive implications for the wind turbine industry, one must first understand how and within what environment a turbofan engine operates.

A turbofan is essentially a standard jet engine, known as a turbojet, with a large diameter ducted fan installed on the front. Turbojets were used on early jet-powered aircraft, such as the Boeing 707, De Haviland Comet, and the Convair B-58 Hustler, and are characterized by a long narrow-diameter cylindrical shape. Figure 8 depicts a B-58 Hustler with its 4 General Electric (GE) J79-GE1 turbojet engines visible beneath the large delta wing.

Figure 8. *Turbojet-powered Convair B-58 Hustler.*

In a turbojet engine, all of the thrust is derived from air passing through the core of the engine, which emerges at a very high speed and temperature. Additionally, due to the fact that all of the thrust was derived from "hot" air, significant increases in turbojet diameter came at a high cost, as all of the fan blades would have to withstand high centripetal loading while subjected to very high temperatures and pressures. In order to solve these scalability and noise problems, the turbofan engine was developed.

In a turbofan engine, on the other hand, the majority of the thrust is derived from air that does not pass through the core of the engine, but instead enters the large-diameter fan on the front and bypasses the core. Not surprisingly, this is referred to as bypass air. This bypass air is not heated, and exits the fan at a lower speed than the air that passes through the core, and is thus significantly quieter air. At the end of the turbofan engine, the loud, hot, and high-velocity air that passed through the core is surrounded by and mixed with the quieter, colder, and lower-velocity bypass air, significantly reducing the noise of the engine. Typical bypass ratios, the ratio of bypass air to air passing through the core of the engine, are around 0.5 to 6:1. The bypass ratio of the GE-90-115B, physically the largest turbofan engine currently in service, is a whopping 9:1, while the Rolls Royce Trent 1000, shown in Fig. 9, which powers Boeing's 787 Dreamliner, has a bypass ratio of 11:1.

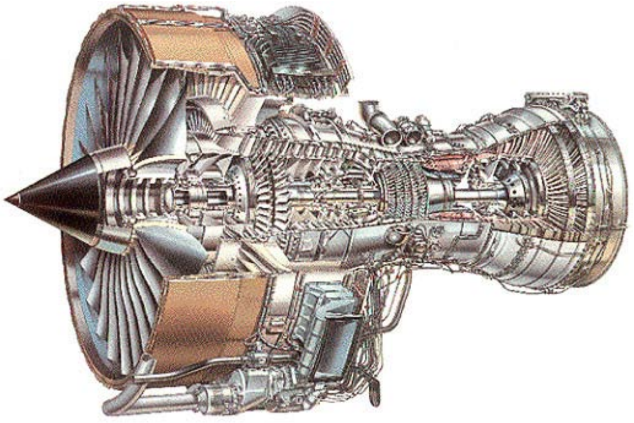

Figure 9. *Rolls Royce Trent 1000 Turbofan engine. Source: Rolls Royce.*

Gas turbo machinery currently represents the most efficient means of converting the chemical energy of fuel into kinetic energy for use as propulsive thrust. In the late 1960s, when engine manufacturers coupled the turbojet with a fan directly linked to the turbine, the amount of useful thrust significantly increased. Current jet engine technology consists of the fan and core rotating on separate shafts. In industry terms, these shafts are simply referred to as "spools."

Turbofan engines currently in-service employ a direct connection between the Low Pressure (LP) turbine and the fan, and thus the two rotate at the same speed. Inherent inefficiencies exist in this configuration, as the large-diameter fan operates most efficiently at lower rpm relative to the LP turbine. This is due to the fact that the smaller-diameter LP turbines can operate at higher rpm before the tips reach supersonic speeds. Once tip speeds reach a supersonic speed, shockwaves and other instabilities significantly reduce the aerodynamic efficiency of the blades, and introduce unwanted stresses.

Pratt and Whitney's insertion of a gearbox between the fan and the LP turbine of a turbofan allows adjustment of the ratio of fan rpm to LP turbine rpm, allowing optimization of the performance of the fan for various flight conditions, and is projected to offer an efficiency increase of approximately 9 percent.

12. GEARED TURBOFAN DEVELOPMENT

The Geared Turbofan (GTF) engine is not a new concept, as Pratt and Whitney understood the theoretical justification behind the concept by the early 1980s. The reason for this concept only now, nearly 30 years later, appearing on actual jet engines is the level of technology and materials development required to satisfy the stringent safety, reliability, and ruggedness requirements of modern jet turbines. Pratt and Whitney suggests that through thousands of hours of development, advances in bearing, gear system, and lubrication design have been made and incorporated into their new family of GTFs. It is reported that their GTF gearbox operates at an efficiency of over 99 percent and a heat load below 50 percent of what was originally expected.

The gearbox currently being tested in the PW1000G, Pratt's new GTF engine, has a diameter of 17 inches, and handles a shaft horsepower (shp) of 32,000. Component, full-scale, and flight tests have currently totaled approximately 2,500 hours on Boeing 747 and Airbus Industries A-340 test bed aircraft. Additionally, a 40,000 shp gearbox is currently undergoing full scale tests. GTF engines have recently been selected to power the Mitsubishi Regional Jet, Bombardier CSeries, and Irkut MC-21 aircraft. The GTF engines for these aircraft will have thrust ratings of between 15,000 and 32,000 lb and have expected Entry Into Service (EIS) dates between 2013 and 2016. Figure 10 depicts a GTF gearbox, the PW8000.

Figure 10. *PW8000 gearbox. Source: Pratt and Whitney.*

13. ADOPTION OF MAGNETIC BEARINGS

Pratt and Whitney goes on to suggest the existence of a proprietary "self-centering" technology to nearly eliminate all instances of stress and gear misalignment, problems discussed by Ragheb [1] on wind turbine gearboxes that cause severe reliability problems.

We surmise that magnetic levitation with permanent or electromagnets is used in lieu of ball bearings to self-align the transmission shafts.

Magnetic bearings offer a host of advantages, including high speed capabilities and the ability to operate lubrication-free and in vacuum environments. They generate no friction, experience minimal wear, and operate contamination free with extremely low vibration.

Magnetic bearings can precisely control shaft position, measure external forces acting on the shaft, and monitor a machine's operating condition. Magnetic-bearing systems electromagnetically suspend shafts by applying electric current to a bearing's ferromagnetic materials. The systems have three main elements: bearing actuators, position sensors, and controller and control algorithms.

Typical units consist of two magnetic radial bearings and one magnetic thrust bearing. They control the shaft along five axes: two axes for each radial bearing and a fifth axis along the shaft. The radial stator is formed by a buildup of laminations, each of which is shaped with poles. The laminations stack together, and coils of wire are wound around each pole. An image of a stator and rotor of a magnetic bearing is presented in Fig. 11, while Fig. 12 depicts the five axis control achievable with two radial and one magnetic thrust bearing.

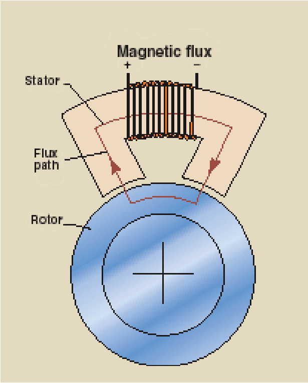

Figure 11. *Magnetic bearing stator and rotor [20].*

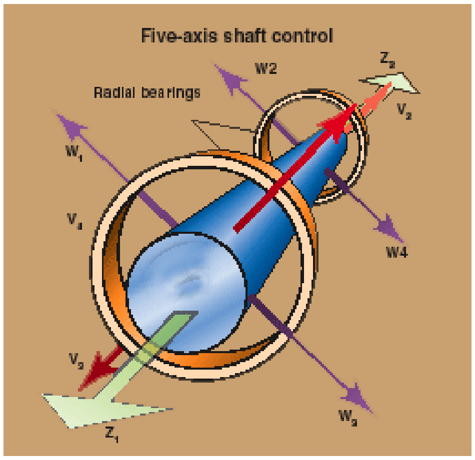

Figure 12. *Five axis control of magnetic bearing [20].*

Controlled electric currents passing through the coils produce an attractive force on the ferromagnetic rotor and levitate it within an air gap. The gap usually measures about 0.5 mm but, in some applications, can be as large as 2 mm. The rotor fits over the shaft, which is in the air gap but need not be centered.

A magnetic thrust bearing provides axial control. The thrust-bearing rotor is a solid steel disk attached to the shaft and positioned at a preset distance from the stator on one or both sides.

During operation, electromagnetic forces produced by the stator act on the rotor and control axial movement.

Magnetic bearing arrangements include touchdown or auxiliary bearings. Their main function is to support the shaft when the machine is idle and protect machine components in case of power outage or failure. The touchdown bearing's inner ring is smaller than the magnetic-bearing air gap to prevent potential damage if the shaft loses its levitation.

14. SIMILARITY BETWEEN WIND AND TURBOFAN GEARBOXES

Planetary spur gearing [1], is also commonly known as epicyclic gearing. The general concept behind this gearing involves multiple outer gears revolving around a single gear; the outer gears are often regarded as the "planets," while the single center gear is viewed as the "sun." In order to achieve a reduction or increase in rpm, an outer ring gear or annulus is required.

Figure 13 depicts a planetary spur-style gearing system. As it would relate to wind turbines, the green annulus would be connected to the rotor hub, while the yellow sun gear would be connected to the generator. Rotation of the annulus by 45 degrees results in the sun gear rotating approximately 135 degrees, yielding a threefold rpm increase or a gearing ratio (G) of 3.

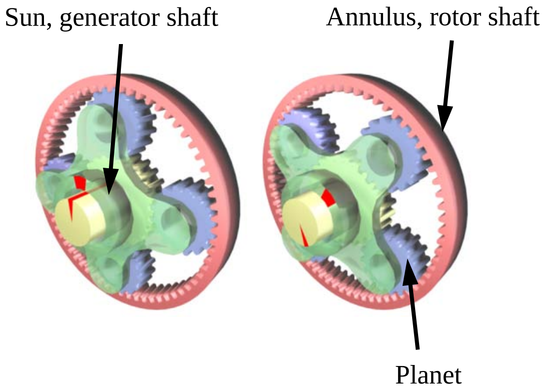

Figure 13. *Planetary spur or epicyclic gearing system.*

Planetary gearing systems exhibit higher power densities than parallel axis gears, and are able to offer a myriad of gearing combinations and a large reduction in a small volume. Disadvantages include the requirement for complex designs, general inaccessibility, and high bearing loads. The latter of the three is suspected to have created the majority of problems for wind turbines.

Minor misalignments due to wind gust loads or manufacturing inconsistencies rapidly wear down the gears, which in turn creates a vicious and ultimately destructive feedback cycle between misaligned components and gear wear.

Somehow the aerospace industry has moved beyond these problems, as helicopters and geared turbofans exhibit the impeccable reliability required for air vehicles – the answer exists somewhere. Pratt and Whitney's PT6 gas turbine engine utilizes an epicyclic gearing system, and has been used on the Bell UH-1 Huey helicopter and the DeHaviland DHC-6 Twin Otter passenger aircraft; this epicyclic gearing system is depicted below in Fig. 14.

Figure 14. *Pratt and Whitney PT6 turbine engine reduction gears.*

As depicted in Fig. 13, a planetary gear system contains three component gears: the sun gear, the planet gears, and the annulus. In order to calculate the reduction potential of a planetary gear system, one must first determine the number of teeth N that each of the three component gears have. These values will be referred to as N_{sun}, $N_{annulus}$, and N_{planet}. Using the relationship that the number of teeth is directly proportional to the diameter of a gear, the three values should satisfy the equality of Eqn. 3 which shows that the gears will fit within the annulus.

$$N_{sun} + 2 * N_{planet} = N_{annulus} \tag{3}$$

where N_{sun}, $N_{annulus}$, and N_{planet} are the number of teeth in the sun gear, annulus gear, and planet gear, respectively.

With Eqn. 3 satisfied, the equation of motion for the three gears is:

$$\left(2 + \frac{N_{sun}}{N_{planet}}\right)\omega_{annulus} + \frac{N_{sun}}{N_{planet}}\omega_{sun} - 2*\left(1 + \frac{N_{sun}}{N_{planet}}\right)\omega_{planet} = 0 \tag{4}$$

where ω_{sun}, $\omega_{annulus}$, and ω_{planet} are the angular velocities of the respective gears. Since angular velocity is directly proportional to the rpm, Eqn. 4 simplifies Eqn. 5 below:

$$\left(2 + \frac{N_{sun}}{N_{planet}}\right)rpm_{annulus} + \frac{N_{sun}}{N_{planet}}rpm_{sun} = 2*\left(1 + \frac{N_{sun}}{N_{planet}}\right)rpm_{planet} \tag{5}$$

Known values may be substituted into Eqn. 5 in order to determine the relative rpm of the sun and annulus gears, noting the following two equalities of Eqns. 6 and 7:

$$rpm_{sun} = \left(\frac{-N_{sun}}{N_{planet}}\right)rpm_{planet} \tag{6}$$

$$rpm_{planet} = \left(\frac{-N_{planet}}{N_{annulus}}\right)rpm_{annulus} \tag{7}$$

15. CONTINUOUSLY VARIABLE TRANSMISSIONS

Another option for solving the gearbox problem is the use of a Continuously Variable Transmission (CVT). This gearing design has only recently reached mass production in passenger vehicles. Table 2 summarizes some of the cars on the road today that utilize CVTs. Transmissions of the CVT type are capable of varying continuously through an infinite number of gearing ratios in contrast to the discrete varying between a set number of specific gear ratios of a standard gearbox.

Table 2. *CVT-Geared Passenger Vehicles.*

Make	Model	Year
Honda	Civic, high torque	1995
Audi	A4, A6	2000
Nissan	Murano	2003
Ford	Five Hundred, Freestyle	2005
Dodge	Caliber	2007
Mitsubishi	Lancer	2008
Nissan	Maxima	2008
Honda	Insight Hybrid	2010

It is this gearing flexibility that allows the output shaft, connected to the generator in wind turbine applications, to maintain a constant rate of rotation for varying input angular velocities. The variability of wind speed and the corresponding variation in the rotor rpm combined with the fixed phase and frequency requirements for electricity to be transmitted to the electrical grid make it seem that CVTs in concert with a proportional Position, Integral, Derivative (PID) controller have the potential to significantly increase the efficiency and cost-effectiveness of wind turbines.

CVTs have been in use in drill presses, lawn tractors, combines, aircraft electrical generators, and racing cars as early as the 1950s. A number of CVT categories exist, including belt-driven, variable diameter-pulley (VDP), infinitely variable transmission (IVT), ratcheting, hydrostatic, cone, and chain driven.

It is the last type that may be of best interest to wind energy, as one disadvantage of CVTs is that their ability to handle torques is limited by the strength of the transmission medium and the level of friction between that medium and the source pulley. Through the use of state-of-the-art lubricants, chain-drive CVTs have been able to adequately serve any amount of torque experienced on buses, heavy trucks, and earth moving equipment.

The Gear Chain Industrial B.V. Company of Japan appears to have initiated work on a wind application for chain-driven CVTs, and have mentioned their interest in such a project.

15. DISCUSSION

The aerospace industry has been using epicyclic gears since the 1960s on turboprops, helicopter transmissions, and the newest technology to emerge, the geared turbofan. While jet engines do operate at lower torques than modern wind turbines, it still seem reasonable that the wind turbine industry could benefit from applying the knowledge of the aerospace industry to its gearboxes, as gearboxes for aerospace applications operate in very challenging environments, with temperature swings from 120ºF to -80ºF, operating envelopes of up to 30,000 rpm, and shaft horsepower ratings of up to 40,000, all while demonstrating unparalleled reliability and robustness.

The difference is that during wind gusts, wind turbines are subjected to larger varying and cyclic stress loadings than jet engines or helicopter blades due to the larger sizes and weights encountered in wind turbines. Theses cyclic stresses significantly affect the shape and alignment of the transmission and gear system. The alignment issue can be addressed through the use of magnetically levitated bearings technology.

Additionally, the new ideas being explored by the wind turbine industry show a large amount of promise, and appear to have the capability to yield significantly more reliable gearboxes while avoiding the problems of scalability and labor costs that may soon become associated with the hand-assembled annular generators. Rotor blade construction technology is already tapping the expertise of the aerospace industry, so it seems a logical progression for the wind energy to once again turn to the aerospace sector to solve its problems with gearbox reliability.

16. REFERENCES

[1] M. Ragheb, “Wind Power Systems. Harvesting the Wind.” https://netfiles.uiuc.edu/mragheb/www, 2010.

[2] Thomas Ackerman, Ed. “Wind Power in Power Systems,” John Wiley and Sons, Ltd., 2005.

[3] American Institute of Aeronautics and Astronautics (AIAA) and American Society of Mechanical Engineers (ASME), “A Collection of the 2004 ASME Wind Energy Symposium Technical Papers,” 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno Nevada, %-8 January, 2004.

[4] Désiré Le Gouriérès, “Wind Power Plants, Theory and Design,” Pergamon Press, 1982.

[5] Joseph E. Brown and Anne Ensign Brown, “Harness the Wind, The Story of Windmills,” Dodd, Mead and Company, New York, 1977.

[6] Frank R. Eldridge, “Wind machines,” 2nd Ed., The MITRE Energy Resources and Environmental Series, Van Nostrand Reinhold Company, 1980

[7] N. G. Calvert, “Windpower Principles: Their Application on the Small Scale,” John Wiley and Sons, 1979.

[8] Volta Torrey, “Wind-Catchers, American Windmills of Yesterday and Tomorrow,” The Stephen Greene Press, Brattleboro, Vermont, 1976.

[9] John F. Walker, and Nicholas Jenkins, “Wind Energy technology,” John Wiley and Sons, 1997.

[10] J. Schmid and W. Palz, “European Wind Energy Technology, State of the Art Wind Energy Converters in the European Community,” D. Reidel Publishing Company, 1986.

[11] Energy Research and Development Administration (ERDA), Division of Solar Energy, “Solar Program Assessment: Environmental Factors, Wind Energy Conversion,” ERDA 77-47/6, UC-11, 59, 62, 63A, March 1977.

[12] http://www.flug-revue.rotor.com/FRHeft/FRH9810/FR9810h.htm.

[13]http://en.wikipedia.org/wiki/Epicyclic_gearing#Advantages_.2F_Disadvantages

[14]http://www.sae.org/aeromag/techinnovations/1298t10.htm

[15]http://www.airbus.com/en/presscentre/pressreleases/pressreleases_items/08_10_14_geared_turbofan_concept.html

[16] http://www.wpdelfzijlzuid.nl/enercon.pdf

[17]http://www.renewableenergyworld.com/rea/magazine/story?id=53850

[18] http://www.multibrid.com/index.php?id=23&L=1

[19]http://www.alliedfsgroup.com/?RhZbkYiCnAlN5wUqbekXqChlg3w2Ukhfhdl7nlfCI6VjbfkaqAl

[20] http://www.machinedesign.com