Fault Detection, Isolation and Fault-Tolerant Control of Wind Turbines

A Takagi-Sugeno and Sliding Mode Approach

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Overview

1. Motivation and Problem Formulation
2. Fault Tolerant Control (FTC) Architecture for Wind Turbine and Sustainable Power Systems
3. Review of Takagi-Sugeno and Sliding Mode Approaches
4. Fault Detection, Isolation and FTC on *Component Level*, *Power plant level* and *Network Level*
5. Conclusion

1. Motivation and Problem Formulation

Motivation

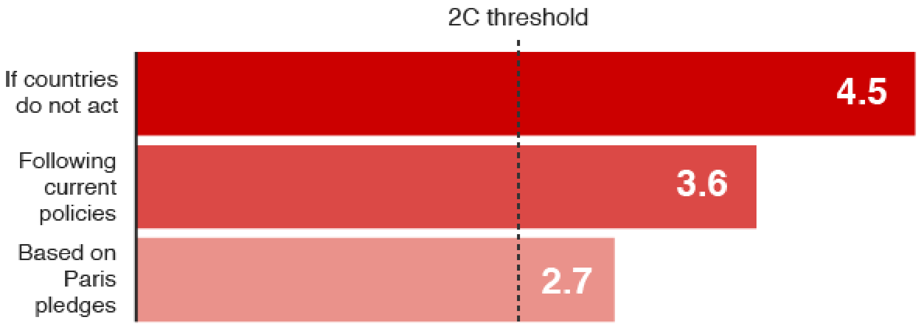
- **Global climate agreement** has been finalised in Paris 12/12/2015
- **Key elements** are
  - To keep global temperatures "well below" 2.0°C (3.6F) and "endeavour to limit" them even more, to 1.5°C
  - To limit the amount of greenhouse gases emitted by human activity to the same levels that trees, soil and oceans can absorb naturally, beginning at some point between 2050 and 2100
  - For rich countries to help poorer nations by providing "climate finance" to adapt to climate change and switch to renewable energy.

PARIS2015
CONFÉRENCE DES NATIONS UNIES
SUR LES CHANGEMENTS CLIMATIQUES
COP21·CMP11

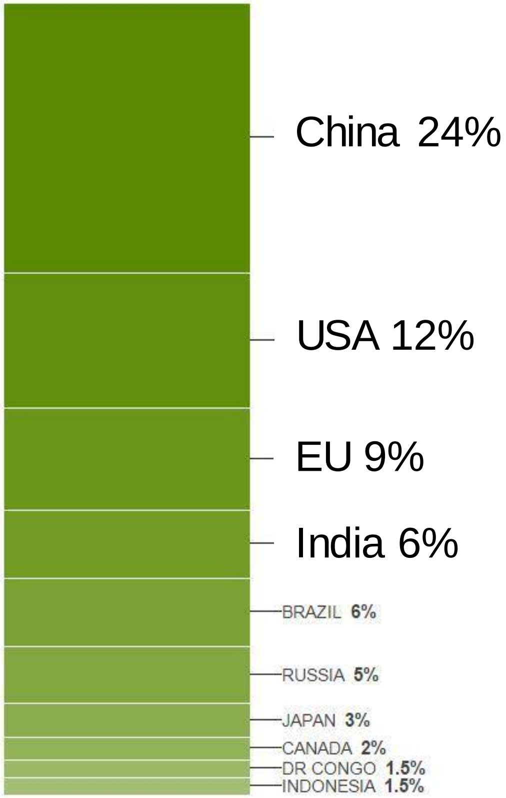
1. Motivation and Problem Formulation

Motivation

- **Global climate agreement** has been finalised in Paris 12/12/2015
- **Import is that**
  - The top 10 greenhouse gas emitters make up over 70% of total emissions
  - Comparison of average warming



Source: Climate Action Tracker, data compiled by Climate Analytics, ECOFYS, New Climate Institute and Potsdam Institute for Climate Impact Research.

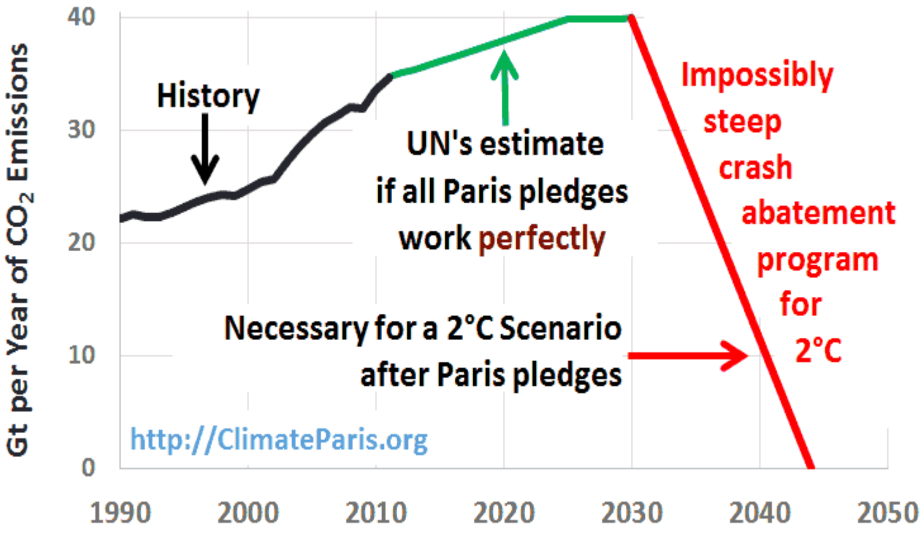


Source: Carbon Brief, figures are for 2012

1. Motivation and Problem Formulation

Motivation

- But the **agreement must be stepped up** if it is to have any chance of curbing dangerous climate change

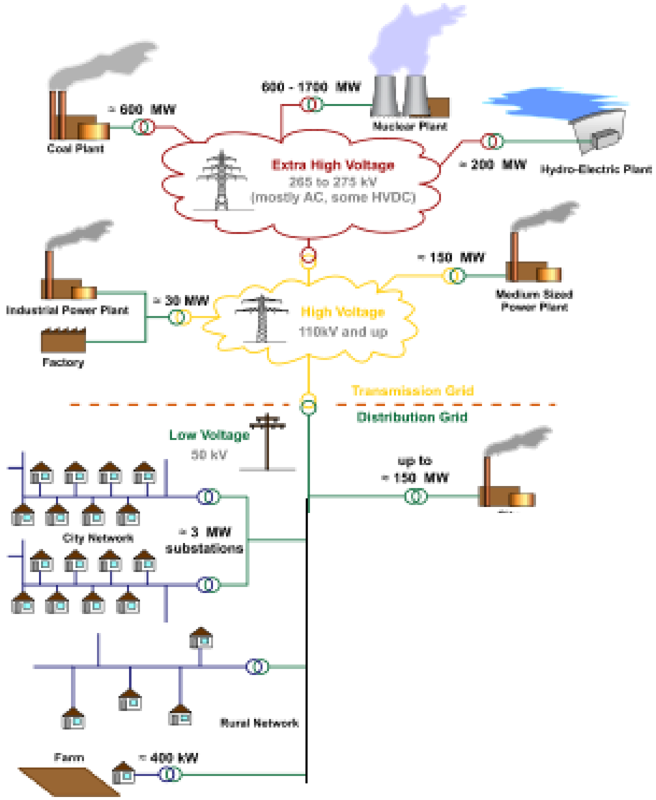


- That means i.e. a rapid expansion and total switch to <u>renewable energy</u>

1. Motivation and Problem Formulation

Motivation

- total switch to <u>renewable energy systems</u> has a couple of consequences



1. Motivation and Problem Formulation

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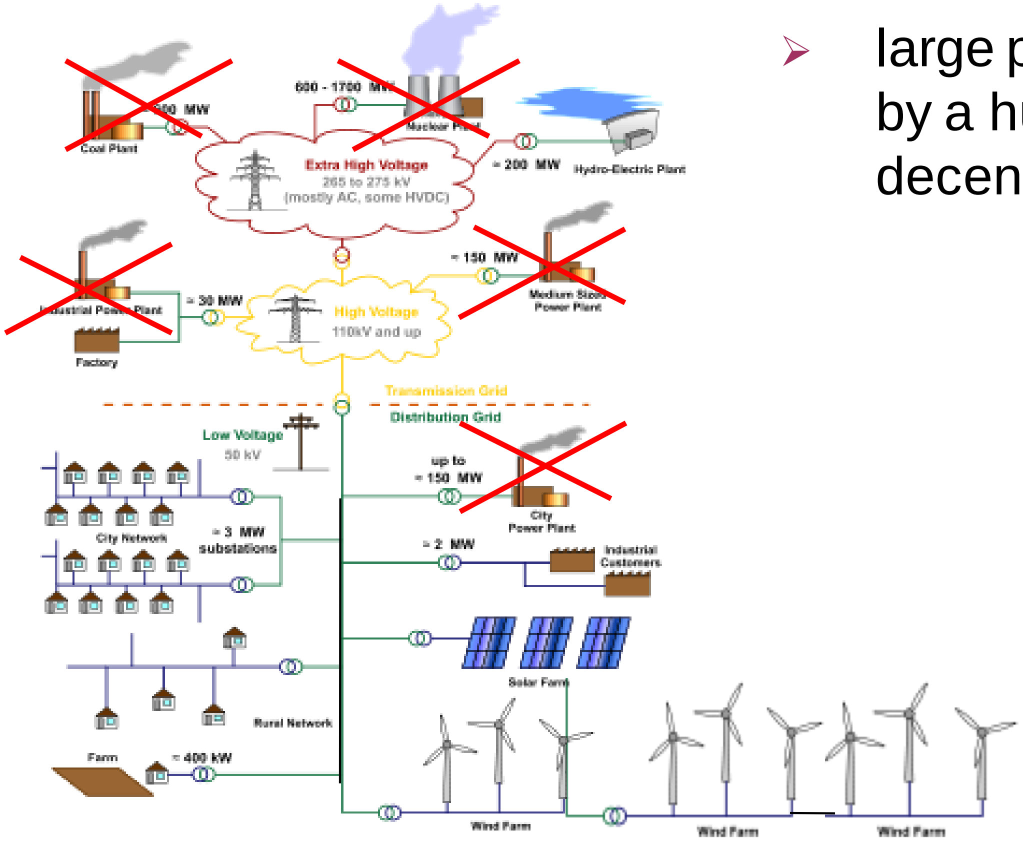

➢ large power plants are replaced by a huge number of small decentralized power sources

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Motivation

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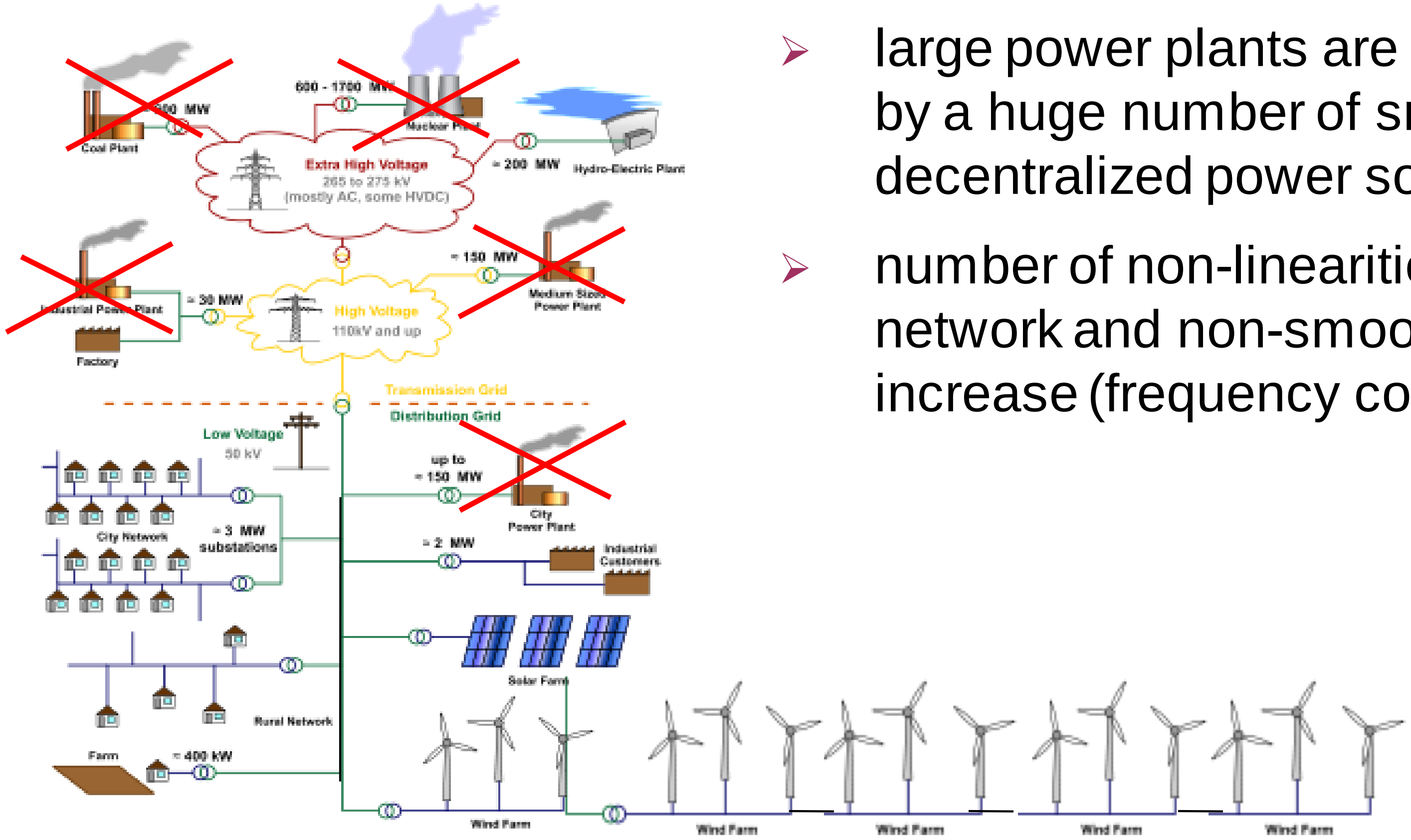

- ➢ large power plants are replaced by a huge number of small decentralized power sources
- ➢ number of non-linearities in the network and non-smoothness increase (frequency converter)

1. Motivation and Problem Formulation

Motivation

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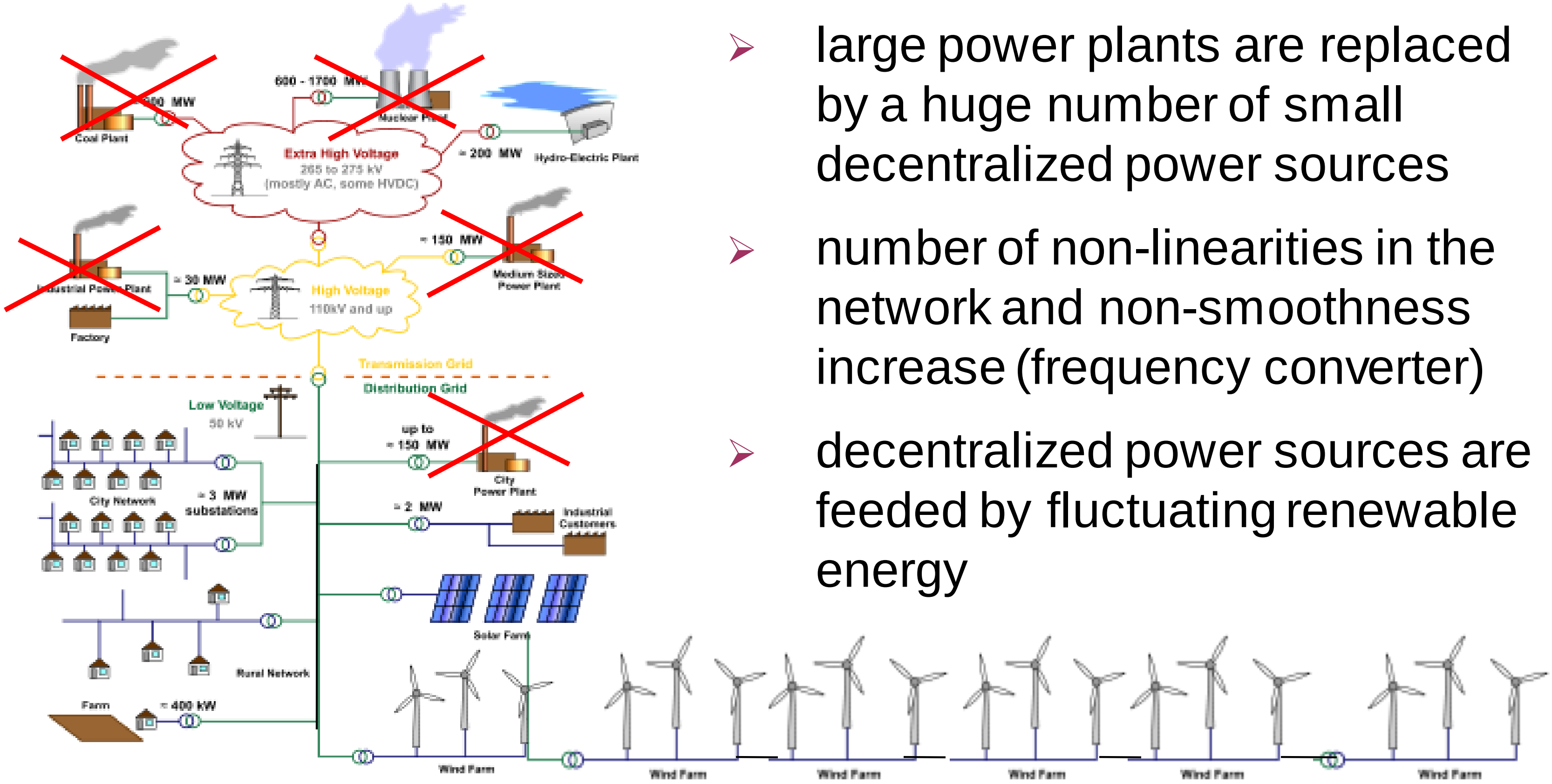


- ➢ large power plants are replaced by a huge number of small decentralized power sources
- ➢ number of non-linearities in the network and non-smoothness increase (frequency converter)
- ➢ decentralized power sources are feeded by fluctuating renewable energy

1. Motivation and Problem Formulation

Renewable Energy Systems

Classification	Technical realization	Open problems	Possible solutions
energy conversion	• **wind turbines** • photo voltaic systems • wave-energy	• **failure probability increase** • **lifetime is to short** • **cost of energy is to high**	• mitigation of induced loads • **FDI and FTC**
energy distribution	• power network with different voltage levels	• control of strongly increasing number of RE sources	• distributed control • fault tolerant control (FTC)
storage	• battery, • flywheel energy storage • power to x	• long-term storage energy density	• active energy management • new materials
load	• private consumers • Industrial consumers • Infrastructure and transportation	• loads have to participate in the regulation process	• smart meetering • distributed control over networks with signal latency

1. Motivation and Problem Formulation

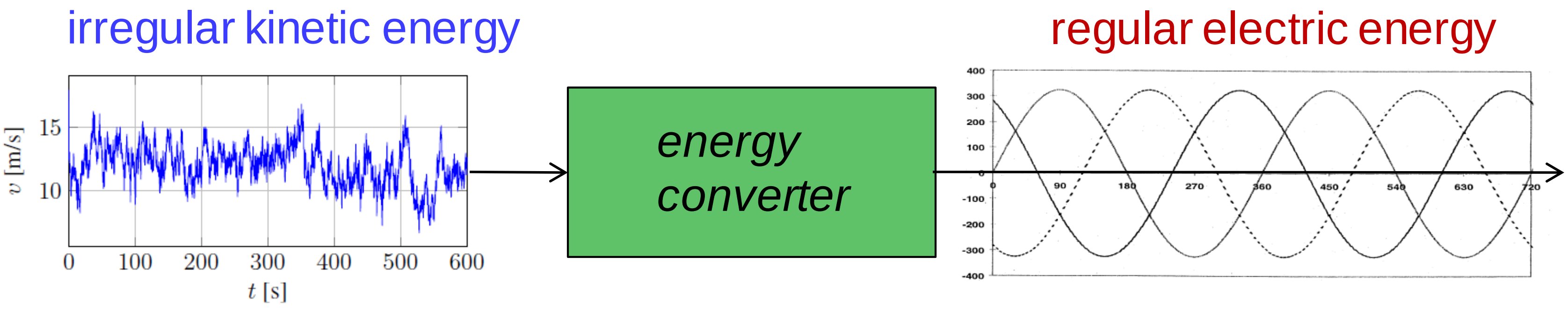
Energy converter : {wind energy system, PV system, …}

- fluctuating renewable energy (1) is converted into three-phase electrical power system (2) with fixed voltage and frequency (50Hz /60Hz)

  1) geothermal-, wind- , solar-, wave-, tidal-, wind-energy

  2) three-phase electrical system:

     - ➢ straightforward AC/AC transformation and distribution
     - ➢ rotating field generation



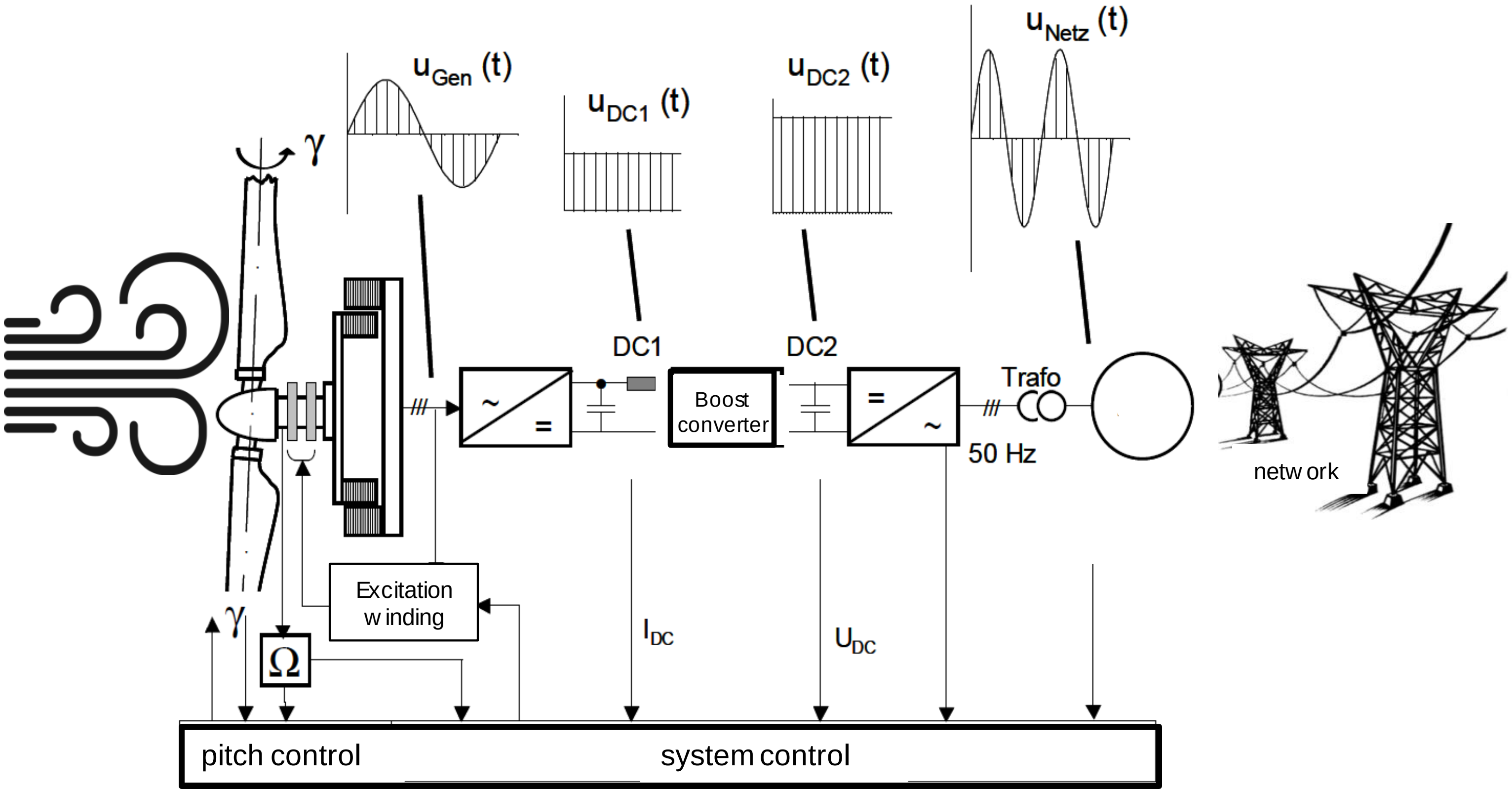
irregular kinetic energy

energy converter

regular electric energy

1. Motivation and Problem Formulation

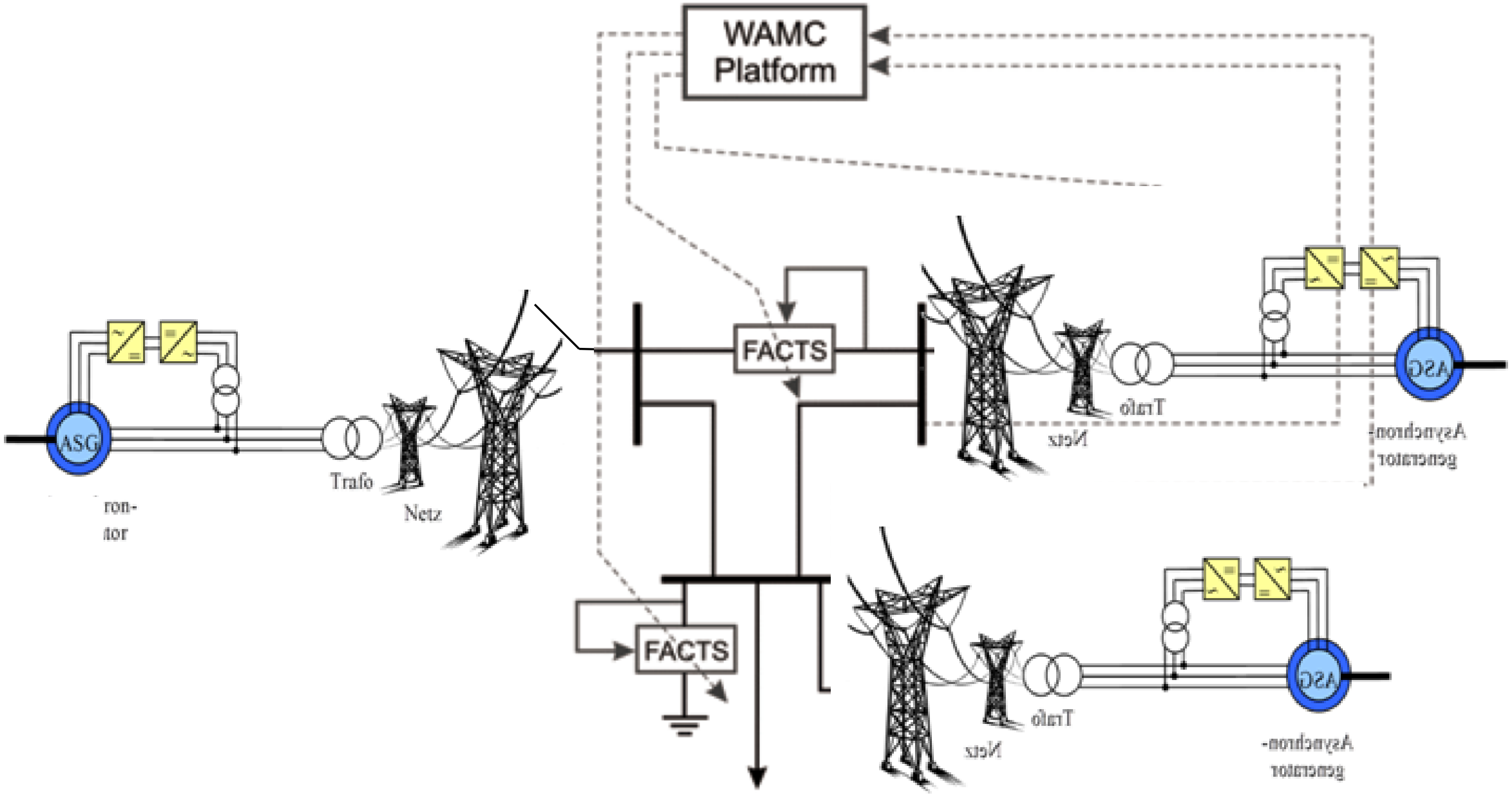
Energy conversion by means of Wind energy systems



→ AC/DC → DC/DC → DC/AC → AC/AC →

1. Motivation and Problem Formulation

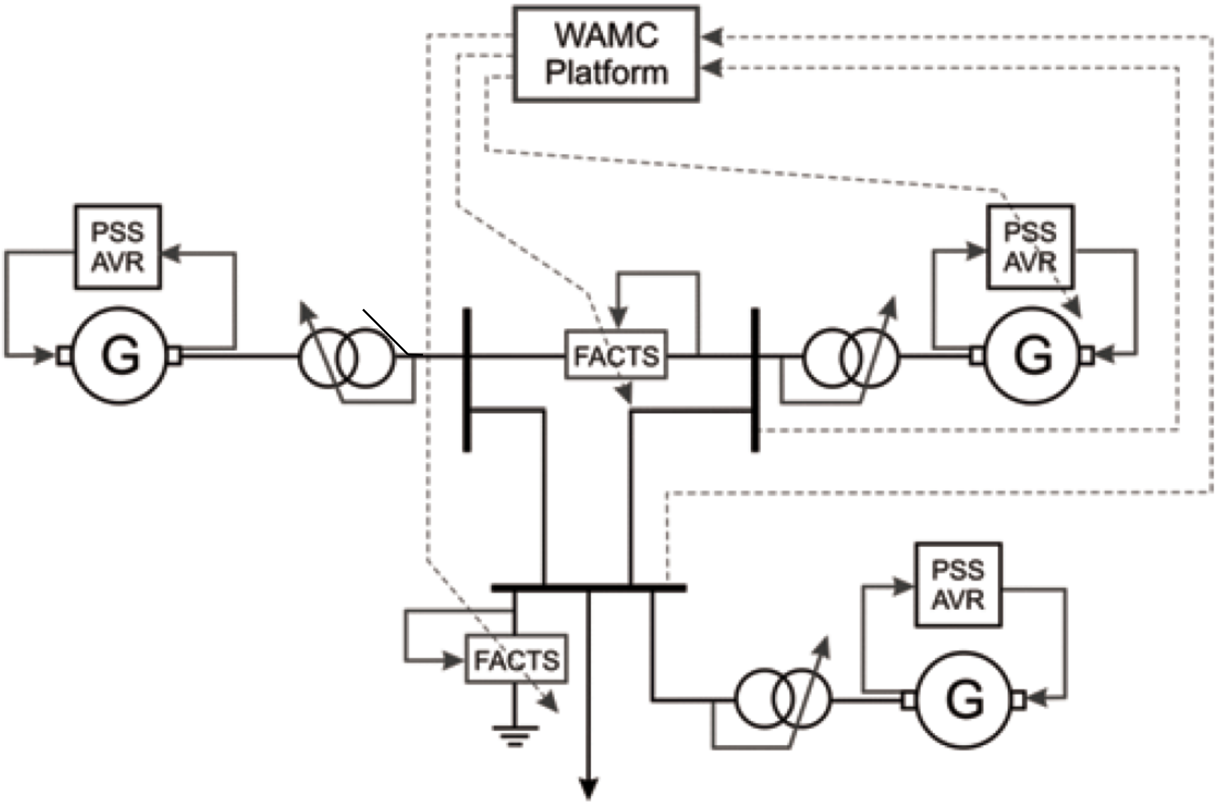
Electrical Power network



- WAMC: wide area monitoring and control

1. Motivation and Problem Formulation

Electrical Power network

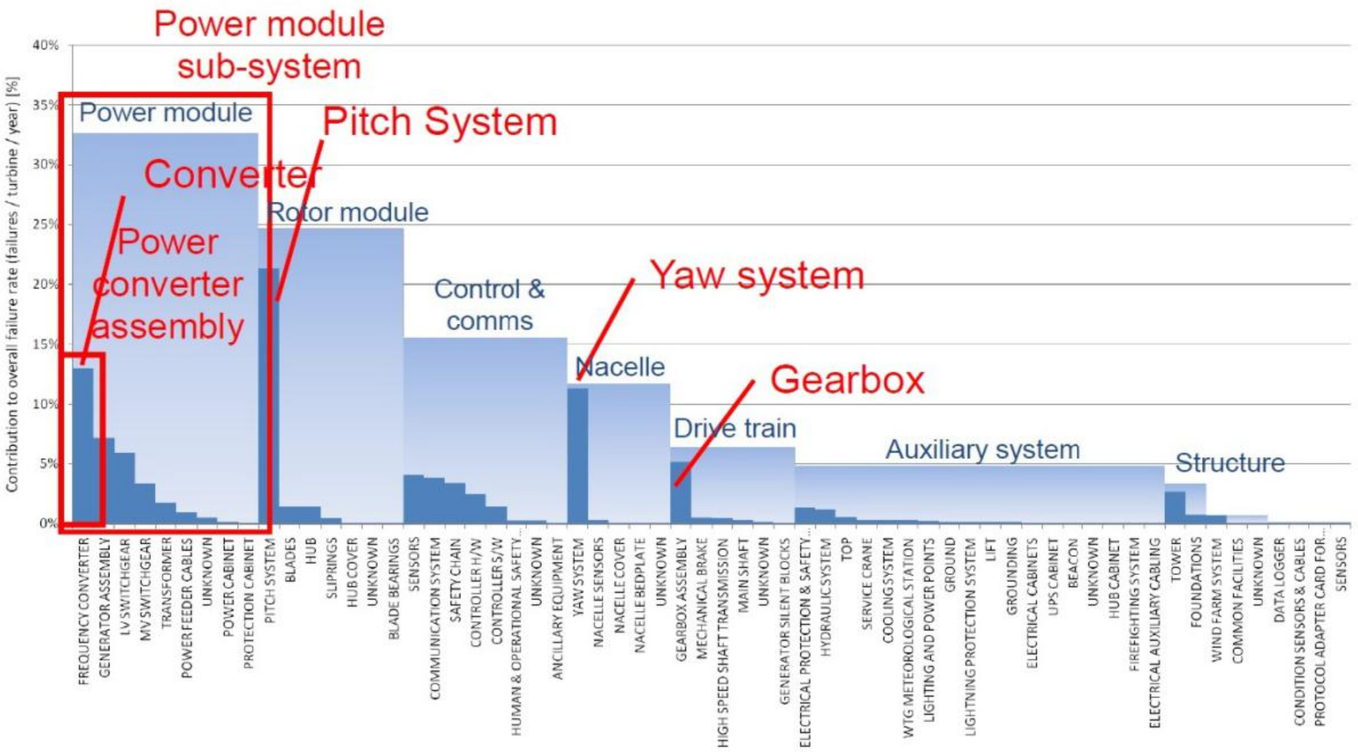


- WAMC: wide area monitoring and control
- AVR: automatic voltage regulation; PSS: power system stabilizer

1. Motivation and Problem Formulation

Need for fault tolerant control: Wind energy systems

Normalized failure rate related to different subsystems [1]



[1] Reliawind Project, FP7 Energy, 2008-03-15 to 2011-03-14

1. Motivation and Problem Formulation

Need for fault tolerant control: Electrical power network

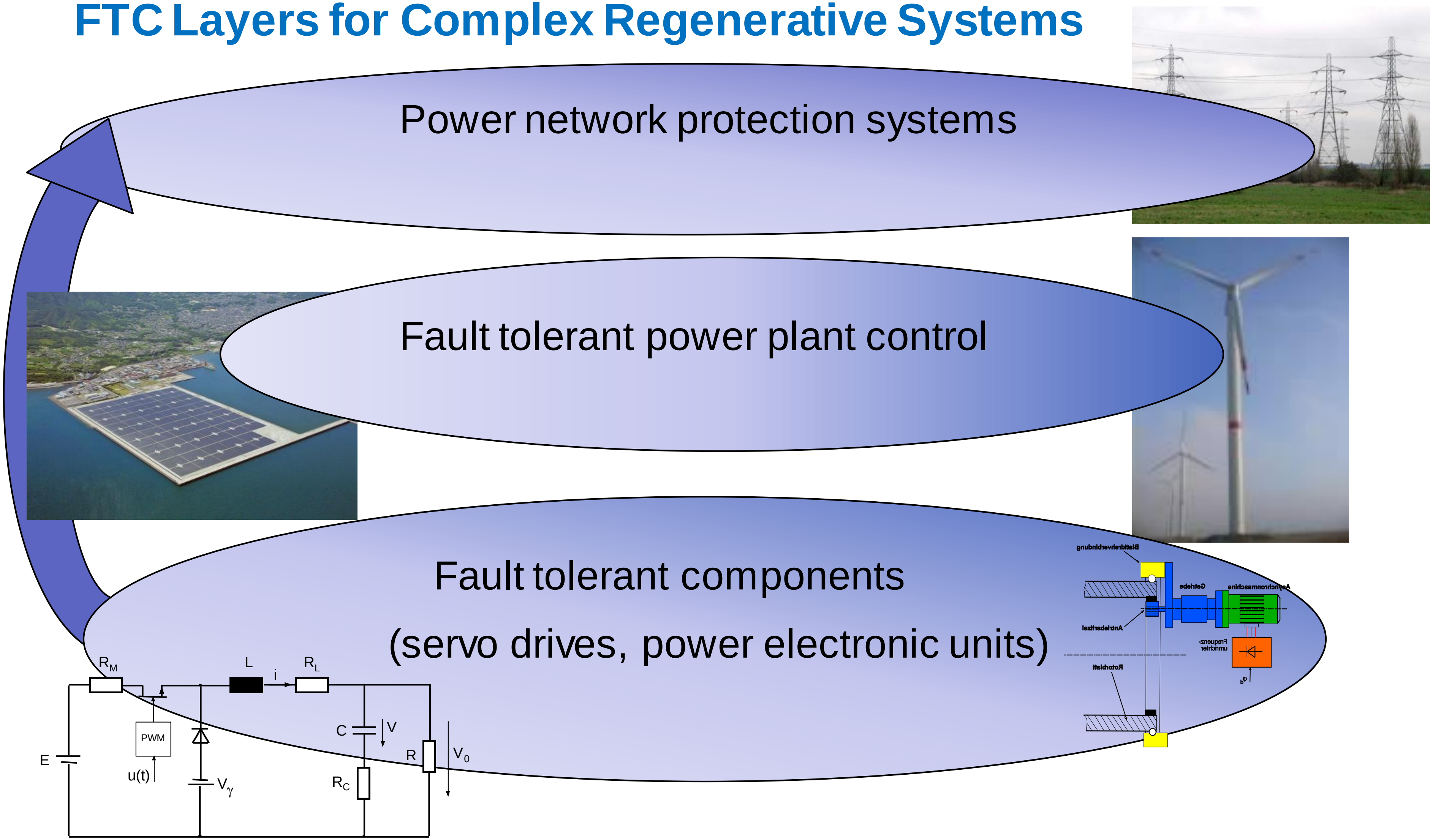
- Electric power networks (EPN) are the backbone of contemporary technical civilization
- EPN is a vast structure embracing a huge number of *generators in conventional and icreasing number of regenerative power plants*
  - hundreds of thousand kilometers of lines
  - thousand of transformators and power electronic devices connected in the grid
- From the very beginning electric power systems had to be protected against faults and other abnormal phenomena (embedded fault tolerance)
- Example of earlier electro-mechanical protection

  - overcurrent

  - undervoltage relays actuated by r.m.s or mean values of rectified signals

2. Fault Tolerant Control Architecture

FTC Layers for Complex Regenerative Systems



Power network protection systems

Fault tolerant power plant control

Fault tolerant components

(servo drives, power electronic units)

2. Fault Tolerant Control Architecture

FTC methods: Requirements

1.) **Robustness** due to uncertainty in power system dynamics

- loads and renewable generation can never be known precisely
- To ensure robust performance, controller design must take into account plausible parameter ranges and system conditions
- challenge due to the nonlinear, nonsmooth, large-scale nature of power systems

$$\dot{\boldsymbol{x}}(t) = \sum_{i=1}^{N_r} h_i(\boldsymbol{z}(t))\Big((\boldsymbol{A}_i + \Delta\boldsymbol{A}_i)\boldsymbol{x}(t) + (\boldsymbol{B}_i + \Delta\boldsymbol{B}_i)\boldsymbol{u}(t) + \boldsymbol{D}_i\boldsymbol{\xi}(t) + \boldsymbol{E}_i\boldsymbol{f}_a(t)\Big)$$

$$\boldsymbol{y}(t) = \sum_{i=1}^{N_r} h_i(\boldsymbol{z}(t))\Big((\boldsymbol{C}_i + \Delta\boldsymbol{C}_i)\boldsymbol{x}(t) + (\boldsymbol{H}_i + \Delta\boldsymbol{H}_i)\boldsymbol{u}(t) + \boldsymbol{F}_i\boldsymbol{\xi}(t) + \boldsymbol{f}_s(t)\Big) \quad ,$$

2. Fault Tolerant Control Architecture

FTC methods: Requirements

2.) **Systematic Design Process**: from linear to nonlinear design

- Scalability
- Consideration of various faults

3.) **Computability**: Synthesis of FTC via computable algorithms

- LMI formulation
- Riccati Equations

2. Fault Tolerant Control Architecture

FTC methods: Review

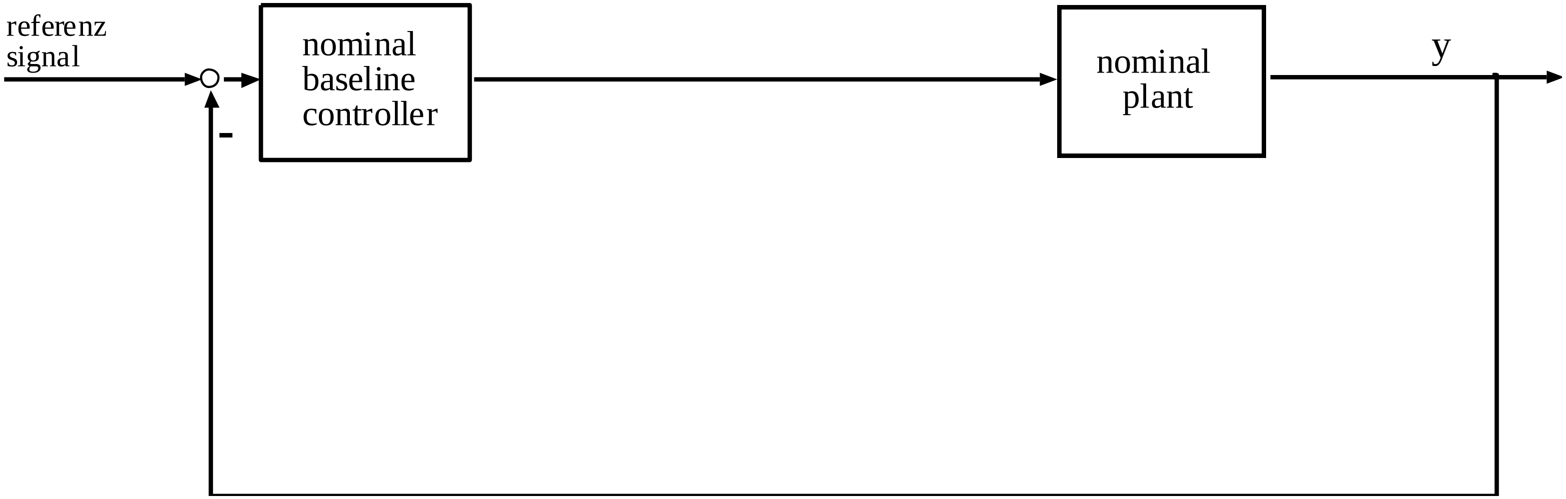
- there are **several approaches to fault tolerant control** (FTC), i.e. [Patton,1997] , [Zhang and Jiang, 2003], [Blanke et al., 2006], [Noura, Theilliol et. Al, 2009]
- FTC can be broadly categorised into **passive** (PFTC) and **active approaches** (AFTC)

- AFTC methods, one can distinguish between fault accomodation and control reconfiguration
  - **Fault accomodation** means the adaptation of the controller parameters to the faulty plant
  - **Control reconfiguration** may involve the use of a different control structure altogether, like different inputs and outputs.

2. Fault Tolerant Control Architecture

FTC methods: Control reconfiguration

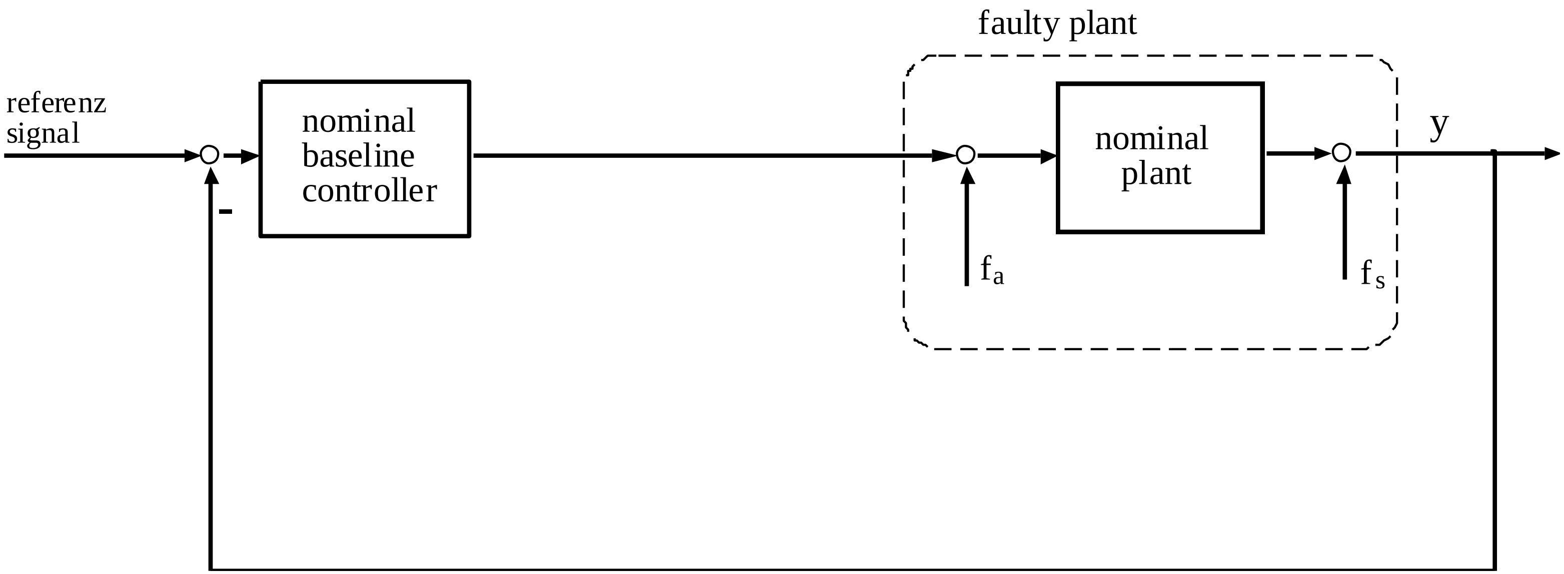
- Fault Tolerant Control architecture



2. Fault Tolerant Control Architecture

FTC methods: Control reconfiguration

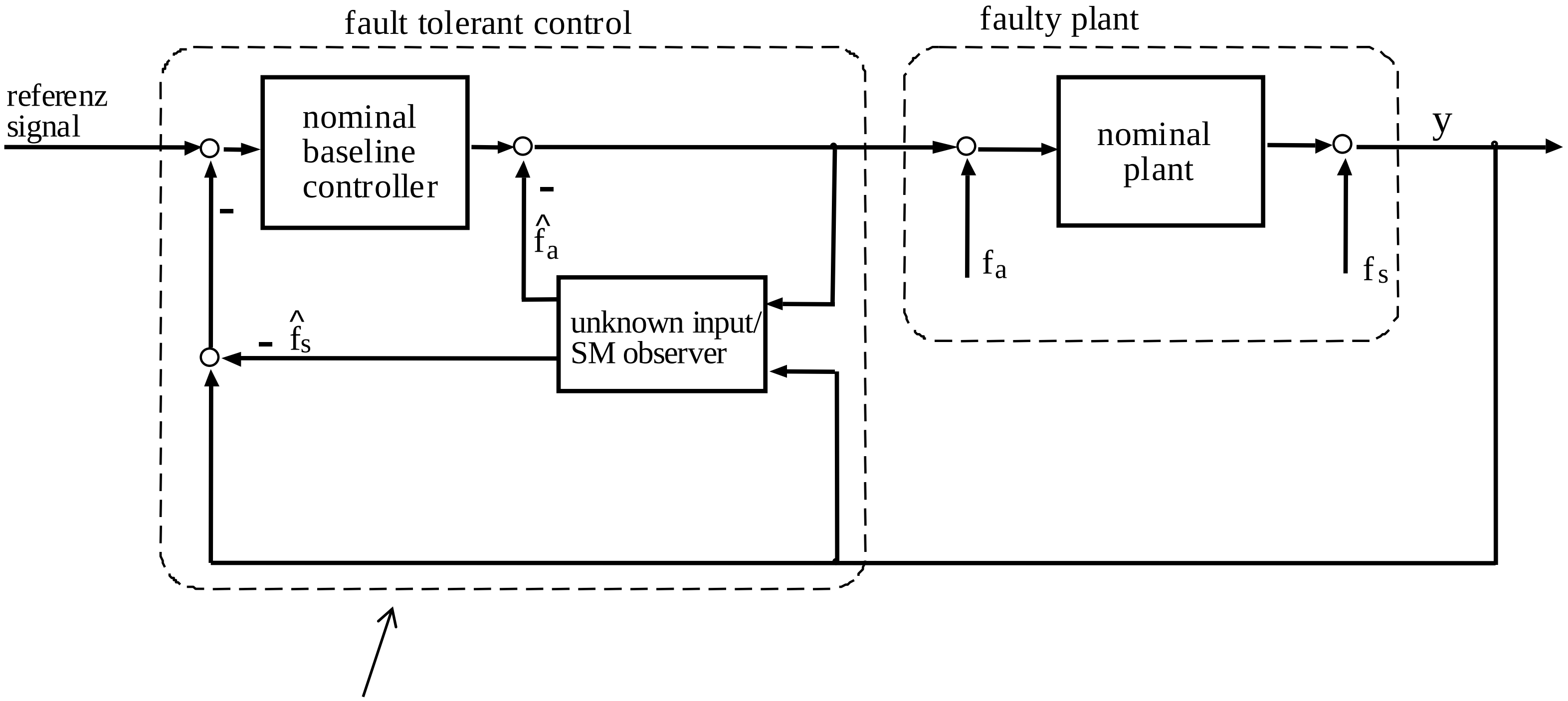
- Fault Tolerant Control architecture



2. Fault Tolerant Control Architecture

FTC methods: Control reconfiguration

- Fault Tolerant Control architecture

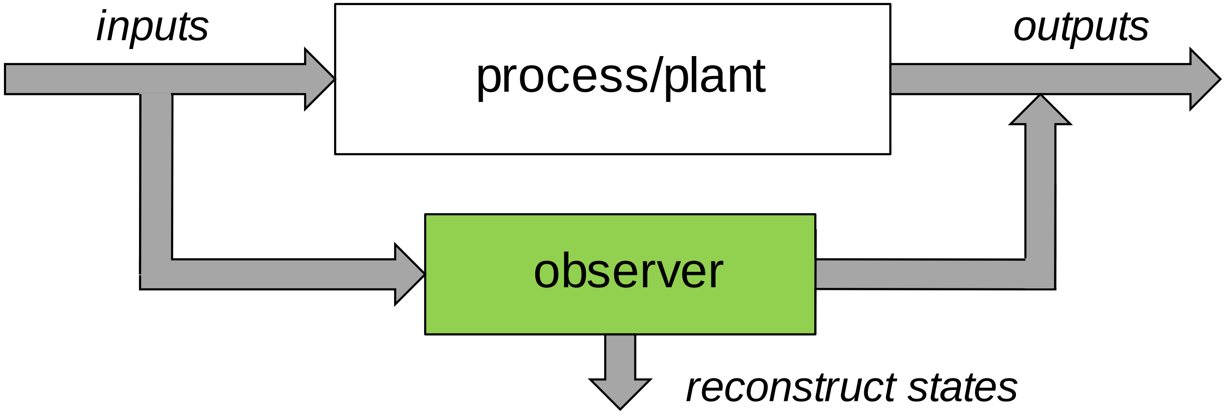


extension of the control structure

3. Review of Takagi-Sugeno and Sliding Mode Approach

Observer / Takagi-Sugeno (TS) Observer

- *Observer* is a dynamical system to reconstruct unmeasurable states
- Observer uses the available information on the *process inputs and outputs*



- *TS fuzzy observer* is a flexible structure to reconstruct unmeasurable states of nonlinear systems

3. Review of Takagi-Sugeno and Sliding Mode Approach

TS Fuzzy Observer

$$\dot{\hat{\mathbf{x}}} = \sum_{i=1}^{N_r} h_i(\mathbf{z}) \left(\mathbf{A}_i \, \hat{\mathbf{x}} + \mathbf{B}_i \, \mathbf{u} + \mathbf{a}_i + \mathbf{L}_i \left(\mathbf{y} - \hat{\mathbf{y}}\right)\right)$$

- Condtion 1: nonlinear plant/process have to formulated as a TS fuzzy system
- Condition 2: the vector of premise variables may comprise states, inputs, and external variables χ

$$\mathbf{z} = \mathbf{z}\left(\mathbf{x}, \mathbf{u}, \chi\right)$$

- Condition 3: membership functions fulfill the conditions

$$\sum_{i=1}^{N_r} h_i(\mathbf{z}) = 1\,, \quad h_i(\mathbf{z}) \geq 0 \quad \forall\, i \in \{1, \ldots, N_r\}$$

3. Review of Takagi-Sugeno and Sliding Mode Approach

Sliding Mode Techniques (Utkin 1977, Edwards 2010 for LPV Systems)

- Nonlinear switching term establishes and maintains a motion on a so-called sliding surface => robustness
- **Takagi-Sugeno Sliding Mode Observer** (Gerland/Schulte et al. 2010)

$$\dot{\hat{\mathbf{x}}} = \sum_{i=1}^{N_r} h_i(\mathbf{z}) \left(\mathbf{A}_i \hat{\mathbf{x}} + \mathbf{B}_i \mathbf{u} - \underbrace{\mathbf{G}_{l,i}\, \mathbf{e}_y}_{\text{TS Luenberg term}} + \underbrace{\mathbf{G}_{n,i}\, \boldsymbol{\nu}}_{\text{switching term}} \right)$$

$$\boldsymbol{\nu} = -\rho \frac{\mathbf{P}_2\, \mathbf{e}_y}{\|\mathbf{P}_2\, \mathbf{e}_y\|} \quad , \quad \text{if } \mathbf{e}_y \neq \mathbf{0} \, ,$$

- Characteristics
  - necessary condition: $p > q$ where $p = \dim(\boldsymbol{u})$
  - robustness with simultaneous disturbances, uncertainties and fault

3. Review of Takagi-Sugeno and Sliding Mode Approach

Sliding Mode Techniques (Gerland/Schulte et al. 2010, Schulte 2015)

- **Takagi-Sugeno Sliding Mode Observer with unmeasurable z**

$$\dot{\hat{\mathbf{x}}} = \sum_{i=1}^{N_r} h_i(\hat{\mathbf{z}}) \left(\mathbf{A}_i \hat{\mathbf{x}} + \mathbf{B}_i \mathbf{u} - \mathbf{G}_{l,i}\, \mathbf{e}_y + \mathbf{G}_{n,i}\, \boldsymbol{\nu}\right)$$

$$\hat{\mathbf{z}} = \mathbf{f}(\hat{\mathbf{x}})$$

- vector of premise variables includes unmeasurable states
- unmeasurable states are reconstructed by the observer himself
- distinguish between: $\hat{\mathbf{z}} \neq \mathbf{z}$

3. Review of Takagi-Sugeno and Sliding Mode Approach

Error dynamics

- error dynamics in the case of unmeasurable premise variables

$$\dot{\mathbf{e}} = \sum_{i=1}^{N_r} h_i(\hat{\mathbf{z}})\Big((\mathbf{A}_i - \mathbf{L}_i\mathbf{C})\mathbf{e} + \mathbf{D}_i\,\boldsymbol{\xi}\Big)$$

apriori knowledge

with $\sum_{i=1}^{N_r} h_i(\hat{\mathbf{z}})\,\mathbf{D}_i\,\boldsymbol{\xi} = \Delta(\mathbf{z},\hat{\mathbf{z}},\mathbf{x},\mathbf{u})$

- error vector is seperated into *measurable* $\mathbf{e}_x$ and *unmeasurable error variables* $\mathbf{e}_y$

$$\dot{\hat{\mathbf{e}}}_x = \sum_{i=1}^{N_r} h_i(\hat{\mathbf{z}})\Big(\tilde{\mathbf{A}}_i\,\hat{\mathbf{e}}_x - \mathbf{G}_{l,i}\,\mathbf{e}_y - \rho\,\mathbf{G}_{n,i}\,\frac{\mathbf{P}_2\,\mathbf{e}_y}{||\mathbf{P}_2\,\mathbf{e}_y||}\Big)$$

3. Review of Takagi-Sugeno and Sliding Mode Approach

Observer Design

- **Condition 1** $\underbrace{\sum_{i=1}^{N_r}\left(h_i(\mathbf{z})-h_i(\hat{\mathbf{z}})\right)\left(\mathbf{A}_i\,\mathbf{x}+\mathbf{B}_i\,\mathbf{u}+\mathbf{a}_i\right)}_{\Delta=\Delta(\mathbf{z},\hat{\mathbf{z}},\mathbf{x},\mathbf{u})}$ unknown but bounded

  => upper bound determine the gain factor ρ to establish a sliding motion

- **Condition 2** All invariant zeros of **($\mathbf{A}_i$, $\mathbf{D}_i$, $\mathbf{C}$)** must lie in $\mathbb{C}_-$

- **Condition 3** q = rank(**C Di**) = rank(**Di**) must be fullfilled

<u>Condition 2 and 3 must be fullfilled</u> to decompose the error vector into measurable states (disturbed and undisturbed) and unmeasurable states

$$\begin{aligned}
\dot{\hat{\mathbf{x}}}_1 &= \sum_{i=1}^{N_r} h_i\,(\mathbf{z})\,\left(\boldsymbol{\mathcal{A}}_{11,i}\,\hat{\mathbf{x}}_1 + \boldsymbol{\mathcal{A}}_{12,i}\,\hat{\mathbf{y}} + \boldsymbol{\mathcal{B}}_{1,i}\,\mathbf{u} - \boldsymbol{\mathcal{A}}_{12,i}\,\tilde{\mathbf{e}}_y\right)\,, \\
\dot{\hat{\mathbf{y}}} &= \sum_{i=1}^{N_r} h_i\,(\mathbf{z})\,\left(\boldsymbol{\mathcal{A}}_{21,i}\,\hat{\mathbf{x}}_1 + \boldsymbol{\mathcal{A}}_{22,i}\,\hat{\mathbf{y}} + \boldsymbol{\mathcal{B}}_{2,i}\,\mathbf{u} - \left(\boldsymbol{\mathcal{A}}_{22,i} - \boldsymbol{\mathcal{A}}_{22}^{s}\right)\tilde{\mathbf{e}}_y + \boldsymbol{\nu}\right)
\end{aligned}$$

3. Review of Takagi-Sugeno and Sliding Mode Approach

Observer Design

- **Condition 1** $\underbrace{\sum_{i=1}^{N_r} \left(h_i(\mathbf{z}) - h_i(\hat{\mathbf{z}})\right)\left(\mathbf{A}_i\,\mathbf{x} + \mathbf{B}_i\,\mathbf{u} + \mathbf{a}_i\right)}_{\Delta=\Delta(\mathbf{z},\hat{\mathbf{z}},\mathbf{x},\mathbf{u})}$ unknown but bounded

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Condition 2 and 3 must be fullfilled to decompose the error vector into measurable states (disturbed and undisturbed) and unmeasurable states

$$\mathbf{G}_{l,i} = \mathbf{T}_i^{-1} \begin{pmatrix} \mathcal{A}_{12,i} \\ \mathcal{A}_{22,i} - \mathcal{A}_{22}^{s} \end{pmatrix}, \quad \mathbf{G}_{n,i} = \mathbf{T}_i^{-1} \begin{pmatrix} \mathbf{0}_{(n-p)\times p} \\ \mathbf{I}_p \end{pmatrix}$$

3. Review of Takagi-Sugeno and Sliding Mode Approach

Reconstruction of faults and unknown inputs

- reconstruction by <u>equivalent output injection (EOI) signal</u>

- it describes the average of the effort to maintain the sliding motion

$$\boldsymbol{\nu}_{\text{eq}} = -\rho \frac{\mathbf{P}_2\,\tilde{\mathbf{e}}_y}{\|\mathbf{P}_2\,\tilde{\mathbf{e}}_y\| + \delta} \quad , \qquad \delta << 1$$

- if the observer error reach the sliding motion then EOI is given by

$$\boldsymbol{\nu}_{\text{eq}} = \sum_{i=1}^{N_r} h_i(\mathbf{z}) \left[\boldsymbol{\mathcal{D}}_{2,i}\ \boldsymbol{\mathcal{F}}_{2,i}\right] \begin{pmatrix} \boldsymbol{\xi} \\ \mathbf{f}_a \end{pmatrix} \qquad \text{or}$$

$$\boldsymbol{\nu}_{\text{eq}} = -\left(\boldsymbol{\mathcal{A}}_{22}(\mathbf{z}) - \boldsymbol{\mathcal{A}}_{21}(\mathbf{z})\,\boldsymbol{\mathcal{A}}_{11}^{-1}(\mathbf{z})\,\boldsymbol{\mathcal{A}}_{12}(\mathbf{z})\right)\mathbf{f}_s$$

3. Review of Takagi-Sugeno and Sliding Mode Approach

Reconstruction of faults and unknown inputs

- actuator faults and unknown inputs can be reconstructed by

$$\begin{pmatrix} \hat{\boldsymbol{\xi}} \\ \hat{\mathbf{f}}_a \end{pmatrix} = \left[\boldsymbol{\mathcal{D}}_2(\mathbf{z}) \;\; \boldsymbol{\mathcal{F}}_2(\mathbf{z})\right]^+ \boldsymbol{\nu}_{\mathrm{eq}}$$

- sensor faults can be reconstructed by

$$\hat{\mathbf{f}}_s = -\boldsymbol{\mathcal{A}}_{\mathrm{FDI}}^{-1}(\mathbf{z})\, \boldsymbol{\nu}_{\mathrm{eq}}$$

if $\boldsymbol{\mathcal{A}}_{\mathrm{FDI}}(\mathbf{z}) := \left(\boldsymbol{\mathcal{A}}_{22}(\mathbf{z}) - \boldsymbol{\mathcal{A}}_{21}(\mathbf{z})\, \boldsymbol{\mathcal{A}}_{11}^{-1}(\mathbf{z})\, \boldsymbol{\mathcal{A}}_{12}(\mathbf{z})\right)$

is non-singular

4. FDI and FTC of Wind Turbine Systems

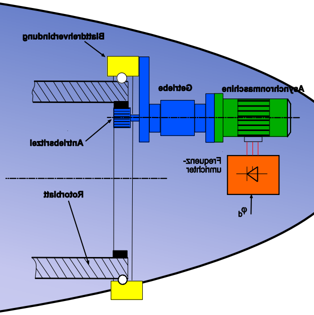
4.1 FDI and FTC on Component Level

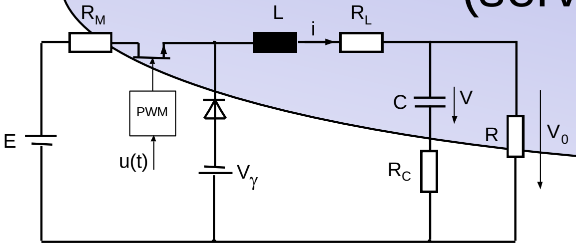
Power network protection systems

Fault tolerant power plant control

Fault tolerant components

(servo drives, power electronic units)





4. FDI and FTC of Wind Turbine Systems

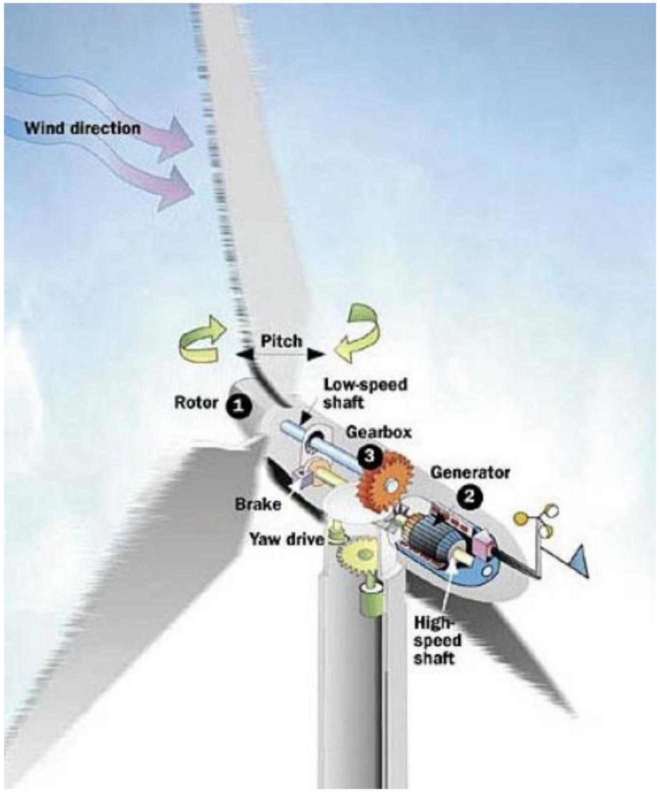
4.1 FDI and FTC on Component Level

Example: Electrical pitch drive of wind turbines

- Motivation

  - safty critical function: shut down

  - power/torque limitation in full-load region



4. FDI and FTC of Wind Turbine Systems

4.1 FDI and FTC on Component Level

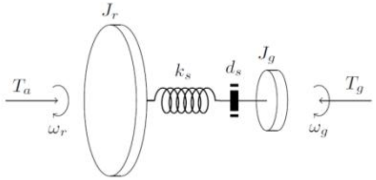
Example: Electrical pitch drive of wind turbines

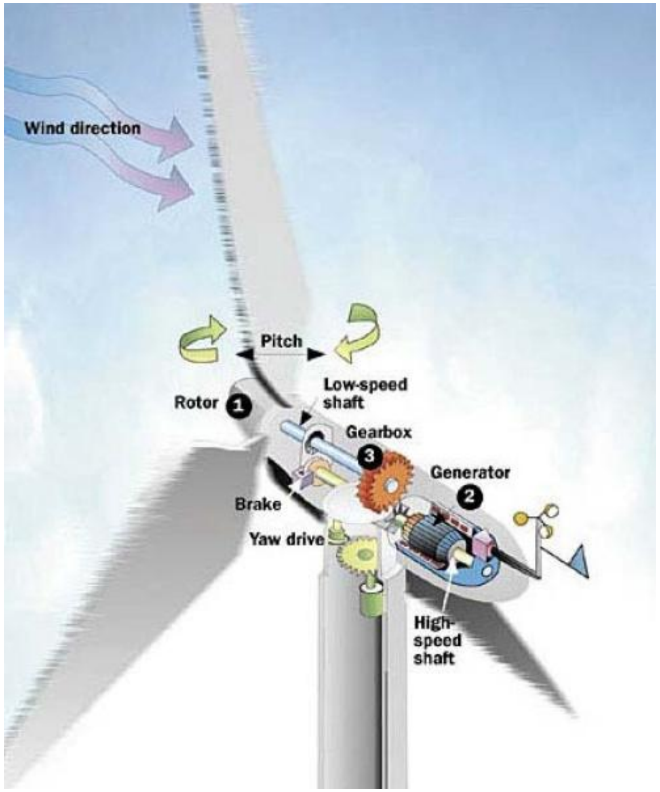
- Motivation

  - safty critical function: shut down

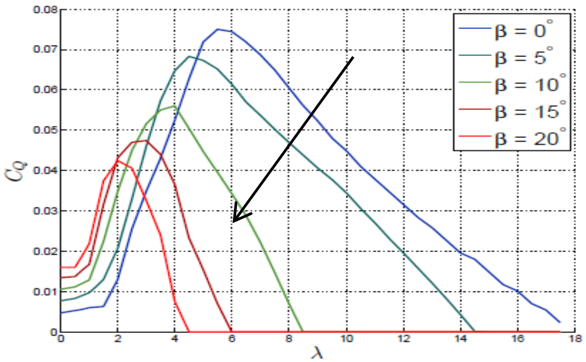
  - power/<u>torque limitation</u> in full-load region

$$T_a = \frac{1}{2}\rho\,\pi\,R^3\,C_Q(\lambda,\beta)\,v^2$$





  - reduction due to increasing pitch angle



4. FDI and FTC of Wind Turbine Systems

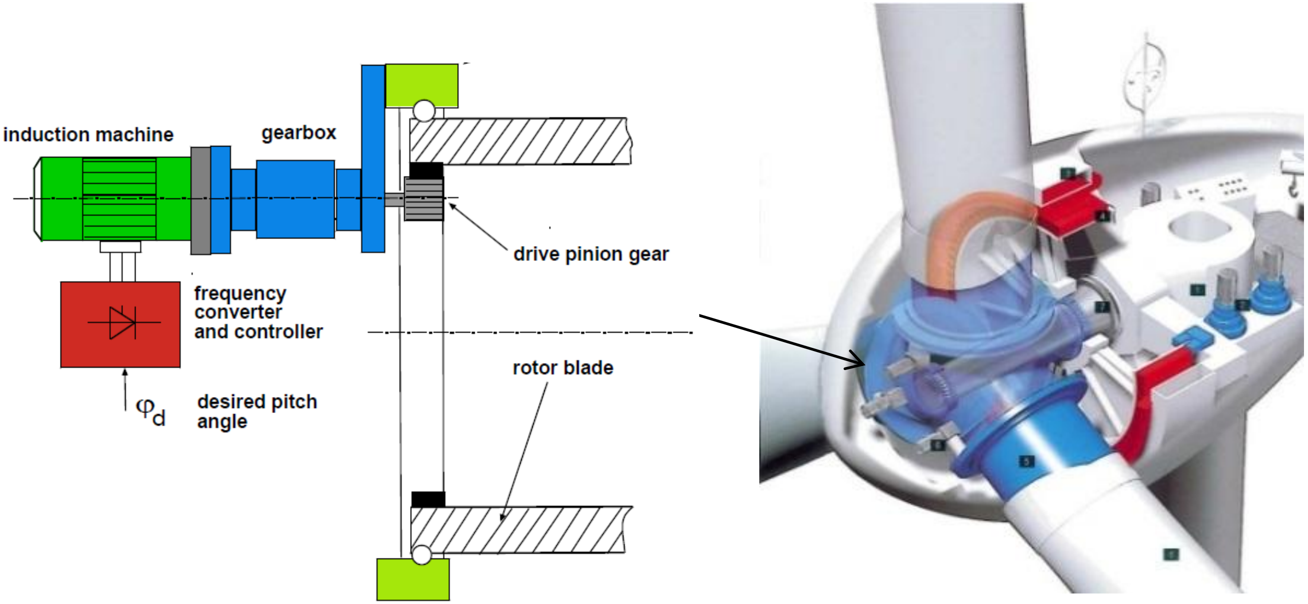
4.1 FDI and FTC on Component Level

Example: Electrical pitch drive of wind turbines

- Objectives

  - FDI/FTC of current sensor faults → component level

  - FDI/FTC pitch angle sensor fault → component or system level



4. FDI and FTC of Wind Turbine Systems

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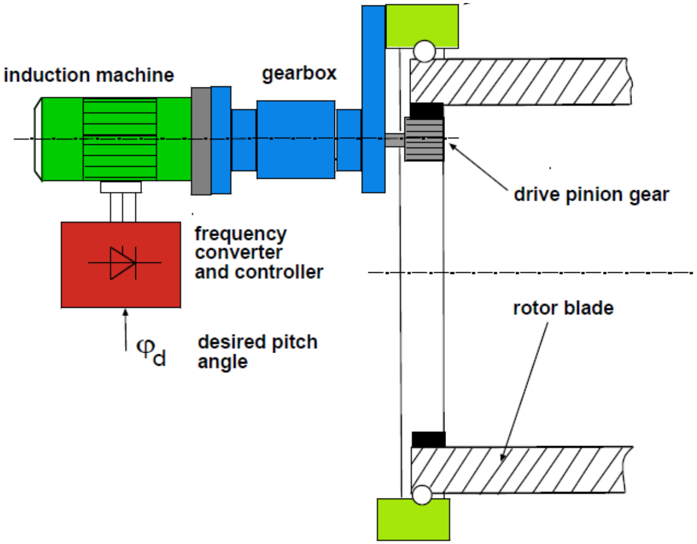


4. FDI and FTC of Wind Turbine Systems

4.1 FDI and FTC on Component Level

Example: Electrical pitch drive of wind turbines

- Approach [Schulte,Zajac, Gerland, SAFEPROCESS 2012]
  - model-based reconstruction of sensor faults by TS-SM Observer
  - sixth order model of induction machine with unknown load T_L

$$\begin{aligned}
\dot{x}_1 &= -\frac{R_S}{\sigma L_S}\left(x_1 - \frac{L_M}{L_R}\, x_3\right) + \omega_1\, x_2 + u_1 \\
\dot{x}_2 &= -\frac{R_S}{\sigma L_S}\left(x_2 - \frac{L_M}{L_R}\, x_4\right) - \omega_1\, x_1 + u_2 \\
\dot{x}_3 &= -\frac{R_R}{\sigma L_R}\left(x_3 - \frac{L_M}{L_S}\, x_1\right) + (\omega_1 - Z_P\, x_5)\, x_4 \\
\dot{x}_4 &= -\frac{R_R}{\sigma L_R}\left(x_4 - \frac{L_M}{L_S}\, x_2\right) - (\omega_1 - Z_P\, x_5)\, x_3 \\
\dot{x}_5 &= \frac{3}{2}\frac{Z_P}{J}\frac{L_M}{\sigma L_S L_R}(x_2\, x_3 - x_1\, x_4) - \frac{T_L}{i_g\, J} \\
\dot{x}_6 &= x_5
\end{aligned}$$

$$\boldsymbol{x} = [\, x_1\ x_2\ x_3\ x_4\ x_5\ x_6 \,]^T := [\, \Psi_{sd}\ \Psi_{sq}\ \Psi_{rd}\ \Psi_{rq}\ \omega_m\ \varphi_m \,]^T$$

$$\boldsymbol{u} = [\, u_1\ u_2 \,]^T := [\, u_{sd}\ u_{sq} \,]^T$$

$$\begin{aligned}
i_{SQ} &= \frac{1}{\sigma\, L_S}\, x_1 - \frac{L_M}{\sigma\, L_S\, L_R}\, x_3 \\
i_{SD} &= \frac{1}{\sigma\, L_S}\, x_2 - \frac{L_M}{\sigma\, L_S\, L_R}\, x_3
\end{aligned}$$

4. FDI and FTC of Wind Turbine Systems

4.1 FDI and FTC on Component Level

Example: Electrical pitch drive of wind turbines

- Observer Structure and Law
  - Reconstruction of current sensor faults by

$$\dot{\hat{\mathbf{x}}}(t) = \sum_{i=1}^{n_r} h_i(\boldsymbol{\alpha}(t))[\mathbf{A}_i\hat{\mathbf{x}}(t) + \mathbf{B}_i\mathbf{u}(t) - \mathbf{G}_{l,i}\mathbf{e}_{\tilde{y}}(t) + \mathbf{G}_{n,i}\boldsymbol{\nu}(t)]$$

$$\hat{\mathbf{y}}(t) = \mathbf{C}\hat{\mathbf{x}}(t)\,,$$

with

$$\mathbf{G}_{l,i} = \mathbf{T}_i^{-1}\begin{bmatrix} \boldsymbol{\mathcal{A}}_{12,i} \\ \boldsymbol{\mathcal{A}}_{22,i} - \boldsymbol{\mathcal{A}}_{22}^{s} \end{bmatrix},\ \mathbf{G}_{n,i} = \mathbf{T}_i^{-1}\begin{bmatrix} \mathbf{0}_{(n-p)\times p} \\ \mathbf{I}_p \end{bmatrix}$$

  - using **equivalent control** that maintain the sliding motion

$$\boldsymbol{\nu}(t) \approx \sum_{i=1}^{N_r}\sum_{j=1}^{N_r} h_i(\hat{\boldsymbol{\alpha}}(t))h_j(\hat{\boldsymbol{\alpha}}(t))\left[\boldsymbol{\mathcal{A}}_{FDI,ij}\ \boldsymbol{\mathcal{D}}_{2,i}\right]\begin{bmatrix} \boldsymbol{f}_s(t) \\ \boldsymbol{\xi}(t) \end{bmatrix} \quad\Bigg|\quad \hat{\boldsymbol{f}}_s(t) = \left[\sum_{i=1}^{N_r}\sum_{j=1}^{N_r} h_i(\hat{\boldsymbol{\alpha}}(t))h_j(\hat{\boldsymbol{\alpha}}(t))\boldsymbol{\mathcal{A}}_{FDI,ij}\right]^{-1}\boldsymbol{\nu}(t)$$

4. FDI and FTC of Wind Turbine Systems

4.1 FDI and FTC on Component Level

Example: Electrical pitch drive of wind turbines

- Results for a 1.2 MW turbine

$R_S = 0.8817\ [\Omega]$ $L_S = 0.1094\ [\mathrm{H}]$ $R_R = 0.4321\ [\Omega]$

$L_R = 0.1071\ [\mathrm{H}]$ $L_M = 0.1054\ [\Omega]$ $J_A = 0.4724\ [\mathrm{kg\ m^2}]$ $Z_P = 3$

$J_G = 0.2\ [\mathrm{kg\ m^2}]$ $i_g = 1200$ $J_B = 1977\ [\mathrm{kg\ m^2}]$

$\xi = [\,\xi_{min}\,,\,\xi_{max}\,] = \left[\,-5.27\cdot 10^4\,\mathrm{Nm}\,,\,5.27\cdot 10^4\,\mathrm{Nm}\right]$ uncertainty load bounds

linear observer gain : $\mathcal{A}_{22}^s = \begin{bmatrix} -10 & 0 & 0 & 0 \\ 0 & -10 & 0 & 0 \\ 0 & 0 & -10 & 0 \\ 0 & 0 & 0 & -10 \end{bmatrix}$ sliding mode gain: $\rho = 80$

$$\mathbf{G}_{l,i=1} = \boldsymbol{T}_i^{-1}\begin{bmatrix} \boldsymbol{\mathcal{A}}_{12,i=1} \\ \boldsymbol{\mathcal{A}}_{22,i=1} - \boldsymbol{\mathcal{A}}_{22}^s \end{bmatrix} = \begin{bmatrix} 4.3711e-003 & 3.8669e+001 & 0 & 0 \\ -3.8669e+001 & 4.3711e-003 & 0 & 0 \\ -1.3229e-003 & 3.9293e+001 & 0 & 0 \\ -3.9293e+001 & -1.3229e-003 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

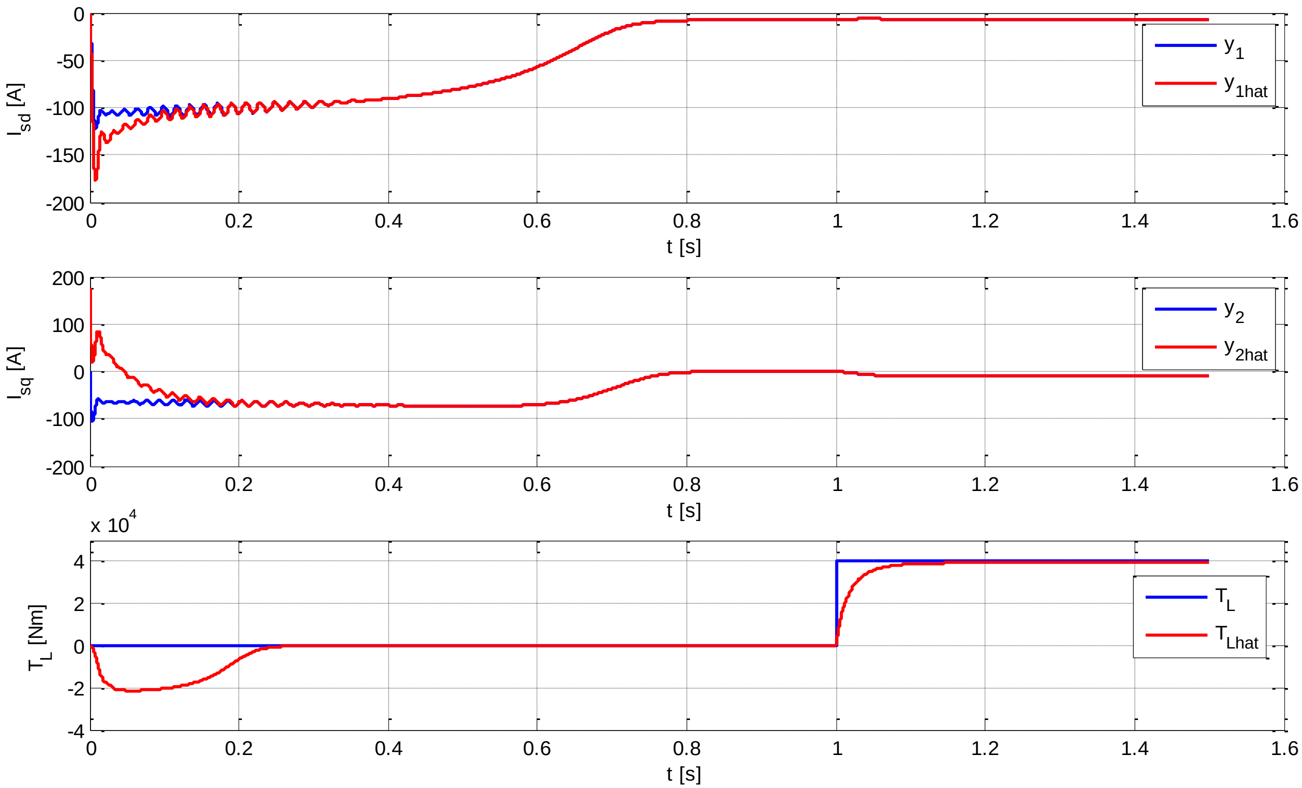
$$\mathbf{G}_{n,i=1} = \boldsymbol{T}_i^{-1}\begin{bmatrix} \mathbf{0}_{(n-p)\times p} \\ \mathbf{I}_p \end{bmatrix} = \begin{bmatrix} 1.4616e+004 & 3.8504e+002 & 0 & 0 \\ -3.8504e+002 & 1.4616e+004 & 4.4436e-012 & 0 \\ 1.4853e+004 & 2.3490e+002 & 3.0000e+000 & 0 \\ -2.3490e+002 & 1.4853e+004 & -3.0000e+000 & 0 \\ 6.3908e+004 & 6.3894e+004 & 1.0000e+001 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

4. FDI and FTC of Wind Turbines Systems

4.1 FDI and FTC on Component Level

Example: Electrical pitch drive of wind turbines

- without sensor faults, with external load step and load reconstruction

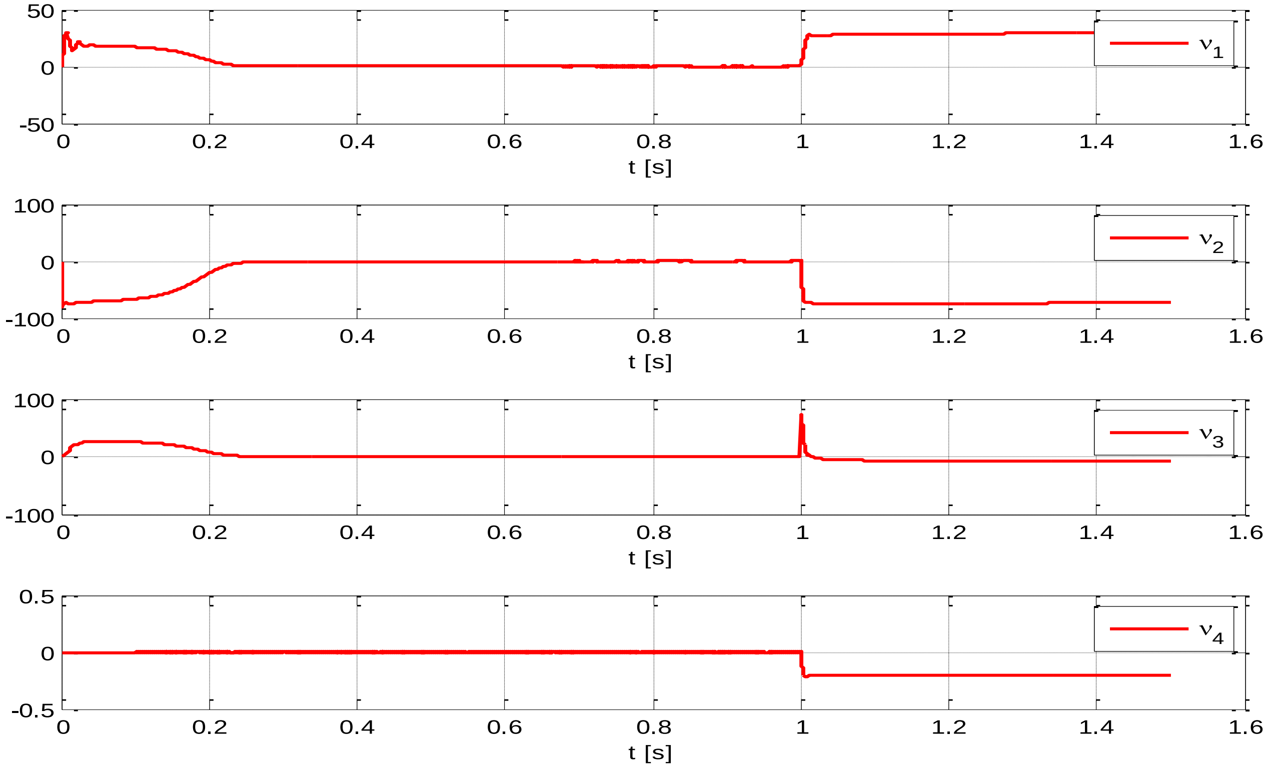


4. FDI and FTC of Wind Turbine Systems

4.1 FDI and FTC on Component Level

Example: Electrical pitch drive of wind turbines

- equivalent output error injection terms ν_{eq_i} of the sliding mode term

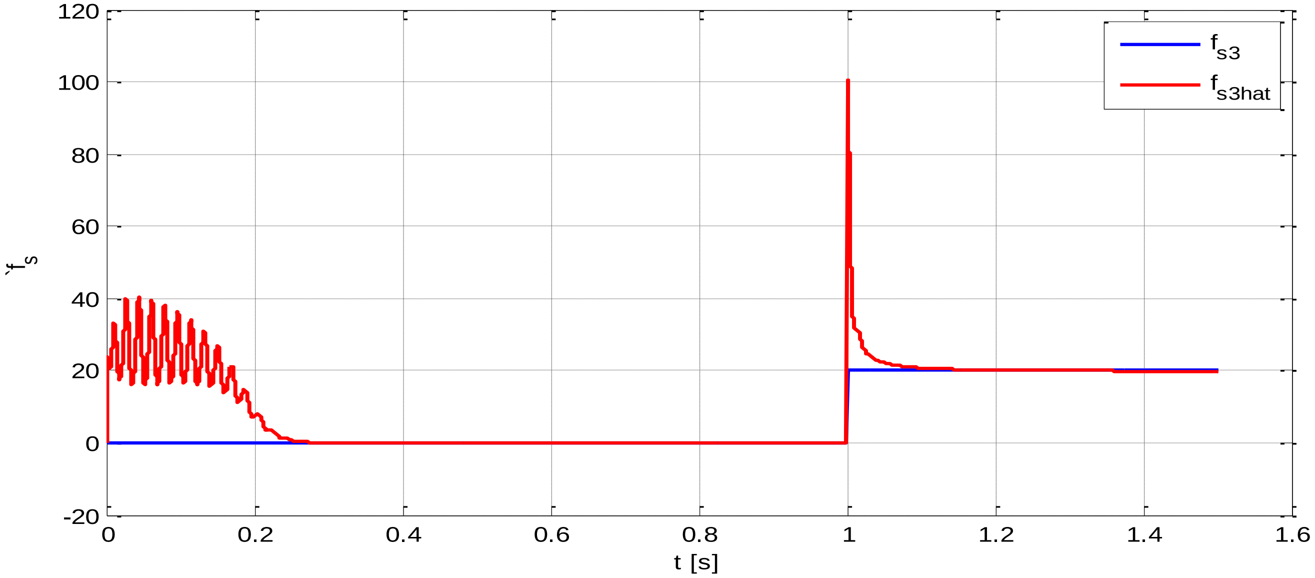


4. FDI and FTC of Wind Turbine Systems

4.1 FDI and FTC on Component Level

Example: Electrical pitch drive of wind turbines

- sensor fault and sensor fault reconstruction $\hat{\mathrm{f}}_s(t) = \mathscr{W}(\alpha(t))\boldsymbol{\nu}_{eq}(t)$



4. FDI and FTC of Wind Turbine Systems

4.2 FDI and FTC on Power Plant Level

Power network protection systems

Fault tolerant power plant control

Fault tolerant Components

(servo drives, power electronic units)

4. FDI and FTC of Wind Turbine Systems

4.2 FDI and FTC on Power Plant Level

- Objectives
- Partial- / full-load region
- Baseline Controller
- FTC scheme
- Results

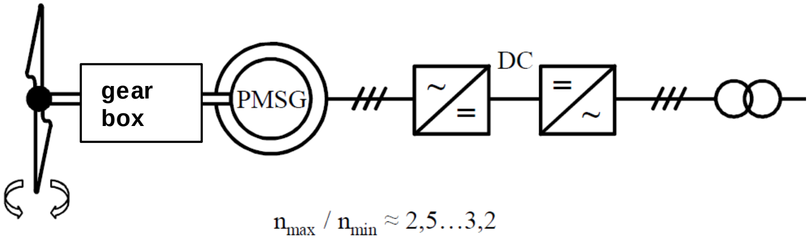
  - Simulation with Hardware-In-the Loop test-bed

4. FDI and FTC of Wind Turbine Systems

4.2 FDI and FTC on Power Plant Level

- **Objectives**: Increasing of availability and reliability
- Reduction of shutdowns caused by sensor and actuator faults

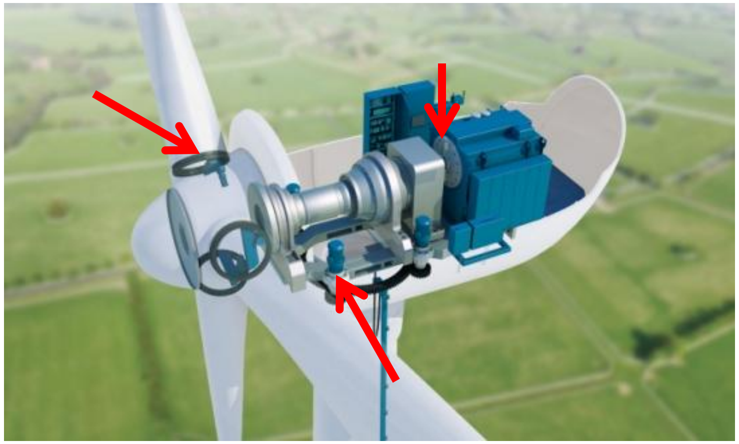
[Siemens 2012]



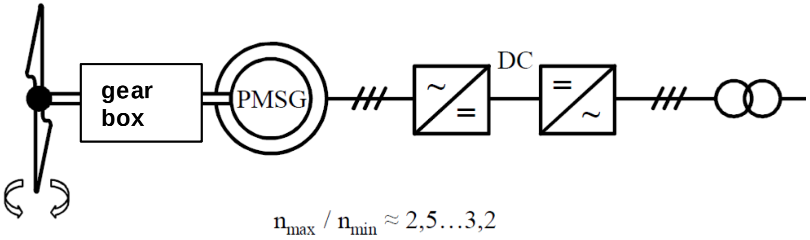
4. FDI and FTC of Wind Turbine Systems

4.2 FDI and FTC on Power Plant Level

- **Objectives**: Increasing of availability and reliability
- Reduction of shutdowns caused by sensor and actuator faults



[Siemens 2012]



sensors for control

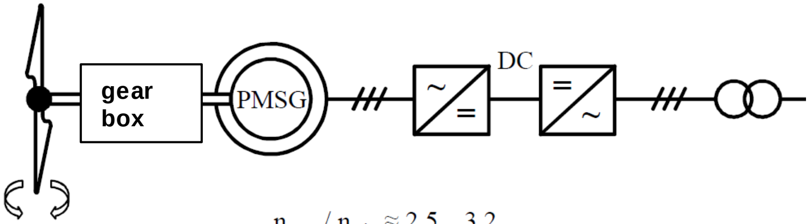
- pitch angle
- yaw angle
- generator speed

4. FDI and FTC of Wind Turbine Systems

4.2 FDI and FTC on Power Plant Level

- **Objectives**: Increasing of availability and reliability
- Reduction of shutdowns caused by sensor and actuator faults

[Siemens 2012]



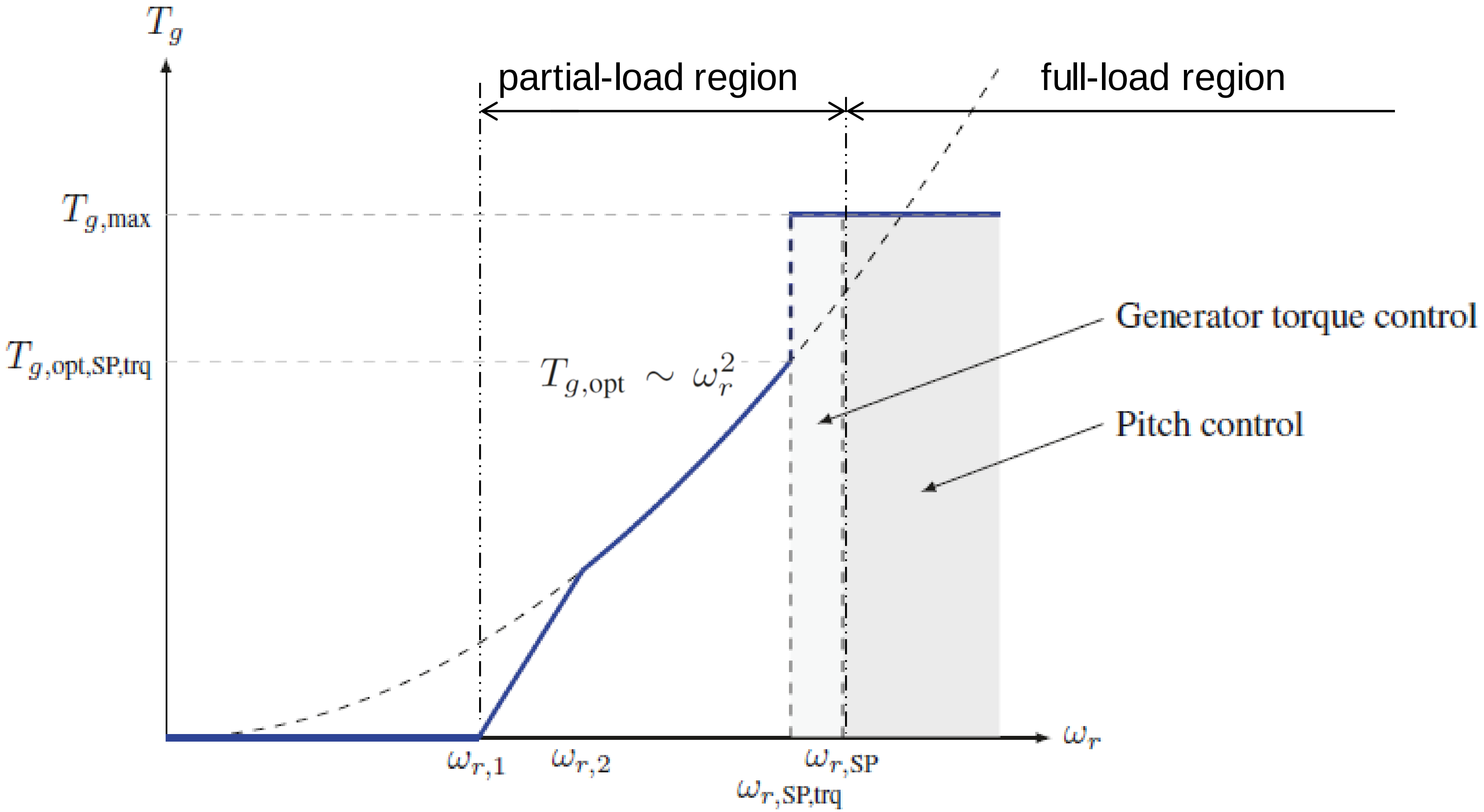
$n_{max} / n_{min} \approx 2,5\ldots3,2$

actuators for control

- pitch drives (full load)
- generator (partial load)

4. FDI and FTC of Wind Turbine Systems

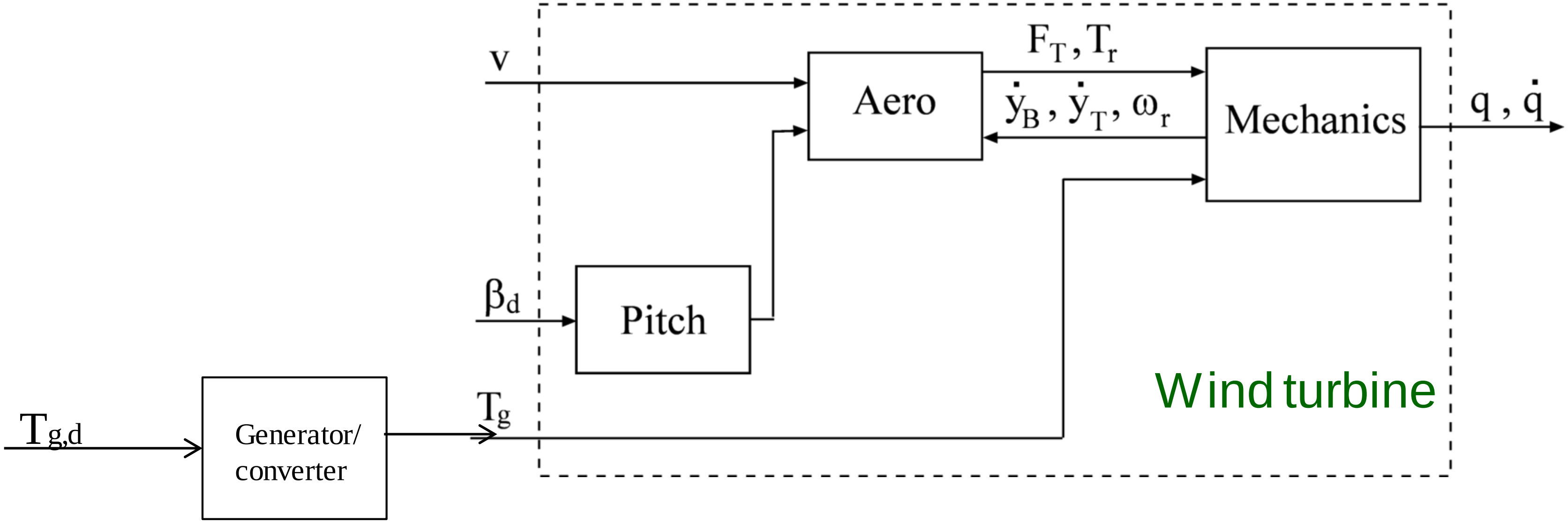
4.2 FDI and FTC on Power Plant Level



4. FDI and FTC of Wind Turbine Systems

4.2 FDI and FTC on Power Plant Level

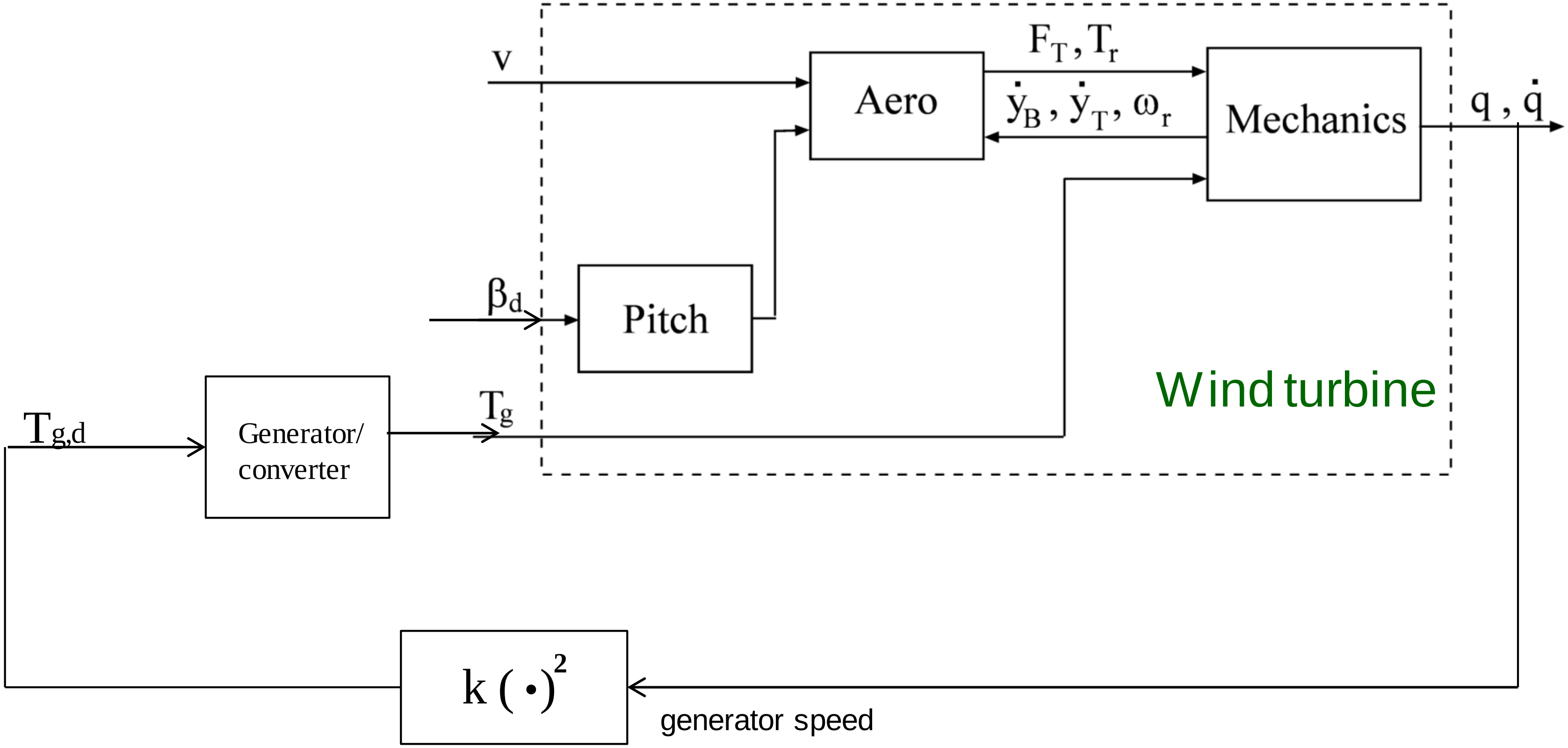
- **Baseline controller**



4. FDI and FTC of Wind Turbine Systems

4.2 FDI and FTC on Power Plant Level

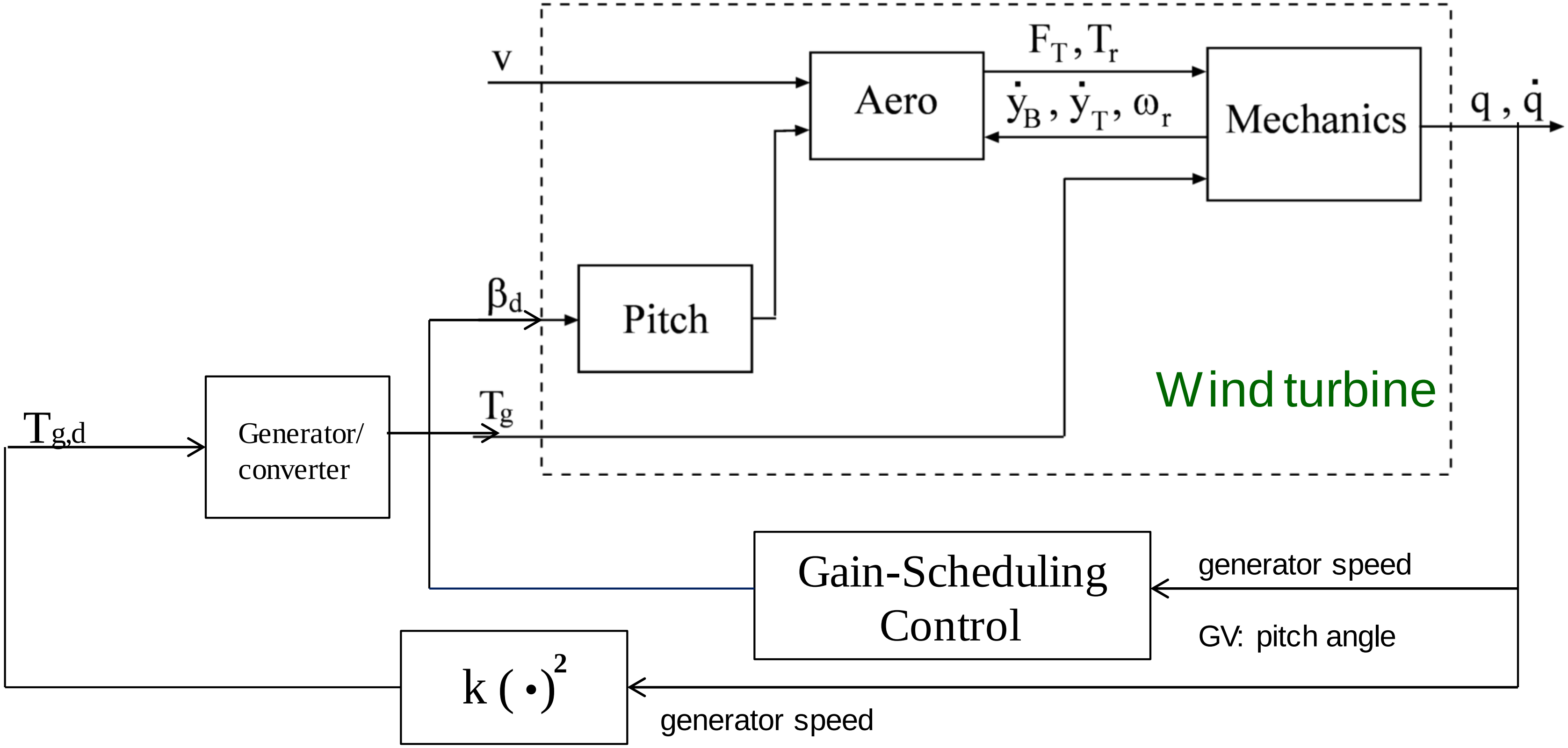
- **Baseline controller**



4. FDI and FTC of Wind Turbine Systems

4.2 FDI and FTC on Power Plant Level

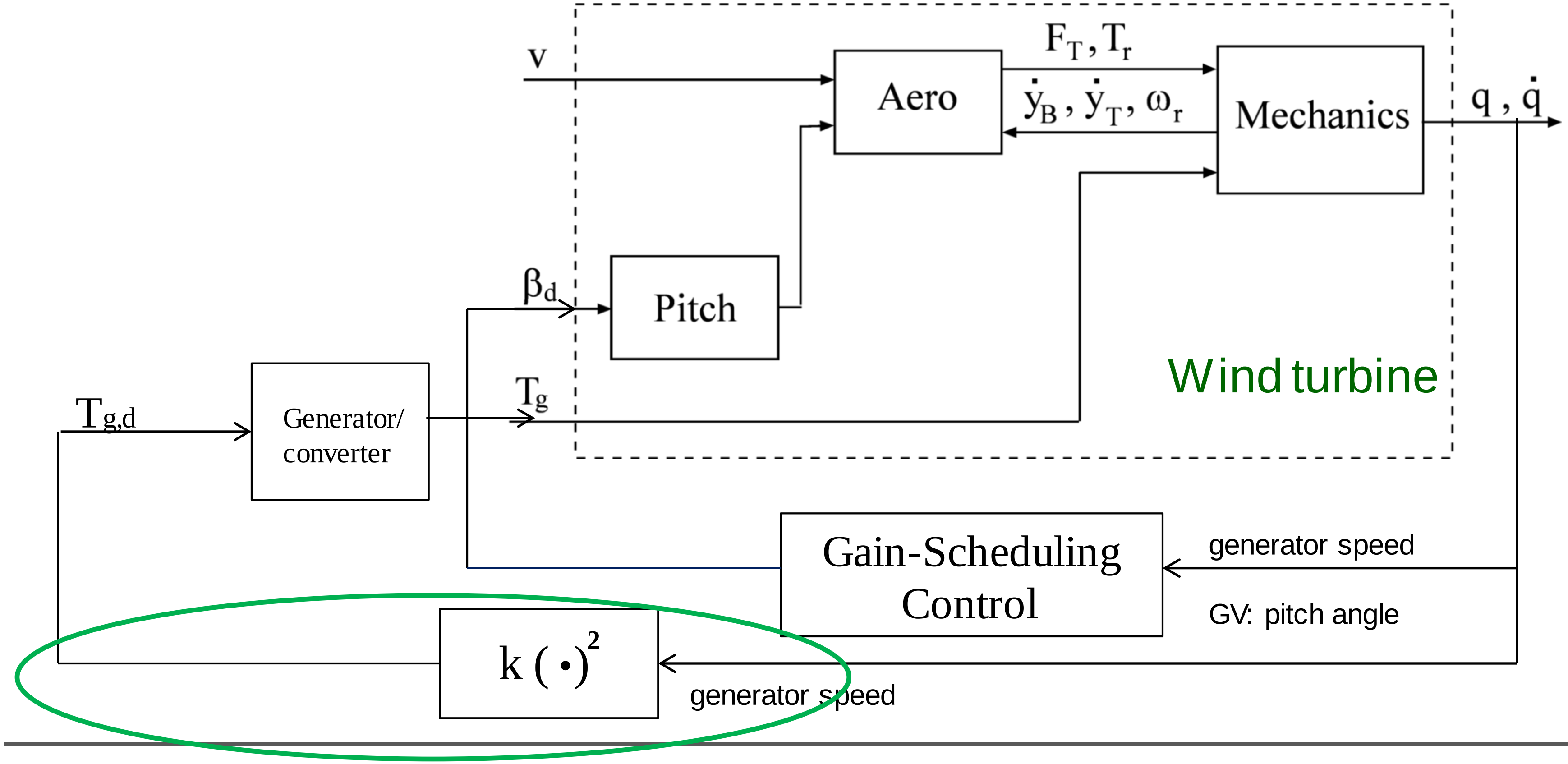
- **Baseline controller**



4. FDI and FTC of Wind Turbine Systems

4.2 FDI and FTC on Power Plant Level

- **Baseline controller**

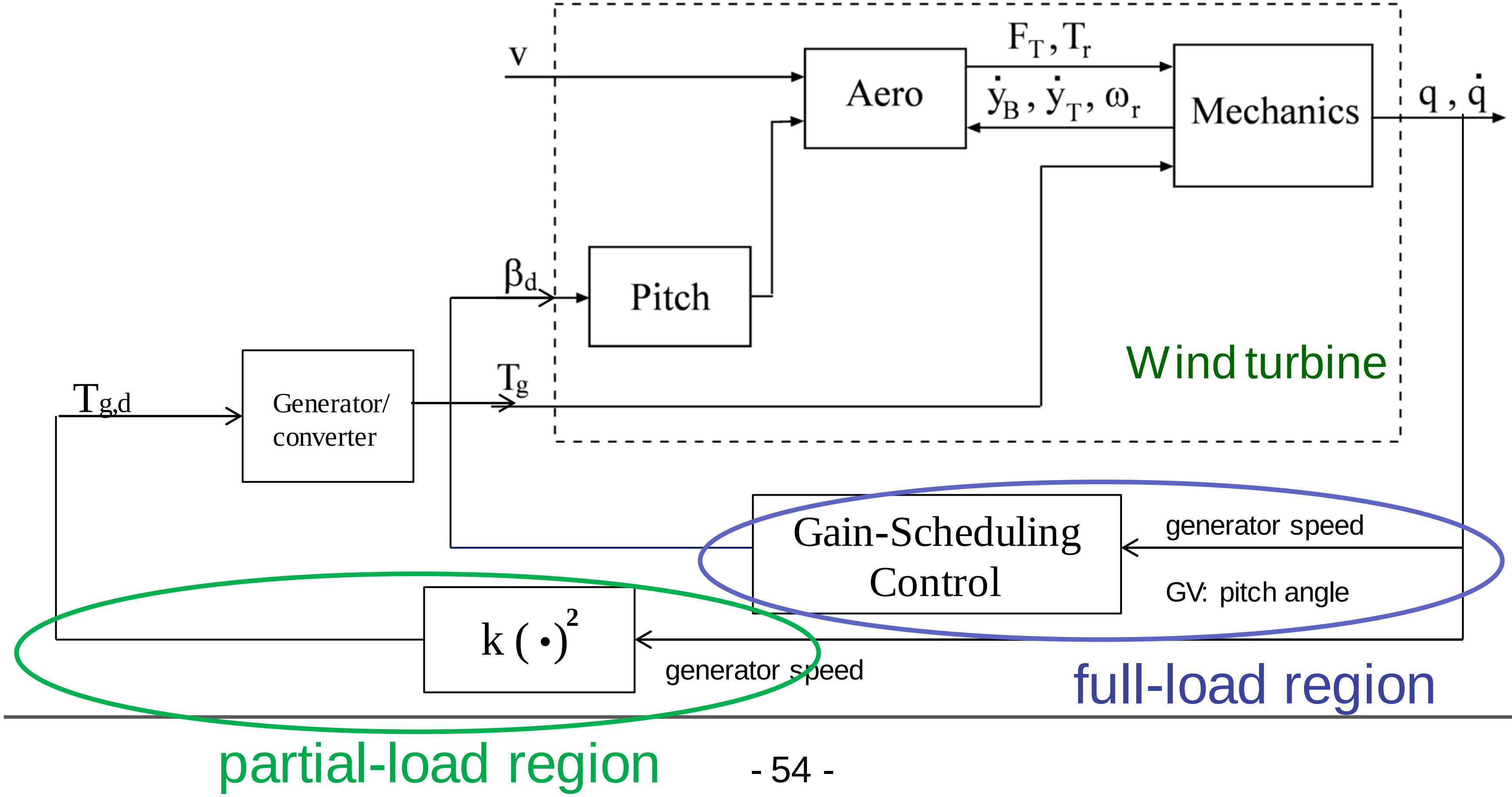


partial-load region

4. FDI and FTC of Wind Turbine Systems

4.2 FDI and FTC on Power Plant Level

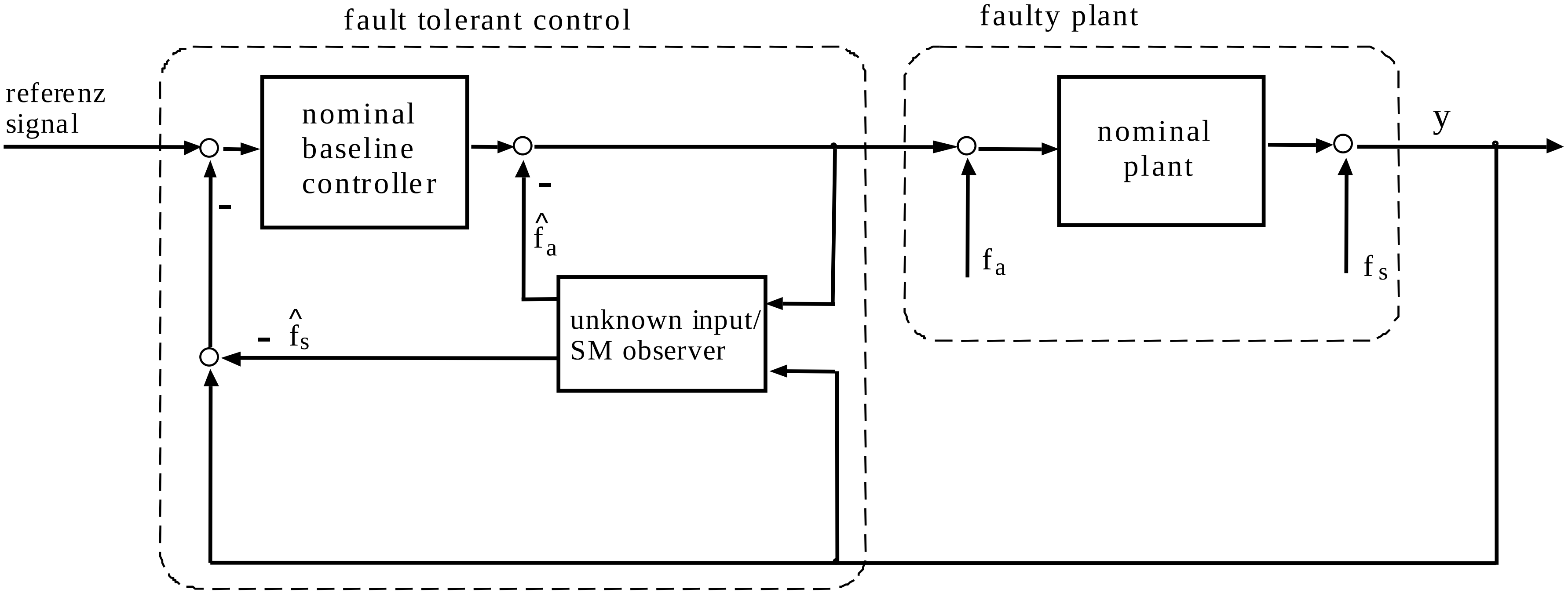
- **Baseline controller**



4. FDI and FTC of Wind Turbine Systems

4.2 FDI and FTC on Power Plant Level

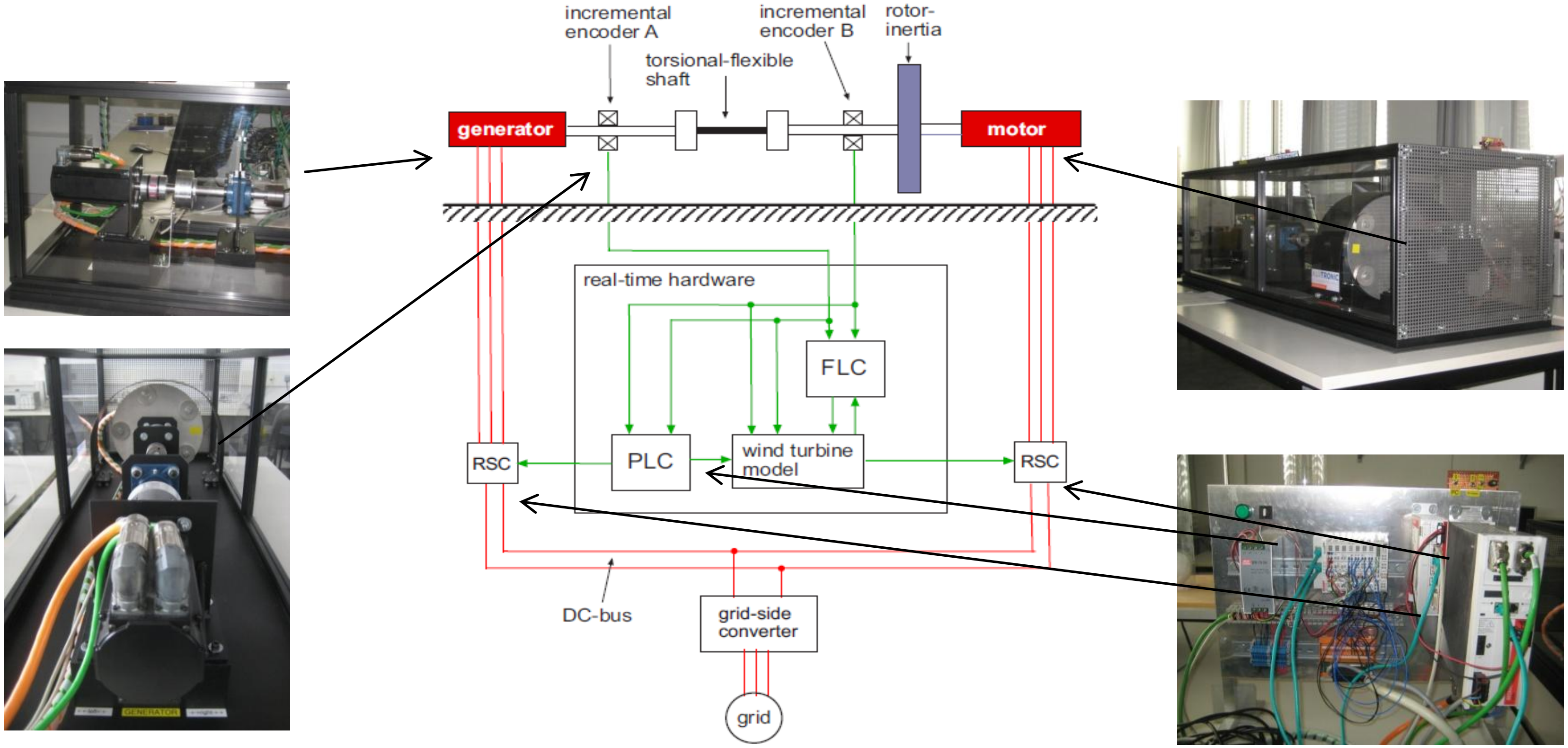
- **FTC scheme**



4. FDI and FTC for Renewable Energy Systems

4.2 FDI and FTC on Power Plant Level

- **Results:** Simulation with Hardware-In-the Loop test-bed



4. FDI and FTC for Renewable Energy Systems

4.2 FDI and FTC on Power Plant Level

- **Experimental design**
  - generator speed sensor fault
  - five different measurements over 120 s period
  - simulated turbulent wind speed with mean value 18 m/s
  - TS fuzzy gain-scheduling controller (full-load region)
- **Test cases**
  - without fault $\mathbf{y}_{\text{corr}} = \mathbf{y}$
  - without fault compensation $\mathbf{y}_{\text{corr}} = (\mathbf{y} + \mathbf{f}_s)$
  - with active compensation: $\mathbf{y}_{\text{corr}} = (\mathbf{y} + \mathbf{f}_s) - \hat{\mathbf{f}}_s$

4. FDI and FTC for Renewable Energy Systems

4.2 FDI and FTC on Power Plant Level

Sensor fault and reconstruction ➡ Speed measurements

--- sensor fault

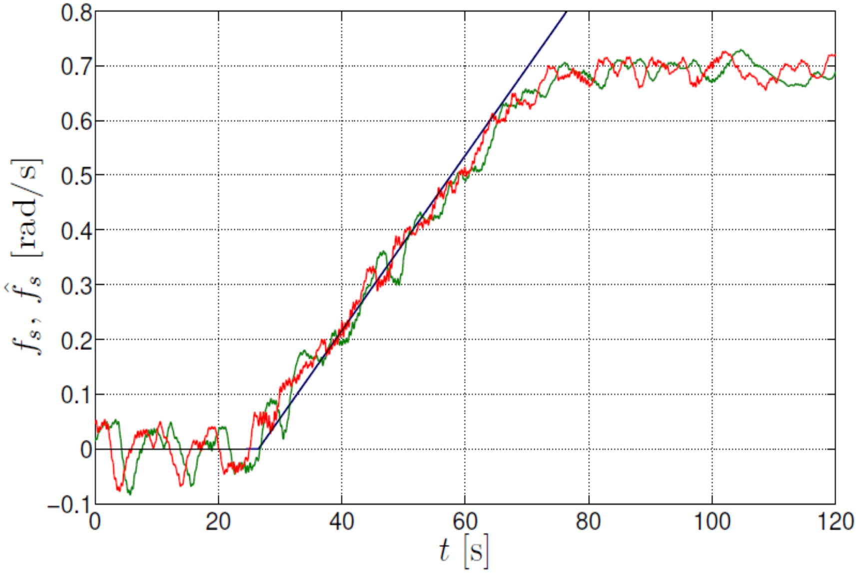
--- fault reconstruction without fault compensation

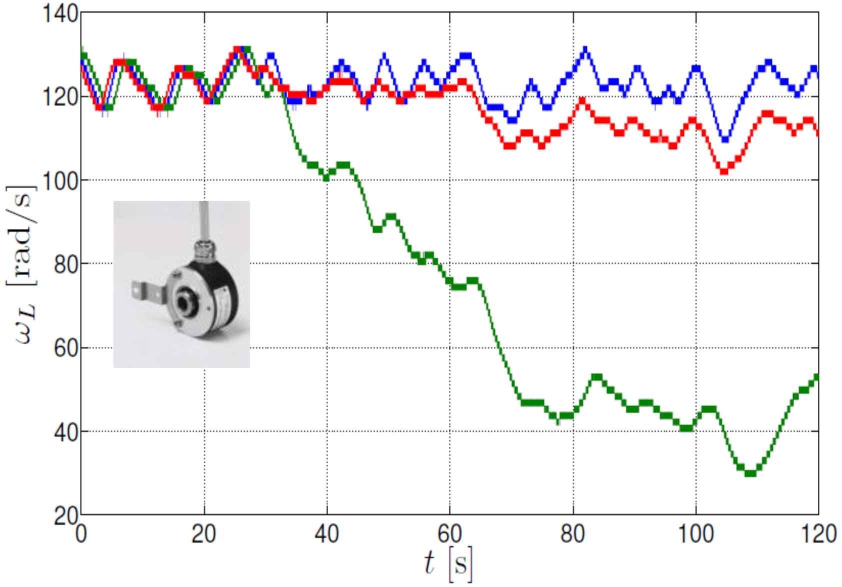
--- fault reconstruction with active fault compensation

--- without fault

--- without fault compensation

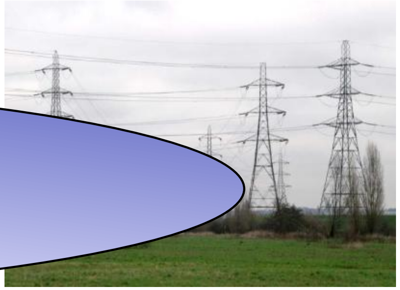
--- with active fault compensation





4. FDI and FTC for Renewable Energy Systems

FTC Layers for Complex Regenerative Systems



Power network protection systems

Fault tolerant power plant control

Fault tolerant Components

(servo drives, power electronic units)

4. FDI and FTC for Renewable Energy Systems

4.3 FDI and FTC on Network Level

Example: Network Protection System

- Motivation
  - number of non-linearities in the network and non-smoothness increase
  - precise determination of the network state is necessary
  - detection of fast changes in the power dynamics is essential
  - protection concepts have to be faster and more agile
- Application: High voltage power network
  - protection device: Siemens SIPROTEC

  - phasor quantities determined by fourier-based (i.e. FFT) algorithms
  - good results for many applications but *limited performance* in dynamic processes

4.3 FDI and FTC on Network Level

Example: Network Protection System

Approach: Prony‘s method

- Mathematical model of the power network is unknown
- state and parameter estimation by observer techniques is not feasible
- measurements are locally available
- Prony’s method is a kind of system identification
  - model structure selection by validation criteria
  - black box model but physical interpretable parameters

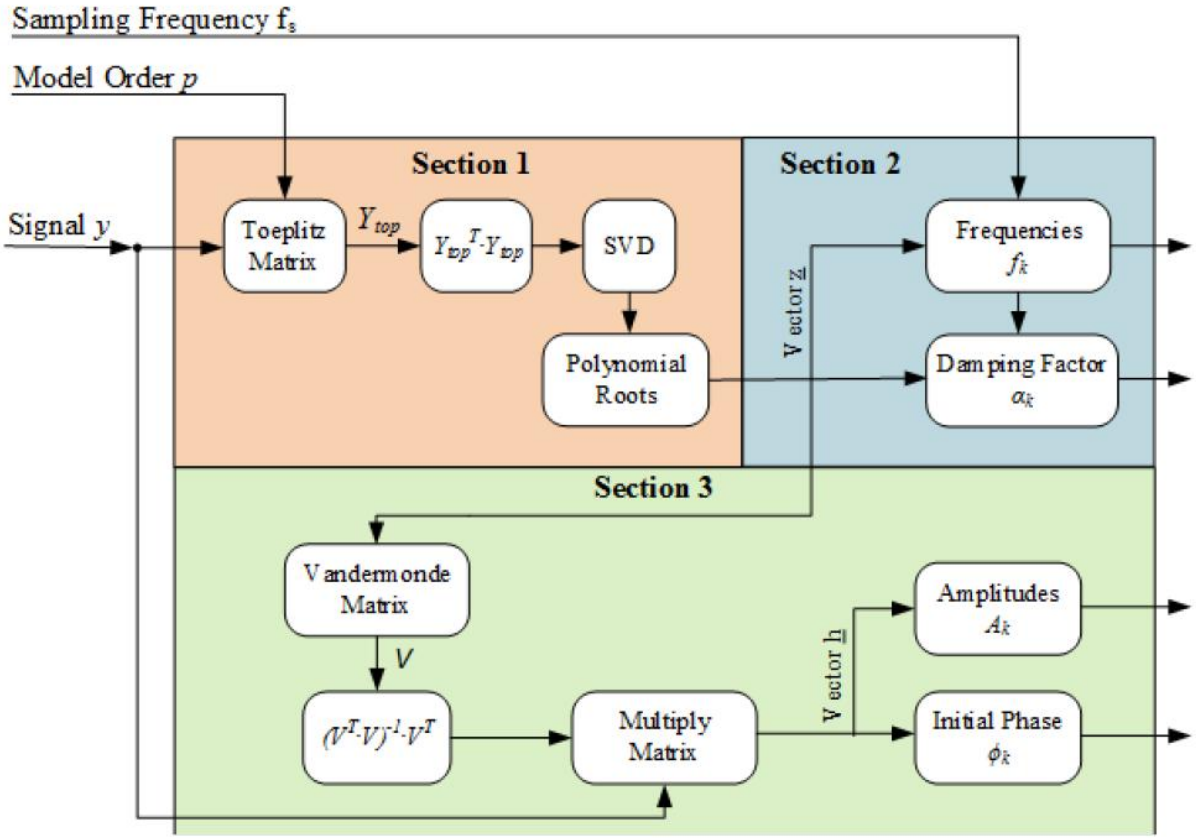
$$\hat{y}[n] = \sum_{k=1}^{p} A_k \cdot \mathrm{e}^{(\alpha_k + j\omega_k)\cdot(n-1)\cdot T_s} \cdot \mathrm{e}^{j\varphi_k}$$

4. FDI and FTC for Renewable Energy Systems

4.3 FDI and FTC on Network Level

Example: Network Protection System

Approach: Prony‘s method



4. FDI and FTC for Renewable Energy Systems

4.3 FDI and FTC on Network Level

Example: Network Protection System

Inrush detection: $T_s = 1\text{ms}$, $p = 20$, $N = 2p$

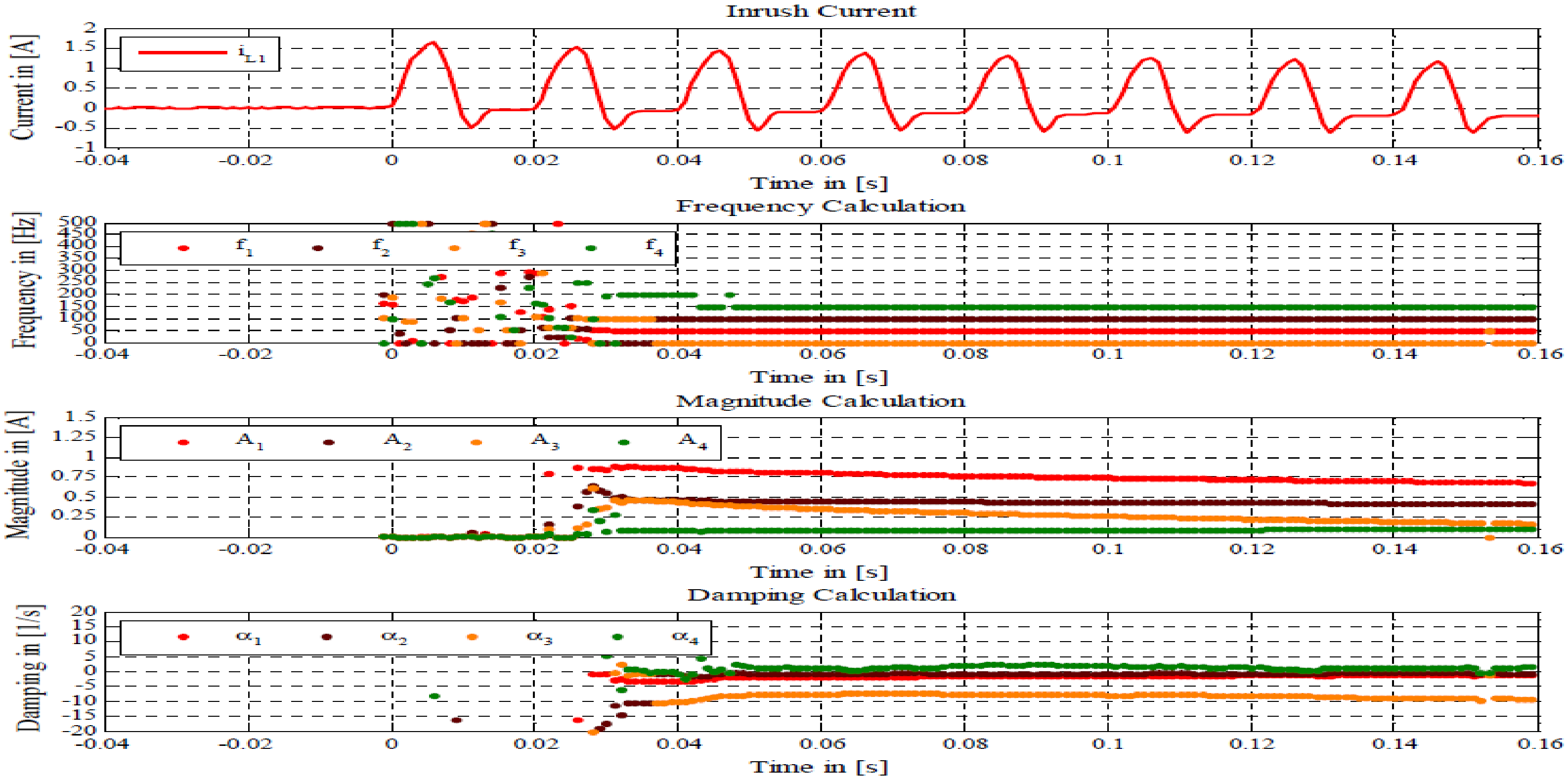
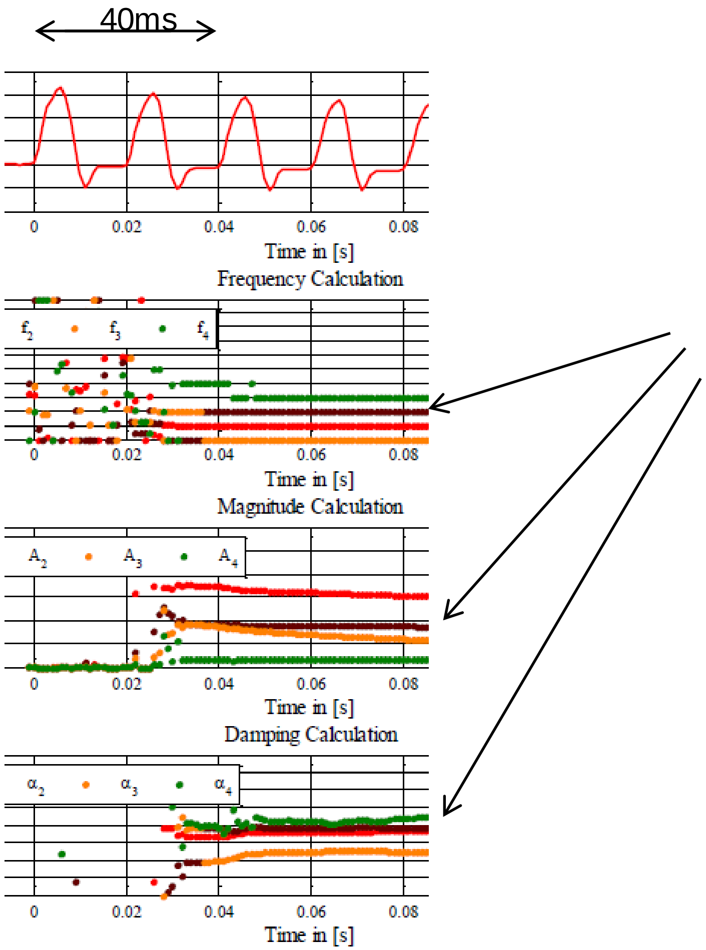


Figure 5. Analysis of a typical inrush current: $p = 20,\ N = 40\ ,\ f_S = 1\ kHz$

4. FDI and FTC for Renewable Energy Systems

4.3 FDI and FTC on Network Level

Example: Network Protection System



Frequency Calculation

Magnitude Calculation

Damping Calculation

- General, power system faults consists of a large ratio of fundamental freq.
- Model order selection is important

  $p = 20,\ N = 2p$

- Second harmonic is an appropriate indicator to detect inrush events
- robust *detection time* is 40 ms
- *faster* as FFT based signal processing

4. Conclusion

Conclusion

- FDI /FTC scheme for renewable energy systems were presented
- Problem was decomposed into three different levels
- 3 examples of FDI and FTC are discussed in detail

Current and Future Work

- RE systems such as wind turbines and PV have to support the power network like conventional power plant with huge inertia
- Output only FDI using machine learning methods

Papers and reports: www.researchgate.net/profile/Horst_Schulte2

Appendix A: Review of TS and Sliding Mode Approach

Reconstruction of faults and unknown inputs

- Existence of pseudo inverse of convex combination of matrices for

$$\begin{pmatrix}\hat{\xi}\\ \hat{\mathbf{f}}_a\end{pmatrix} = \left[\mathcal{D}_2(\mathbf{z}) \;\; \mathcal{F}_2(\mathbf{z})\right]^{+} \boldsymbol{\nu}_{\mathrm{eq}}$$

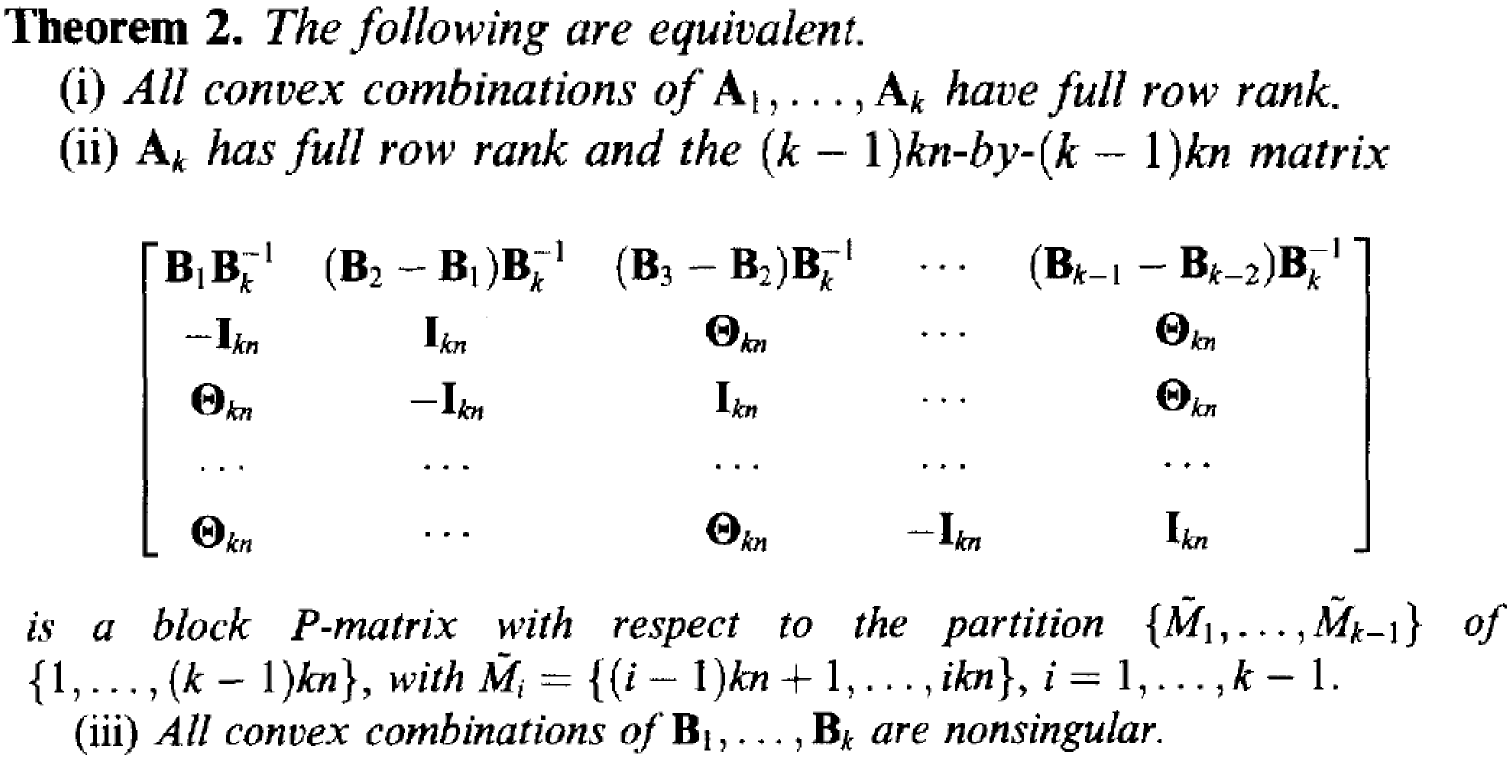
where $\mathcal{D}_2(\mathbf{z}) := \sum_{i=1}^{N_r} h_i(\mathbf{z})\, \mathcal{D}_{2,i}$ $\qquad$ $\mathcal{F}_2(\mathbf{z}) := \sum_{i=1}^{N_r} h_i(\mathbf{z})\, \mathcal{F}_{2,i}$

if the Theorem 2 in [Kolodziejczak, Szulc, *Linear Algebra and its Application* 287, 1999] is fullfilled ,

Appendix A: Review of TS and Sliding Mode Approach

Reconstruction of faults and unknown inputs

- [Kolodziejczak, Szulc, *Linear Algebra and its Application* 287, 1999, (215-222)]



Theorem 2. *The following are equivalent.*

(i) *All convex combinations of* $\mathbf{A}_1, \ldots, \mathbf{A}_k$ *have full row rank.*

(ii) $\mathbf{A}_k$ *has full row rank and the* $(k-1)kn$*-by-*$(k-1)kn$ *matrix*

$$\begin{bmatrix} \mathbf{B}_1\mathbf{B}_k^{-1} & (\mathbf{B}_2 - \mathbf{B}_1)\mathbf{B}_k^{-1} & (\mathbf{B}_3 - \mathbf{B}_2)\mathbf{B}_k^{-1} & \cdots & (\mathbf{B}_{k-1} - \mathbf{B}_{k-2})\mathbf{B}_k^{-1} \\ -\mathbf{I}_{kn} & \mathbf{I}_{kn} & \mathbf{\Theta}_{kn} & \cdots & \mathbf{\Theta}_{kn} \\ \mathbf{\Theta}_{kn} & -\mathbf{I}_{kn} & \mathbf{I}_{kn} & \cdots & \mathbf{\Theta}_{kn} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \mathbf{\Theta}_{kn} & \cdots & \mathbf{\Theta}_{kn} & -\mathbf{I}_{kn} & \mathbf{I}_{kn} \end{bmatrix}$$

is a block P-matrix with respect to the partition $\{\tilde{M}_1, \ldots, \tilde{M}_{k-1}\}$ *of* $\{1, \ldots, (k-1)kn\}$, *with* $\tilde{M}_i = \{(i-1)kn + 1, \ldots, ikn\}$, $i = 1, \ldots, k-1$.

(iii) *All convex combinations of* $\mathbf{B}_1, \ldots, \mathbf{B}_k$ *are nonsingular.*