A Wind Turbine Benchmark Model for a Fault Detection and Isolation Competition

Silvio Simani

Department of Engineering, University of Ferrara

Via Saragat 1E 44123 Ferrara (FE), ITALY

Ph./Fax:+390532974844

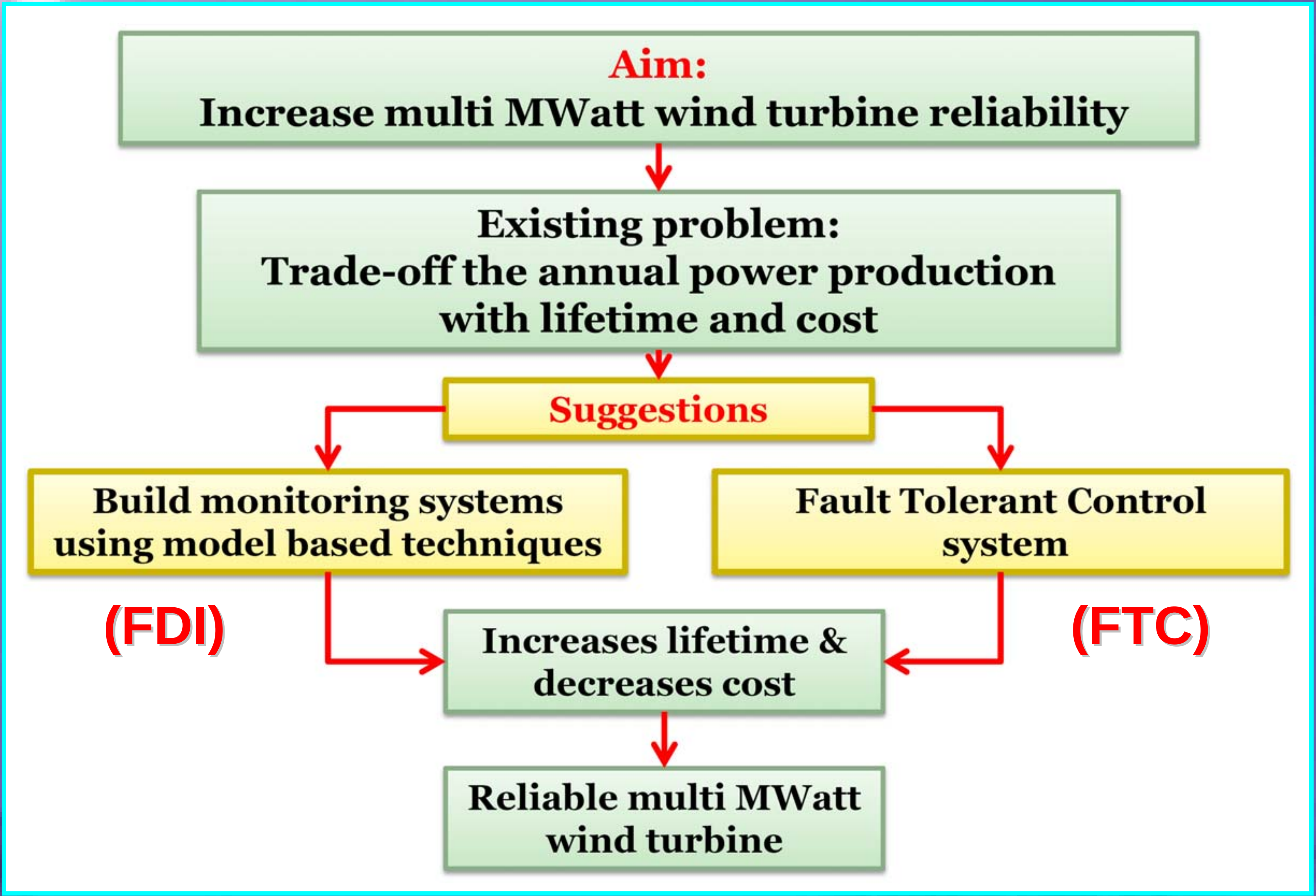
Email: silvio.simani@unife.it, URL: www.silviosimani.it

(available at `http://www.silviosimani.it/talks.html`)

Energy and Related Issues

- ✓ Control systems have high influence on the total **cost of energy**
- ✓ Focus on **supervision** and **control solutions**
- ✓ The design of suitable strategies is enhanced by **high-fidelity benchmark** models and prototypes
- ✓ Solutions characterised by craftsmanship, quality, **reliability**, and proven technology

Energy, Cost, Fault Tolerance



Safety-Critical Systems

- ✓ **Model-based FDI** and **FTC** are proposed as new approaches for **sustainable** (*keyword*, high degree of reliability and availability) wind turbine control
- ✓ Keypoints: **loads** (storms, …), **failures and faults**
- ✓ *NOTE: FTC was firstly 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*

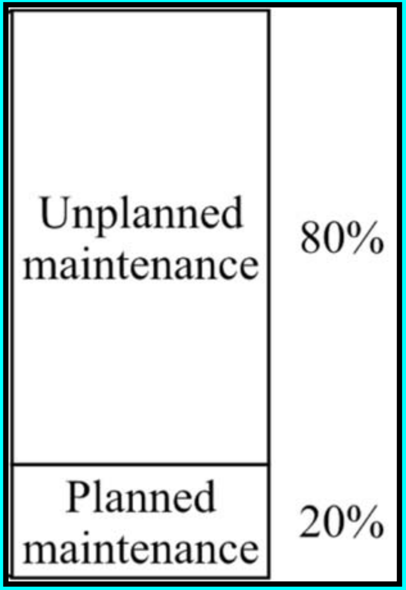
Motivations

- ✓ Harsh environment - system well protected
- ✓ **Offshore wind turbines** are stand-alone power plants in **inadequate** service and maintenance attendance
- ✓ Safety-related control systems to manage incidents from **lightning, storms, gusts and other periodic incidents, as well as faults** affecting the energy drive train (system/components) and the electricity production
- ✓ **Production maintained even in case of failures** (abrupt breakdown) **and incipient faults** (e.g. slowly developing and hard to detect malfunctions – their effects can be accommodated by FDI+FTC)

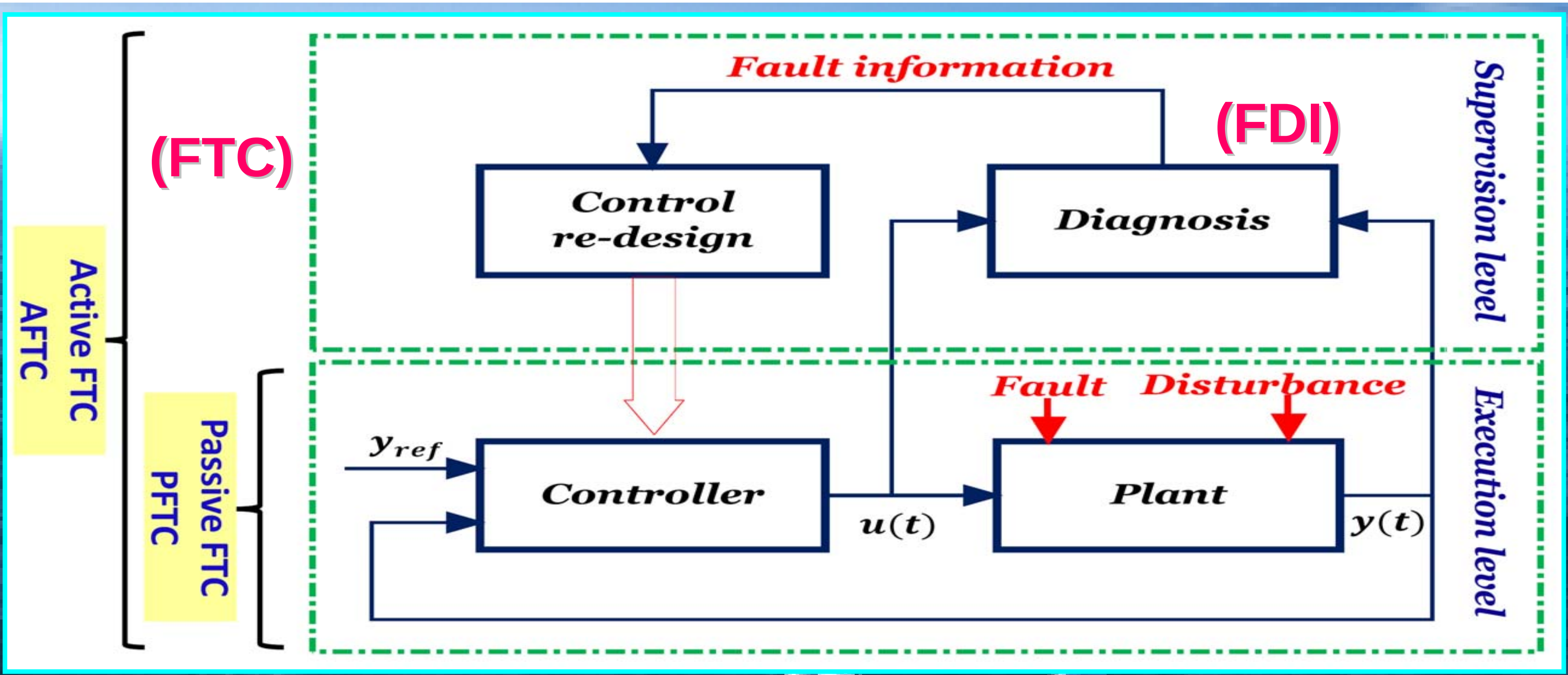
Example…

- ✓ **A 5 MW wind turbine stopped will loose 24 MWh per day in production if 40% wind capacity is assumed**
  - Difficult accessibility - it might take days before a fault is cleared
  - About $1.3 million to $2.2 million per MW capacity installed (2012)
  - Production costs from $75/MWh to $97/MWh (2010)
  - Advanced **FDI** and **FTC** included in the control system **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

Operation & Mainenance Cost of energy (20-35%)

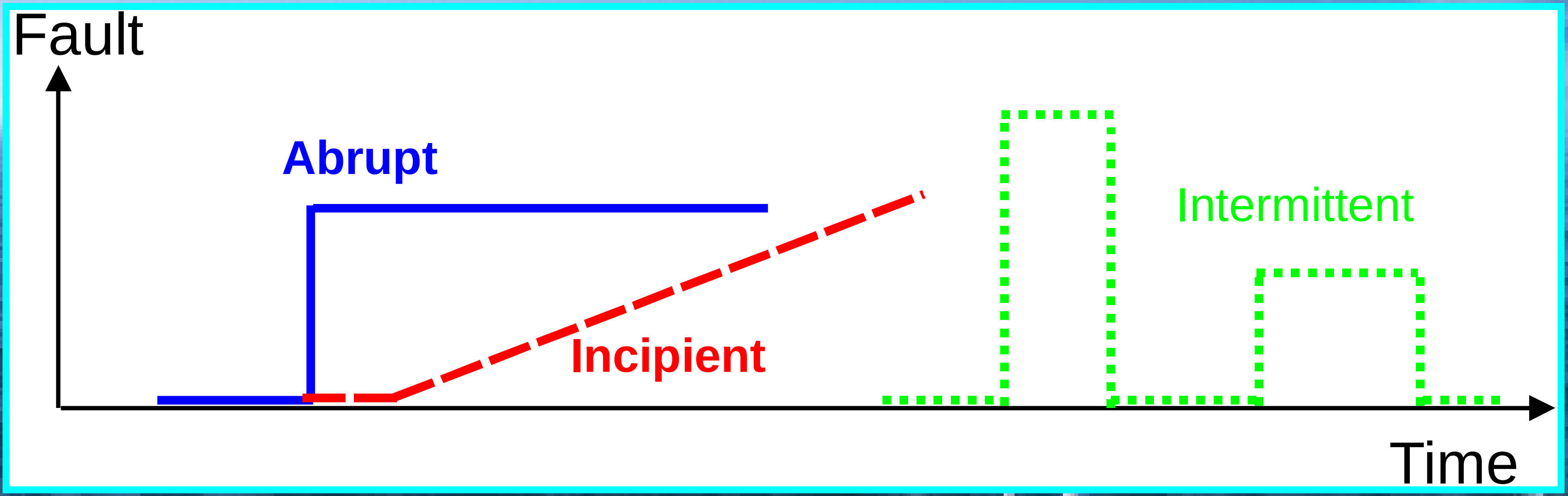


General FDI / FTC Structures



- ✓ **PFTC: Robust fixed structure controller**
  - No fault information provided
- ✓ **AFTC: Real-time controller reconfiguration**
  - Fault reconstruction by FDI – maintenance enhanced

General Fault Types



- ✓ **Abrupt fault:** breakdown due to e.g. weather conditions
- ✓ **Incipient fault:** e.g. ageing, slowly developing malfunctions (system/components)
- ✓ **Intermittent fault**: e.g. sensor bias/offset, disconnections

International Competition

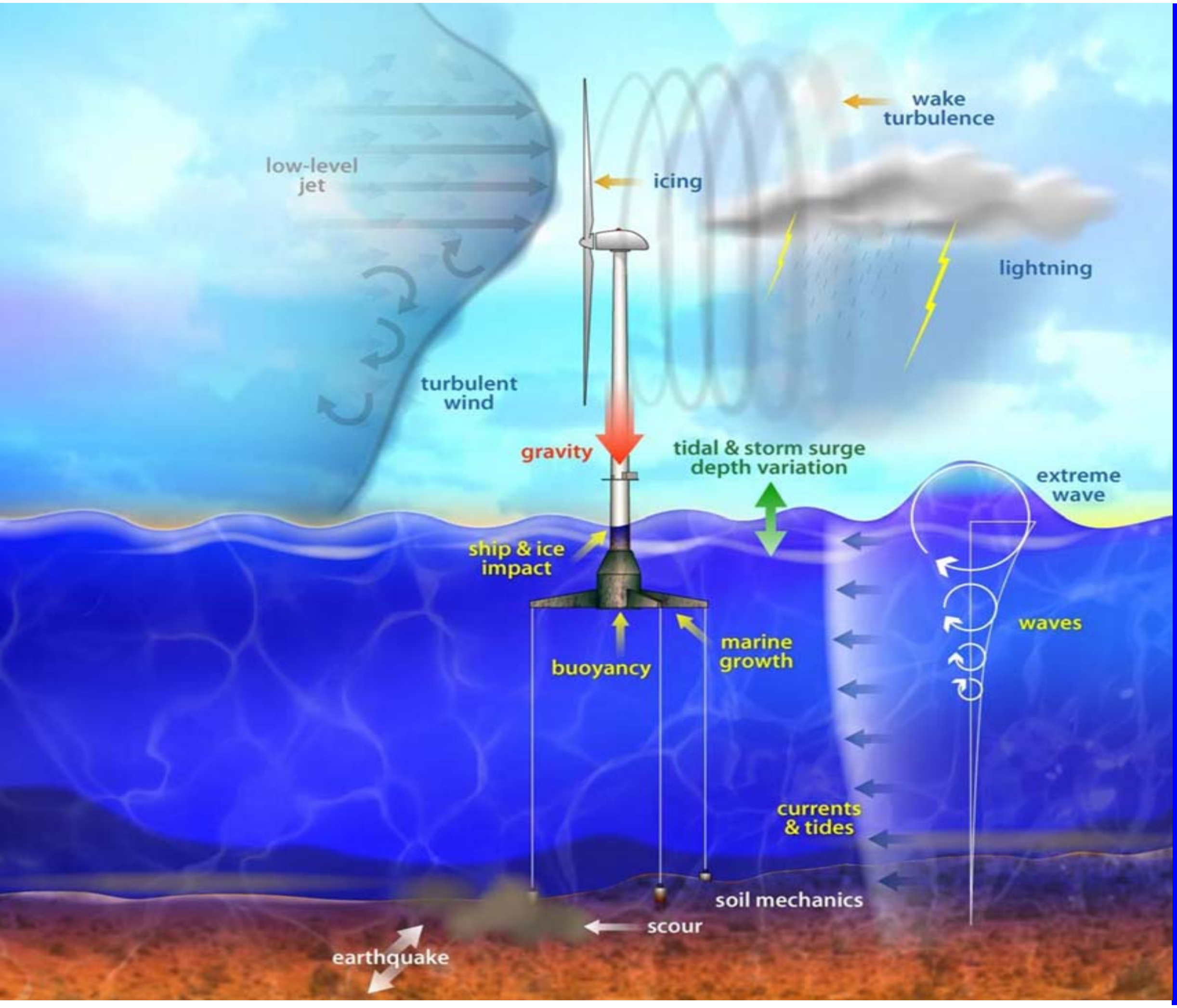
- ✓ ***kk-electronic*** **(Denmark) together with *MathWorks* launched a number of benchmark models for fault detection and accommodation, which allows both *industrial and academic researchers* to find the best schemes to handle different faults**
- ✓ **Based on these models a series of competitions and challenges have been proposed**
  - **Simple Wind Turbine FDI/FTC benchmark model**
  - **Advanced WT FDI / FTC benchmark model**
  - **Wind farm FDI/FTC benchmark model**
- ✓ **Benchmarks developed by *kk-electronic* in Matlab and Simulink environments**
- ✓ **Extensible and easily integrated with other codes (.dll, s-functions)**

http://www.kk-electronic.com/wind-turbine-control/competition-on-fault-detection.aspx

Competition Focus

- ✓ Wind turbine benchmark models proposed by *kk-electronic* in order to provide generic platforms for design and test different FDI and FTC solutions
- ✓ The target group was researchers in the FDI and FTC community
- ✓ Matlab enhances the application and comparison of these methods on wind turbine application
- ✓ Since the model is generic it can be provided to the public

Modelling Requirements

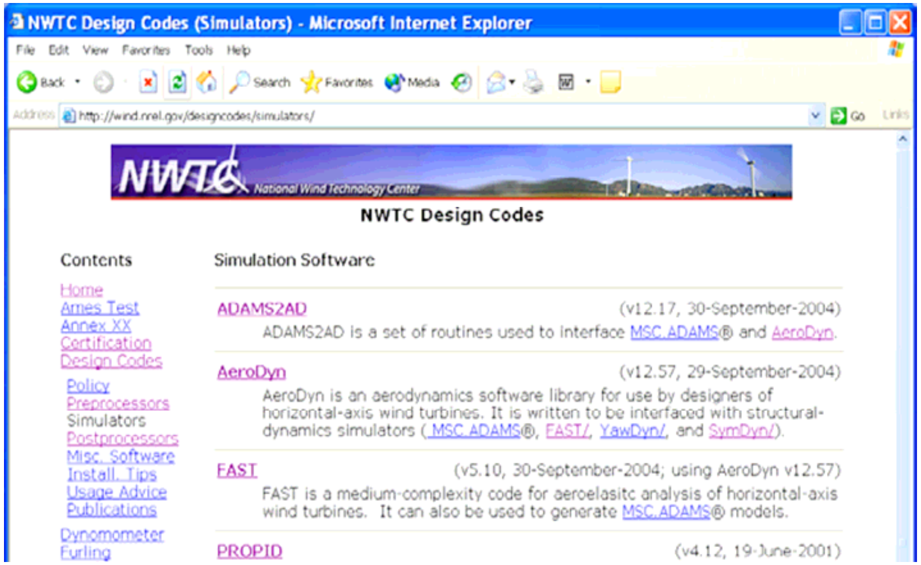


- Coupled aero-hydro-servo-elastic interaction
- Models originate from different disciplines
  - Wind-Inflow
  - Waves
  - Aerodynamics
  - Hydrodynamics
  - Structural dynamics
  - Control systems
- Multi-Physics Simulation Tools

NREL Design Codes

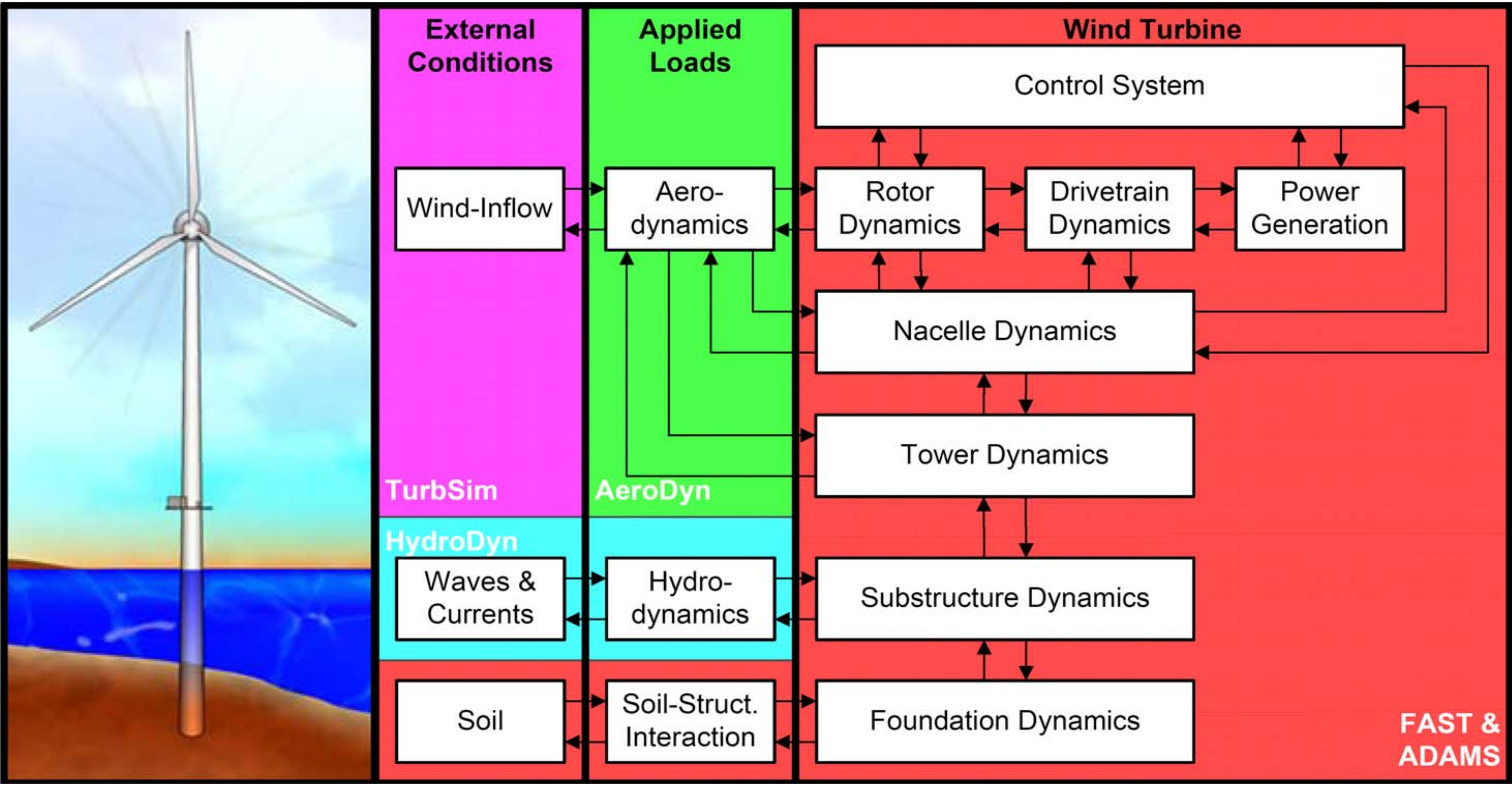
National Renewable Energy Laboratory

- ✓ **http://wind.nrel.gov/designcodes**
  - FAST (Fatigue, Aerodynamics, Structures, and Turbulence) – aeroelasticity
  - TurbSim – turbulent inflow
  - ADAMS (Automatic Dynamic Analysis of Mechanical Systems)
  - NASTRAN – flexible blade model



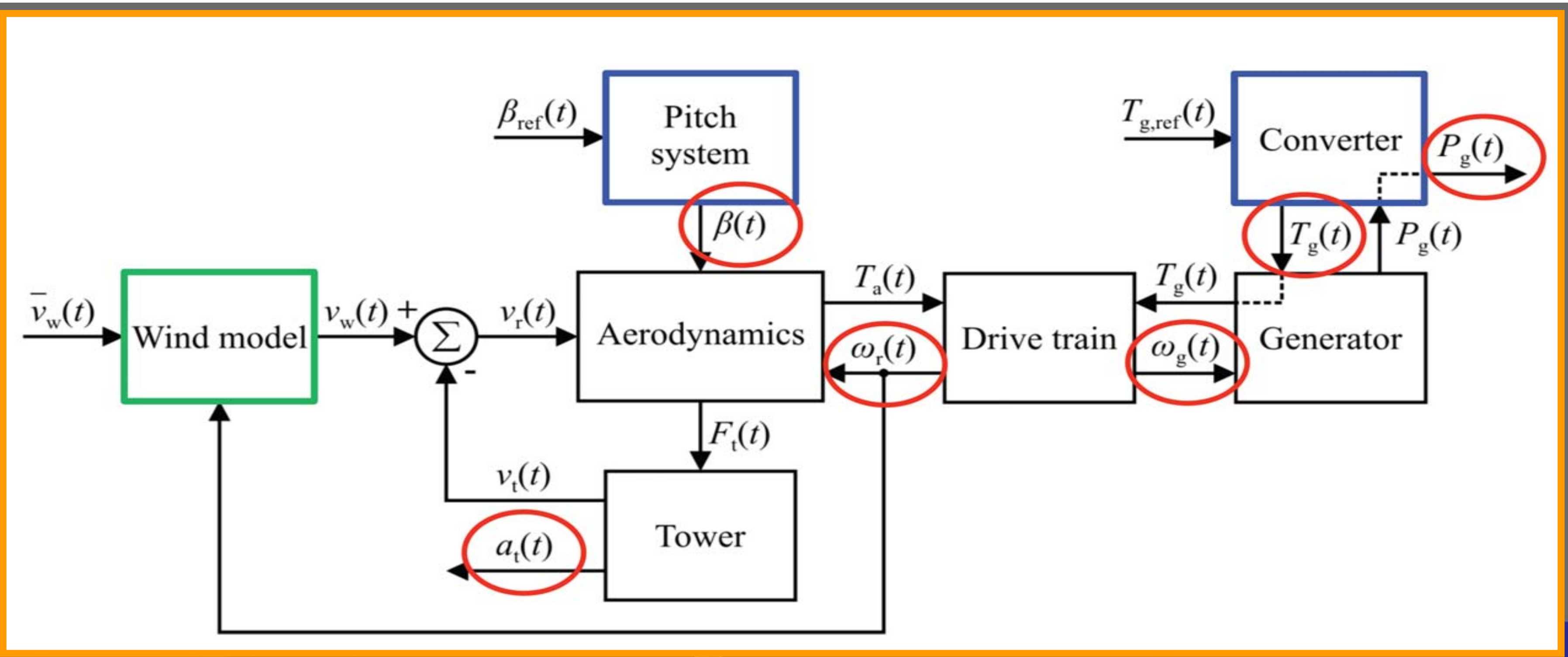
- ✓ Used heavily in industry, academia and other governmental research organizations
- ✓ Important for control systems design

Design Codes



Coupled Aero-Hydro-Servo-Elastic Simulation

Wind Turbine Model



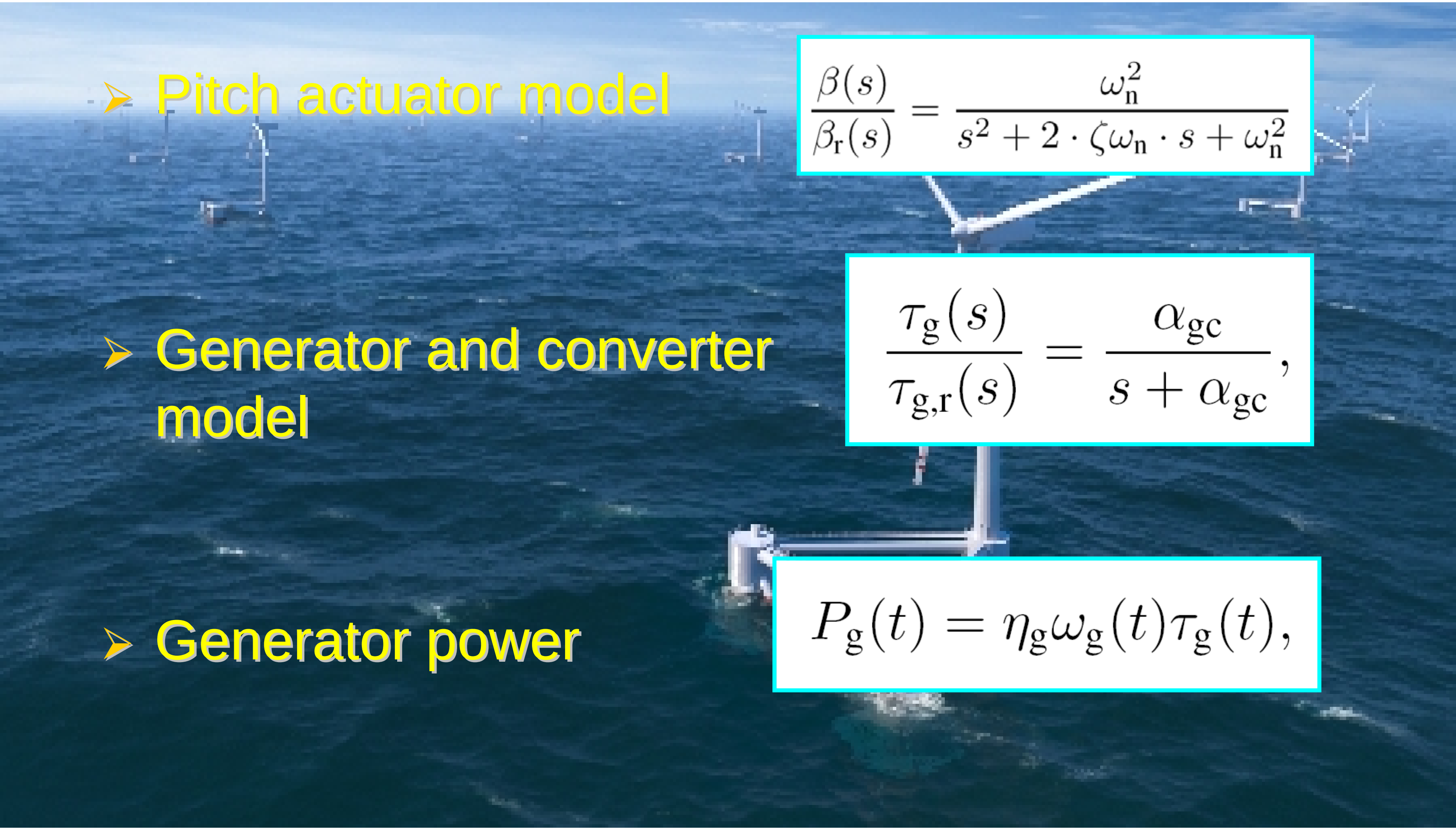
- Stochastic wind model including tower shadow and wind shear
- Actuator models
- Zero-mean Gaussian distributed measurement noise

Odgaard, P.F. ; Stoustrup, J. ; Kinnaert, M. Fault-Tolerant Control of Wind Turbines: A Benchmark Model. IEEE Transactions on Control Systems Technology, 2013

Sensor Models

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	$5 \cdot 10^{-2}$

Actuator Models



- Pitch actuator model

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

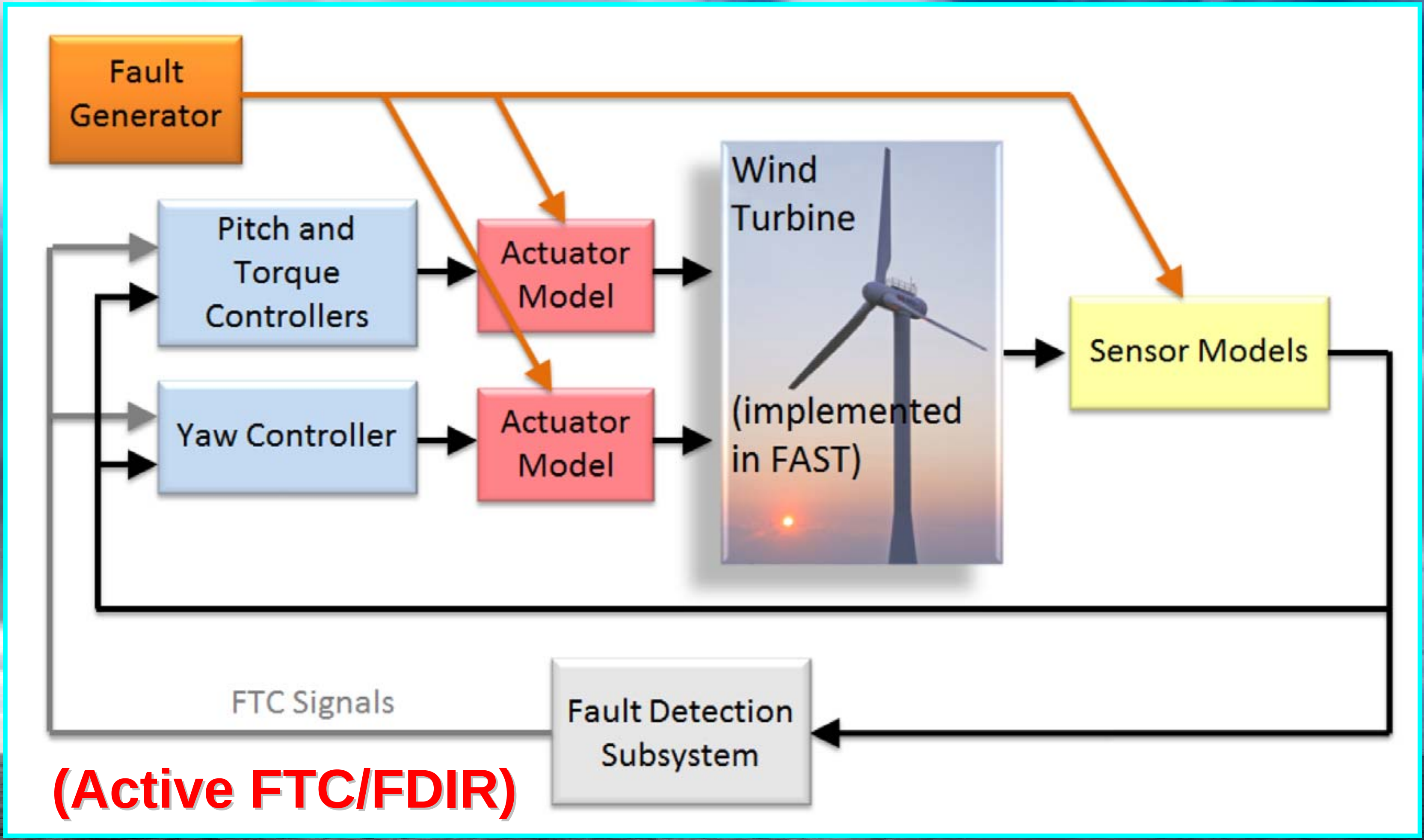
- Generator and converter model

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

- Generator power

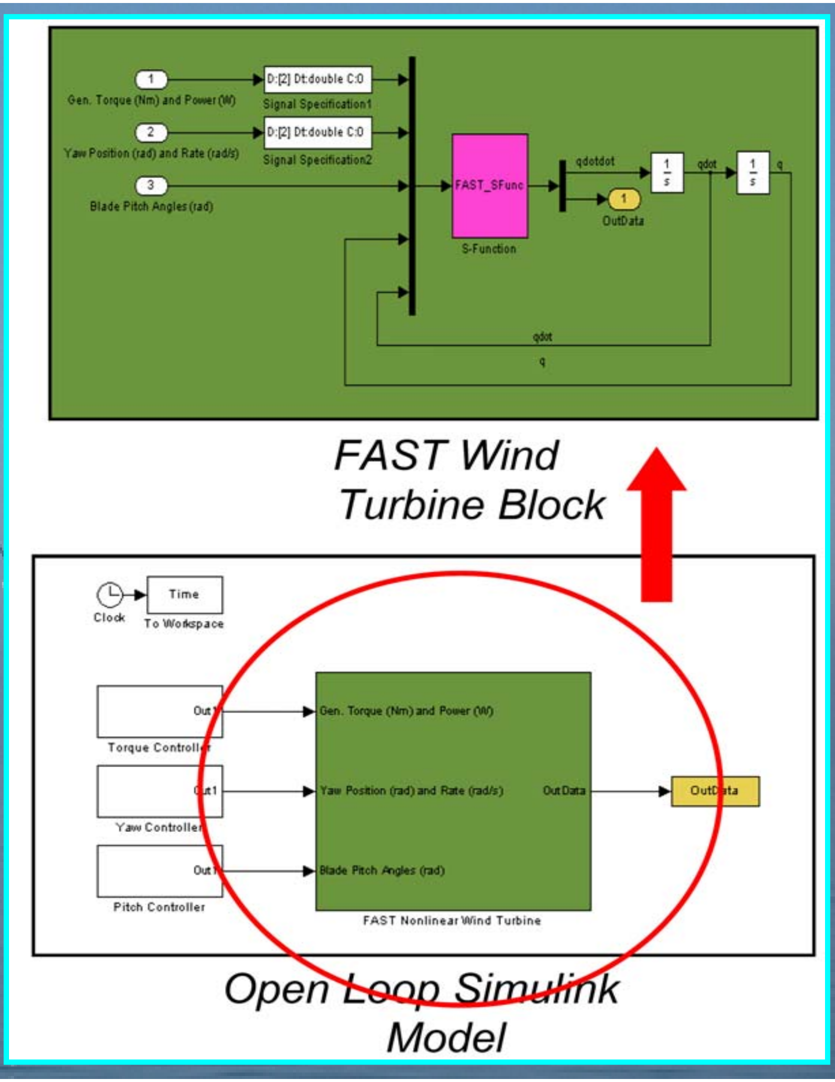
$$P_g(t) = \eta_g \omega_g(t) \tau_g(t),$$

Simulink-based Scheme

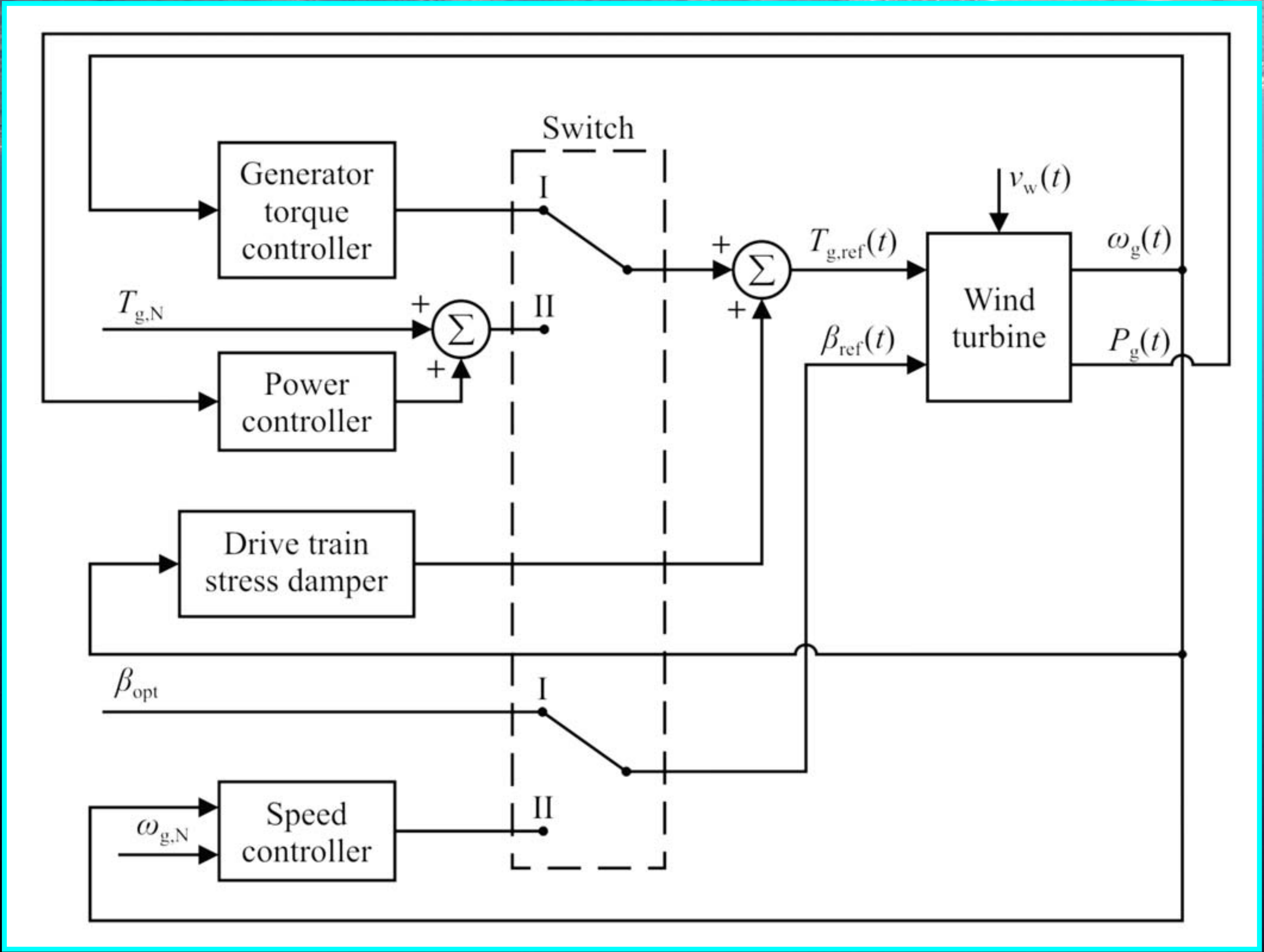


Turbine Model & Controller

- 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



- ✓ Approximates the configuration of an existing control system
- ✓ Used in the design of the fault diagnosis algorithms

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

Odgaard, P.F. ; Stoustrup, J. ; Kinnaert, M. Fault-Tolerant Control of Wind Turbines: A Benchmark Model. IEEE Transactions on Control Systems Technology, 2013

Fault Scenario (cont'd)

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

Odgaard, P.F. ; Stoustrup, J. ; Kinnaert, M. Fault-Tolerant Control of Wind Turbines: A Benchmark Model. IEEE Transactions on Control Systems Technology, 2013

FDI and FTC Solutions

- ✓ A competition in two parts was launch on the **WT benchmark model** (2009)
  - Part I on FDI: solutions were presented in two invited sessions at IFAC World Congress, Milan, Italy, **2011**
  - Part II on FTC: solutions were presented in two and a half invited sessions at IFAC Safeprocess, Mexico City, Mexico, **2012**
  - Three prizes sponsored by kk-electronic a/s and Mathworks

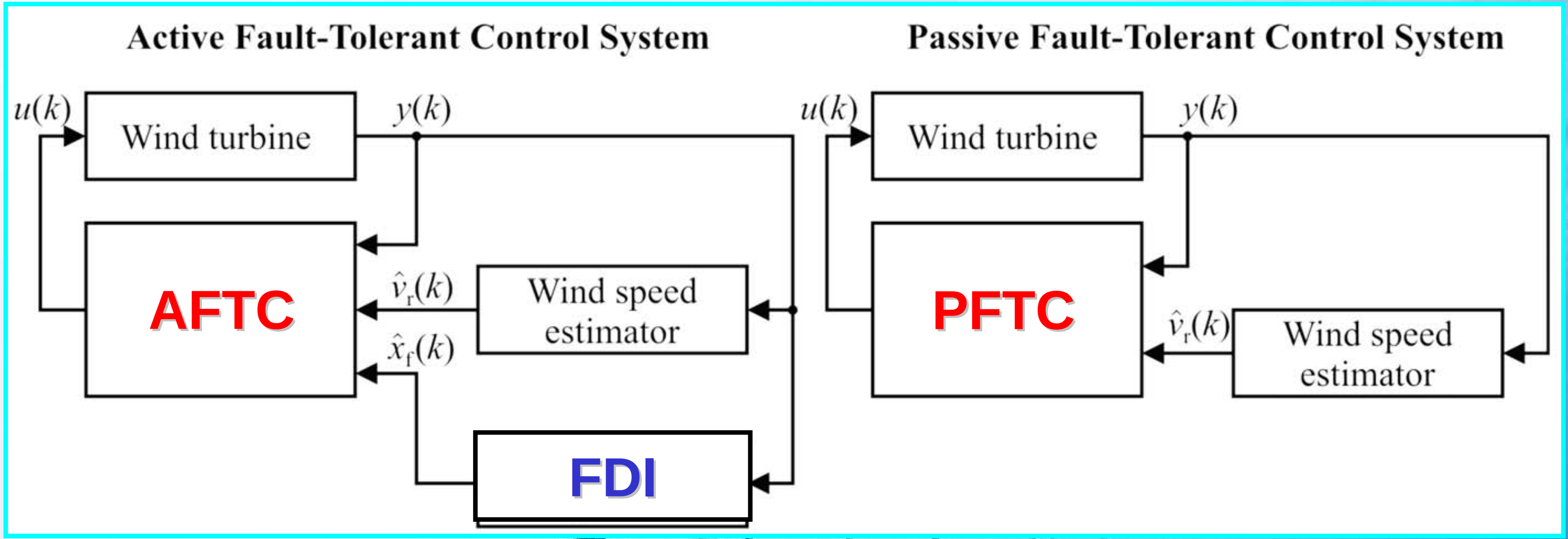
http://www.kk-electronic.com/wind-turbine-control/competition-on-fault-detection.aspx

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)

http://www.kk-electronic.com/wind-turbine-control/competition-on-fault-detection.aspx

Active and Passive FTC



Active FTC	Passive FTC
Dependent on fault diagnosis	Independent of fault diagnosis
Reconfigures according faults	Robust w.r.t. faults

Conclusion

- ✓ **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

FDI/FTC recent challenges

Recent Challenges

- ✓ **Original benchmark model is combined with NREL's FAST** with a more detailed aerodynamic and structural model
- ✓ Contributions were submitted as invited session at **ACC 2013** (June 17–19, Washington, DC)
- ✓ A benchmark model for FDI and FTC of wind turbines on a **wind farm level** have been proposed, and a new competition in two parts – **FDI and FTC have been launched and running**
- ✓ **FDI solutions** under evaluation for the next **CDC 2013** (December 10-13, Florence, Italy)
- ✓ Prizes sponsored by MathWorks and kk-electronic

Open Research Issues