The dynamics of the (future) electrical power system: A systems theoretical point of view

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20.04.2017

Outline

Outline

1. Motivation: Why will dynamics become more important?
   - The future power system: A likely guess
   - The dynamics of the (future) power system
   - Dynamic models considering unbalanced faults: Rarely investigated
   - Build on many assumptions: The swing equation

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Why will dynamics become more important?

The future power system: A likely guess

- more distributed generation / **renewable energy systems**
- diminishing mechanical inertia
- hybrid grid and transmission topologies (e.g. AC & DC)
- more **unbalanced faults** ($> 75\%$ of faults already today)
- more loosely-coupled & unbalanced micro-grids
- more **power electronics**

$\Longrightarrow$ Faster dynamics/transients, more harmonics & weaker overall grid!

$\Longrightarrow$ Stationary models considering fundamental only *not* sufficient!

$\Longrightarrow$ Multi-phase multi-wire state-space models crucial!

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Why will dynamics become more important?

The dynamics of the (future) power system

Coupled, time-varying partial differential algebraic system (PDAS):

$$\boldsymbol{f}\left(\tfrac{\partial}{\partial t}\boldsymbol{z}(t,x),\, \tfrac{\partial}{\partial x}\boldsymbol{z}(t,x), \boldsymbol{z}(t,x), \ldots, t\right) = \boldsymbol{0}_n$$

$$\text{where} \quad \boldsymbol{z}(t,x) := \begin{pmatrix} \boldsymbol{\omega}(t) \\ \boldsymbol{\delta}(t) \\ \boldsymbol{v}(t,x) \\ \boldsymbol{i}(t,x) \end{pmatrix}$$

Several simplifying assumptions have to be **re**considered, e.g.

- $\frac{\partial}{\partial x}\boldsymbol{z}(t,x) = \boldsymbol{0}_m$, i.e. Π- or T-models (?)
- $\frac{\partial}{\partial t}\boldsymbol{z}(t,x) = j\omega \underline{\boldsymbol{Z}}(x)\mathrm{e}^{j\omega t}$, $\omega > 0$ (?)
- losses (?)
- time-variance (?)
- detailed low-level models (?)
- …

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Why will dynamics become more important?

Dynamic models considering **unbalanced faults**: Rarely investigated

522 IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 15, NO. 2, MAY 2000

Symmetrical Components in the Time Domain and Their Application to Power Network Calculations

Gerardus C. Paap, *Senior Member, IEEE*

1062 IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 15, NO. 3, AUGUST 2000

Analysis of Asymmetrical Faults in Power Systems Using Dynamic Phasors

Aleksandar M. Stanković, *Member, IEEE,* and Timur Aydin

IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 30, NO. 5, SEPTEMBER 2015 2349

Dynamic Modeling of Power Systems Experiencing Faults in Transmission/Distribution Networks

Sajeeb Saha, *Member, IEEE*, and Mohammad Aldeen, *Senior Member, IEEE*

***Abstract*—In this paper we address some shortcomings in existing nonlinear dynamic models of power system experiencing symmetrical and unsymmetrical faults in their transmission/distribution networks. The shortcomings relate to: 1) approximations relating to stator dynamics, internal voltage of the positive sequence network and the dynamics of the negative and zero sequence networks, and 2) existing models are time -variant, which may not be suitable for system studies such as stability and fault detection studies that require time invariant model. The approximations outlined in 1) adversely affect the modeling accuracy, especially that of the system response during the period immediately after the occurrence of faults. We present in this paper a full**

T_e	Electric torque.
$\bullet_{LD}$	Load bus quantities.
$\bullet_{GU}$	Generator bus quantities.
SLG, LLG, LL, 3φ	Single line to ground, double line to ground, line to line, and three phase fault, respectively.

I. INTRODUCTION

> "[In most power systems simulation tools] …full transient behavior is not captured …as they approximate the stator dynamics by a static (algebraic) model …[or an] exponentially DC decaying term." [1]

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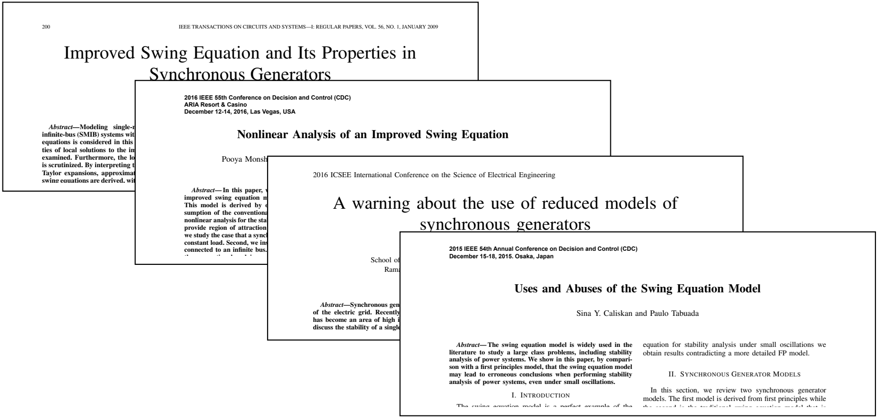
Why will dynamics become more important?

Build on many assumptions: **The swing equation**

$$\boxed{M\frac{\mathrm{d}^2}{\mathrm{d}t^2}\delta + D_\mathrm{d}\frac{\mathrm{d}}{\mathrm{d}t}\delta = p_\mathrm{t}(t) - \hat{p}_\mathrm{el}\sin(\delta)}$$



"…the results in this paper call into question the scientific foundations upon which the current power grid has been built." [2]

Outline

2. Scientific background
   - Interdisciplinary expertise
   - Research group “Control of renewable energy systems (CRES)”
   - Running projects and third-party funding
   - Teaching experience

Outline

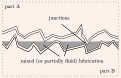
2 Scientific background

- Interdisciplinary expertise
- Research group "Control of renewable energy systems (CRES)"
- Running projects and third-party funding
- Teaching experience

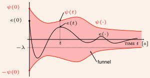
Scientific background

Interdisciplinary expertise (>80 peer-reviewed publications, e.g. one monograph)

System identification [11–15]



Dynamic friction [16, 17]



Non-identifier based adaptive control [16, 18–33]

Paper coating machines [6–10]

Teaching (EOF Award ’13) [33, 93–99]

Robotics / mechatronics [16, 17, 33–44]

Systems & control
(dynamical systems)

Electro-active polymers [3–5]

Power electronics [33, 33, 45–64]

Renewable energy systems [15, 30, 32, 33, 46, 47, 50, 54, 55, 57–59, 61, 63, 64, 69–71, 74, 76, 82–92]

Electrical drives (machines/generators) [15, 16, 18, 20, 21, 31, 33, 39, 43, 56, 65–82]

Outline

2 Scientific background

- Interdisciplinary expertise
- Research group “Control of renewable energy systems (CRES)”
- Running projects and third-party funding
- Teaching experience

Scientific background

Head of research group “Control of renewable energy systems (CRES)” (since January 2014)

Team


H. Eldeeb, M.Sc.
(CRES, 09/2015)


C. Dirscherl, M.Sc.
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(CRES, 01/2014)


M. Landerer, M.Sc.
(CRES, 06/2016)

External PhD students


Z. Zhang, Dr.-Ing.
(CRES/EAL,07/2015)


S. Krüner, M.Sc.
(SINNPower,11/2015)


A. Birda, M.Sc.
(BMW, 04/2016)

. . . and PhD collaborations with EAL (R. Kennel)


F. Bauer, M.Sc.
(EAL)


M. Abdelrahem,
M.Sc. (EAL)


A. Ayad,
M.Sc. (EAL)

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- Interdisciplinary expertise
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Scientific background

Running projects & third-party funding ($>$ 2 million €; e.g. DAAD, Baveria, BMBF, BMWi, DFG, EU)

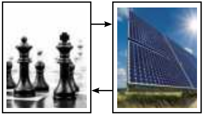
Large-scale WTS

Efficiency+Reliability

Small-scale WTS

Reluctance SM

Model predictive control for RES



Real-time applicability

Airborne Wind Energy

Fault-tolerant control

Geothermal energy

Fault-tolerant control

Wave energy (SinnPower)

Efficiency+Reliability

Electric vehicles (BMW)

Efficiency+Reliability

Electrical power system

Three-phase four-wire system dynamics

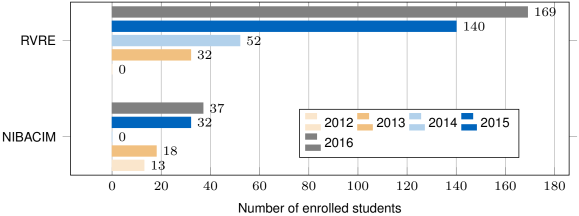
Outline

2 Scientific background

- Interdisciplinary expertise
- Research group “Control of renewable energy systems (CRES)”
- Running projects and third-party funding
- Teaching experience

Scientific background

Teaching experience (since 2004)



- Lectures, tutorials, practical courses & student projects, e.g.
  - “**R**egelung **v**on **r**egenerativen **E**nergiesystemen” (WS, 3SWS; since 2013)
  - “**N**on-**i**dentifier **b**ased **a**daptive **c**ontrol in **m**echatronics” (SS, 4SWS; since 2012)
  - “Projektstudium Antriebstechnik” [97–99] (EOF Lehrpreis 2013, WS1415)
- International / PhD teaching activities
  - Lecture & Seminar on “Modeling and control of renewable energy systems” (TUM-CREATE, Singapore; May-July 2017)
  - EU H2020 ITN Workshop “Electrical Drives and Predictive Control” (2016)
  - MSE Winter School “Holistic Modeling and Control of Energy Systems” (2015)
  - Block course on “Modeling and control of wind turbine systems: An introduction” (South Africa, University of Stellenbosch, 2014)

Outline

3 Research and teaching concept
- Research concept
- Teaching concept
- Current activities
  - Four-leg modular multi-level power converters (Collaboration with Chile)
  - Online detection of grid conditions
  - Refinement of the swing equation

Outline

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Research and teaching concept

Research concept: **Bottom-up approach** (and, meanwhile, **Top-down approach**)

simulation ↔ control ↔ optimization ↔ monitoring ↔ laboratory

(model reduction / model simplification)

$$\boldsymbol{f}\left(\frac{\partial}{\partial t}\boldsymbol{z}(t,x), \frac{\partial}{\partial x}\boldsymbol{z}(t,x), \boldsymbol{z}(t,x), t\right) = \boldsymbol{0}_n \quad \text{where} \quad \boldsymbol{z}(t,x) := \begin{pmatrix} \boldsymbol{\omega}(t) \\ \boldsymbol{\delta}(t) \\ \boldsymbol{v}(t,x) \\ \boldsymbol{i}(t,x) \end{pmatrix}$$

sources | lines | loads | storage | actuators

Unbalanced multi-phase multi-wire **AC & DC** power system dynamics

Outline

3 Research and teaching concept

- Research concept
- **Teaching concept**
- Current activities
  - Four-leg modular multi-level power converters (Collaboration with Chile)
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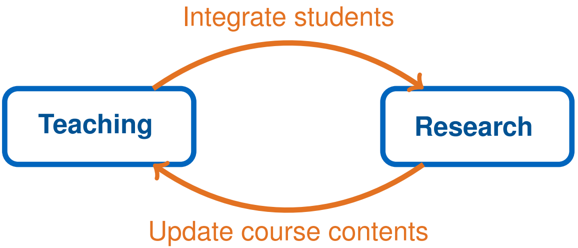
Research and teaching concept

Teaching concept (interactive and up-to-date)



Possible courses / projects (e.g.):

- Introduction to renewable energy systems (BA)
- Modeling and control of renewable energy systems (MA)
- Electrical power transmission (MA)
- Power electronics in electrical power systems (MA)
- Unbalanced multi-phase multi-wire systems (MA)

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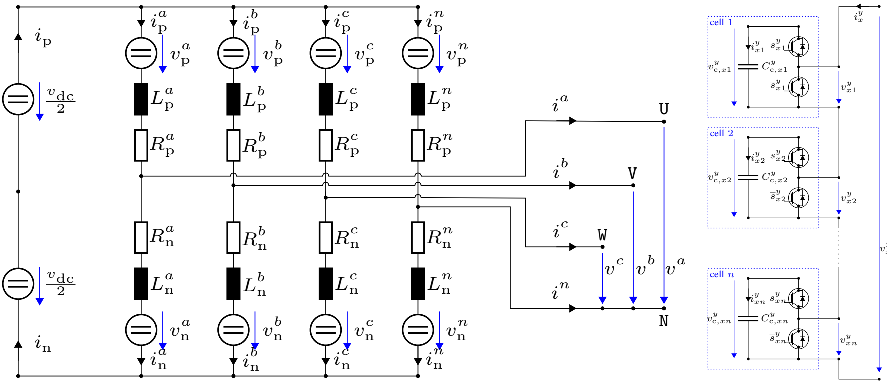
Research and teaching concept

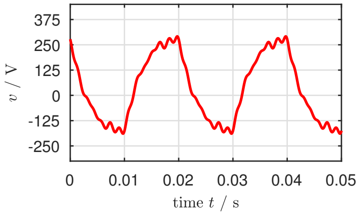
Current activities: **Four-leg modular multi-level power converters**

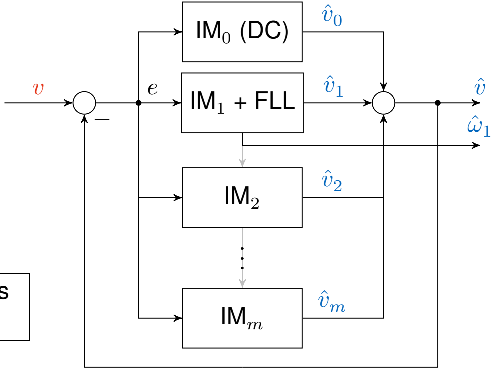


- Goal: Compensation of unbalanced grid conditions
- Joint research project with **R. Cardenas** (Universidad de Chile) and **F. Rojas** (Universidad de Santiago de Chile)

Research and teaching concept

Current activities: **Online detection of grid conditions** [paper in preparation]



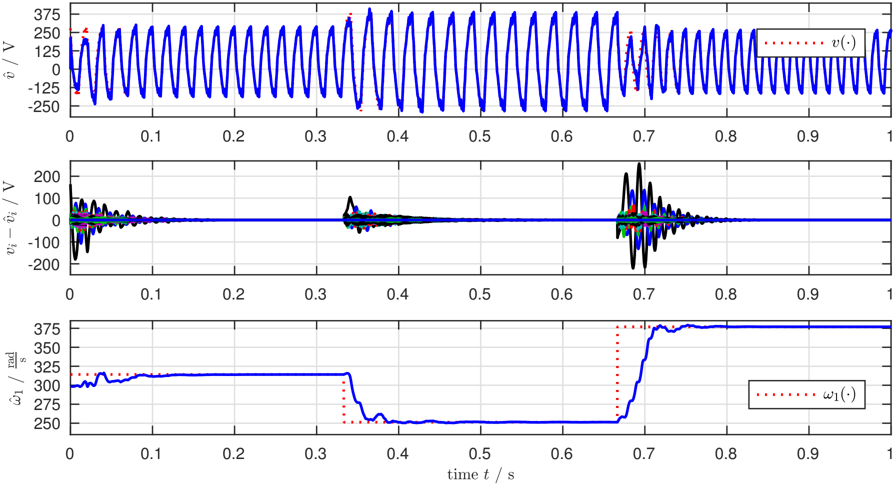


Parallelized internal models
(globally stable)

$$v = v_0 + \sum_{i=1}^{n} \underbrace{a_i \cos\left(\phi_i + \phi_{i,0}\right)}_{=:v_i} = \hat{v}_0 + \sum_{i=1}^{m \leqslant n} \underbrace{a_i \cos\left(\hat{\phi}_i + \hat{\phi}_{i,0}\right)}_{=\hat{v}_i} + \Delta(a_{m+1,\dots,n})$$

Research and teaching concept

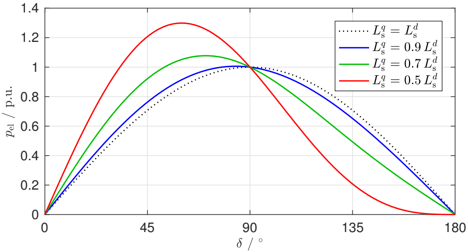
Current activities: **Online detection of grid conditions** [paper in preparation]



Research and teaching concept

Current activities: **Refinement of the swing equation** [paper in preparation]

- $$p_{\mathrm{el}}(\delta) = \frac{3}{2}\frac{\hat{u}_{\mathrm{s}}\hat{u}_{\mathrm{p}}}{\omega_{\mathrm{r}} L_{\mathrm{s}}^{d}} \sin(\delta) + \frac{3}{4}\frac{\hat{u}_{\mathrm{s}}^{2}}{\omega_{\mathrm{r}}}\left(\frac{1}{L_{\mathrm{s}}^{q}} - \frac{1}{L_{\mathrm{s}}^{d}}\right)\sin(2\delta)$$ (considering anisotropy)



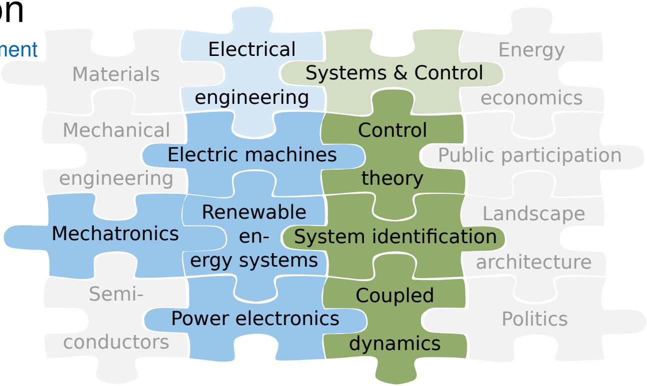
- $$p_{\mathrm{el}}(\delta) = \frac{3}{2}\frac{R_{\mathrm{s}}\hat{u}_{\mathrm{p}} - R_{\mathrm{s}}\hat{u}_{\mathrm{s}}\cos(\delta) + L_{\mathrm{s}}^{d}\hat{u}_{\mathrm{s}}\omega_{\mathrm{r}}\sin(\delta)}{(R_{\mathrm{s}}^{2} + L_{\mathrm{s}}^{d}L_{\mathrm{s}}^{q}\omega_{\mathrm{r}}^{2})^{2}} \cdot \Big[R_{\mathrm{s}}^{2}\hat{u}_{\mathrm{p}} + (L_{\mathrm{s}}^{q})^{2}\hat{u}_{\mathrm{p}}\omega_{\mathrm{r}}^{2} - L_{\mathrm{s}}^{q}\hat{u}_{\mathrm{s}}\omega_{\mathrm{r}}^{2}\left(L_{\mathrm{s}}^{q} - L_{\mathrm{s}}^{d}\right)\cos(\delta) + R_{\mathrm{s}}\hat{u}_{\mathrm{s}}\omega_{\mathrm{r}}\left(L_{\mathrm{s}}^{d} - L_{\mathrm{s}}^{q}\right)\sin(\delta)\Big]$$
  (considering copper losses & anisotropy)
- Swing equation considering losses, anisotropy & (nonlinear) flux/current dynamics

Outline

4 Conclusion

Conclusion

Personal assessment



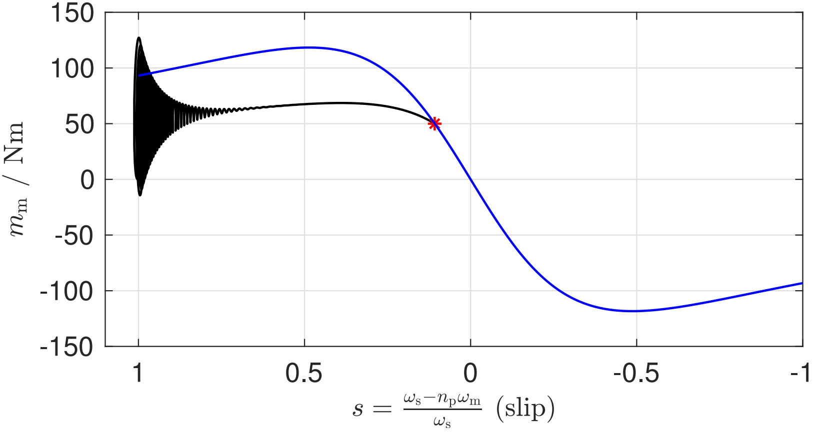
- **interdisciplinary** background $\Longrightarrow$ detailed models (**bottom-up approach**)
- over 10 years of
  - **teaching experience** (lectures, tutorial, practical courses, etc.; also international)
  - **research experience** (over 80 peer-reviewed publications, e.g. one monograph)
  - **project experience** with industry and research institutions (also international)
- successful in winning several **research grants** (currently over 2.5 Mio. EUR)
- **national/international network**

Outline

Outline

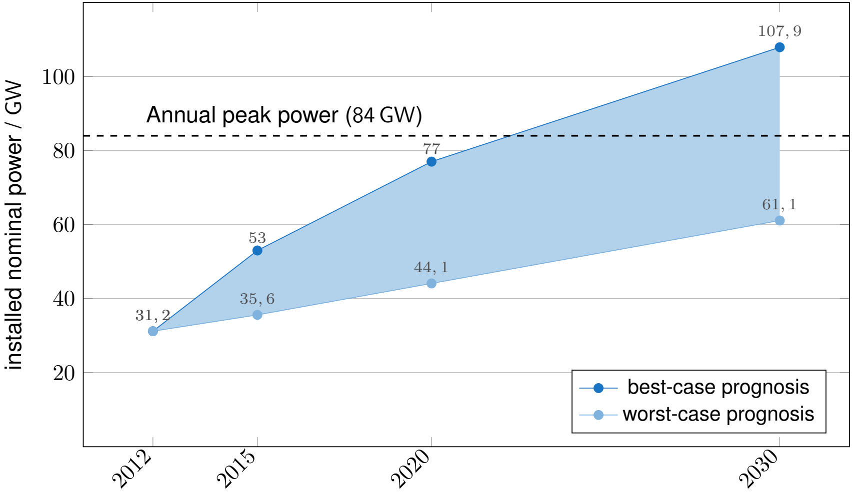
Why will dynamics become more important?

Example: “Torque-over-slip” trajectory of induction machines



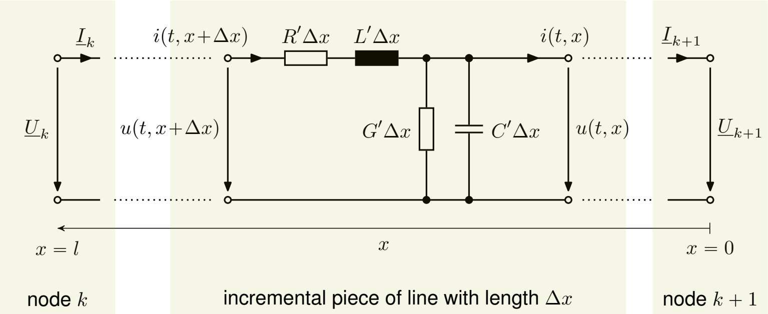
Why will dynamics become more important?

Expected evolution of installed wind power capacity in Germany



Why will dynamics become more important?

Line model for sinusoidal signals **without** harmonics (e.g. $u(t,x) = U(x)\mathrm{e}^{j\varphi_u}\mathrm{e}^{j\omega t} = \underline{U}(x)\mathrm{e}^{j\omega t}$)



$$\begin{aligned} \frac{\partial}{\partial x} u(t,x) &= R' i(t,x) + L' \frac{\partial}{\partial t} i(t,x) \\ \frac{\partial}{\partial x} i(t,x) &= G' u(t,x) + C' \frac{\partial}{\partial t} u(t,x) \end{aligned}$$

and

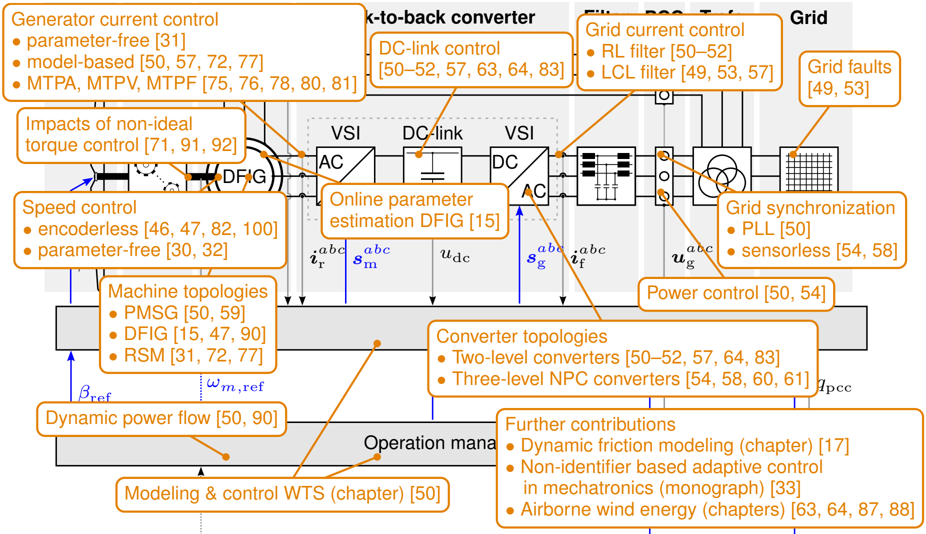
$$\left.\begin{aligned} \frac{\partial^2}{\partial x^2} u(t,x) &= L'C' \frac{\partial^2}{\partial t^2} u(t,x) + (R'C' + L'G') \frac{\partial}{\partial t} u(t,x) + R'G' u(t,x) \\ \frac{\partial^2}{\partial x^2} i(t,x) &= L'C' \frac{\partial^2}{\partial t^2} i(t,x) + (R'C' + L'G') \frac{\partial}{\partial t} i(t,x) + R'G' i(t,x) \end{aligned}\right\}$$

$$\Longrightarrow \boxed{\begin{pmatrix} \underline{U}(x) \\ \underline{I}(x) \end{pmatrix} = \begin{bmatrix} \cosh(\underline{\gamma} x), & \underline{Z}_W \sinh(\underline{\gamma} x) \\ \underline{Z}_W^{-1} \sinh(\underline{\gamma} x), & \cosh(\underline{\gamma} x) \end{bmatrix} \begin{pmatrix} \underline{U}_{k+1} \\ \underline{I}_{k+1} \end{pmatrix}}$$

Outline

Scientific background

Current research focus and CRES publications (e.g. **electrical** components of WTSs)



Scientific background

Laboratory setup: Some photos

Reluctance and Permanent-magnet SMs

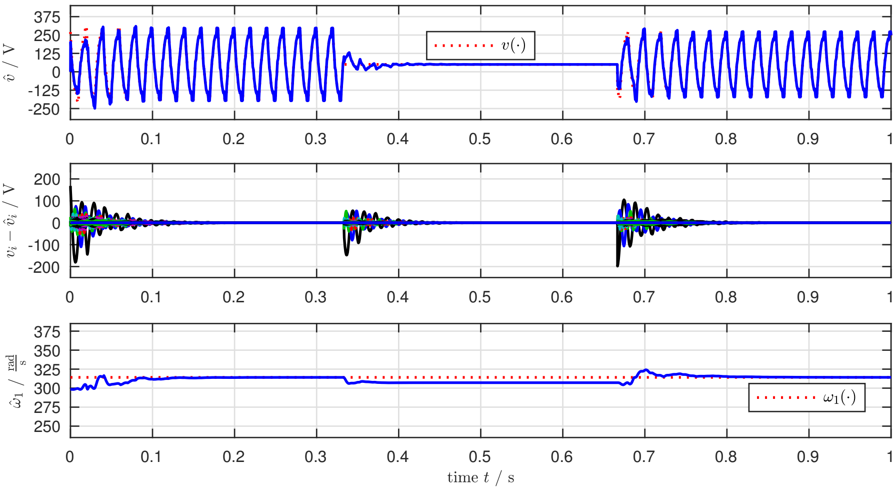
Electrically-excited SM and doubly-fed IM

Real-time system and VSIs

Outline

Research and teaching concept

Current activities: **Online detection of grid conditions** (zoom)



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