



# Design of closed loop control for region 2 of a wind turbine operated with CVT

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## Outline of the presentation



- Motivation for wind turbine speed control.
- Introduction to power electronics for grid integration of different wind turbine topologies.
- The continuously variable transmission (CVT) as a feasible solution.
- System Modeling. (Rotor – Drivetrain - Generator).
- CVT control (Open Loop – Development of closed loop control)
- Performance analysis of full modeled system (Simulations run with 10 minutes of wind data sampled at 50 Hz)



## Motivation

- An economic feasibility study of CVT wind turbines predicts that using a CVT would help reduce the cost of energy by up to 11.2 % as compared with a DFIG variable speed machine with PE [Cotrell, J. NREL].



## Objectives

- Study findings can be used to develop a plan to reduce the cost of wind energy, improve energy capture and mitigate inverter reliability concerns.

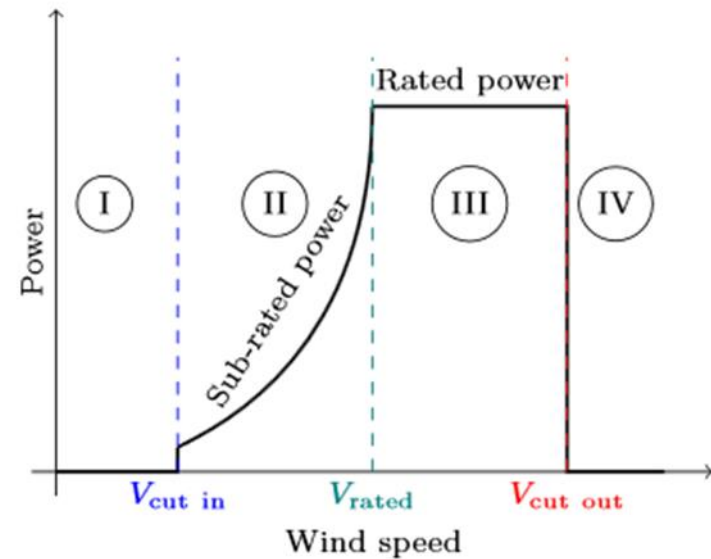
## Fundamental question

- Can we design a closed loop control system based on our understanding of the dynamics of the CVT, that maximizes the electric power generated by the wind turbine?

# Regions of operation of variable speed wind turbines



- In region 1, the wind speed is too low for the turbine to generate power.
- Region 2 for each wind speed we need  $w$  such that  $c_p$  is MAX
- In region 3, the power output is limited by the turbine; this occurs when the wind is sufficient for the turbine to reach its rated output power.
- Region 4 is the period of stronger winds where the power in the wind is so great that it could be detrimental to the turbine, so the turbine shuts down.





# Control of Regions 2 and 3

We are particularly interested in studying the Region 2 control whose objective is to maximize wind energy capture ( $C_p$ )

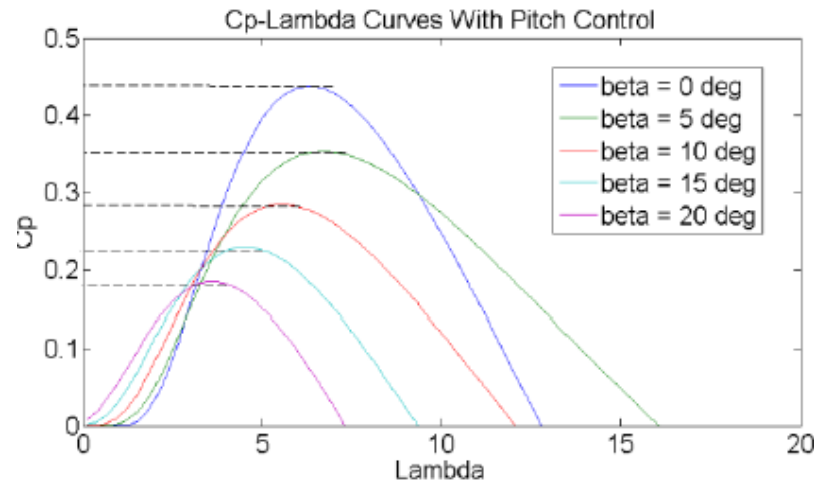
$$C_p = \frac{P}{P_{wind}}$$

where

$$P_{wind} = \frac{1}{2} \rho A v^3 \quad P = \tau_{aero} \omega$$

The power coefficient  $C_p(\lambda, \beta)$  is a function of the tip-speed ratio (TSR)  $\lambda$  and the blade pitch  $\beta$ . The turbine operates at  $C_p$  Max at a certain pitch angle and TSR.

$$\lambda = \frac{\omega_{LSS} \cdot R}{v}$$



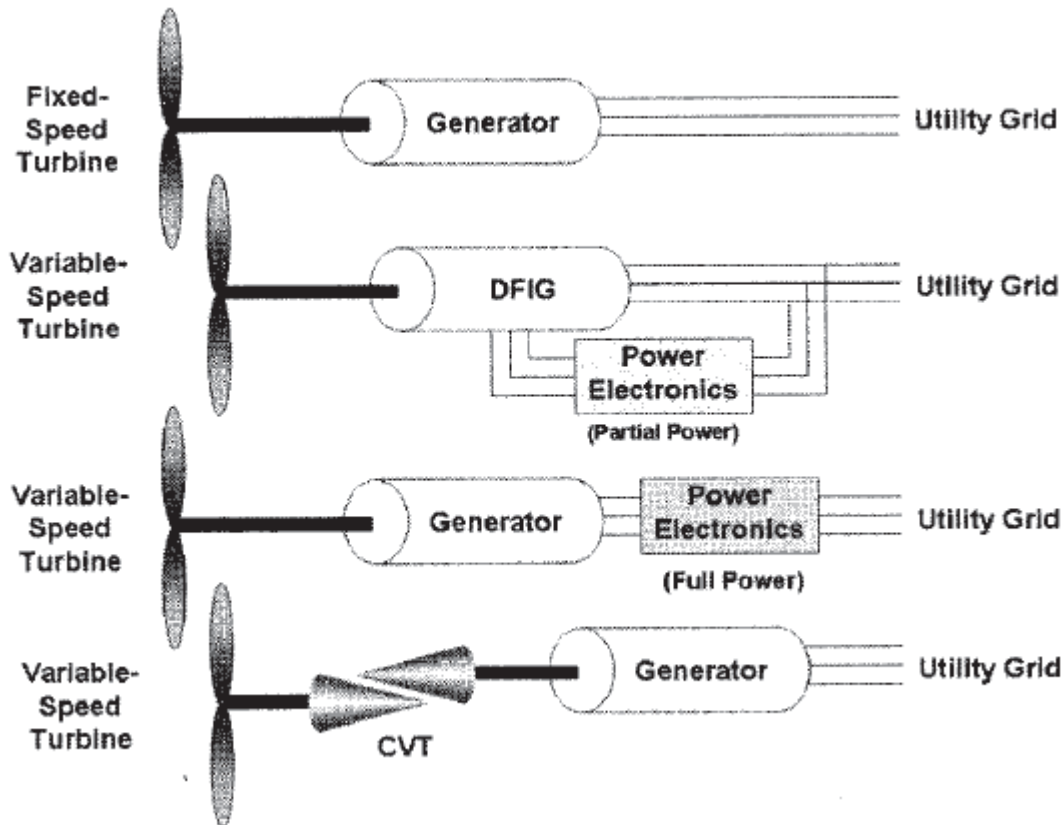
**The pitch angle can be easily maintained at the optimal efficiency point, thus Region 2 control is primarily concerned with varying the turbine speed to track the wind speed.**

Region 3 control is typically performed via a separate pitch control loop.



# Variable Speed operation

- Variable speed turbines can capture more power than fixed speed turbines operating in the same wind conditions because they can track its maximum aerodynamic efficiency point.



Power electronics in the feedback loop of a doubly fed induction generator, in which the slip is controlled.

Power electronics to rectify the variable speed (variable frequency) AC produced by the generator. And the invert it to match the grid frequency.

CVT is an attractive alternative to power electronic technologies



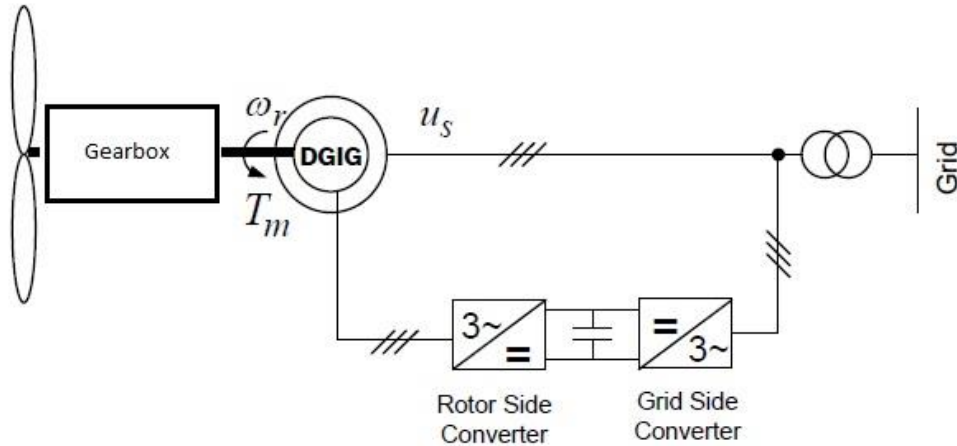
# Wind turbine topologies in the market

Previous studies claim that using a CVT would reduce the cost of energy by up to 11.2 % as compared to a DFIG variable speed machine.

<i>Turbine Concept</i>	<b>World-Market Share</b>
<i>Fixed speed</i> (Stall or active stall, gearbox), System I, II, III	28%
<i>Dynamic slip control</i> (Limited variable speed, pitch, gearbox), System IV	5%
<i>Doubly-fed generator</i> (Variable speed operation, pitch control, gearbox), System V	47%
<i>Direct-driven</i> (variable speed operation, pitch control), System VIII	20%
TOTAL	<b>100%</b>



# Gearbox vs CVT



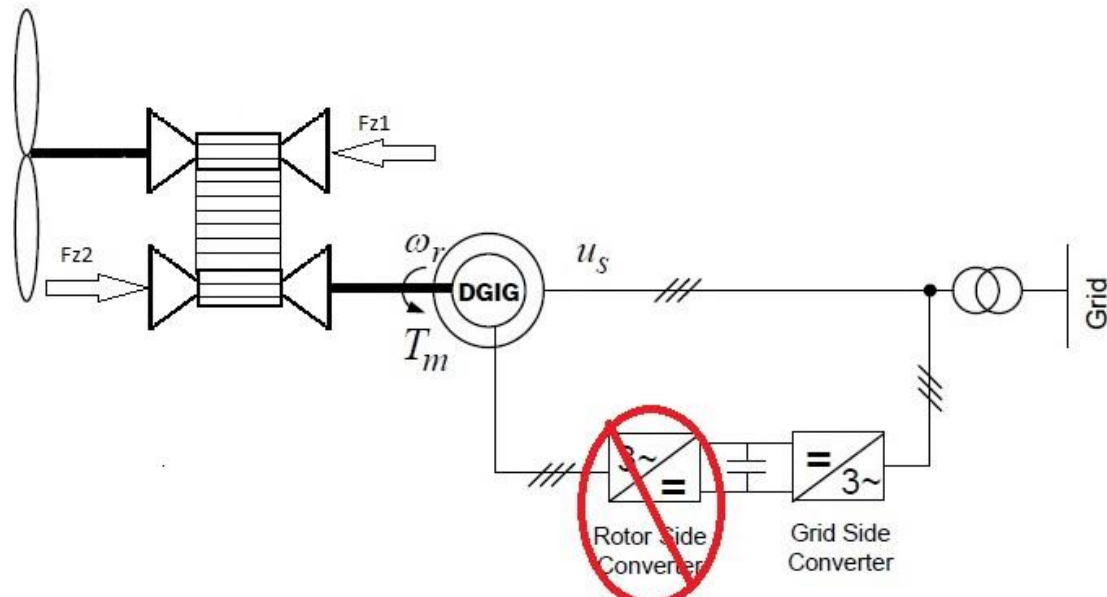
$$I_r \cdot \dot{\omega}_{rotor} = \tau_{wind} - \tau_{em}$$

Where  $\tau_{em}$  is a function exclusively of generator currents ( $I_r$  and  $I_s$ )

$$I_r \cdot \dot{\omega}_{rotor} = \tau_{wind} - \tau_{cvt,p}$$

$$I_g \cdot \dot{\omega}_{gen} = \tau_{cvt,s} - \tau_{em}$$

Control of CVT can be done thru Fz1 and Fz2

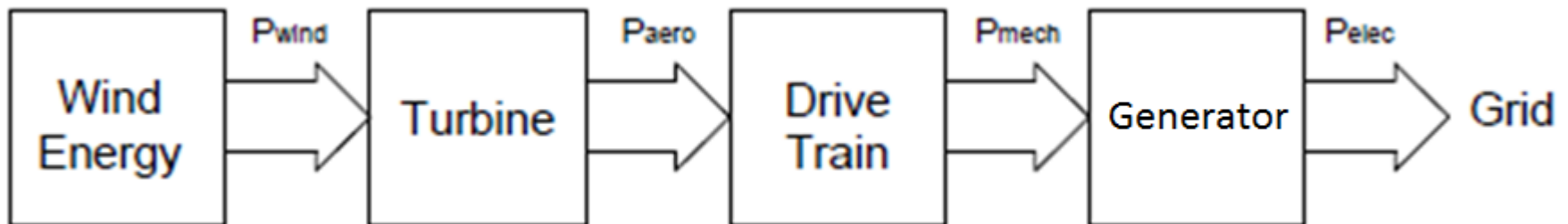




# Advantages of CVT

Allows the generator to operate at “fixed speed” while being driven by a variable speed rotor. This brings

- A CVT can improve energy capture (wider speed range)
- A CVT can downsize pitch control
- A CVT can downsize switching electronics needed to ensure a constant grid frequency of 60 Hz.





# Active and reactive Power control

## Active Power Control

$$P_g^d = P_s + P_r \quad \text{and we want } P_s \text{ to be } P_s^{rated}$$

In region 2

$$P_{turbine} = \frac{1}{2} \rho \cdot C_p \cdot A \cdot V^3$$

Speed control ensures  $\omega_{low}$  tracks it's optimal value such that  $C_p$  is Max.

Case 1:

$$P_s = P_s^{rated}$$

$$P_r = P_g^d - P_s^{rated} \quad \text{and} \quad P_r < P_r^{rated}$$

Design control for  $\omega_{Hes}$  and  $i_{dr}$   
also to inject power to grid DFIG must be running in Supersynchronous mode

Case 2:

$$P_s = P_s^{rated}$$

$$P_r = P_g^d - P_s^{rated} \quad \text{BUT} \quad P_r > P_r^{rated}$$

The grid demand can not be met

Case 3:

$$P_s = P_s^{rated}$$

$$P_r = P_g^d - P_s^{rated} < 0$$

Control DFIG to run in Sub-Synchronous mode

## Reactive Power control:

$$Q_g^d = Q_s + Q_r^{\text{ref}}$$

Check that the grid demands do not exceed the rotor and stator rated power

Case 1:  $Q_g^d < Q_s^{rated}$

$$Q_r^d = 0 \quad \text{and} \quad Q_g^d = Q_s$$

From  $Q_s$  we get the required  $i_{dr}$  and we design RSC/GSC to track it

Case 2:  $Q_g^d > Q_s^{rated}$

$$Q_g^d = Q_s^{rated} + Q_r^{\text{ref}}$$

$$Q_r = Q_g^d - Q_s^{rated} \quad \text{as long as} \quad Q_g^d - Q_s^{rated} < Q_r^{rated}$$

Again, these could be achieved by controlling  $i_{dr}$  and  $i_{qr}$

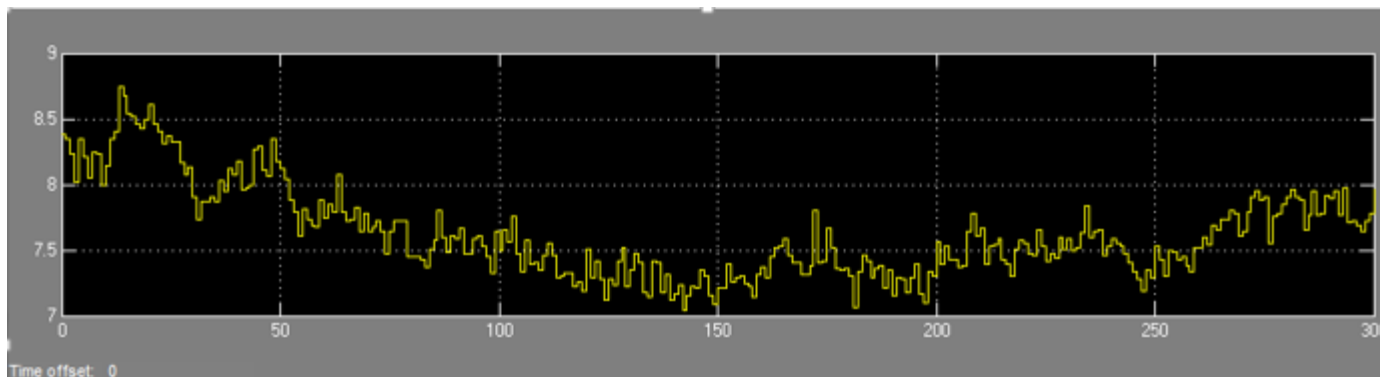
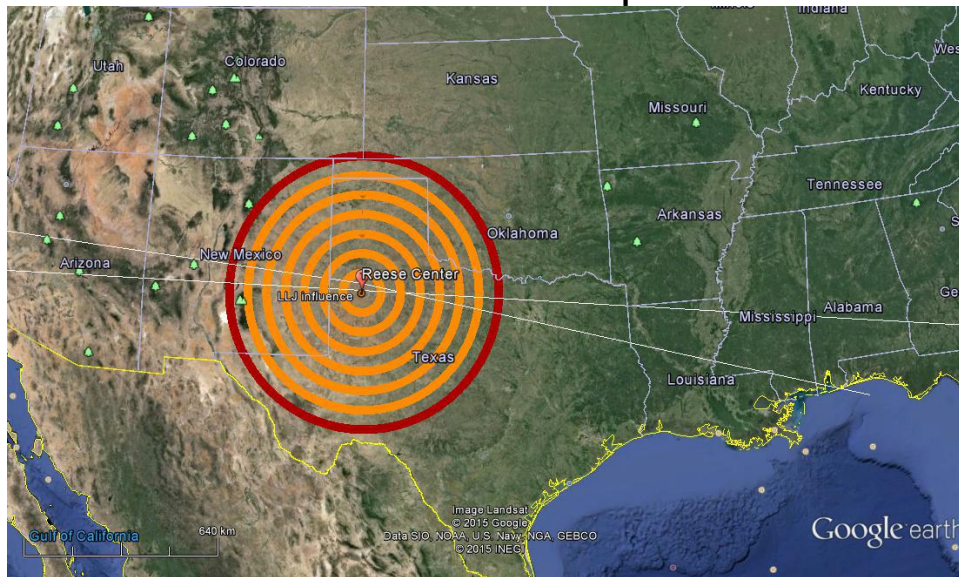
Case 3:  $Q_g^d > Q_s^{rated} + Q_r^{rated}$

Reactive power demand can't be met



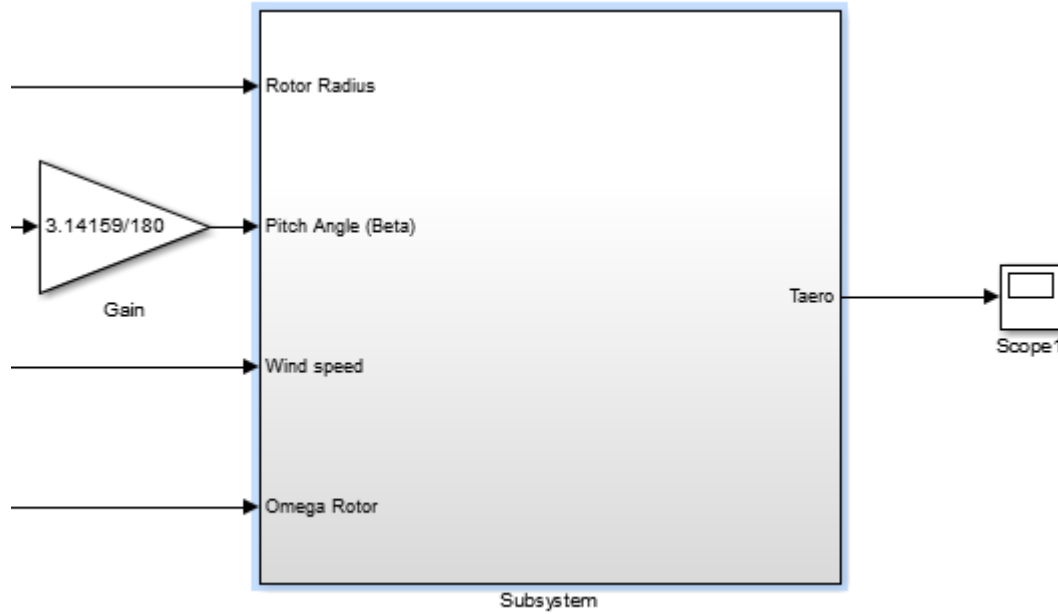
# Real wind speed data

For our simulations instead of using a wind model typically involves specifying the x-component hub-height wind speed we are using a sample of data recorded by met towers at the Reese center just outside of Lubbock, Tx. The recorded data was sampled at 50 Hz for 10 minutes.





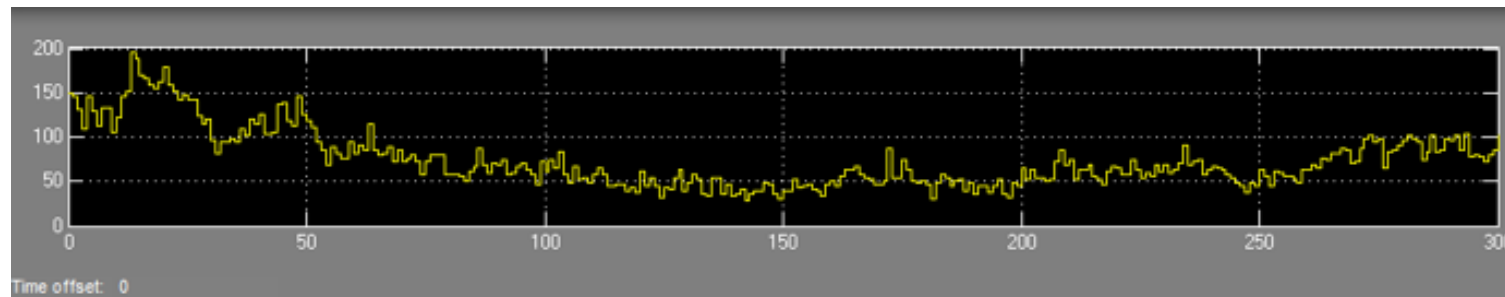
# Rotor Model



The  $C_p(\lambda, \theta)$  curve is approximated as follows as proposed on 'Power System Modelling and Scripting' By Federico Milano

$$C_p = 0.22 \left( \frac{116}{\lambda} - 0.4\beta - 5 \right) e^{-12.5/\lambda}$$

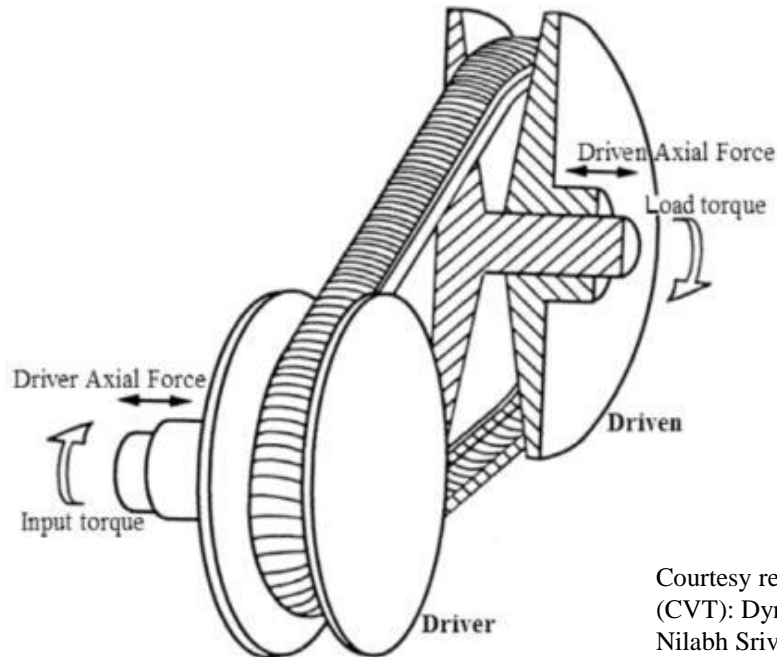
$$\tau_a = \frac{1}{2} \rho \pi R^3 \frac{C_p}{\lambda} U^2$$





# CVT Dynamic Modelling

- We developed a model that describes both the steady state and the shifting behaviors of the V belt CVT.
- This model is non linear, to explain how the rate of change of the speed ratio is related to the actual value of the axial clamping forces.
- The Model uses the dynamics published by Carbone-Mangialardi to explain the shifting dynamics During creep mode shifting, and the model by Shafai in Slip Mode shift.



Courtesy review on belt and chain continuously variable transmissions (CVT): Dynamics and control  
Nilabh Srivastava



Dynamic description of CVT behavior:

$$C_1 \cdot \omega_1 + (I_{tr} + I_p) \cdot \frac{d}{dt} \omega_1 = \tau_{aero} + \tau_{f1}$$

Similarly:

$$C_2 \cdot \omega_2 + (I_g + I_s) \cdot \frac{d}{dt} \omega_2 = \tau_{f2} - \tau_{em}$$

$\tau_{f1}$  and  $\tau_{f2}$  are primary and secondary friction torques. The value they take during operation is not trivial and depends of other factors (Belt-pulley contact normal force, belt running radius, direction of the relative velocity between the belt and pulley).

For example we use variables named  $v_1$  and  $v_2$  as slip indicators.

$$\frac{d}{dt} v_1 = \frac{-\left( r_1 \cdot v_1 \cdot \frac{d}{dt} \omega_1 + \omega_1 \cdot v_1 \cdot \frac{d}{dt} r_1 \right)}{r_1 \cdot \omega_1}$$

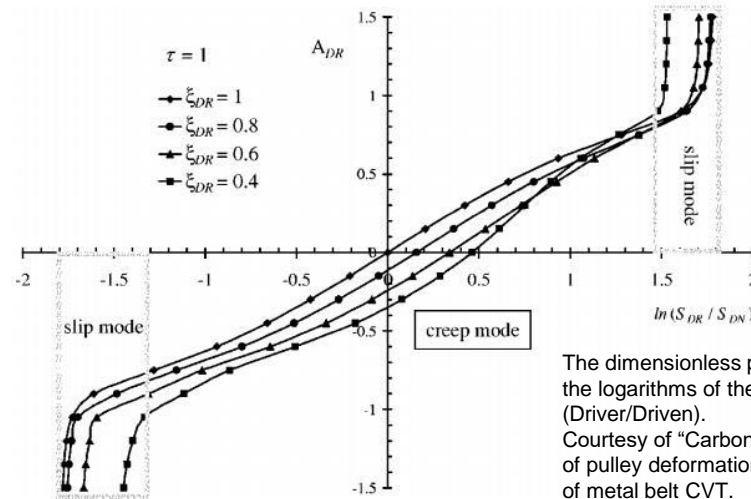
$$\frac{d}{dt} v_2 = \frac{-\left( r_2 \cdot v_2 \cdot \frac{d}{dt} \omega_2 + \omega_2 \cdot v_2 \cdot \frac{d}{dt} r_2 \right)}{r_2 \cdot \omega_2}$$

This EQ's are important because they explain how the belt is related to the shifting gradients.



# Shifting models

The CVT model recognizes two shifting regimes: 1) slow shifting due to pulley bending, and 2) fast shifting due to belt macroscopic slip.



The dimensionless parameter ADR as function of the logarithms of the clamping forces (Driver/Driven).  
Courtesy of "Carbone, et al. 2005, "The influence of pulley deformations on the shifting mechanism of metal belt CVT."

We consider the system-level approach of Carbone to represent shifting under creep or micro slip conditions.

$$\dot{r}_{g\_CMM} = K_{CMM} \omega_p \left( \ln \left( \frac{F_p}{F_s} \right) - \ln(\Psi) \right)$$

Accordingly, the Shafai model is used to predict shifting dynamics under slip conditions

$$\dot{r}_{g\_Shafai} = \frac{(r_g^2 \alpha_p + r_g \alpha_s)(F_p - AF_s r_g^m)}{2\beta_s \tan(\beta) r_p \alpha_s}$$



CMM Regime:

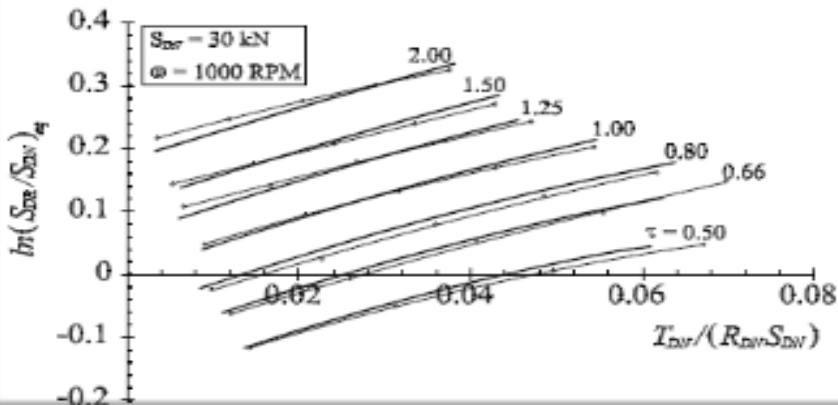
$$r_g = \frac{r_1}{r_2}$$

$$\frac{d}{dt} r_g = r_2 \cdot \frac{d}{dt} r_1 - r_1 \cdot \frac{d}{dt} r_2$$

$$\frac{d}{dt} r_2 = - \left( \frac{d}{dt} r_1 \cdot \left( \frac{\alpha_1}{\alpha_2} \right) \right)$$

$$\frac{d}{dt} r_1 = \frac{r_2^2 \cdot (\alpha_2) \cdot \frac{d}{dt} r_g}{r_2 \cdot \alpha_2 + r_1 \cdot \alpha_1}$$

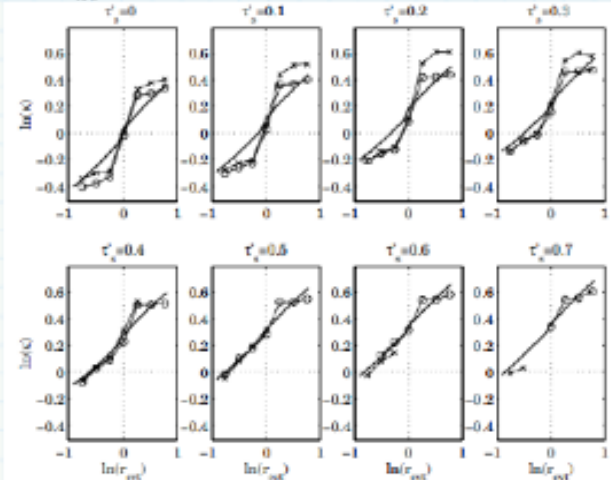
$$\frac{d}{dt} r_g = K_{CMM} \cdot \omega_1 \cdot \left[ \ln \left( \frac{F_{z1}}{F_{z2}} \right) - \ln(\psi) \right]$$



Logarithms of pulley thrust ratios versus speed ratios. Courtesy of "Vroemen, B. G., 2001, Component control for the zero inertia powertrain".

Shafai Regime:

$$\frac{d}{dt} r_1 = \frac{(F_{z1} - F_{z1}^*)}{2 \cdot C_s \cdot \tan(\beta)}$$



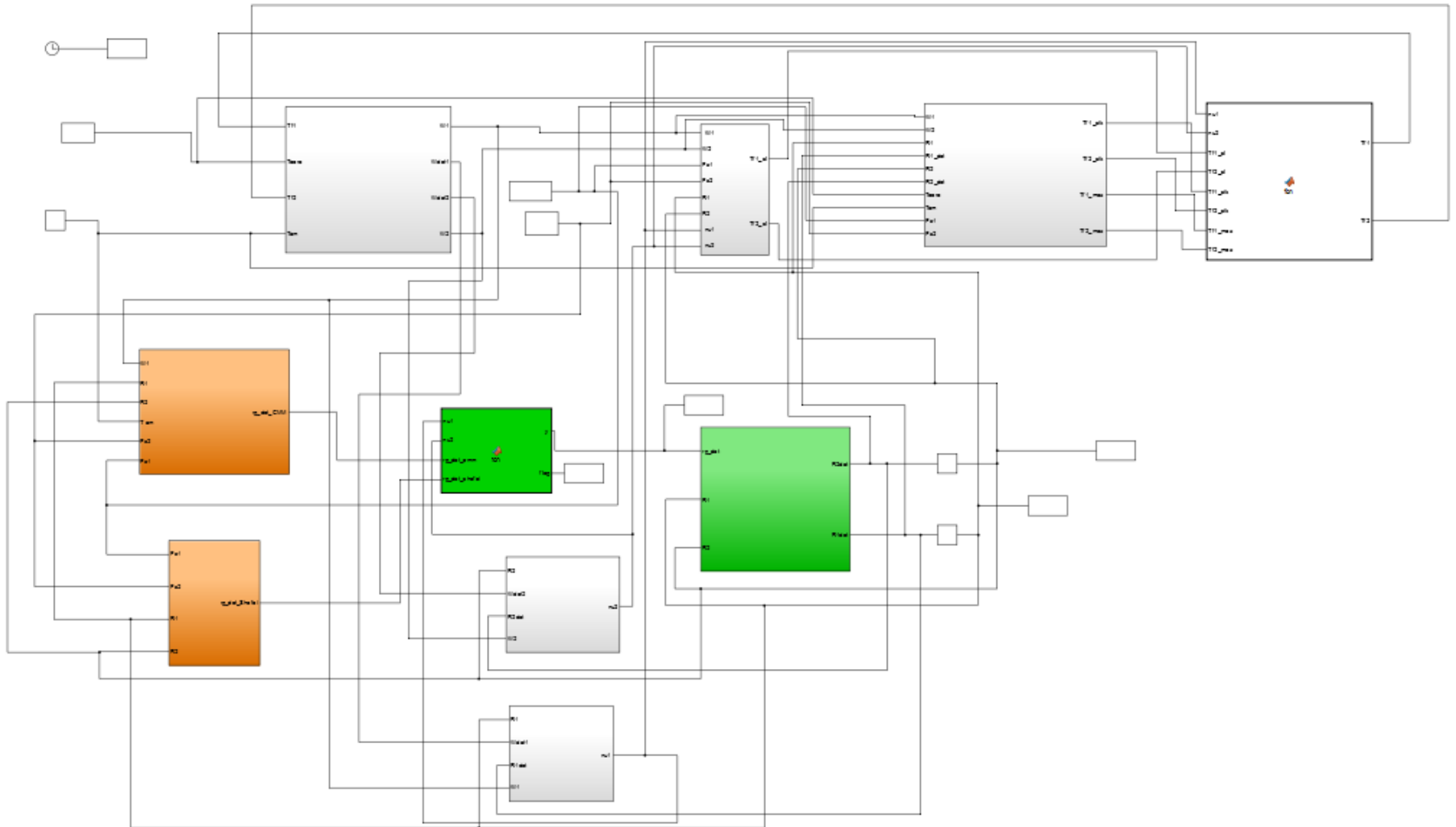
$$F_{z1}^* = K \cdot F_{z2}$$

$$K = A \cdot r_g^n = K = A \cdot \left( \frac{r_1}{r_2} \right)^n$$

At the transition:

$$\frac{d}{dt} r_{gCMM} = \frac{d}{dt} r_{gShafai}$$

# CVT Model



# CVT, Rotor Side



- Tracking the wind maximum coefficient of performance requires maintaining the rotor blades at a specific tip-speed ratio.
- This necessity of speed control makes controlling the wind turbine (WT) with a CVT a logical choice, as load torques can be controlled through variation of the clamping forces on the primary and secondary sides.



- Typical wind turbine torque control is used but in the context of CVT actuation instead of the usual generator torque.

Initial Conditions in all cases:

$$r1\_init = 2.5 \text{ inches}$$

$$r2\_init = 5 \text{ inches}$$

$$w1\_init = 7 * 3.5 / 40;$$

$$w2\_init = w1\_init * (r1\_init / r2\_init) * 1.2;$$

$$r1\_max = 7 \text{ inches} = r2\_max$$

$$r1\_min = 0.5 \text{ inches} = r2\_min$$

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PAPER IN FALL 2015**



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IN FALL 2015



- The key objective of Region 2 is to track  $\lambda_{opt}$  while pitch is fixed.

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