



Control of wind power plants

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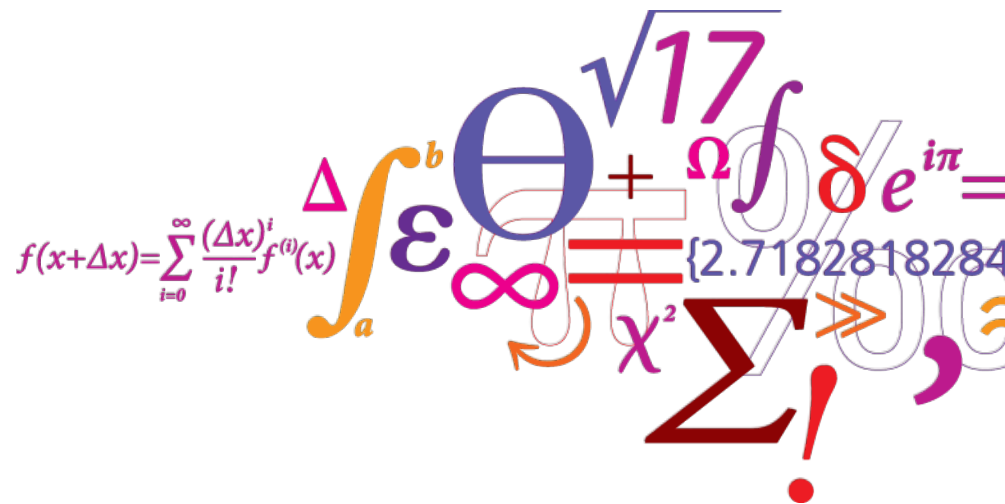
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Control of wind power plants

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Braulio Barahona, Post Doc





Østerild test station



Hovsøre test station



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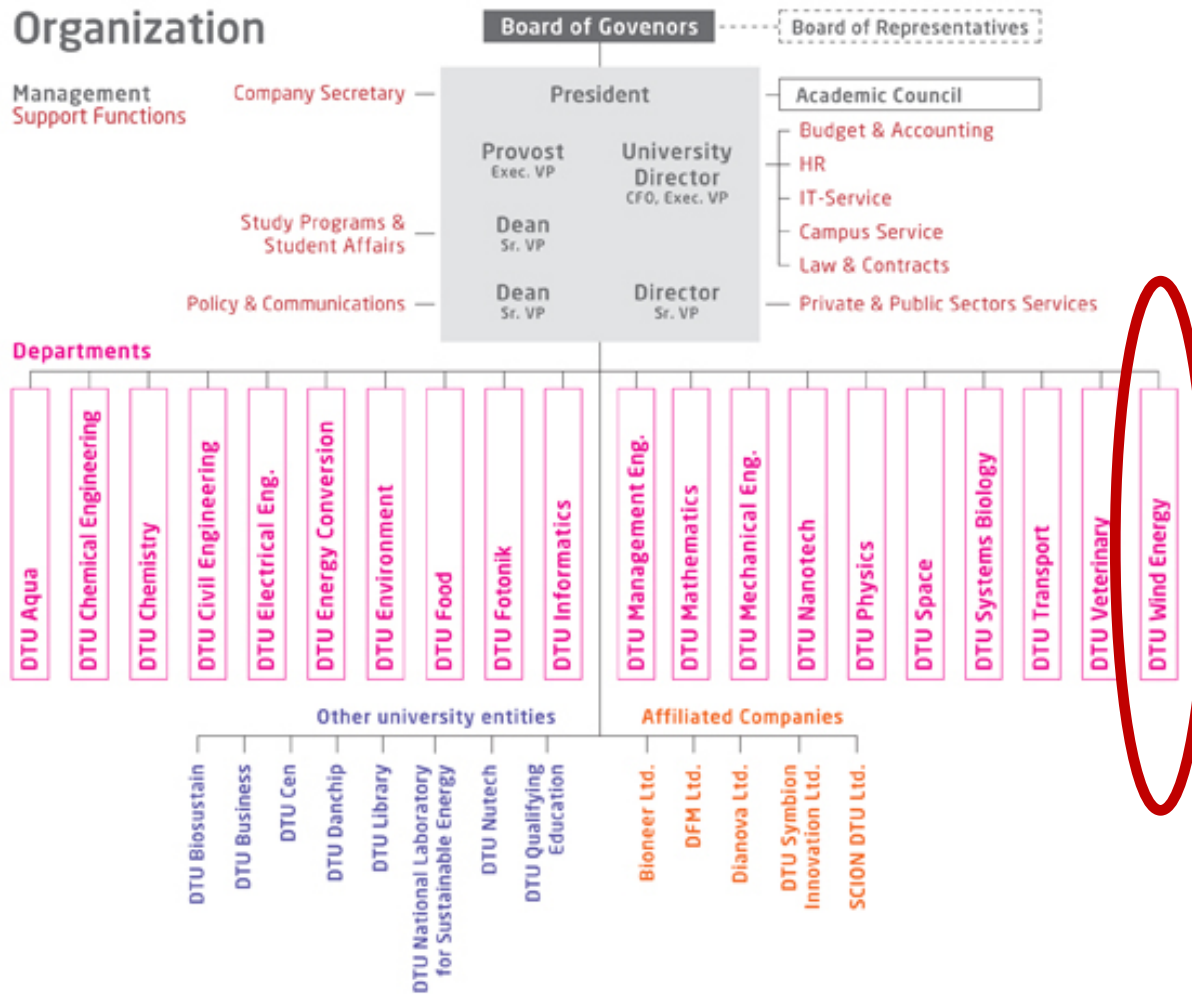


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Risø DTU
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Wind Energy Division

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for Sustainable Energy



Materials Research Division



Fluid Dynamics



Composite Mechanics

DTU Wind Energy
Department of Wind Energy

Composites and Materials Mechanics

Materials Science and Characterisation

Fluid Mechanics

Test and Measurements

Wind Turbines Structures

Aerolastic Design

Meteorology

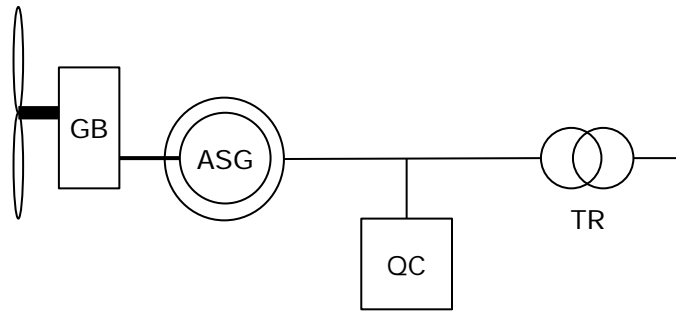
Wind Energy Systems

Control issues

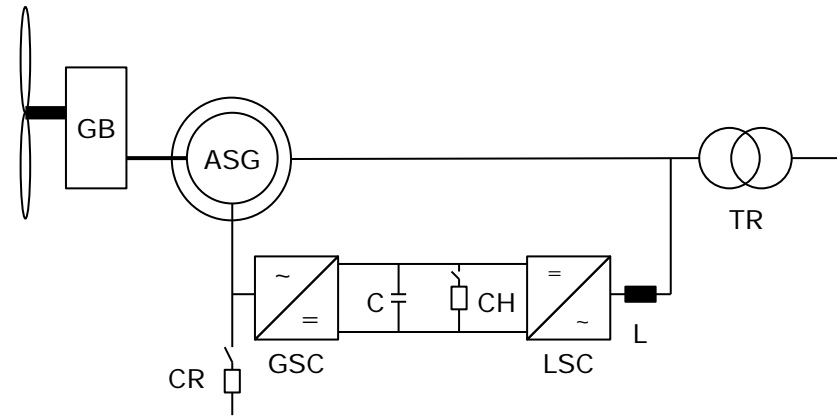


- List purposes of controlling wind power plants:

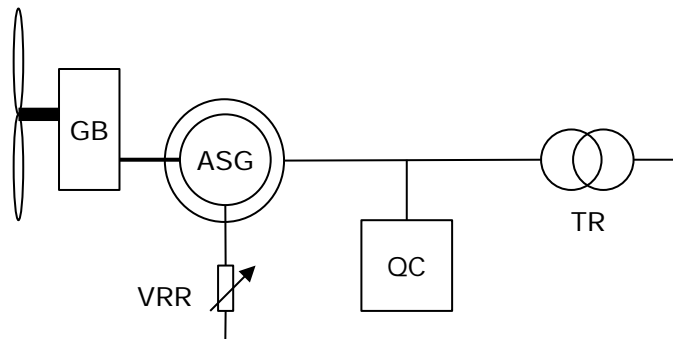
4 wind turbine types



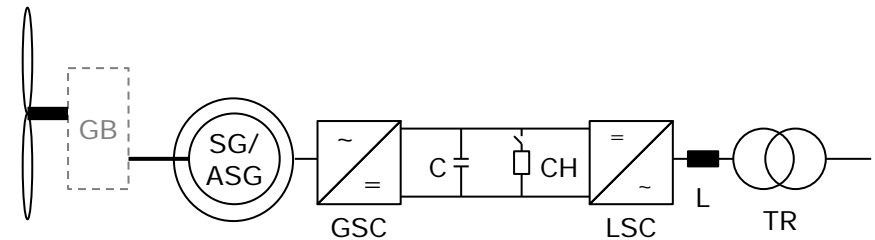
Type 1



Type 3



Type 2



Type 4

ASG: Asynchronous generator
 GB: Gearbox
 QC: Reactive power compensation
 SG: Synchronous generator
 TR: Transformer
 VRR: Variable rotor resistance

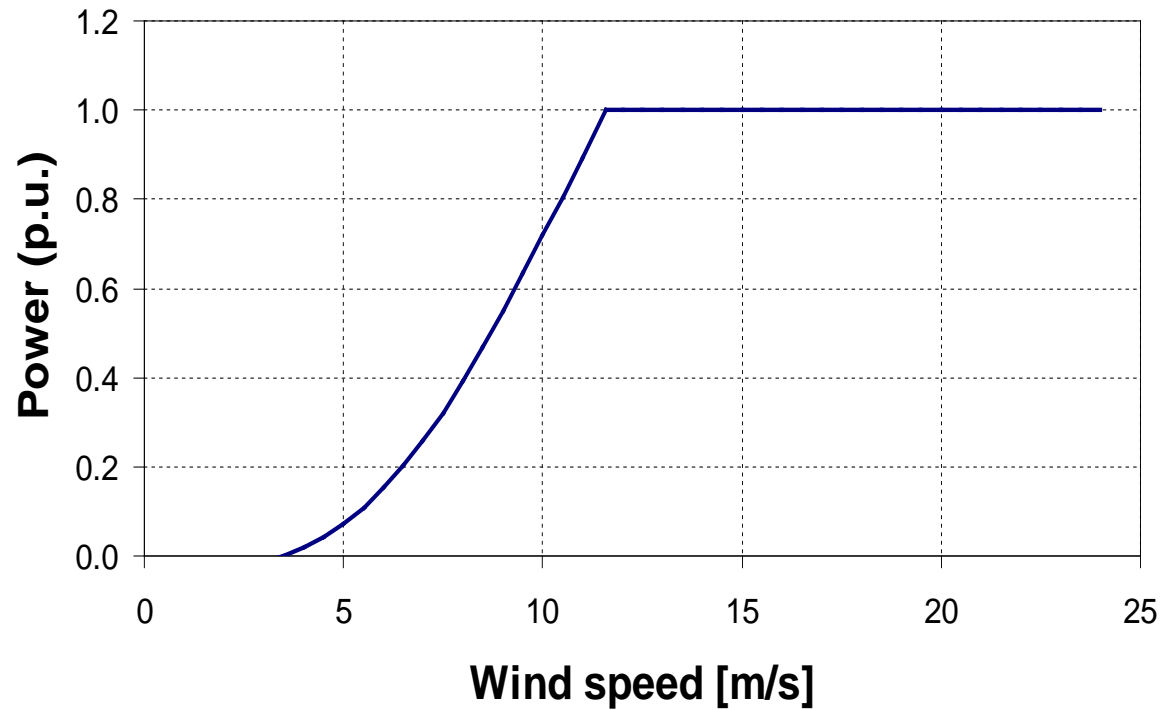
GSC: Generator side converter
 LSC: Line side converter
 CR: Crowbar
 C: DC link capacitor
 CH: Chopper
 L: Series inductance

- General about wind turbine control
 - blade angle control
 - rotor speed control
- Electrical design and controllability / control strategies
 - fixed speed
 - variable speed
- Control examples
 - Normal wind turbine operation control
 - Fixed speed example (Active stall control)
 - Variable speed example (doubly-fed and pitch control)
 - Fault ride through wind turbine control
 - Active stall
 - Doubly fed
 - Wind turbine load reducing control
 - Wind farm control

Aerodynamic power – power curve

- P : aerodynamic power [W]
- U : wind speed

Power curve based
on 10 min averages

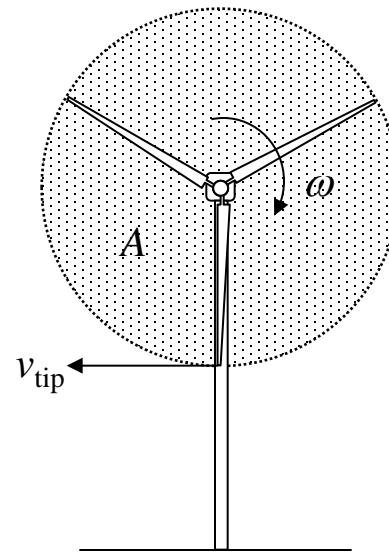


Aerodynamic power – power coefficient

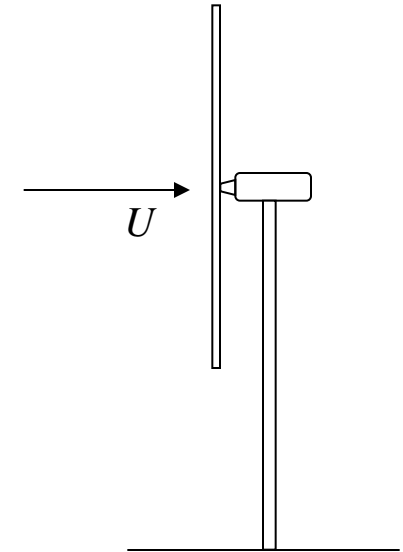
$$P = \frac{1}{2} \rho A U^3 C_p(\lambda, \varphi)$$

- P : aerodynamic power [W]
- ρ : air density [kg/m³]
- A : rotor (swept) area
- U : wind speed
- C_p : power coefficient
- φ : blade pitch angle
- λ : tip speed ratio

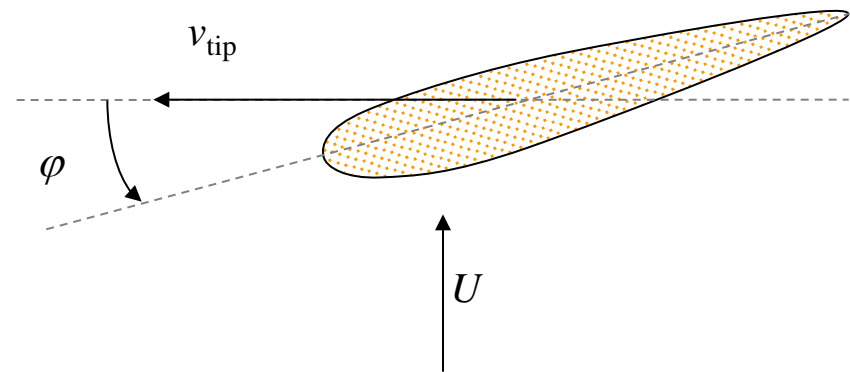
$$\lambda = \frac{v_{\text{tip}}}{U} = \frac{\omega \cdot R}{U}$$



Front view



Side view

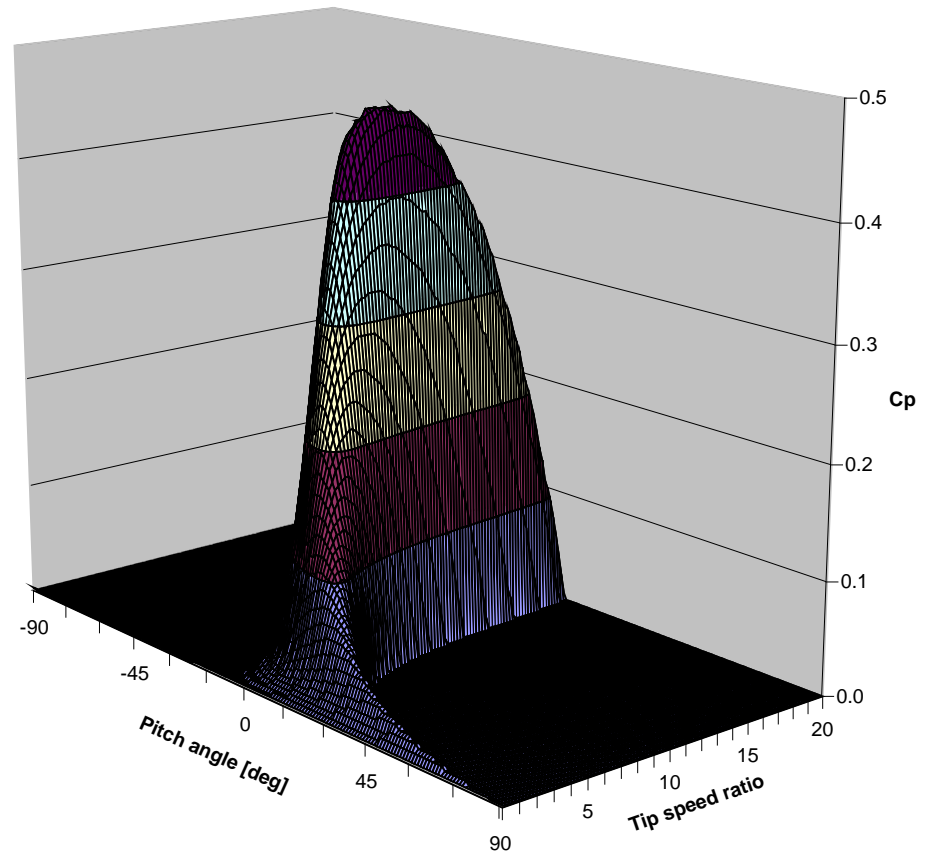


Top view

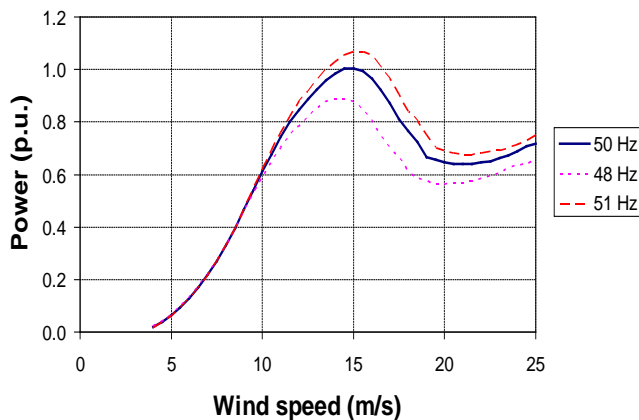
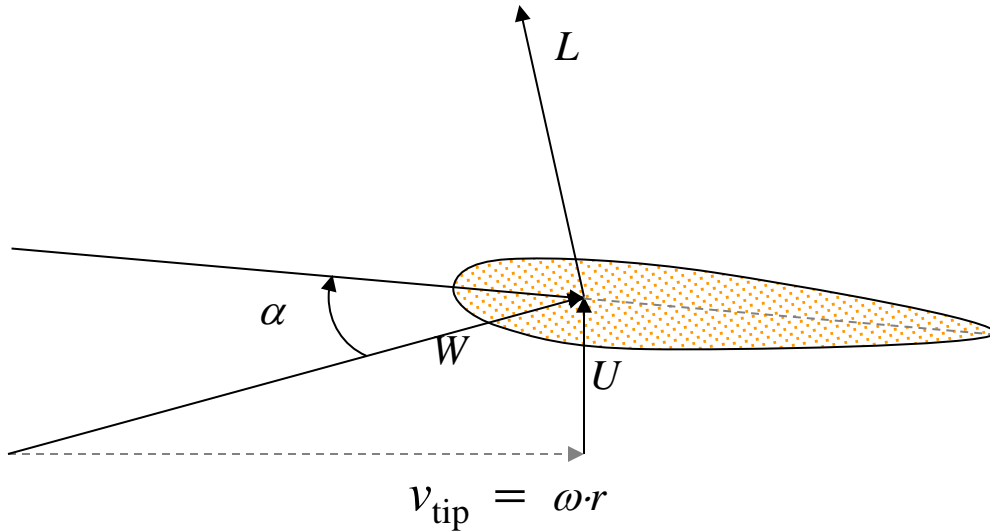
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- U : wind speed
- ρ : air density [kg/m³]
- A : rotor (swept) area
- φ : blade pitch angle
- λ : tip speed ratio
- C_p : power coefficient



Passive stall control



W : relative speed seen from rotating blade

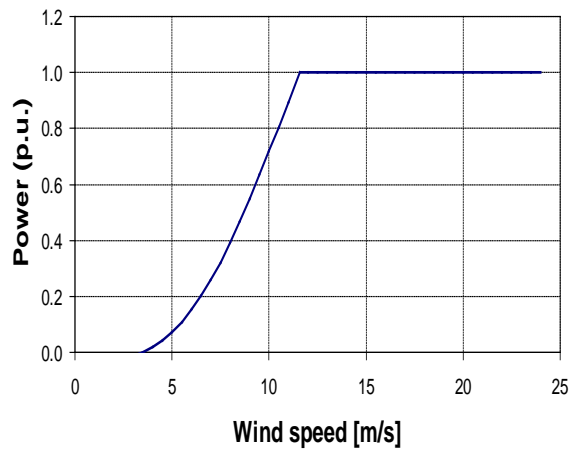
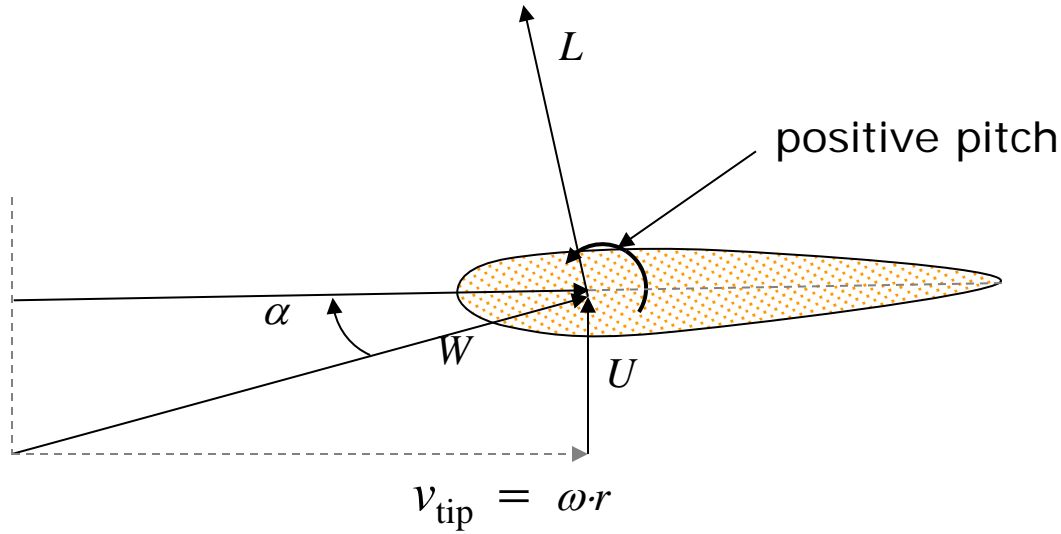
α : angle of attack

L : lift

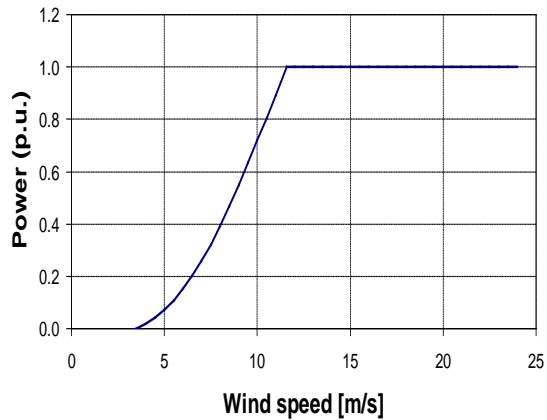
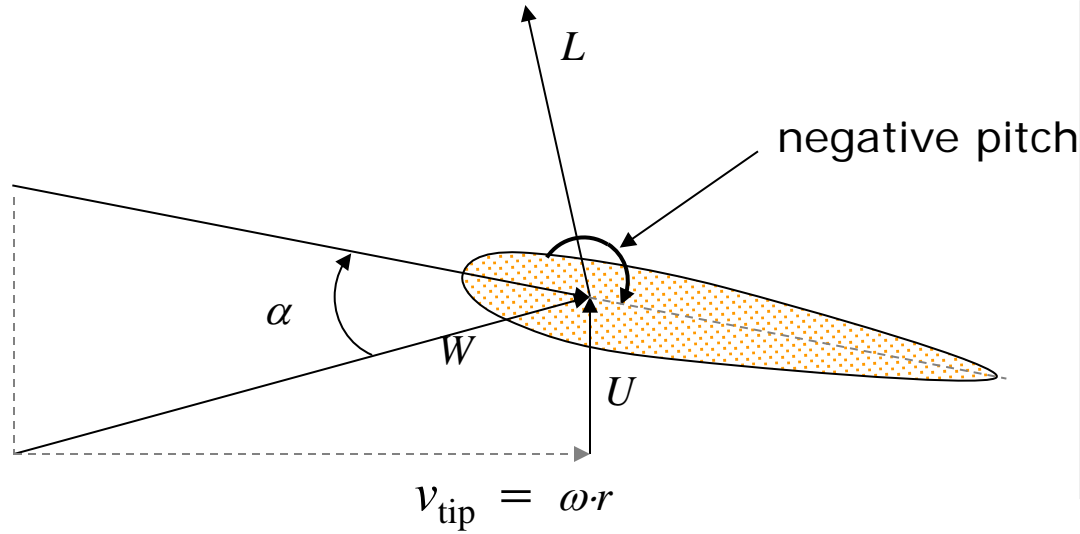
Power curve sensitive to

- electrical grid frequency (3rd order)
- air density (1st order)
- dirt on blades

Pitch control



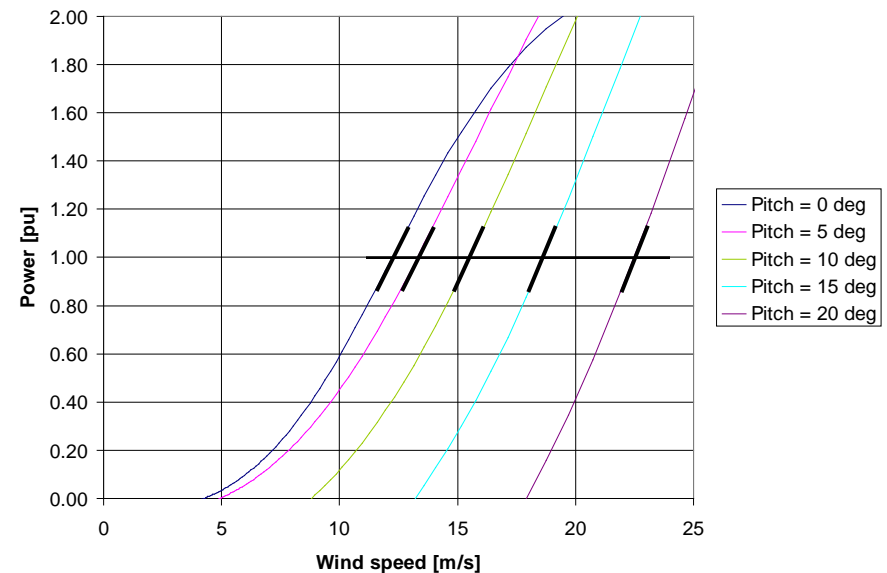
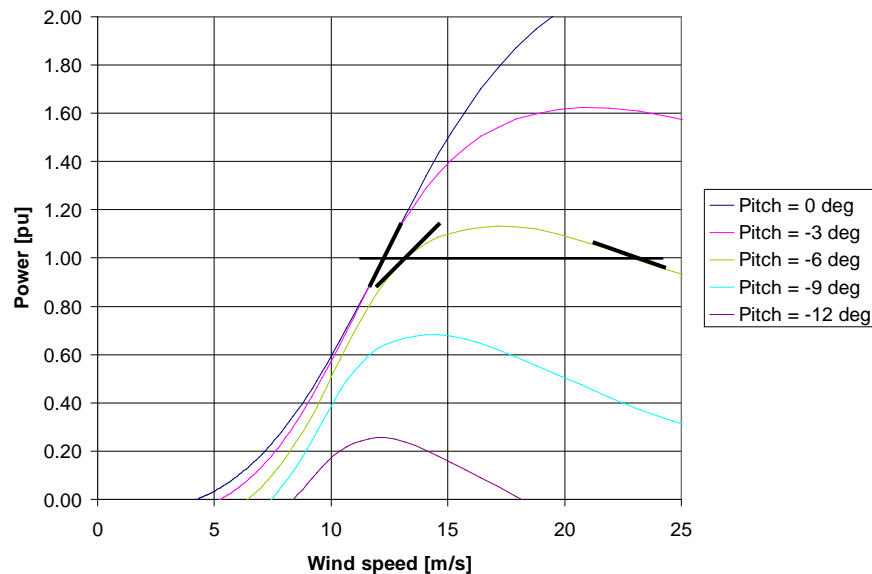
Aktiv stall control (or kombi-stall)



Fixed speed – active stall or pitch control

- Active (Combi) stall
- Moderate instantaneous response gradients (fixed speed no problem)
- Slow blade angle control sufficient

- Pitch control
- Large instantaneous response gradients for power limitation (variable speed desirable)
- Fast blade angle control necessary



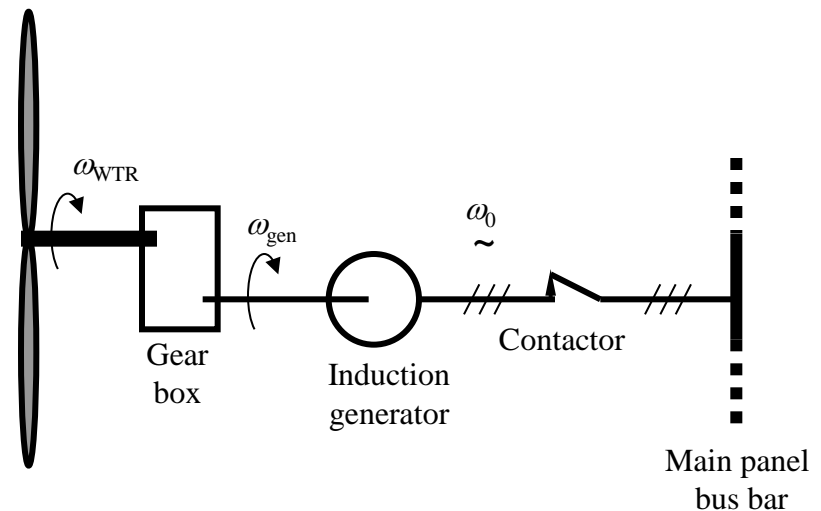
Fixed speed – directly connected induction generator

$$\omega_{\text{gen}} = g \cdot \omega_{\text{WTR}}$$

- ω_{WTR} : wind turbine rotor speed
- ω_{gen} : generator speed
- g : gear ratio

$$\omega_{\text{gen}} = \frac{1-s}{N_{\text{pp}}} \cdot \omega_0$$

- ω_0 : electric grid radial speed ($2\pi \cdot 50$ in Europe, $2\pi \cdot 60$ in USA)
- N_{pp} : number of generator pole pairs (typically 2 or 3)
- $s \ll 1$: generator speed almost "constant"



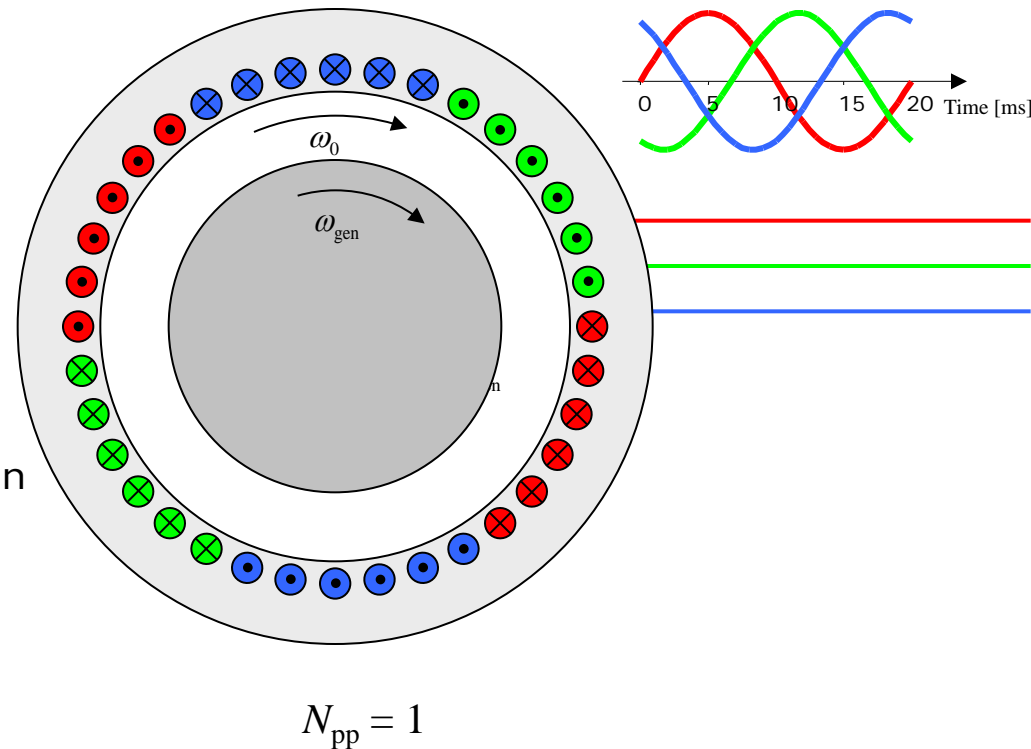
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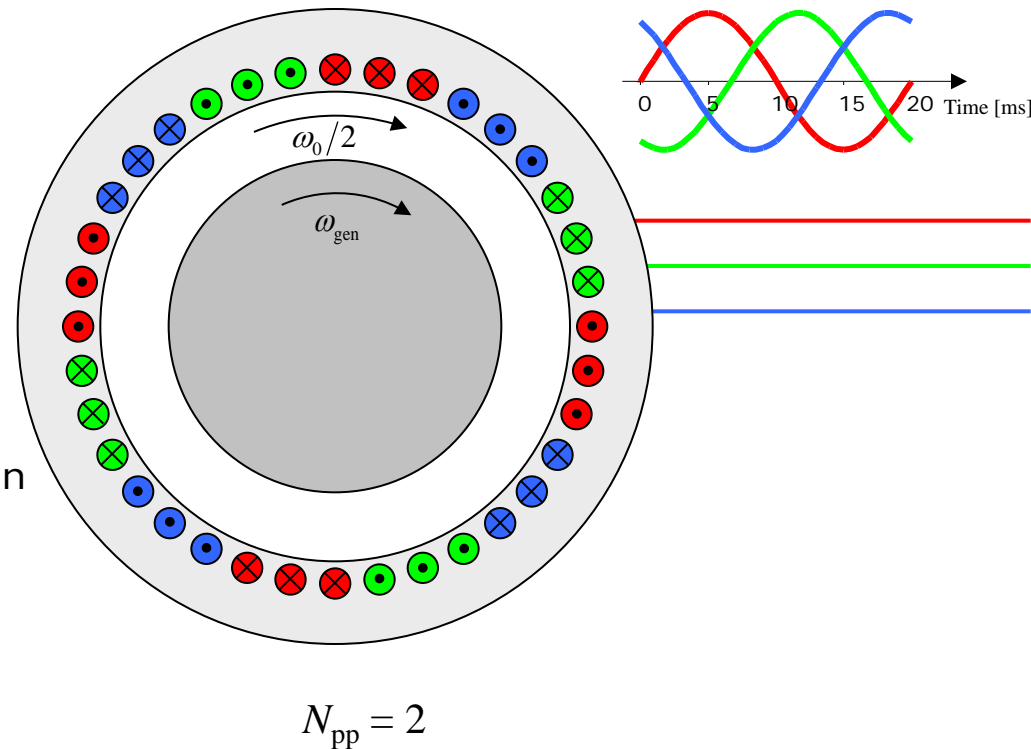
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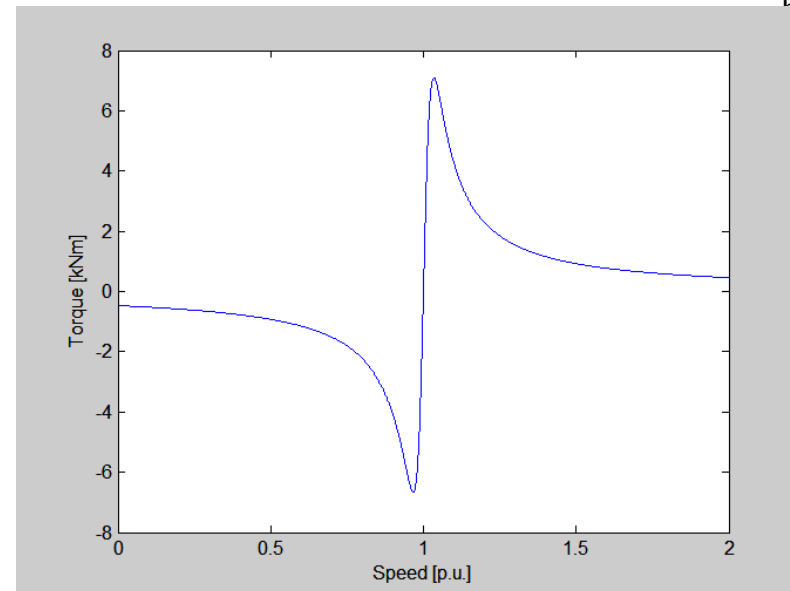
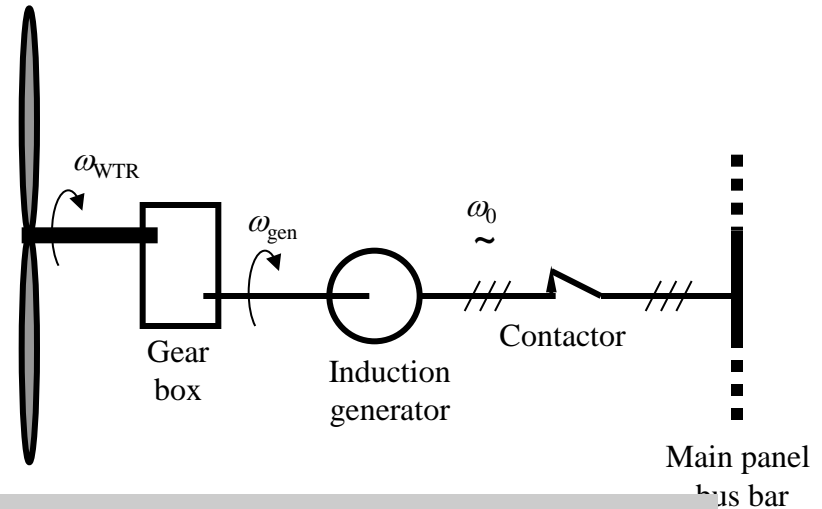
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Fixed speed continuous operation - summary

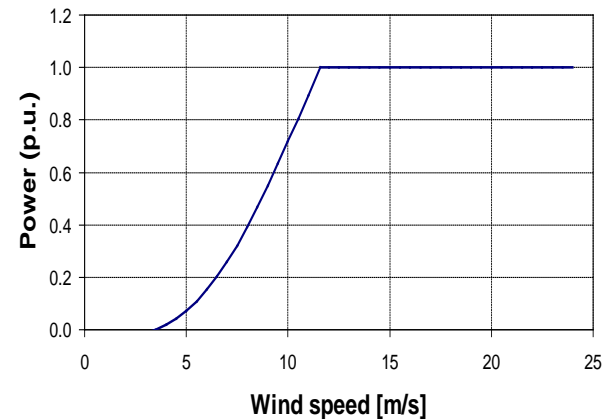
- Wind turbines with directly connected induction generators are speed controlled by the generator torque, which is approximately proportional to the slip (slip is difference between grid synchronous rotor speed and actual generator rotor speed).
- The generator can be “geared” by increasing the number of pole pairs
- Fixed speed turbines can control the speed by changing the number of pole pairs, typically between 2 and 3, depending on the wind speed.

Exercise 1: fixed speed

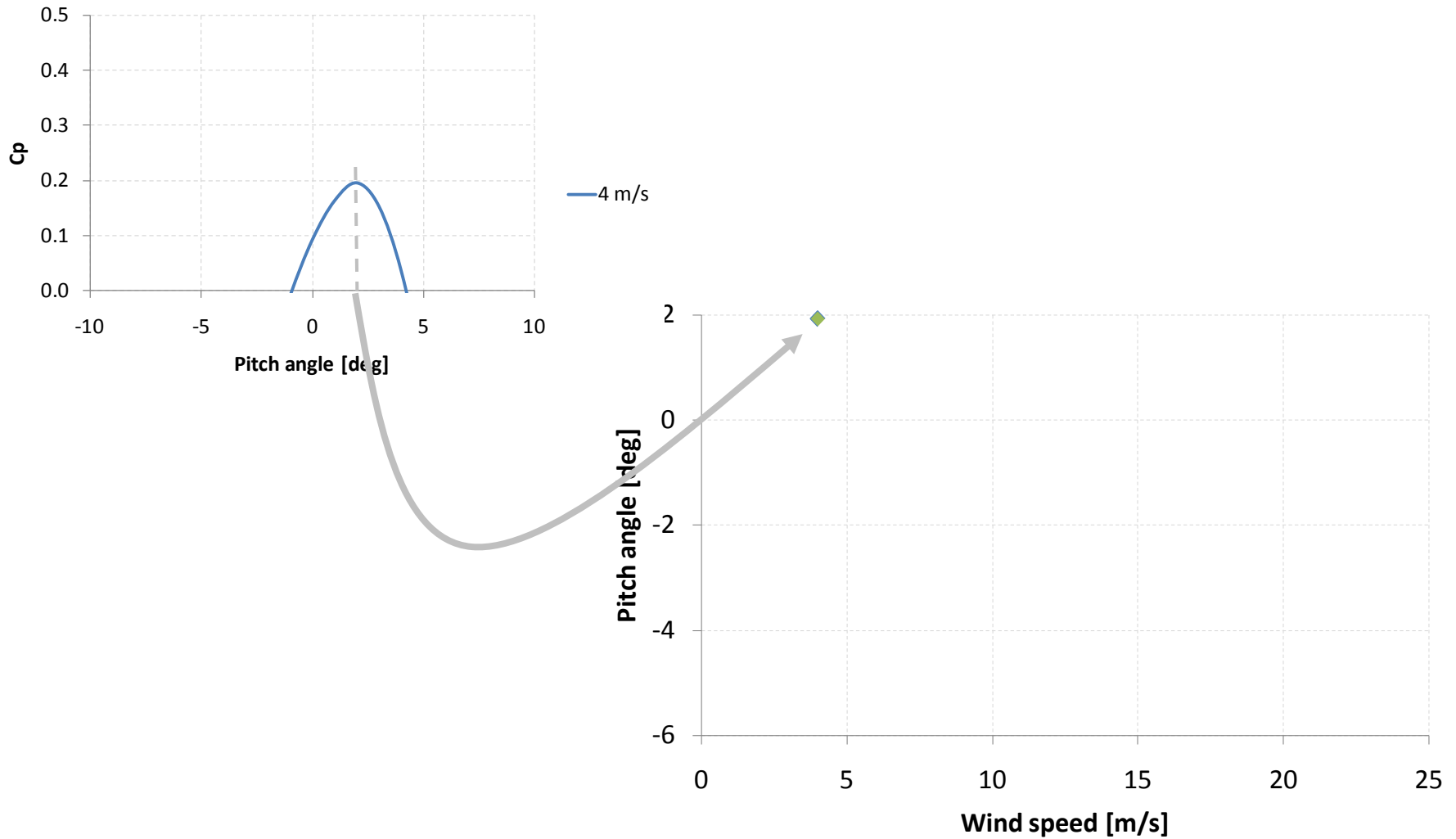
- Open excel sheet with C_p data
- A fixed speed wind turbine with the C_p data in table has rotor diameter 40 m, tip speed 70 m/s. Make the power curve if the pitch angle is 0 deg.
- At which pitch angle (integer degree) should the blades be mounted to the hub to obtain the maximum power 600 kW? Hint: try to increase the pitch angle negatively step by step and observe the power curve until you get the desired maximum.
- The turbine uses $N_{pp}=2$ coupling of generator windings for high wind speeds and $N_{pp}=3$ for low wind speeds. What is the tip speed for low wind speeds?
- The turbine is passive stall controlled. Show the power curve for low wind speeds and high wind speeds, and identify the wind speed at which switching between generator speeds is feasible.

Active Stall example

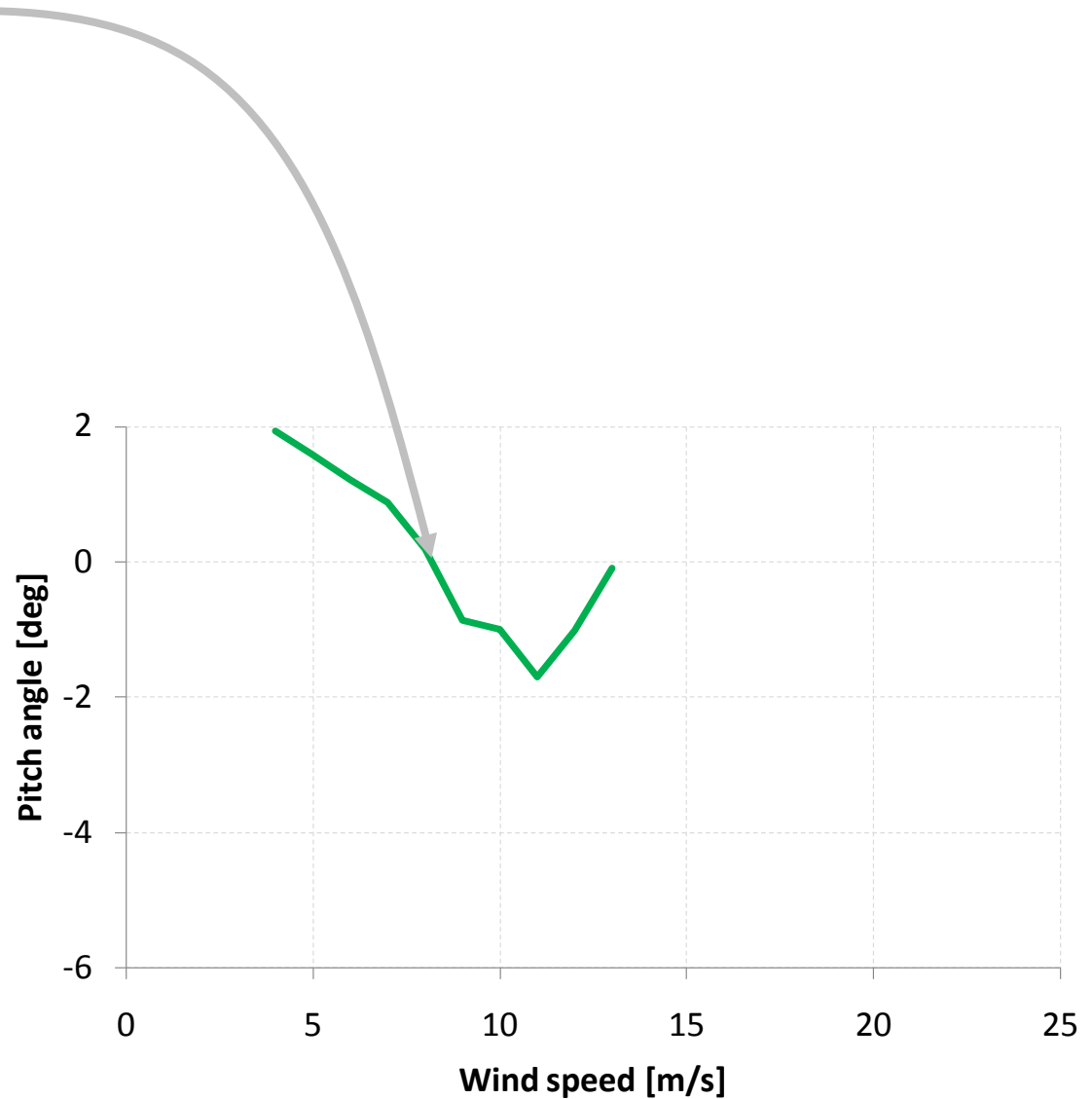
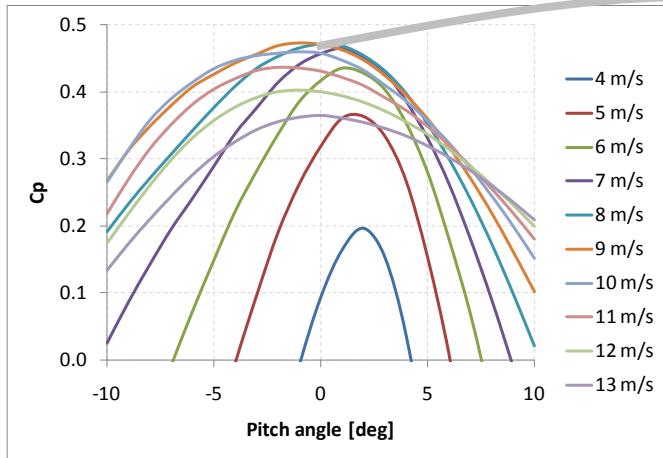
- General operation modes active stall
 - Power optimisation (lookup table)
 - Power limitation (closed loop power control)
 - Normal operation (averaged power, sample & hold)
 - Overpower protection (instant. power, continuous pitching)
 - Transition between optimisation and limitation



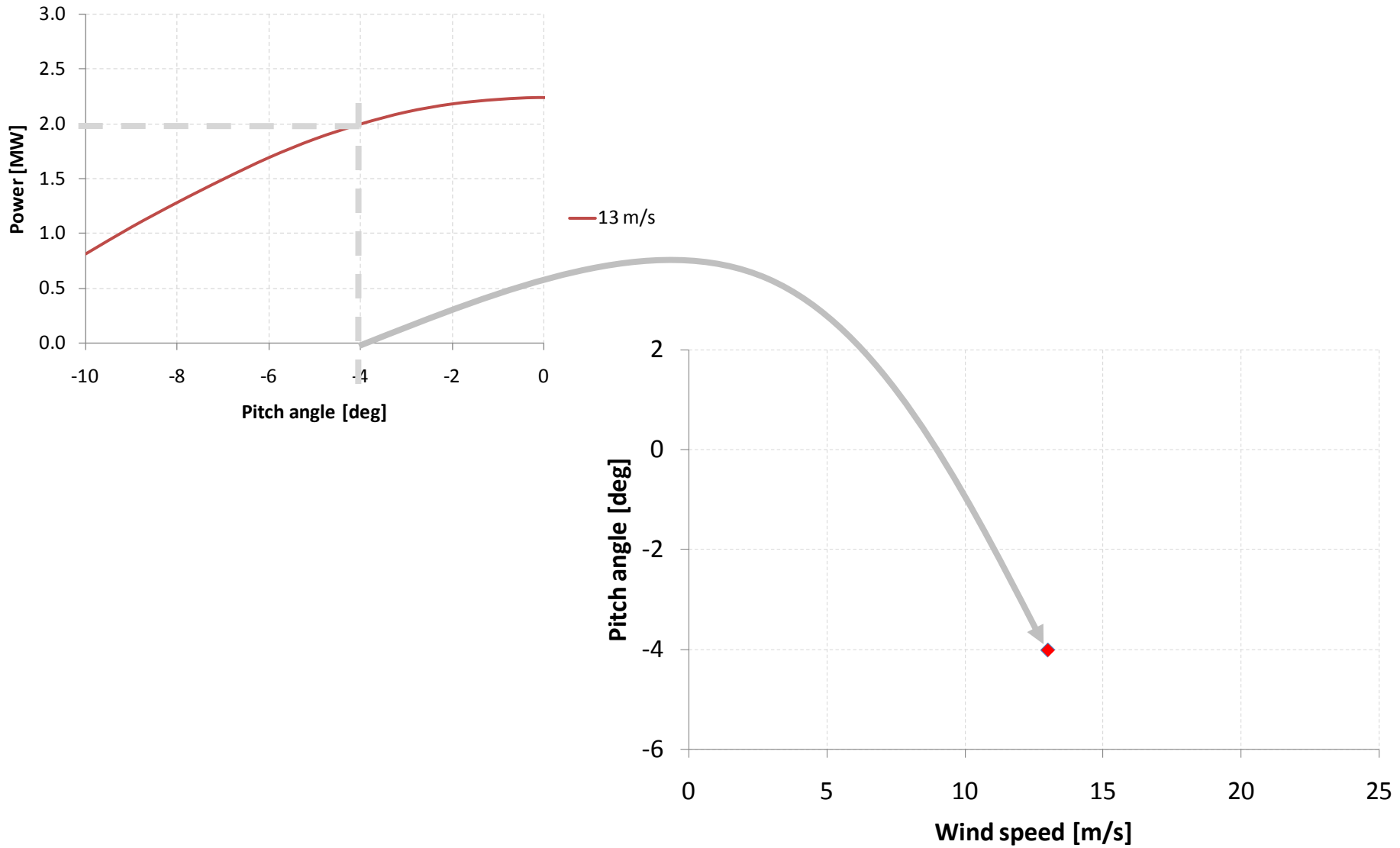
Power Optimisation



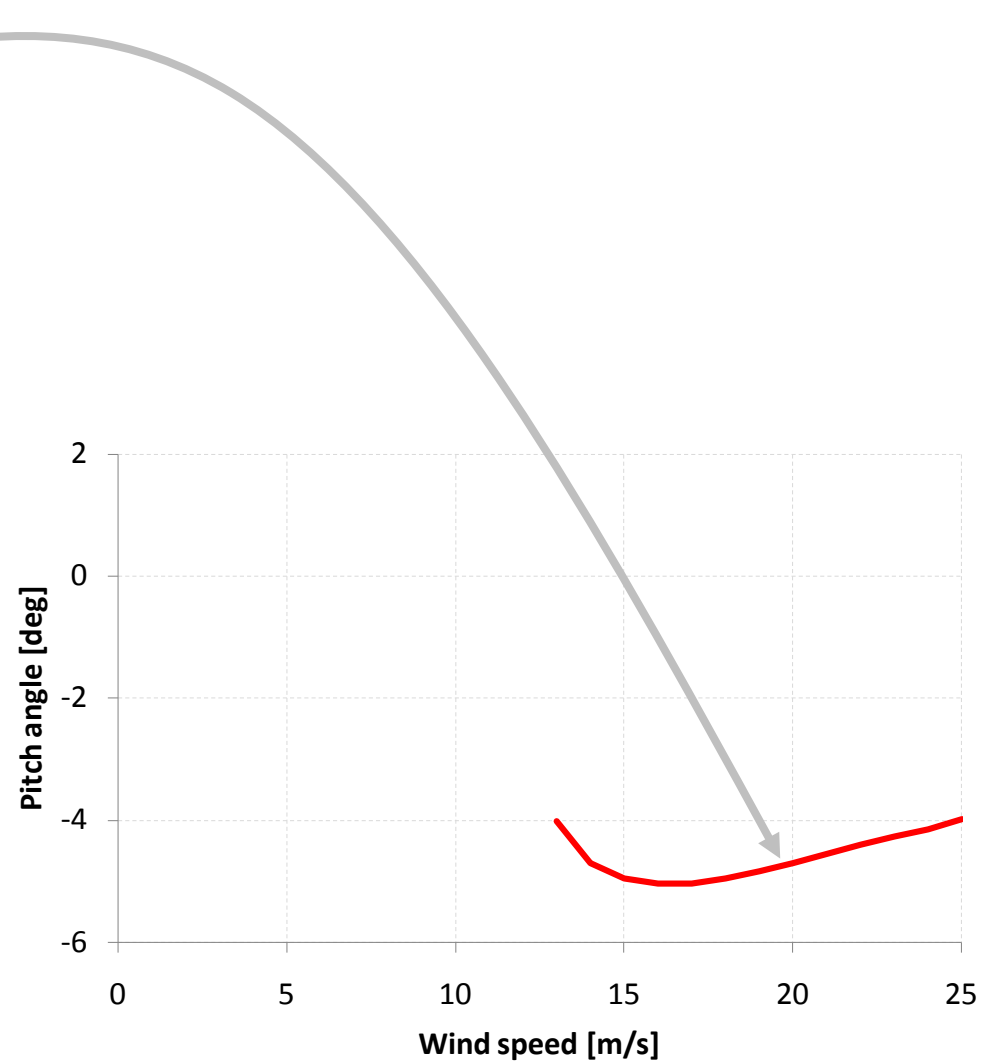
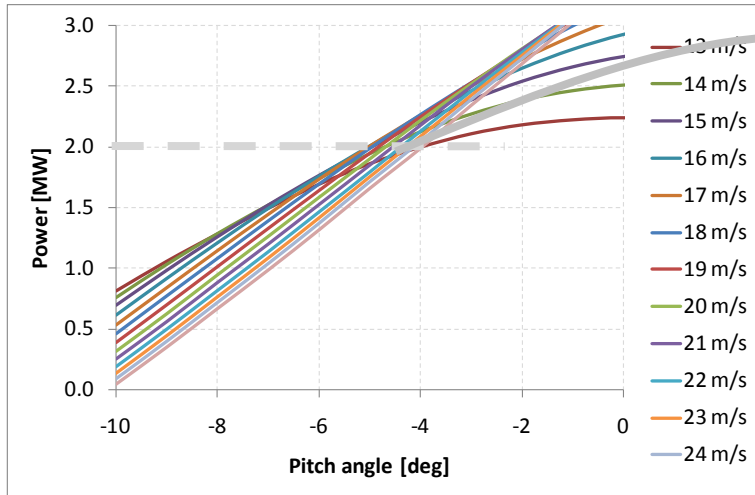
Power Optimisation



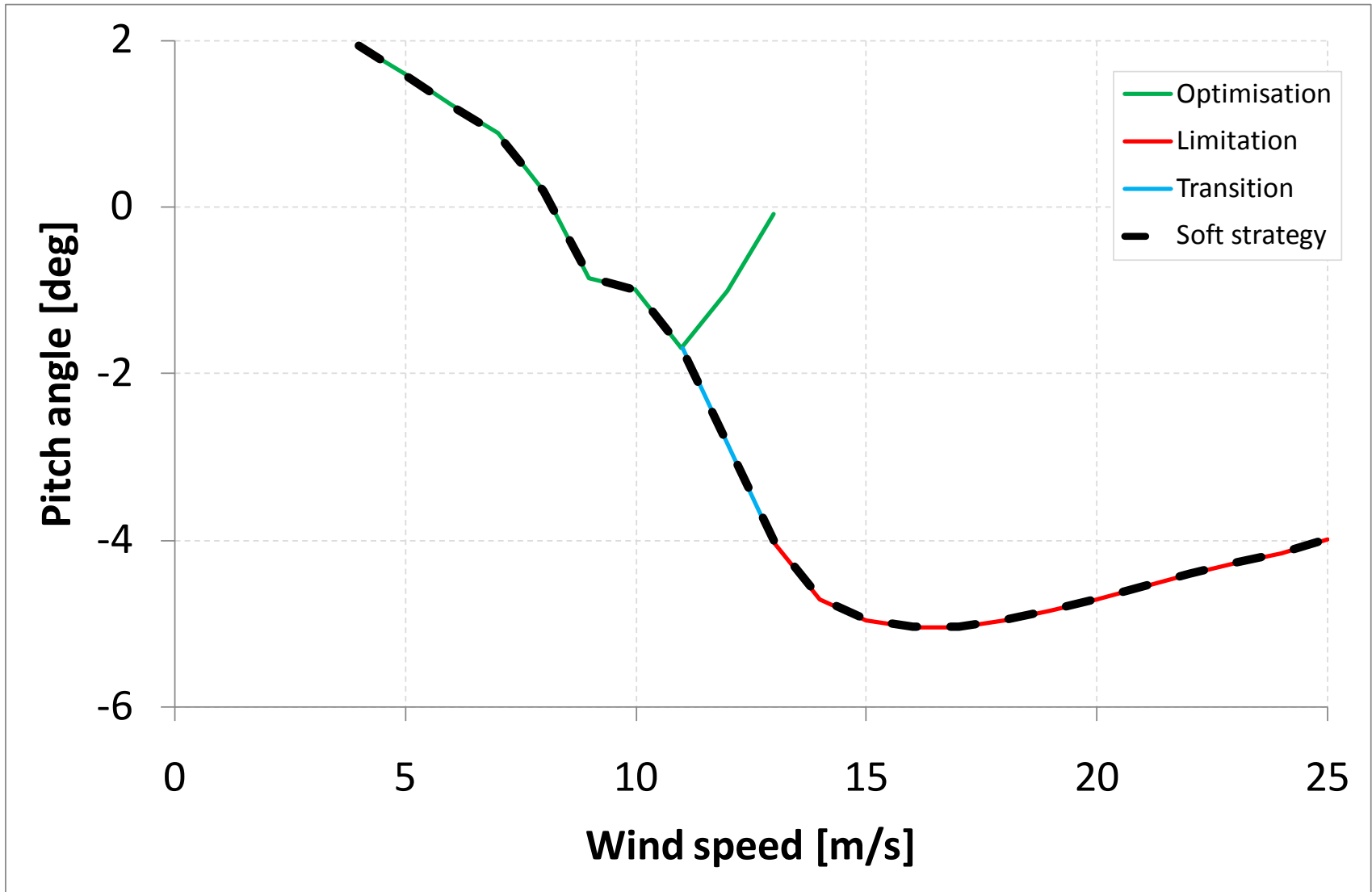
Power Limitation



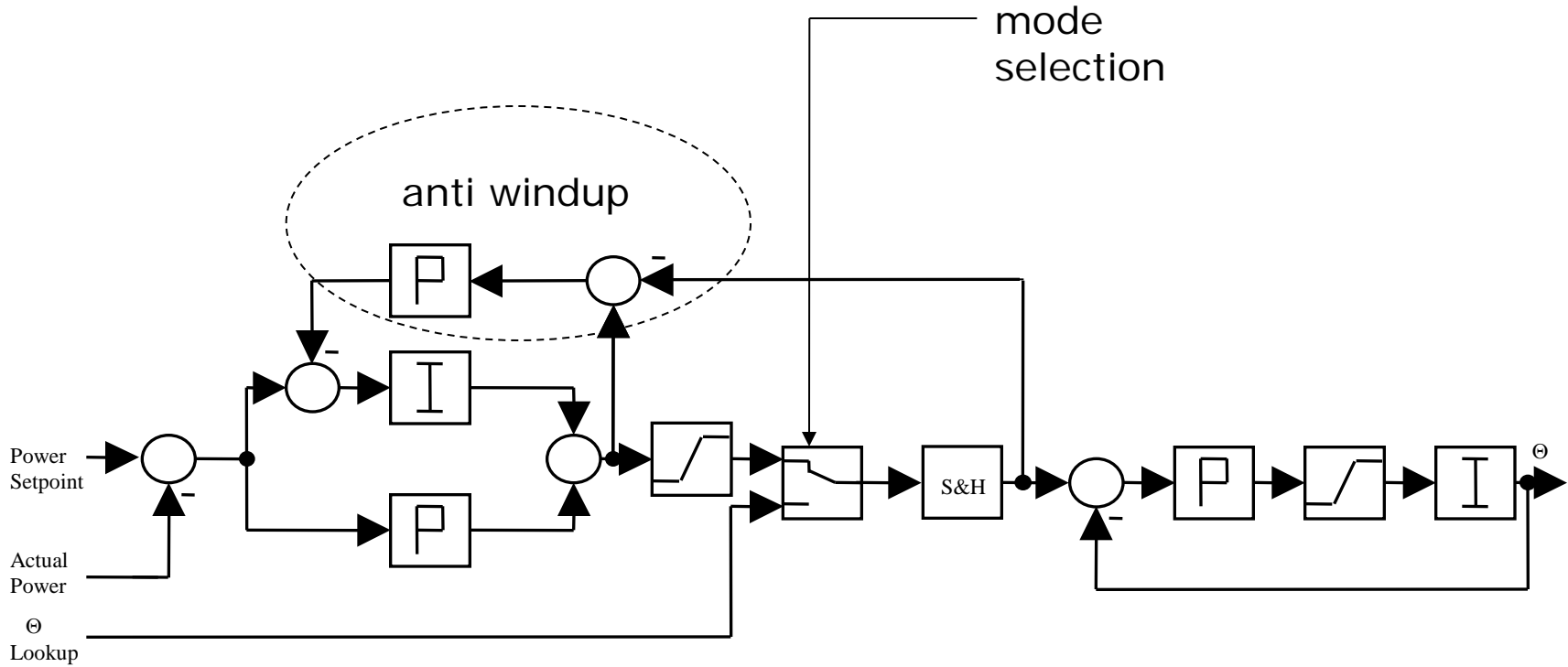
Power Limitation



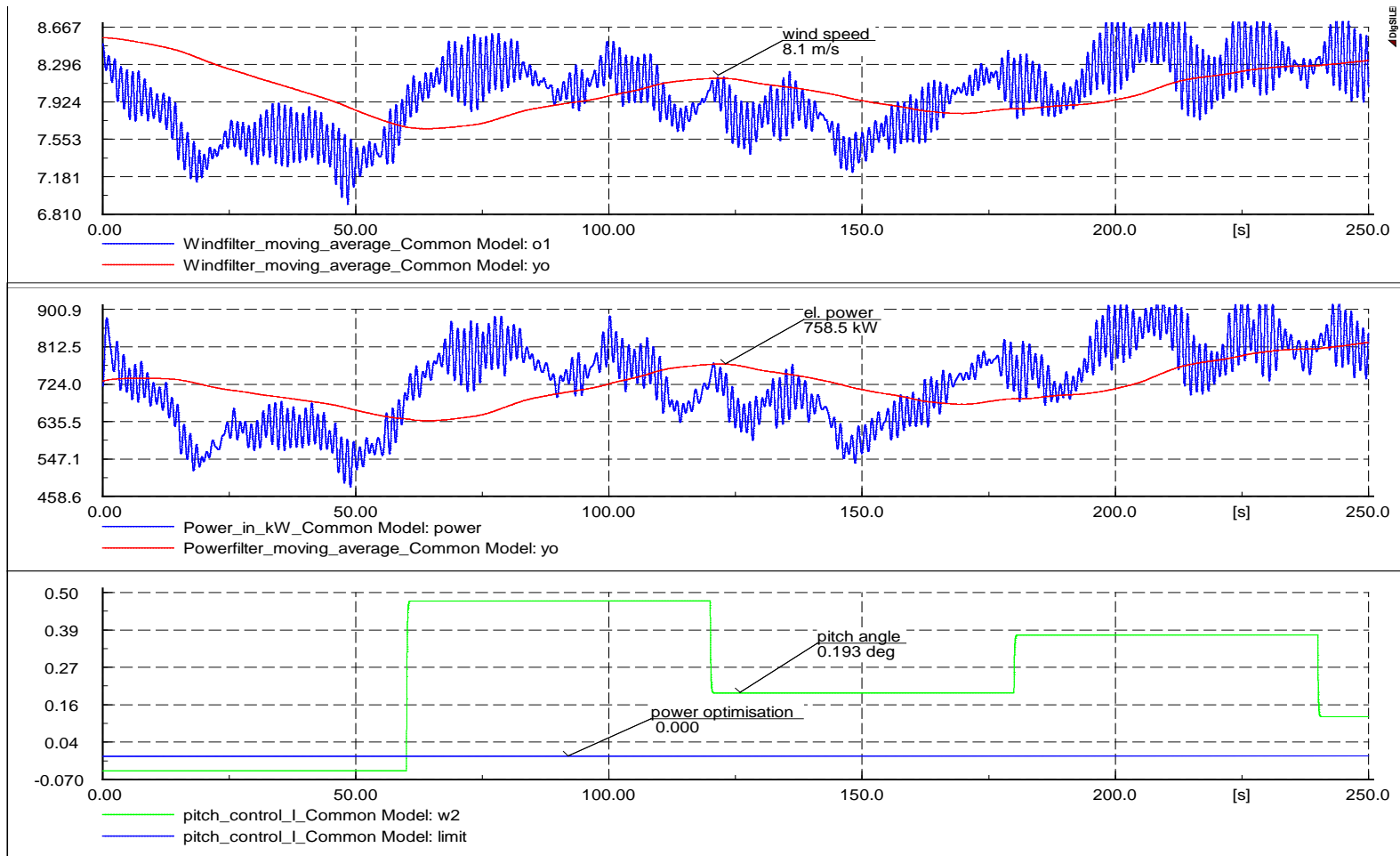
Transition



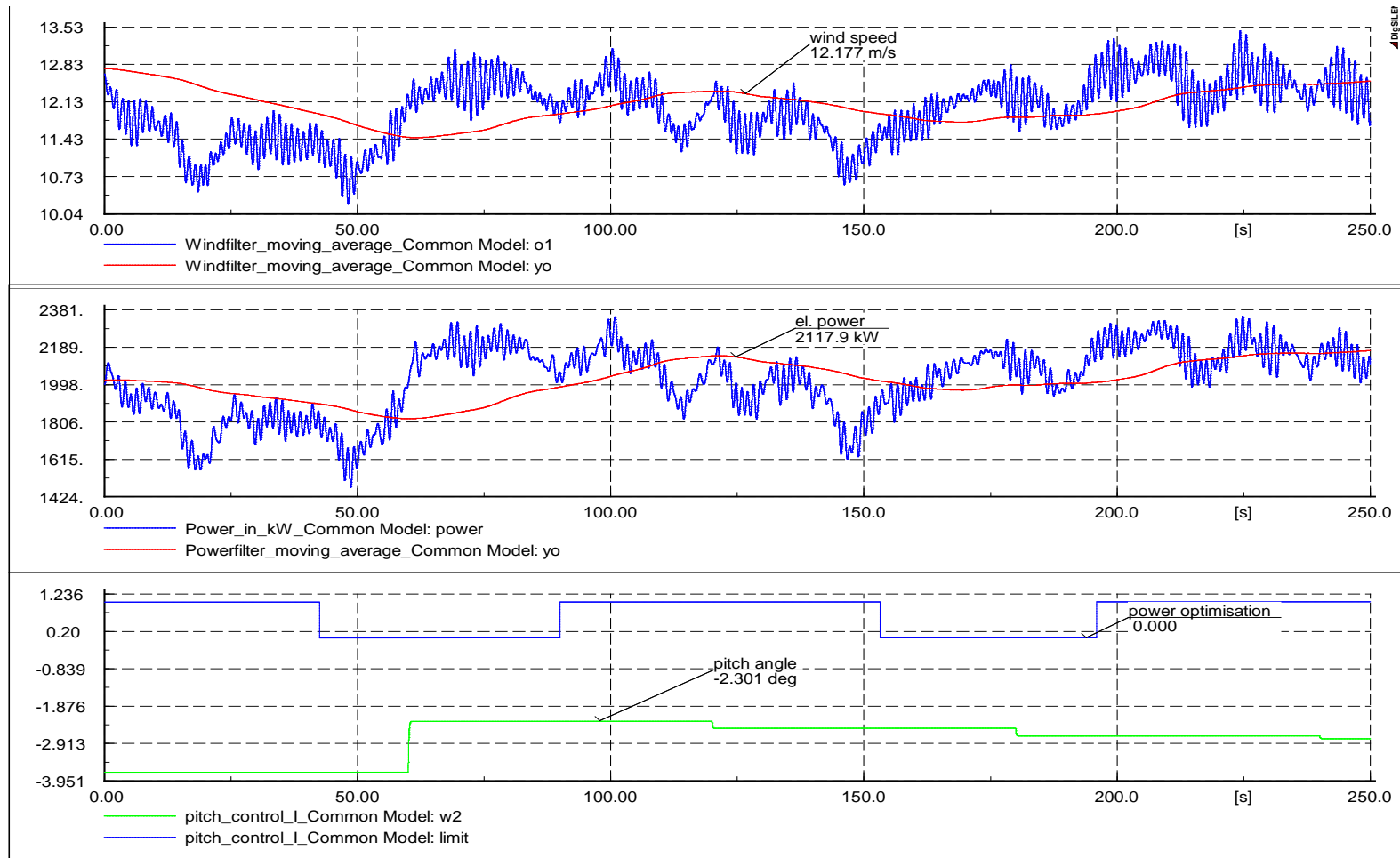
Control Circuit



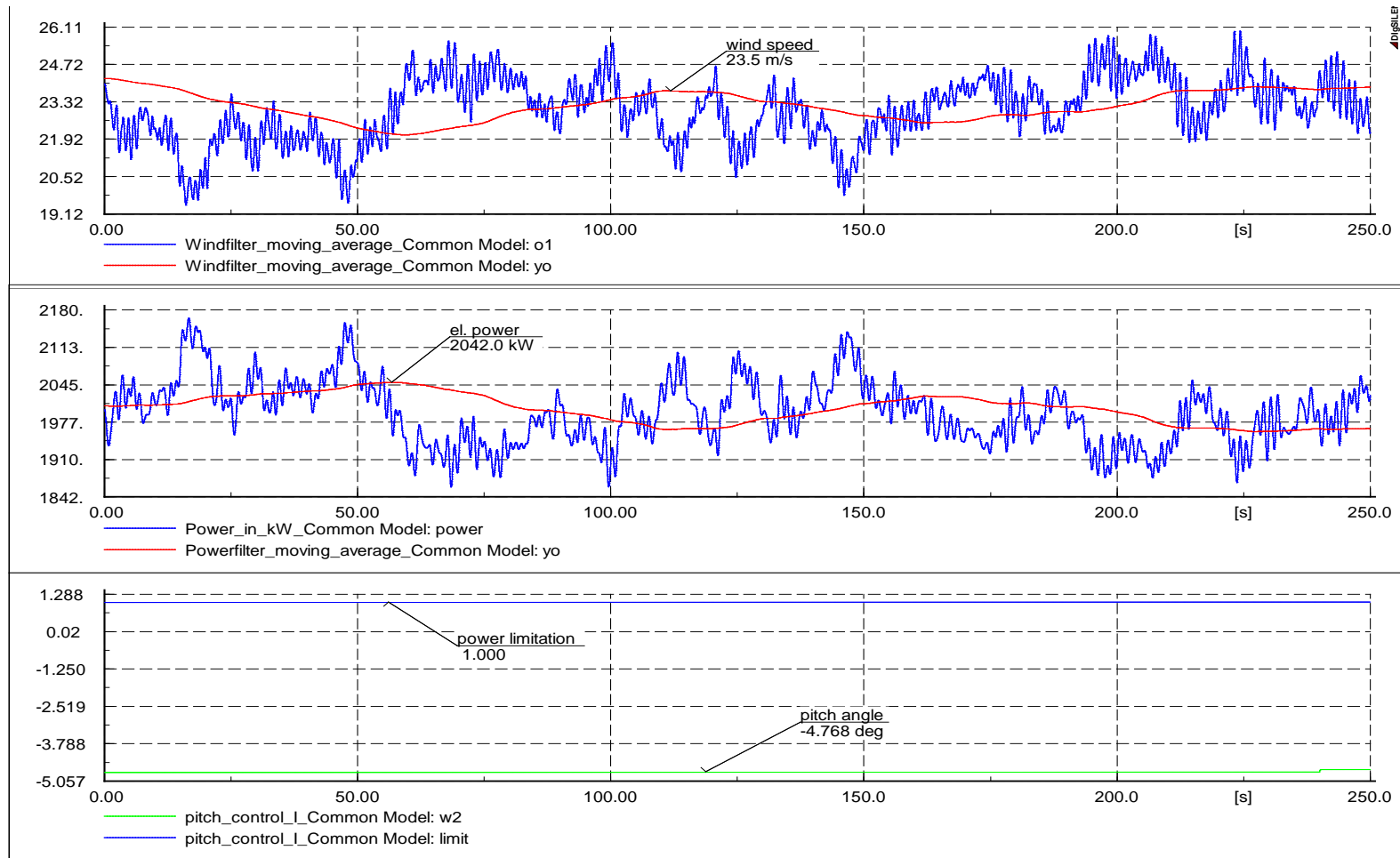
Simulation Power Optimisation



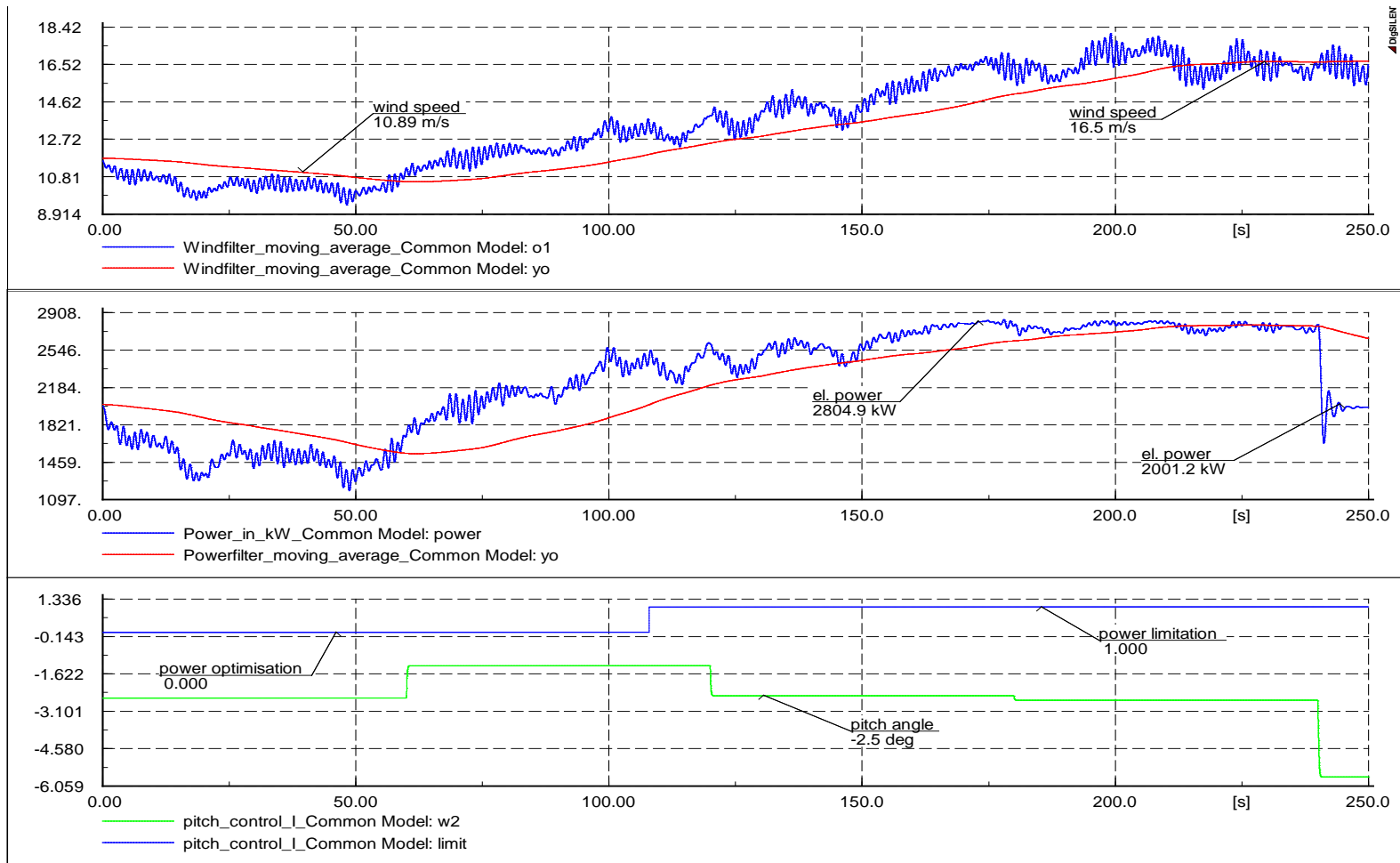
Simulation Transition



Simulation Power Limitation



Simulation Overpower

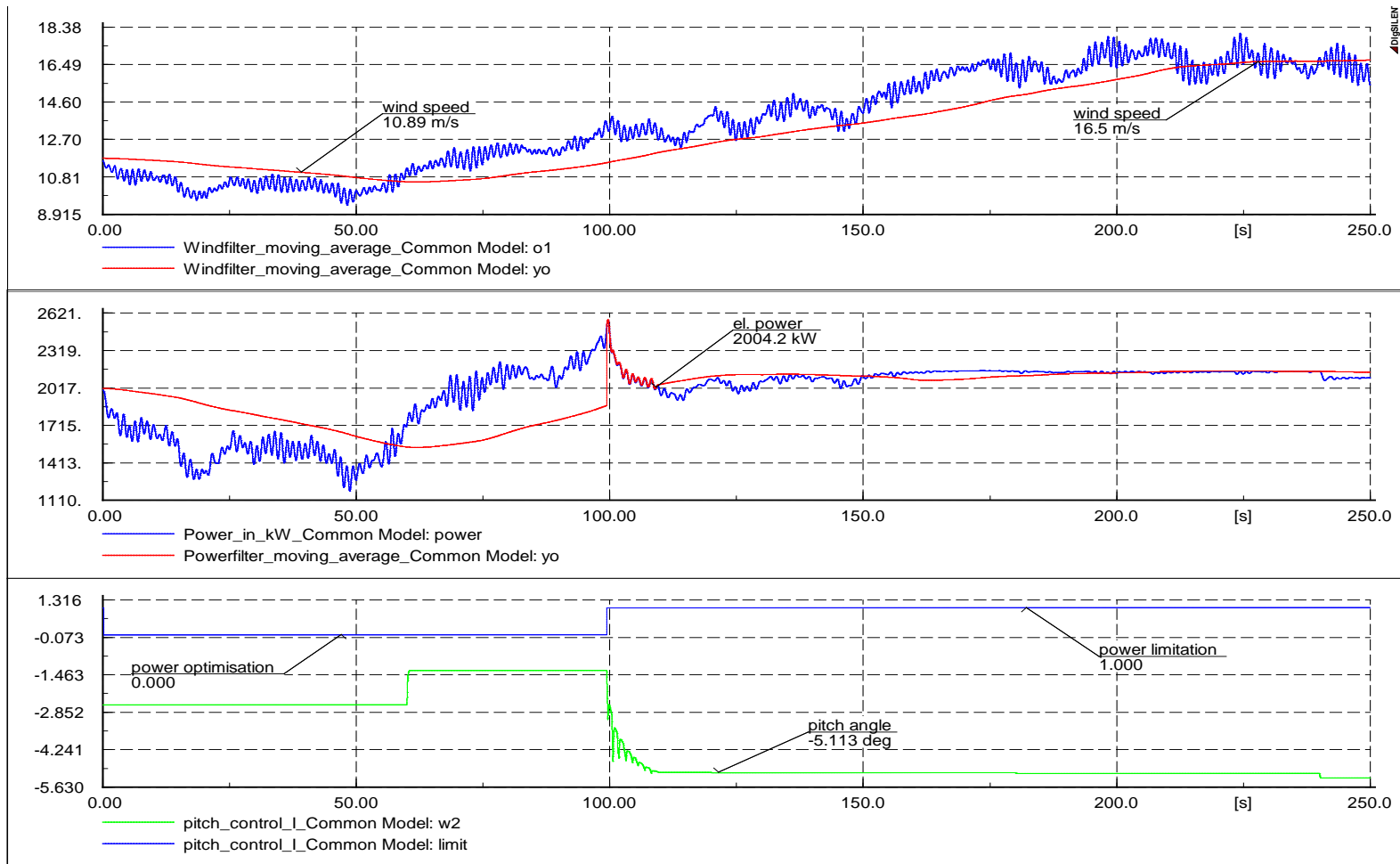


Overpower Protection

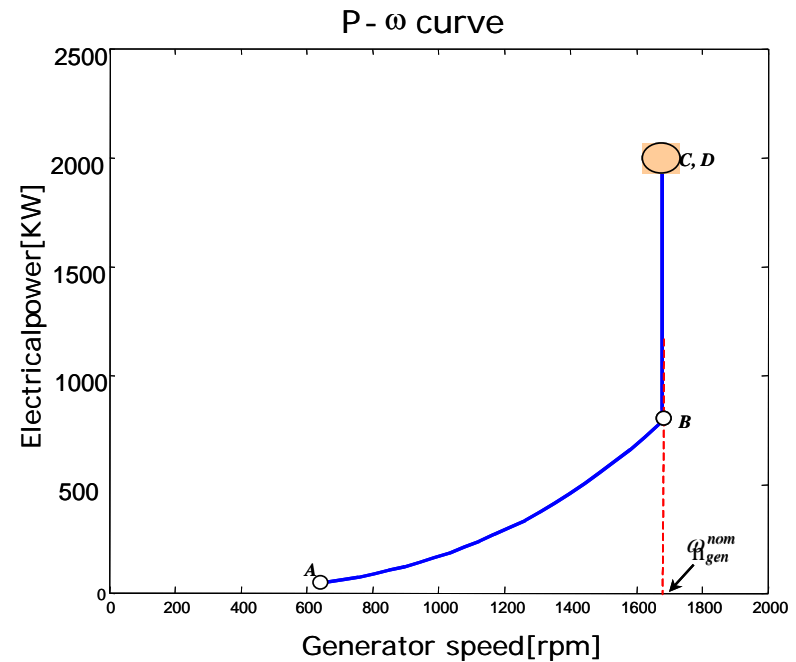
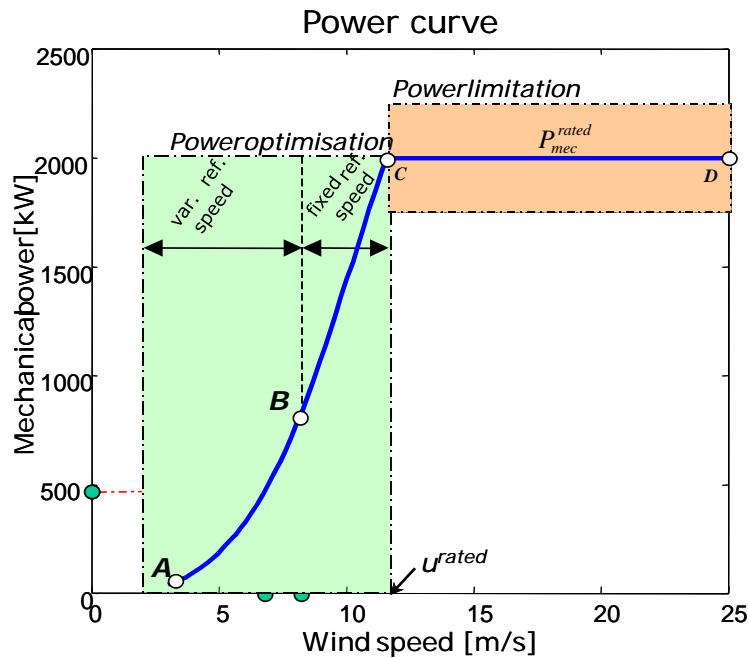


- Function of overpower protection
 - Disable sample and hold
 - (continuous controller action possible)
 - Instantaneous power signal for power controller
 - (controller uses instantaneous power instead of averaged power)
 - Overpower protection active for fixed period of time

Simulation Overpower Protection



Variable speed control strategy – continuous operation

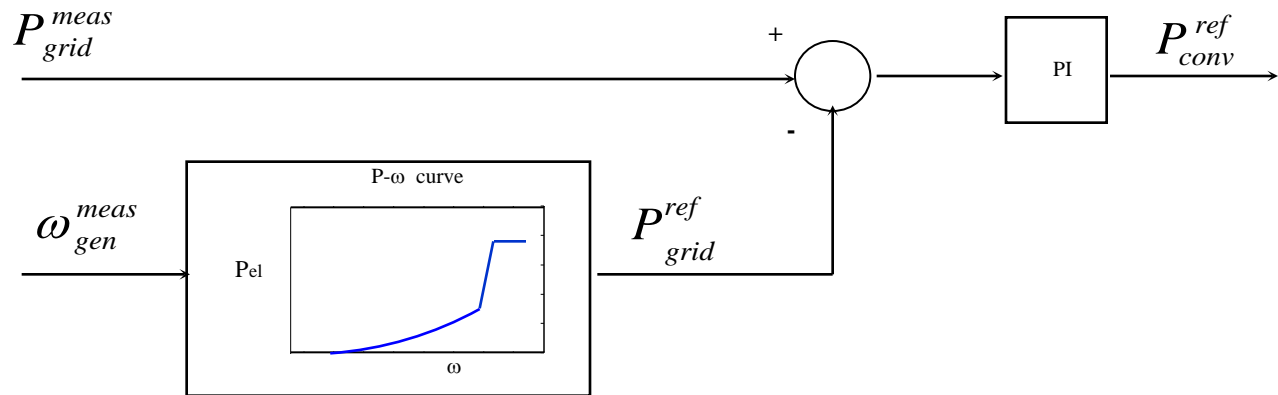


Exercise 2 – variable speed

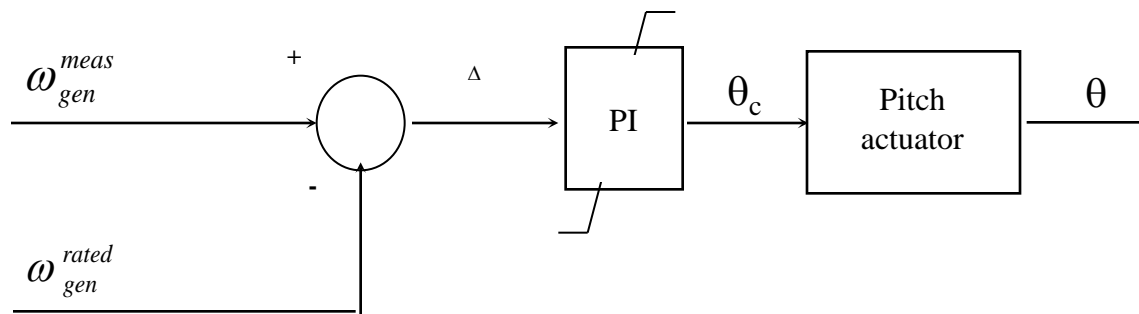
- The C_p data is used for a variable speed / pitch controlled wind turbine with rotor diameter 80 m. Specify equation for power curve in optimisation region A-B
- Specify the corresponding relation between wind turbine rotor speed and power
- The generator is a doubly fed induction generator with two pole pairs ($N_{pp}=2$). The generator speed at rated wind speed is 1650 rpm (i.e. the maximum generator speed). The rated grid frequency is 50 Hz. Find the generator slip corresponding to rated wind speed.
- The rated rotor tip speed (rotor speed at rated wind speed) is 70 m/s. Find the gear ratio.
- Specify the relation between generator speed and power in region A-B
- Specify the relation between generator speed and torque in region A-B

Variable speed control loops

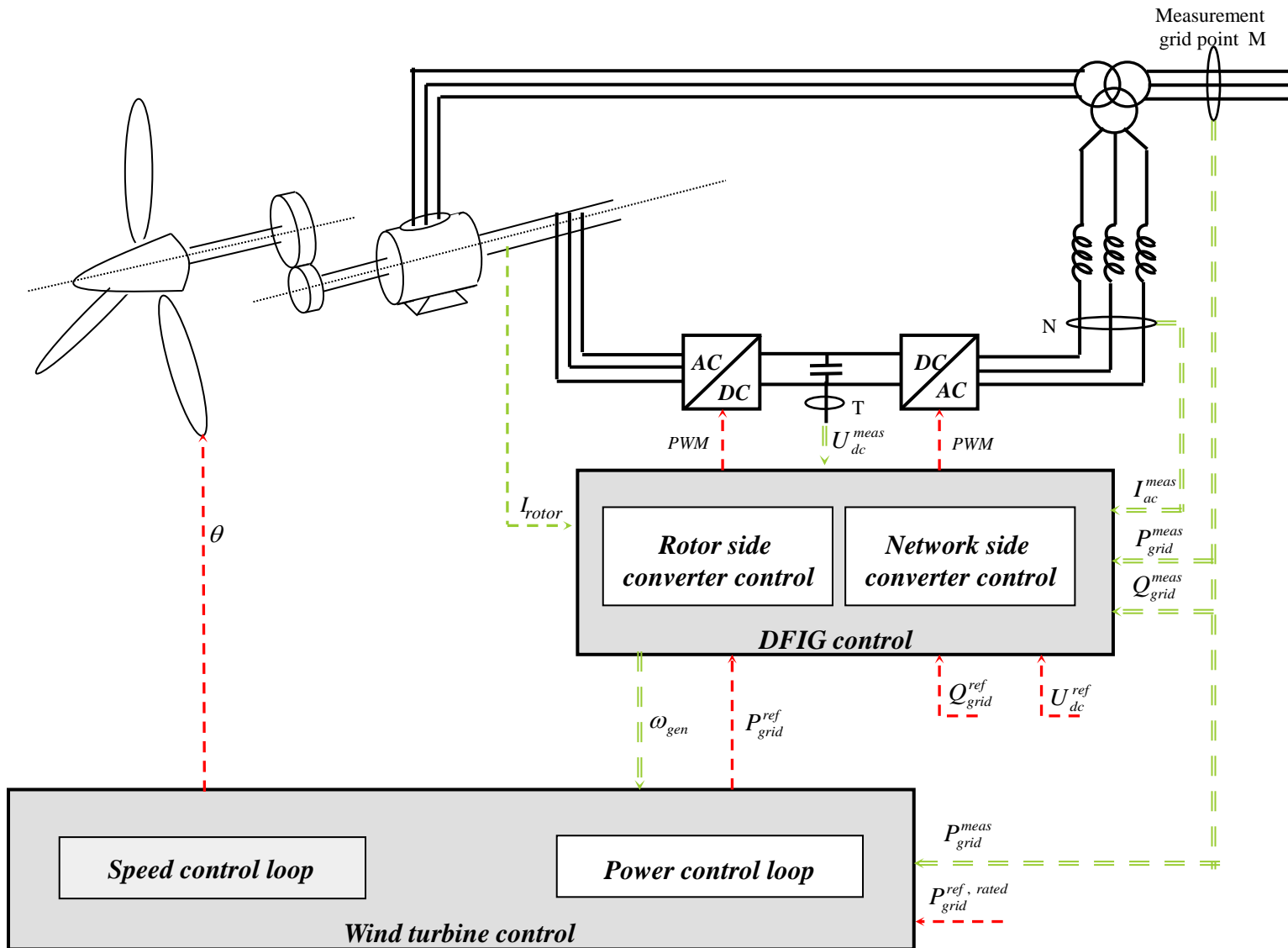
Power loop



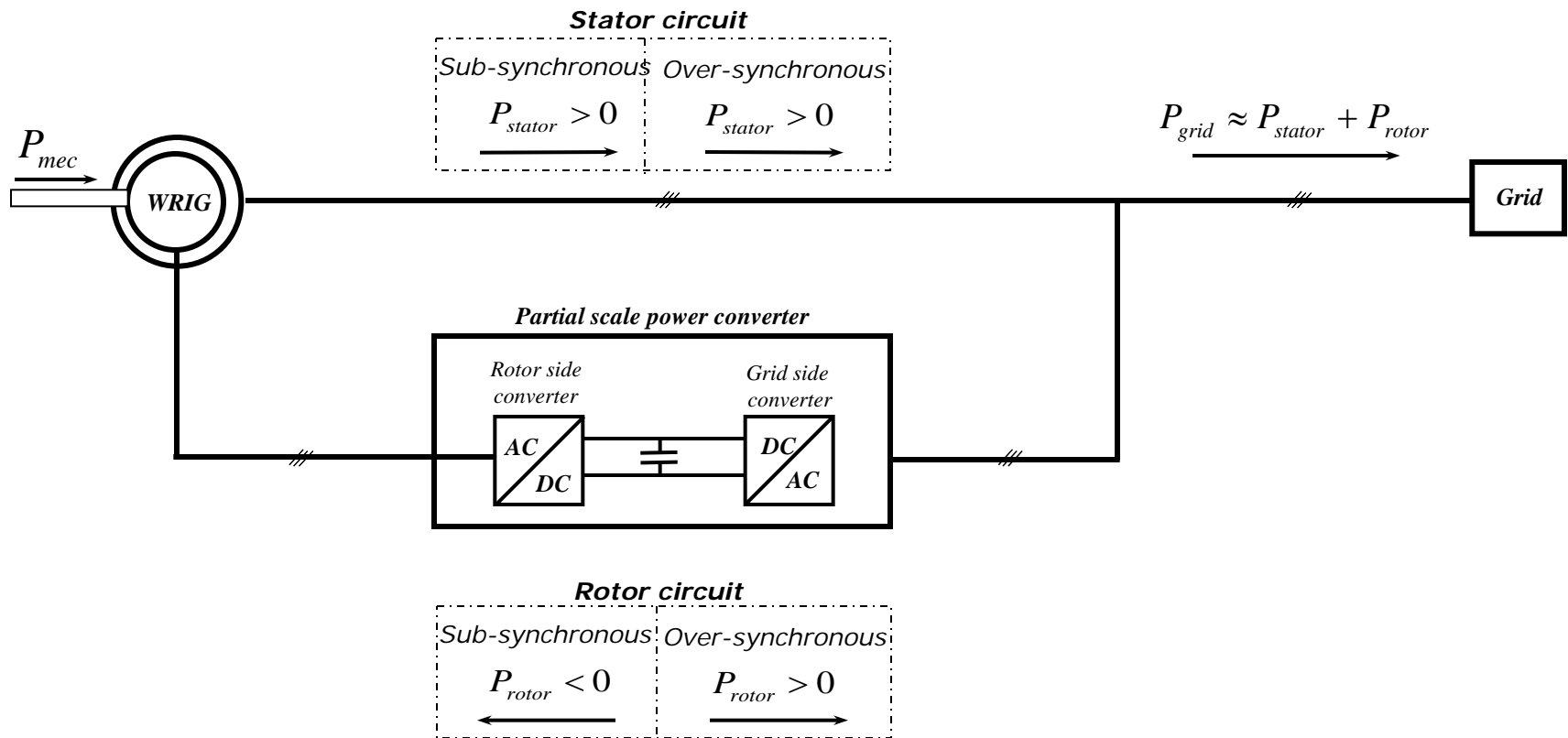
Speed loop



Doubly fed generator (DFG)



Doubly fed generator – power flow vs. rotor speed



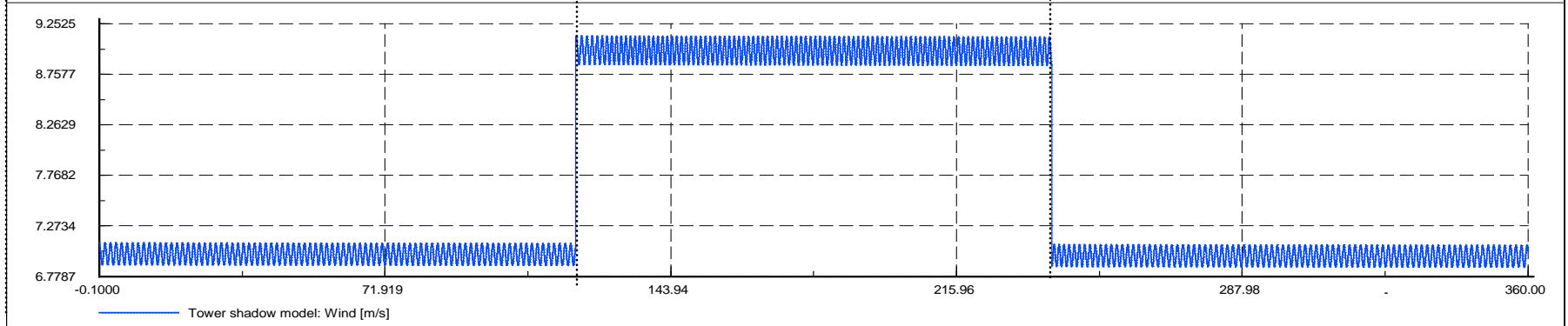
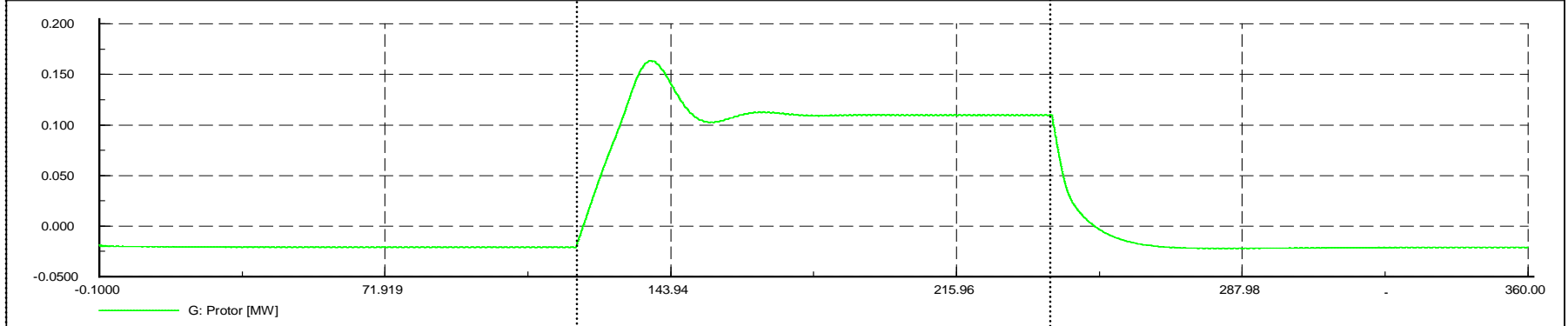
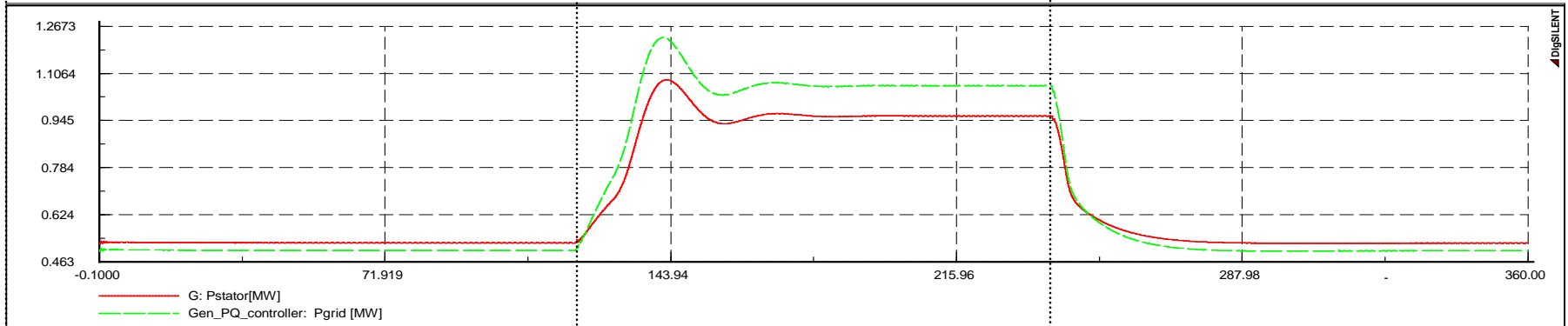
Simulation – optimal power control (AB)



*Below synchronous
(variable reference speed)*

*Above synchronous
(fixed reference speed)*

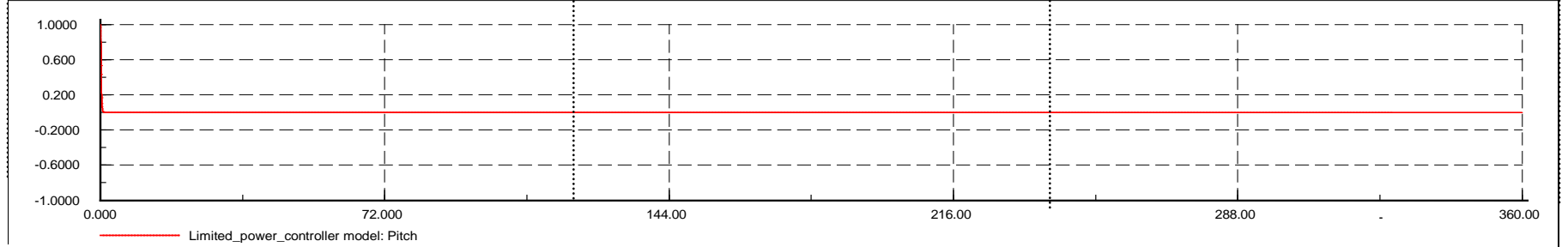
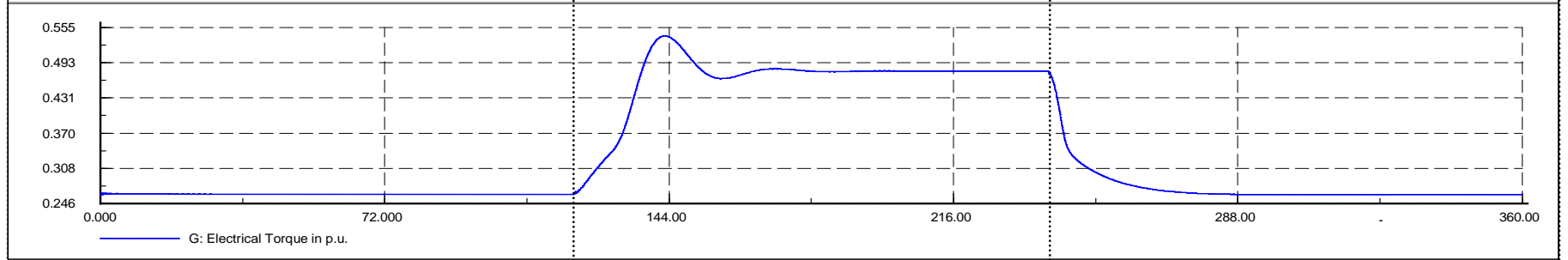
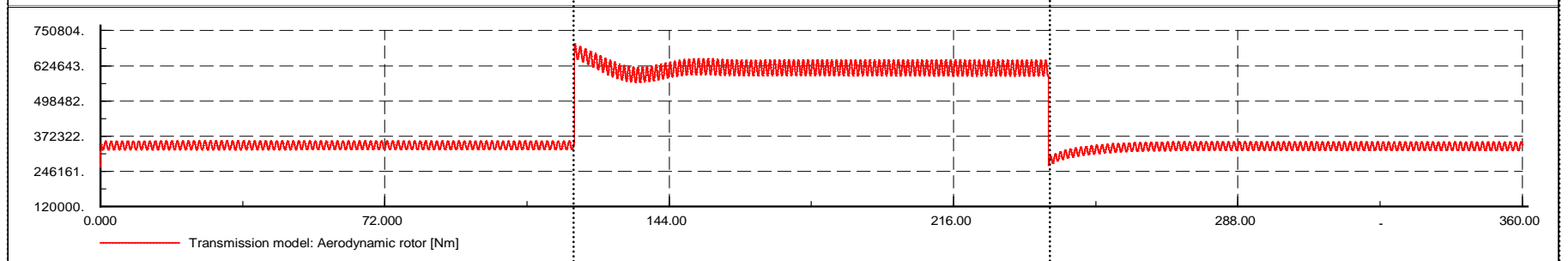
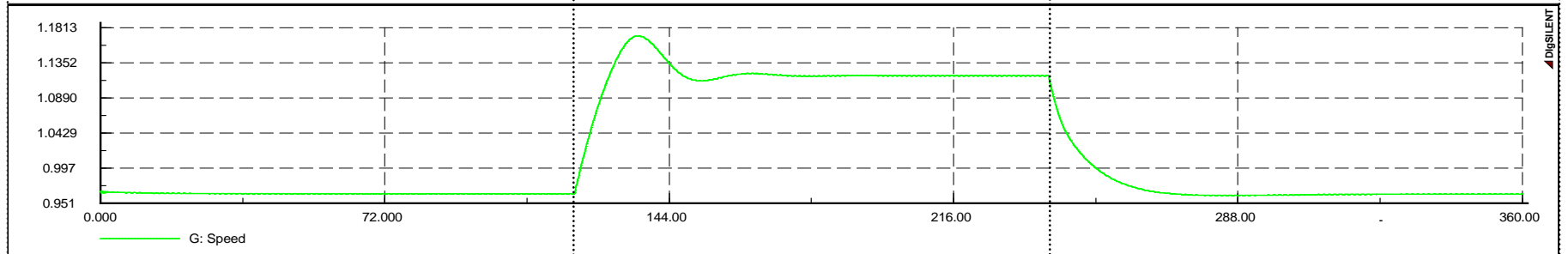
*Below synchronous
(variable reference speed)*



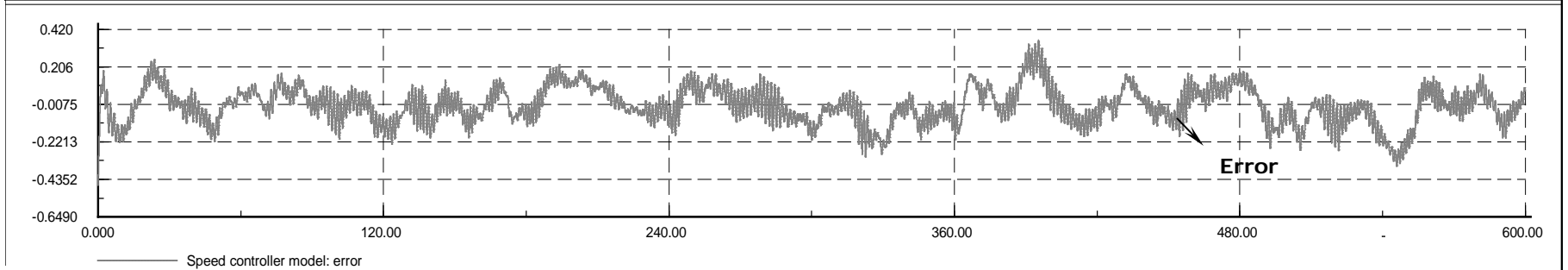
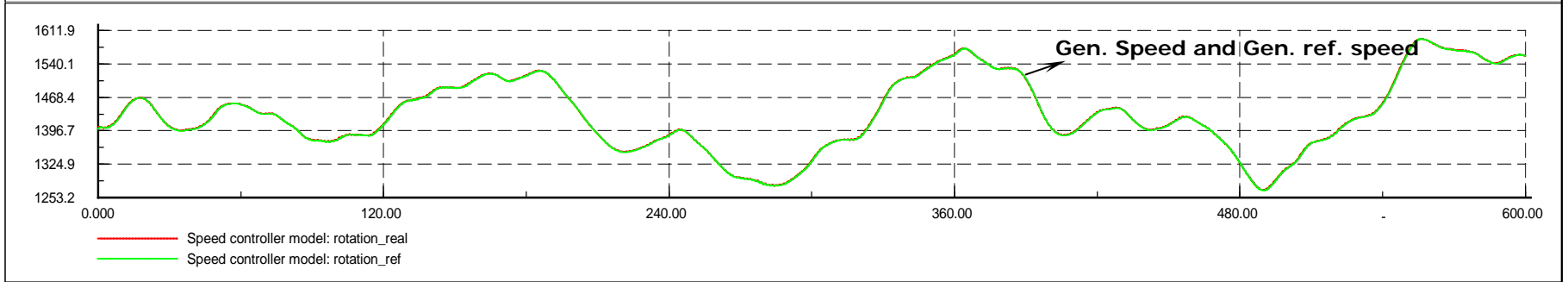
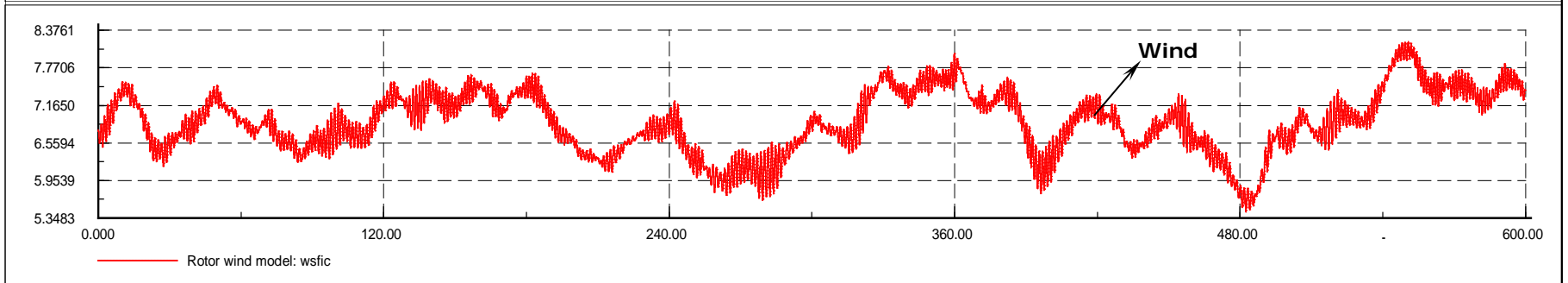
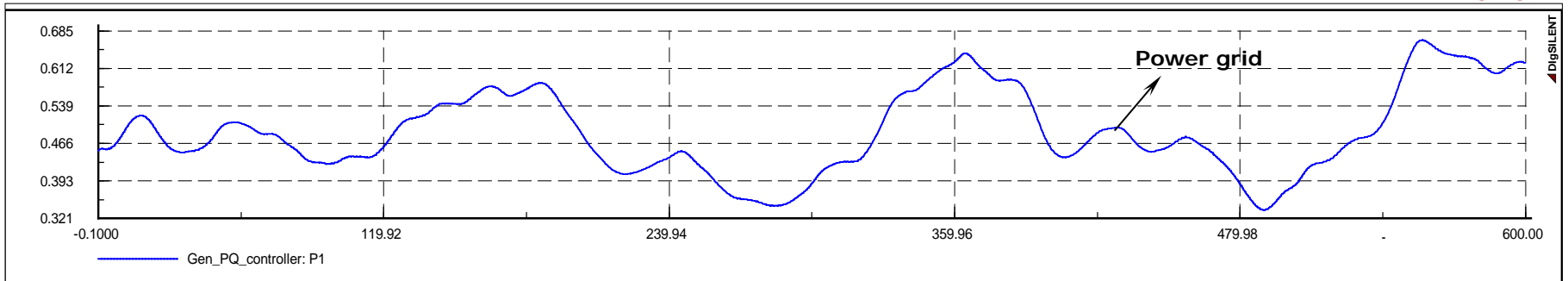
Simulation – optimal power control (AB)



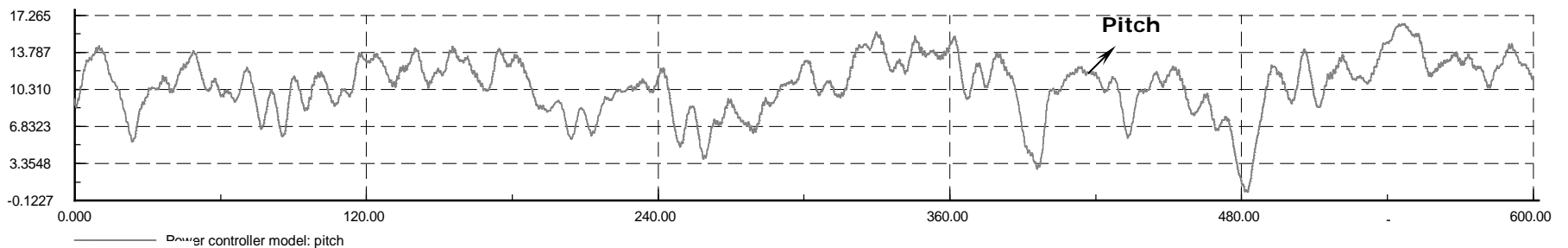
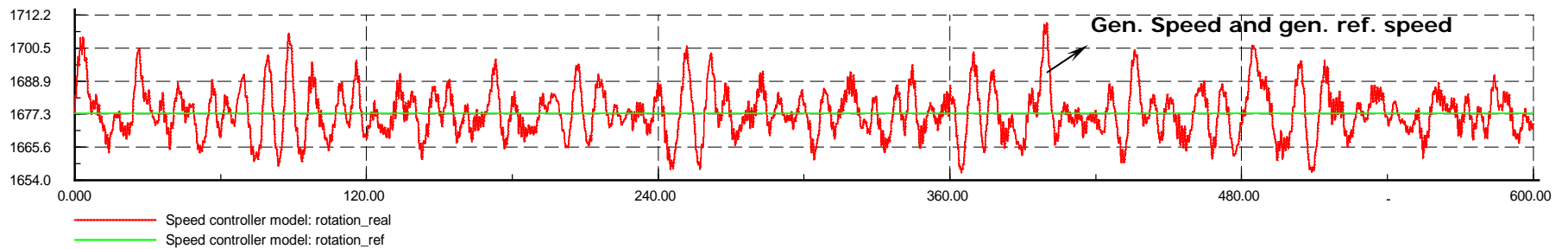
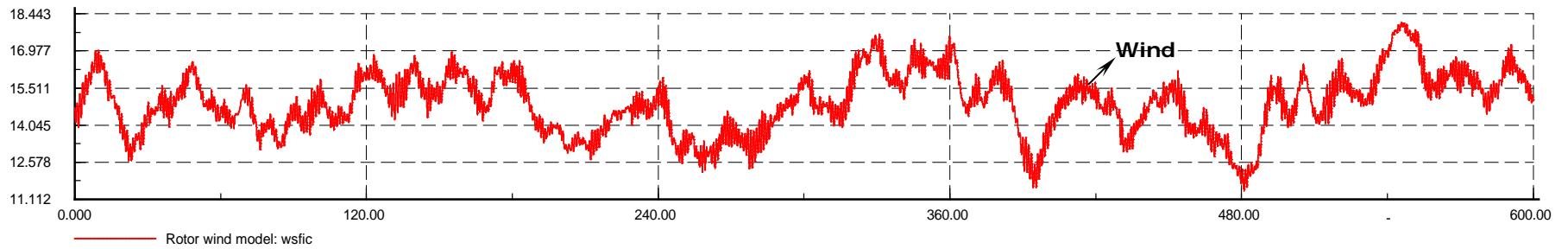
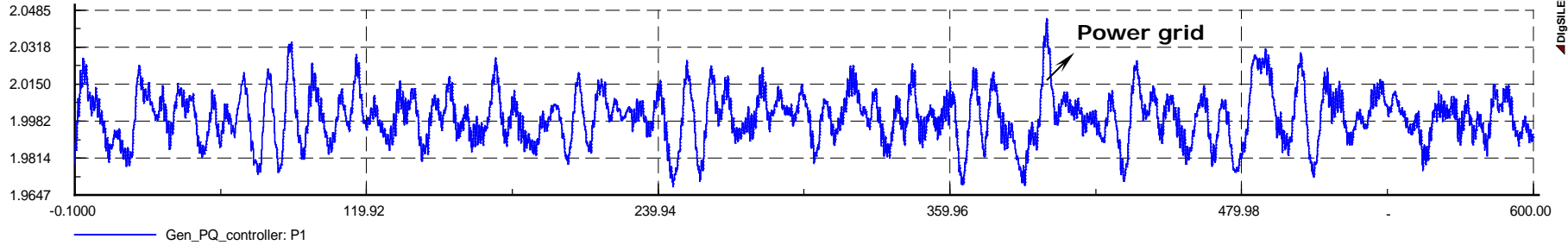
← Below synchronous (variable reference speed) → ← Above synchronous (fixed reference speed) → ← Below synchronous (variable reference speed) →



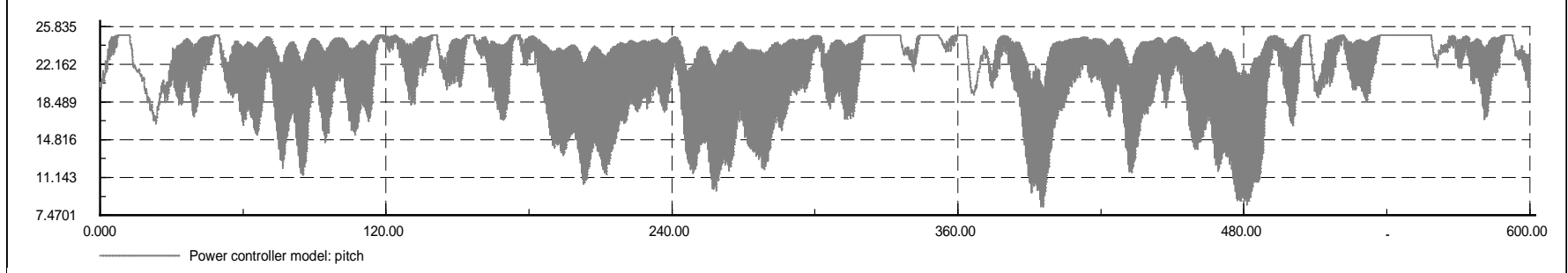
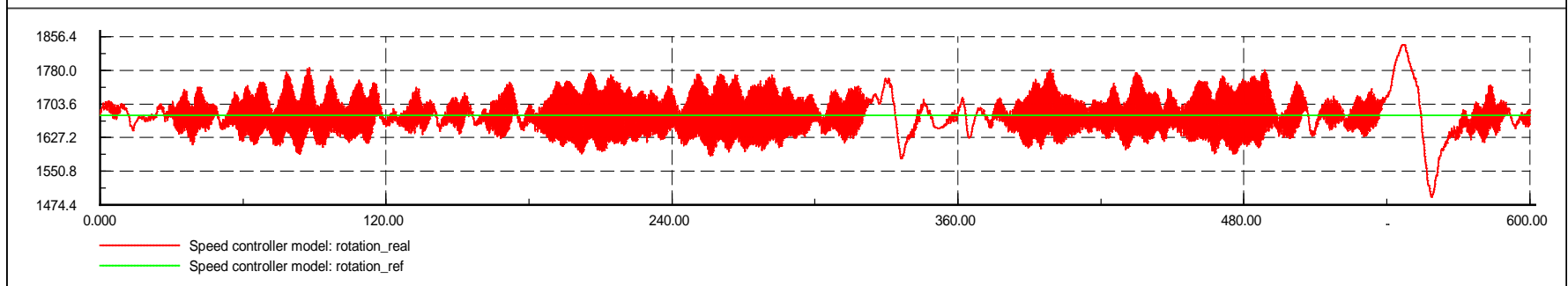
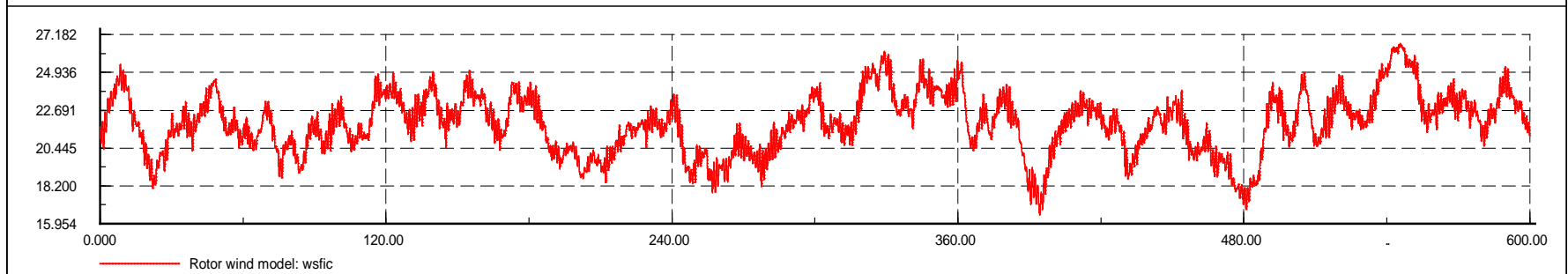
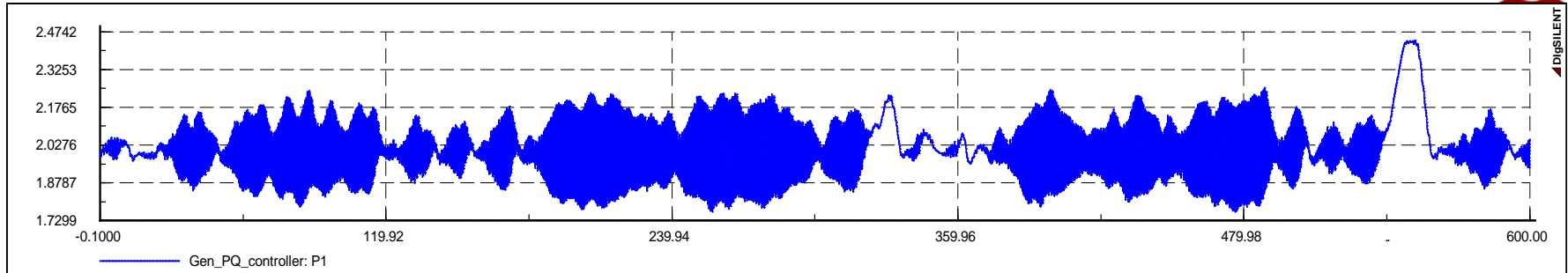
Simulation - wind 7m/s – optimisation



Simulation - wind 15 m/s

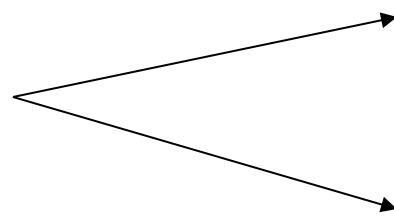


Simulation - wind 22 m/s



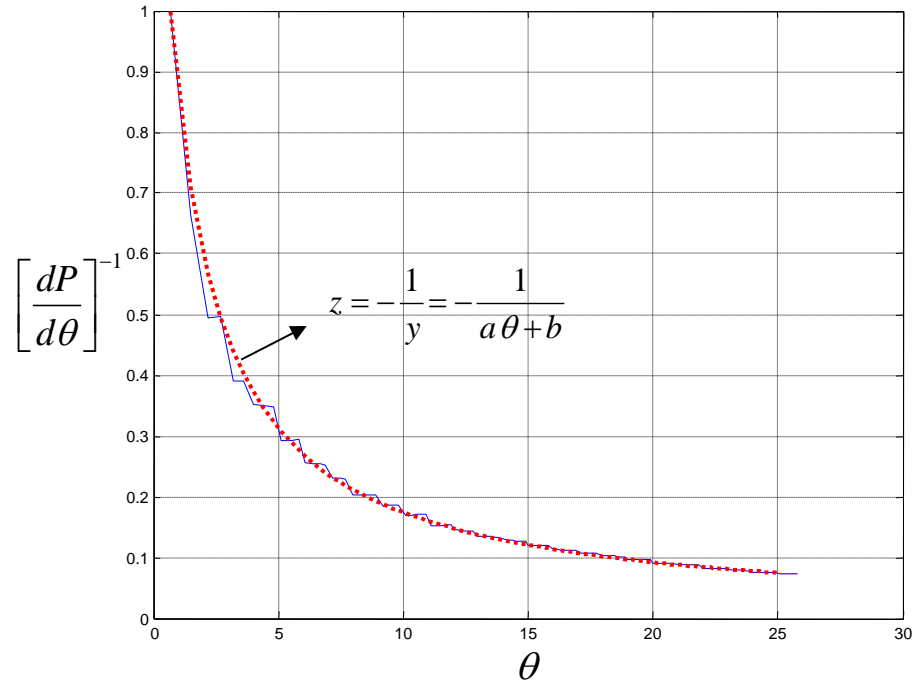
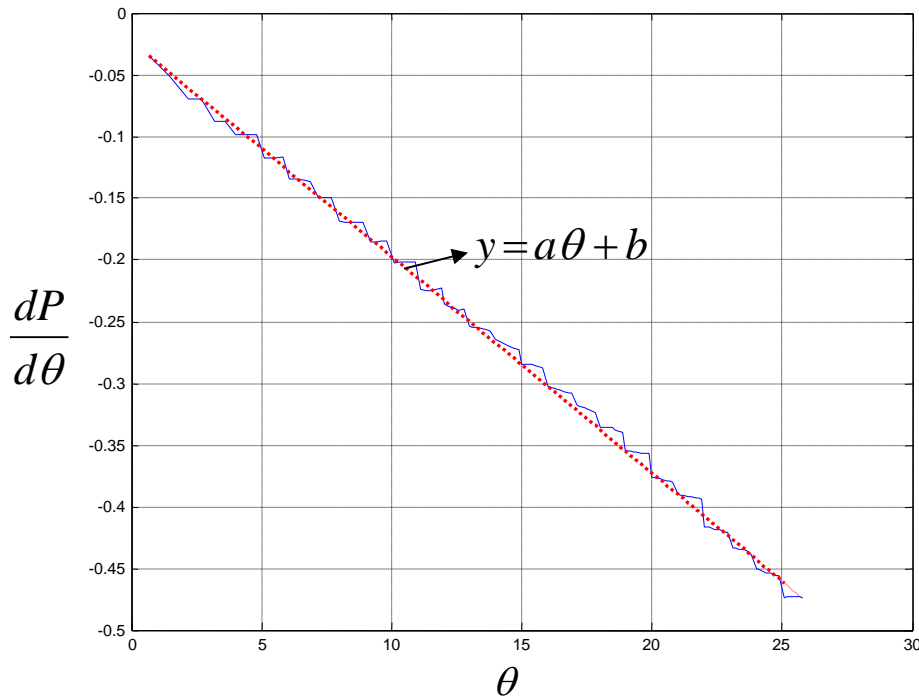
Gain scheduling

$$K_{system} = K_{PI} \left[\frac{dP}{d\theta} \right]$$



$$K_{PI} = K_{pitch}$$

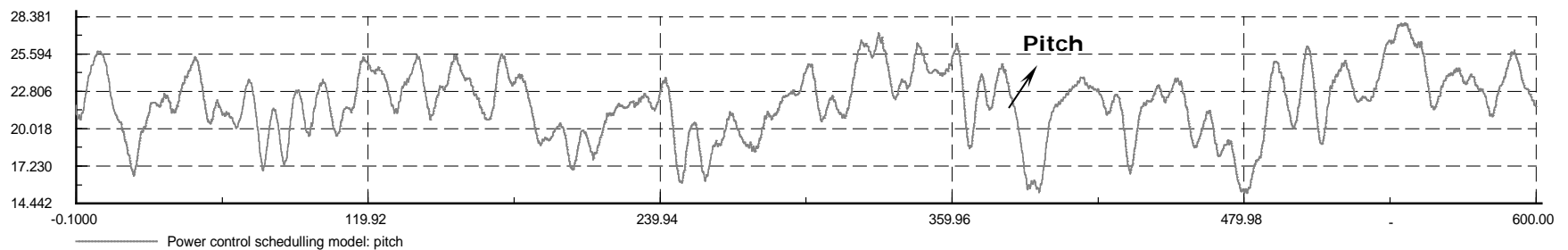
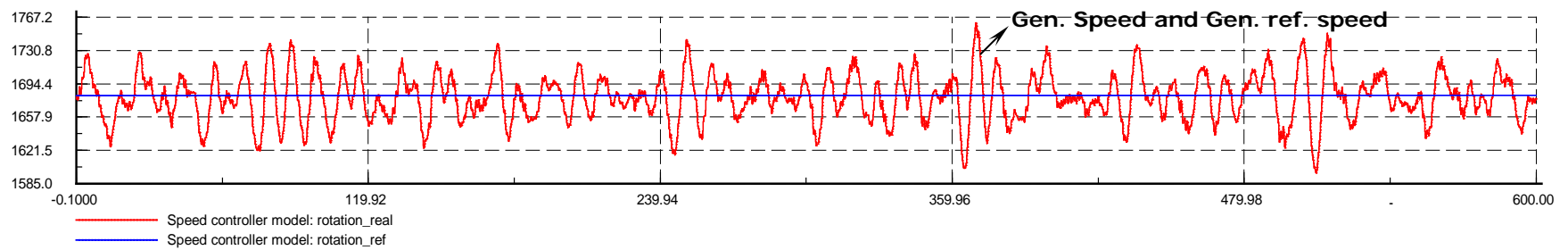
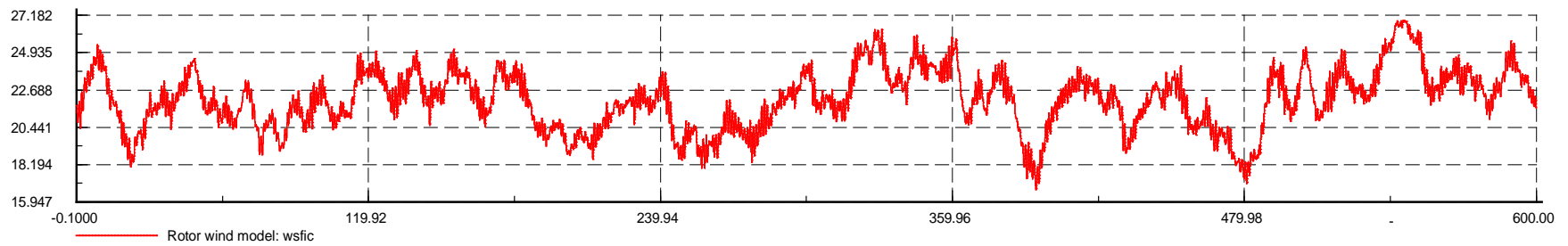
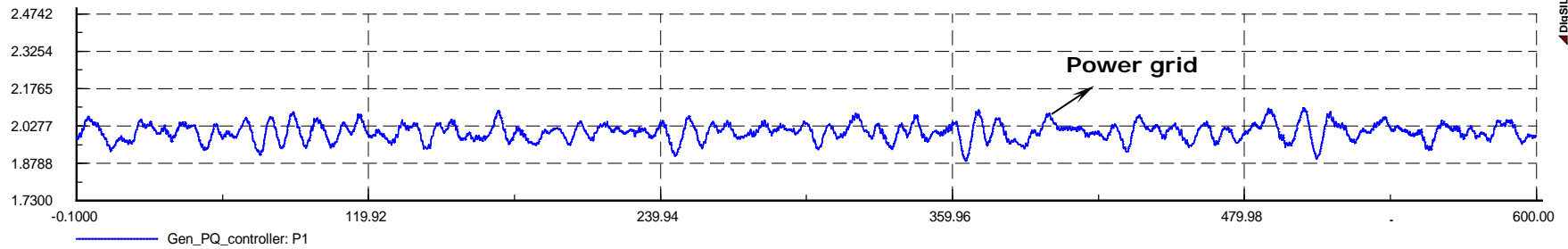
$$K_{PI} = K_{pitch} \left[\frac{dP}{d\theta} \right]^{-1}$$



Simulation - wind 22 m/s – gain scheduling

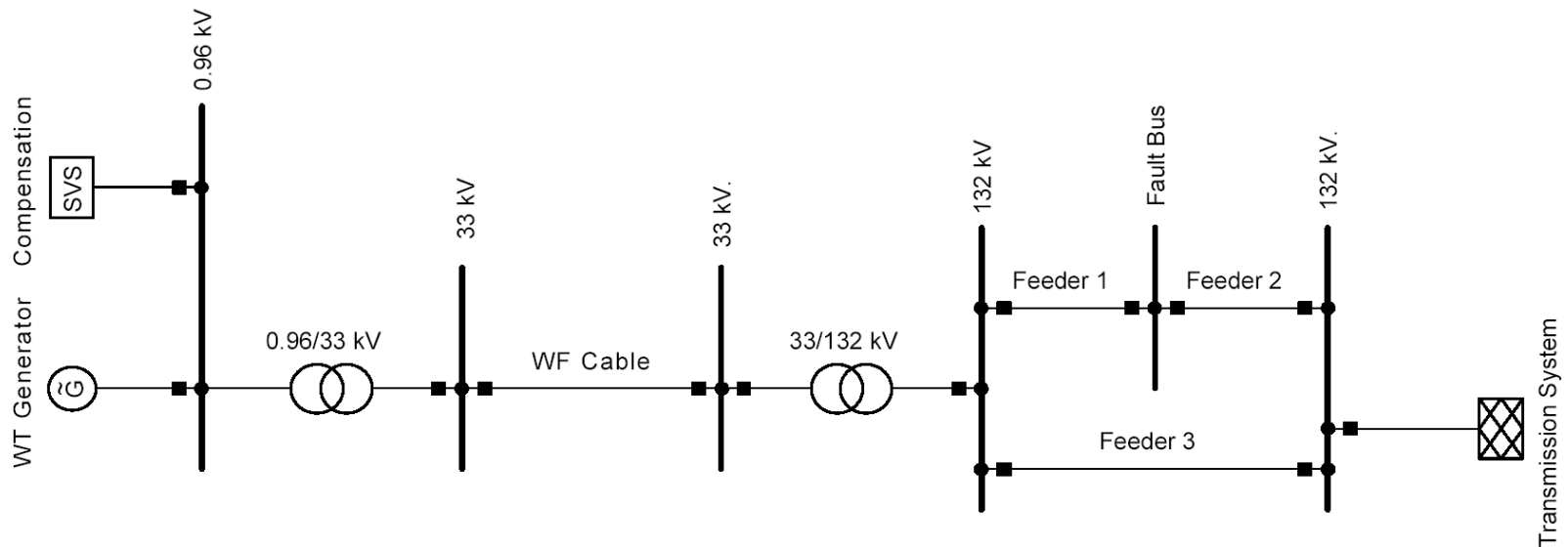


DTU
DIGSILEN

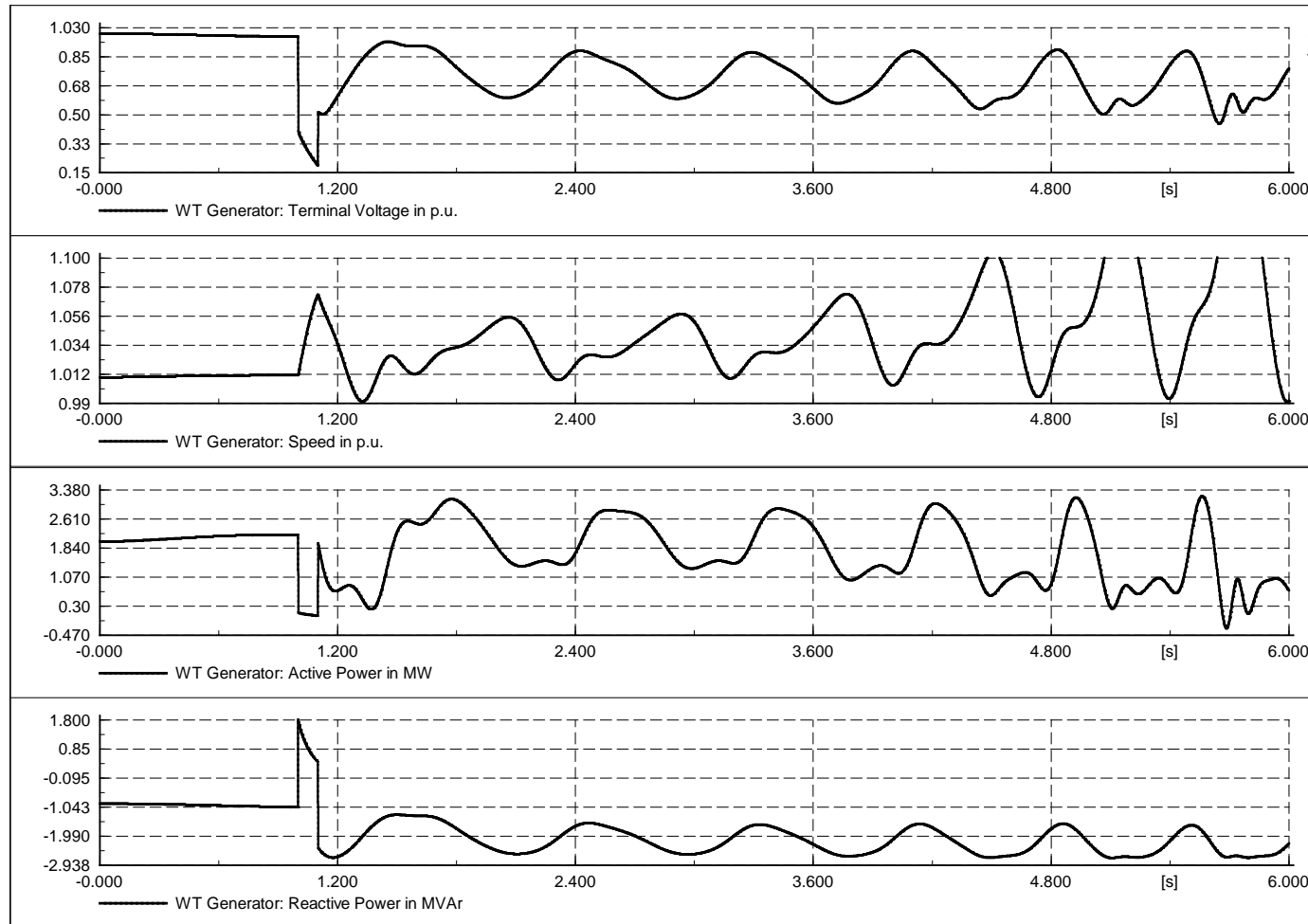


Fault-ride-through control

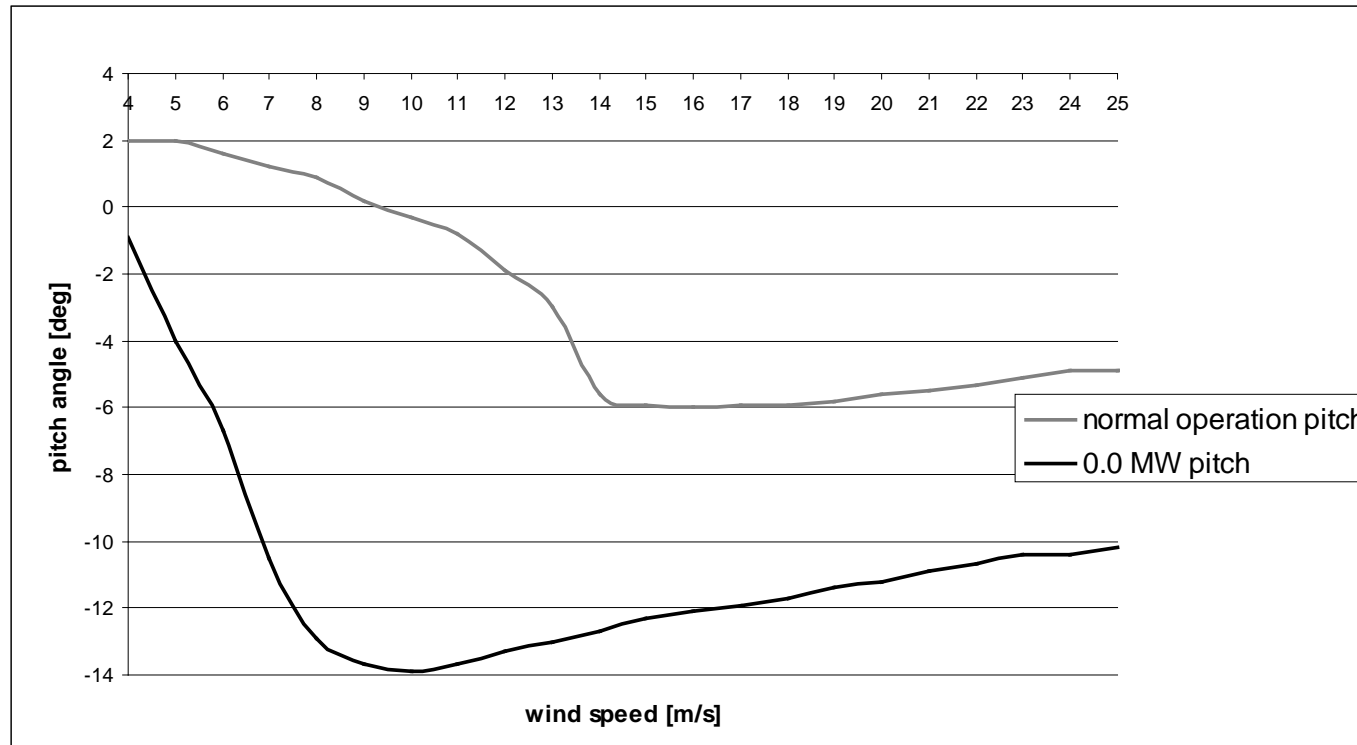
- Example active stall
 - short circuit at “Fault Bus”
 - isolation of fault



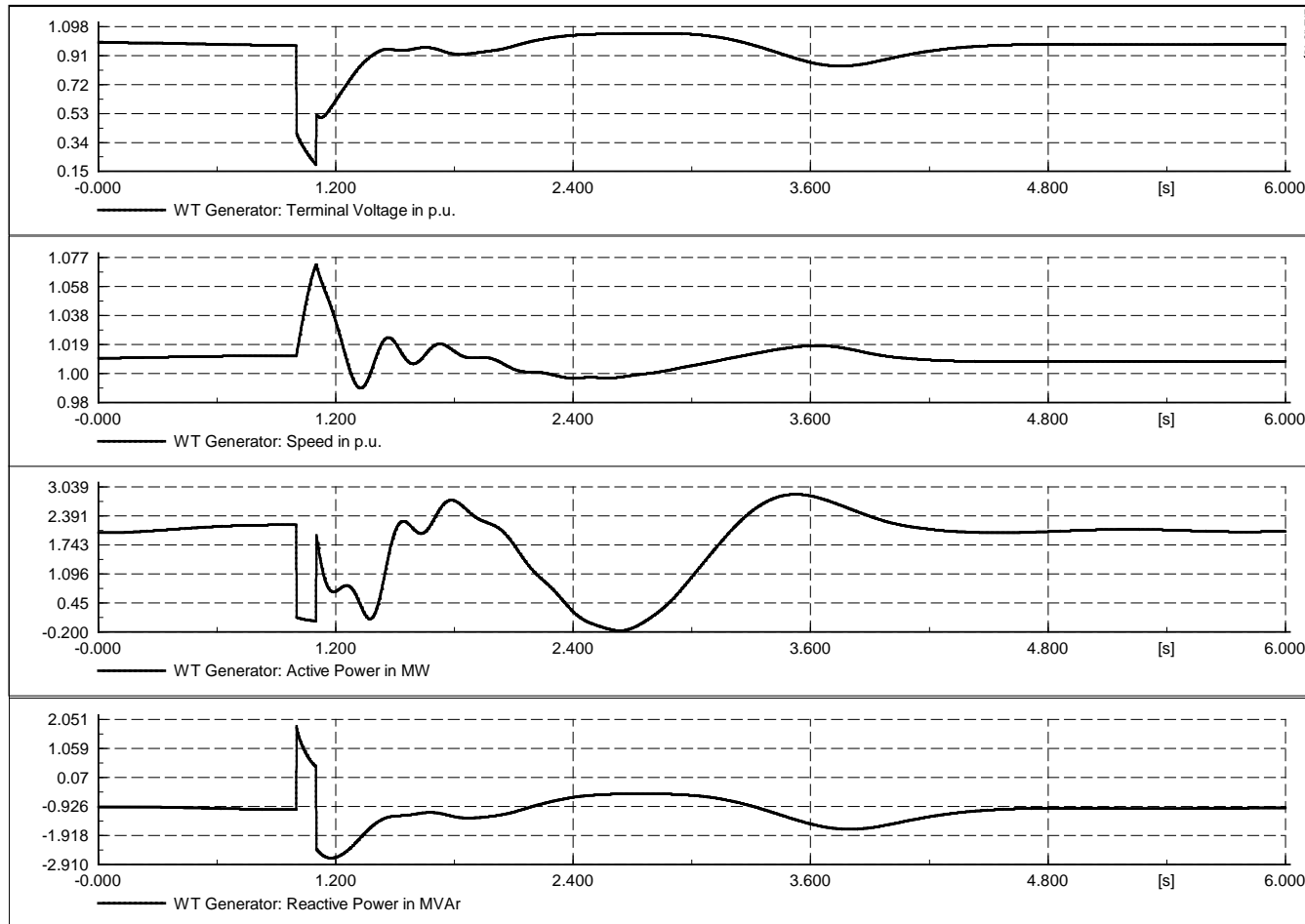
No fault-ride-through control



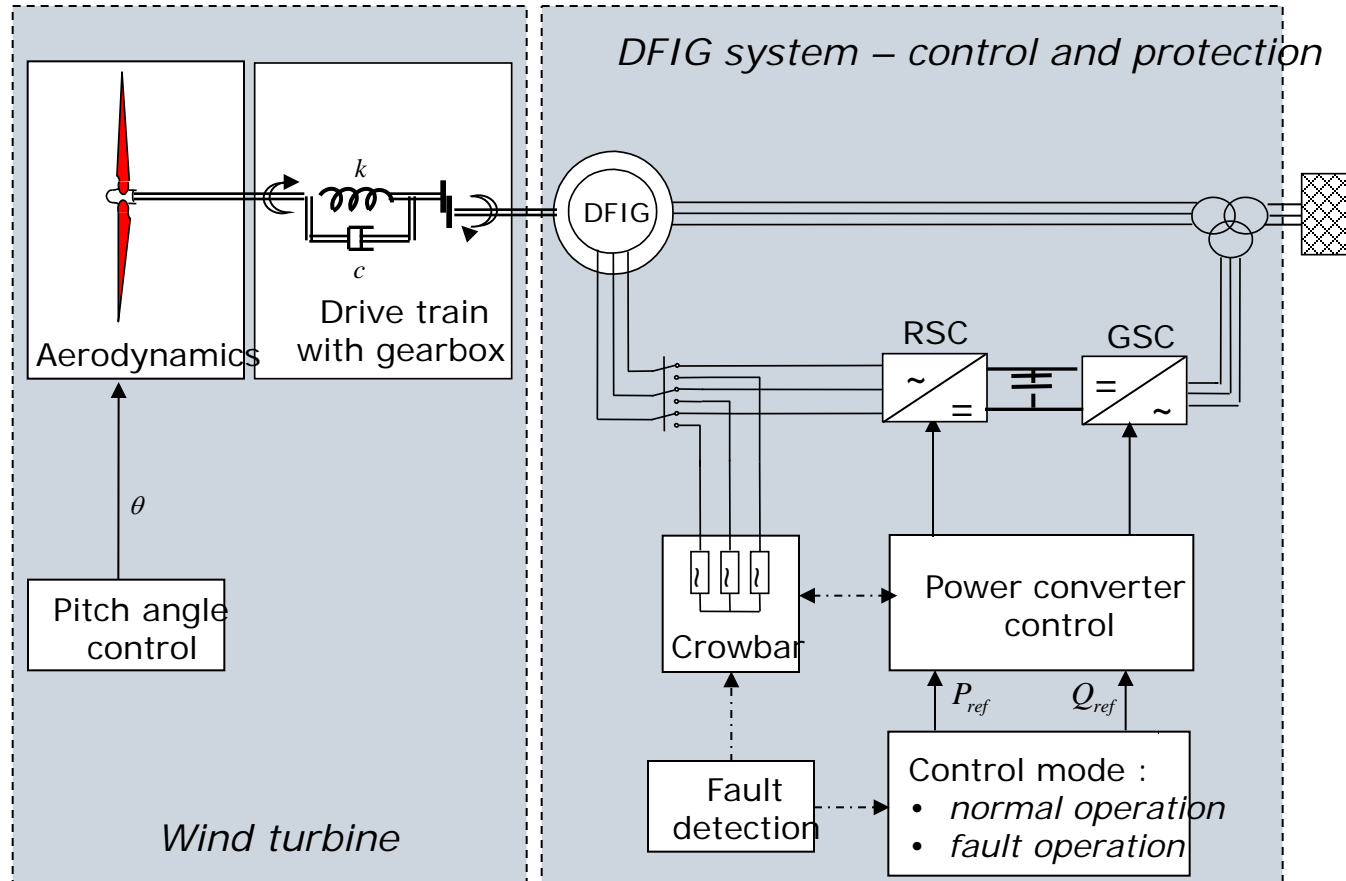
Simple fault-ride-through control: fast pitch to zero-power



Short circuit simulated with fault-ride-through control

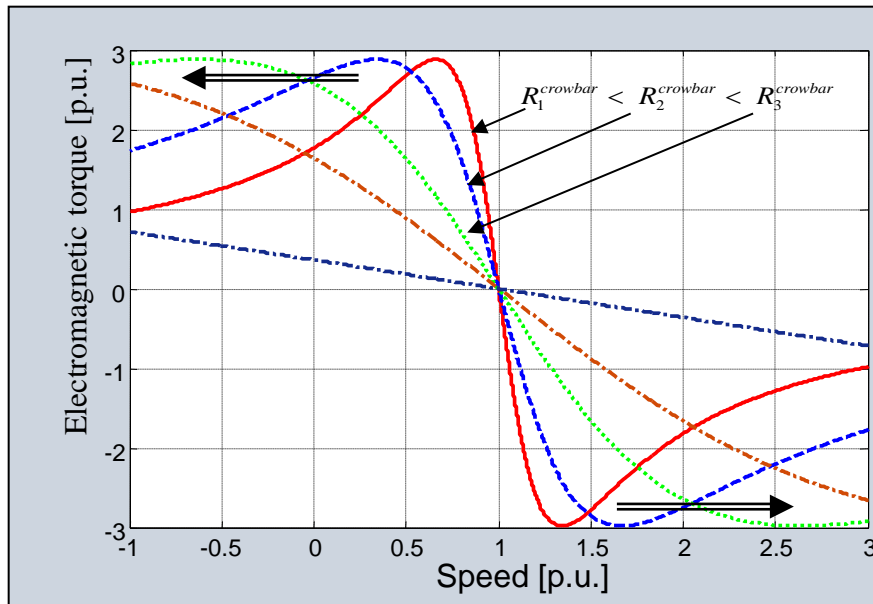


Fault ride through – DFIG with crowbar

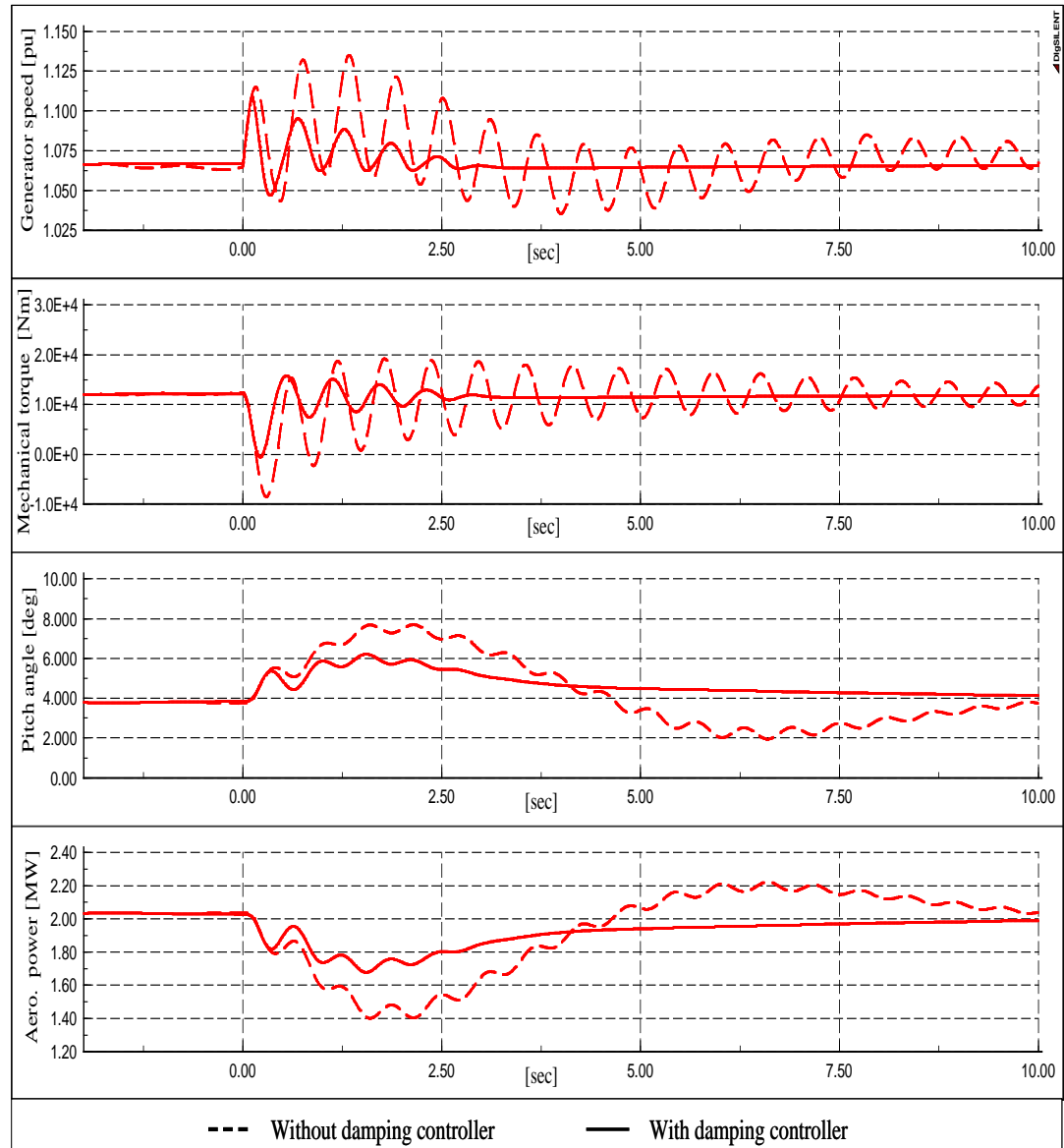
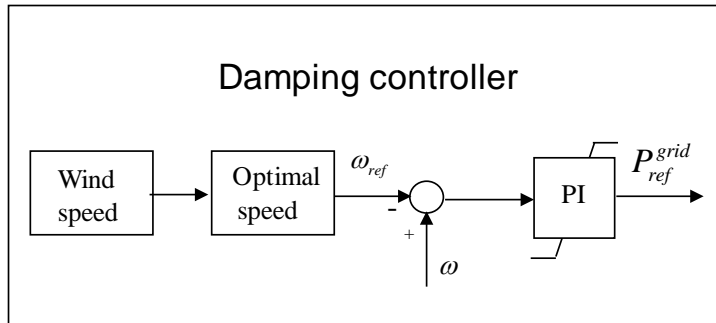


Crowbar effects

- On voltage dip:
 - RSC overcurrents
 - Crowbar activates / RSC disconnects
 - DFG behaves as SCIG (no control)
 - GSC can still be used as a STATCOM
- Effect of increased crowbar resistance :
 - improves the torque characteristic
 - reduces reactive power demand
 - improves dynamic stability of the generator

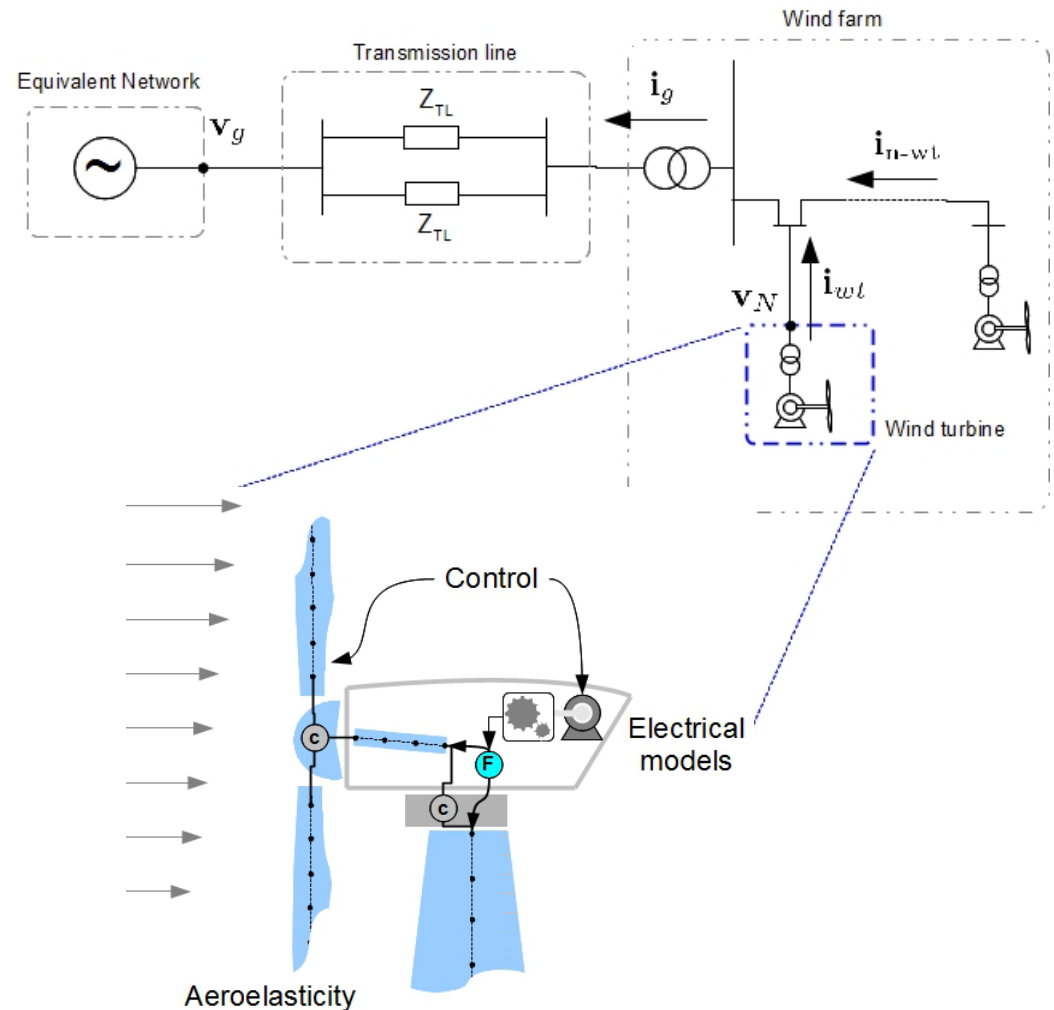


Load reduction – active damping



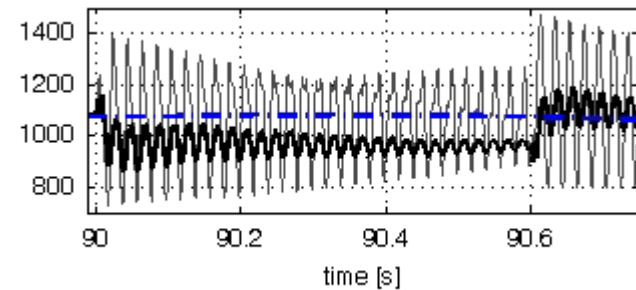
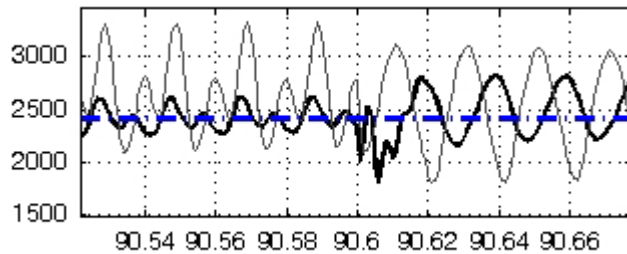
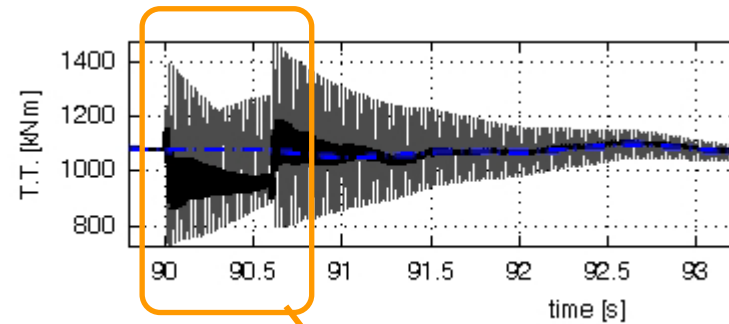
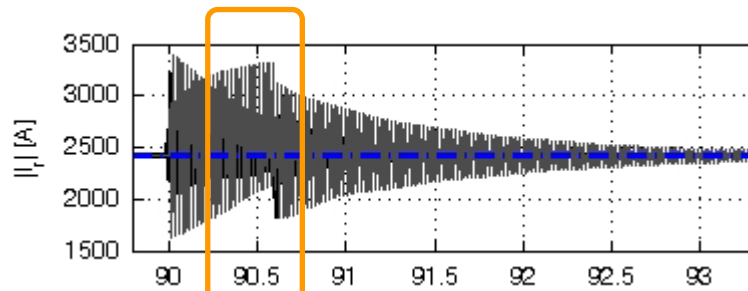
Integrated design analysis and load reduction

- Integrated analysis model
 - Aeroelastic model of wind turbine (HAWC2)
 - Pitch control
 - Asynchronous machine + control
 - Rotor and Stator fluxes
 - Current and power control of rotor side converter
 - Resonant damping control



Resonant damping control – load reduction

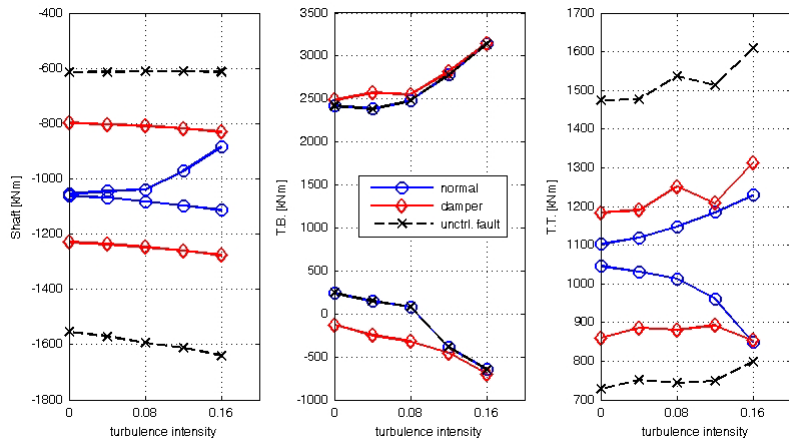
Unbalanced fault



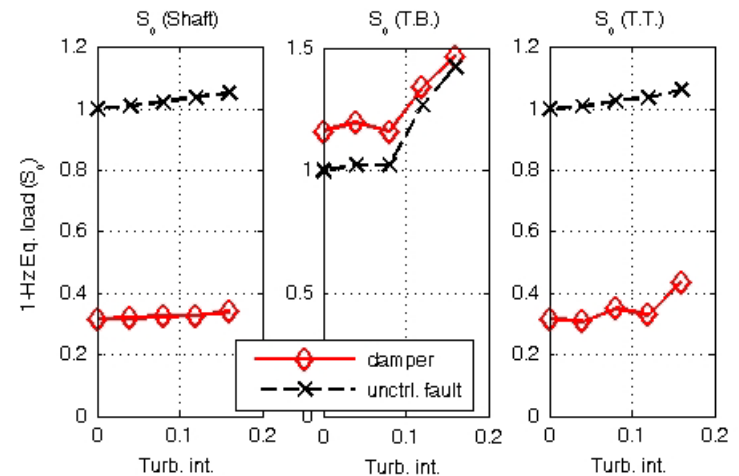
Electrical loads:
Generator rotor current

Structural loads:
Tower top side-to-side moment

Resonant damping control – load reduction



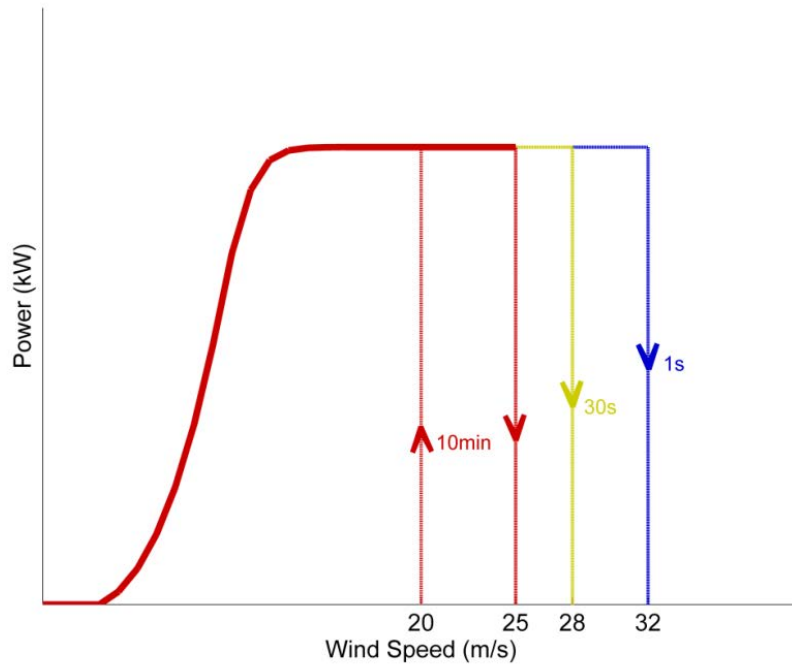
Load ranges
(max – min)



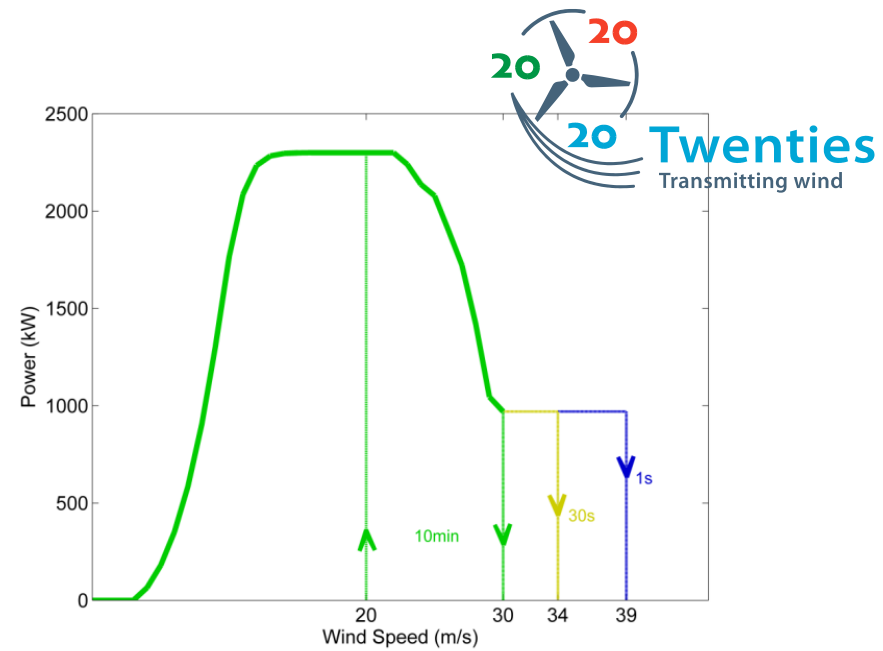
Equivalent loads
(fatigue)

Storm control

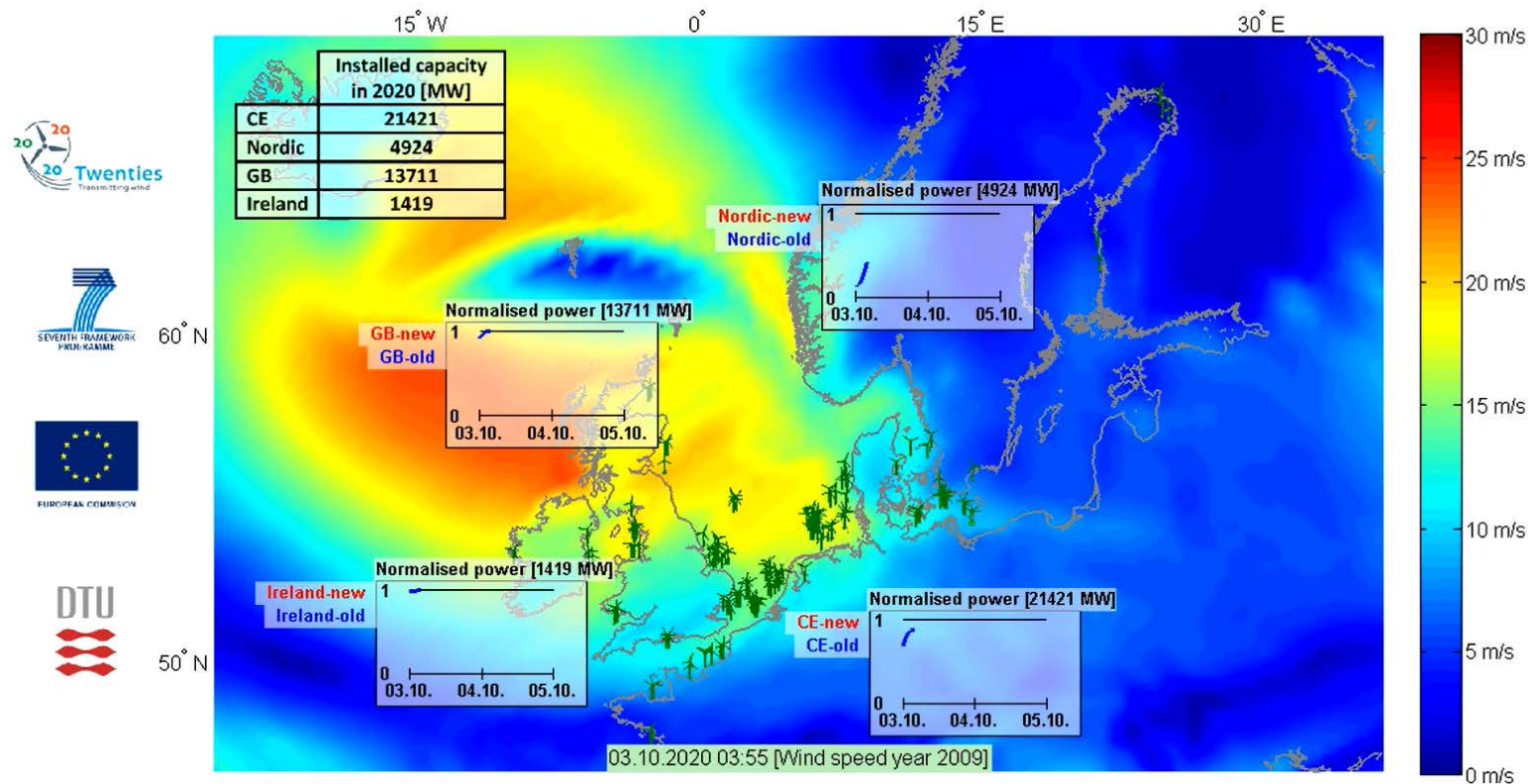
High Wind Shut Down



High Wind Ride Through (SIEMENS HWRT™)

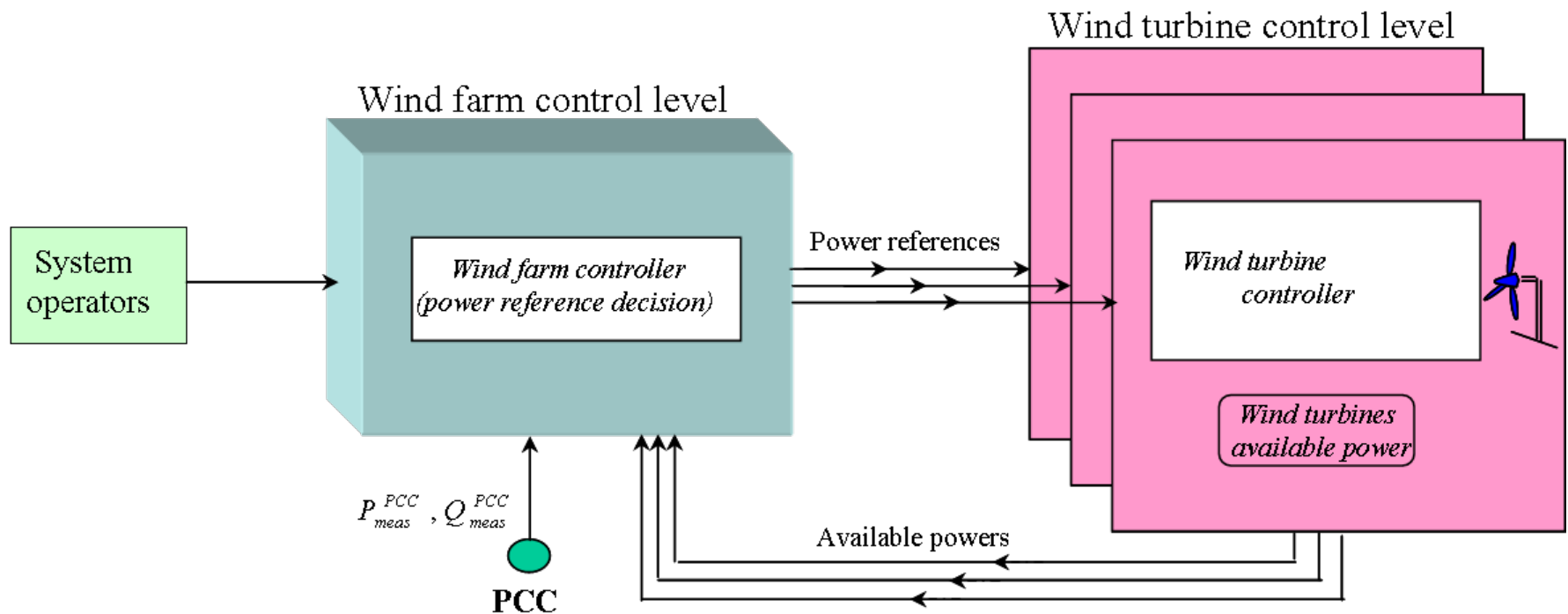


Offshore wind power variability 2020



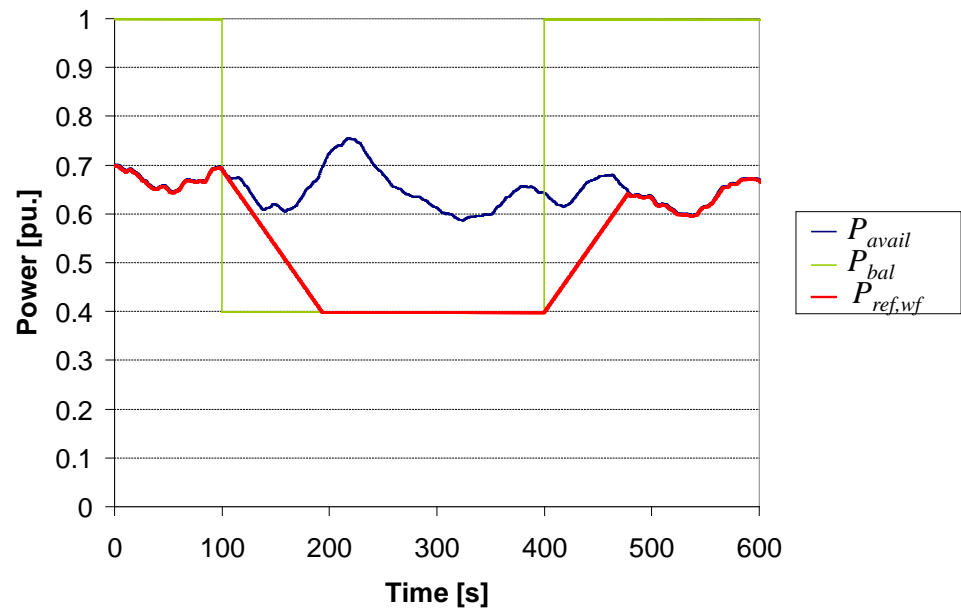
Wind farm control – wind power plants

- Contribute to control of grid voltage: amplitude and frequency, like other power plants
- Indirect grid control: active and reactive power control



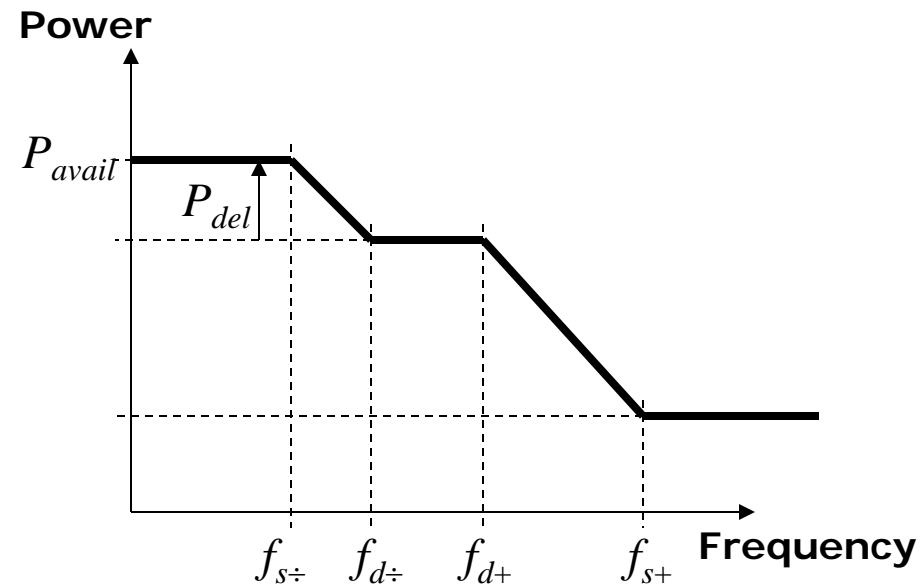
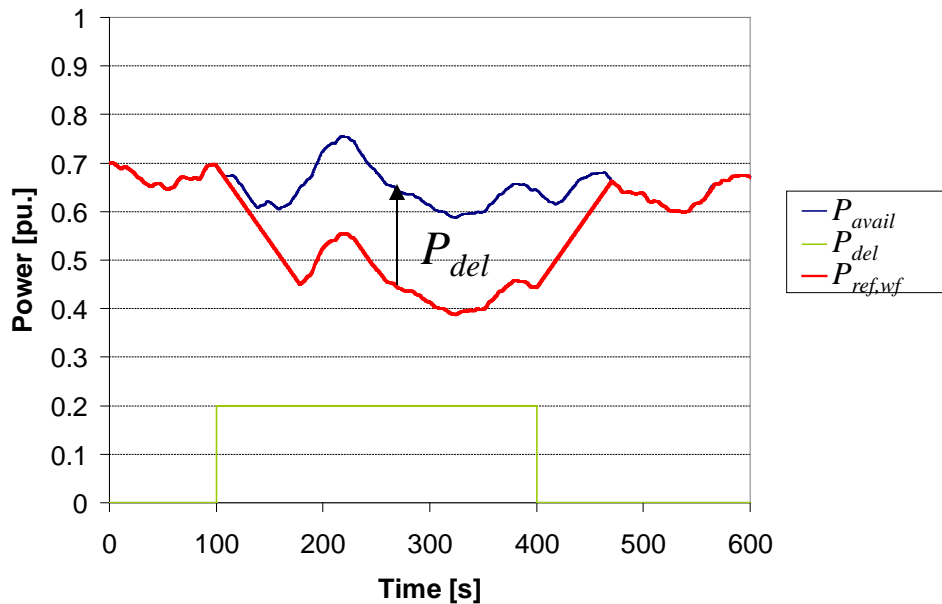
Balance control

- Balance control provides
- Balance control already implemented in Horns Rev and Nysted
- Why ramp limitation

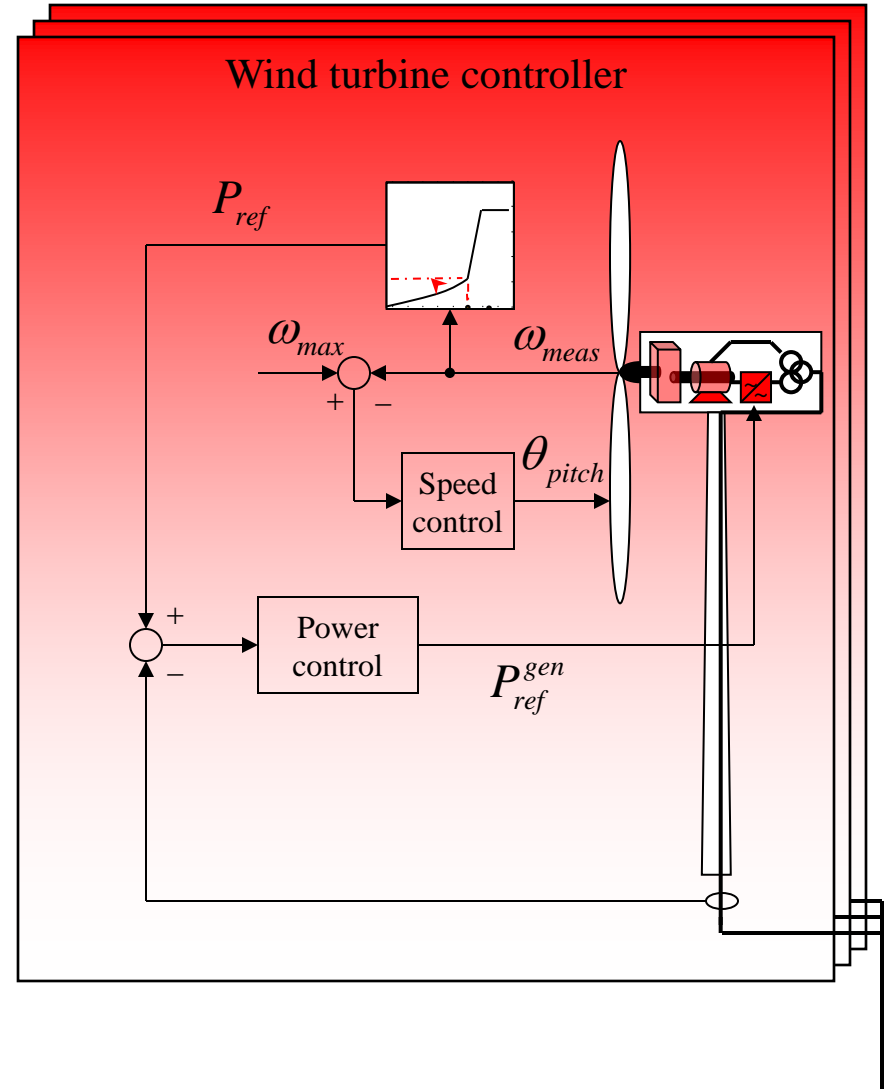


Delta control

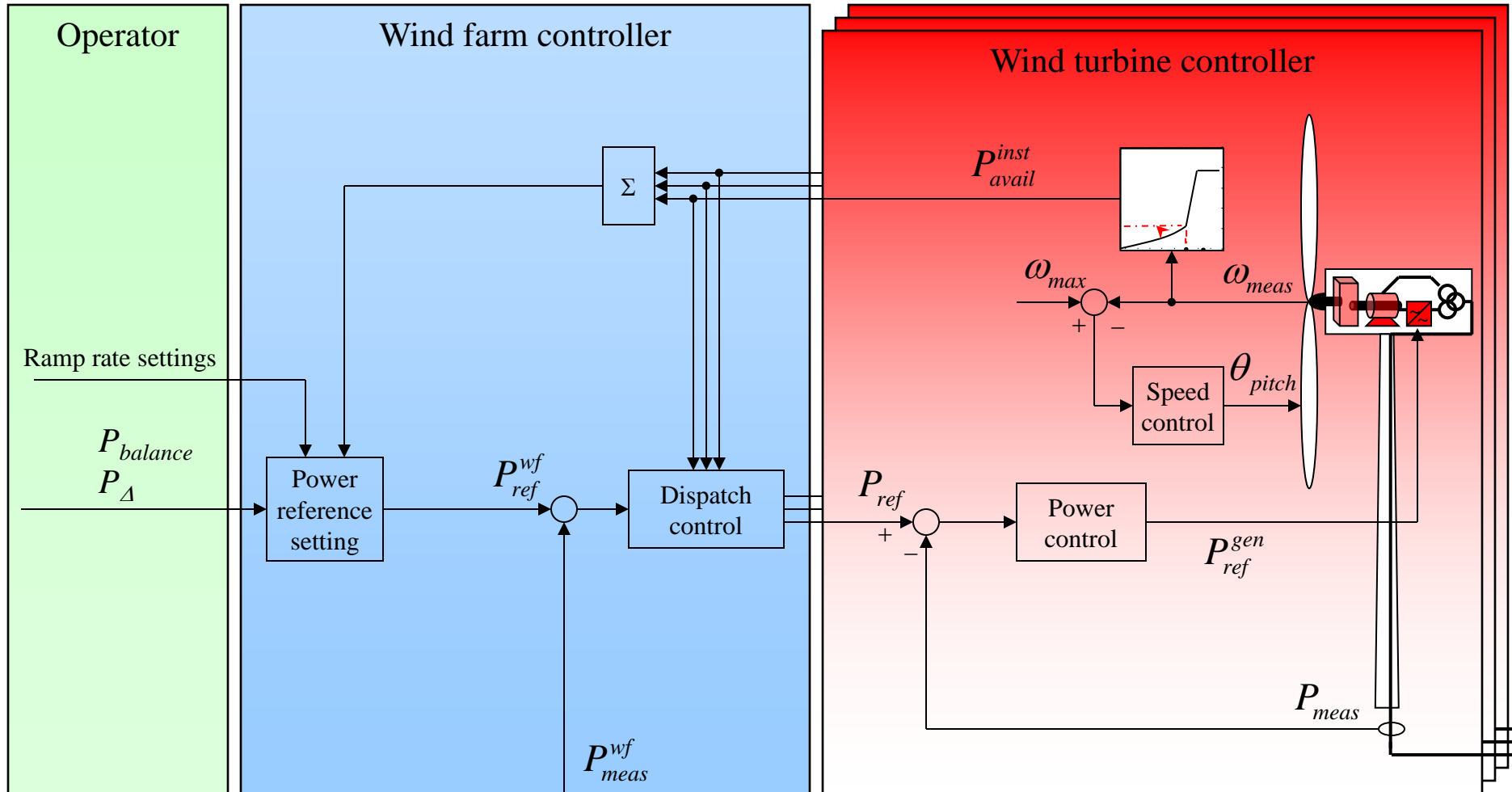
- Delta control provides fixed reserve
- Delta control already implemented in Horns Rev and Nysted
- Reserve can be utilised in frequency control (droop and deadband)



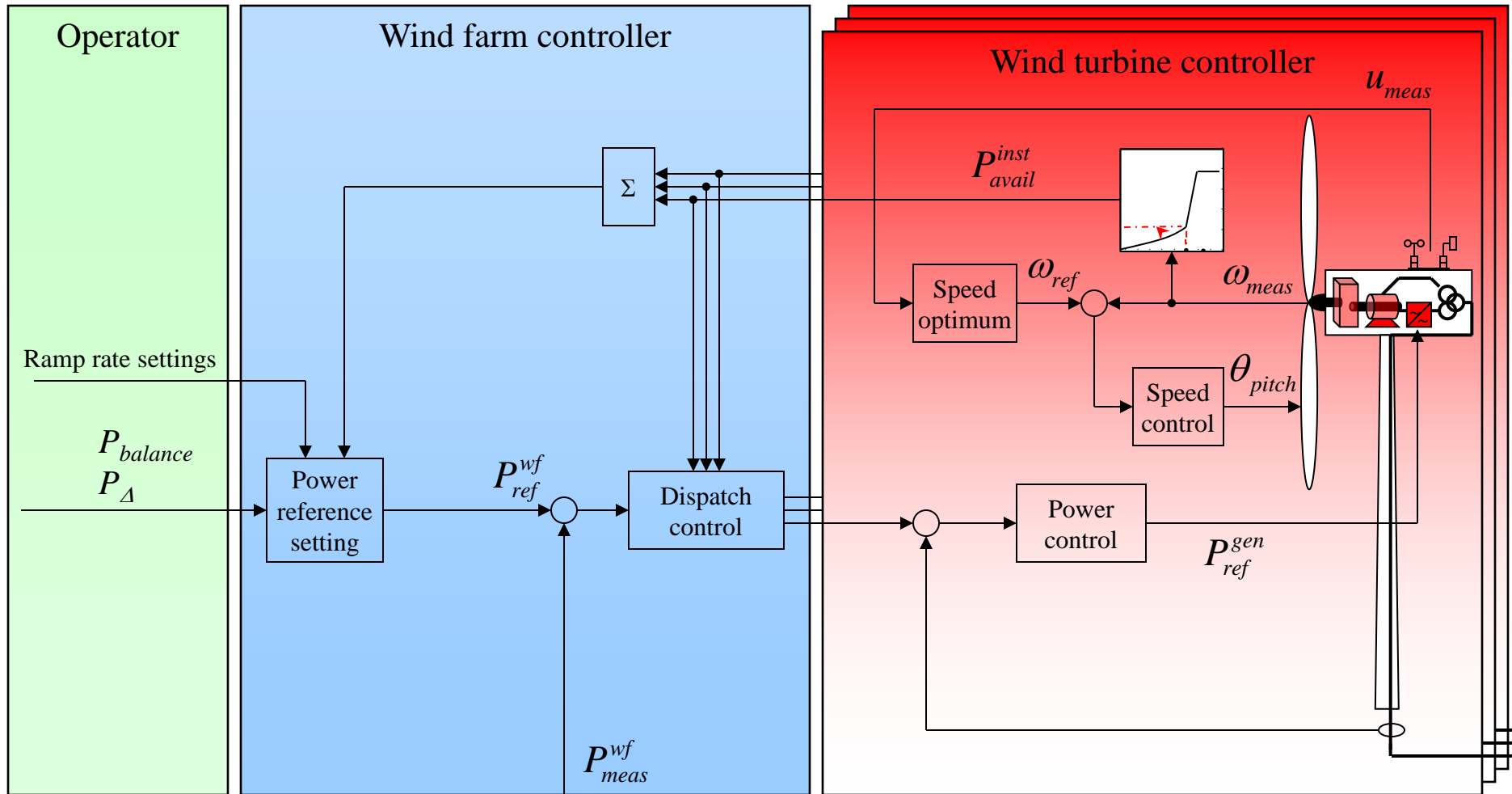
Double fed wind turbine – power control



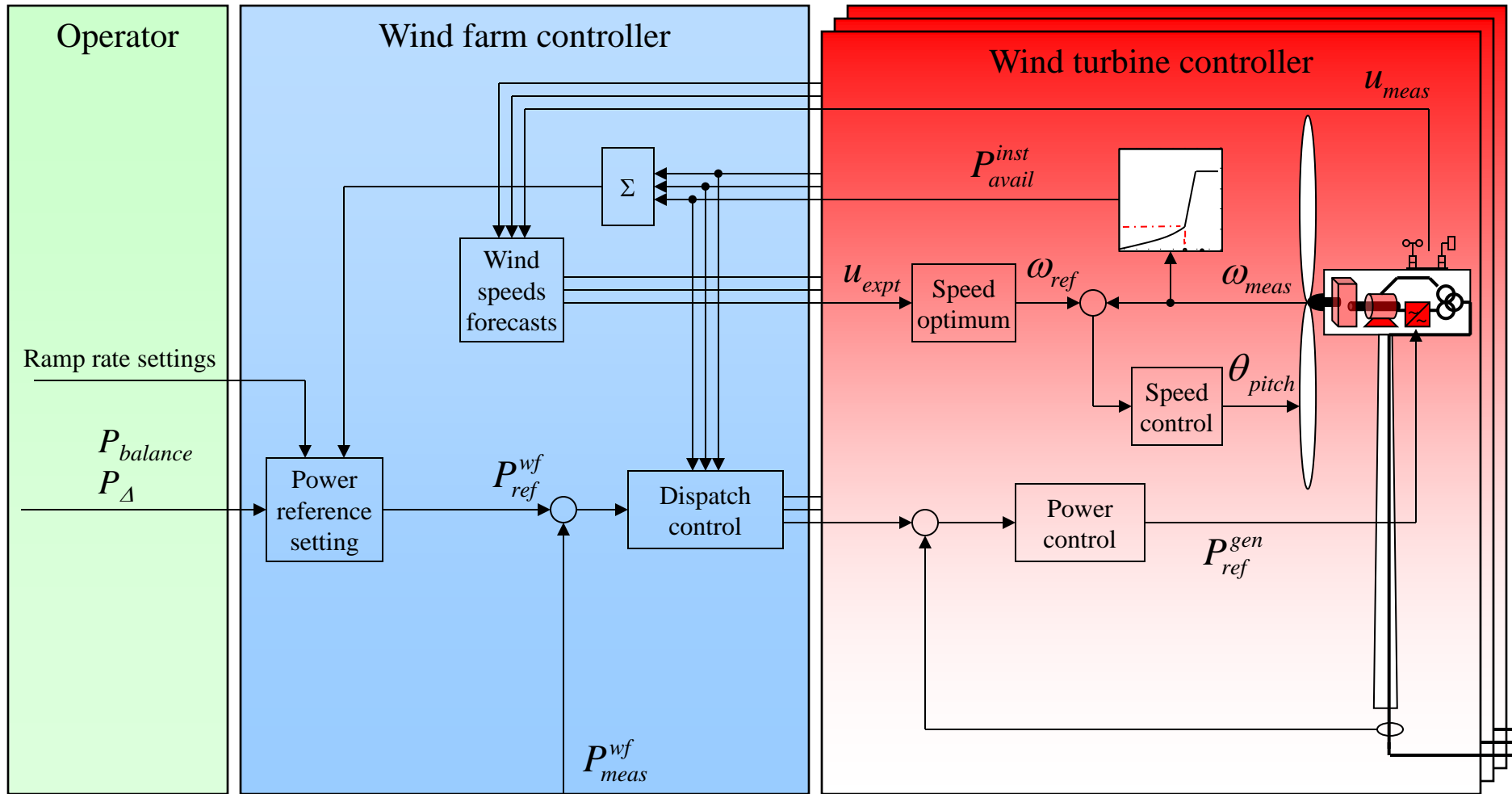
Double fed wind farm – power control



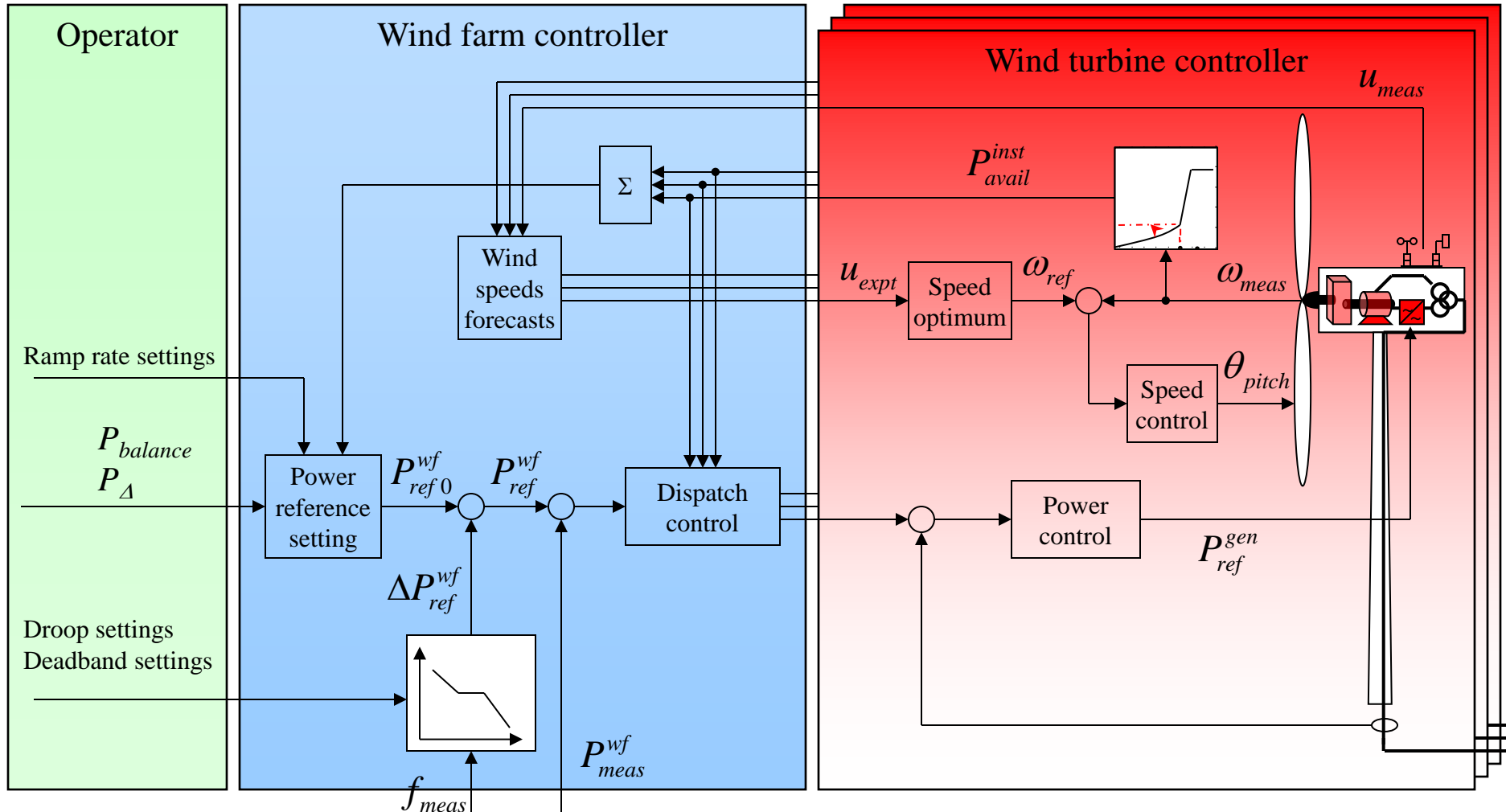
Double fed wind farm – power control



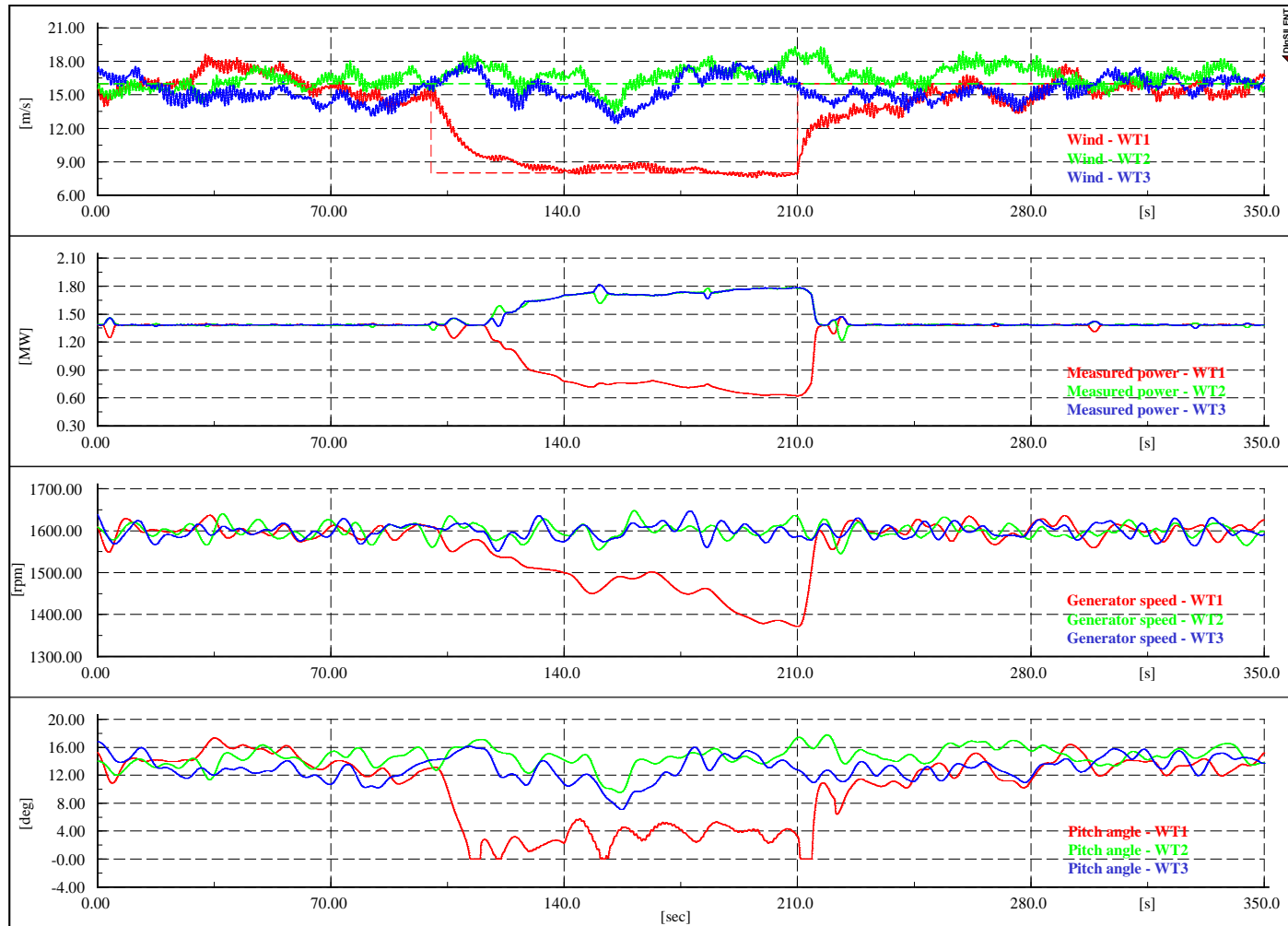
Double fed wind farm – power control



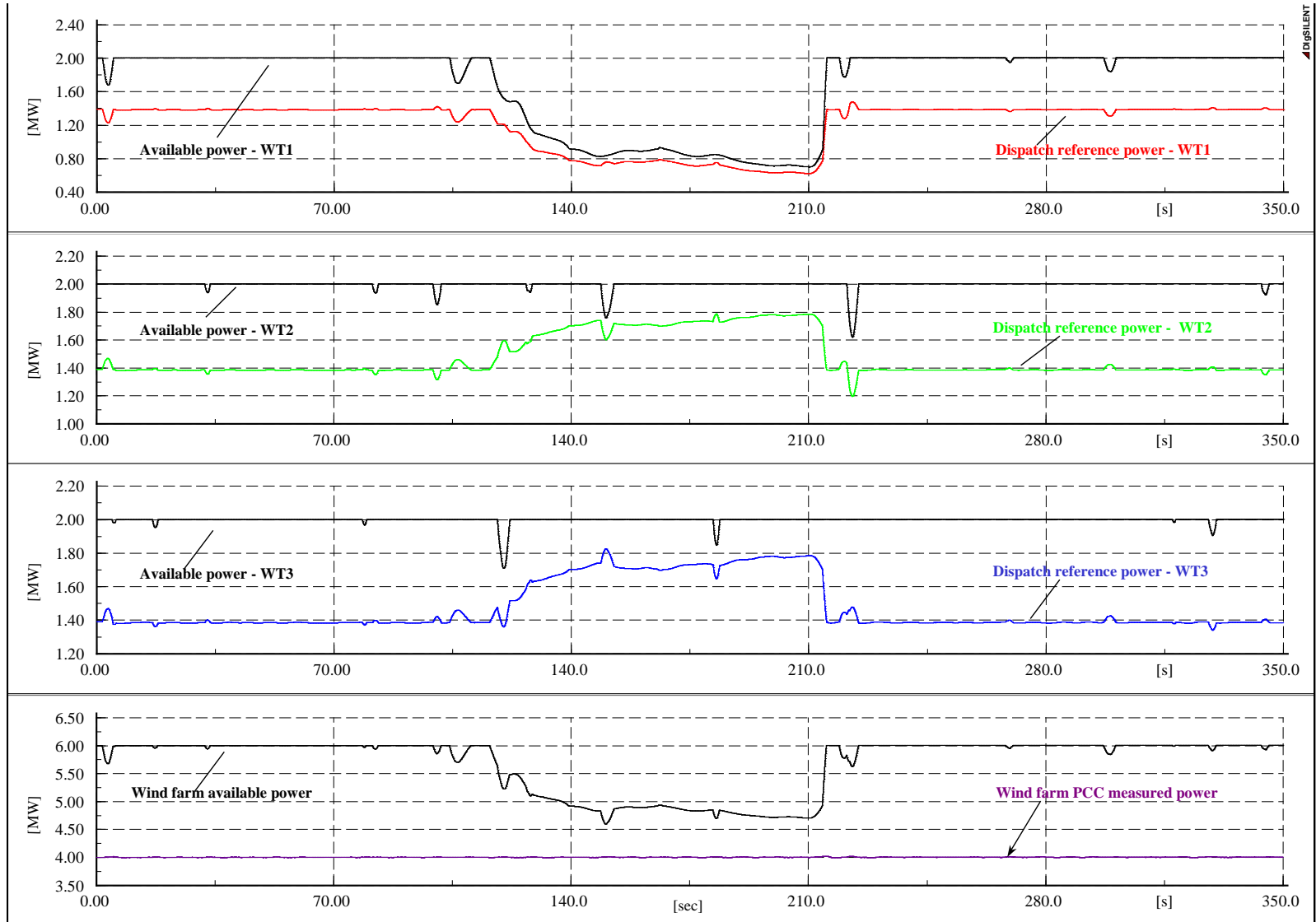
Double fed wind farm – frequency control



Wind farm power control – wind turbines



Wind farm power control



Summary / conclusions

- Control can
 - optimise production
 - reduce structural loads
 - support grid integration
- Controllability varies very much, depending on turbine design (fixed/var speed, fixed/var pitch)