Fault Diagnosis & Sustainable Control of Wind Turbines:

Robust Data-Driven & Model-Based Strategies

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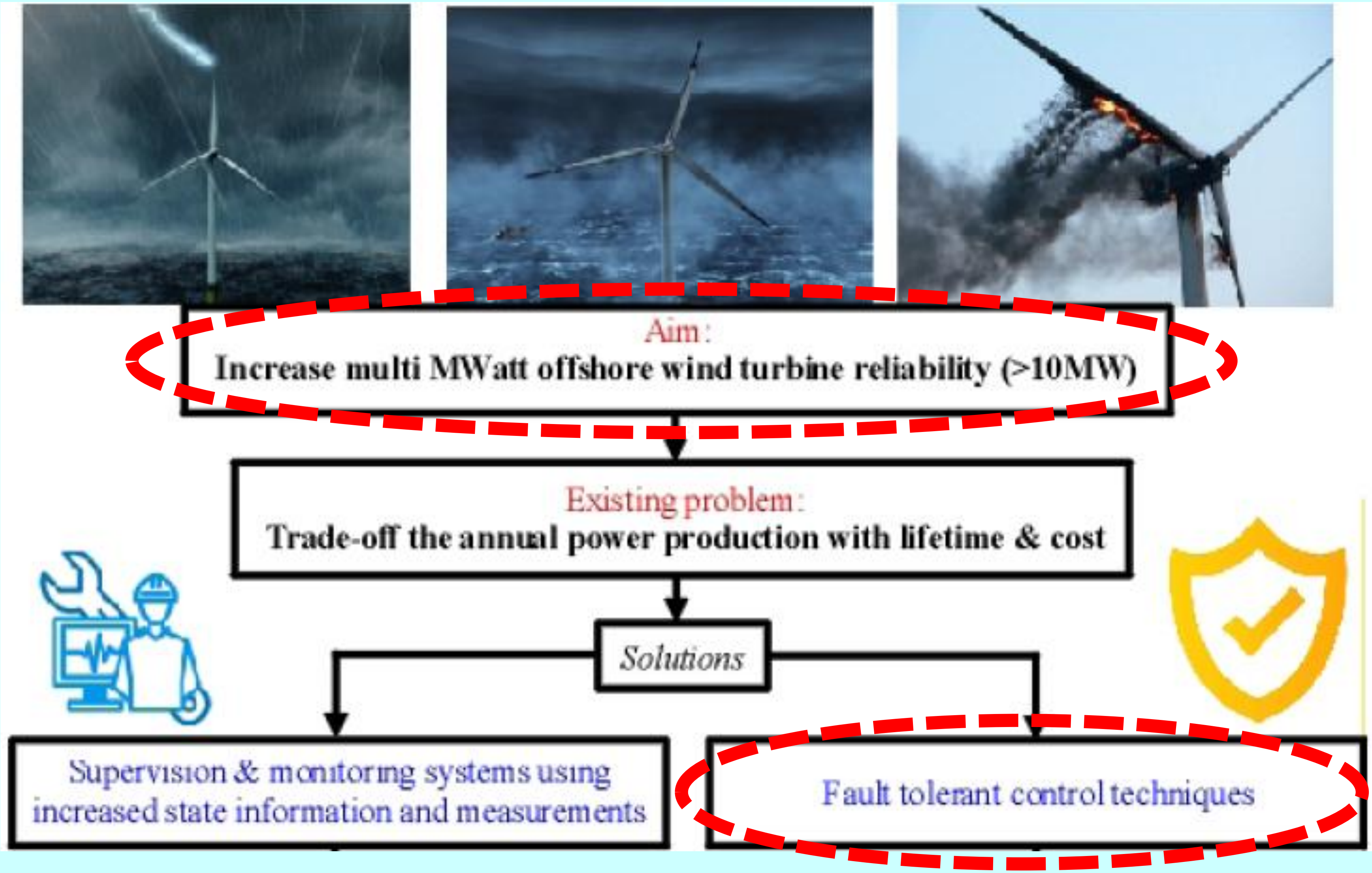
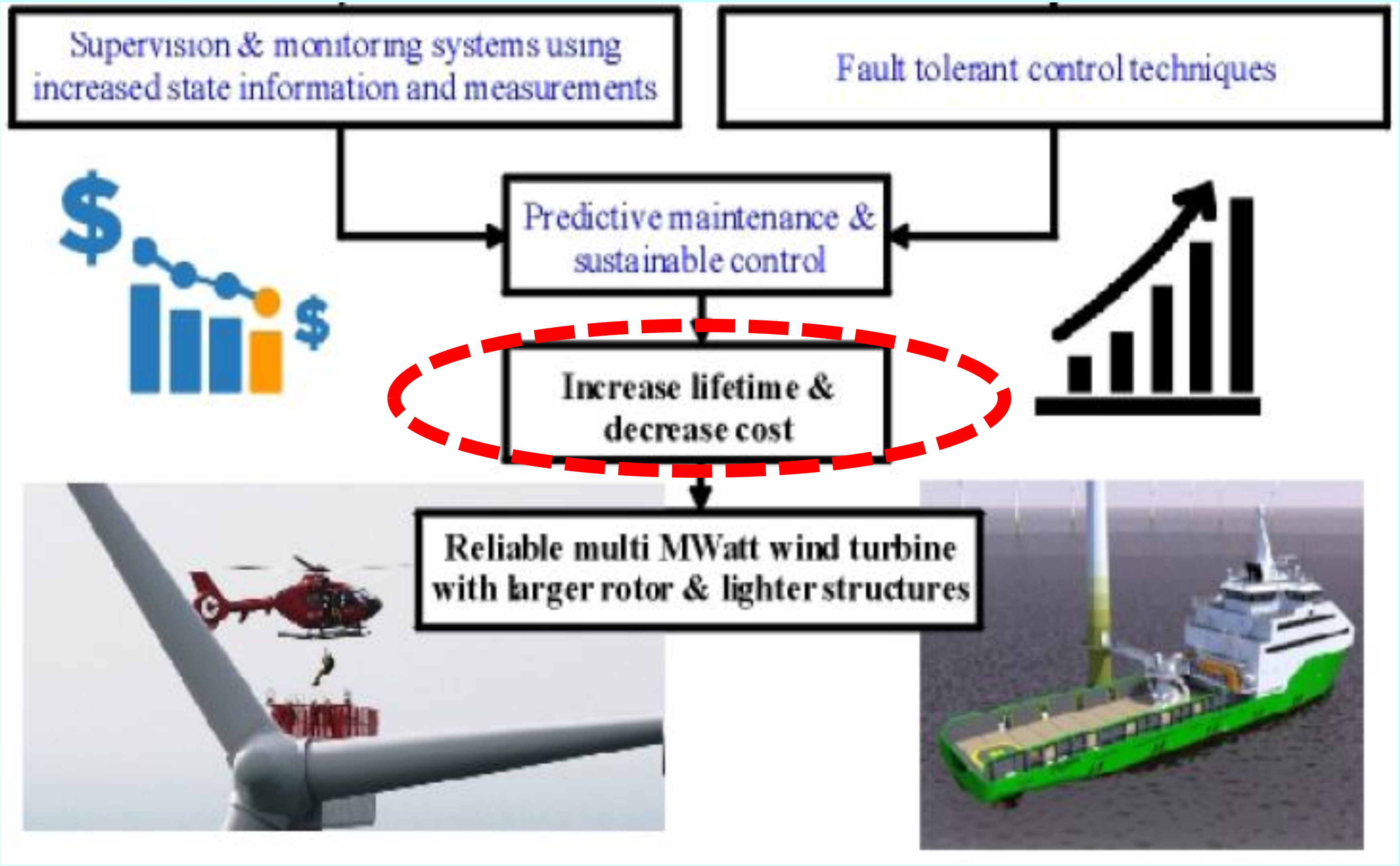
Discussion Topics

- **Motivations**
  - Enhancing reliability & efficiency of offshore wind turbines
- FDI/FTC general structures
- Fault models
- Wind turbine modelling issues
- Benchmarks
- Concluding remarks, references, open issues

Sustainable Control: Problem



Sustainable Control: Solutions



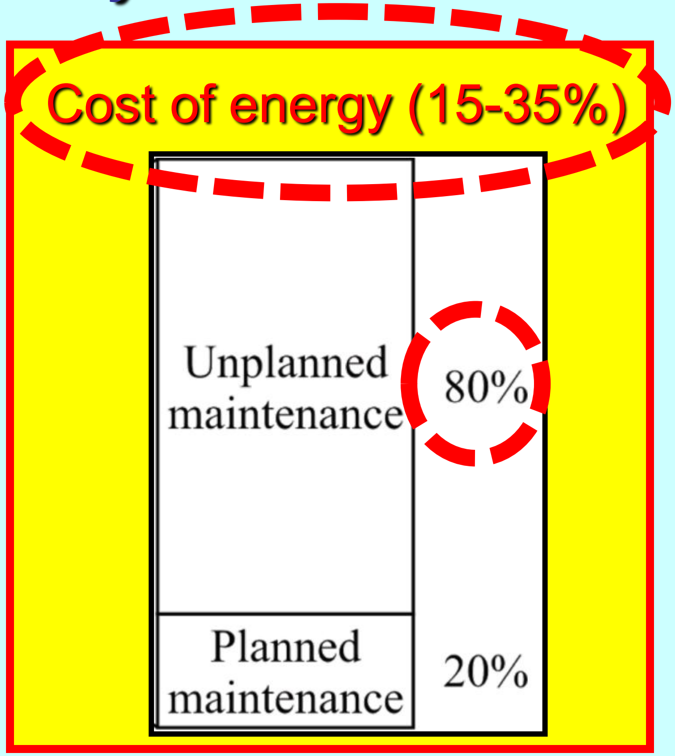
- ✓ **Model-based & data-driven FDI** & **FTC** are proposed as new approaches for ‘**sustainable’** (high degree of reliability & availability) wind turbine control
- ✓ Manage **disturbances** (loads, storms, …) **& faults**
- ✓ ***NOTE****: FTC was developed as aerospace topic, focused mainly on NASA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

Motivations

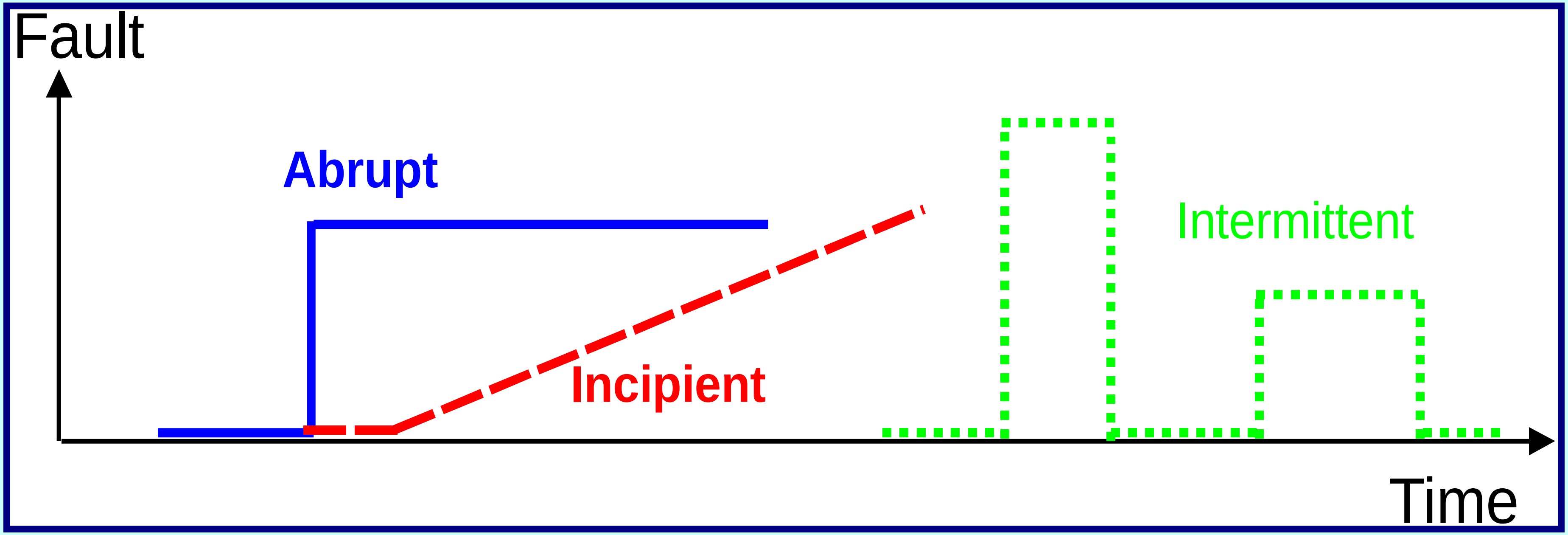
Example…

✓ A 5 MW wind turbine stopped will ***lose 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*



FDI/FTC Fundamentals



- **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 ('health aware control')***
- ✓ **Ensure redundant system capabilities to allow production until service & maintenance (O&M) are possible -> *sustainability***

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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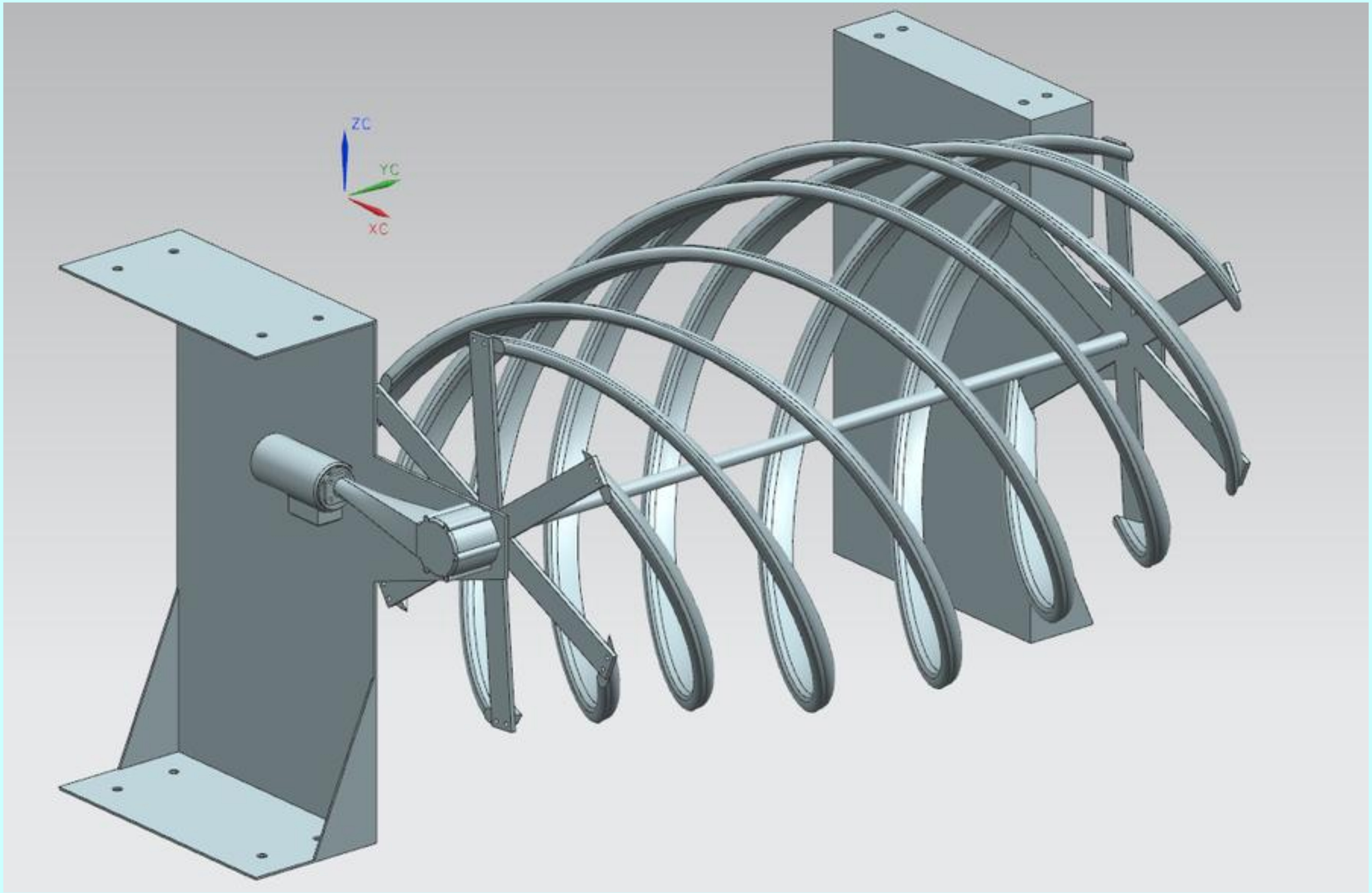
Wind Turbine Benchmarks

- ✓ Provide generic platforms (freely available) for designing & testing different FDI/FTC solutions
- ✓ **Apply & compare their methods on wind turbine realistic installations**
- ✓ If the model is generic, it can be provided to the public (*e.g.* researchers)
- ✓ Solutions can finally be 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

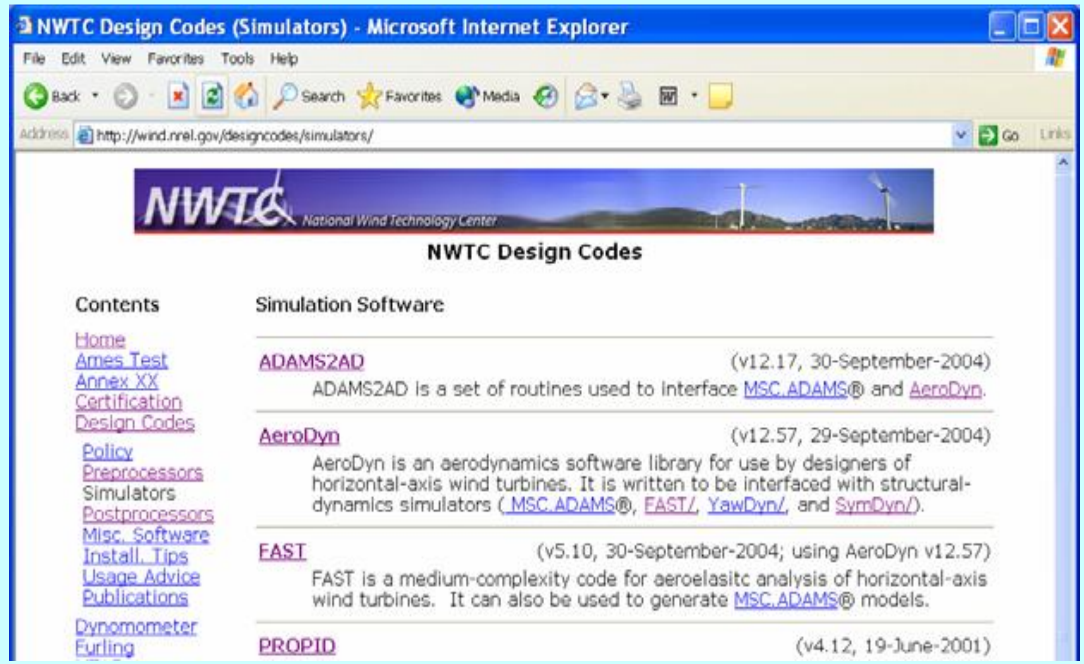
Modelling Topics



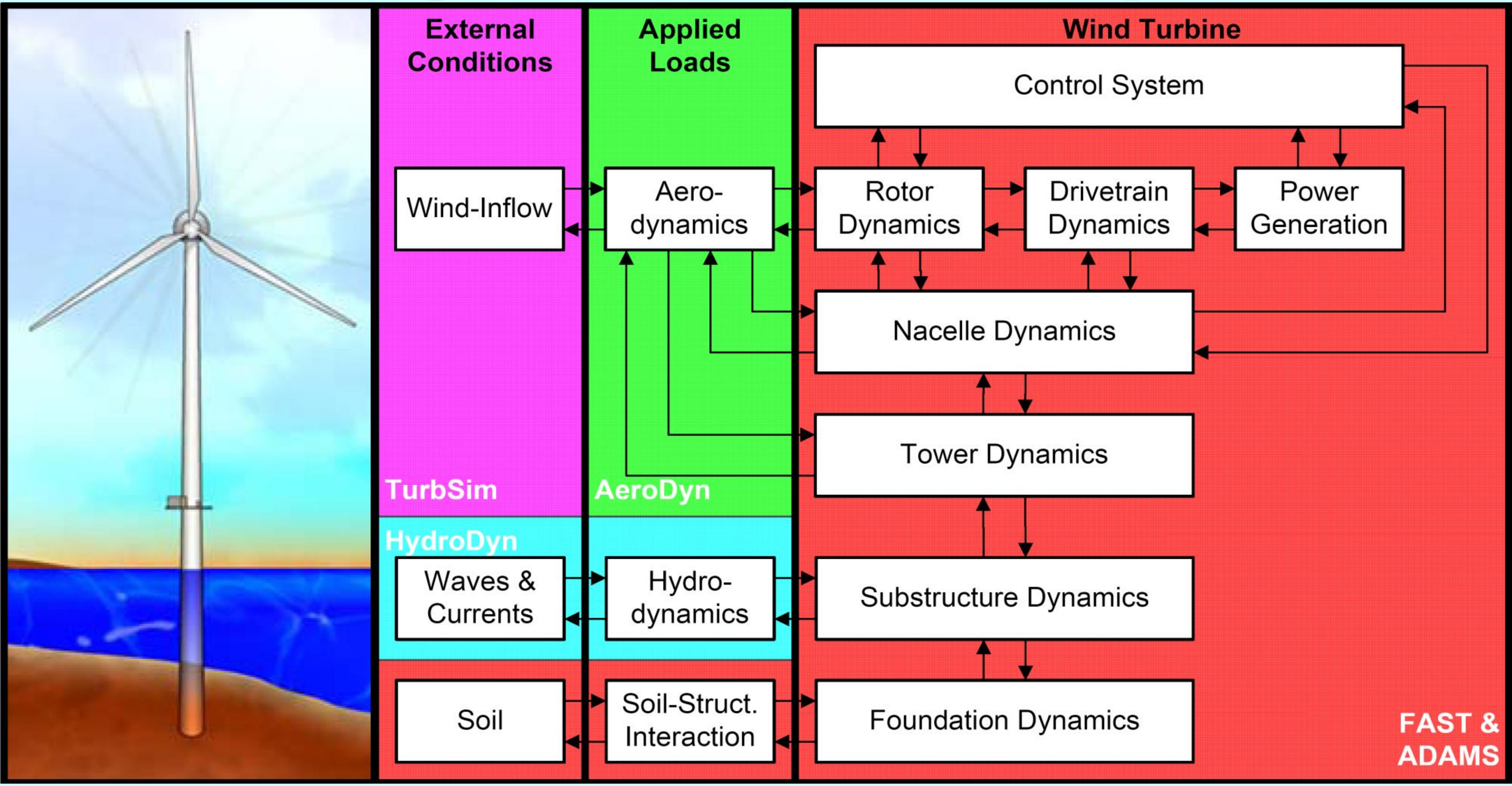
NREL Design Codes

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

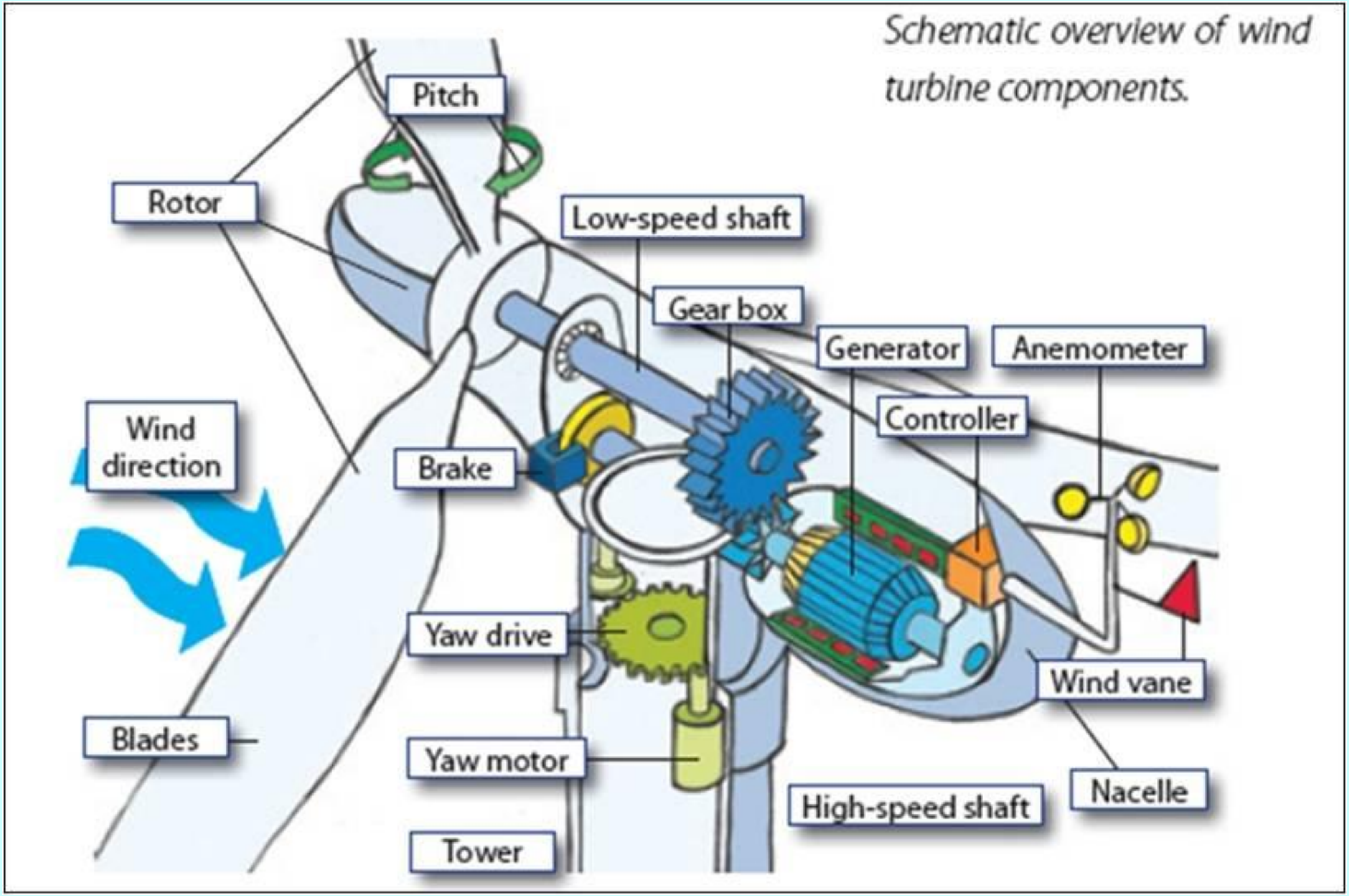


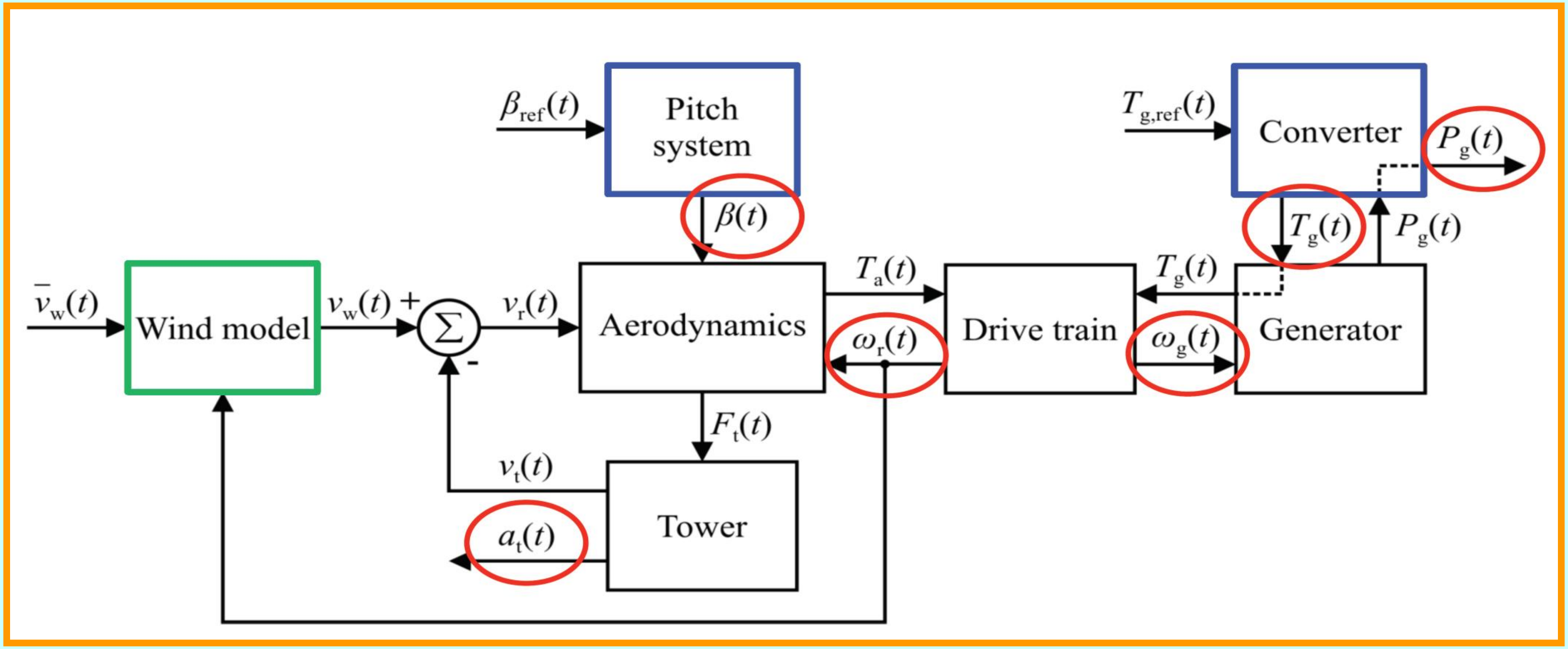
Design Codes Examples



Coupled Aero-Hydro-Servo-Elastic Simulation

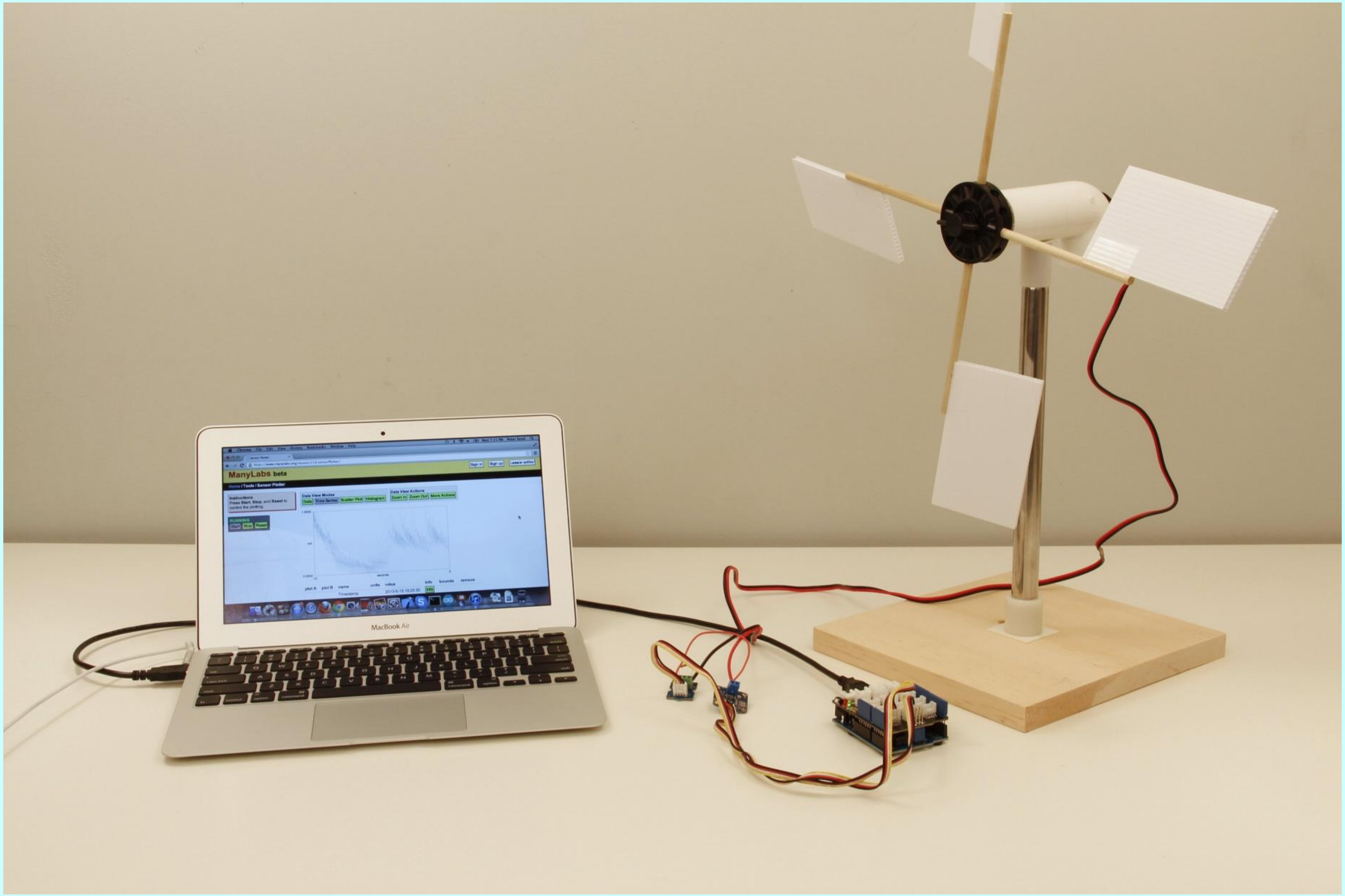
Wind Turbine Components





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

Measurement Sensors

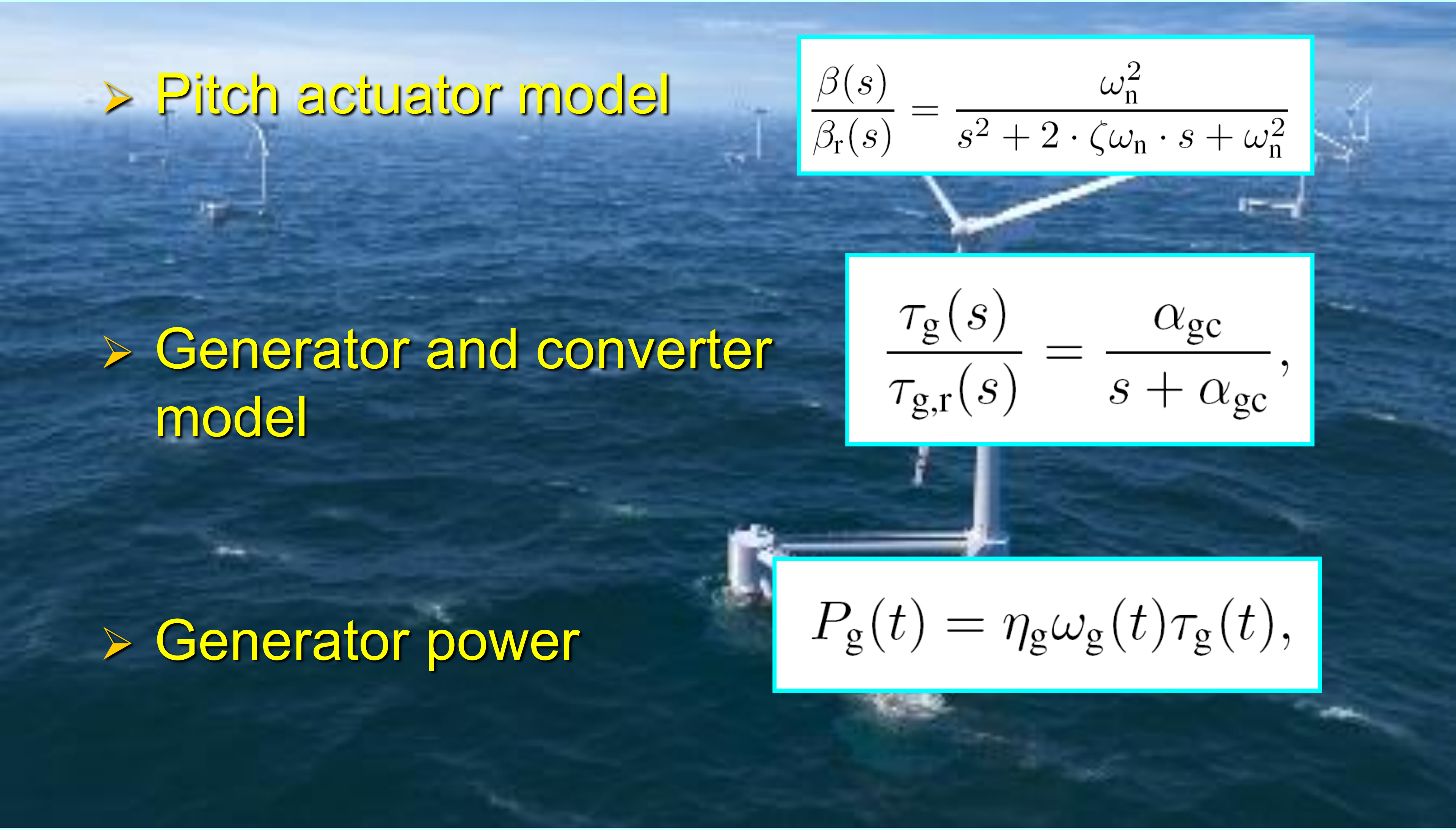


Measurements

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

Wind Turbine Actuators

Simple Models



- Pitch actuator model

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

- Generator and converter model

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

- Generator power

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

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

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

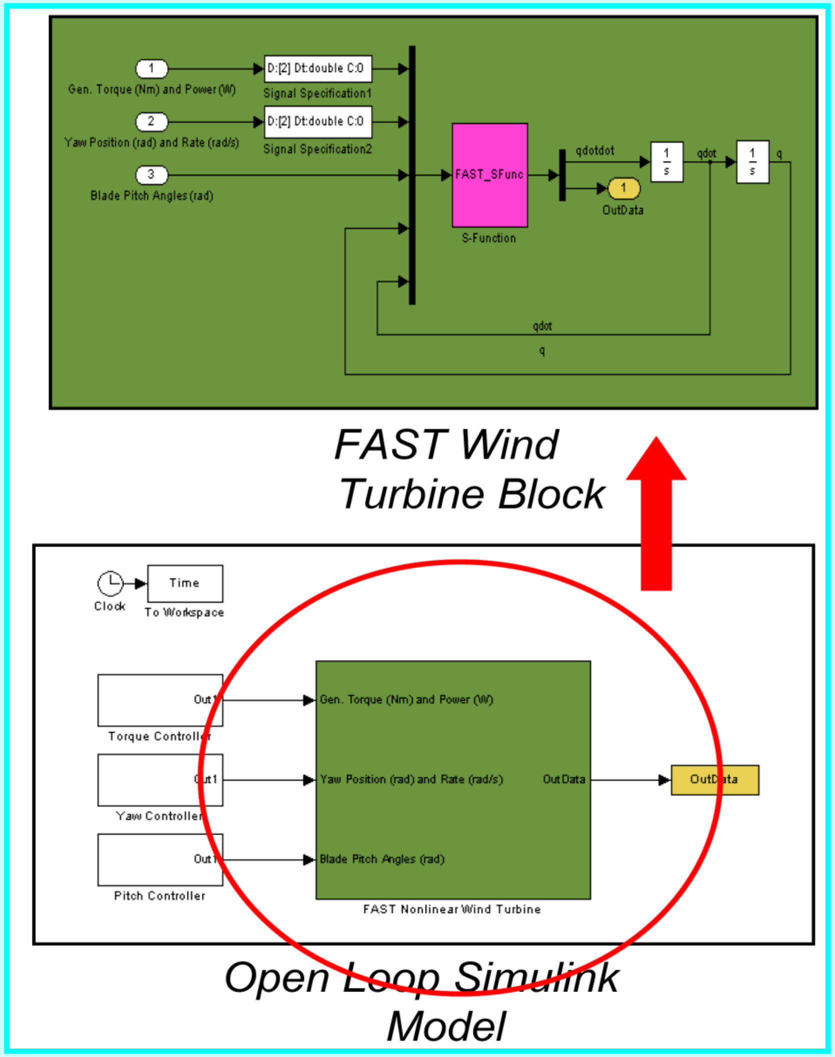
$$\frac{\tau_g(s)}{\tau_{g\,r}(s)} = \frac{\alpha_{gc}}{s + \alpha_{gc}}$$

Generator & converter models

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

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

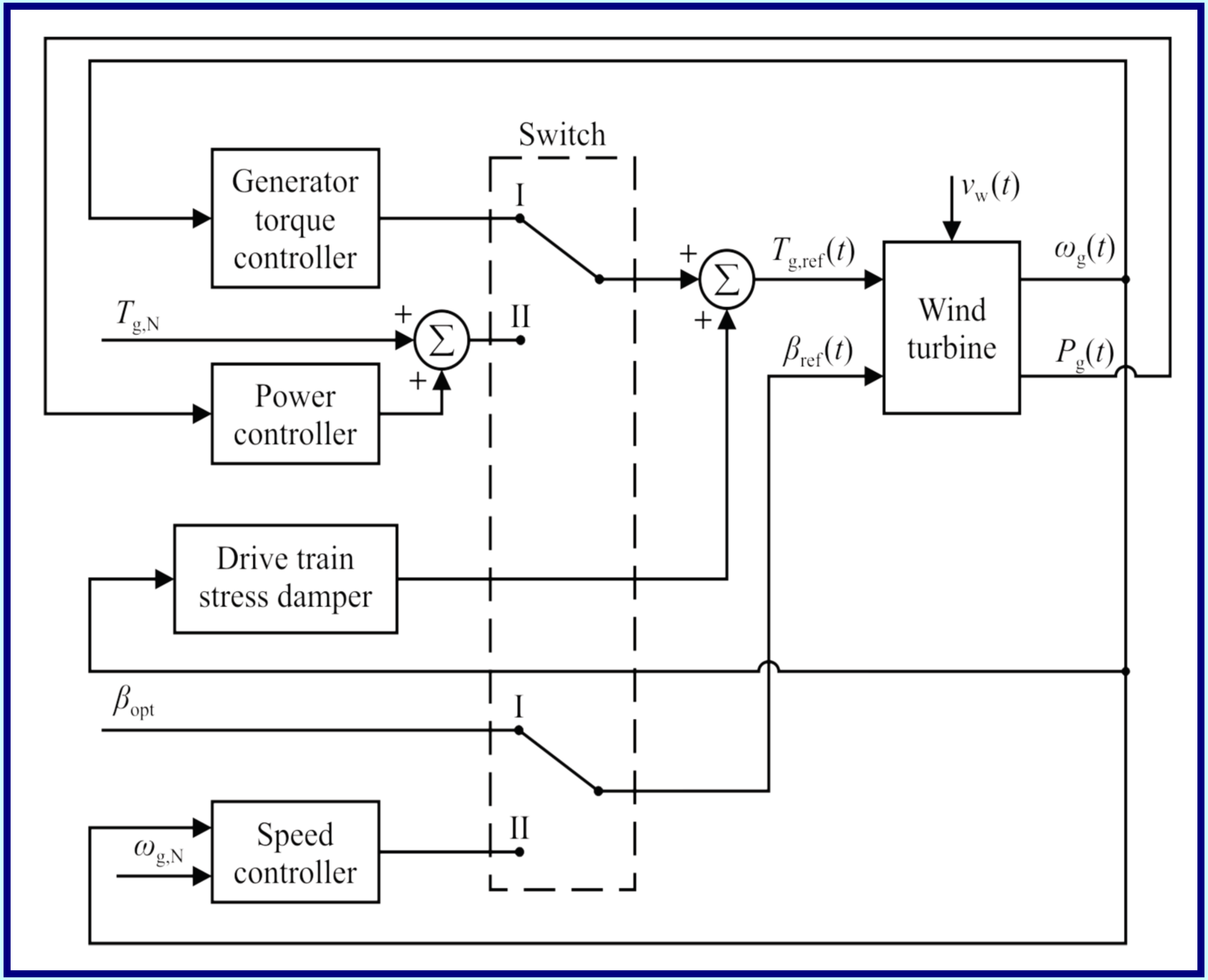


FAST Wind Turbine Block

Open Loop Simulink Model

Reference Controller

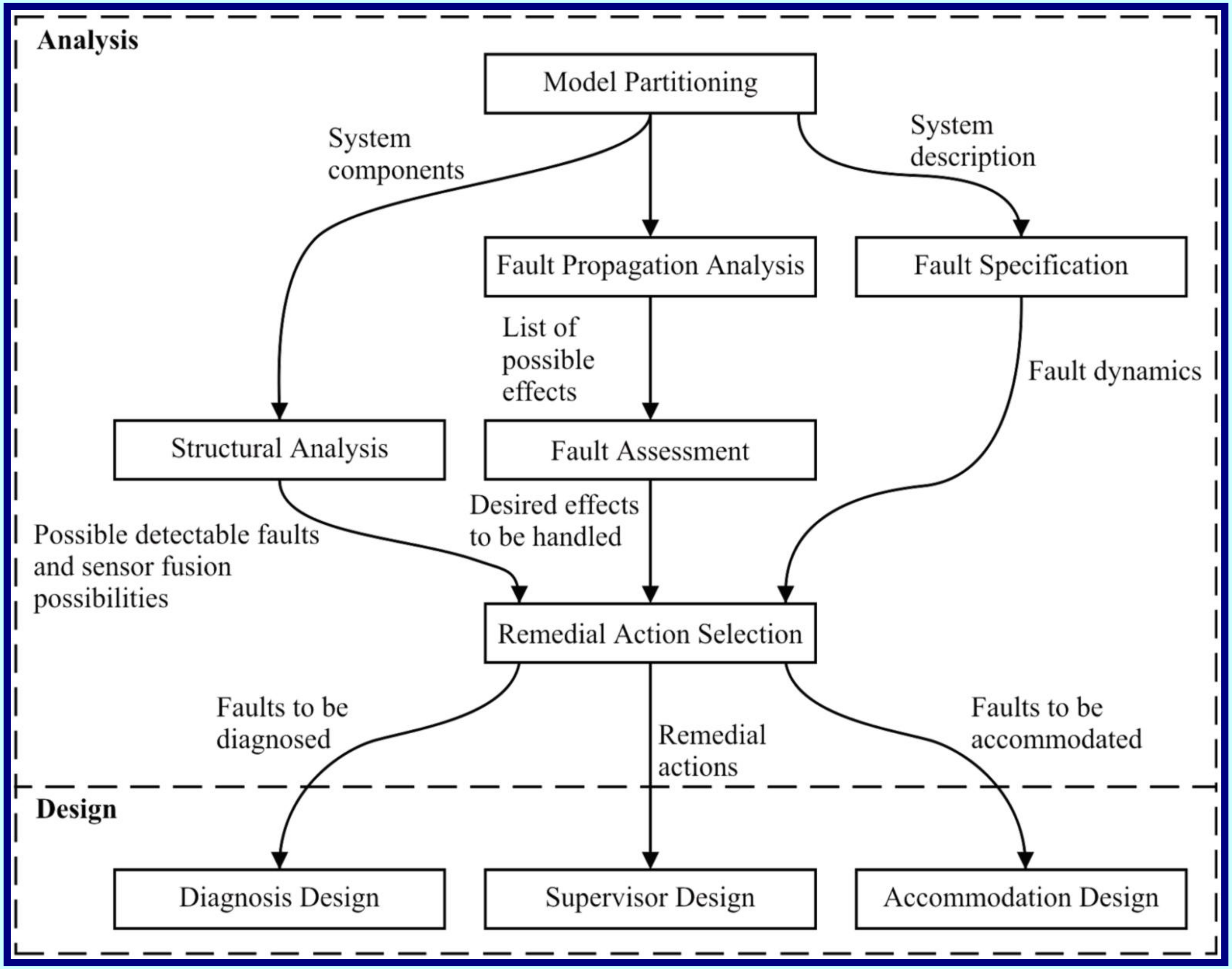
Reference Controller



- ✓ 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
Possible detectable faults and sensor fusion possibilities
Desired effects to be handled
Remedial Action Selection
Faults to be diagnosed
Remedial actions
Faults to be accommodated
Design
Diagnosis Design
Supervisor Design
Accommodation Design

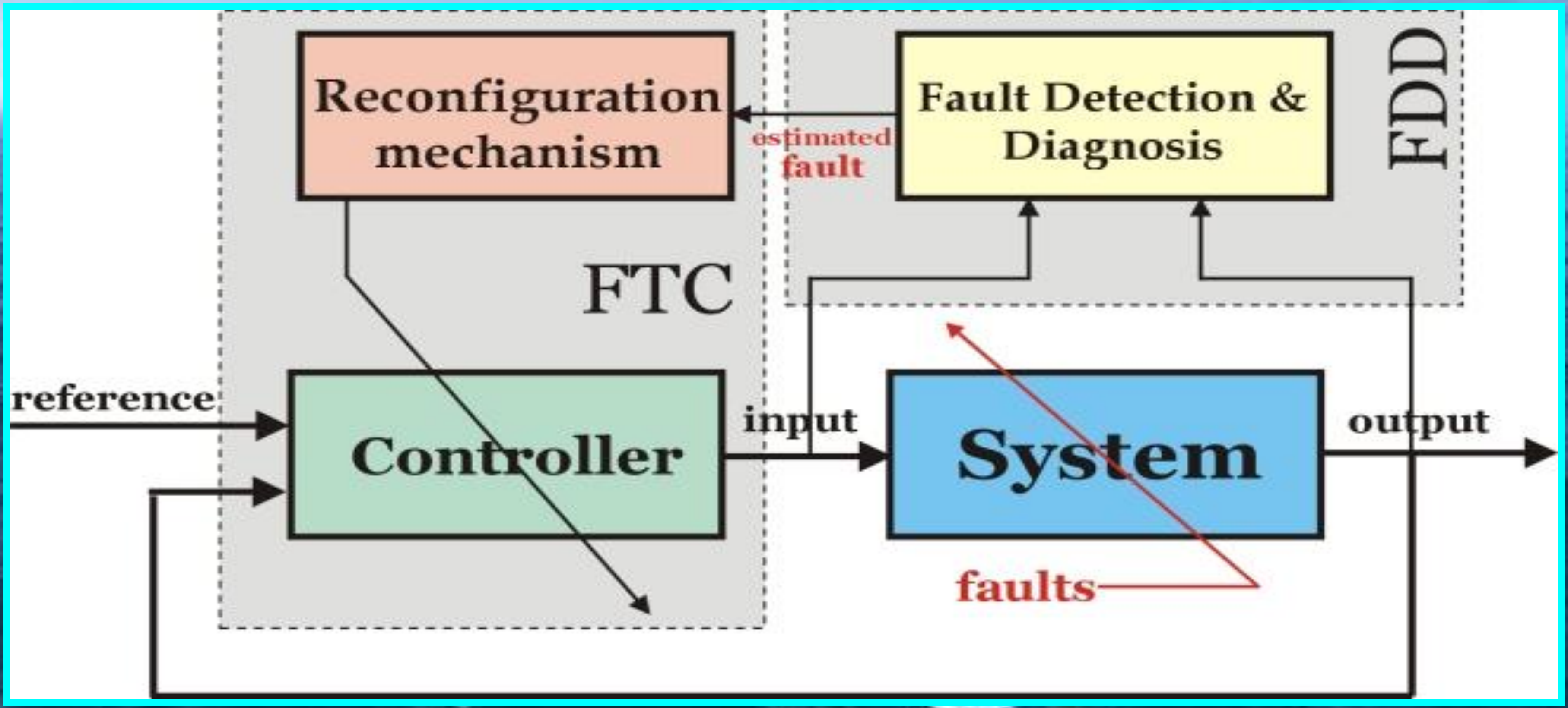
Fault Scenario

Component	Fault	Impact
Pitch sensor	Biased output	Reduced control precision
Pitch actuator	Pump wear	Gradual loss control
	High air oil content	
	Hydraulic leakage	
	Valve blockage	
	Pump blockage	
Generator speed sensor	Proportional error	Severe control degradation
	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

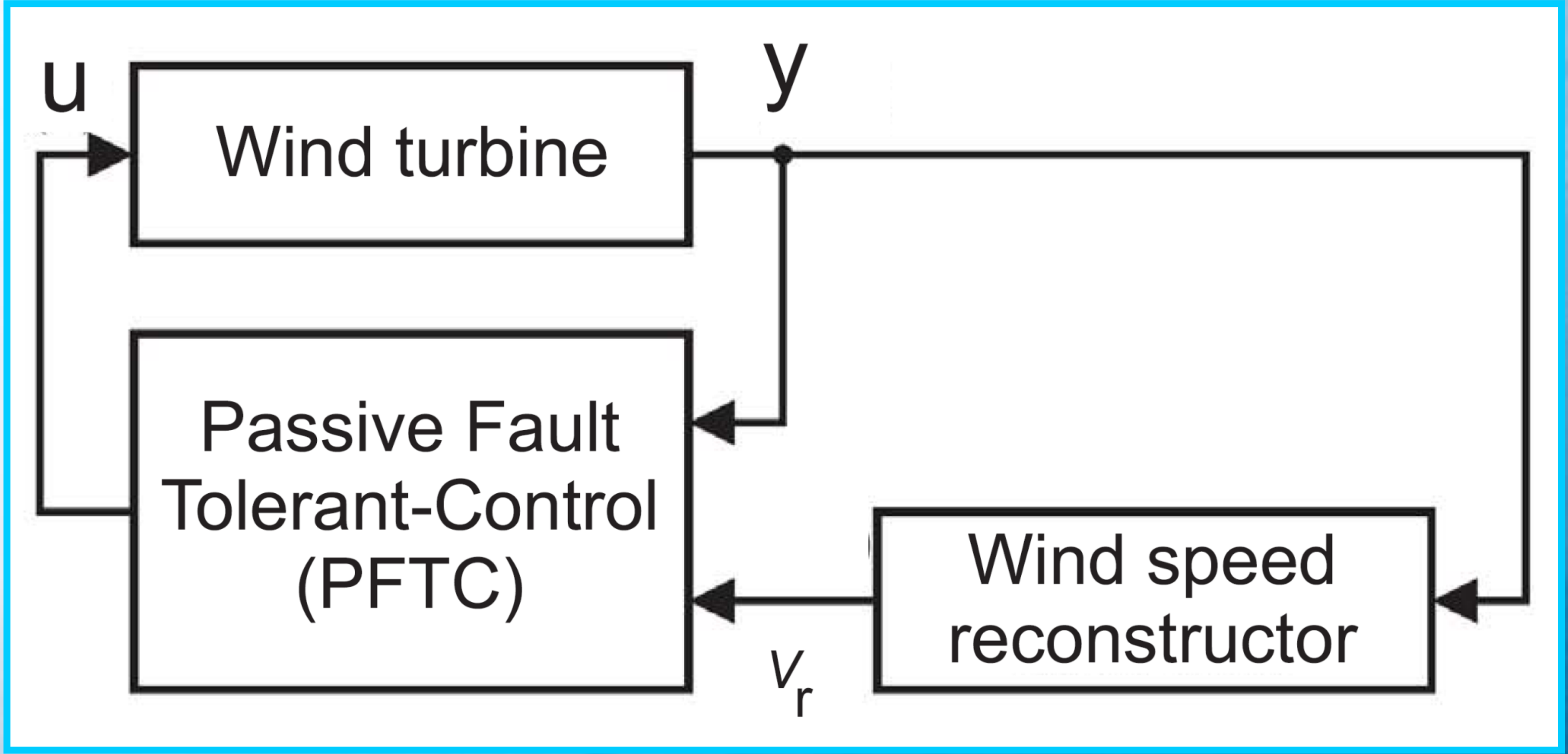


- ✓ **PFTC**: Robust fixed structure controller
- ✓ **AFTC**: Real-time controller reconfiguration

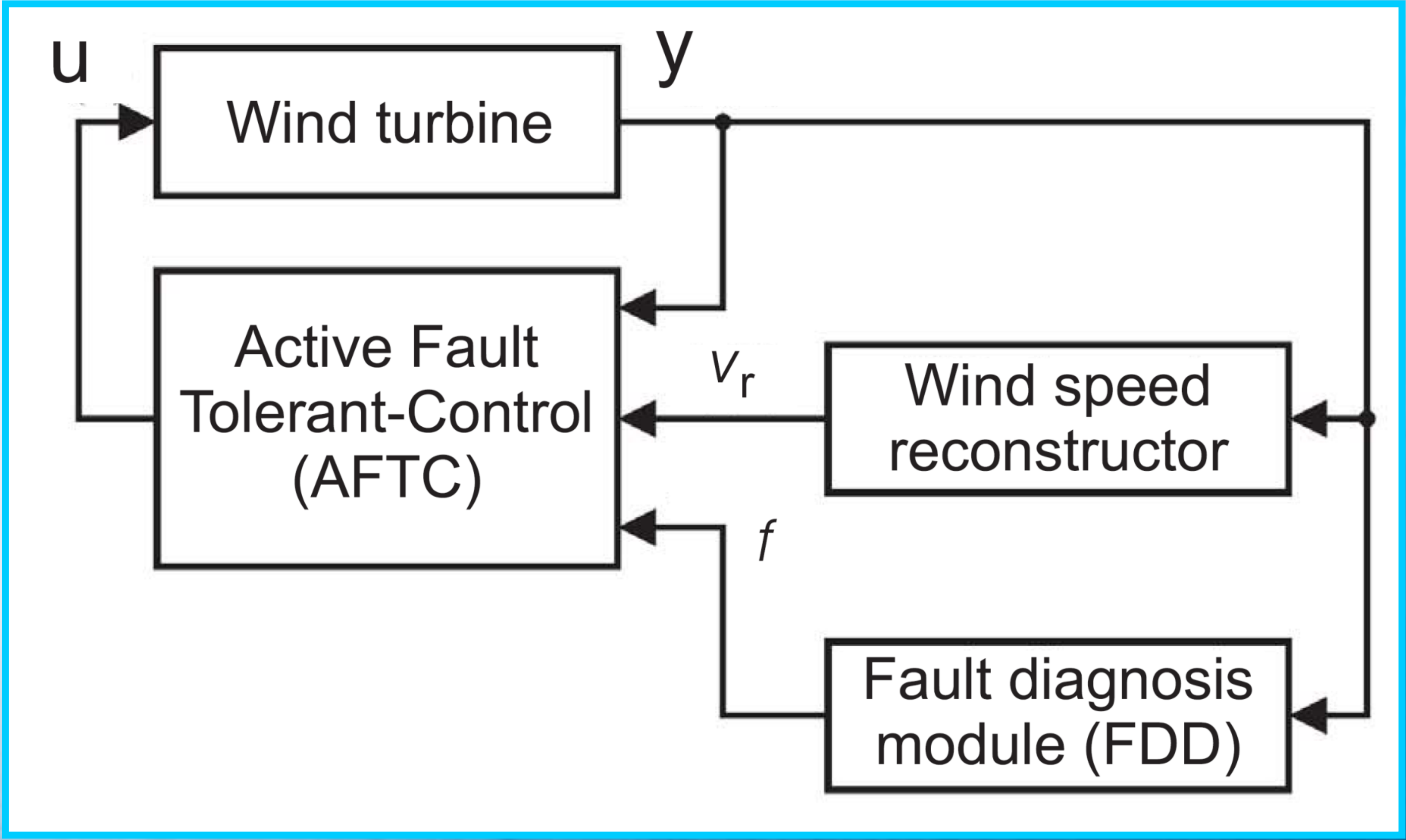
Fault Accommodation

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)

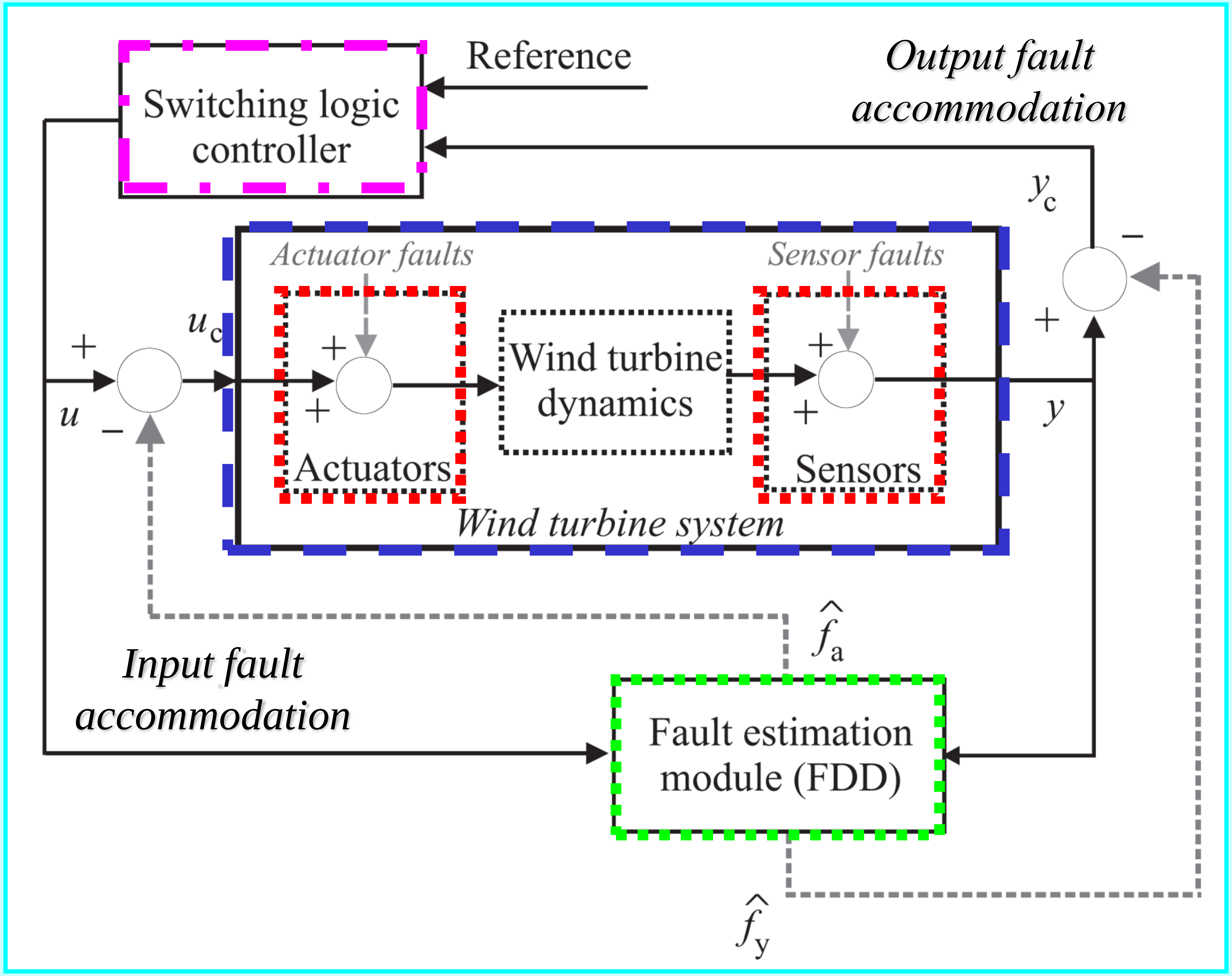
FTC Solutions: *Passive*



FTC Solutions: *Active*



FTC Solutions: *Active* Approach



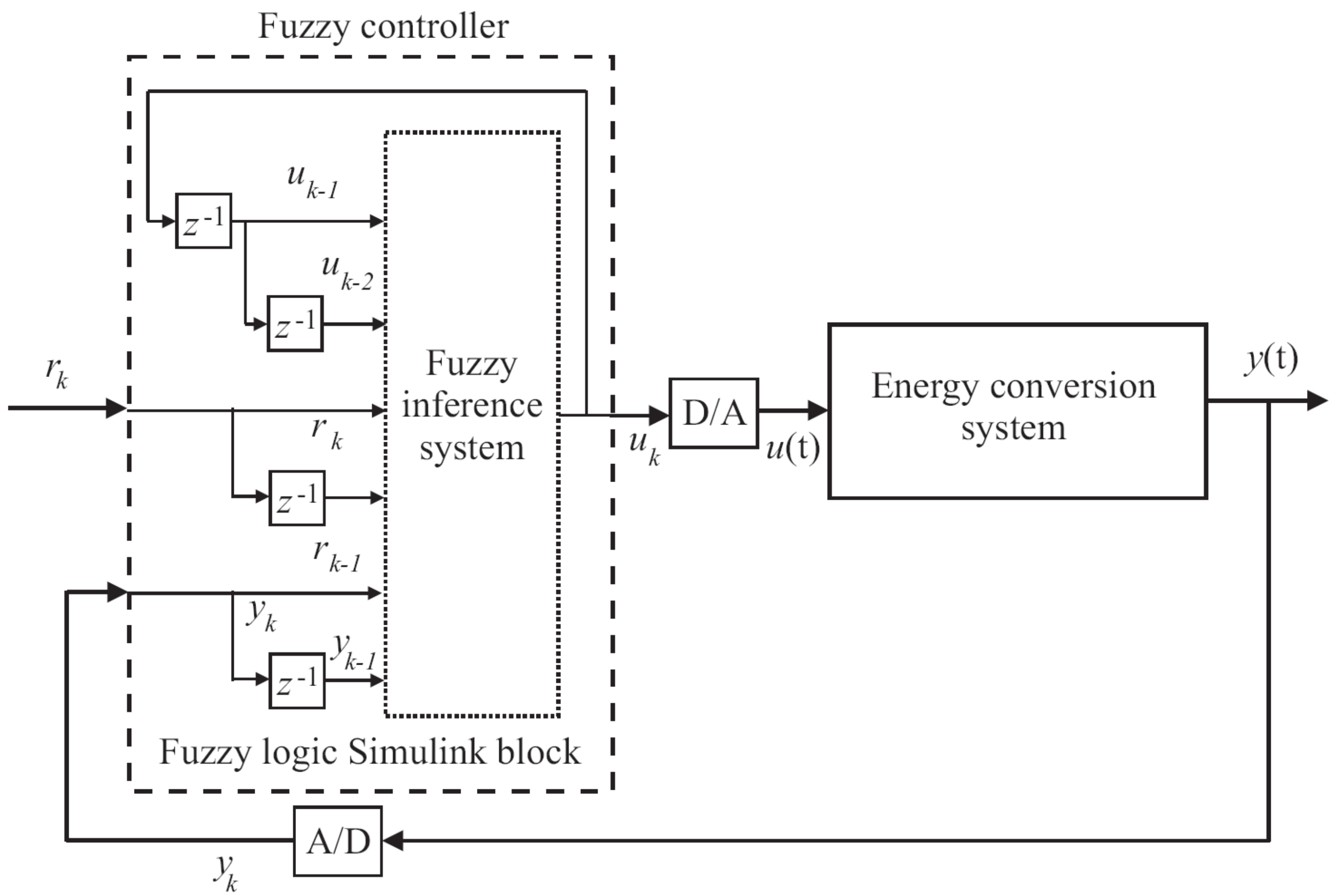
Active FTC Tools

- **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

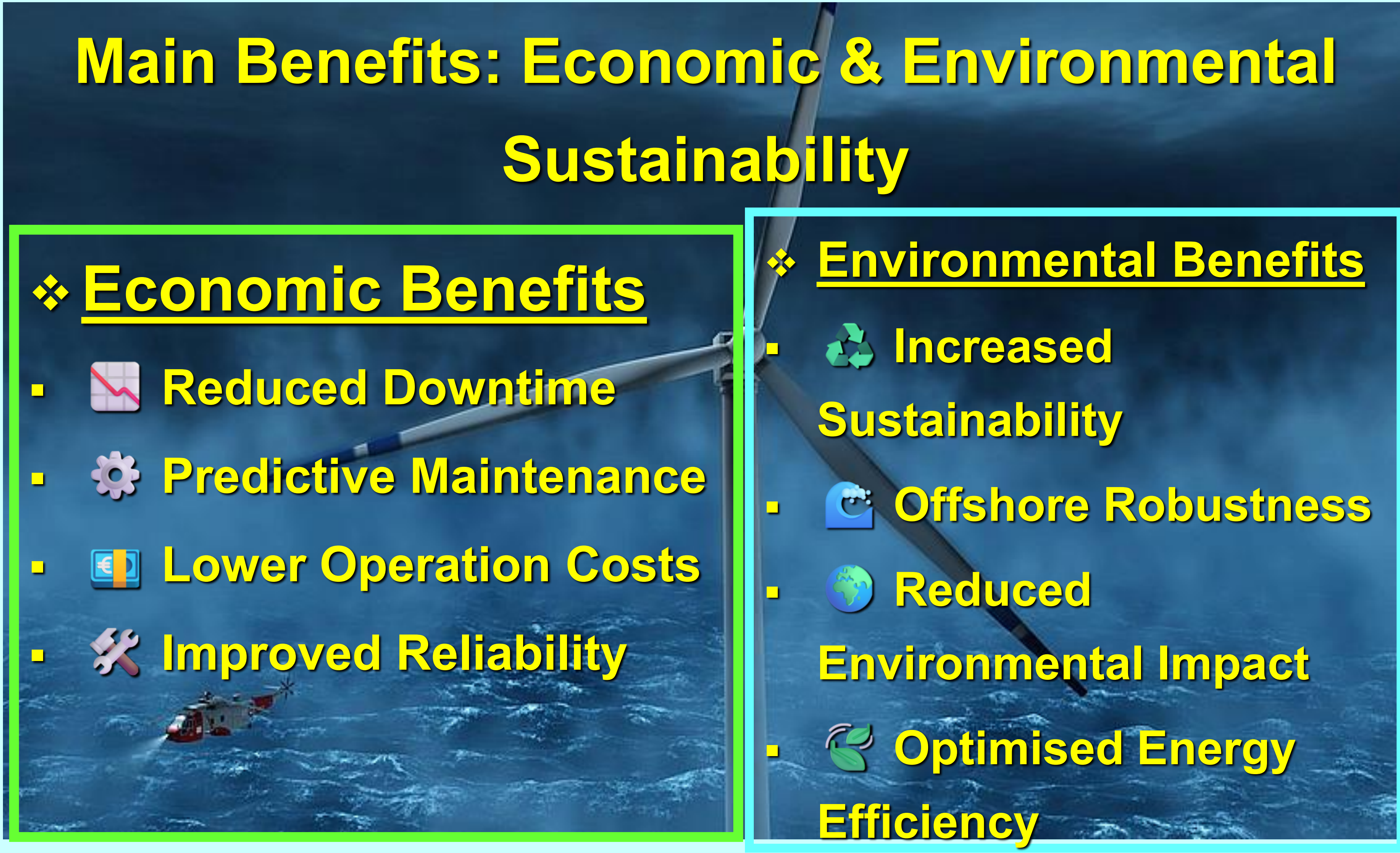
- ✓ Part I.I on FDI: solutions were presented in two invited sessions at IFAC World Congress, Milan, Italy, 2011
- ✓ Part I.II on FTC: solutions were presented in two and a half invited sessions at IFAC SafeProcess, Mexico City, Mexico, 2012
- ➢ Three prizes for each part was sponsored by kk-electronic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



Main Benefits: Economic & Environmental Sustainability

❖ **Economic Benefits**

- Reduced Downtime
- Predictive Maintenance
- Lower Operation Costs
- Improved Reliability

❖ **Environmental Benefits**

- Increased Sustainability
- Offshore Robustness
- Reduced Environmental Impact
- Optimised Energy Efficiency

Challenges

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

Research Issues

Benchmark Overview (2025)

- Floating Offshore Wind Farm Fault Detection and Isolation (FDI) Benchmark
- **Objective**: Enhance reliability and efficiency of offshore wind energy systems through advanced Fault Detection and Isolation (FDI) and Fault-Tolerant Control (FTC) techniques
- **Layout**
  - Simulator: FOWLTY toolbox (Simulink-based, user-friendly, accessible to non-experts)
  - Floating Offshore Wind Farm: 7 turbines (5 MW each, NREL design) on DeepCWind floating platforms

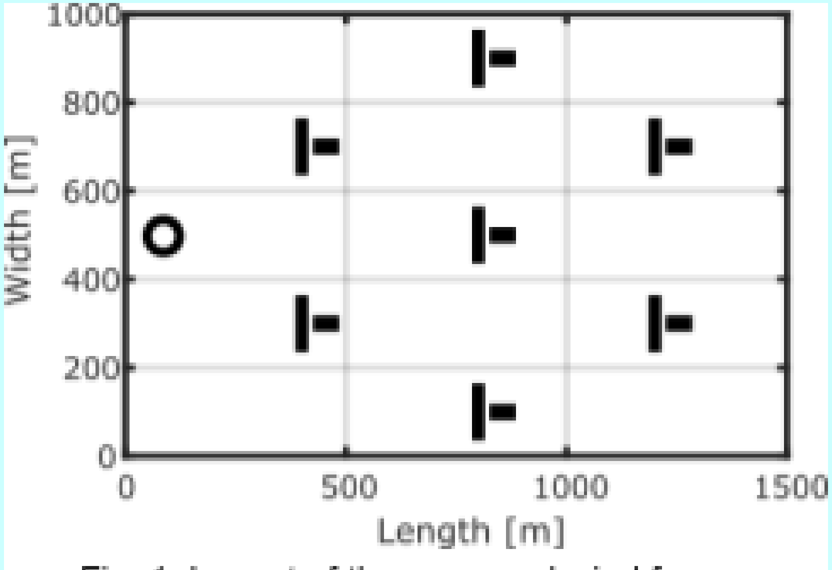


Fig. 1: Layout of the proposed wind farm.

Benchmark Overview (cont'd)

Key features

- Diverse Wind Conditions: 10 distinct wind scenarios (mean wind speeds: 7 to 23 m/s)
- Fault Severity Variation: Faults with varying magnitudes and durations (10–50 s)
- Customisable Training Data: Ability to generate additional scenarios for model training and validation
- Already applied in IFAC 2023: improvements in fault detection accuracy (+20%) and reduced false alarms (-15%)
- DOI: `10.1016/j.ifacol.2023.10.1506`

Fault Scenarios

- **Sensor Faults**
  - Pitch sensors: stuck, scaling (up to 20%), drifting (max. 1 deg/s)
  - Generator sensors: power scaling (up to 10%), speed scaling (up to 5%)
- **Actuator Faults**
  - Pitch actuators: stuck, offset (max. 3 deg), dynamics change
  - Generator actuator: torque offset (max. 1 kNm)

Evaluation Criteria

- **Fault Detection Performance**
  - False Alarm Rate (FAR)
  - Missed Detection Rate (MDR)
  - Detection Time
- **Fault Isolation Accuracy**
  - Correct Isolation Rate
  - Ranking accuracy of identified faults
- **Computational Efficiency**
  - Normalised computation time

Open Issues and Challenges (1)

1. **Platform Motion Compensation** *(critical for safety and structural integrity)*
   – Effective mitigation of dynamic responses to waves and wind-induced motions
   – Robustness against coupled dynamics (aerodynamic, hydrodynamic, structural)
2. **Advanced Control Strategies** *(key for adapting to unpredictable conditions offshore)*
   – Nonlinear and adaptive control methods for floating structures
   – Robustness and resilience to environmental uncertainties
3. **Fault Detection and Isolation (FDI)**
   – Accurate real-time detection and isolation of faults under varying operational conditions
   – Reliable sensor and actuator fault handling strategies
4. **Load and Fatigue Management**
   – Reducing structural fatigue through intelligent control actions
   – Optimal balancing of power production against structural stress minimisation

Open Issues and Challenges (2)

5. **Wake and Farm-level Control**
   - Management of turbine-to-turbine wake interactions within floating farms
   - Optimal collective control strategies to maximise energy yield and minimise wear
6. **Sensor Reliability and Redundancy**
   - Enhanced sensor fault-tolerance and redundancy mechanisms
   - Data-driven sensor fusion approaches for improved reliability
7. **Model Accuracy and Validation**
   - High-fidelity, yet computationally efficient, dynamic modelling
   - Improved model validation techniques based on real-world data
8. **Digital Twin and Predictive Maintenance**
   - Development of digital twins for real-time monitoring and control optimisation
   - Data-driven predictive maintenance scheduling to enhance reliability

Topics for Further Study

- **AI and Machine Learning Integration**
  - Employing machine learning algorithms to optimise and adapt controller parameters in real-time
- **Energy Storage and Hybrid Solutions**
  - Control integration of floating wind turbines with storage systems and hybrid renewable sources
- **Scalable Control Architectures**
  - Developing scalable control methods applicable from single units to large floating wind farms
- **Environmental and Economic Optimisation**
  - Multi-objective control strategies balancing environmental impacts and economic benefits

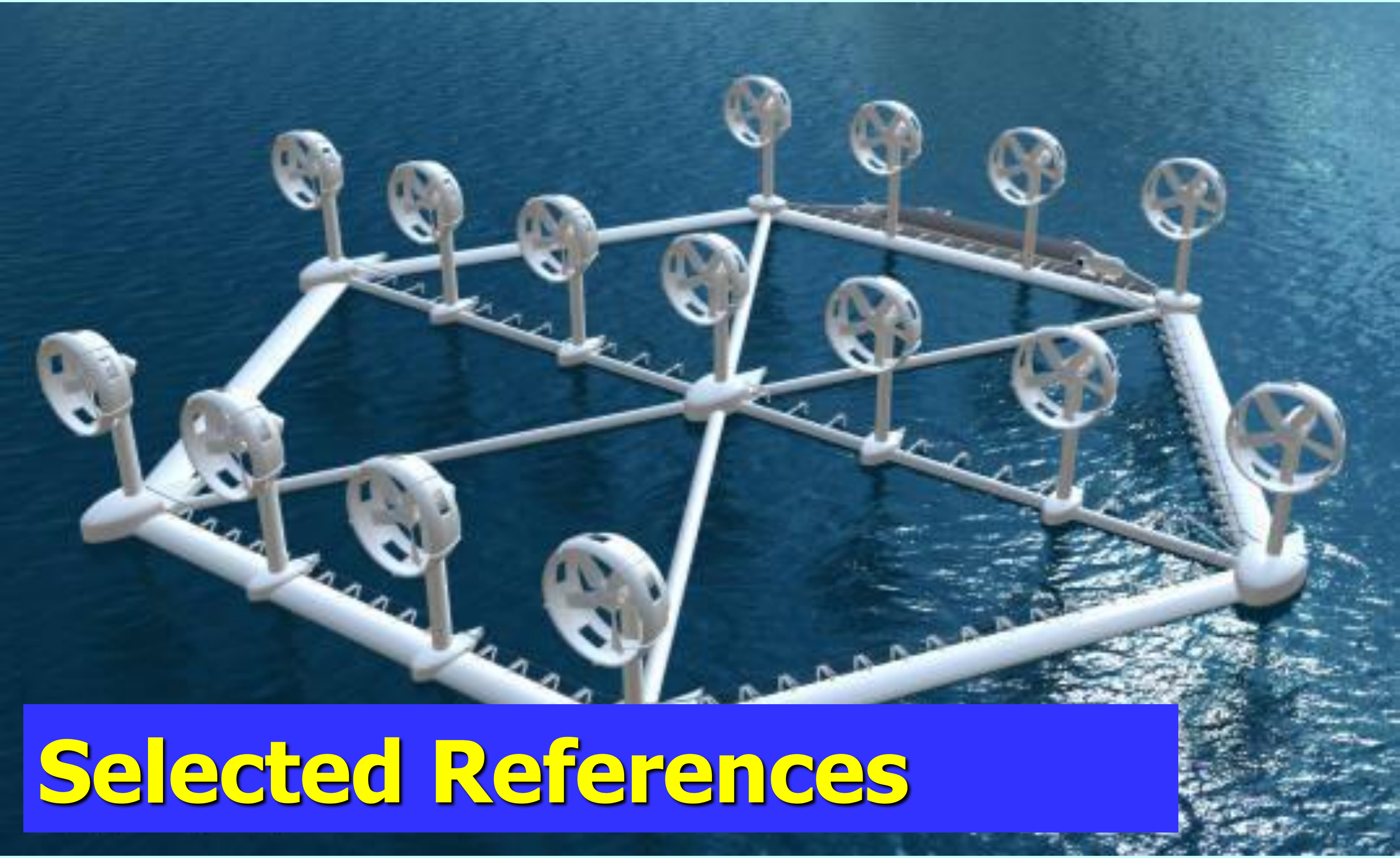
Forthcoming Events

SAFEPROCESS 2027

13th IFAC Symposium on Fault Detection, Supervision and Safety for Technical Processes

Delft, Netherlands

2027



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Thanks for your attention