Sustainable Control of Wind Turbines: Robust Data-Driven and Model Based Strategies

Silvio Simani

Department of Engineering, University of Ferrara

Via Saragat 1E 44122 Ferrara (FE), ITALY

Ph./Fax:+390532974844

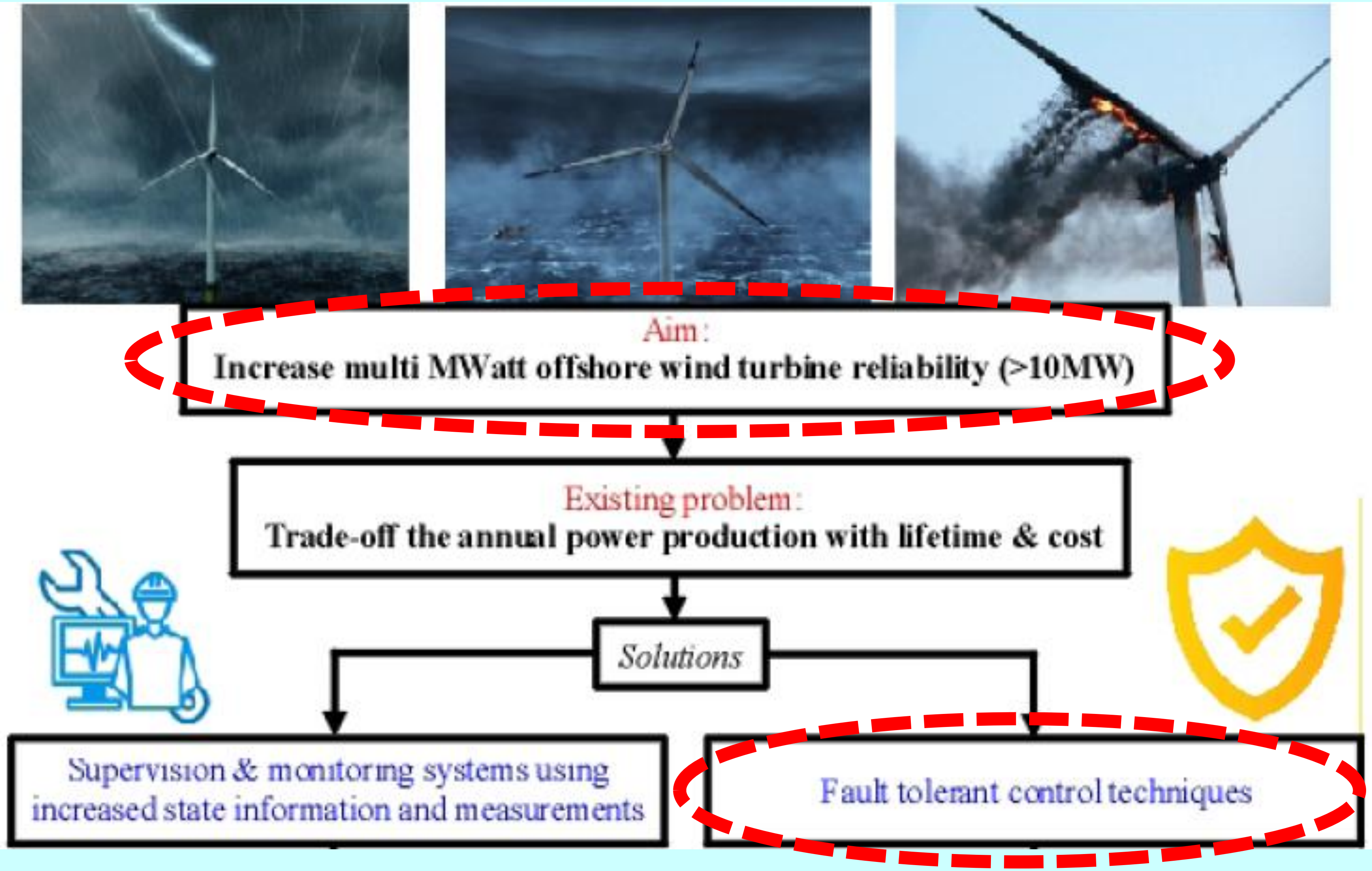
Email: silvio.simani@unife.it. URL: www.silviosimani.it

http://www.silviosimani.it/talks.html

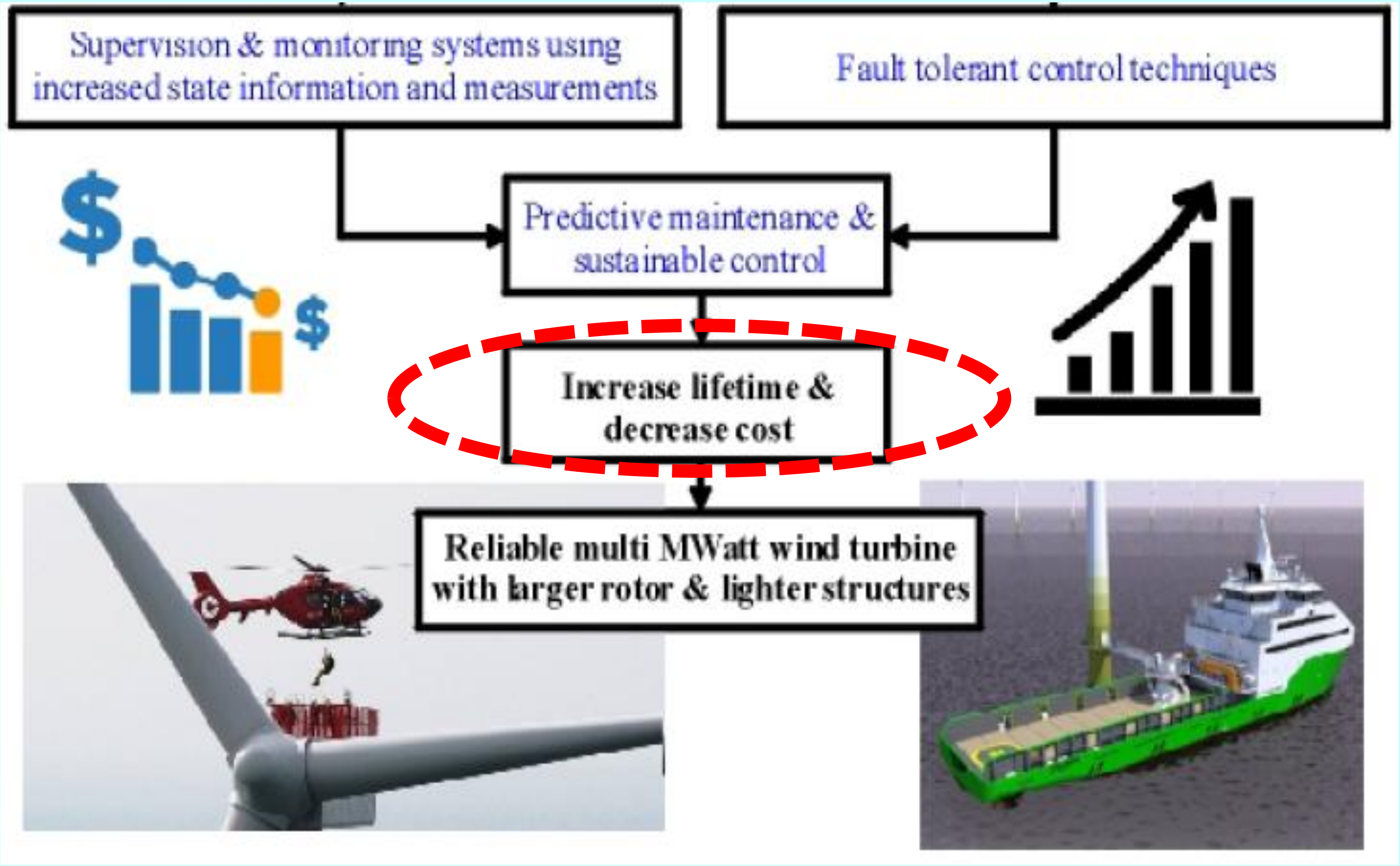
Discussion Topics

- **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

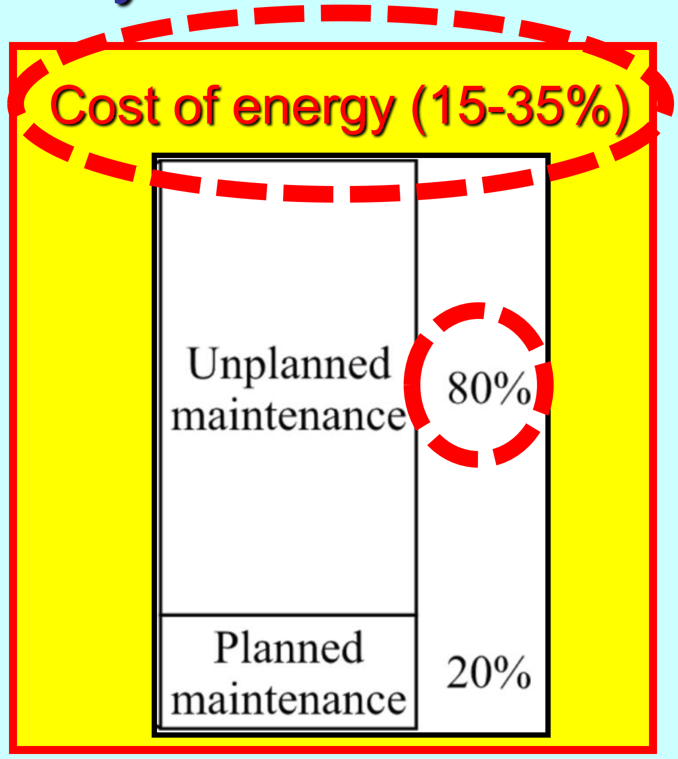


- ✓ **Model-based & data-driven FDI** & **FTC** are proposed as new approaches for '**sustainable**' (high degree of reliability & availability) wind turbine control
- ✓ Manage **disturbances** (loads, storms, …) **& faults**
- ✓ ***NOTE***: *FTC was developed as aerospace topic, focused mainly on NASA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

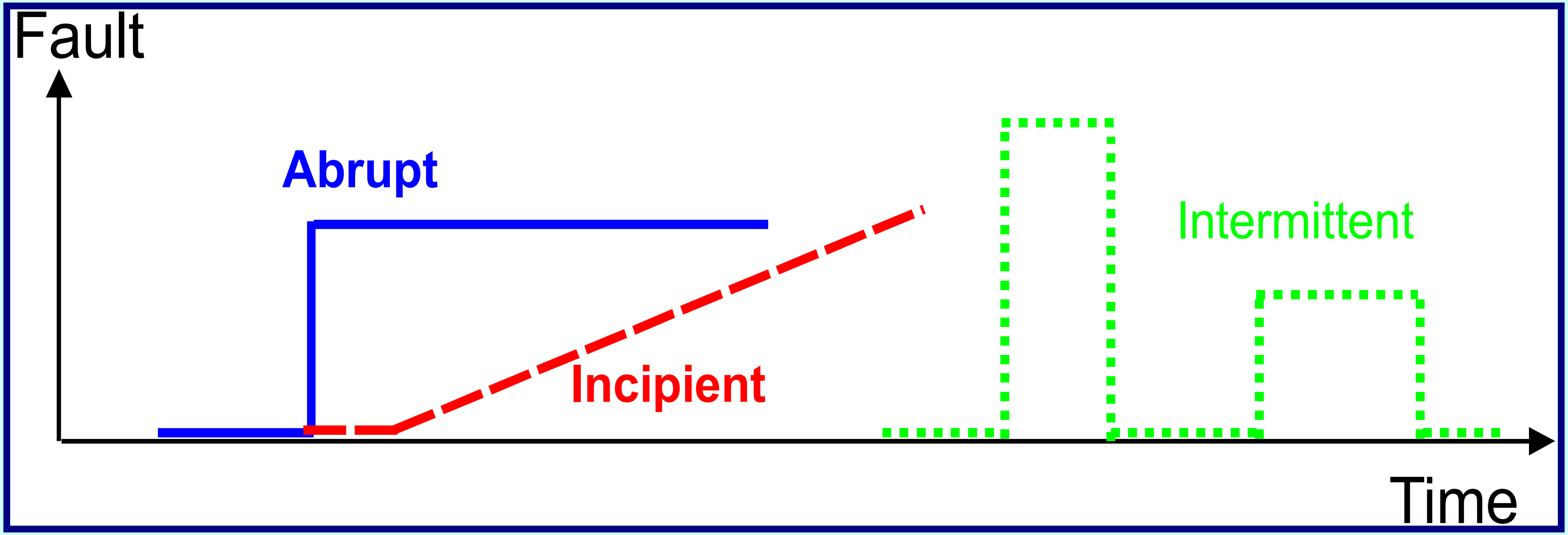
Motivations

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

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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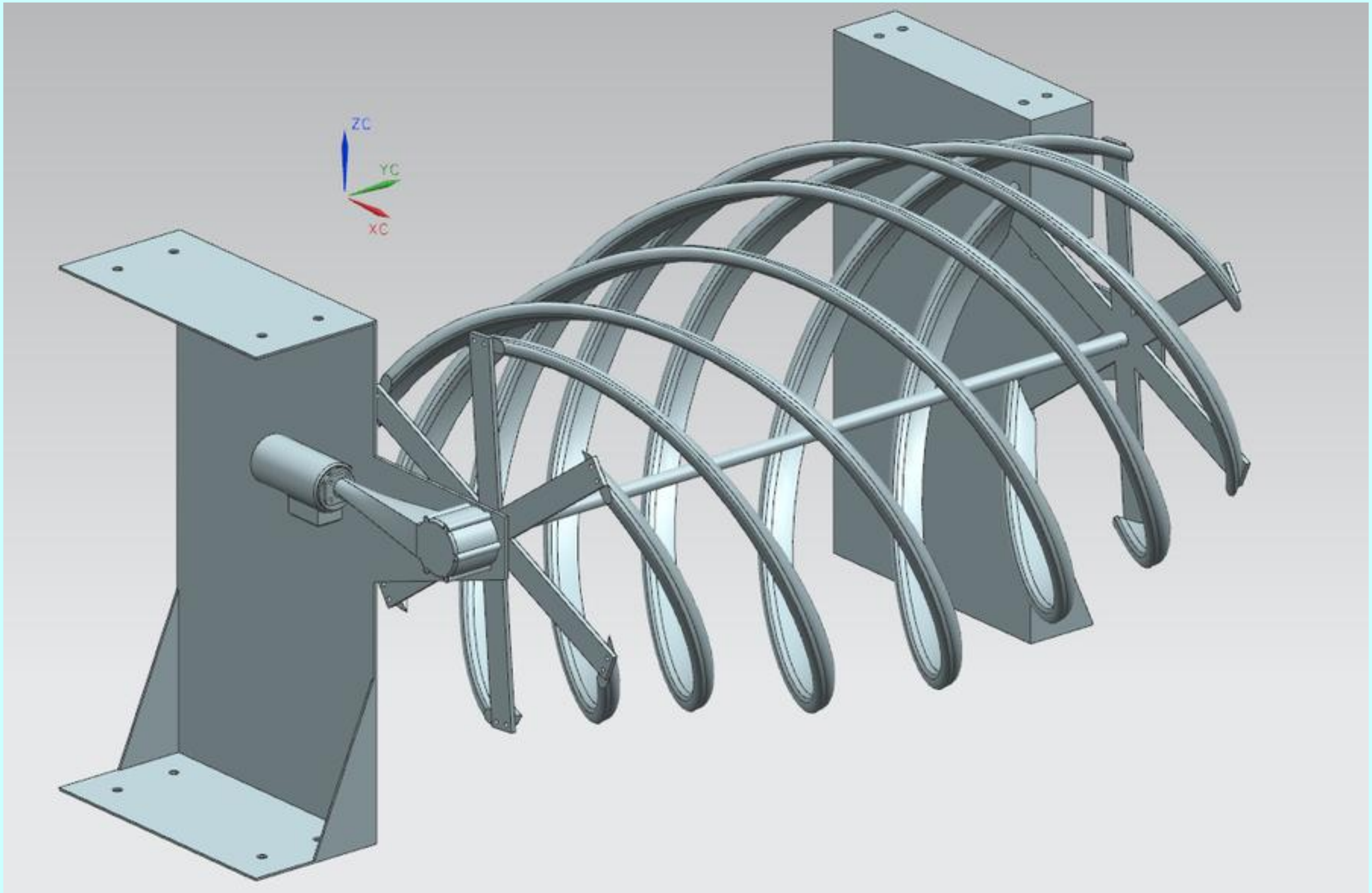
Wind Turbine Benchmarks

- ✓ 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

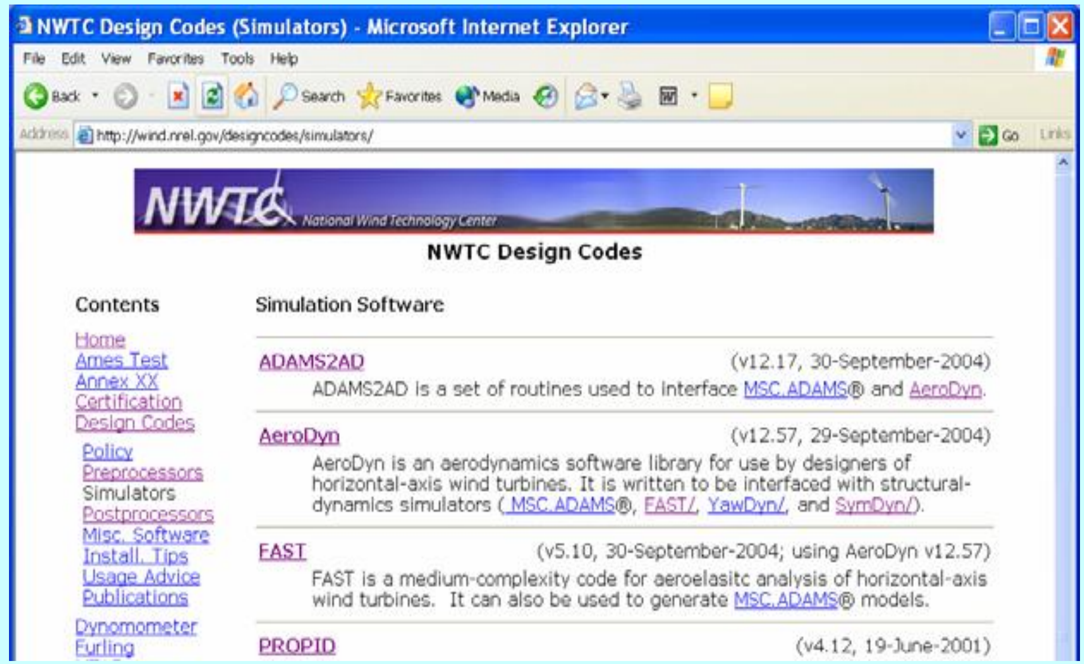
Modelling Topics



NREL Design Codes

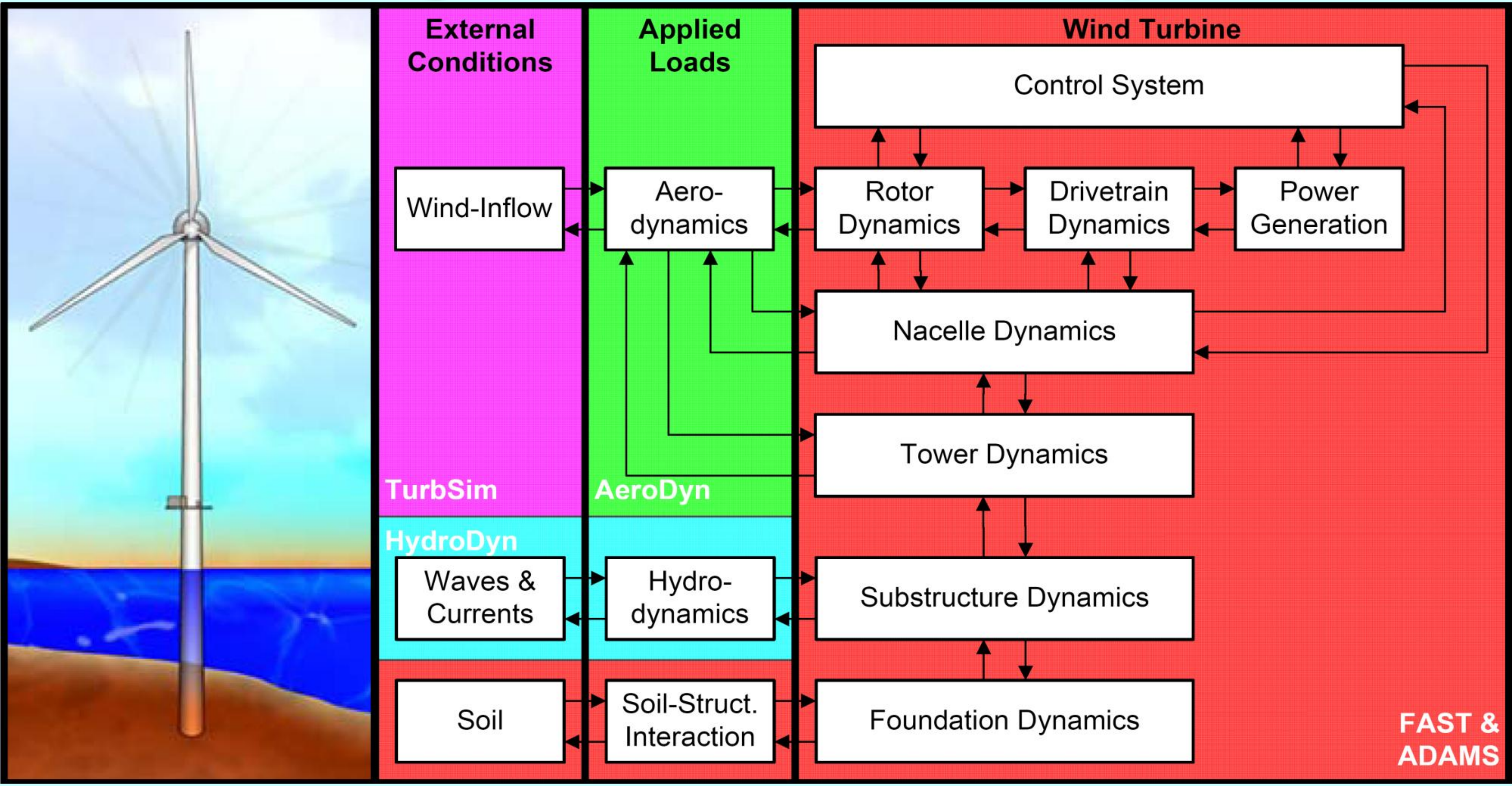
National Renewable Energy Laboratory

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



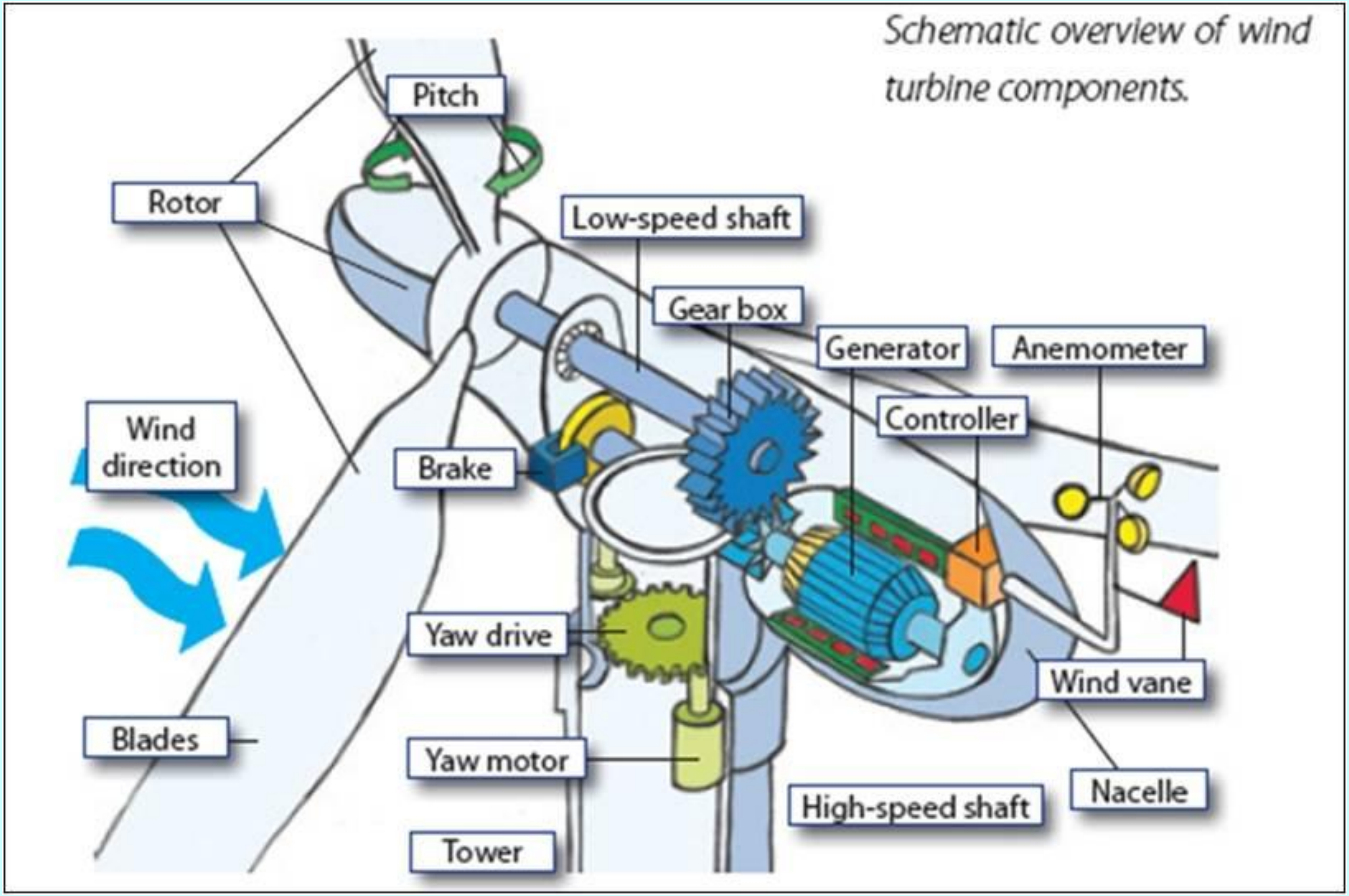
- ✓ Freely available
- ✓ Used heavily in industry, academia & other governmental research organizations
- ✓ Important for control system design

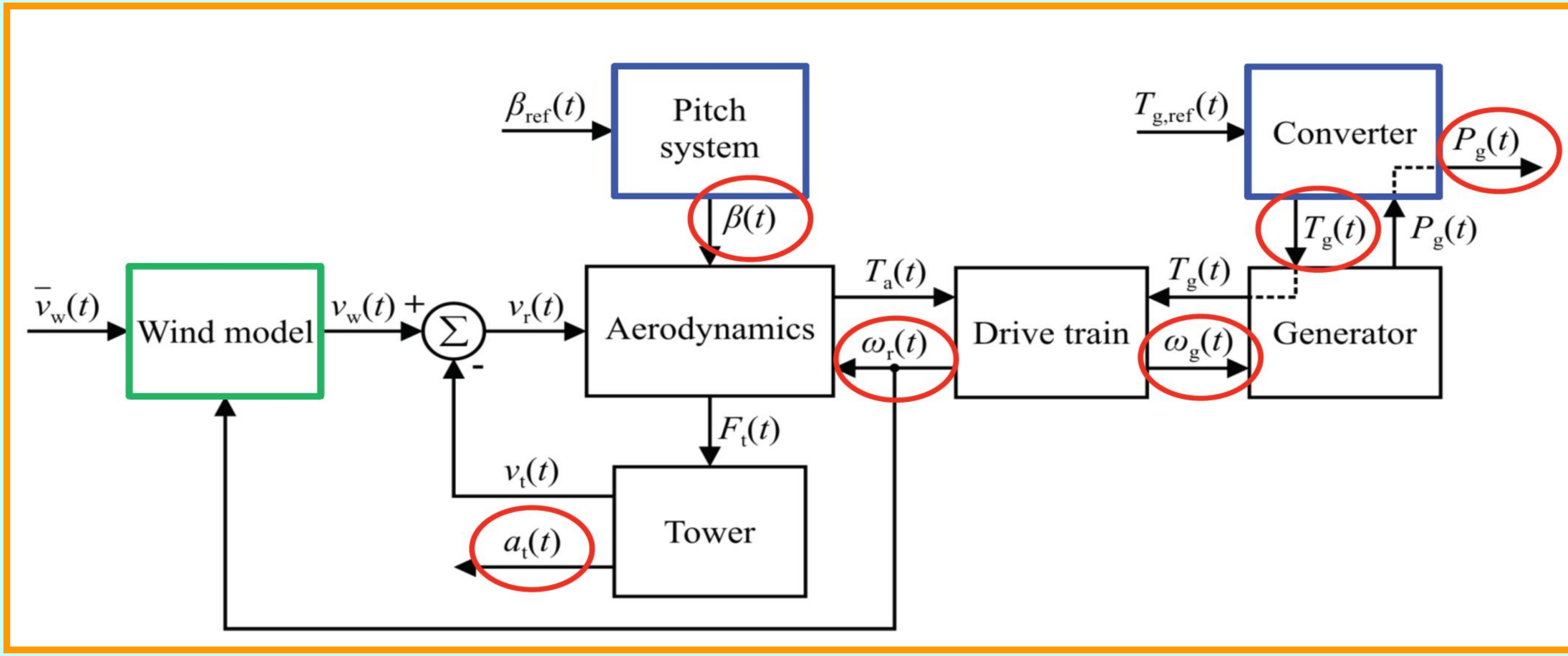
Design Codes Examples



Coupled Aero-Hydro-Servo-Elastic Simulation

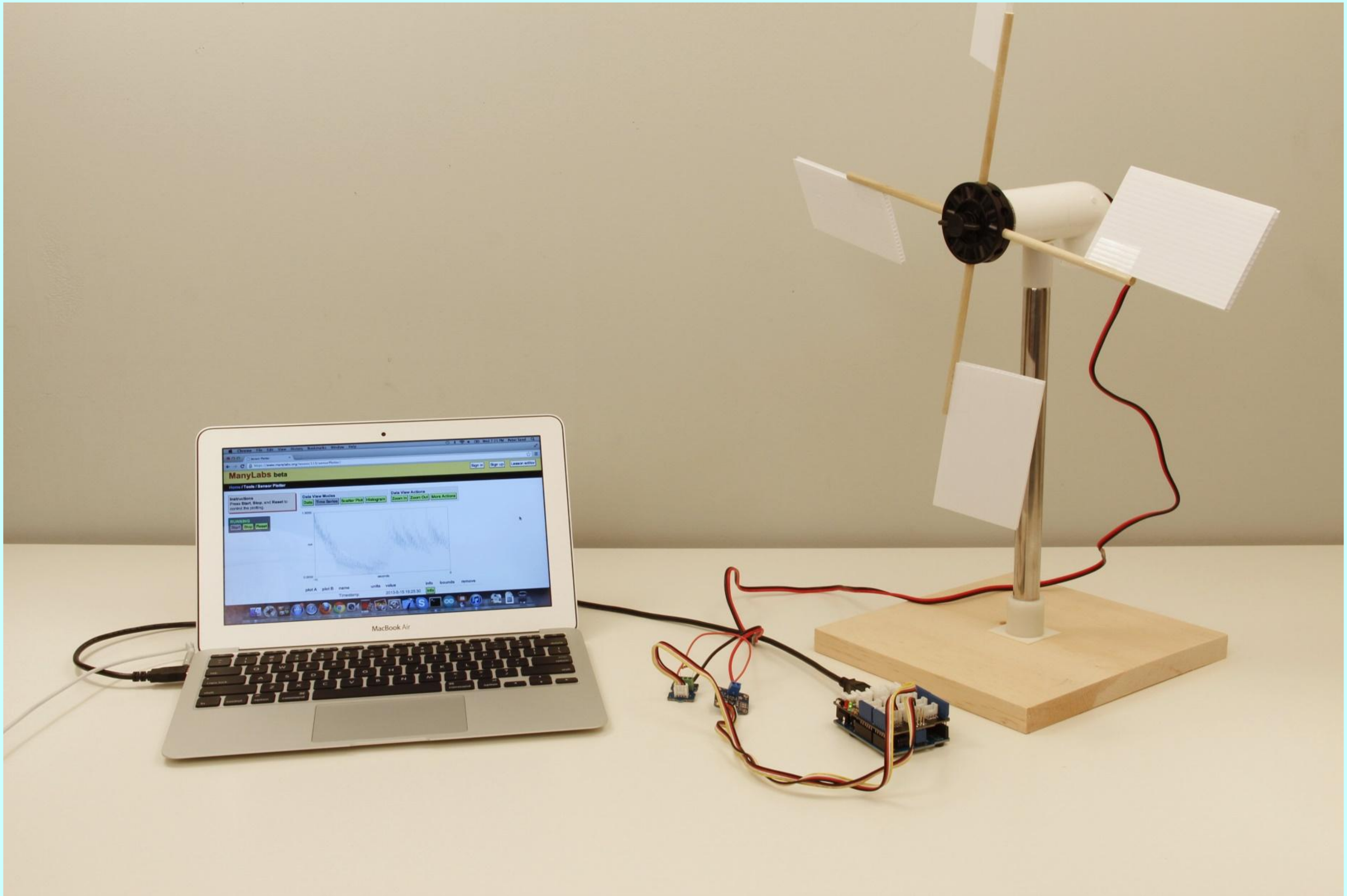
Wind Turbine Components





- 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

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

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

Drive-train model

Hydraulic pitch system

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

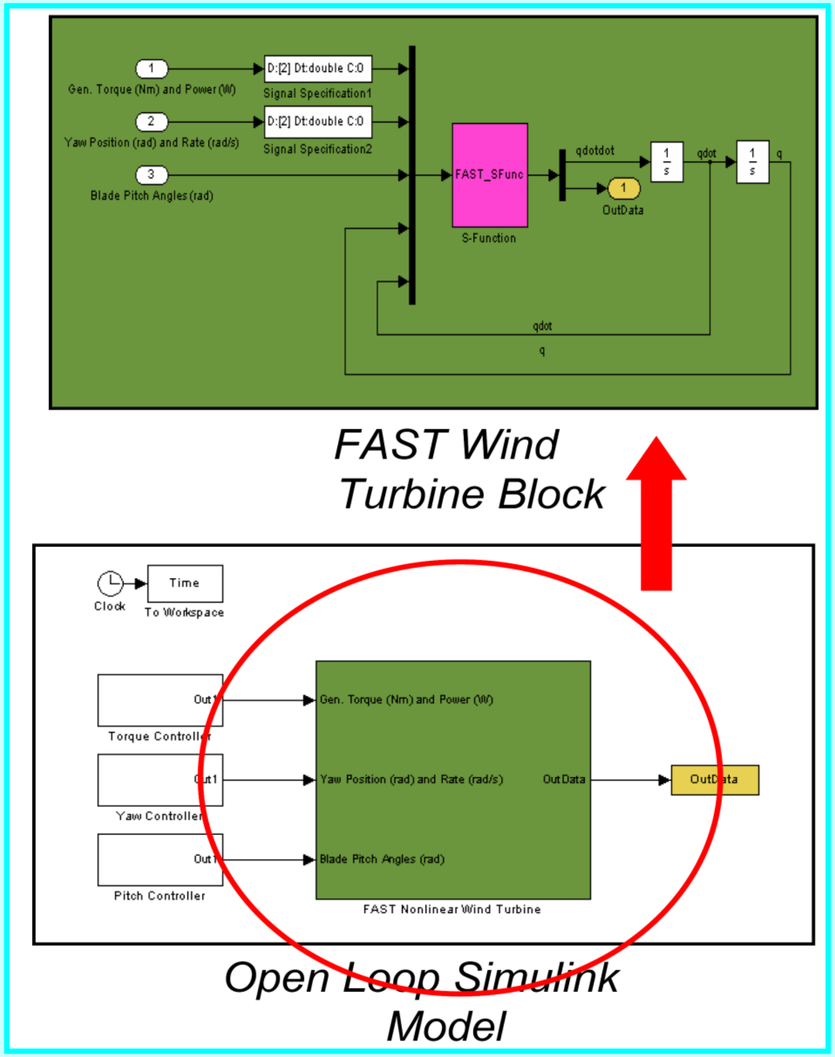
$$\frac{\tau_g(s)}{\tau_{gr}(s)} = \frac{\alpha_{gc}}{s + \alpha_{gc}}$$

Generator & converter models

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

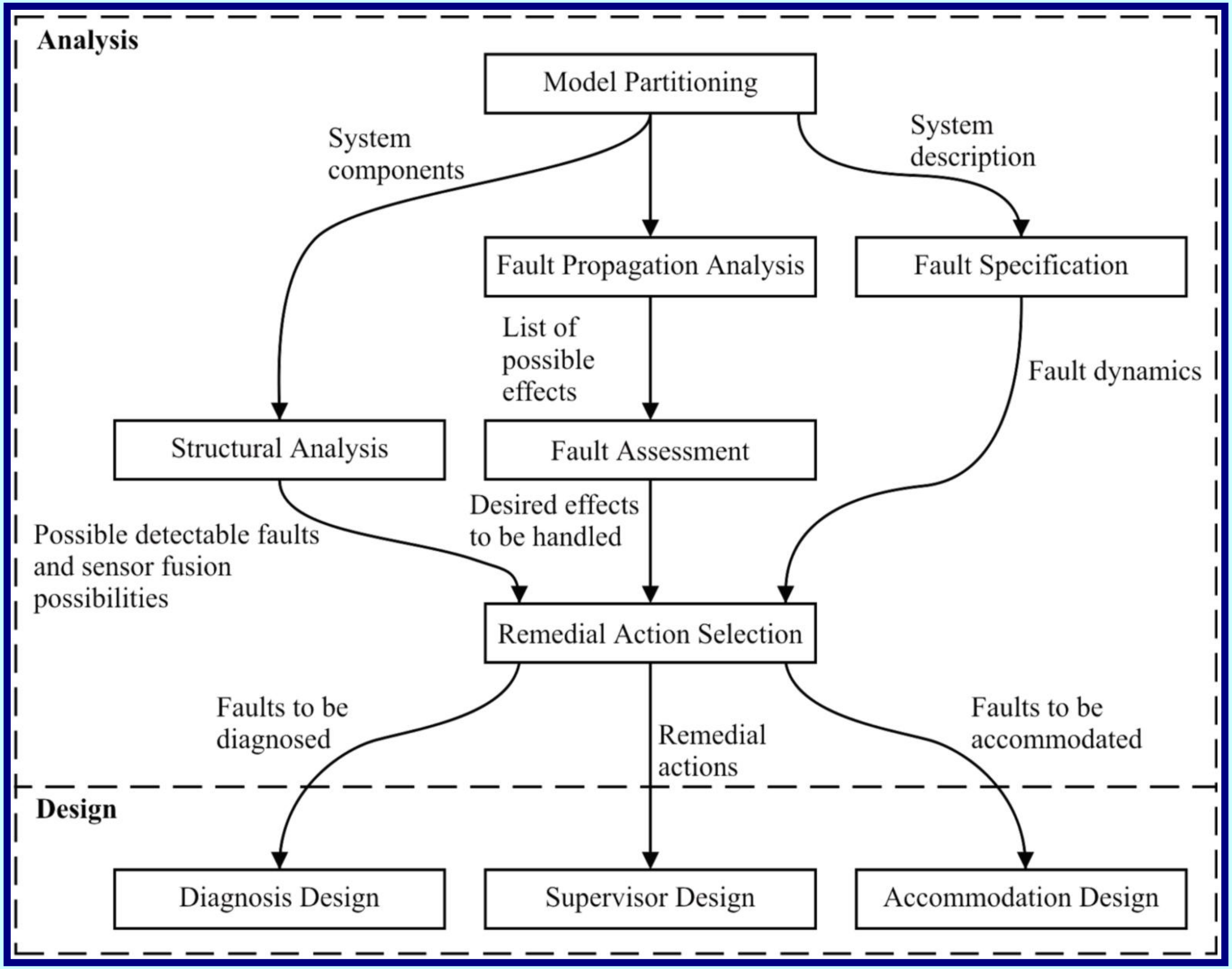
Turbine Model & Controller

- ✓ 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



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

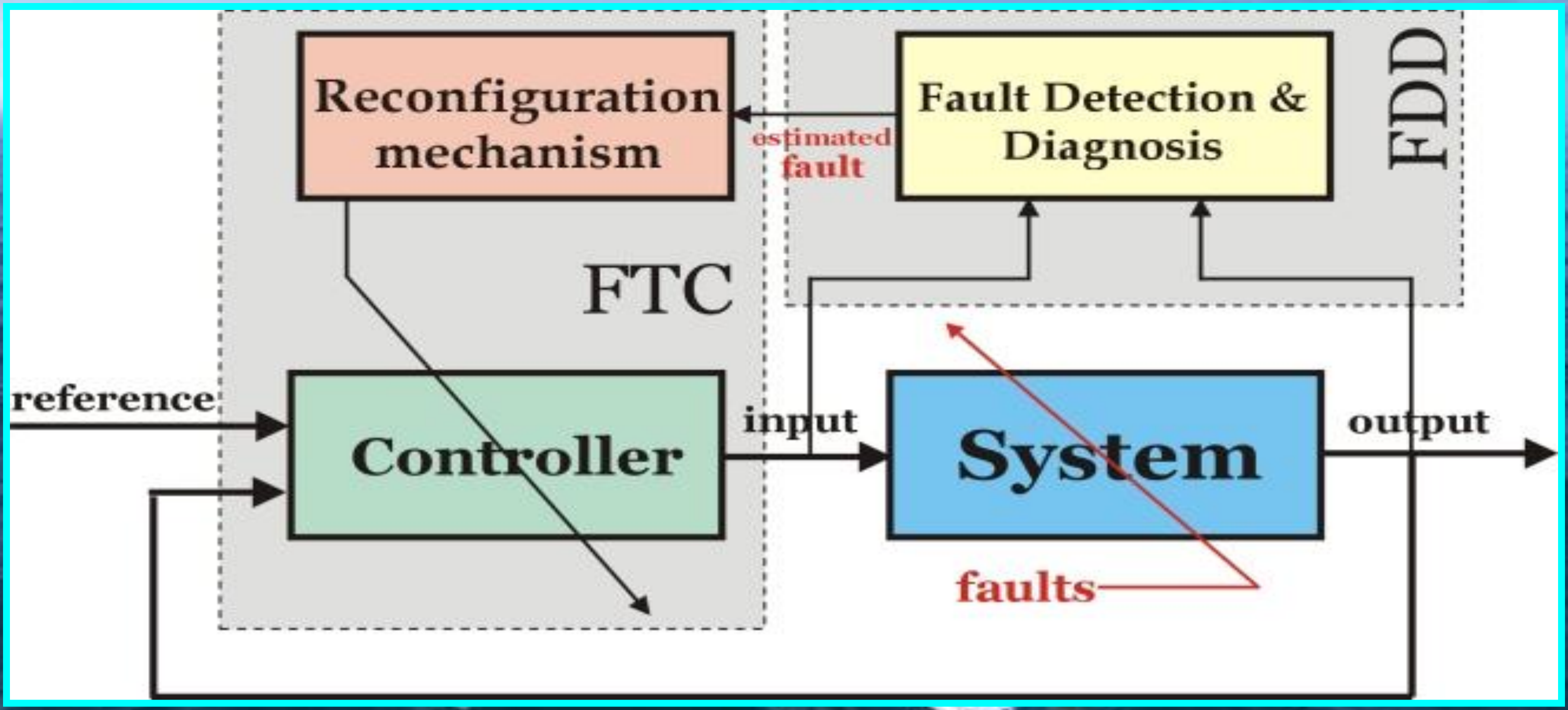
Fault Scenario

Component	Fault	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)

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

Research Issues

Benchmark (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

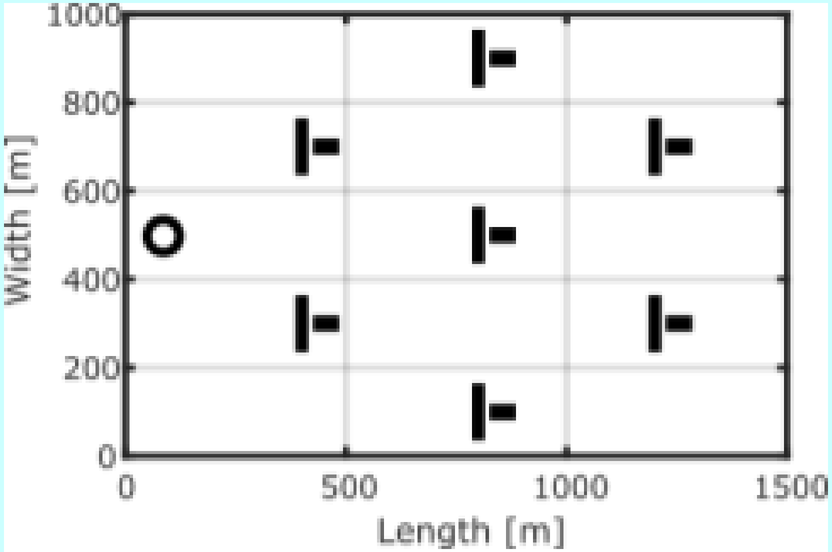


Fig. 1: Layout of the proposed wind farm.

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

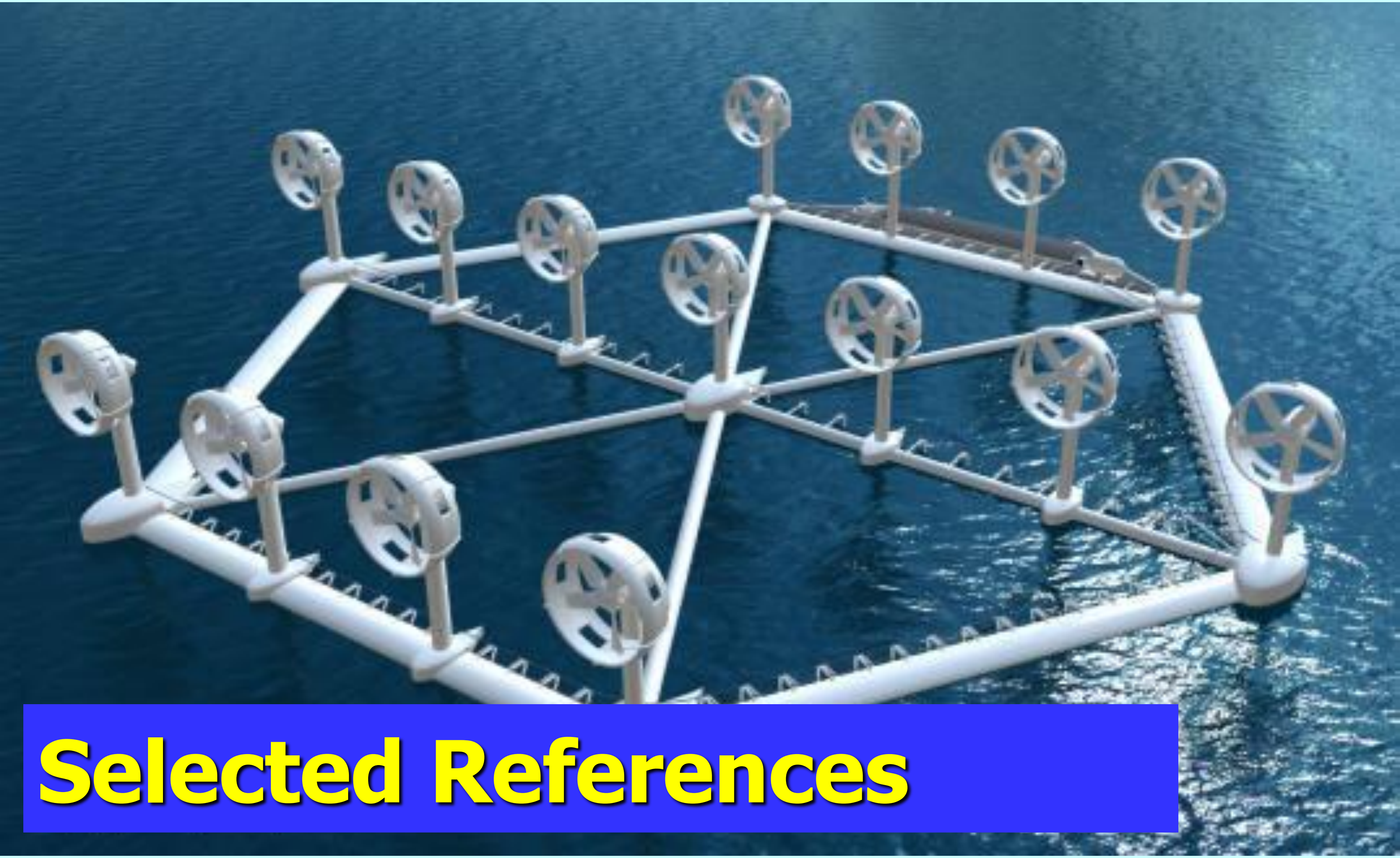
Forthcoming Events

SAFEPROCESS 2027

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

Delft, Netherlands

2027



Selected References

Selected References

1. **Fekih, A., Habibi, H., & Simani, S.** (2022). Fault Diagnosis and Fault Tolerant Control of Wind Turbines: An Overview. *Energies*, 15(19), 7186. https://doi.org/10.3390/en15197186

2. **Peña-Sánchez, Y., Penalba, M., Nava, V., & Puig, V.P.** (2023). Fault diagnosis of floating offshore wind farms, a benchmark case study. *IFAC World Congress 2023*, Yokohama, Japan, 2–9.

3. **Fernandez-Navamuel, A., Peña-Sánchez, Y., & Nava, V.** (2024). Fault detection and identification for control systems in floating offshore wind farms: A supervised Deep Learning methodology. *Ocean Engineering*, 310, 118678. https://doi.org/10.1016/j.oceaneng.2024.118678

4. **Stadtmann, F., & Rasheed, A.** (2024). Diagnostic Digital Twin for Anomaly Detection in Floating Offshore Wind Energy. *arXiv preprint*, arXiv:2406.02775. https://arxiv.org/abs/2406.02775

5. **Simani, S., & Castaldi, P.** (2014). Active actuator fault-tolerant control of a wind turbine benchmark model. *International Journal of Robust and Nonlinear Control*, 24(8–9), 1283–1303

References (1)

6. **Dallabona, A., Blanke, M., Pedersen, H.C., & Papageorgiou, D.** (2025). Fault Diagnosis and Prognosis Capabilities for Wind Turbine Hydraulic Pitch Systems. *arXiv preprint*, arXiv:2312.09018. https://arxiv.org/abs/2312.09018

7. **Mousavi, Y.** (2023). Optimal and Robust Fault Tolerant Control of Wind Turbines Working under Sensor, Actuator, and System Faults. *arXiv preprint*, arXiv:2308.12550. https://arxiv.org/abs/2308.12550

8. **Papini, G., Faedo, N., & Mattiazzo, G.** (2024). Fault diagnosis and fault-tolerant control in wave energy. *Tethys Engineering*. https://tethys-engineering.pnnl.gov/sites/default/files/publications/Papini-et-al-2024.pdf

9. **Zhang, D., Qian, L., Mao, B., Huang, C., Huang, B., & Si, Y.** (2018). A Data-Driven Design for Fault Detection of Wind Turbines Using Random Forests and XGBoost. *IEEE Access*, 6, 21020–21031. https://doi.org/10.1109/ACCESS.2018.2818678

10. **Cho, S., Cho, M., Gao, Z., & Moan, T.** (2021). Fault detection and diagnosis of a blade pitch system in a floating wind turbine based on Kalman filters and artificial neural networks. *Renewable Energy*, 169, 1–13.

Selected References (2)

11. **González-Esculpi, A., Verde, C., & Maya-Ortiz, P.** (2023). Nonlinear servocompensator for fault-tolerant control of a wave energy converter. *Journal of the Franklin Institute*, 360(1), 1–20.

12. **Casau, P., Rosa, P., Tabatabaeipour, S.M., & Silvestre, C.** (2014). A set-valued approach to FDI and FTC of wind turbines. *IEEE Transactions on Control Systems Technology*, 23(1), 245–263.

13. **Fu, Y., & Yan, W.** (2024). One Masked Model is All You Need for Sensor Fault Detection, Isolation and Accommodation. *arXiv preprint*, arXiv:2403.16153. https://arxiv.org/abs/2403.16153

14. **Yang, X., & Maciejowski, J.M.** (2012). Fault-tolerant model predictive control of a wind turbine benchmark. *IFAC Proceedings Volumes*, 45(20), 337–342.

15. **Odgaard, P.F., & Stoustrup, J.** (2012). Fault tolerant control of wind turbines using unknown input observers. *IFAC Proceedings Volumes*, 45(20), 313–318.

Selected References (3)

16. **Sloth, C., Esbensen, T., & Stoustrup, J.** (2011). Robust and fault-tolerant linear parameter-varying control of wind turbines. *Mechatronics*, 21(4), 645–659.

17. **Badihi, H., Zhang, Y., & Hong, H.** (2014). Fuzzy gain-scheduled active fault tolerant control of a wind turbine. *Journal of the Franklin Institute*, 351(9), 3677–3706.

18. **Lan, J., Patton, R.J., & Zhu, X.** (2018). Fault-tolerant wind turbine pitch control using adaptive sliding mode estimation. *Renewable Energy*, 116, 219–231.

19. **Shi, F., & Patton, R.** (2015). An active fault tolerant control approach to an offshore wind turbine model. *Renewable Energy*, 75, 788–798.

20. **Kamal, E., Aitouche, A., Ghorbani, R., & Bayart, M.** (2012). Robust fuzzy fault tolerant control of wind energy conversion systems subject to sensor faults. *IEEE Transactions on Sustainable Energy*, 3(2), 231–241.


Thanks for your attention