Fault Diagnosis & Sustainable Control of Wind Turbines:

Robust Data-Driven & Model-Based Strategies

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Discussion Topics

- General considerations
- Advanced control (‘sustainable’) - motivations
- FDI/FTC general structures
- Fault models
- Wind turbine modelling issues
- Benchmarks
- Concluding remarks

The Story Begins (1)

The Story Begins (2)

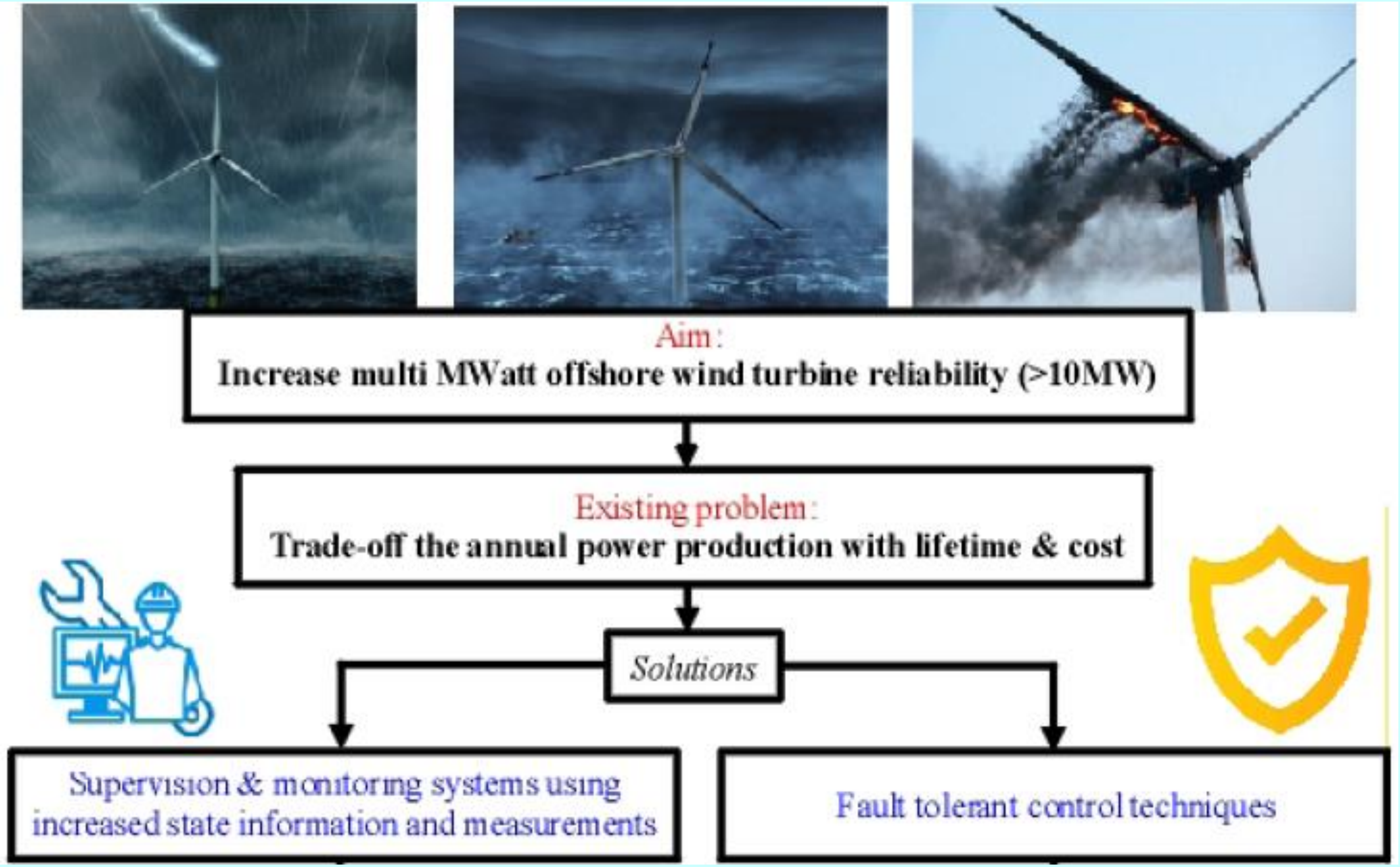
Energy & Control Issues

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

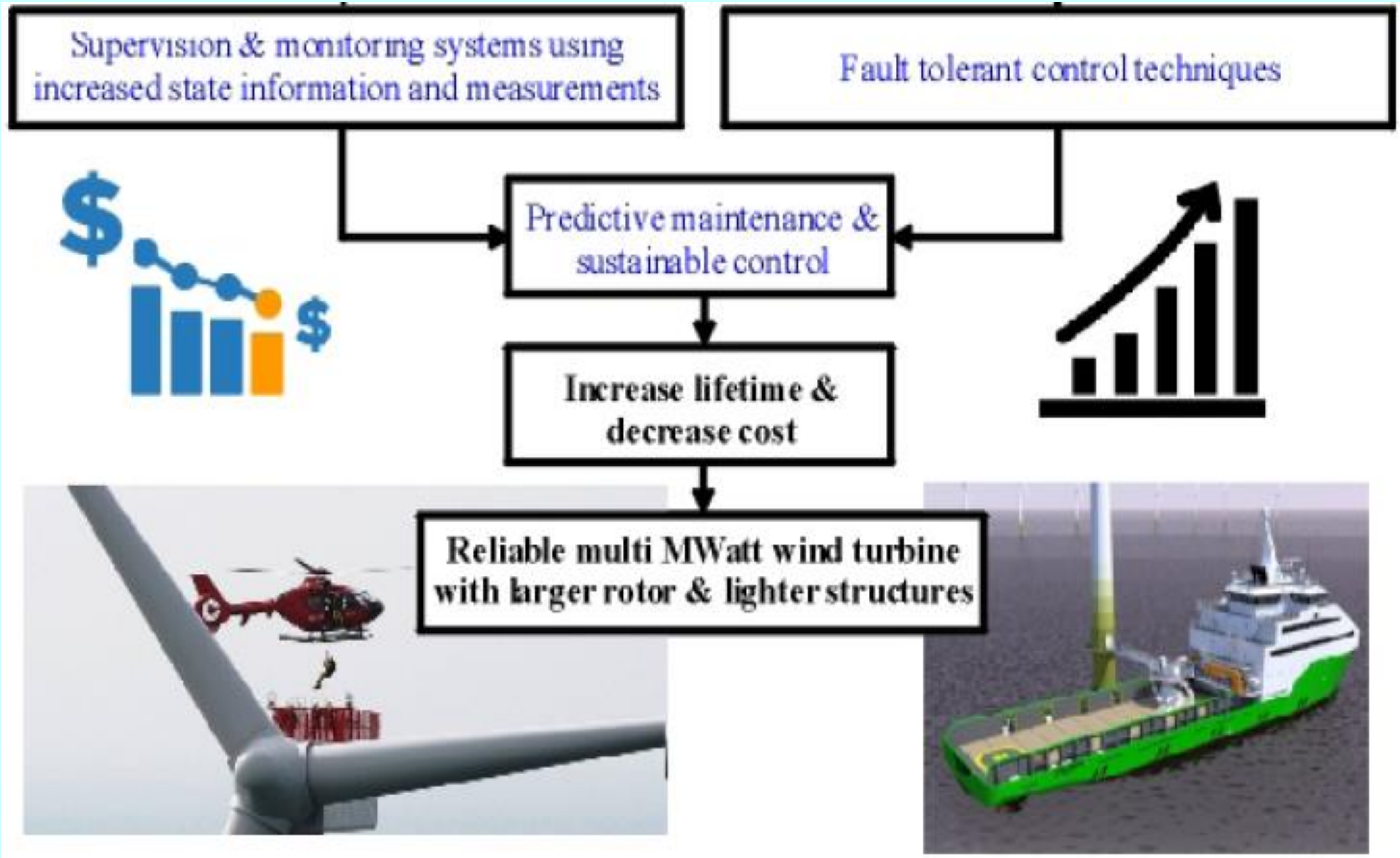
‘Advanced’ Control Solutions

"Sustainable"

Sustainable Control (1)



Sustainable Control (2)



Safety-Critical Systems

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

Motivations

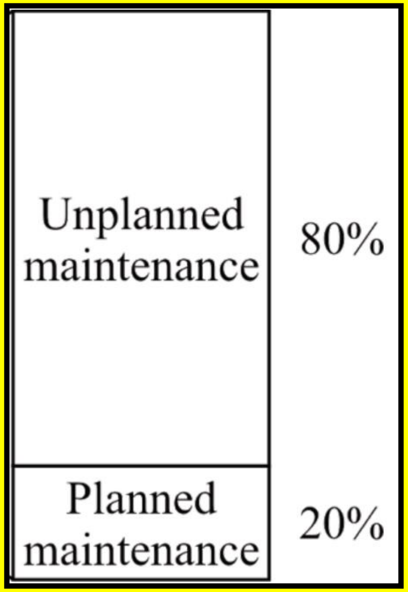
Motivations (cont'd)

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

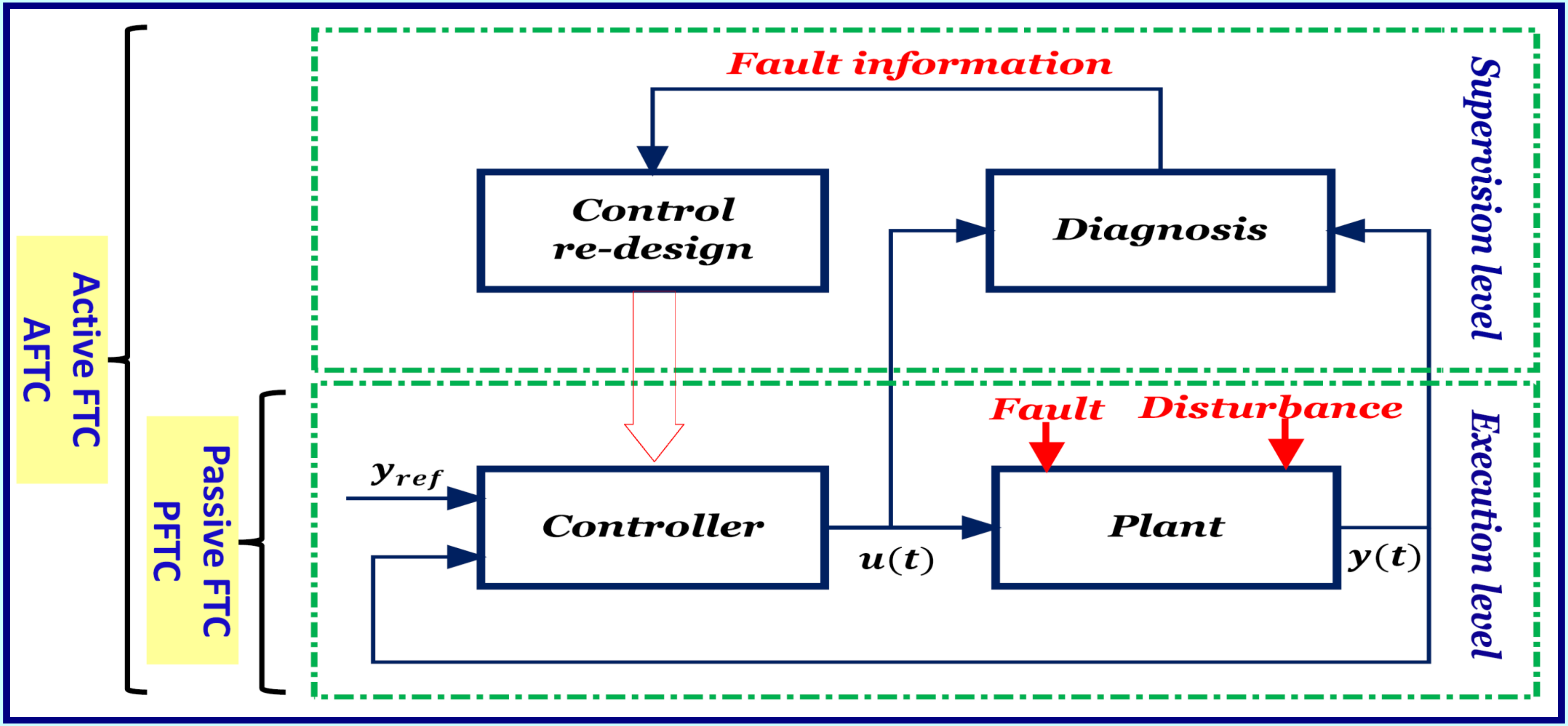
Example…

- ✓ 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 & FTC** included in the control system **could provide information on the fault**, thus allowing for correct & faster repair if required, and/or **continued energy generation** eventually at lower level until maintenance service -> *sustainability*

Cost of energy (15-35%)

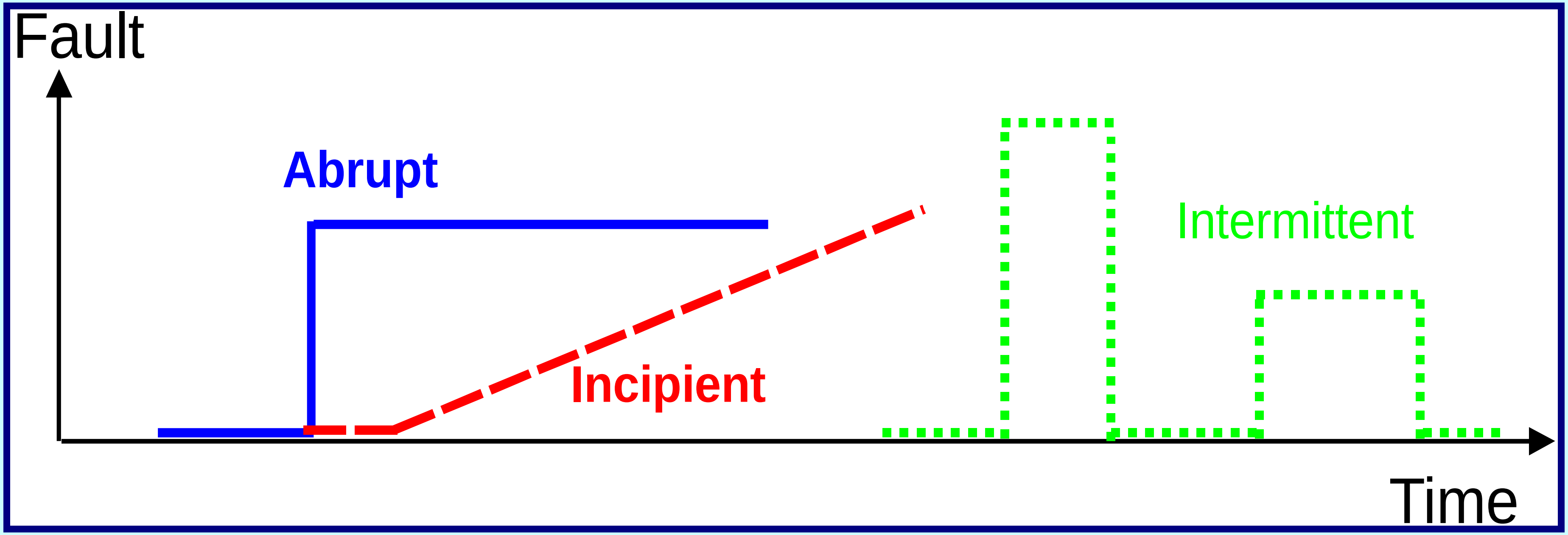



FDI/FTC
Fundamentals



- ✓ **PFTC: Robust fixed structure controller**
  - No fault information provided
- ✓ **AFTC: Controller reconfiguration, fault compensation**
  - Fault reconstruction (real time)

General Fault Modes



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

Fault example…

System Requirements

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

Wind Turbine Maintenance

- ✓ **High degree of reliability & availability (sustainability) is required; at the same, expensive & safety critical maintenance work can occur**
- ✓ **Site accessibility**, system availability not always ensured, *severe weather conditions (+ sea installations)*
- ✓ FTC & FDI researches are stimulated in this application area since important aspects for **decreasing wind energy cost & increasing electrical grid penetration**
- ✓ FTC can enhance specific control actions to prevent plant damage and ensure system availability during malfunctions
- ✓ **Maintenance costs (O&M) & 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 & accommodation, which allows turbine owners & researchers to find the best schemes to handle different faults
- ✓ Based on these models, a series of competitions & challenges were launched (2009 – 2015)
  - Simple Wind Turbine FDI/FTC benchmark model
  - Advanced WT FDI / FTC benchmark model
  - Wind farm FDI/FTC benchmark model

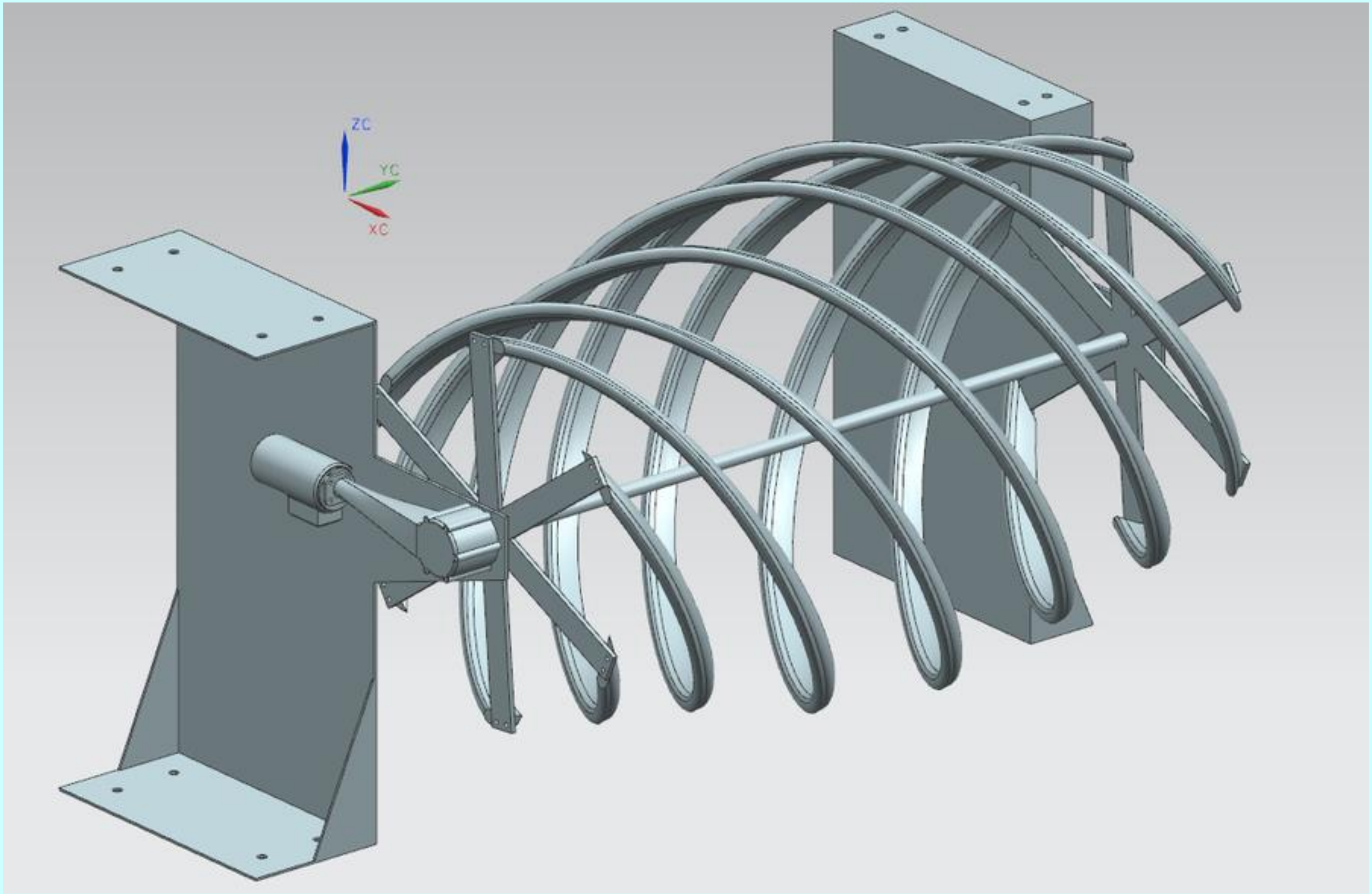
Benchmark Model Motivations

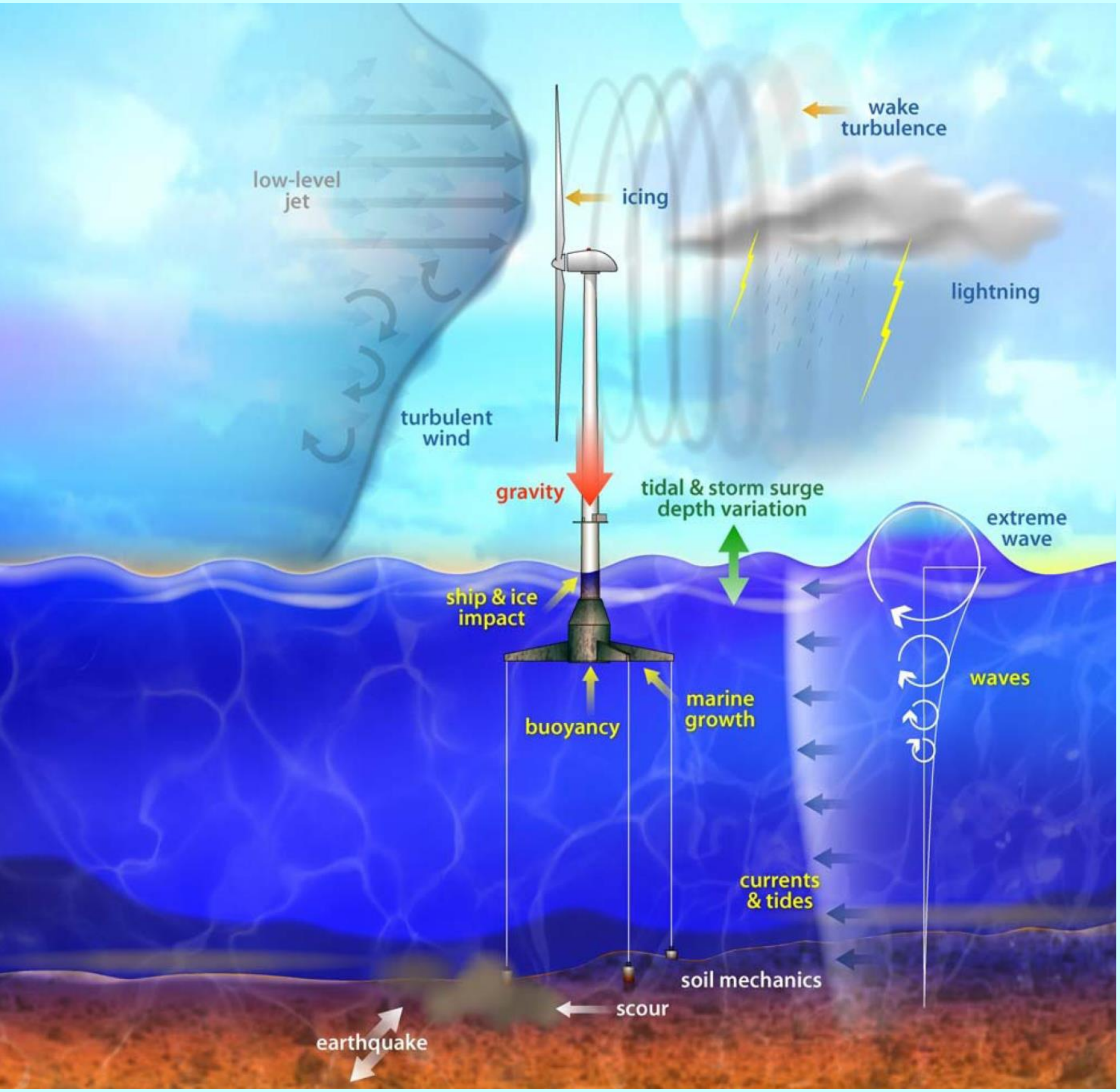
- ✓ Wind turbine benchmarks were proposed to provide generic platforms (freely available) for designing & testing different FDI/FTC solutions
- ✓ **The target was researchers in the FDI & FTC community, such that they can apply & compare their methods on wind turbine realistic installations**
- ✓ The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

Competition Challenges

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

Modelling Topics



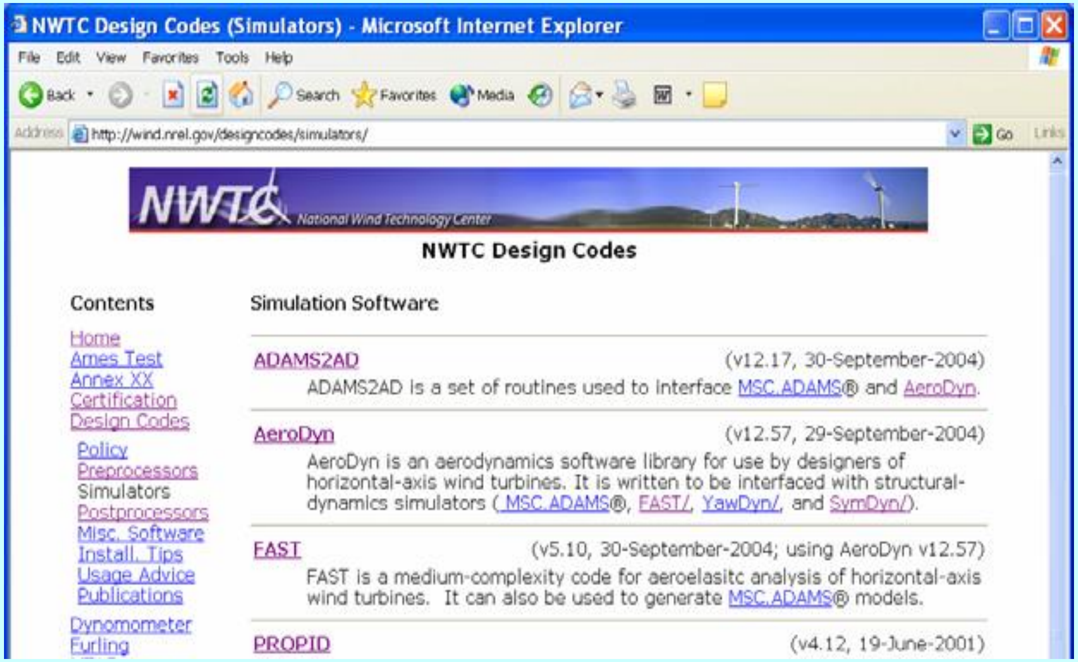


- Coupled aero-hydro-servo-elastic interaction
- Models originate from different disciplines
  - Wind-Inflow
  - Waves
  - Aerodynamics
  - Hydrodynamics
  - Structural dynamics
  - Control systems
- **Multi-Physics Simulation Tools**

NREL Design Codes

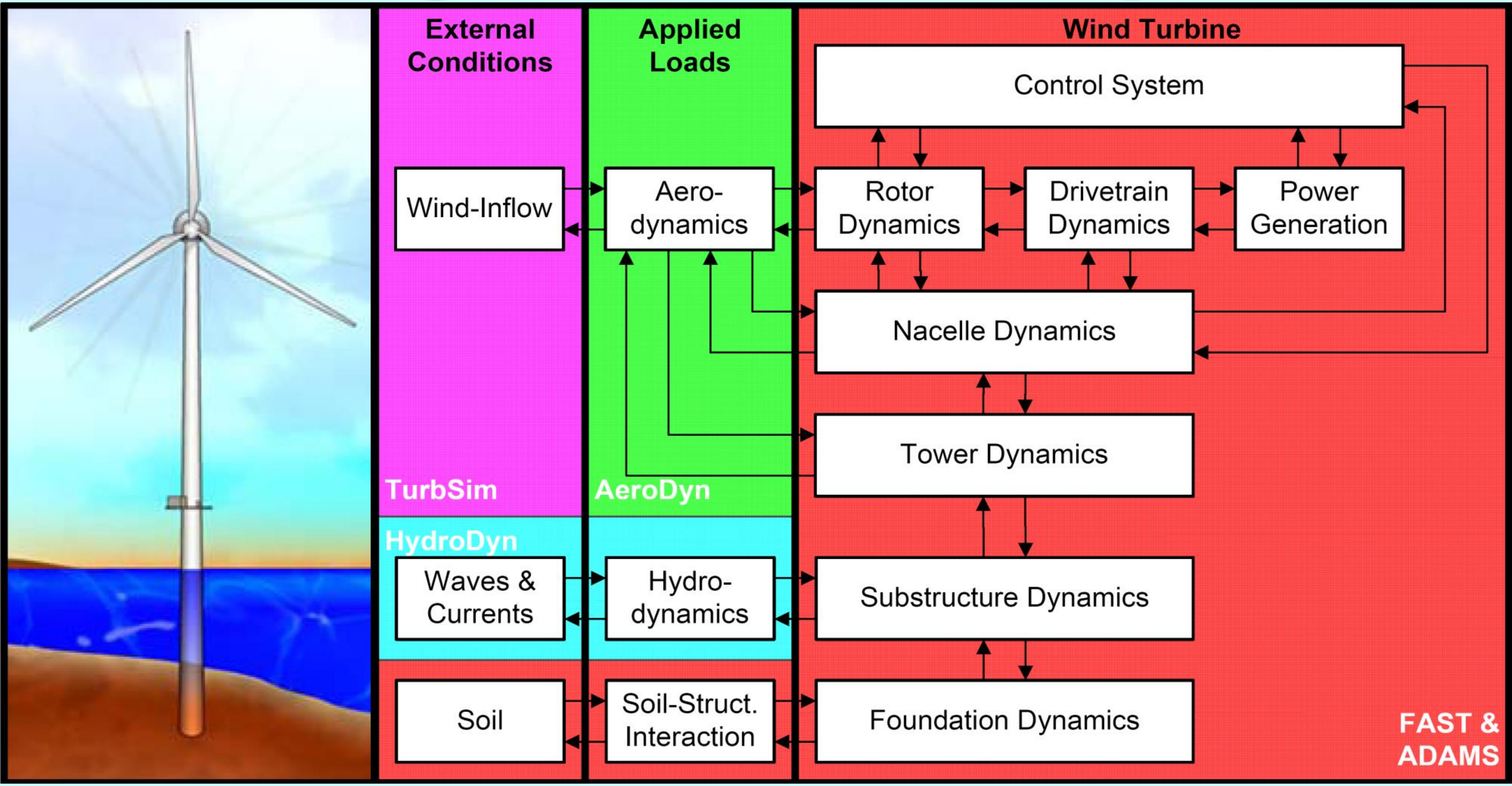
National Renewable Energy Laboratory

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



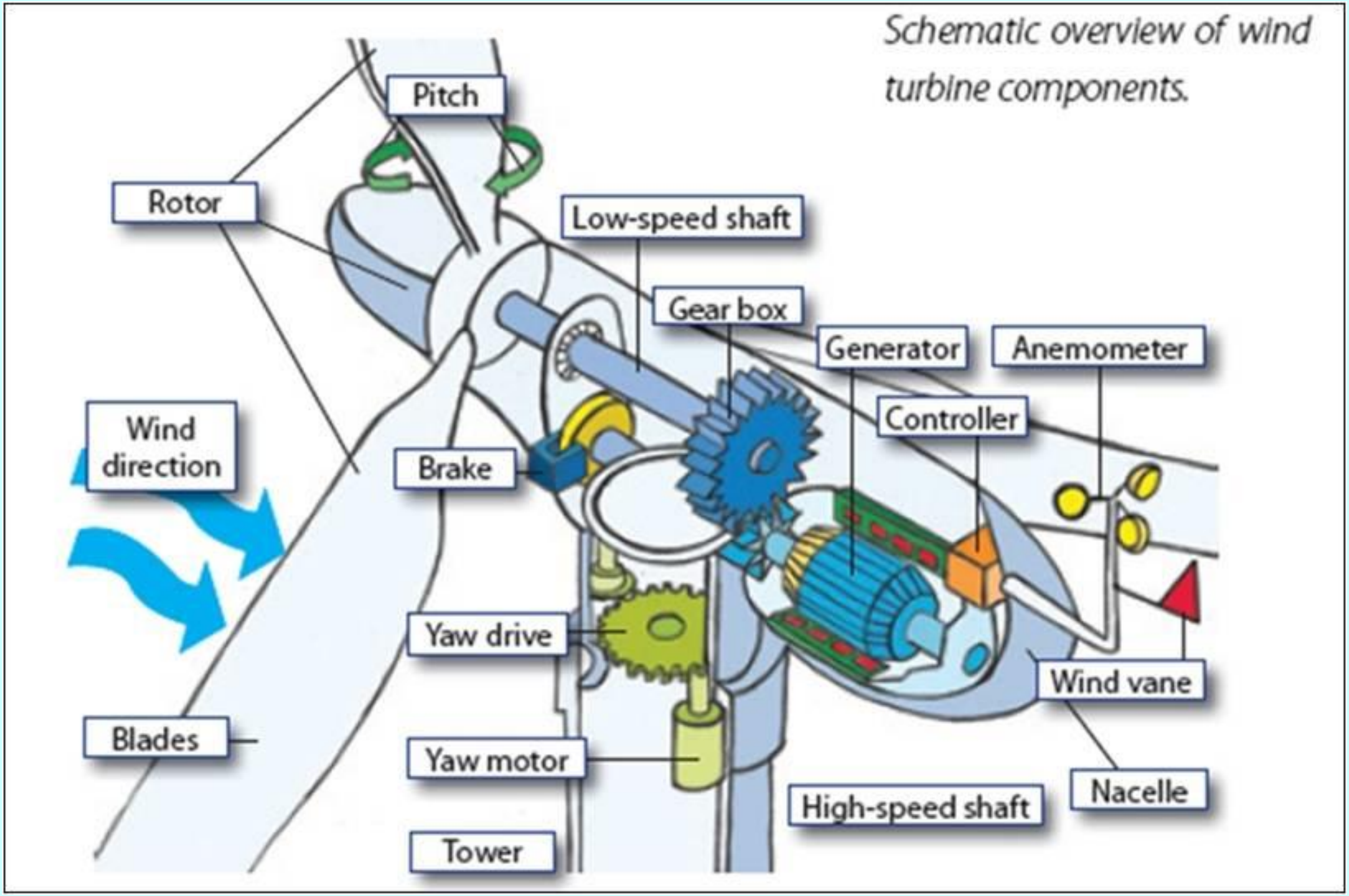
- ✓ Freely available
- ✓ Used heavily in industry, academia & other governmental research organizations
- ✓ Important for control system design

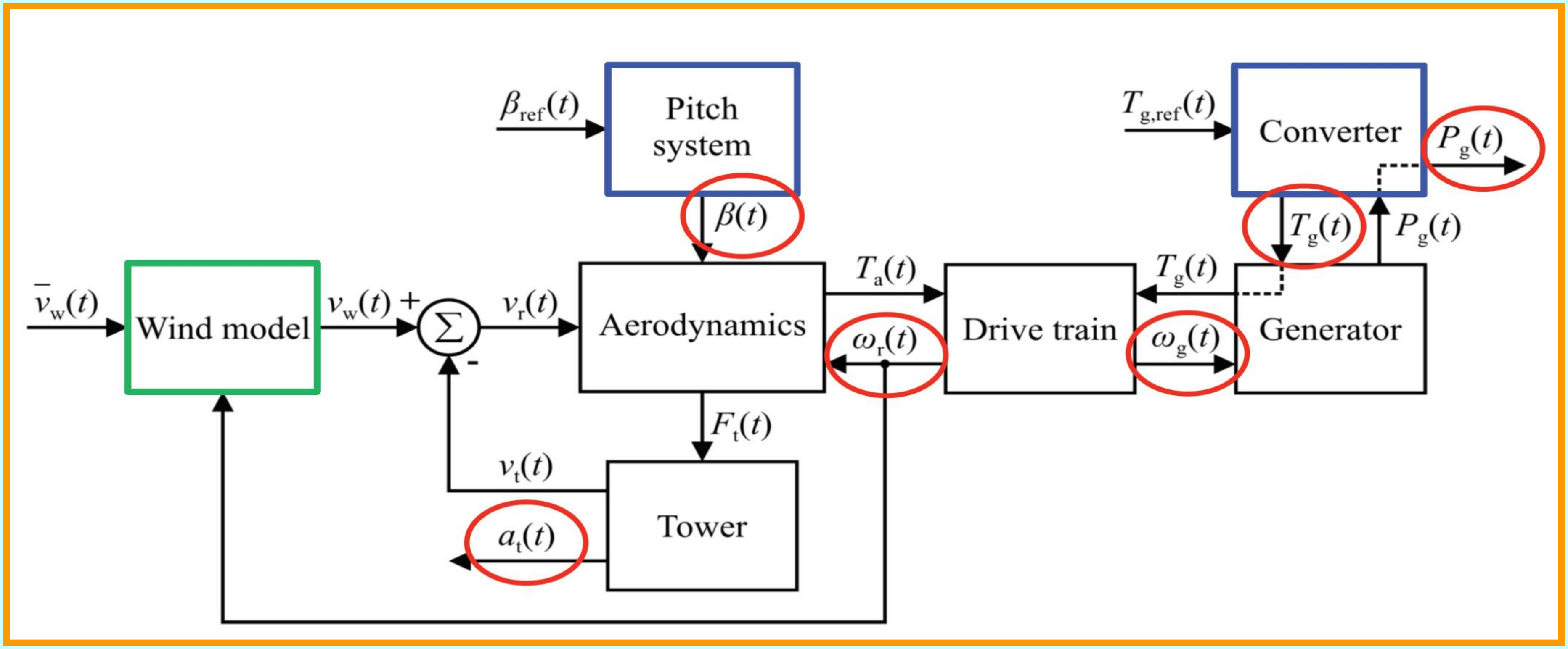
Design Codes Examples



Coupled Aero-Hydro-Servo-Elastic Simulation

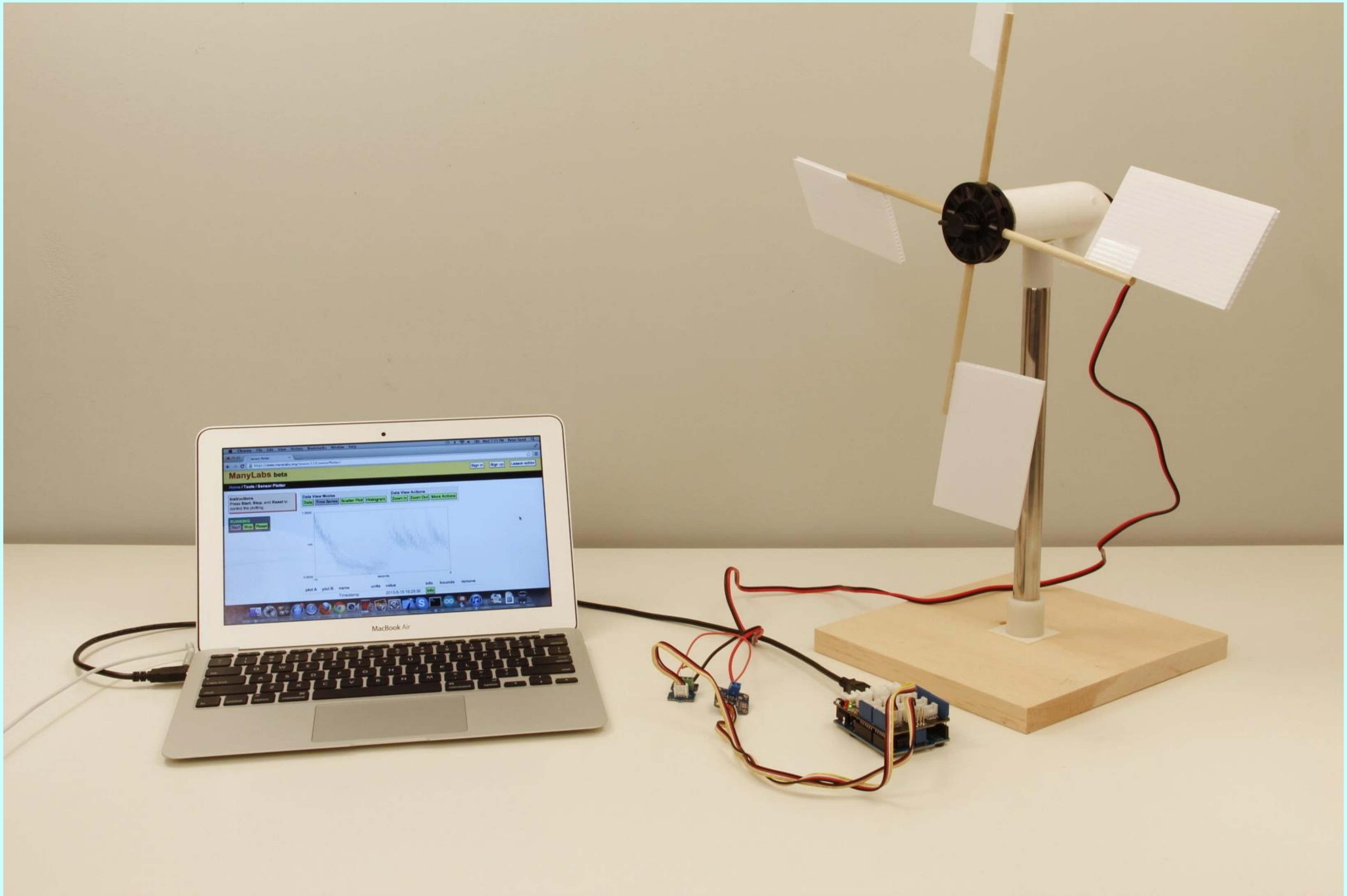
Wind Turbine Components





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

Measurement Sensors

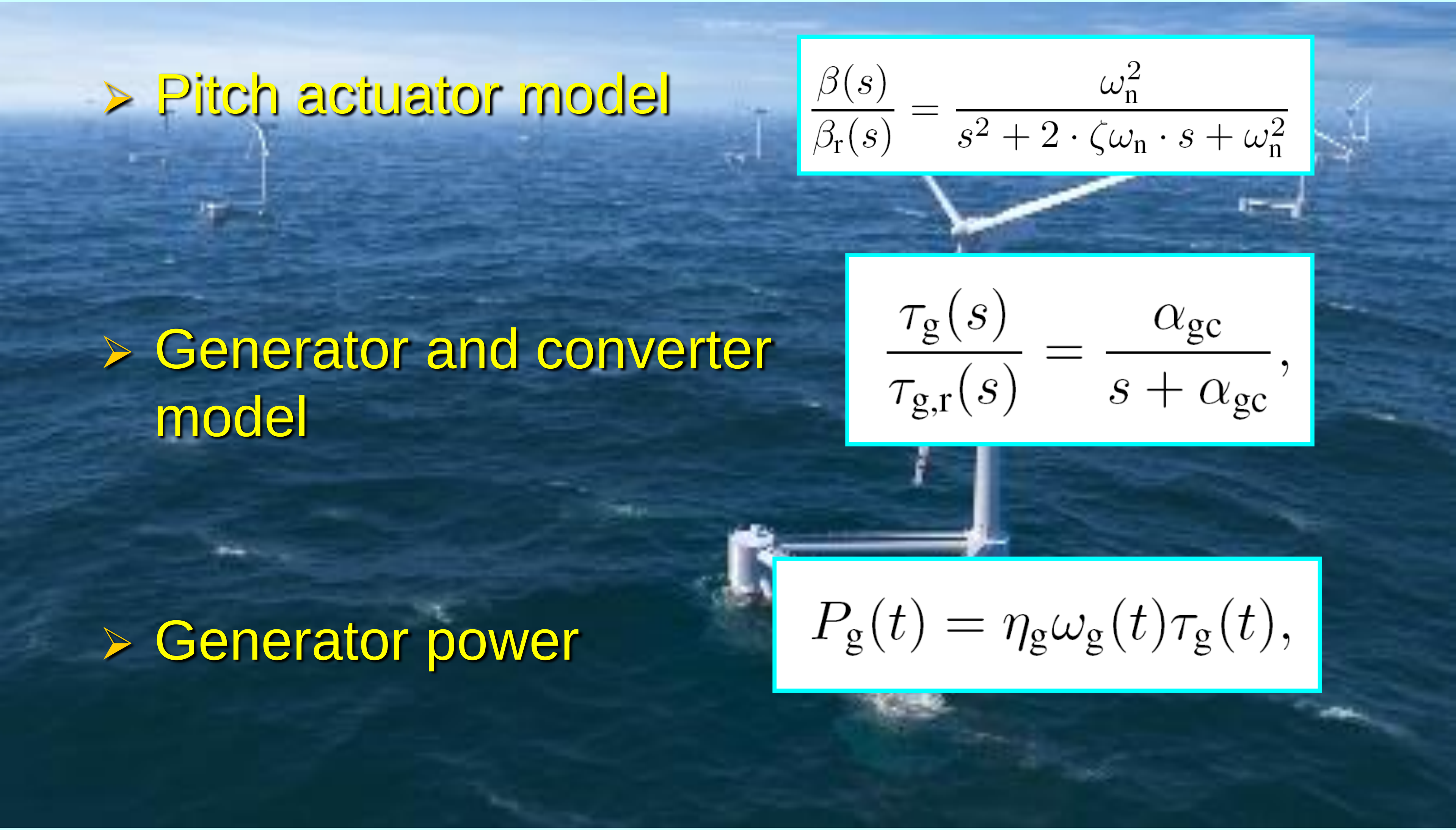


Measurements

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	$\begin{bmatrix} \ddot{x}_{\mathrm{x,m}} \\ \ddot{x}_{\mathrm{y,m}} \end{bmatrix}$	m/s^2	$5 \cdot 10^{-4}$
Yaw error	$\Xi_{\mathrm{e,m}}$	deg	$5 \cdot 10^{-2}$

Wind Turbine Actuators

Simple 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

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

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

Drive-train model

Hydraulic pitch system

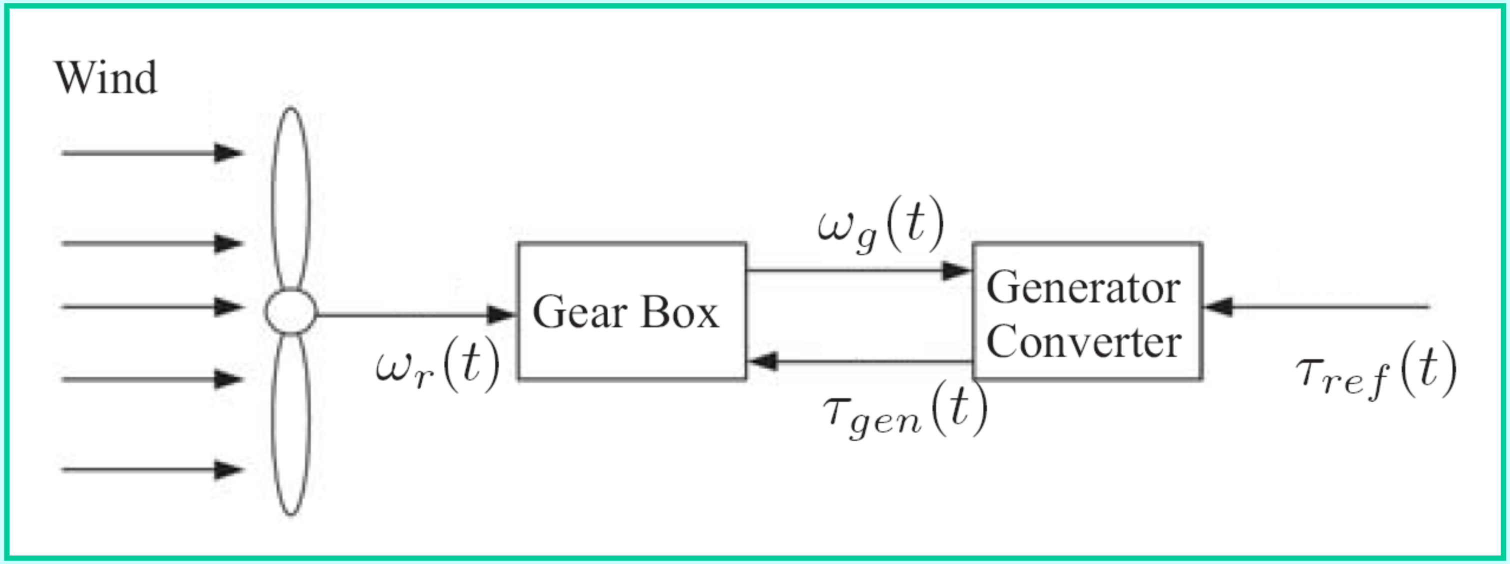
$$\frac{\beta(s)}{\beta_r(s)} = \frac{\omega_n^2}{s^2 + 2\,\zeta\,\omega_n\,s + \omega_n^2}$$

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

Generator & converter models

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

Aerodynamic Model



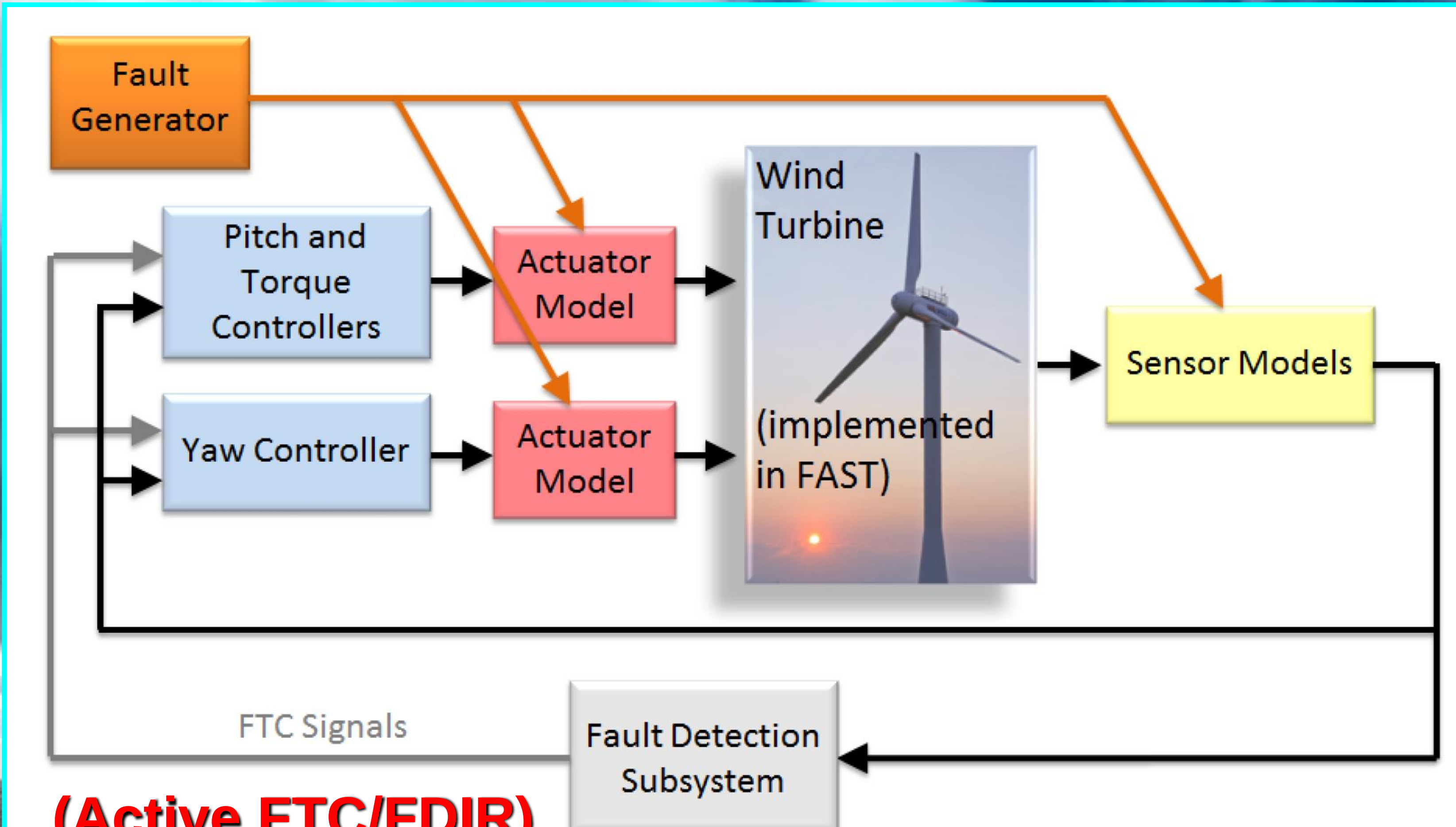
$$\tau_{aero}(t) = \frac{\rho\, A\, C_p\,(\beta(t),\ \lambda(t))\, v^3(t)}{2\,\omega_r(t)}$$

Aerodynamic torque and tip-speed ratio

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

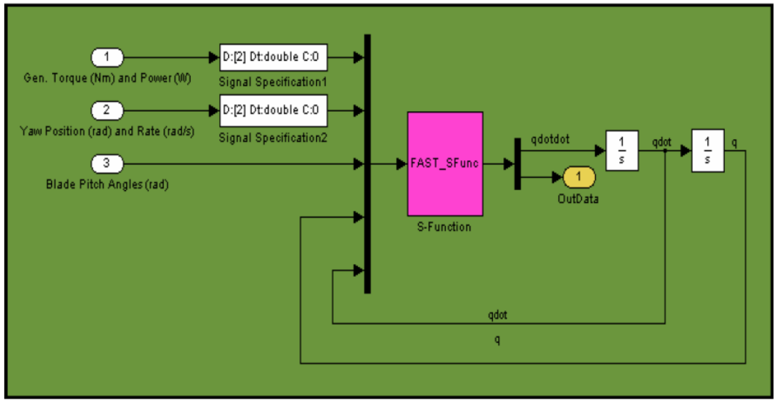
Wind speed is not unknown, but measured & highly noisy

Simulink-based Scheme

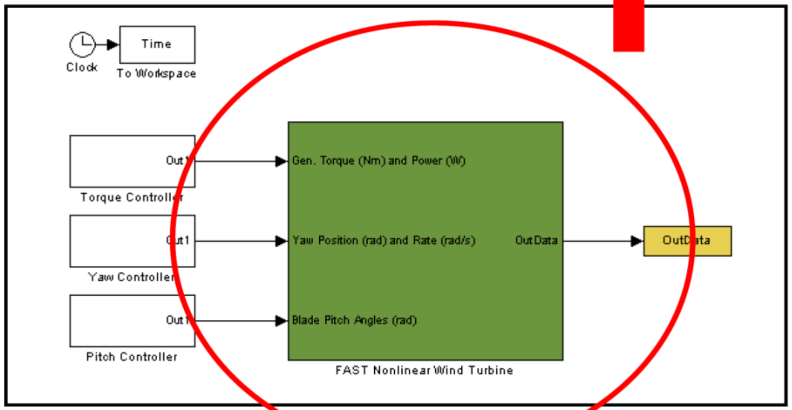


(Active FTC/FDIR)

Wind Turbine Simulators



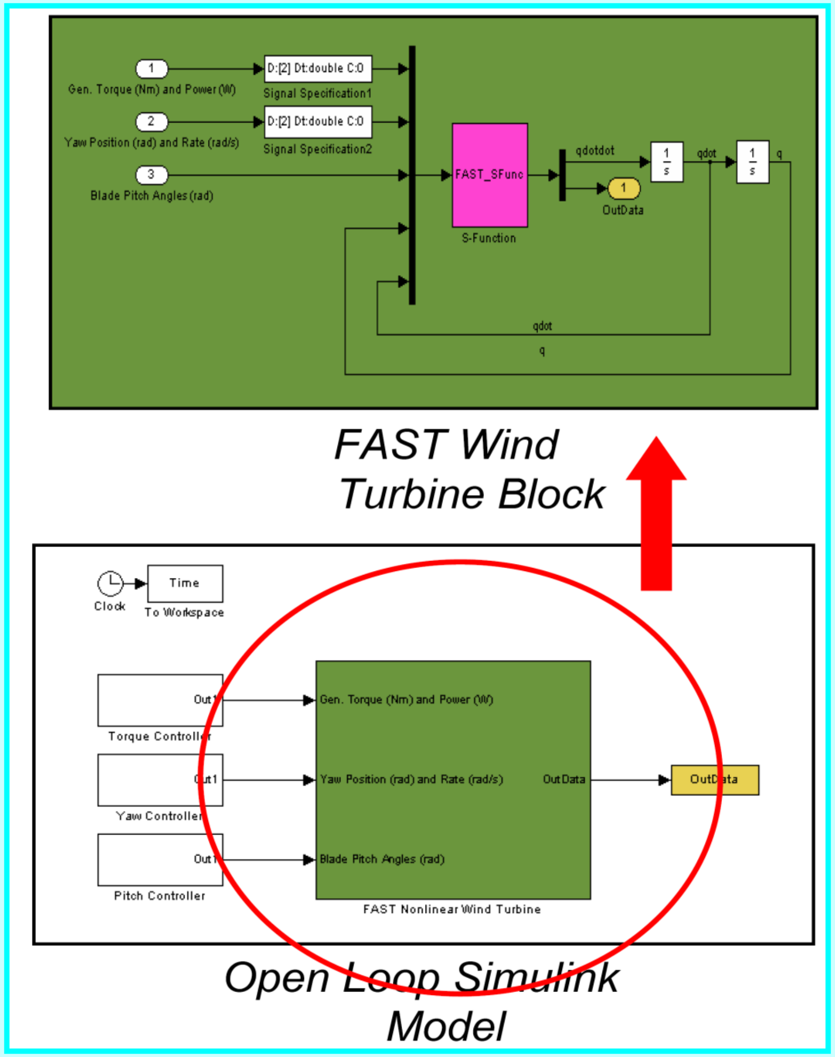
FAST Wind Turbine Block



Open Loop Simulink Model

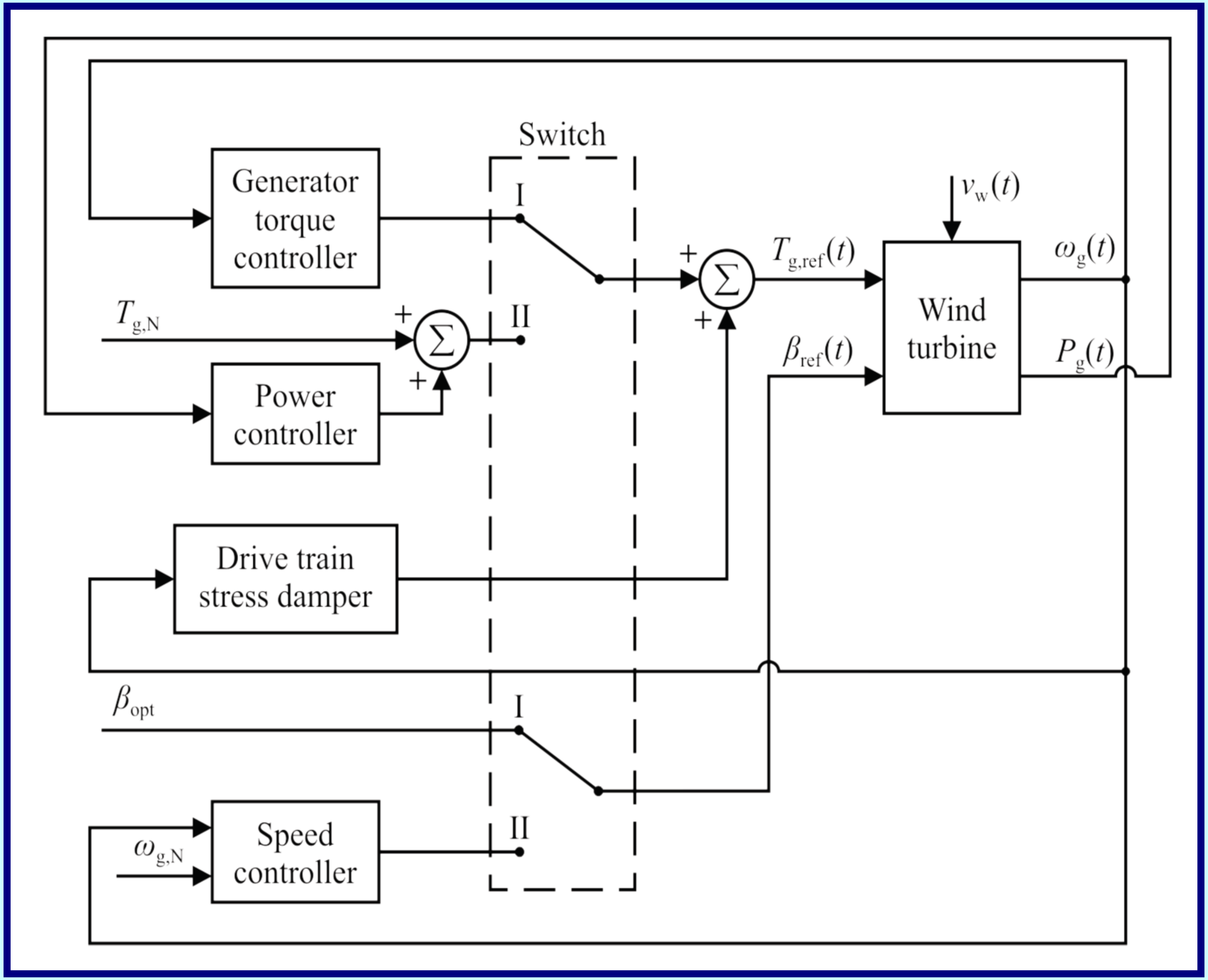
Turbine Model & Controller

- ✓ 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

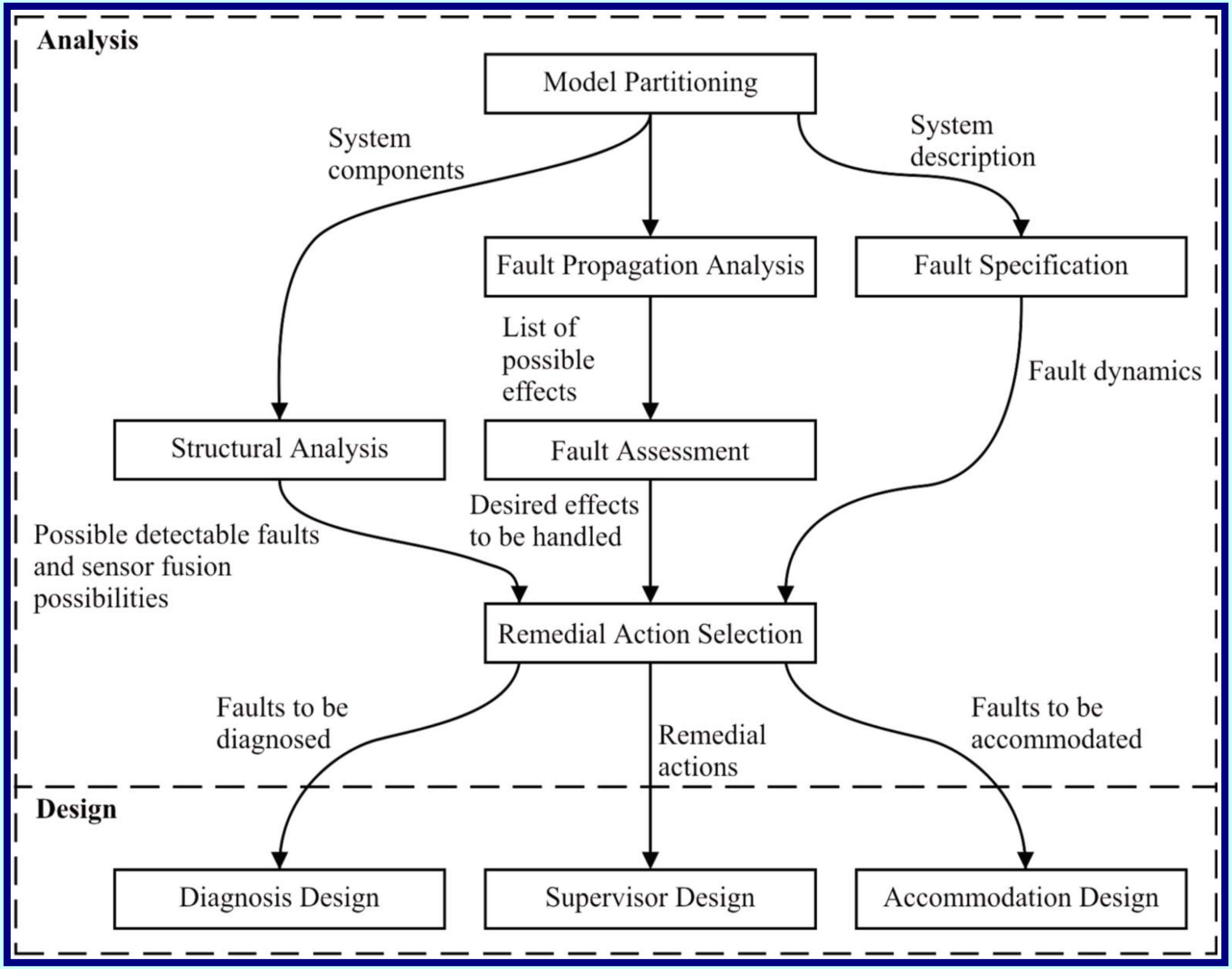
Reference Controller



- ✓ 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

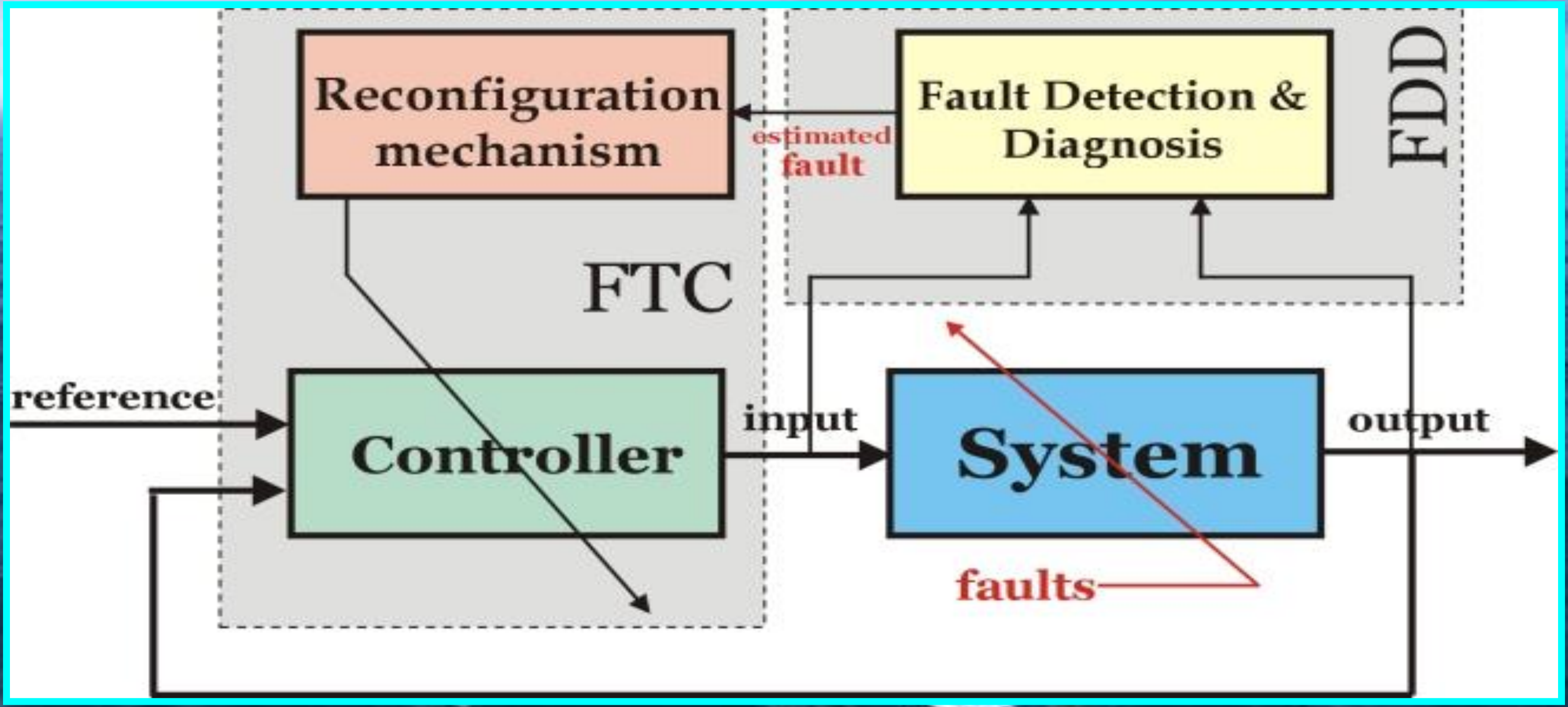
Fault Scenario

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

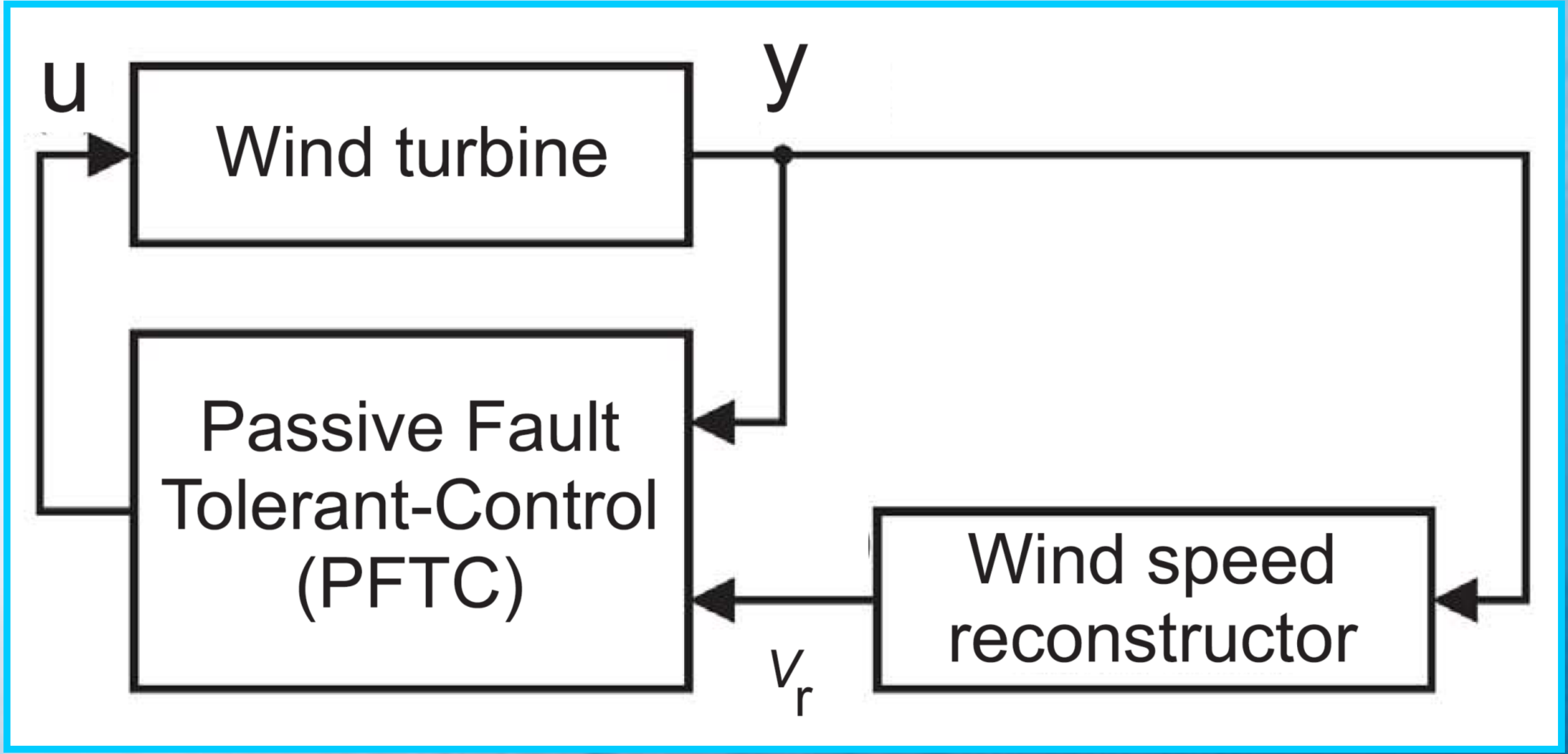


- ✓ **PFTC**: Robust fixed structure controller
- ✓ **AFTC**: Real-time controller reconfiguration

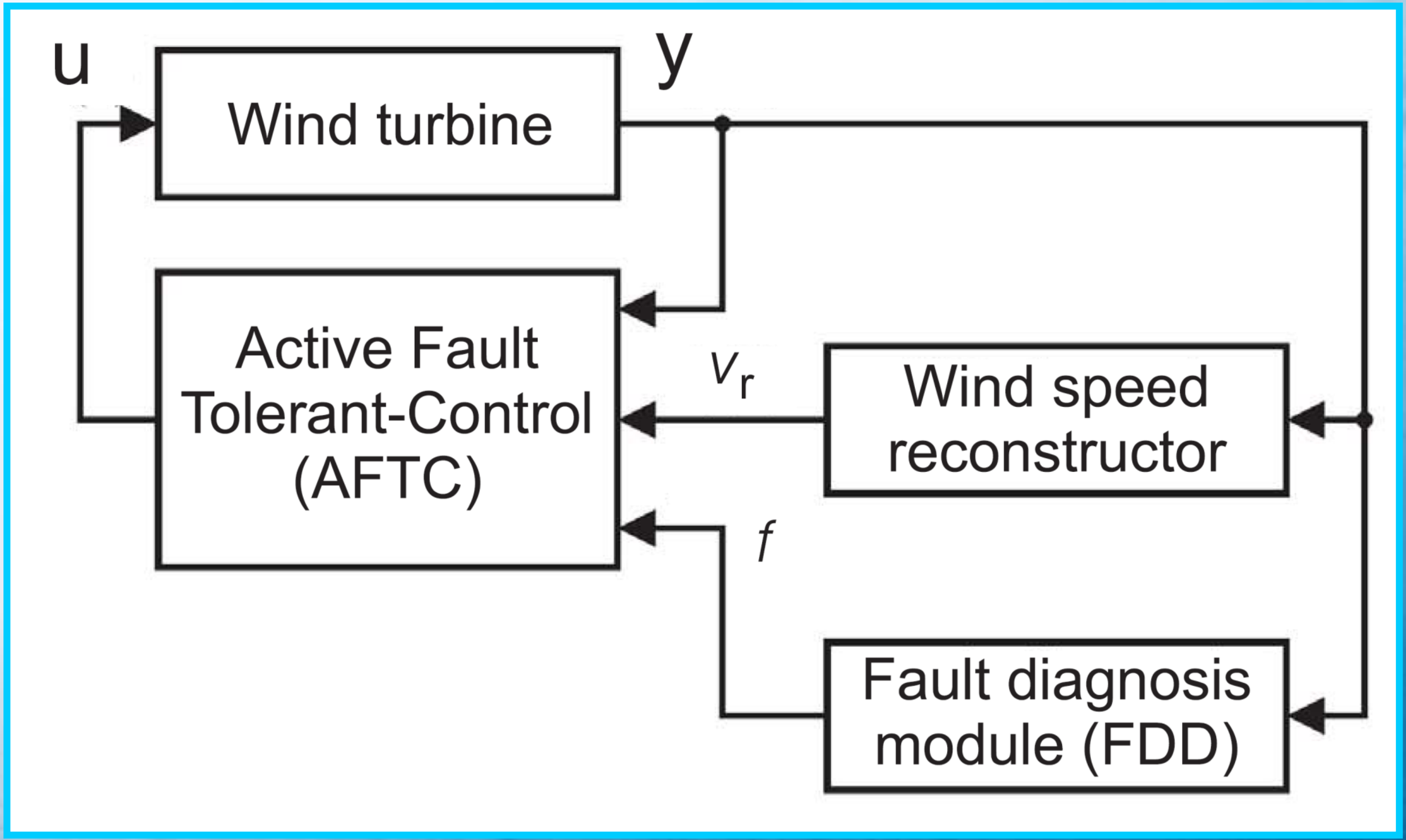
Fault Accommodation

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)

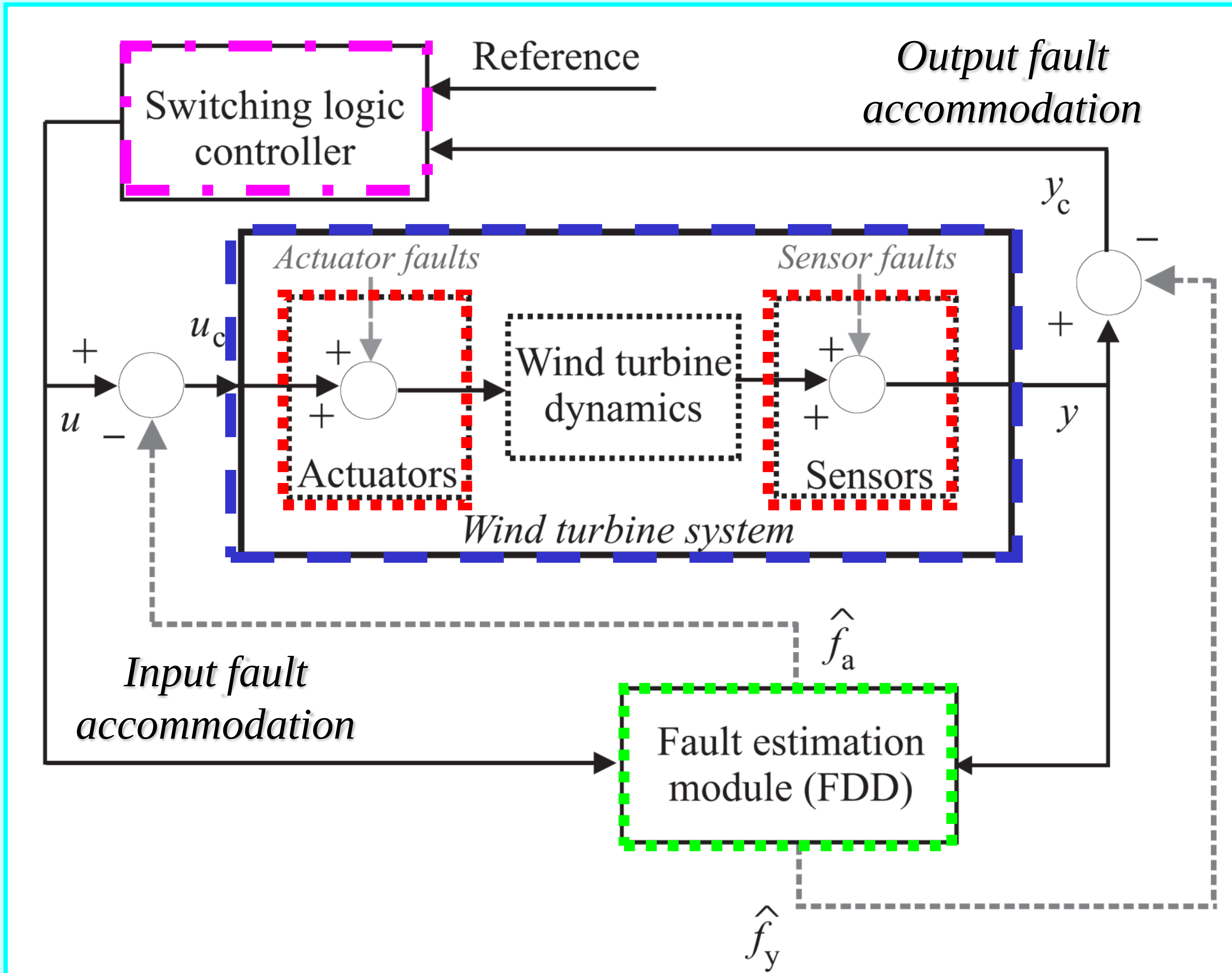
FTC Solutions: *Passive*



FTC Solutions: *Active*



FTC Solutions: *Active* Approach



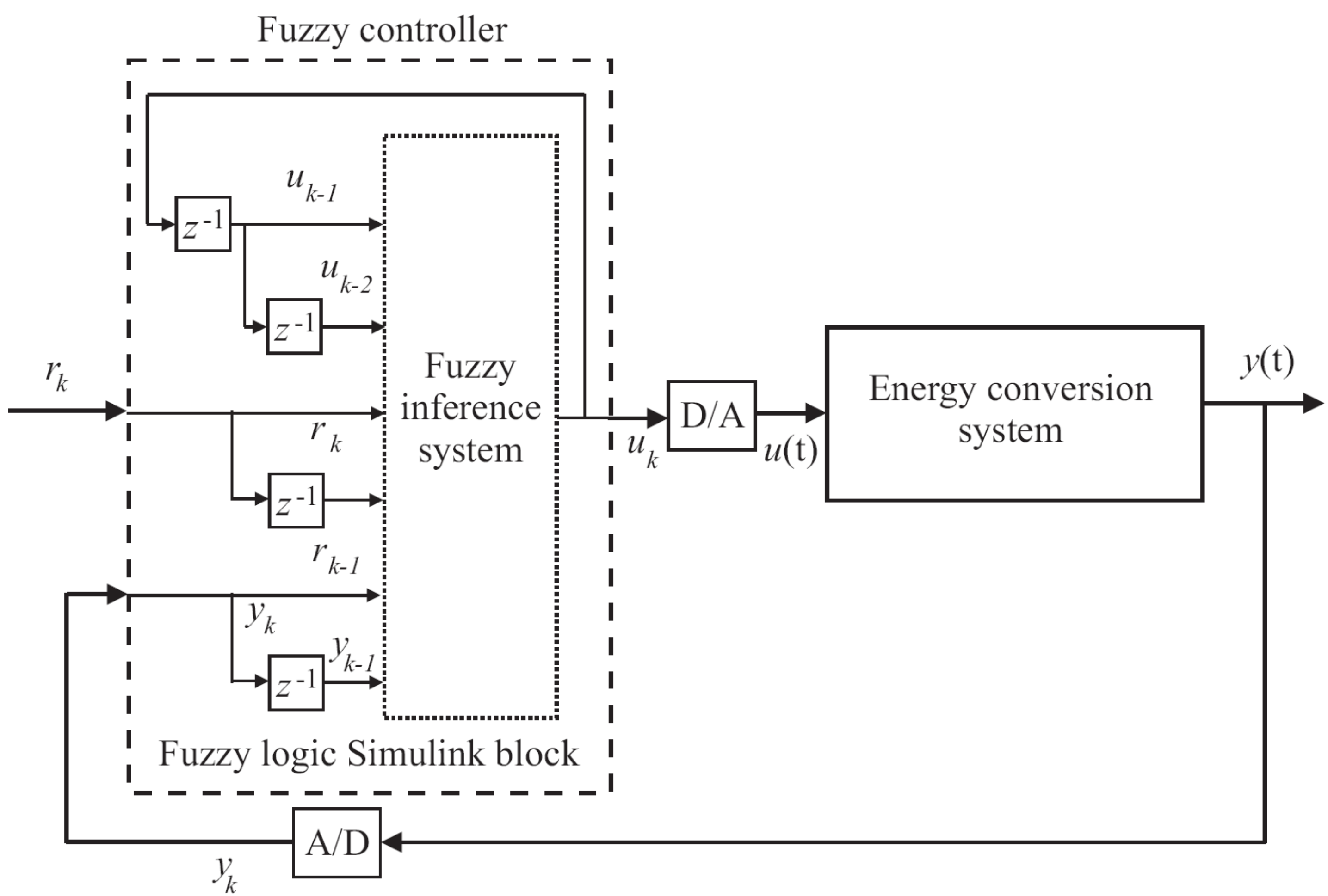
***Active* FTC Tools**

- ➢ Data-driven or mixed model-based & data-driven

- ✓ Kalman filter + disturbance distribution identification
- ✓ Adaptive (recursive) model estimation
- ✓ Adaptive filter + nonlinear geometric approach
- ✓ Takagi-Sugeno fuzzy modelling & identification
- ✓ Quasi-static multi-layer perceptron backpropagation neural network

- ❖ Fault reconstruction
- ❖ Robust solutions

FTC Solutions: *Passive*



Passive FTC Tools

- Data-driven & model-based mixed methods

- ✓ Controller parameter recursive identification (PID)
- ✓ Takagi-Sugeno fuzzy modelling & identification
- ✓ Quasi-static multi-layer perceptron backpropagation neural network

- ❖ FDI is by-product
- ❖ Robustness w.r.t. disturbance & faults

FDI & FTC Competitions

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

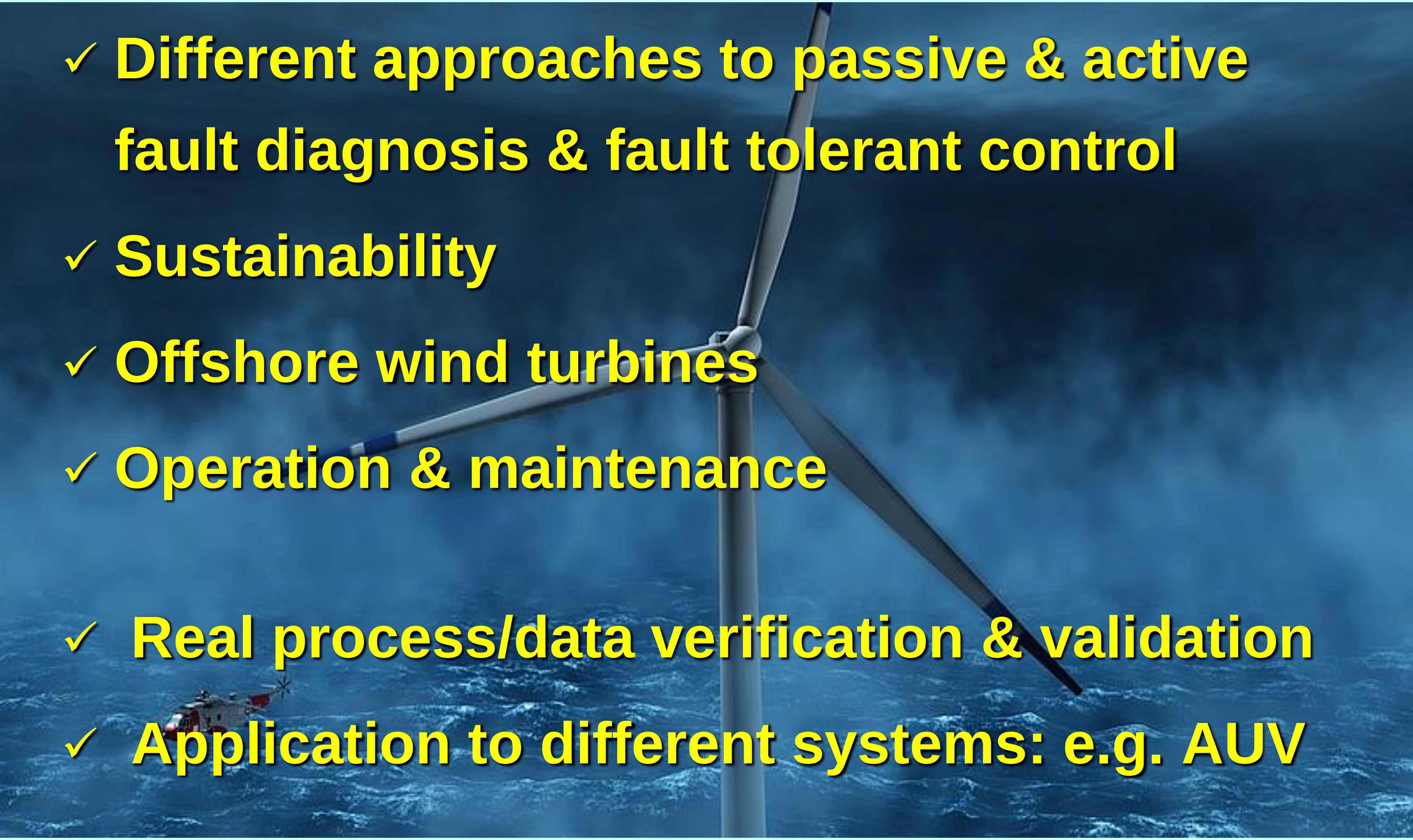
- ✓ Part I.I on FDI: solutions were presented in two invited sessions at IFAC World Congress, Milan, Italy, 2011
- ✓ Part I.II on FTC: solutions were presented in two and a half invited sessions at IFAC SafeProcess, Mexico City, Mexico, 2012
- ➢ Three prizes for each part was sponsored by kk-electronic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



- ✓ Different approaches to passive & active fault diagnosis & fault tolerant control
- ✓ Sustainability
- ✓ Offshore wind turbines
- ✓ Operation & maintenance
- ✓ Real process/data verification & validation
- ✓ Application to different systems: e.g. AUV

Challenges

- **Original benchmark models combined with NREL's FAST** to provide a FDI & FTC test case with more detailed aerodynamic & structural model

Research Issues

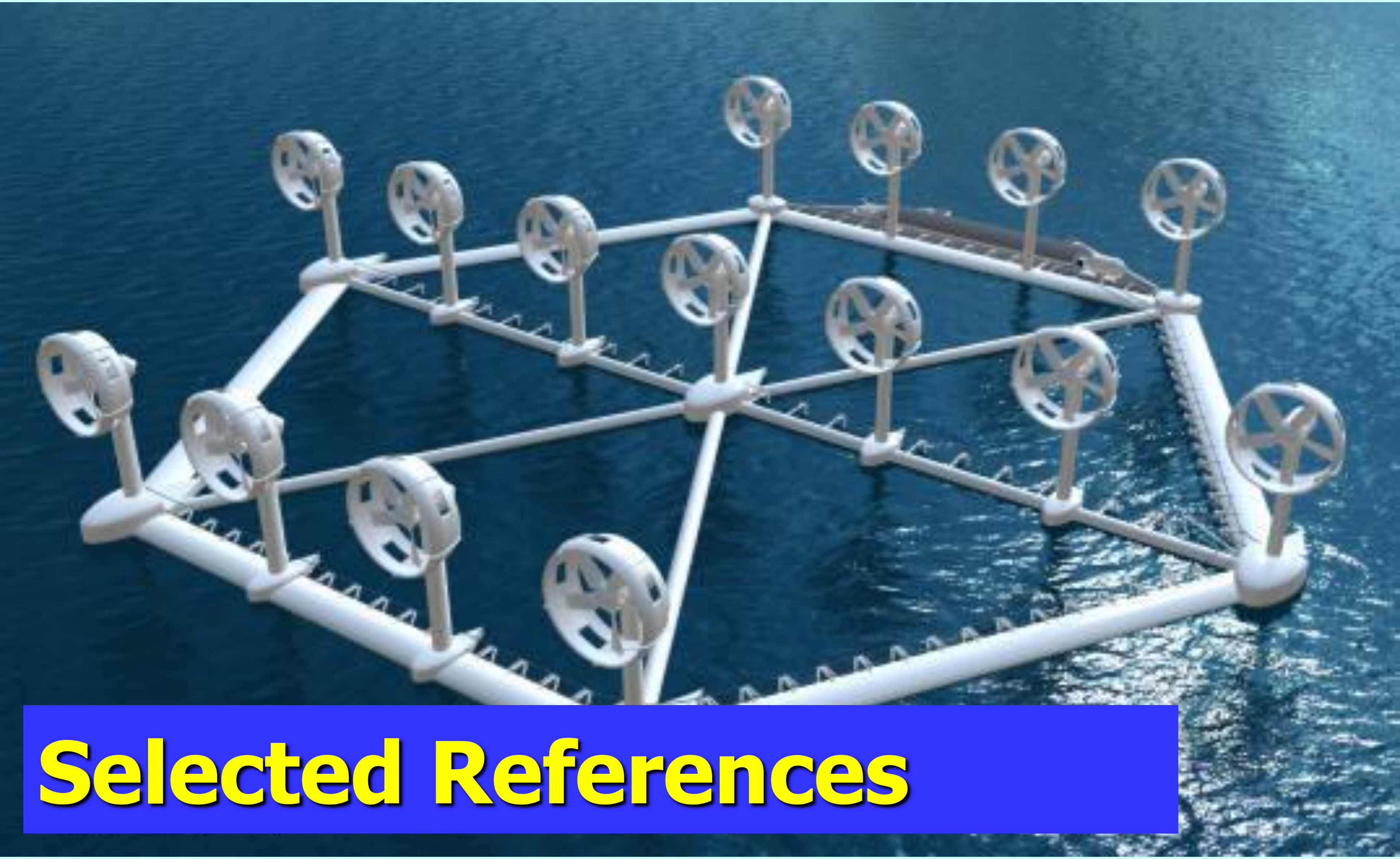
Forthcoming Events

SAFEPROCESS 2022

11th IFAC Symposium on Fault Detection, Supervision and Safety for Technical Processes

Pafos, Cyprus

7-10 June 2022



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- **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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Thanks for your attention