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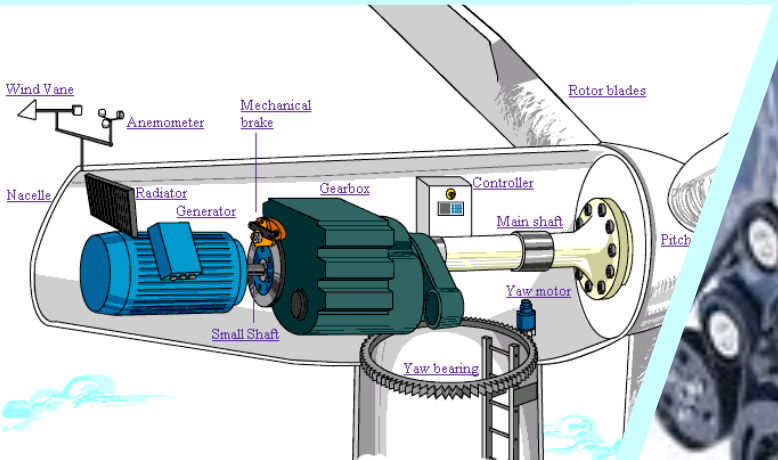


From Fault Diagnosis to Reliable Control in Energy Systems

Abstract: *Modern energy systems must operate efficiently, safely, and reliably under increasingly demanding and uncertain conditions. In this context, monitoring, fault diagnosis, and control play a key role in improving performance, reducing maintenance costs, and enhancing operational resilience. This presentation provides an overview of research activities that move from fault diagnosis towards reliable control, with particular reference to energy-related applications. The talk discusses how modelling, identification, data analysis, and intelligent monitoring strategies can support the early detection of faults and the design of control solutions that maintain acceptable performance even under abnormal operating conditions. Examples drawn from gas turbines, wind energy systems, hydroelectric plants, and thermal processes illustrate the evolution from diagnosis-oriented methods to integrated approaches for supervision and control. The overall aim is to highlight how advanced control and monitoring techniques can contribute to the reliability, sustainability, and future development of modern energy systems.*

Introduction

Research's main points

- Selected applications

Current research topics

- Recent activities & projects

Research perspective overview

- Near, medium & long term focusses

Research Main Issues

Application Example (1)

Gas turbine simulator
Matlab & Simulink

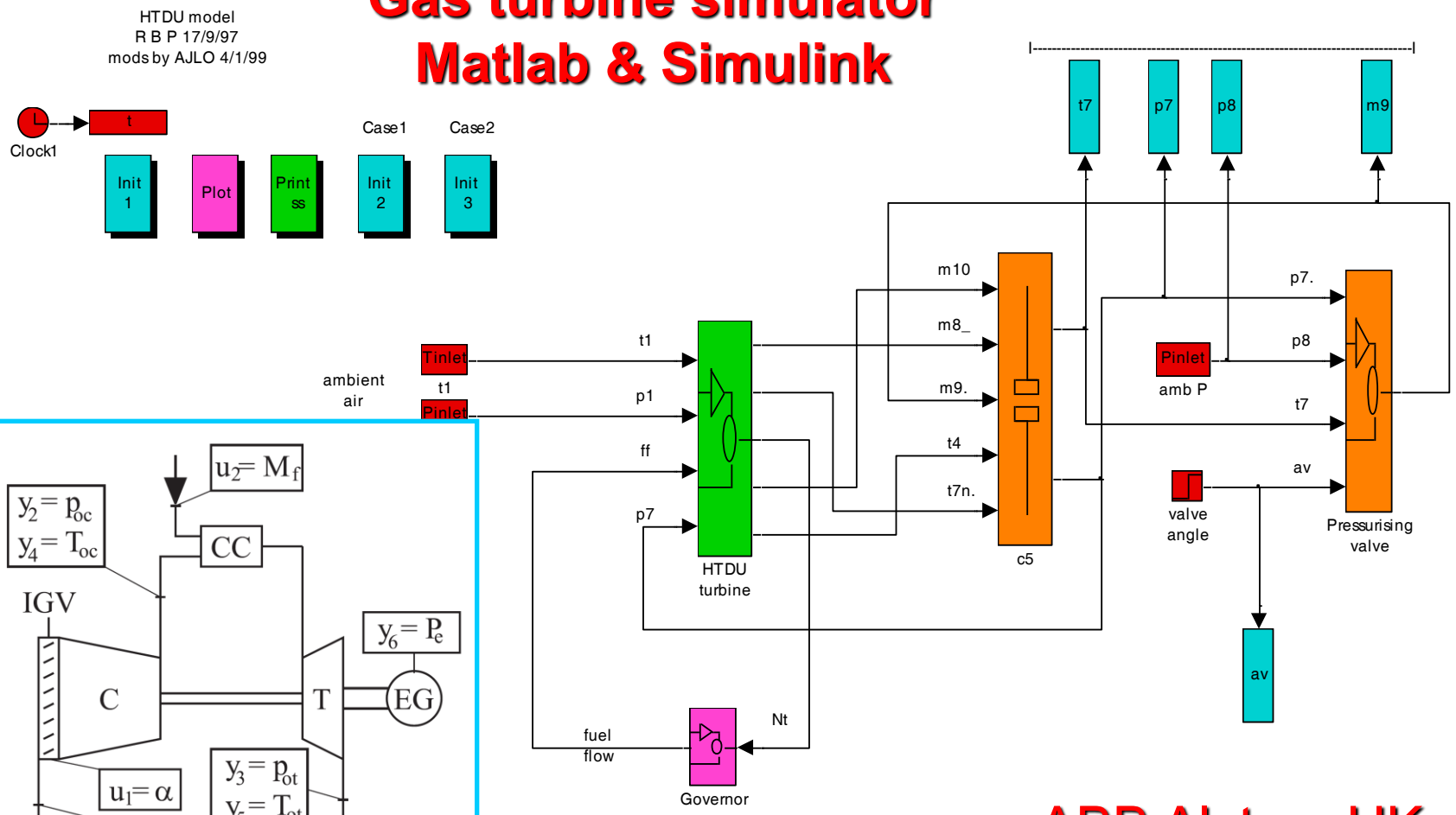
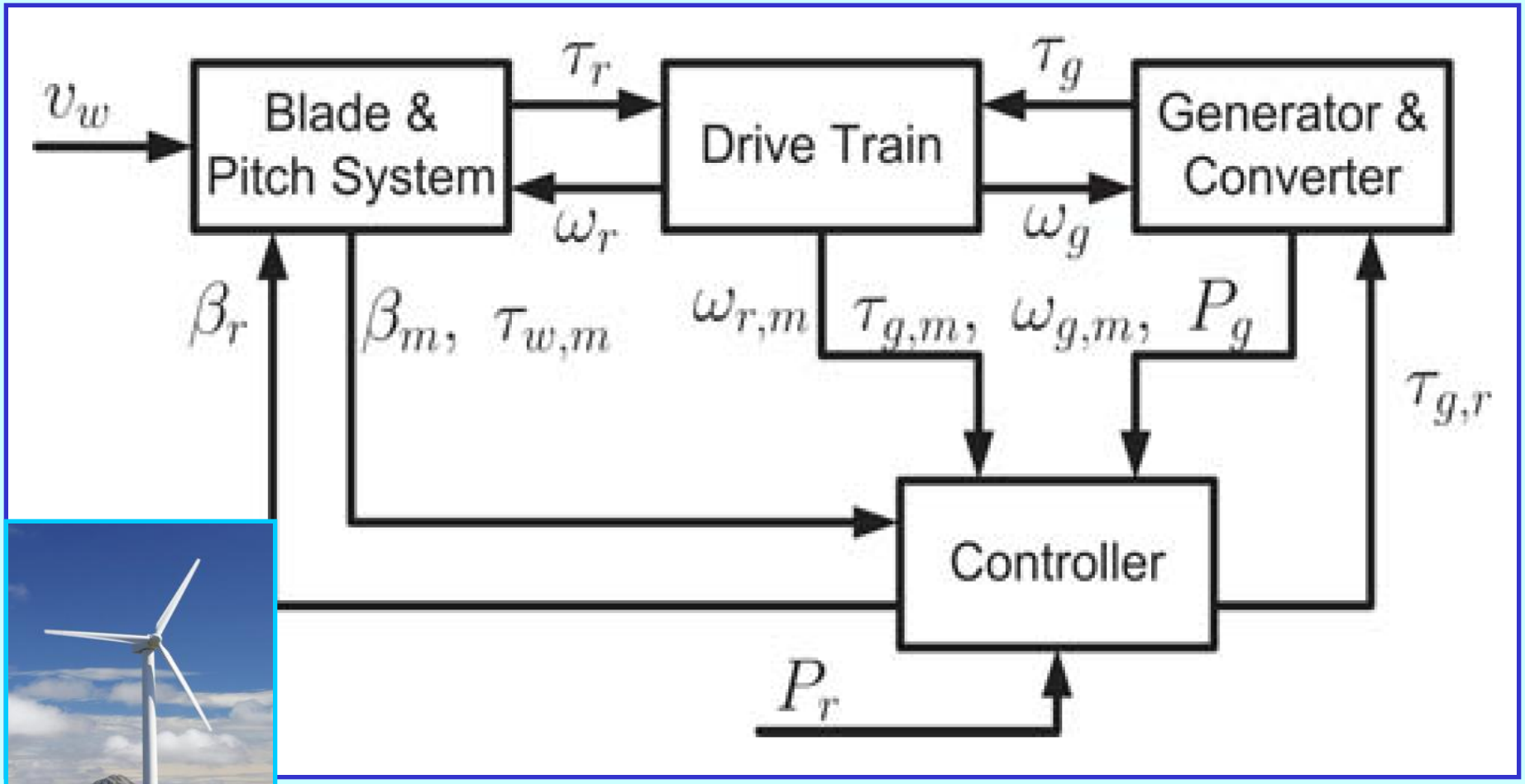


ABB Alstom UK

Application Example (2)

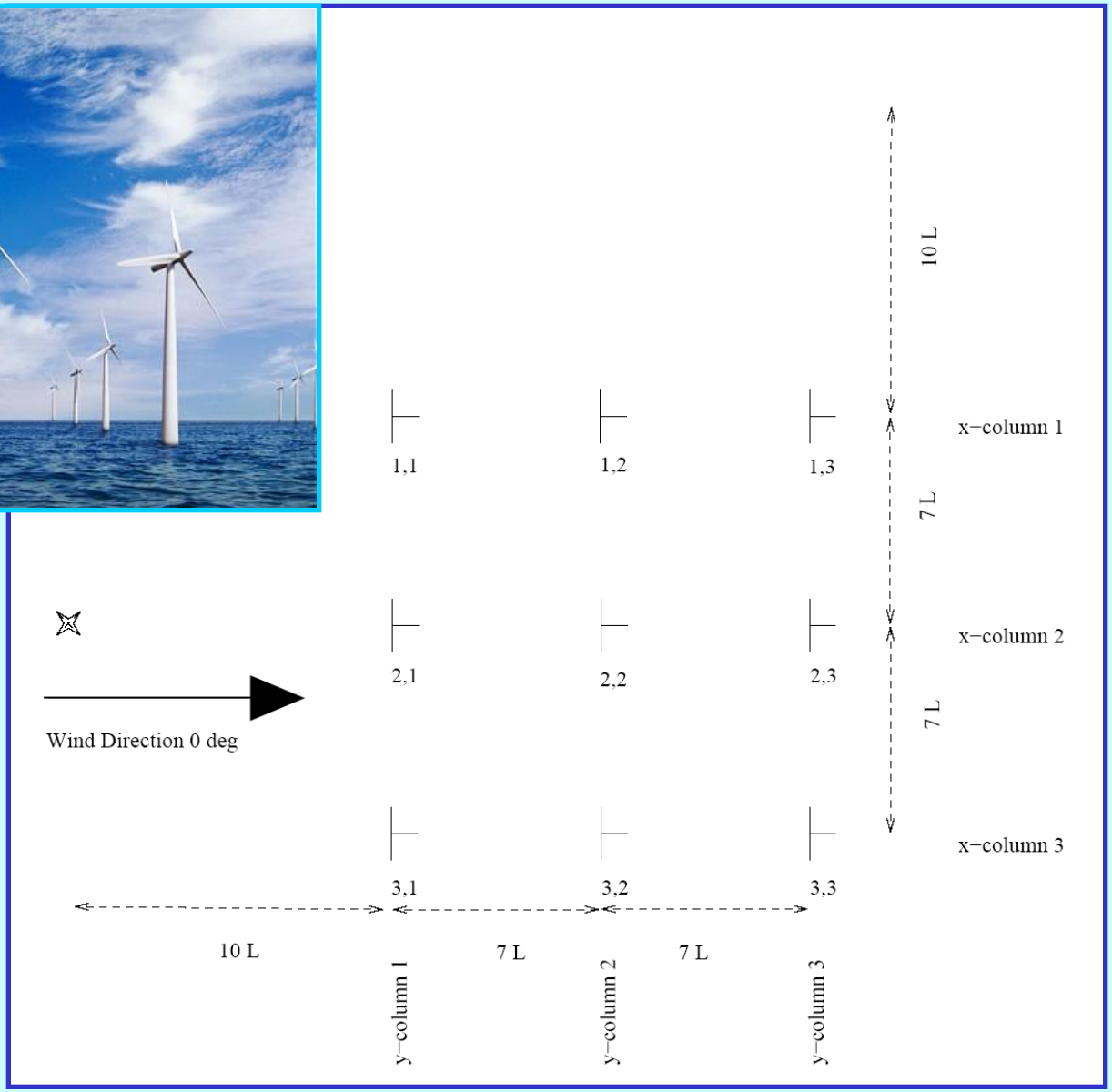


Wind turbine simulator (Matlab & Simulink)

kk-electronic (DK)

Application Example (3)

Wind farm simulator (Matlab & Simulink)
kk-electronic (DK)



Research Main Results (1)

- **Fault diagnosis feasibility study for a gas turbine**
- **Motivations**
  - Proposed by ABB Alstom UK (1999)
  - Ron J. Patton, Mike Grimble & S. Daley (UK)
- Challenge of developing ***effective & viable*** **diagnostic tools**
  - Predictive maintenance – detect slowly developing (incipient) faults in their earlier occurrence
- Application of **model-based FDI approaches**

Research Main Results (1.1)

- **Main contributions**
  - Complex thermodynamic model not required
  - Linear system identification methods
  - Linear output estimators for residual generation
- Advantageous in terms of **solution complexity & performance** (arbitrary trade-off)
- Robust & reliable solutions are designed
  - Enhances the model-reality mismatch minimisation & the fault effect maximisation
  - Model identification used for FDI purposes
- Fundamental when proper **certification & validation** procedures are under customer operation

Research Main Results (1.2)

- **Strength points**
  - **International cooperation**
    - Technology transfer purpose
  - **Viable application** of model-based FDI to complex systems
  - **Methodologies assessed & applied to other systems**
    - Aircraft & spacecraft simulators (**PRIN**)
    - **EU Project (ESA, Astrium, Hull University)**: ROBEST - "Robust Estimation for Failure Detection", Ref: EAA.TCN.89079.ASTR

Research Main Results (2)

- **Fault tolerant control for wind turbines**
- **Motivations**
  - International "Competition on Fault Detection and Fault Tolerant Control for Wind Turbines“, award sponsored by kk-electronic (DK) & MathWorks (USA)
  - **Wind turbine benchmark: d**eveloped by P.F. Odgaard (kk-electronic, DK)
  - **Key issue for *offshore* wind turbine installations**
  - Guarantee proper working conditions even in case of severe malfunctions before the planned maintenance operations take place

Research Main Results (2.1)

- **Main contributions**

- **Fault tolerant ("sustainable") control (FTC) design**

- Disturbance decoupled nonlinear filters for fault estimation (Active FTC – AFTCS)
  - **The nonlinearity of the wind turbine is identified** (C_p map)
  - **A nonlinear geometric approach can be applied**
  - Controller accommodation scheme exploits the on-line estimate of the faults from the nonlinear filters
- Extensive simulations are practical tools for assessing experimentally the AFTCS efficacy
  - Comparisons with different fault-tolerant schemes

Research Main Results (2.2)

- **Strength points**
  - Award & 3rd prize received @ the "Competition on Fault Diagnosis and Tolerant Control for Wind Turbines" (IFAC SafeProcess 2012, Mexico City)
  - IFAC activities, different workshops & plenaries
  - Validated on more complex wind turbines
    - Reliable, effective and viable procedures for the *sustainable* control of wind turbines
- Challenging topic in international projects
  - Operation & management (O&M) highly affects the final cost of the energy production (@UniFE)

Research Main Results (3)

- **Fault diagnosis for wind turbines & farms**
- **Motivations**
- International "Competition on Fault Detection and Fault Tolerant Control for Wind Turbines and Wind Farms"
- **Wind turbine + wind farm benchmarks**
  - kk-electronic (DK) & MathWorks (USA)
- FDI important for *offshore* wind turbines
  - Fundamental the detection of faults in their earlier occurrence
  - Fault diagnosis for **preventive/predictive maintenance**

Research Main Results (3.1)

- **Main contributions**

- Development of a **fault diagnosis scheme relying on identified fuzzy models**
  - Model uncertainty & data noise
- Residual generators used for FDI
  - Organised into banks for **fault isolation**
  - **Fuzzy identification** enhances the bank design
- Monte-Carlo analysis: performance optimisation
- Comparison with different solutions from the international competition

Research Main Results (3.2)

- **Strength points**

- Award & 3rd prize received @ the "Competitions on Fault Detection and Isolation for Wind Turbines and Wind Farm" (IFAC WC 2011, Milan & IFAC WC 2014, Cape Town)
- **Data-driven "plug&play" strategies**
- IFAC activities, workshops & plenaries
- **Technology transfer projects**
  - **Fuzzy modelling applied to diesel engine real data** - "Towards the virtual motor thermal-fluid-dynamic modelling of advanced diesel engines via software tools, practical experiments, and test rigs"

Recent Research Topics

Current Research Topics (1)

1. Modelling, control, fault diagnosis & fault tolerant control for hydroelectric systems
   - ❖ Fuzzy & adaptive approaches
   - – Cooperation with Civil & Industrial Engineering Groups @ EnDiF
   - – Local funds & technology transfer projects
2. Modelling & control of a thermal unit
   - ❖ Fuzzy, MPC, NN
   - – Cooperation with Coventry & Izmir (HVAC)
   - – Horizon Europe calls

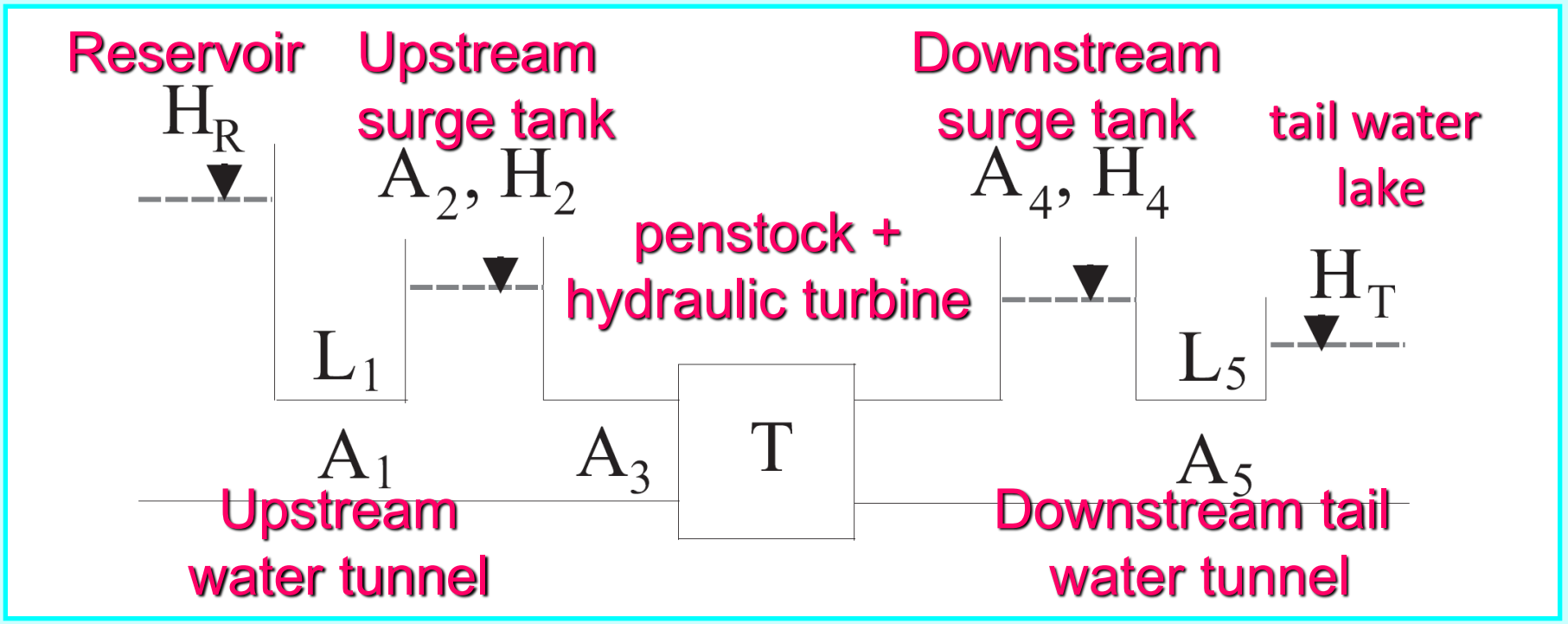
Current Research Topics (2)

3. FDI & FTC for wind turbine installations
   - ❖ Strategy validation & performance assessment
   - – **FDI & FTC joint design** (control oriented ident.)
   - – IFAC & IEEE activities, international consortium
   - – Horizon Europe calls (*e.g.* LCE)
4. FDI/FTC for satellites & aircrafts
   - ❖ Strategy validation & performance assessment
   - – Cooperation with Aerospace Dept. (UniBO)
   - – Technological demonstrator (LAURA)

Research Perspectives

Research Perspectives (1)

- Control of grid-connected hydroelectric systems (extension to networks with PAT)
  - Cooperation with Hydraulic & Industrial Depts. @ UniFE
  - Modelling, FDI & FTC

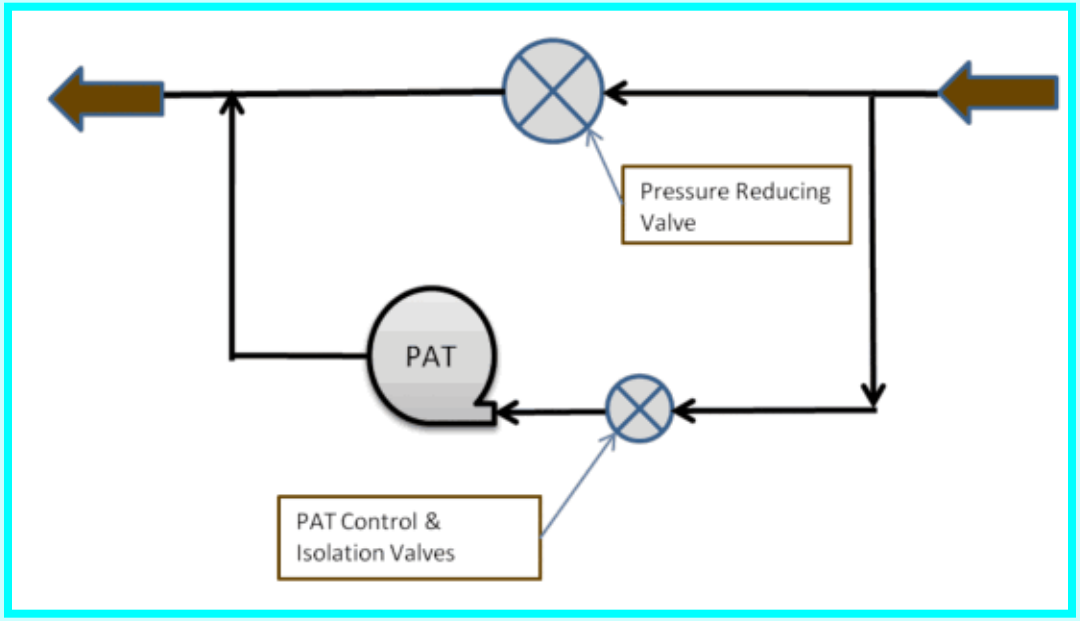


Research Perspectives (2)

- FTC for *floating* offshore wind farms
  - More complex benchmark (wake/wind models)

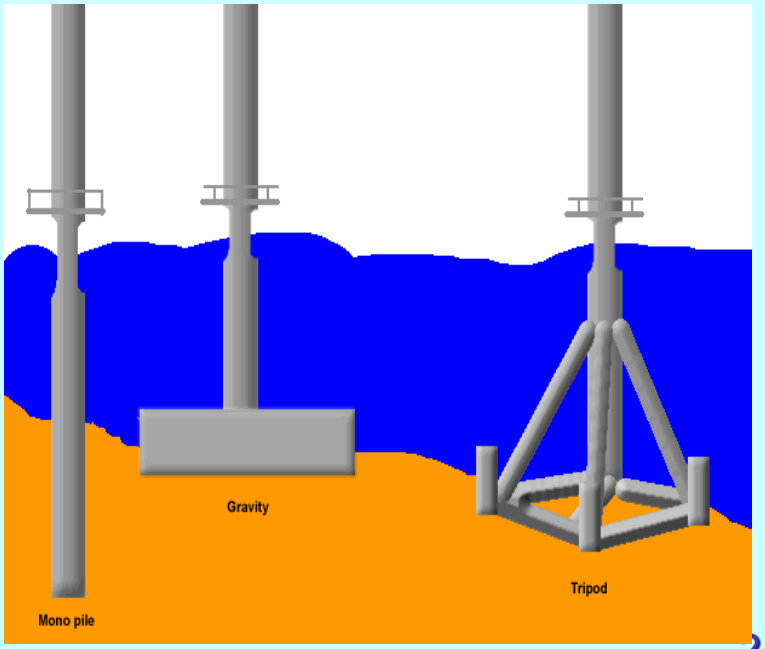
Research Perspectives (3)

- Pumps used As Turbines (PATs) to exploit *residual* hydraulic energy
  - Cooperation with Hydraulic & Industrial Depts. @ UniFE
  - **Water distribution networks + parallel PATs**
  - Cheaper than classic hydraulic turbines
  - **Challenging control issues (limit excessive pressures)**



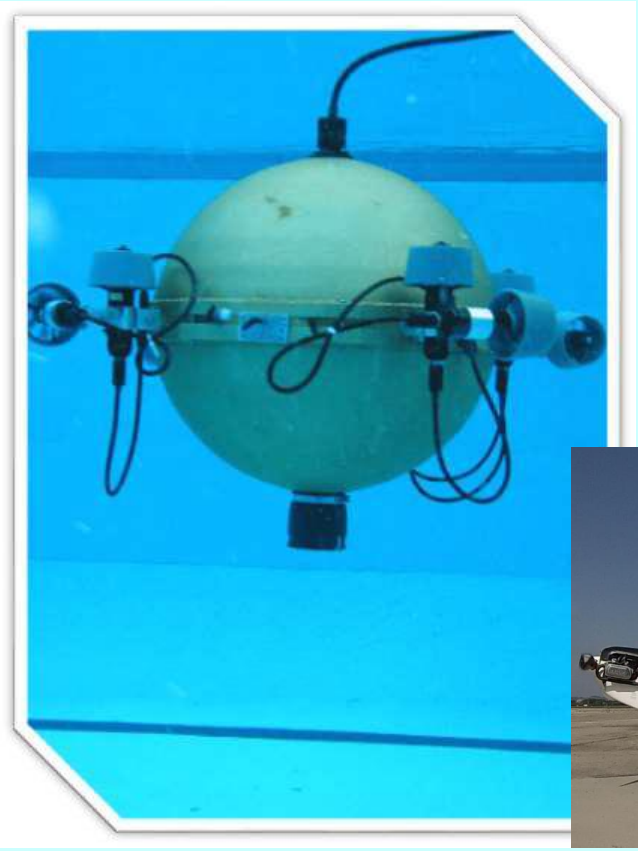
Research Perspectives (4)

- Innovative design & control concepts for FOWT
  - Smart & lighter (floating) structures
  - **Large rotor disturbance** + O&M reduction
  - Co-design (fault diagnosis, control, fault tolerance)



Research Perspectives (5)

- University LAboratorio of Aerospace Research – LAURA (UniBO)
  - Collaboration with DEI @ UniBO
  - FDI/FTC real case studies
  - Wind & wave decoupling



Selected References (1)

1. S. Simani, “Identification and Fault Diagnosis of a Simulated Model of an Industrial Gas Turbine,” *IEEE Transactions on Industrial Informatics*, vol. 1, no. 3, pp. 202–216, 2005.
2. S. Simani and P. Castaldi, “Active Actuator Fault-Tolerant Control of a Wind Turbine Benchmark Model,” *International Journal of Robust and Nonlinear Control*, vol. 24, no. 8–9, pp. 1283–1303, 2014.
3. S. Simani, S. Farsoni, and P. Castaldi, “Fault Diagnosis of a Wind Turbine Benchmark via Identified Fuzzy Models,” *IEEE Transactions on Industrial Electronics*, vol. 62, no. 6, pp. 3775–3782, 2015.
4. H. Habibi, I. Howard, and S. Simani, “Reliability Improvement of Wind Turbine Power Generation Using Model-Based Fault Detection and Fault Tolerant Control: A Review,” *Renewable Energy*, vol. 135, pp. 877–896, 2019.
5. S. Simani and P. Castaldi, “Intelligent Fault Diagnosis Techniques Applied to an Offshore Wind Turbine System,” *Applied Sciences*, vol. 9, no. 4, art. 783, 2019.
6. S. Farsoni, S. Simani, and P. Castaldi, “Fuzzy and Neural Network Approaches to Wind Turbine Fault Diagnosis,” *Applied Sciences*, vol. 11, no. 11, art. 5035, 2021
7. S. Simani, S. Farsoni, and P. Castaldi, “Data-Driven Wake Steering Control for a Simulated Wind Farm Model,” *International Journal of Robotics and Automation Technology*, vol. 10, pp. 14–26, 2023.

Selected References (1)

8. R. Johnson, J. J. Zhang, F. K. Manchu, and S. Simani, “Advancing Fault Detection in Floating Offshore Wind Turbines: An Interpretable Machine Learning Ensemble Approach,” *Proc. 6th International Conference on Control and Fault-Tolerant Systems (SysTol)*, 2025.
9. M. Benini, M. Bonfè, P. Castaldi, W. Geri, and S. Simani, “Design and Analysis of Robust Fault Diagnosis Schemes for a Simulated Aircraft Model,” *Journal of Control Science and Engineering*, vol. 2008, Article ID 274313, 2008.
10. S. Simani, S. Alvisi, and M. Venturini, “Fault Tolerant Control of a Simulated Hydroelectric System,” *Control Engineering Practice*, vol. 51, pp. 13–25, 2016.
11. C. Turhan, S. Simani, I. Zajic, and G. G. Akkurt, “Performance Analysis of Data-Driven and Model-Based Control Strategies Applied to a Thermal Unit Model,” *Energies*, vol. 10, no. 1, art. 67, 2017.
12. S. Simani, S. Farsoni, and P. Castaldi, “Application of Data-Driven Fault Diagnosis Design Techniques to a Wind Turbine Test-Rig,” in *Intelligent Computing*, Lecture Notes in Networks and Systems, 2021.
13. S. Simani and S. Farsoni, “Hardware-In-The-Loop Assessment of Fuzzy and Neural Network Fault Diagnosis Schemes for a Wind Turbine Model,” *IFAC-PapersOnLine*, vol. 55, no. 6, pp. 91–95, 2022.

Thank You for Your Attention