# RESEARCH ON HYDROSTATIC WIND TURBINES

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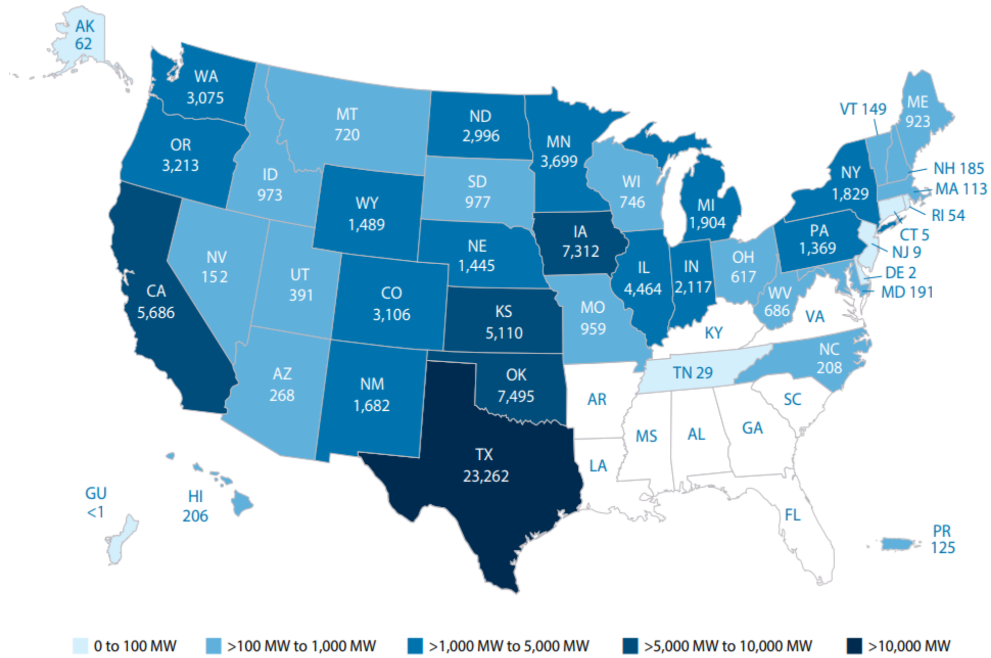
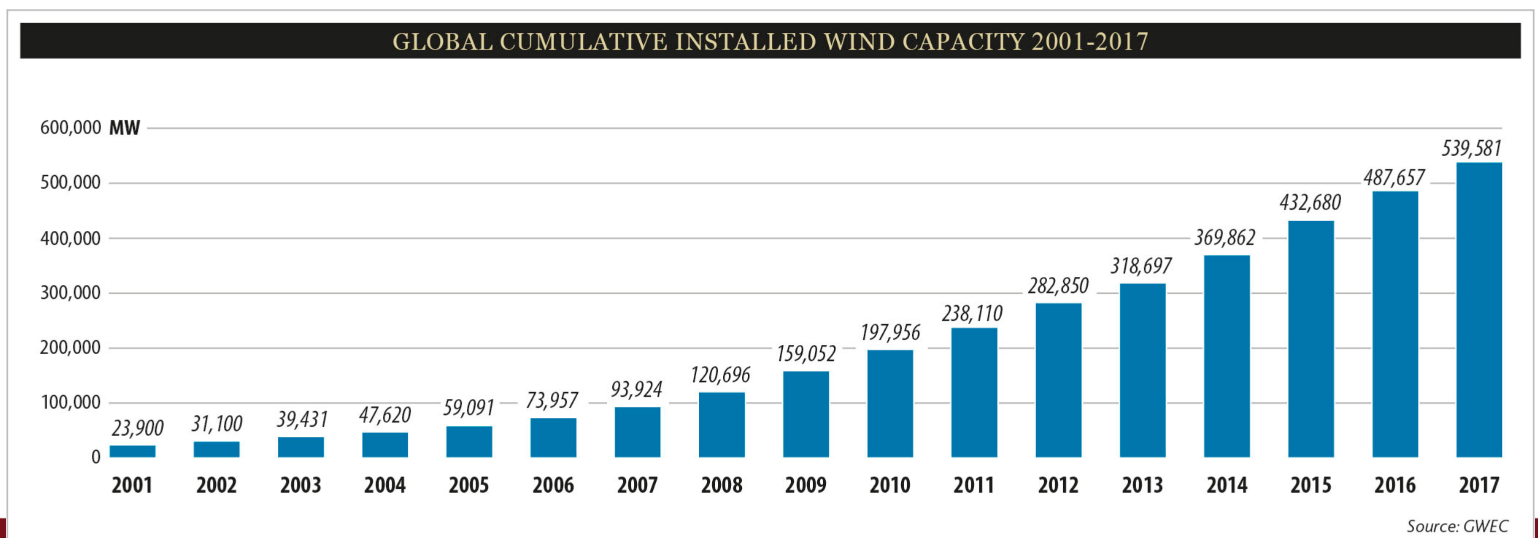
Driven to Discover®

# Wind statistics

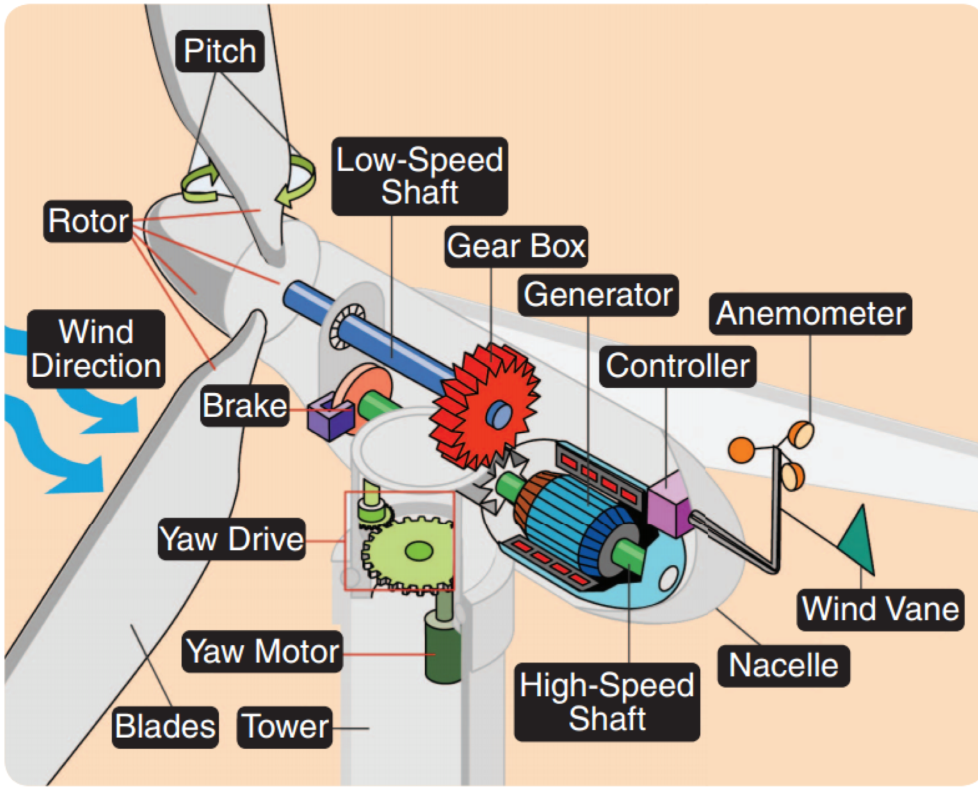
- Fastest growing new energy source
- 540 GW by 2017, 5% of the global electricity demand
- 90 GW by 2018, 6% of the U.S. electricity demand
- DOE set goal of 20% of U.S. energy from wind by 2030
- Distributed wind turbines (<1 Mw) are an attractive but under recognized means to meet this goal

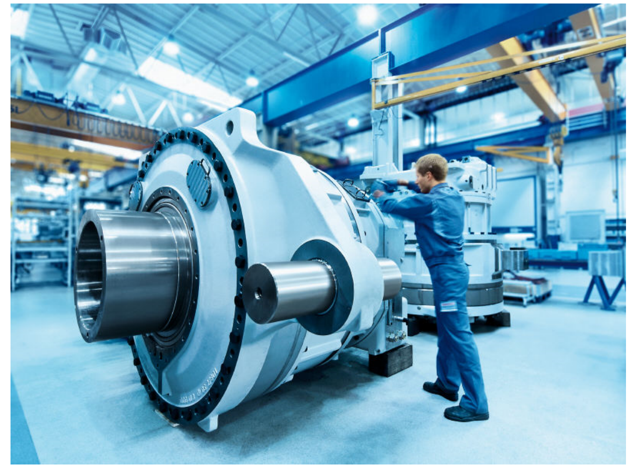



American Wind Energy Association | U.S. Wind Industry Second Quarter 2018 Market Report | Public Version



# Conventional wind turbine

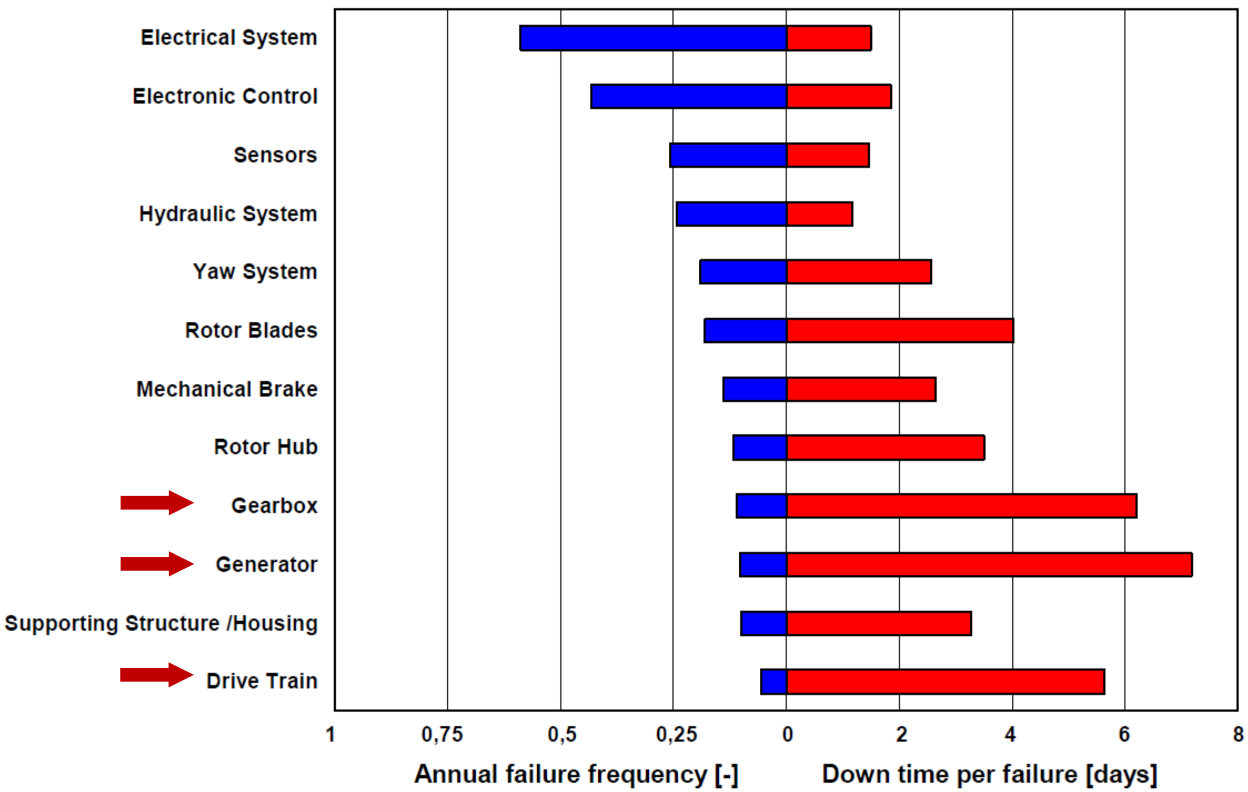


| Two-Stage Planetary with One-Stage Parallel Shaft | |
|---|---|
| Power: | 2.3 - 2.9 MW @ 14 - 16 RPM input speed |
| Input Torque: | 1500 - 1920 kNm |
| Ratio: | 78:1 - 136:1 |
| Output Shaft Type/ Location: | Horizontal output shaft located at a 550 mm centerline distance |
| Approx. Weight: | 21,100 kg (46,500 lbs) |
| Overall Length: | 2550 mm |

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

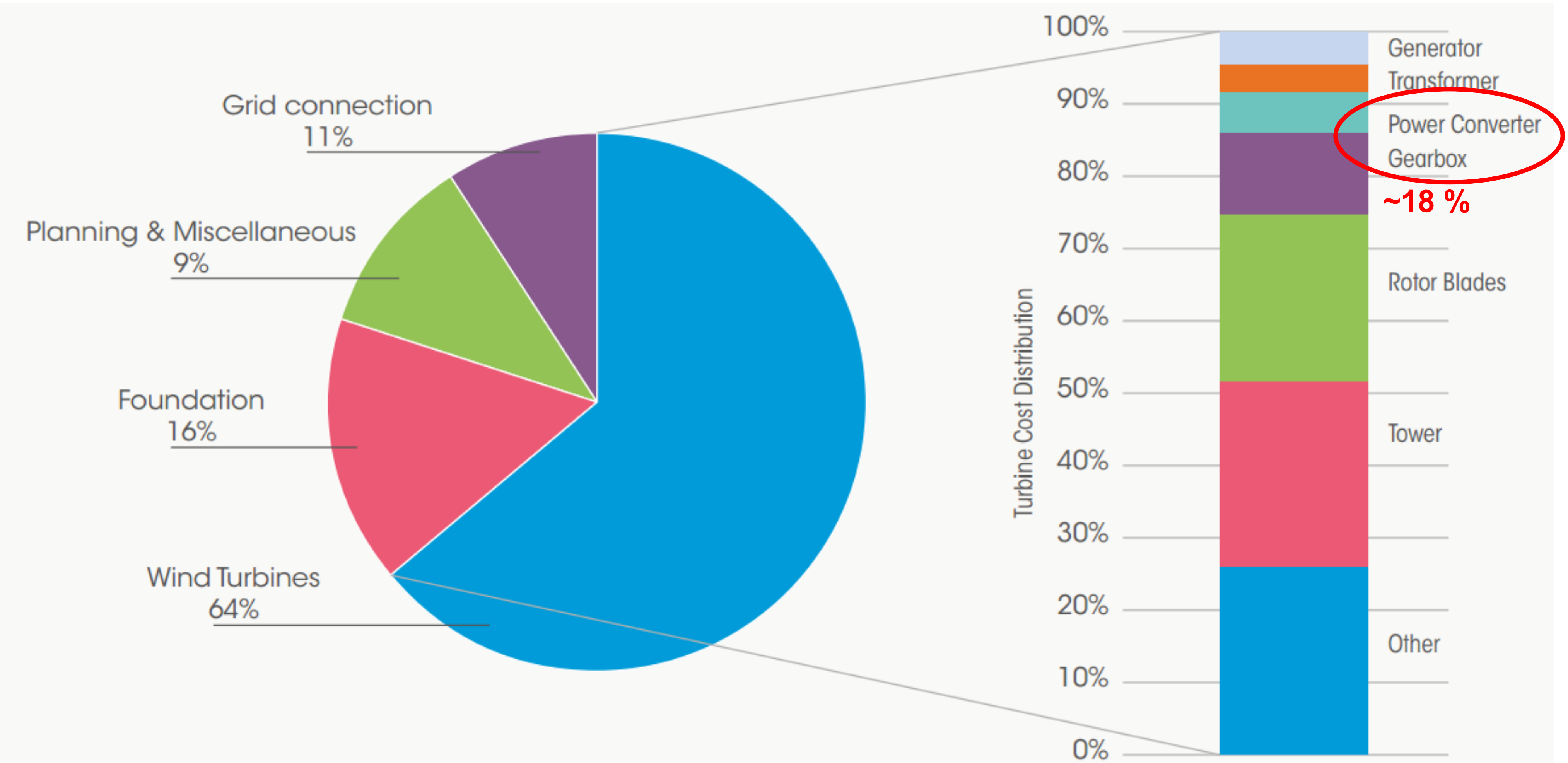
# Conventional wind turbine



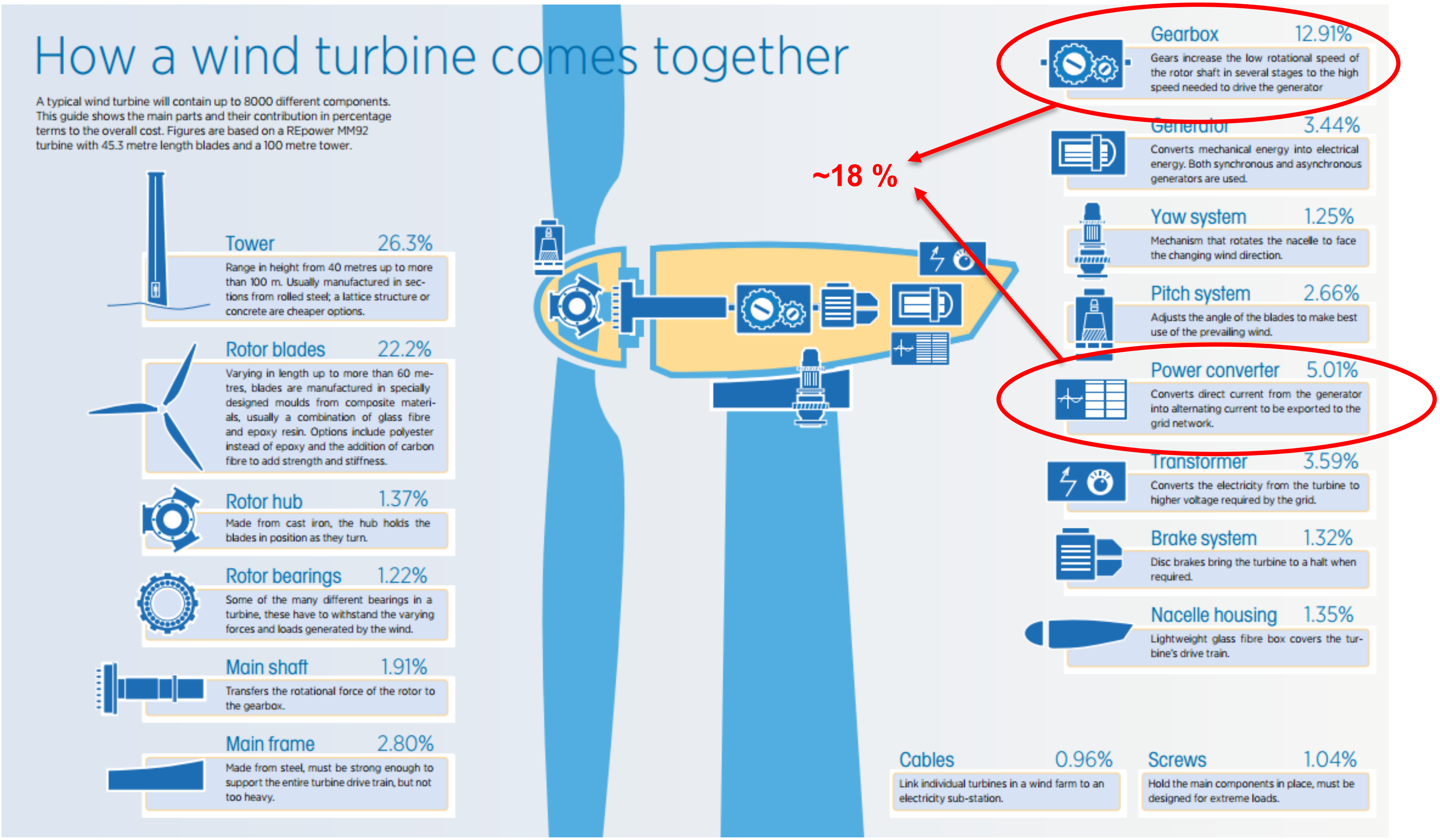

Failure frequency and downtimes of components

- Studies show the major components contributing to low reliability and increased downtime of turbines are found to be the **gearbox, generator and the drive train**.*

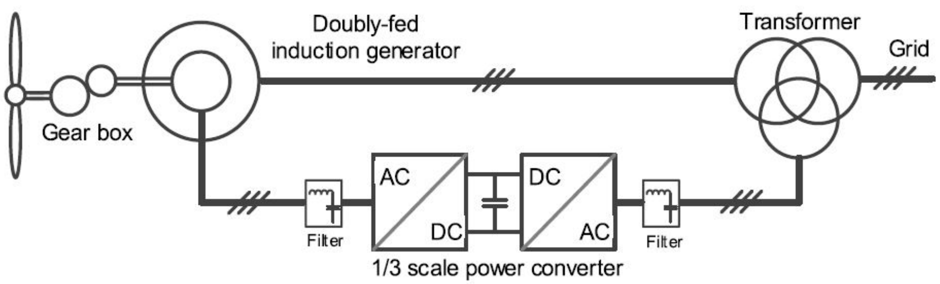
# Turbine Cost (Onshore Turbine)



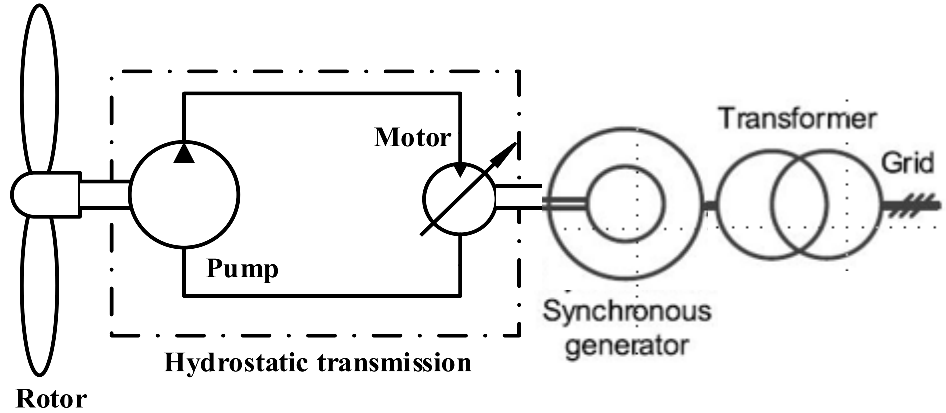
# Turbine Cost (Offshore Turbine)



# Potential of HST wind turbine




Conventional gearbox turbine




Hydrostatic wind turbine

**Performance Objective**

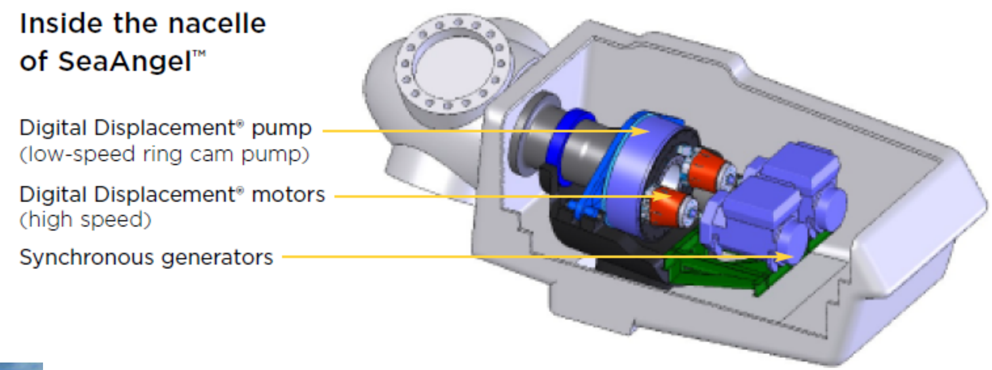
- ❑ Maximize power capture
- ❑ Minimize loads
- ❑ Reduce downtime
- ❑ Reduce maintenance cost

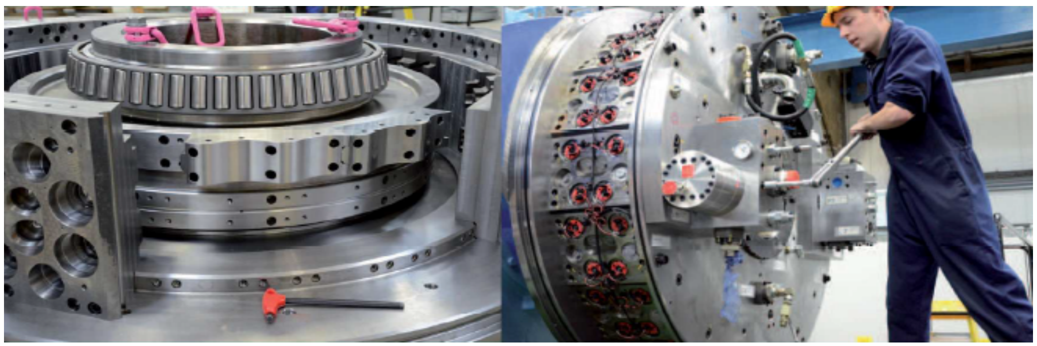
**Hydrostatic transmission (HST)**

- ❑ 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

# HST wind turbines

1. Windera Power System (Florida)
2. WindSmart (Canada)
3. Mitsubishi Heavy Industries



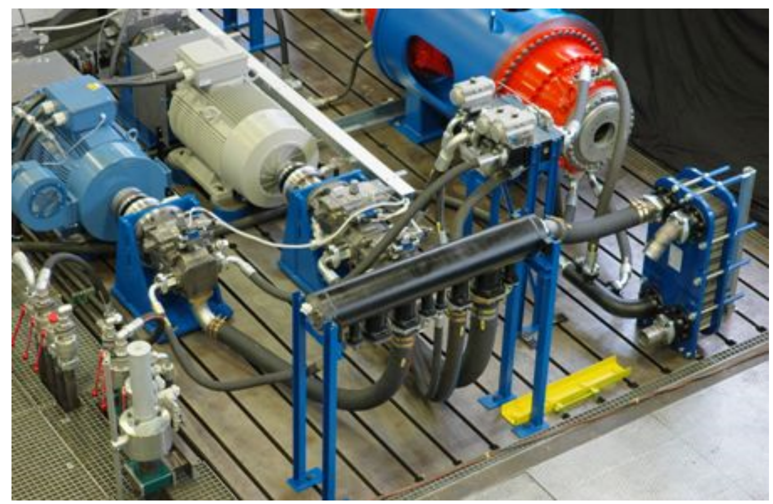



Mitsubishi 7MW Sea Angel offshore turbine

Core technology: Digital displacement technology by Artemis

93.5% peak efficiency from shaft-to-shaft compared to 92% peak efficiency for conventional wind turbine gearbox.

Aachen University IFAS 1 MW HST wind power test stand



# Distributed wind opportunity

Distributed wind (<1 MW):

- ➢ Community wind - cost-effective for farms, communities, factories and rural electric cooperatives.
- ➢ Relatively easy permitting process
- ➢Mid-size turbines can operated in local niches, eliminating the need for costly electric power transmission upgrades.
- ➢ Distributed wind makes the power grid more stable and reliable.
- ➢ Few midsize turbines in the market today
- ➢ Commercially hydrostatic units are available in required size.

Community wind

# Our Goals

- Develop a controller for the HST wind turbine
  - Dynamic Modeling
  - Controller Design

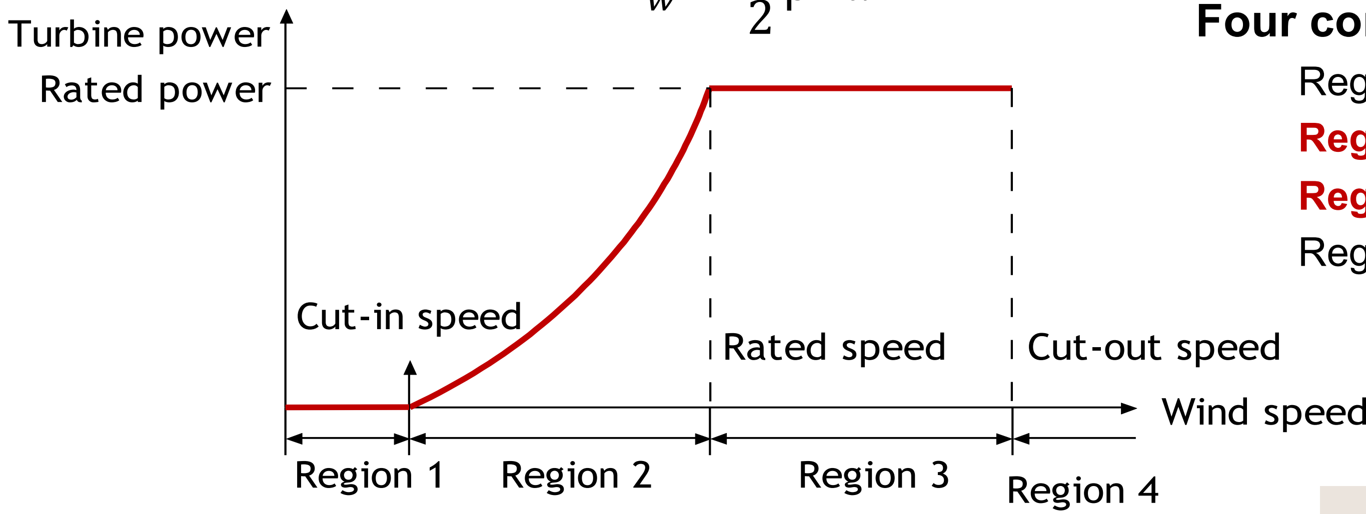
- Demonstrate and validate  the performance of the HST wind turbine
  - Power regenerative HST wind turbine
  - New components and fluid performance

- Model interaction of the HST wind turbine with the grid

- Understand the effect of unsteady wind over pitching blade

# Turbine Control

$$P_w = \frac{1}{2}\rho A u^3$$




**Four control regions:**

Region 1: Standby mode

**Region 2: Control to maximize power**

**Region 3: Control to rated power**

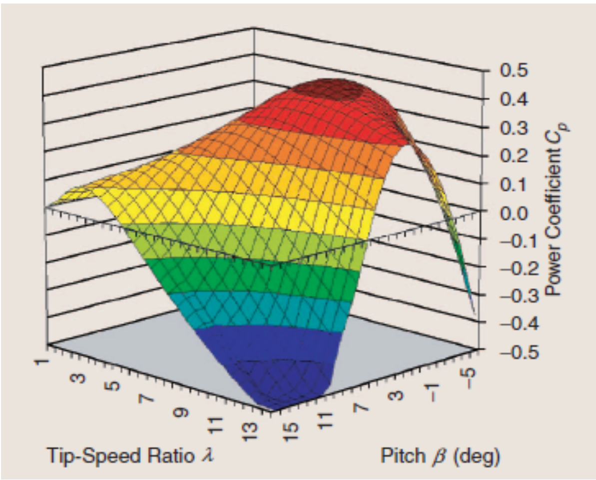
Region 4: Turbine shut down

➢ **Rotor power coefficient (Cp)** is the fraction of wind power captured by the rotor:

$$C_P = \frac{P_r}{P_w} = C_P(\lambda, \beta)$$

➢ **Rotor tip speed ratio:**

$$\lambda = \frac{\omega_r R}{u}$$




➢ According to **Betz Law,** the maximum energy that can be captured by the rotor is **59.3%** of the kinetic energy of the wind

* Johnson, K. E. , Pao, L. Y. , Balas, M. J. , Fingersh, L. J. Control of variable-speed wind turbines: standard and adaptive techniques for maximizing energy capture. IEEE Control Systems Magazine, Vol. 26(3), pp.70–81, 2006.

# Region 2 Control (Existing)

- Objective: Maximize power captured
- Strategy: Constant pitch angle β and use $\tau_g$ to operate turbine at optimum point

➢ **Torque control law -** control rotor reaction torque:

$$\tau_g = \tau_c = K\omega_r^2$$

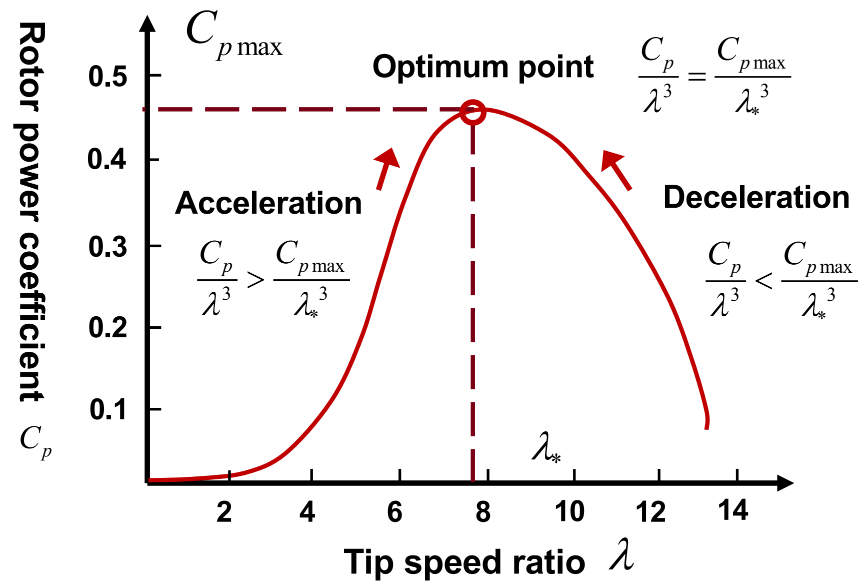
where the gain K is given by blade parameters.

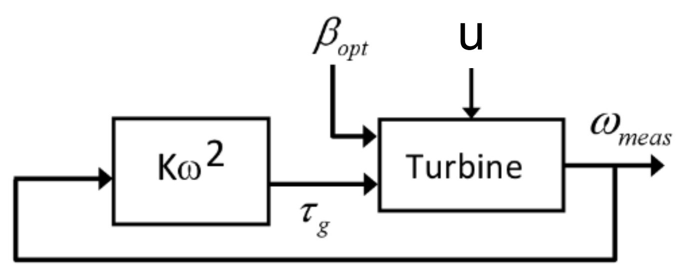
$$K = \frac{1}{2}\rho A R^3 \frac{C_{pmax}}{\lambda_*^3}$$

➢ **Dynamics of the rotor**

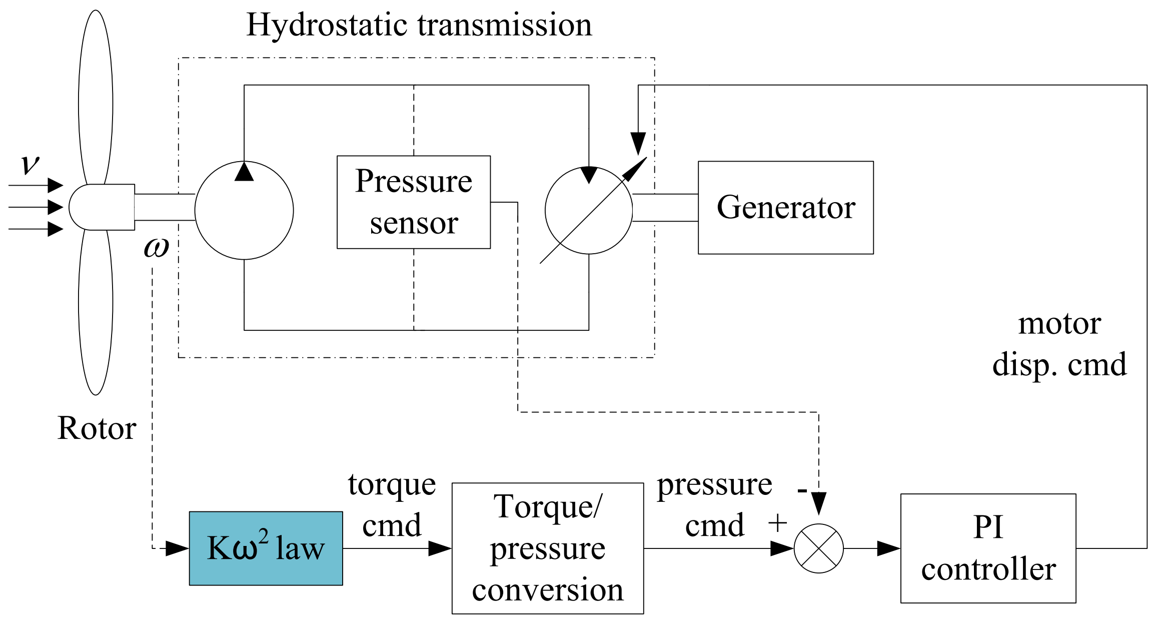
$$\dot{\omega}_r = \frac{1}{2J}\rho A R^3 \omega_r^2 \left(\frac{C_p}{\lambda^3} - \frac{C_{pmax}}{\lambda_*^3}\right)$$

➢**The beauty of the kω² law:** bring the turbine to optimal point only with rotor speed and it **does not require wind speed information**.



# HST turbine control in region 2




HST turbine control scheme in region 2

Rotor reaction torque generated by the pump

- The relationship between the **pump torque command** and the **line pressure command**:

$$p_c = \tau_c \cdot \frac{\eta_p}{D_p}$$

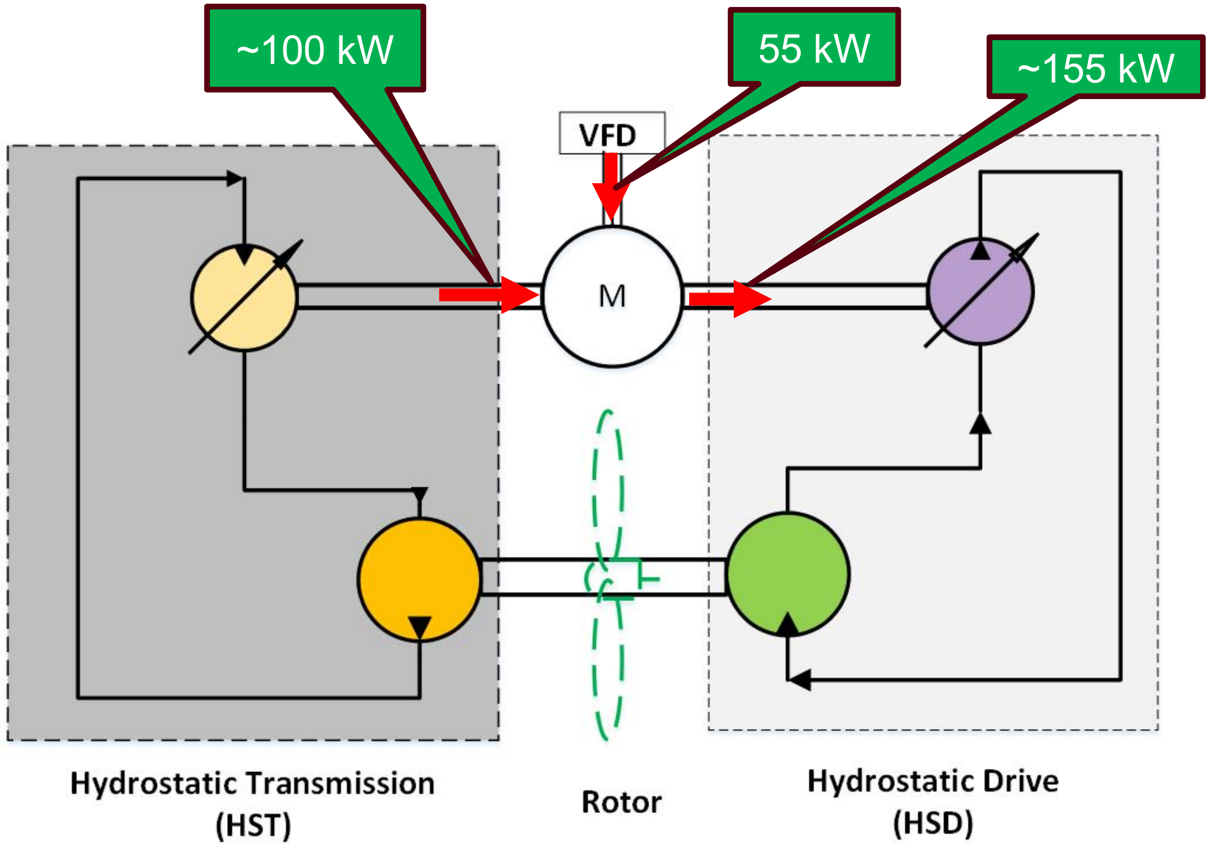
where $\eta_p$ is the pump mechanical efficiency.

- To give accurate control, the pump mechanical efficiency is estimated by **previewing the pump efficiency map** from the historical rotor speed and line pressure data.

**Control strategy**

1. Use rotor speed to generate **rotor reaction torque (pump torque) command** ($k\omega^2$ law)
2. Convert **pump torque command** to **line pressure command**
3. Track the line pressure by **adjusting motor displacement** through PI controller

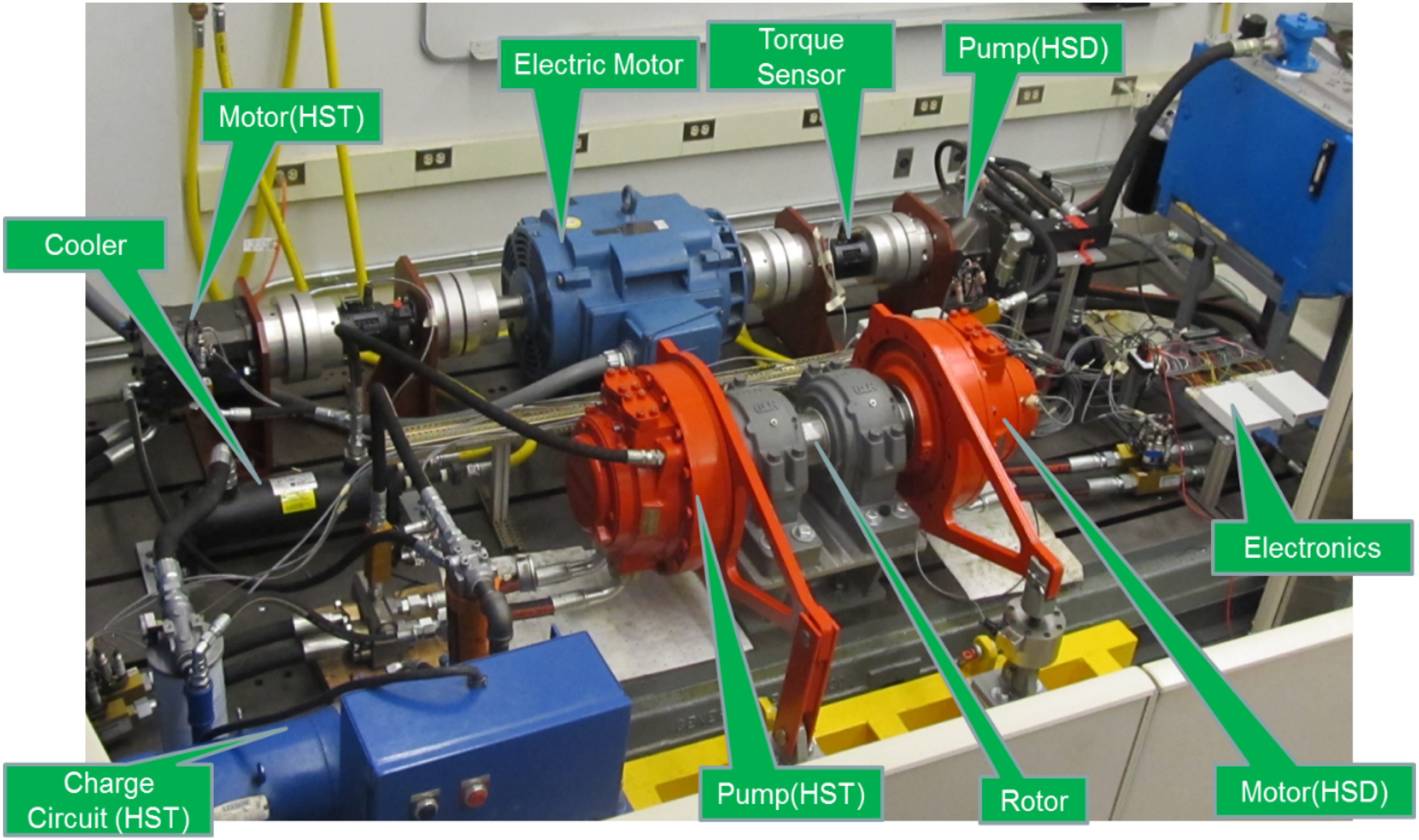
# Power regenerative test platform




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

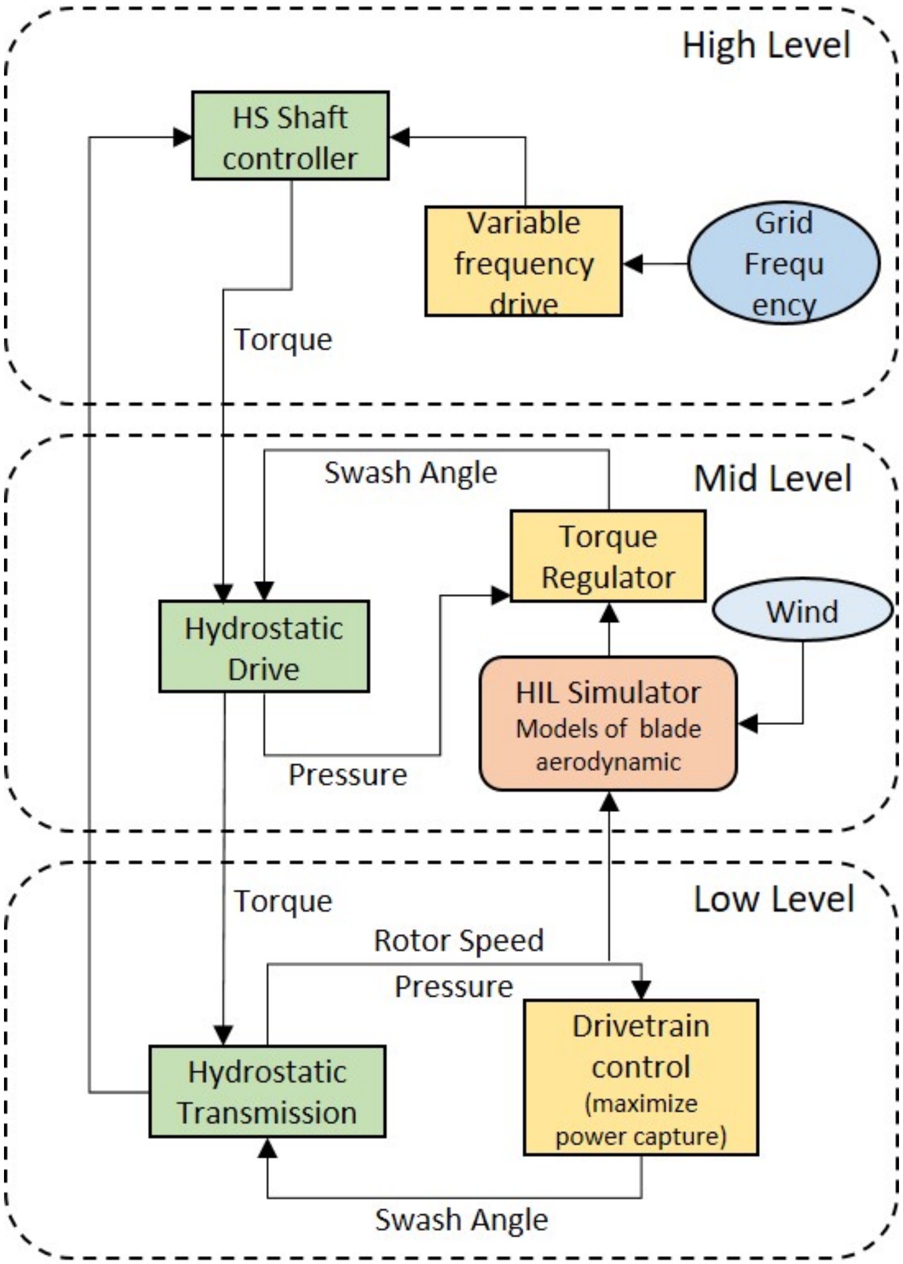
1. Capable of simulating a turbine output power of 100 kW
2. Small electric motor (55kW) to compensate for losses in the components

# Power regenerative test platform



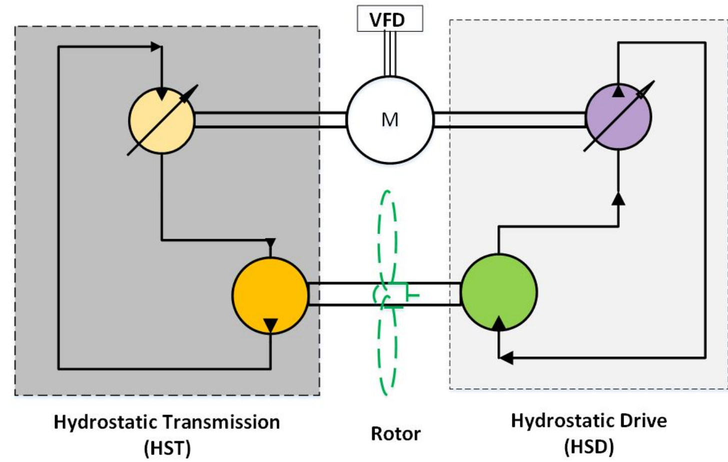
# Controller Design

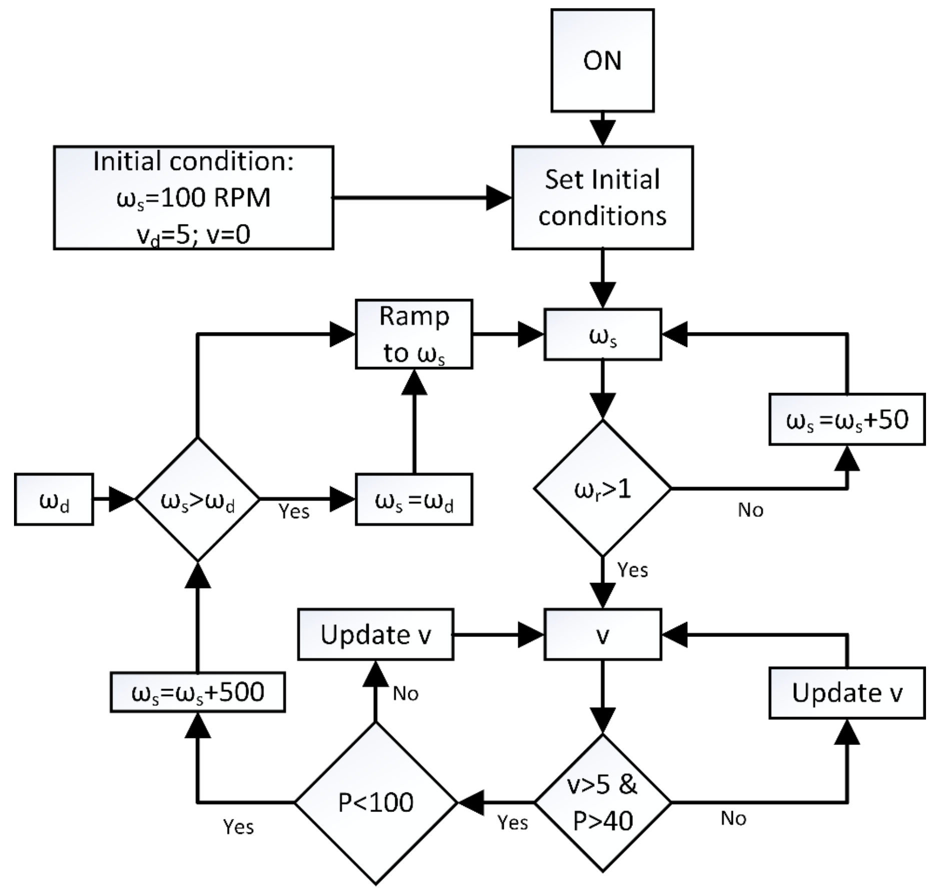
- High Level: Grid frequency is simulated by an electric motor and a variable frequency drive
- Mid Level: HIL simulator is used to simulate rotor torque from wind data and rotor speed. The rotor torque is then emulated by controlling swash angle of HSD pump.
- Low Level: Swash plate of the HST motor is controlled to optimize the power capture.
- The power from drivetrain is fed to the test platform to drive HSD pump along with electric motor.



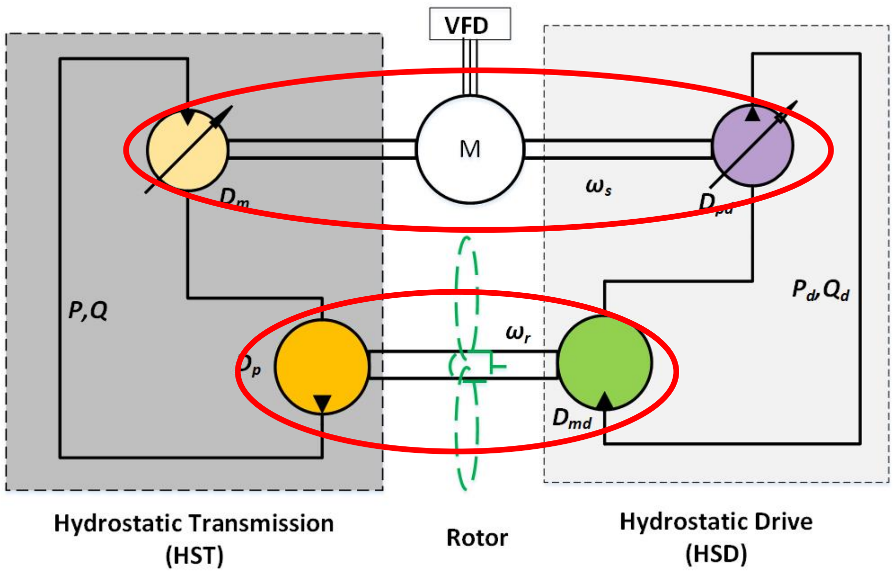
# Controller Design: Start up

- Particular attention is required to avoid cavitation and pressure spikes during start and stop cycle for smooth operation and safety of the testbed.
- Start cycle: HS shaft speed is brought to synchronous speed
- Test cycle: Mid and low level controllers are design to regulate the HSD pressure to emulate the rotor torque from wind input and HST pressure to optimize the power capture.
- Stop cycle: High speed shaft speed is brought to rest from synchronous speed.



# Modeling of the test platform




## High Speed Shaft Dynamics:

$$\dot{\omega}_s = \frac{1}{J_s}\left[-b_s\omega_s + \alpha D_m P + \tau_e - \chi D_{pd} P_d\right]$$

## HSD Pressure Dynamics:

$$\dot{P}_d = \frac{\beta_{ed}}{V_d}\left[\chi D_{pd}\omega_s - D_{md}\omega_r - Q_{ld}\right]$$

$$\frac{1}{\beta_{ed}} = \frac{1}{\beta_f} + \frac{1}{\beta_h} + \frac{s}{1.4P_d}$$

## Low Speed Shaft Dynamics:

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

## HST Pressure Dynamics:

$$\dot{P} = \frac{\beta_e}{V}\left[D_p\omega_r - \alpha D_m\omega_s - Q_{lt}\right]$$

- **Control Input: Swashplate angle:** $\alpha, \chi, \tau_e$
- **States:** $\omega_r, P_d, P, \omega_s$
- **Unknown parameters:**

  **Leakage:** $Q_{ld}, Q_{lt}$

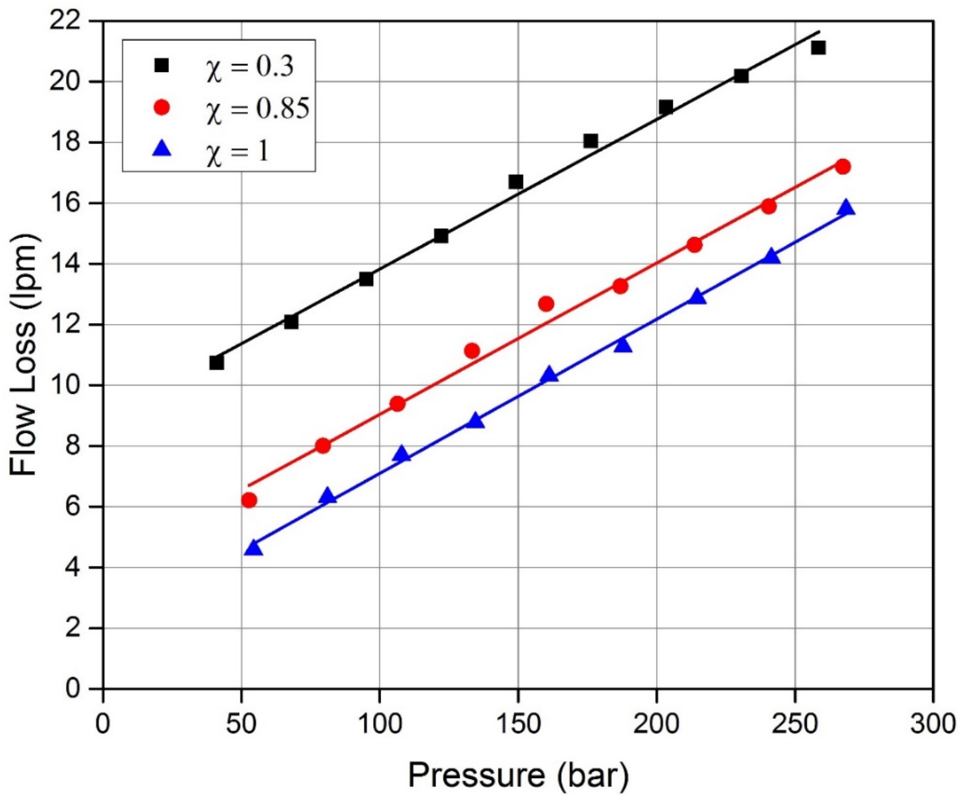
  **Viscous damping:** $b_r$

# Parameter Identification : Leakage Loss

- Leakage loss of the radial piston HSD motor and HST pump are negligible.
- Internal flow losses through cylinder-piston gap and port plate gap.
- Leakage flow increases with pressure and decreases with swash plate angle.
- Flow losses are modeled as a linear proportional to the pressure.
- Loss coefficient for the HSD pump is 0.049 lpm/bar.
- Loss coefficient for the HST motor is 0.010 lpm/bar.

$$\dot{P}_d = \frac{\beta_{ed}}{V_d}\left[\chi D_{pd}\omega_s - D_{md}\omega_r - Q_{ld}\right]$$

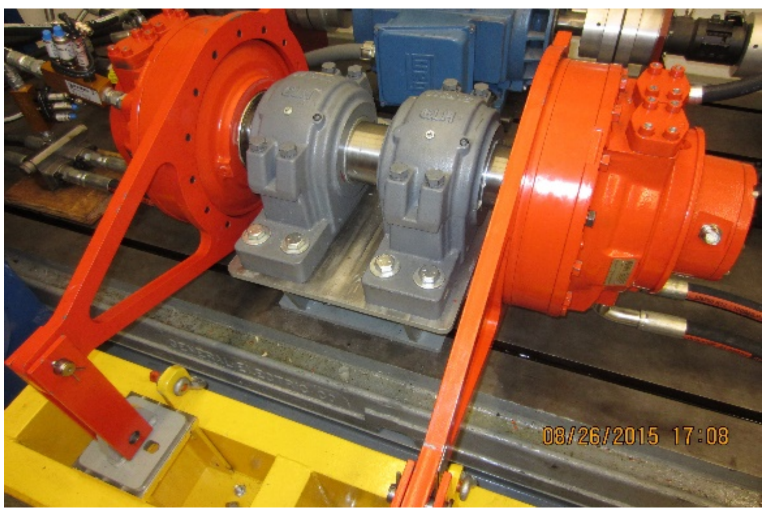
$$Q_{ld} = \chi D_{pd}\omega_s - Q_{out} = L_d P_d$$

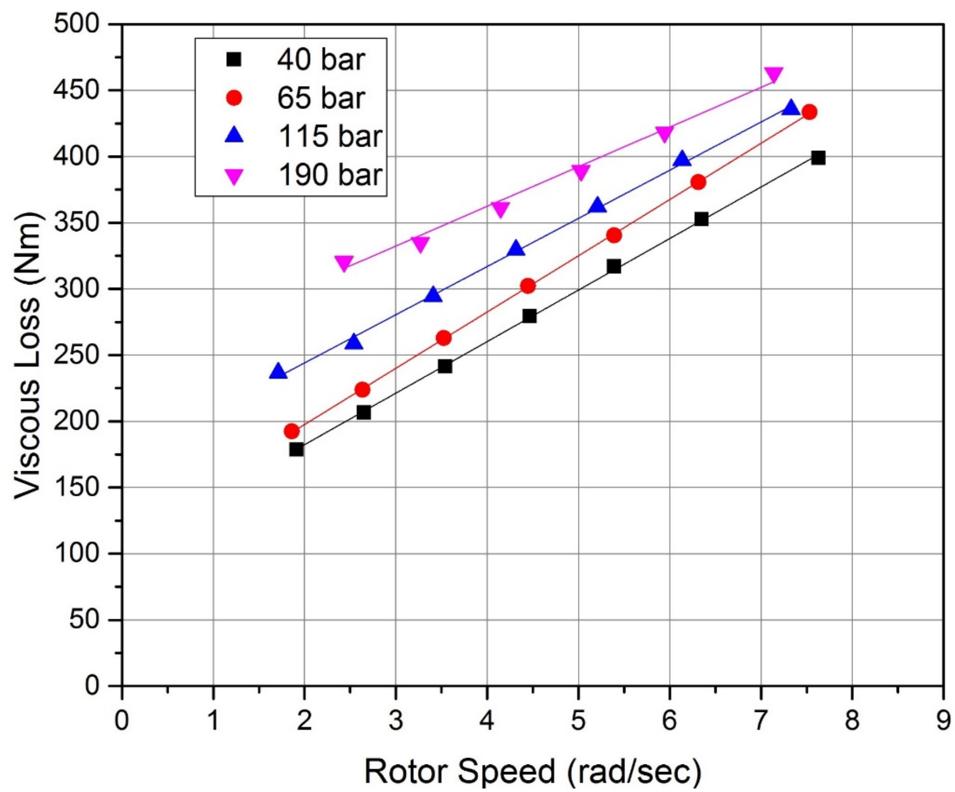


# Parameter Identification : Viscous Loss

- Viscous friction is directly proportional to rotor speed.
- At steady state (constant $\omega_r$), viscous loss is computed from rotor speed, HST and HSD pressure measurement.
- Viscous damping coefficient is computed from the slope, which is 38.9324 Nm-sec.

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





# Experimental Validation

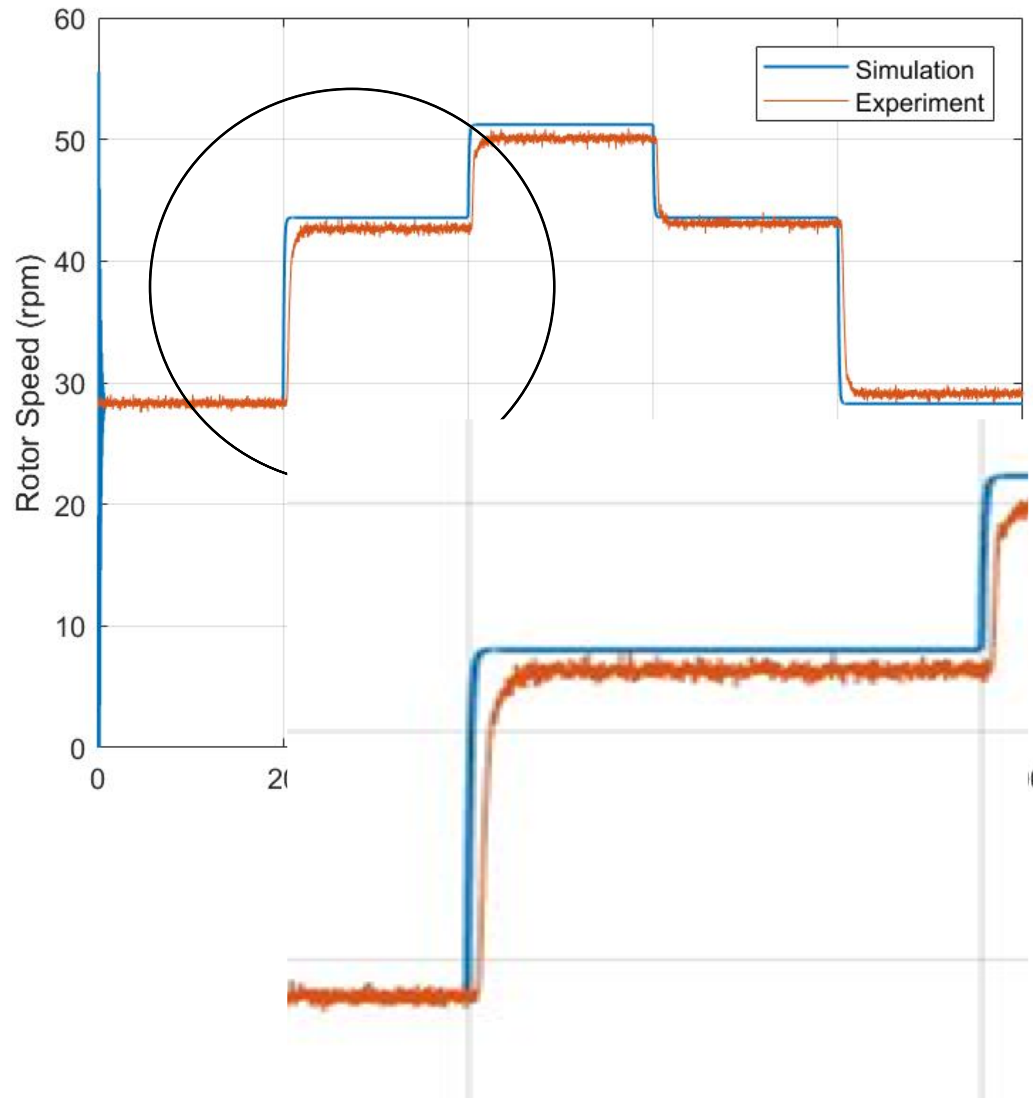
➢ Experimental set up:

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

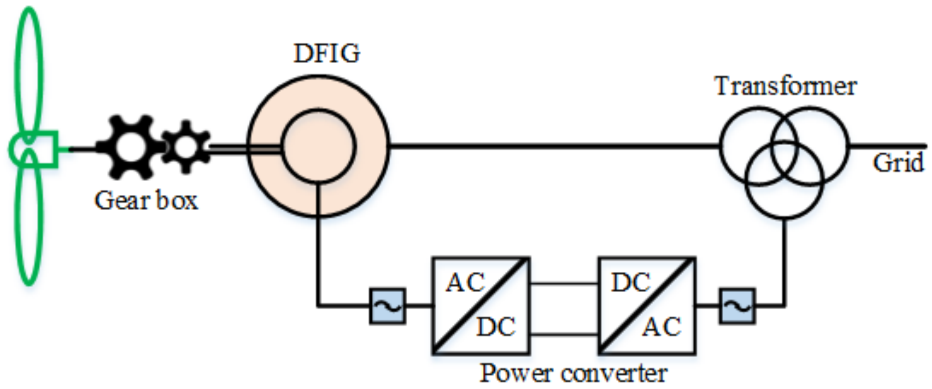
➢ At steady state, experimental results matches with simulation with maximum steady state error is 2 RPM.

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

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

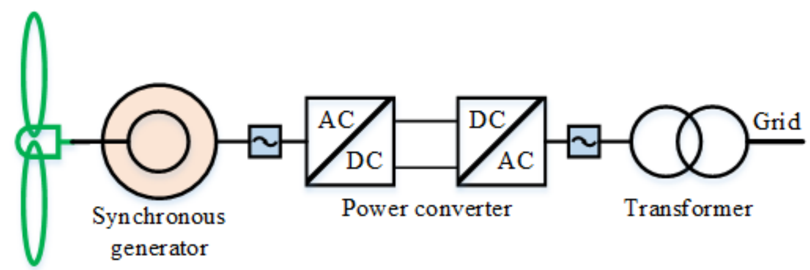


# Model interaction of the HST with the grid

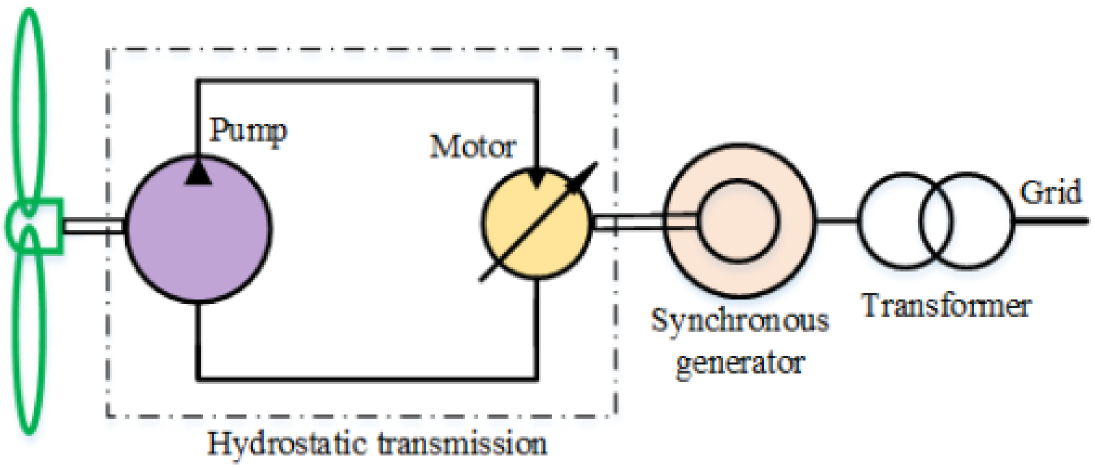


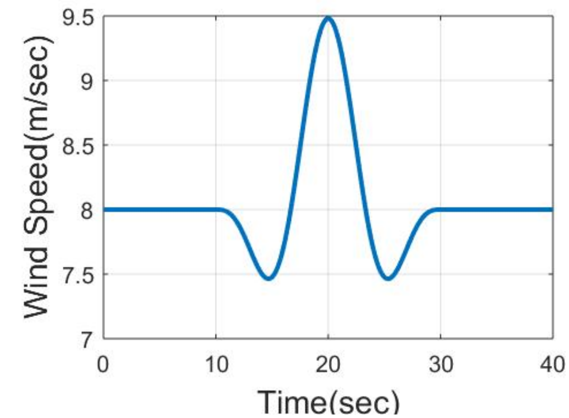

- Frequency and current of the rotor of the generator are controlled to maximize the power
- Slip ring with compromised reliability
- Power electronics interfaces in such topologies are around 30% of the turbine power

- Elimination of slip ring, even gear box
- More stressed and expensive power electronics
- Power-electronics interface has to be rated at the same power level of the turbine power



# Model interaction of the HST with the grid



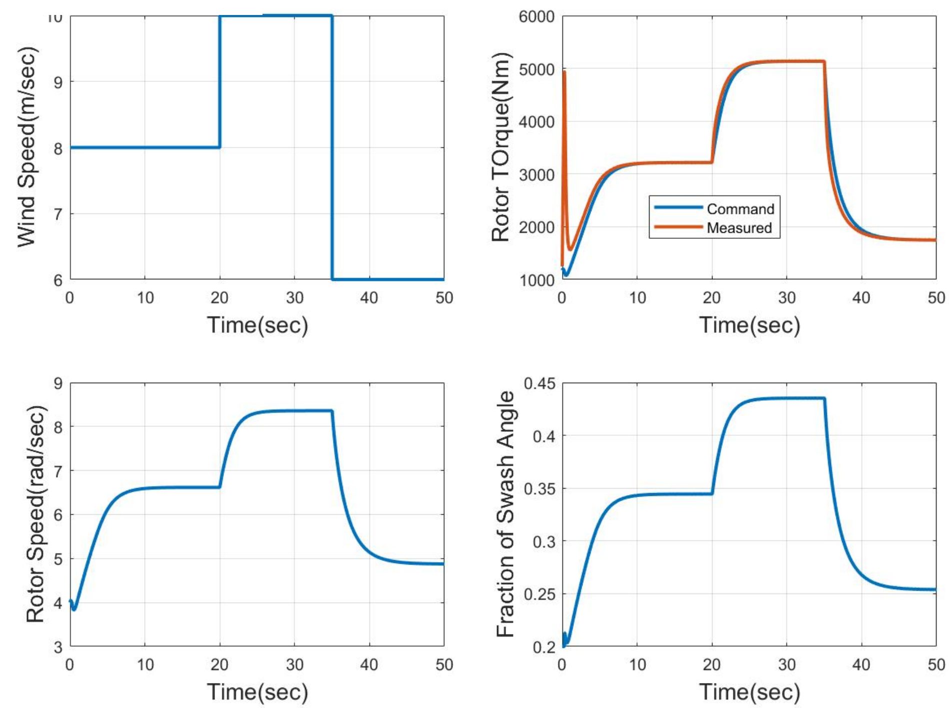

## Synchronous Generator Dynamics

$$\dot{\delta} = \omega_g - \omega_s$$

$$\dot{\omega}_g = \frac{\omega_s}{2H}\left[P_m - P_e - D_g(\omega_g - \omega_s)\right]$$

$$\dot{E}'_q = \frac{1}{T'_{do}}\left[E_{fd} - E'_q - (X_d - X'_d)\, I_d\right]$$

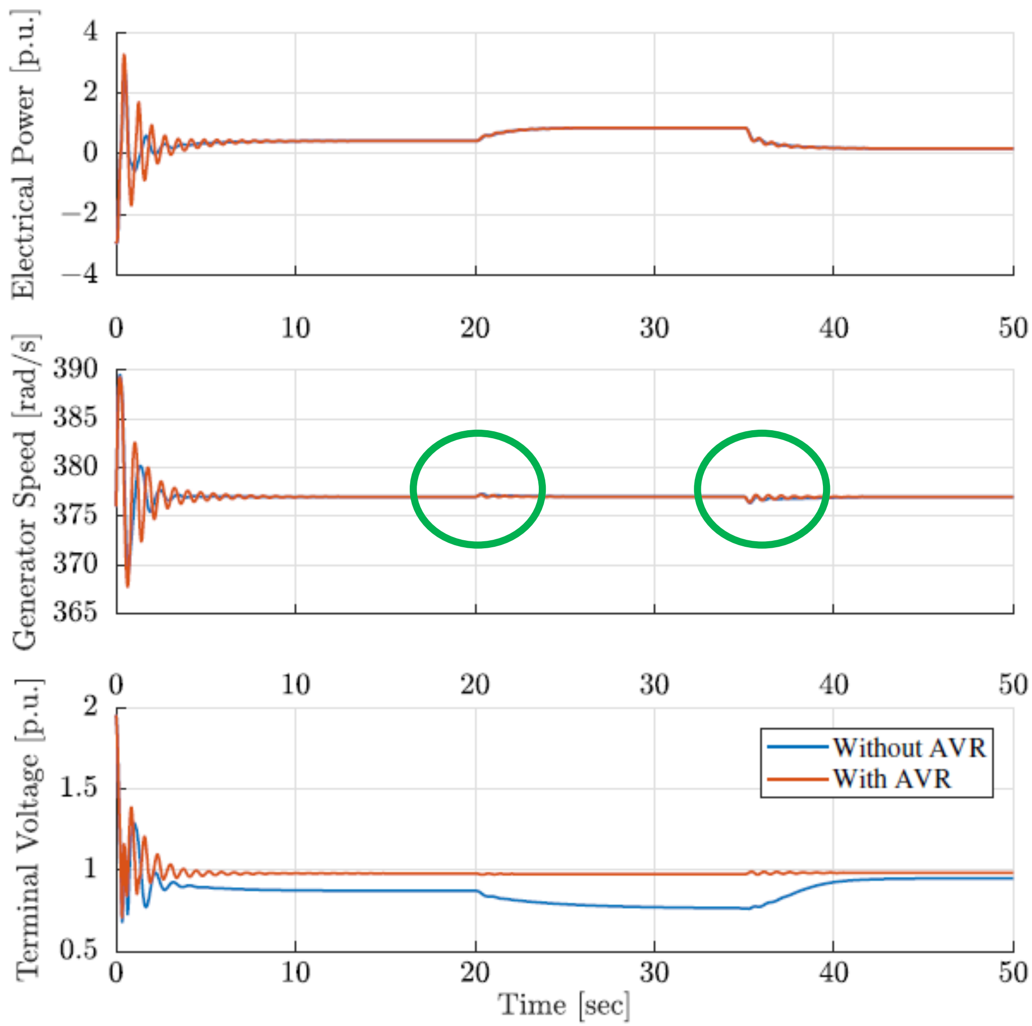
$$\dot{E}'_d = \frac{1}{T'_{qo}}\left[-E'_d + (X_q - X'_q)\, I_q\right]$$



# Model interaction of the HST with the grid

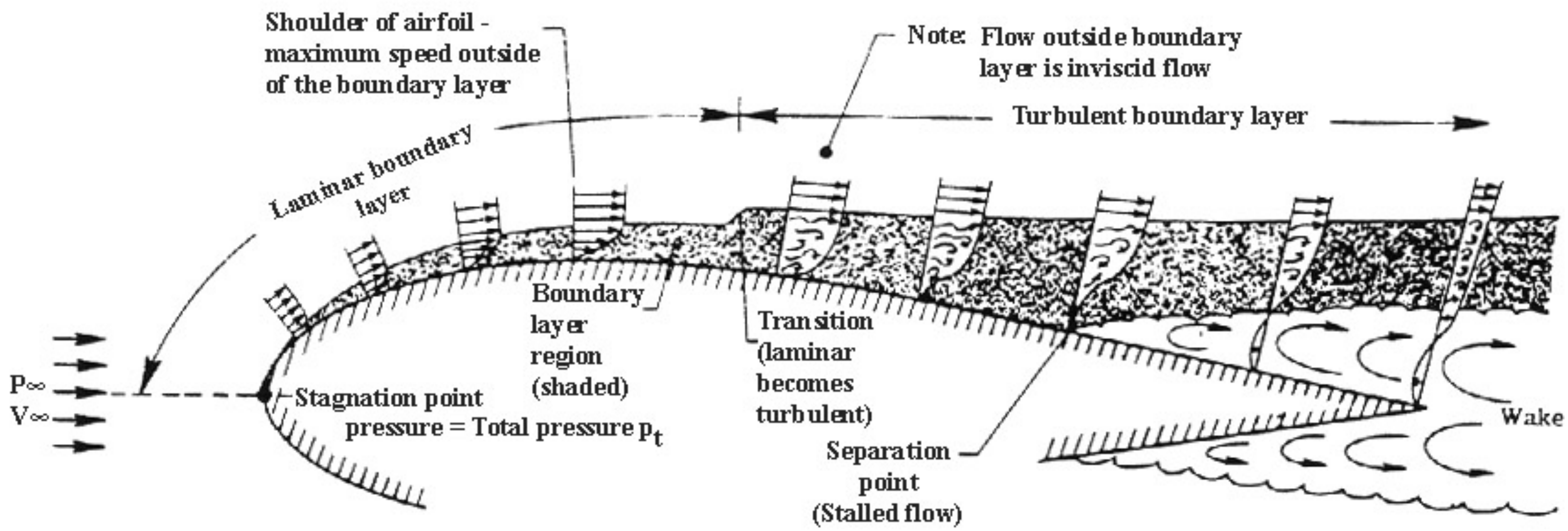
- The electrical power increases with increase in the wind speed.
- The compressibility of the fluid attenuates the effect of the wind gust transients and allows the generator speed to operate at synchronous speed.
- The AVR controls the field voltage of the generator to produce a constant terminal voltage.
- The frequency deviation is well under the regulation.

| Input | Generator Freq (Hz) | Terminal Voltage (pu) |
|---|---|---|
| Step Up | 0.047 | 0.09 |
| Step Down | 0.095 | 0.18 |
| Wind Gust | 0 | 0.11 |



# Effect of Unsteady Wind over Pitching Blade

- Fluid mechanics of unsteady flow with variable pitch is not well understood
- Combined effect will be studied to design an improved controller to capture more energy from the wind.
- A multivariable controller with combined pitch and torque control will be investigated.



# Dynamic Model for the Unsteady Wind

## Initial Experiment Design

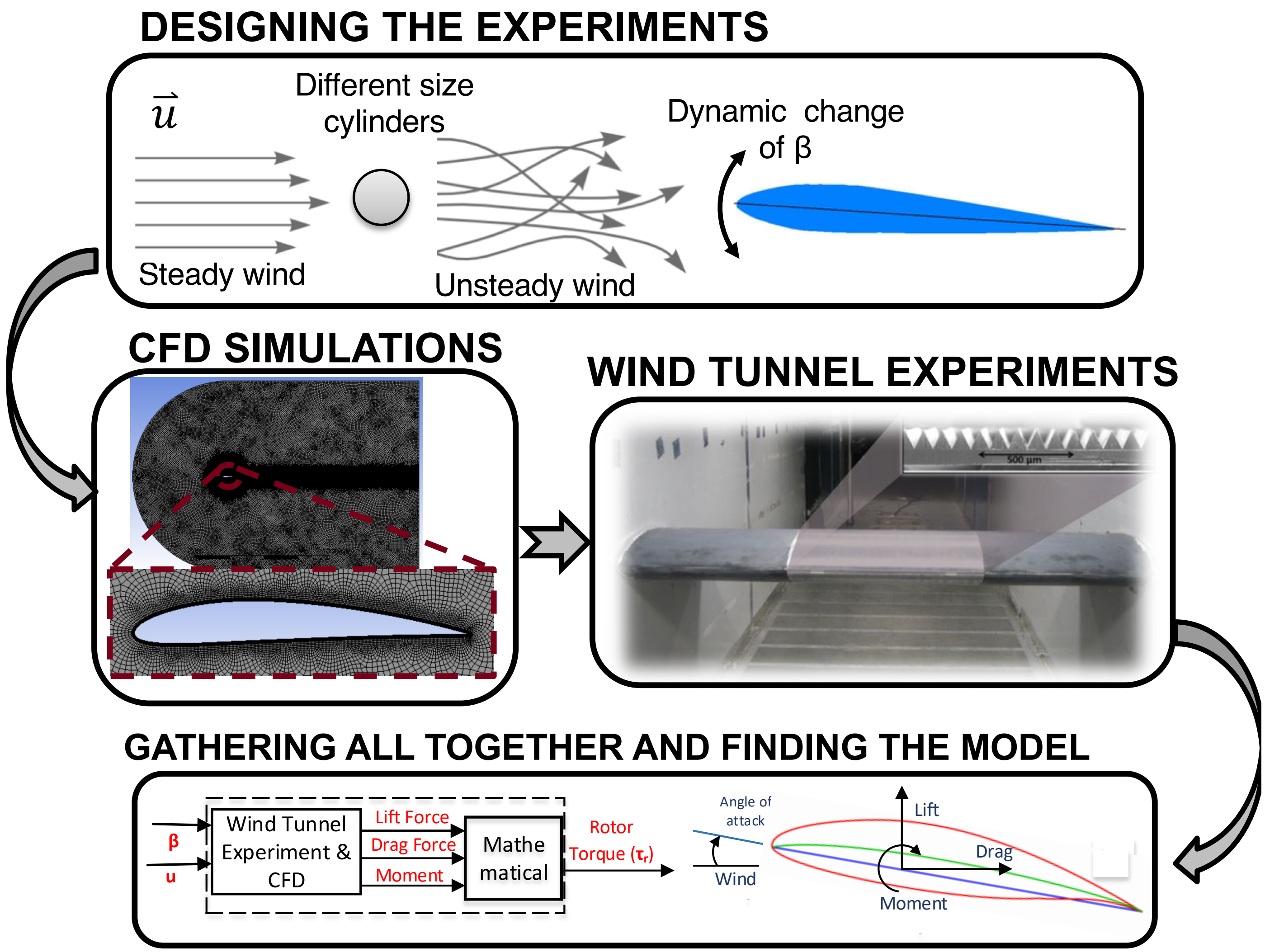
- Static airfoil with steady flow
- Static airfoil with unsteady flow
- Dynamic pitching of the airfoil with steady flow
- Dynamic pitching of the airfoil with unsteady flow

## CFD + Experimental Verification

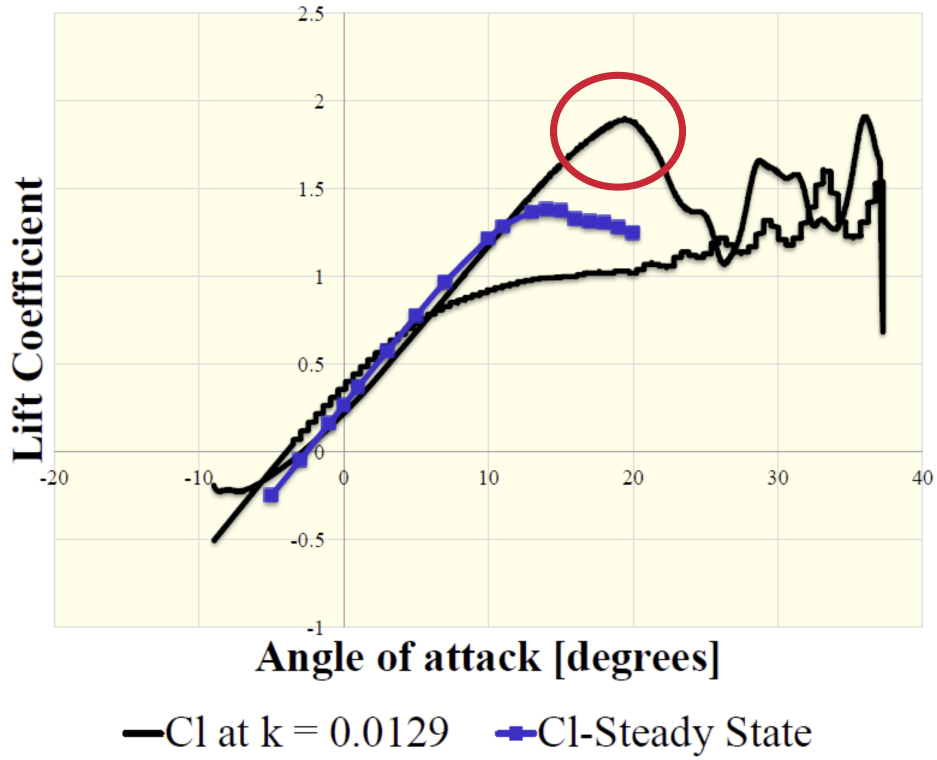
Analyzing both numerical and real data for obtaining reliable results.

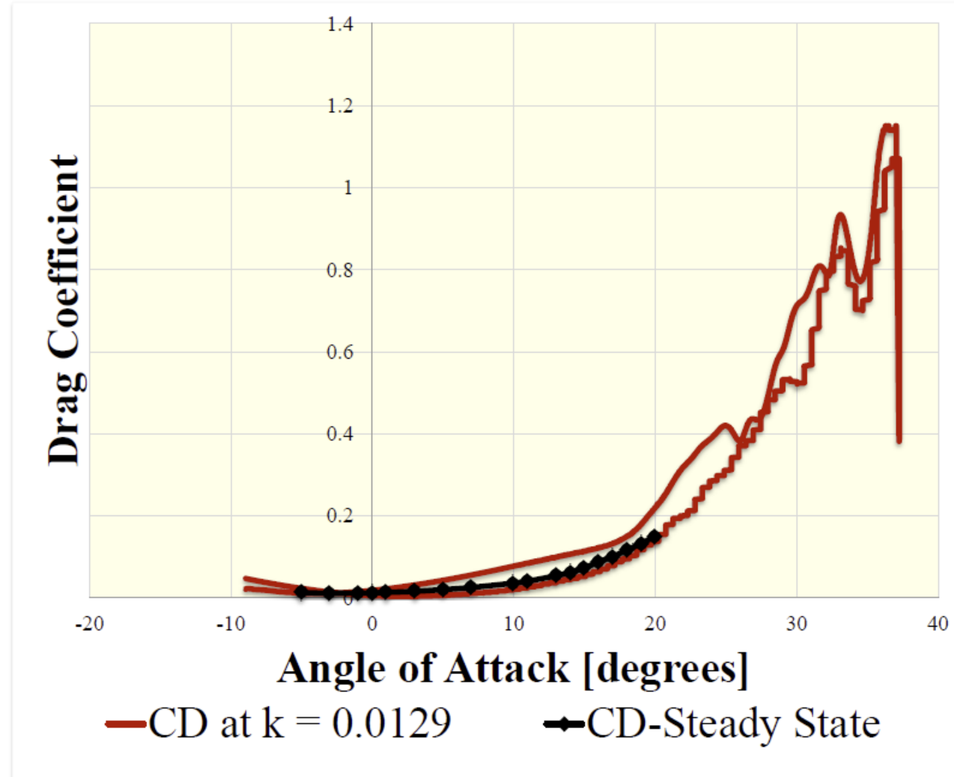
## System Identification

Using the gathered data and system identification tools for defining a dynamic model of the wind based on lift, drag and moments.



# CFD Simulation Results (Dynamic Pitching of an Airfoil under Steady Wind)




$k = \frac{\omega c}{2U}$ [dimentionless], $c = Chord\ length[meters(m)]$, $U = Wind\ Velocity \left[\frac{m}{s}\right]$ $\omega = Angular\ velocity \left[\frac{rad}{s}\right]$

- 50% lift coefficient improvement at 19 degrees under specific conditions. Higher improvements should be possible to achieve.
- Drag coefficient barely changes.

# 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.
- Midsize wind is a great opportunity to increase wind resources while preserving stability and reliability of the grid.
- Wind tunnel studies are underway to develop a model of combined unsteady wind and pitch.
- An HST transmission is a variable ratio, reliable, and cost effective alternative to a fixed ratio mechanical gearbox.

# Thank you!

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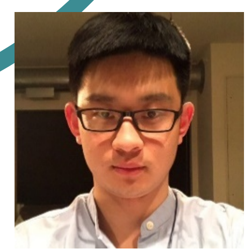

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