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On some research/practical challenges in future power systems

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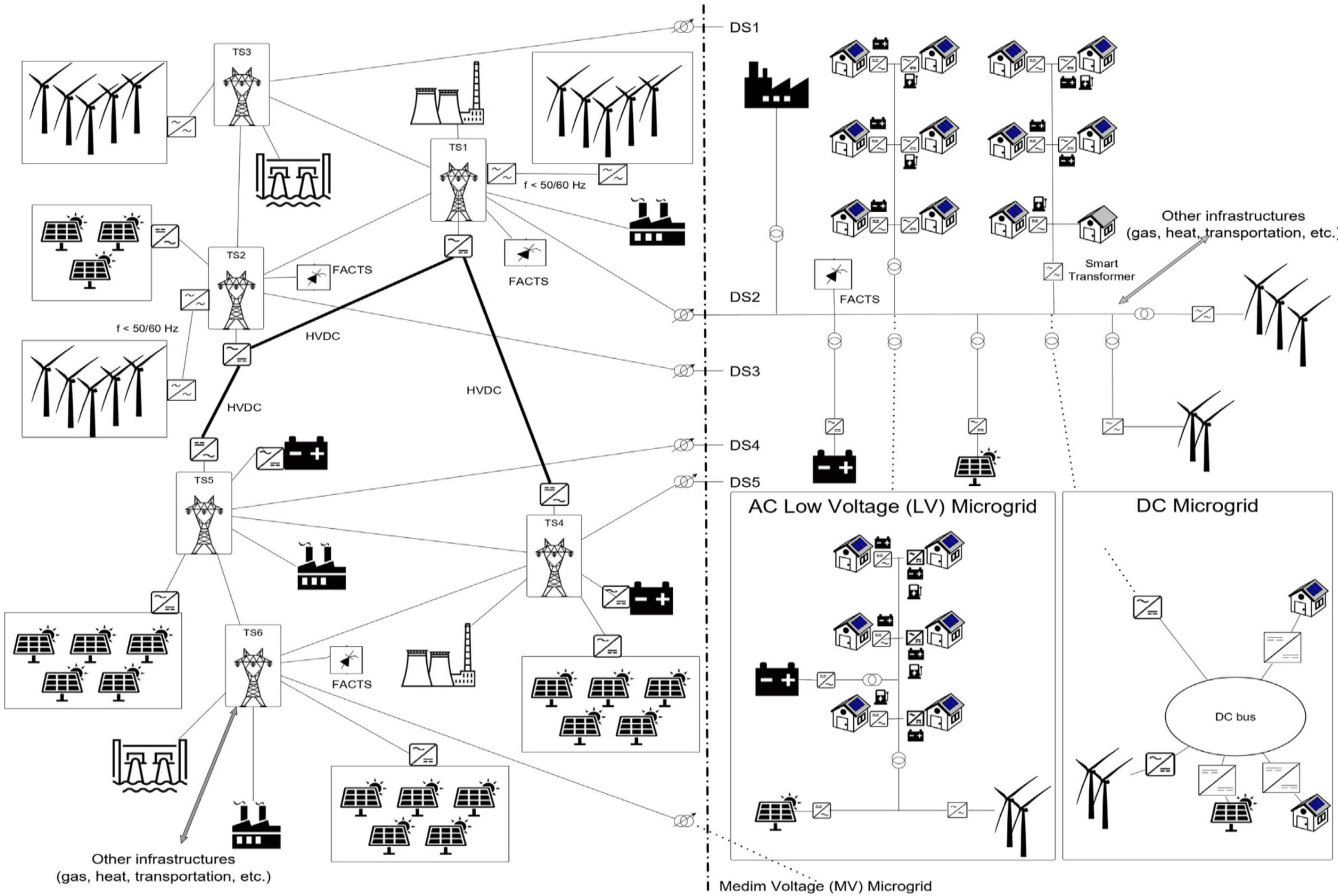
Outline of the presentation

- Structure of future power systems.
- Characteristics of future power systems.
- Power system stability: basics and future challenges.
- Cyber-Physical Power System of the future.
- Power system security: basics and future challenges.
- Operation in an information rich environment: opportunities and challenges.
- Operation with increased uncertainties.
- On the use of AI in power systems.

Structure of future power systems



Picture taken from: M. Glavic, S. Greene:"Voltage stability in future power systems, Elsevier Encyclopedia, 2023.

Characteristics of future power systems

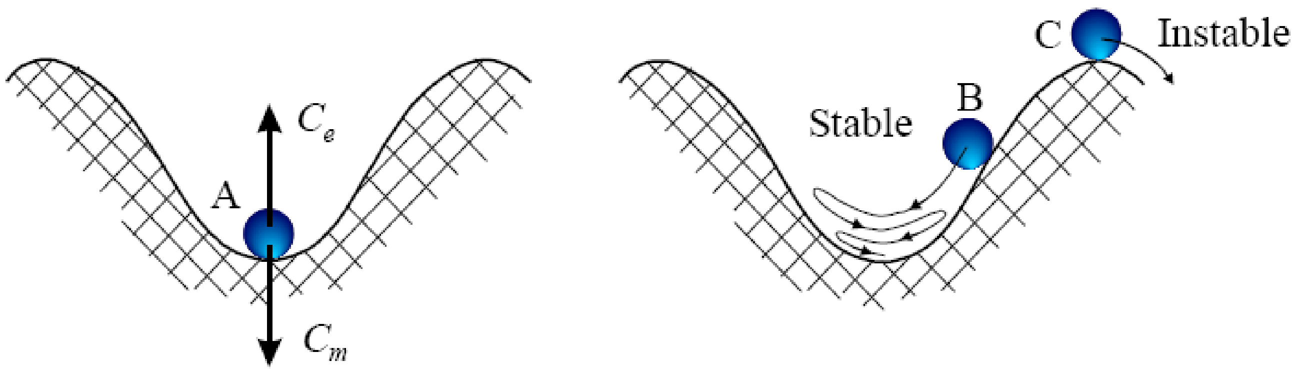
- Massive integration of RES.
- New types of loads.
- Operation with increased uncertainties.
- Deployment of power electronics (HVDC, FACTS, PE Converters,…).
- Integration of power systems with other infrastructures (transportation, heat, water, gas).
- Emergence of new entities (microgrids, energy communities,…).
- Deployment of small-scale devices (so-called edge-devices)

Power system stability - 1

Future power systems: cyber-physical systems:

- **cyber: communications, computation devices, etc.**
- **physical: electro-magnetic-mechanical**

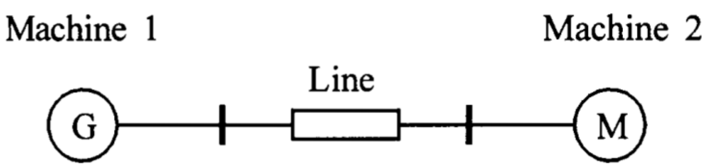
What is system stability: a simple example from classical mechanics

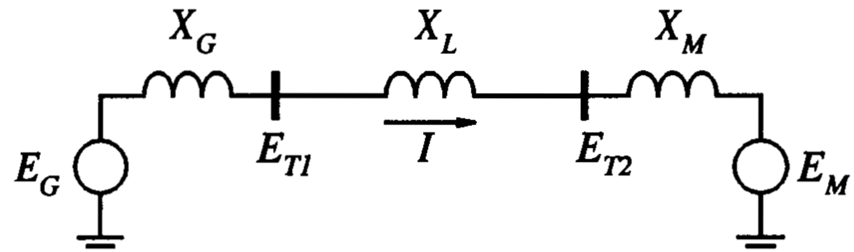


Picture taken from Handbook of Electrical Power System Dynamics: Modeling, Stability, and Control, IEEE-Wiley, 2013.

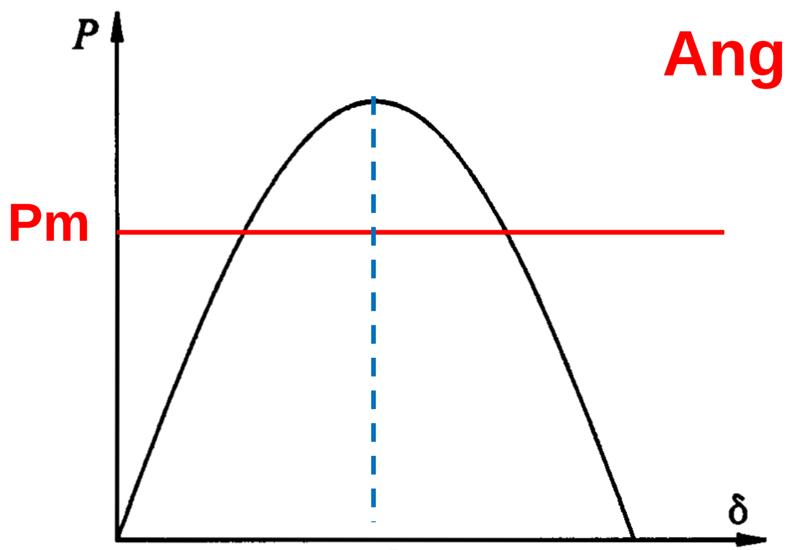
Power system stability - 2

physical: electro-magnetic-mechanical

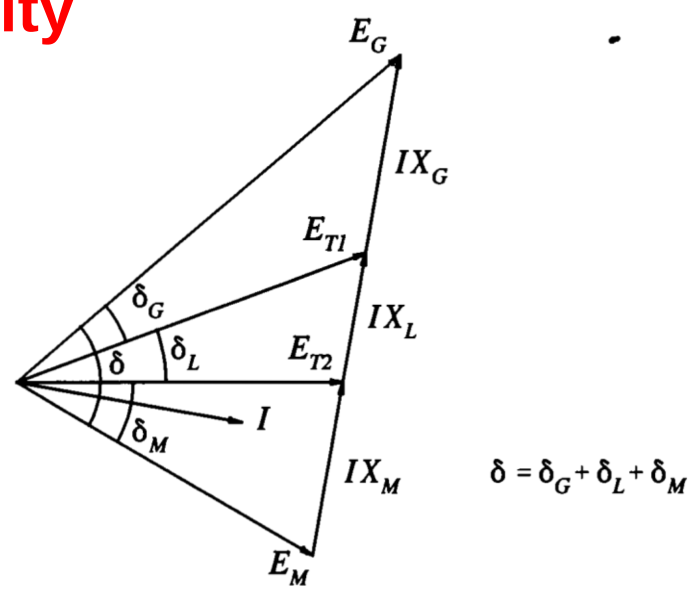




Angle stability

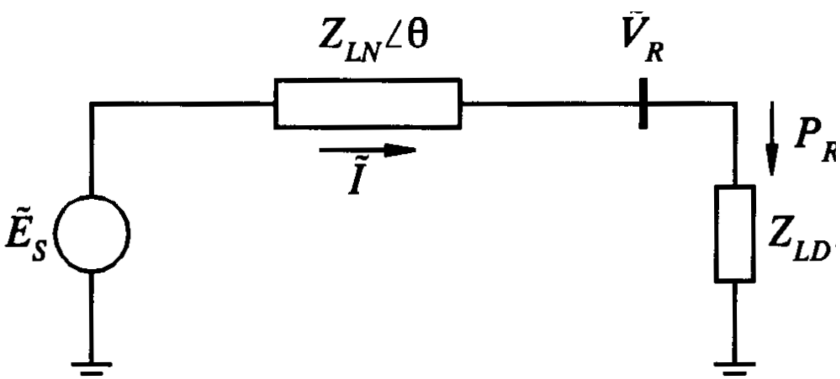


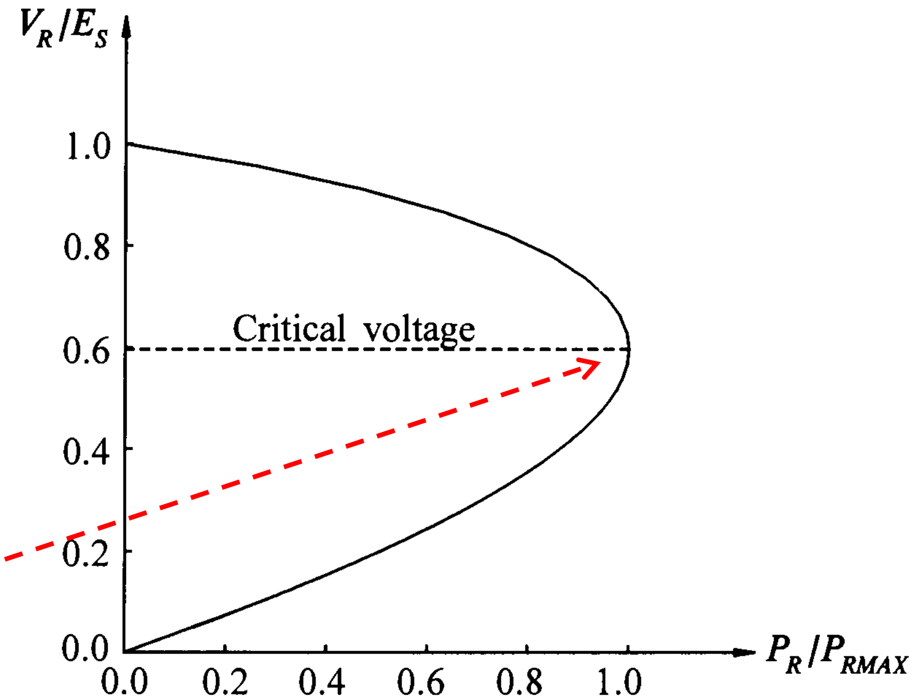
90 deg.



Source: P. Kundur: “Power System Stability and Control, IEEE-Wiley, 1994.

Power system stability - 3





$Z_{LN}/Z_{LD}=1$

Frequency is normal (50 Hz)

Voltage stability

Source: P. Kundur: “Power System Stability and Control, IEEE-Wiley, 1994.

Power system stability – Defin. and manifest.

Power system stability is a single problem:

“is the property of a power system which enables it to remain in a state of equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after a disturbance”

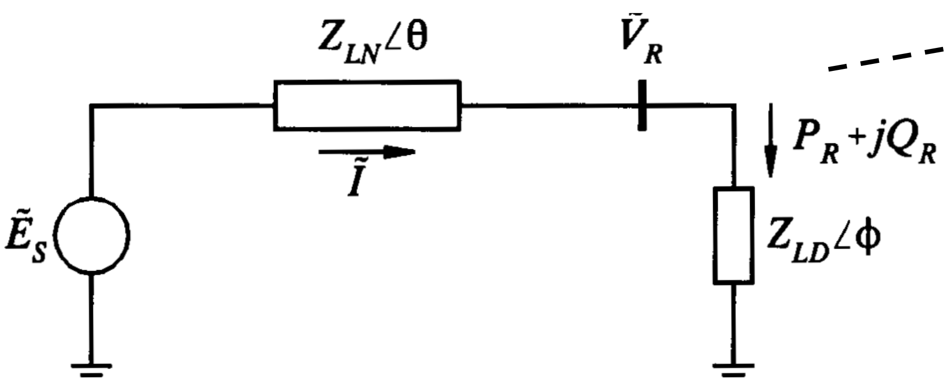
Power system instability manifests as:

- Angle (small-signal, transient),
- Voltage (very short-term, short-term, long term, static),
- Frequency (long-term).

Power system stability – new challenges1

Is there clear distinction between different instability manifestations: NO, and this problem is going to be more pronounced in future power systems

Impedance-based stability assessment (from power electronics):



$$Z_{LN}/Z_{LD} = 1$$

$Z_{LN}(s)/Z_{LD}(s)=1$

Nyquist stability criterion

Power system stability – new challenges2

New problems:

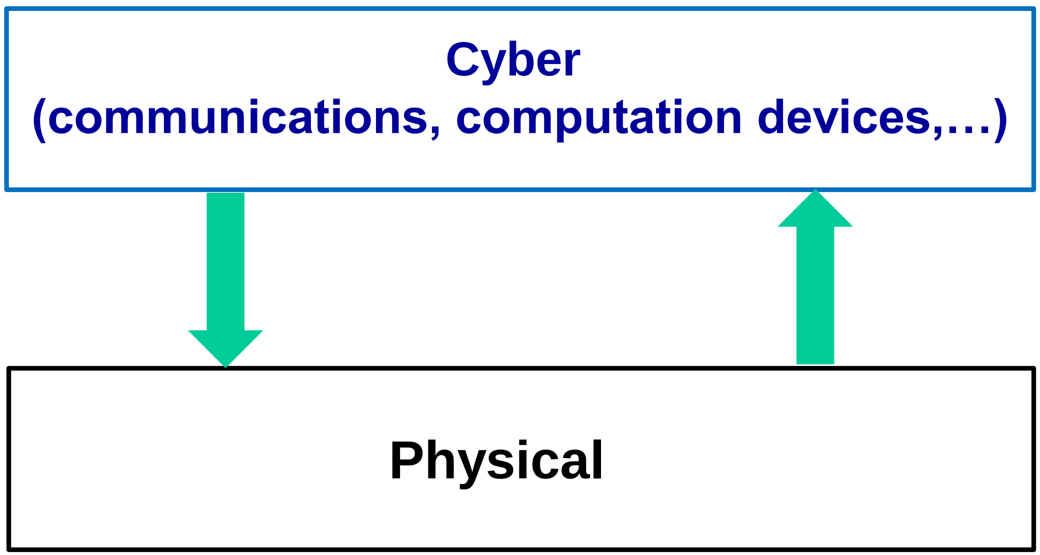
- **Converter driven instability (very fast),**
- **Over-voltages (particularly in transmission networks),**
- **….**

Better synergy between power system and power electronics is absolutely needed There are some efforts but not sensible improvement so far).

Use of combined electro-magnetic transient (EMT) and "classical" phasor simulations.

Cyber-physical power system

cyber-electro-magnetic-mechanical



Ways to deal with:
- co-simulation,
- digital twins.

A serious challenge:
- system security

A new type of disturbance for power system:
- cyber-attacks

Cyber-physical power system: security1

What is power system security:

"ability of a power system to withstand any disturbance from a pre-defined set (credible contingencies or contingencies with a reasonable probability of occurrence)".

Physical power system security:

- **static (N-1, N-2,…)**
- **dynamic (using simulations).**

Power system security control:
- preventive,
- corrective.

A viable solution for control
(security-constrained optimal power flow):
Min F(X)
s.t.
Power flow equations (for each credible contingency)

A challenge:

- **how to deal with cyber-attacks?**

Cyber-physical power system: security2

A pragmatic opportunity:

- **continue to use "classical" physical power system security assessment,**
- **treat cyber-attacks as the new set of contingencies (to complement physical ones) and follow the logic of physical credible contingencies.**

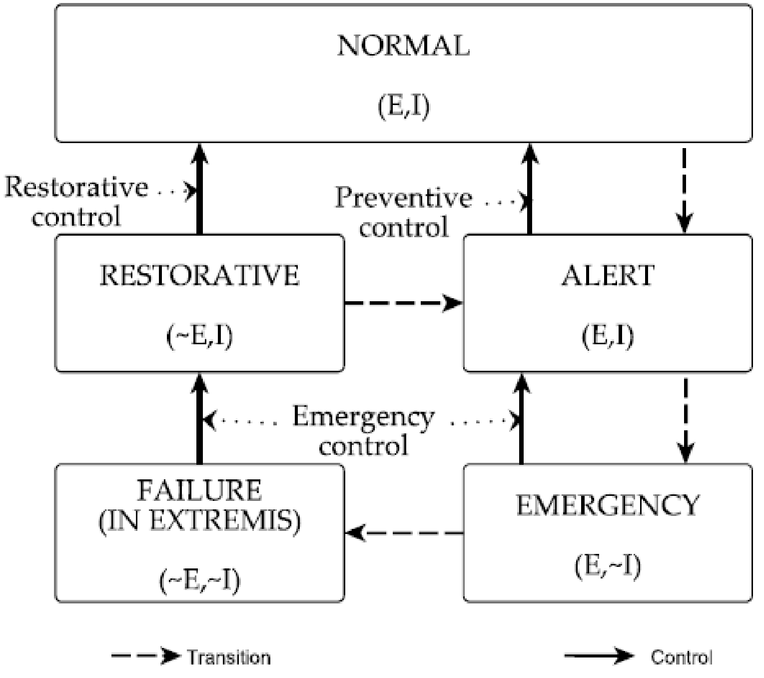
How to create a credible cyber contingencies:

- **probability of occurrence,**
- **easiness to realize,**
- **finally: explore impact on physical system.**

An alternative:

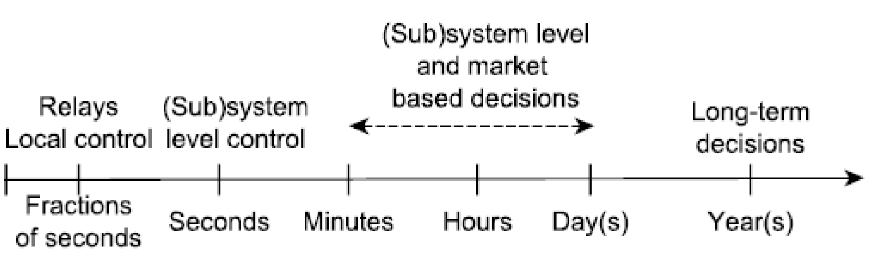
- **use co-simulation or digital twins.**

Stability, security and more…



Power system operating states

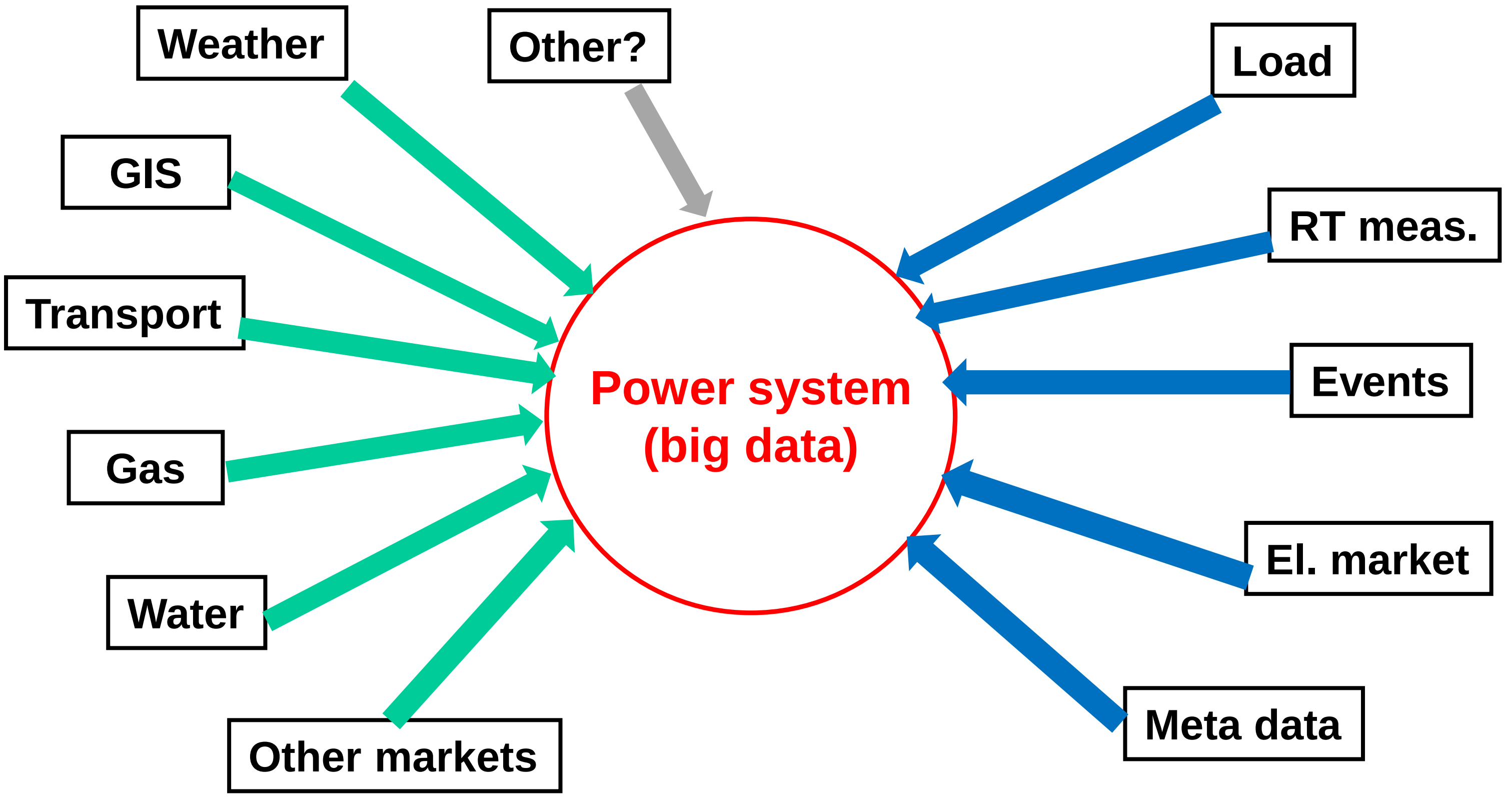
Recall your OPF lecture:
- **E (equality constraints)**
- **I (inequality constraints)**



Stability might be a concerns in security (but not always)

Source: M. Glavic et al., IFAC World Congress, 2017.

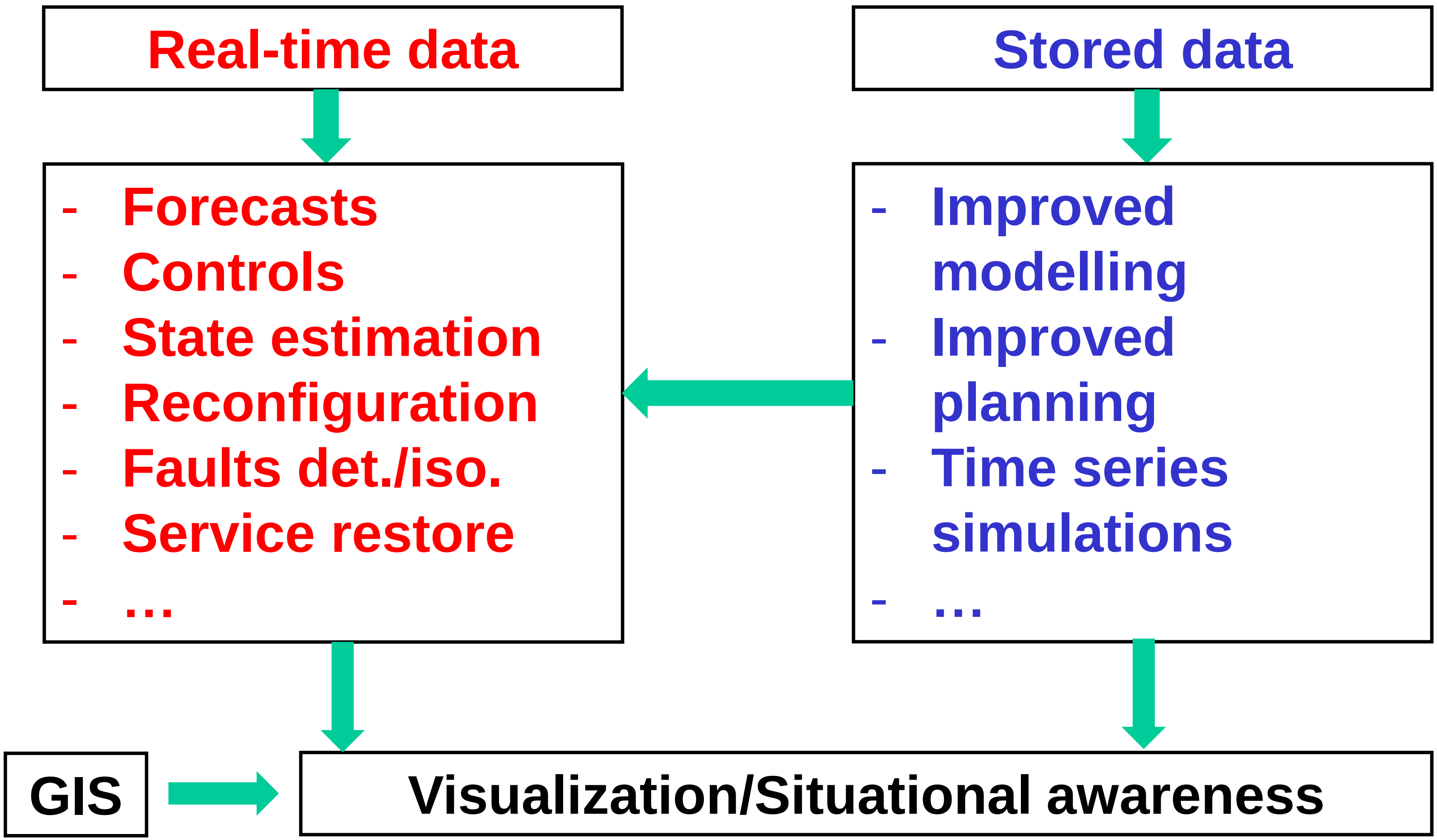
Information rich environment-1



Form other domains

Form power system

Information rich environment-2



Information rich environment: real-time (some)
NOTE: No unique terminology

Data-driven operation and control:

- Predictive controls,
- Update inputs/model parameters,…

Data assimilation:

- Use the data as they come and at the rate they come (the idea is from meteorology),
- Improved state estimation and awareness,…

Context-aware control:

- Desing the controls that act differently in different situations (contexts),
- AI, fault-tolerant control, reconfigurable control,….

Uncertainties!

Sources of uncertainties:

Models	Measurements	Simulations
- Uncertain parameters - Initial/boundary conditions - Model simplifications	- Limited accuracy or resolution od sensors - Limited or incomplete data	- Hardware failures - Round off - Coding errors

Types of uncertainties:

- Aleatoric (Statistical, Stochastic or Irreducible): parameters, measurements,… (usually handled in a probabilistic framework)
- Epistemic (Systemic): modelling errors.

Uncertainty quantification

- "relates to the identification, quantification, and reducing uncertainties associated with mathematical models, numerical algorithms, experiments, and predicted outcomes of quantities of interest."

Methods:

- Sensitivity analysis (local, global),
- Surrogate model based: polynomial chaos expansion, regression,…
- Bayesian inference,
- Machine learning,
- …

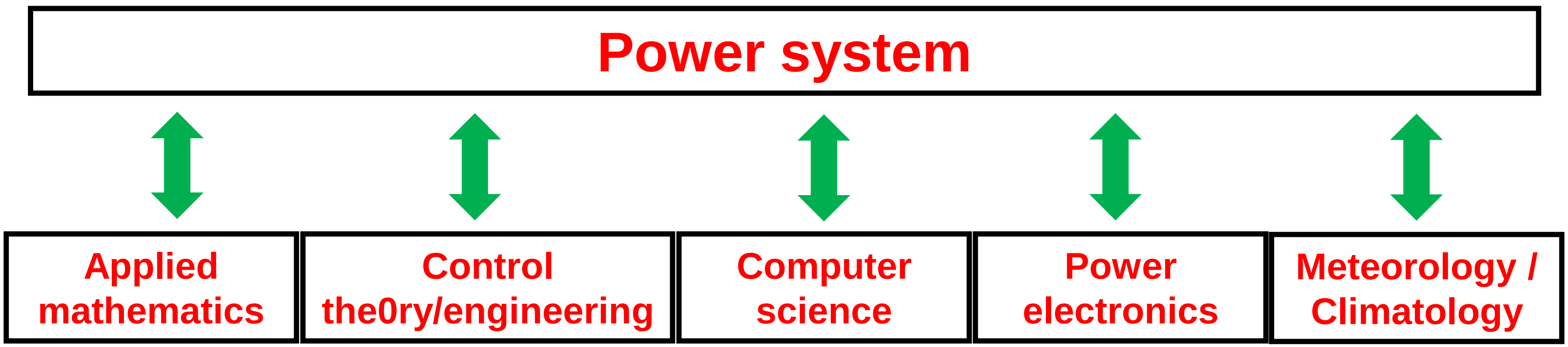
- Related problem: uncertainty propagation (how a system model transforms input uncertainties).

- Uncertainty quantification + AI = Trustworthy AI

Synergy with other research/engineering fields

- Power systems: always capitalized on the development in other research/engineering fields.

- The opposite is also true: other fields benefited from power systems development.



Also: chemical engineering, mechanical engineering, data science,…

On the use of AI in power systems

- AI is very vibrant research field and new result are coming at fast pace (so, follow the development in the field).

Many AI approaches have been successfully considered to solve different power system problems (forecasting,…).

- Practice never accepts something not well-supported and easy to understand.

- In line of the above, trustworthy AI is needed (explainable, interpretable,…).

- Embedding a domain knowledge is always helpful.

Some useful links (instead of Conclusions)

- ULiege Open Repository and Bibliography (ORBi): orbi.uliege.be
- ETH Zurich Research collection: www.research-collection.eth.ch
- UW-Madison, Power Systems Engineering Research Center: pserc.wisc.edu
- University of Illinois at Urbana-Champaign: publish.Illinois.edu
- Cypress project: cypress-project.be

Thank you for your attention !