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Digital Nonlinear Power Systems

Green Hydrogen Electrolysers in Forming Future Grids – Power Electronics Perspective

Kassel, August 4th 2025

Michael Fette

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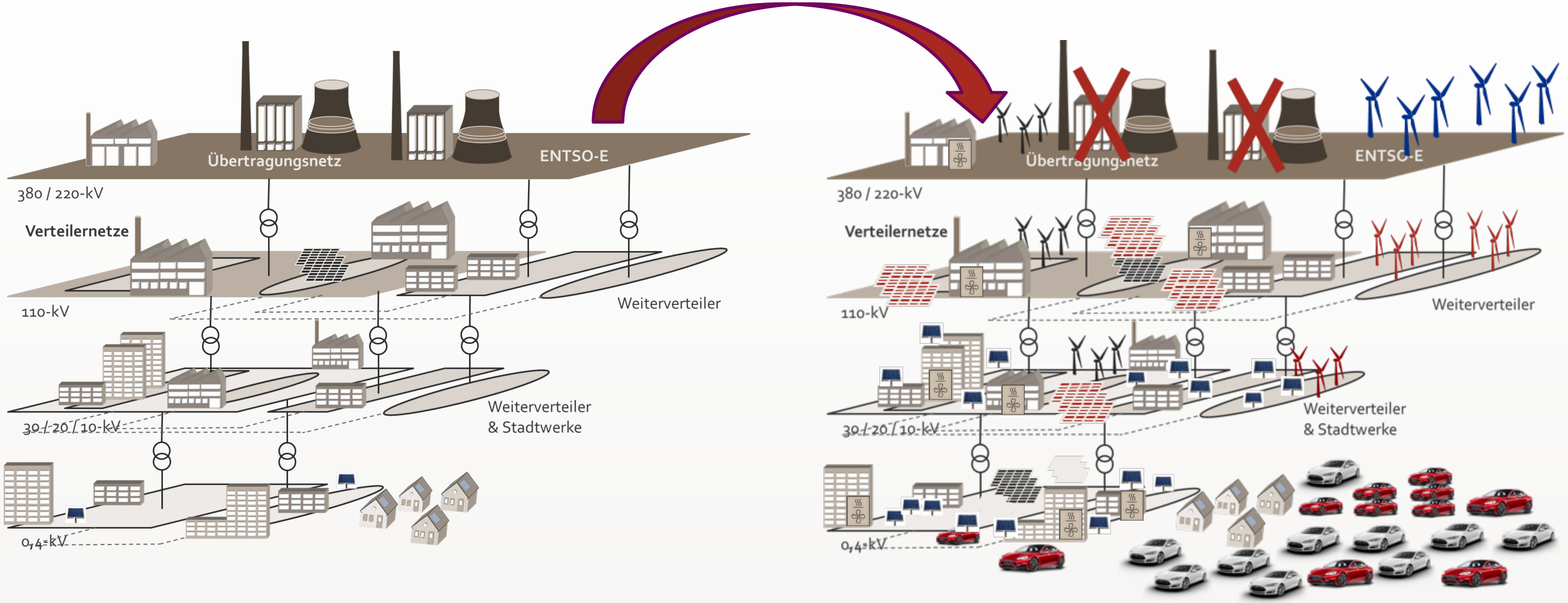
Vom Netz zum System

Fundamental changes in future system require transition with clear vision and new solutions



Vom Netz zum System

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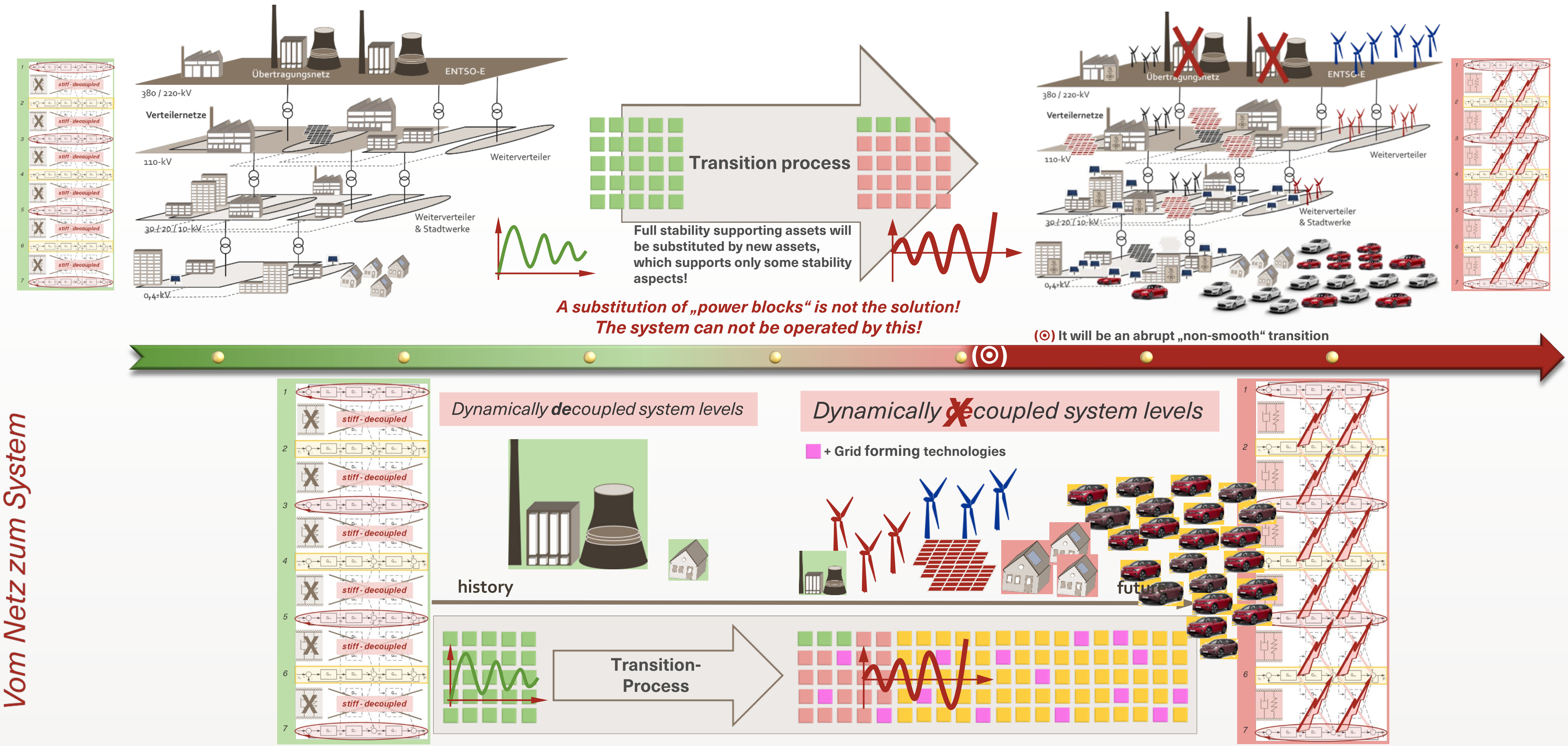
From passive participation to active contributions - at all levels

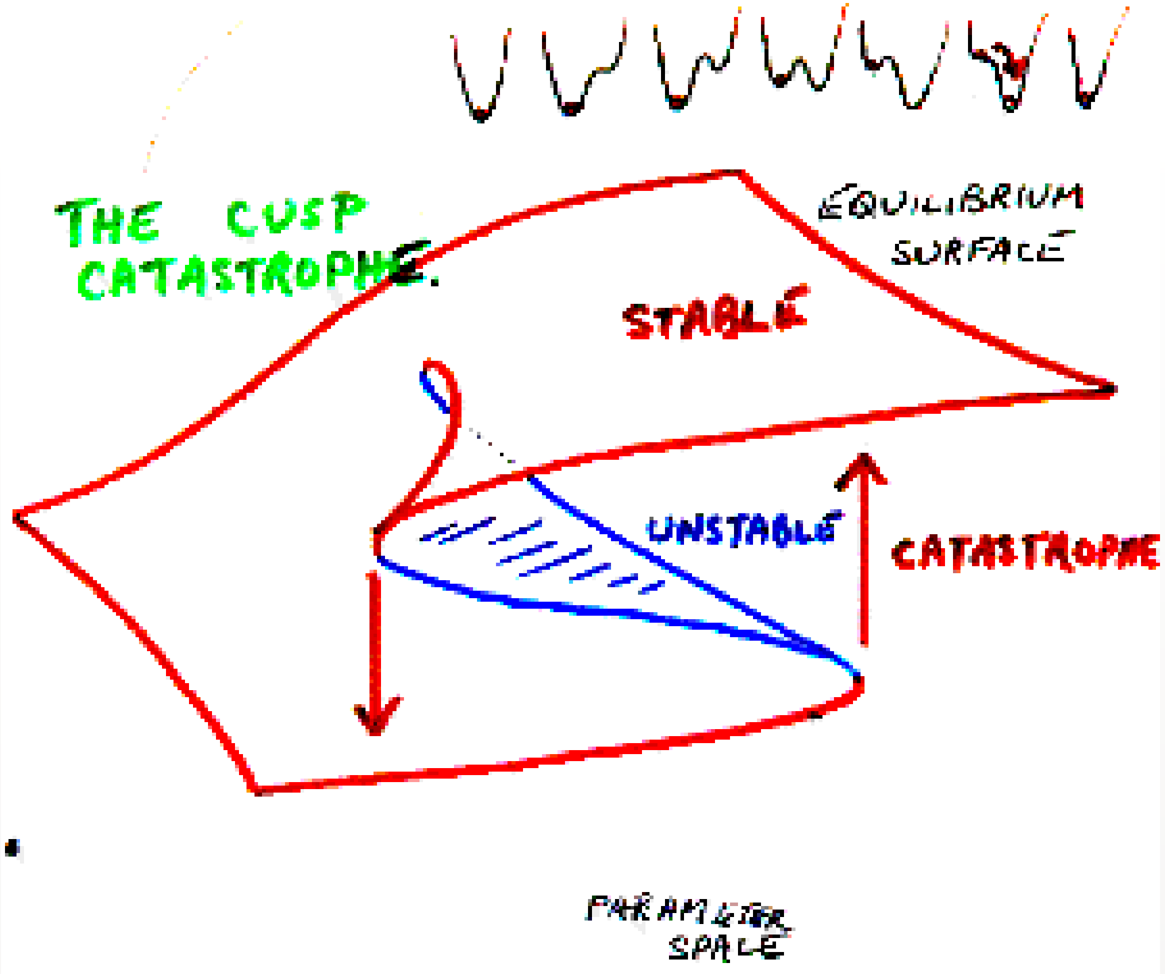


Vom Netz zum System

Rene Thom

Hand drawing to illustrate catastrophe theory

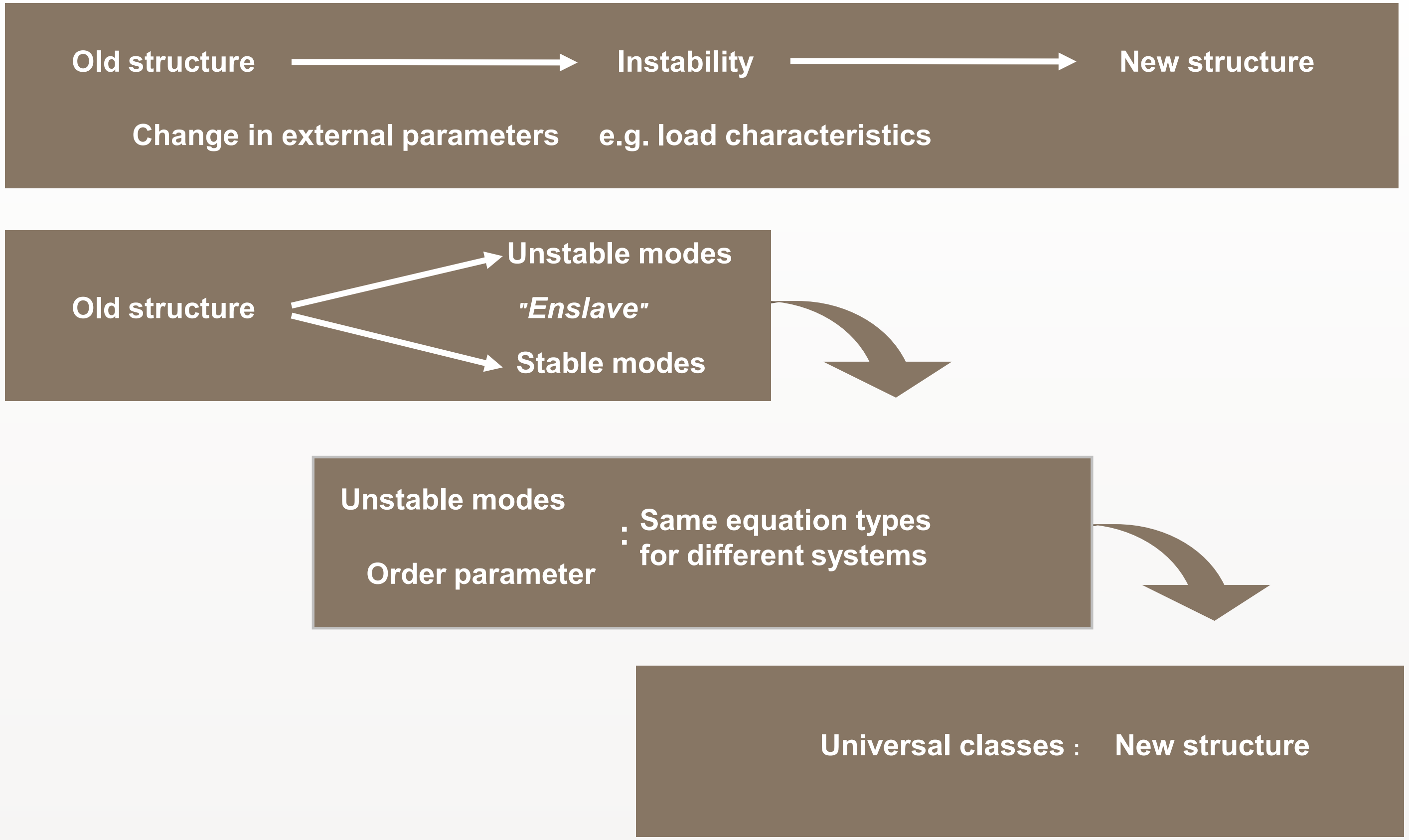
It represents the charactistics of magnetic material – saturation curve



Vom Netz zum System

Changes in dynamic properties (Synergetics)

- Models must be suitable for non-linear analyses
- All frequency ranges must be represented!
- Synergetics uses structurally correct replacement models for description according to Hermann Haken – determination of external influence parameters on model properties



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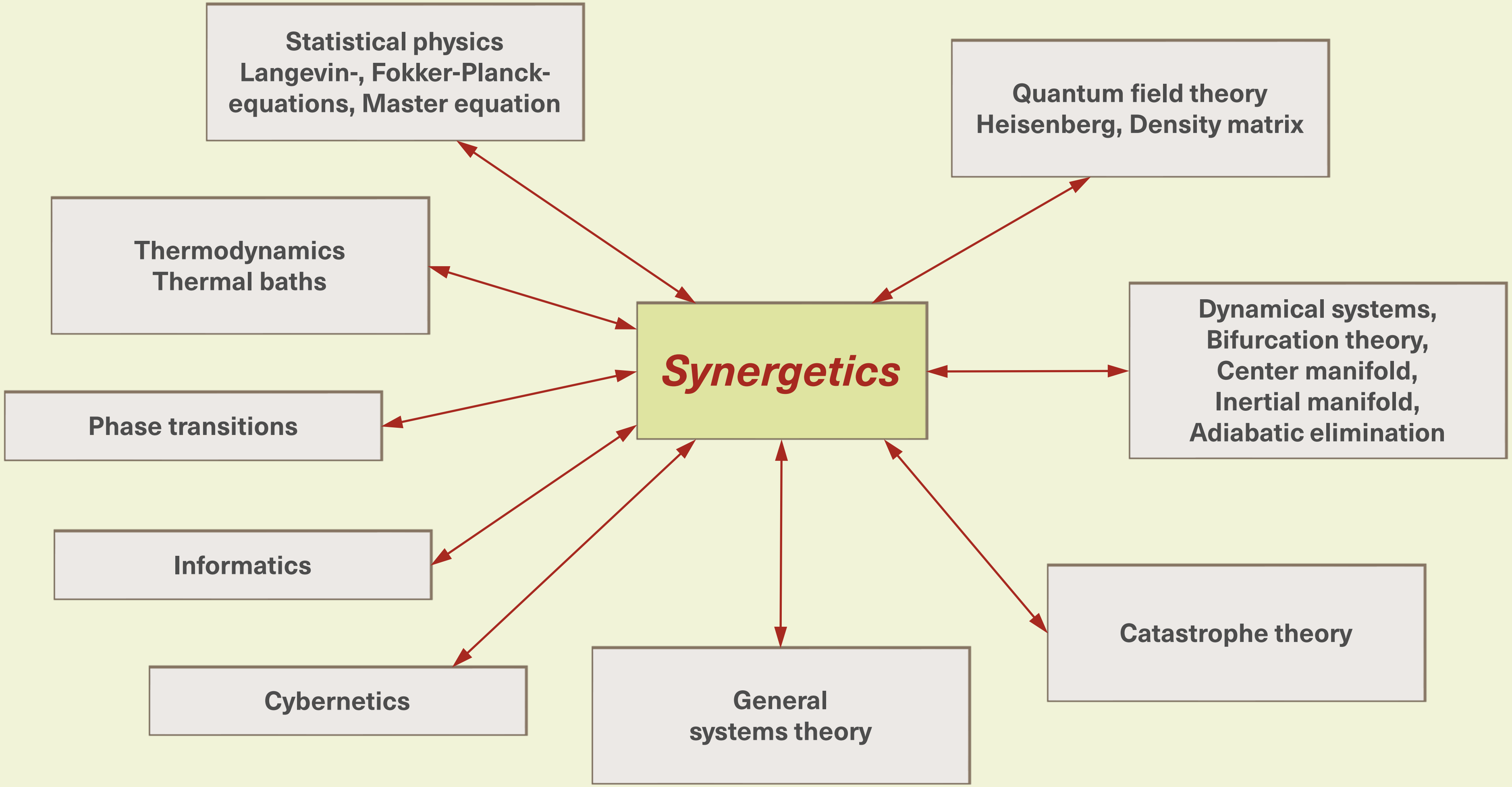
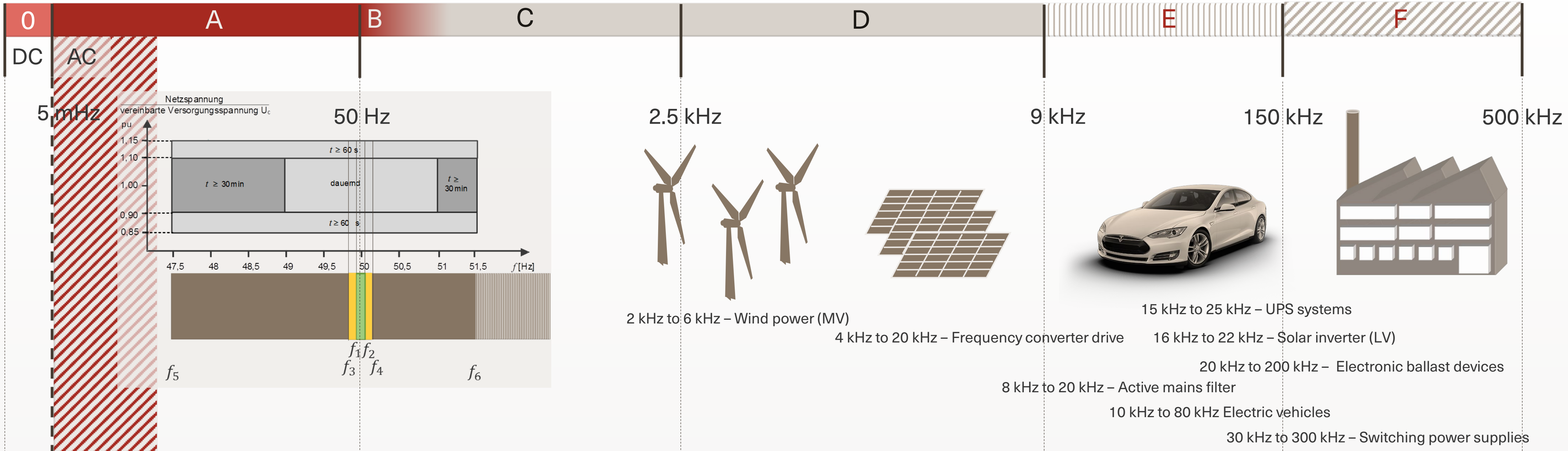
Classification of synergetics within the framework of mathematical theories



Source: Hermann Haken, Synergetik, University of Stuttgart

The new EC-Grid-Codes gives a framework for devices and operation of grids in all situation from emergency to regular operation – all voltage levels

Frequency Range of VDE|FNN TAR / EC-Grid-Codes *plus Extended Range*



- **Low frequency processes**
- U, I, 4-phase, unsymmetrical

- class A EN 61000-4-30
- U, I, 4-phase, unsymmetrical

- class A EN 61000-4-30
- from 2,5 kHz in frequency bands of 200 Hz – width - FNN TAR
- U, I, 4-phase, unsymmetrical

- IEC 61000-2-2 (up to 150 kHz)
- Extended emission spectra
- E-Mobility, industry (robotic), PLC, ...
- U, I, 4-phase, unsymmetrical

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Impact of Time Delays on Power System Stability

Figure a) … c)

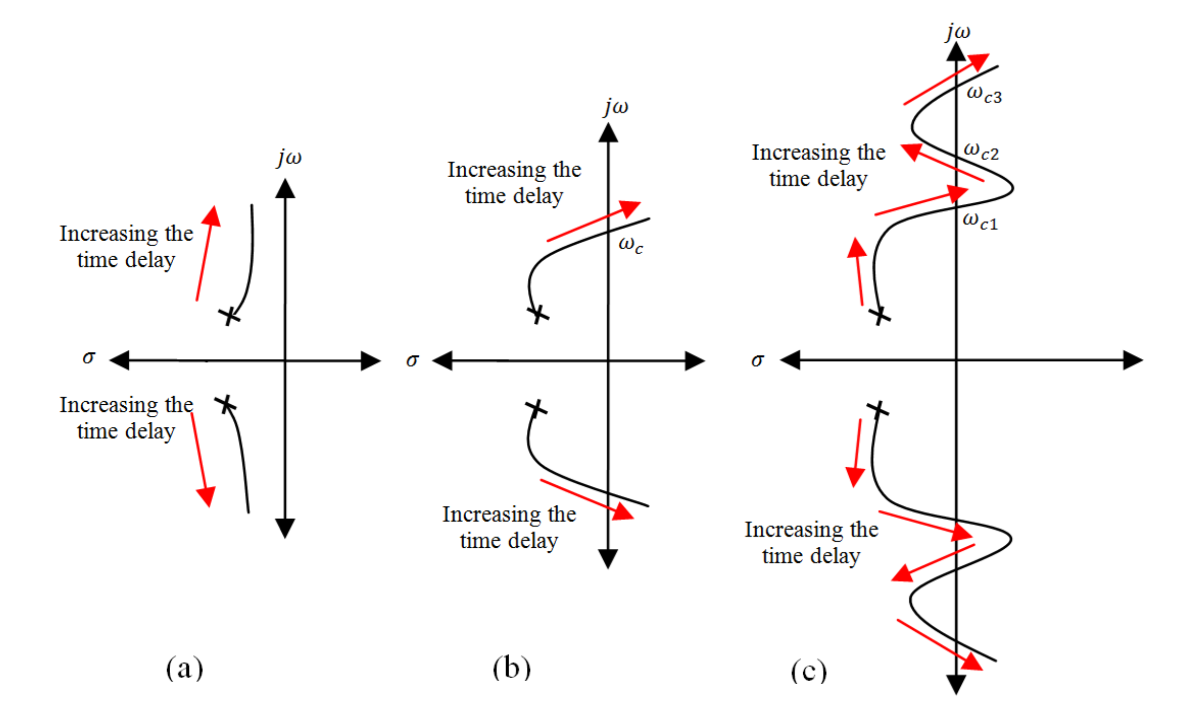
a) A delay-independent system

b) A delay-dependent system with a single delay margin

c) A delay-dependent system with multiple delay margins

Source:
„An Accurate Method for Delay Margin Computation for Power System Stability“
Ashraf Khalil, Ang Swee Peng, 2018, energies 11-03466

Case Study: Impact of Time Delays



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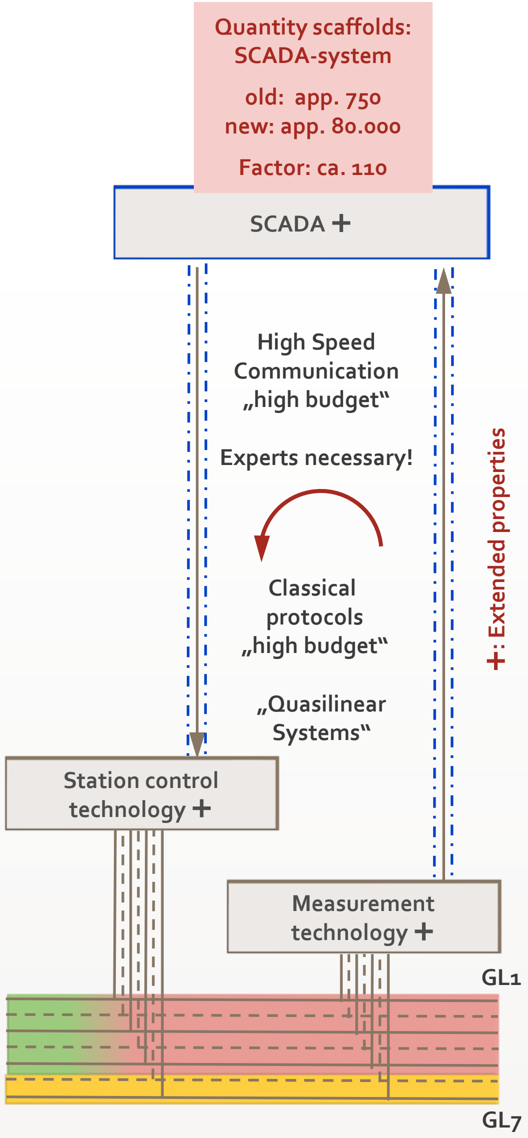
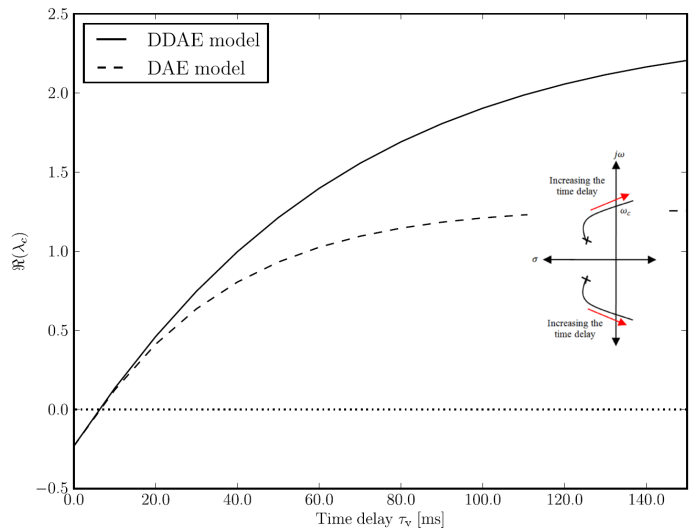




Qualitative dependency of the biggest eigen value on the values of latency time

Differences between models of power systems with and without consideration of latency time

Studies show in comparison of both models (IEEE-models) a qualitative change of the bifurcational behavior if the delay is **> 15 ms**

The critical Hopf-Bifurcation of the IEEE-14-node-model can be detected at $\tau_v \approx 6{,}3\ ms$

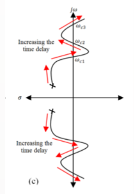
Data transfer latency has a fundamental effect on system stability!

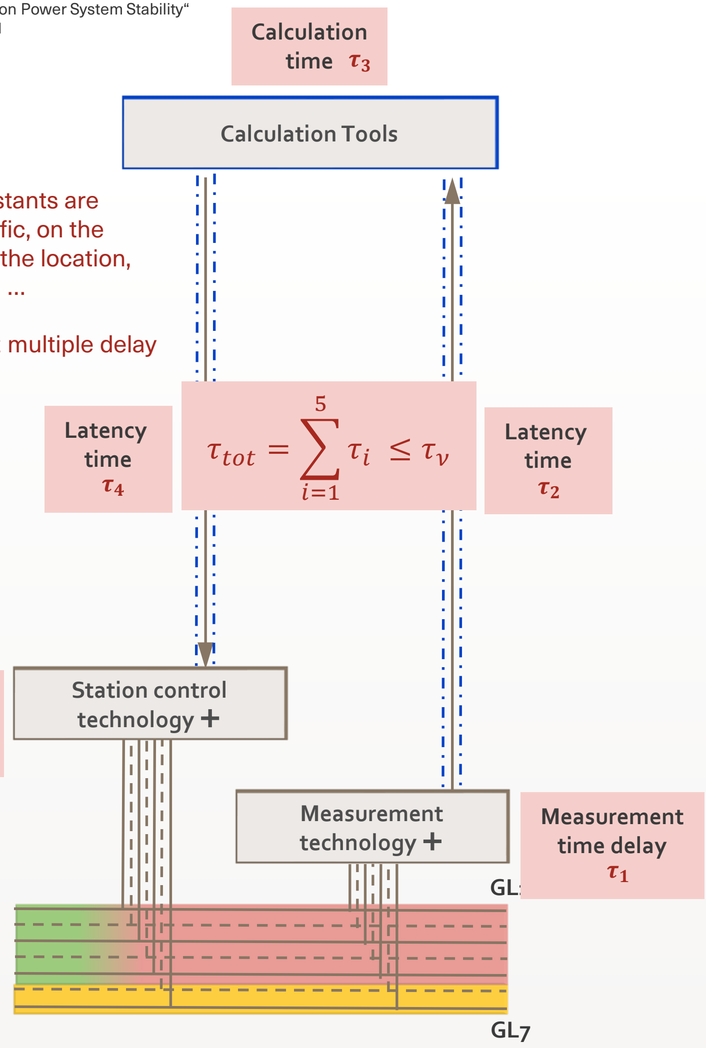
DDAE – Delay Differential Algebraic Equations
DDE – Differential Algebraic Equations

Source: „Impact of Time Delays on Power System Stability"
F. Milano, M. Anghel, IEEE, 2011

The latency time constants are depending on the traffic, on the network topology, on the location, on router capacity, on ...

In practice there exist multiple delay margins.





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To discuss, one have to consider a complex and very sophisticated case in power system dynamics.

Why does it work in history?

Important Paper

- The irrelevance of electric power system dynamics for the loading margin to voltage collapse and its sensitives
  Ian Dobson, Nonlinear Theory and Its Applications, IEICE, Vol. 2, No. 3, pp. 263 – 280, 2011

  „We analytically justify the use of static models to compute loading margins and their sensitivities and explain how the results apply to underlying dynamic models.

  …

  This result enables commercial software used by the power industry to monitor and avoid voltage collapse blackouts.“

Remarkable Result

- „The paper shows that the load power margin is independent of dynamics and we suspect that this useful property is also shared by the energy function index.

  …

  Therefore these indices require for a power system model either a full set of differential equations or differential-algebraic equations **with the assumption or knowledge that the algebraic equations are enforced by underlying dynamics that are both *fast and stable*.**“

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Some Remarks

- Power systems are complex systems with a wide range of time scales
- In the past, due to the characteristics of synchronous generators, the complete analysis of the behavior of the system could be concentrated on the mains frequency. This implies,
  - ***All other dynamical processes are fast and stable, so that they can be neglected – this is an inherent behavior***
  - ***The overall system behaves as a „dissipative system", which has the ability, to reach stable operating points***
  - ***All other dynamical process like „power quality" could be separated, they are processes by their own, locally restricted with no impact on the overall dynamcis.***
  - ***There are no interacting processes between grids or devices, or … (if, they are stable – see above)***

- Therefore, it was sufficient, to take some measures only, as an representant of the the system status
- All other values could be predicted or estimated on a „simple" model basis
- All control actions are not critical in real time – sometimes the basis for real time was bigger than 1 minute.
- Due to the expected overall stable processes, there were no special requirements on a critical time base (DSO-level).
- If there are any further problems, in the past the device or subgrid are separated from the grid, which contradicts with the actual EC-grid codes (RfG)

- The design and equipment of SCADA systems including the data transfer take this into account!

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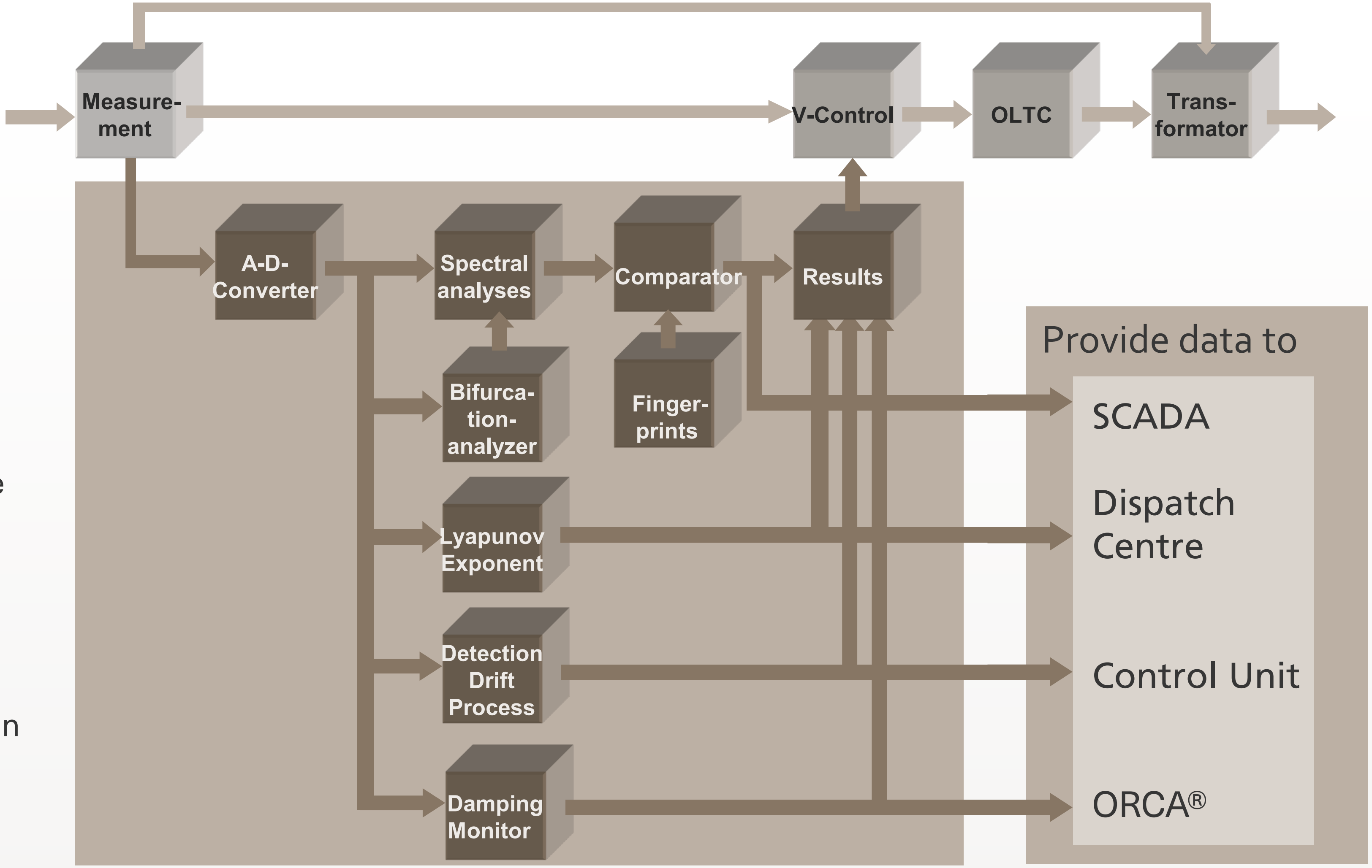
Starting in 1987 with Nonlinear Analysis of Power Systems

2002 – CPR-D Collapse Prediction Relay (Manufacturer: A.Eberle GmbH & Co. KG; Nuremberg)

CPR-D – Analysis Blocks

- 35 years of scientific research in the field of nonlinear power systems
- Developement of measurement devices – based on nonlinear systems theory – with industrial partners
- More than 350 projects, in more than 180 companies, 30 countries - all voltage levels



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Interaction Processes Solar Park (South France)

Asset life time estimation

- Example: Large solar park
- Operation time app. 2,5 years
- Our Task: „The“ question to be solved:

  15 from 9 transformers burnt!

  What is the reason?
- Analysis of Grid Dynamics gives the necessary answers!
- Repaired Transformers – life time: 2 weaks!

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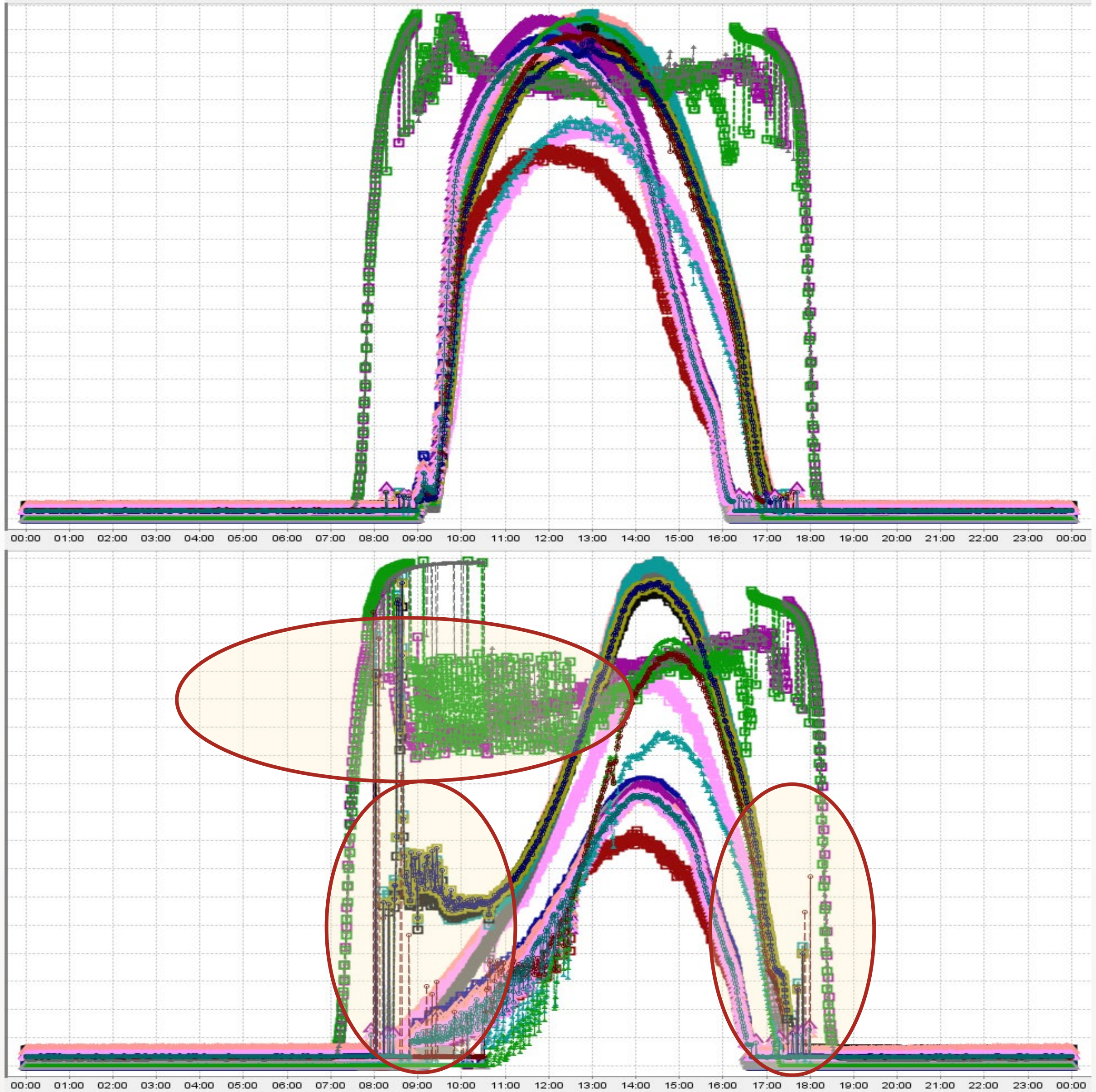
Measures from the SCADA-System – two different days

Above: 0,5	Behavior of the plant after a period of years operating time
Down:	Behavior of the plant immediately after starting a further part in the direct neighborhood
Remark:	Everything is tested! Everything is certified!
Red curve:	Solar irradiation



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10 – the scaling factor for transformers with such kind of loadings.
Result of PQ-Measurements according to ANSI C 57.110

Malfunction of the Converters via Interaction Processes

- Red Curve: Solar Irradiation
- Other colours: currents

- Within the red labeled areas, a hugh amount of reactive power will be interchanged between the converters.

- **Transformers must be scaled up for such a load type by a faktor of 10, or the must be reduced up to a load level app. 20%**

  Factor: *10* (ANSI C.57.110 – worst case)

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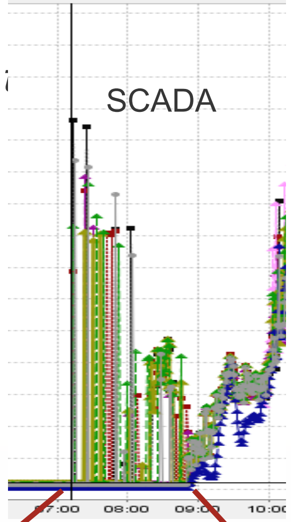
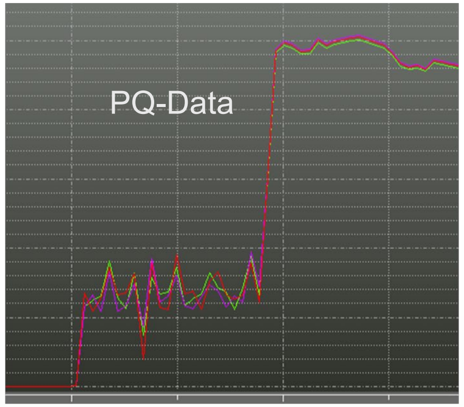
Converters detect their neighbours as the grid and try to deliver them energy. - That will not work!

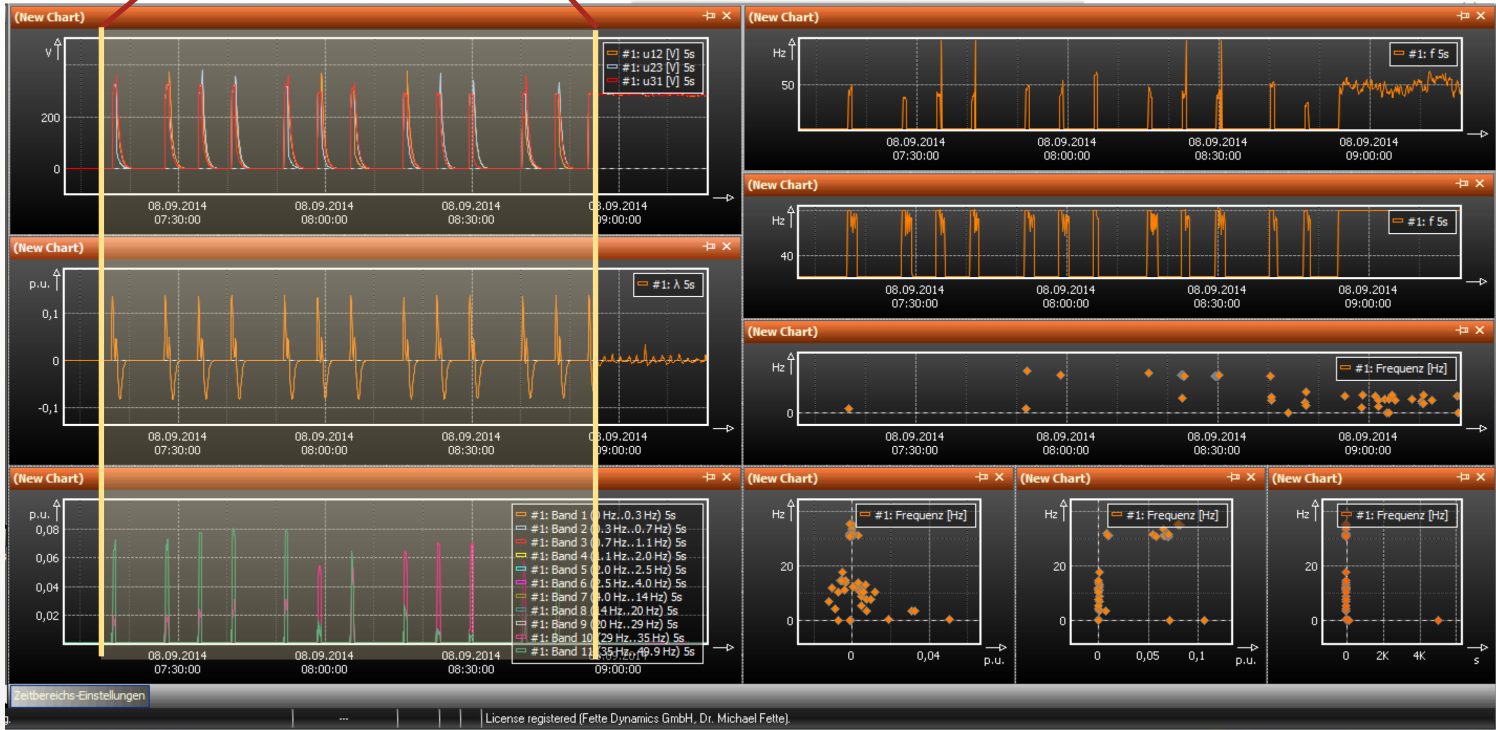




Dynamical Interactions

- SCADA-Systems do not give any inside into the real behavior
- Power Quality Analysis according to e.g. EN 50160 does not help – the standard is limited to some frequencies only and uses averaging processes.
- Low frequency processes with big time constants.
- Currents behave like DC-currents.

- ***Assets will be destroyed by overload in the morning and evening hours – with „zero"-classical load conditions.***



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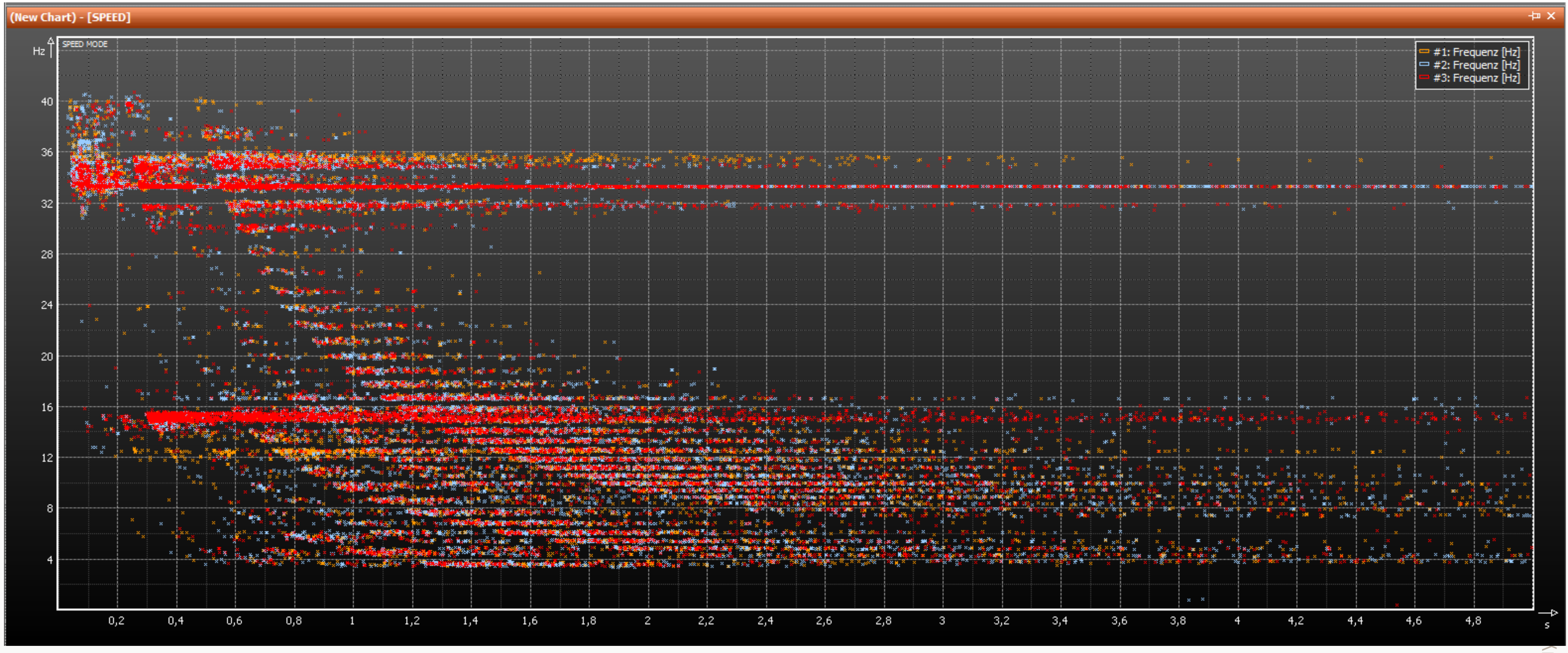
Loading of the system is immense!
Thank`s to e.Power Quality Standards, the world is in order! - Or not?

Frequency-Distributions vs. Duration of Events

- Complete measurement interval.
- Color code with respect to 3 different measurement periods.

- Frequencies from 0 to 45 Hz
- Durations from 0 to 5 seconds
- Some interacting processes last more than some minutes!



- Frequency bands are visible clearly.
- Reflexions could be obervered – analogously to the old analog TV-sets, where the pictures were disturbed, when the characteristic wave impedance was not matched to each other.
- The frequency band are typical for devices and manufacturers – we have a lot of „patterns“ from the grid, to find solutions very fast. **The associated aging behavior is now well known by us!**

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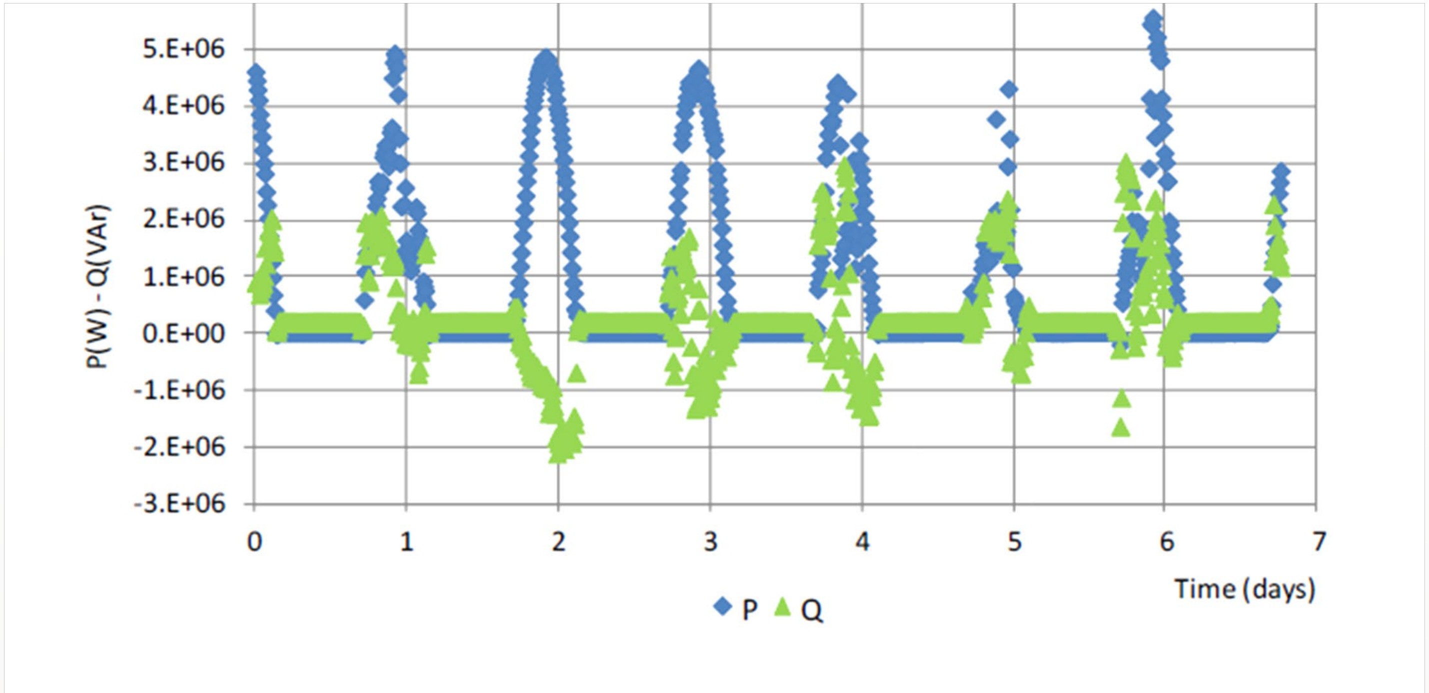
Reactive power behavior

- The park exchanges reactive power with inductive and capacitive behavior
- Same situation, we measured in other locations
- This is only possible, if there is a driver for this behavior to force the inverters to do something different.

  This could be done, by a partner, who has the the same or better capabilities



- Report of the same topic by spanish consulting company – page 66
- The direction of Q-insection into the grid depends on the capability of the grid – or if there is another partner, who leads the processs.

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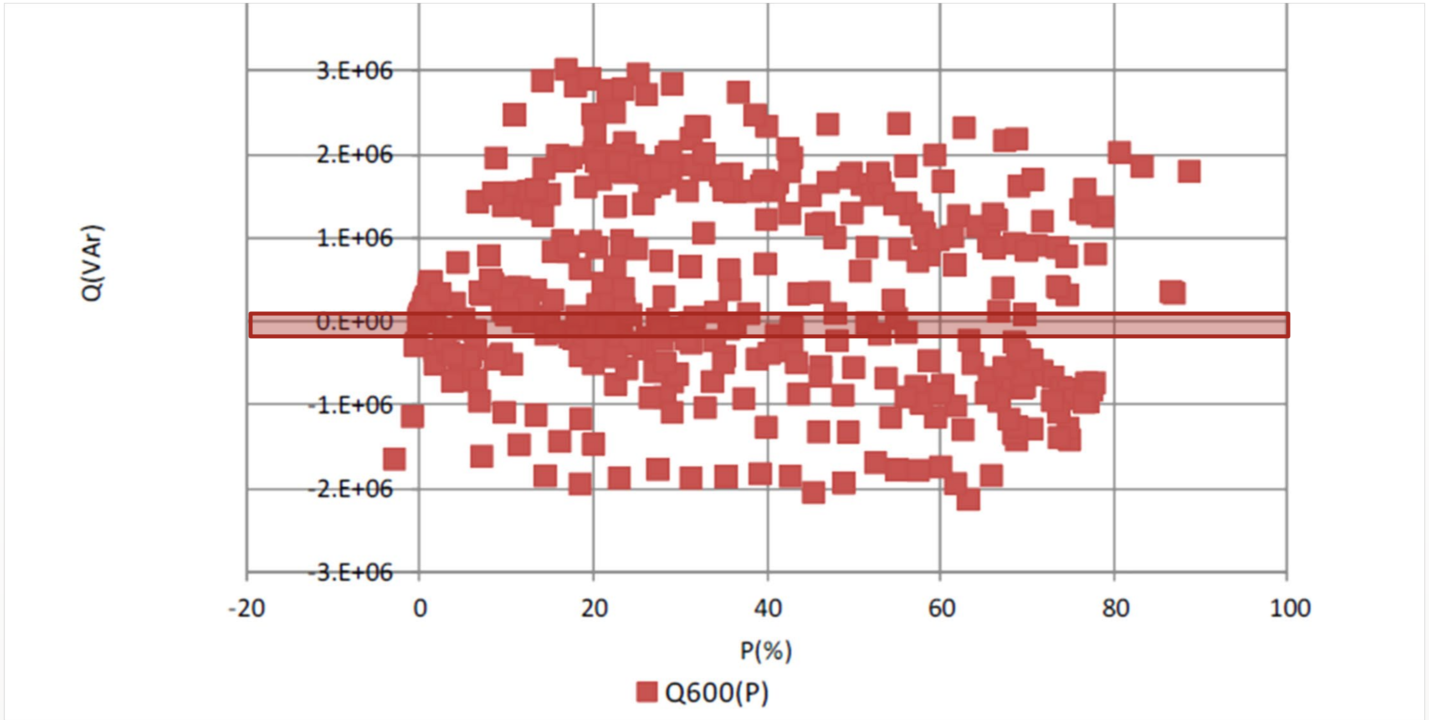
The classical mathematical framework is no longer applicable!

Reactive power depending on real power generation

- The distribution of the values shows, that there is no fixed operating point.

  If the inverters operate in a normal mode with a cos phi app. 1, then the values for Q are displaced around zero, only.

- The picture reflects the situation of the cos phi, as mentioned above.



- Report of the same topic by spanish consulting company – page 66

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The cos phi – values play an important role in any industrial power supply and grid connection.

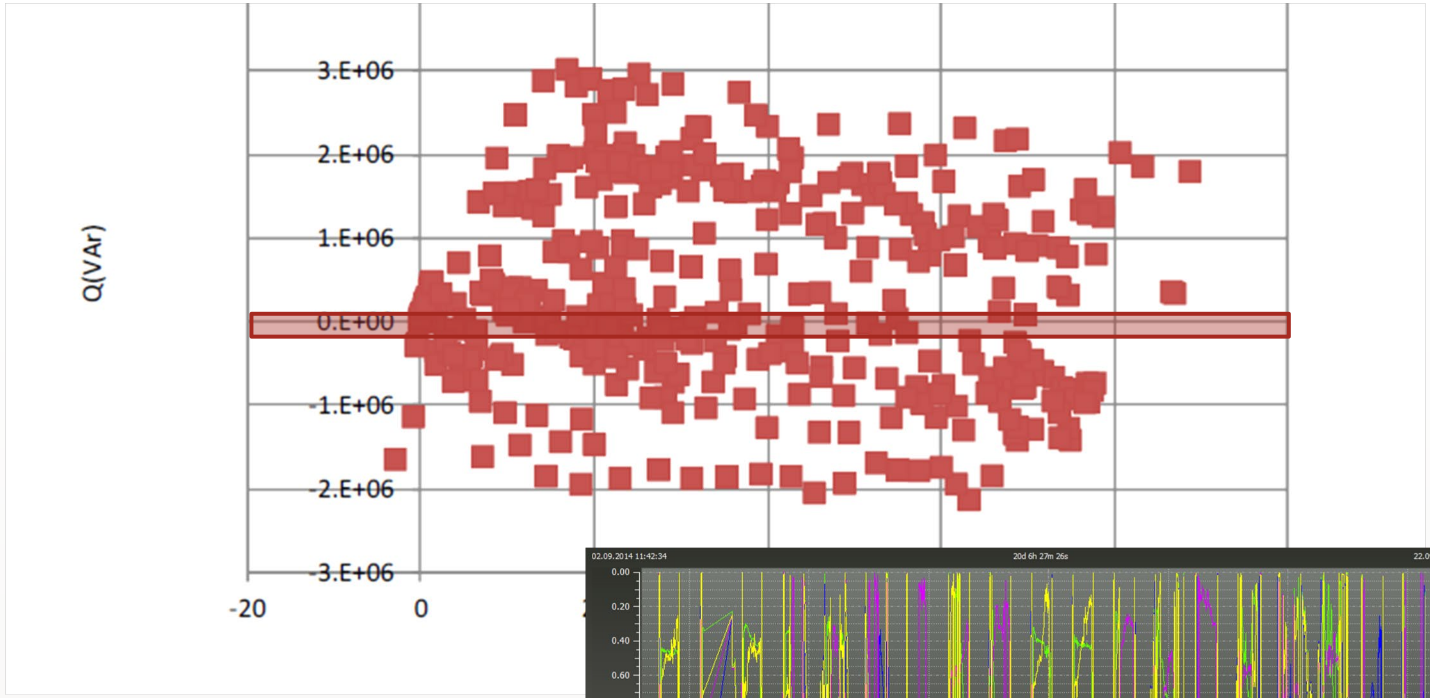
And in the future???

Reactive power depending on real power generation

- The distribution of the values shows, that there is no fixed operating point.

  If the inverters operate in a normal mode with a cos phi app. 1, then the values for Q are displaced around zero, only.

- The picture reflects the situation of the cos phi, as mentioned above.



- Report of the same topic by spanish consulting company – page 66

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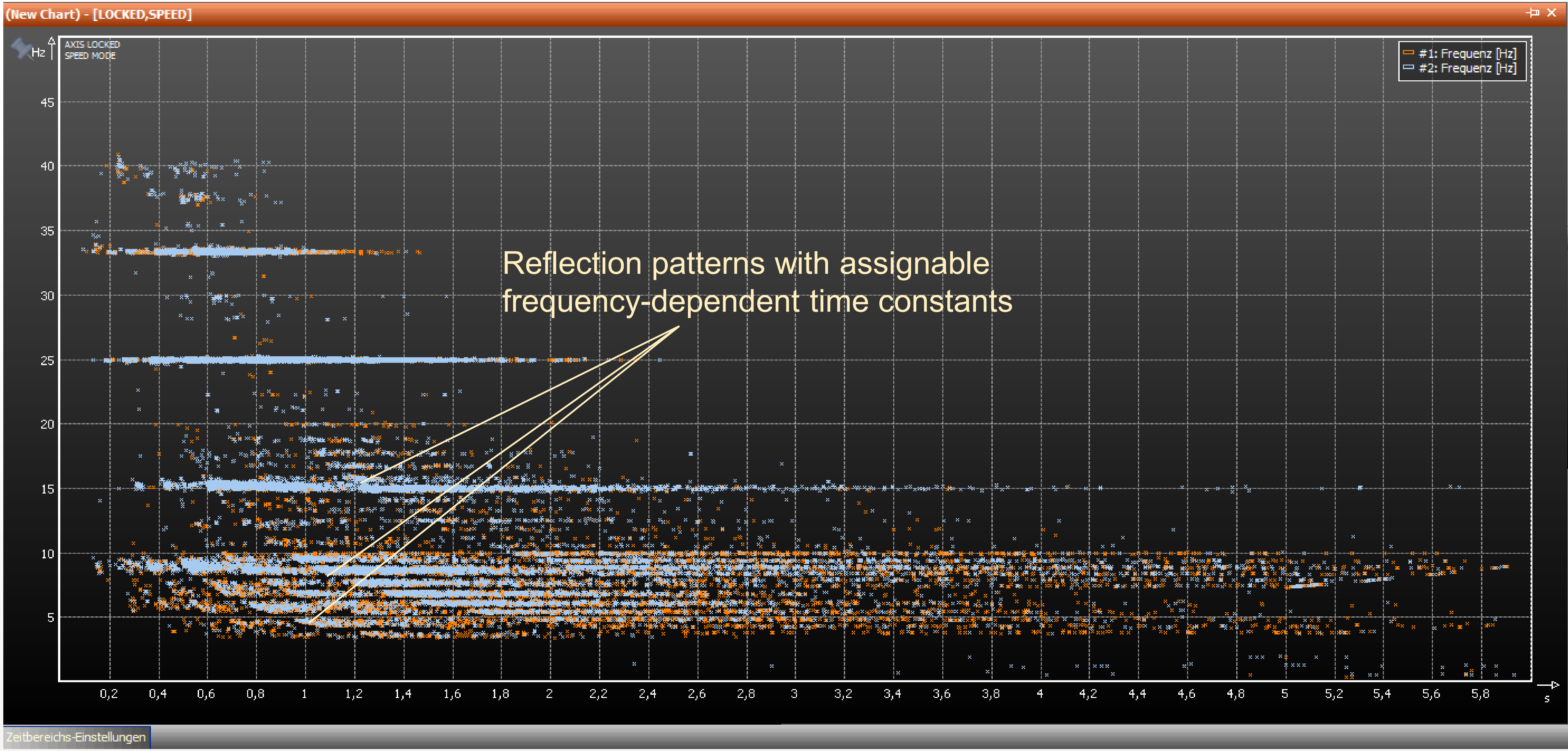
Frequency-duration of interaction processes in the range 0 to 50 Hz – measurement in Germany



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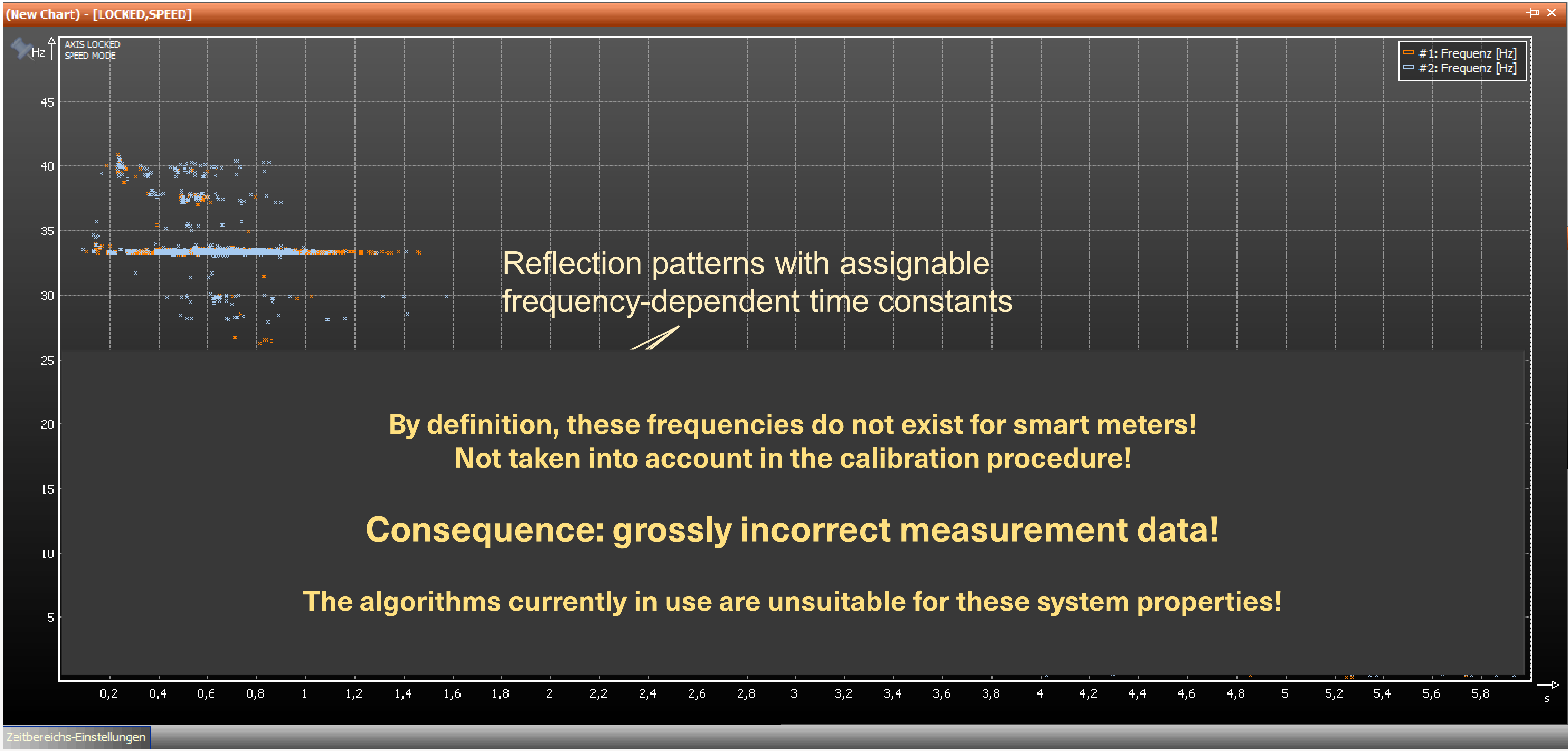
Frequency-duration of interaction processes in the range 0 to 50 Hz – measurement in Germany



By definition, these frequencies do not exist for smart meters!
Not taken into account in the calibration procedure!

Consequence: grossly incorrect measurement data!

The algorithms currently in use are unsuitable for these system properties!

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Authors are from Linde GmbH, Linde Engineering and Technical University of Munich, TUM, Institute of Plant and Process Technology

Paper: Dynamic multi-physics 1D-model of a proton exchange membrane electrolysis cell

1st-Paper – 2025 – with a simple dynamic model

- **The dynamic operation of proton exchange membrane (PEM) electrolysis plants is crucial for optimizing the use of renewable energy in green hydrogen production.**
- To investigate the physical aspects of such a dynamic operation, this work presents a novel one-dimensional (1D) dynamics multi-physics model for a PEM water electrolysis cell, which is discretized across the membrane.

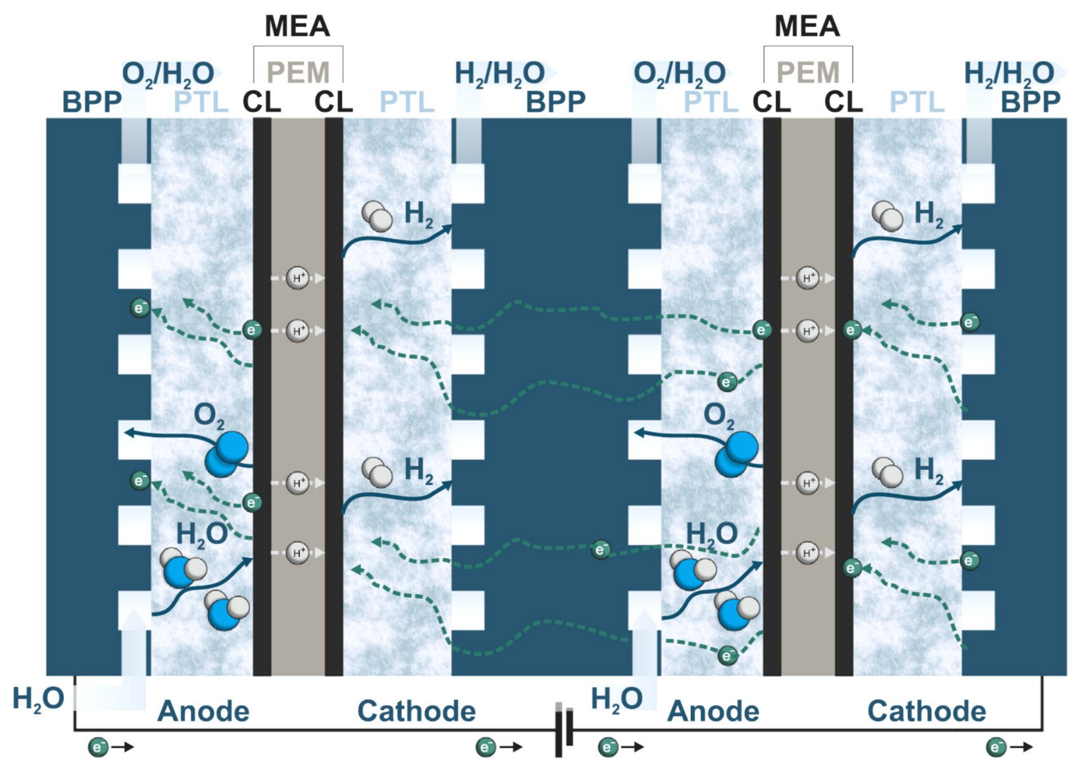

Fig. 1. PEM electrolysis cell design based on Hemauer et al. [9].

Source: Engel, F.K.; Wodak, S.; Zander, H.J.; Ulmer S.; Fahr, S.; Geraldy, I.; Rehfeld, S.; Klein, H.: Dynamic multi-physics 1D-model of a proton exchange membrane electrolysis cell; International Journal of Hydrogen Energy 119 (2025) 56-72

Vom Netz zum System

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Paper: Dynamic multi-physics 1D-model of a proton exchange membrane electrolysis cell

1st-Paper – 2025 – with a simple dynamic model

- Comment:

  Simple electrical model to simulate step functions as inputs

- 1st step in the evaluation of dynamic behavior

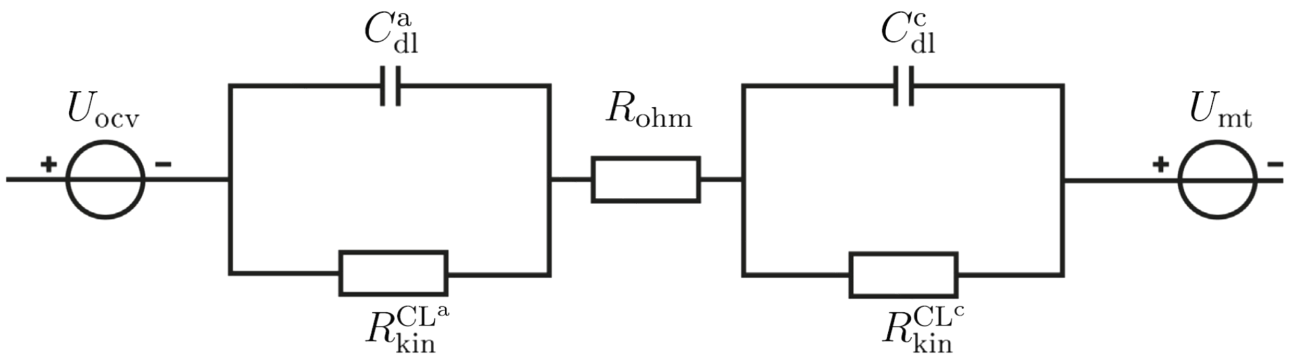

Fig. 4. Equivalent circuit of voltage model. All ohmic resistances of the different cell layers are summarized in R_{ohm}.

Source: Engel, F.K.; Wodak, S.; Zander, H.J.; Ulmer S.; Fahr, S.; Geraldy, I.; Rehfeld, S.; Klein, H.:
Dynamic multi-physics 1D-model of a proton exchange membrane electrolysis cell; International Journal of Hydrogen Energy 119 (2025) 56-72

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Paper: Dynamic multi-physics 1D-model of a proton exchange membrane electrolysis cell

1st-Paper – 2025 – with a simple dynamic model

- Internal Heat Transport Model

- Remark:

  These dynamics can be "manipulated" by external inputs!

  with low frequency dynamics!

  Stability???

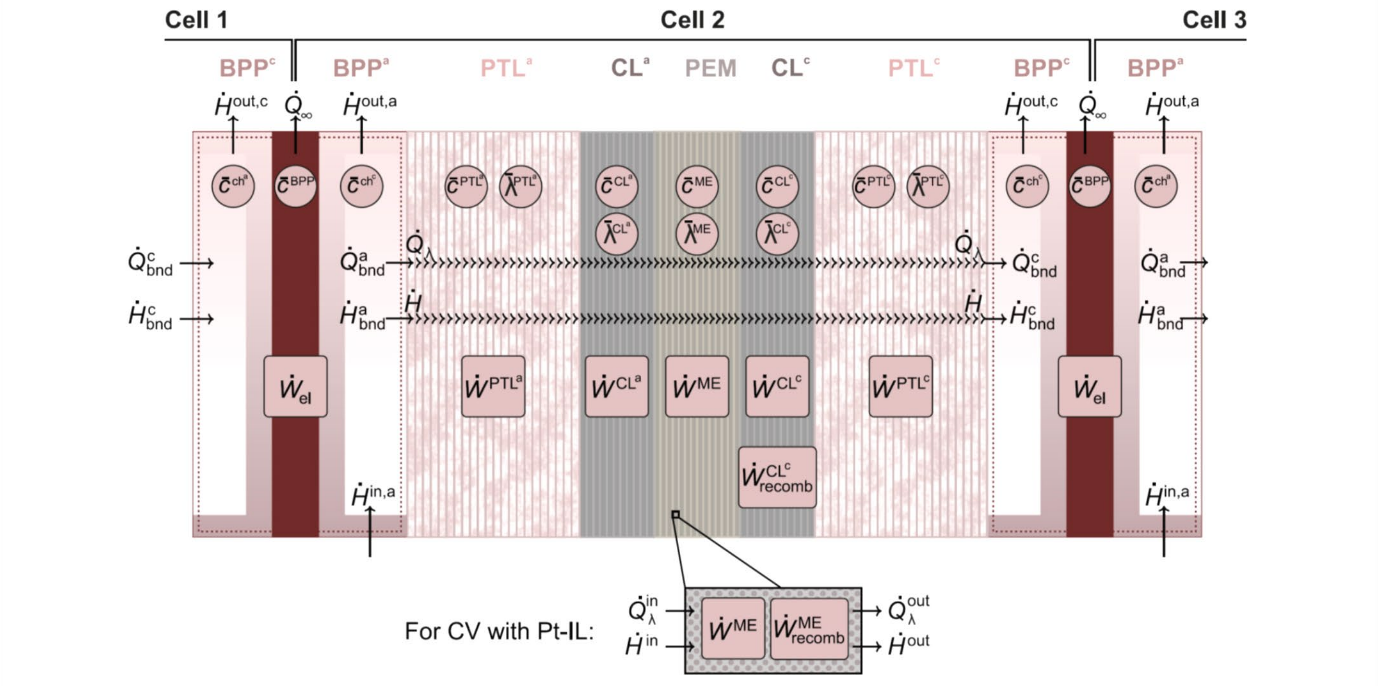

Fig. 5. Overview of control volumes in heat transport model for the discretized membrane, CLs, PTLs and lumped compartments for BPP and channels, layer sizes not to scale.

Source: Engel, F.K.; Wodak, S.; Zander, H.J.; Ulmer S.; Fahr, S.; Geraldy, I.; Rehfeld, S.; Klein, H.:
Dynamic multi-physics 1D-model of a proton exchange membrane electrolysis cell; International Journal of Hydrogen Energy 119 (2025) 56-72

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Paper:
Dynamic multi-physics 1D-model of a proton exchange membrane electrolysis cell

1st-Paper – 2025 – with a simple dynamic model

- Remark:

  Electrolysis plants need an "interface" to the grid, to guarantee stable operation conditions.

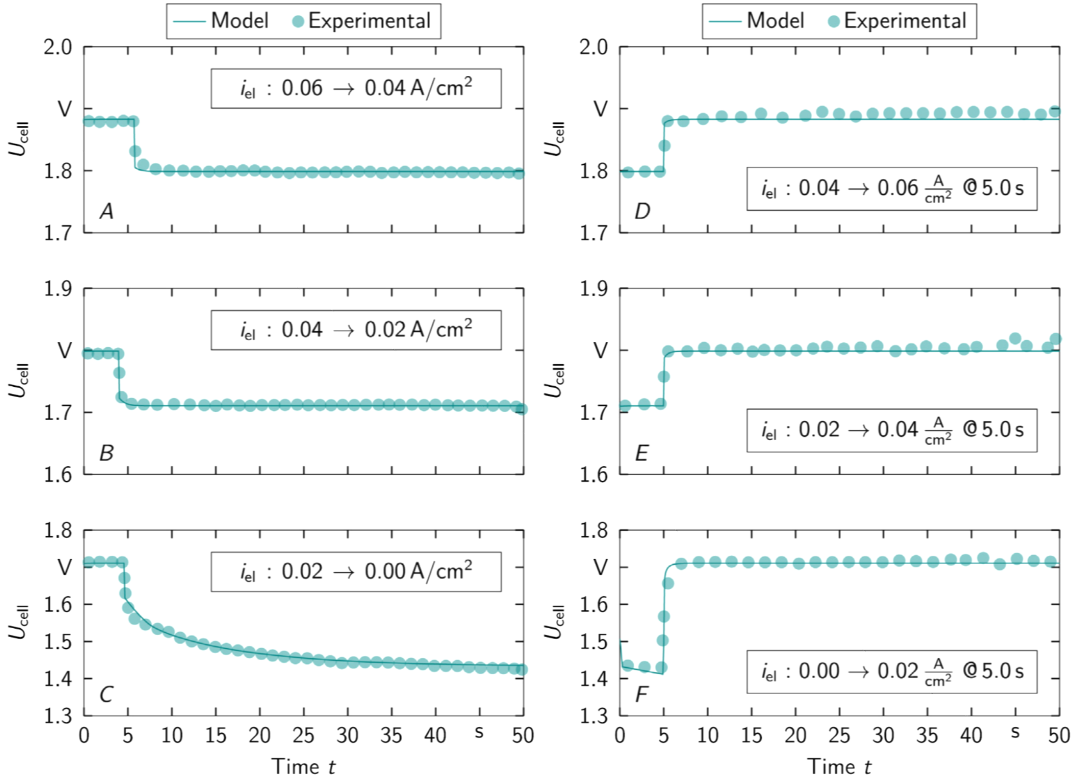

Fig. 12. Voltage response on current step test of Hernández-Gómez et al. [54] using parameters: $R_{el} = 3.7\,\Omega\,cm^2$, $U^0_{rev} = 1.49\,V$, $\alpha^a = 2.4$, $i^a_0 = 410 \cdot 10^{-9}\,\frac{A}{cm^2}$, $c^a_1 = 6$, $c^a_2 = 6$, $c^a_3 = 5$. Parameter setup: As specified in table A.1 (base case) and table A.7 in the SI.

Source: Engel, F.K.; Wodak, S.; Zander, H.J.; Ulmer S.; Fahr, S.; Geraldy, I.; Rehfeld, S.; Klein, H.:
Dynamic multi-physics 1D-model of a proton exchange membrane electrolysis cell; International Journal of Hydrogen Energy 119 (2025) 56-72

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Michael Fette
Digital Nonlinear Power Systems

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A comprehensive policy picture is needed

Electrolyser as the central element of sector coupling: electricity to gas

- Example: Wunsiedel H2
  Siemens Energy Silyzer 300

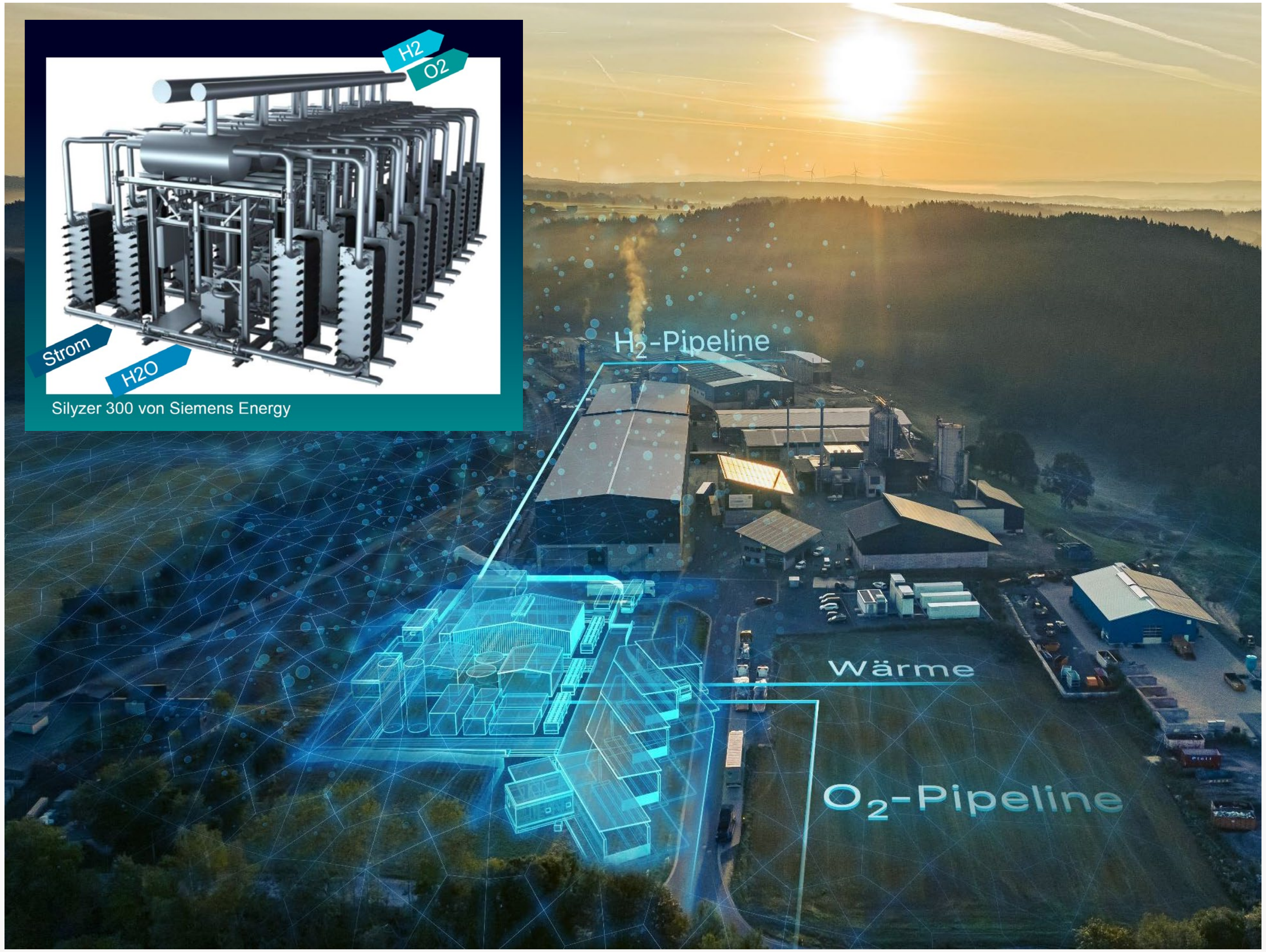
- Some key findings:

  "Hydrogen production must be viewed systematically from the perspective of stabilising the electricity grids."

  "Away from efficiency and full utilisation, towards utilisation and a holistic view."

  "We need small, local solutions to actually avoid grid expansion."

  "Think in terms of the system."



Silyzer 300 von Siemens Energy

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Transition of low-frequency dynamics through the integration of predominantly power electronic feeders, storage devices and loads

Bent, non-linear – but "static"

Source: Potatoes (pixabay)

Bent, non-linear – but "unstable"

Photo: House of Food / Bauer Food Experts KG

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ORCA®

Operational **R**eliability **C**enter **A**pplications

Preparation system operating
Analysis, settings, regulation, protection, planning

Dashboard, Analytics, Design of the stability aspects

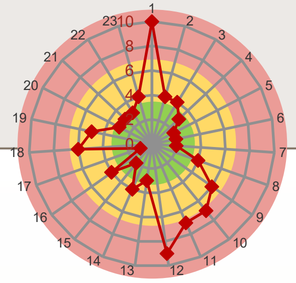
Operating System for Digital Nonlinear Power Systems

Business Variables

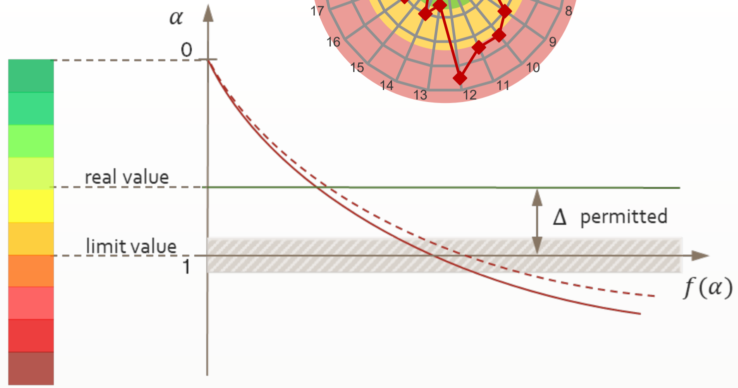
Finance, technology, safety, quality, legal, image, environment, organization, efficiency

Economical based frequency control

Easy Smart Grid Technology



Rating technical aspects
Predictive, curative, operative



Rating economical aspects
Local markets
Specific system oriented tariffs
Ancillary services

The evaluation functions are determined from the **Sy**nergetic **Mo**del functions.

DMP® EMCP

Digital Multifunctional Platform,
Evaluation, Measurement, Control, Protection
EDGE-based technology

KRI® Key Reliability Indicator

KRI® - Control	KRI® - Aging	KRI® - Smart City	KRI® - Compliance
KRI® - Protection	KRI® - E-Mobility	KRI® - Quality	KRI® - Islanding
KRI® - Stability	KRI® - Flexibility	KRI® - Modelling	KRI® - Blackout

KRI® - Modules ...

Complete frequency range

Vom Netz zum System

1 **Corporate management – decision-making processes**

2 **Integration into business processes**

Technical, organisational, regulatory, legal, etc. aspects

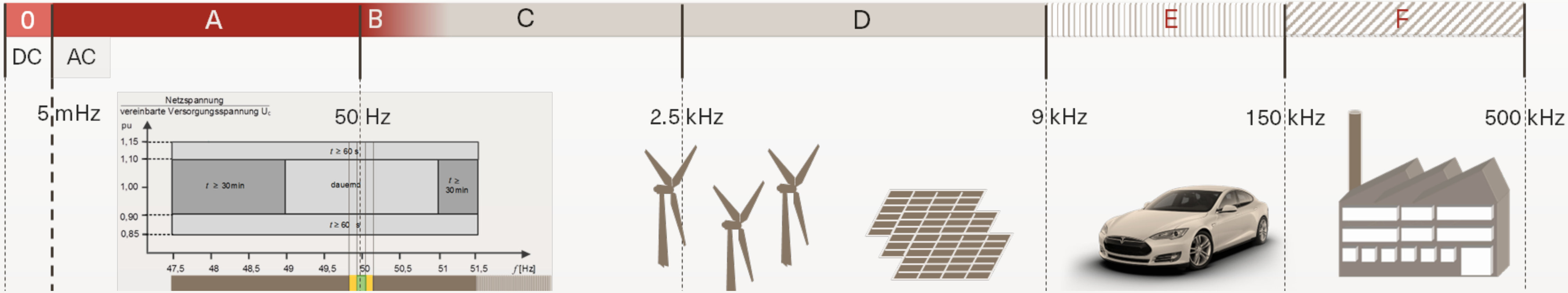
Derivation of preventive, operational and curative measures for operational management, planning, coordination

3 Processes according to fields of action
Processes according to coordinating institutions
Processes by sub-goals

Comparative stability assessment (vertical, horizontal)

41 Stability aspects
...

Vom Netz zum System



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Intelligent Nonlinear Systems are our Profession

Preserving the tried and tested – shaping the new!

KRI® the applications and algorithms that the system needs to recognise and evaluate non-linear system behaviour, adapt processes and make decisions so that the system can be operated stably and safely now and in the future – locally and globally. ***KRI***® use intelligent pre-processing to encode the measurement data in such a way that the amount of data to be exchanged is reduced to a minimum and the relevance of the information can be recognised. - Complementary to known process KPIs.

DMP-EMCP® , the EDGE-based hardware platform that records measurement variables across the entire frequency and time range in high resolution in terms of time and frequency, determines indicators for individual values or complex values or for complex network dynamics based on non-linear systems, can be used directly within control and protection algorithms locally or in hierarchically structured control and protection concepts. Cyber security aspects can be implemented in the traditional way, or new dual cyber security solutions can be used through intelligent coding of the measurement and evaluation variables to make future-proof, low-cost communication secure.

Based on ***XAI*** – Explainable Artificial Intelligence – powered by Synergetics!

Pooling algorithms and marketplaces can be directly docked, and intelligent solutions can be implemented and operated, in which, for example, electric vehicles are also used as storage in the distribution network with services for the transmission network.

The operator of ***ORCA***® receives direct support in line with corporate values, covering the following areas: finance, technology, security, quality, legal, image, environment, organisation and efficiency. The ***KRIs***® identify problems, highlight solutions and explain the challenges – always in line with all corporate values and with evidence to ensure clarity for all involved!

... a complete, strictly modular, highly automated system management – for

DNPS® Digital Nonlinear Power Systems

Vom Netz zum System

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