WIND TURBINE GEARBOX TECHNOLOGIES

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INTRODUCTION

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 consideration of Continuously Variable Transmissions (CVT) and Geared Turbofan Engine (GTF) technology from the aerospace industry and discuss its promise in addressing the gearbox problems currently encountered by existing wind turbine technology.

Figure 1. View inside a Liberty wind turbine transmission or gearbox.

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 after 5-9 years. That 20 years lifetime goal is itself a reduction from an earlier 30 years lifetime design goal.

OPERATIONAL EXPERIENCE

Among insurers, who raced into 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 requirements requiring wind producers to replace 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, 2.
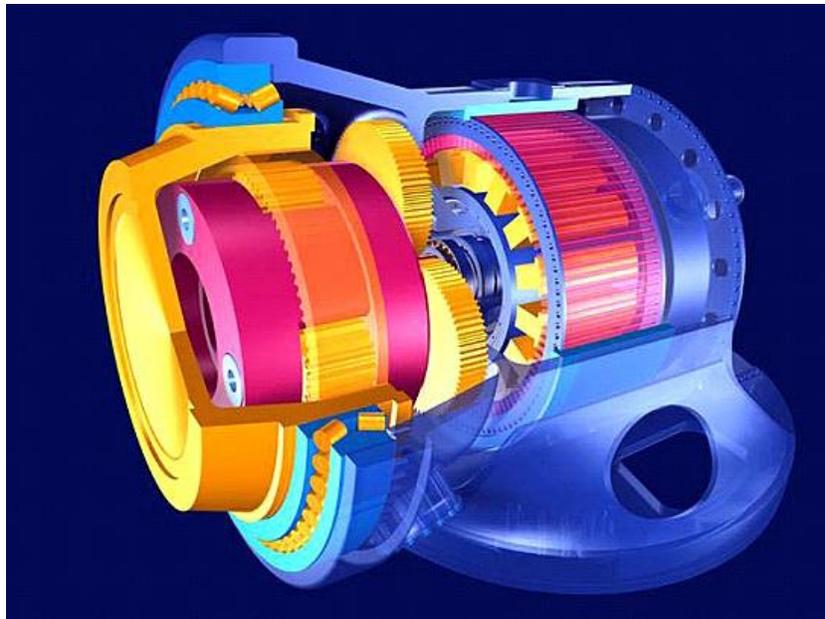

Figure 2. Rotor bearings, gearbox and generator assembly of M5000 wind turbine.
Source: Multibrid.

The purpose of this work is to 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).

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 in the assembly stage is shown in Fig. 3.
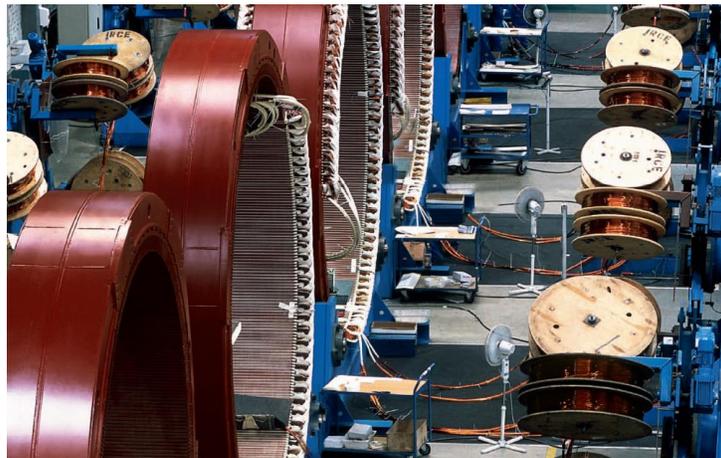

Figure 3. Multipole annular generators under assembly. Source: Enercon.
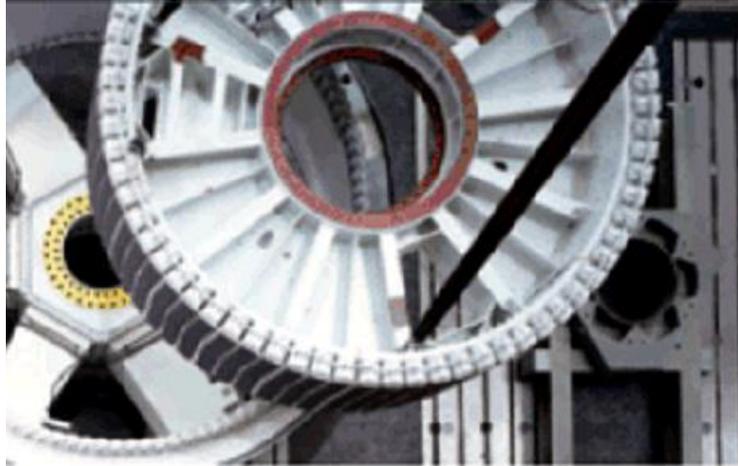
Figure 4. Stator and rotor of E-70 wind turbine. Source: Enercon.

Figure 5. Multipole annular generators coupling to the rotors hub and structural tower. The forward weight of the generator and rotors is not balanced. Source: Enercon.

Figure 6. Japan Steel Works (JSW) J82 permanent magnet synchronous generator gearless wind turbine. To balance the forward weight, the nacelle contains the transformer and the converter instead of having them placed on the ground. Source: JSW.

GENERATOR ROTATIONAL "SYNCHRONOUS SPEED"

In order to produce AC power at the required 50 Hz for Europe or 60 Hz for the USA, as the number of poles of a generator increases, the rpm required to operate the generator decreases linearly:

$$\omega_{generator} = 60f\,\frac{2}{N}\,rpm$$
$$= 120\,\frac{f}{N}\,rpm$$

(1)

where: $\omega_{generator}$ is the rotational speed in revolutions / minute, rpm

f is the frequency in Hz

N is the number of generator poles

The factor of 2 is introduced because for each full rotation of the alternator there are 2 Hz generated. Effectively there are always two physical poles per phase.

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

$$\omega_{generator} = \frac{7,200}{N} \, rpm \, ,$$

so that an 8-pole generator would need to operate only at approximately 900 rpm, and a 200-pole generator at only 36 rpm to produce a grid 60 Hz electrical current.

In the USA a portable generator with 2 poles runs with a "synchronous speed" of 7,200 / 2 = 3,600 rpm, for a design frequency of 60 Hz. A heavier-duty portable 4-pole generator would need to run at a nominal rotational speed of about 7,200 / 4 = 1,800 revolutions per minute (rpm), while a 6-pole generator would operate at a setting of around 7,200 / 8 = 900 rpm. Most portable generators are wound to have a 240 VAC single phase output, which is center tapped and delivered as two 120 VAC hots with one neutral, but virtually any voltage can be delivered.

Generators in the USA with 4 poles are usually designed to run at 7,200 / 4 = 1,800 rpm, as the engine and generator will have less wear at lower speeds, and the engine and generator will be quieter.

Generally, the "synchronous speed" of two pole alternators and motors is 3000 RPM for 50 Hz and 3600 RPM for 60 Hz devices. Four pole devices have synchronous speeds of 1500 RPM or 1800 RPM depending upon line frequency.

TRANSMISSION GEARING RATIO

The gearing ratio G for a transmission is defined as:

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

where: $\omega_{generator}$ is the generator's rotational speed, rpm

ω_{rotor} is the rotor's rotational speed, rpm

For a 4-poles generator operating at 1,500 rpm and rotor blades rotating at 20 rpm, the gearing ratio of the transmission would be:

$$GR = \frac{1,500}{20} = 75$$

On the other hand, for a 200-poles generator operating at 30 rpm and rotor blades also rotating at 30 rpm, the gearing ratio becomes:

$$GR = \frac{30}{30} = 1$$

thus requiring no gearbox component.

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 the 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 DC link and inverter. This achieves a high degree of speed variability.

STATOR AND ROTOR

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.

The advantages of continuous winding are:
1. Prevents processing faults in the production of electrical connections.
2. Maintains the high quality copper wire insulating system.
3. Eliminates the contact resistance.
4. Eliminates weak points that are susceptible to corrosion or 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 (RD) 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.

GEARBOX DESIGN OPTIONS

The weakest link of a wind turbine has been its gearbox. As turbine sizes increased, the design gearboxes able to handle the torque generated by longer and heavier blades has become a major 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.

The frequency of failures can be reduced by regular turbine realignments.

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.

Manufacturers in Germany and under license in Japan 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.

TORQUE SPLITTING, DISTRIBUTED GEARING

A California based wind turbine manufacturer in the USA, improved reliability by using distributed gearing using multiple paths and 4 generators to ensure continued turbine operation even if one of the generators fails.

It encountered a problem with its 2.5 MW turbine design, which experienced 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.

The turbines use a unique approach in their gearboxes to cope with the large torque generated by the turbine blades; that are longer than the wing of a Boeing 747 airplane, on the gear box. The drive train of the wind turbine uses torque splitting and feed it into four turbo generators operating in parallel. An advantage is that the turbine can continue operation with one generator out of service and awaiting repair.
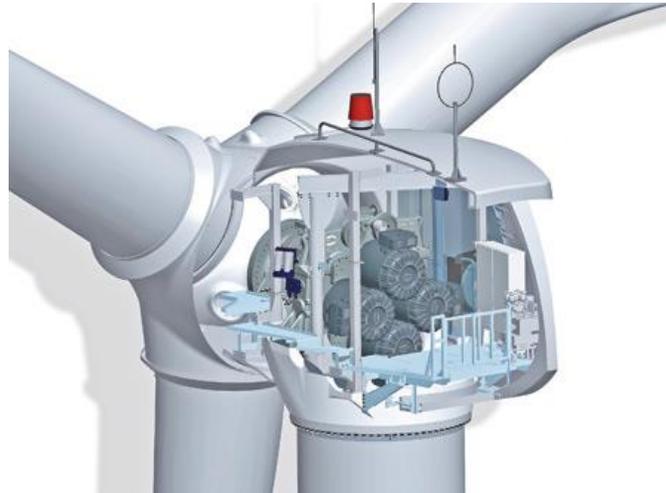

Figure 7. Torque splitting between four electrical generators operated in parallel. The turbine can continue operation with one generator out of service. Source: Clipper Wind Power Inc.

MANUAL LABOR VERSUS AUTOMATION

The general trend in the manufacturing industry is to move away from manual labor and automate as much production as possible or outsource it. Outsourcing solves the problems associated with increasing labor costs and lengthy work stoppages, both of which may at least in part be attributed to unions. The Boeing Company of Chicago, Illinois was dealt a significant blow by an eight-week machinist strike at the end of 2008, which delayed the deliveries of around 50 aircraft, further delayed the already-late 787 test program, and caused further damage to the reputation of the company.

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, money is 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 industrialized First World nations. For these reasons, it can be inferred that hand-built electrical generators for wind turbines are not viable in the far-term.

WIND TURBINE INDUSTRY STRATEGIES

In July 2008, Siemens Energy embarked upon a 2-year testing program for a 3.6 MW experimental direct drive turbine. This concept machine was installed near the coast of Ringkøbing, Denmark, with a second slightly-different generator design to be 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.

HISTORY OF DIRECT DRIVE

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 power 100 kW to 6 MW and about 12,600 systems produced by 2009. Enercon's flagship model is the E-126, which features a 12 meter diameter annular generator and a 127 meter blade diameter.

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.

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 have yet to result in any sort of commercial impact.

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.

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, and they are summarized below in Table 1.

Table 1. Current Direct-Drive Market Entrants.

Country	Company	Rated turbine Power MW
The Netherlands	DarWinD	4.7
Italy	LeitWind	1.2, 1.5
Spain	Mtorres	1.65
Germany	Vensys	1.2, 1.5, 2.5

| Norway | ScanWind | 3.5 |
| 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 recently, 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.

GEARED TURBOFAN, GTF 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, DeHaviland Comet, and the Convair B-58 Hustler, and are characterized by a long narrow-diameter 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. In order to solve these scalability and noise problems, the turbofan engine was developed.

In a turbofan engine, 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 in existence, is a whopping 9:1, while the Rolls Royce Trent 1000, slated to power the Boeing's 787 Dreamliner design, shown in Fig. 9, has a bypass ratio of 11:1.
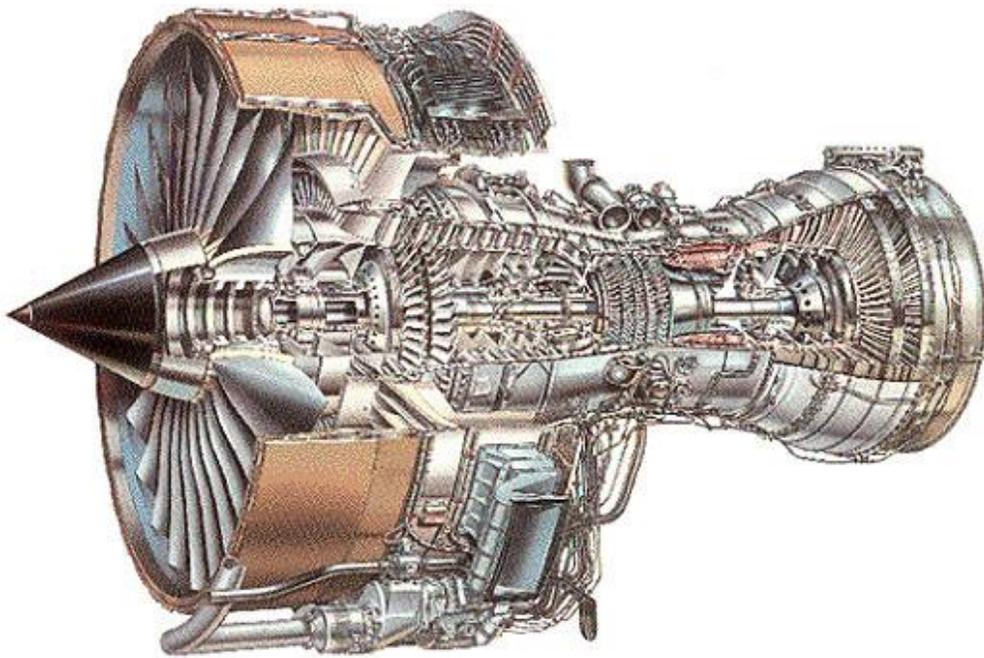
Figure 9. Rolls Royce Trent 1000 Turbofan engine. Source: Rolls Royce.

Currently, in-service turbofan engines employ a direct connection between the core and the fan, and thus the fan operates at whatever speed the core of the engine operates. Inherent inefficiencies exist in this configuration, as the large-diameter fan tends to operate most efficiently at lower rpm, while the compressors and turbines of the core operate in a more efficient manner at high rpm due in part to the increased pressure and temperature of

the core, and the fact that smaller-diameter fans can operate at higher rpm before the tip speeds 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 core and the fan of a jet engine allows independent adjustment of the fan and core rpm, and is projected to offer an efficiency increase of approximately 9 percent.

GEARED TURBOFAN, GTF DEVELOPMENT

The geared turbofan 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.

Pratt and Whitney reports that their GTF gearbox in Fig. 10, operates at an efficiency of over 99 percent and a heat load below 50 percent of what was originally expected.

The PW8000 gearbox currently being tested in 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 747 and A-340 testbed aircraft. Additionally, a 40,000 shp gearbox is currently 100 hours into its full scale tests.

Figure 10. PW8000 gearbox.

MAGNETIC BEARINGS

Pratt and Whitney goes on to claim 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 (Figs. 11, 12).

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.
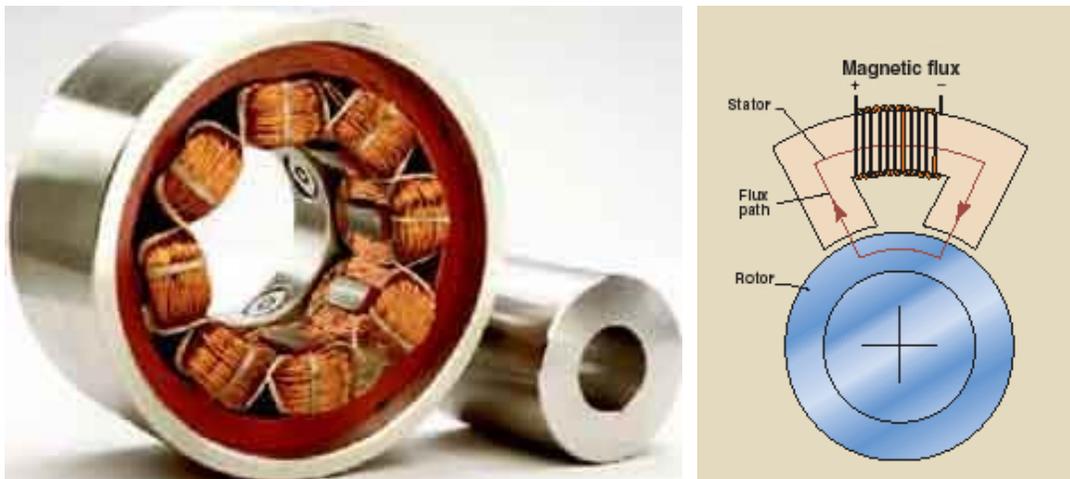
Figure 11. Magnetic bearing stator and rotor. The electrically excited magnets can be replaced by permanent Neodymium magnets.
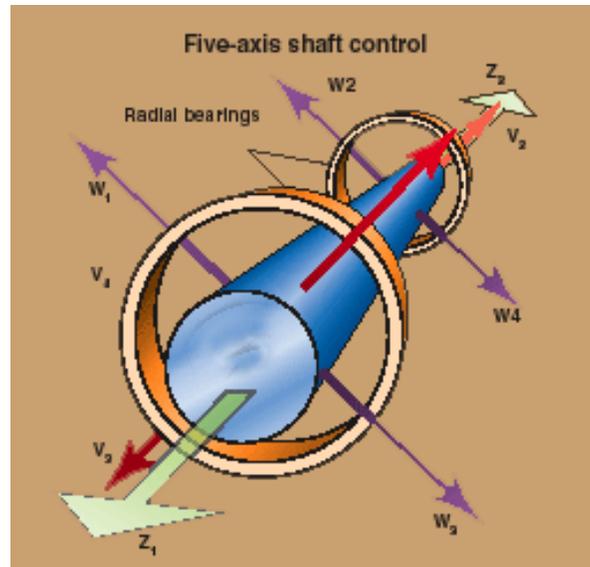
Figure 12. Five axes control of magnetic bearing: Two axes for each axial bearing and one running along the shaft axis. Source: machinedesign.com.

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 de-levitates.

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 7 below 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 of 3.
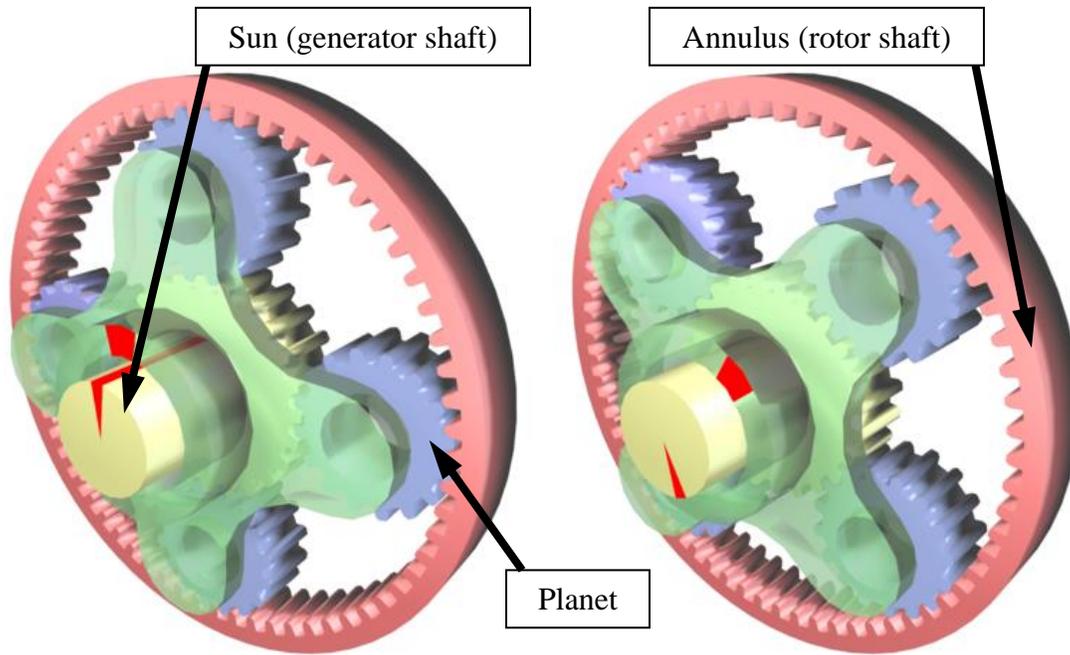
Figure 13. Planetary spur or epicyclic gearing system.

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. It is the latter of the three that has created the majority of problems for wind turbines.

Minor misalignments due to 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.

Figure 14 shows the planetary gearing system of Pratt and Whitney's PT6 gas turbine engine, which has been used on the Bell UH-1 Huey helicopter and the DeHaviland DHC-6 Twin Otter passenger aircraft.

Figure 14. Pratt and Whitney PT6 turbine engine reduction gears (UH-1 Huey, DHC-6).

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 valid assumption 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} is the number of teeth in the sun gear

       $N_{annulus}$ is the number of teeth in the annulus gear

       N_{planet} is the number of teeth in the planet gear

Assuming that Eqn. 3 is satisfied, the equation of motion for the three gears becomes:

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

where: ω_{sun} is the angular velocity of the sun gear

       $\omega_{annulus}$ is the angular velocity of the the annulus gear

       ω_{planet} is the angular velocity of the the planet gear

where ω represents the angular velocity of the respective gears. Since angular velocity is directly proportional to RPMs, Equation 2 may be simplified to yield Equation 3 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 plugged into Equation 3 in order to determine the relative RPMs of the sun and annulus gears, noting the following two equalities of Equations 4 and 5:

$$RPM_{sun} = \left(\frac{-N_{sun}}{N_{planet}}\right) RPM_{planet} \tag{4}$$

$$RPM_{planet} = \left(\frac{-N_{planet}}{N_{annulus}}\right) RPM_{annulus} \tag{5}$$

CONTINUOUSLY VARIABLE TRANSMISSION, CVT

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 below summarizes some of the cars on the road today that utilize CVTs.

Table 2. CVT-Geared Passenger Cars.

Make	Model	Year
Honda	Civic, high torque	1995
Audi	A4	2000
Nissan	Murano	2003
Ford	Five Hundred	2005
Ford	Freestyle	2005
Dodge	Caliber	2007
Jeep	Patriot	2007
Mitsubishi	Lancer	2008

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 specified gear ratios of a standard gearbox.

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, Velocity (PIV) 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 already begun work on a wind application for chain-driven CVTs, as they have mentioned their interest in such a project.

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 120°F to -80°F, 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 magnetic 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. 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.

EXERCISES

1. In order to produce AC power at the required 50 Hz for Europe or 60 Hz for the USA, as the number of poles of a generator increases, the rpm required to operate the generator decreases linearly:

$$\omega_{generator} = 120 \frac{f}{N} rpm$$

i) Calculate the rotational speed of an USA 8-pole generator.

ii) Calculate the rotational speed of an USA 200 pole generator.

iii) Calculate the rotational speed of an EU 8-pole generator.

iv) Calculate the rotational speed of an US 200 pole generator.

2. For a 4-poles generator operating at 1,500 rpm and rotor blades rotating at 20 rpm, calculate the gearing ratio of a wind turbine transmission.

On the other hand, for a 200-poles wind turbine generator operating at 30 rpm and rotor blades also rotating at 30 rpm, calculate the gearing ratio.

Discuss the implication of these results.

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