Power Systems Control
Discussion of **Future** Research Topics

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We talked about a whole range of topics

"Power Systems Control – from Circuits to Economics"

All these topics have been expensively studied in the past, and they remain important in the future — possibly with a different emphasis:

- increasing uncertainty in generation
- deregulated markets & pricing schemes
- more and more power electronics sources
- new technologies for sensing/comm/actuation
- new elasticity in demand and batteries
- advances in distributed control & optimization
- . . .

Other very important topics that we did not touch upon

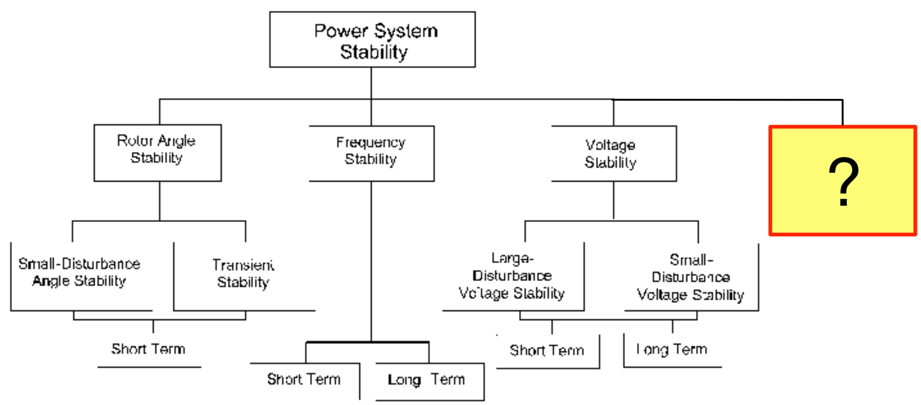
- **wide-area estimation:** PMUs, load identification, etc.
- **DC components** in HVDC transmission, microgrids, etc.
- **power system optimization** using latest start of the art tools
- role of **battery storage** for balancing
- **load control & demand response**
  (vehicle charging, thermostatically-controlled loads, etc.)

"There are more papers on electric vehicles than there are electric vehicles out there."

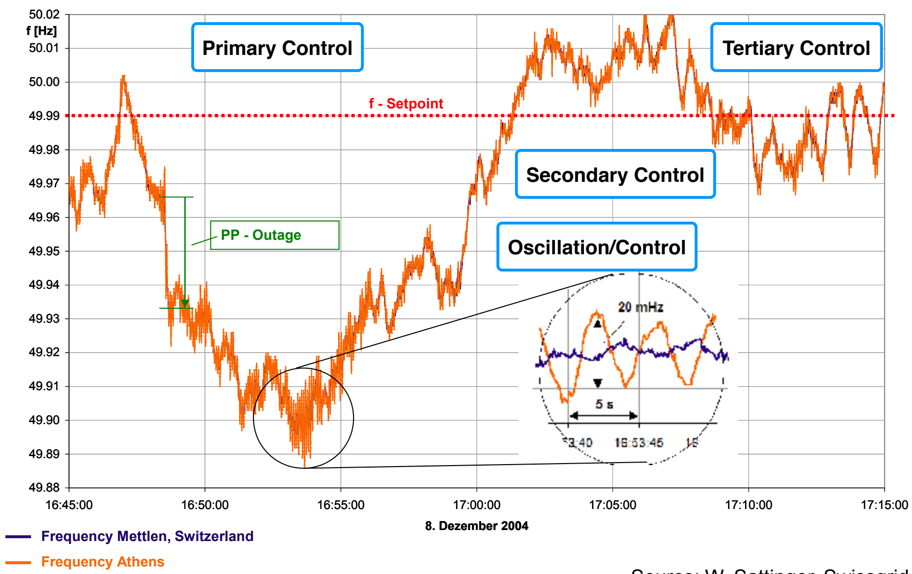
— [Alejandro Garcia-Domingiez, Allerton '15]

Remember? — to be resolved on the last day

the very near future (actually today) holds a new (and very dominant) stability issue



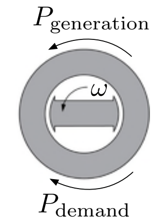
A little summary of almost everything we talked about



Source: W. Sattinger, Swissgrid

System operation centered around synchronous generators

At the beginning was Tesla with the **synchronous machine**:



$$M \frac{d}{dt}\omega(t) = P_{\text{generation}}(t) - P_{\text{demand}}(t)$$

change of kinetic energy = instantaneous power balance

The **AC power grid** has been designed around synchronous machines.

All of **power system operation** has been designed around them as well.

Recently: increasing renewables = retiring synchronous machines

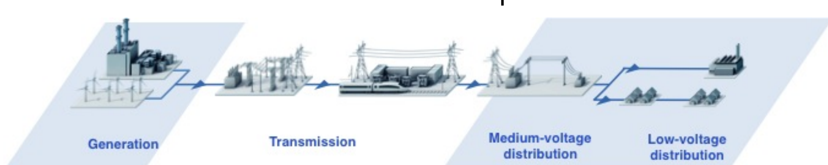
Recall: a few (of many) game changers

synchronous generator

new workhorse

scaling

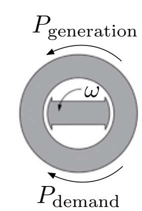
location & distributed implementation



Almost all operational problems can principally be resolved . . . **but one (?)**

Fundamental challenge: operation of low-inertia systems

We slowly loose our giant electromechanical low-pass filter:



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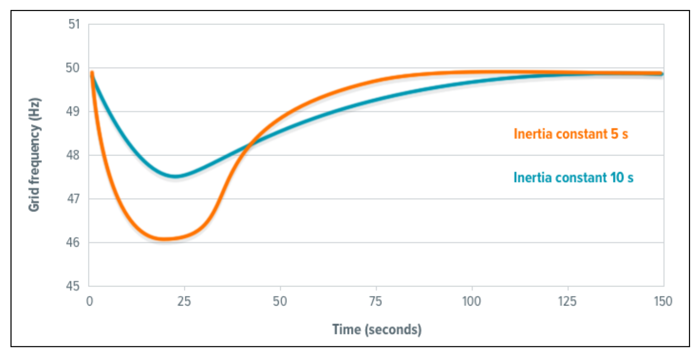
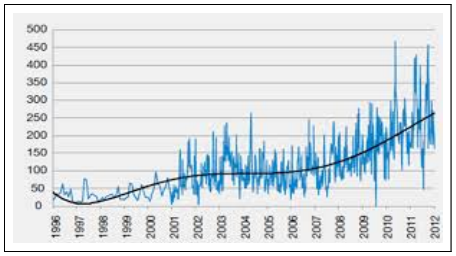
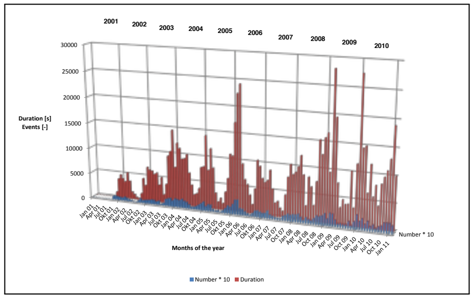


Low-inertia stability = true # 1 problem with renewables



frequency violations in Nordic grid (source: ENTSO-E)

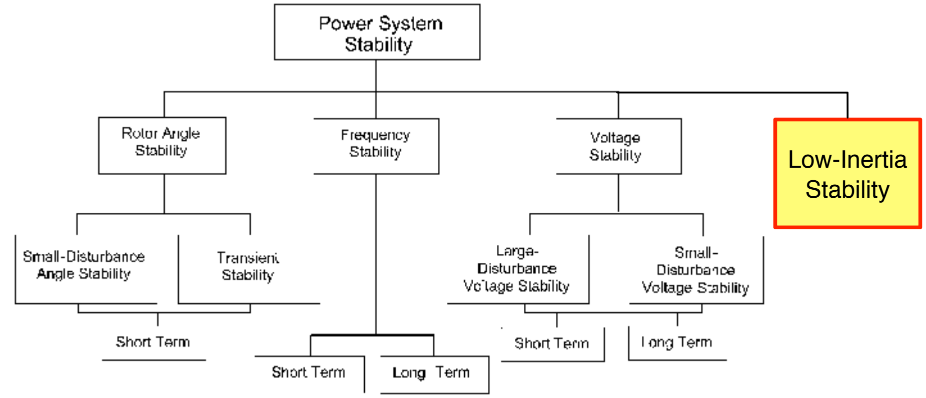


same in Switzerland (source: Swissgrid)

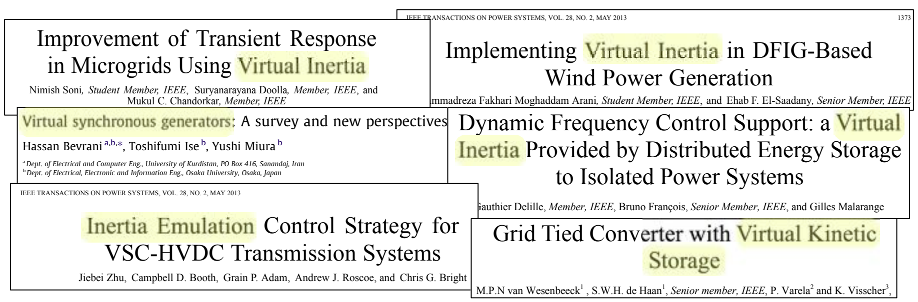
inertia is shrinking, time-varying, & localized, . . . & increasing disturbances

Solutions in sight: none really . . . other than **emulating virtual inertia** through fly-wheels, batteries, super caps, HVDC, demand-response, . . .

Resolution — the dominant future stability issue



Virtual inertia emulation



Improvement of Transient Response in Micrograds Using Virtual Inertia
Nimish Soni, Student Member, IEEE, Suryanarayana Doolla, Member, IEEE, and Mukul C. Chandorkar, Member, IEEE

Implementing Virtual Inertia in DFIG-Based Wind Power Generation
...mmadreza Fakhari Moghaddam Arani, Student Member, IEEE, and Ehab F. El-Saadany, Senior Member, IEEE

Virtual synchronous generators: A survey and new perspectives
Hassan Bevrani, Toshifumi Ise, Yushi Miura

Dynamic Frequency Control Support: a Virtual Inertia Provided by Distributed Energy Storage to Isolated Power Systems
...authier Delille, Member, IEEE, Bruno François, Senior Member, IEEE, and Gilles Malarange

Inertia Emulation Control Strategy for VSC-HVDC Transmission Systems
Jiebei Zhu, Campbell D. Booth, Grain P. Adam, Andrew J. Roscoe, and Chris G. Bright

Grid Tied Converter with Virtual Kinetic Storage
M.P.N van Wesenbeeck, S.W.H. de Haan, Senior member, IEEE, P. Varela and K. Visscher

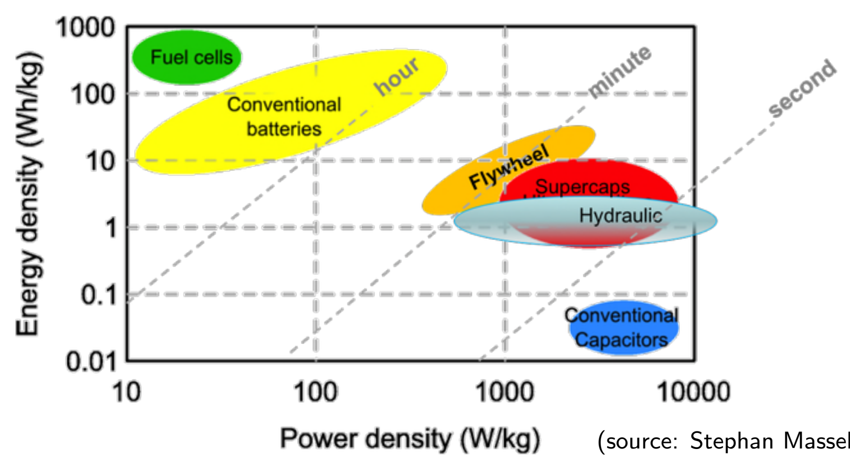
$$M \frac{d}{dt}\omega(t) = P_{\text{generation}}(t) - P_{\text{demand}}(t)$$ . . . essentially **D-control**

☺ decentralized & plug-and-play (passive mechanical loop)

☹ suboptimal, wasteful in control effort, & need for new actuators

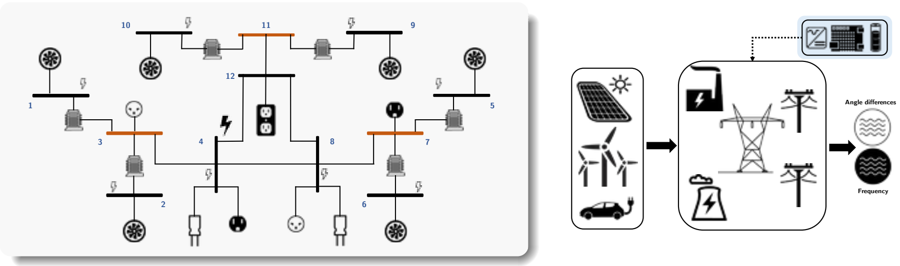
Classification & choice of actuators

Feasibility: what are the key actuators to emulate inertia or other transient control approaches? (how) can this be realized in large?



(source: Stephan Masselis)

It actually matters **where** you emulate inertia!



Optimal Placement of Virtual Inertia in Power Grids

Bala Kameshwar Poolla Saverio Bolognani Florian Dörfler*

January 14, 2016

Abstract

A major transition in the operation of electric power grids is the replacement of bulk generation based on synchronous machines by distributed generation based on low-inertia power electronic sources. The accompanying "loss of ro- ...

synthetic) inertia [4–6] through a variety of devices (ranging from wind turbine control [7] over flywheels to batteries [8]), as well as inertia monitoring schemes [9] and even inertia markets [10]. In this article, we pursue the questions raised in [3] regarding the detrimental effects of spatially hetero-geneous inertia profiles, and how they can be alleviated by

2016

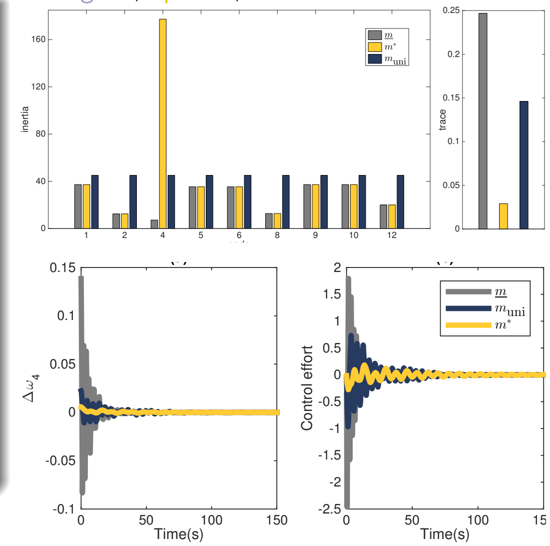
Heuristics outperformed by $\mathcal{H}_2$ - optimal allocation

Scenario: disturbance at #4

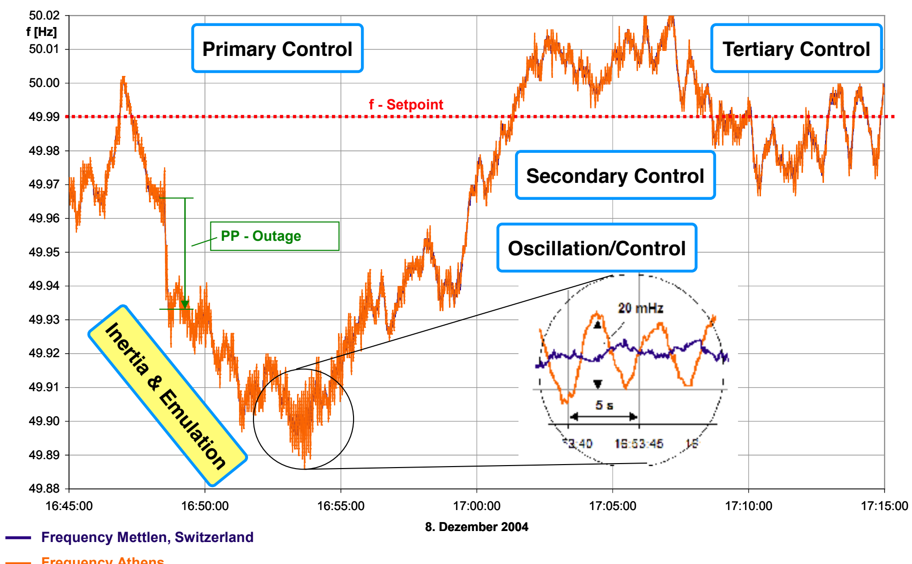
- locally optimal solution **outperforms heuristic** uniform allocation
- optimal allocation ≈ **matches disturbance**
- inertia emulation at all undisturbed nodes is actually **detrimental**

⇒ **location** of disturbance & inertia emulation matters

original, optimal, & uniform inertia cost



An updated summary of almost everything we talked about



Source: W. Sattinger, Swissgrid

A control perspective of almost everything we talked about

Classic power electronics control: **emulate generator physics & control**

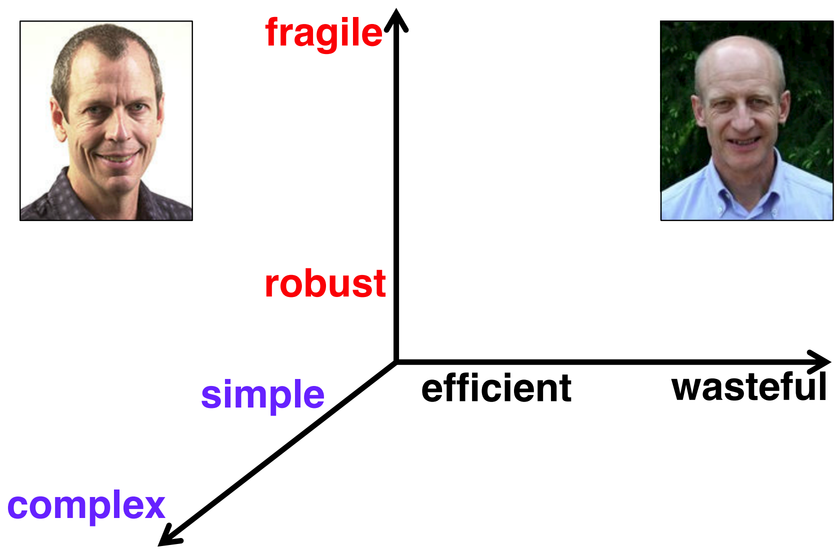
$$\underbrace{M\dot{\omega}(t)}_{\text{(virtual) inertia}} = \underbrace{P_{\text{mech}}}_{\text{tertiary control}} - \underbrace{D\omega(t)}_{\text{primary control}} - \underbrace{\int_0^t \omega(\tau)\,d\tau}_{\text{secondary control}} - P_{\text{elec}}$$

Essentially all **PID + setpoint control** (simple, robust, & scalable)

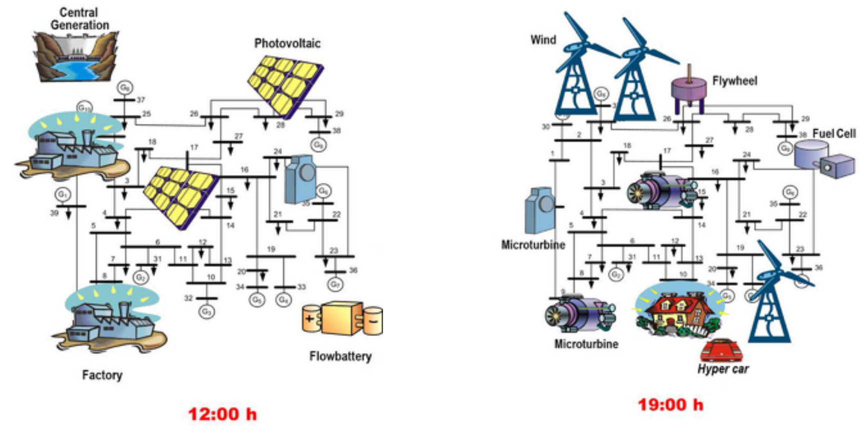
$$\underbrace{M\dot{\omega}(t)}_{\text{D}} = \underbrace{P}_{\text{set-point}} - \underbrace{D\omega(t)}_{\text{P}} - \underbrace{\int_0^t \omega(\tau)\,d\tau}_{\text{I}} - P_{\text{elec}}$$

Control engineers should be able to do better ...

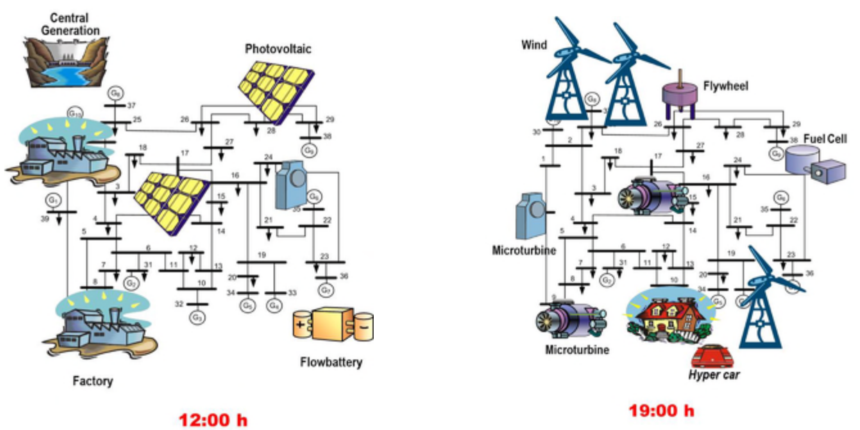
When searching for solutions remember John and Göran



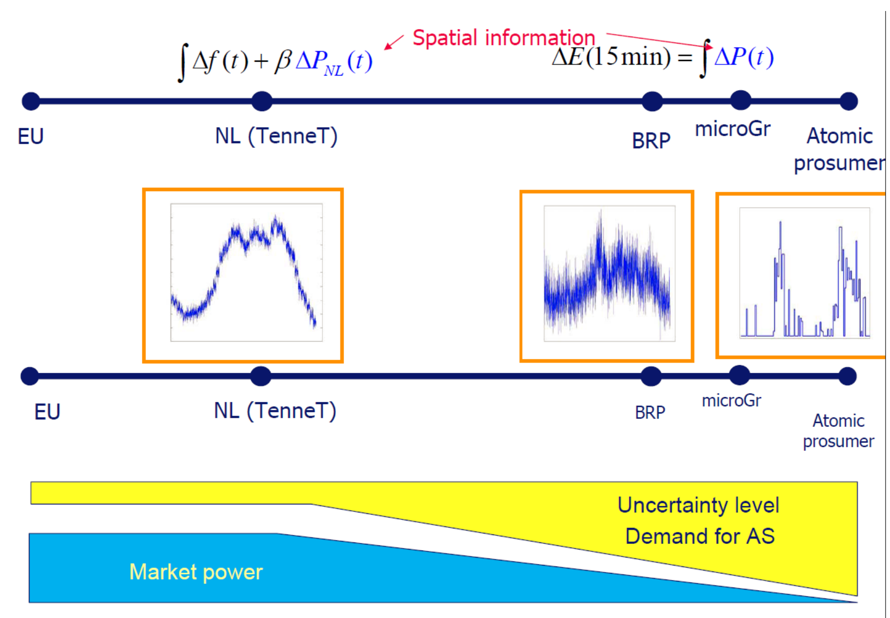
The business case



- Who and how keeps track of system-wide inertia level and its spatial distribution? How to schedule / monitor / bring it "online" / bill?
- Inertia as market commodity? Or obligation? Who buys? Single sided market? Double sided markets for balancing? (Why should I buy a flywheel or install more complex control on my wind turbine?)



- from predictability and **repetitiveness** to uncertainty
- Power flow volatility. Trade-off: spatial resolution versus aggregation of uncertainties. Challenge: Exploit the networking! (old idea, currently often neglected in research). How to manage uncertainity on global (EU) level?



From macroscopic to "atomic" world and back

- There is a benefit from aggregation: BRPs as building blocks on macro-scale with good incentives. Good incentives for atomic end-users?
- Challenge: Economical incentives and built-in feedbacks for "good level of" localisation of "desirable macroscopic properties" (inertia, controllable primary and secondary power). "Good level" $\leftarrow$ exploit the networking by mastering and controlling inherent trade-offs
- Challenge: Solution architecture is crucial ("hidden" and "invisible": local incentives form global behaviour), together with well defined modules as open systems with well defined protocols and distributed information / algorithms.

the end