Hybrid Dynamics of Wind Turbine Models

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Background

- As the amount of wind generation grows, its impact on power system dynamic behavior may become significant.

- Individual utilities must sign nondisclosure agreements (NDAs) to obtain accurate models from wind turbine generator (WTG) manufacturers.
  - The NDAs prevent use of manufacturer models in system-wide multi-utility studies.

- The Western Electricity Coordinating Council (WECC) has developed generic WTG models.
  - The aim is to determine parameter sets for the generic models by matching (as best possible) their behavior to the accurate manufacturer models.

- This talk focuses on Type 3 WTGs.
  - Doubly fed induction generators (DFIGs).
Model overview

Doubly fed induction generator

Converter Control Model

Generator/Converter Model

Pitch Control Model

Wind Turbine Model

Collector System (e.g., 3.4 kV bus)
Generator model

- Controlled current source.
- Phase locked loop is modeled.
Reactive power control

- Various different control modes are used.
  - Regulate generator terminal voltage.
    - Not a good idea, as difficult to coordinate setpoints with adjacent WTGs in a windfarm.
  - Regulate power factor or reactive power output.
    - Setpoint may be established by a centralized controller that's regulating the collector bus.

Typical collector system topology
**Torque control**

- **Anti-windup limits on PI integrator:**
  - If $P_{ord}$ is on its upper limit and $\omega_{err}$ is positive then the PI integrator is frozen.
  - Similar logic for lower limit.
  - This logic can result in sliding-mode behavior.
- **The error signal driving the PI integrator is** $\omega - \omega_{ref}$
  - Keep this in mind for later.
• The error signal driving the pitch control integrator is $\omega - \omega_{ref}$
  – A second integrator with this same input.
• If the pitch $\theta$ is on a limit, then a blocking strategy (similar to before) is used for the pitch control and pitch compensation integrators.
  – Again, sliding-mode behavior can result. (Example later.)
The figure shows the single-mass model; a two-mass model is also defined.

The simplified aerodynamic model is based on a simplification of the turbine $C_p$ curves.

When $\theta_0 = 0^o$, which is normally the case, mechanical power becomes

$$P_{mech} = P_{mo} - K_{aero} \theta^2$$

- Linearizing gives $\Delta P_{mech} = 0$ and an eigenvalue becomes zero.
- The influence of pitch angle on mechanical power is lost.
Sliding-mode behavior

• Disturbance: Three-phase fault followed by line tripping.
• Initial pitch angle \( \theta_0 = 0^\circ \) therefore damping is poor.

- Hysteresis logic: If
  - Input to \( x_C \) integrator is negative AND
  - (Pitch angle is on minimum limit OR
    - (Pitch angle lies within hysteresis band AND
      - \( x_C \) is already blocked ))
- Then block \( x_C \) integrator.
Sensitivity to hysteresis

- Trajectory sensitivities indicate that the width of the hysteresis band has no lasting effect on dynamic behavior.
- But hysteresis is necessary to generate solutions without resorting to Fillipov concepts.
Consequences of duplicate integrators

• Equilibrium conditions are underdetermined, and describe a 1-manifold.
  – The system can (theoretically) converge to any point on that manifold.

• Linearizing gives an A matrix that has linearly dependent rows.
  – The eigenvector corresponding to the 0-eigenvalue is locally tangent to the equilibrium manifold.
  – When $x_c$ is free to vary, it involves only $x_c, x_p$
  – When $x_c$ is fixed on a limit, it primarily involves $x_p, \theta$ but also couples with $P_{ord}, T_\omega$
Duplicate integrators (2)

- The system model includes the two integrators:
  \[
  \frac{dT_\omega}{dt} = K_{itrq}(\omega - \omega_{ref}) \\
  \frac{dx_p}{dt} = K_{ip}(\omega - \omega_{ref})
  \]

- If an input to either integrator is slightly in error, then the only solution is \( \omega = \omega_{ref} = 0 \)
  
  - This corresponds to the wind turbines stopped!
Initialization at a limit

- The state $x_c$ is usually on a limit at initialization.
- As noted previously, behavior is very different depending upon whether or not the limit is enforced.
  - These two situations generically result in different eigenvalues.
- The system cannot be linearized at an equilibrium point that sits on a switching surface.
- Switching becomes infinitely fast as the system converges to an asymptotically stable equilibrium point on a switching surface.
Conclusions

• It is very important that system-wide studies incorporate wind turbine dynamics.
  – This is only feasible with generic models.

• Wind turbine dynamics display fairly complicated interactions between continuous dynamics and discrete events.
  – A typical 10 second simulation involved 25 switching events.

• The existing WECC generic model for type 3 (DFIG) wind turbines gives rise to behavior that is mathematically rich but unintended.
  – This model is being used routinely in industry for assessing the impact of wind turbines!