A brief history of Power Systems Dynamics: from synchronous machines to power electronics

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ACS | Automation of Complex Power Systems
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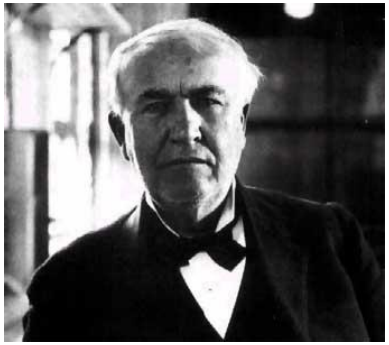
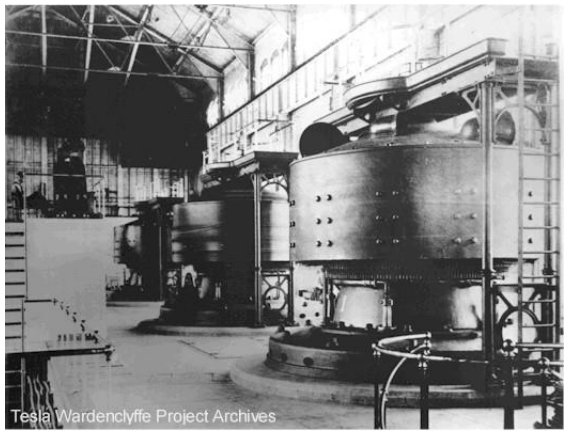
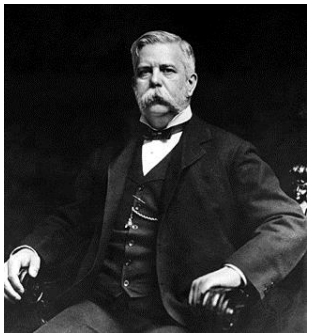
Looking back at the beginning …



Thomas Edison

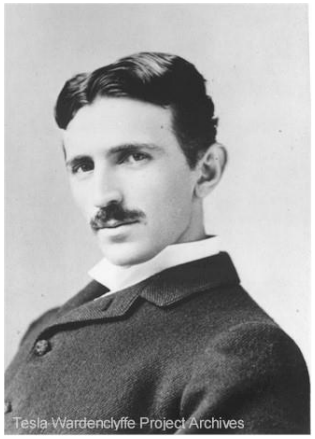


Hydro-electric power plant Niagara



George Westinghouse

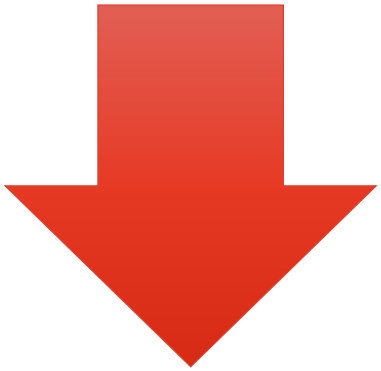
- DC Current:
  - Small Plants
  - Low Voltage
  - Distributed Generation



- AC Current:
  - Big Plants
  - High Voltage
  - Lumped Generation

What we can learn from history

- The main reason AC was selected is because of the transformer. There was no efficient way at the time to convert DC in high voltage and back
- The following focus on thermal power plants pushed for lumped generation characterized by significant rotating masses able to smooth transients
- Reliability brought to design the system as interconnected as possible



We developed the most complex infrastructure built by human beings around the concept of synchronous operation and based on an extremely efficient communication channels: frequency

And now …..

- High Power DC/DC Converters are possible

Source: E.ON ERC RWTH Aachen

- The growth of power electronics driven small power sources is changing the availability of inertia in the grid

Source: www.vt.edu

Is that a problem?

- General Answer is: NO!!! (even if issues are emerging ☺)
- We should interpret the new situation as an opportunity and not as a problem
- Bottom line: we have new degrees of freedom

Frequency as a degree of freedom

Voltage as a degree of freedom

Interconnection as a degree of freedom

Frequency as a degree of freedom

- Two main questions:

Should we stay with AC?

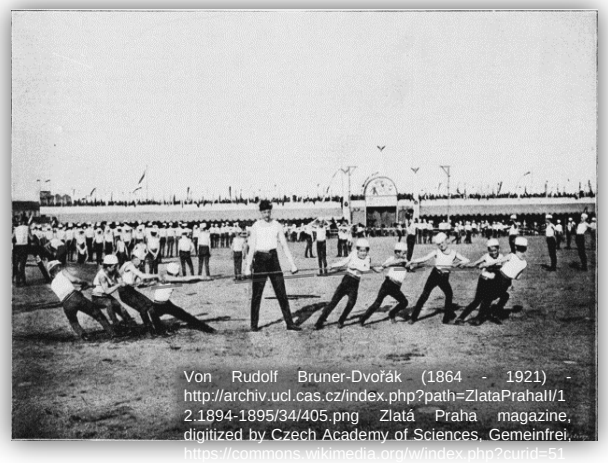
If yes, how do we manage frequency?

Should we stay with AC?
Maybe not …. Why not DC?

AC: Like rope skipping

Deliberate synchronisation required.
Only two can turn, few can jump.
Different height is a problem.

DC: Like tug-o'-war



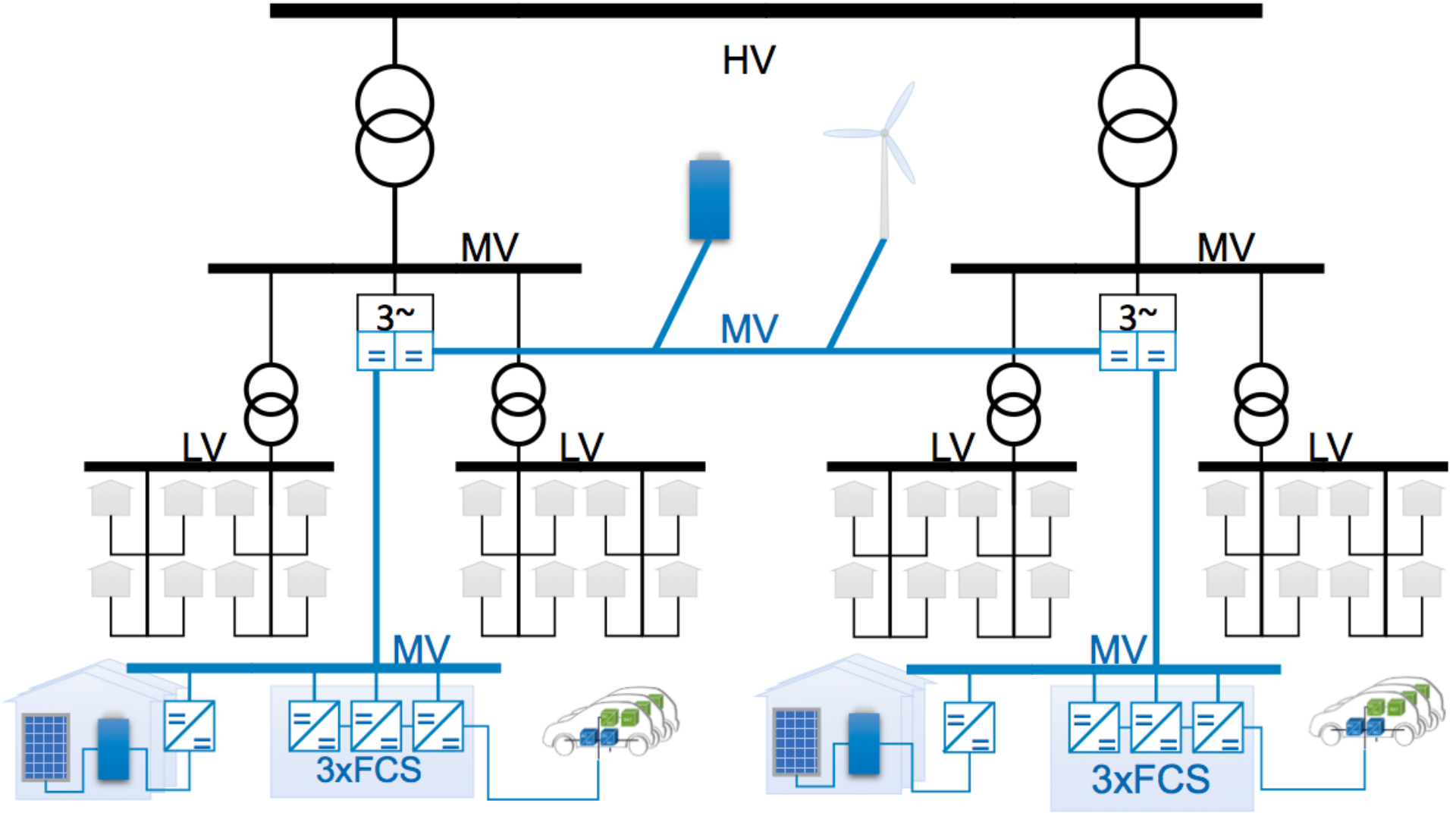
Straight-forward. Simple.
Many can join on either side.
Height doesn't matter.

DC Advantages:

- Better use of material
- Higher efficiency rate
- No reactive power
- No need of synchronous operations

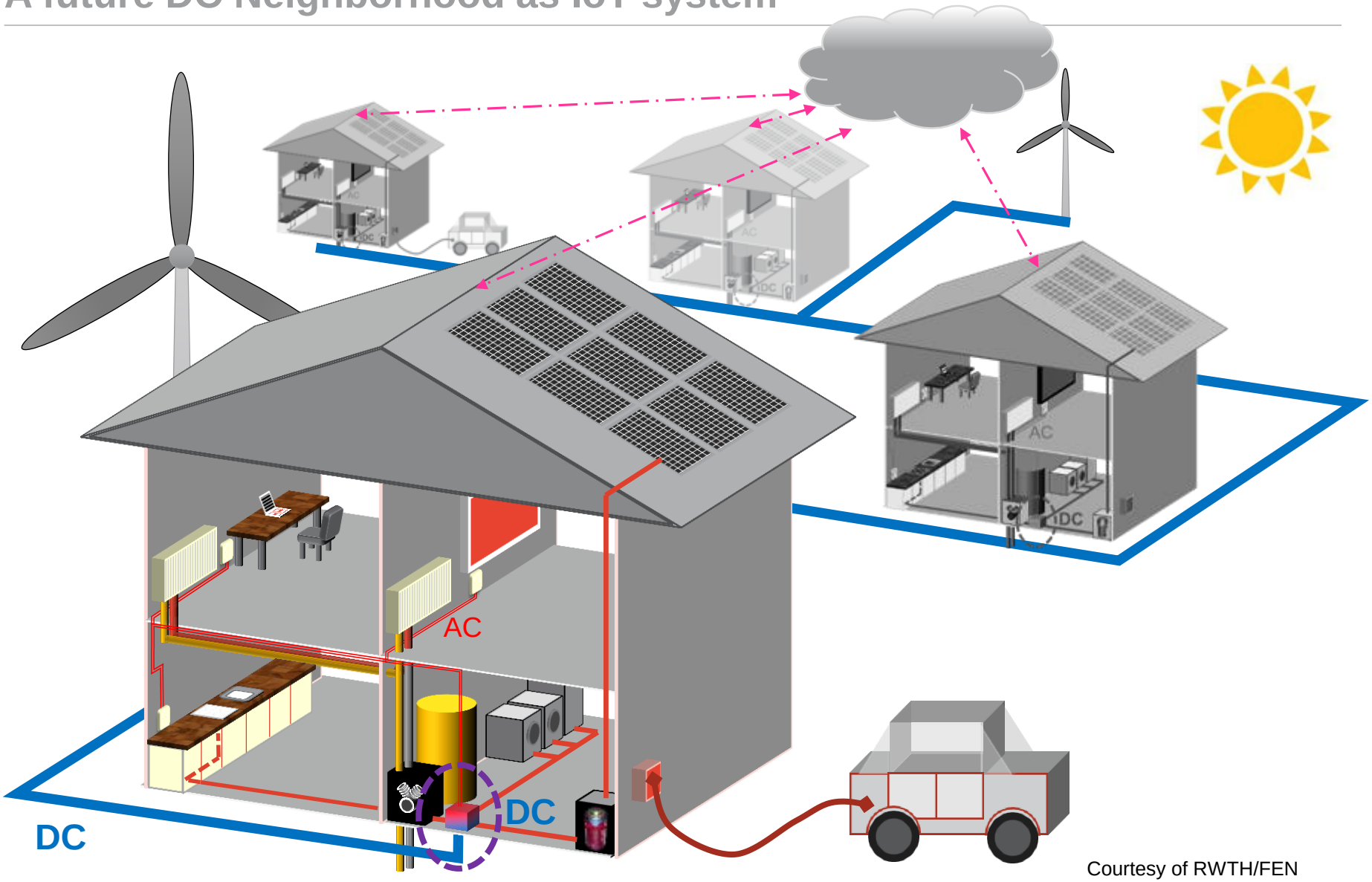
Courtesy of RWTH/FEN

A transition process is possible



Courtesy of RWTH/FEN

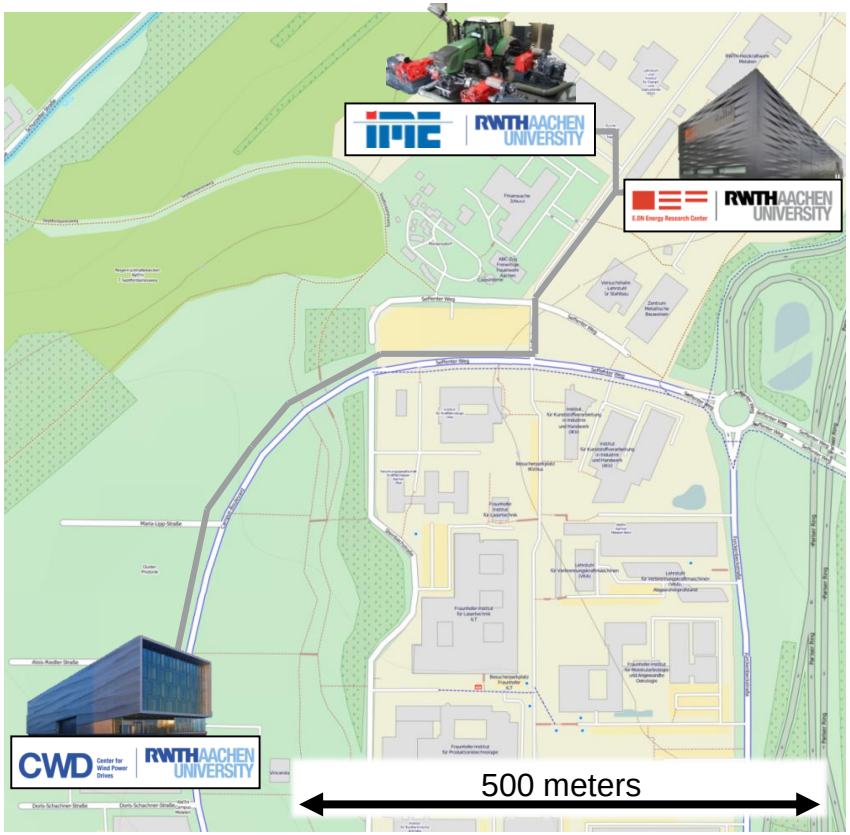
A future DC Neighborhood as IoT system



Courtesy of RWTH/FEN

Exploring the idea in real life
RWTH Campus Grid in MVDC

Flexible Electrical Networks



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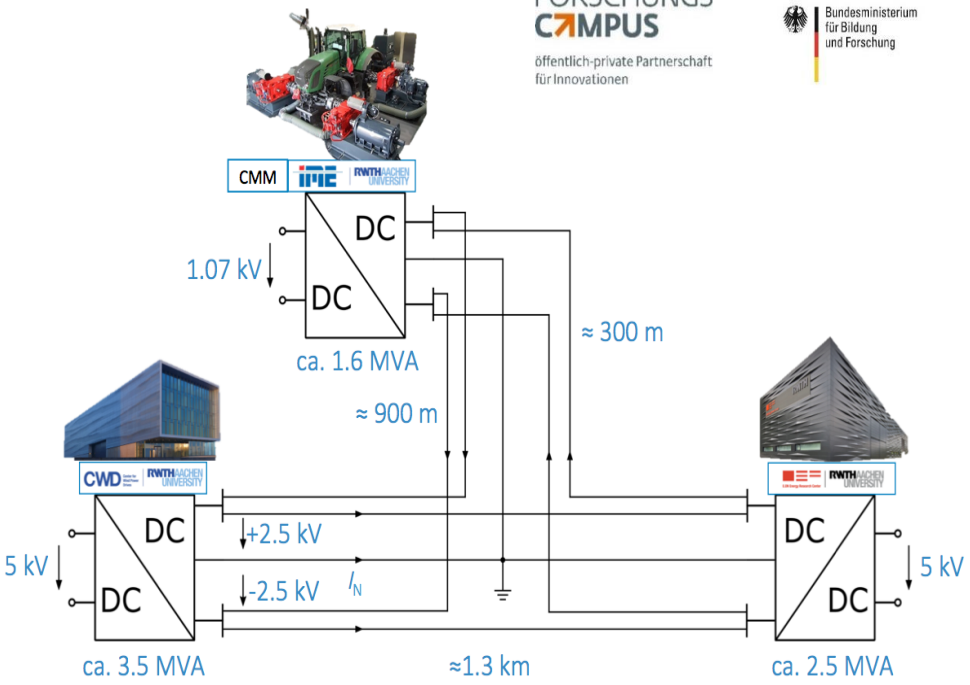


And if yes … how do we manage the frequency?

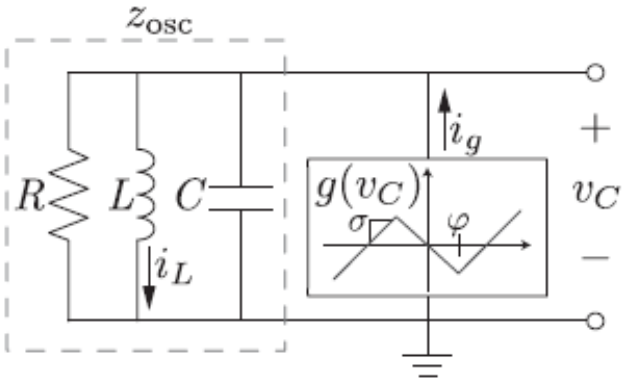
- Two options:

Self Synchronous Networks

Virtual Inertia

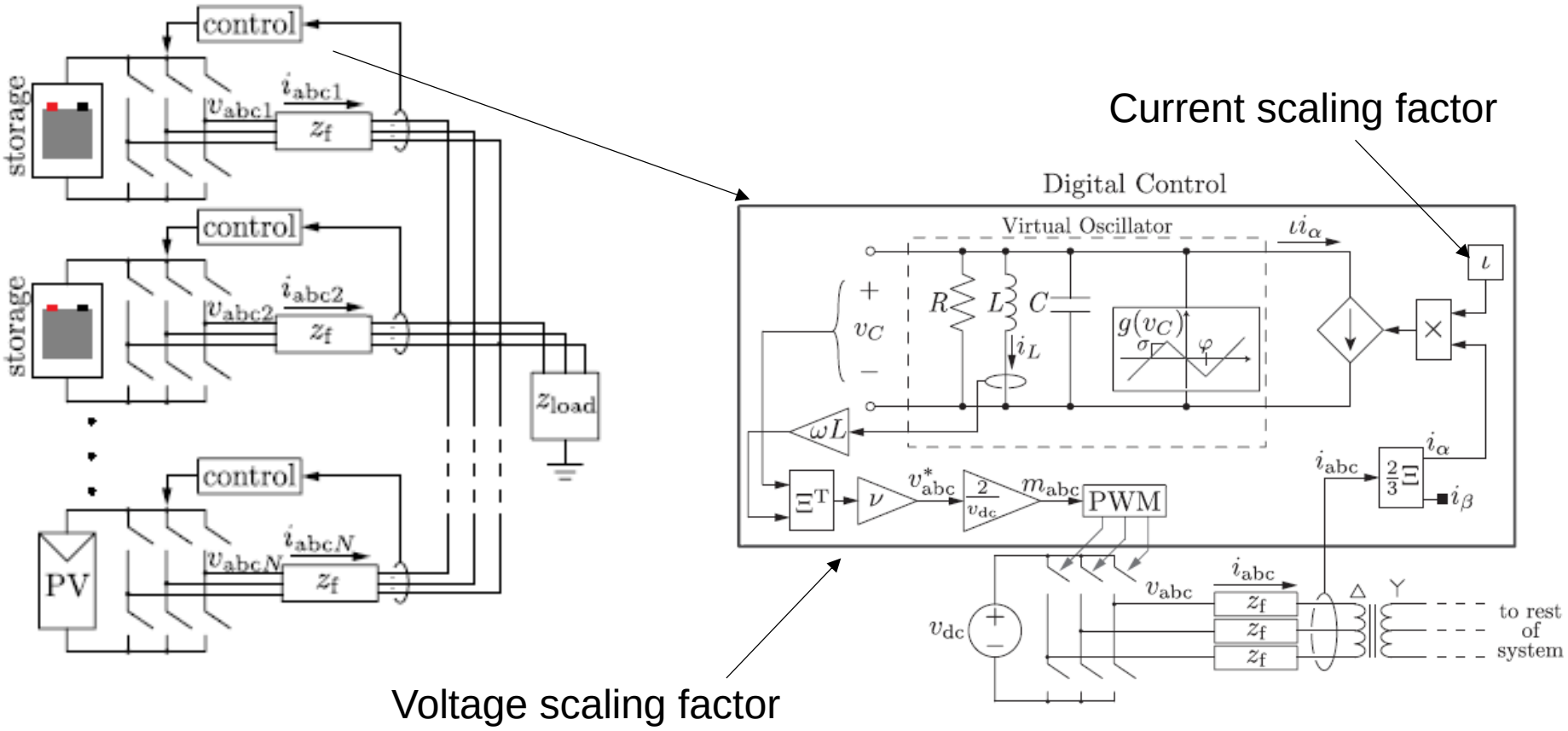
Self synchronous networks: Virtual Oscillator Control

- VOC is based on Based on fundamental of Dead Zone Oscillator in which energy is fed into small oscillations and removed from large oscillations.
- Advantages
  - VOC is a time-domain approach that enables interconnected inverters to stabilize arbitrary initial conditions to a synchronized sinusoidal limit cycle
  - VOC does not require computation of active and reactive power output, PID controller and PLL technique
  - VOC does not require explicit frequency and voltage amplitude command for the inverter output.



B. B. Johnson, S. V. Dhople, J. L. Cale, A. O. Hamadeh and P. T. Krein, "Oscillator-Based Inverter Control for Islanded Three-Phase Microgrids," in *IEEE Journal of Photovoltaics*, vol. 4, no. 1, pp. 387-395, Jan. 2014.

Interconnecting inverters through VOC



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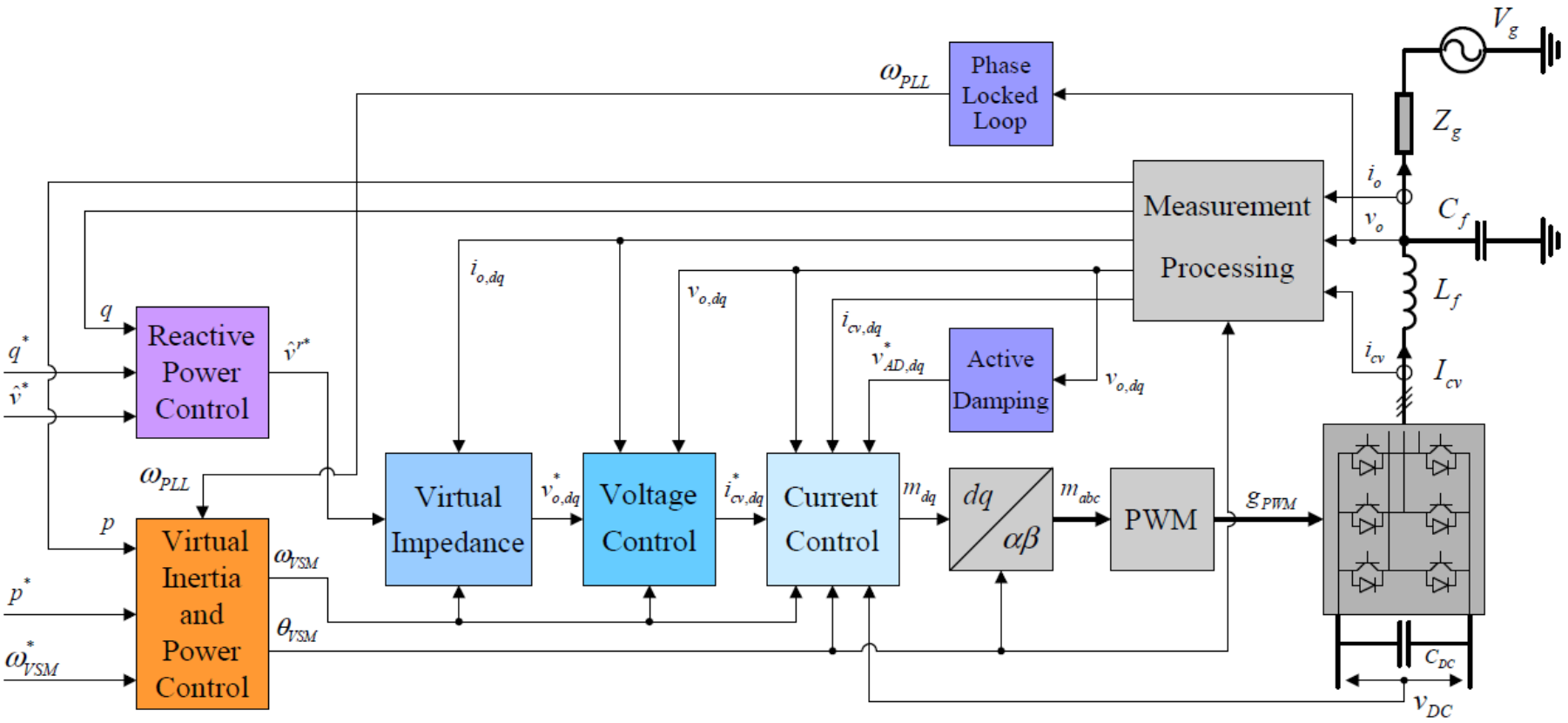
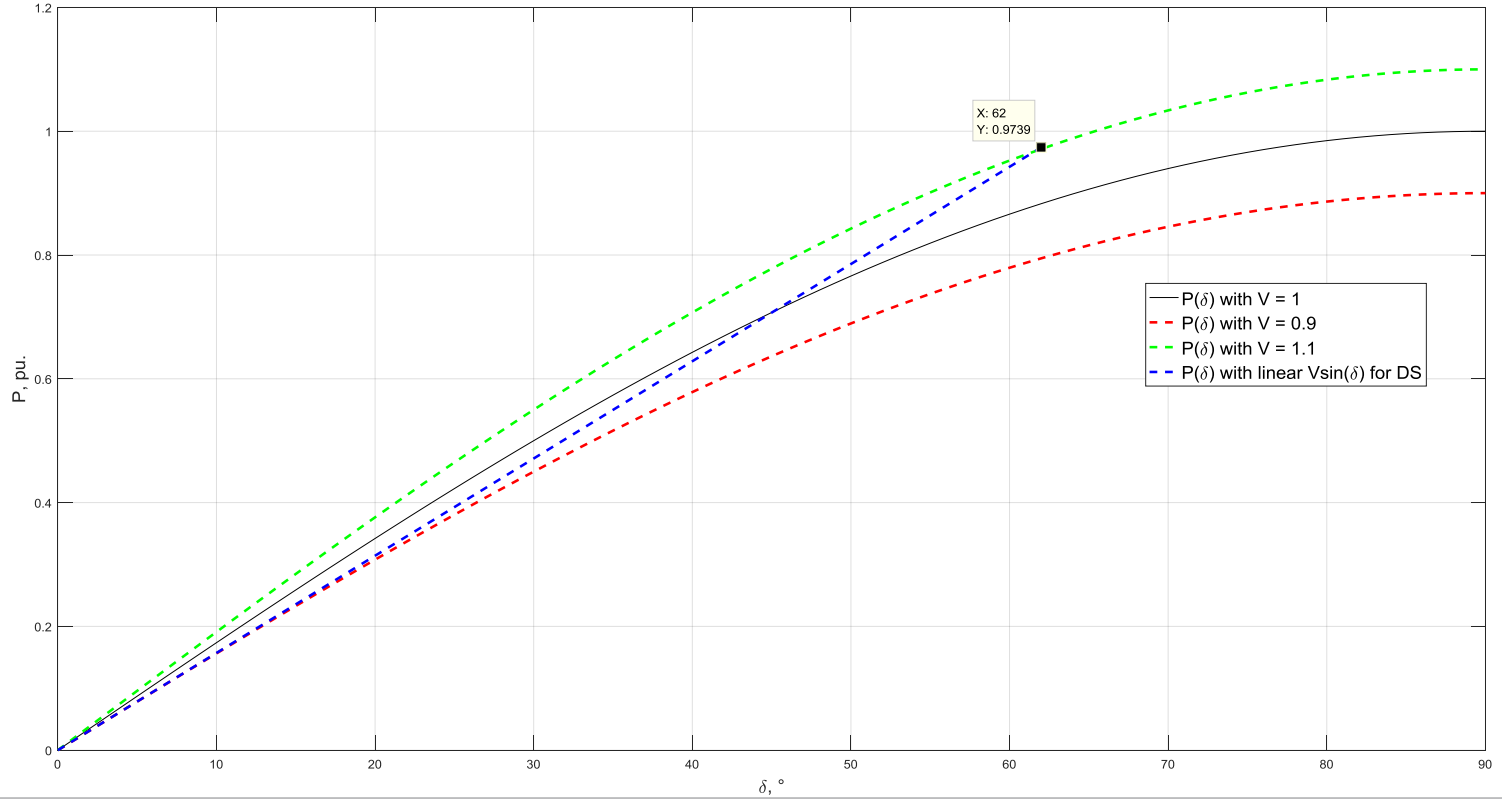
Virtual Inertia



S. D'Arco, J. A. Suul and O. B. Fosso, "Small-signal modelling and parametric sensitivity of a Virtual Synchronous Machine," *2014 Power Systems Computation Conference*, Wroclaw, 2014, pp. 1-9.

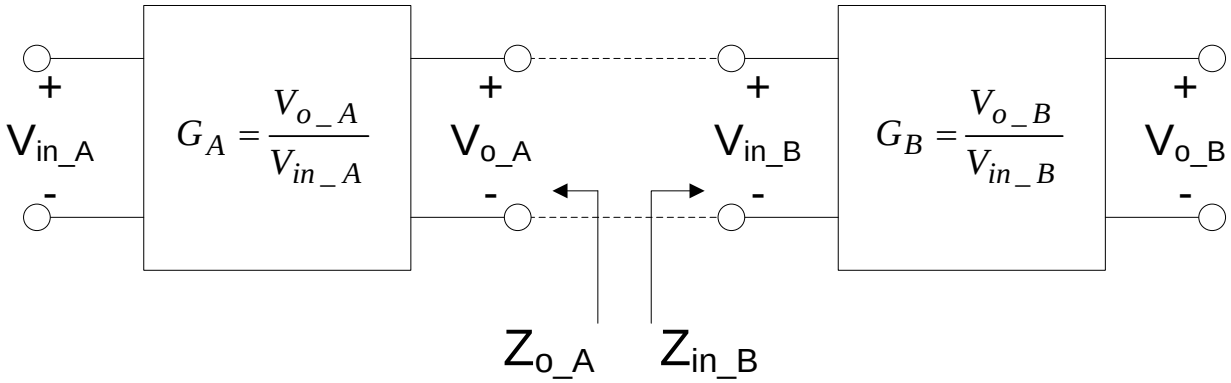
Beyond Virtual Synchronous Machine

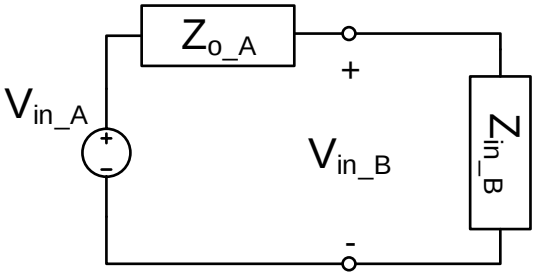
- Why should we define the system based on legacy solutions?
- Dynamics are actually a degree of freedom and should be defined in support of system level requirements
- Overall behavior could be defined to simplify the system level view (Linear Swing Dynamics)



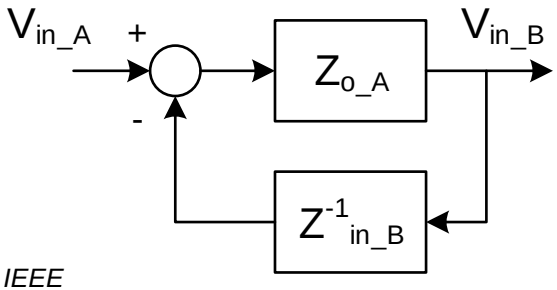
Voltage as a degree of freedom

- On one hand with power electronics voltage stability becomes a problem over a wide range of frequencies and not a 50Hz question
- On the other hand with power electronics is possible to create virtual impedances able to shape the frequency domain response



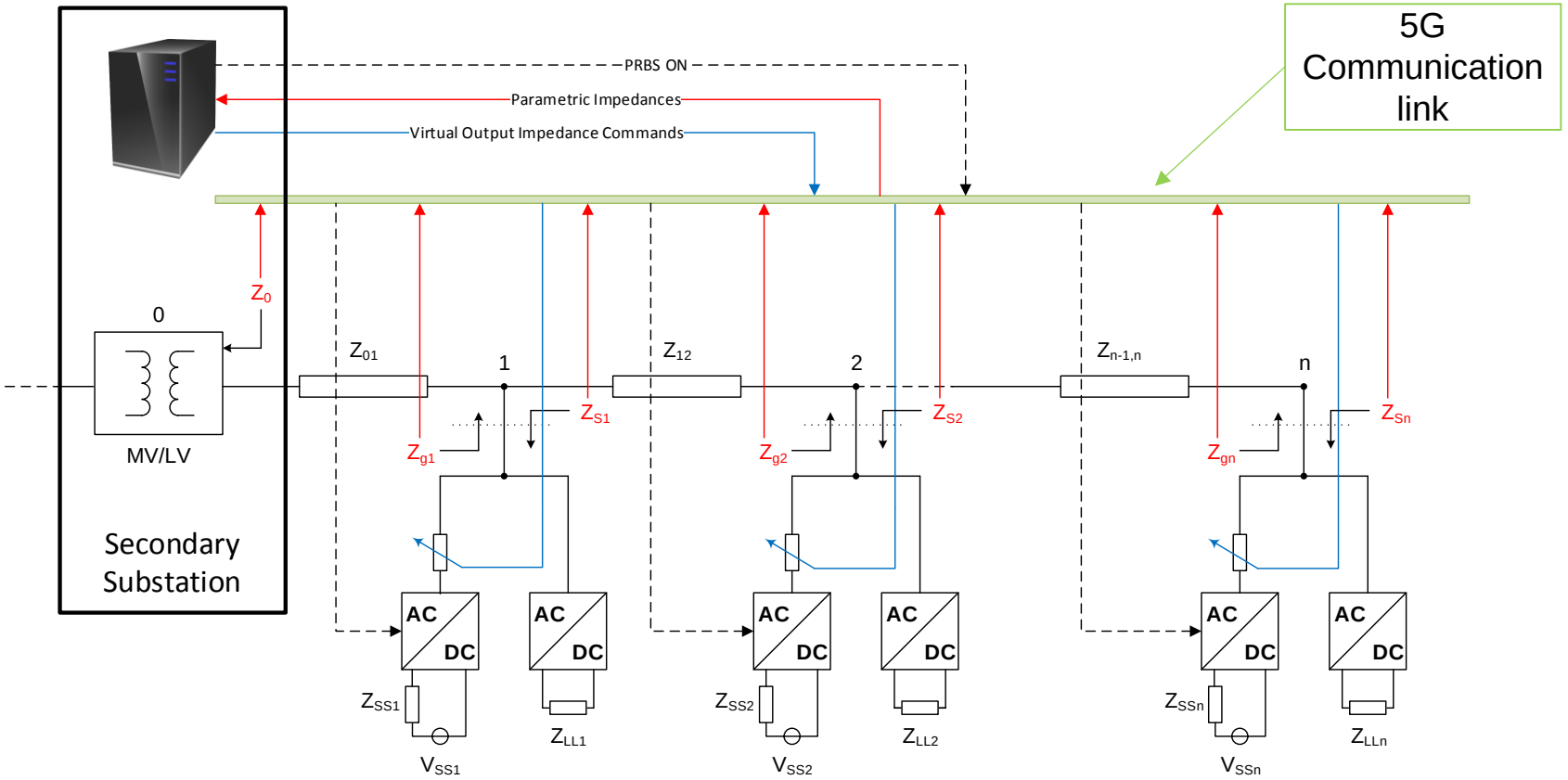


$$G_{AB} = G_A G_B \cdot \frac{Z_{in\_B}}{Z_{in\_B} + Z_{o\_A}} = \frac{G_A G_B}{1 + T_{MLG}} \quad \text{where} \quad T_{MLG} = \frac{Z_{o\_A}}{Z_{in\_B}}$$

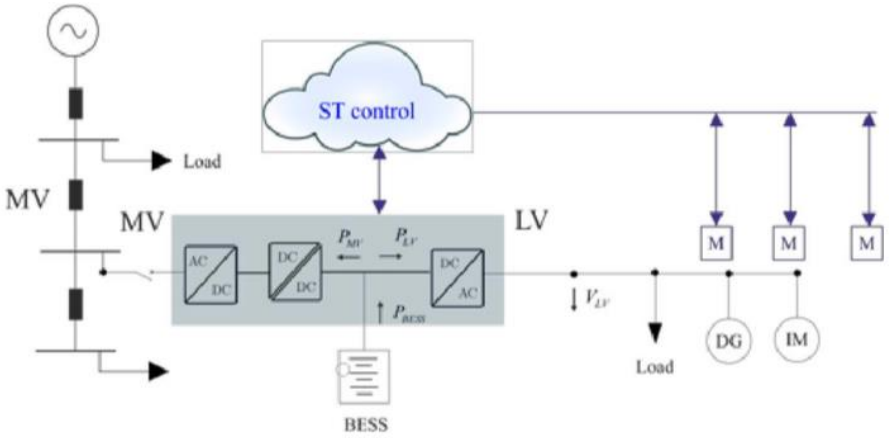


A. Riccobono and E. Santi, "Comprehensive Review of Stability Criteria for DC Power Distribution Systems," in *IEEE Transactions on Industry Applications*, vol. 50, no. 5, pp. 3525-3535, Sept.-Oct. 2014

- Review impedance concept to span over a large frequency region
- Control shapes the impedances and not only passive components
- On-line estimation of the frequency response as a key tool to ensure stability of operation



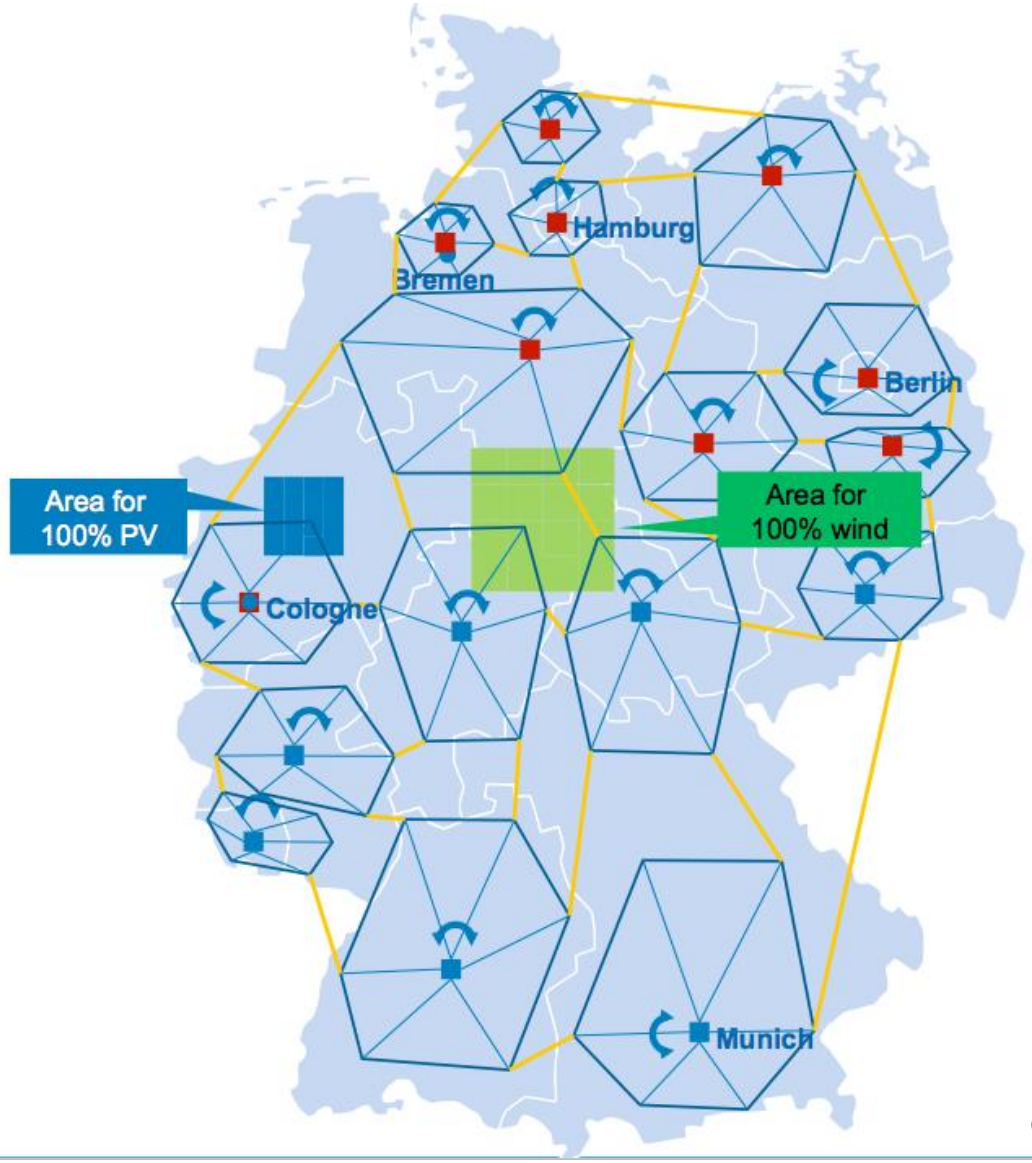
Interconnections as a degree of freedom: Smart Transformers



- Grids do not need to be fully interconnected
- Frequency deviations are possible
- Portions of a grid can act a unit offering services to the rest of the system
- Power does not flow “freely” among the different levels of the power systems

F. Sossan, K. Christakou, M. Paolone, X. Gao and M. Liserre, "Enhancing the provision of ancillary services from storage systems using smart transformer and smart meters," *2017 IEEE 26th International Symposium on Industrial Electronics (ISIE)*, Edinburgh, United Kingdom, 2017, pp. 1715-1720.

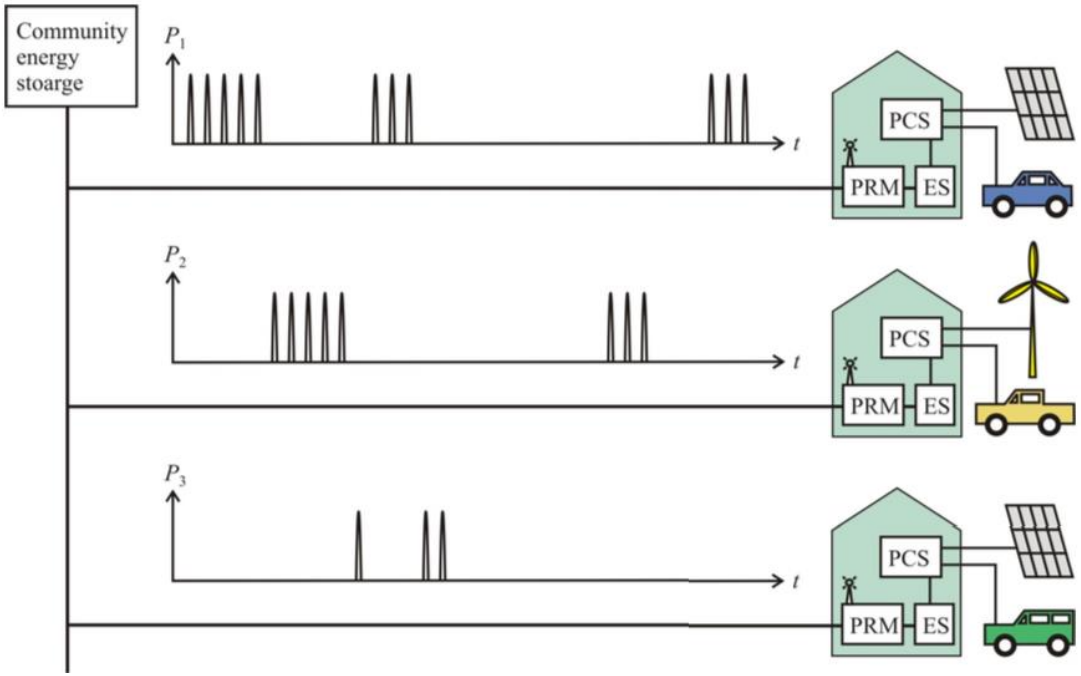
Germany as a bottom-up grid



Courtesy of RWTH/FEN

Internet of Energy or Energy Internet?

- Those terms are today overused: the real meaning is not always clear
- We can go from the simple interpretation: using internet technology to support energy system operation …..
- ..... To a more complex physical interpretation of using internet technology directly in the energy flow (Energy Packets)



K. A. Corzine, "Energy packets enabling the energy internet," *2014 Clemson University Power Systems Conference*, Clemson, SC, 2014, pp. 1-5.

Come on … there must be also some problems!!

- Interconnection of infrastructures and corresponding consequences in reliability
- Cybersecurity
- A solid approach to Cyberphysical system design that can support power system design
- Over-simplifications used in the design of power electronics (e.g. linearity)
- New testing procedures to de-risk the technologies without risking the infrastructure

Conclusions

- Power Electronics is completely transforming the options around which power systems should be designed
- Future system will have a higher level of flexibility
- It is time to rethink main theoretical preconditions in the new context

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