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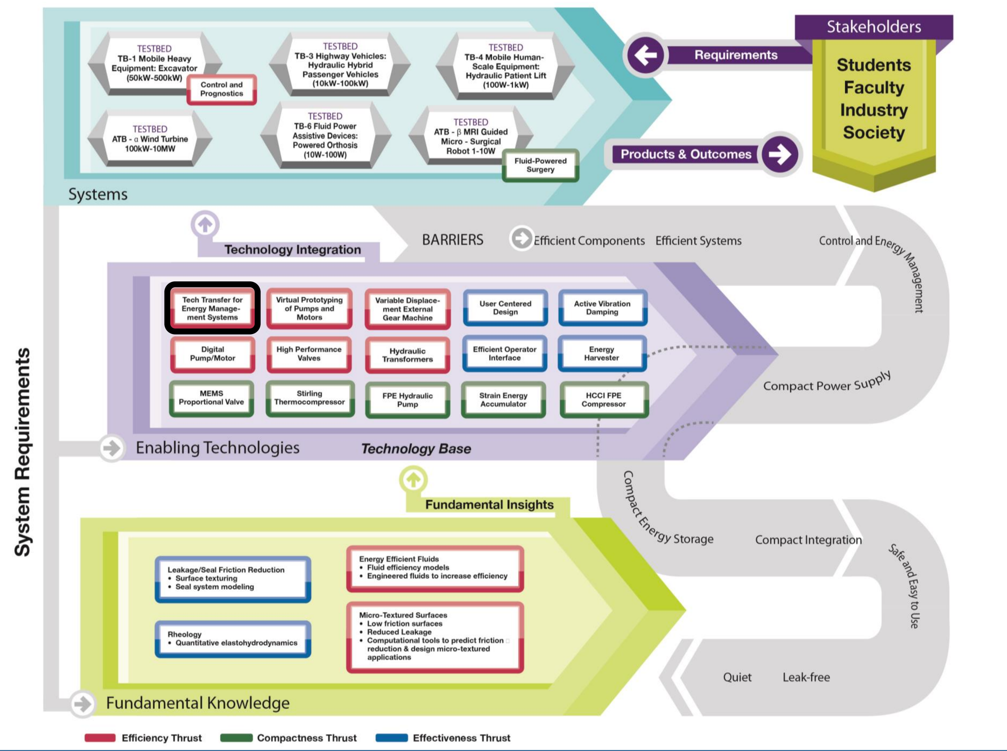

Hybridizing Wind Turbine Transmissions: Continued simulation and Experimentation

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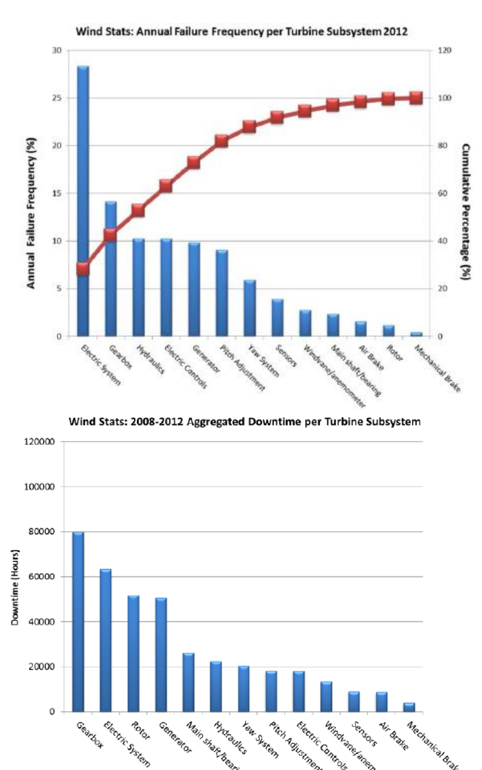
Background

Mid-size wind (100 kW-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.

Hydrostatic Wind Turbine



WindStats Data

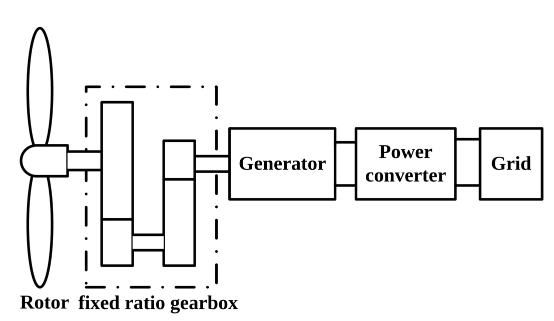
- Electrical system has highest failure rate and Gear Box has longest downtime per failure

Performance Objective

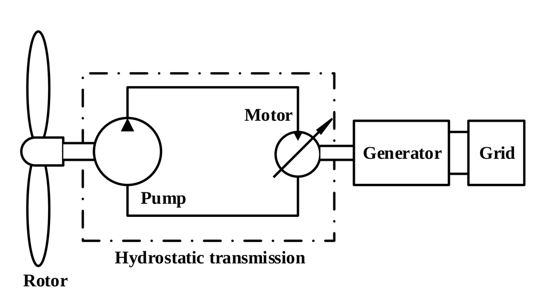
- Maximize power capture
- Minimize loads
- Reduce downtime
- Reduce maintenance cost

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

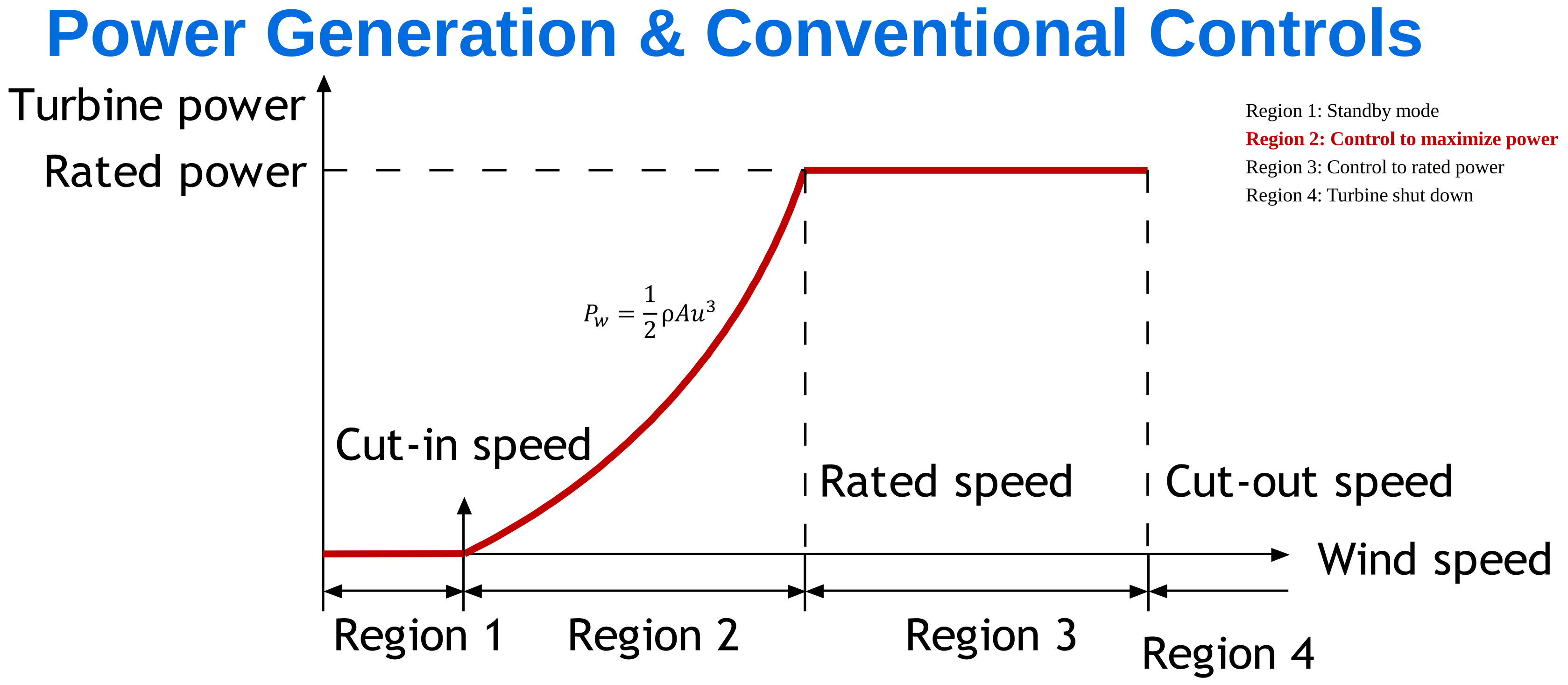


Conventional gearbox turbine



Hydrostatic wind turbine

Power Generation & Conventional Controls



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

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:**

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

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

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

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

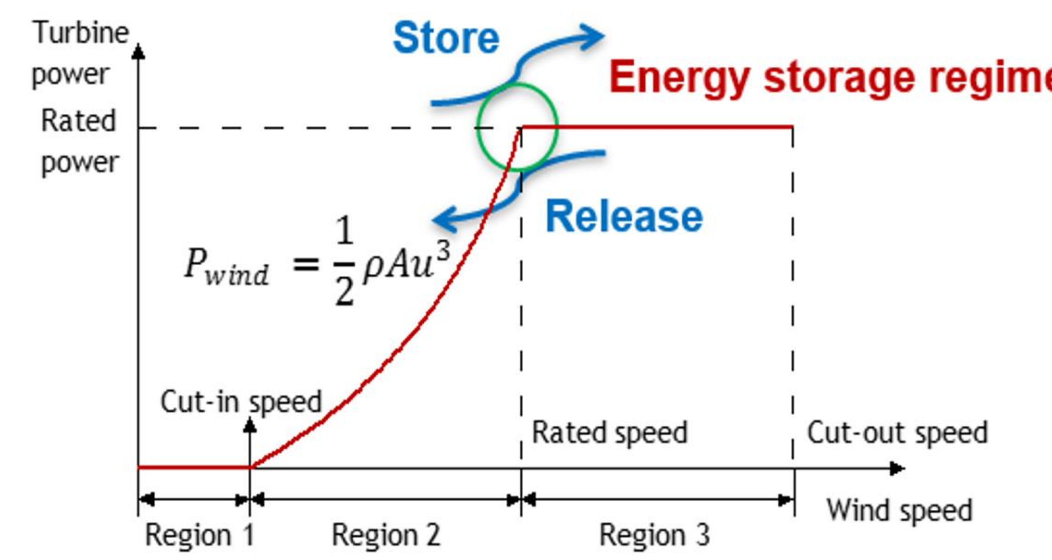
- **Dynamics of the rotor**

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

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

Energy Storage

- Temporarily store excess energy due to turbulent wind
- Release energy once wind speed drops
- Use a simple hydraulic accumulator to add a method of energy storage
- Hybridization technique produces usable energy normally wasted



Accumulator Dynamics

Adiabatic Assumption: (Fast Charging)

$P_0V_0^{1.4} = P_1V_1^{1.4} = P_2V_2^{1.4} = PV^{1.4}$

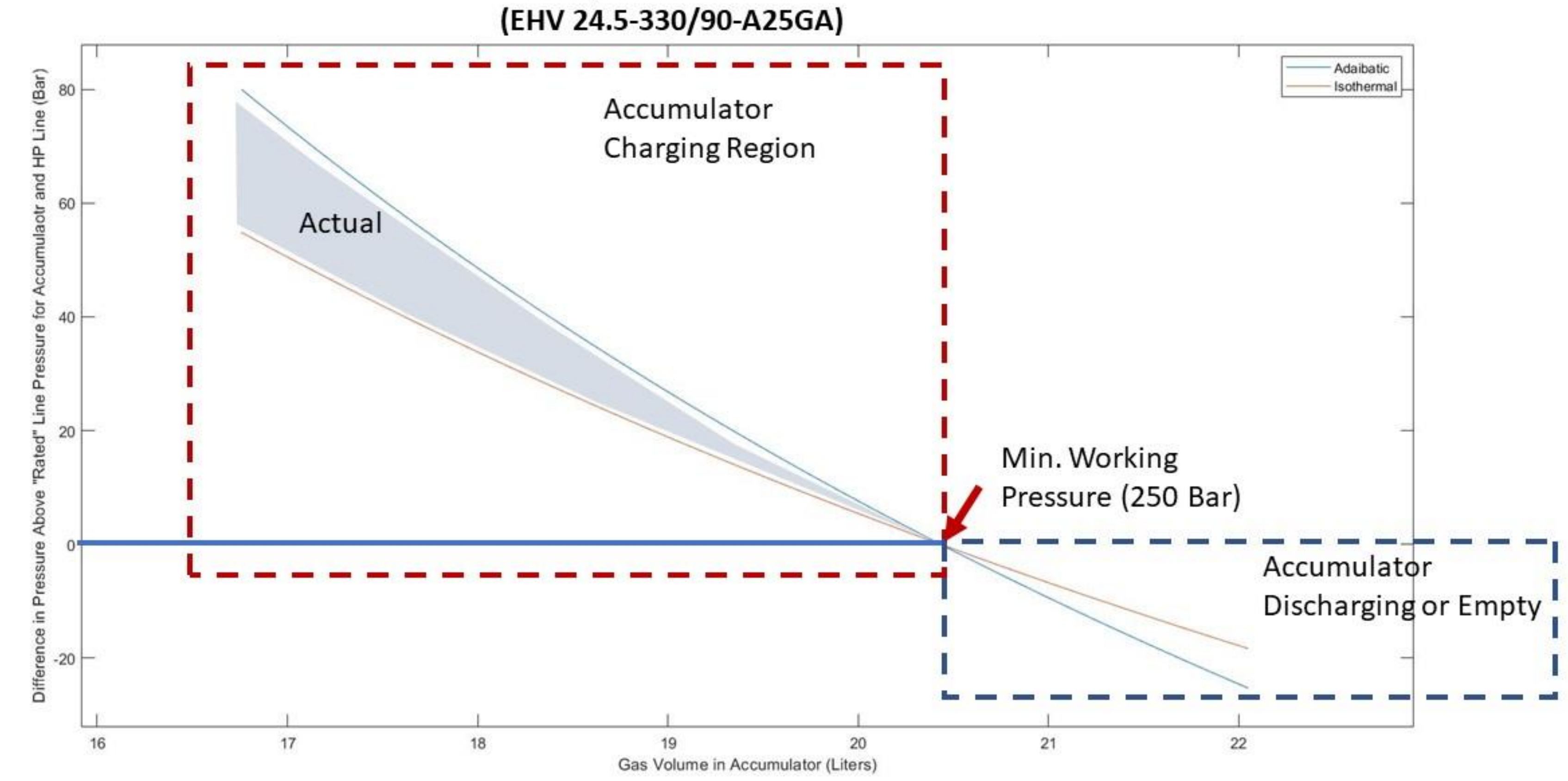
Isothermal Assumption: (Slow Charging)

$P_0V_0 = P_1V_1 = P_2V_2 = PV$

Parameters

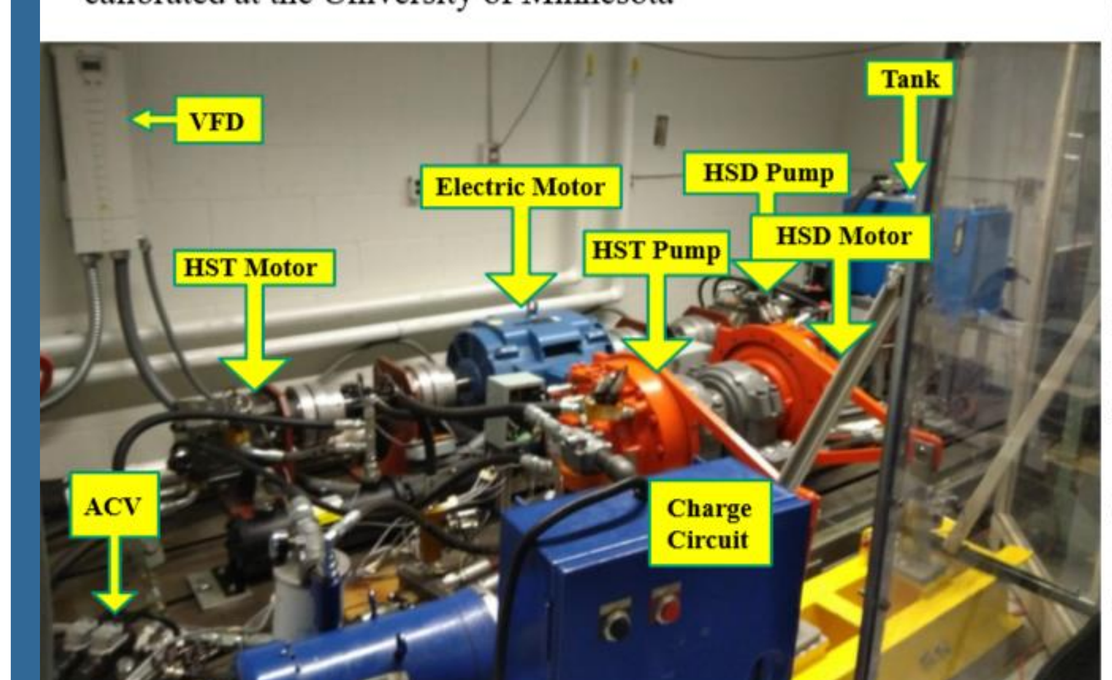
P_0 = *Precharge Pressure*	P_1 = *Working Pressure*	P_2 = *Max Working Pressure*
V_0 = *Precharge Volume (N2 Gas)* (90-95% of Accumulator Volume)	(*Pressure to charge*) V_1 = *Working Volume (N2)*	V_2 = *Min Volume (N2)*

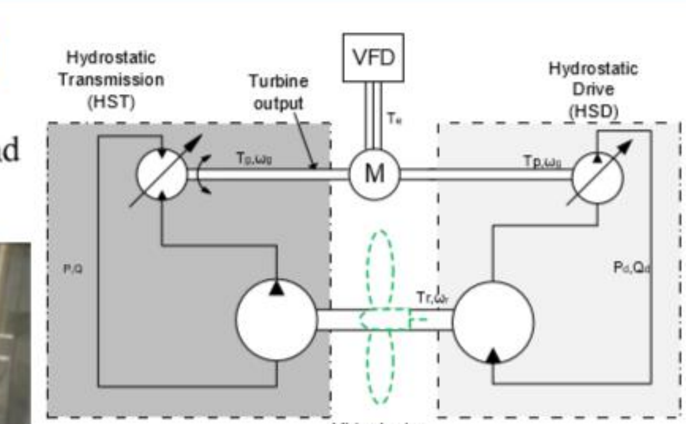
330Bar, 24.5 Liter Accumulator (EHV 24.5-330/90-A25GA)



Power Regenerative Test Bed

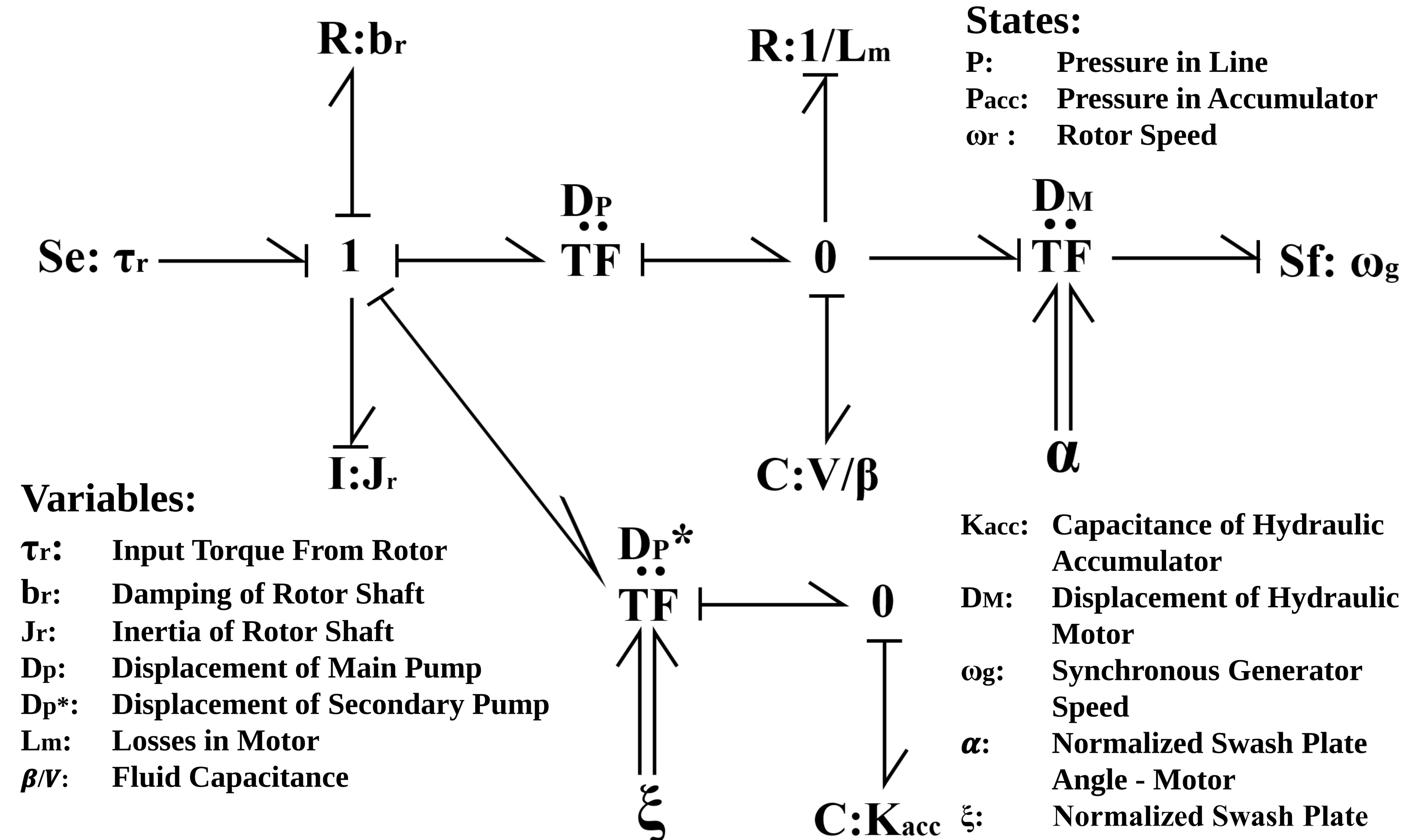
- A Power regenerative test bed has been built, characterized, and calibrated at the University of Minnesota





- A HydroStatic Drive (HSD) with Hardware-in-the-loop simulation is capable of creating turbulent wind simulations with real-life torque
- VFD powered electric motor supplements system to keep full operation
- Goal: Perform experiments with installed accumulator

Dynamics of HST With Accumulator



States:

P:	**Pressure in Line**
Pacc:	**Pressure in Accumulator**
ωr :	**Rotor Speed**

Variables:

τr:	**Input Torque From Rotor**
br:	**Damping of Rotor Shaft**
Jr:	**Inertia of Rotor Shaft**
Dp:	**Displacement of Main Pump**
Dp*:	**Displacement of Secondary Pump**
Lm:	**Losses in Motor**
β/V:	**Fluid Capacitance**
Kacc:	**Capacitance of Hydraulic Accumulator**
DM:	**Displacement of Hydraulic Motor**
ωg:	**Synchronous Generator Speed**
α:	**Normalized Swash Plate Angle - Motor**
ξ:	**Normalized Swash Plate Angle – Secondary Pump**

High-Fidelity Dynamic Equations

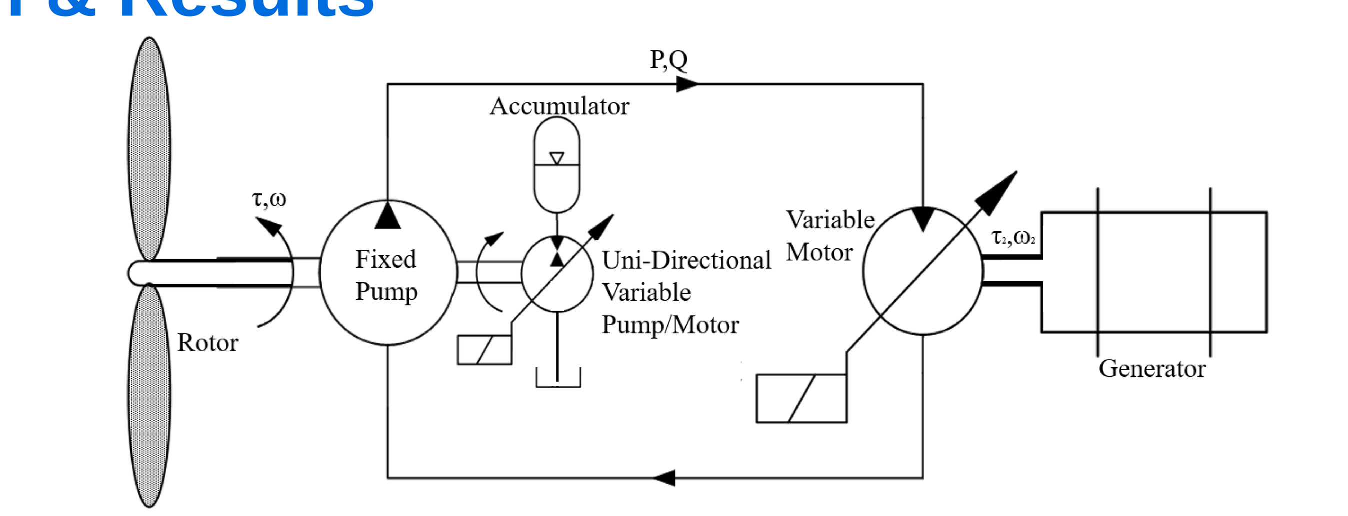
$$J_r\dot{\omega}_r + b_r\omega_r = \tau_r - D_P P - D_P^* P_{acc}$$

$$\frac{V}{\beta}\dot{P} = D_P\,\omega_r - L_m P - \alpha D_m \omega g$$

$$K_{acc}\dot{P} = \xi D_P^*\,\omega_r$$

$$K_{acc} = \frac{P}{\gamma P_{min} V_{max}^{\gamma}}$$

Design & Results



- In simulation, the above design showed preliminary results of an additional 130 kJ of energy were captured in a specific five-minute period.
- Outside of the extent of this UROP project, the experiments are underway, as well as additional optimization methods in simulation

Conclusions, References, Acknowledgements

- Hydrostatic transmissions are a more cost-effective and reliable solution for midsize wind applications.
- Short-term energy storage with a hydraulic accumulator can improve the turbine energy production
- The power regenerative wind turbine test platform provides a powerful tool to simulate real world HST turbine behavior, and has experimental potential for validation of simulation

1. R. Dutta, F. Wang, B. Bohlmann, and K. Stelson, "Analysis of short-term energy storage for mid-size hydrostatic wind turbine," Trans. ASME, J. Dyn. Syst., Meas., Control, vol.136, no.1, 2014.
2. F. Wang, B. Trietch, and K. A. Stelson, "Mid-sized wind turbine with hydro-mechanical transmission demonstrates improved energy production," in Proc. 8th Int. Conf. Fluid Power Transmission and Control, Hangzhou, China, 2013.
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