Operational, modelling and control challenges of future net-zero power systems

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Outline of presentation*

- Drivers for change of design and operation of electrical power systems
- Challenges facing designers and operators of net-zero power systems to ensure system resilience
- Approaches to address some of the identified challenges
- Summary

* Contrary to all advices that I (and others) give to students regarding the number of slides that they should prepare for a presentation, I have probably double of that number

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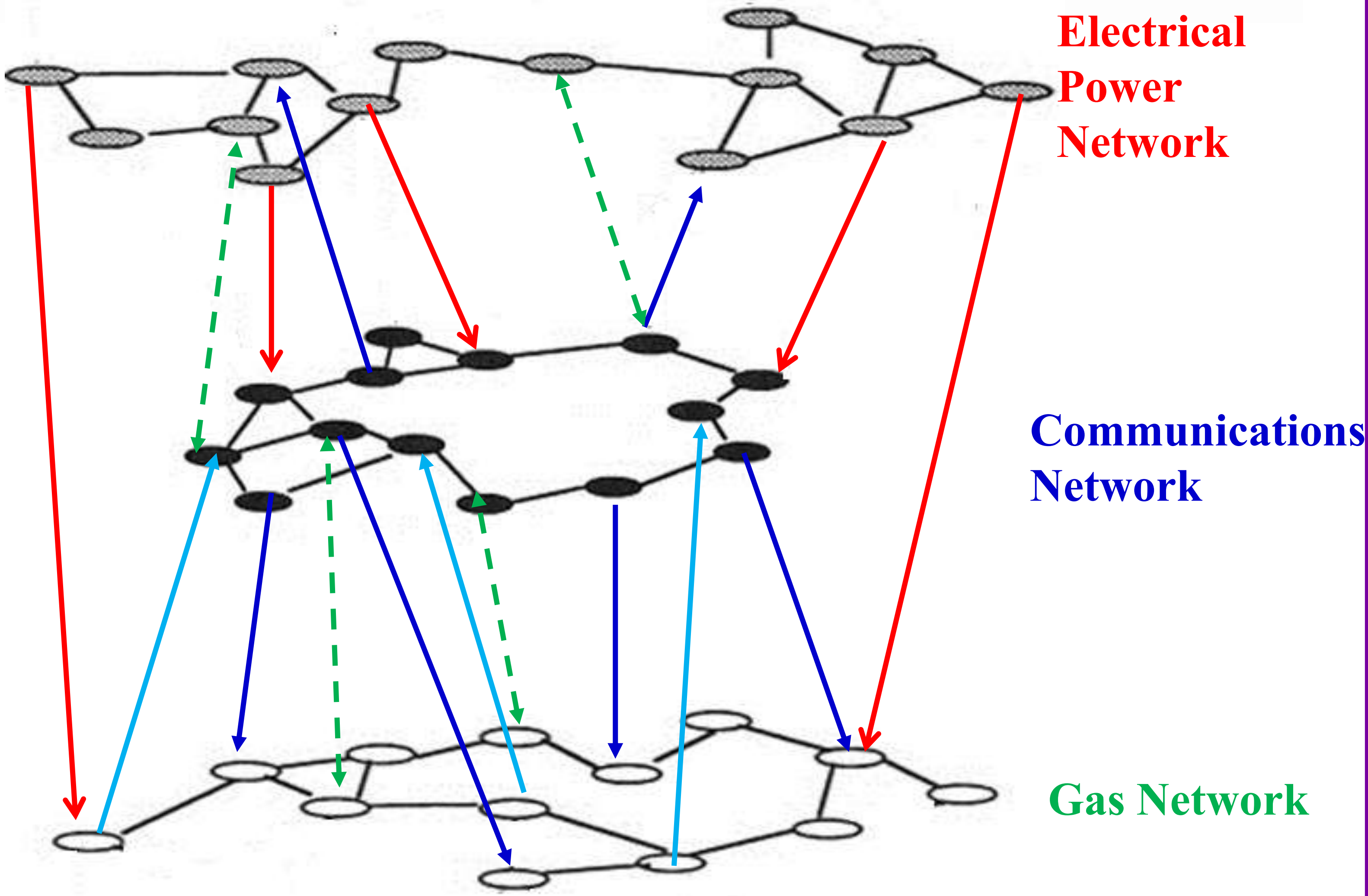
“ID” of Future Power & Energy Networks

- Evolving/new market structures/operation
- Ageing assets approaching the end of life
- New, largely uncertain, generation/storage (PE connected) technologies
- Proliferation of PE based “transmission facilitating” technologies
- New types (many PE based) and operational patterns of temporally and spatially varying and uncertain load
- Abundance of (raw) data
- Energy & information security requires integrated approach

Integrated systems - System of systems



Smart * (Building, City, Network…)

Now, the question is, how to

Is this
a future model of
"Smart City/Network"

Natalie Wolchover, "Treading S… magazine, March 18, 2013, https://www.quantamagazine.org/20130318-treading-softly-in-a-connected-world/

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Abundance of, and increasing amount of data

- SCADA *(Supervisory Control And Data Acquisition)* systems (1-5min updates)
- WAMS *(Wide Area Monitoring Systems)* (50-60 updates per second) (by the end of 2013 China State Grid Corporation installed 2027 PMUs at V>110kV)
- Advanced metering devices, IEDs ("Intelligent/Smart" meters with some degree of monitoring capabilities - even in low cost smart meters for hundreds of thousands household customers)
- Bi-directional communication enabled mobile (e.g. EVs) and stationary devices (e.g. domestic appliances)
- Conventional PQ monitoring and energy/power metering at load and generation (including RES) buses (3-5sec updates)
- Historical monitoring and incident/control reporting data
- Customer surveys
- Internet resources (related to network and generation performance, customer behaviour and preferences, user and generation groups /associations)

Integrated monitoring system reporting to some other hierarchical systems such as distribution or transmission management system

Challenges - 1

- **DATA:** Efficient use and reliance on existing and newly acquired data through deployed local measurement devices and two-way communications enabled meters and global monitoring data (WAMS) for state estimation, static and dynamic equivalents and control (including real time control)
  - Efficient data management (signal processing, aggregation, transmission) and ICT network reliability are essential for both static and dynamic observability as well as for operation and control of the system

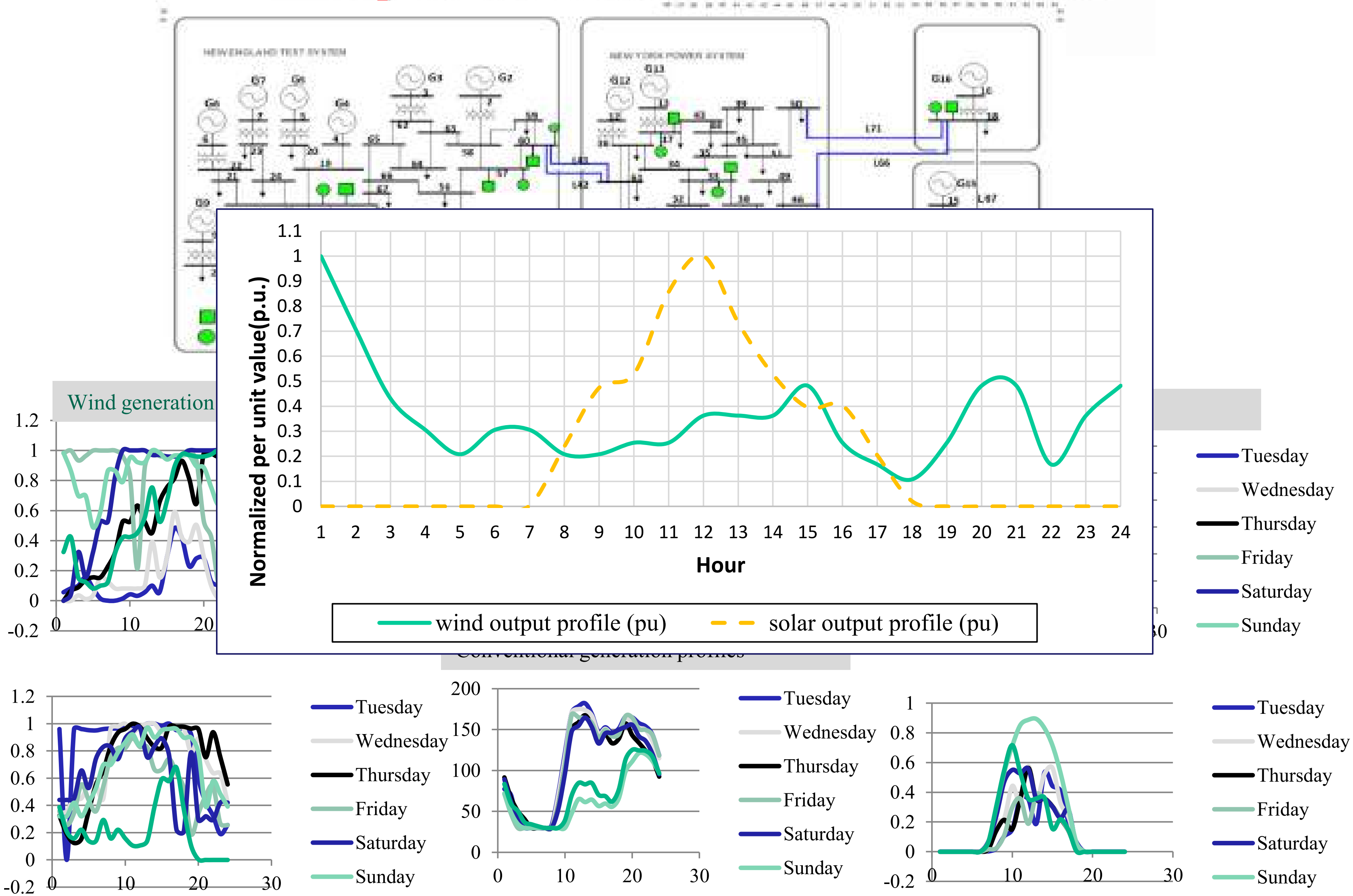
Data Analitics –

Data is not information

Abundance of, and increasing uncertainties

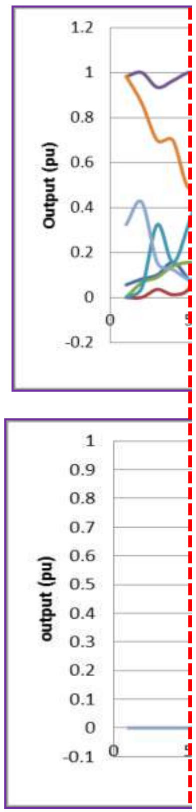
- Network
  - topology, parameters & settings (e.g., tap settings, temperature dependent line ratings)
  - observability & controlability
- *Generation*
  - *pattern (size, output of generators, types and location of generators, i.e., conventional, renewable, storage, RES at distribution level)*
  - *parameters (conventional and renewable generation and storage)*
- Load (time and spatial variation in load, load composition (mix), models and parameters)
- Controls
  - parameters of generator controllers (AVRs, Governors, PSSs, PE interface), network controllers (secondary voltage controller), FACTS devices and HVDC line controllers
- Contractual power flow (consequence of different market mechanisms and price)
- Faults (type, location, duration, frequency, distribution, impedance)
- ICT related uncertainties (noise, measurement errors, time delays, loss of signals, bandwidth)
- Weather/climate related uncertainties (wind speed, wind direction, temperature, solar irradiation, tidal/wave conditions)

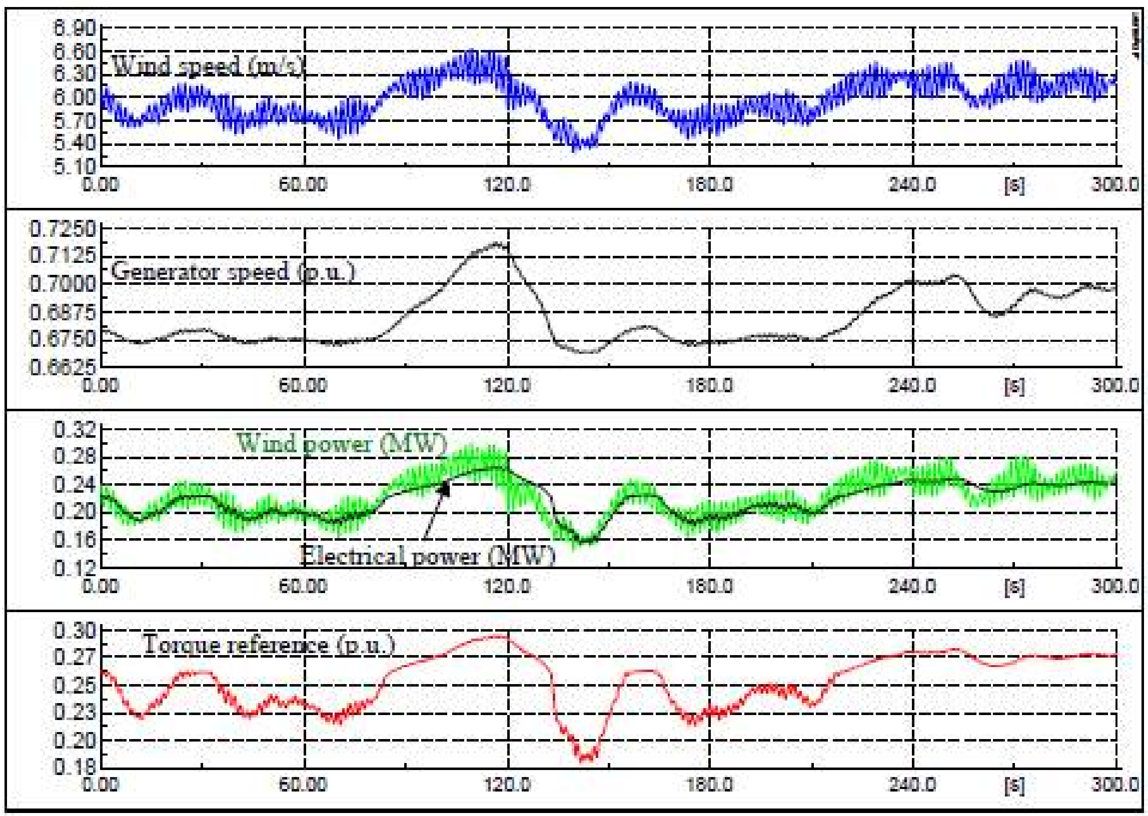
Operational uncertainties

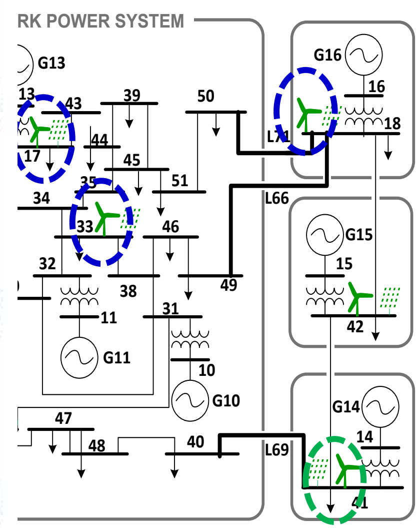


The impact of RES on system dynamics

- Increased uncertainty in the pre-fault operating conditions due to the intermittent behavior of RES and their availability, both temporal and spatial

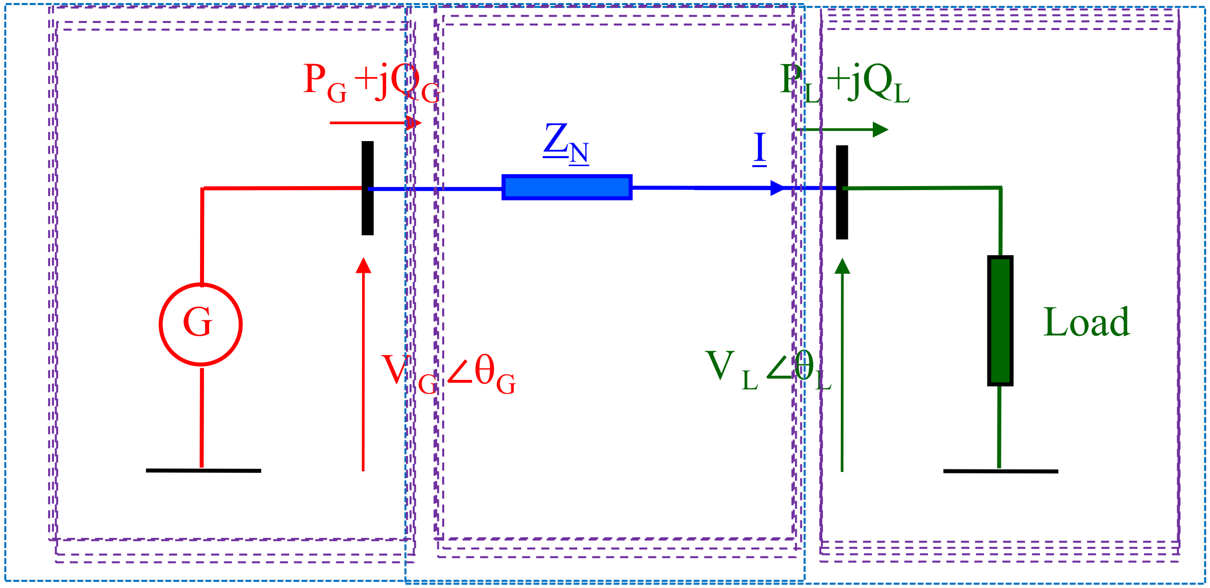






The nature of the problem

"Smart grid" or not, has not fundamentally changed since 1882 Pearl Street station. The individual components though, have, as well as, the way they interact.



We still need equivalent/aggregate models for steady state or dynamic studies, the complexity is coming from developing models ***accurate enough for the type of the study of interest***, and ***interactions*** among them

Challenges - 2

- **MODELLING**: for steady state & dynamic studies
  - Variable, and to extent stochastic, operating conditions influenced by market forces and uncertainty in generation and load
  - Clusters of RES (generation and storage) of the same or different type some of those not visible at transmission level
  - Demand, including new types of energy efficient and PE controlled loads, heat pumps, customer participation and behavioural patterns, EV, etc.
  - Storage technologies for provision of ancillary services
  - Large interconnected networks with mixed generation technologies including highly stochastic renewable generation, FACTS and short/long distance bulk power transfers using HVDC lines
  - Modelling/analysis of efficient and effective integration of different energy carriers into self sufficient energy module/cell
  - Interconnected critical infrastructure systems, “system of systems”

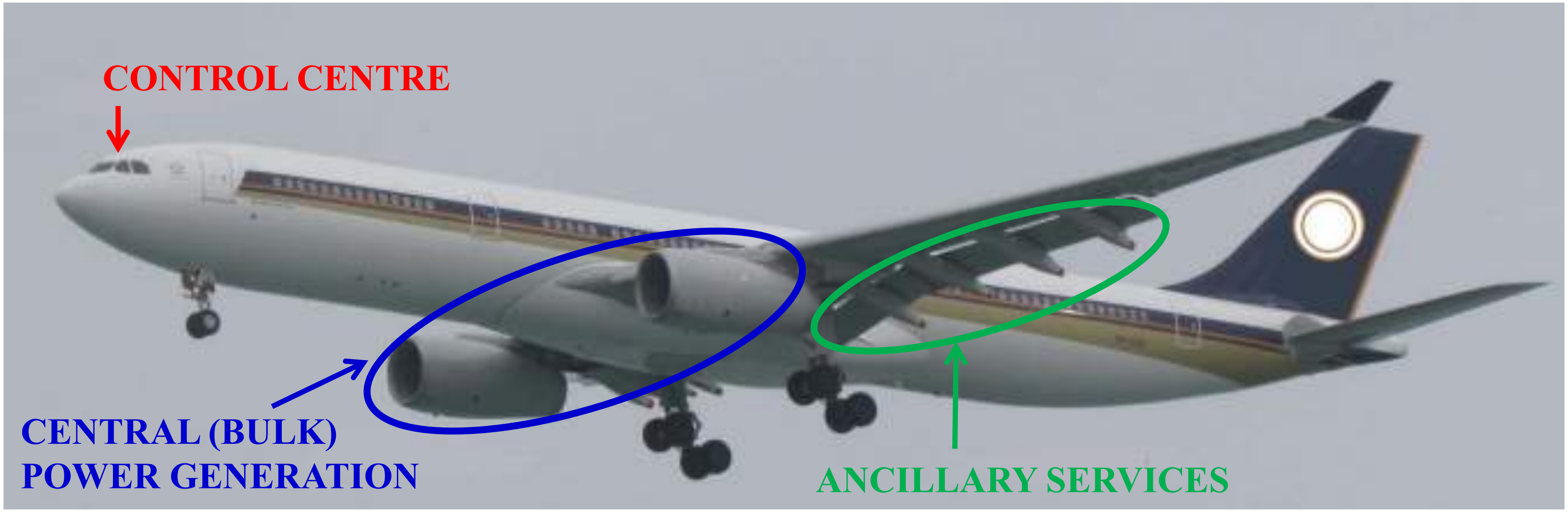
Too many uncertainties to justify conventional deterministic modelling – the probabilistic modelling is necessary

Controllability challenge

- The participation of conventional controllable (that can be both, controlled and used for control) plant in generation mix is reducing
- Renewable, uncertain and variable, generation is increasingly supported/complemented by energy storage (there is a lack of operational experience with these technologies)
- The nature and behaviour of load has changed and is changing (e.g., spatial in addition to temporal variation)
- New transmission components (still insufficiently understood) are being added to the system
- Systems to control are becoming significantly more complex

Controllability challenge

- The complexity and vulnerability of the system is increasing
- The system control, stability and security are becoming increasingly important and much more time dependent than before



"Every little helps" is becoming very important

- Additional/Advanced controllability of RES
- Deployment and control of energy storage (centralised and distributed)
- Efficient Demand Side Management (DSM)

Challenges - 3

- **CONTROL**: Design of advanced controllers and control structures – increased network automation
  - Design of supplementary controllers based on WAMS to control and stabilise large system (including real-time) or parts of it (which may vary) with uncertain power transfers and load models and stochastically varying and intermittent PE connected generation, demand and storage – *stochastic/probabilistic control of systems with reduced inertia*
  - Design of new control systems/structure *(distributed, cooperative or hierarchical, adaptive, close to real time)* for power networks with fully integrated sensing, ICT technologies and protection systems – *risk limiting control*

Real time risk limiting control

Risk is an uncertain event or condition that, if it occurs, has an effect on at least one objective, it is the probability of something happening multiplied by the resulting cost or benefit if it does.

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Acknowledgement

The figures and results below are adopted from research results of my former and current PhD Students and Postdoctoral Research Associates who worked or are working with me in these areas:

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Dr Tingyan Guo
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Dr Panagiotis N. Papadopoulos
Dr Kazi Nazmul Hasan

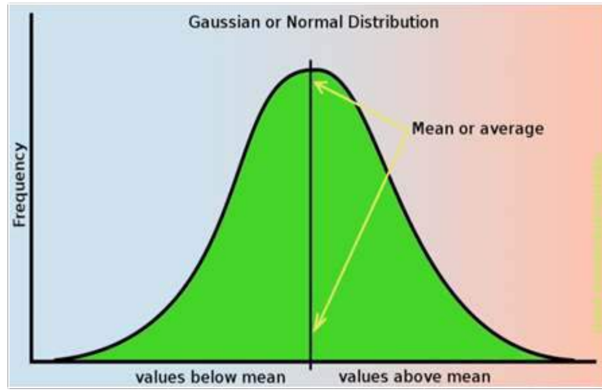
Dr Jelena Ponocko
Dr Yue Zhu
Dr Buyang Qi
Dr Wentao Zhu
Dr Juan Morales Alvarado
Mr Mengxuan Wang

Some of their papers providing further information on the related issues are listed at the end of the presentation.

Probabilistic Modelling

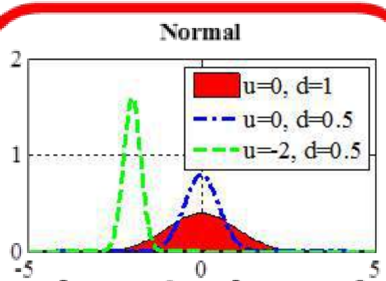
Monte Carlo simulations using different probability distribution functions

Minimum

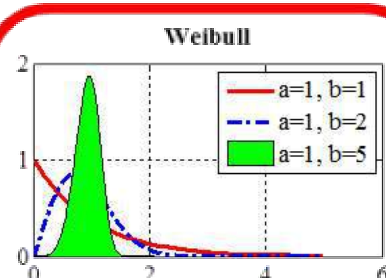


Maximum

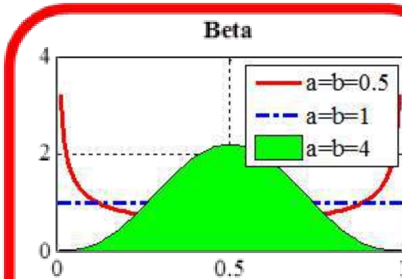
-3σ   μ   +3σ



Electrical Load

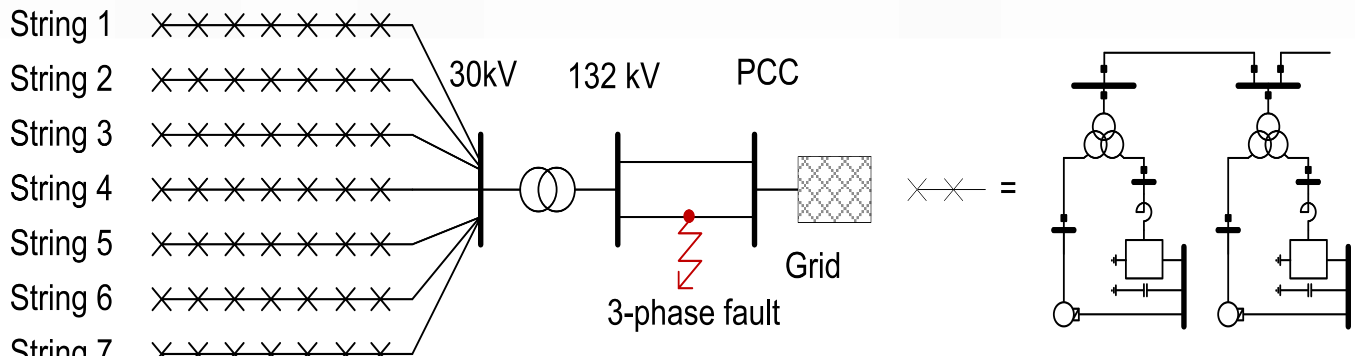


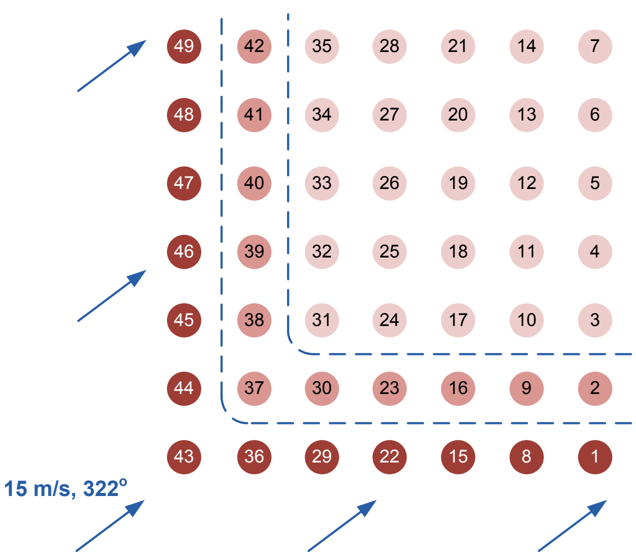
Wind Speed



Solar PV

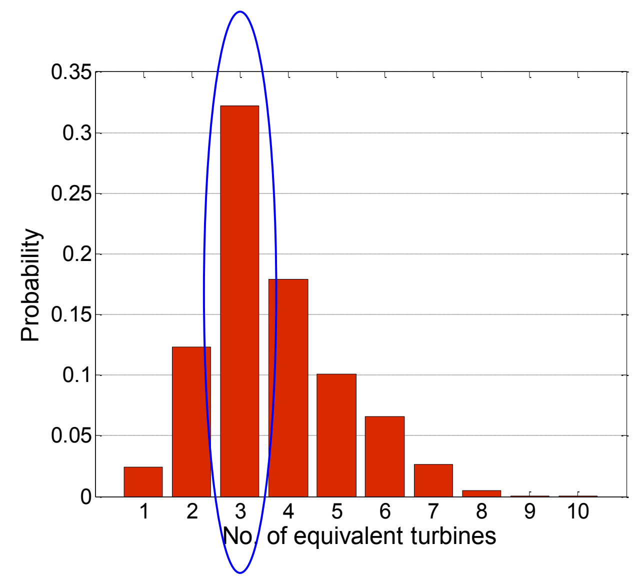
E1: Dynamic equivalent models of Wind farm using probabilistic clustering





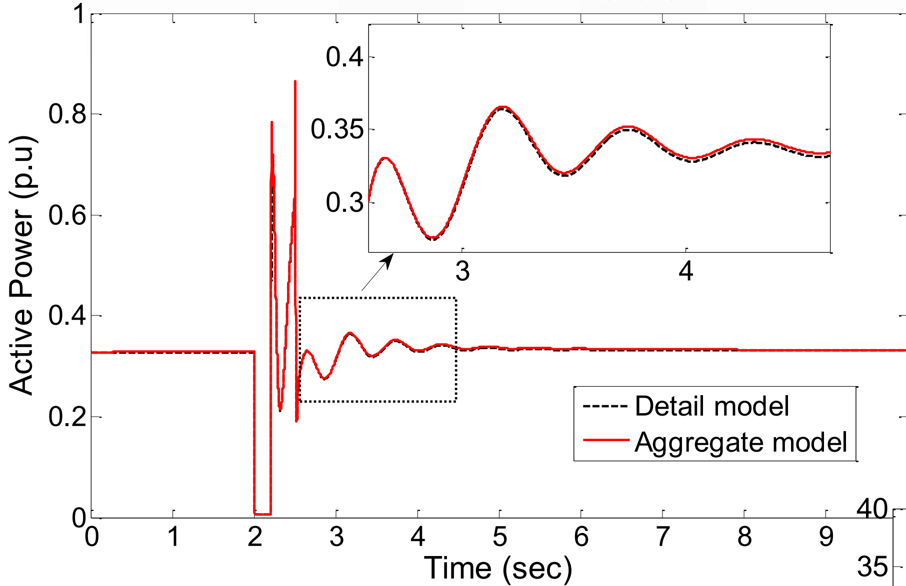
Wind speed variation inside a wind farm at 15 m/s, 322°

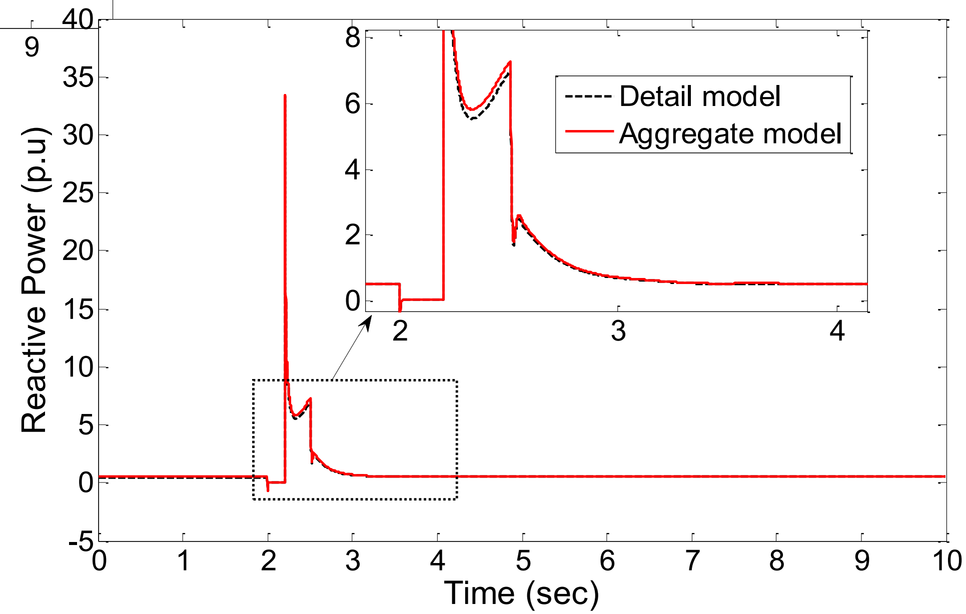
Support Vector Machine (SVM) based clustering



Probability of equivalent turbines needed to represent the WF

E1: Dynamic equivalent models of Wind farm using probabilistic clustering

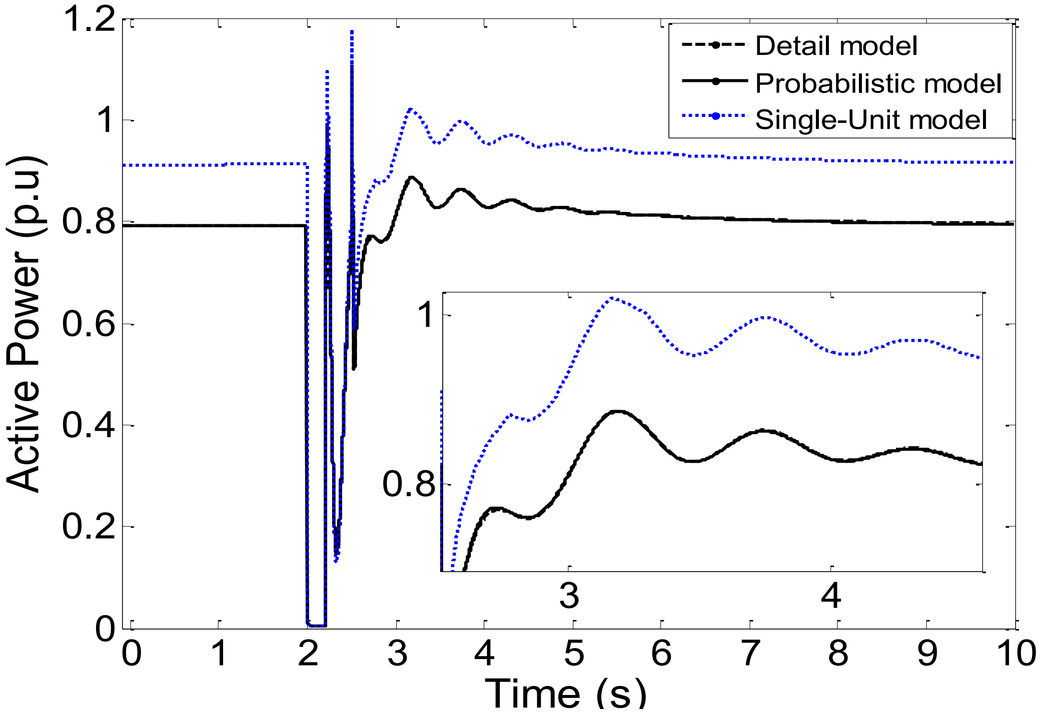




P and Q response for Detailed and Probabilistic model at wind speed = 10 m/s, wind direction = 100°

In the case studied, simulation time was reduced by up to 96%.

E1: Dynamic equivalent models of Wind farm using probabilistic clustering



P and Q response for Detailed , Probabilistic and single unit model at wind speed **WS = 12 m/s, WD = 349°**

Both P and Q are **over-estimated** by the **single-unit model** as it ignores variation in wind speed due to wake effects (pre-disturbance operating point is the major cause of difference in responses)

Single-unit equivalent model is generally most suitable for simulating wind farm behavior at **full wind speed only**.

This modelling approach does not require changes in equivalent model every time the wind speed or direction changes.

Probabilistic estimation of demand profile and controllability

Metering Data

Customer Surveys

General Knowledge of Demand Composition

DDLC Based on Load Classes

Participation of Load Categories in Different Load Classes

DDLC Based on Load Categories & Controlability

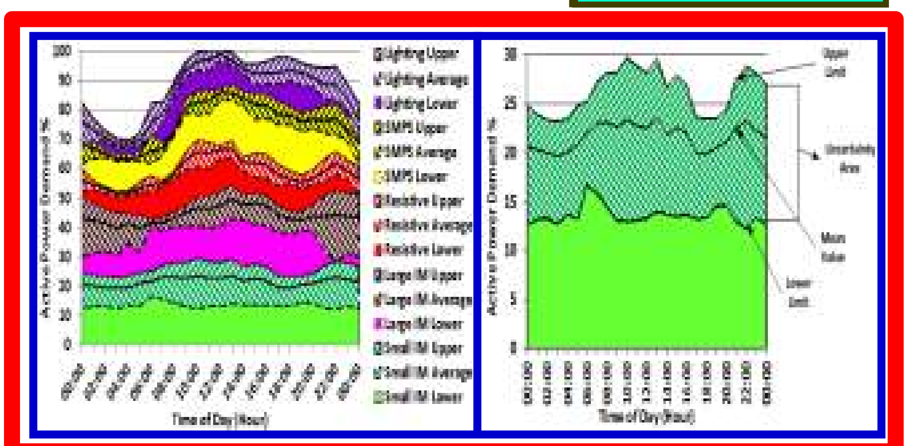
Data Processing with Parameter Uncertainty

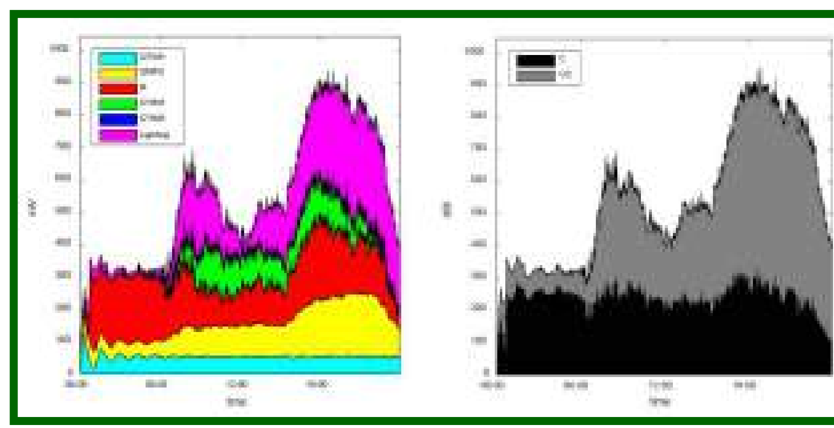
Probabilistic DDLC **Based on Categories & Controlability**

On-line measurement using Smart Meters

Data processing & Aggregation based on Load categories & controlability

Deterministic DDLC **Based on Categories & Controlability**





E2: Examples of advanced demand side management applications

Practical application within EU H2020 project "Nobel Grid"

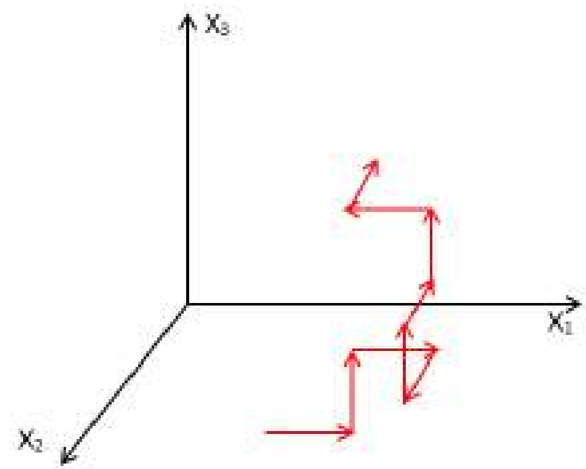
(€12million, 42 months, 1/1/2015 - 30/6/2018)

**Illustration of the process of
demand forecasting and disaggregation**

J. Ponocko, Jiawei Cai, Yusong Sun and J. V. Milanović, "Real-time visualisation of residential load flexibility for advanced demand side management", 19th IEEE Mediterranean Electrotechnical Conference (MELECON 2018), Marrakesh, Morocco May 2-7, 2018, (1570409786)

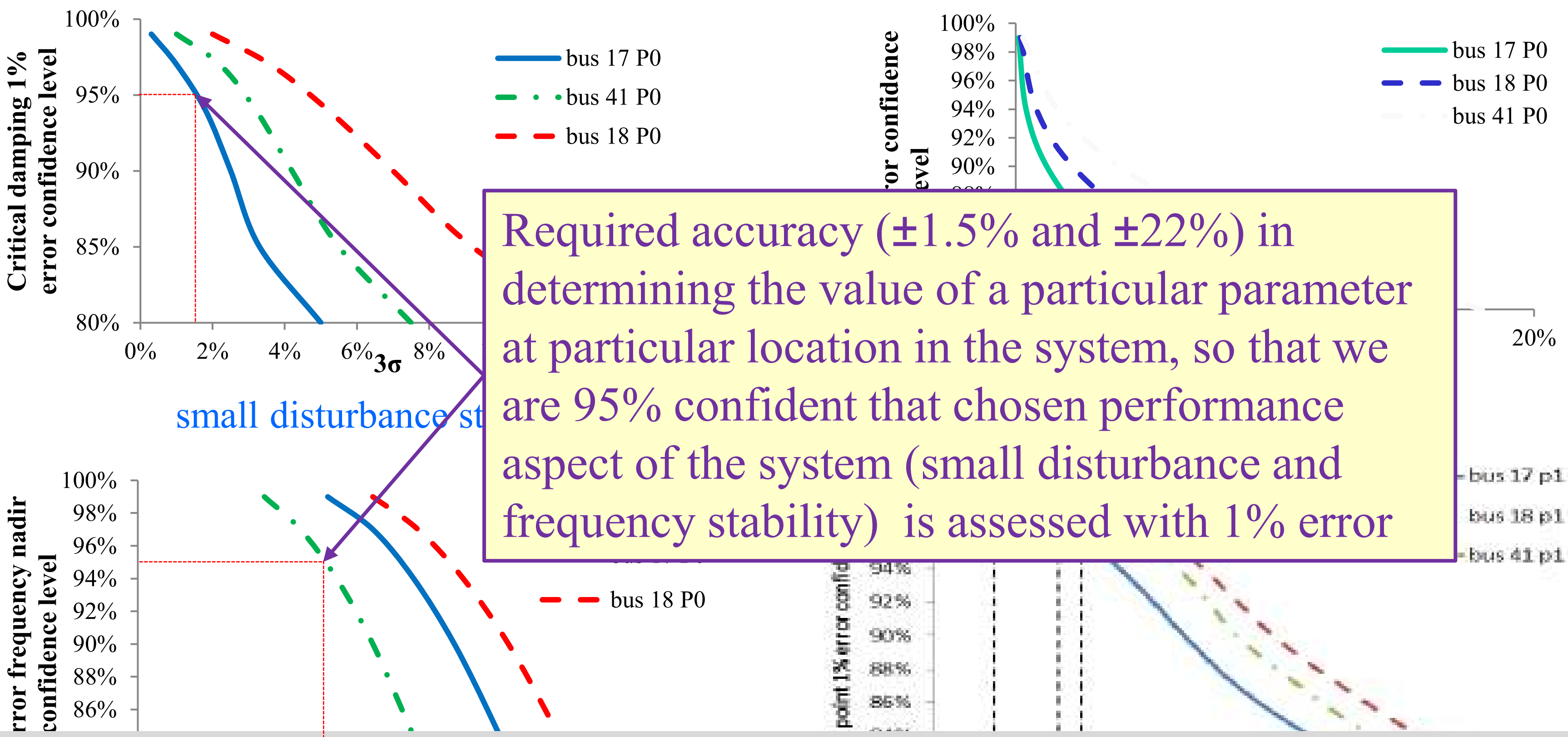
Probabilistic Assessment and Sensitivity Analysis in Stability Studies

- Probabilistic modelling of power system uncertainties
  - Load: normal dist., Wind: Weibull dist., Solar (PV): beta dist.
- Probabilistic simulation method: Monte Carlo simulation
- Sensitivity analysis techniques
  - Local, screening, and global methods
  - The technique used in this work:
    Morris screening method
- Correlation of uncertain parameters
  - Modelling stochastic dependence:
    Gaussian copula method



trajectory in the input **parameter** space

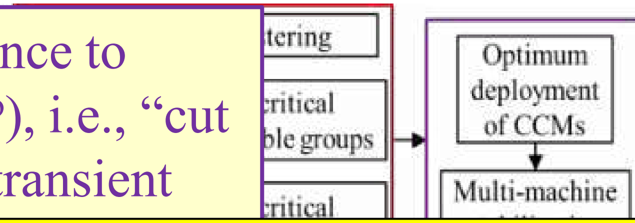
E3: 1% error confidence levels of Critical Load Model Parameter



Required accuracy (±1.5% and ±22%) in determining the value of a particular parameter at particular location in the system, so that we are 95% confident that chosen performance aspect of the system (small disturbance and frequency stability) is assessed with 1% error

The (required) accuracy of the model should be judged based on its **influence on the accuracy** of the assessment of **different aspects of the system** (not necessarily power system alone) **performance**

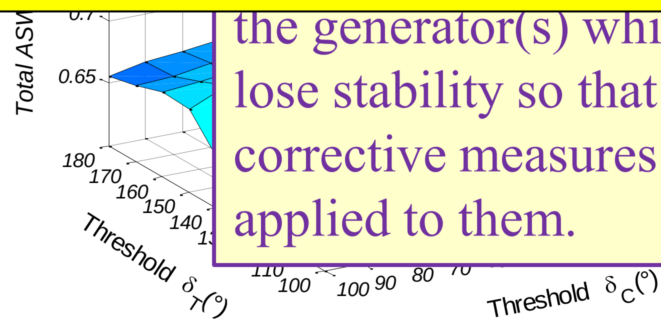
E4: Data Analytics: Optimal Deployment of Corrective Control



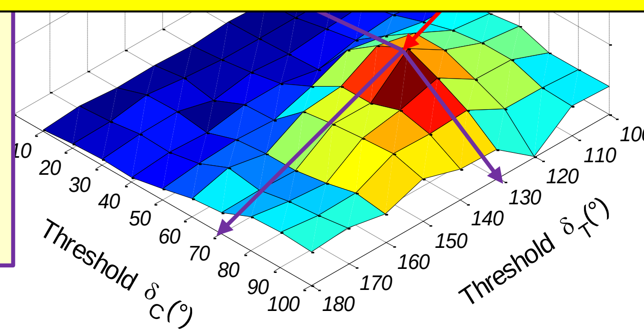
The time after disturbance to cluster generators (70°), i.e., “cut the dendrogram”, and transient

The mean time to detect instability would reduce from 816ms to 402ms if 240° threshold is used instead of 360° and to 405ms if 130° threshold is used instead of 180°, hence the reduction in time to make decision is about 410ms.

the generator(s) which would first lose stability so that appropriate corrective measures can be applied to them.



(a)

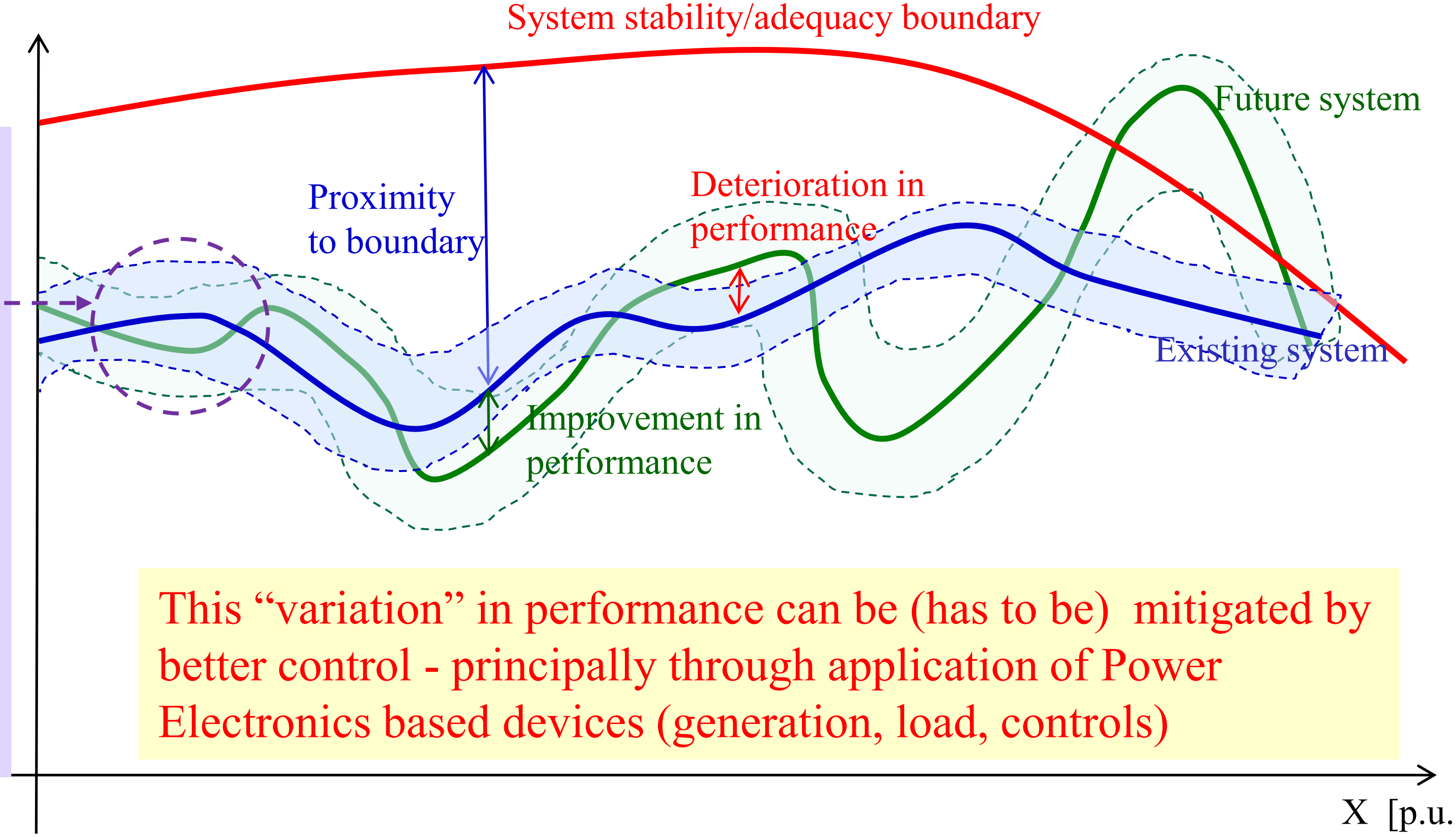


(d)

Results of the statistical clustering assessment over the entire clustering parameters’ region. (a) Average Silhouette Width - ASW. (d) Total Grouping Pattern ASW - TGPASW index.

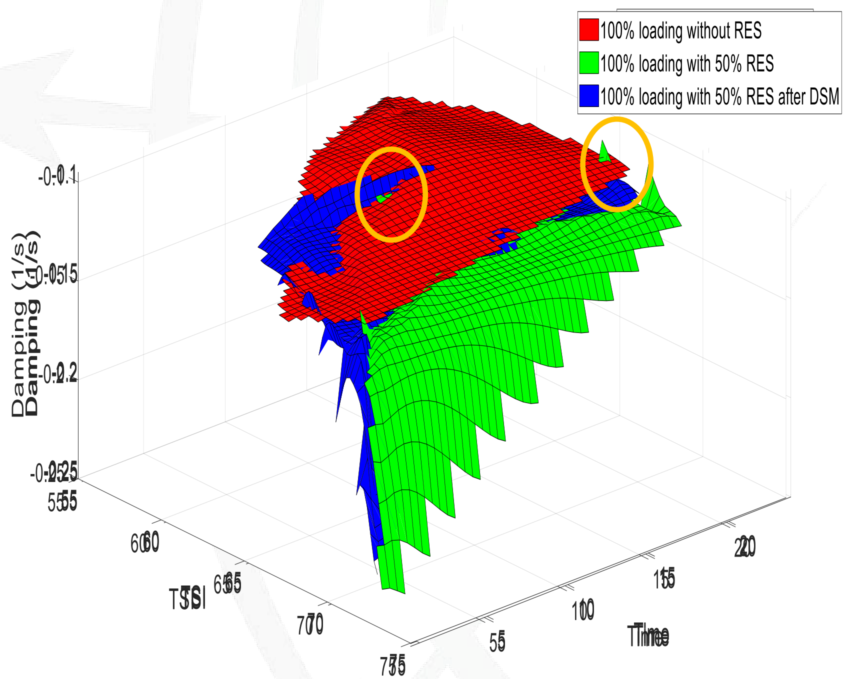
System stability/adequacy variation due to uncertainities in load and generation

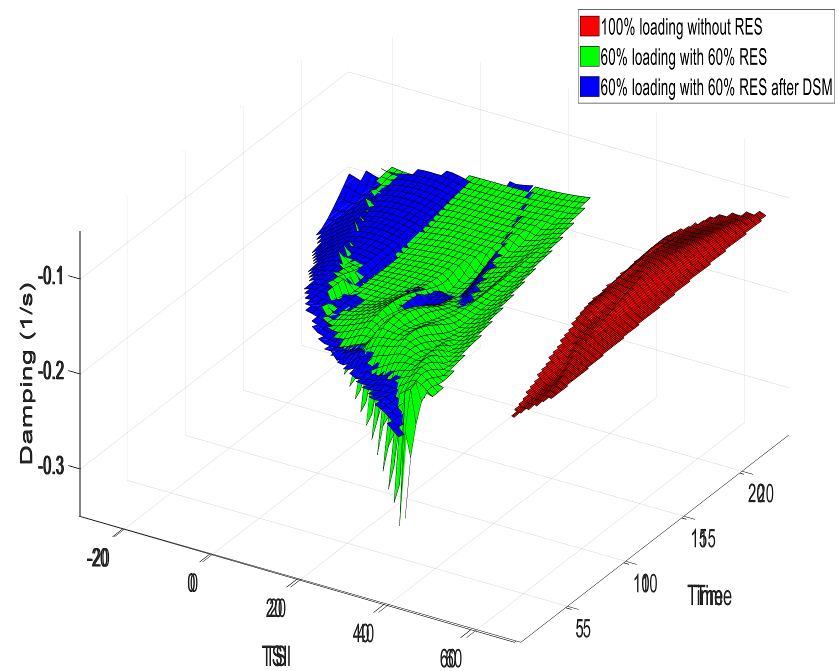
Deterministic approach shows improvement in case of future system, while due to the uncertainty the conclusions could be opposite



This "variation" in performance can be (has to be) mitigated by better control - principally through application of Power Electronics based devices (generation, load, controls)

E5: Multi dimensional interactions

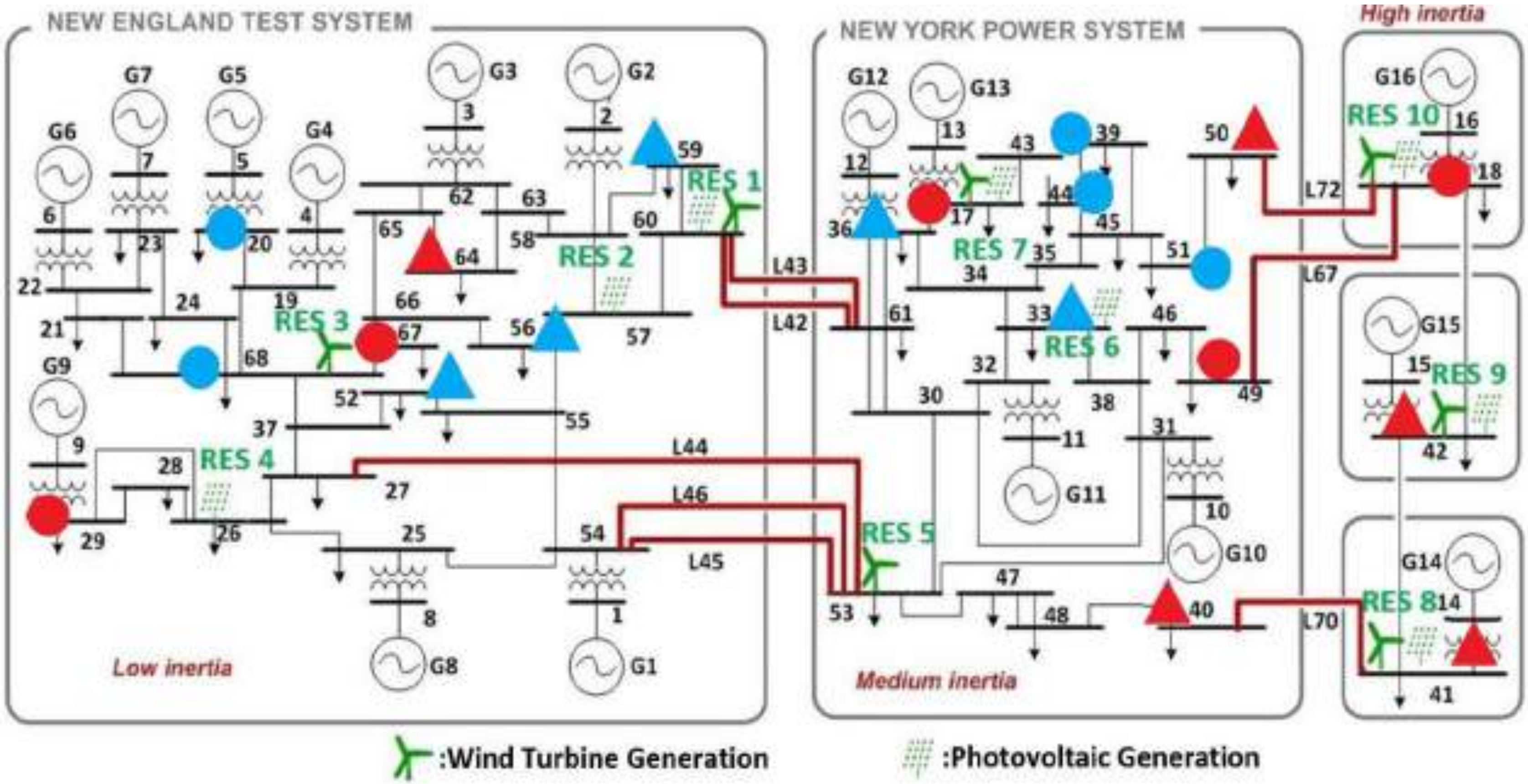




100% system loading with 50% RES penetration, fixed system inertia.

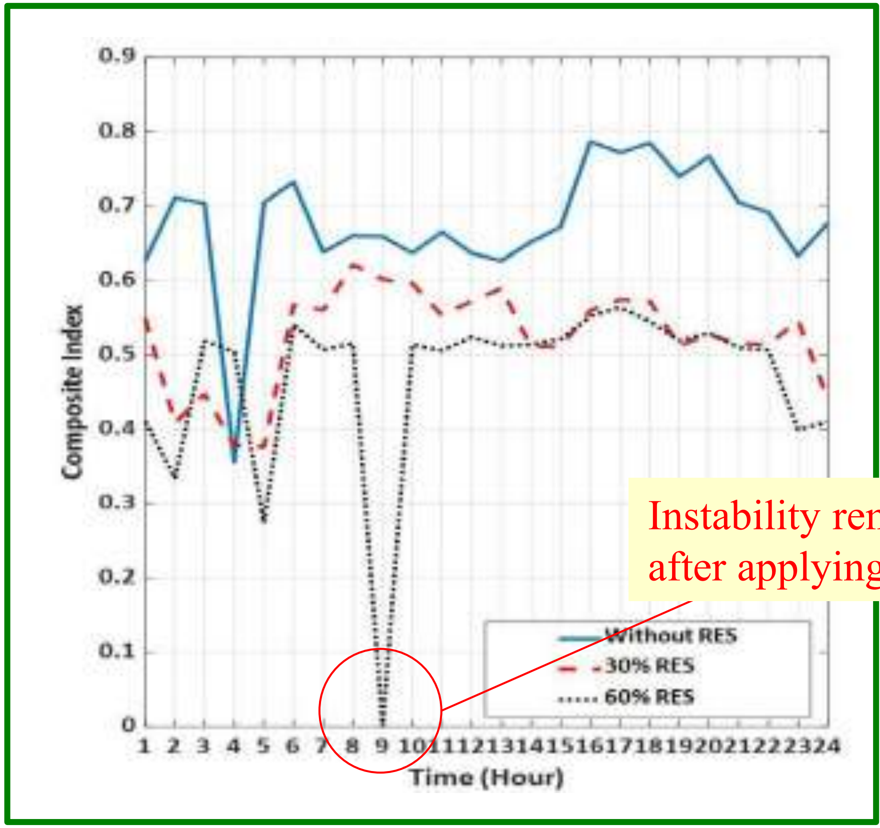
60% system loading with 60% RES penetration, reduced system inertia.

E5: Multi dimensional interactions

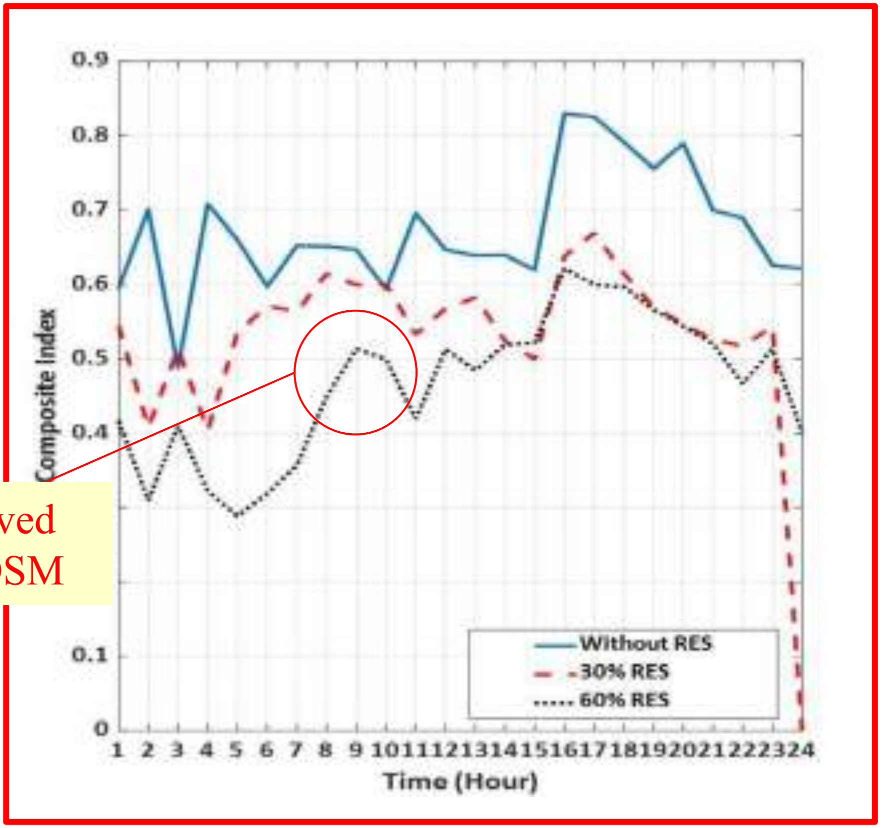


The modified IEEE 68-bus test system with the indicated locations of flexible DSM assets (circles for large ICs and triangles for DNs)

E5: Use of composite index

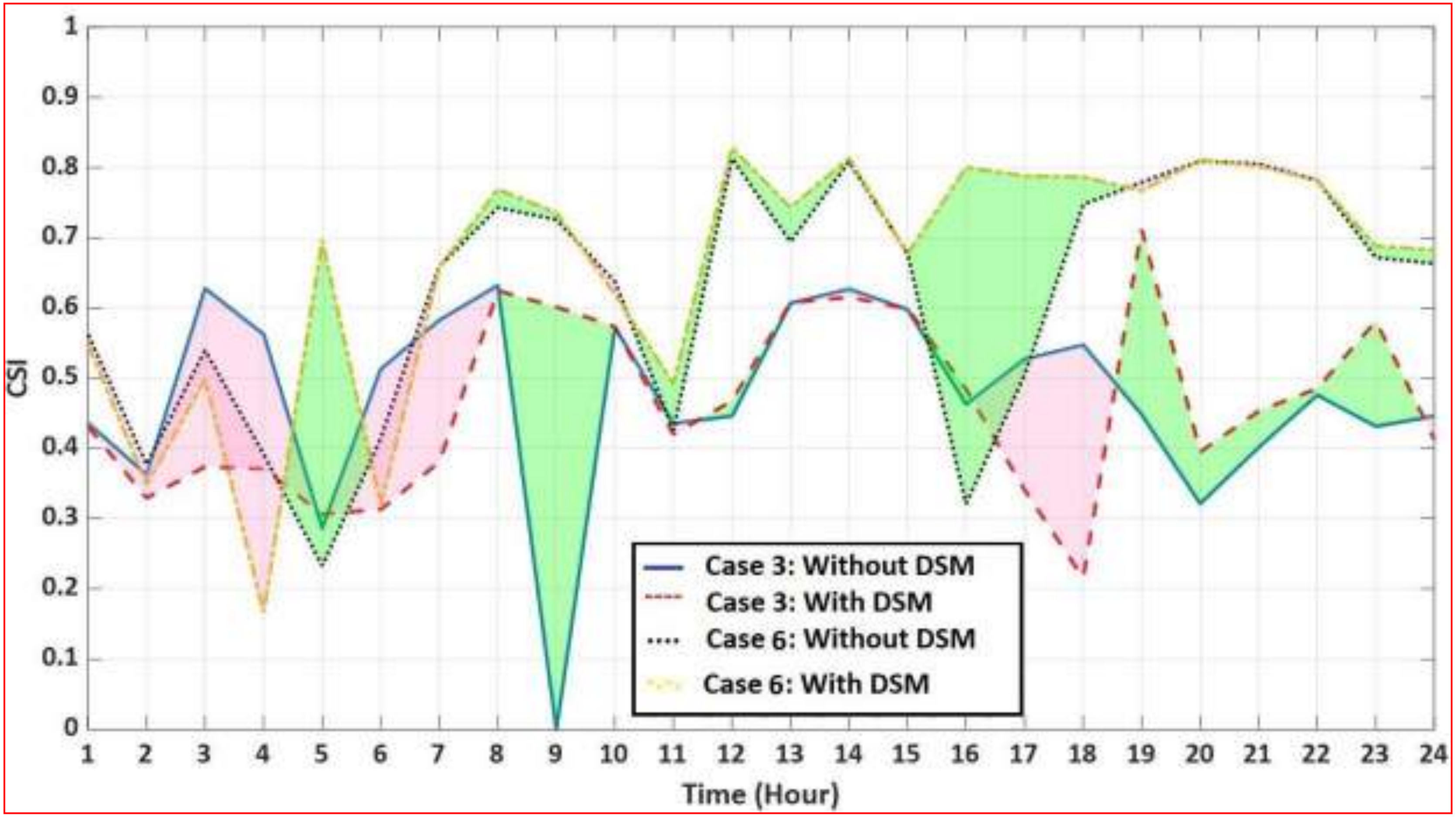


Instability removed after applying DSM



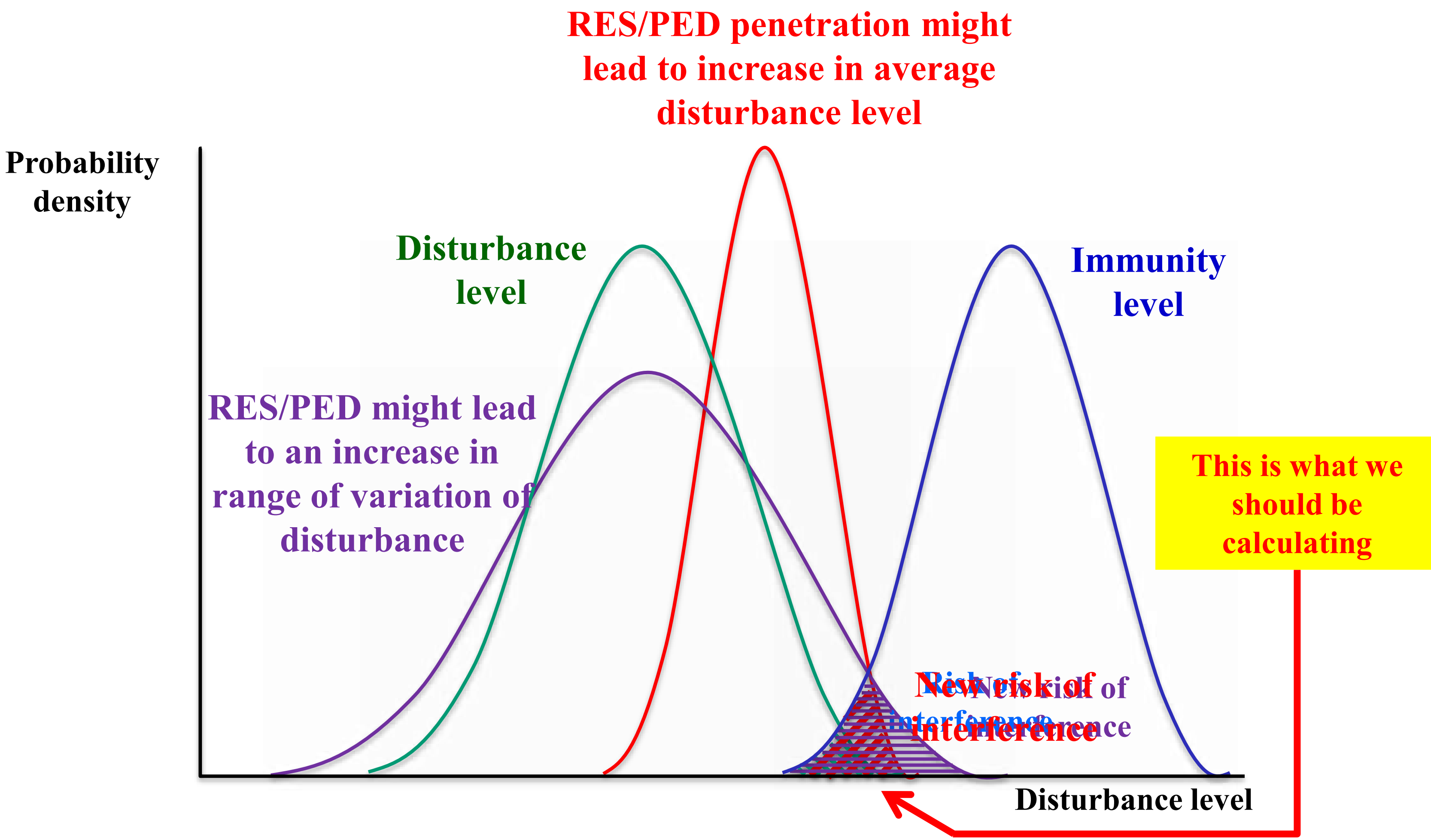
Composite Stability Index throughout the day without (left-hand side) and with (right-hand side) DSM application for different RES penetration levels.

E5: Use of composite index

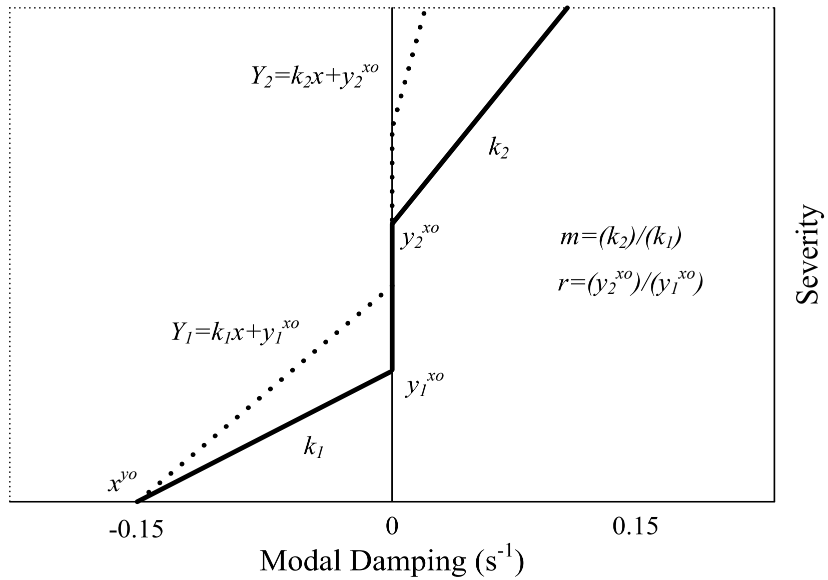


Change in composite stability index throughout the day for 60% RES penetration level and 18% DSM capacity (based on system peak demand) with constant power (Case 3) and composite (Case 6) load model (green – improved performance, red – deteriorated performance)

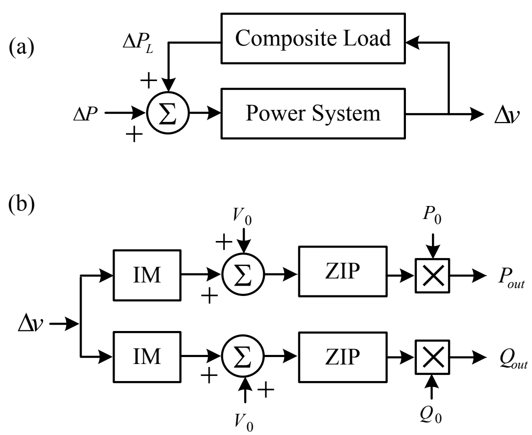
Risk based assessment of "interference" in power networks

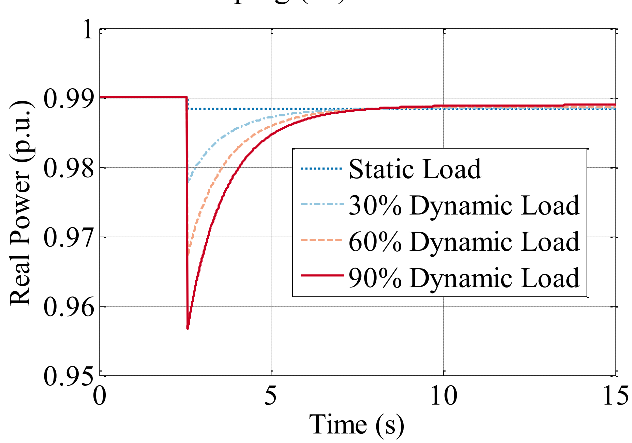


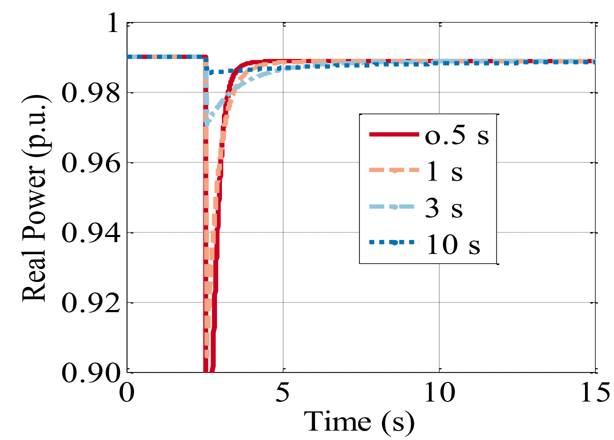
E6: Risk-based Small-Disturbance Security Profile



Continuous severity functions for risk calculation considering small-disturbance stability.

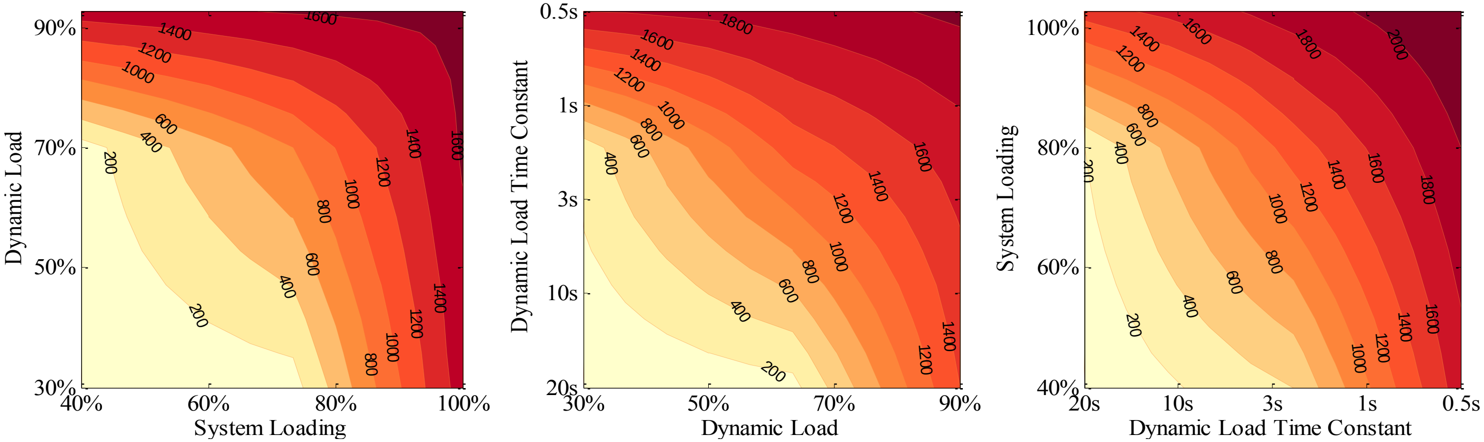




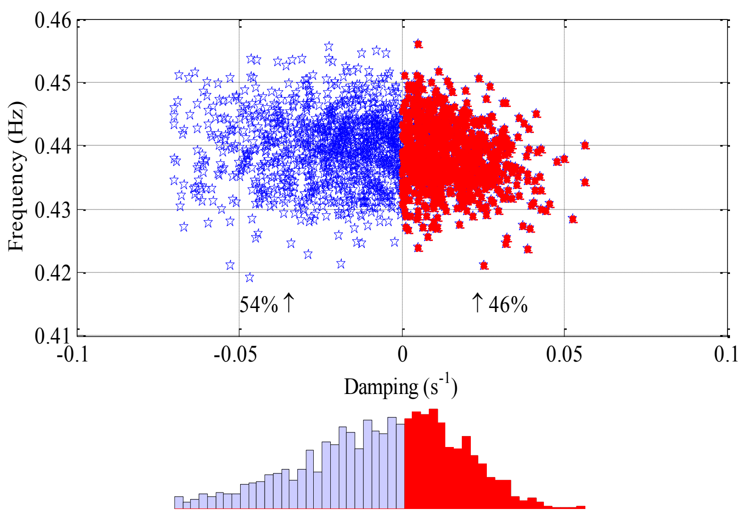


(a) system-load interaction, (b) composite load model, and 1st order recovery of dynamic load (c) with respect to different proportion of dynamic load, and (d) at different dynamic load time constants

E6: Risk-based Small-Disturbance Security Profile



Risk-contour with a) dynamic load vs. system loading; b) dynamic load vs. dynamic load time constant; c) system loading vs. dynamic load time constant

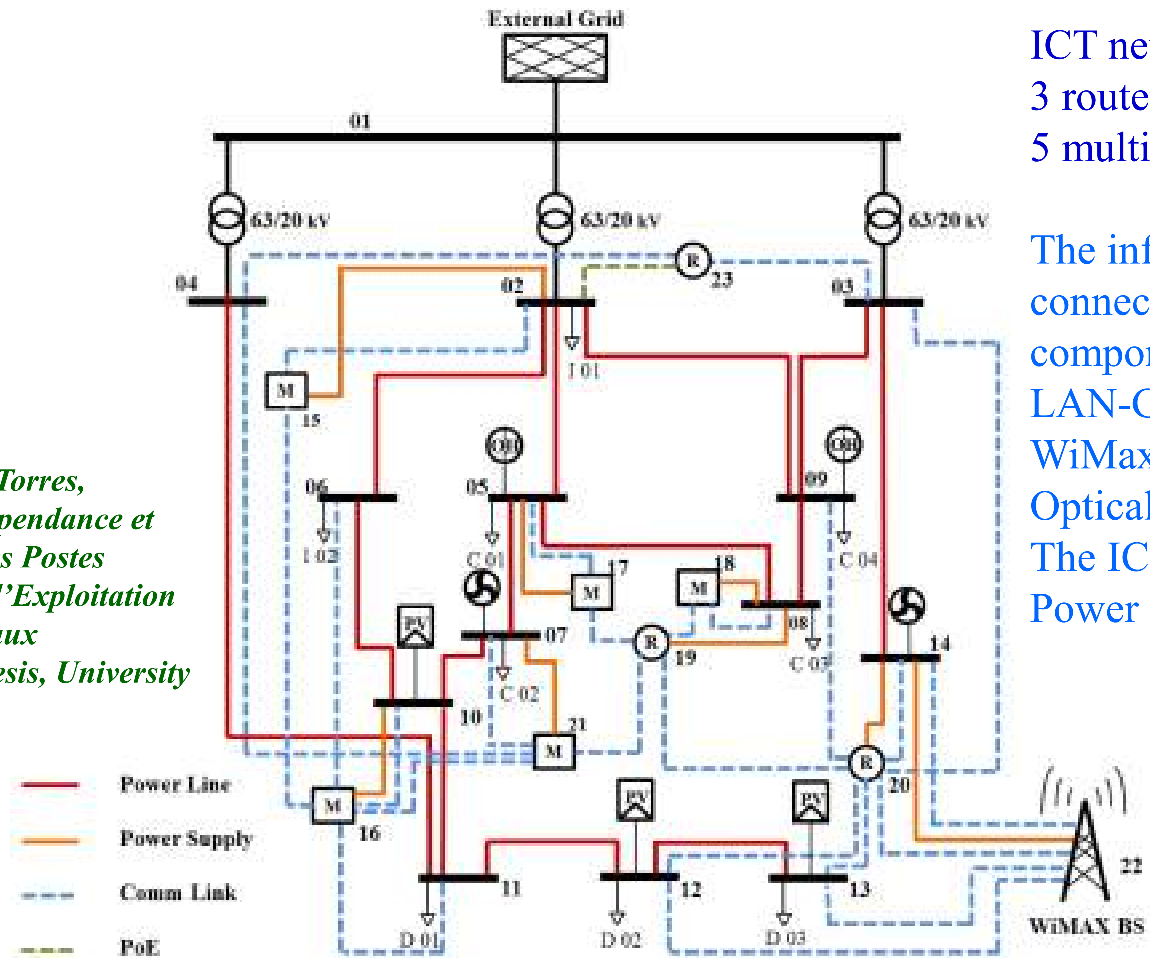


Illustrative eigenvalue plot of a **highly stressed network, which exceeds security margin** of the system loading, proportion of dynamic load, and dynamic load time constant.

E7: Modelling of Interconnected Infrastructure Systems (Using Complex Network Theory)

EPS netwrok
14 buses,
17 lines,
7 DGs
9 loads
3 HV/MV
transformers,

José Libardo Sanchez Torres, "Vulnérabilité, Interdépendance et Analyse des Risques des Postes Sources et des Modes d'Exploitation décentralises des Réseaux Electriques", PhD Thesis, University of Grenoble, 2013

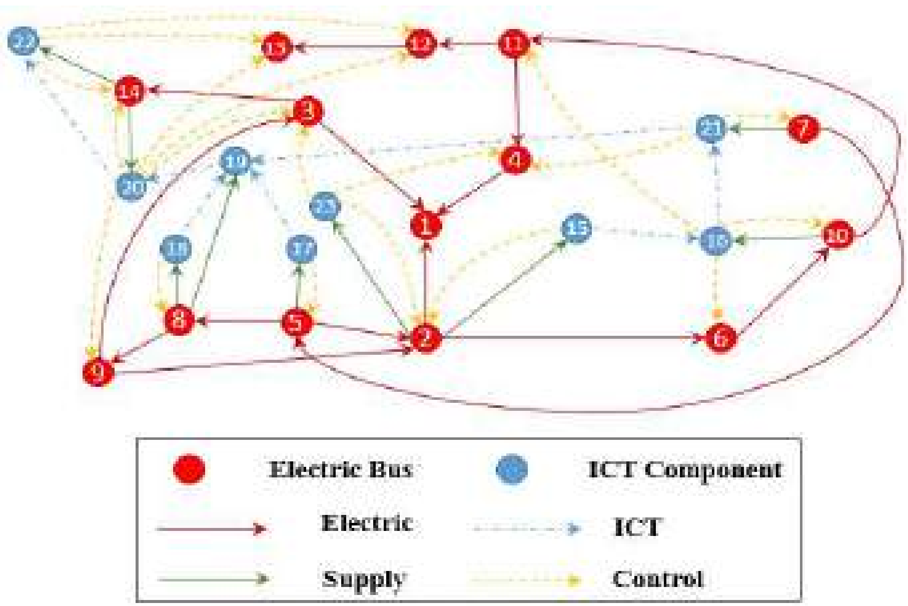


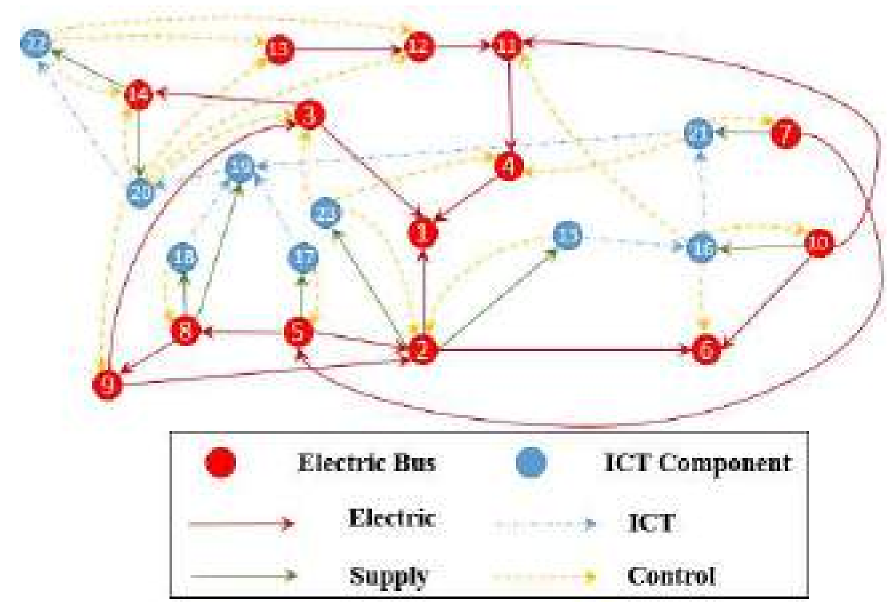
ICT netwrok
3 routers
5 multiplexers

The information channels connecting ICT components, utilize LAN-Giga Ethernet, WiMax, Ethernet and Optical Fiber
The ICT link 2-23, uses Power over Ethernet

14-bus test system incorporating power and communications networks

E7: Graphical representation

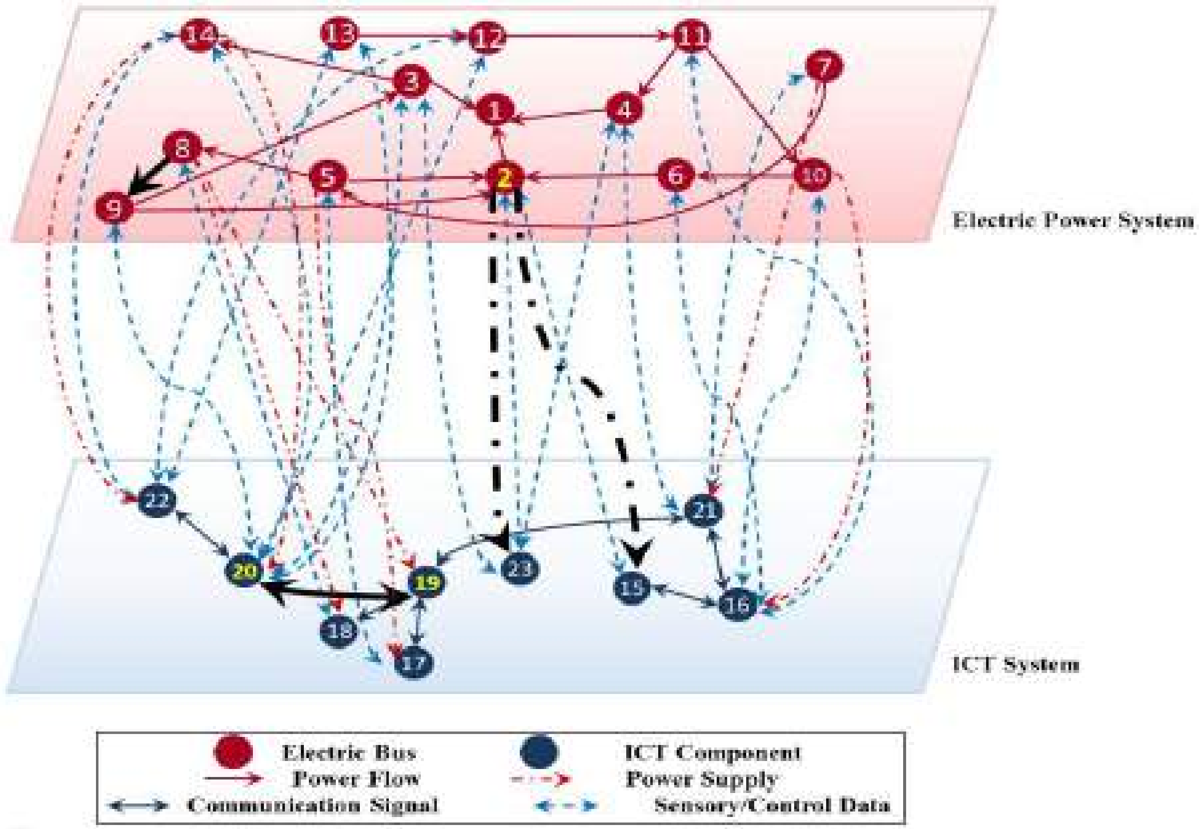




Unidirectional EPS-ICT model
(minimum loading)

Unidirectional EPS-ICT model
(average loading)

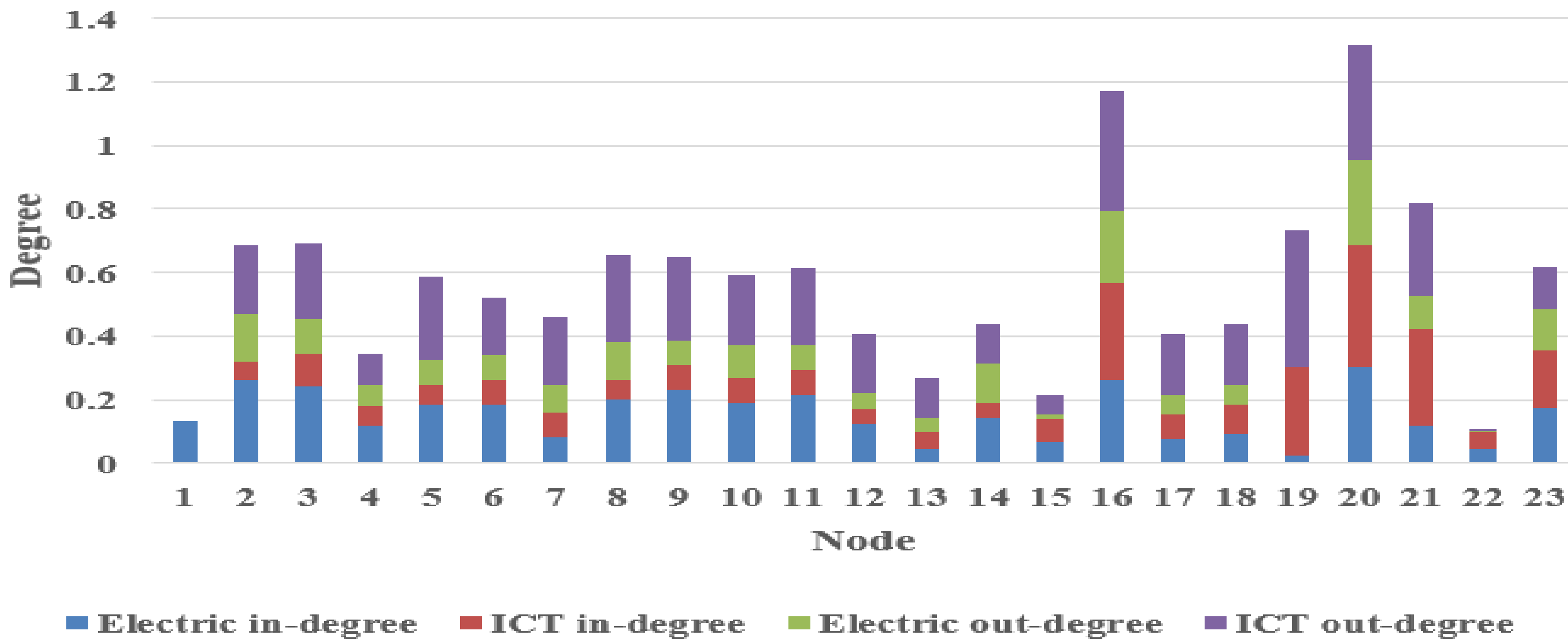
E7: Graphical representation



Three-dimensional interconnected EPS-ICT model (maximum loading condition)

The yellow colored nodes and black thick edges are the most critical components identified in subsequent analysis (max loading)

E7: Graphical representation of "contingencies"



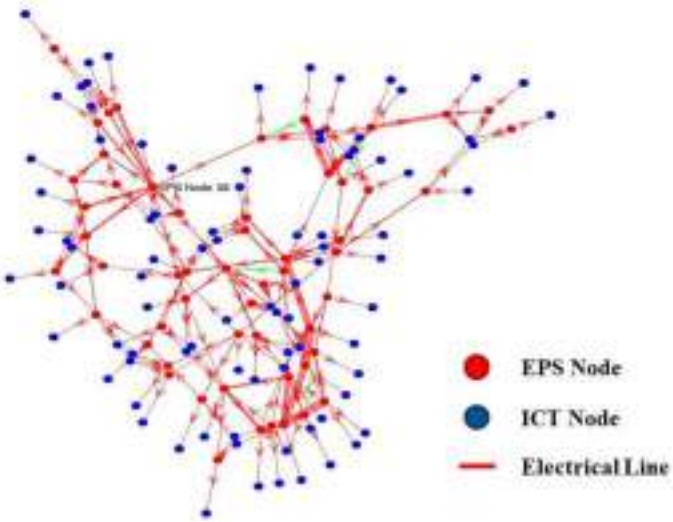
Vulnerability-weighted Node Degree identifying importance and dependency of each cyber and electrical node (power system maximum loading condition)

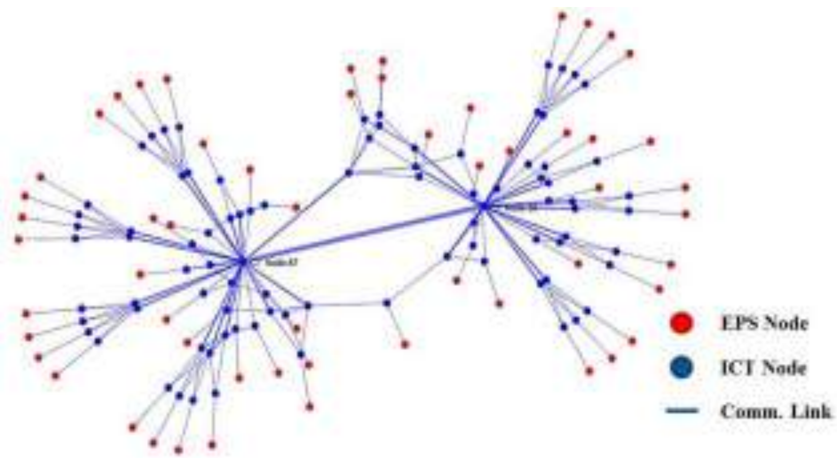
Standard Indices: Degree centrality (DC); Betweenness Centrality (BC); Closeness Centrality (CC); Eigenvector Centrality (EC); Efficiency; Vulnerability

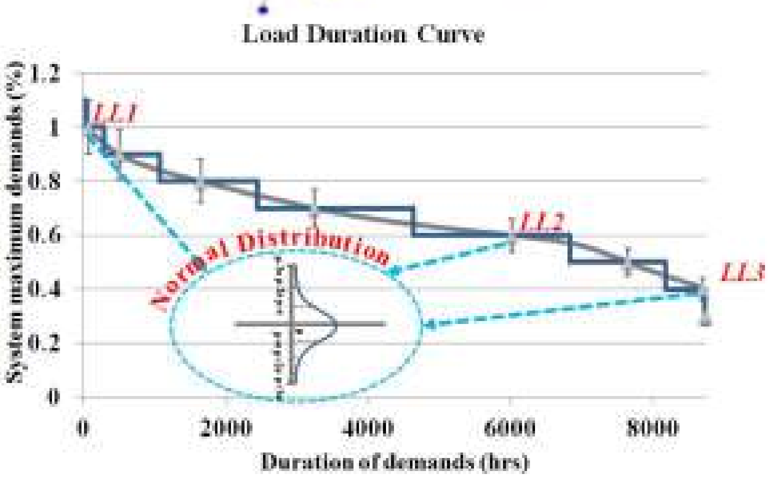
Vulnerability-weighted Node Degree (VWND) - integrates the degree-based centrality metrics and the Vulnerability indices

E7: Influence of Uncertainties in Cyber-physical System (CPS) Vulnerability Analysis

Realistic 1326-bus power transmission grid and an 88 star-connected ICT network divided into 6 control zones. (Due to the complexity of the network, only 21 buses at 400 kV level and 35 buses at 220 kV level are presented)

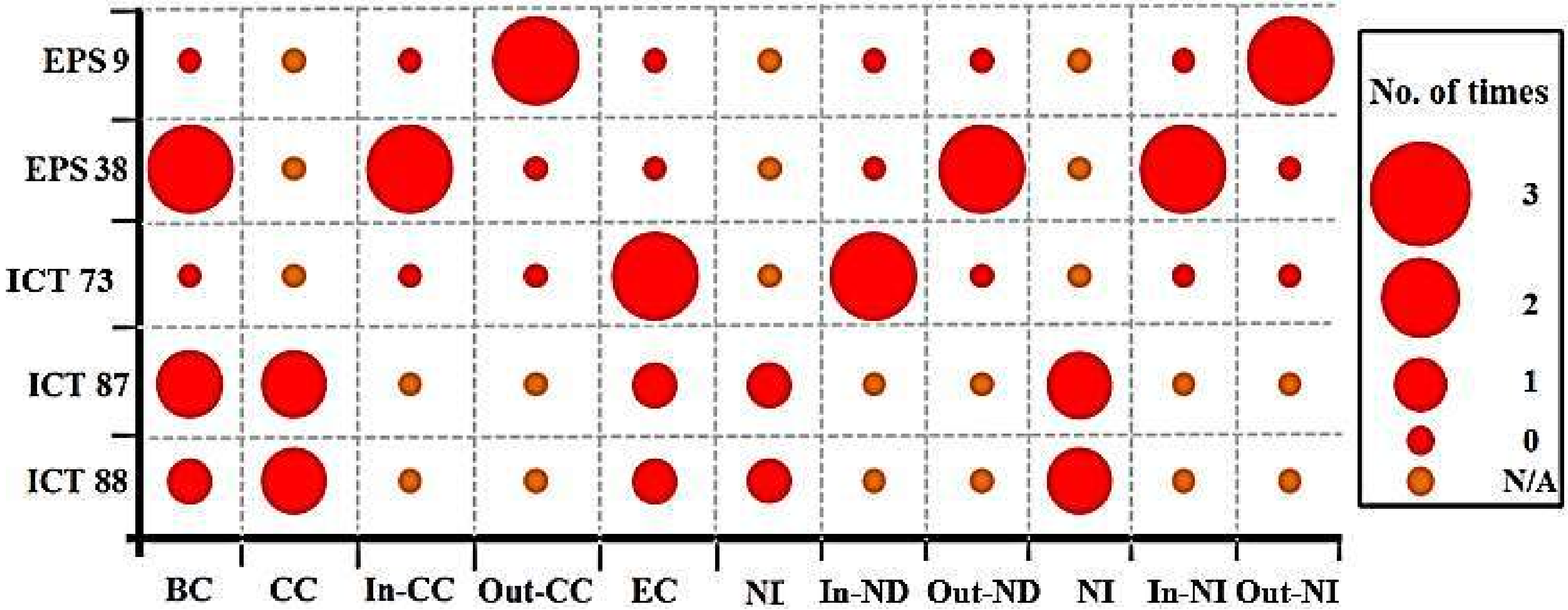






Probabilistic distribution of end-to-end delays

E7: Influence of Uncertainties in Cyber-physical System (CPS) Vulnerability Analysis



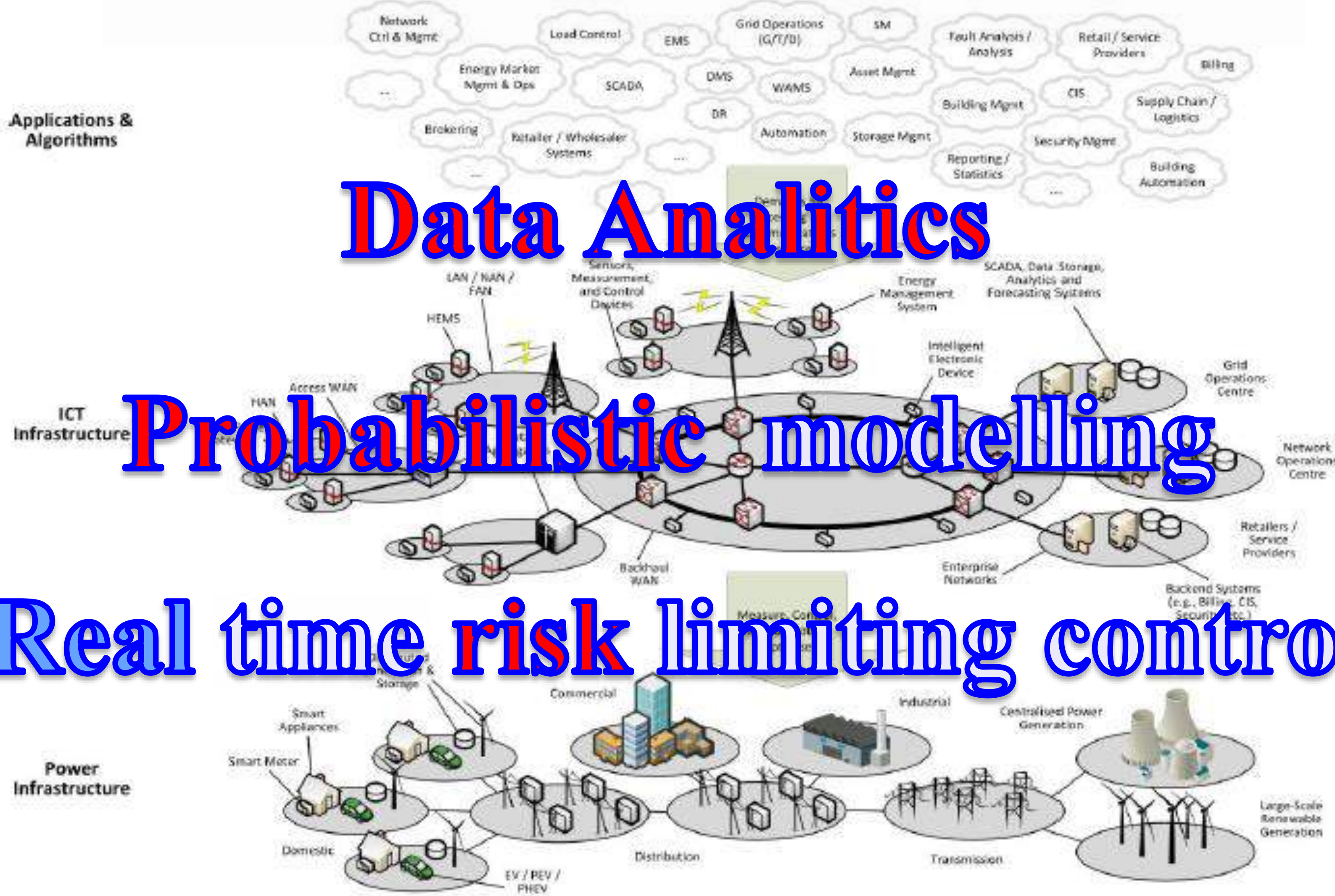
Number of times that nodes are identified as the most critical nodes by different indices

Betweenness Centrality (BC); Closeness Centrality (CC); Eigenvector Centrality (EC); Node Importance that combines the “strength” and the “degree”(NI)

Outline of presentation

- Drivers for change of design and operation of electrical power systems
- Challenges facing designers and operators of net-zero power systems to ensure system resilience
- Approaches to address some of the identified challenges
- Summary

Key areas to focus on to ensure resilience of future power grids



Data Analitics

Probabilistic modelling

Real time risk limiting control

Addressing identified challenges

DATA: Introduce Data analytics for planning, operation and control

- New skills of the workforce are required: re-training, re-skilling and employment of people from non-engineering (e.g., computer science, mathematics, communications, social science, etc.) backgrounds

MODELLING: Strong emphasis will need to be put on developing appropriate, most likely probabilistic models of components, processes and events

- New skills of the workforce are required: re-training, re-skilling and employment of people from non-engineering (e.g., mathematics, social science) backgrounds

CONTROL: New control approaches (stochastic distributed control), greater network automation, deliver real time risk limiting control of the system.

- New skills of the workforce are required: re-training, re-skilling and employment of people from non-engineering (e.g., control systems, mathematics, communications) backgrounds

One way to answer these challenges is

I have a key

I know how to use particular software/tool/ algorithm/ technique

Let’s find the door that it opens

Let’s find a problem that I can apply it to

There have been too many (to my liking) and still are research papers written using this approach

and the other

The door is locked

I have a practical problem that needs solving

I need the right key to open it

I have to find the best (simplest, cheapest, most effective) approach/tool/method to solve it

Some may argue though that a master key/picklock could be used in this case?

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