APPLICATION OF PERICYCLIC CONTINUOUSLY VARIABLE TRANSMISSION TO WIND TURBINES

Theme 3: Renewable Electricity

3.07 Wind Energy

Dr. Sameer Hameer

Department of Mechanical and Industrial Engineering, University of Dar-es-Salaam, Dar-es-Salaam (Tanzania)

1. Introduction

Variable speed wind turbines have been used since 1970. And over the 30 year span, several variable wind speed technologies have come along and matured with the technological progress in the electronics industry. Wind turbines can be classified to their speed control (fixed/Variable RPM) and power control abilities such as stall control, pitch control, and active stall control (Jensen, 2007). Variable speed transmission is important because it allows the optimization of each section of the rotor to operate at its best lift to drag ratio. Varying the speed of the rotor along with pitch and yaw control form the basis of the control system of a wind turbine. The wind speed is not constant; therefore, a variable speed unit must be incorporate such that the rotor speed is a linear function of the wind speed. The use of variable speed wind turbines provides 20% more power than a fixed wind speed turbine. Current variable speed wind turbines vary the speed electrically, as opposed to mechanically. The most common electrical variable speed wind turbine is the doubly fed induction generator. The major obstacle with electrical variable speed transmissions lies in the power electronic conversion from AC to AC, which involves the conversion from AC-DC and then DC-AC. This whole process results in an energy loss of 10%. The major concern with electrical variable transmission is the low reliability of the slip ring system. The use of a mechanically continuously variable transmission reduces torque spikes and increases component reliability. The Department of Energy, USA, concludes that the use of mechanical continuously variable transmissions to wind turbines provides an economic benefit of reducing the cost of energy by 11.2%. Based on the wind speed, the variable speed unit must control the rotor RPM and torque. Research done on traction and non-traction based continuously variable transmissions have resulted in the selection of the non-traction, positive engagement, pericyclic continuously variable transmission (P-CVT) as the optimum transmission of the wind turbine, as traction based transmissions are highly inefficient. The P-CVT is a 2 degree of freedom system that features a

reaction control rotor, pericyclic motion converter, and an output rotor illustrated in Figure 1.

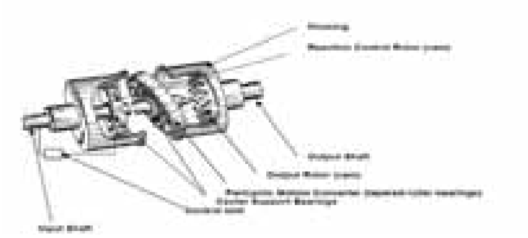


Fig. 1: Pericyclic Continuously Variable Transmission (Lemanski et al (2006)).

The P-CVT is an electromechanical CVT consisting of a reaction control rotor, pericyclic motion converter, and an output control rotor. The mating of the reaction control rotor with pericyclic motion converter at the reaction control rotor side results in the mating of the output control rotor with the pericyclic motion converter at the output side[5]. This arrangement varies the speed of the output rotor. An illustration of a P-CVT split torque design is shown in Figure 2.

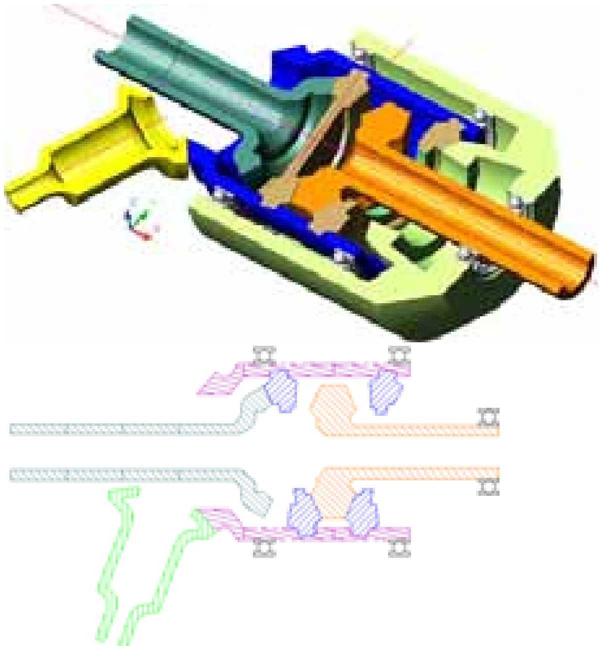


Fig.2: Split Torque P-CVT (Lemanski et al (2006)).

The P-CVT falls under the class of a nutating mechanical transmission. The P-CVT undergoes nutation, rotation and precession to achieve variable speed operability at a design coneing angle that is selected based on gear design mating principles and it is typically in the range of 2 to 5 degrees[Ref Lemanski et al (2006). The P-CVT mechanism is illustrated in Figure 3.

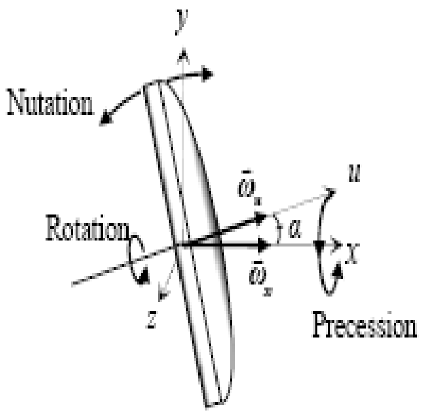


Fig.3: P-CVT Electromechanical Transmission (Lemanski et al (2006)).

.

The advantages of the P-CVT according to Alfonse J. Lemanski[5] are:

- High Contact ratios (> 5:1) which results in a quarter of the teeth of the PMC mating with the reaction control rotor and a quarter of the teeth of the PMC mating with the output rotor. This allows for high torque transfer and efficiency resulting in high power density, low gear vibration excitation and noise
- P-CVT analysis done on a K-MAX helicopter has resulted in a 17% weight reduction and a 40% reduction in envelope size
- Large single stage reduction (> 50:1)
- Static laboratory tests and flight test of the A-160 Hummingbird UAV has proven the "optimal speed rotor" concept
- NASA-Army-Industry-University design study has demonstrated importance of variable speed technology for Heavy lift Missions. Studies looked into Nutating Mechanical Transmissions (NMT)
- Application to mechanically variable speed wind turbines
- Research conducted on traction and nontraction based continuously variable transmissions have resulted in the selection of the nontraction pericyclic continuously variable transmission (P-CVT) as the best approach for a wind turbine, as traction based transmissions are highly inefficient .

Wind turbines are getting larger – scales proportionally with power. Variable Speed Wind turbines have been used since the 70's. In the 30 years span, several variable wind speed technologies have come along and matured with the technological progress in the electronics industry. The wind speed is not constant – it's fluctuating (varying with time). In order to have constant power output from the electrical generator, a variable speed unit must be incorporated in a wind turbine. The rotor speed is a linear function of the wind speed.

The need for a mechanical variable speed transmission is justified by the statements below.

- The use of variable speed wind turbines provides 20% more wind power than fixed wind speed turbines
- The major obstacle with electrical variable speed transmissions is that the variable electricity must be rectified and then converted to AC electricity using an inverter, so that it can be fed into the power grid. This process causes an increase in overall cost and results in an energy reduction by 10% due to the heat dissipation from the power electronics
- The use of continuously variable transmission reduces torque spikes and therefore, increases component reliability
- Recent research has shown that a continuously variable transmission would improve wind capture and reduce fatigue torque loading
- The use of continuously variable transmissions to wind turbines provides an economic benefit in terms of reducing the cost of energy by 11.2%

The technical challenges of wind turbines is justified by the statements below (Melicio and et al). Wind turbines have three types of controls namely yawing, pitching, and RPM control. The wind turbine control problem has at least three important requirements:

- setting upper bounds on and limiting the torque and power experienced by the drive train, principally the low-speed shaft;
- minimizing the fatigue life extraction from the rotor drive train and other structural components due to changes in wind direction, speed (including gusts), and turbulence, as well as start-stop cycles of the wind turbine; and
- Maximizing the energy production.
- The control problem is the judicious balancing of these requirements.

- The back pressure from the tower causes torque pulsations equal to the rotor rpm multiplied by the number of blades

The Variable Speed Wind Turbine Schematic is illustrated below in Figure 4.

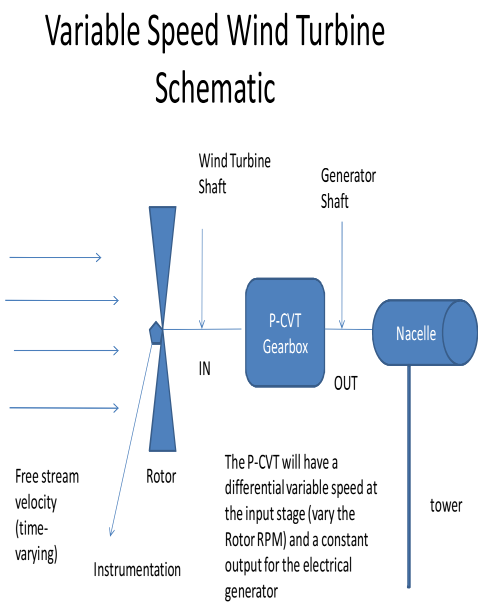


Fig.4: Variable Speed Wind Turbine Schematic.

The wind technology flow chart is shown in Figure 5.

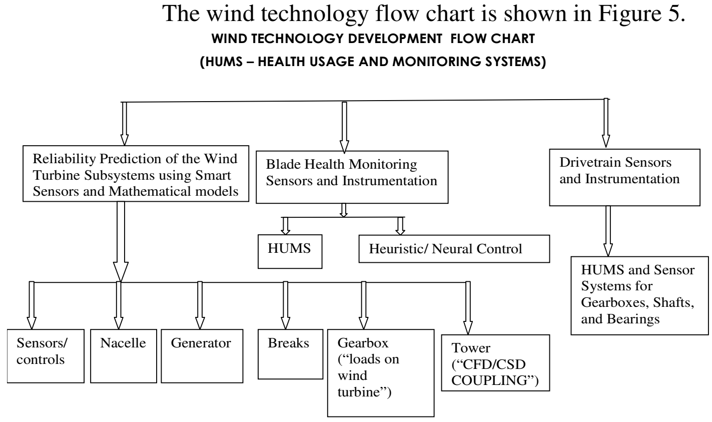


Fig.5: Wind Technology Flow Chart.

The researchers at Sandia Research Laboratories have stressed the importance of sensors and structural health monitoring for wind turbines in terms of developing cost effective and reliable diagnostic and prognostic smart sensor systems. Researchers at Aither Engineering, Inc have focused on sensor blade shape using embedded fiber optic based strain sensors. Researchers at Purdue University have focused on sensor blade loads, shape, and structural health monitoring using accelerometry. Researchers at Micron Optics, Inc have focused on sensor blade operational loads and temperature distribution using surface mounted fiber optic sensors. Researchers at TPI composites, Inc have focused on sensor blade manufacture in an open shop floor environment. Researchers at Sandia National Laboratories have focused on sensor blade tip deflections using processed video images. Researchers at USDA-ARS have focused on sensor blade field test on an operational wind turbine. Researchers at NREL/NWTC have focused on sensor blade static and fatigue tests in the laboratory. Gearbox failures is a major cause of concern in wind turbines . Therefore, the National Renewable Energy Laboratory (NREL) lists planetary gear bearings, low speed, and high speed shaft bearings. A three point plant developed by NREL is shown in Figure 6.

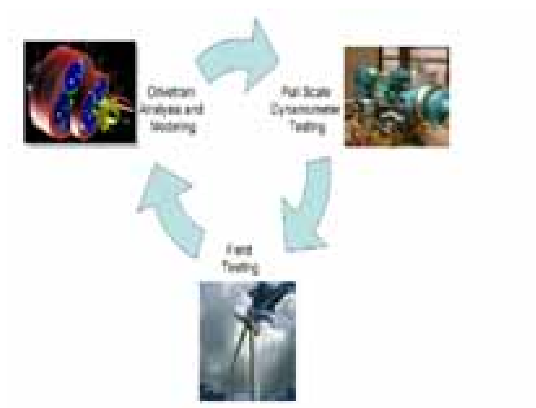


Fig. 6: A Three Point Plant (NREL).

Currently mechanically variable wind turbines use the Nuvinci transmission which varies the speed by using a set of rotating and tilting balls placed between the input and output components, as shown in Figure 7.

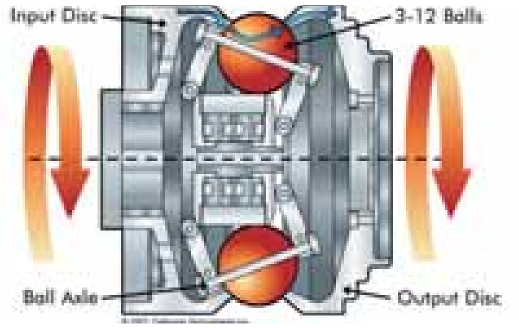


Fig.7: Nuvinci Transmission (Fallbrook Technologies, Inc).

2. Transmission Design

Inputs (just the relevant parameters)

a. Engine RPM
b. Rotor RPM
c. Tip speed
d. Rotor radius
e. Maximum rotor power
f. Shaft length/thickness
g. Bearing loads/dimensions
h. Housing loads/dimensions
i. Material properties
j. Critical speeds

- Outputs
  - Efficiency
  - Noise
  - Weight
  - Size

Gearing:

- Inputs
  - Maximum rotor power
  - Engine RPM
  - Rotor RPM
  - Outputs
  - Gear dimensions
  - Speeds for gears
  - Weight
- Outputs
  - Gear dimensions
  - Speeds for gears
  - Weight

Shafting:

- Inputs
  - Power and RPM of shaft
  - Length of shaft
  - Inner and outer diameters of the shaft
  - Area Moment of Inertia
  - Output
  - Weight of shaft(sum of the tube weight, couplings, and bearings)
  - Critical speeds
  - Number of shaft segments if sub synchronous operation : wshaft < wcritical
  - Critical length
- Output
  - Weight of shaft(sum of the tube weight, couplings, and bearings)
  - Critical speeds
  - Number of shaft segments if sub synchronous operation : wshaft < wcritical
  - Critical length

Stress Analysis

- Based on AGMA formulae for contact and bending stresses
- Inputs
  - Facewidth and gear sizing factor/s
  - RPM'S and dimensions
  - Power
  - Outputs
  - Thickness of the hollow shaft
  - Stresses
- Outputs
  - Thickness of the hollow shaft
  - Stresses

A Matlab program for calculating gear dimensions and facewidth is shown in Figure 8.

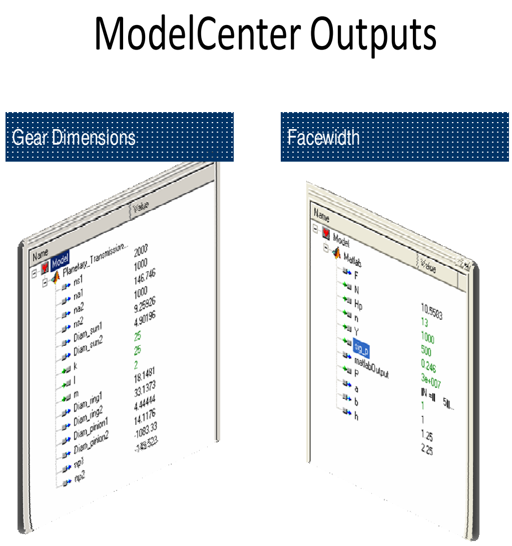


Fig.8: ModelCenter Outputs.

3. P-CVT ANALYSIS

The analysis is obtained from Ref. (Dr. Zihni Saribay,2010). And is illustrated in Figures 9 through 14 (Dr. Zihni Saribay,2010).

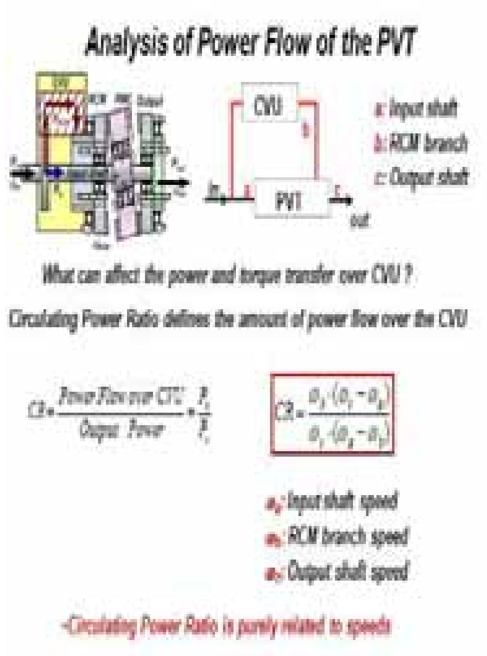


Fig.9: Analysis of Power Flow of the PVT.

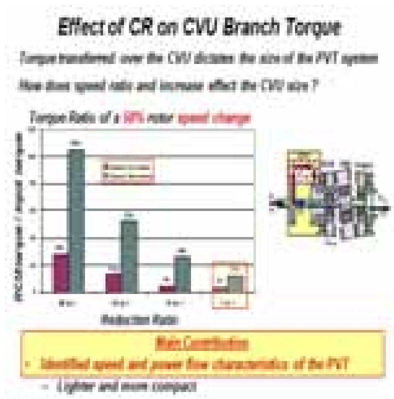
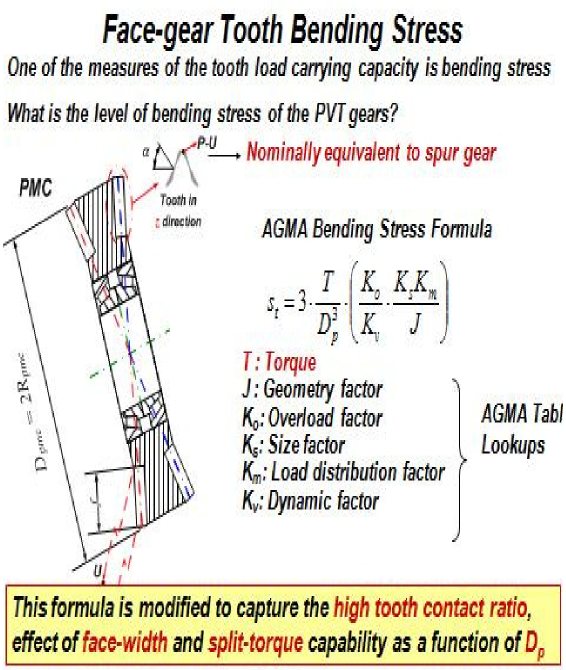


Fig.10: Effect of CR on CVU Branch Torque.

Fig.11: Meshing Face-Gear Pairs(above) and Face-gear Tooth Bending Stress(Below).



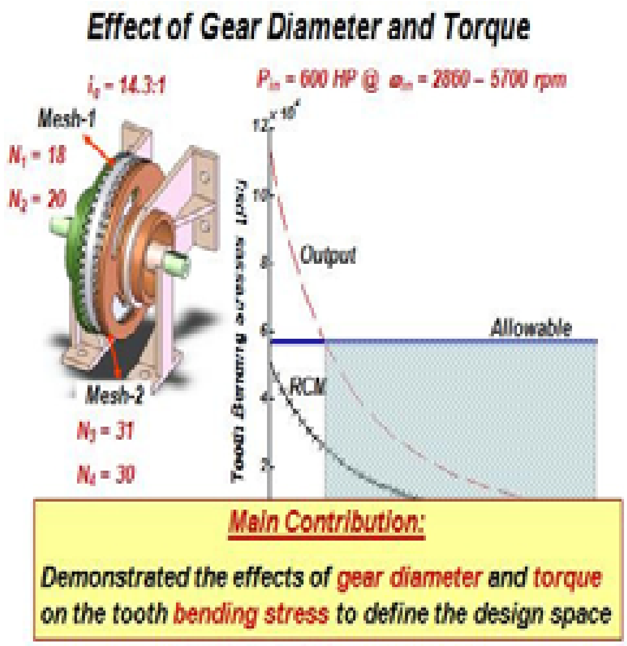


Fig.12: Effect of Gear Diameter and Torque.

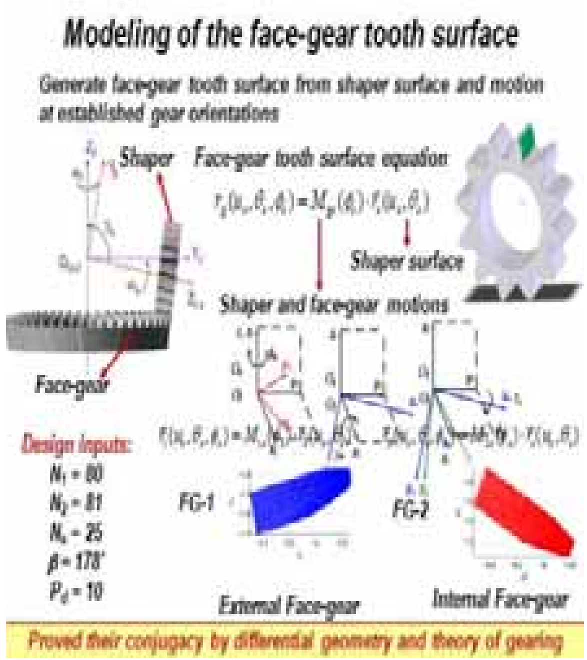


Fig.13: Modeling of the Face-gear Tooth Surface.

Fig.14: PVT Design Process.

- Evaluates all geometric parameters and constraints to estimate the design space
- Variables:
  - No of tooth
  - Gear diameter and height
  - Nutation angle
  - Gear tooth geometry
  - Bearing geometry
- Constraints
  - Tooth load capacity
  - Bearing load capacity
  - Efficiency
- Result
  - PVT Design Space

5. Conclusion

Based on the wind speed, the variable speed unit must control the rotor RPM and Torque Current Variable speed wind turbines use doubly fed induction generators (DFIG) having a speed controller, voltage controller, and a pitch .The DFIG are highly unreliable with respect to the slip ring assembly, complexity in the control system, and having a limited speed variation capability of about 33% above the synchronous speed (Melicio and et al).Research done on traction and non- traction based continuously variable transmissions have resulted in selection of the non-traction pericyclic continuously variable transmission (P-CVT) as the optimum transmission for the wind turbine, as traction based transmissions are highly inefficient. The use of self aligning bearingless planetary gears will reduce gearbox failures. Recent research has shown that a continuously variable transmission would improve wind capture and reduce fatigue torque loading. The use of continuously variable transmissions to wind turbines provides an economic benefit in terms of reducing the cost of energy by 11.2%. Variable speed turbines have an advantage of reducing gear and rotor blade loads. RPM variations of about 10-20% cause a reduction in mechanical stresses dramatically in tandem with an increase in the overall efficiency of the turbine (Jensen, 2007). Wind turbine design concepts have changed from fixed speed, stall-controlled, drive trains to variable speed, pitch controlled gearboxes or direct drive technologies(Jensen, 2007).

6. References

Lemanski, A.J., Elmoznino, J.M, 2006. Design of P-CVT: Rotorcraft Applications. AHS 62nd annual forum.

Melicio, Doubly Fed Induction Generator Systems for Variable Speed Wind Turbine. ISEL/DEEA.

Saribay, 2010. Analytical Investigation of the Pericyclic Variable-Speed Transmission System for Helicopters.

Jensen, Meyer, 2007. Wind Energy Pocket Reference. ISES.