Hydraulic Transmissions for Wind Energy

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Outline

1. Introduction
2. Control of wind turbines
3. Power regenerative wind turbine test platform
4. Future work
5. Conclusions
Opportunity

- Fastest growing green energy source
- 432 GW by 2015, 5% of the global electricity demand
- 74.82 GW by 2015, 5.13% of the U.S. electricity demand
- DOE set goal of 20% of U.S. energy from wind by 2030
- Midsize wind turbines are an attractive but under recognized means to meet this goal
Midsize wind opportunity

Midsize 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.
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

### Two-Stage Planetary with One-Stage Parallel Shaft

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>2.3 - 2.9 MW @ 14 - 16 RPM input speed</td>
</tr>
<tr>
<td>Input Torque</td>
<td>1500 - 1920 kNm</td>
</tr>
<tr>
<td>Ratio</td>
<td>78:1 - 136:1</td>
</tr>
<tr>
<td>Output Shaft Type/Location</td>
<td>Horizontal output shaft located at a 550 mm centerline distance</td>
</tr>
<tr>
<td>Approx. Weight</td>
<td>21,100 kg (46,500 lbs)</td>
</tr>
<tr>
<td>Overall Length</td>
<td>2550 mm</td>
</tr>
</tbody>
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Components reliability

- WindStats Data
  - 5,000 turbines from Denmark, 24,000 from Germany & 1,200 from Sweden
- Electrical system has highest failure rate
- Gear Box has longest downtime per failure
- Drive train repairs are more expensive due to the crane costs.
Potential of HST 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 Industry

Mitsubishi 7MW Sea Angel offshore turbine

Core technology: Digital displacement technology by Artemis

93.5% peak efficiency from shaft-to-shaft, and also very efficient in part load too
Conventional wind 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.

Conventional wind turbine control in region 2

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

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

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

where the gain $K$ is given by blade parameters.

$$K = \frac{1}{2} \rho AR^3 \frac{C_{p_{\text{max}}}}{\lambda_*^3}$$

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**Dynamics of the rotor**

$$\dot{\omega}_r = \frac{1}{2J} \rho AR^3 \omega_r^2 \left( \frac{C_p}{\lambda^3} - \frac{C_{p_{\text{max}}}}{\lambda_*^3} \right)$$

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**The beauty of the $k\omega^2$ 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

Control strategy

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

\[ p_c = \tau_c \cdot \frac{\eta_p}{D_p} \]

where \(\eta_p\) is the pump mechanical efficiency.

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

- 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.

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 105 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:  
\[
\dot{\omega}_g = \frac{1}{J_g} \left[ -b_g \omega_g + x D_m P \eta_{mm} + \tau_e - \frac{x_d D_{pd} P_d}{\eta_{mpd}} \right]
\]

HSD  
\[
\dot{P}_d = \frac{B_d}{V_d} \left[ x_d D_{pd} \omega_g \eta_{vp} - \frac{D_{md} \omega_r}{\eta_{vmd}} \right]
\]

HST  
\[
\dot{\omega}_r = \frac{1}{J_r} \left[ -b_r \omega_r + \tau_r (\omega_r, u, \beta) - \frac{D_p P}{\eta_{mp}} \right]
\]

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

States: \( \omega_g, \omega_r, P, P_d \)
Controller: \( x, \tau_e, x_d \)
Rotor torque simulation

- Aerodynamic torque is a function of pitch angle, rotor speed and wind speed.
- To generate steady state aero dynamic torque (wind velocity is constant), the blade dynamics of the FAST code is used.
- To simulate real dynamics of the rotor of a turbine, the effect of the large blade inertia will be virtually simulated and the modified torque is applied on the rotor of the test platform:
  \[ \tau_d = \tau_r - (J_r - J_s)\dot{\omega}_r \]
- Design a controller to track desired torque using HSD circuit.
Short-term energy storage

Energy storage configuration

- **Sensitivity study**: accumulator size on annual energy production (AEP) in a 50 kW turbine:
  - 40 liter accumulator increases AEP by 3.4%
  - 60 liter accumulator increases AEP by 4.1%
- **A cost analysis** is required to determine whether the AEP increase will offset the cost increase of implementing the system.

Future work

- Parameter identification of the test platform. (Ongoing)
- Performance of the HST with standard torque controller.
- Create dynamic model for the effect of unsteady wind and blade pitching from experiments
- Develop a multivariable optimal control strategy to enhance energy capture.
- Investigate the performance of a hybrid drivetrain with a hydraulic accumulator for better energy management.
Conclusions

- Midsize wind is a great opportunity to increase wind resources while preserving stability and reliability of the grid.
- Hydrostatic transmissions are a more cost-effective and reliable solution for midsize wind applications.
- The proposed HST turbine control strategy based on torque control law is applicable to a real world HST turbine.
- 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.
- Further improvements could come from advanced turbine control strategies, more efficient hydraulic transmissions and new hydraulic fluids.
Thank you!

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