Project 1J.1: Hydraulic Transmissions for Wind Energy

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Outline

1. Introduction
2. Research topics
   - Hydrostatic turbine control
   - Short-term energy storage
   - Hydro-mechanical transmission
3. Power regenerative wind turbine test platform
4. Conclusions
Introduction

- Fastest growing clean and green energy sources
- 370 GW by 2014, 5% of the global electricity demand
- Denmark has goal of 50% wind by 2020
- 67.87 GW till June 2015, 5.13% of the U.S. electricity demand
- DOE set goal of 20% of U.S. energy from wind by 2030
Turbine Components

- 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>Feature</th>
<th>Specification</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>
</table>
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 captured power
- 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. ChapDrive (Norway)
2. Windera Power System (Florida)
3. WindSmart (Canada)
4. 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
Midsize HST turbine in CCEFP

CCEFP target: midsize wind (100 kW-1 MW):

- Community wind - cost-effective way for farms, communities or factories
- Relatively easy permitting process
- Few midsize turbines in the market today
- Commercially available hydrostatic units

Mid-size turbines can be designed as locally distributed type, eliminating the costly electric power transmission and improving energy use efficiency.
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** (\(C_P\)) 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

Region 2 Control (Existing)

- **Objective**: Maximize power captured
- **Strategy**: Constant pitch angle $\beta$ 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.

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

- **Dynamics of the rotor**

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

- **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.
Control strategy

1. Use rotor speed to generate rotor reaction torque (pump torque) command (kω² law)
2. Convert pump torque command to line pressure command
3. Track the line pressure by adjusting motor displacement through PI controller

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.

HST turbine control in region 2

Dynamic simulation model

Main features of the simulation model:
1. Physical equation based components model;
2. Use bond graph method to determine the causality;
3. Use FAST code to generate rotor efficiency map;
4. Use pump/motor efficiency map to determine the HST losses;
5. Use distributed line model to simulate line dynamics and losses.
6. Take the charge pump power into consideration.
Short-term energy storage

➢ To increase the energy capture of an HST wind turbine, a short-term energy storage system using a hydraulic accumulator is proposed.

\[ P_{\text{wind}} = \frac{1}{2} \rho A u^3 \]

➢ Captures excess energy when the wind speed is above rated (region 3)
➢ Release stored energy when the wind speed is below rated (region 2).

Wind turbulence: Gaussian distribution

10 minutes turbulent wind profile

Short-term energy storage

Energy storage configuration

- Rotor
- Accumulator
- Fixed pump
- Displacement control
- M1 – Variable motor
- M2 – Variable pump/motor
- Generator

Generator power with and without storage

- **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.

Hydro-mechanical wind turbine

- A hydro-mechanical transmission combines the advantages of **high efficiency of a gearbox** and variable function of an HST.

- **HMT vs HST (real-world components data)**

![Diagram of Hydro-mechanical wind turbine (PGS+HST)]

A. 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 (assuming overall efficiencies of the pump and motor are 90% each)
A. Power Regenerative Test Platform

- **Virtual rotor**
  - 2512 cc Hagglunds motors (act as pump)

- **Electric power input**
  - 135 cc Linde variable motor

- **Turbine output**
  - 2512 cc Hagglunds motors

- **Additional components**
  - 180 cc Bosch variable pump
  - Heat Exchanger
  - Charge pump
A. Power Regenerative Test Platform (Status)
A. Wind turbine rotor simulation

- Aerodynamic torque is a function of pitch angle, rotor speed and wind speed
- 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

\[ \tau_d = \tau_r - (J_r - J_s)\omega_r \]

- Design a controller to track desired torque using HSD circuit
- To generate aero dynamic torque for 105 kW turbine by modifying the blade dynamics of the FAST code
Conclusions

- The proposed HST turbine control strategy based on torque control law is applicable to the real world HST turbine.

- Short-term energy storage with hydraulic accumulator can improve the turbine energy production. A cost analysis is required to determine whether the energy increase will offset the cost increase of implementing such system.

- A hydro-mechanical transmission combines the advantages of high efficiency of a gearbox and variable function of an HST, resulting in a high turbine energy production. The cost and reliability analysis is still required.

- The power regeneration wind turbine test platform enables simulating the real word HST turbine behaviors in the lab, providing a powerful tool to investigate research topics.

- New improvements could come from advanced turbine control strategies, more efficient hydraulic transmissions and new hydraulic fluids.
Thank you!

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