Advanced Issues of Wind Turbine Modelling and Control

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Discussion Topics

- General considerations
- Advanced control
- FDI/FTC general structures
- Fault models
- Competition challenges
- Wind turbine modelling issues
- Concluding remarks
- Selected references

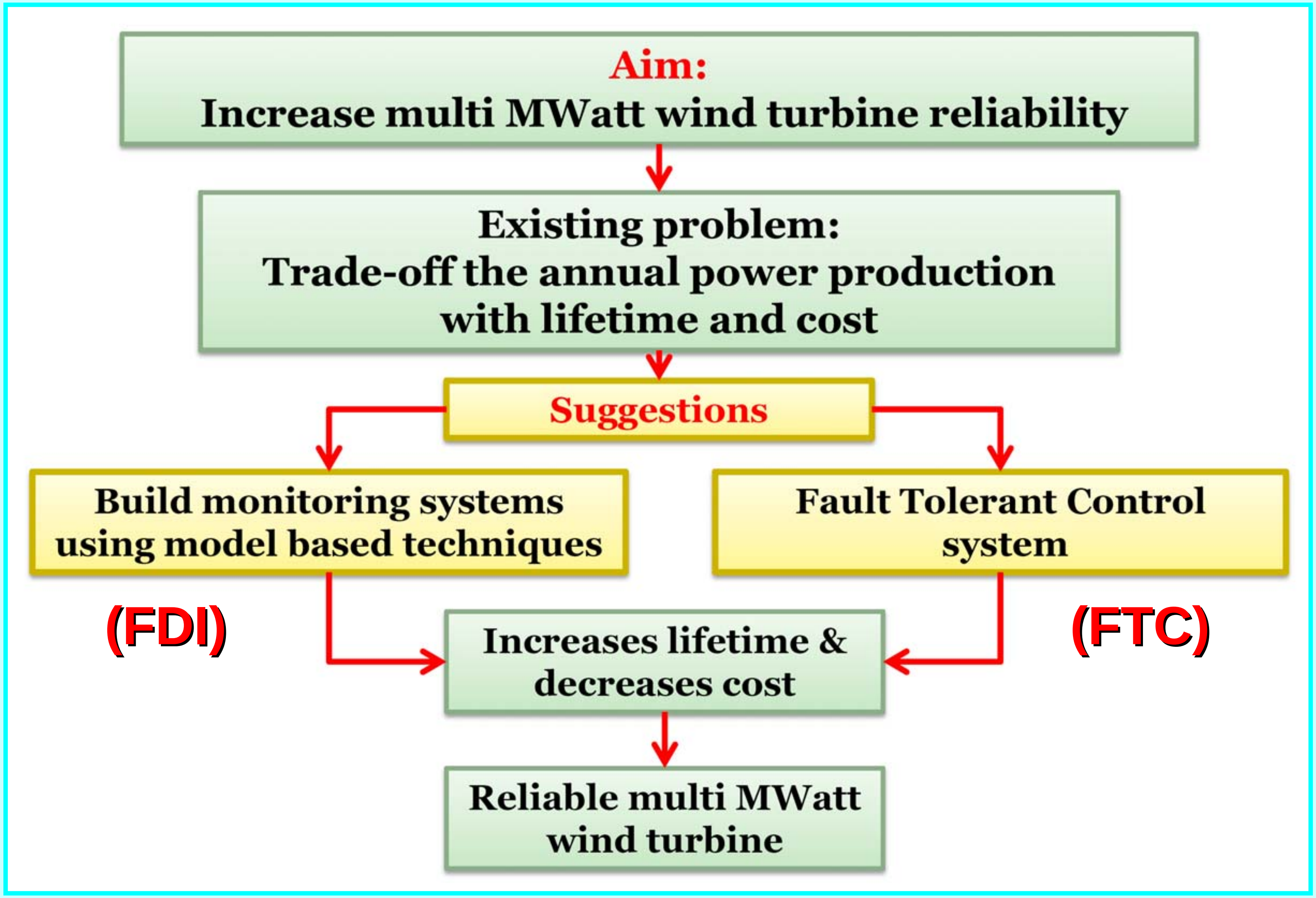
Energy and Control Issues

- ✓ Control systems have high influence on the total **cost of energy**
- ✓ Focus on **advanced control solutions**
  - **Condition monitoring**
  - **Fault diagnosis and fault tolerant control**
- ✓ The design of control solutions is enhanced by the development of **high-fidelity benchmark** models and prototypes
  - **Modelling issues**
- ✓ Solutions characterised by craftsmanship, quality, **reliability**, and proven technology

Advanced Control Solutions

“Sustainable Control”

Advanced Control



Safety-Critical Systems

- ✓ **Model-based FDI** and **FTC** are proposed as new approaches for **sustainable** (high degree of reliability and availability) wind turbine control
- ✓ Manage **loads** (storms, …) **and faults**
- ✓ ***NOTE****: FTC was developed as aerospace topic, focussed mainly on NASA projects, motivated by advanced aircraft that could be reconfigured by control through a high degree of flight surface redundancy*

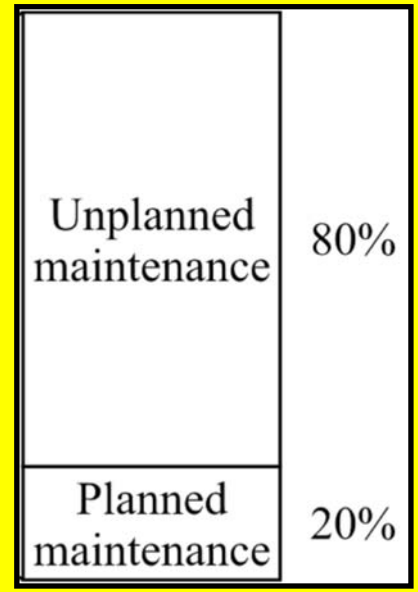
Motivations

- ✓ **Harsh** environment asks for the system to be well protected
- ➢ **<u>Offshore</u> wind turbines** are stand-alone power plants in inadequate service and maintenance attendance
- ✓ Safety-related control systems to help avert major incidents resulting from lightning, storms, gusts and other <u>periodic</u> <u>incidents</u>, and **<u>faults</u>** that affect the energy drive train and the electricity production

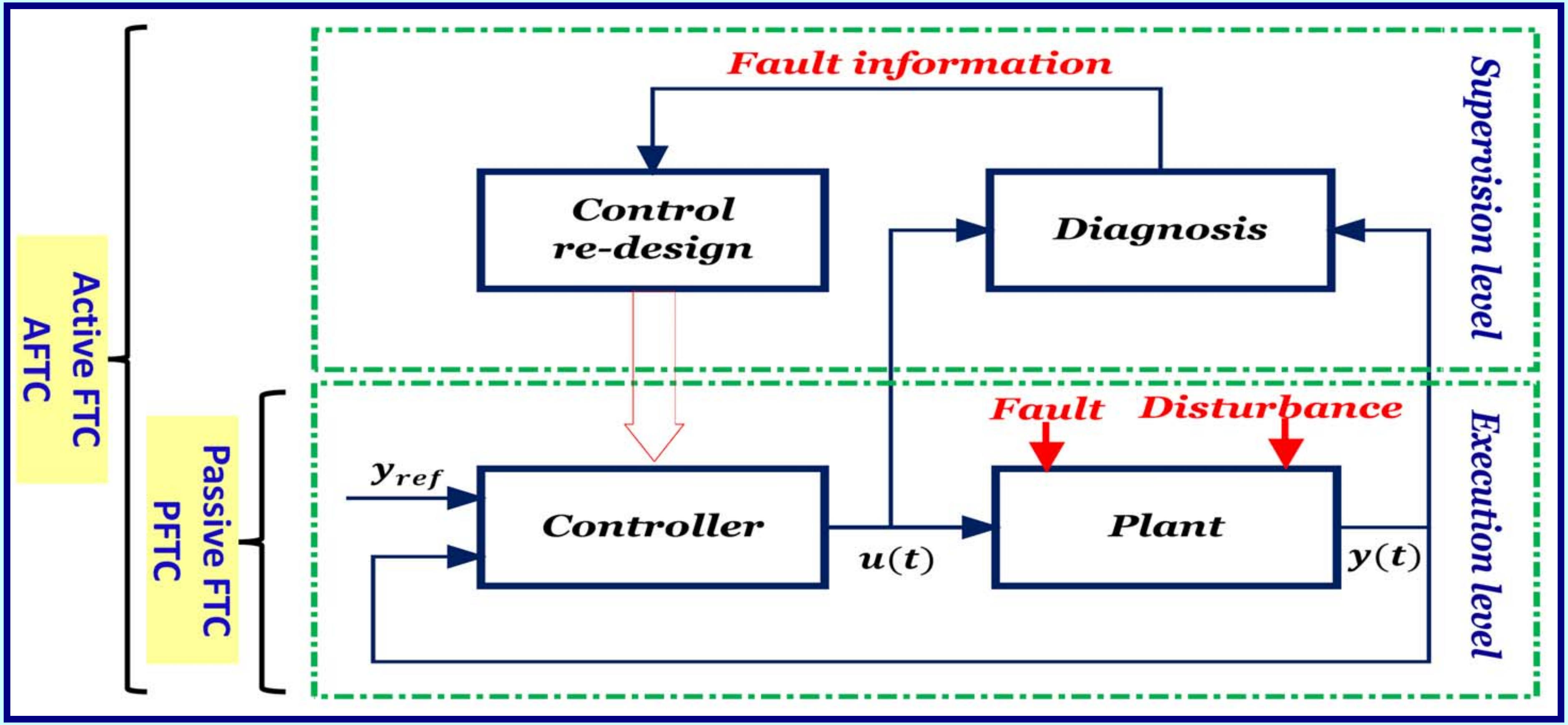
Example…

- ✓ A 5 MW wind turbine stopped will loose 24 MWh per day in production if 40% wind capacity is assumed
  - Combine this with **difficult accessibility** at an offshore wind farm, it might take days before a fault is cleared
  - Advanced **FDI** and **FTC** included in the control system **could provide information on the fault**, thus allowing for correct and faster repair if required, and/or **continued energy generation** eventually at lower level until maintenance service

Cost of energy (15-35%)

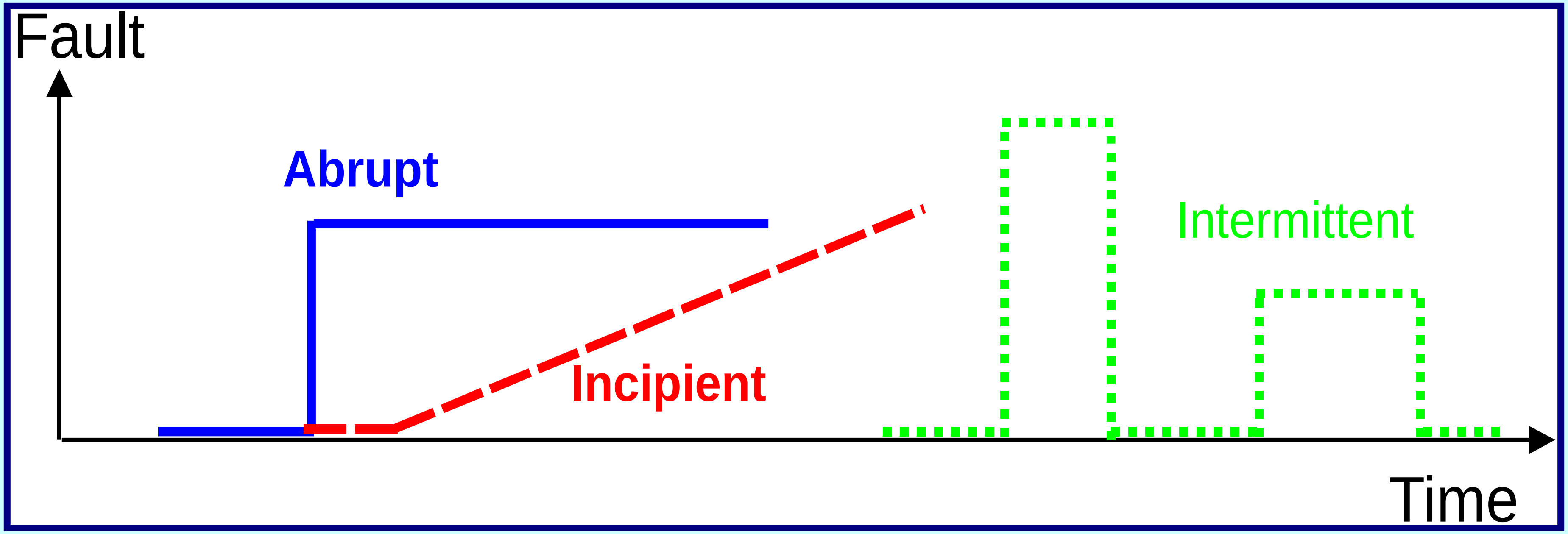



FDI / FTC
Fundamentals



- ✓ **PFTC: Robust fixed structure controller**
  - No fault information provided
- ✓ **AFTC: Real-time controller reconfiguration**
  - Fault reconstruction

General Fault Modes



- ✓ **Abrupt fault:** *e.g.* failures
- ✓ **Incipient fault:** *i.e.* hard to detect
- ✓ **Intermittent fault**: *e.g.* disconnections

Fault example…

System Requirements

- ✓ Safeguard w.r.t. all the different types of loads that inflict a wind turbine and regulate accordingly
  - **loads from the environment** (e.g. storms, waves, wind shear and wakes),
  - **loads from the wind turbine** itself (e.g. blades aerodynamic imbalances, yaw misalignments),
  - **loads from the system** (start/stop and turbine failures)
- ✓ Analyse system performance to avoid instabilities
- ✓ Balancing efficient production with lifetime considerations
- ✓ **Ensure redundant system capabilities to allow production until service and maintenance (O&M) are possible**

Wind Turbine Maintenance

- ✓ **High degree of reliability and availability (sustainability) is required and at the same expensive and safety critical maintenance work can occur**
- ✓ **Site accessibility**, system availability not always ensured, *severe weather conditions (+ sea installations)*
- ✓ FTC and FDI researches are stimulated in this application area since important aspects for **decreasing wind energy cost and increasing electrical grid penetration**
- ✓ FTC can enhance specific control actions to prevent plant damage and ensure system availability during malfunctions
- ✓ **Maintenance costs (O&M)** and **off-time** can be significantly **reduced**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International Challenge

- ✓ *kk-electronic* (Denmark) together with *MathWorks* launched a number of benchmark models for fault detection and accommodation, which allows turbine owners and researchers to find the best schemes to handle different faults.
- ✓ Based on these models, a series of competitions and challenges have been launched
  - Simple Wind Turbine FDI/FTC benchmark model
  - Advanced WT FDI / FTC benchmark model
  - Wind farm FDI/FTC benchmark model

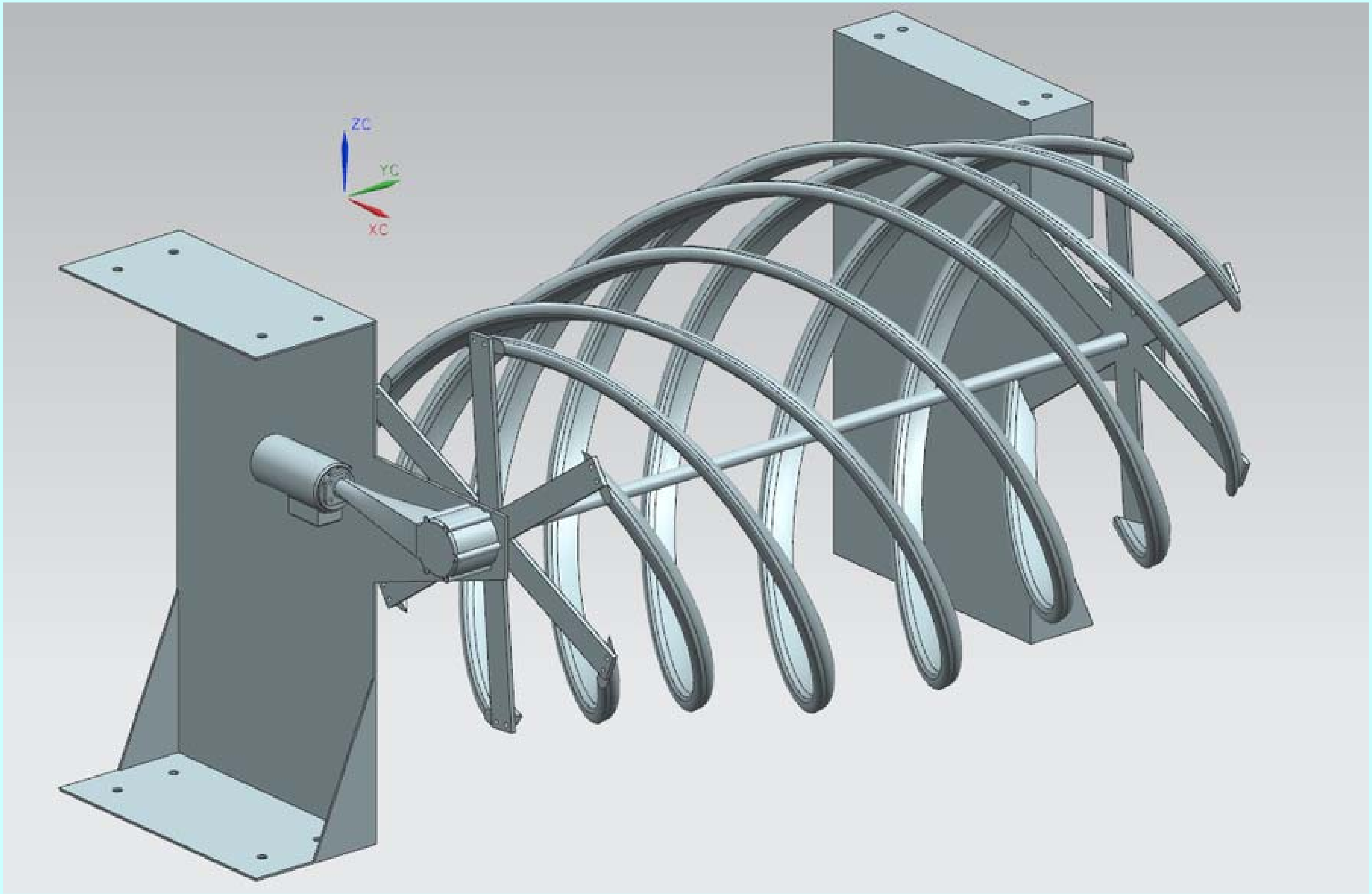
Benchmark Model Motivations

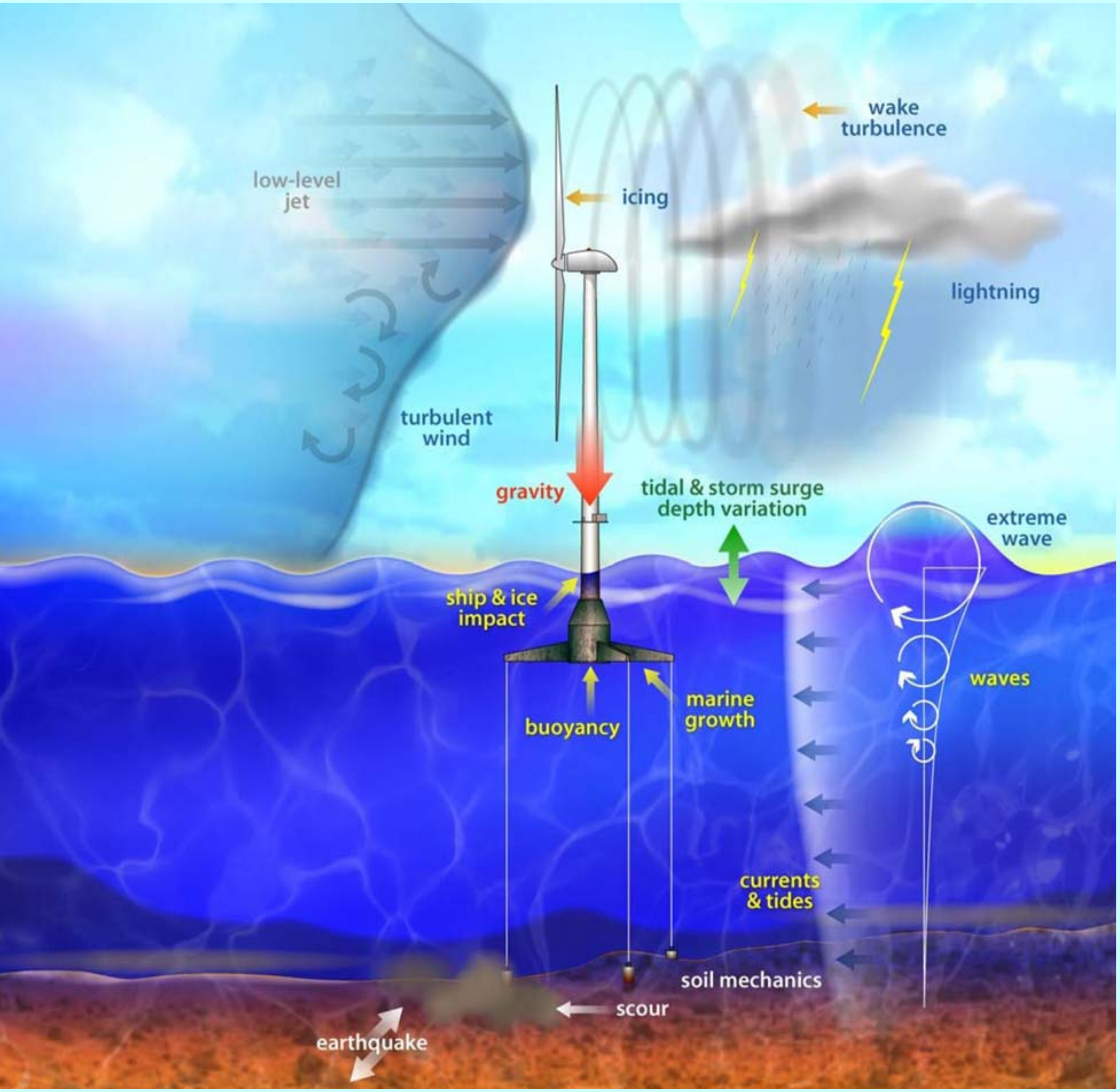
- ✓ Wind turbine benchmarks were proposed to provide generic platforms (freely available) for designing and testing different FDI and FTC solutions
- ✓ **The target was researchers in the FDI and FTC community, such that they can apply and compare their methods on wind turbine realistic installations**
- ✓ The model is generic, it can be provided to the public
- ✓ Solutions finally verified on accurate wind turbine models (confidential)

Competition Challenges

- ✓ **Fault diagnosis and fault-tolerant control scheme designs**
- ✓ Design procedure
  - Modelling
- ✓ Describe the considered system
  - Fault analysis
- ✓ Identify faults to be handled
  - Detect, isolate (and estimate faults)
  - Fault-tolerant control
- ✓ Based on signal correction
- ✓ Based on scheduling and reconfiguration of the controller

Modelling Topics



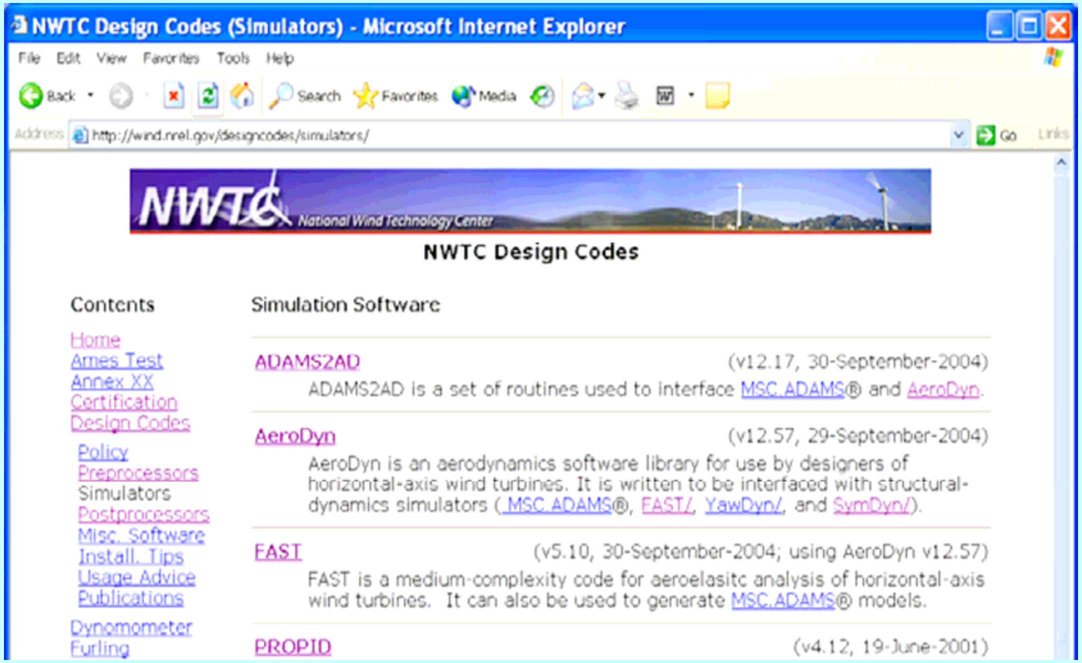


- Coupled aero-hydro-servo-elastic interaction
- Models originate from different disciplines
  - Wind-Inflow
  - Waves
  - Aerodynamics
  - Hydrodynamics
  - Structural dynamics
  - Control systems
- **Multi-Physics Simulation Tools**

NREL Design Codes

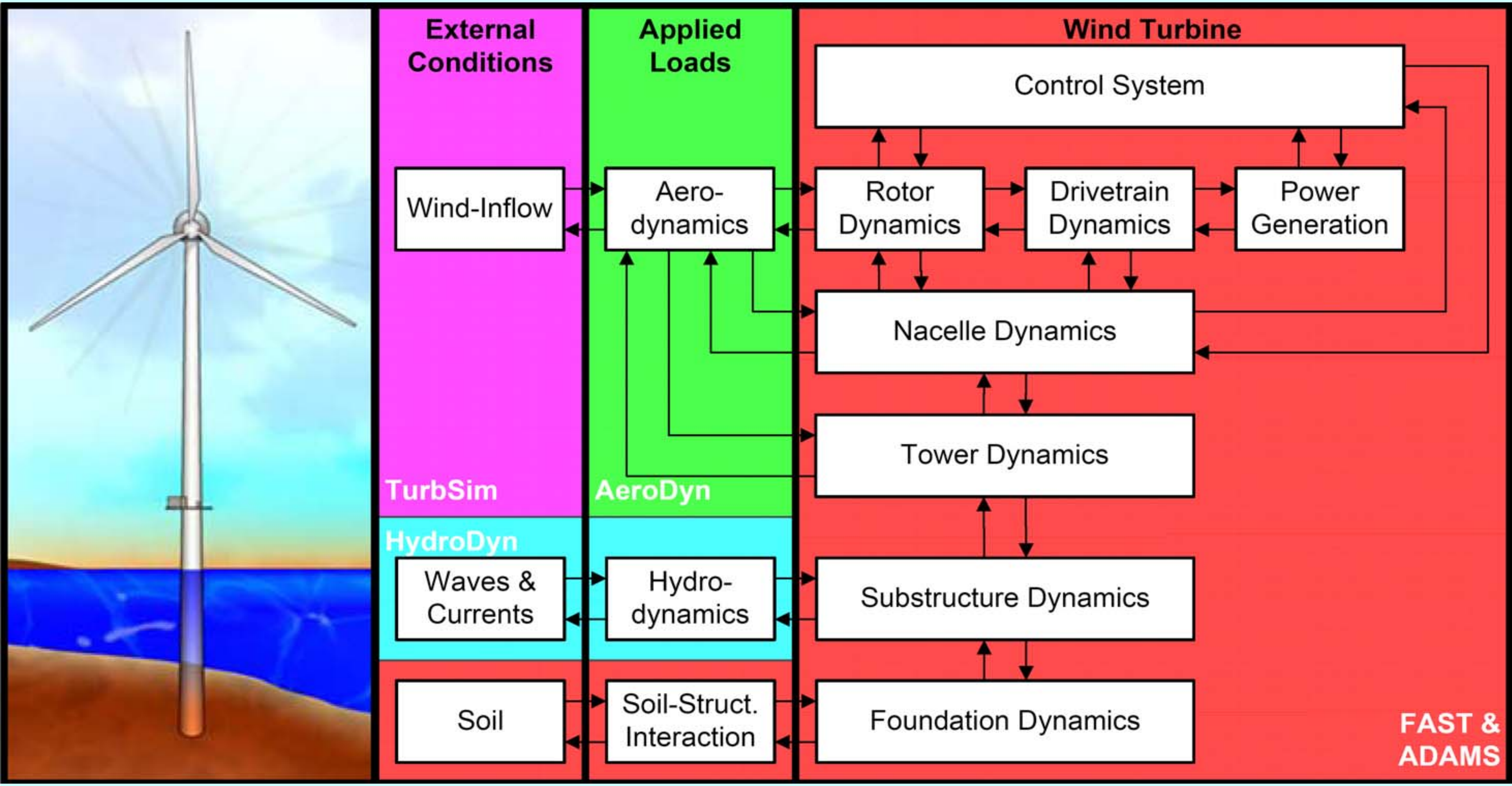
National Renewable Energy Laboratory

- ✓ **http://wind.nrel.gov/designcodes**
- ✓ One set of models
  - **FAST**
    - – aeroelasticity
  - TurbSim
    - – turbulent inflow
  - Others… *e.g.* ADAMS (MSC)
- ✓ Freely available



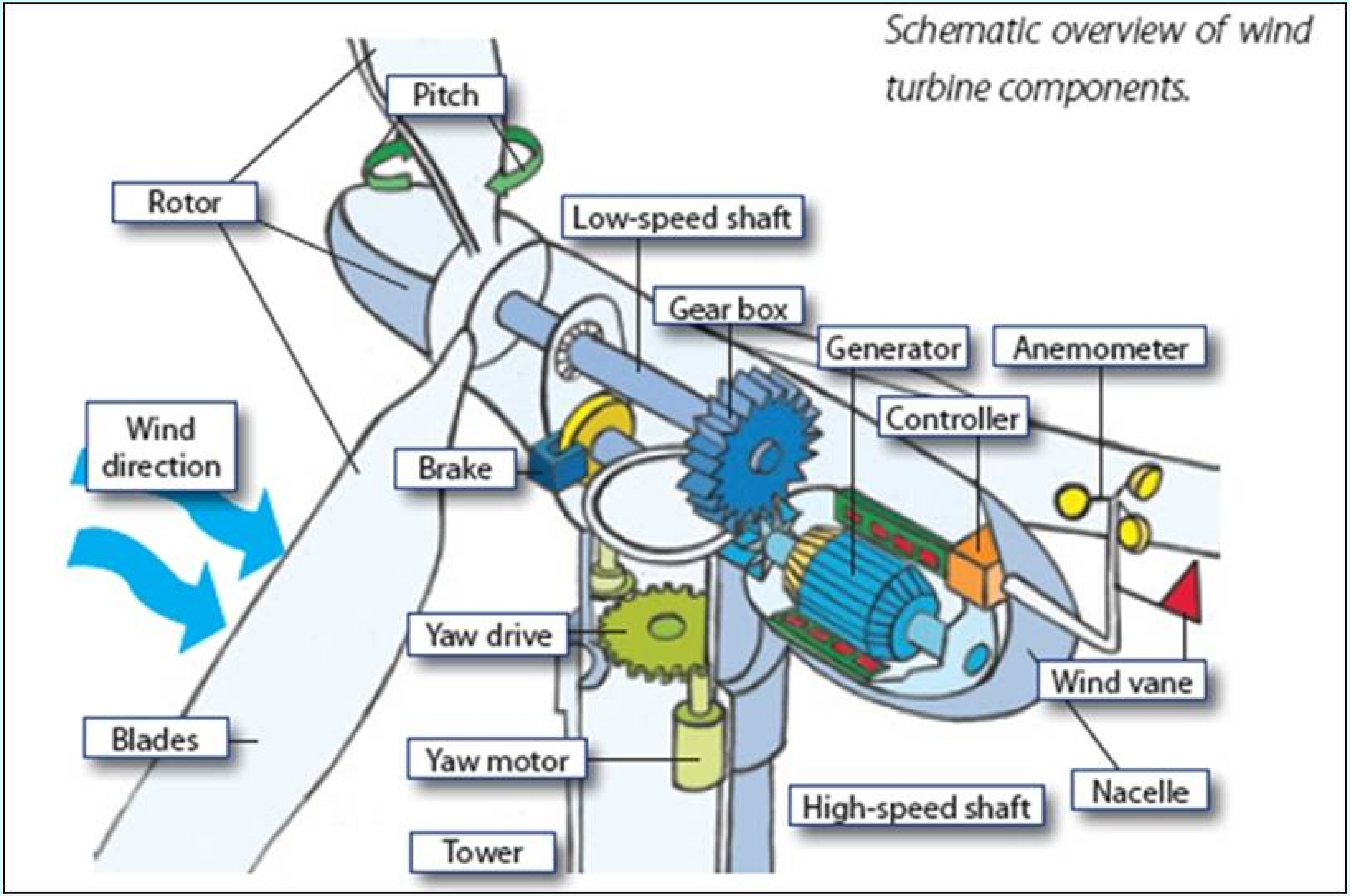
- ✓ Used heavily in industry, academia and other governmental research organizations
- ✓ Important for control systems design

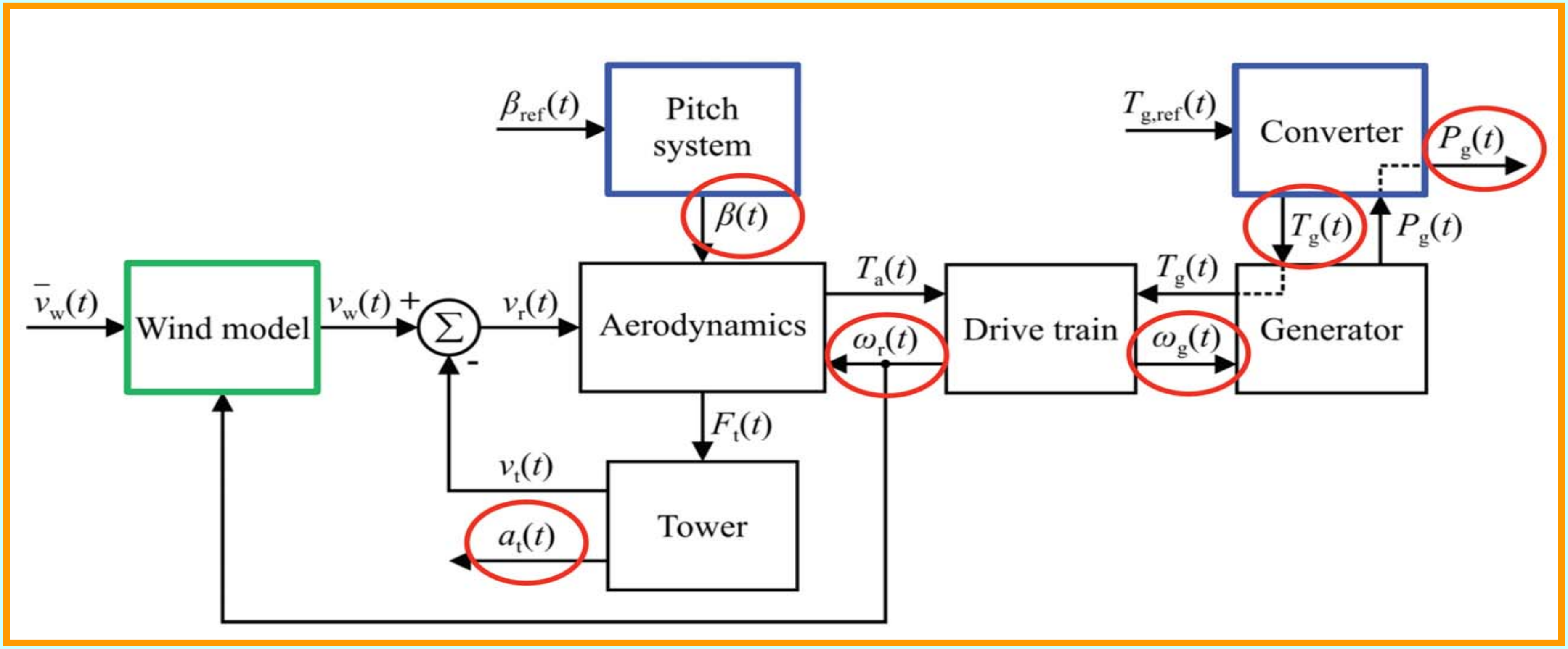
Design Codes Examples



Coupled Aero-Hydro-Servo-Elastic Simulation

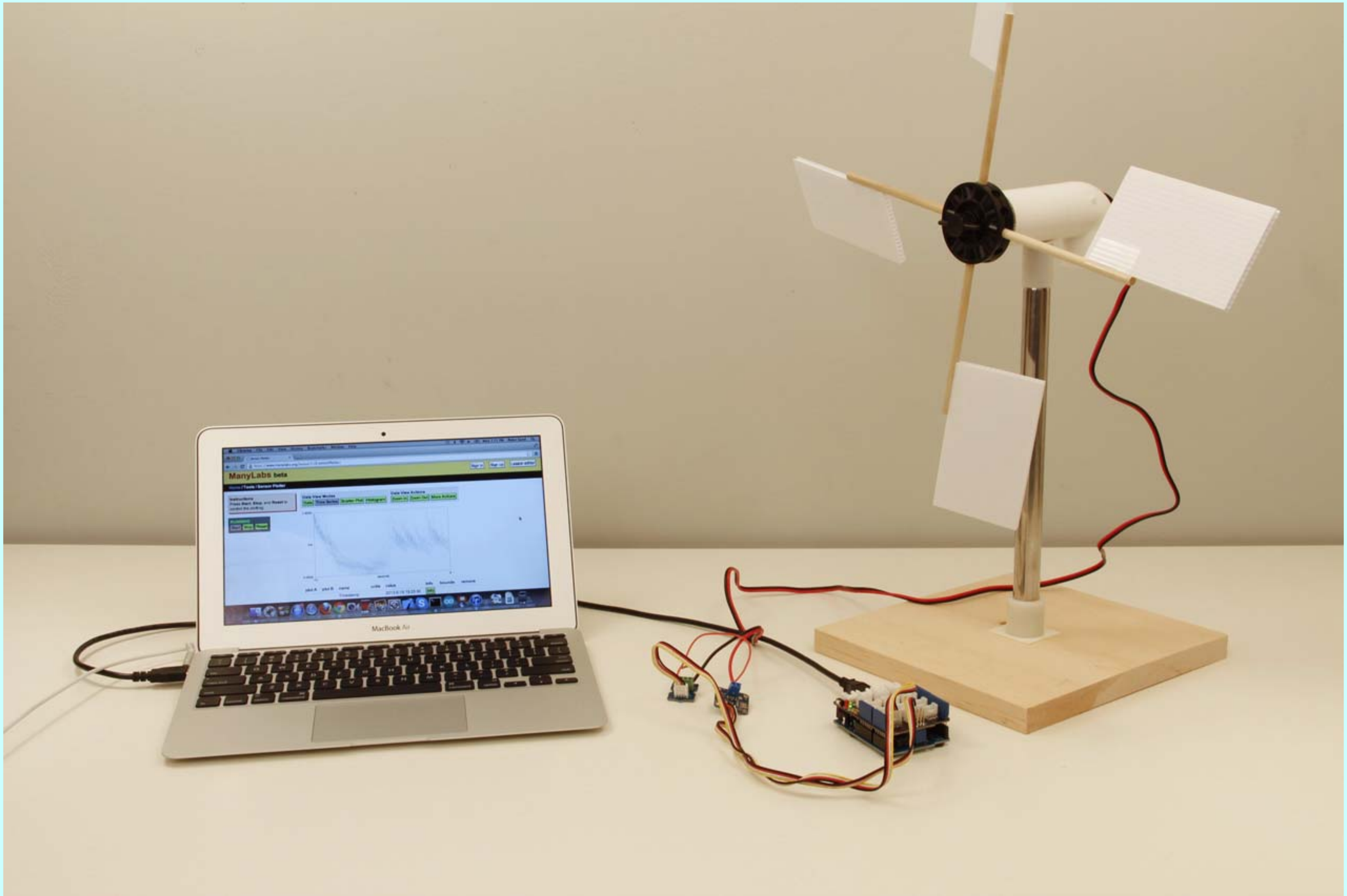
Wind Turbine Components





- Stochastic wind model including tower shadow and wind shear
- Actuator models
- Zero-mean Gaussian distributed measurement noise

Measurement Sensors

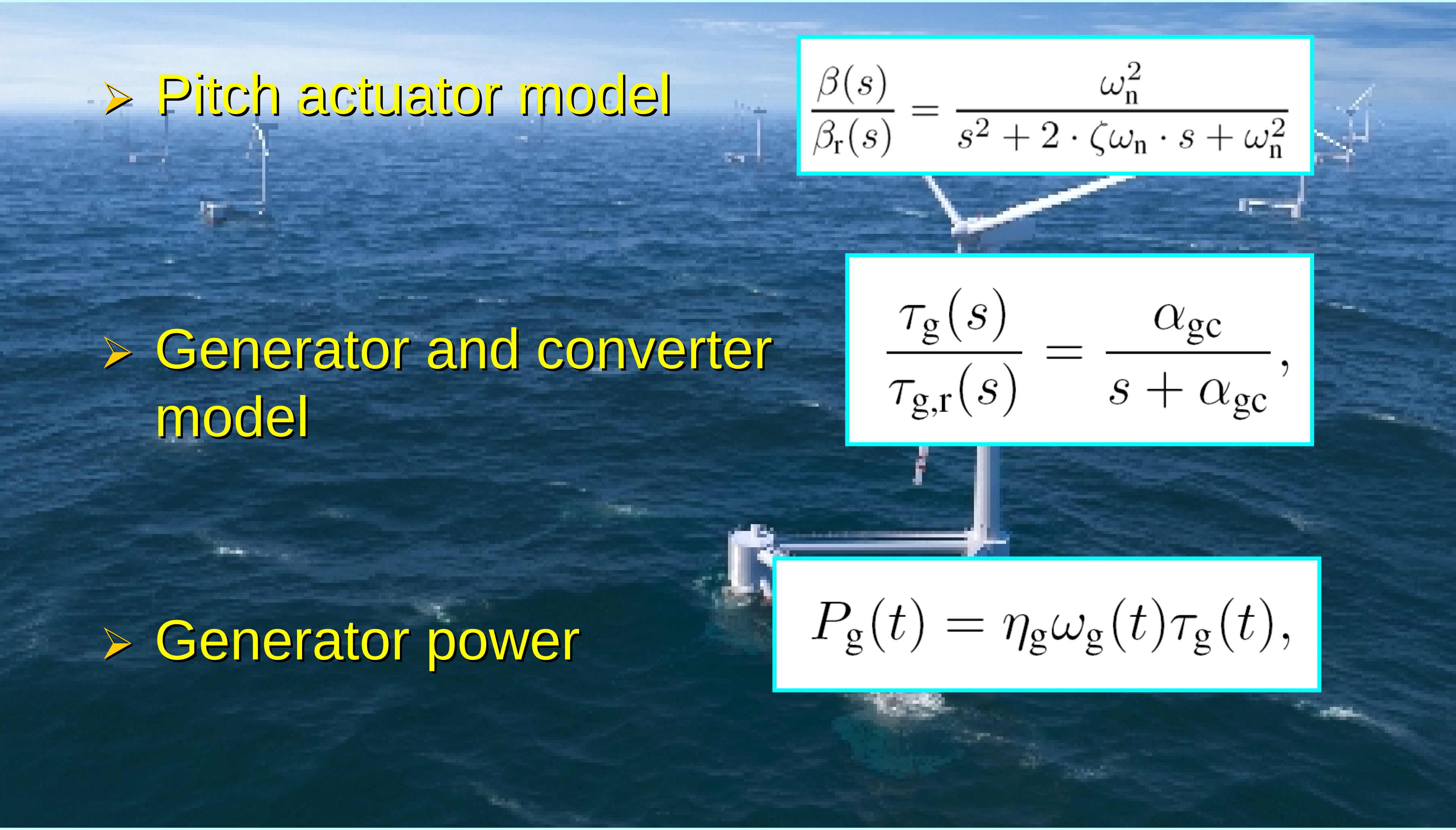


Measurements

Sensor Type	Symbol	Unit	Noise Power
Anemometer - Wind speed at hub height	$v_{\mathrm{w,m}}$	m/s	0.0071
Rotor Speed	$\omega_{\mathrm{r,m}}$	rad/s	10^{-4}
Generator Speed	$\omega_{\mathrm{g,m}}$	rad/s	$2 \cdot 10^{-4}$
Generator Torque	$\tau_{\mathrm{g,m}}$	Nm	0.9
Generated Electrical Power	$P_{\mathrm{g,m}}$	W	10
Pitch Angle of i th Blade	$\beta_{i,\mathrm{m}}$	deg	$1.5 \cdot 10^{-3}$
Azimuth angle low speed side	ϕ_{m}	rad	10^{-3}
Blade root moment ith blade	$M_{\mathrm{B},i,\mathrm{m}}$	Nm	10^3
Tower top acceleration (x and y directions) measurement	$\begin{bmatrix} \ddot{x}_{\mathrm{x,m}} \\ \ddot{x}_{\mathrm{y,m}} \end{bmatrix}$	$\mathrm{m/s^2}$	$5 \cdot 10^{-4}$
Yaw error	$\Xi_{\mathrm{e,m}}$	deg	$5 \cdot 10^{-2}$

Wind Turbine Actuators

Actuator Models



- Pitch actuator model

$$\frac{\beta(s)}{\beta_{\mathrm{r}}(s)} = \frac{\omega_{\mathrm{n}}^2}{s^2 + 2 \cdot \zeta\omega_{\mathrm{n}} \cdot s + \omega_{\mathrm{n}}^2}$$

- Generator and converter model

$$\frac{\tau_{\mathrm{g}}(s)}{\tau_{\mathrm{g,r}}(s)} = \frac{\alpha_{\mathrm{gc}}}{s + \alpha_{\mathrm{gc}}},$$

- Generator power

$$P_{\mathrm{g}}(t) = \eta_{\mathrm{g}}\omega_{\mathrm{g}}(t)\tau_{\mathrm{g}}(t),$$

Wind Turbine Submodels

$$\dot{\omega}_r(t) = \frac{1}{J}\left(\tau_{aero}(t) - \tau_{gen}(t)\right)$$

$$\dot{\tau}_{gen}(t) = p_{gen}\left(\tau_{ref}(t) - \tau_{gen}(t)\right)$$

Drive-train model

Hydraulic pitch system

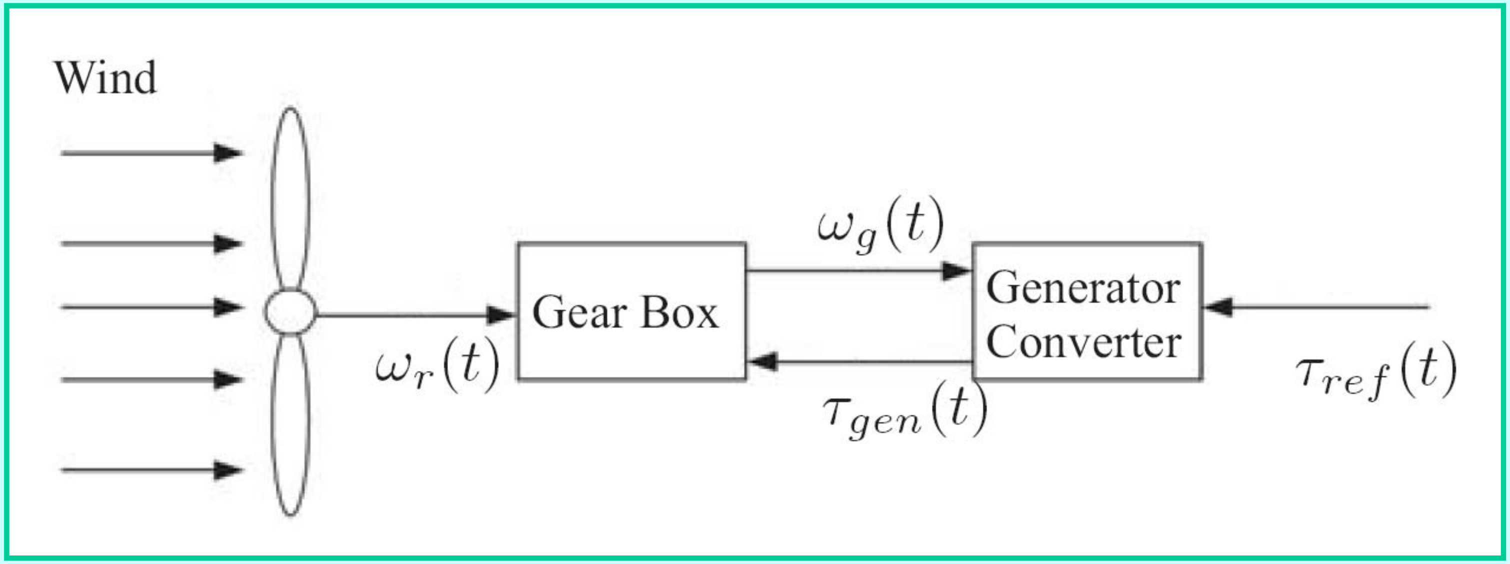
$$\frac{\beta(s)}{\beta_r(s)} = \frac{\omega_n^2}{s^2 + 2\,\zeta\,\omega_n\,s + \omega_n^2}$$

$$\frac{\tau_g(s)}{\tau_{gr}(s)} = \frac{\alpha_{gc}}{s + \alpha_{gc}}$$

Generator & converter models

$$P_g(t) = \eta_g\,\omega_g(t)\,\tau_g(t)$$

Aerodynamic Model



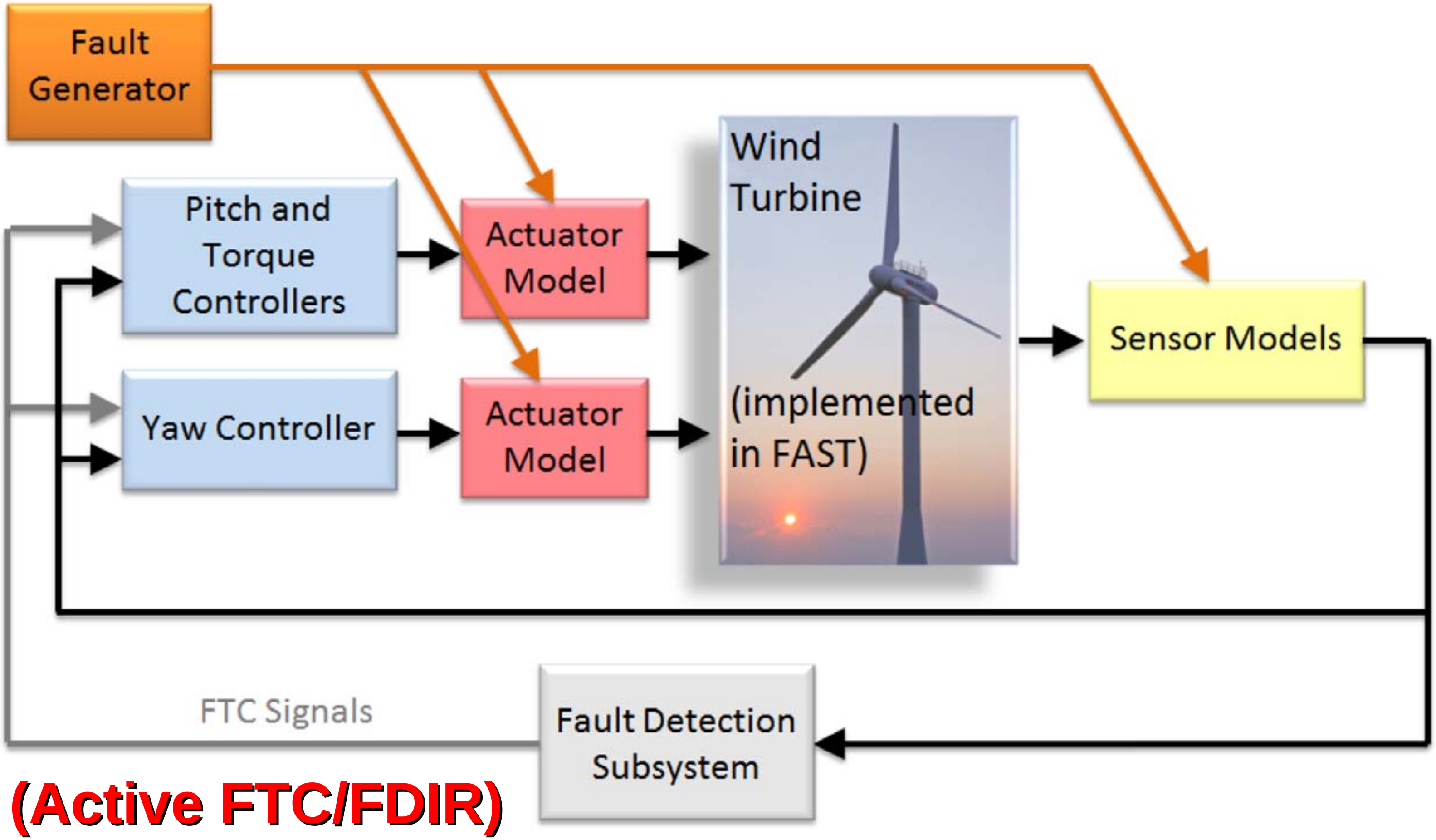
$$\tau_{aero}(t) = \frac{\rho\, A\, C_p\,(\beta(t),\ \lambda(t))\, v^3(t)}{2\,\omega_r(t)}$$

Aerodynamic torque and tip-speed ratio

$$\lambda(t) = \frac{\omega_r(t)\, R}{v(t)}$$

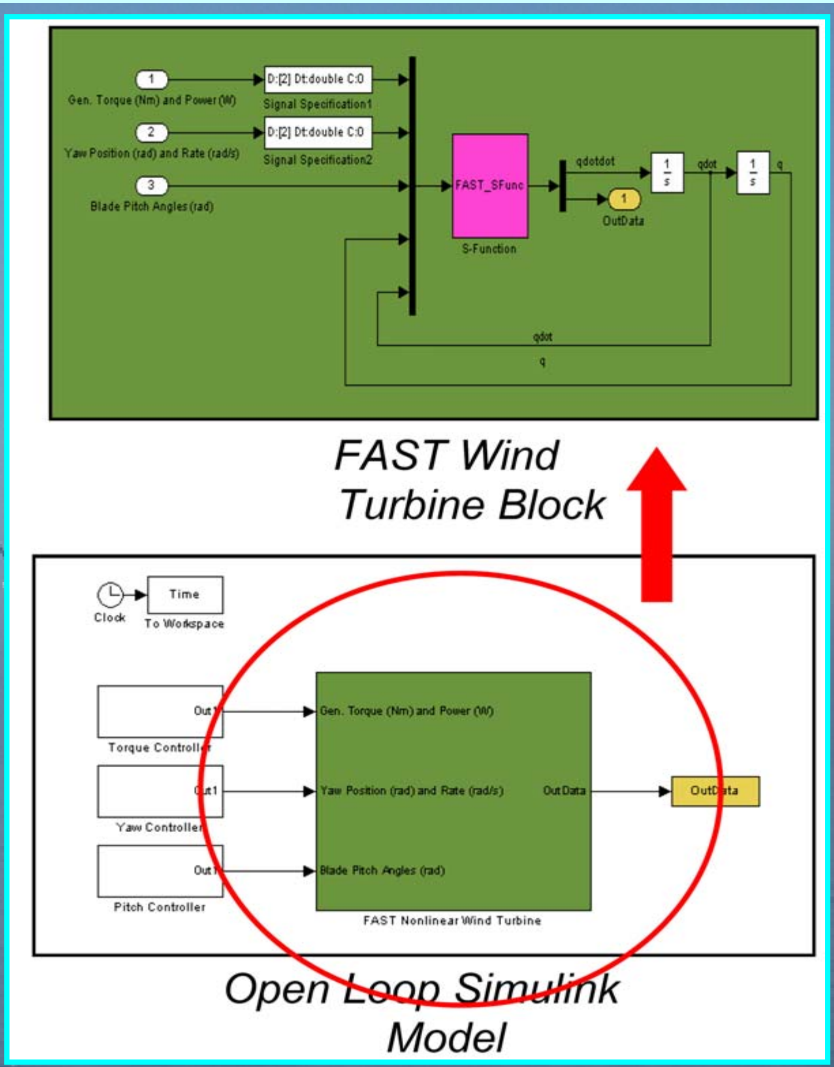
Wind speed is not unknown, but measured but highly noisy

Simulink-based Scheme



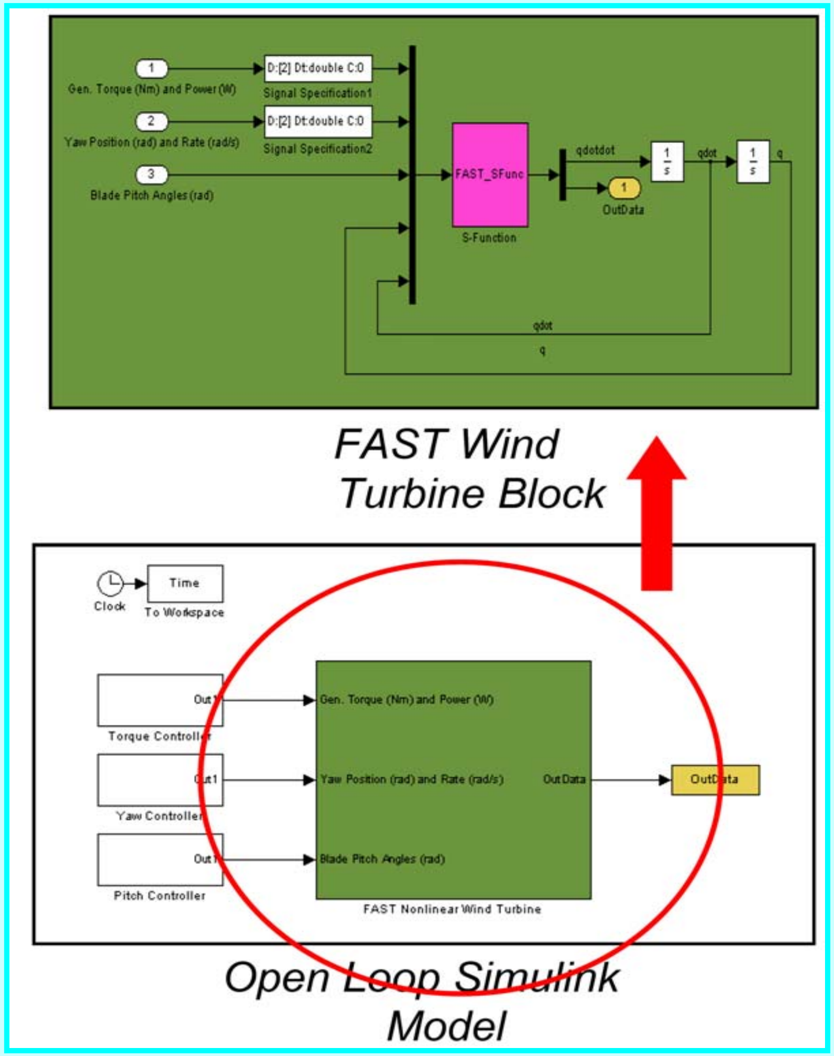
(Active FTC/FDIR)

Wind Turbine Simulators



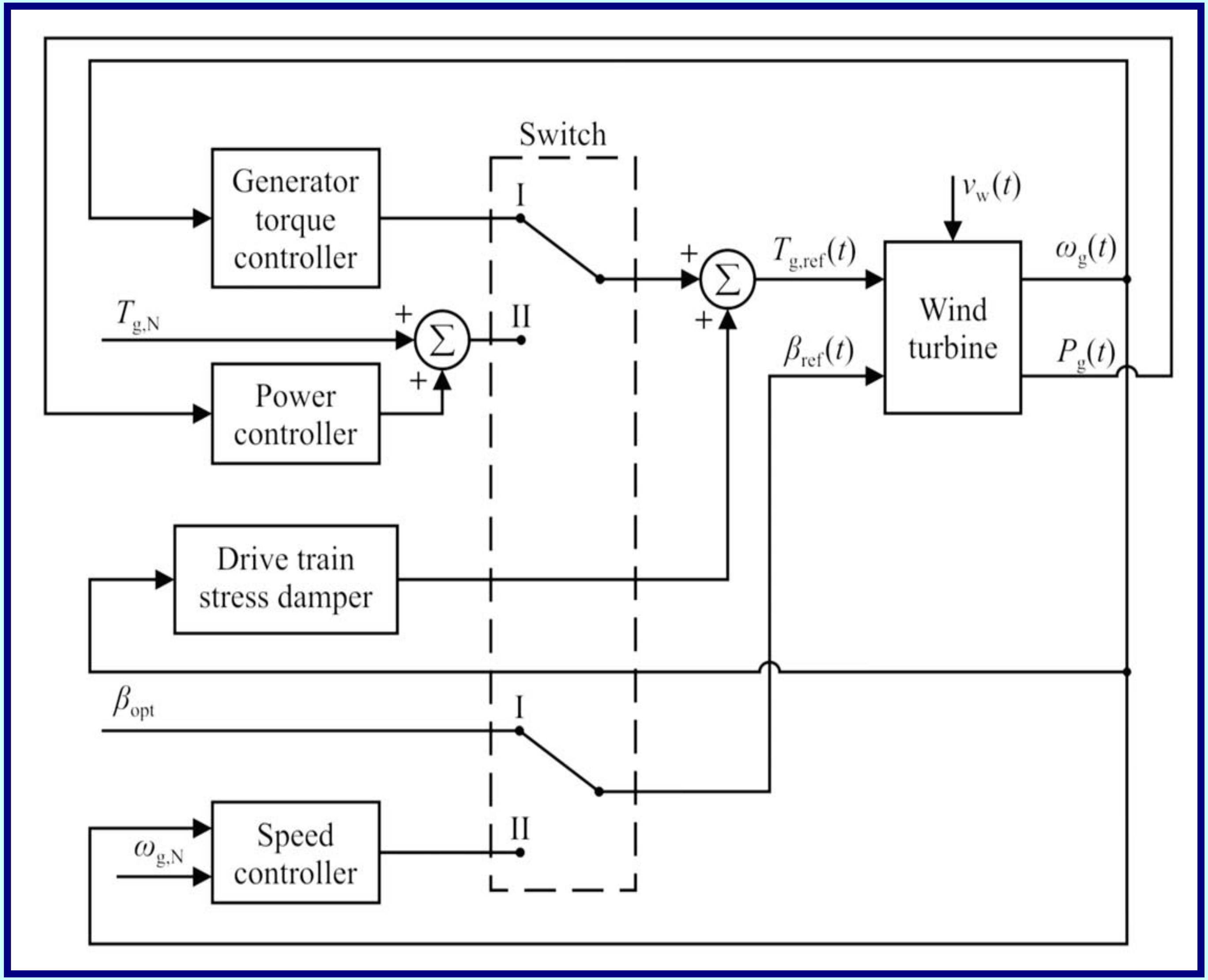
Turbine Model & Controller

- ✓ Routines for pitch, torque, & yaw controllers
- ✓ Dynamic link library (DLL):
  - – DLL interface routines included with FAST archive
  - – Can be Fortran, C++, etc.
- ✓ **MATLAB/Simulink**:
  - – **FAST** implemented as S-Function block
  - – Controls implemented in block-diagram form



Reference Controller

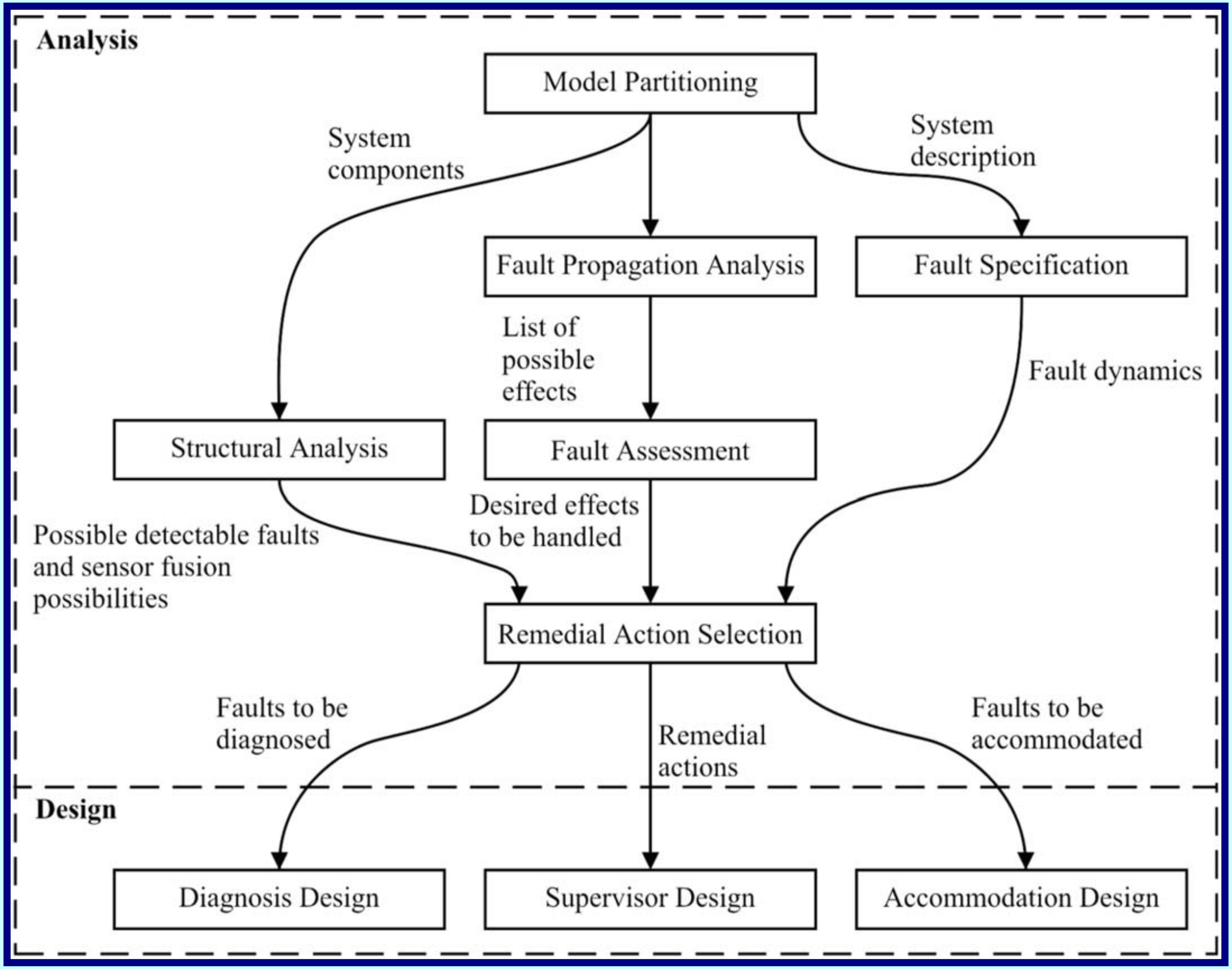
Reference Controller



- ✓ 2 working conditions: (I) partial & (II) full load
- ✓ Approximates the configuration of an existing control system
- ✓ Used in the design of the fault diagnosis algorithms

Fault Analysis

FMEA


Analysis
Model Partitioning
System components
System description
Fault Propagation Analysis
Fault Specification
List of possible effects
Fault dynamics
Structural Analysis
Fault Assessment
Desired effects to be handled
Possible detectable faults and sensor fusion possibilities
Remedial Action Selection
Faults to be diagnosed
Remedial actions
Faults to be accommodated
Design
Diagnosis Design
Supervisor Design
Accommodation Design

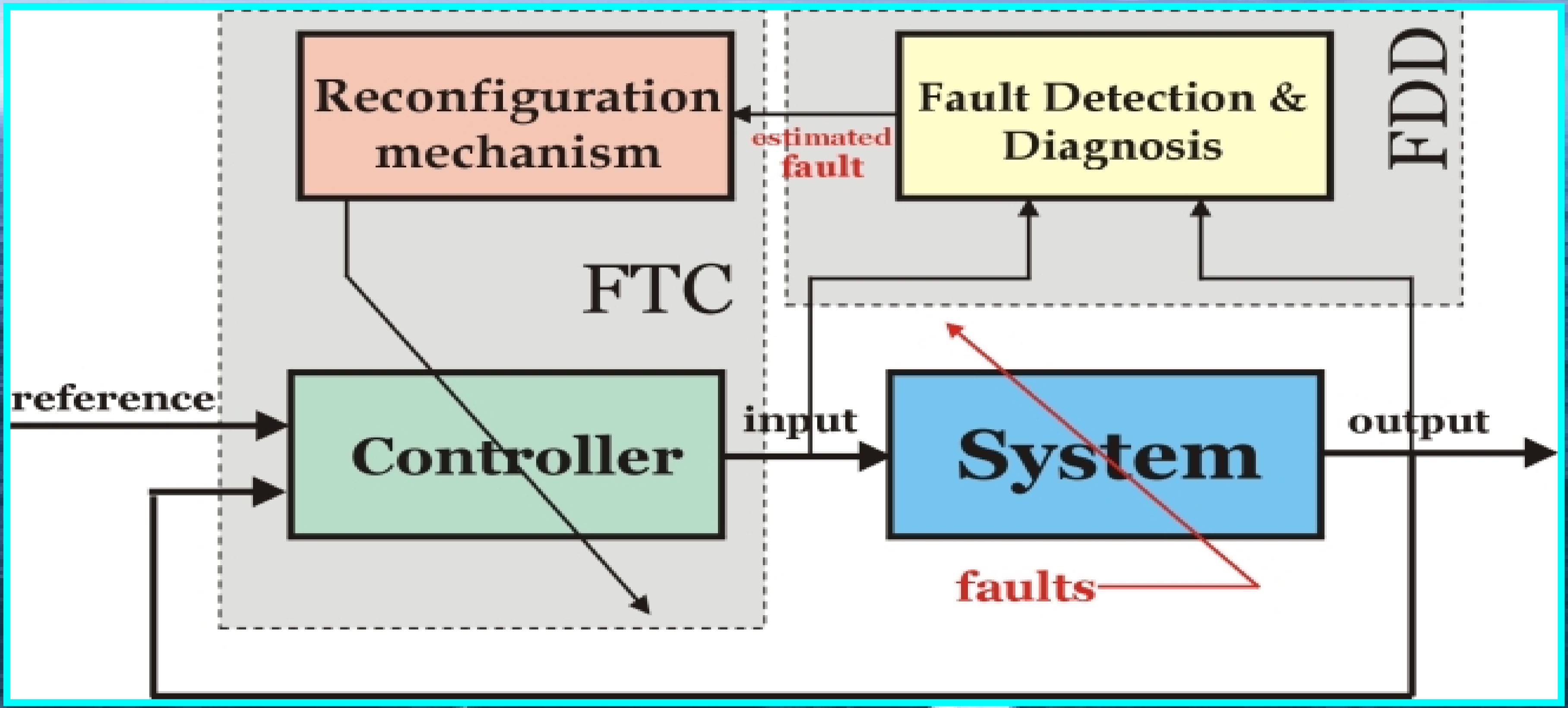
Fault Scenario

Component	Fault
Pitch sensor	Biased output
Pitch actuator	Pump wear
	High air content in oil
	Hydraulic leakage
	Valve blockage
	Pump blockage
Generator speed sensor	Proportional error
	Fixed output
	No output

Fault Examples

No.	Fault	Type
1	Blade root bending moment sensor	Scaling
2	Accelerometer	Offset
3	Generator speed sensor	Scaling
4	Pitch angle sensor	Stuck
5	Generator power sensor	Scaling
6	Low speed shaft position encoder	Bit error
7	Pitch actuator	Abrupt change in dynamics
8	Pitch actuator	Slow change in dynamics
9	Torque offset	Offset
10	Yaw drive	Stuck drive

FTC General Structure

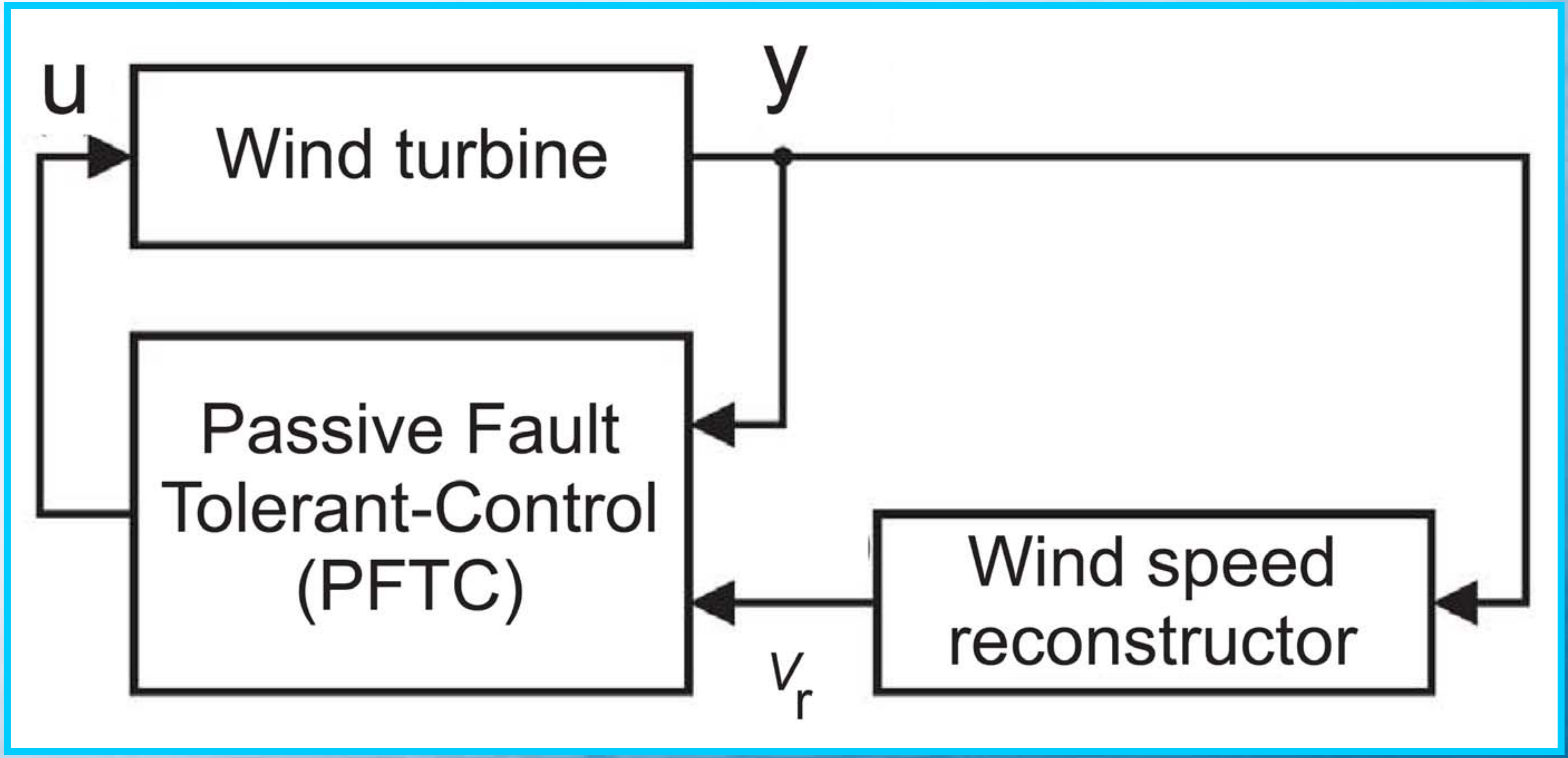


- ✓ **PFTC**: Robust fixed structure controller
- ✓ **AFTC**: Real-time controller reconfiguration

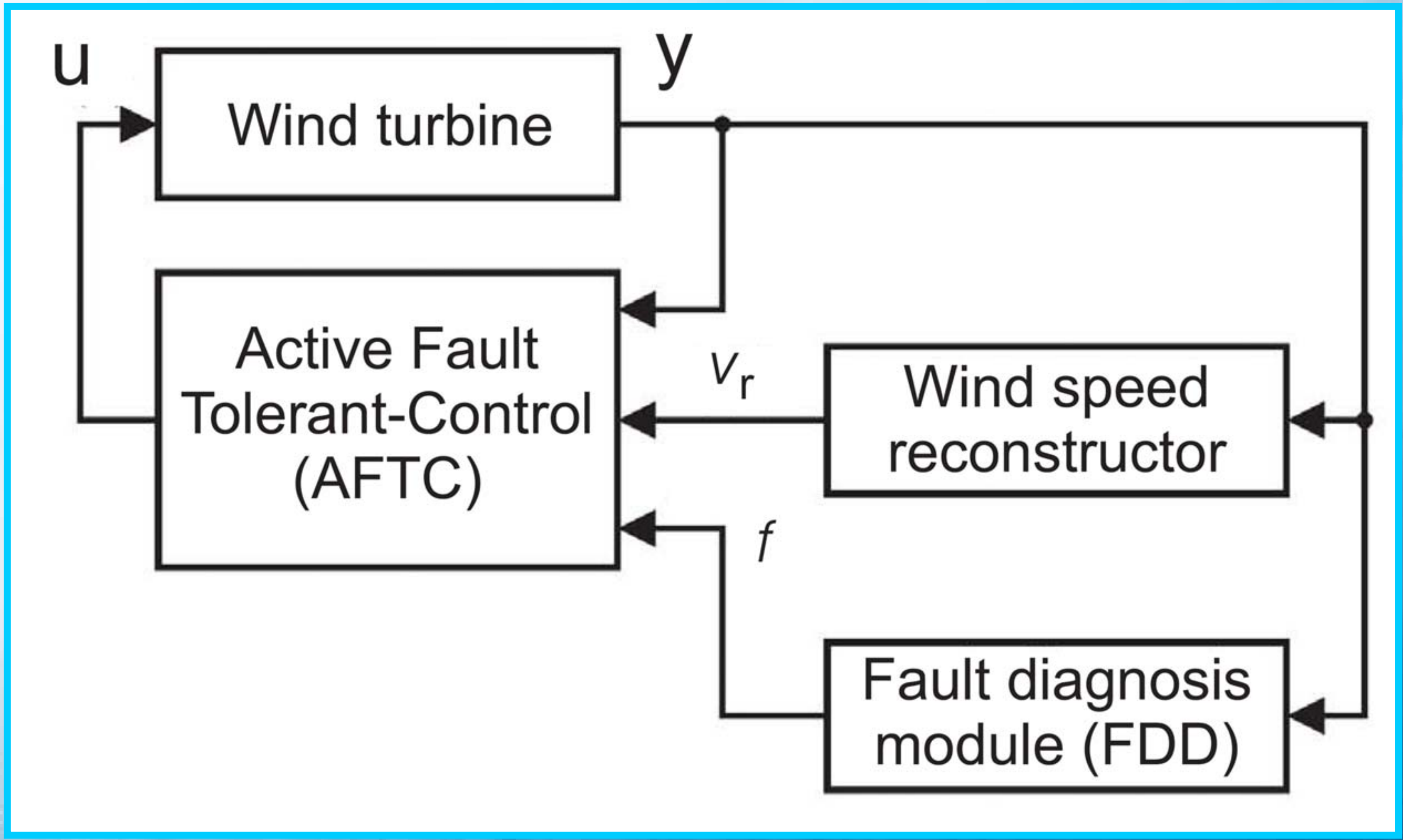
Fault Accommodation

Component	Fault	Fault Accommodation Method
Pitch sensor	Biased output	Signal correction of measurement and reference signals
Pitch actuator	High air content in oil	Active and passive fault-tolerant control
	Pump wear	
	Hydraulic leakage	Shut down the wind turbine
	Valve blockage	
	Pump blockage	
Generator speed sensor	Proportional error	Signal correction of measurement signal
	Fixed output	Signal correction of measurement signal (PL)
	No output	Active and passive fault-tolerant control (FL)

FTC Solutions: Passive



FTC Solutions: Active



FDI & FTC Competitions

Two competitions in two parts launched on (I) wind turbine and (II) wind farm benchmark models

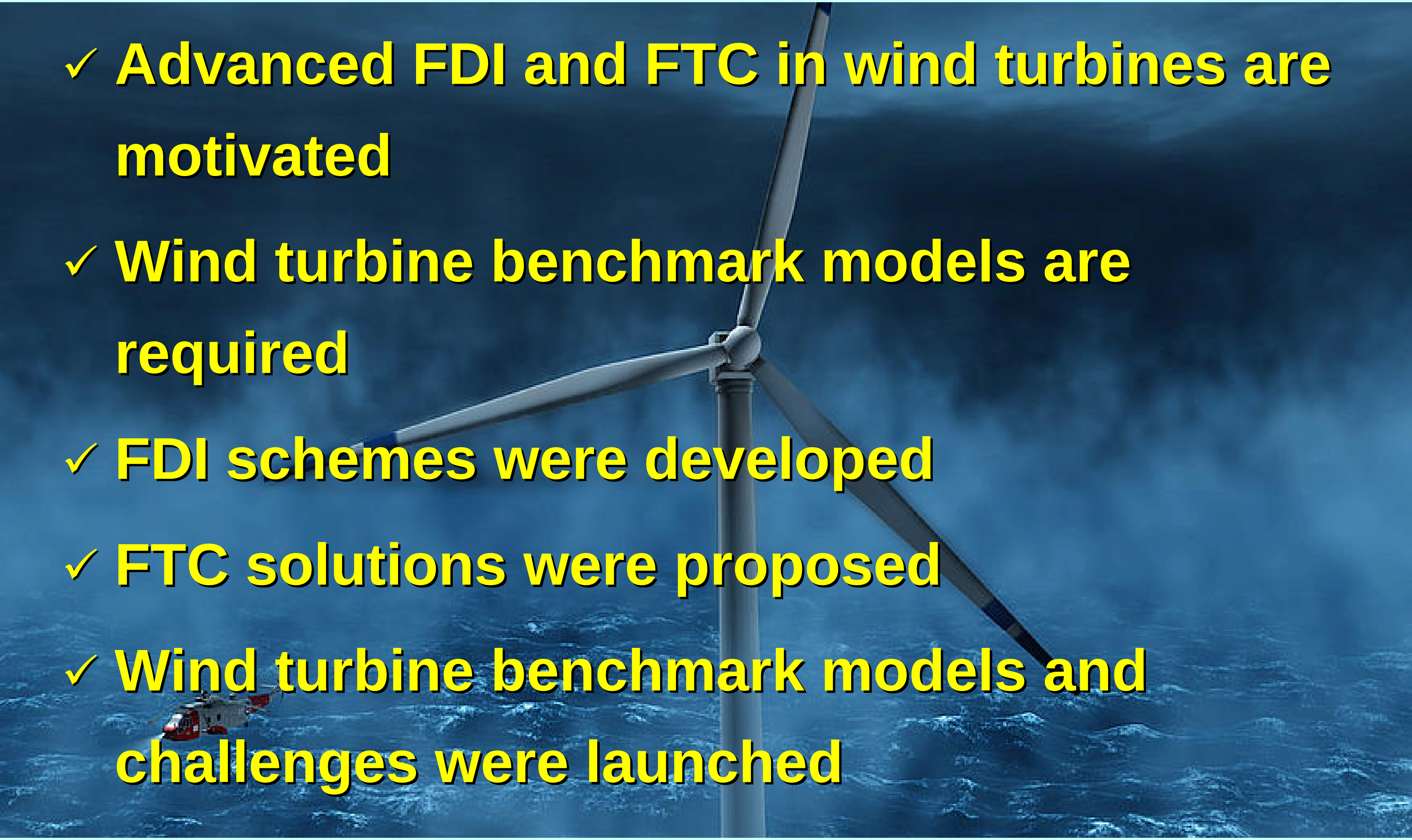
- ✓ Part I.I on FDI: solutions were presented in two invited sessions at IFAC World Congress, Milan, Italy, 2011
- ✓ Part I.II on FTC: solutions were presented in two and a half invited sessions at IFAC SafeProcess, Mexico City, Mexico, 2012
- ➢ Three prizes for each part was sponsored by kk-electronic a/s and Mathworks

- ✓ Part II.I on FDI: solutions were presented in one invited session at 2014 IFAC World Congress, Cape Town, South Africa, August 2014
- ✓ Part II.II on FTC: solutions were presented in one invited session at IFAC SafeProcess, Paris, France, September 2015
- ➢ Three prizes for each part was sponsored by Mathworks

FTC Competition: Results

- **CUSUM Based Detection (Borchersen et al. 2014)**
  - Wind direction and speed estimation
  - Comparison of different sets of wind turbines with similar operational conditions, used to generate residuals
  - CUSUM method for FDI
- **Interval Parity Equation (Blesa et al. 2014)**
  - Interval parity equations for FDI.
  - Bounded description of noise and modelling errors
  - FDI based on on-line interval prediction bound violations + structural analysis
- **Fuzzy Residual Generators (Simani et al. 2014)**
  - Takagi-Sugeno models for residual generation
  - Data-driven approach
  - Adaptive thresholding logic for FDI

Conclusion



- ✓ Advanced FDI and FTC in wind turbines are motivated
- ✓ Wind turbine benchmark models are required
- ✓ FDI schemes were developed
- ✓ FTC solutions were proposed
- ✓ Wind turbine benchmark models and challenges were launched

Conclusion (cont'd)

- ✓ **Current state-of-the-art design tools**
  - Originate in separate disciplines
- ✓ **Classical modelling tools**
  - Good for turbines that are operating below rated wind speed
  - Structurally stiff
  - Very little yaw
  - Low turbulence
- ✓ **Next generation turbines**
  - Larger and more flexible
  - More accurate models
  - Closer coupling
  - Advanced control schemes

Recent Challenges

- ✓ **Original benchmark model is combined with NREL's FAST** to provide a FDI and FTC test case with a more detailed aerodynamic and structural model
- ✓ Contributions were submitted as invited session at **ACC 2013** (June 17 – 19, 2013, Washington, DC)
- ✓ A benchmark model for FDI and FTC of wind turbines on a **wind farm level** have been proposed, and a competition in two parts – FDI and FTC have been launched and still running
- ✓ The wind farm model is quite (too?) simplified

Research Issues

Open problems

Forthcoming Events

- ✓ **SysTol'16**: 3rd Conference on Control and Fault-Tolerant Systems, September 7-9, 2016 – Barcelona, Catalonia, Spain
- ❖ **IFAC WC 2017**: World Congress, Toulouse, France. 9-14 July, 2017
- ❖ **SafeProcess 2018 (**announced during the SafeProcess in Paris, August 2015): August/Sept. (to be defined) 2018, Warsaw, Poland

Recent Publications

- **Simani S., Overview of Modelling and Advanced Control Strategies for Wind Turbine Systems. 14 October 2015. *Energies* 2015. "Special issue on Wind Turbines 2015".**
- **"Special issue on wind turbines and wave energy devices". Organised by John V. Ringwood & Silvio Simani *Annual Reviews in Control*, Available online 23 October 2015.**
  - Selection of papers from previous IFAC events
- In particular, regarding wind turbines…

- **Gearbox fault detection using time-frequency based methods**, by P. F. Odgaard, J. Stoustrup
- **Fault Detection and Isolation for a Wind Turbine Benchmark using a mixed Bayesian/Set-membership Approach**, by R. M. Fernandez-Cantia, J. Blesa, S. Tornil-Sin, V. Puig
- **Active Power Control Design for Supporting Grid Frequency Regulation in Wind Farms**, by H. Badihi, Y. Zhang, H. Hong
- **Fault-Tolerant Control of Wind Turbines with Hydrostatic Transmission using Takagi-Sugeno and Sliding Mode Techniques**, by H. Schulte, E. Gauterin

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