Hybrid Dynamics of Wind Turbine Models

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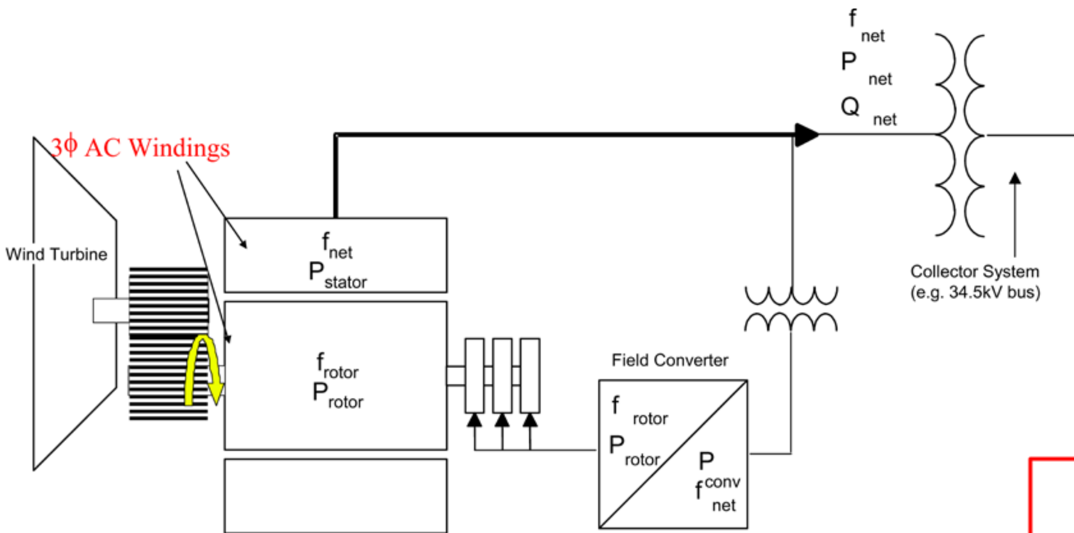
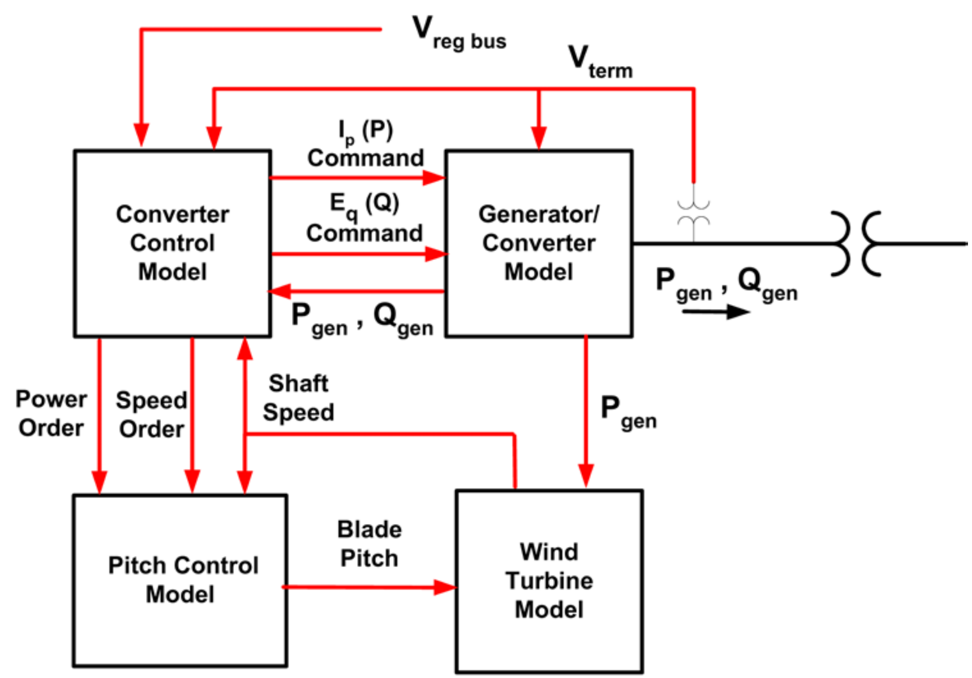
Background

- 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

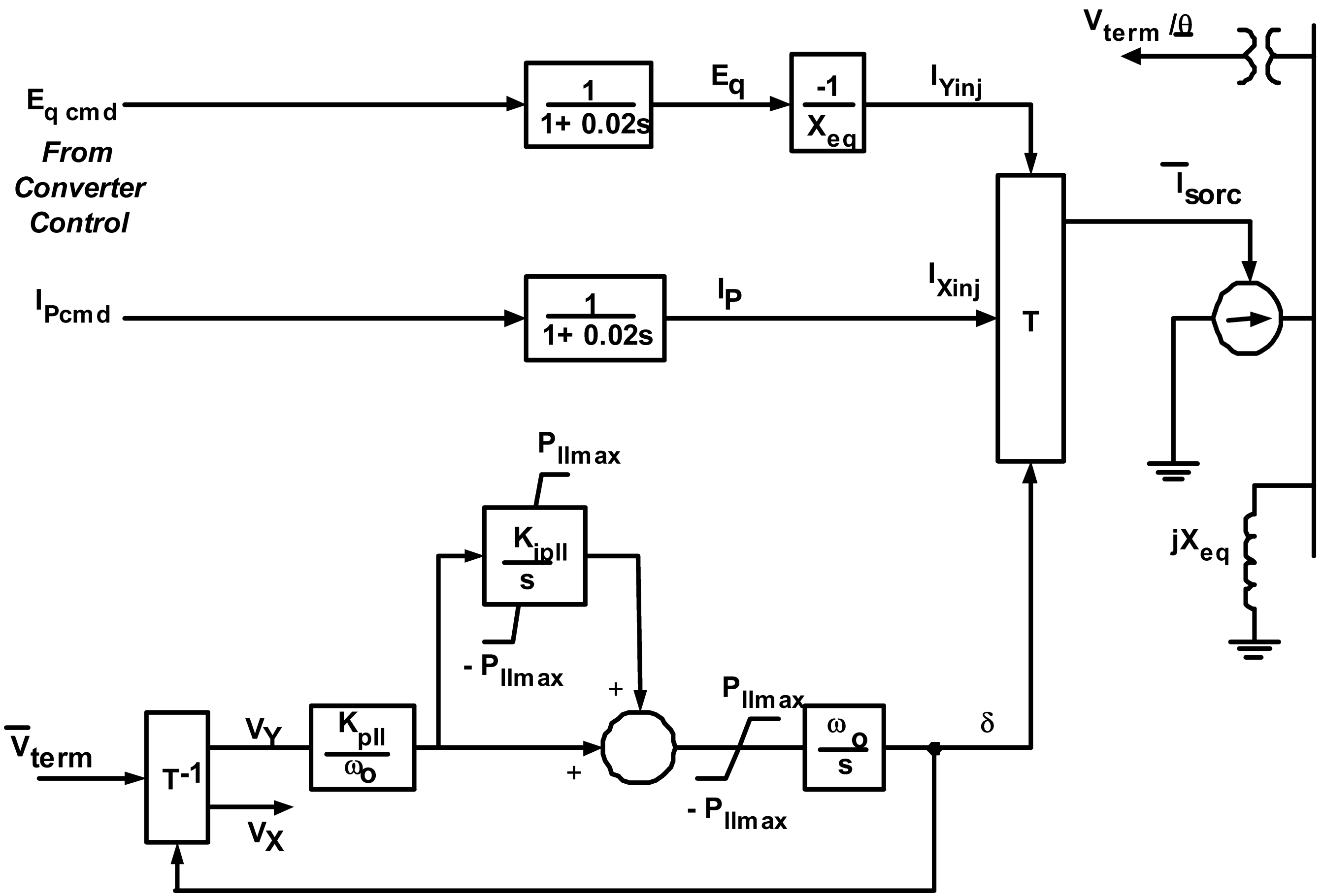


Doubly fed induction generator



Generator model

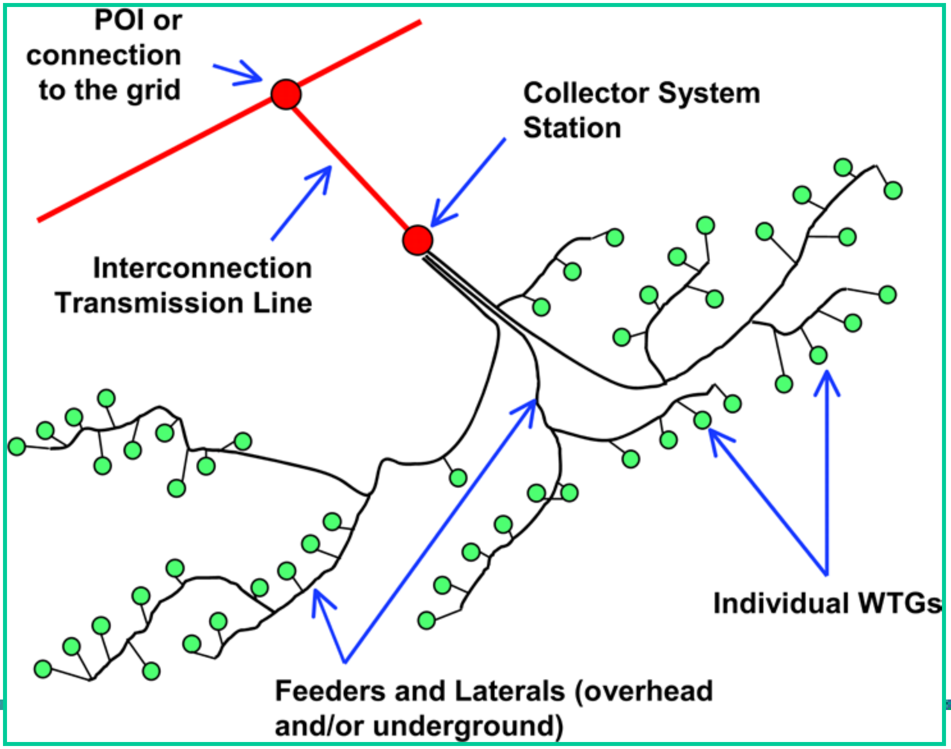
- Controlled current source.
- Phase locked loop is modeled.



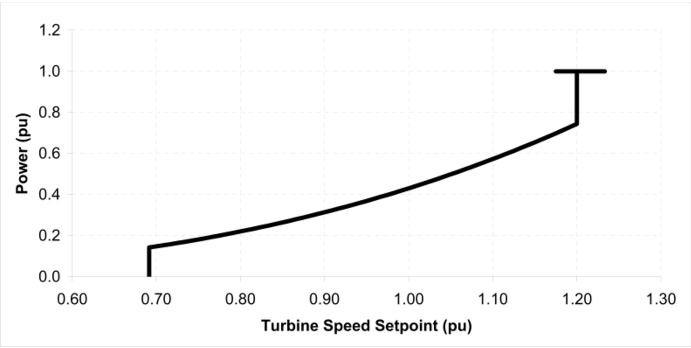
Reactive power control

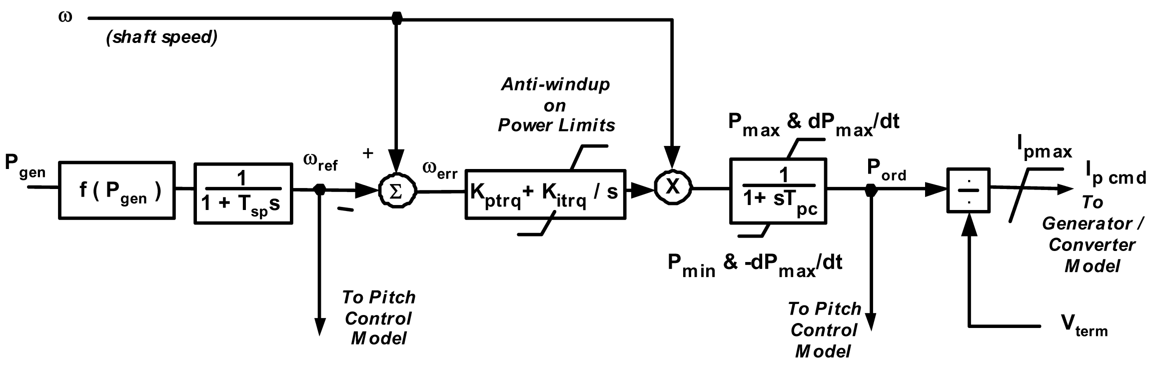
- Various different control modes are used.
  - Regulate generator terminal voltage.
    - Not a good idea, as difficult to coordinate setpoints with adjacent WTGs in a windfarm.
  - Regulate power factor or reactive power output.
    - Setpoint may be established by a centralized controller that's regulating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

Typical collector system topology



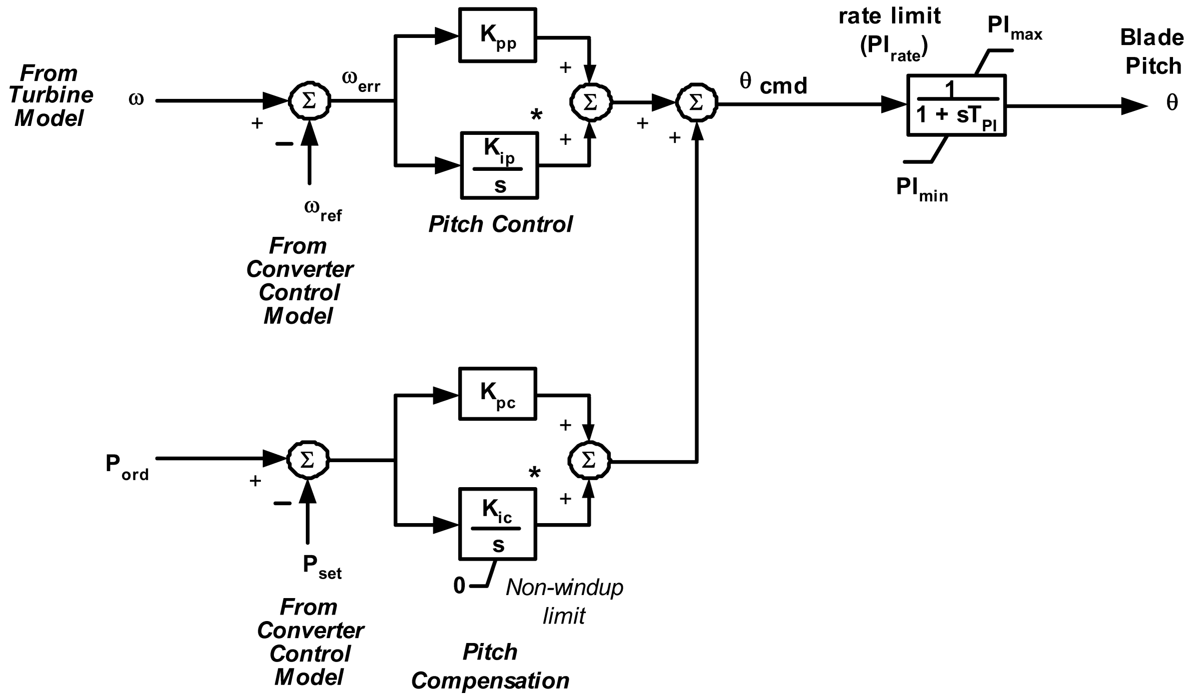
Torque control





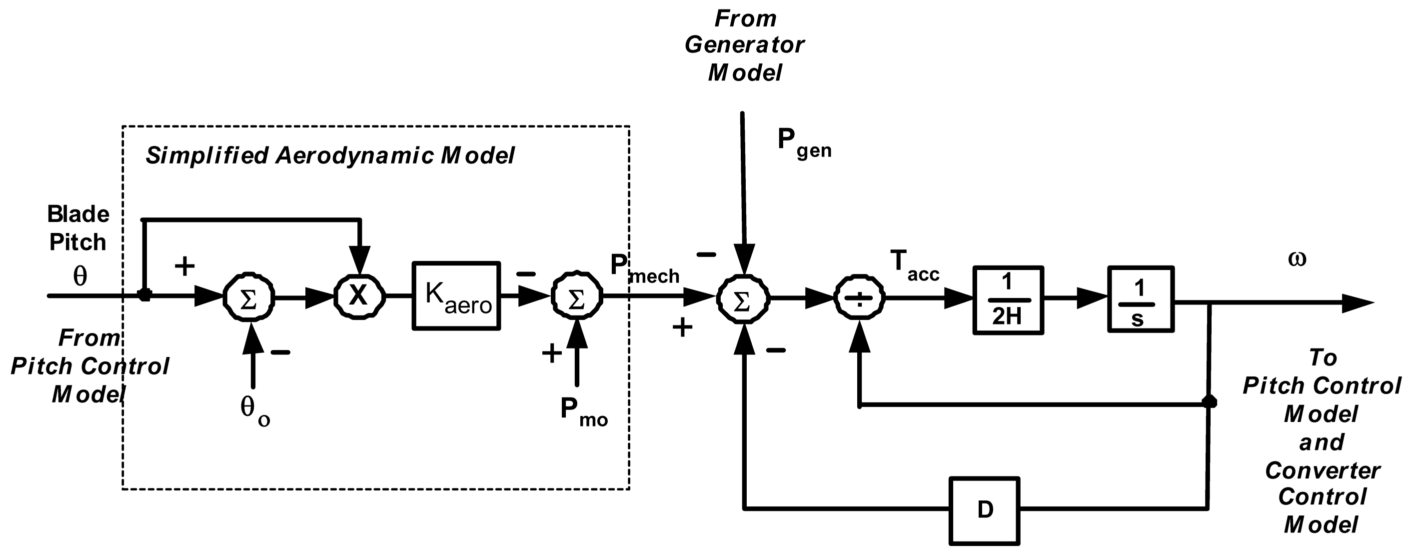
- Anti-windup limits on PI integrator:
  - If P_{ord} is on its upper limit and ω_{err} is positive then the PI integrator is frozen.
  - Similar logic for lower limit.
  - This logic can result in sliding-mode behavior.
- The error signal driving the PI integrator is $\omega - \omega_{ref}$
  - Keep this in mind for later.

Pitch control



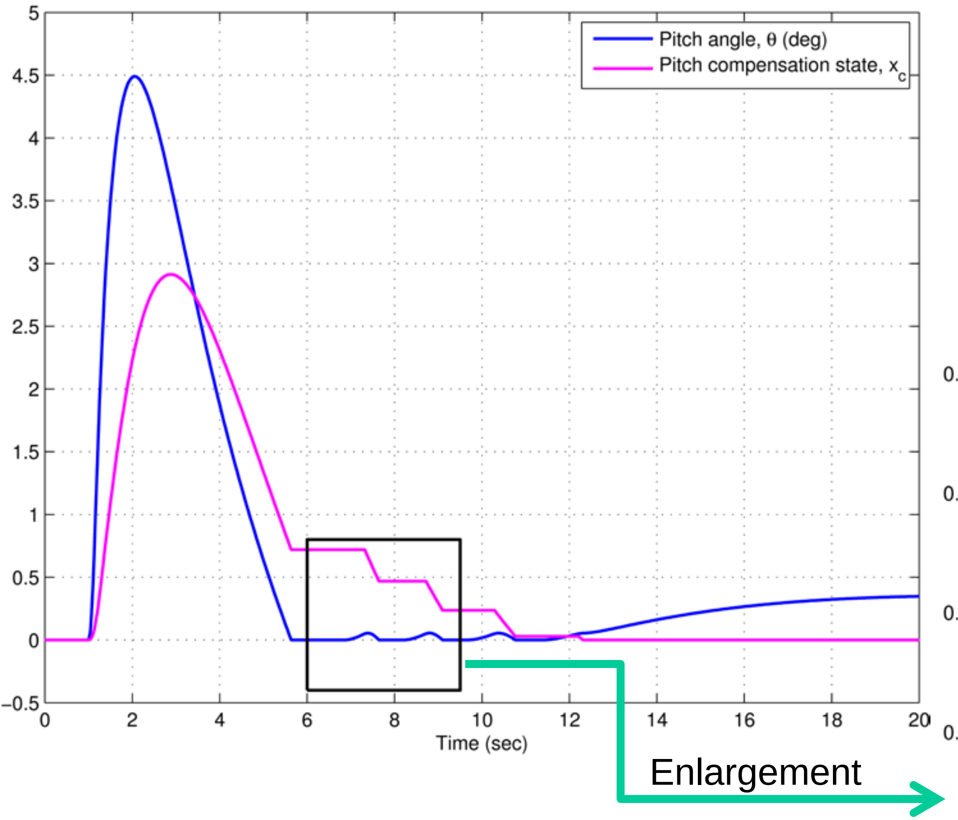
- The error signal driving the pitch control integrator is $\omega - \omega_{ref}$
  - A second integrator with this same input.
- If the pitch θ is on a limit, then a blocking strategy (similar to before) is used for the pitch control and pitch compensation integrators.
  - Again, sliding-mode behavior can result. (Example later.)

Turbine model

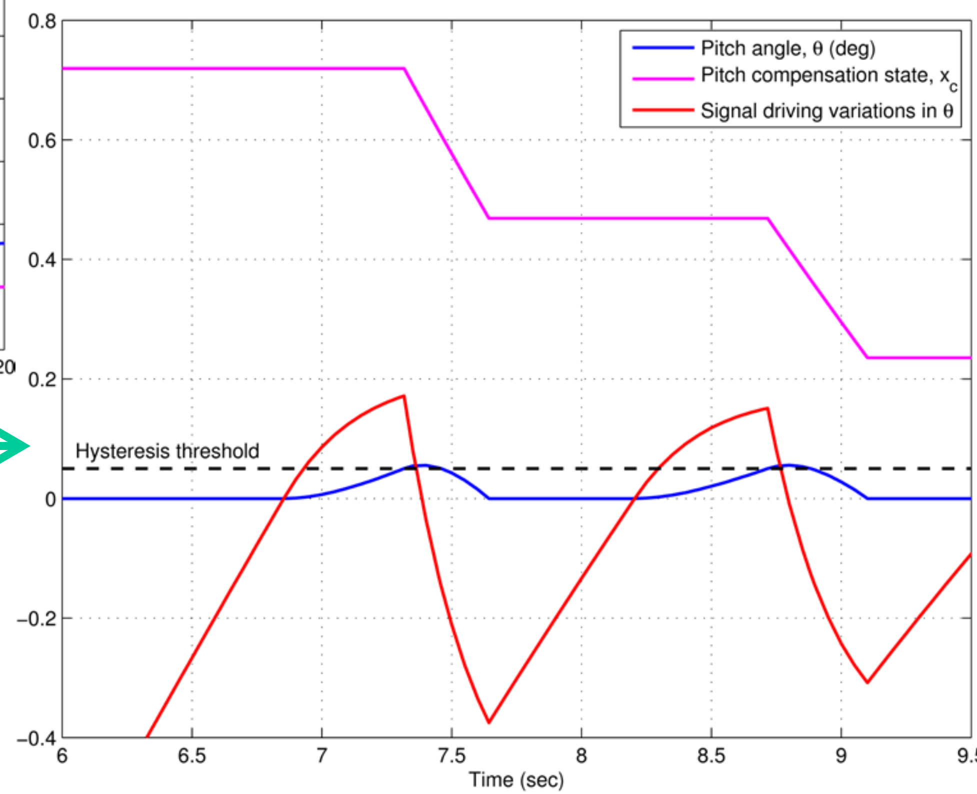


- The figure shows the single-mass model; a two-mass model is also defined.
- The simplified aerodynamic model is based on a simplification of the turbine C_p curves.
- When $\theta_0 = 0^o$, which is normally the case, mechanical power becomes $P_{mech} = P_{mo} - K_{aero}\theta^2$
  - Linearizing gives $\Delta P_{mech} = 0$ and an eigenvalue becomes zero.
  - The influence of pitch angle on mechanical power is lost.

Sliding-mode behavior



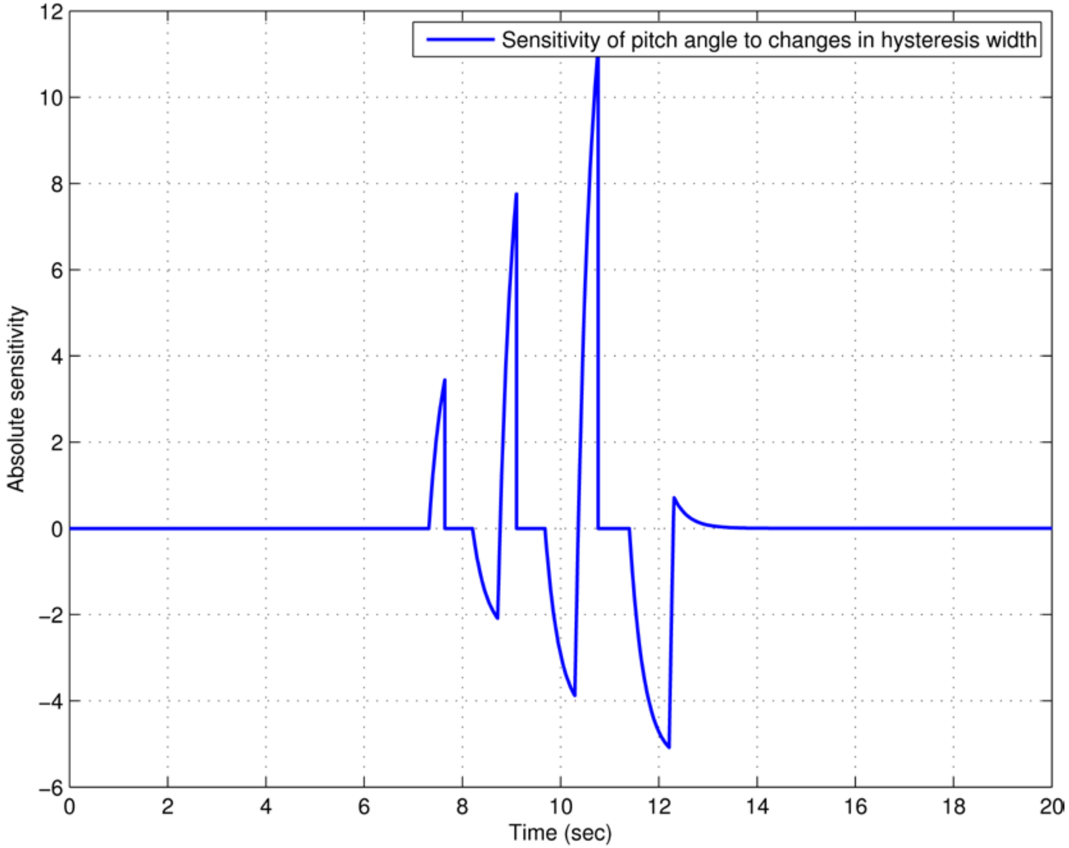
- Disturbance: Three-phase fault followed by line tripping.
- Initial pitch angle $\theta_0 = 0^o$ therefore damping is poor.



- 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

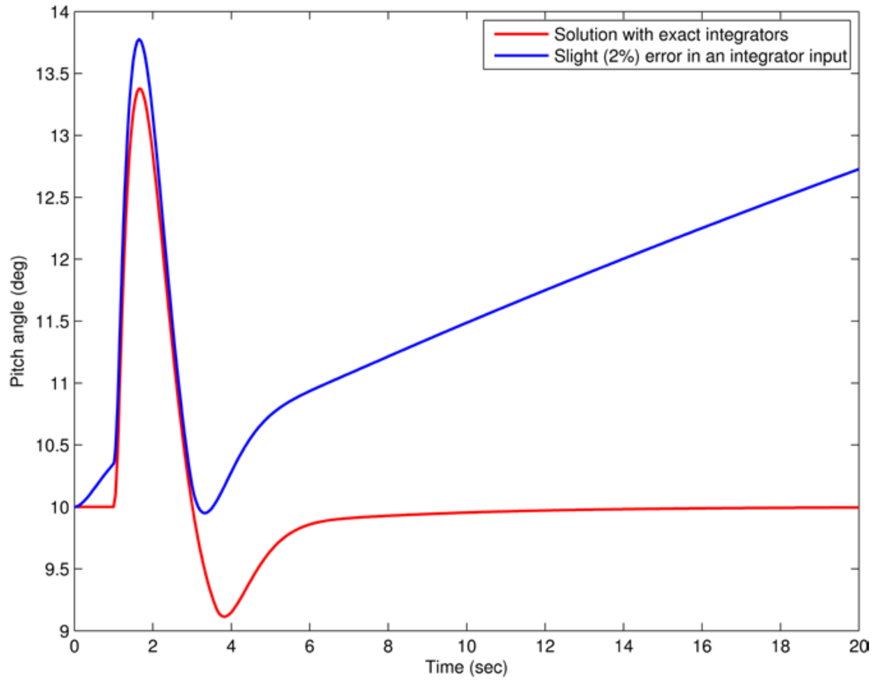
- Equilibrium conditions are underdetermined, and describe a 1-manifold.
  - The system can (theoretically) converge to any point on that manifold.
- Linearizing gives an A matrix that has linearly dependent rows.
  - The eigenvector corresponding to the 0-eigenvalue is locally tangent to the equilibrium 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, θ but also couples with P_{ord}, T_ω

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!