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Digital Nonlinear Power Systems

Blackout Spanien/Portugal

Fette
Competence in Energy

Hamburg, Mai 2025

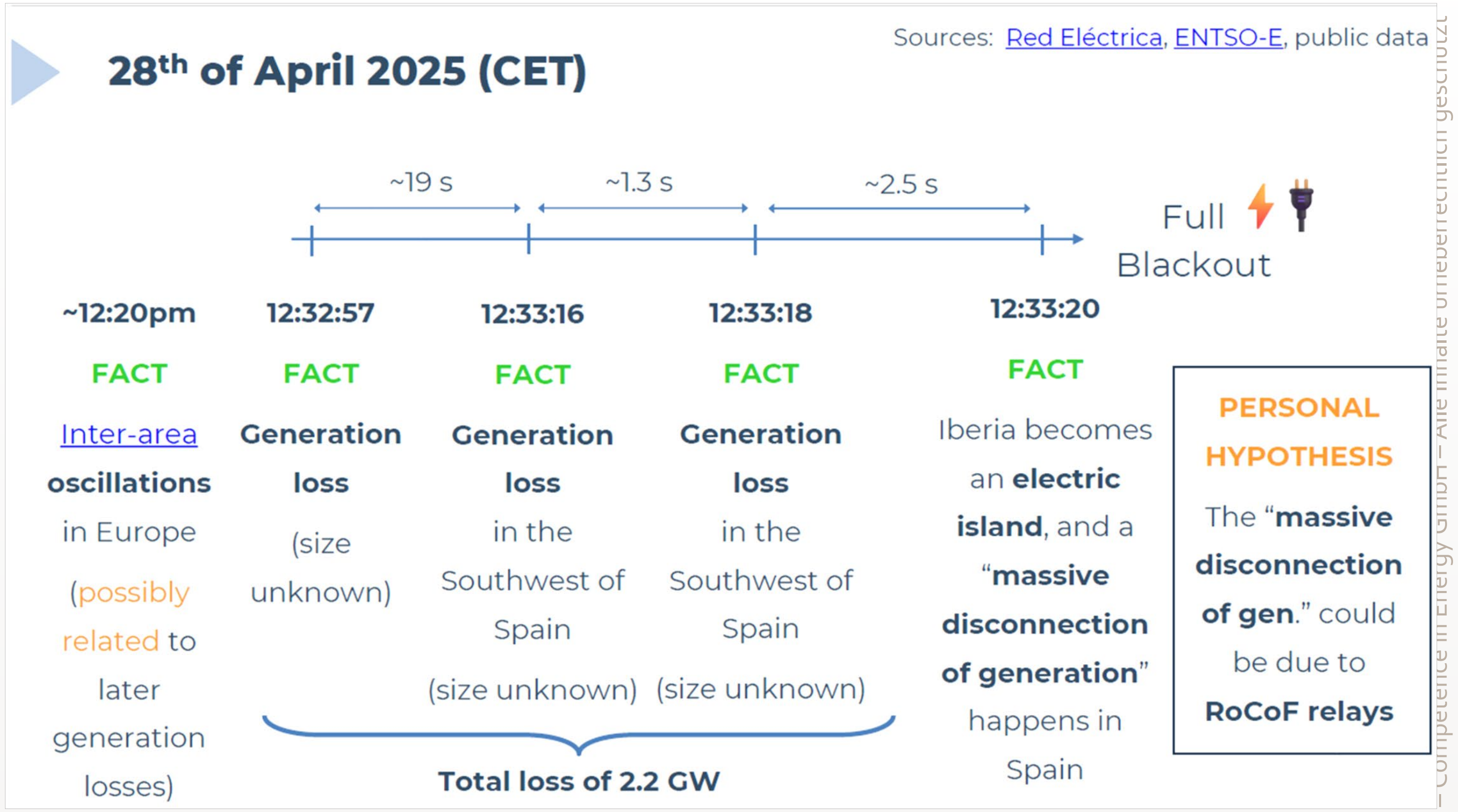
Michael Fette

Vom Netz zum System

Ablauf des Blackout – letzte Phase

Viele Analysen konzentrieren sich auf die letzte Phase des Blackout

Eine gute Zusammenstellung und Analyse von Prof. Luis Badesa, UPM

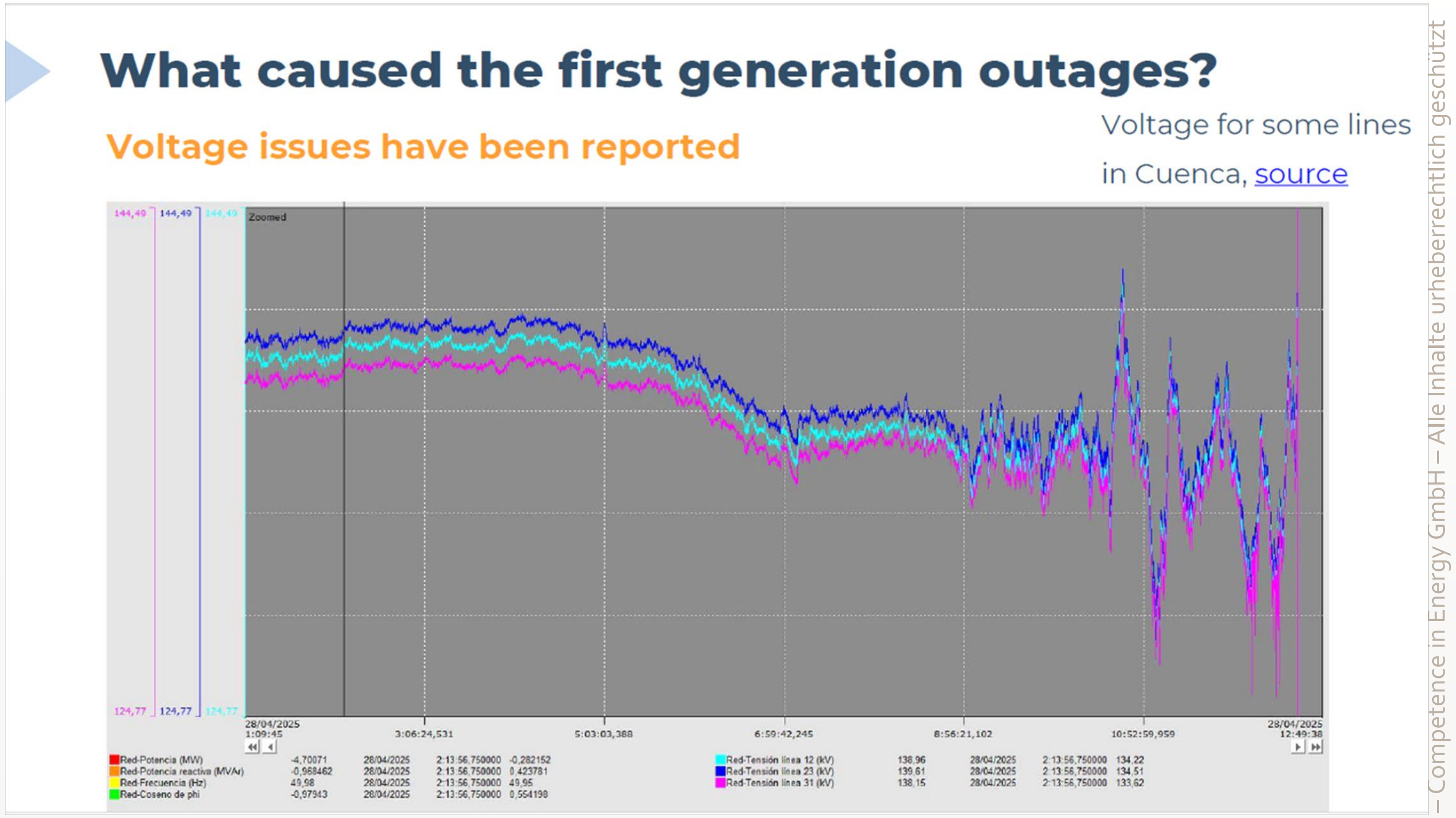


Quelle: Luis Badesa, Associate Professor at UPM

Vom Netz zum System

Ablauf des Blackouts

Spannungsprobleme des Systems seit Tagen im Vorfeld bekannt!



Quelle: Luis Badesa, Associate Professor at UPM

Ablauf des Blackouts

Unterschiedliche Quellen berichten von sehr hohen Spannungsbeträgen – in allen Spannungsebenen

What caused the first generation outages?

Voltage issues have been reported

There have been reports of **voltages reaching up to 470 kV in 400 kV lines**, supposedly in the Southwest region where everything started

- I have not found data to support this claim, but the statement can be found in several news articles such as this one (in Spanish)
- Other mentions to overvoltages here and here

There could be a relation with the previous inter-area oscillations (this is completely speculative, but **see next slide**)

Quelle: Luis Badesa, Associate Professor at UPM

Ablauf des Blackouts

Bereits vor ca. 3 Monaten ist ein Kraftwerksblock Almaraz mit ca. 1 GW Leistung vom Netz gegangen

Genau hier, wurden am 28.04.2025 weitere Probleme „weit vor dem Blackout" beobachtet.

What caused the first generation outages?

Voltage issues led to **generation tripping in the Southwest of Spain** just **3 months ago**

Almaraz nuclear plant (one reactor operating at 1 GW) **tripped**

Source

Oscillations are mentioned in the report for the January 2025 event (see above link)

Quelle: Luis Badesa, Associate Professor at UPM

Vom Netz zum System

Ablauf des Blackouts

Rückschau auf den Störfall im Juli 2021

Teile des spanischen Netzes sind zusammengebrochen

Aber: kein Blackout!

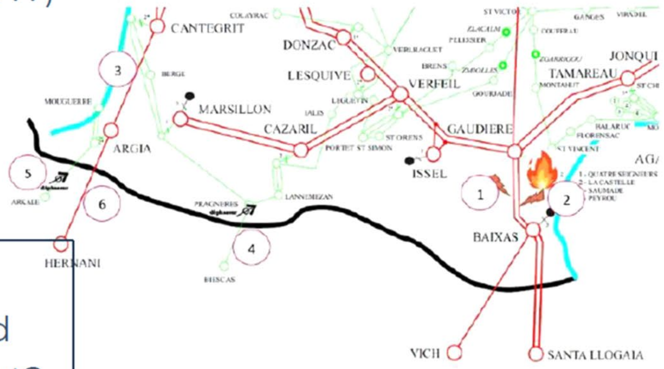
Related event: Iberia islanding in July 2021

Iberia became an **electric island** due to a fire in Southern France

- Some **load was disconnected** (~6 GW)

But **most of the system survived**

Graph: ENTSO-E



Then, **why didn't this "firewall" work this time**, why wasn't some load disconnected to avoid the full blackout?

Two options, either voltage issues or RoCoF issues (I see more likely the latter)

Quelle: Luis Badesa, Associate Professor at UPM

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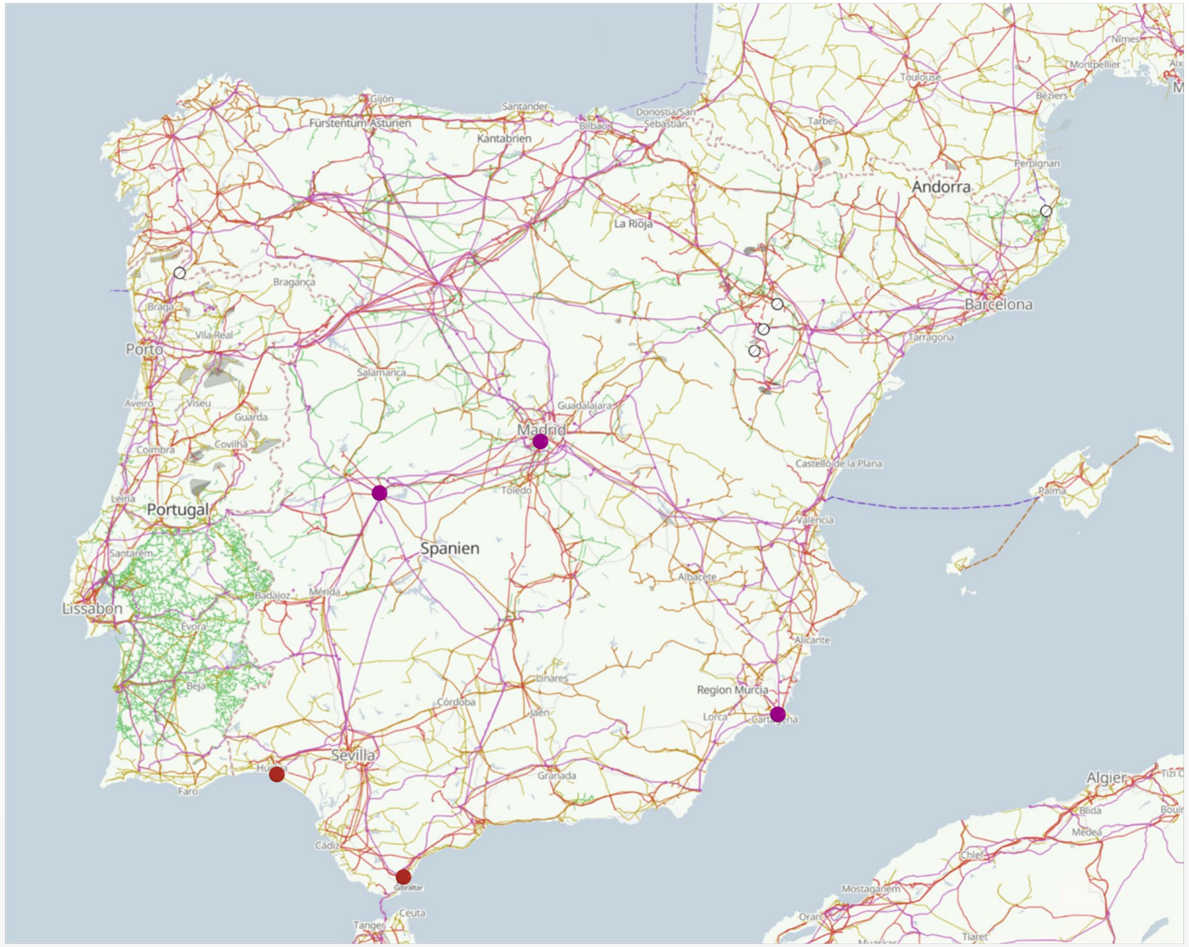
Spannungsprobleme im spanischen Netz

Quelle: elEconomista.es
15. April und folgende Tage: um Netzknoten Almaraz – starke Spannungsschwankungen

22. April: “starker Spannungsanstieg”: Ausfall der Repsol-Raffinierie in Cartagena, ebenso im Schienennetz von Madrid – Ausfall der Charmarton-Station für einige Stunden

GuD-Kraftwerke in Huelva und San Roque waren nicht in Betrieb



Karte: Open Infrastructue Map – https://openinframap.org

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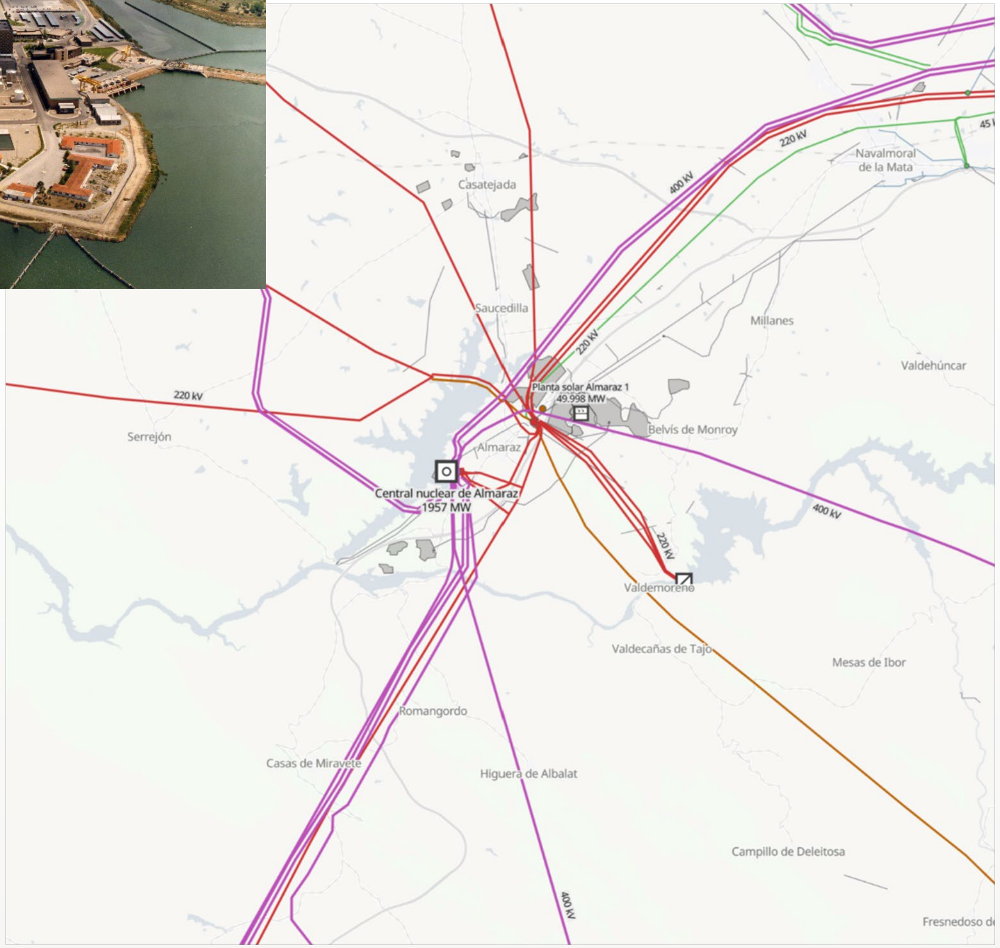
Quelle: Almaraz Nuclear Power Plant - Homepage

Spannungsschwankungen um den Knoten Almaraz

Seit 15. April 2025 deutliche Spannungsschwankungen im Südwesten Spaniens – insbesondere in der Nähe von Almaraz

In Almaraz befindet sich ein Kernkraftwerk mit zwei Blöcken mit ca. 2.000 MW plus PV-Parks

In den Knoten speist auch das Wasserkraftwerk Presa de Valdecanas ein



Karte: Open Infrastructue Map – https://openinframap.org

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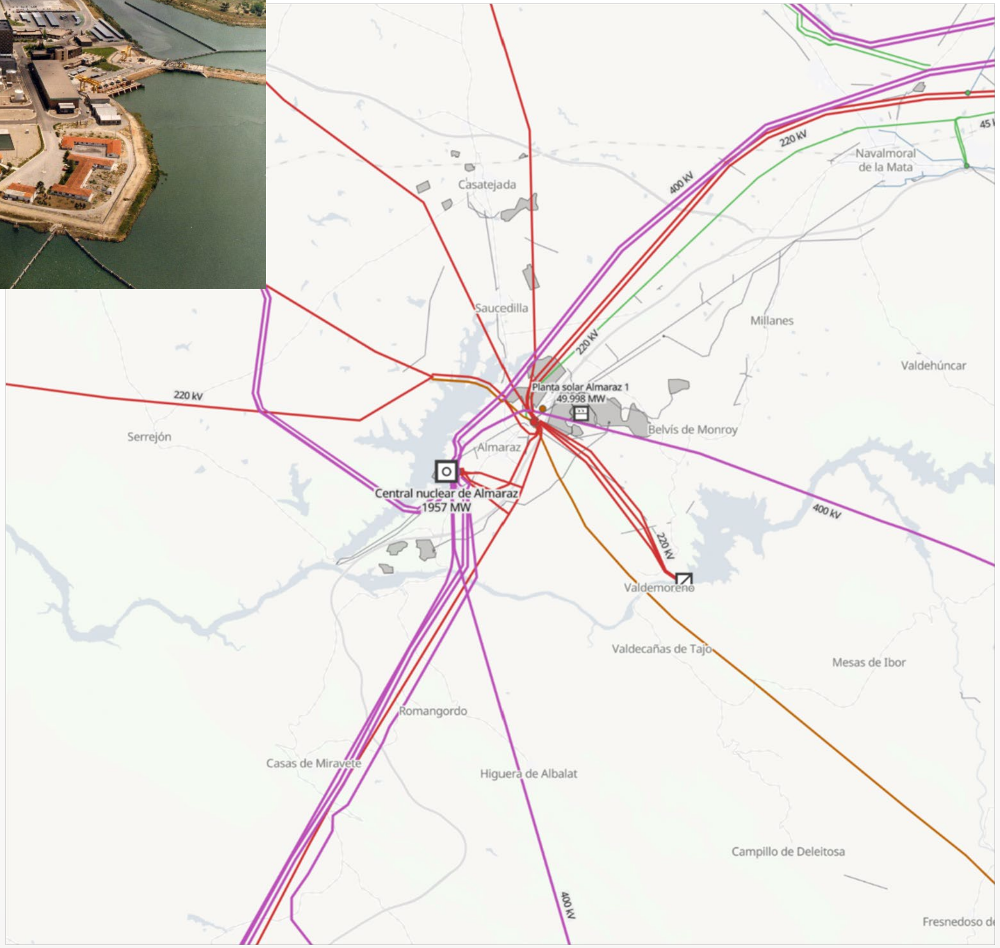


Spannungsschwankungen um den Knoten Almaraz

Vor ca. 3 Monaten „Tripping“ Almaraz Nuclear Plant – ein Generator mit ca. 1 GW „tripped“.

Als Grund wurden „Oszillationen“ angegeben.

Quelle: LinkedIn: Jorge Antonio Gonzales Sanchez

https://www.linkedin.com/in/jorge-antonio-gonz%C3%A1lez-s%C3%A1nchez65396844?miniProfileUrn=urn%3Ali%3Afsd_profile%3AACoAAAlli58BuIMXxzd_SGWQ3_vkegR7CxRHjQ8&lipi=urn%3Ali%3Apage%3Ad_flagship3_detail_base%3BnflwBA6IQJ2eArFEeL009A%3D%3D

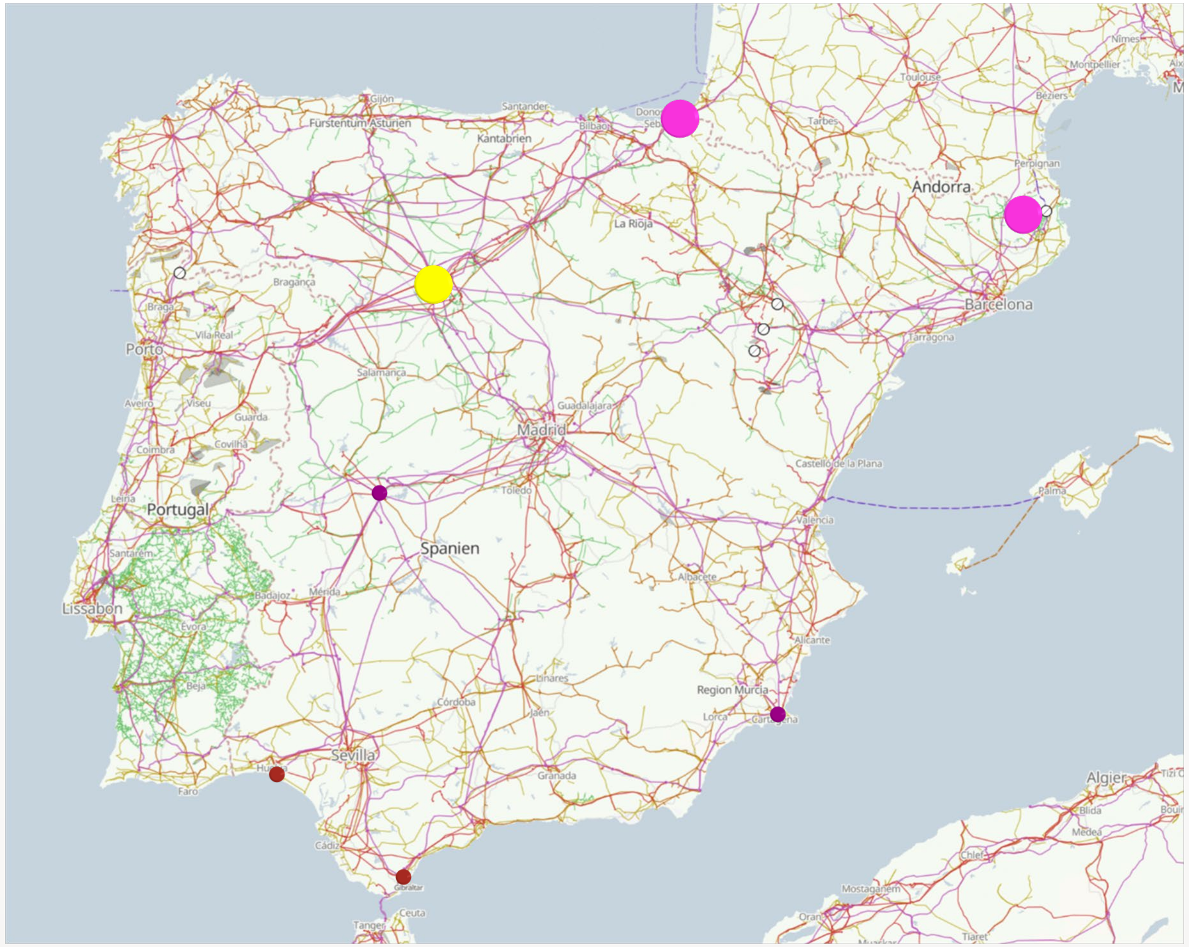
Karte: Open Infrastructue Map – https://openinframap.org

Vom Netz zum System

Anbindung an das ENTSO-E-Netz

Schwache Anbindung an das französische Netz

Historisch bedingt, aber auch Abschottung des französischen Marktes



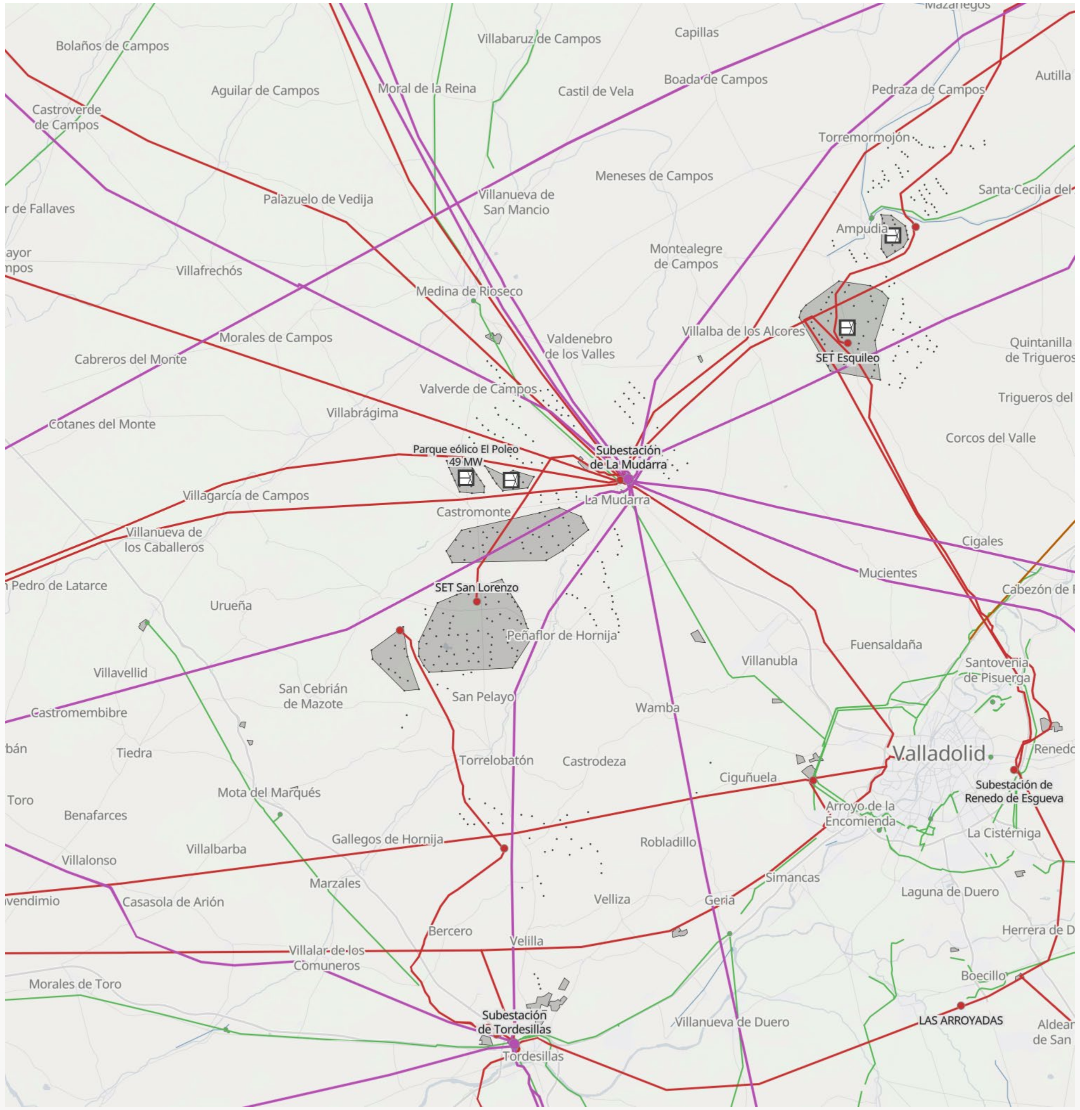
Karte: Open Infrastructue Map – https://openinframap.org

Netzknoten La Mudarra

Sehr interessanter Netzknoten La Mudarra

Kopplung der 220-kV und 400-kV-Ebene

Sternförmige Zusammenführung verschiedener Hoch- und Höchstspannungssysteme



Karte: Open Infrastructue Map – https://openinframap.org

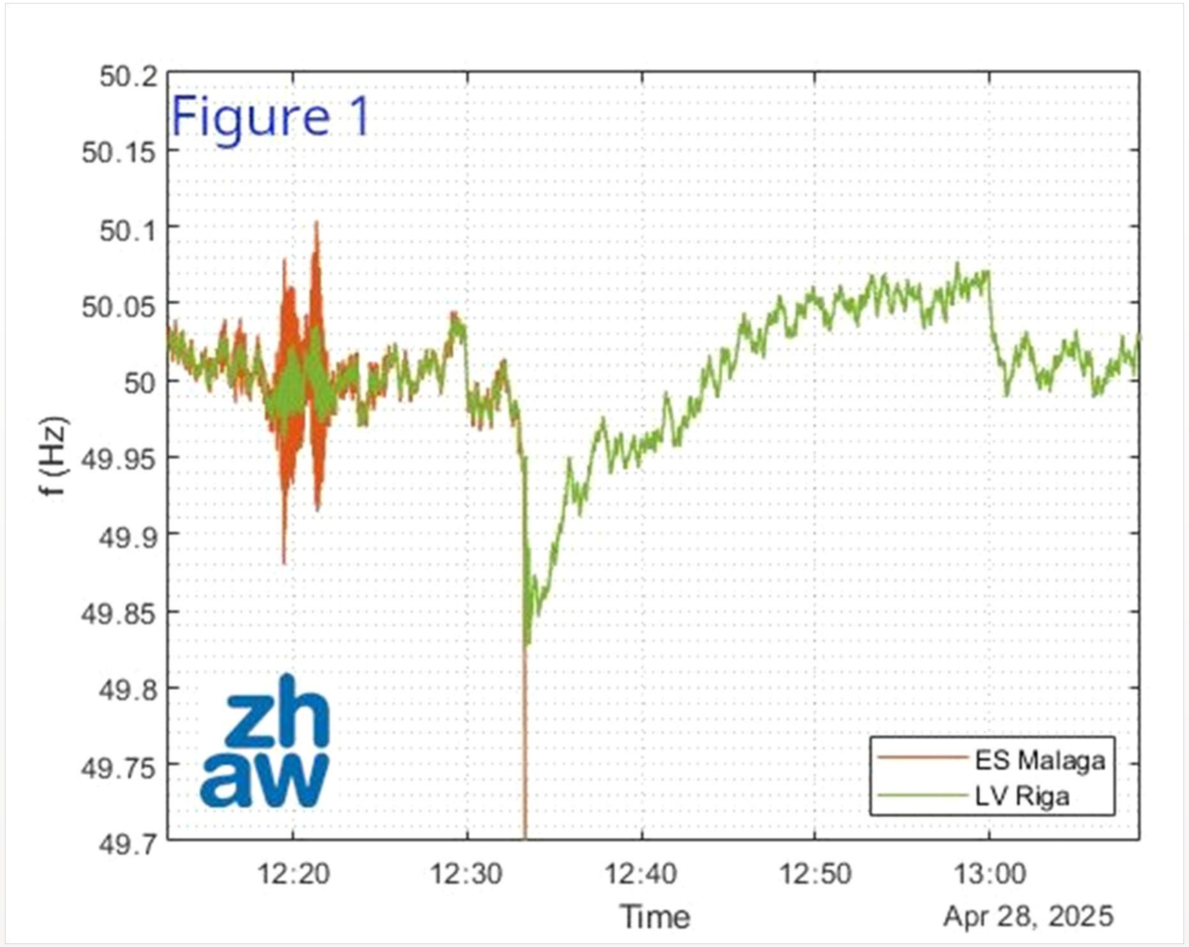
Vom Netz zum System

Veröffentlichte Charts von zhaw (Zürich, Schweiz)

Etwas detaillierte Sichtweise

12:15 Uhr – 13:15 Uhr

Kollaps des Netzes



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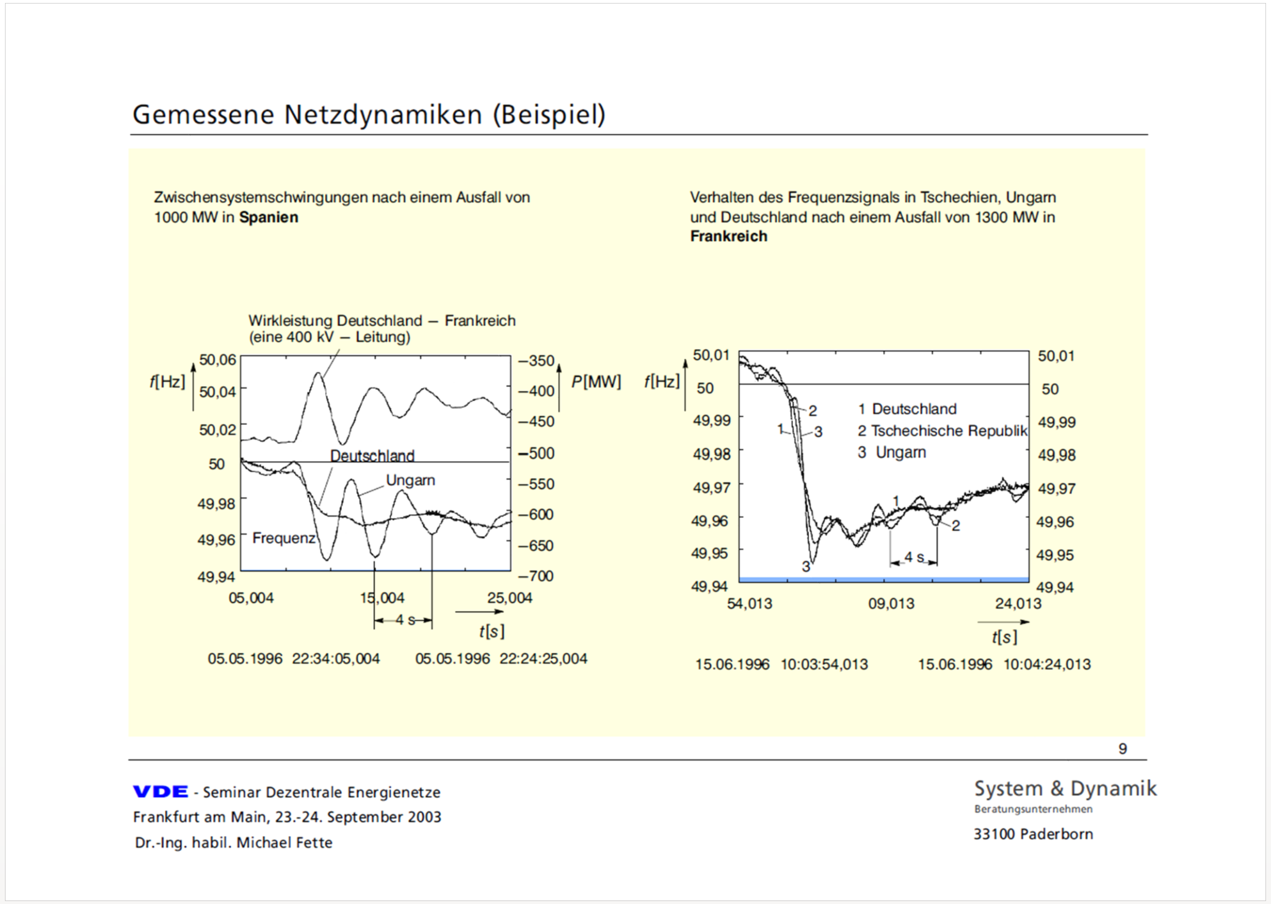
Zwischensystemschwingungen – ein „altes Thema"

Hier zwei Beispiele aus dem Jahr 1996

Ohne Leitungselektronik im Netz

Reaktionen an unterschiedlichen Messpunkten



Quelle: Dr. Michael Fette - 2003

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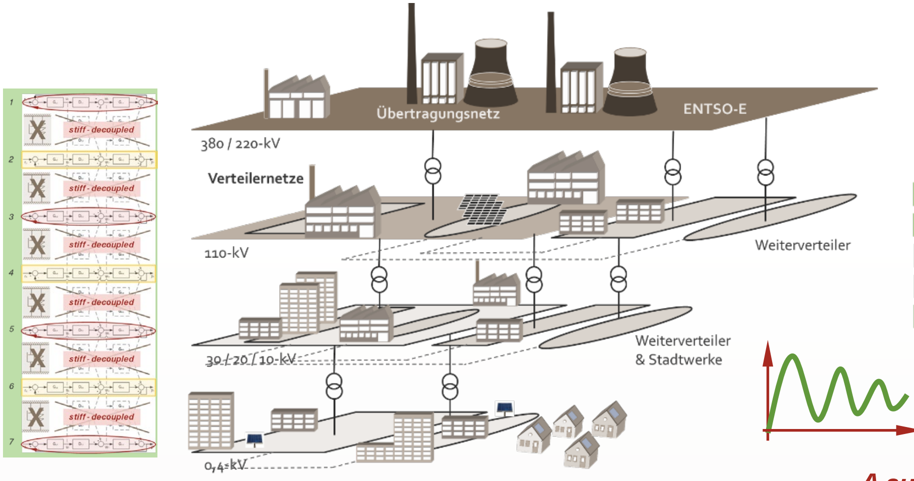
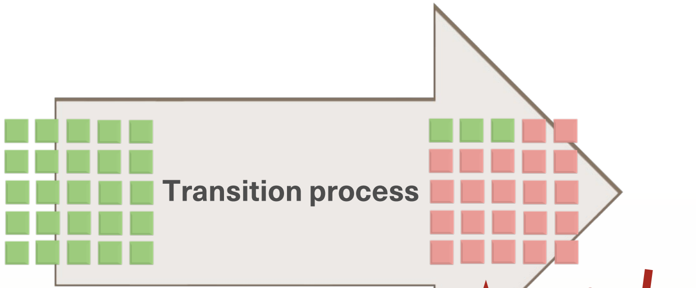
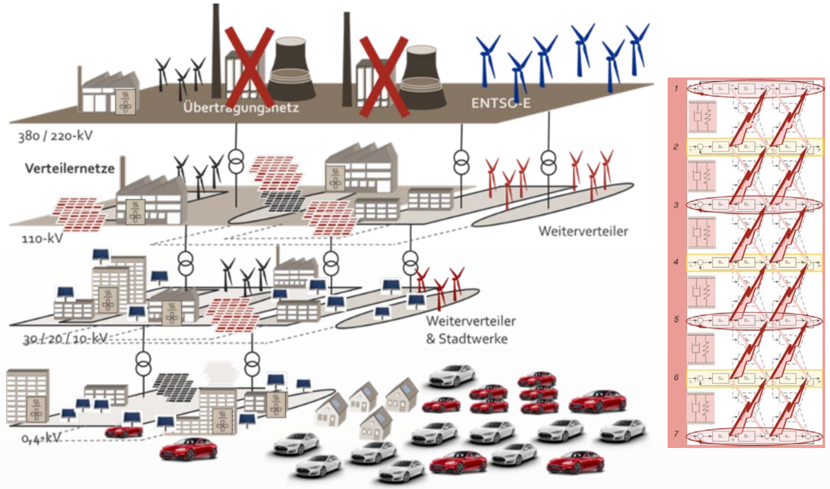
From passive participation to active contributions - at all levels





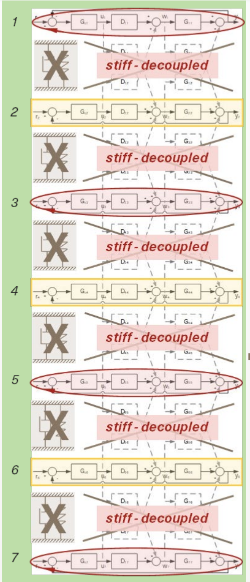
Full stability supporting assets will be substituted by new assets, which supports only some stability aspects!



A substitution of „power blocks“ is not the solution!
The system can not be operated by this!

(⦾) It will be an abrupt „non-smooth“ transition

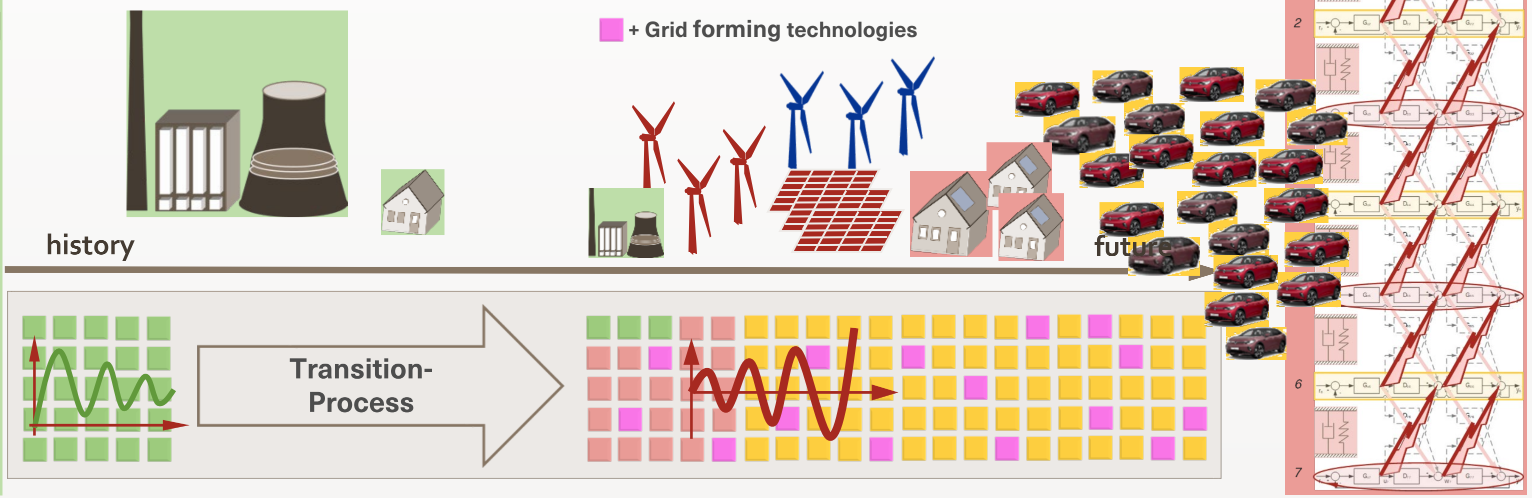
Vom Netz zum System



*Dynamically **de**coupled system levels*

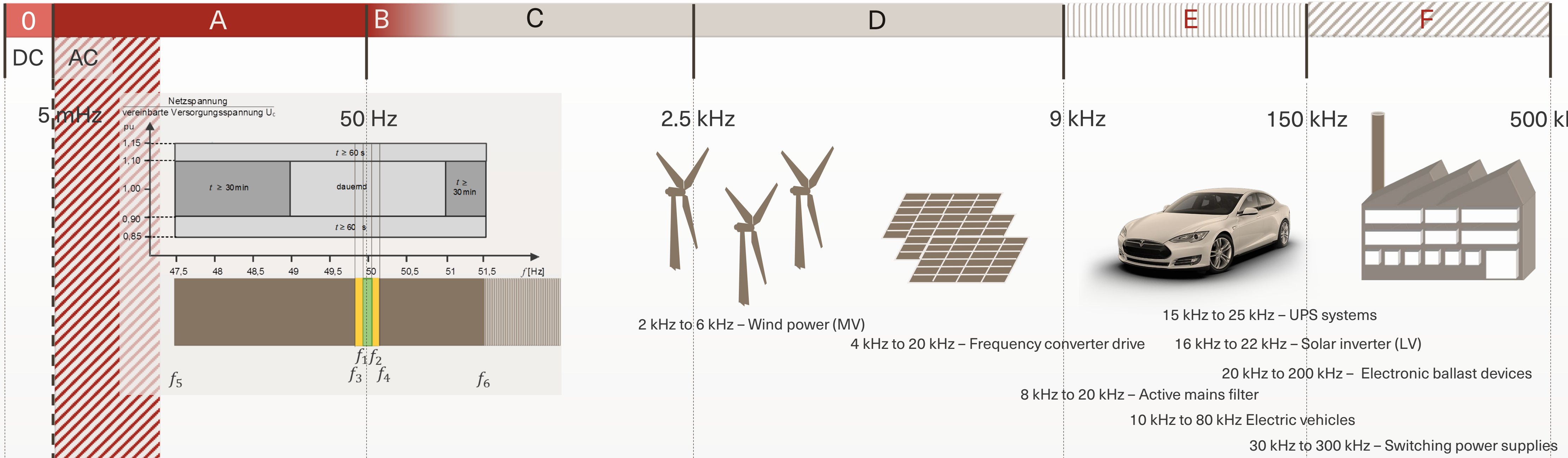
Dynamically ~~de~~coupled system levels

+ Grid forming technologies



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

Vom Netz zum System

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Impact of Time Delays on Power System Stability

Figure a) … c)

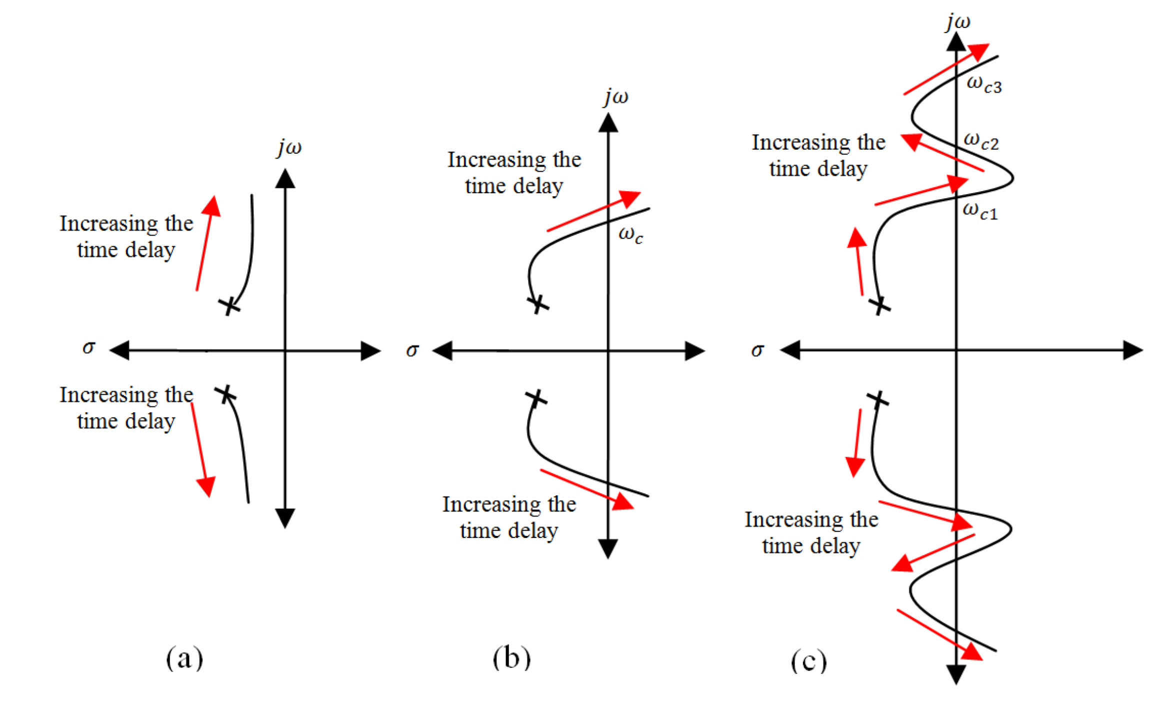
a) A delay-independent system

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



Vom Netz zum System

Integration von KRI® in das SGAM

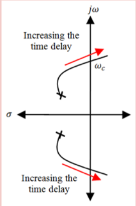
Geschäftsgrundlage
Regulierung, Netzbetrieb, etc.

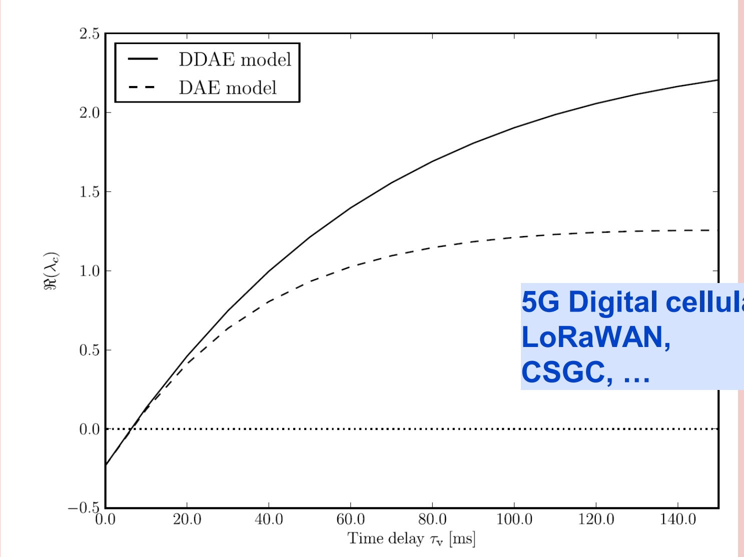
Qualitativer Einfluss der Verzögerungszeit auf die Werte des größten Eigenwertes

Differenzen in der Betrachtung der Modelle mit und ohne Berücksichtigung der Verzögerungszeit

In Vergleichsstudien (IEEE-Modelle) zeigt sich ein Unterschied auf das Bifurkationsverhalten > 15 ms

Die kritische Hopf-Bifurkation kann beim IEEE-14-Knoten Modell bei $\tau_v \approx 6{,}3\ ms$ festgestellt werden.





5G Digital cellular networks, LoRaWAN, CSGC, …

DDAE – Delay Differential Algebraic Equations
DAE – Differential Algebraic Equations

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

Latenzzeiten von Datenübertagungen wirken sich grundlegend auf die Systemstabilität aus!

Geschäfts-
prozesse
Kommerzielle
Steuerung
ssleit-
n
Umsetzung
Wertschöpfung
Kundenanlage
(Privat, Gebäude, Industrie, EV, Mobilität …)

Integration von KRI® mit doppelter CyberSecurity

1. Stufe:
Kodierung im Gerät

2. Stufe:
Schutz der Datenkanäle

Nutzung vorhandener Infrastrukturen mit bekannten Protokollen

oder „industrielle“ – massengeschäfts-taugliche Kommunikation

Vom Netz zum System

Kommende EU-Verordnung zur CyberSecurity sieht ein SOC vor!

Michael Fette
Digital Nonlinear Power Systems

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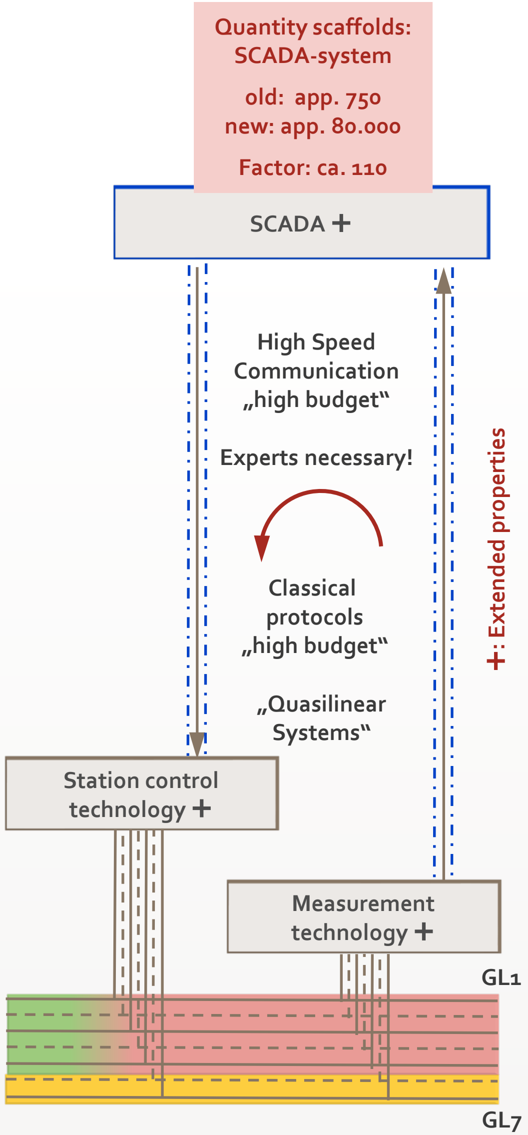
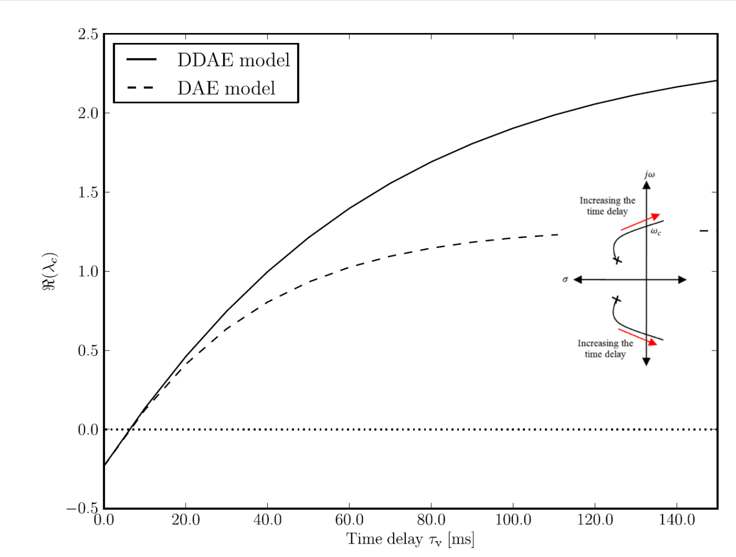
Vom Netz zum System





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 $\tau_v \approx 6{,}3\ ms$

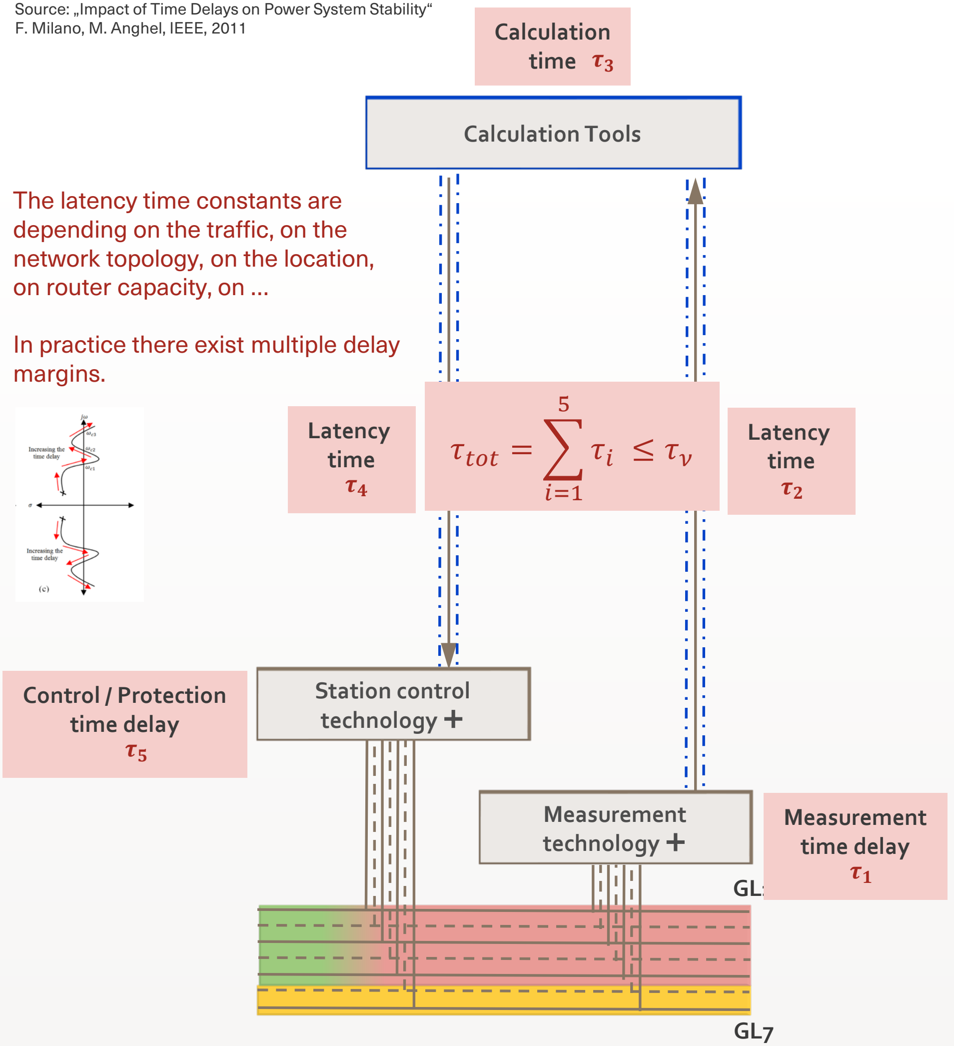
Data transfer latency has a fundamental effect on system stability!

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.



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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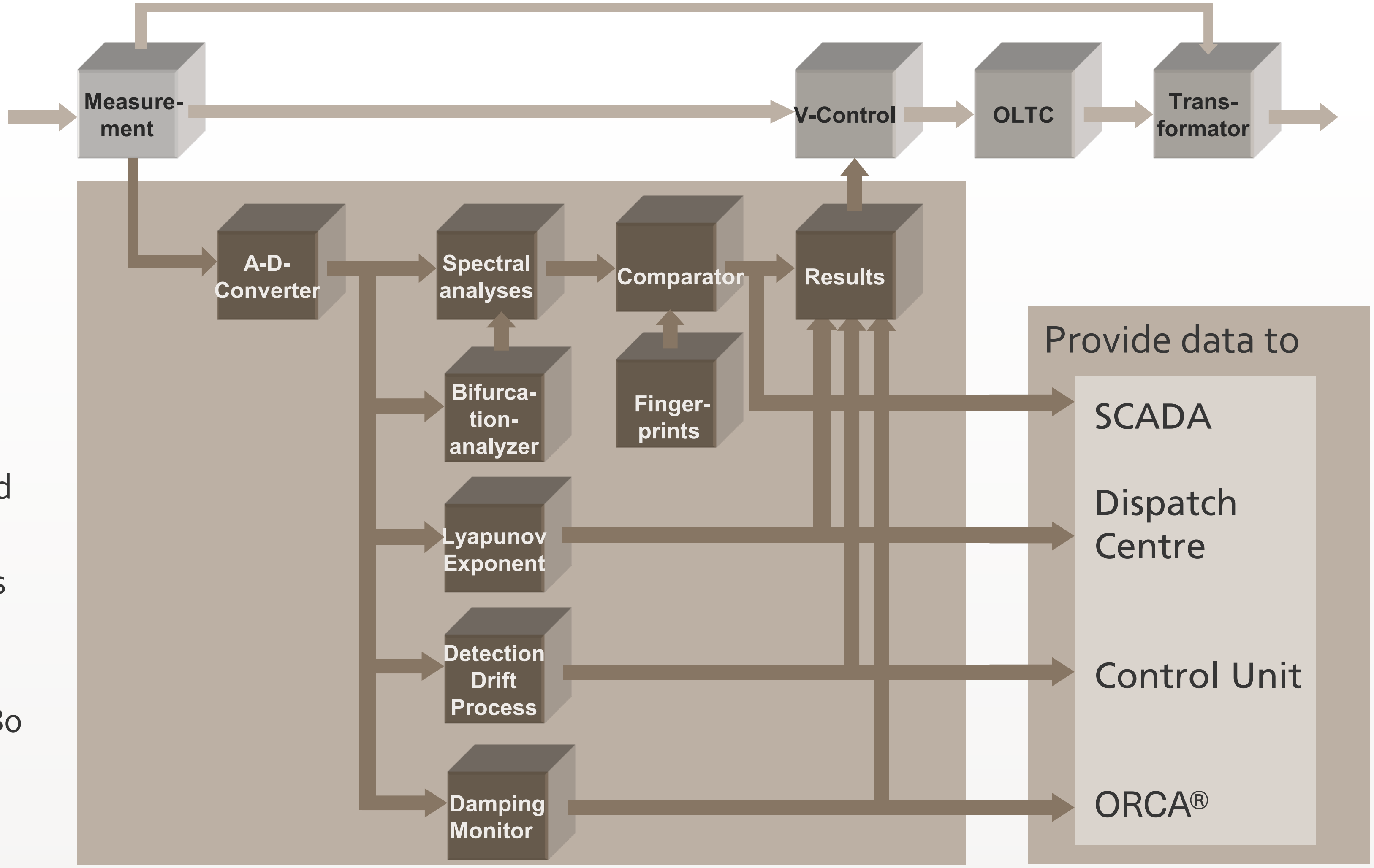
Starting in 1987 with Nonlinear Analysis of Power Systems

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

Vom Netz zum System

Measurements in 2007 TSO-level with some devices on different locations

- The grid was highly stressed by „eco-dynamics" – change of plans for power station.
- Different reaction on different locations.
- In nominal frequency (50 Hz) one can observe some effects of this low frequency behavior

Analysis of measurement results - Case 3
2 CPR-D in different locations

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The CPR-D records all oscillation incidents over a threshold value and values them with a different mathematical method

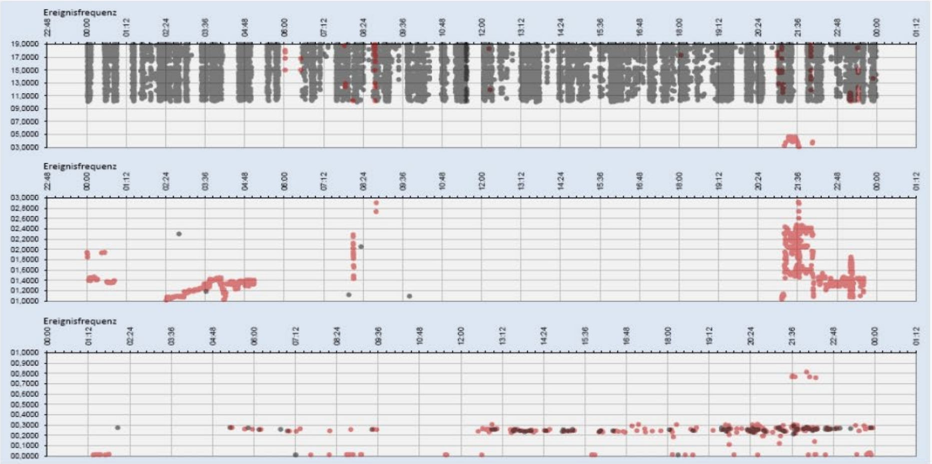
Frequency range - overview
time frame 24 hours

- Both Stations are viewing different net situations
- The "red" CPR-D is installed inside a net
- The "grey" CPR-D is installed between 2 nets
- The following diagram shows every frequency range

Frequency
3 Hz – 19 Hz

Frequency
1 Hz – 3 Hz

Frequency
0,005 Hz – 1 Hz



The analysis of the CPR-D pictures measured and valued damping masses. Every measured value is analyzed in detail and is identified with time stamps

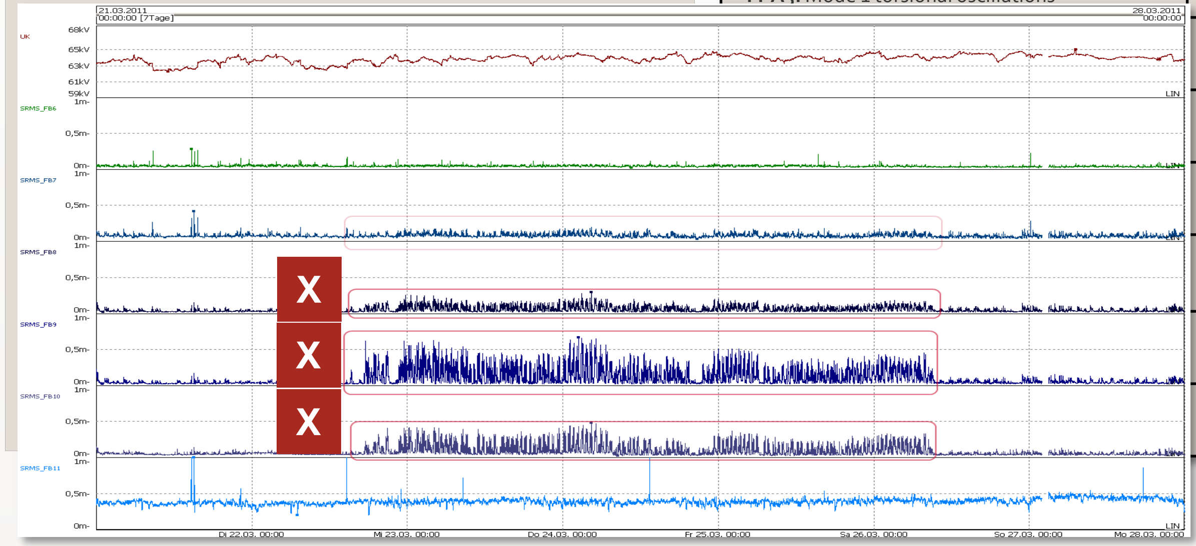
On the other hand further independent measurements are detected which value the same dynamic with different methods. In this case it is important to know:
- Stability exponent
- Analyze Fingerprint

Legend
- CPR-D 1
- CPR-D 2

Measurements of „Frequency Classes“ - Detection of „Patterns“

- Example (Germany, MV-Grid)
- Measurement of torsional modes within a grid

Frequency / Hz	1. 0,0 0,3	2. 0,3 0,7	3. 0,7 1,1	4. 1,1 2,0	5. 2,0 2,5	6. 2,5 4,0	7. 4,0 14,0	8. 14,0 20,0	9. 20,0 29,0	10. 29,0 35,0	11. 35,0 49,9	12. 49,9 50,1	13. >50,1
FPA1: Intermediate frequency oscillations	X	X											
FPA2: Locally limited oscillations			X	X									
FPA3: Mode 1 torsional oscillations								X					
									X				
										X			
									X	X	X		X
							X						
		X	X										
	X	X											



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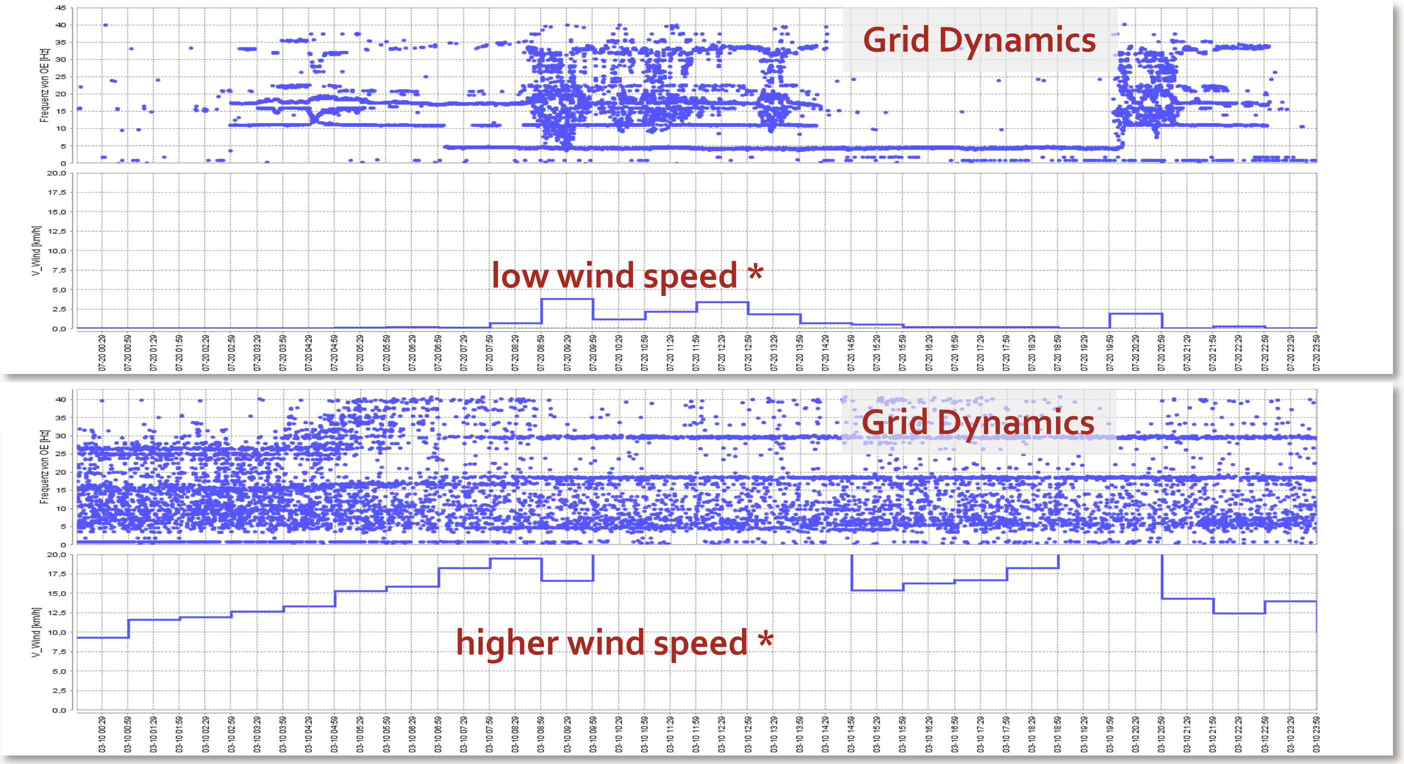
Measurement Wind Park MV-Grid (2009)

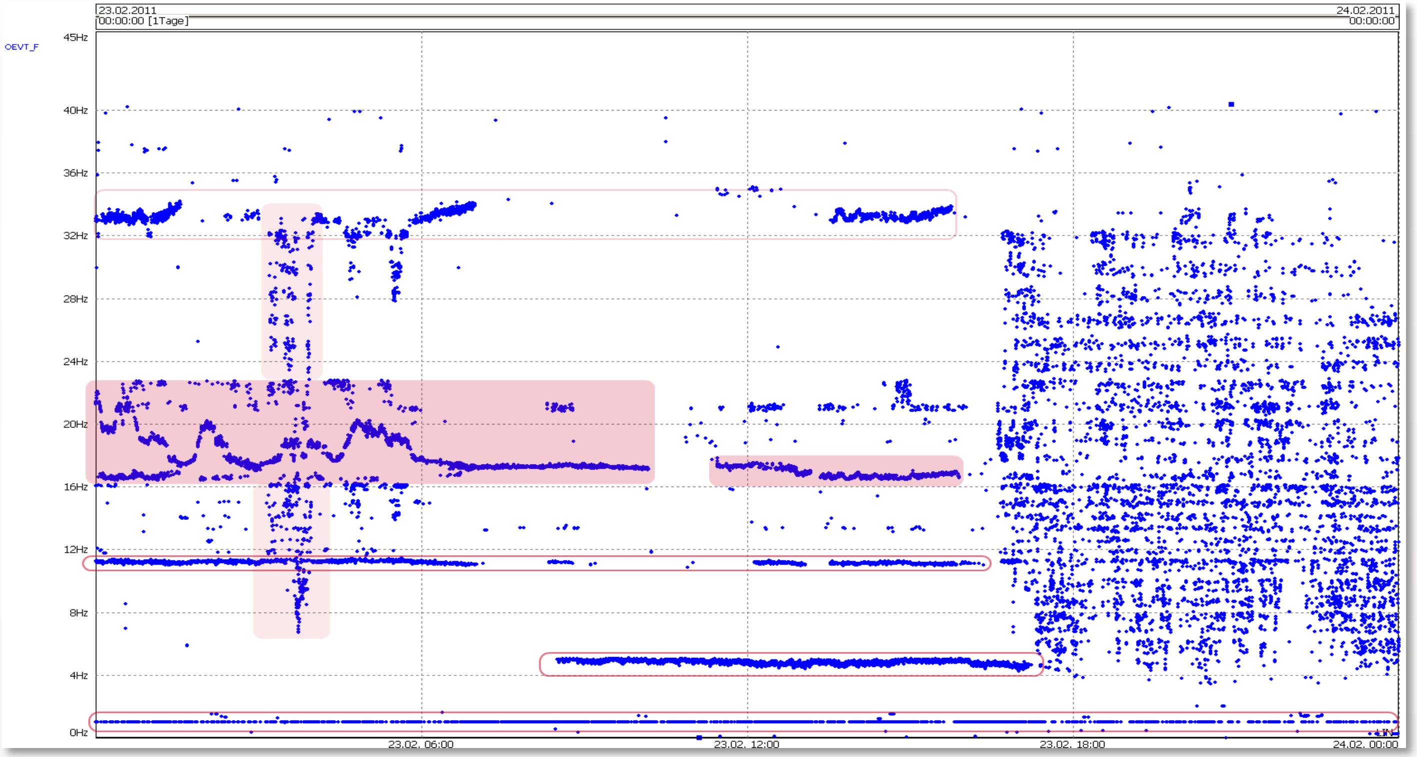
- Grid Dynamics – Measurements in MV-Grid (Germany)
- Different daily patterns can be observed

*) Measurements of grid dynamics and windspeed is separated by app. 10 km



Measurement Windpark MV-Grid (2009)

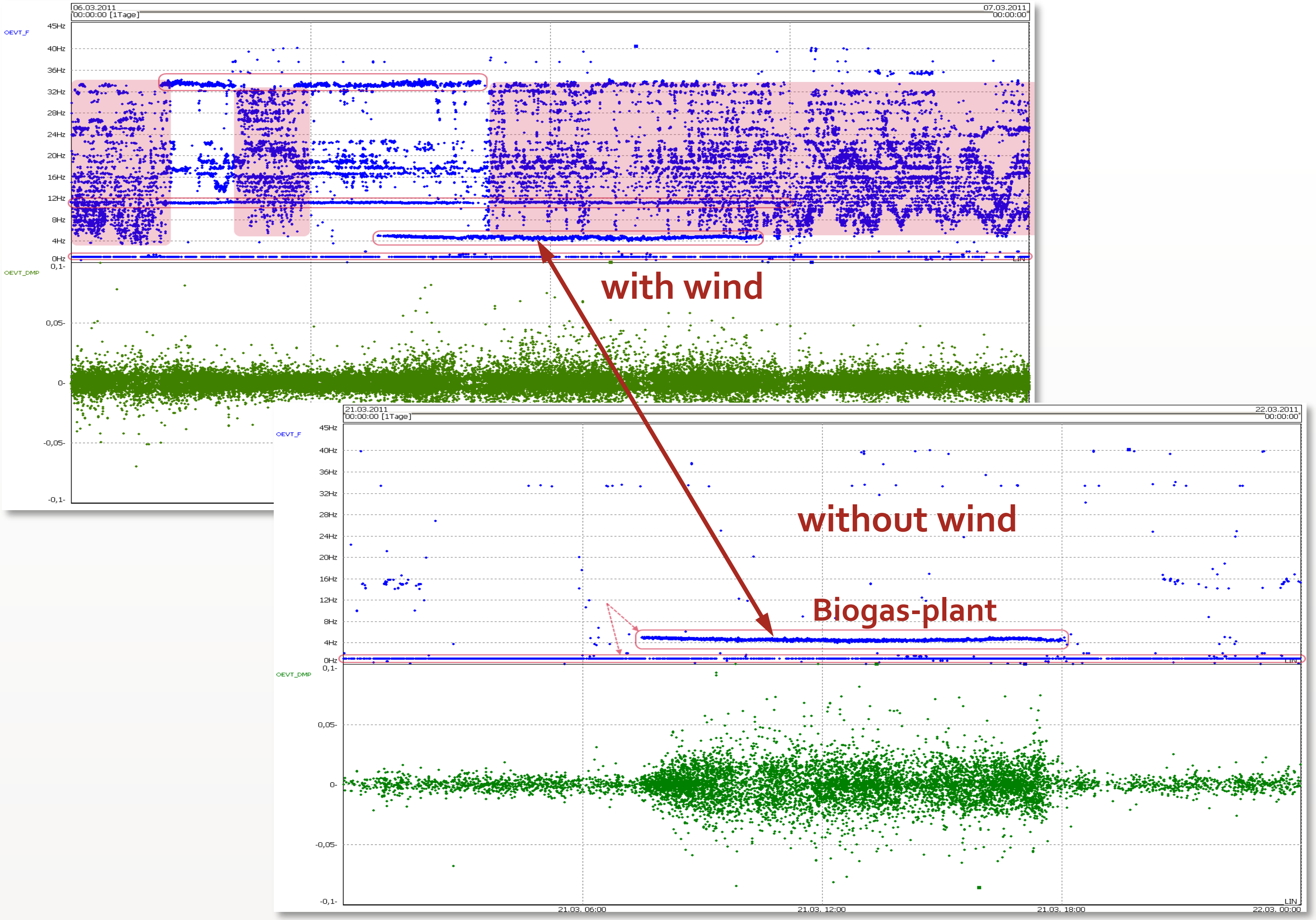
- Measurements from 1 day – with different dynamical patterns within the day
- Dynamics are dominated by wind turbine generators
- Influences on the grid can be observed
- Some dynamical patterns are very problematical.



Vom Netz zum System

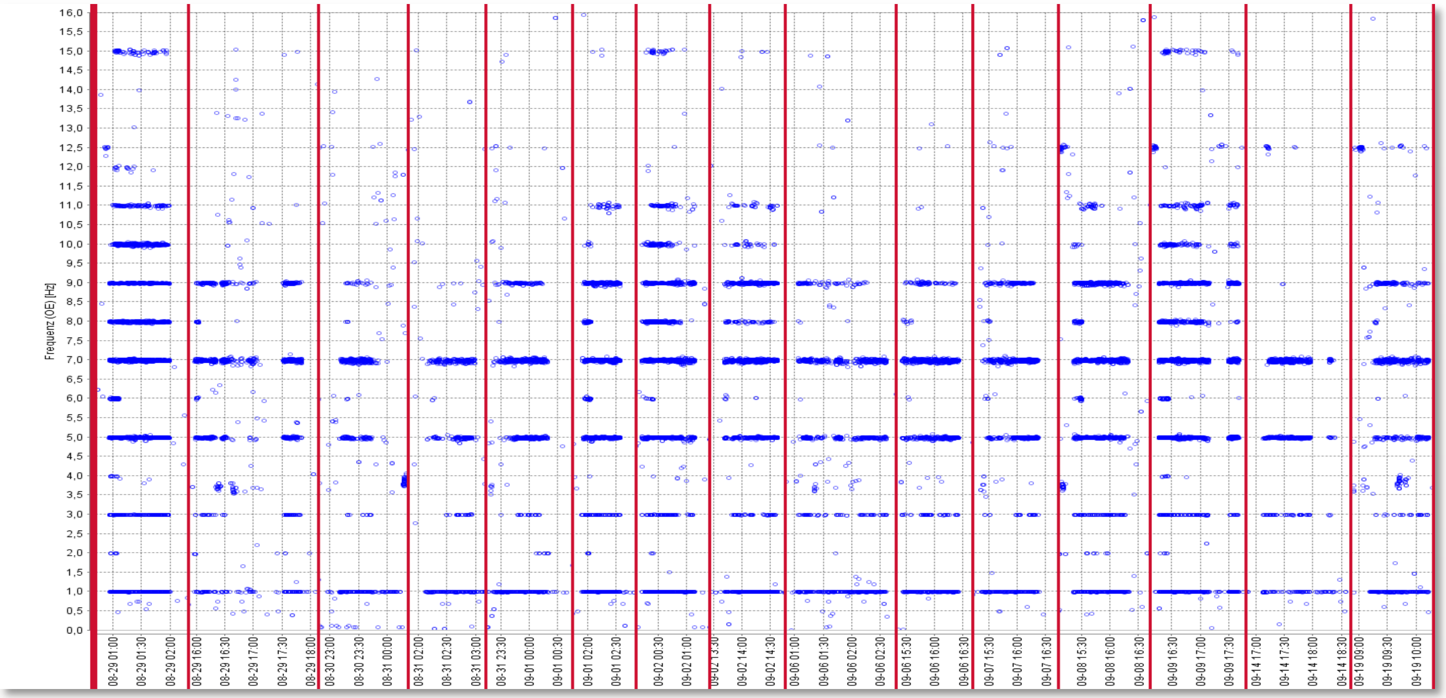
Wind or no Wind? – What does it mean for the grid?

- Dynamical finger prints could be used, to detect different dynamical situations of a grid area or specific node to find out a suitable solution.
- Changes in controller actions or settings are necessary, sometime the structure of the controllers must be revised.
- **Intelligent grid control!**



Measurement MV-Grid
Dynamics of an Industrial Park in the Center of a City

- Every grid node has its own dynamical pattern.
- Some pattern could be used – as basic patterns, to detect individual characteristics.
- From our fundus of a hugh amount of measurements we can detect the types of loads, generators – even of specific manufacturers



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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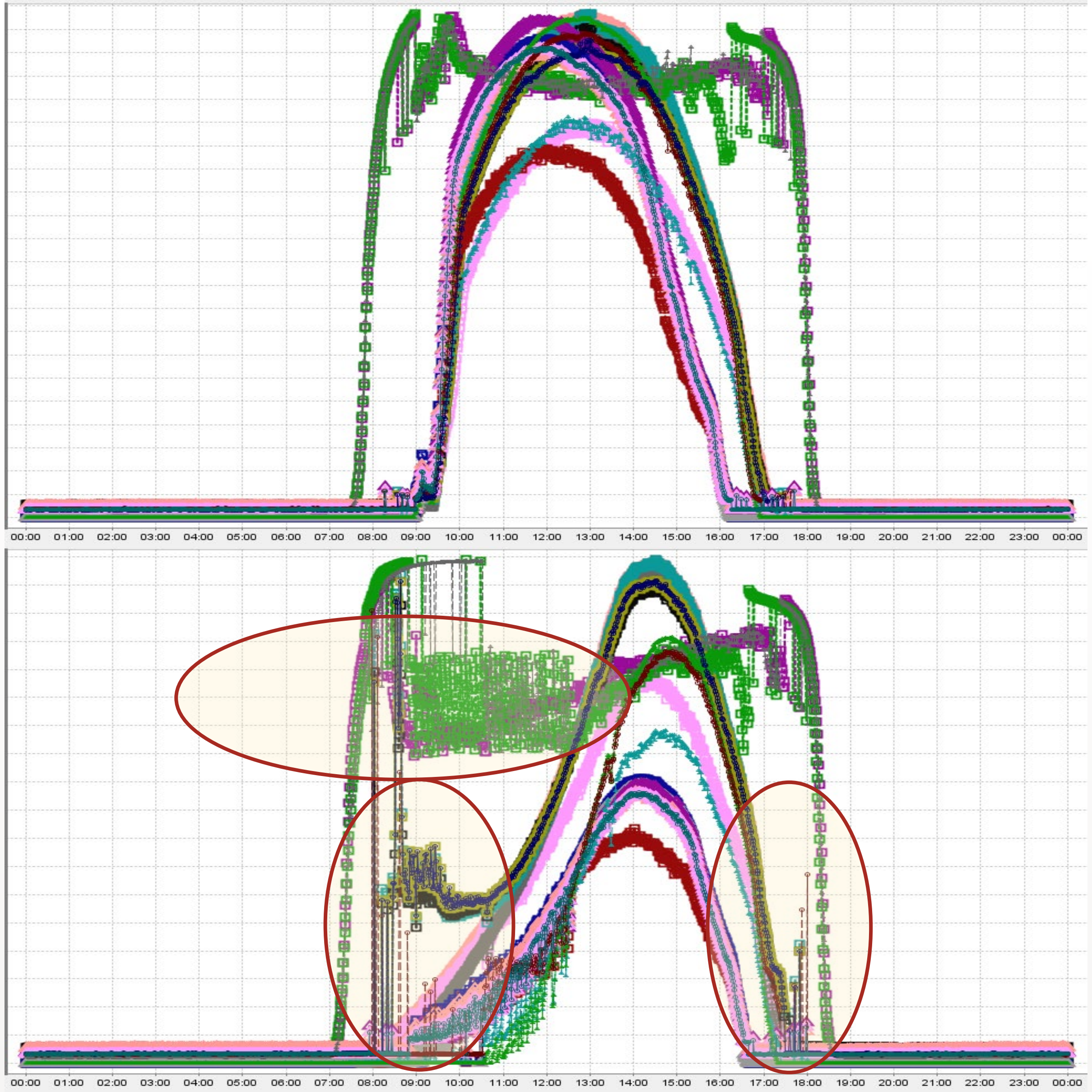
Measures from the SCADA-System – two different days

Above:	Behavior of the plant after a period of 0,5 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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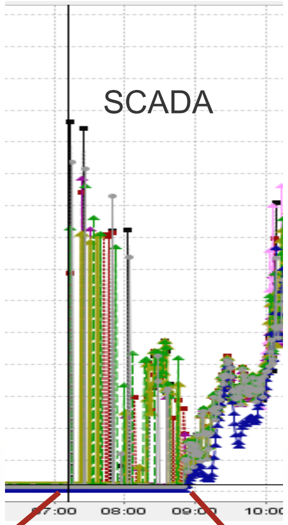
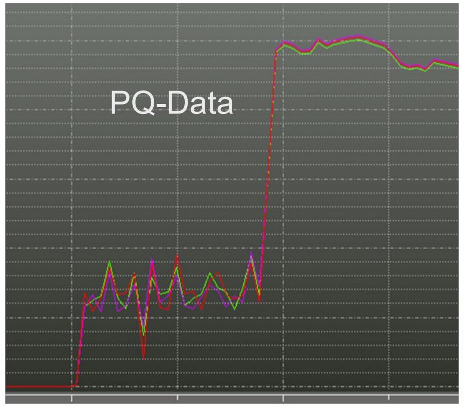
Converters detect their neighbours as the grid and try to deliver them energy. - That will not work!

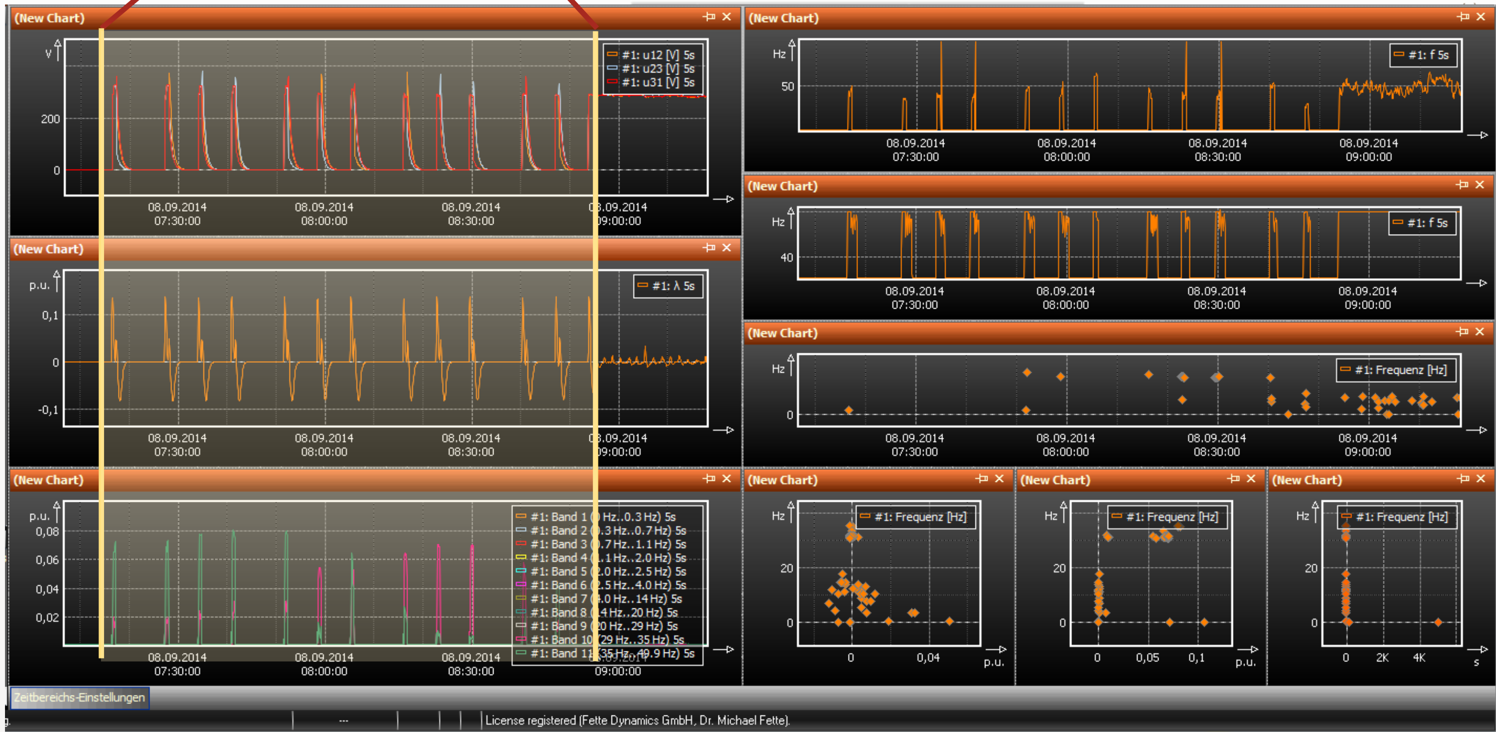




Dynamical Interactions

- 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.***

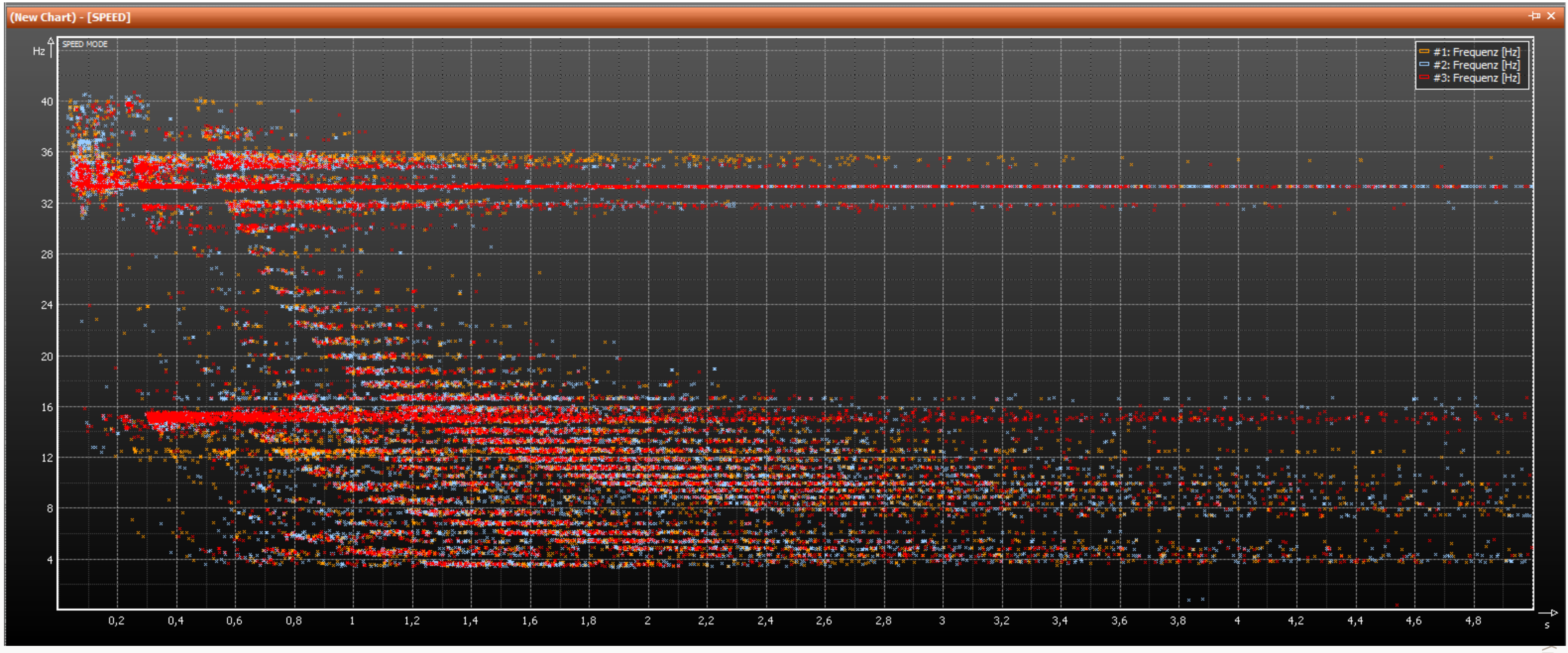


Vom Netz zum System

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!

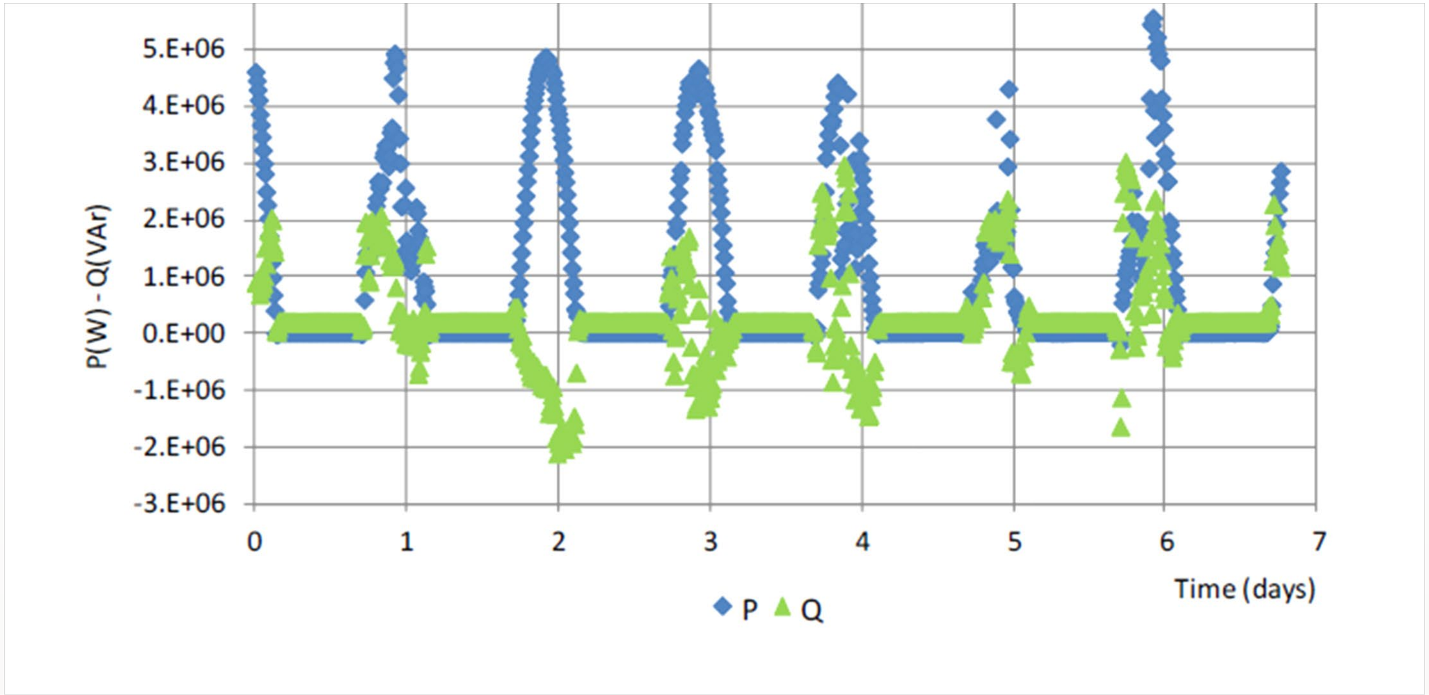


- Frequency bands are visible clearly.
- Reflexions could be obervered – analogously to the old analog TV-sets, where the pictures were disturbed, when the characteristic wave impedance was not matched to each other.
- The frequency band are typical for devices and manufacturers – we have a lot of „patterns“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

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.

Vom Netz zum System

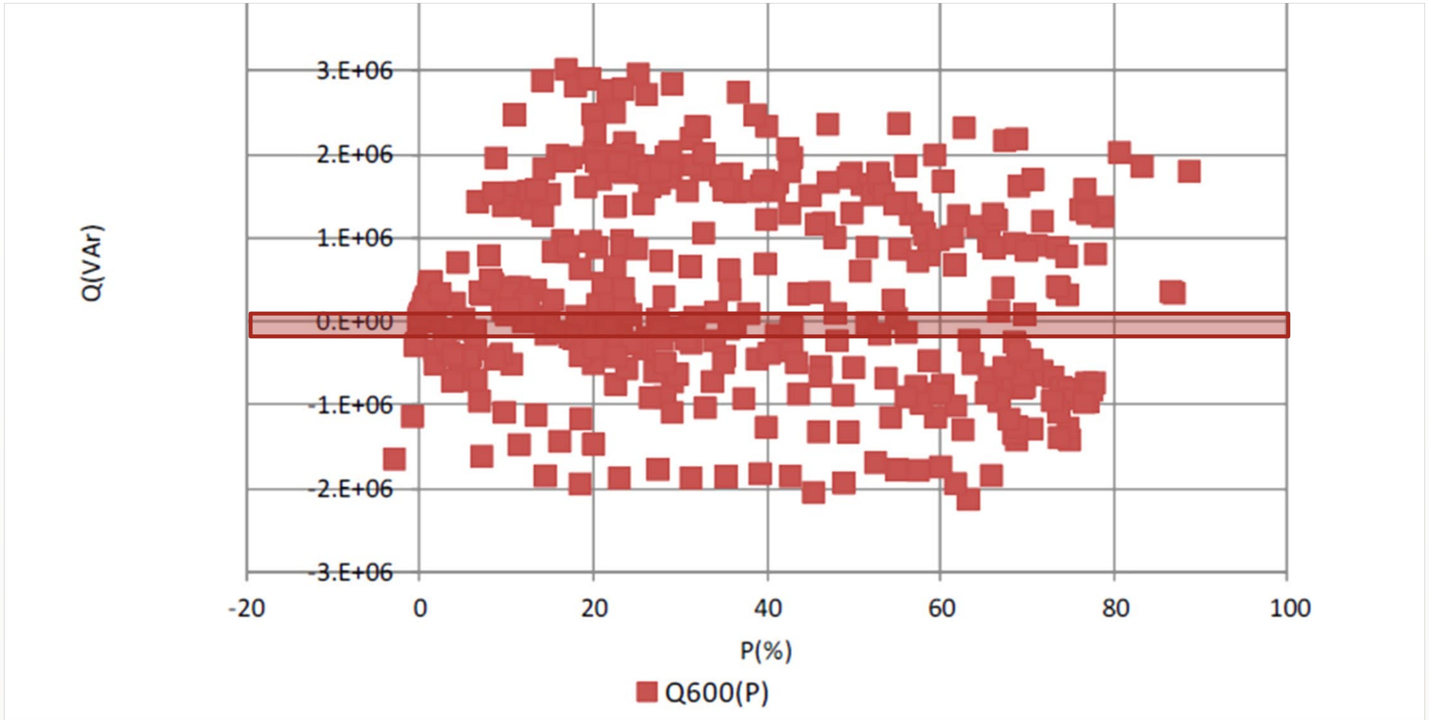
The classical mathematical framework is no longer applicable!

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

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.

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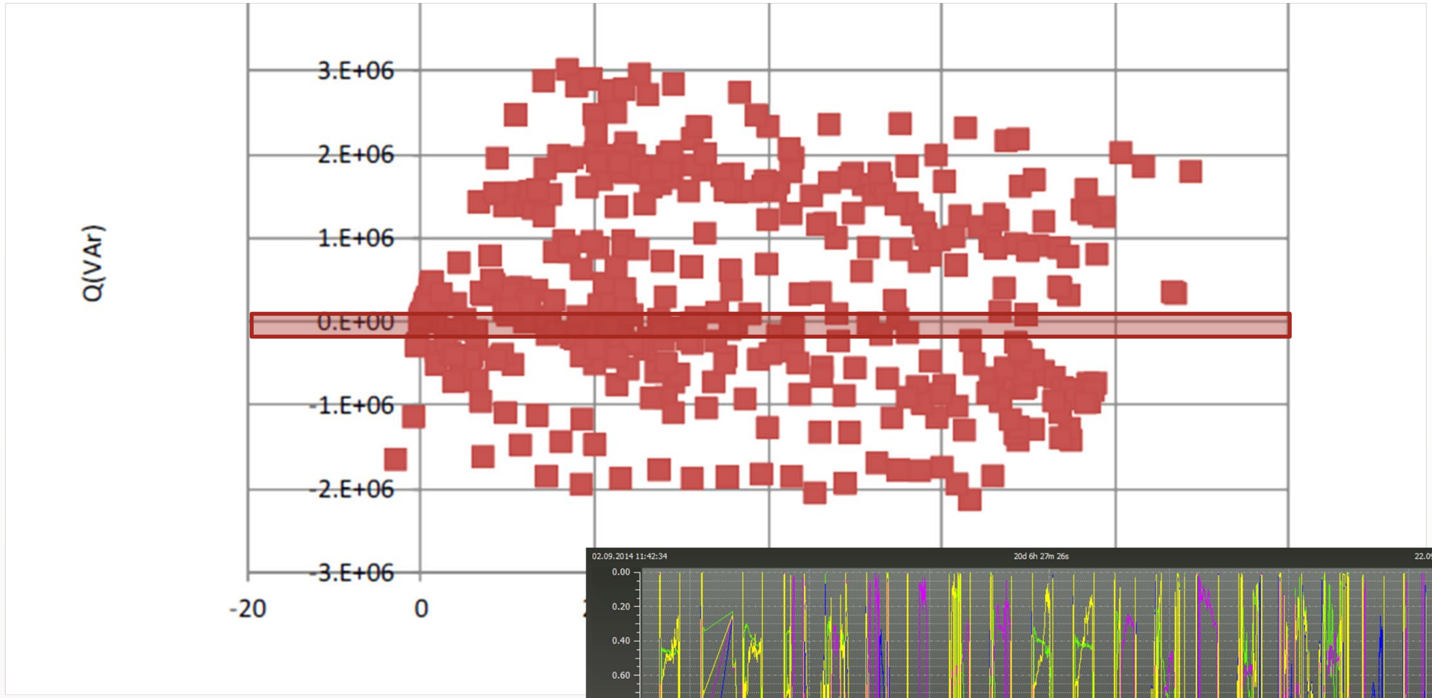
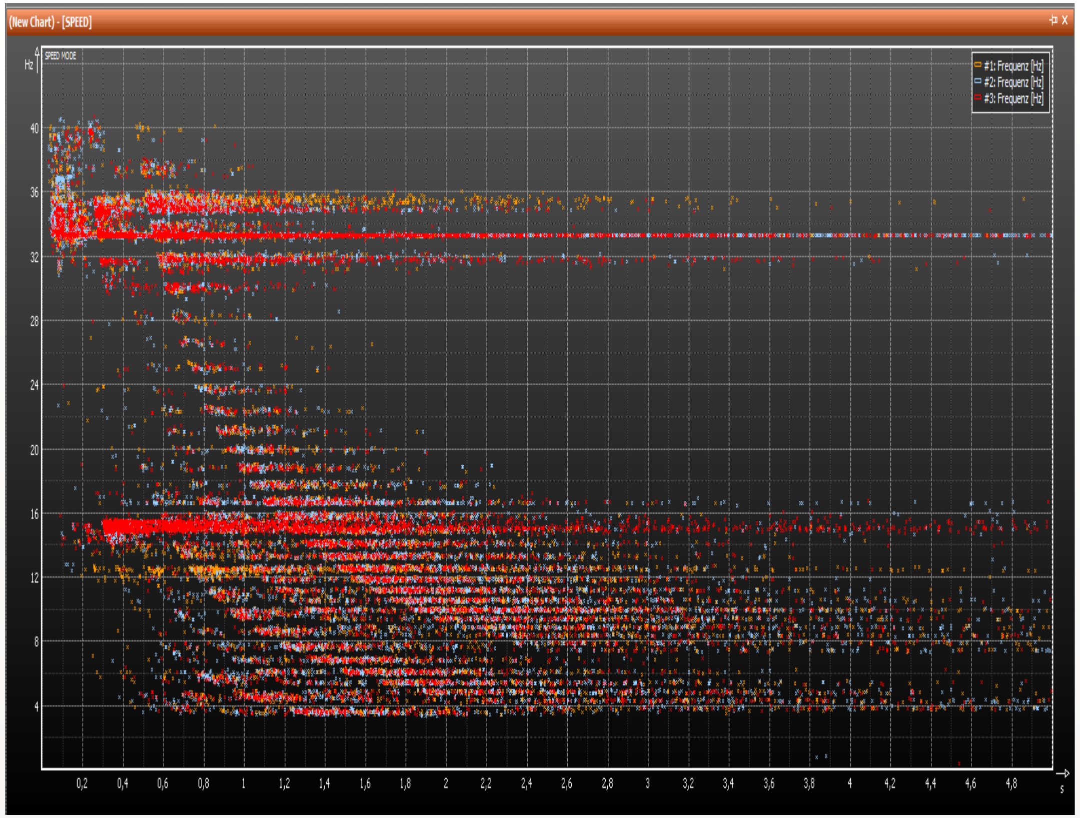


- Report of the same topic by spanish consulting company – page 66

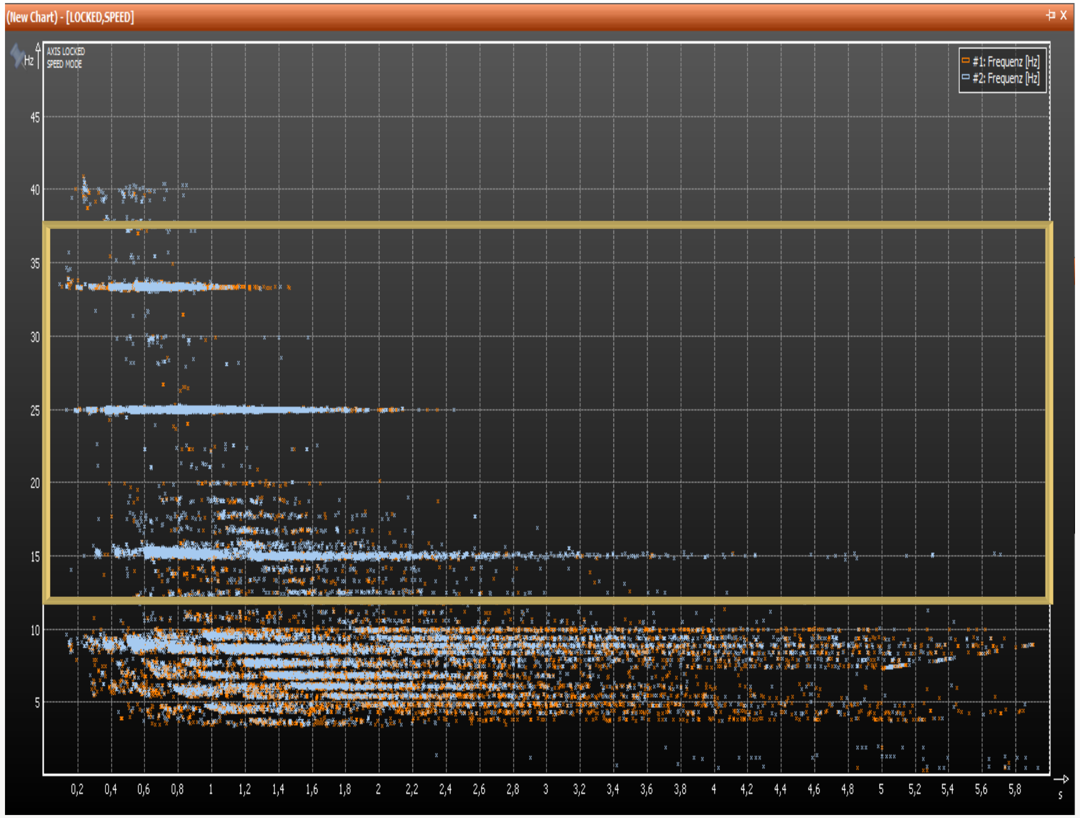
Do not think South France is far away! Our grid is different?

(Frequency over Time-Patterns)

South France – PV Plant (2016)

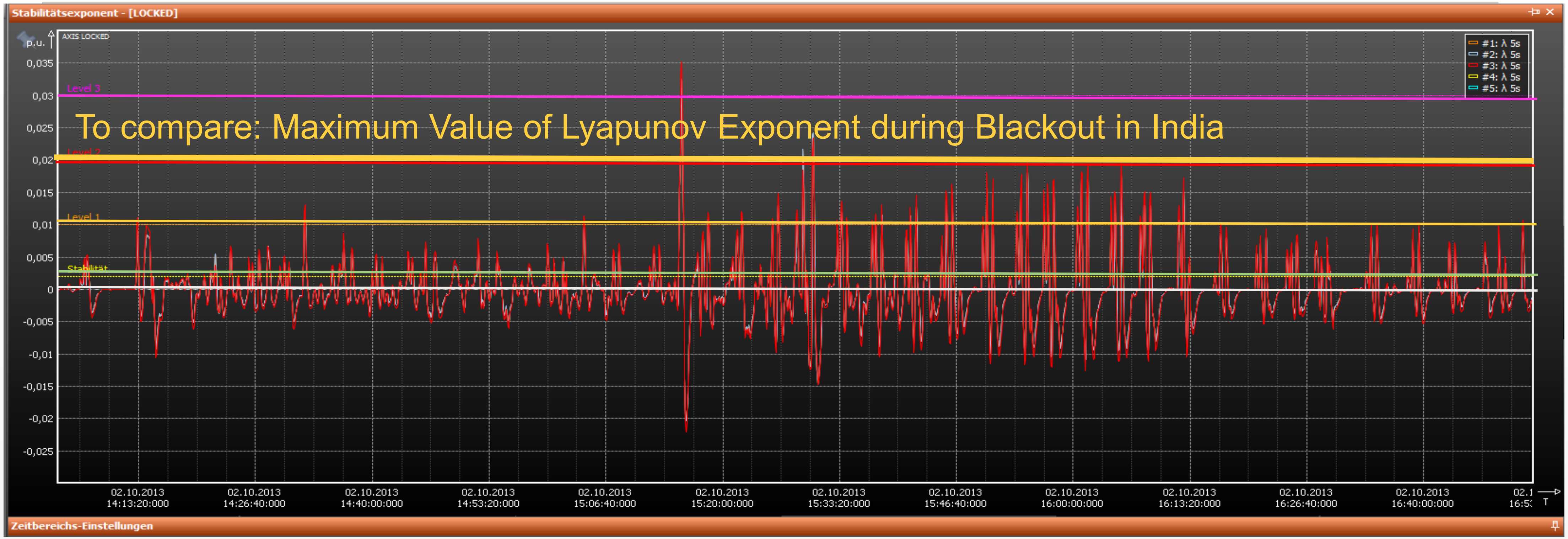


Germany – MV-Grid (2015)



Vom Netz zum System

Hugh Amount of Dynamical Interaction Processes caused by Industrial Plant

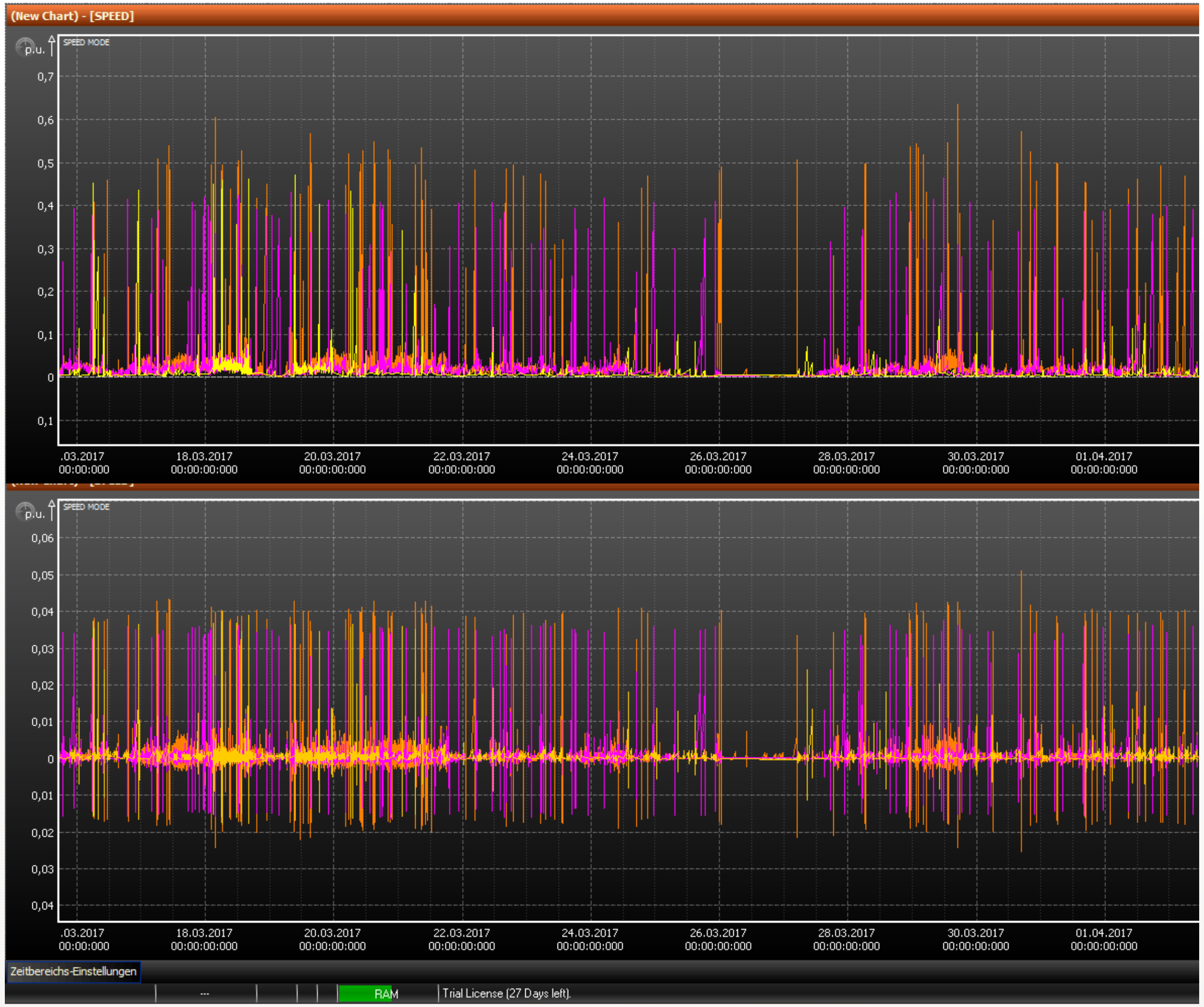


Nach 3 Jahren wird ein Standort nachgemessen – 110-kV-Netz!
Was kann man feststellen?

Windpark 2017

- 3 Messstandorte
- Veränderungen der Messwerte gegenüber Messungen vor 3 Jahren:
- Stabilitätsexponent: **Faktor 50 größer**
- Frequenzbänder: Im Detail **Faktor 500 größer**
- Zeitkonstanten: **mittlere Werte 40s bis 100s**

  Verschiebung hin zu sehr langsamen Vorgängen mit deutlich größeren Amplituden

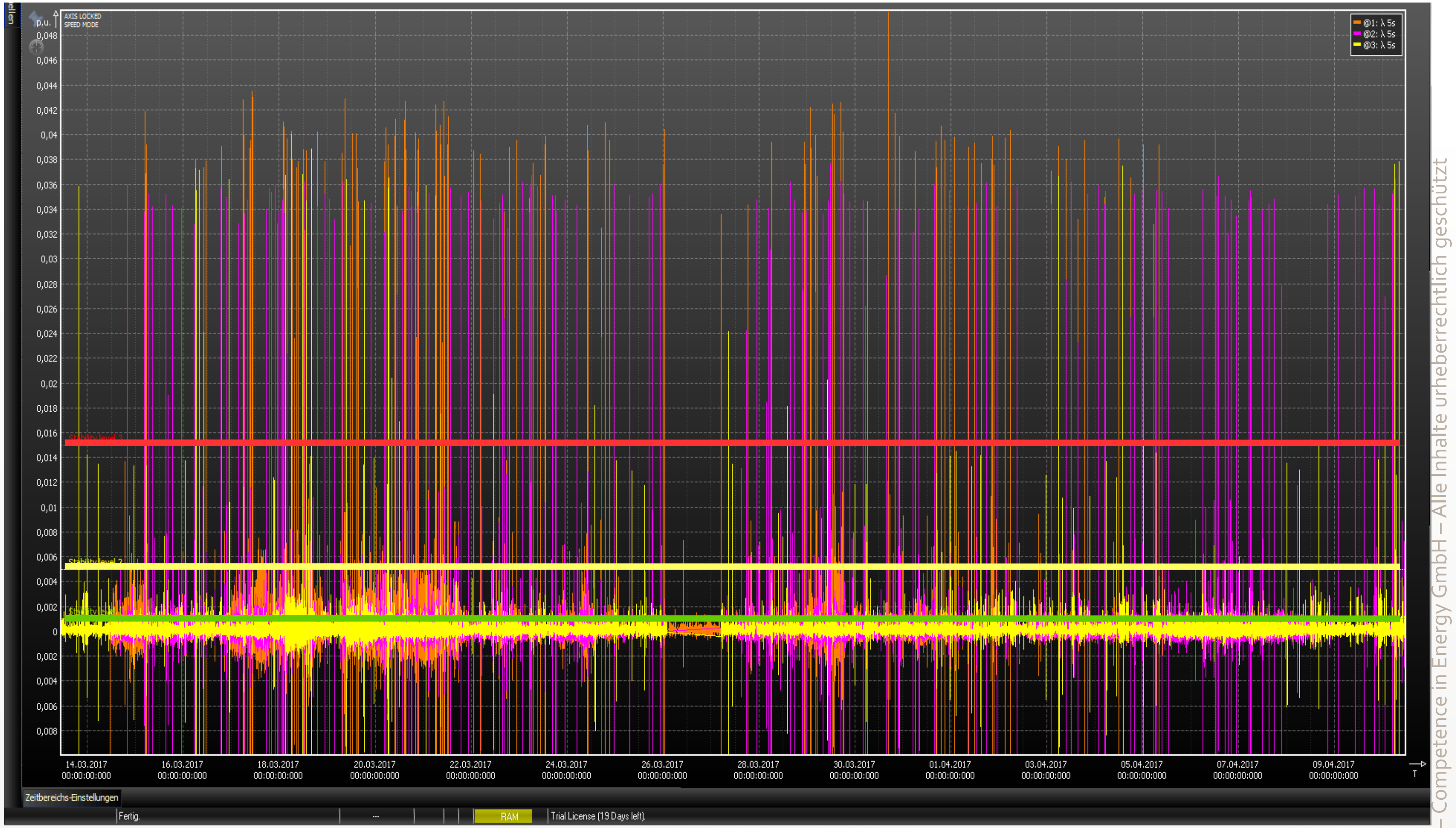


Vom Netz zum System

Fette
Competence in Energy

Windpark 2017

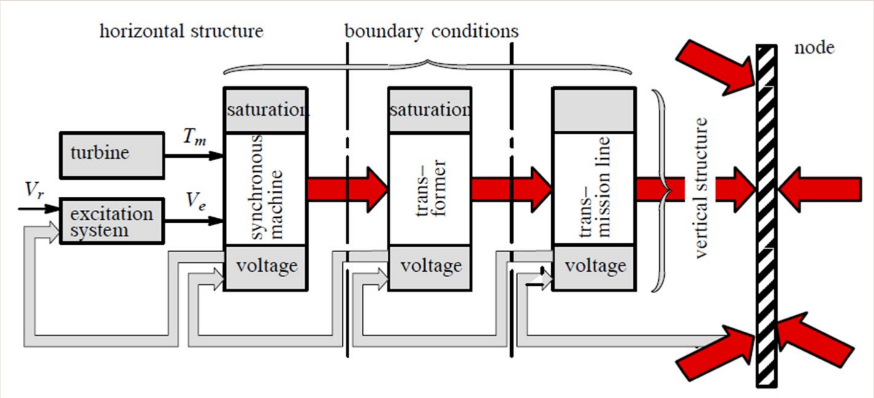
- Grün:
  maximaler L-Exp zu Beginn der Messungen 2004
- Gelb:
  maximaler L-Exp Messung Windpark 2014
- Rot:
  maximaler L-Exp bei Blackout in Indien

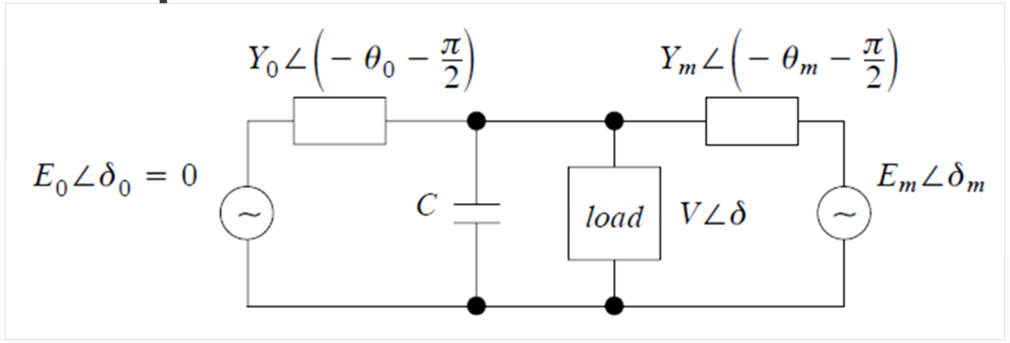


Vom Netz zum System

Structured models but with classical assumptions

- Analysis of power systems with nonlinear differential/algebraic methods
- Complex load characteristics must be incorporated





$$M\ddot{\delta}_m + d_m\dot{\delta}_m = P_m - P_e$$

$$M\ddot{\delta}_m = -d_m\dot{\delta}_m + P_m + E_m^2 Y_m \sin(\theta_m) + E_m Y_m V \sin(\delta - \delta_m - \theta_m)$$

Load characteristics

$$P_d = P_0 + P_1 + K_{p\omega}\dot{\delta} + K_{pv}\left(V + T\dot{V}\right)$$

$$Q_d = Q_0 + Q_1 + K_{q\omega}\dot{\delta} + K_{qv}V + K_{qv2}V^2$$

In 1942 Liwschitz postulated after his reseach of stability problems of synchronous machines, that reactance based models of synchronous maschines are no basis for stability analysis. His result:

It is no longer allowed to use reactance based models of synchronous machines for stability analysis!

Model used for Bifurcation Analysis

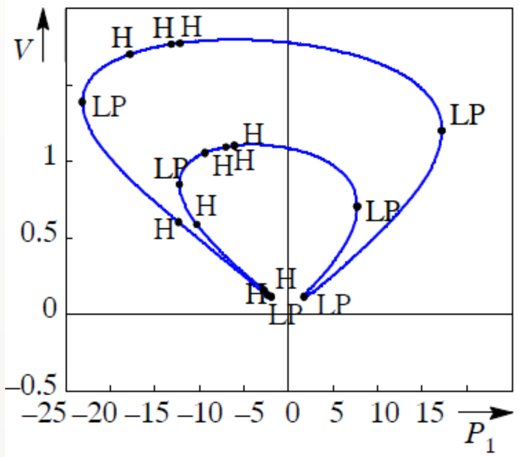
- Basis: Well known osciallation behavior of power system in different frequency areas
- Of interest: limiting bifurcation points, their characterstics and prediction to new behavior
- Analysis / comparision with real grid dynamics
- Models predict limiting bifurcation points – Hopf-Bifurcations within operating area of the system
(Phenomena analysed in 1942 with simpler, but very good models)

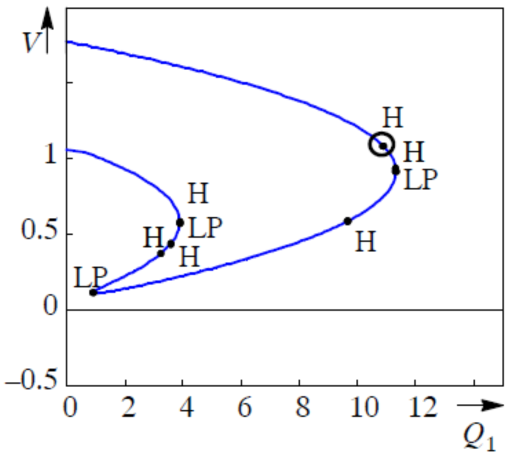
$$\dot{\delta}_m = \omega$$

$$M\dot{\omega} = -d_m\omega + P_m + E_m^2 Y_m \sin(\theta_m) + E_m Y_m V \sin(\delta - \delta_m - \theta_m)$$

$$K_{q\omega}\dot{\delta} = Q_d - Q_0 - Q_1 - K_{qv}V - K_{qv2}V^2$$

$$K_{pv}T\dot{V} = P_d - P_0 - P_1 - \frac{K_{p\omega}}{K_{q\omega}}\left(Q_d - Q_0 - Q_1 - K_{qv}V - K_{qv2}V^2\right) - K_{pv}V$$





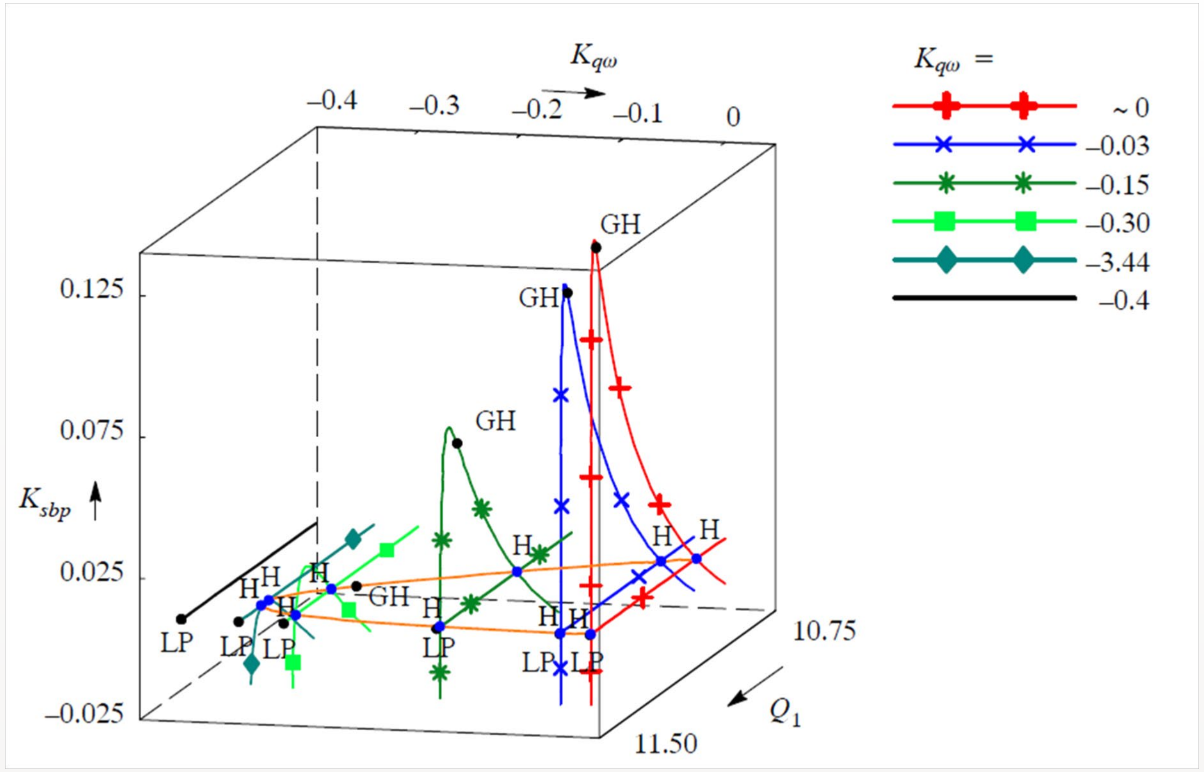
Vom Netz zum System

The models shows us a „dramatic" change in dynamical behavior – the more inverters will be incorporated in the system the more the operating areas of synchronous generators will be limited!

Detailed Analysis of Load Parameters

- Studies with different load parameters
- Detection of different dynamical behavior, in dependence of starting conditions
- Incorporation of inverter models to find out, how the power system dynamics will be changed by their behavior

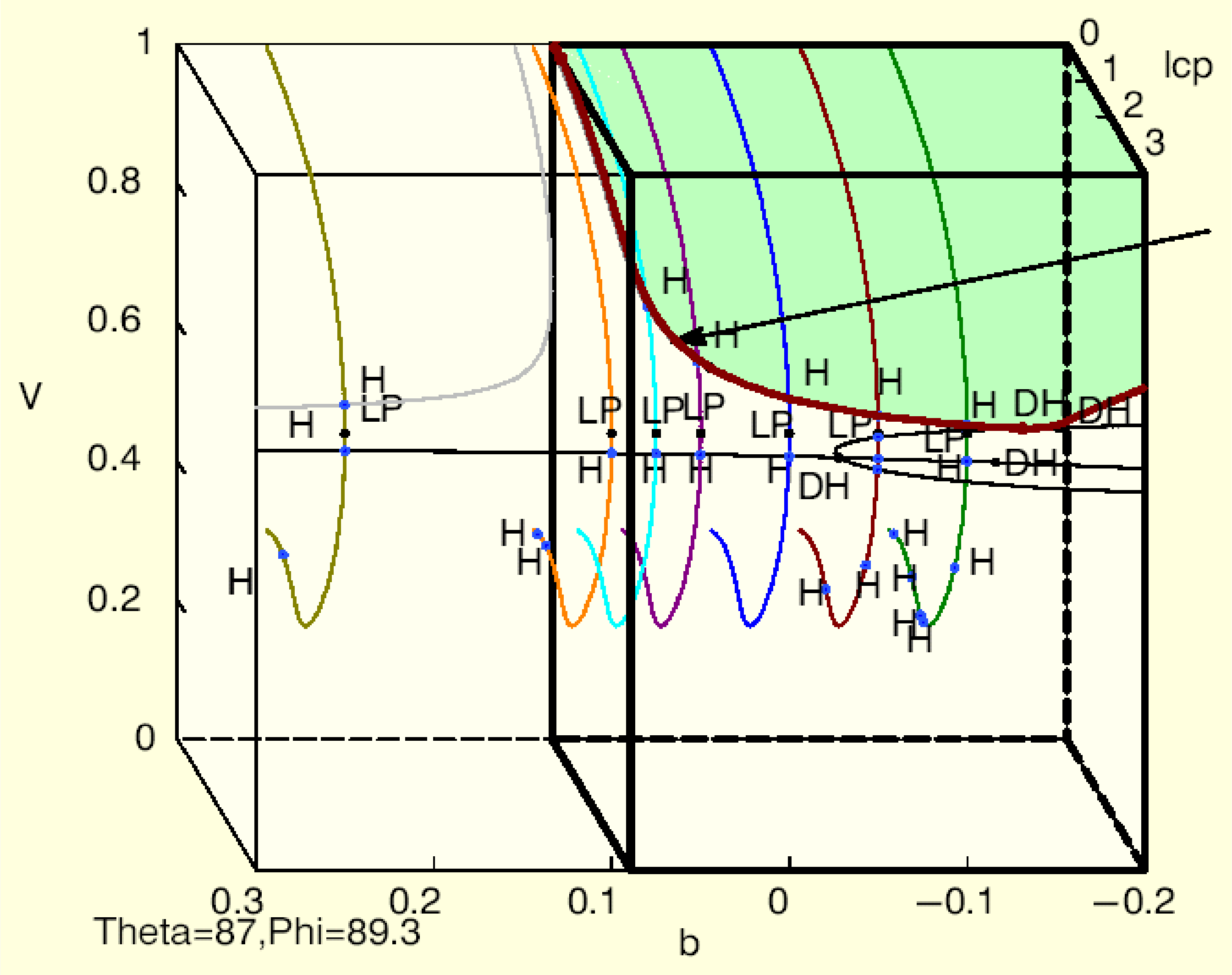
- Question: A lot of studies, but what is with the real system? Are the models correct???
- We need devices to measure the effects – based on nonlinear system theory.



Vom Netz zum System

Example:
Control of SVC

- In dependence of a load factor, the area of operation could be observed, which is limited by a curve of Hopf bifurcations
- It could be observed, that some settings of the SVC-controller gain „b" will lead to no operation situations
- If voltage dips are to big, there are no operating conditions, which it is similar to a wrong gain „b".



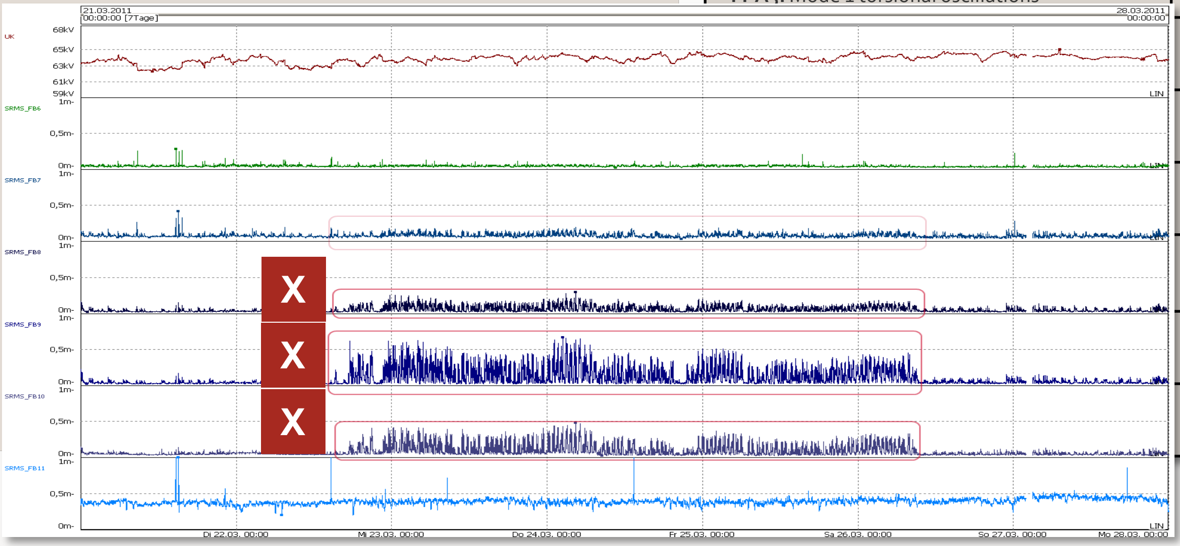
Quelle: Dr. Michael Fette, 1999

Vom Netz zum System

Measurements of „Frequency Classes“ - Detection of „Patterns“, 2011

- Example (Germany, MV-Grid)
- Measurement of torsional modes within a grid

Frequency / Hz	1. 0,0 0,3	2. 0,3 0,7	3. 0,7 1,1	4. 1,1 2,0	5. 2,0 2,5	6. 2,5 4,0	7. 4,0 14,0	8. 14,0 20,0	9. 20,0 29,0	10. 29,0 35,0	11. 35,0 49,9	12. 49,9 50,1	13. >50,1
FPA1: Intermediate frequency oscillations	X	X											
FPA2: Locally limited oscillations			X	X									
FPA3: Mode 1 torsional oscillations								X					
									X				
										X			
									X	X	X		X
							X						
		X	X										
	X	X											



Vom Netz zum System

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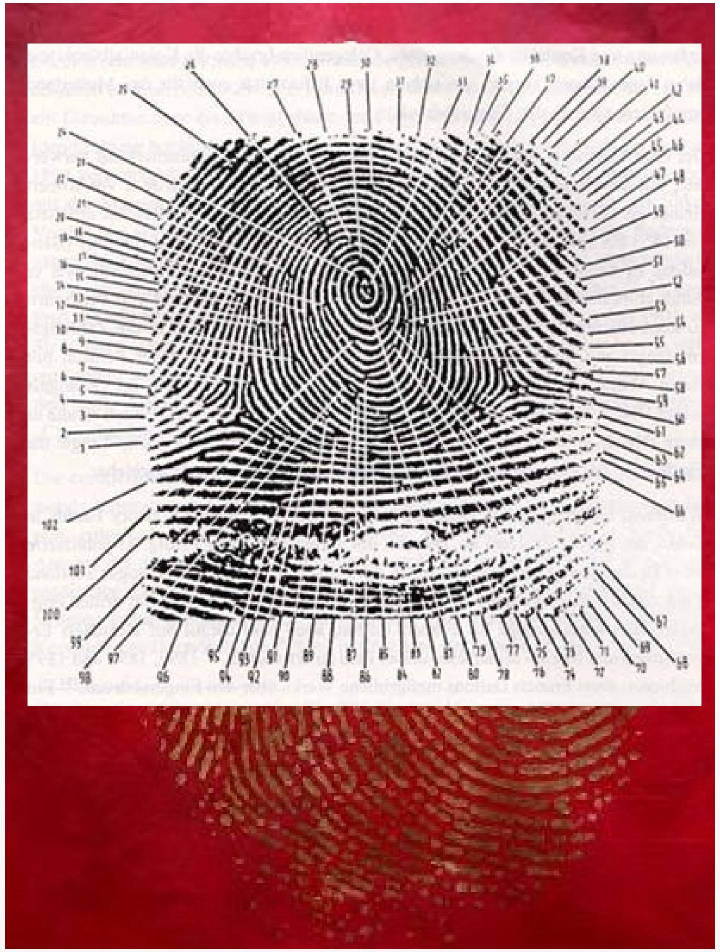
Competence in Energy

Fingerprint Analysis

More than 100 special characteristics are used
to identify/detect a human being based on their finger prints!

This can be done for power systems, also!



Vom Netz zum System

Michael Fette
Digital Nonlinear Power Systems

Fette
Competence in Energy

The EC-Grid-Code regulations make the monitoring of operating conditions, including complex interrelationships, mandatory!
The KRI – Key Reliability Indicator – can measure and evaluate all required interrelationships!

Provision, assurance and quality assurance of new system services

Selection of available KRI

KRI® - Key Reliability Indicator

KRI #	Key Reliablity Indicator	KRI #	Key Reliablity Indicator	KRI #	Key Reliablity Indicator
1	Islanding Detection	25	VPE Cable - Reliability Status	200	Control Schemes
2	FRT-Monitoring	26	Paper isolated Cable - Reliability Status	201	V-Control
3	Protection Schemes – Coordination	27	HVDC Cable - Reliability Status	202	Q-Control
4	Protection Schemes – Reliability Status	28	Flexibility Condition - Reliability Status	203	Damping Monitoring – Control
5	Nonlinear Stress – Ferroresonance	29	CIM-BIM-TGA Condition - Reliability Status	204	Intertia Monitoring
6	Nonlinear Stress – VT´s / CT´s-Reliability	30	E-Mobility Control	205	EV Load Control - Wallboxes etc.
7	Nonlinear Stress – Converter Reliability	31	Bifurcational Control – Hopf	206	BHKW – Control
8	ANSI C57.110 k-Factor-Rating	32	Stability Monitoring – Subsystem	207	FACTS – Control
9	Low Frequency Bands – Stability	33	Nonlinear Distortion Factor ABCEDF	208	Bifurcation Control II - Bogdanov Takens
10	Low Frequency Bands – Dynamics	34	Dynamically Efficient Short Circuit Power	209	Damping Control – Coordination
11	Modelling – State observation	35	Damping Monitoring	210	SSR-Control Subsynchronous Resonances
12	Modelling – Controller settings – Reliability	36	Stability Coefficient – Lyapunov	211	Gas Turbine Control
13	Modelling – Aging Process – Reliability	37	Relaxation-Time Constant (Stab-Exp)	212	Co-Generation Plant Gas Engine
14	Modelling – Aging Process – Health Index	38	SSR - Subsynchronous Resonances	213	Co-Generation Plant Diesel Engine
15	Modelling – ITIC Characteristic Industrial Load	39	Interarea Modes	214	CHP Power Station (GuD)
16	PQ-Analysis – Extended Standard – E-Mobility	40	Local Dynamical Mode	215	Bumpless- controller – general properties
17	Unsymmetry Management – NS-Netze	41	Torsional Mode #1	216	Mastercontroller for Intelligent Substations
18	Compliance-Monitoring	42	Torsional Mode #2	217	PV-Inverter Control (current source type)
19	Synchronization	43	Torsional Mode #3	218	PV-Inverter Control (voltage source type)
20	Resilience-Status	44	Supersynchronous Mode		
21	FRT-Monitoring – Frequency	45	Cusp	106	New Load Flow Calculation 2.0 – dyn. Aspects
22	RoCoF	46	Tower Effect > 1 MW	107	New Short Circuit Calculation 2.0 – dyn. Aspects
23	Frequency-Authorizing	47	Tower Effect < 1 MW	108	Damping Calculation – Frequency Domain
24	Motor Drives - Reliability Status	48	Wind Turbine – DFIG	109	Damping Calculation – Time Domain

Vom Netz zum System

Rot: *obligatorisch nach EU-Grid-Code-Verordnungen*
Schwarz: *ergänzende Aspekte, notwendig zur Systembewertung*

Frequenz- und Zeitbereichs-Analysen zur Messung und Bewertung von Systemeigenschaften

Synergetic**Mo**delle zur Ermittlung von speziellen physikalischen Effekten – Nutzung von nichtlinearen Analysen, insbesondere Bifurkations-Analysen sowie Resonanzprozesse

Bewertungen und Gewichtungen der SMo bezogen auf deren Wirkungen im System sind mit ***KRI***® – Key Reliability Indicators - abgebildet

- Nutzung von Zeit- und Frequenz-Bereich des Systems
  - A: Subharmonische Oszillationen
  - B: Nennfrequenzbereich - TAR
  - C: PQ-Bereich nach ISO 61000-4-30
  - D: Erweiterter Frequenz-Bereich TAR bis 9 kHz in 200 Hz-Intervallen beginnend von 2,5 kHz
  - T: Zeitbereich
- Evaluierung von dynamischen Eigenschaften mit spezifischen SMo
- Gewichtete und bewertete SMo sind die Grundlage für ***KRI***® (Key Reliability Indicator)

KRI	Description	Frequency domain				Time
		A	B	C	D	T
KRI 1	Islanding Detection	x	x	x		
KRI 2	FRT-Monitoring	x	x			x
KRI 3	Protection Schemes – Coordination	x	x			x
KRI 4	Protection Schemes – Reliability Status	x	x	x		x
KRI 5	Nonlinear Stress – Ferroresonance	x	x			
KRI 6	Nonlinear Stress – VT´s / CT´s-Reliability	x	x			
KRI 7	Nonlinear Stress – Converter Reliability	x	x			
KRI 8	ANSI C57.110 k-Factor-Rating	x	x	x	x	
KRI 9	Low Frequency Bands – Stability	x	x			
KRI 10	Low Frequency Bands – Dynamics	x	x			
KRI 11	Modelling – State observation	x	x			x
KRI 12	Modelling – Controller settings – Reliability	x	x			x
KRI 13	Modelling – Aging Process – Reliability	x	x	x	x	
KRI 14	Modelling – Aging Process – Health Index	x	x	x	x	
KRI 15	Modelling – ITIC Characteristic Industrial Load	x		x	x	x
KRI 16	PQ-Analysis – Extended Standard – E-Mobility			x	x	
KRI 17	Unsymmetry Management –LV-Grids	x	x	x		x
KRI 18	Compliance-Monitoring	x	x	x		x
KRI 19	Synchronization	x	x	x		x
KRI 20	Resilience-Status	x	x	x		x
KRI 21	FRT-Monitoring – Frequency	x	x	x		x
KRI 22	RoCoF	x	x	x		x
KRI 23	Frequency-Authorizing	x	x	x		x
KRI 24	Motor-Drives – Reliability Status	x	x	x		x
KRI 25	VPE-Cable – Reliability Status	x	x	x	x	x
KRI 26	Paper isolated Cable – Reliability Status	x	x	x	x	x
KRI 27	HVDC Cable – Reliability Status	x	x	x	x	x
KRI 28	Flexibility Condition – Reliability Status	x	x	x		x
KRI 29	E-Mobility-Control	x	x	x		x
KRI 30	Bifurcational Control	x	x	x		
KRI 31	Stability Monitoring	x	x	x	x	
KRI ...	Efficient Dynamical Short Circuit Power	x	x	x		x

Vom Netz zum System

Rot: *obligatorisch nach EU-Grid-Code-Verordnungen*
Schwarz: *ergänzende Aspekte, notwendig zur Systembewertung*

Frequenz- und Zeitbereichs-Analysen zur Messung und Bewertung von Systemeigenschaften

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  - T: Zeitbereich
- Evaluierung von dynamischen Eigenschaften mit spezifischen SMo
- Gewichtete und bewertete SMo sind die Grundlage für ***KRI***® (Key Reliability Indicator)

Edge-Computing im Feld

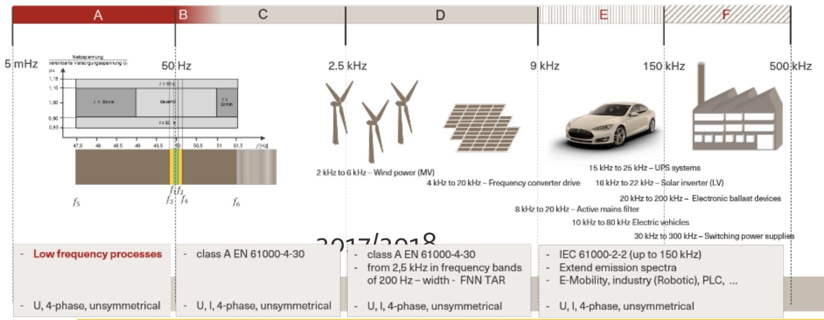
- Messen
- Bewerten
- Steuern
- Regeln
- Schützen

dezentral vor Ort auf der Basis von XAI-Systemen

KRI	Description	Frequency domain				Time
		A	B	C	D	T
KRI 1		x	x	x		
KRI 2		x	x			x
KRI 3		x	x			x
KRI 4		x	x	x		x
KRI 5		x	x			
KRI 6		x	x			
KRI 7		x	x			
KRI 8		x	x	x	x	
KRI 9		x	x			
KRI 10		x	x			
KRI 11		x	x			x
KRI 12		x	x			x
KRI 13		x	x	x	x	
KRI 14		x	x	x	x	
KRI 15		x		x	x	x
KRI 16				x	x	
KRI 17	Unsymmetry Management –LV-Grids	x	x	x		x
KRI 18	Compliance-Monitoring	x	x	x		x
KRI 19	Synchronization	x	x	x		x
KRI 20	Resilience-Status	x	x	x		x
KRI 21	FRT-Monitoring – Frequency	x	x	x		x
KRI 22	RoCoF	x	x	x		x
KRI 23	Frequency-Authorizing	x	x	x		x
KRI 24	Motor-Drives – Reliability Status	x	x	x		x
KRI 25	VPE-Cable – Reliability Status	x	x	x	x	x
KRI 26	Paper isolated Cable – Reliability Status	x	x	x	x	x
KRI 27	HVDC Cable – Reliability Status	x	x	x	x	x
KRI 28	Flexibility Condition – Reliability Status	x	x	x		x
KRI 29	E-Mobility-Control	x	x	x		x
KRI 30	Bifurcational Control	x	x	x		
KRI 31	Stability Monitoring	x	x	x	x	
KRI ...	Efficient Dynamical Short Circuit Power	x	x	x		x

Vom Netz zum System

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



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Incorporation of further ***KRI®*** as „test functions“ for reliability status

Synergetic Digital Twin

At the moment: > 120 KRI®

Special models for
- E-Mobility applications
- Cable (stress factors)
- Aging models
- ...

Synergetic submodels **SMo** for the detection of special effects – related to bifurcation analysis – especially resonance processes

TAR

New Requirements

	Q3	Q4		Q4

- KRI 1: Islanding Detection
- KRI 2: FRT-Monitoring
- KRI 3: Protection Schemes – Coordination
- KRI 4: Protection Schemes – Reliability Status
- KRI 5: Nonlinear S
- KRI 6: Nonlinear S
- KRI 7: Nonlinear S
- KRI 8: ANSI C57.1
- KRI 9: Low Freque
- KRI 10: Low Freque
- KRI 11: Modelling -
- KRI 12: Modelling -
- KRI 13: Modelling -
- KRI 14: Modelling -
- KRI 15: Modelling -
- KRI 16: PQ-Analysis
- KRI 17: Unsymmetri
- **KRI 18 Complianc**
- KRI 19 Synchroniz
- KRI 20 Resilience-
- KRI 21 FRT-Monitoring – Frequency
- KRI 22 RoCoF
- KRI 23 Frequency-Authorizing

For every ***KRI®***, there exist an inverse **SMo**, with which it is possible to „play“ the dynamics

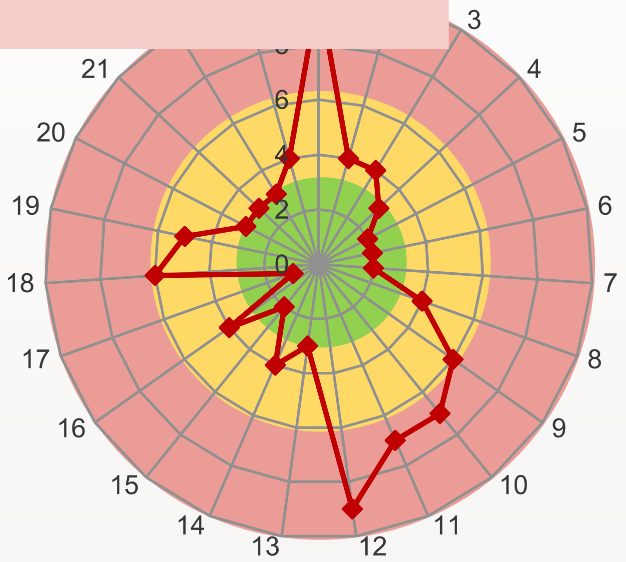
Like an „MP3-Player“

Part of our
Synergetic Digital Twin

KRI®

- Islanding, FRT-U
- Protection Scheme
- Stress Factors
- Stability
- Models
- Aging
- PQ extended
- Compliance
- Frequency

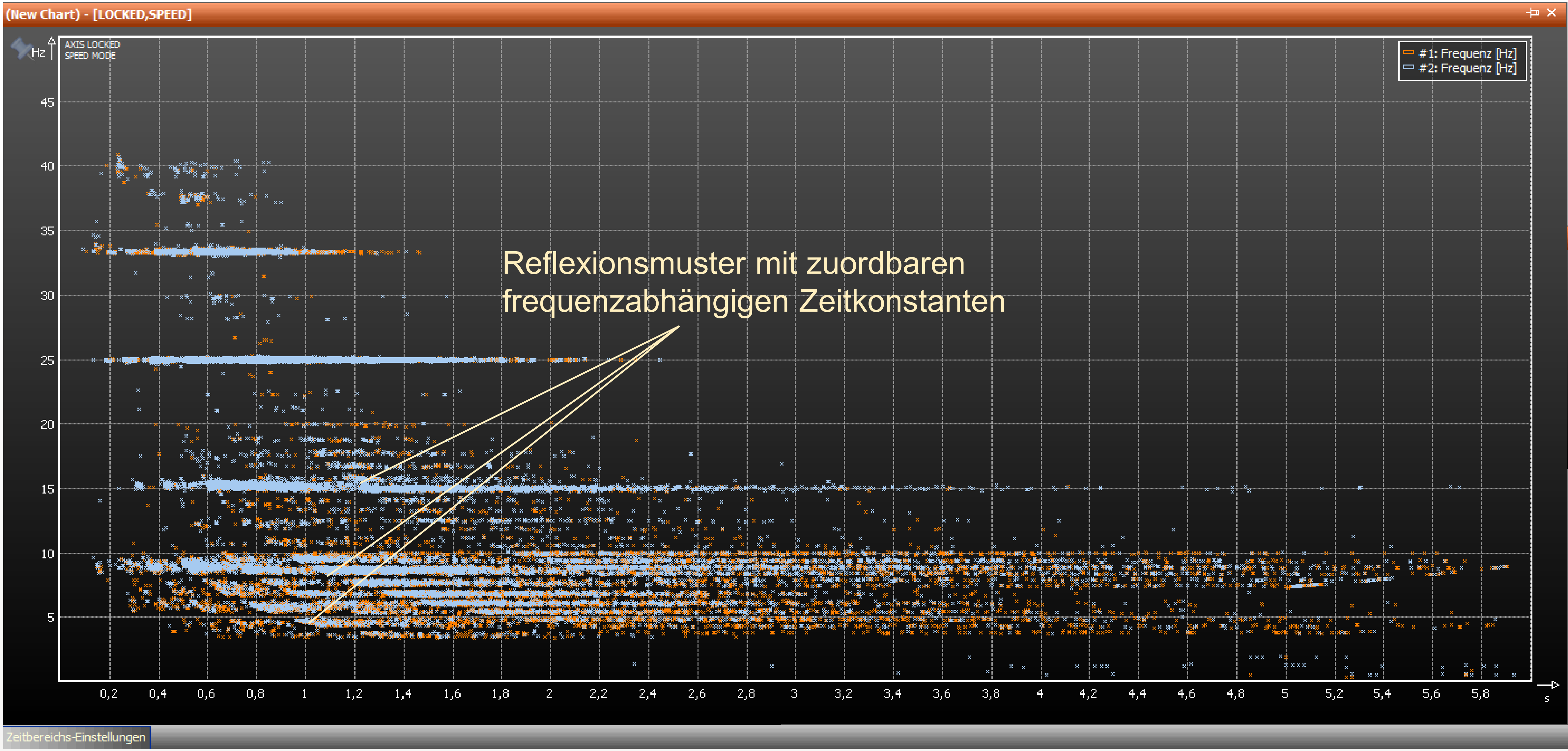
KRI®



Vom Netz zum System

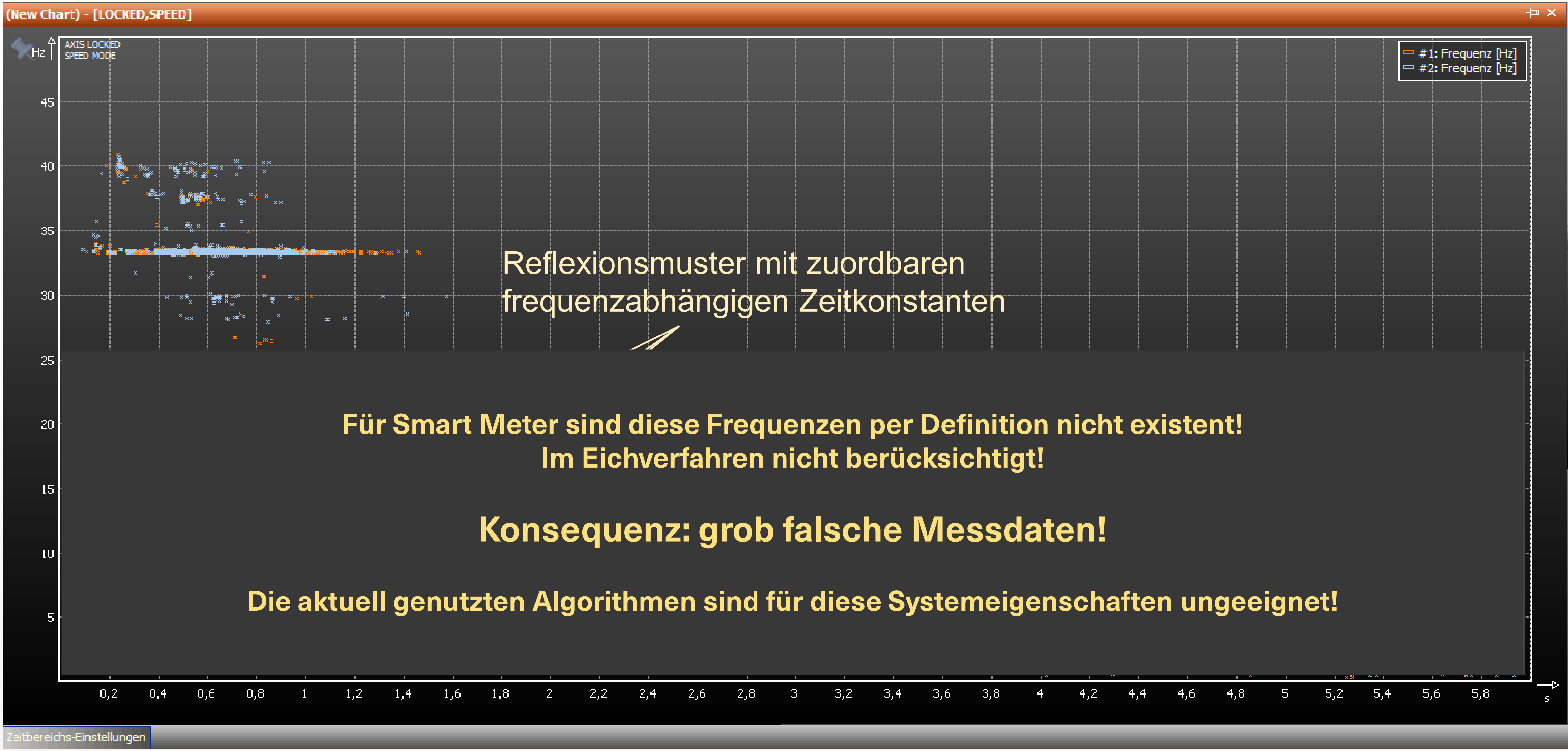
Fette
Competence in Energy

Nochmals Frequenz-Dauer der Wechselwirkungsprozesse im Bereich 0 bis 50 Hz – Messung in Deutschland



Vom Netz zum System

Nochmals Frequenz-Dauer der Wechselwirkungsprozesse im Bereich 0 bis 50 Hz – Messung in Deutschland



Reflexionsmuster mit zuordbaren frequenzabhängigen Zeitkonstanten

Für Smart Meter sind diese Frequenzen per Definition nicht existent!
Im Eichverfahren nicht berücksichtigt!

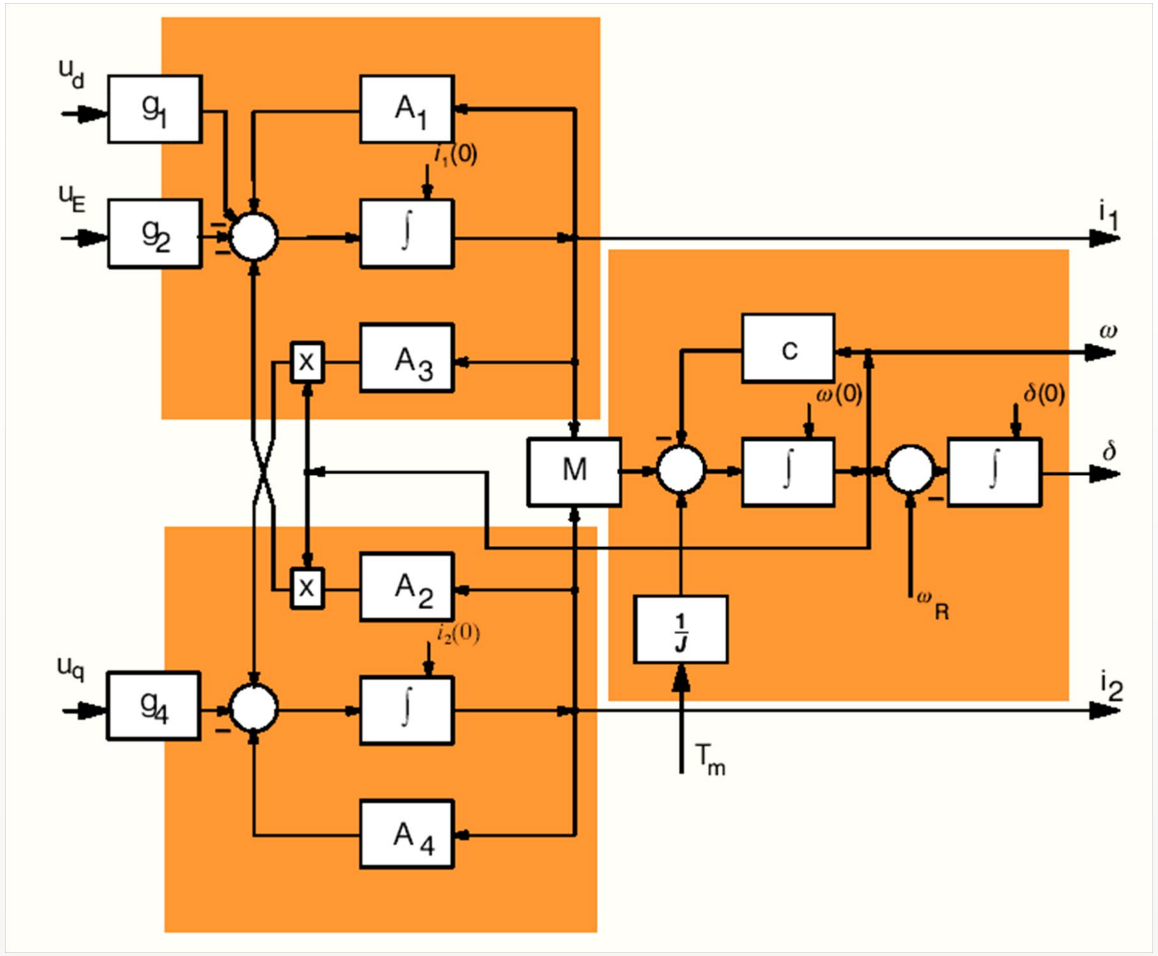
Konsequenz: grob falsche Messdaten!

Die aktuell genutzten Algorithmen sind für diese Systemeigenschaften ungeeignet!

Inertia!!! – Inertia???

Synchronous Machine Model

- Orthogonal structure in 0dq-coordinates
- Mechanical and electrical systems are coupled
- Feedback of the frequency is essential
- Model is prepared for use of nonlinear analysis method



Quelle: Dr. Michael Fette - 1993

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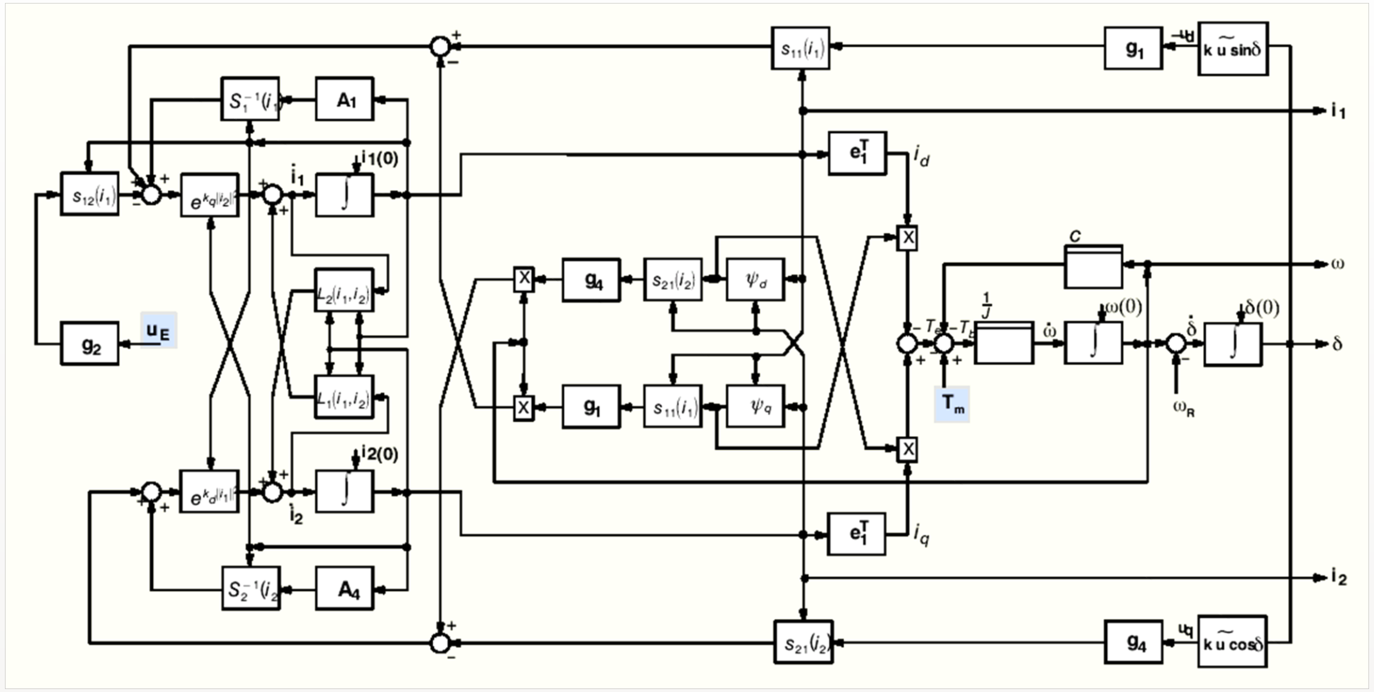
Synchronous Machine with Saturation

- Model converges in the case of small currents to the model without saturation „limit model properties“ are reached
- Structural analysis is possible – Calculation of bifurcation-characteristics



Quelle: Dr. Michael Fette - 1993

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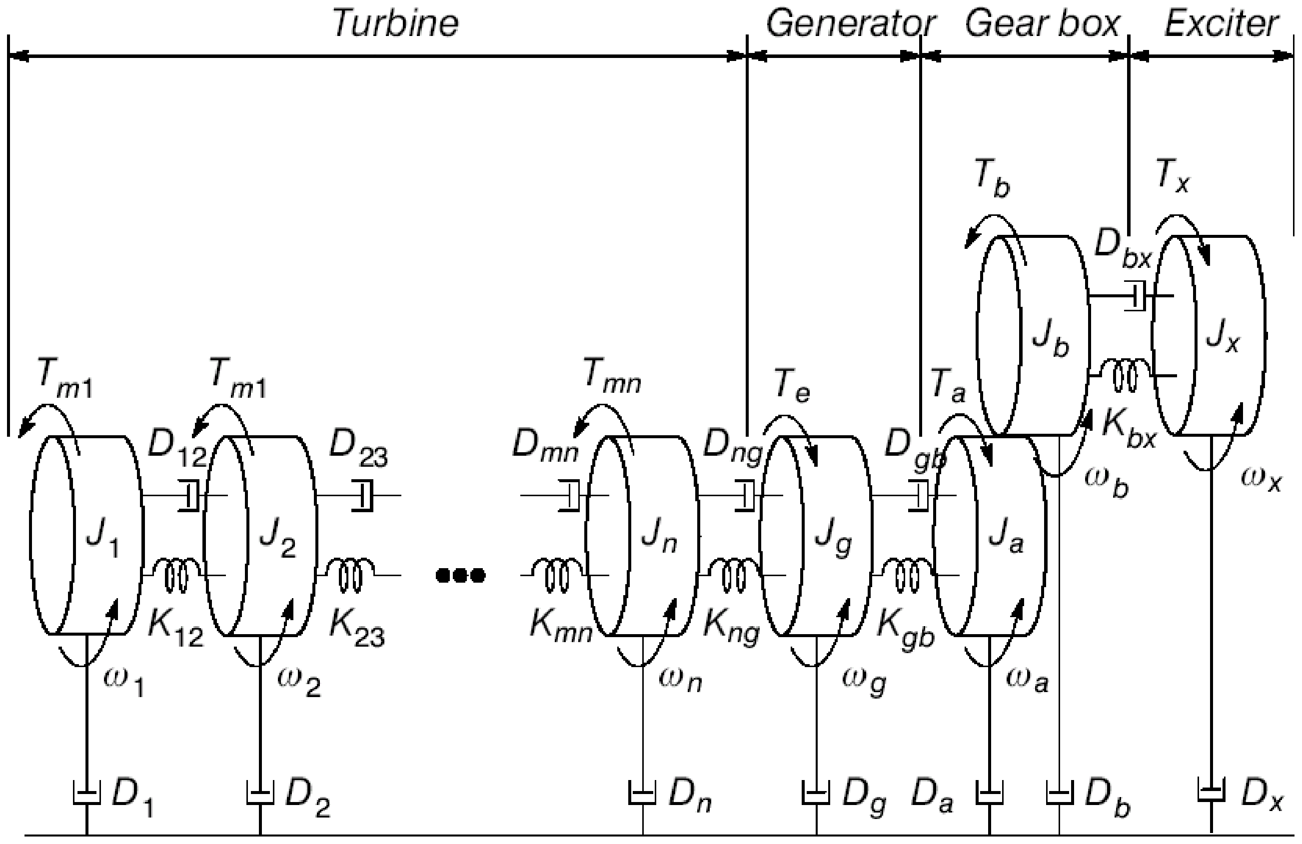
Inertia!!! – Inertia???

Mechanical Subsystem

- Mechanical subsystem with identical structural dynamics as the model of a saturated synchronous machine
- Coupling of mechanical and electrical subsystem is essential for the calculation of subsynchronous resonances or inter area oscillations



Quelle: Dr. Michael Fette - 1993

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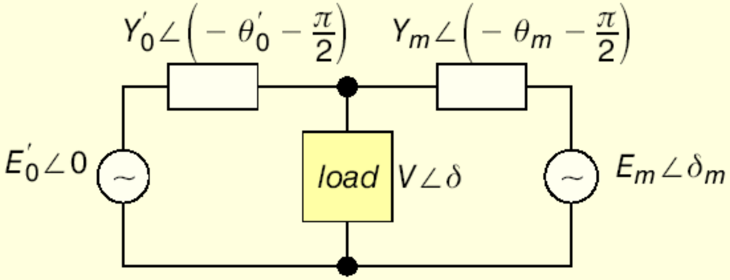
PMU-Daten liefern keine Informationen – um diese Frage zu beantworten!

Load Dynamics

Analysis of load dynamics with multi-parameter-dependencies

Bifurcation-Analysis

Question:
Which parameter change process is most important for the various stability aspects of the system?



load model

$$P_d = P_1 + P_0 + K_{p\omega}\dot{\delta} + K_{pv}(V + T\dot{V})$$

$$Q_d = Q_1 + Q_0 + K_{q\omega}\dot{\delta} + K_{qv}V + K_{qv2}V^2$$

$$\dot{\delta}_m = \omega$$

$$\dot{\omega} = \frac{1}{M}\left[-d_m\omega + P_m + E_m^2 Y_m \sin(\theta_m) + E_m Y_m V \sin(\delta - \delta_m - \theta_m)\right]$$

$$\dot{\delta} = \frac{1}{K_{q\omega}}\left[Q_d - Q_1 - Q_0 - K_{qv}V - K_{qv2}V^2\right]$$

$$\dot{V} = \frac{1}{K_{pv}T}\left[P_d - P_1 - P_0 - \frac{K_{p\omega}}{K_{q\omega}}\left(Q_d - Q_1 - Q_0 - K_{qv}V - K_{qv2}V^2\right) - K_{pv}V\right]$$

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Wesentliche Eigenschaften nichtlinearer Elektroenergiesysteme

- ➔ Ein dynamisches System kann nicht jeden beliebigen Zustand annehmen
- ➔ Ein dynamisches System durchläuft auf dem Weg von einem Zustand zu einem Nächsten nur dynamisch „erreichbare" Zustände
- ➔ Welche Zustände überhaupt eingenommen werden können, hängt von den Eigenschaften des Systems ab – von der Struktur der beteiligten Nichtlinearitäten
- ➔ Der Übergang von einem Zustand zu einem Anderen, wobei das System qualitativ seine Eigenschaften ändert, hängt von nur sehr wenigen Parametern (Ordnungsparameter) ab (Synergetik).
- ➔ Eigenschaften stochastischer Prozesse können auf äquivalente Nichtlinearitäten umgerechnet werden!
- ➔ **Die Eigenschaften können in einer praktischen Umsetzung direkt ausgewertet werden!**
- ➔ **KRI´s werten die Eigenschaften aus und „übersetzen" den dynamischen Zustand des Systems!**

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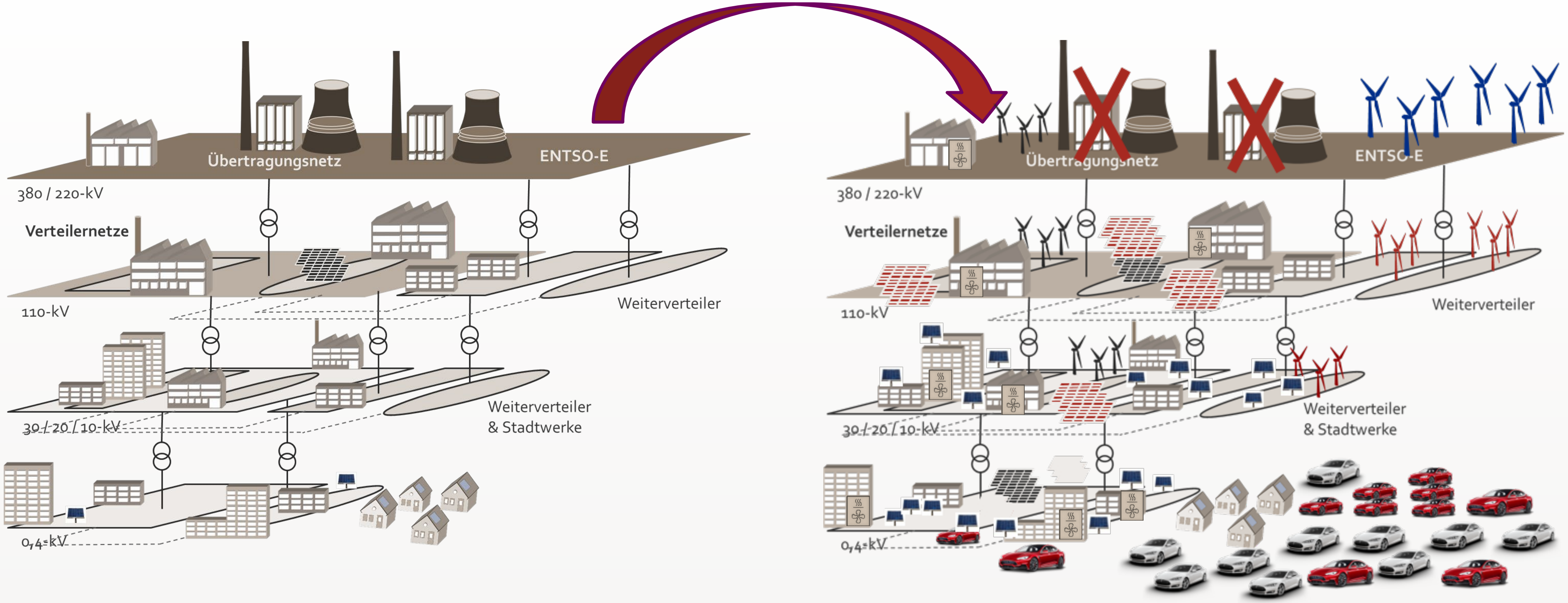
Forderungen aus der Theorie nichtlinearer Systeme

- ➔ Modellunabhängige Methoden und Verfahren
  - Kein Modell der Welt entspricht der tatsächlichen Netzsituation
  - On-line-Identifikation von Modellparametern sehr schwierig (oder unmöglich)
  - Lasteigenschaften unbekannt und nicht online identifizierbar
- ➔ Ausschließlich Analysen der Dynamiken
  - dezentral
  - lokale Intelligenz
  - unabhängig von koordinierender Stelle
- ➔ Ausschließlich Methoden basierend auf der Theorie nichtlinearer und stochastischer Systeme
  - Unabhängigkeit von Formparametern der Systemgrößen (z.B. sinusförmig)
- ➔ ABER: Lokale Repräsentanz der Gesamtdynamik notwendig

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



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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*.**“

Vom Netz zum System

Transition der niederfrequenten Dynamiken durch die Integration überwiegend leistungselektronischer Einspeiser, Speicher und Lasten

Verbogen, nichtlinear – aber „statisch"

Quelle: Kartoffeln (pixabay)

Verbogen, nichtlinear – aber „instabil"

Foto: House of Food / Bauer Food Experts KG

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Zwischenfazit

- Aktuell vorliegende Messdaten weisen auf einen „prototypischen“ Blackout hin, der alle Merkmale der nichtlinearen Theorie zu Kollaps-Vorgängen (Spannungs-Kollaps) erfüllt.
- Das grundlegende Problem wird im Spannungs-/Blindleistungshaushalt des Netzes liegen.
- **Abstimmung der diversen Reglereinstellungen / Schutzeinrichtungen müssen verbessert / koordiniert werden. Dämpfungsverhältnisse müssen verbessert werden!**

  Das ist zukünftig ein permanenter Prozess – und nicht nur einmalig im Netzanschlussverfahren!
- **Der Störfall ist reproduzierbar!**

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Preserving the tried and tested – shaping the new!

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KRI® die Anwendungen und Algorithmen, die das System benötigt, um das nichtlineare Systemverhalten zu erkennen und zu bewerten, Prozesse anzupassen und Entscheidungen zu treffen, damit das System jetzt und in Zukunft stabil und sicher betrieben werden kann - lokal und global. ***KRI®*** kodieren mit einer intelligenten Vorverarbeitung die Messdaten so, dass die auszutauschenden Datenmengen auf ein Minimum reduziert und die Relevanz der Information erkannt werden kann. - Komplementär zu bekannten Prozess-KPI.

DMP-EMCP® die EDGE-basierte Hardwareplattform, die die Messgrößen im gesamten Frequenz- und Zeitbereich in Zeit und Frequenz hochaufgelöst erfasst, Indikatoren für Einzelwerte oder komplexe Werte oder für komplexe Netzdynamiken auf Basis nichtlinearer Systeme ermittelt, kann direkt innerhalb von Steuerungs- und Schutzalgorithmen lokal oder in hierarchisch strukturierten Steuerungs- und Schutzkonzepten eingesetzt werden. CyberSecurity-Aspekte können traditionell implementiert werden, oder es können neue duale CyberSecurity-Lösungen durch intelligente Kodierung der Mess- und Auswertegrößen genutzt werden, um eine zukünftig nutzbare "low cost"-Kommunikation sicher und zukunftssicher zu machen.

Basiert auf ***XAI*** - **EX**plainable **A**rtificial **I**ntelligence – powered by Synergetics!

Pooling-Algorithmen und Marktplätze können direkt angedockt werden, intelligente Lösungen, bei denen z.B. E-Fahrzeuge auch als Speicher im Verteilnetz mit Dienstleistungen für das Übertragungsnetz eingesetzt werden, können realisiert und betrieben werden.

Der Betreiber von ***ORCA®*** erhält direkte Unterstützung im Rahmen von Unternehmenswerten mit den Perspektiven: Finanzen, Technik, Sicherheit, Qualität, Recht, Image, Umwelt, Organisation und Effizienz. Die ***KRI®*** identifizieren Probleme, zeigen Lösungen auf und begründen die Herausforderungen - immer im Sinne aller Unternehmenswerte, ... mit Nachweisen, so dass Klarheit für alle Beteiligten geschaffen wird!

... ein komplettes, streng modulares, hoch automatisiertes Systemmanagement - für

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Fette - Competence in Energy GmbH develops solutions for system management and system operation of energy systems that meet future requirements with predominantly decentralized and converter-based plants.

- 35 years of experience in research and development of nonlinear systems
- Over 800 man-years of development power in IT systems, hardware and software solutions, algorithms, and analysis and evaluation methods - self-funded without third party rights or dependencies
- Over 350 projects in more than 30 countries in industrial, distribution and transmission networks (AC and DC), to determine and assess system dynamics - usually when there have been disturbances or destruction of equipment and networks, identifying causes and proposing solutions – evaluating theory and practice
- For more than 15 years permanent observation of the dynamics and change processes in the systems
- Over 100 projects for the development of customer-specific solutions
- Over 500 consulting projects

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Fette – Competence in Energy GmbH
Hohenzollernring 30
22763 Hamburg
Germany
+49 155 588 49 807

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Priv.-Doz. Dr.-Ing. habil.

Michael Fette

former Professor for
„Renewable Energy Systems and Automatic Control"
venia legendi in „System theory / System dynamics"

michael.fette@fette-competence-in-energy.com

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*Please request the **KRI**®-Catalogue or ORCA®-Modules – Intelligent Solutions for Digital Nonlinear Power Systems*

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Vielen Dank!

Vom Netz zum System