ENHANCING ENERGY CAPTURE IN WIND TURBINES USING A HYDROSTATIC TRANSMISSION AND DYNAMIC PITCHING

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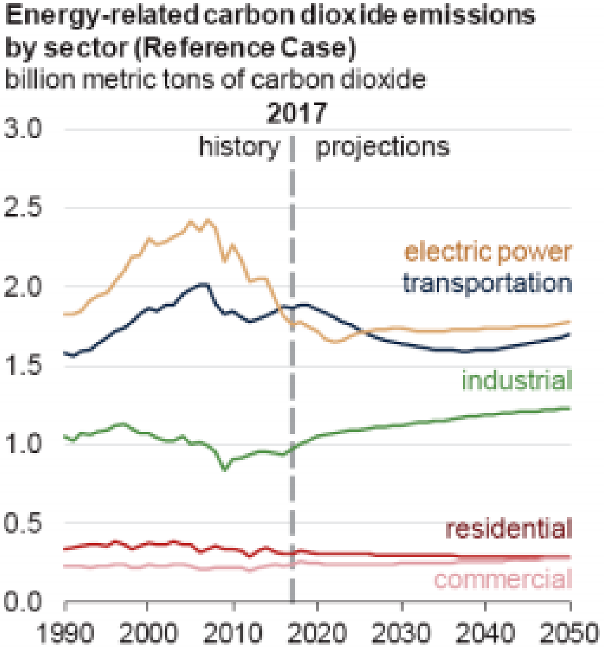
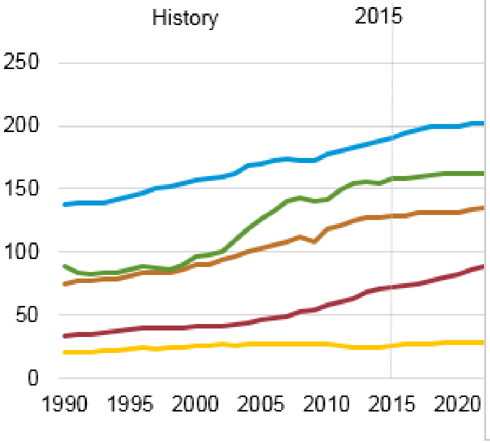
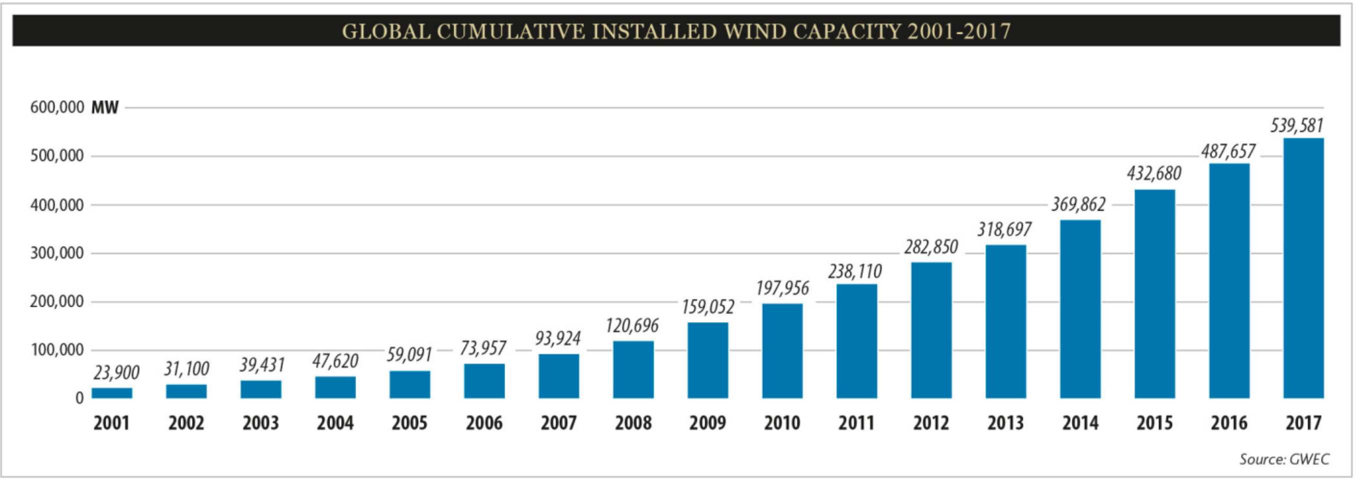
Wind statistics


Energy-related carbon dioxide emissions by sector (Reference Case)
billion metric tons of carbon dioxide

- Fastest growing new energy source
- 600 GW by 2018, 6% of the global electricity demand
- 97 GW by 2019, 7% of the U.S. electricity demand
- DOE set goal of 20% of U.S. energy from wind by 2030
- Distributed wind turbines (<1 Mw) are an attractive but under recognized means to meet this goal

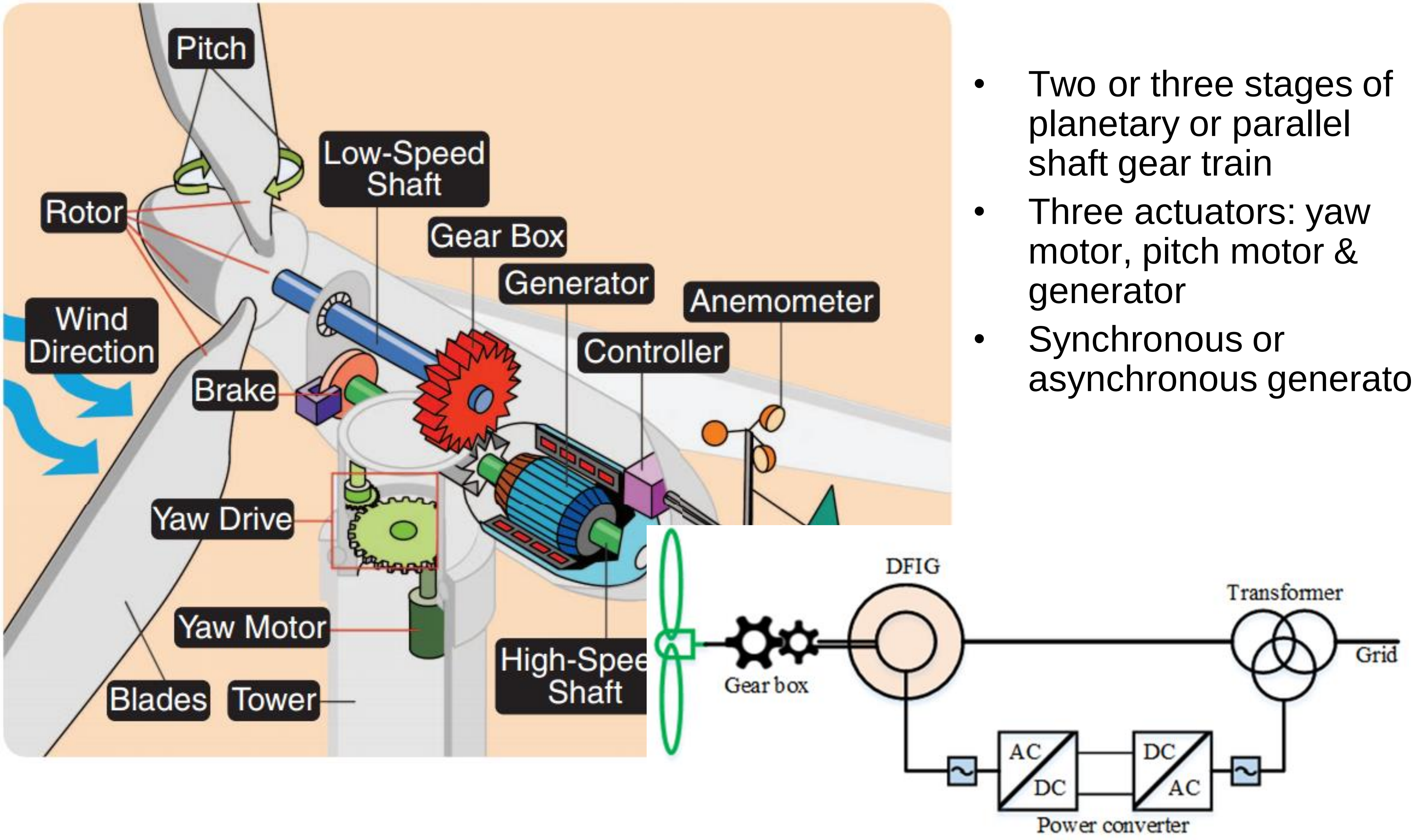



GLOBAL CUMULATIVE INSTALLED WIND CAPACITY 2001-2017

Source: GWEC

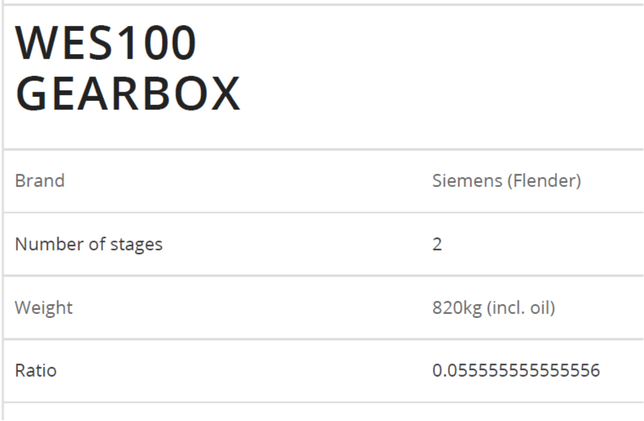
Source: EIA, International Energy Outlook 2017

Conventional wind turbine



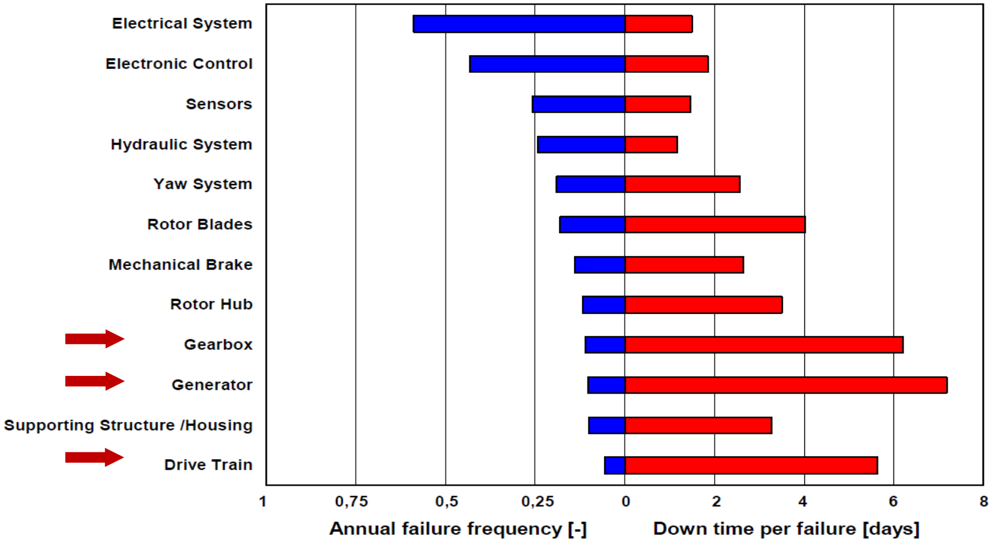
- Two or three stages of planetary or parallel shaft gear train
- Three actuators: yaw motor, pitch motor & generator
- Synchronous or asynchronous generator

Conventional wind turbine



WES100 GEARBOX

Brand	Siemens (Flender)
Number of stages	2
Weight	820kg (incl. oil)
Ratio	0.0555555555555556



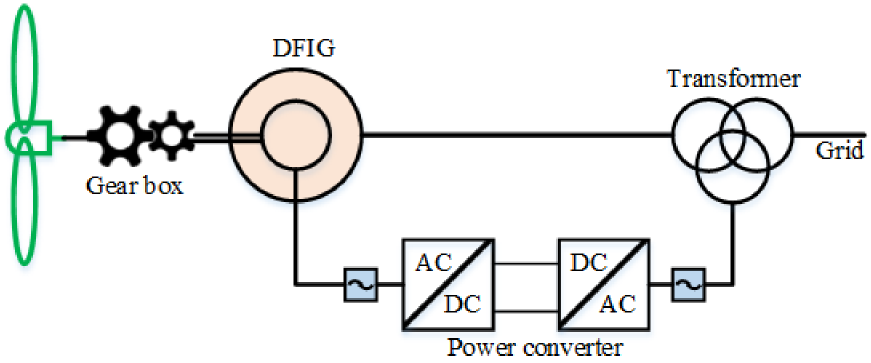
Failure frequency and downtimes of components

- Conventional drivetrain are bulky, heavy and not reliable.

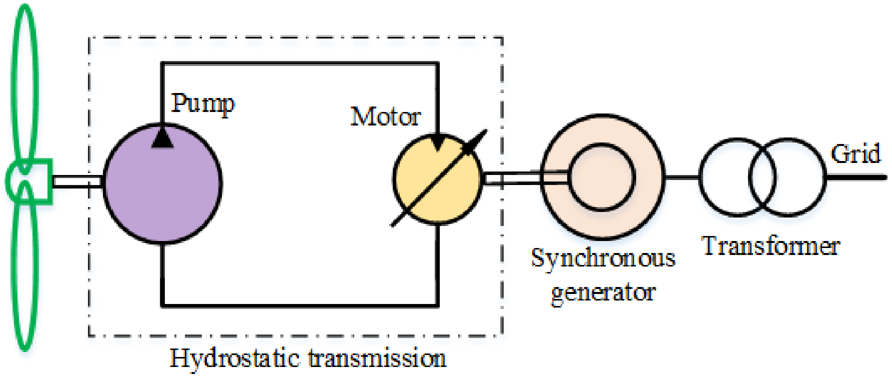
* http://www.reliawind.eu/

* C Ensslin, M Durstewitz, B Hahn, B Lange, K Rohrig (2005) German Wind Energy Report 2005. ISET, Kassel

Potential of HST wind turbine



Conventional gearbox turbine



Hydrostatic wind turbine

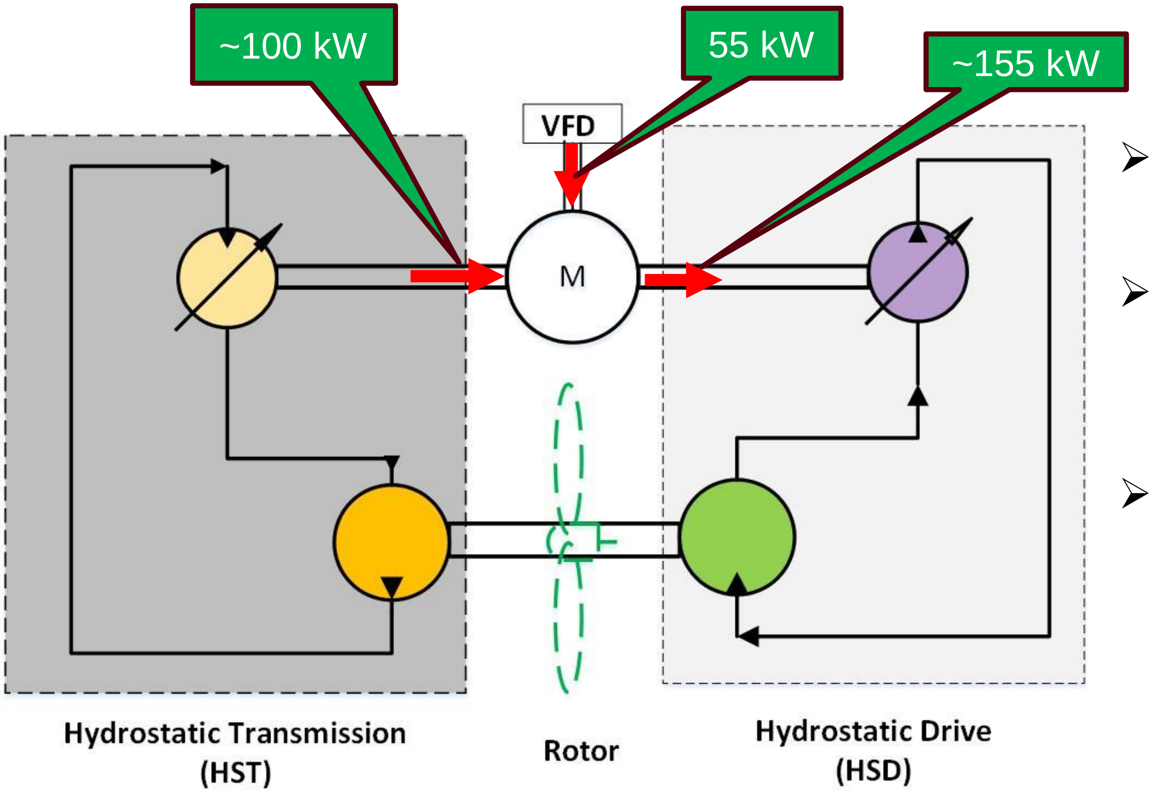
Performance Objective

☐ Maximize power capture
☐ Minimize loads
☐ Reduce downtime
☐ Reduce maintenance cost

Hydrostatic transmission (HST)

☐ Simple system structure
☐ Continuous variable transmission ratio
☐ No need of power converter
☐ All power transmitted through a fluid link; hence less stiff
☐ Improves reliability and reduce cost

Power regenerative test platform



- **Components**

  Pump and Motor
- **Transmission**

  Speed down transmission (HSD)

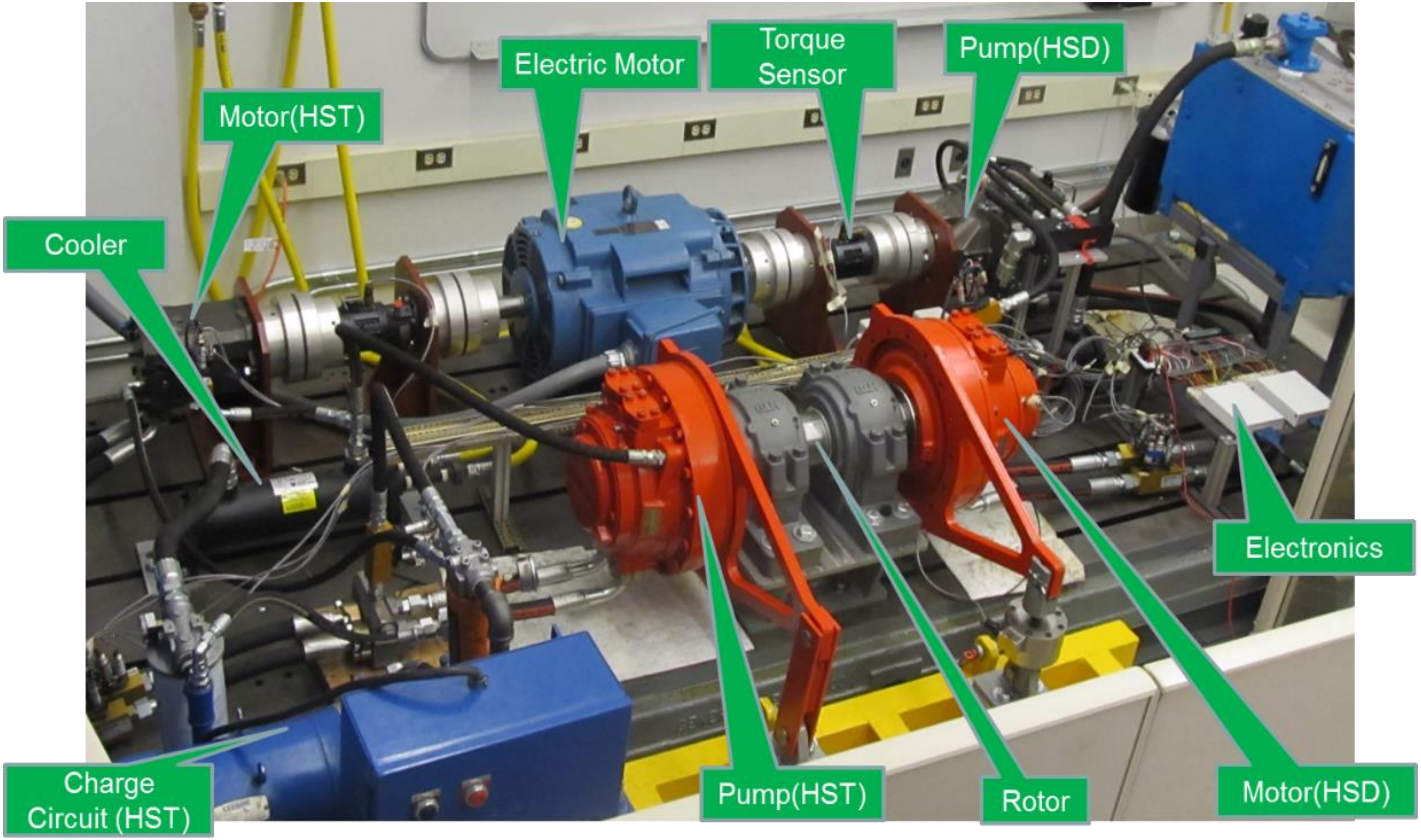
  Speed up transmission (HST)
- **Fluid Testing**

  Independent hydraulic circuit for HSD and HST with temperature

- **To Investigate the performance of hydrostatic transmission**
- **To test the advanced control algorithm**

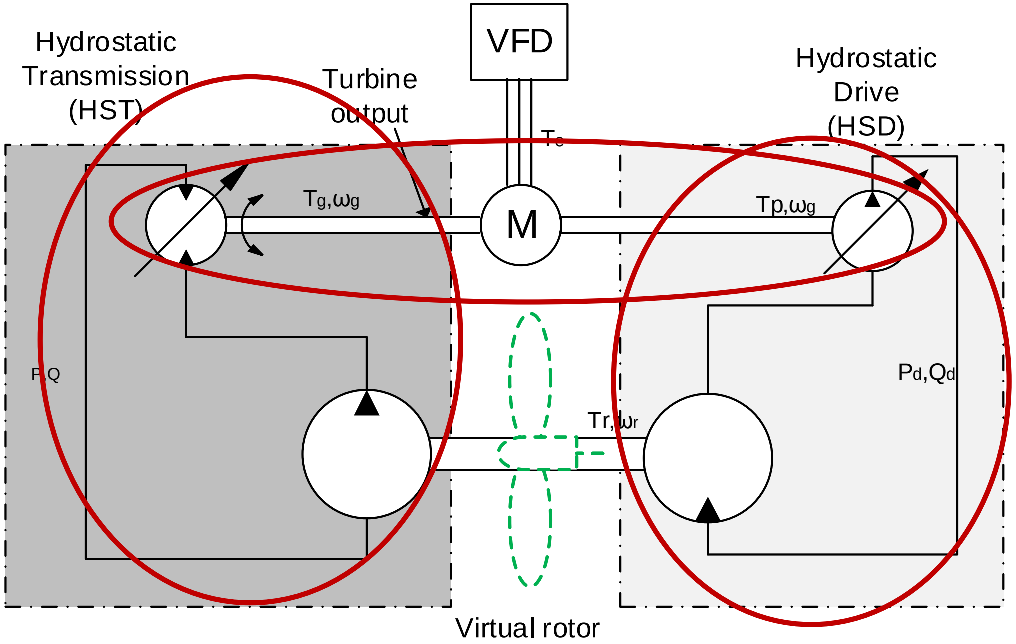
1. Capable of simulating a turbine output power of 100 kW
2. Small electric motor (55kW) to compensate for losses in the components

Power regenerative test platform



Dynamics of the test platform

High Speed Shaft: $\dot{\omega}_s = \frac{1}{J_s}\left[-b_g\omega_s + \alpha D_m P + \tau_e - \gamma D_{pd} P_d\right]$



HSD

$$\dot{P}_d = \frac{B_d}{V_d}\left[\gamma D_{pd}\omega_s - D_{md}\omega_r - L_d P_d\right]$$

$$\dot{\gamma} = \frac{1}{T_d}\left[-\gamma + K_d v_d\right]$$

HST

$$\dot{\omega}_r = \frac{1}{J_r}\left[-b_r\omega_r + D_{md}P_d - D_p P\right]$$

$$\dot{P} = \frac{B}{V}\left[D_p\omega_r - \alpha D_m\omega_s - L_t P\right]$$

$$\dot{\alpha} = \frac{1}{T}\left[-\alpha + Kv\right]$$

Input	Description	Output
$\boldsymbol{\tau_e}$	Variable Frequency Drive	$\boldsymbol{\omega_s}$
$\boldsymbol{v_d}$	HSD Pump Swash Voltage	$\boldsymbol{P_d, \omega_r, P}$
$\boldsymbol{v}$	HST Motor Swash Voltage	

Rotor Torque: $\boldsymbol{\tau_r}(\omega_r, u, \beta) = D_{md}P_d\eta_{mmd}$

Experimental Validation

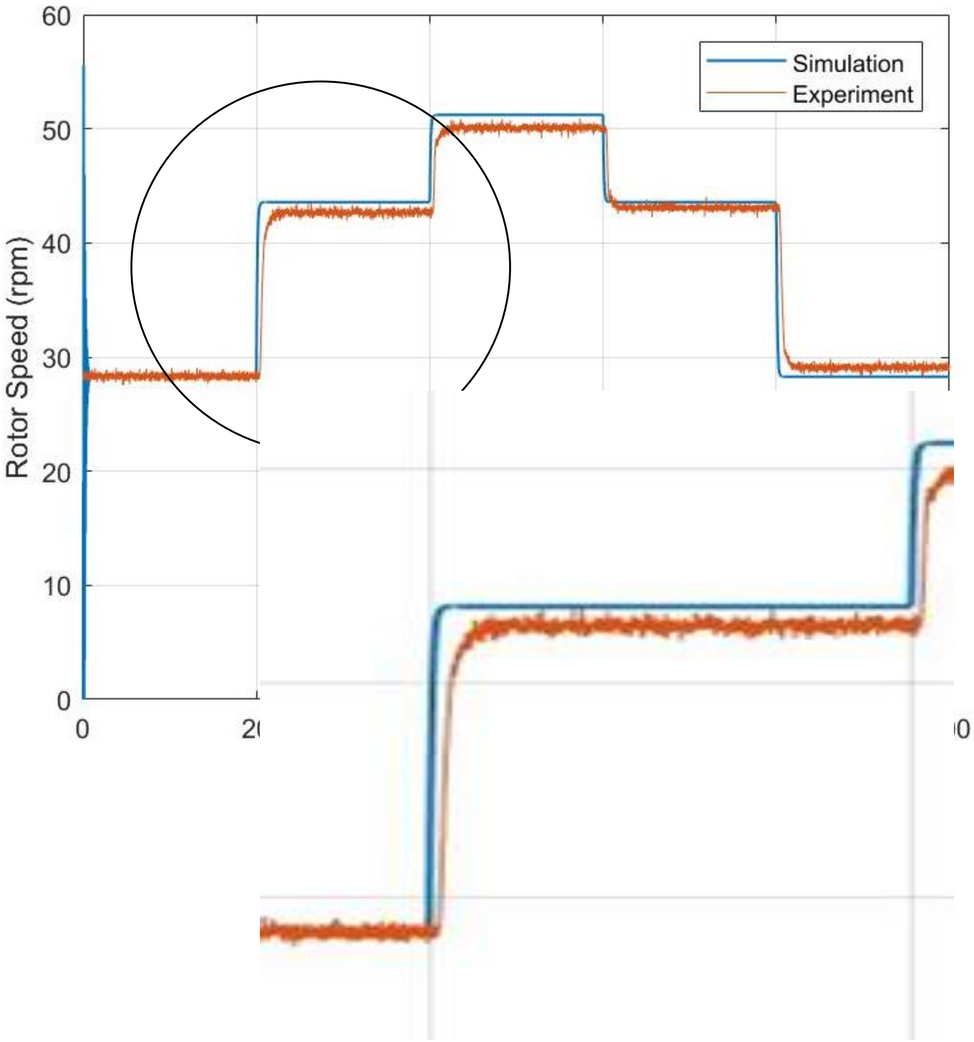
➢ Experimental set up:

- HS Shaft Speed (ω_s):=1000 rpm
- HST Pressure (P) = 100 bar
- HSD Swash angle (α): Step of 4-6-7-6-4 volts

➢ At steady state, experimental results matches with simulation with maximum steady state error is 2 RPM.

➢ In transient case, the experimental data has slower response than the simulation.

➢ Because, swash plate dynamics is not included in simulation.

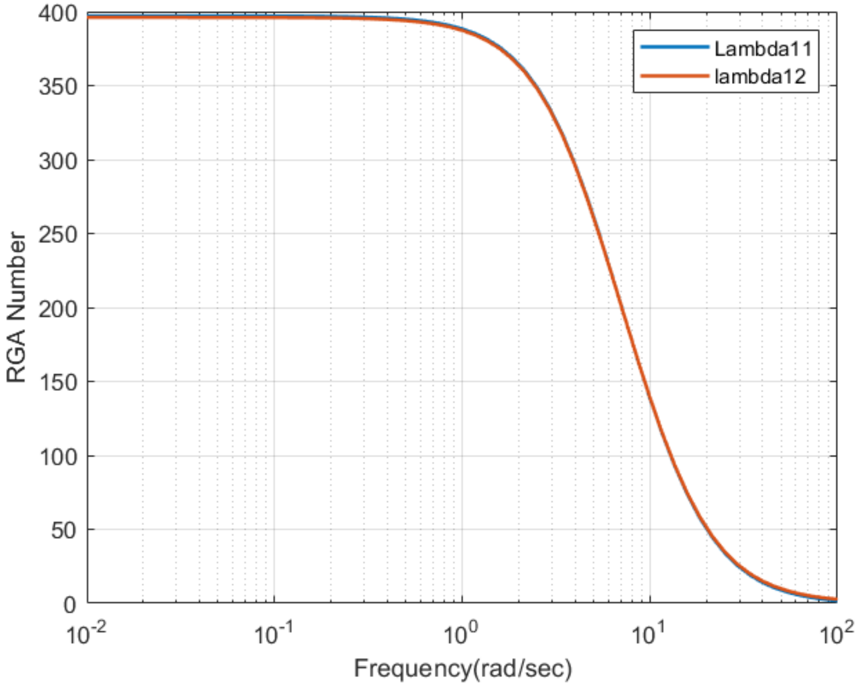


RGA Analysis

Input	Description	Output
τ_e	Variable Frequency Drive	ω_s
v_d	HSD Pump Swash Voltage	P_d, ω_r, P
v	HST Motor Swash Voltage	

Y=[Pd P], U=[Vd V]

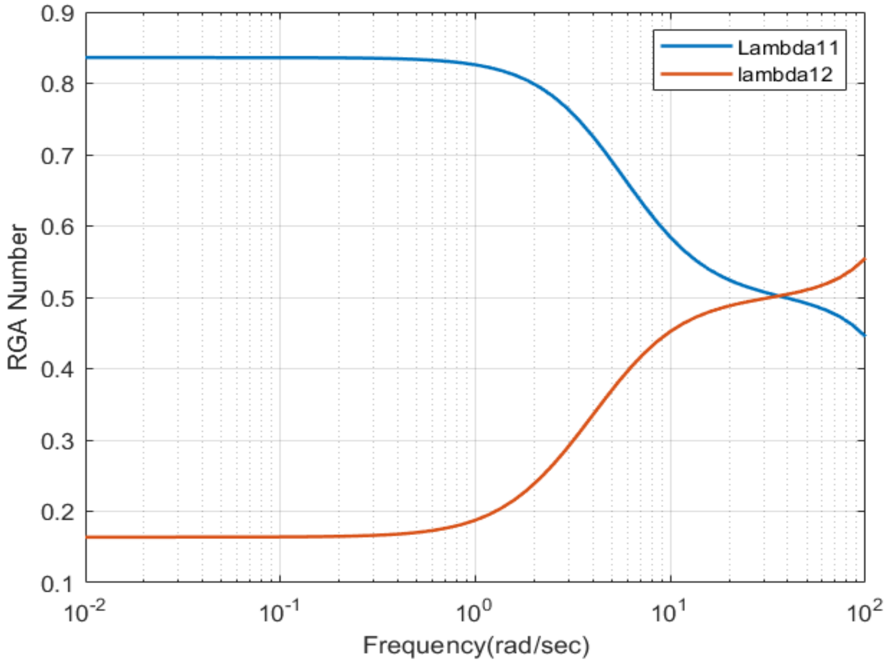
397.09 - 0.0110i	-396.09 + 0.0110i
-396.09 + 0.0110i	397.09 - 0.0110i



The coupling is ill conditioned

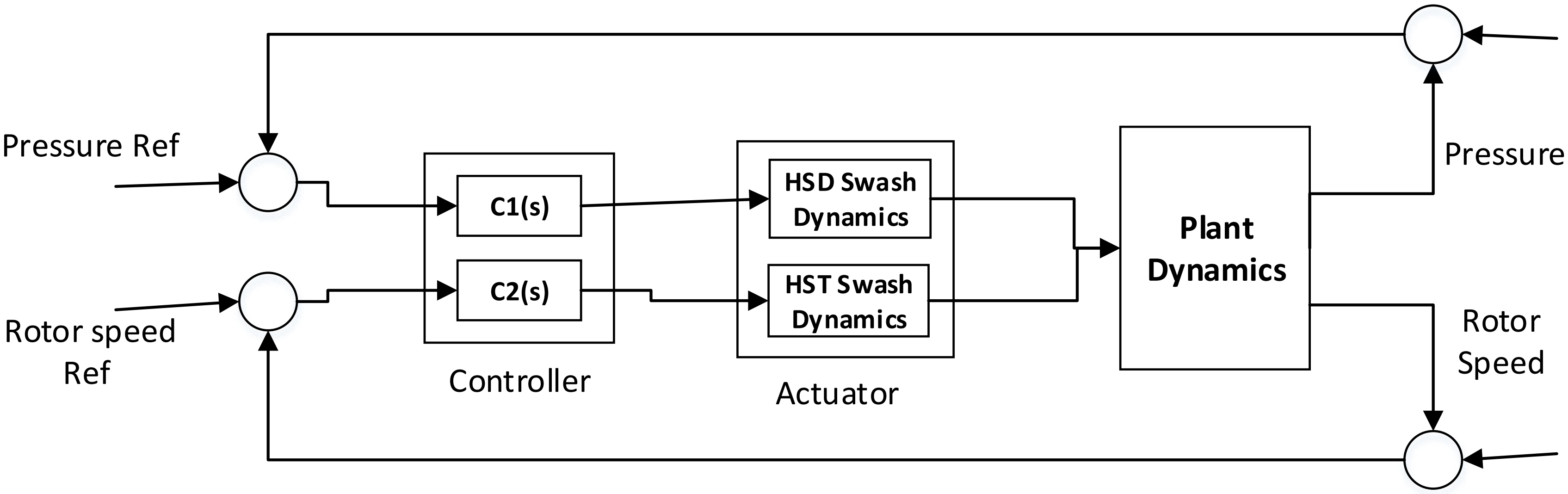
Y=[Pd Wr], U=[Vd V]

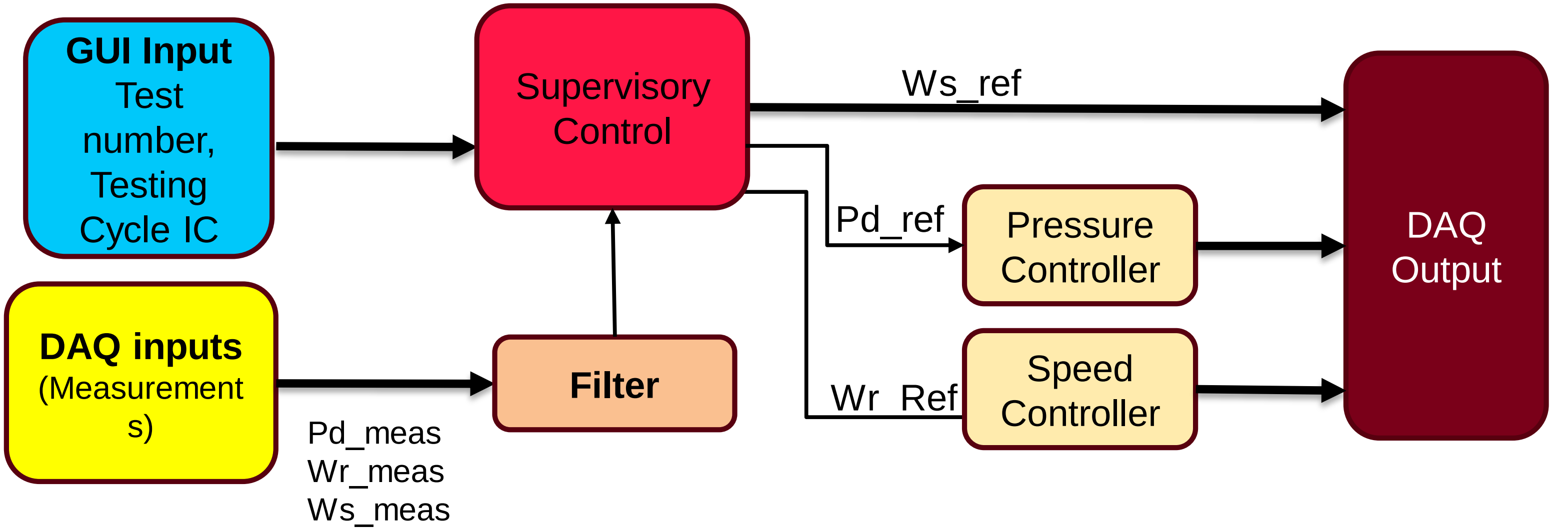
0.8361 - 0.0007i	0.1639 + 0.0007i
0.1639 + 0.0007i	0.8361 - 0.0007i



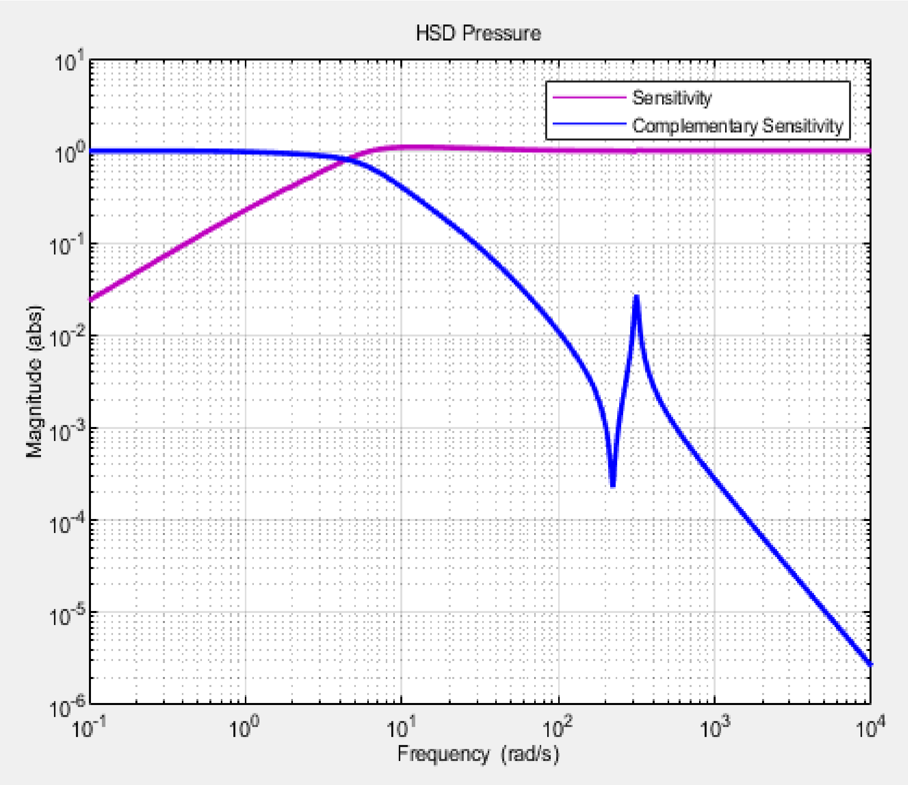
The coupling is diagonal

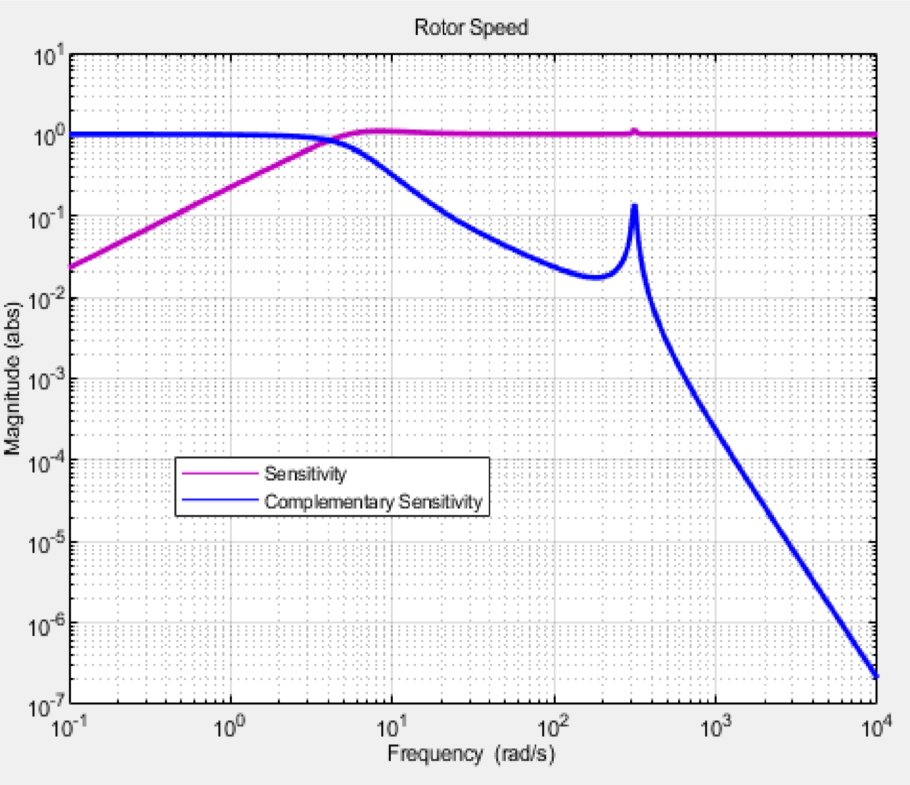
Decentralized Control Architecture





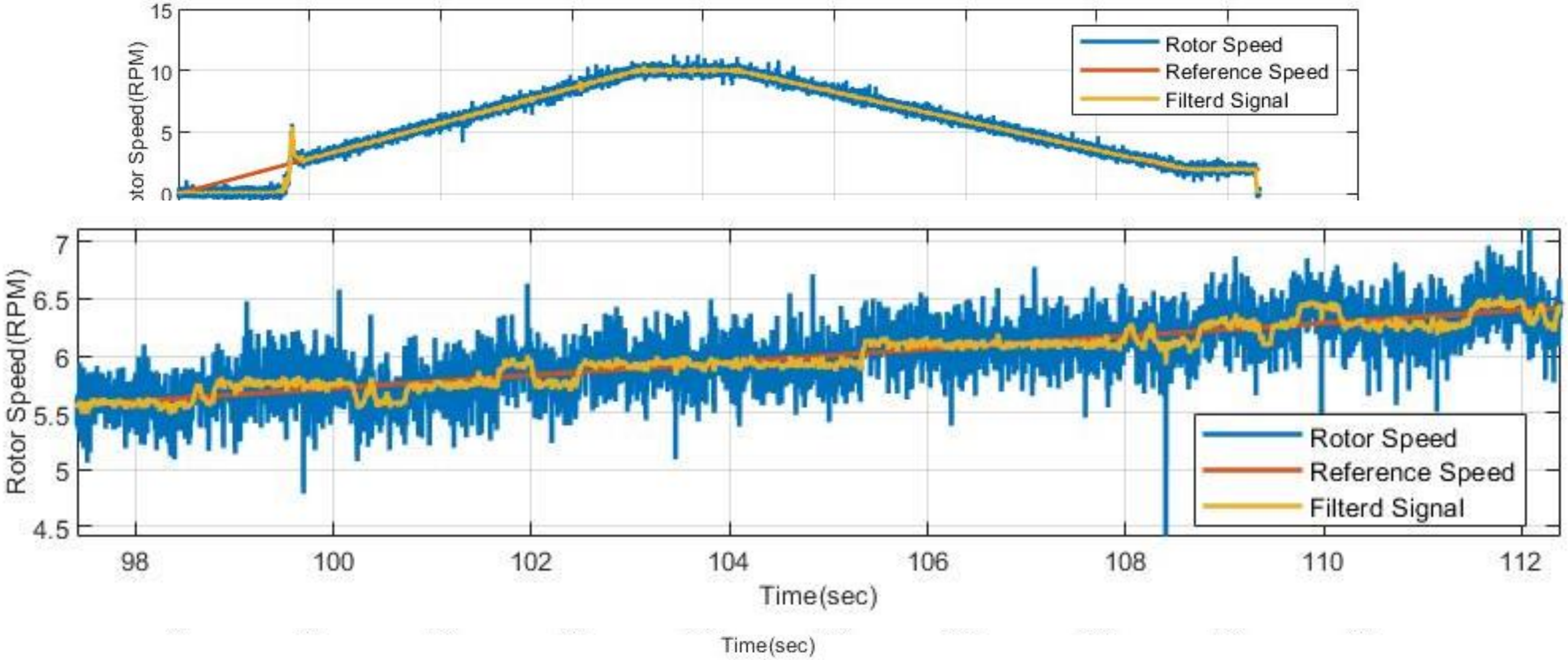
Sensitivity Analysis

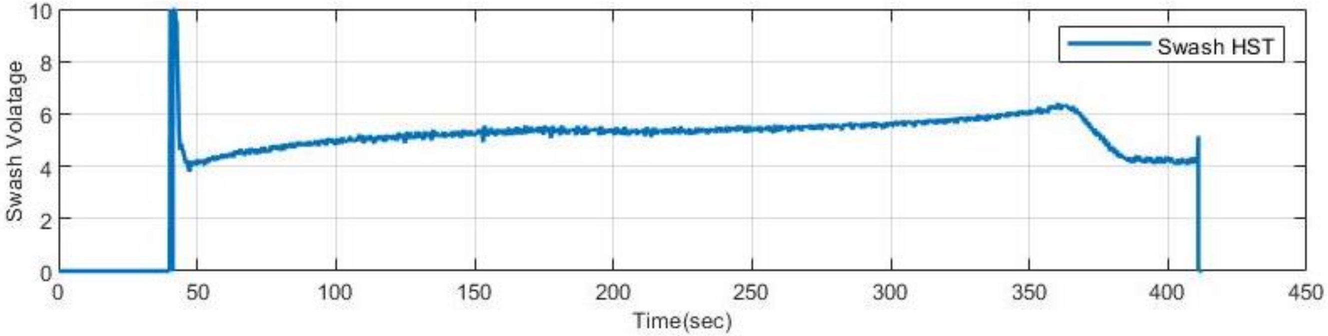




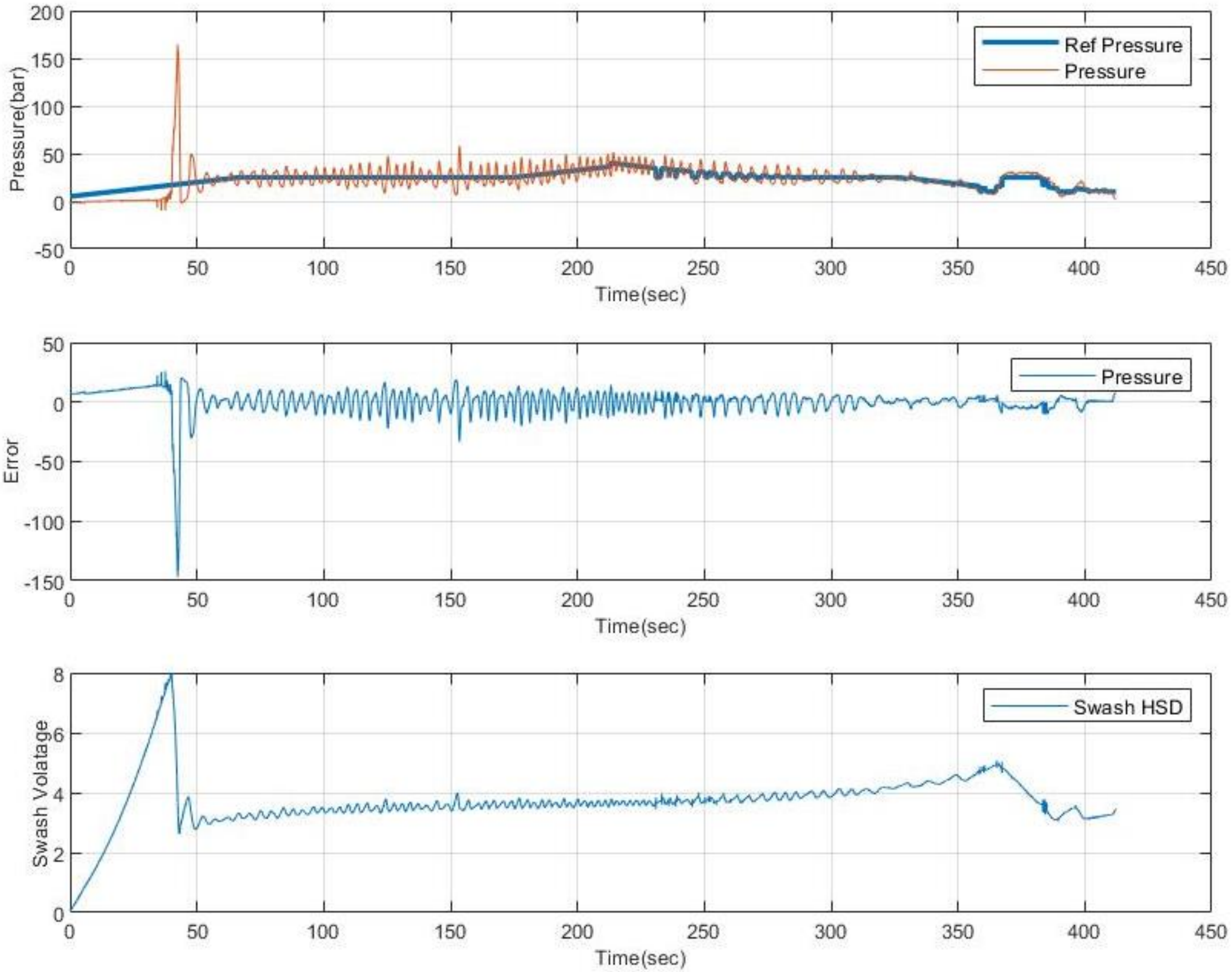
Sensitivity (S): Output/ Disturbance
Compl. Sensitivity (T): Output/Reference

Experimental Results: Speed

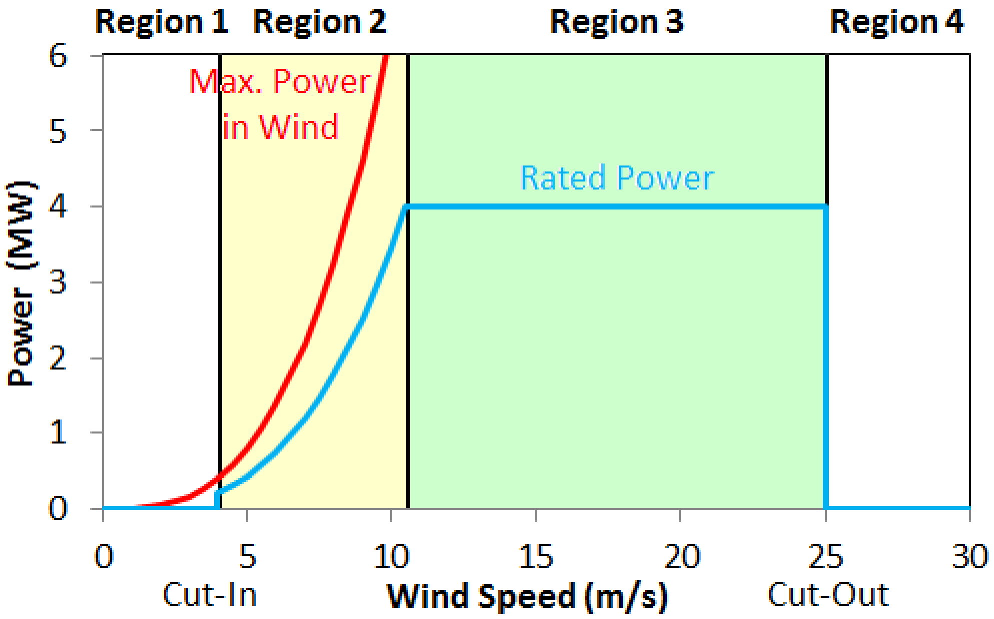




Experimental Results: Pressure



Wind Turbine Control



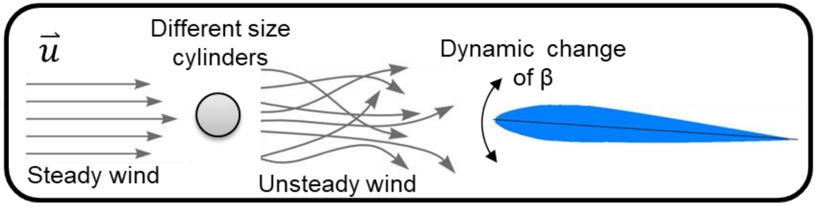
- **Four control regions:**
  - **Region 1: Standby mode**
  - **Region 2: Control to maximize power**
  - **Region 3: Control to rated power**
  - **Region 4: Turbine shut down**
- **Steady wind assumed**
- **According to Betz Law, the maximum energy that can be captured by the rotor is 59.3% of the kinetic energy of the wind**
  - **Best turbines nowadays harvest up to 45%**
  - **There is room for improvement!**

Dynamic Pitching Objective

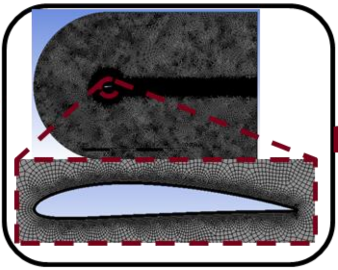
Understanding the interaction of unsteady wind and the transient response of blade pitching with the aim of improving energy capture from wind turbines

How?

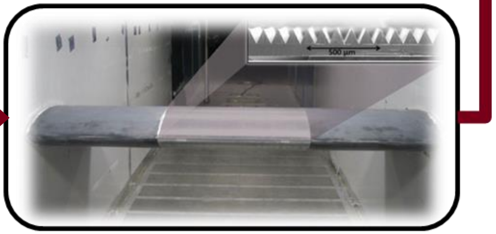
DESIGNING THE EXPERIMENTS



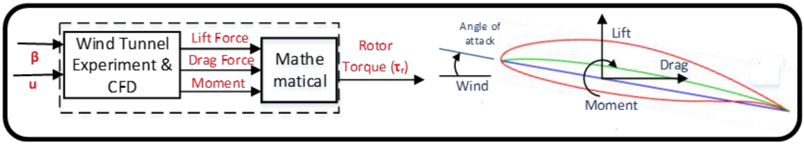
CFD SIMULATIONS



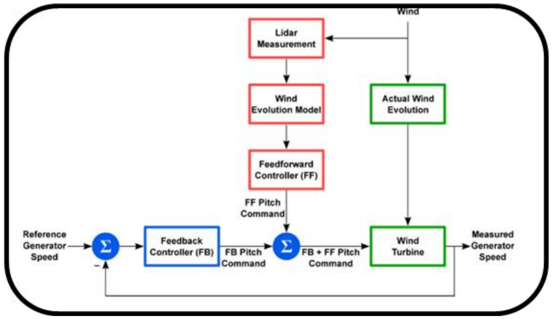
WIND TUNNEL EXPERIMENTS



GATHERING ALL TOGETHER AND FINDING THE MODEL

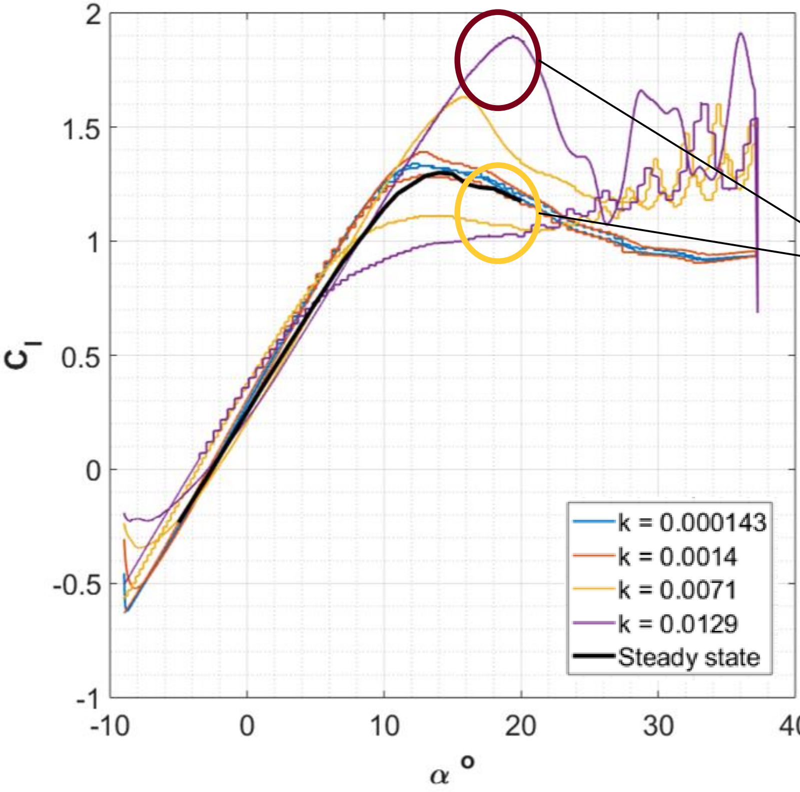


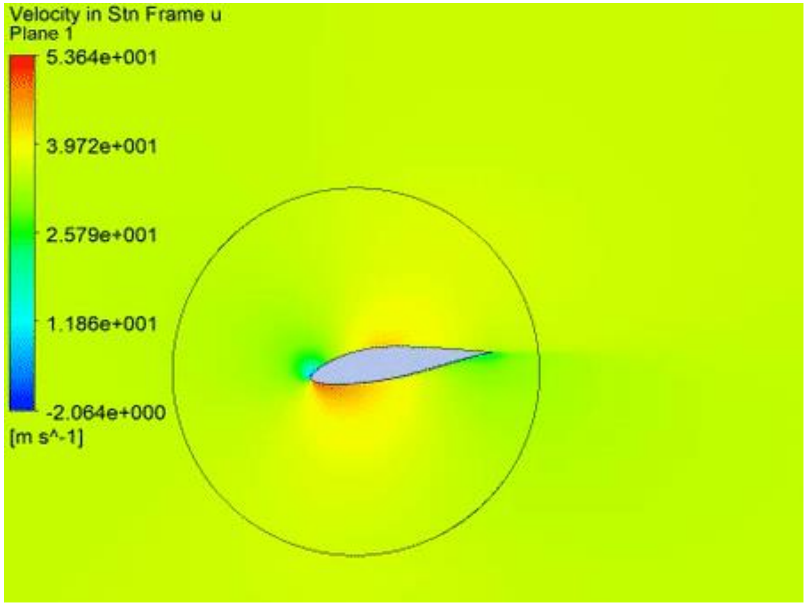
IMPLEMENTING A CONTROL STRATEGY



CFD Simulations

- Dynamic pitching simulations using ANSYS
- Steady state data in good correlation with published data





50% improvement in max lift coefficient for the dynamically pitched blade with respect to steady state

Where $k = \frac{\omega C}{2V}$ is the reduced frequency

- ω rate of rotation $(\frac{rad}{s})$
- C chord length (m)
- V wind speed $(\frac{m}{s})$

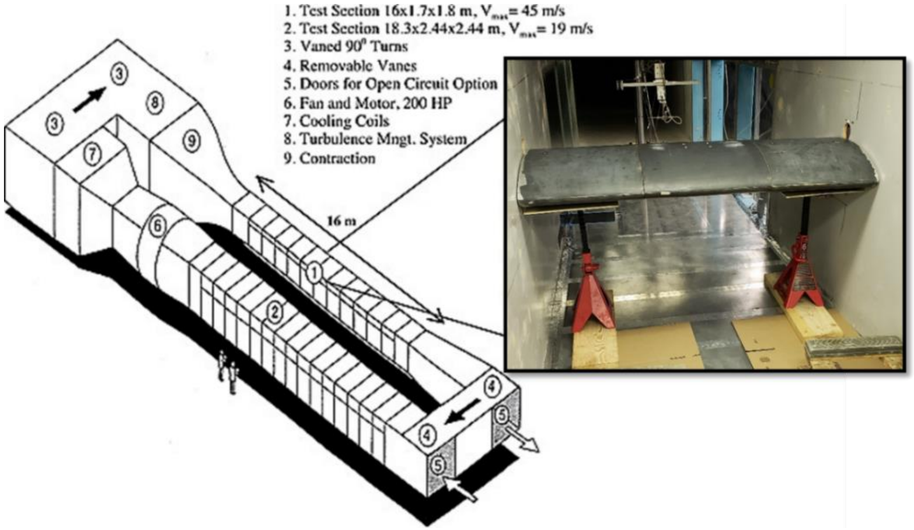
I. J. G. Holierhoek, J. B. de Vaal, A. H. van Zuijlen, and H. Bijl, “Comparing different dynamic stall models,” Wind ENERGY, vol. 16, pp. 139–158, 2013

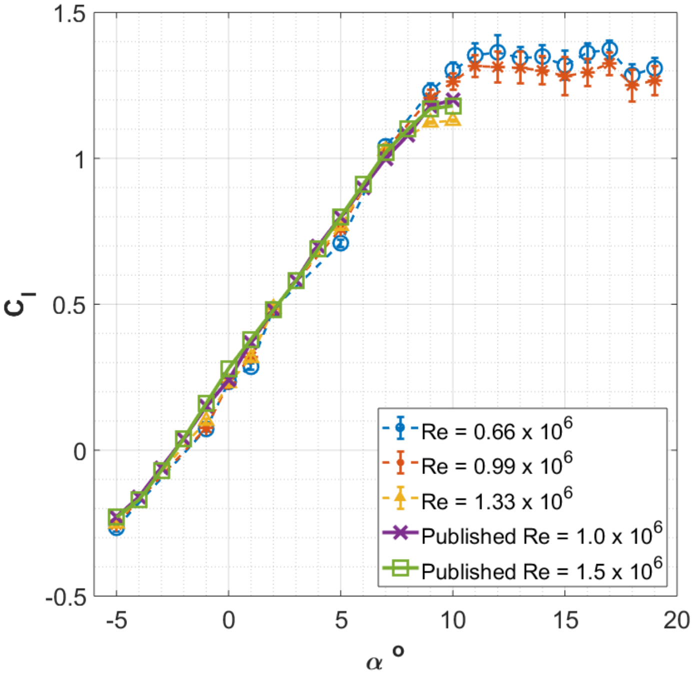
Wind Tunnel Experiments

$$Re = \frac{UC}{\nu}$$

- Recreate real-life conditions at SAFL Wind Tunnel
- Using a DU96-W-180 airfoil (commonly used in Wind Turbines)
- High Reynolds numbers (10^6)
  - Higher wind speeds ($25\frac{m}{s}$)
  - Smaller chord ($\sim 1\ m$)

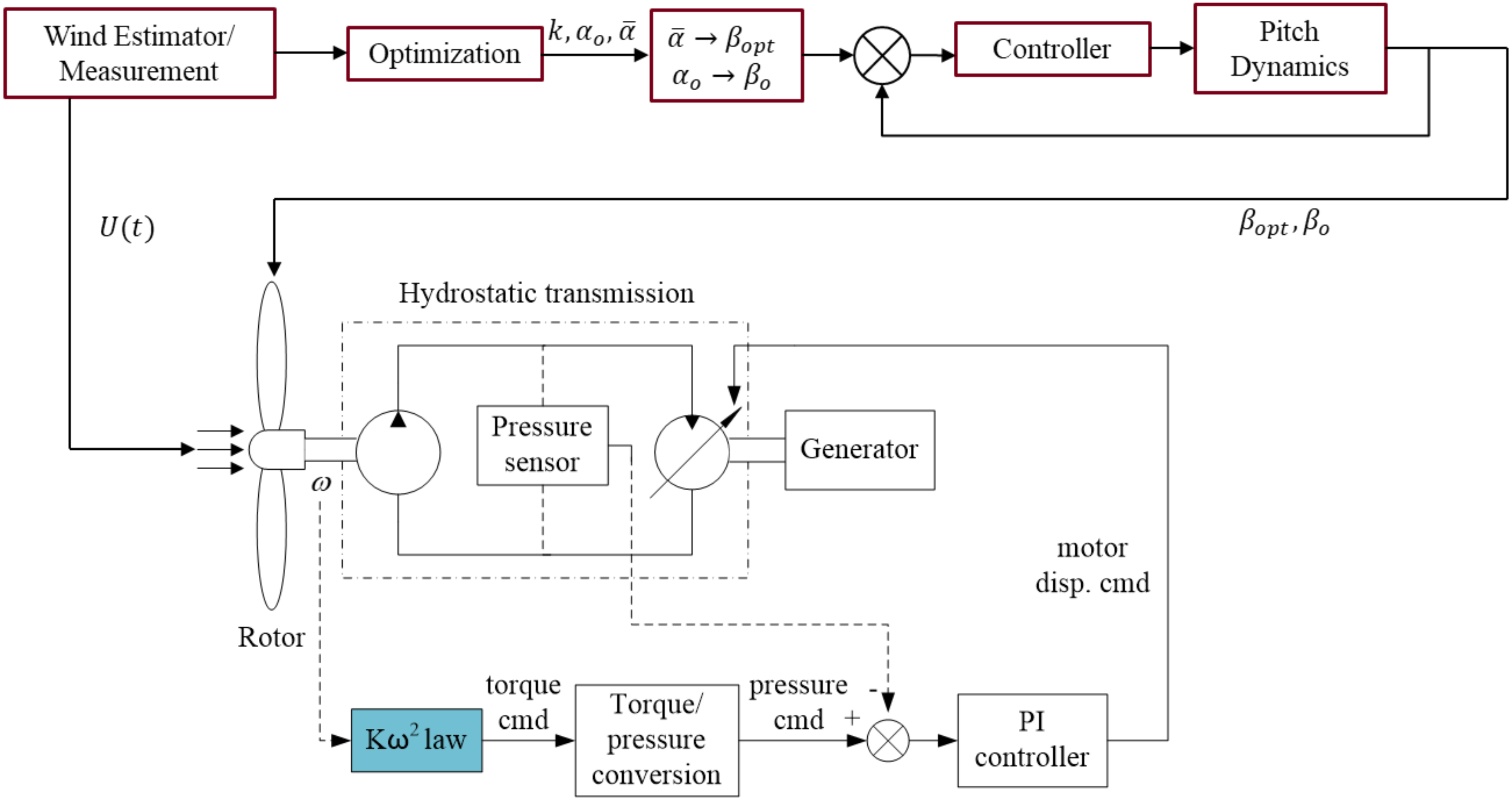
$$1.33 \times 10^6$$





- Good correlation between experimental and published data for steady state experiments

Controls



Wind Estimator/ Measurement

Optimization

$k, \alpha_o, \bar{\alpha}$

$\bar{\alpha} \rightarrow \beta_{opt}$

$\alpha_o \rightarrow \beta_o$

Controller

Pitch Dynamics

$U(t)$

β_{opt}, β_o

Hydrostatic transmission

Pressure sensor

Generator

ω

Rotor

motor disp. cmd

torque cmd

$K\omega^2$ law

Torque/ pressure conversion

pressure cmd

-

+

PI controller

Conclusions

- A unique power regenerative test platform has been built at the University of Minnesota to demonstrate and validate the performance of the HST. It also allows us to test different components and fluids.
- The high fidelity dynamic model closely matches the experiment data. The dynamic model will help us develop more efficient and robust controllers.
- Real time controller has been implemented on regenerative testbed.
- An HST transmission is a variable ratio, reliable, and cost effective alternative to a fixed ratio mechanical gearbox.
- Dynamics of pitch control on transient wind will be faster than the standard torque control. Faster pitch control can be achieved by using hydraulic actuators.
- Superposition of 2 controllers will improve the power capture in unsteady wind but coupling between the 2 dynamics needs to be studied

Thank you!

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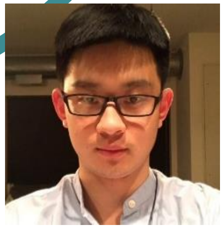

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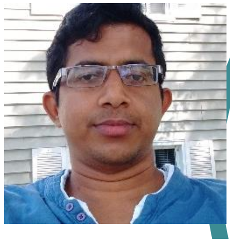

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