Impact of Converter Properties on the System Behavior of Electric Grids

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April 20-22, 2015
Presentation at JST-NSF-DFG-RCN
Workshop on Distributed Energy Management Systems

Outline

- Energy Research at Leibniz University of Hannover
- Example 1: Fault Ride-Through Capability of Large Converters
- Example 2: Wind Turbine & Grid Instability Phenomena
- Example 3: Parallel Operation of Independant Decentralized Infeeds
- Conclusions

Welcome to the City of Hannover

- Ca. 500.000 inhabitants
- Distance to Berlin ca. 220 km
- Distance to Hamburg ca. 150 km

Leibniz University of Hannover

Leibniz University of Hannover

Gottfried Wilhelm Leibniz: Inventor of the binary system

TU9

Leading German technical universities

25% of all third party funds

57% of all engineering PhD degrees

51% of all engineering student degrees

16% of all foreign students

Leibniz University of Hannover

- Founded in 1831
- 9 departments
- > 25000 students
- 270 full professors
- > 2900 scientific staff
- > 100 Mio.€ p.a. of third-party funding

Department of Electrical Engineering and Computer Science

- 16 institutes, 27 chairs (full professors) and 13 junior professors
- ca. 2500 students
- Focus research areas:
  - Electrical Power Engineering
  - Biomedical Engineering
  - Digital Society

Focus Research Area: Electrical Power Engineering

Prof. Lutz Hofmann:
Electric Power Systems

Prof. Axel Mertens:
Power Electronics

Prof. Bernd Ponick:
Electric Machines

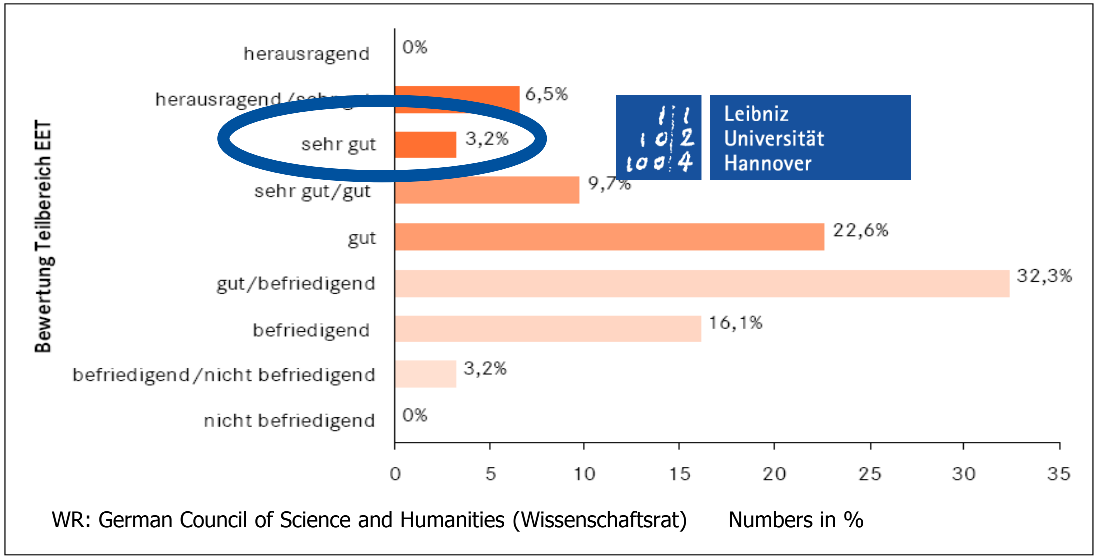
Prof. Bernard Nacke:
Electric Processes

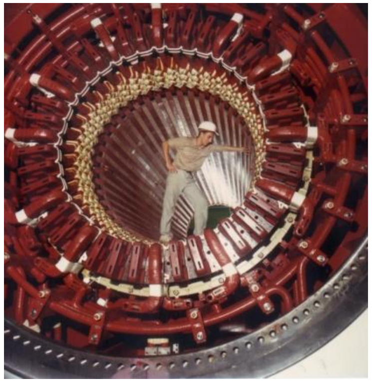
Prof. Hanke-Rauschenbach:
Electric Energy Storage Systems

Prof. Peter Werle:
High-voltage Engineering
and Asset Management

Third-party funds:
about 3 m € p.a. (2010-12)

WR Research Quality Rating of Electrical Power Engineering in 31 German Institutions (2011)





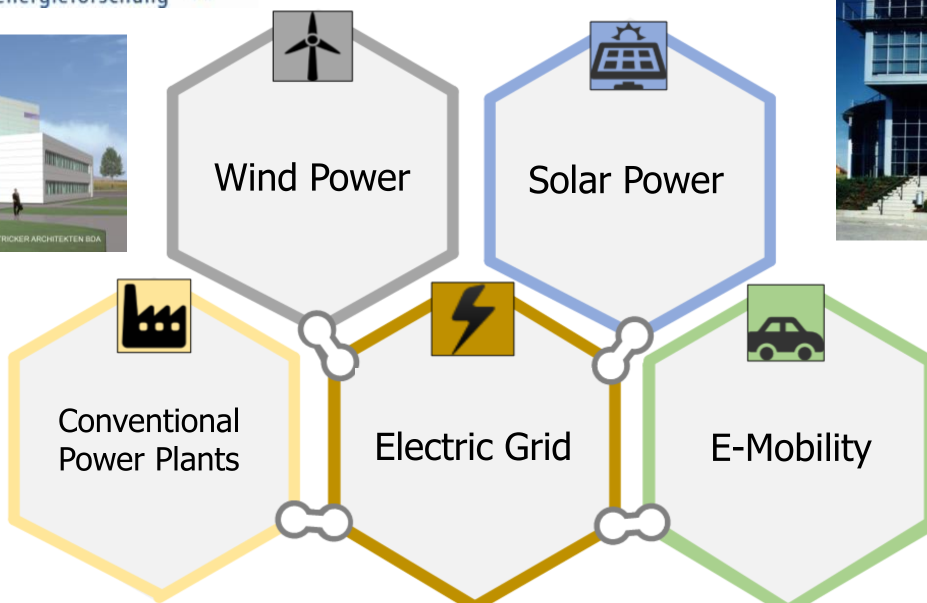
Leibniz Research Center "LiFE 2050"

- Covers 5 research fields where Leibniz University Hannover excels, often with interdisciplinary research networks across locations
- Dedicated research facilities:

ForWind
Zentrum für Windenergieforschung

Fraunhofer
IWES

25 Jahre
ISFH



NIEDERSÄCHSISCHES FORSCHUNGSZENTRUM FAHRZEUGTECHNIK

Dynamik der Energiewandlung

Fraunhofer
IFAM

Research Association Wind Energy

DLR-ForWind-IWES

Largest wind power research cluster in Germany

- 7 German states
- 14 sites
- Approx. 600 staff members
  - DLR (6 institutes)
  - **ForWind (28 institutes)**
  - IWES (10 departments)
- Master co-operative agreement
- Representation of industry in advisory board

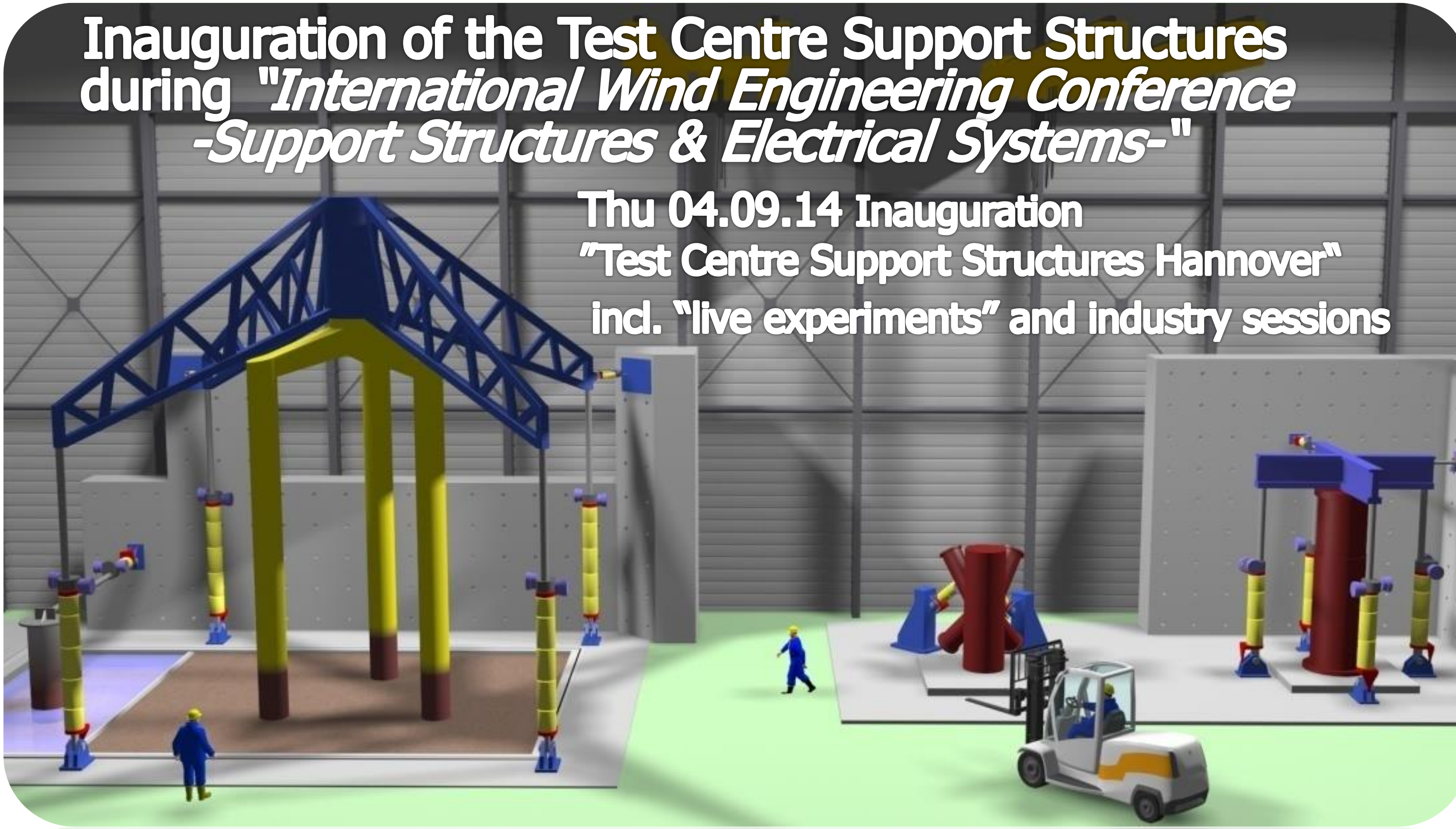
Forschungsverbund Windenergie

Deutsches Zentrum für Luft- und Raumfahrt DLR

ForWind Zentrum für Windenergieforschung

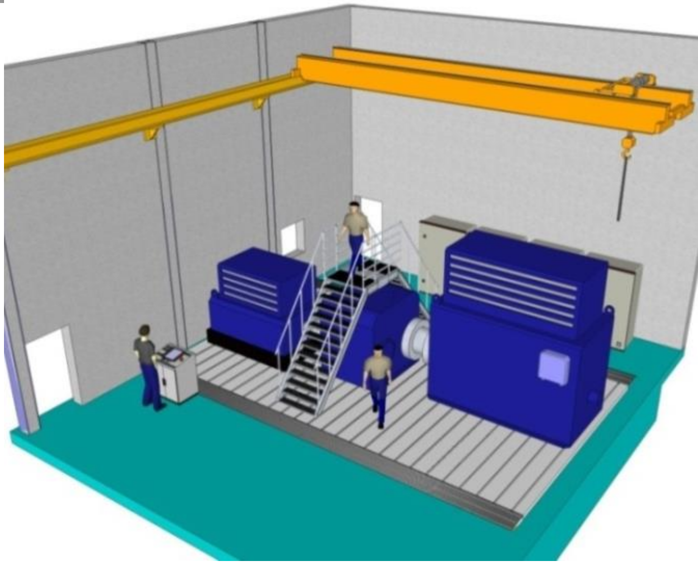
Fraunhofer IWES

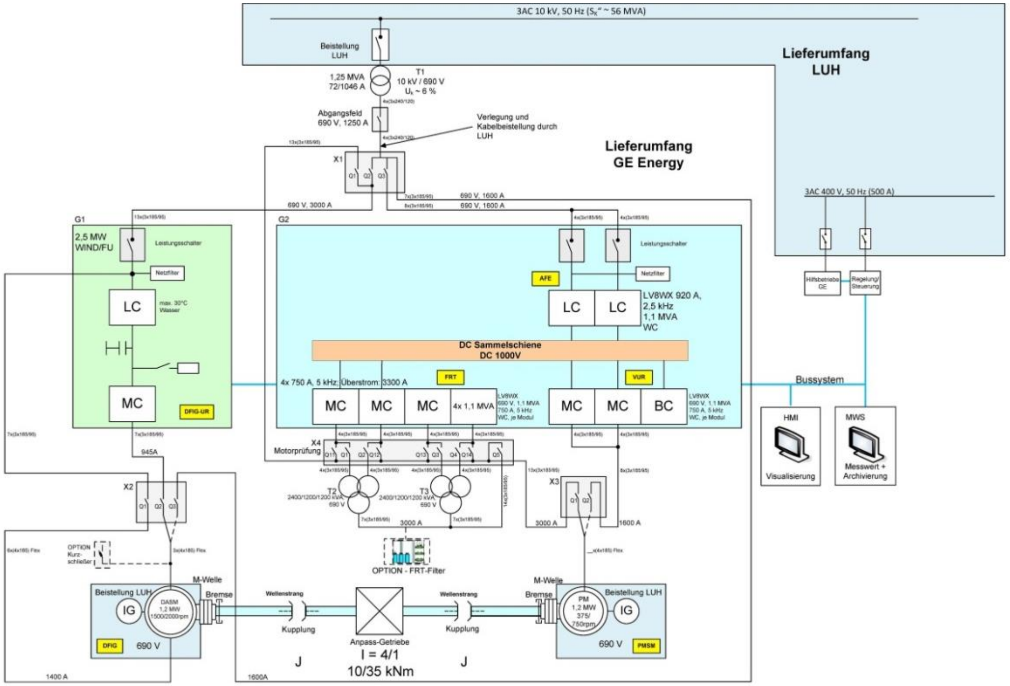
New building for wind power research at LUH



Generator and **Co**nverter **Lab**oratory Hannover (GeCoLab)

- Installation at present, commissioning in April 2015
- 1.2 MW DFIG and PMS generators incl. converters
- 4 MVA converter-based grid emulator
- LVRT (asymmetrical voltages), lower order harmonics
- Voltage level: 690 V





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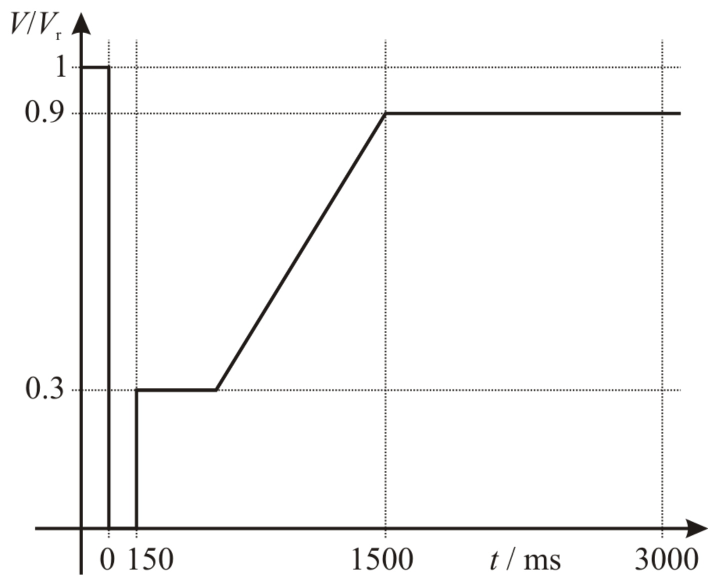
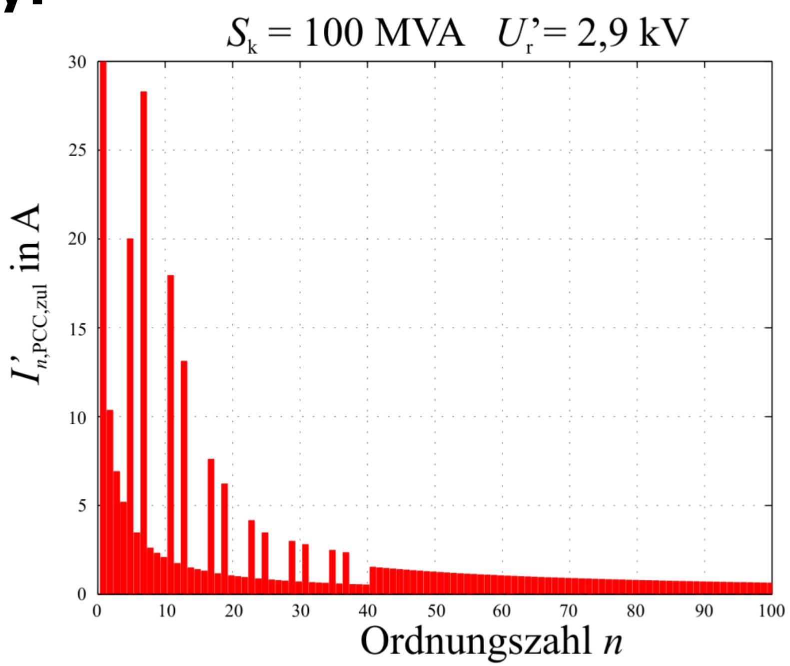
Problem

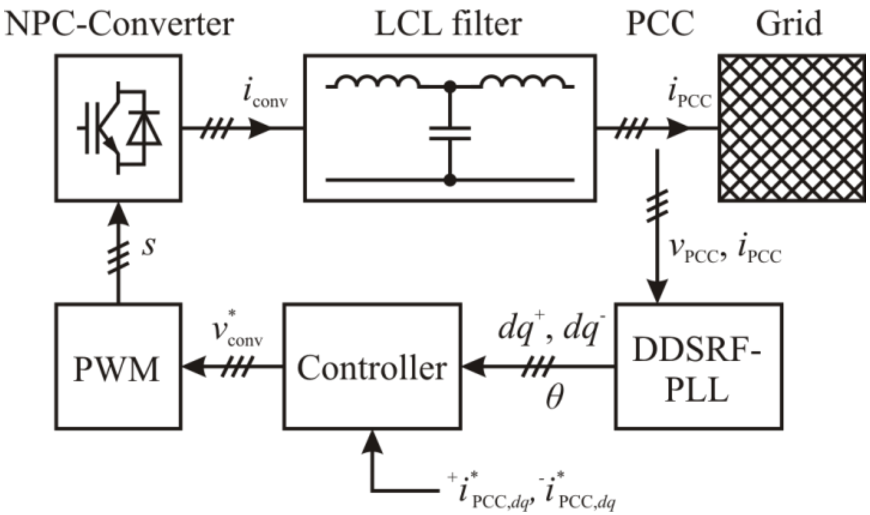
- **The installed power of wind farms increases rapidly**
- **Large wind mills (> 5 MW) with full-sized converter are the trend**
- **3-level inverters with low switching frequency (< 1000 Hz)**
- **Voltage quality limits require large LCL filters, f_{res} 250..350 Hz**
- **How does this affect FRT capability?**





FRT requirement and static harmonic limits according to German medium-voltage grid code

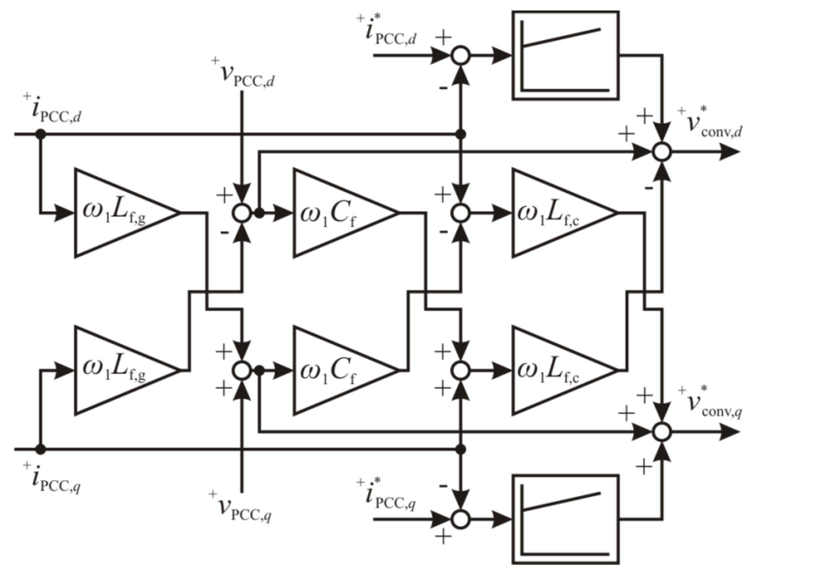
Conventional control: PI-control in the *dq*-frame



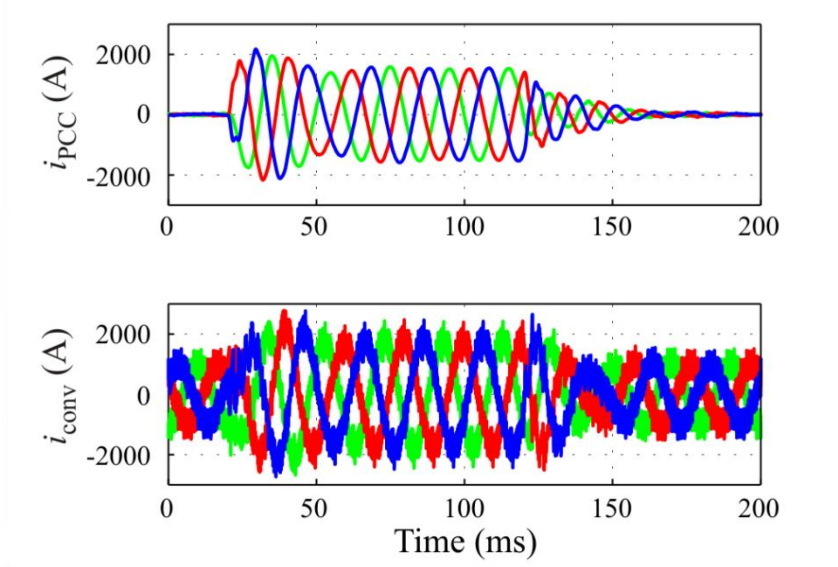
Parameters of a 5 MW wind turbine system

Rated grid voltage	V_r = 2700 V
Fundamental frequency	f_1 = 50 Hz
Rated power of the generator	S_r = 5 MVA
Power factor cosφ	0.9 ind. – cap.
Minimum short-circuit power	$S_{k,min}$ = 100 MVA
DC link voltage	V_{DC} = 4800 V
Carrier frequency of the PWM	f_c = 1650 Hz
Average switching frequency	f_s = 825 Hz
LCL filter: Converter-side inductance	$L_{f,c}$ = 109 µH
LCL filter: Grid-side inductance	$L_{f,g}$ = 272 µH
LCL filter: Capacitor (star-connected)	C_f = 1.46 mF

- **PI-control of the grid current**
- **DDSRF-PLL**
- **Positive and negative sequence**
- **Cross-coupling compensation**
- **Voltage feed-forward**
- **Standard SVM**

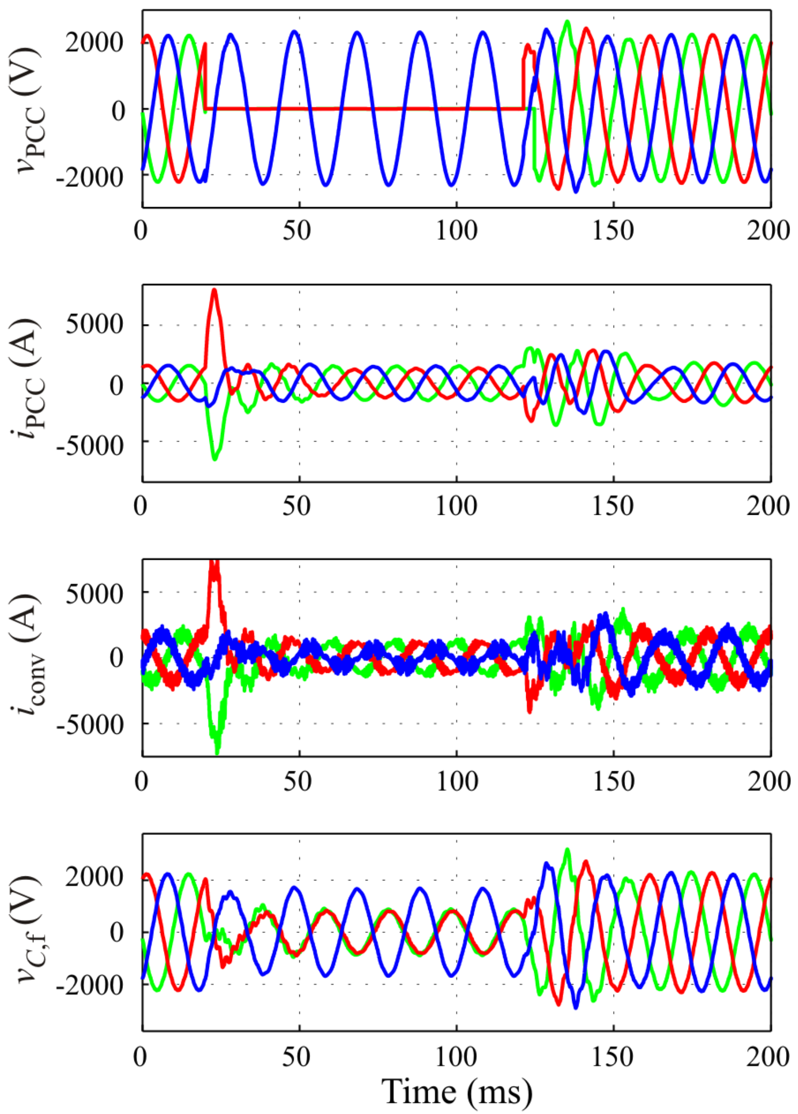


Conventional control: PI-control in the *dq*-frame



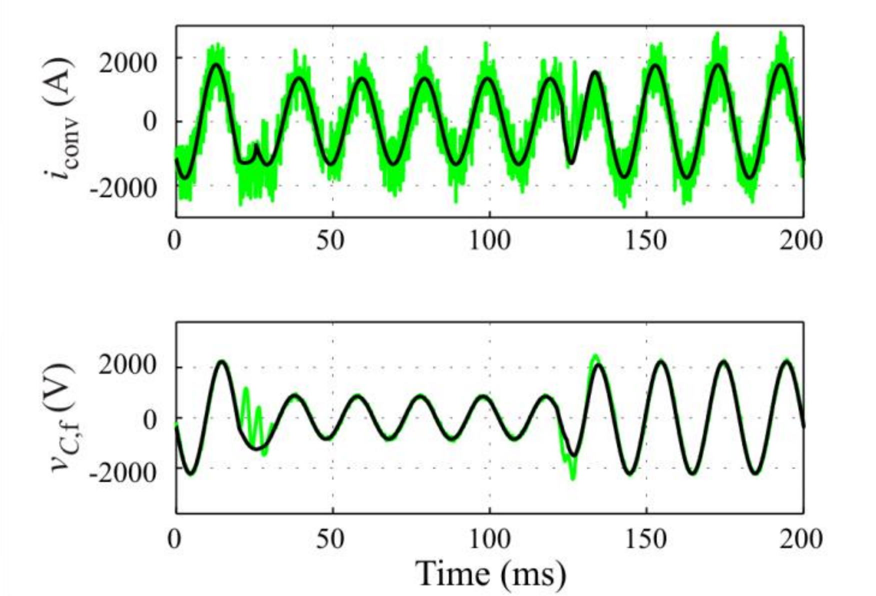
- **Good behavior in steady-state and for reference value steps**
- **Large transient overcurrents caused by sudden voltage dips**

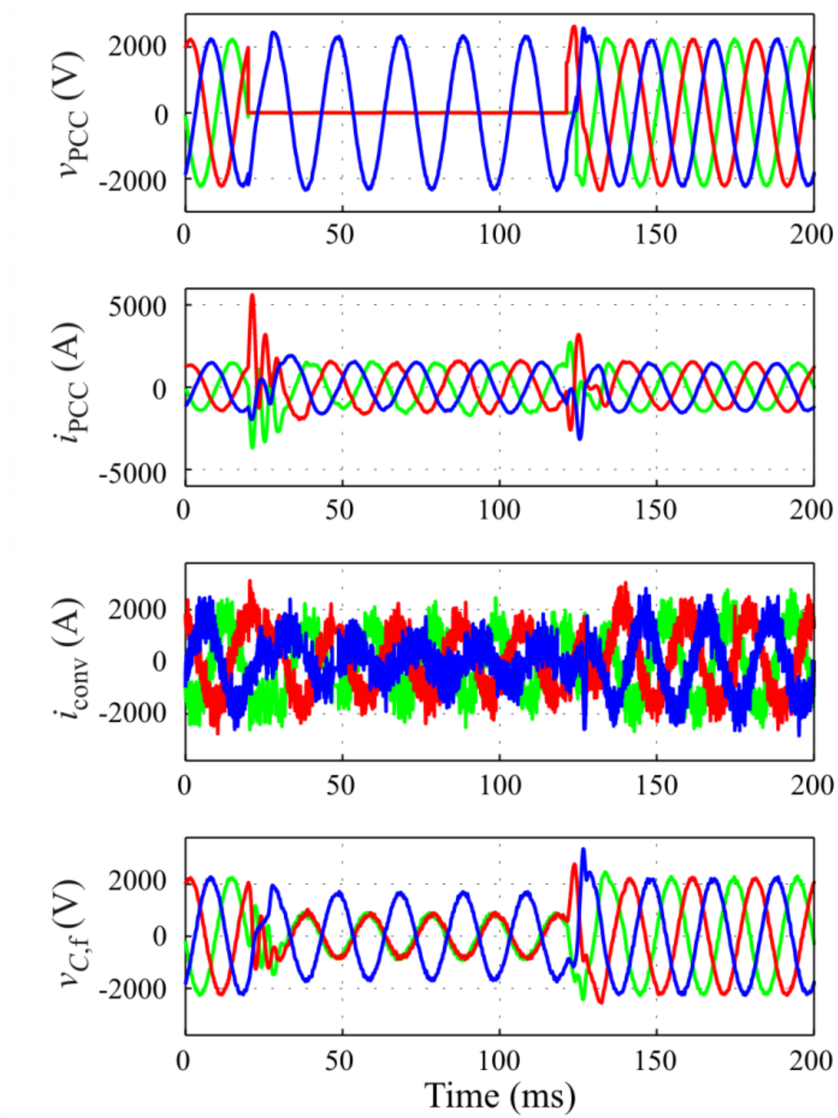
→ **Destruction of the power semiconductors**



Novel control approach: Predictive current control

- **Weighting factor relation**
  - $\uparrow \lambda_v/\lambda_i \rightarrow \downarrow i_{conv}$ and $\uparrow v_{C,f}$
  - Here: $\lambda_v/\lambda_i=10$
- **Sampling Frequency**
  - As much as $f_{s,av}$ allows
  - Here 9.9 kHz $\rightarrow f_{s,av} \approx 850$ Hz





Improved current control

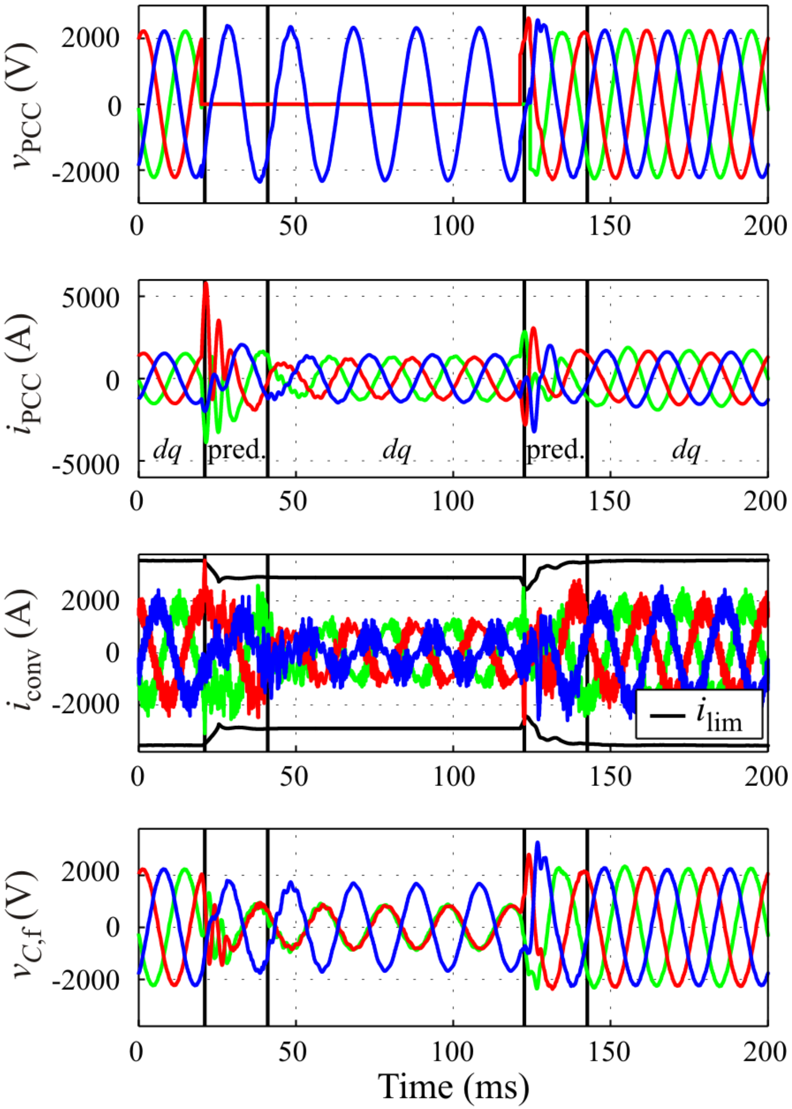
- **Use of PI-control with PWM for normal operation**

→ **Voltage spectrum without interharmonics**

- **Defining converter current limits**
  - Fixed (depends on rated current, here 170 %)
  - Variable (depends on reference current, here 200 %)

- **Current limit violation → use of predictive control for a specified time without limit violation (here 30 ms)**

→ **Fast current control in case of grid faults**



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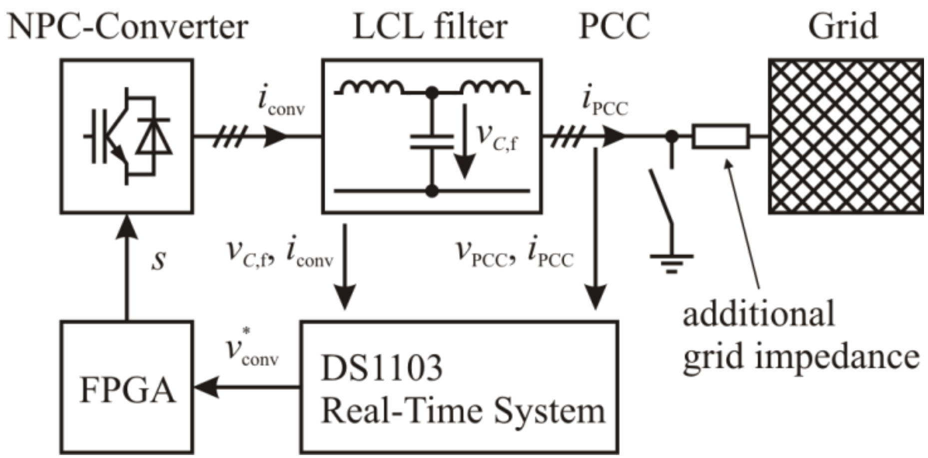
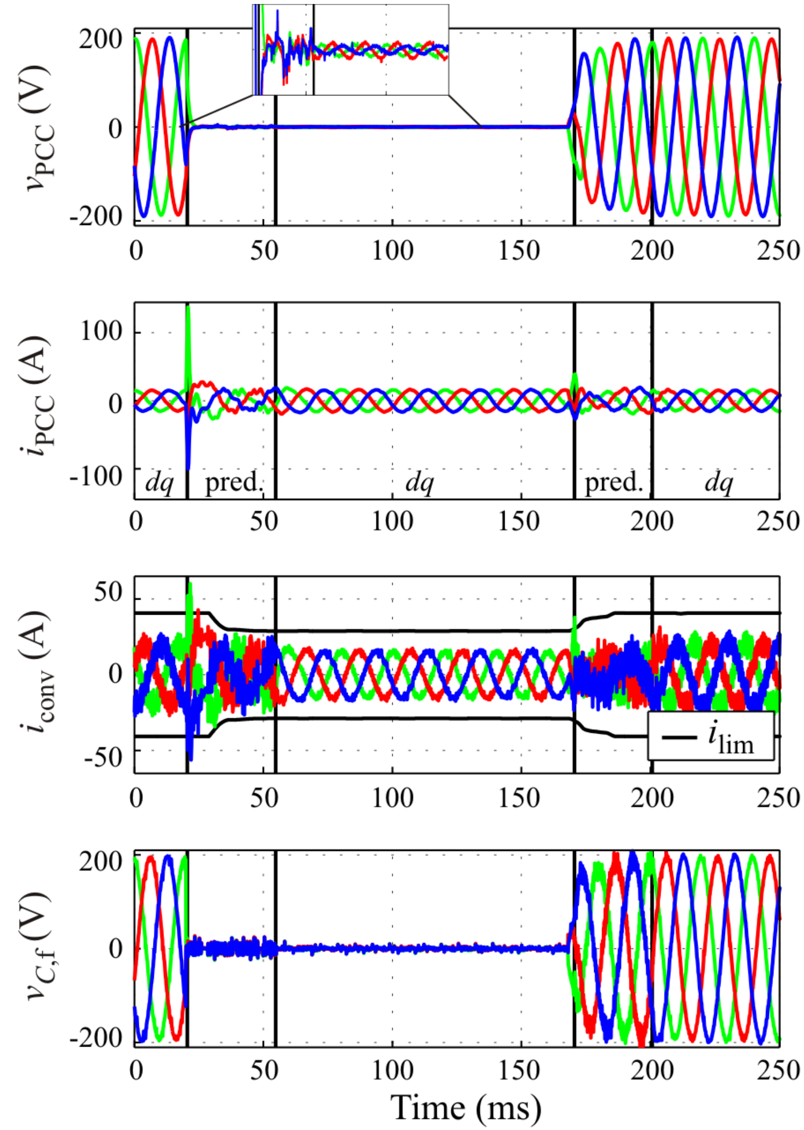
Experimental results

Scaled low-voltage system



Rated grid voltage	V_r = 250 V
Fundamental frequency	f_1 = 50 Hz
Rated power of the system	S_r = 4.5 kVA
DC link voltage	V_{DC} = 440 V
Carrier frequency of the PWM	f_c = 1.65 kHz
Sampling frequency	f_{sam} = 9.9 kHz
LCL filter: Converter-side inductance	$L_{f,c}$ = 625 µH
LCL filter: Grid-side inductance	$L_{f,g}$ = 1.53 mH
LCL filter: Capacitor (star-connected)	C_f = 258 µF



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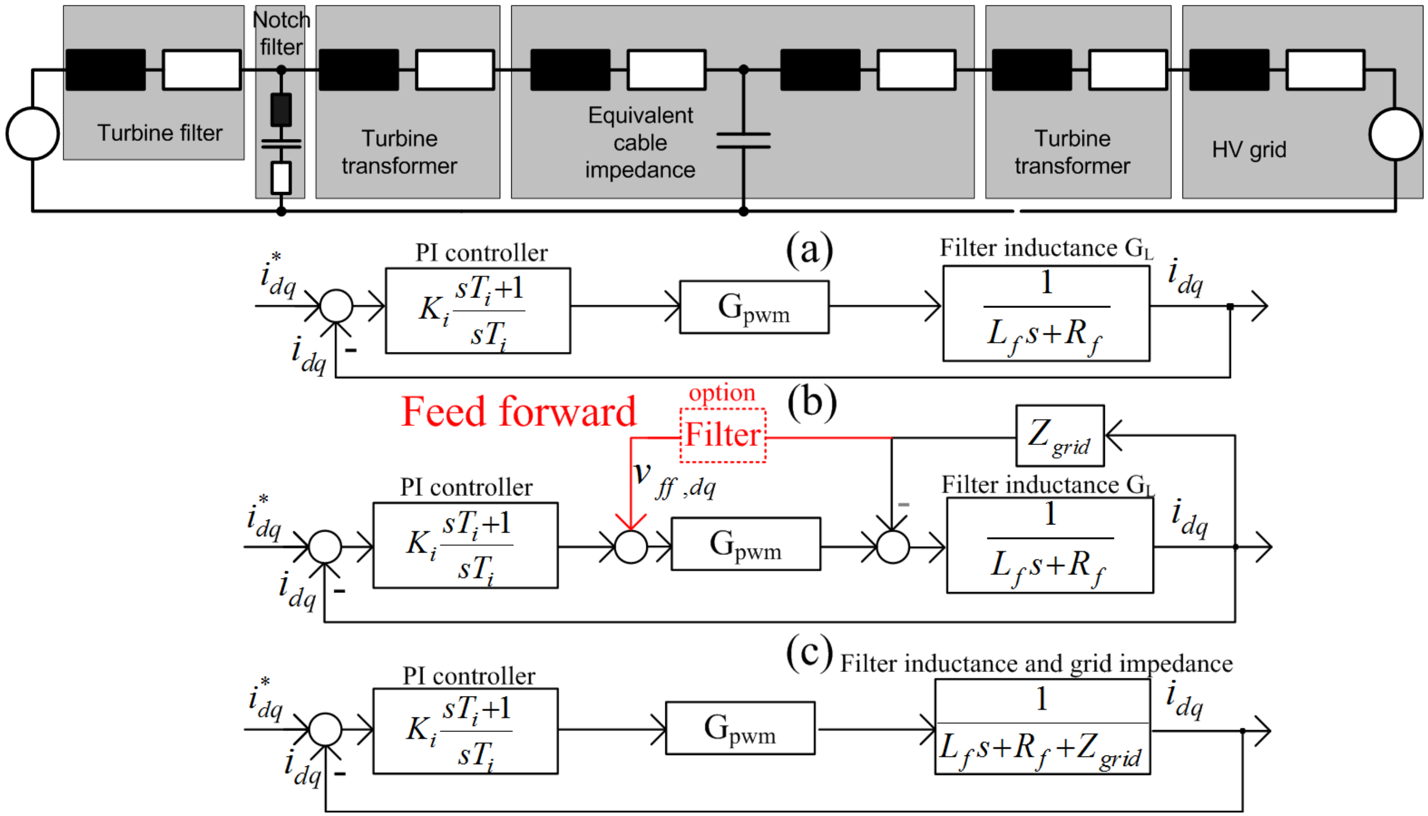
Problem

- **Resonant frequency of the grid impedance and current controller bandwidth are often in the same order of magnitude**
- **Grid impedance varies widely with the load situation**
- **In systems with large amount of converter infeeds, the resonant grid impedance might interact with the current controller**
- **Phenomena have been observed where unexpected frequencies occur with large amplitudes (several 100 Hz)**
- **Is it possible to predict in which situation such instability will occur?**

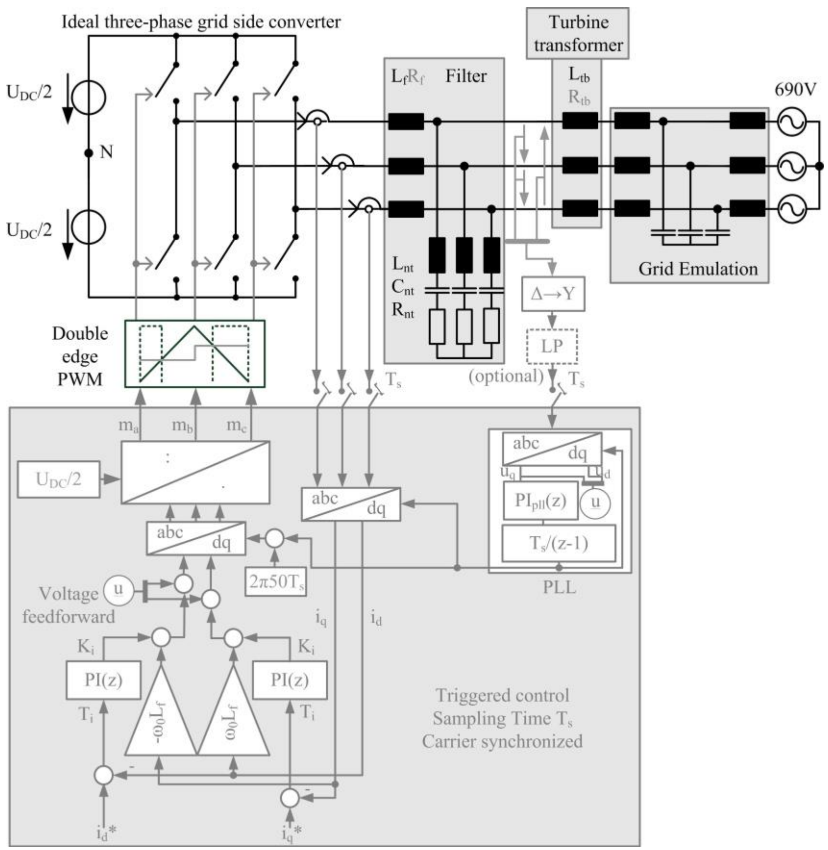
Wind Turbine & Grid Instability Phenomena

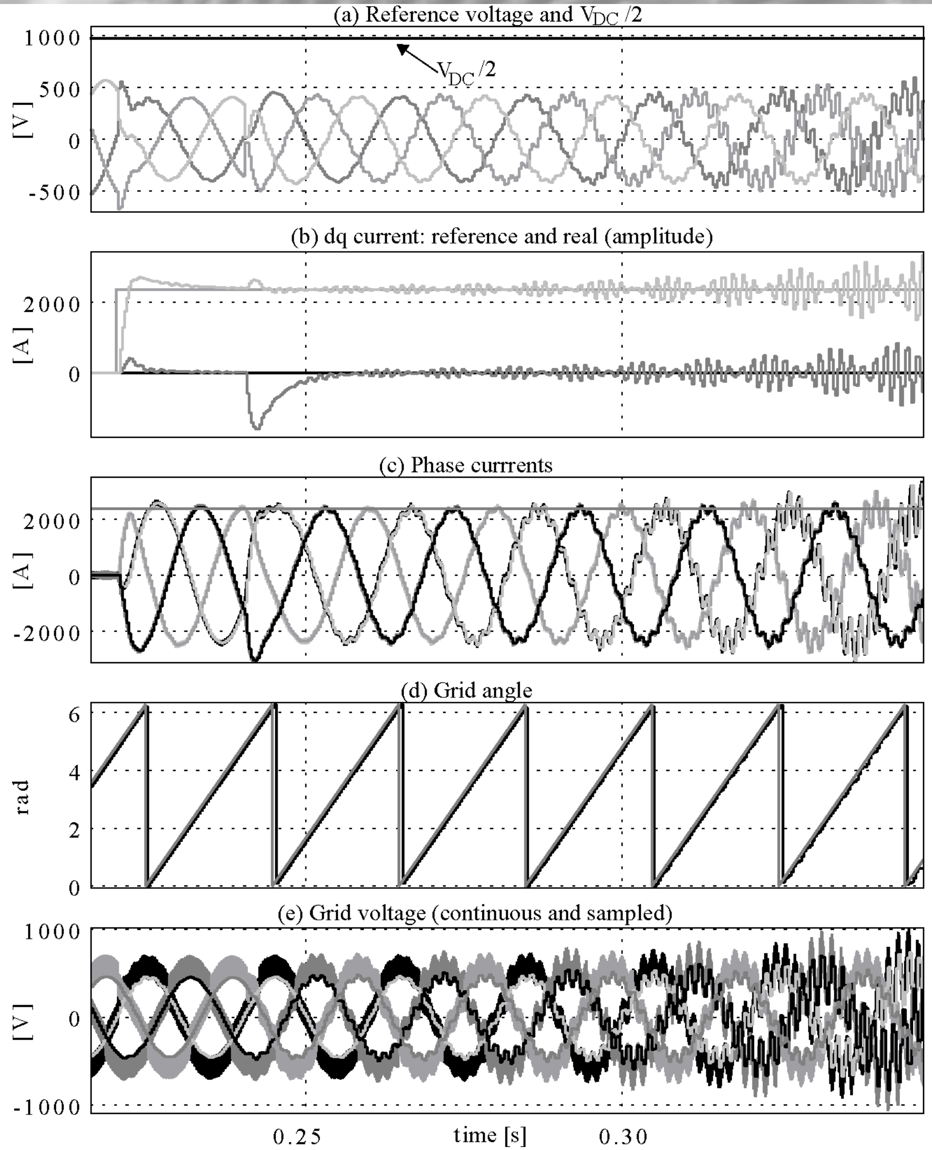
- **Analysis by control theory**
- **A better mathematical description is the basis for better control design**



Transfer Function Based Analysis

- **Simulation results for critical combination of control and grid parameters**
- **Predicted instability is validated**





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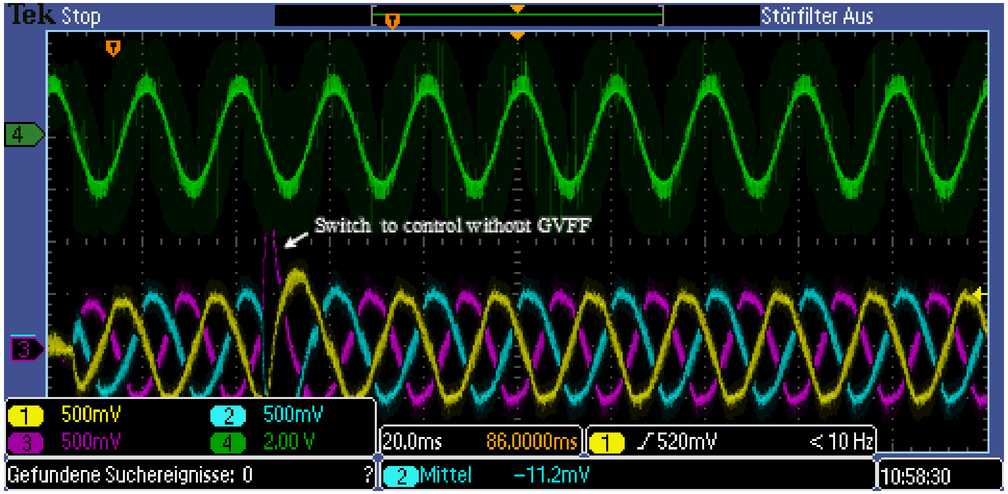
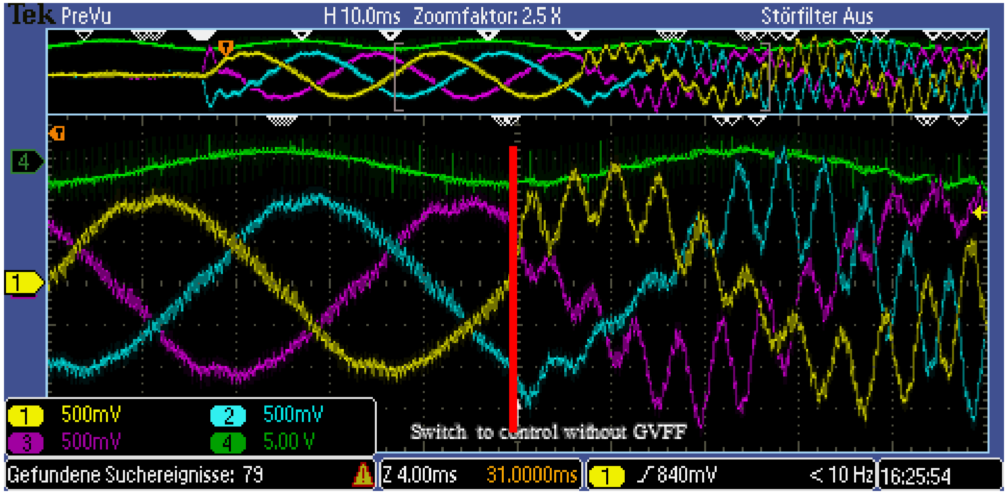
Experimental Validation

- Predicted Instability not observable, due to higher resistances in laboratory
- Including higher resistances in predictions, instability with increased controller gain (285%) is predictable
- **Control with GVFF tends to result in a more stable system**
- **Inner loop of converter control has an impact on grid stabilty**

Smart Nord



Deactivation of GVFF



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Problem

- **In conventional grids, voltage and frequency stability is provided by a few large power generation facilities**
- **PV and wind power converters use „inverse droop" statics to assist in frequency and voltage control, still requiring a strong grid**
- **In converter dominated grids , a large number of converters must combine to control the grid voltage and frequency**
- **They also have to find a reasonable load sharing at the same time**
- **In droop control, a coupling between P and Q and a nonideal dynamic behavior is observed. How can this be improved?**

Simplified Schematic of a Droop Controlled System

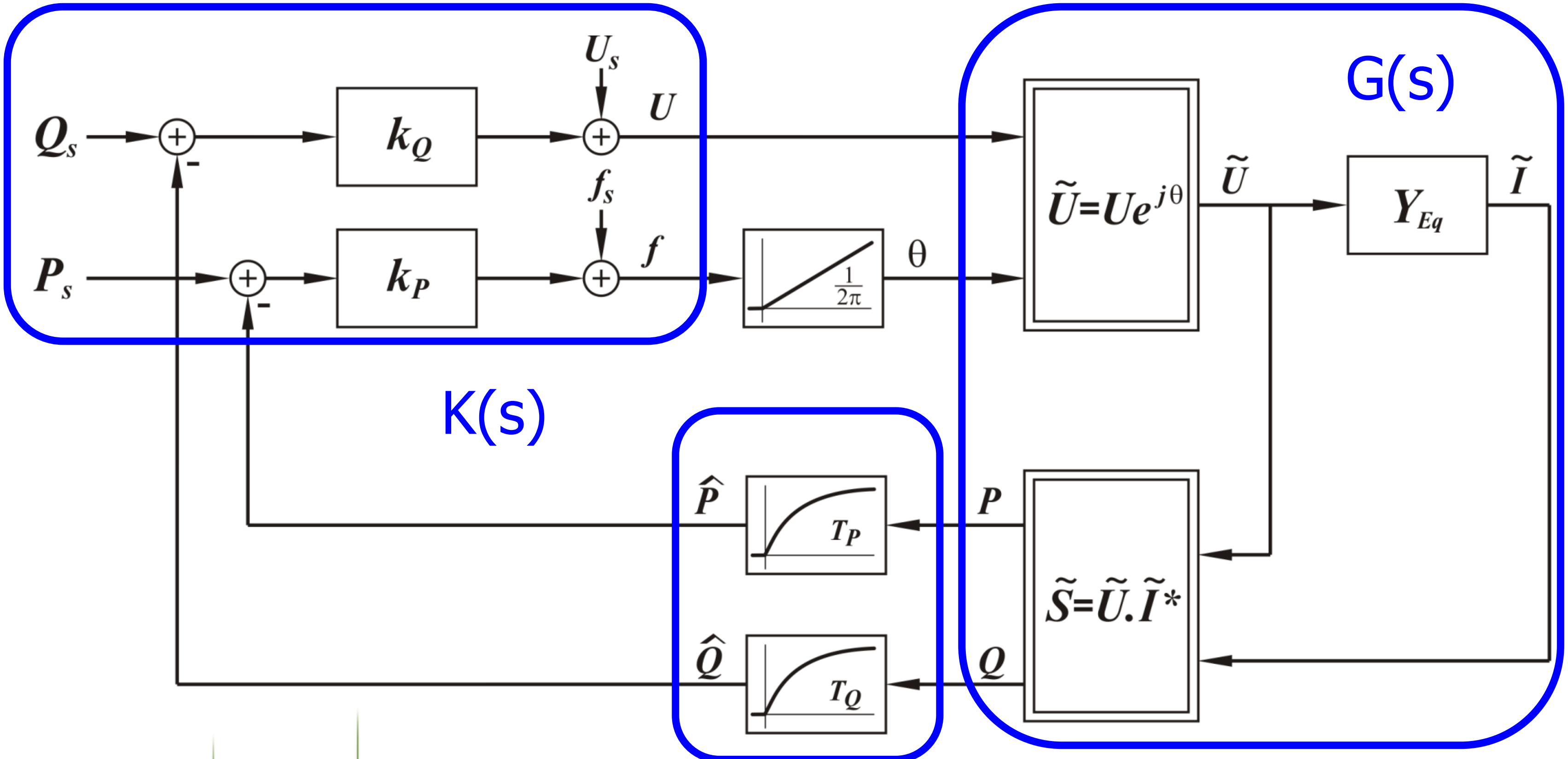
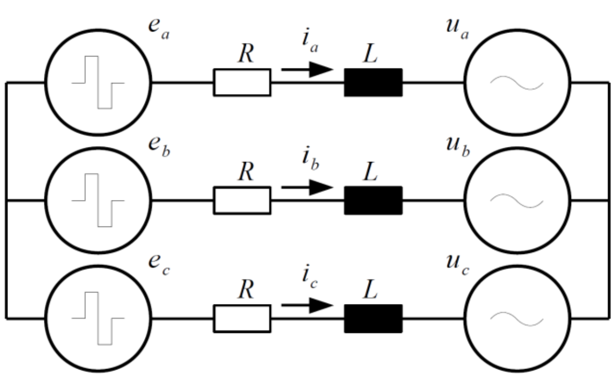


Figure: M. Calabria, W. Schumacher, TU Braunschweig

Properties of Conventional Droop Controlled System

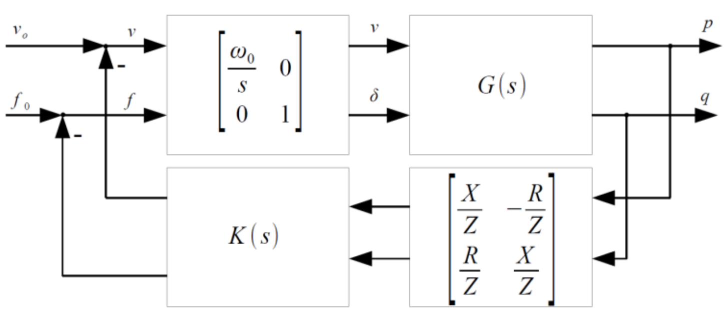
- Conventional Static Control with Decoupling after K. Brabandere



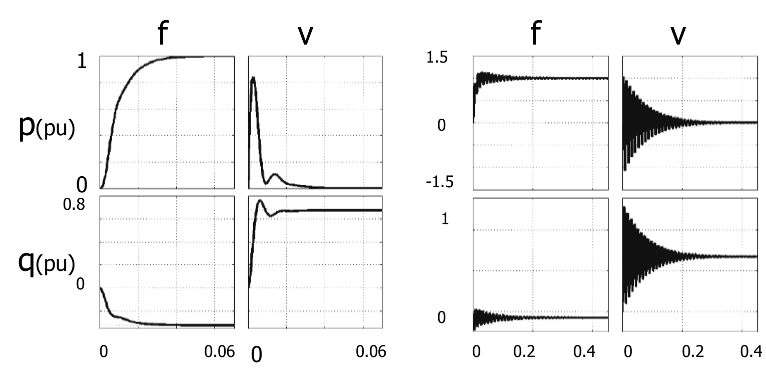
$$P = \frac{3}{2}\frac{\left(\hat{U}\hat{E}\cos(\delta) - \hat{U}^2\right)\cdot(R + sL) + (\omega L)\hat{U}\hat{E}\sin(\delta)}{(sL+R)^2 + (\omega L)^2}$$

$$Q = \frac{3}{2}\frac{\left(\hat{U}\hat{E}\cos(\delta) - \hat{U}^2\right)\cdot(-\omega L) + (R + sL)\hat{U}\hat{E}\sin(\delta)}{(sL+R)^2 + (\omega L)^2}$$

$$G(s) = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial \hat{E}} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial P}{\partial \hat{E}} \end{bmatrix} \qquad KS\begin{pmatrix} \sin(\delta) \Rightarrow \delta \\ \cos(\delta) \Rightarrow 1 \end{pmatrix} \qquad K(s) = \begin{bmatrix} \frac{K_d}{\tau s + 1} & 0 \\ 0 & \frac{K_q}{\tau s + 1} \end{bmatrix}$$



Decoupling



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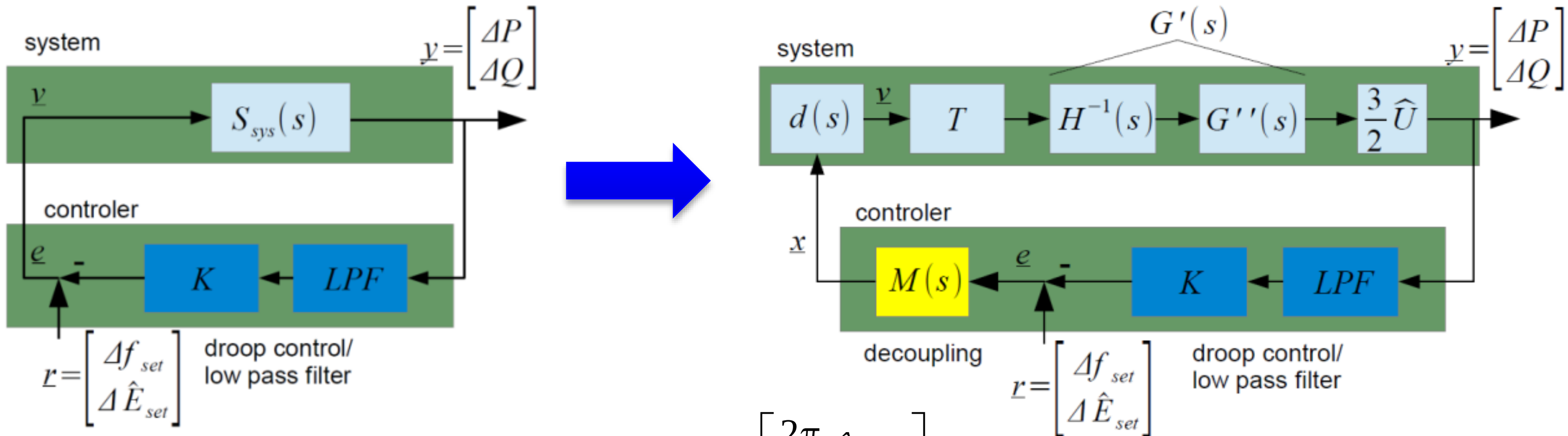
Dynamic Decoupling of the System Control

- Representation of the system equations by a more elaborate model
- Introduction of a decoupling matrix M(s) in the control

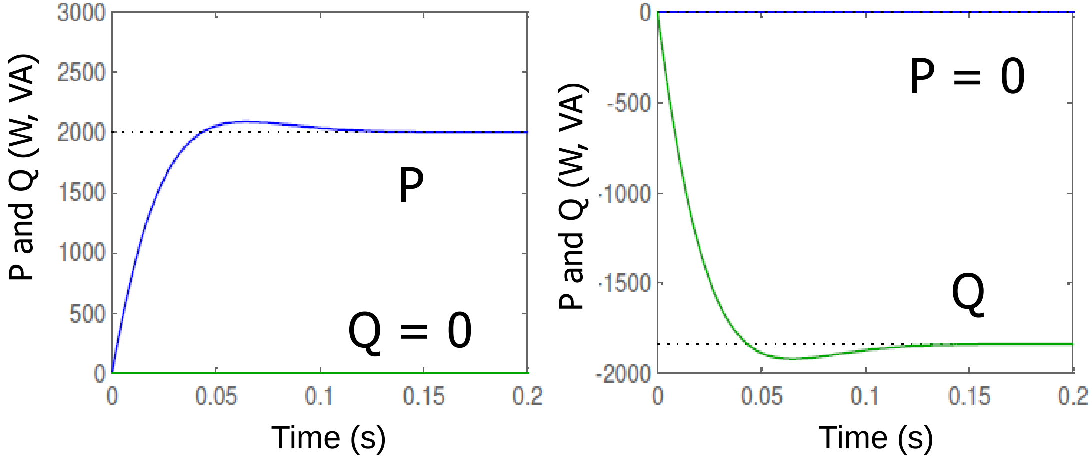


$$S_{sys}(s) = G(s) \cdot d(s) \qquad d(s) = \begin{bmatrix} \frac{2\pi}{s}\hat{E} & 0 \\ 0 & 1 \end{bmatrix}$$

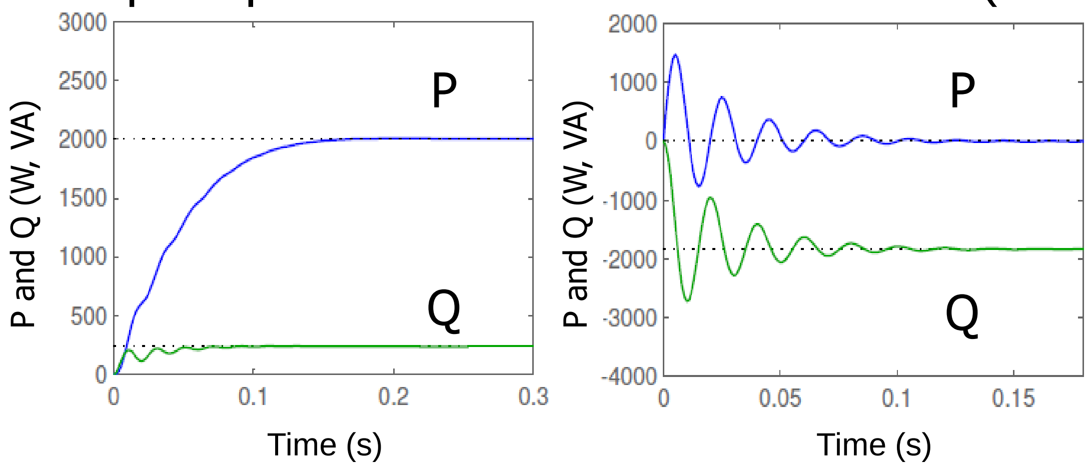
$$M(s,\hat{E},\delta,R,L) = d(s,\hat{E})^{-1} \cdot T(\delta)^{-1} \cdot H(s,R,L)$$

Dynamic Decoupling of the System Control

Step responses of decoupled control (simulation results)



Step responses of conventional control (simulation results)



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Conclusions

- **Inverters and their control have a strong impact on the behaviour of future energy systems.**
- **Large inverters with low switching frequency need special attention when it comes to dynamic reactions, e.g. in FRT**
- **Other kinds of high-power converters may have different restrictions**
- **The implementation of the current control loop in wind farms has a large impact on instability phenomena at frequencies below 1000 Hz**
- **In future power grids, the control of grid voltage, frequency and load sharing with independant converter controls has to be solved**

Thank you for your attention!

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Germany

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The Lower Saxony Research Association 'Smart Nord' acknowledges the support of the Lower Saxony Ministry of Science and Culture through the "Niedersächsisches Vorab" grant programme (grant ZN 2764).