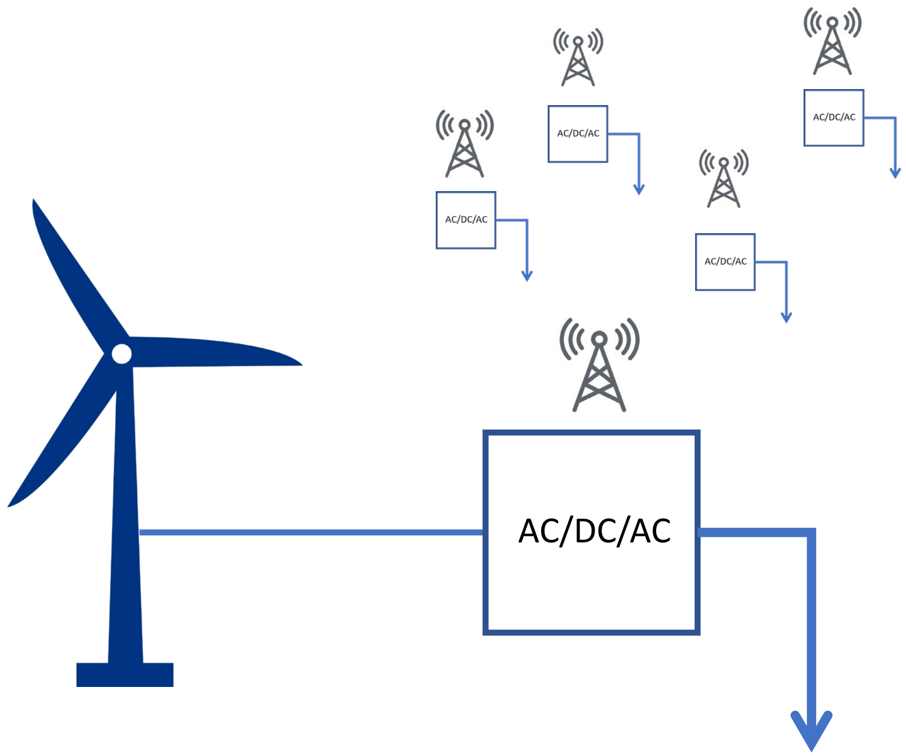
Micro-Flexibility: Challenges for Power System Modelling and Control

Spyros Chatzivasileiadis[1], Petros Aristidou[2], Ioannis Dassios[3], Tomislav Dragicevic[1], Daniel Gebbran[1], Federico Milano[3], Claudia Rahmann[4], Deepak Ramasubramanian[5]

[1] Technical Univ. of Denmark (DTU), [2] Cyprus Univ. of Technology, [3] University College Dublin, [4] Univ. of Chile, [5] EPRI

All authors contributed equally

Millions of Controllable Devices



Millions of micro-flexibility sources

- Supply follows Demand **and** Demand can follow Supply
- Full P-Q control (4-quadrant)
- Extensive communication
  - Direct Control
  - Local Control
  - Coordinated Control

BUT: How do these affect the dynamic response of the power system? And how can we take advantage of them?

The German 50.2 Hz Problem

- EN50438:2007 directive:
  micro-generators must shut off if frequency exceeds 50.2Hz

- But: they had not predicted the massive installation of solar PVs (several GWs)

- What happened?

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  "Flapping"

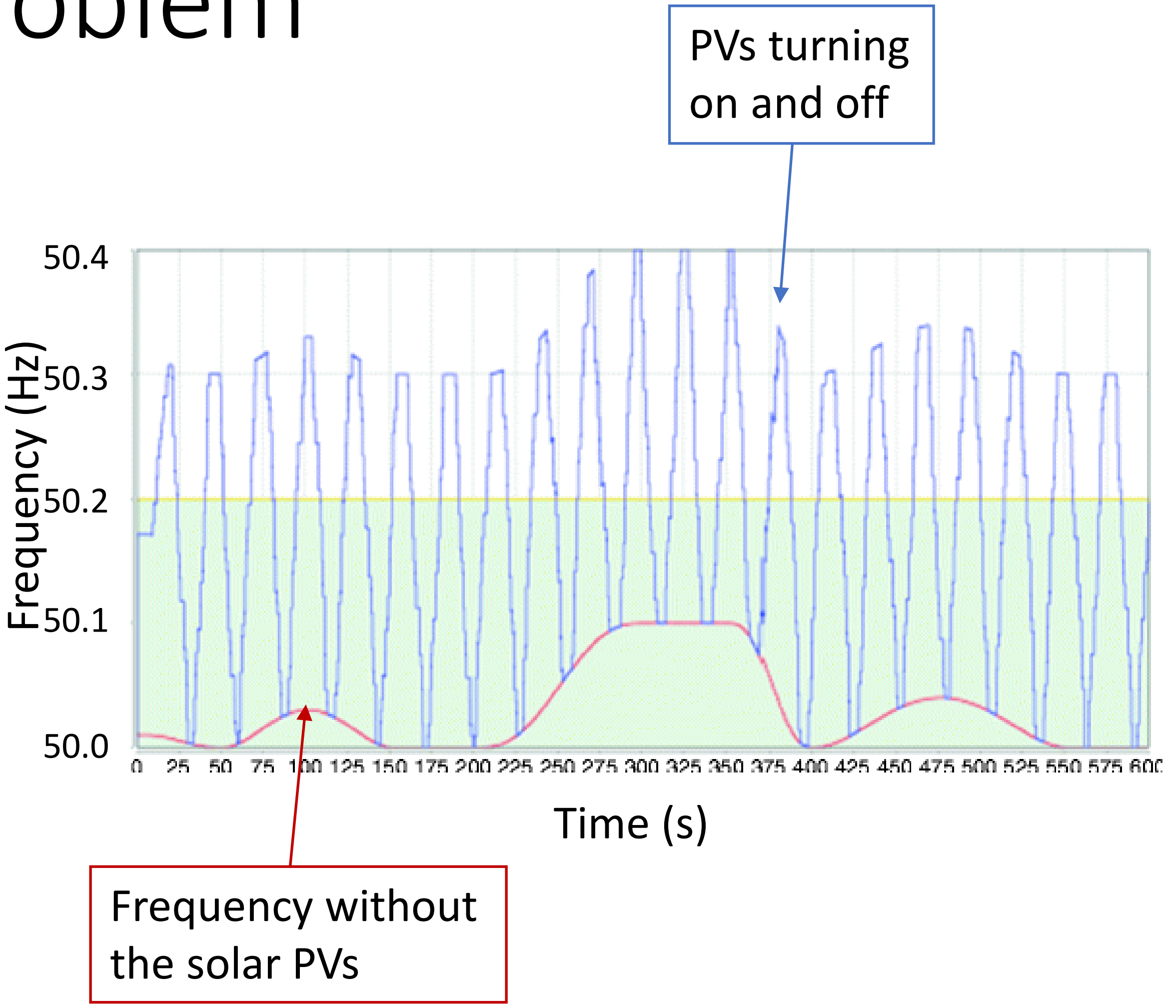


Figure from H. Hermanns, H. Wiechmann, Demand-Response Management for Dependable Power Grids, in Embedded Systems for Smart Appliances and Energy Management, 2012

The German 50.2 Hz Problem

Why did this happen?

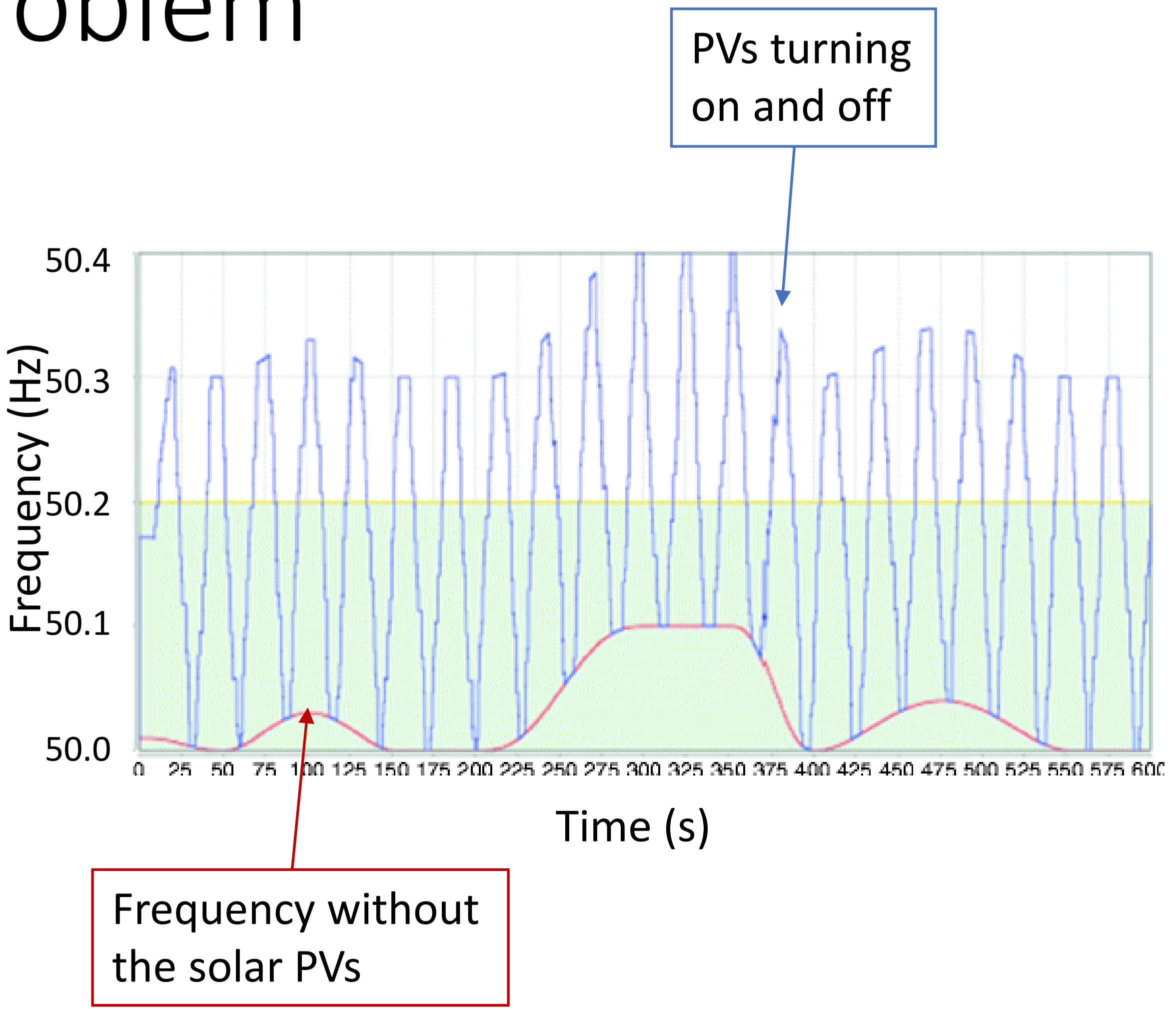
1. Discrete control (ON/OFF)

2. Stochasticity: difficult to plan how many generators to commit

3. Very large population of devices

4. No communication (local control)

5. Time delays (lag in measurement and in reaction)



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Millions of Devices

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Electric Vehicles

Solar PV

and many others...

Battery Storage

Heat Pumps

Electric Drives

Scope of this Paper

- Focus is on how the intrinsic characteristics and control of these devices affect our ability to simulate and assess the stability of power systems

- We identify challenges. Hopefully, you will find them exciting enough to work on their solutions

Outline

- Inverter-based resources: the key to extract the micro-flexibility
    - Opportunities and challenges from the shift to discrete modeling and control
- From the micro-level to the T&D interactions
- A Case Study

Inverter-based resources:

Opportunities and challenges from the shift to discrete modeling and control

Conventional Power System Models are no longer sufficient

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{y})$$

$$\mathbf{0} = \mathbf{g}(\mathbf{x}, \mathbf{y})$$

1. Do not capture the electromagnetic transients
2. Do not capture the discrete behavior
3. Do not capture the stochastic processes (noise, randomness, etc.)
4. Do not capture the communication and control time delays

From DAEs to Hybrid Stochastic DAEs

1. Need to capture the **discrete behavior →** move to Hybrid Differential Algebraic Equations (**HDAEs**)

$$\dot{\mathbf{x}} = \mathbf{f}^i(\mathbf{x}, \mathbf{y}), \quad i \in M = \{1, \ldots, N_f\}$$
$$\mathbf{0} = \mathbf{g}^i(\mathbf{x}, \mathbf{y})$$

Different sets of smooth DAEs for each interval, which are separated by the discrete variables

From DAEs to Hybrid Stochastic DAEs

1. Need to capture the **discrete behavior →** move to Hybrid Differential Algebraic Equations (HDAEs)

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Different sets of smooth DAEs for each interval, which are separated by the discrete variables

2. Need to capture the **stochastic behavior →** move to Hybrid Stochastic Differential Algebraic Equations (**HSDAEs**)

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \dot{\eta}),$$
$$\mathbf{0} = \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \eta),$$
$$d\eta = \boldsymbol{a}(\eta, t)dt + \boldsymbol{b}(\eta, t) \odot d\boldsymbol{w}(t)$$

Stochastic variables

Drift Term of the Wiener process

Diffusion Term of the Wiener process

Wiener process increments

HSDAEs: Studying system stability is no longer straightforward

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1. Need to capture the **discrete behavior:** move to Hybrid Differential Algebraic Equations (HDAEs)

2. Need to capture the **stochastic behavior:** move to Hybrid Stochastic Differential Algebraic Equations (HSDAEs)

Challenges

Very difficult to study the stability of the system. **Impossible** to perform a small-signal stability

- **Linearizing HSDAEs is not possible**. Sensitivities w.r.t. discrete variables are always null

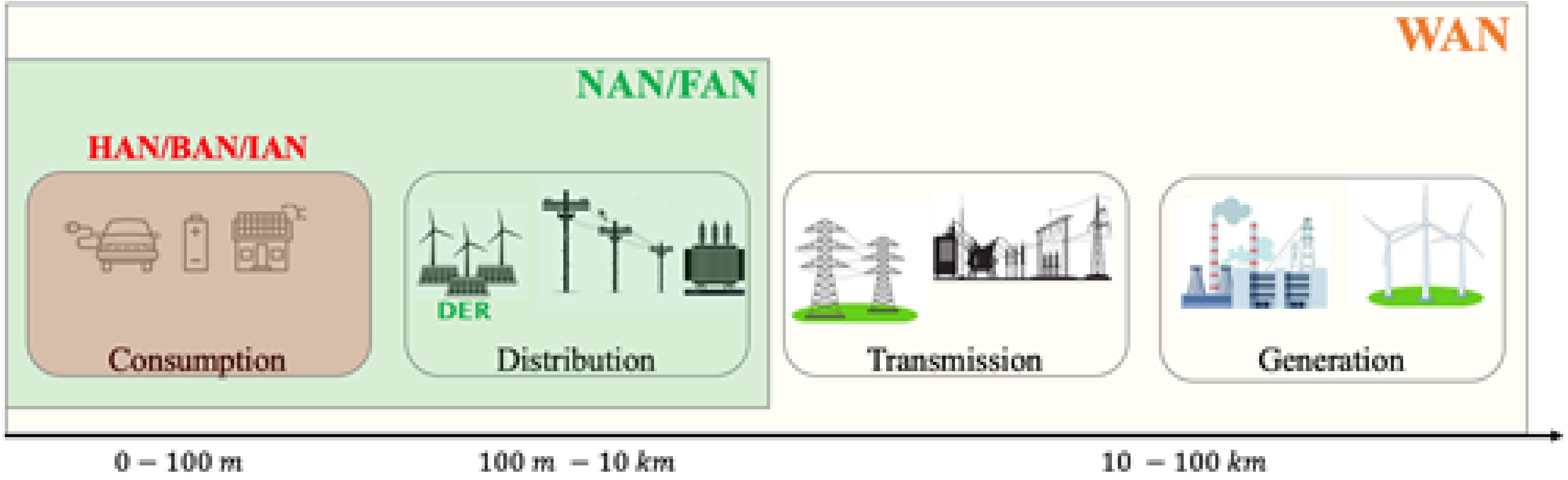
- **Average models** can address stochasticity by substituting the diffusion term with the expectation → **lose the added information** from discrete variables and noise

And what about Time Delays?
Besides measurements, also communication delays

- Communication belongs to the key infrastructures to extract the micro-flexibility and efficiently control the millions of controllable devices

Three Layers

Home-Area Network (HAN)	Neighborhood-Area Network (NAN)	Wide-Area Network (WAN)



Communication Network Requirements

	Bandwidth required	Latency
Home-Area Network • Home Automation • Energy Management • Central Control of Critical Devices	Up to 100 kbps per device Up to 100 m (0.1 km)	**200 ms – 15 s**
Neighborhood/Field-Area Network • Demand Response • EVs • Outage and Restoration Mgmt. • AMI	100kbps – 10 Mbps Up to 10 km	**200 ms – 1 min**
Wide-Area Network • Wide-area Monitoring • Wide-area Control • Wide-area Protection	10 Mbps – 1 Gbps Up to 100 km	**<0.1s** Most utility vendors seem to prefer cellular technologies (fast and efficient). Satellite as a backup

Modeling Time Delays

Need to capture time delays

$$D_i(s) = e^{-T_{di}s} \simeq \frac{1 - \frac{1}{2}T_{di}s}{1 + \frac{1}{2}T_{di}s}$$

Time Delays are exponential functions in the Laplace domain → non-linearity makes stability assessment with Nyquist cumbersome

First-order Padé approximation

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First-order Padé approximation

Challenges

Time delays make the modeling and numerical solution much more complicated

- **Padé approximants** is a solution: transform a delay into a set of ordinary differential equations
- **Still, loss of some intrinsic idiosyncrasies**, e.g. the "quenching" phenomenon (system unstable with constant delay can become stable if we apply time-varying delays)

Stochasticity and Randomness do not only introduce challenges. They also offer Opportunities.

- **Stochasticity** can be exploited to achieve synchronization (e.g. oscillators) or **smoother response to a disturbance**

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- **Randomness** can be exploited to implement effective decentralized controllers that **deal well with large numbers of discrete devices** (more about this in our Case Study)
  - From a modeling and control point of view, it is too large a computational effort to apply continuous control to each single micro-device.

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- **Stochasticity** can be exploited to achieve synchronization (e.g. oscillators) or **smoother response to a disturbance**
- **Randomness** can be exploited to implement effective decentralized controllers that **deal well with large numbers of discrete devices** (more about this in our Case Study)
  - From a modeling and control point of view, it is too large a computational effort to apply continuous control to each single micro-device.
- The key point of the decentralized approach is to introduce a stochastic decision process.
  - **Higher number of devices = more predictable behavior** = better response of the stochastic control
  - Challenge: Probability function must be stationary and ergodic (~"steady-state" and "stable")

Adoption and practical use also face challenges

- **"Trustworthiness" of the resource availability**: the operator needs to build trust in that a certain class of devices will always be available and reliable to offer power reserves; otherwise, conventional power reserves will remain necessary

- **Incentives to participate to grid services** from the consumer side:
  - Usually a monetary award;
  - But cannot guarantee that the device will react as desired all the time; this is only in "expectation" and over a long period of time. In specific instances, micro-devices can behave even in an opposite way from what is desired

- Implementation issues: **require** a vast **standardization** campaign

Standardization: Interconnection requirements shall be Control-agnostic

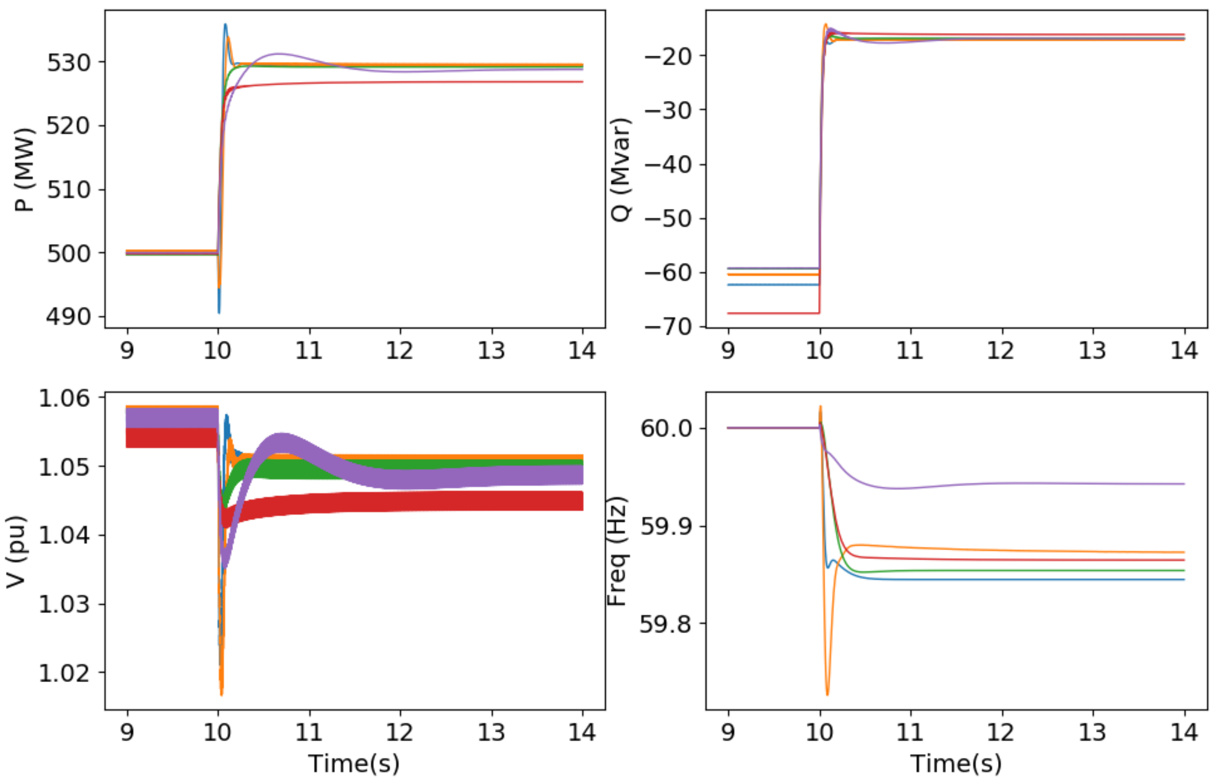
Example:

- 5 types of different inverter controls
- **All different control types show a similar response**

Details:

- 1 Virtual-oscillator based
- 1 PLL-based
- 3 droop-based with different control loop implementations
- 4 have 5% droop, 1 has 2% droop

National Grid and Germany (VDE) already follow this paradigm: have issued performance based requirements; do not mention any particular inverter control structure



From the micro-level to the T&D interactions

What is the impact of the millions of "micro-devices" at the "macro-level"?

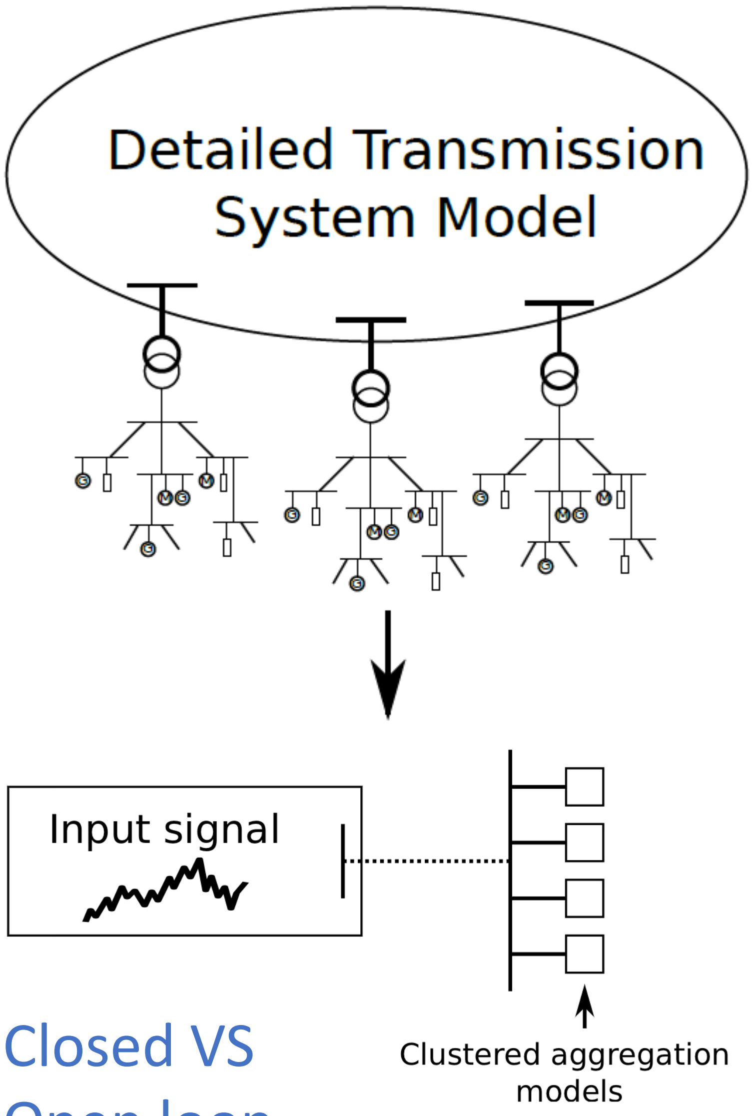
- The aggregate response of millions of devices can significantly affect the bulk transmission system – or, so we hope
- How do we model and analyze the overall system response?
- Computationally **impossible** to handle the granularity
    - Dynamic analysis: 100'000s of Hybrid DAEs
    - Operational planning: non-convex problems with 100'000s of variables
- Two approaches:
    - Aggregate models
    - Equivalent models

Aggregate Models

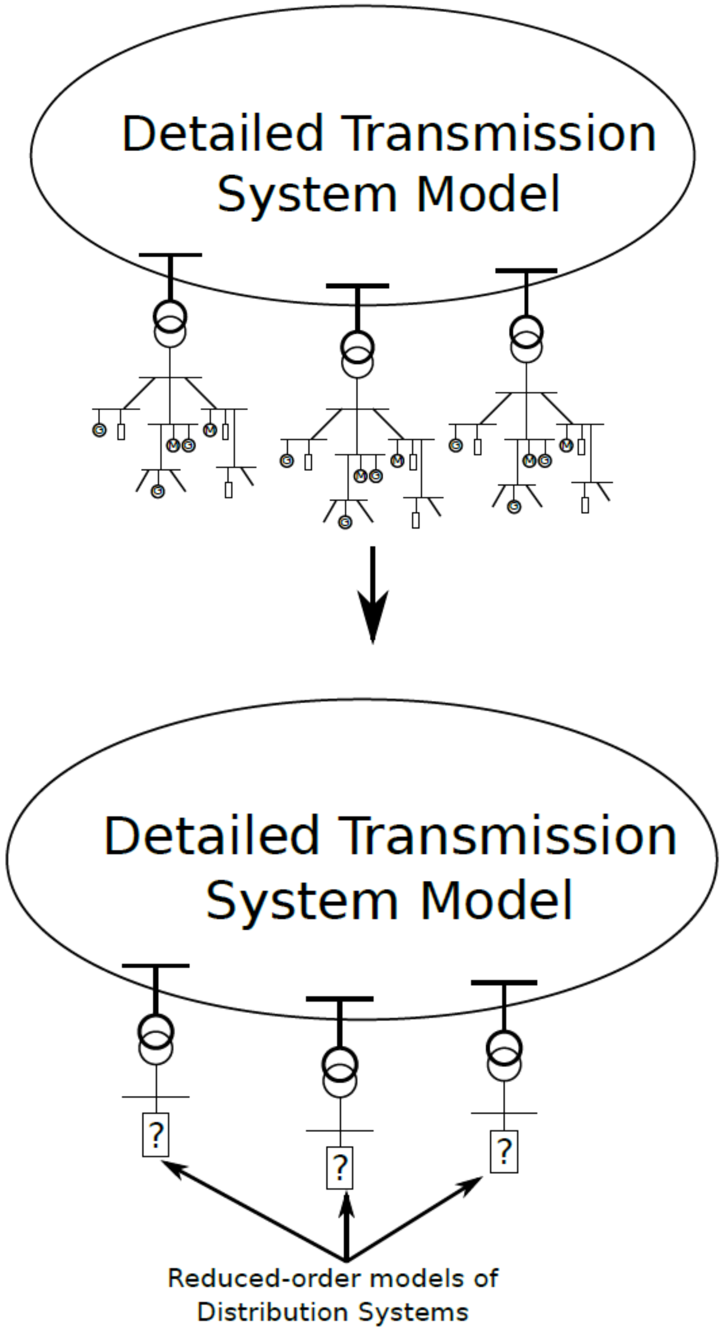
- Model the collective response of **similar** units
  - Across voltage levels
  - Across geographical locations

- Computationally efficient → reduces the original model from 100’000 to a few states

- Challenges:
  - **Can only capture the impact on global variables**
  - **Cannot consider** different controls in different **geographical locations**
  - Disregard the network-related security constraints; constraints related only to the type of the devices can be modeled, e.g. ramp-rates, max. power output, etc. → optimistic estimation of the response
  - Behavior w.r.t. grid-code requirements is ignored



Closed VS
Open loop



Equivalent Models

- Equivalents of individual distribution networks including all DERs, flexible loads, and controls
- Allows to keep the TN model intact
- Can model the DN response including centralized controls and communication
- Challenges:
  - Disregard the network-related security constraints inside DNs
  - Behavior w.r.t. (most) grid code requirements is ignored

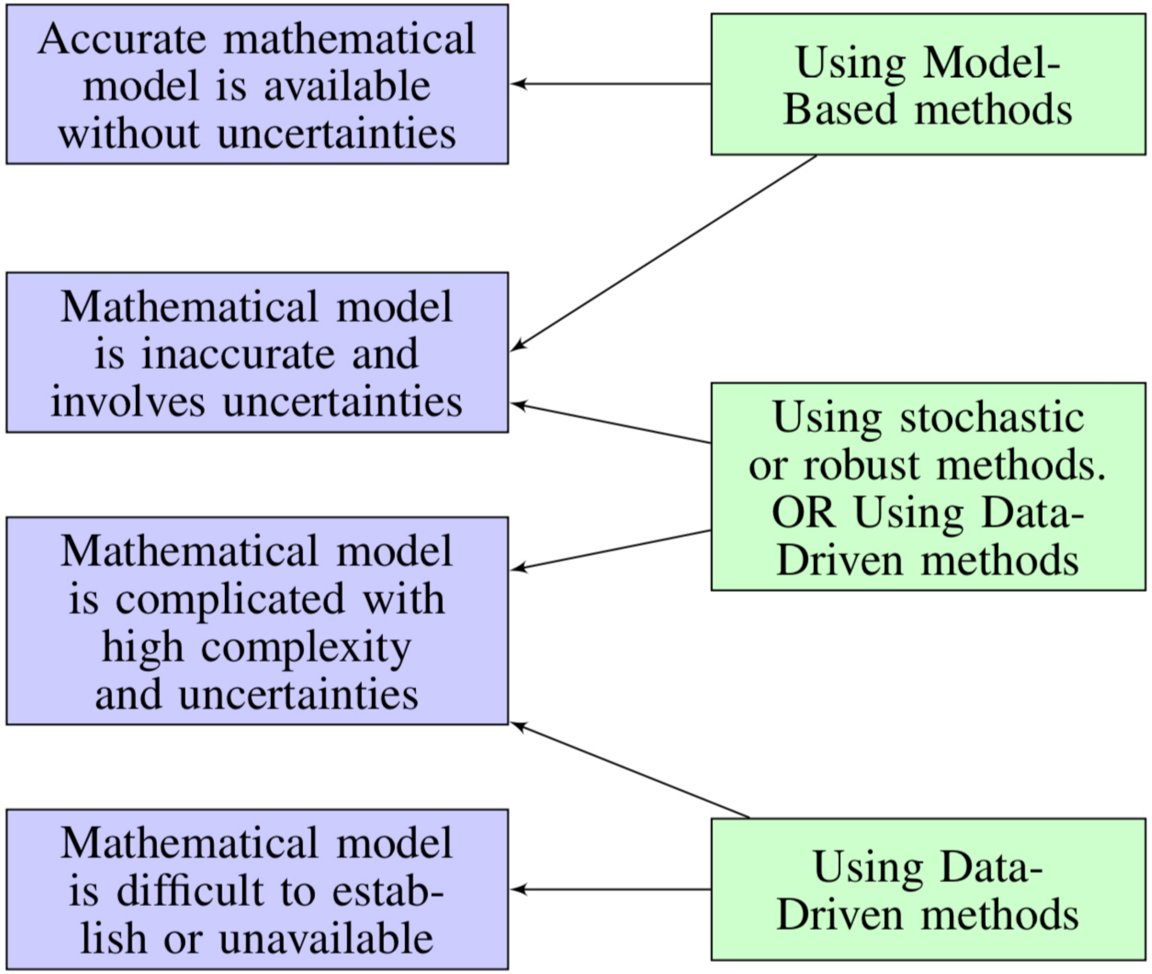
Both aggregate and equivalent models

Model-Based or Data-Driven?

- As the systems get larger and more complex, the model error and uncertainty increases
  - The details of some models are not available (i.e. black-box ML-based controls)
  - Very challenging to build an accurate aggregate or equivalent model

- Model-based methods:
  - Need accurate models of the network, units and controls, and communication
  - Need ways to handle uncertainty (in most methods surveyed Monte Carlo approach)

- Data-driven methods:
  - Learn from the data → need enough data
  - Need ways to handle uncertainty



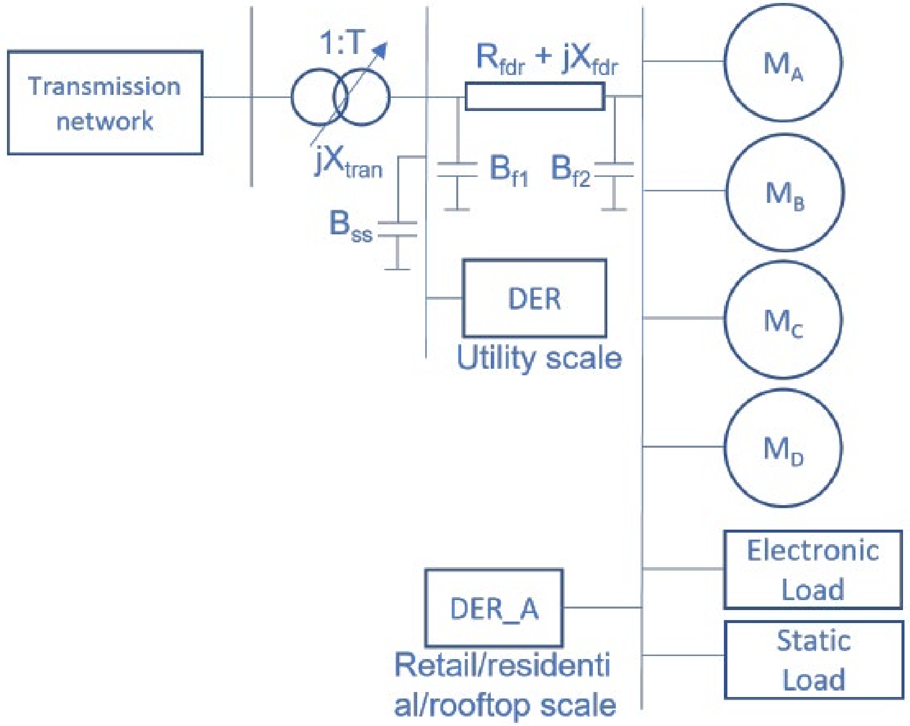
Aggregate and Equivalent Models: Uses in the Industry

- Widely used in the industry
  - Aggregate models to get a first “idea” of the system behavior
  - Equivalent models for more detailed analysis

- **Immediate need: Ability to parameterize aggregate/equivalent models**
  - Often missing measurement data, especially event-based data which are crucial for the parameterization

Parameterizing Models: Challenges

In the paper, we include an example of parameterizing an equivalent DN model

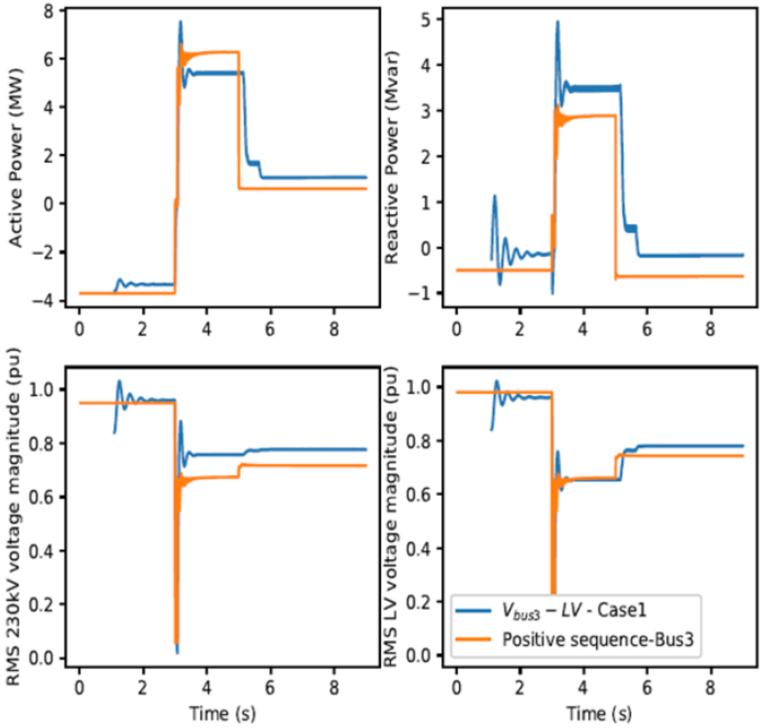


Challenges

- Capture the behavior of 1ϕ faults or unbalanced operation
- Capturing response to protection and grid-code requirements (aggregating discrete "events")
- Capturing uncertainty (optimistic, robust, averaged?)

Equivalent Models and Full T&D Models

- **Equivalent models** need to be appropriately parameterized, so that their response is neither too "optimistic" nor too "pessimistic"



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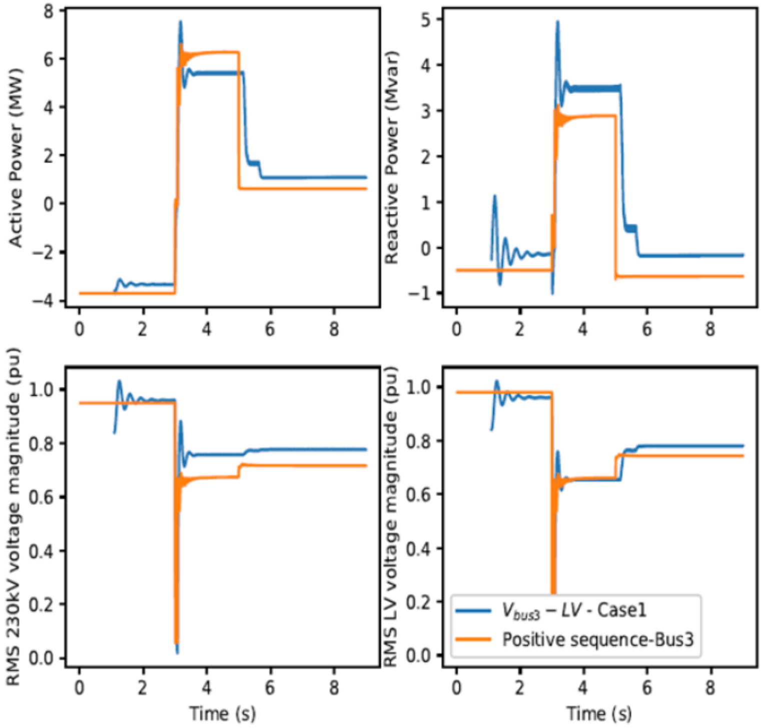


- **Full T&D Models** are <u>not</u> out of the question

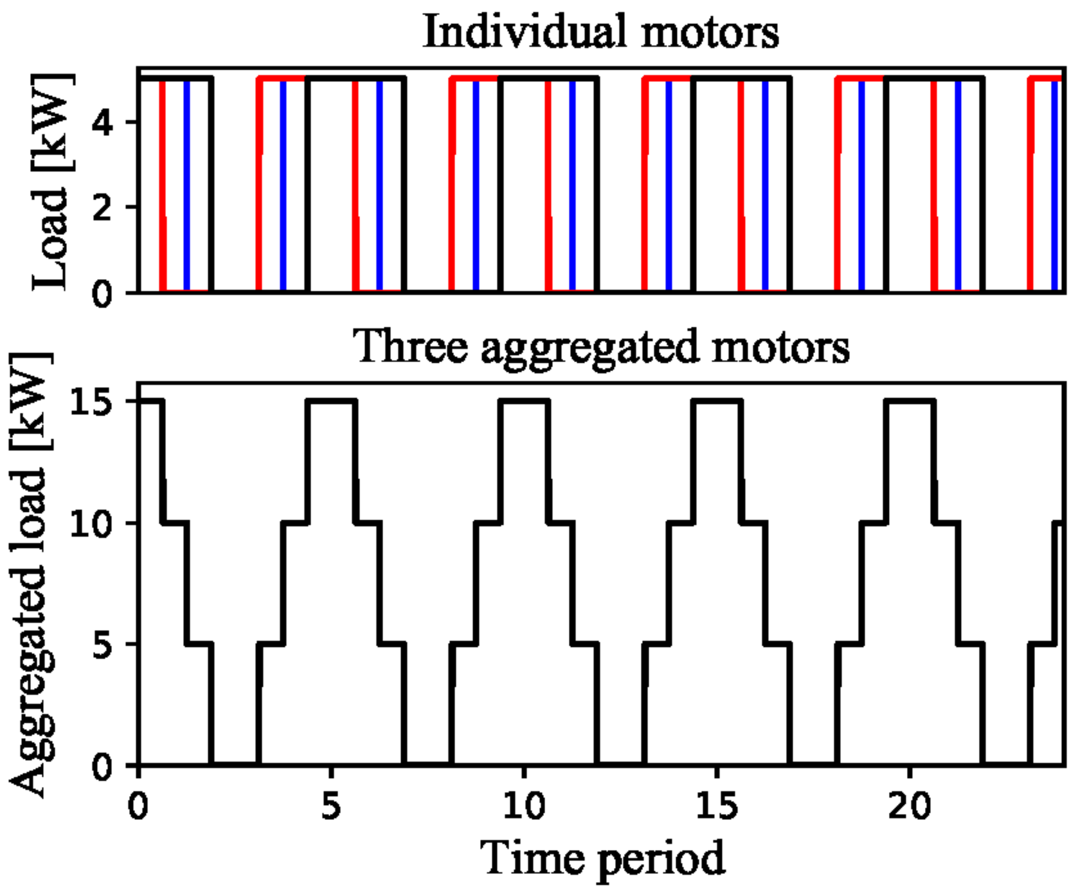
- Pros:
  - accurately capture the full level of detail

- Cons:
  - besides computational complexity, data might not be available

- **Research track**: synthetic data available; **design simulation approaches for the full T&D model,** e.g. co-simulation, better solvers, etc.

A Case Study

Extracting micro-flexibility: a simple example
Baseline Case

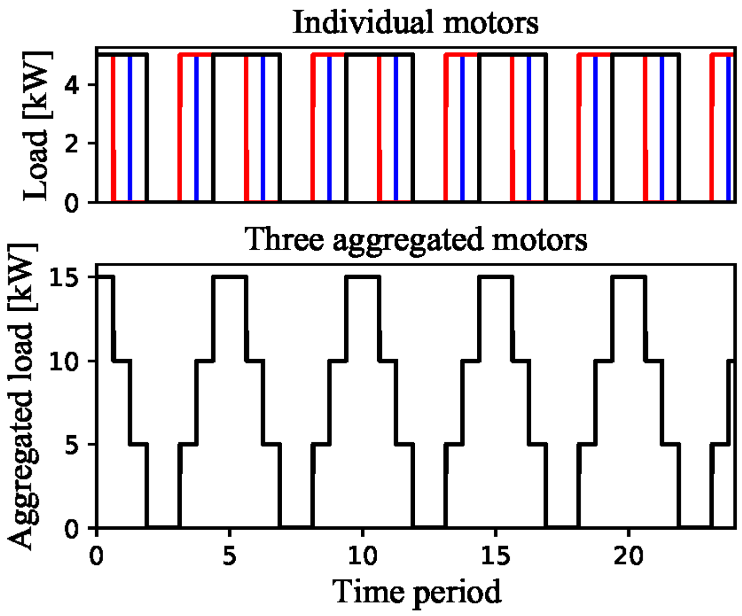


- 3 motors of 5 kW each
- 50% Duty Cycle each
- They turn on/off at different times

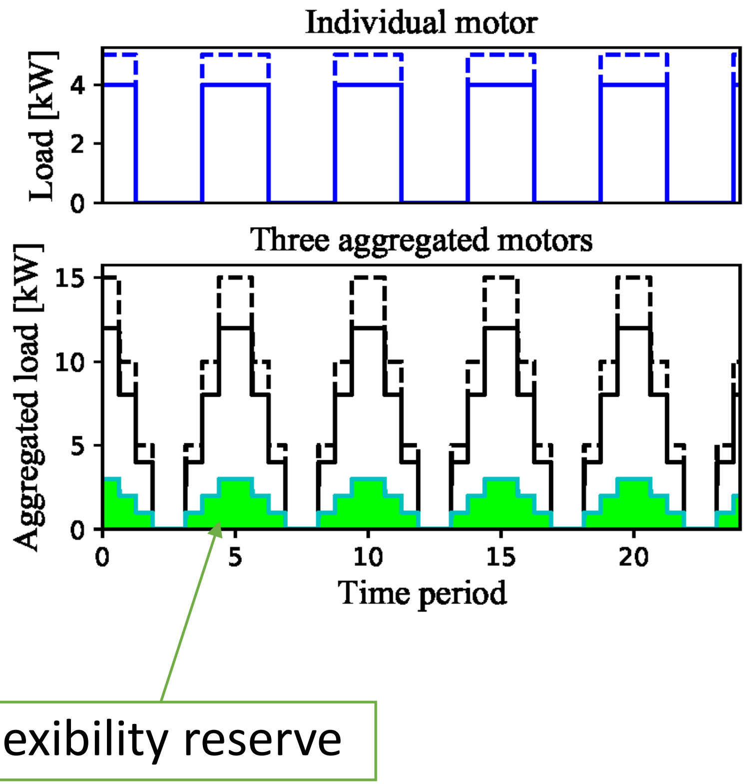
- The aggregated demand varies

Extracting micro-flexibility: a simple example

Base Case



Flexibility in Demand



Micro-flexibility: Aggregator can control 20% of the demand of each motor

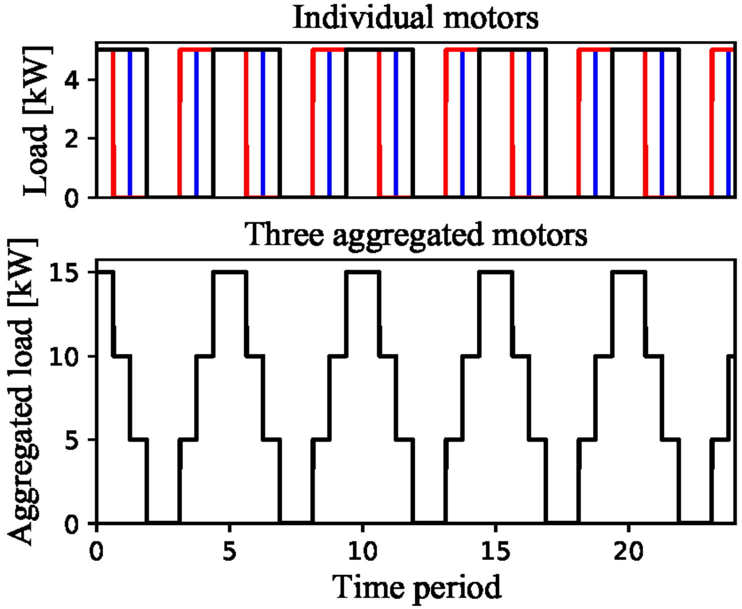
Inconsistent, varying flexibility reserve

Why?

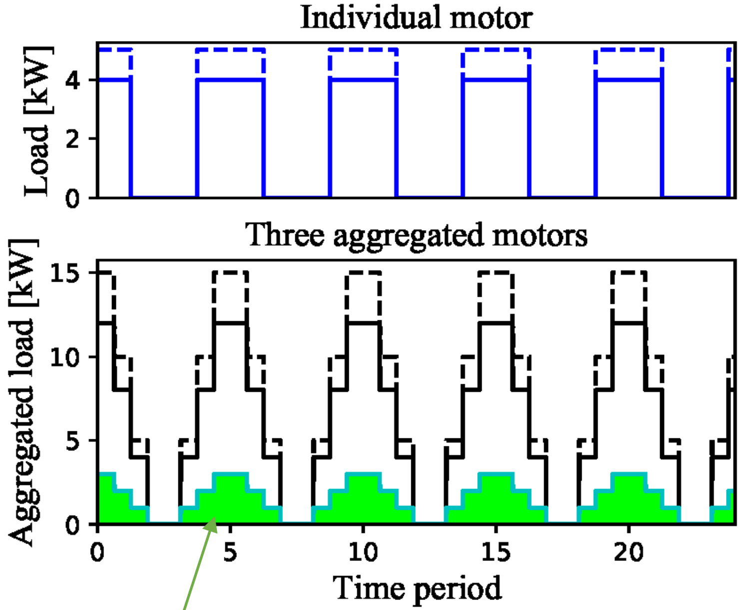
1. **Very few devices, and/or**
2. **Devices operate in a "synchronized way"**

Extracting micro-flexibility: a simple example

Base Case

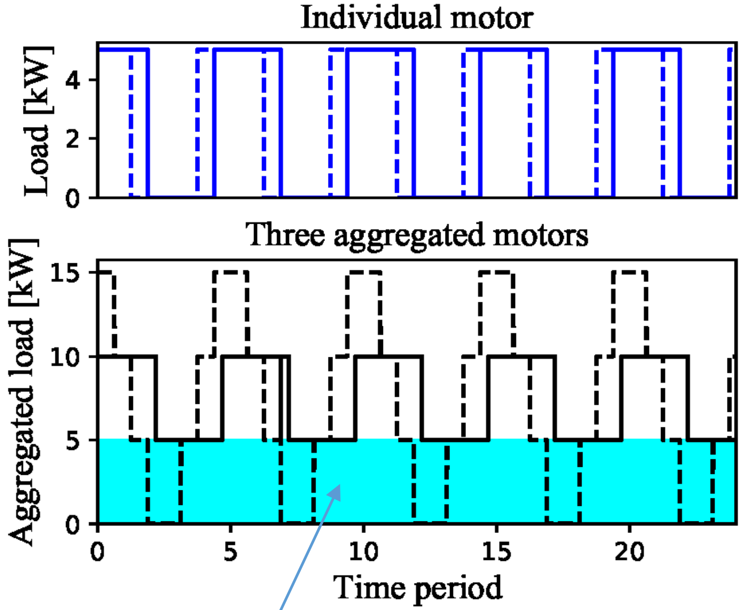


Flexibility in Demand



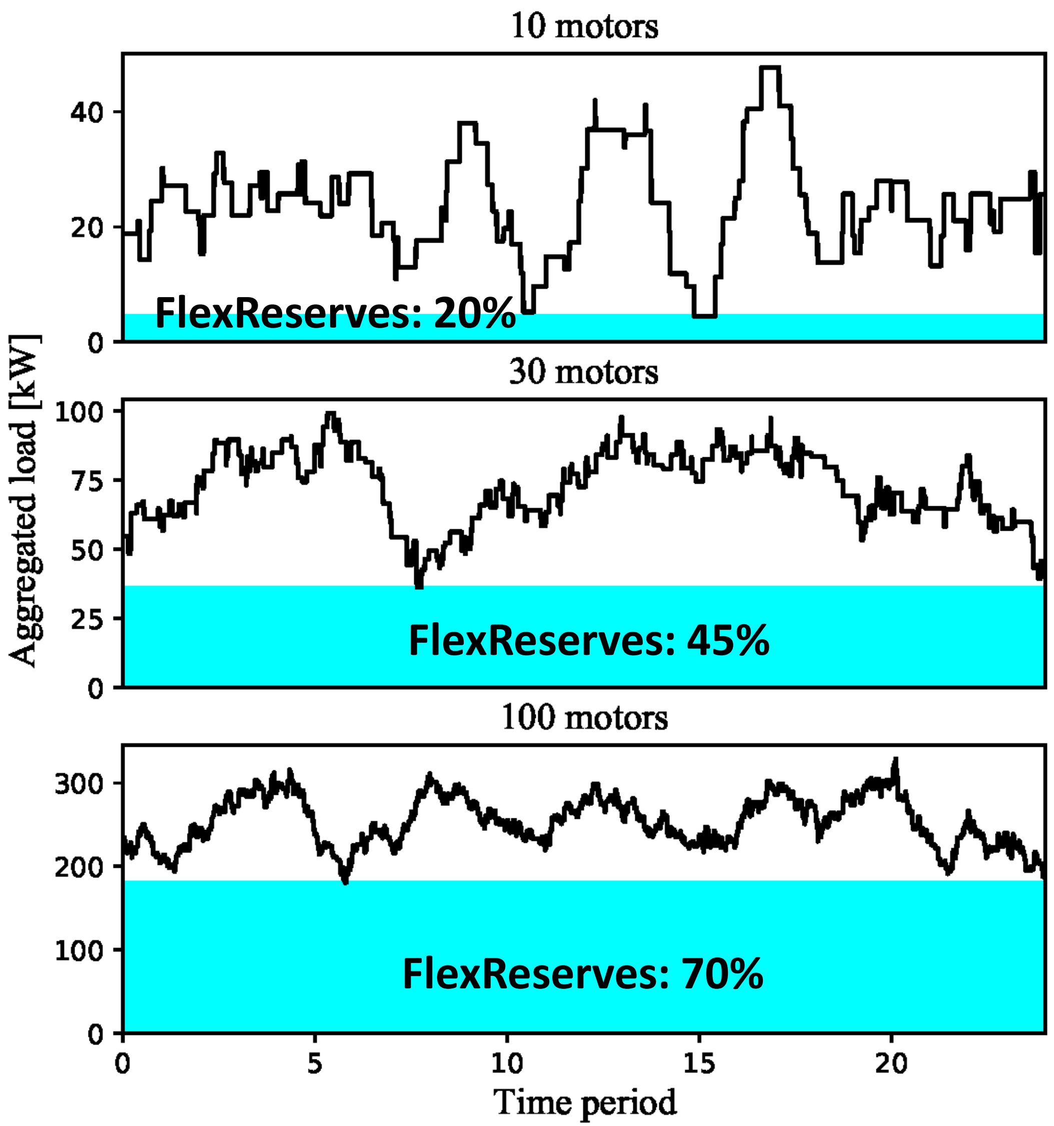
Inconsistent flexibility reserve

Shifting one motor in time

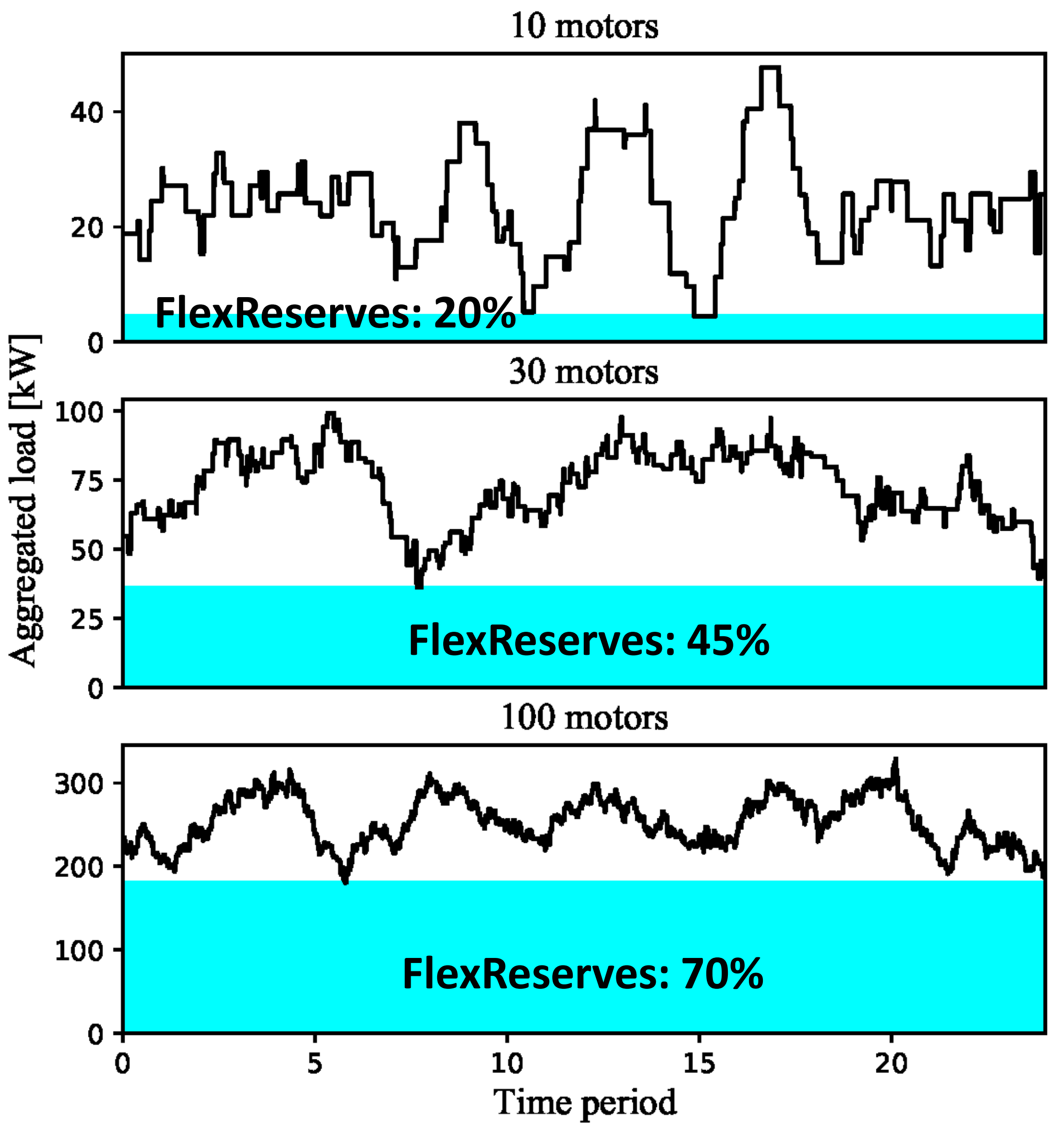


"Inducing Randomness": Can achieve a continuous constant flexibility reserve

(Population) Size does matter



(Population) Size does matter

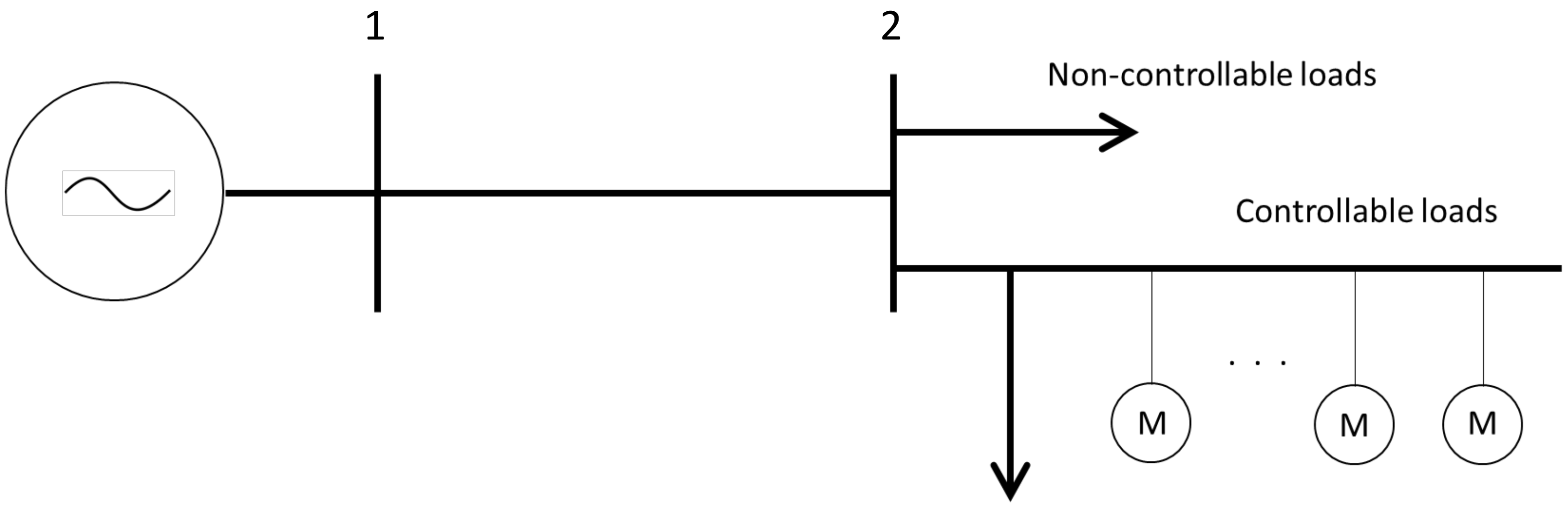


- **"Trustworthiness":** If we want DER to become a reliable participant in grid services, we need them to achieve a satisfactory reliability across stochastic operation

Takeaways:

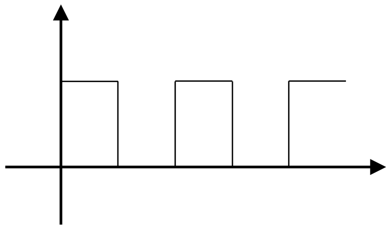
1. A certain degree of **randomness** is important
2. **Larger populations** increase reliability of flexibility offers
3. **Aggregating** randomly operating loads with similar behavior/characteristics can play a central role in handling the modeling and control challenges

Case Study:
Two-bus system with Controllable Loads



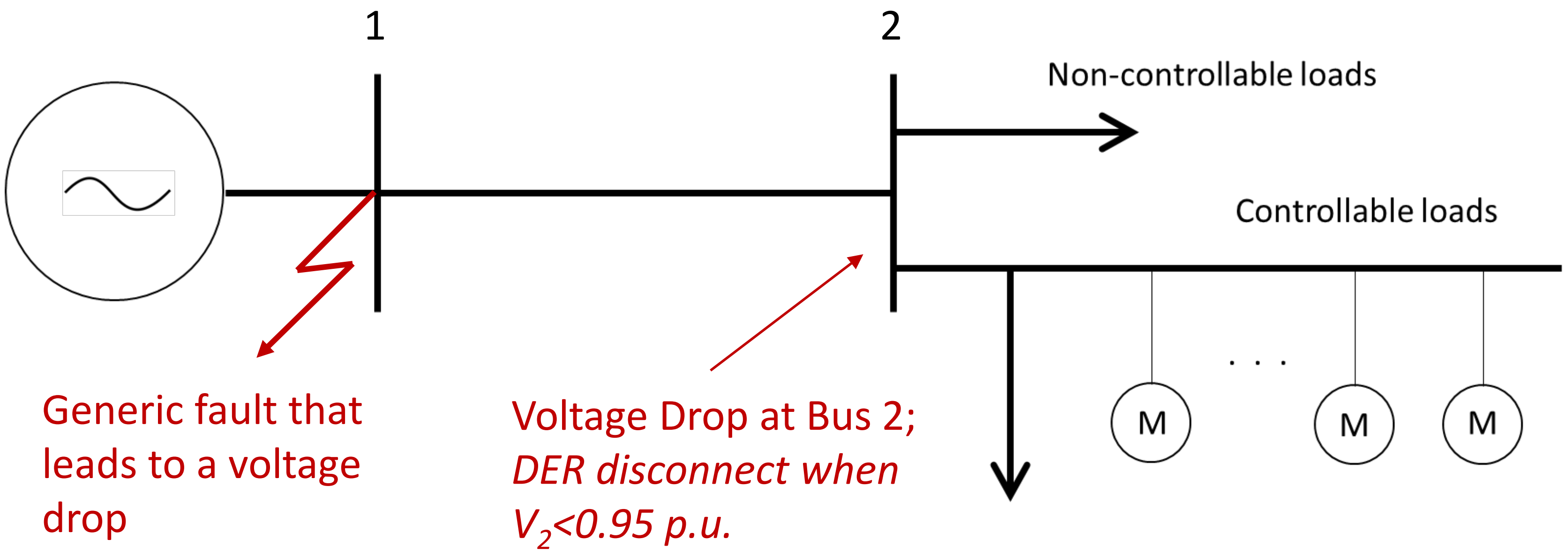
- Total Load: 200 devices (~5 kW each)
- Controllable Load: 100 devices

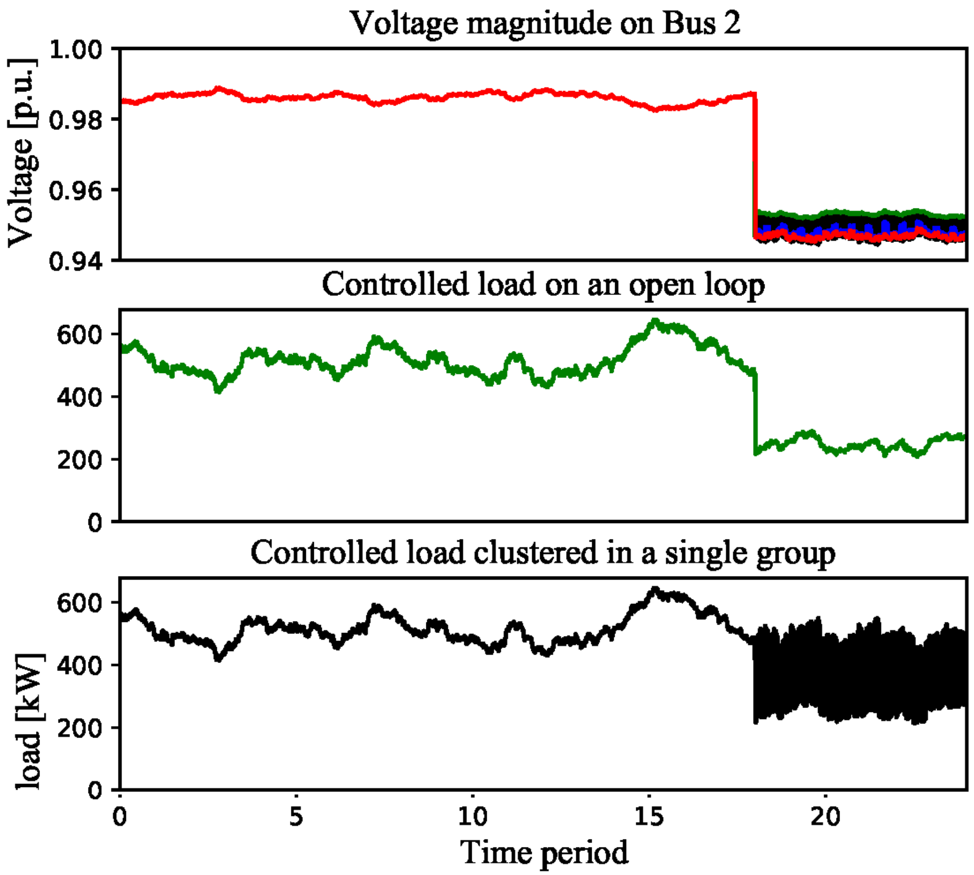
- Many different types of controllable loads
- One example: Heat Pumps



For every load:
50% Duty Cycle

Case Study:
Two-bus system with Controllable Loads





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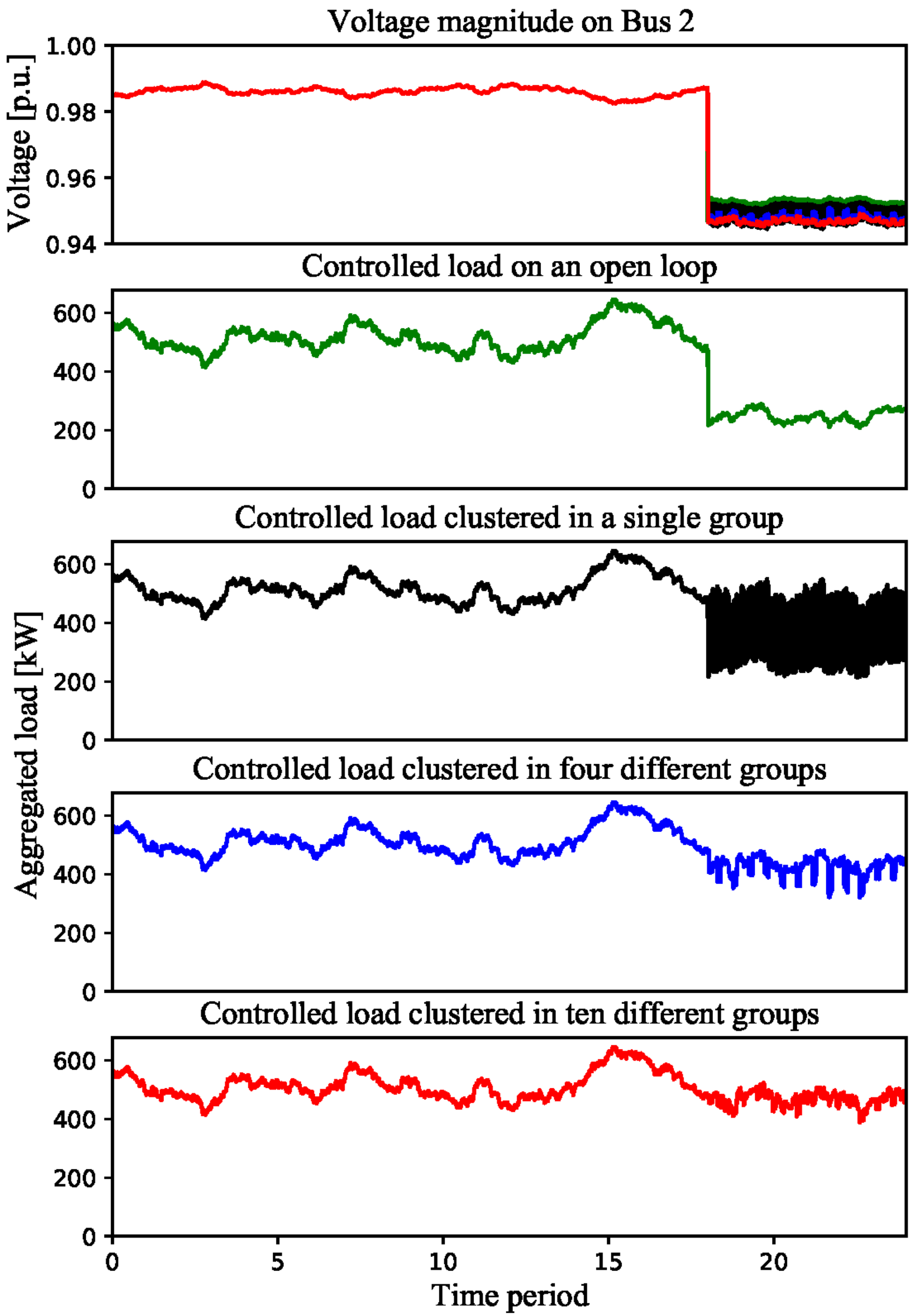
Open-loop vs Closed-loop

- Open-loop control:
    1. All controllable devices disconnect when V_2<0.95 p.u..
    2. Voltage stabilizes a bit above 0.95 p.u.
    3. All remaining devices can continue operating safely
- Closed loop control
    1. If designed naively, endless "flapping" can occur
    2. Known to happen in the Volt-Var Control of PV inverters (see also the German 50.2 Hz problem)

Takeaway: Naïve closed-loop control is worse than open-loop control



Clustering helps

- Cluster devices with similar characteristics (i.e. equivalent models) and apply different control parameters

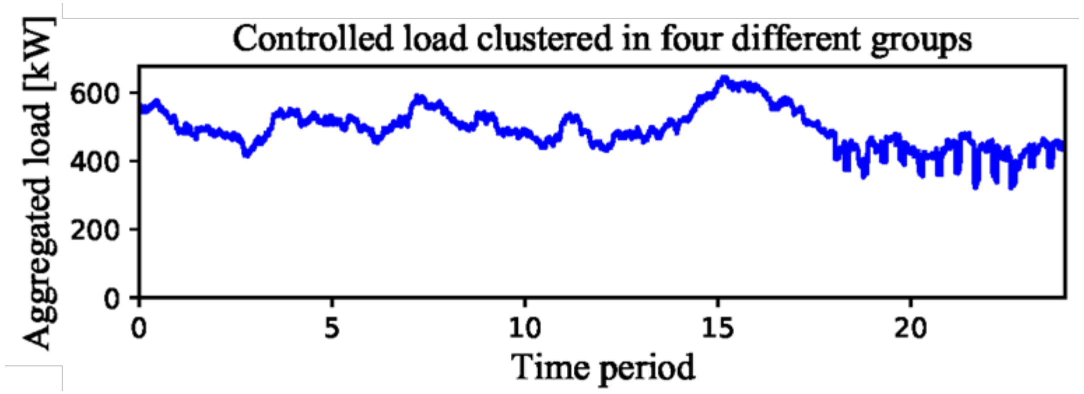
- Reduces the control effort of each device.
  - If clustered in 4 groups, devices respond 4 times slower (i.e. one group at a time)
  - If clustered in 10 groups, devices responds 10 time slower

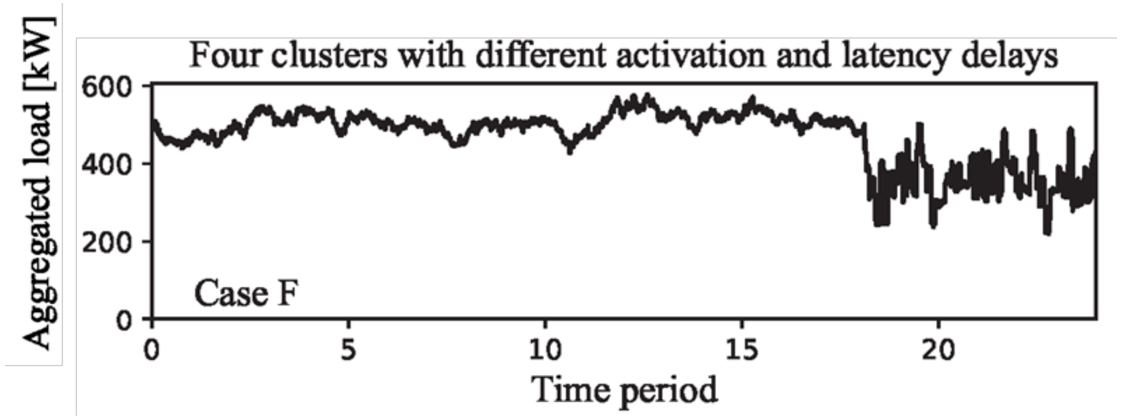
- More clusters, less flapping

- But:
  - By increasing the number of clusters, we increase the time delays → can result in too slow response.
  - Protection devices might act sooner → we render the flexibility obsolete

Takeaway: no simple answer; more clusters result to a smoother <u>but</u> slower response

The effect of Time Delays

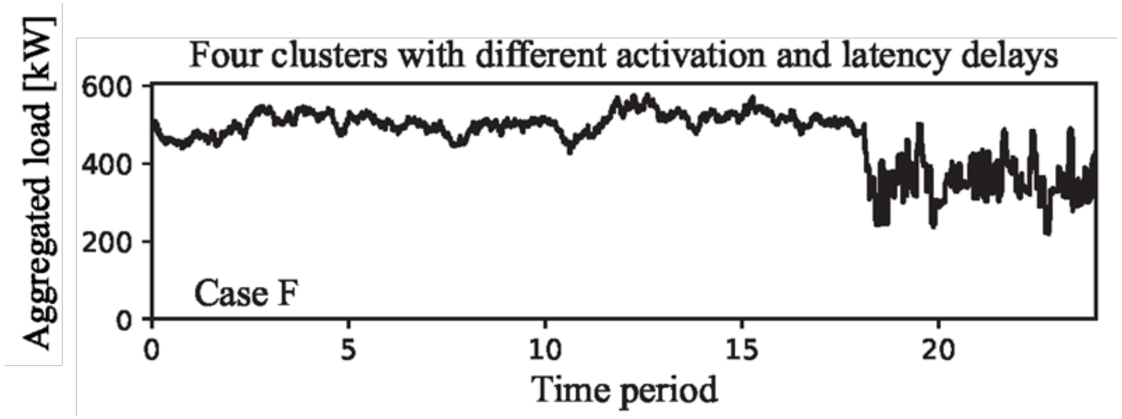


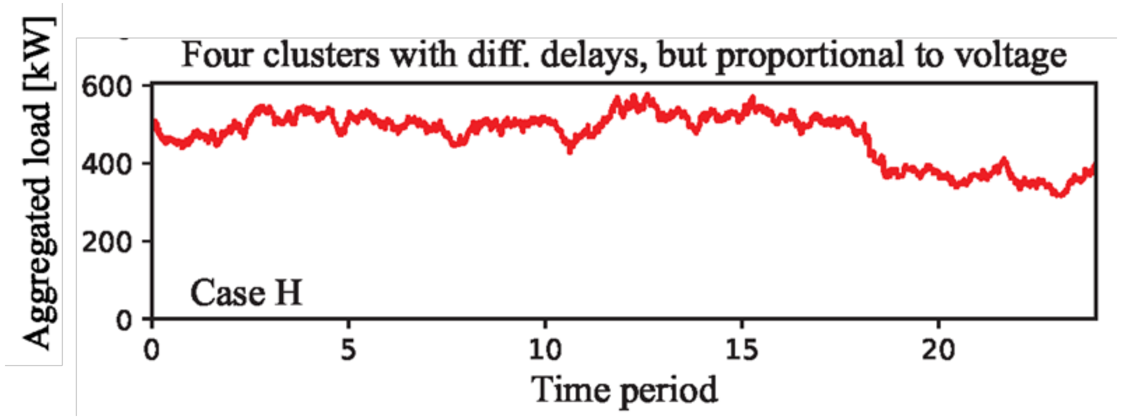


- Individual clusters of devices responding with a different latency (e.g. corresponding to different classes of devices) may not necessarily lead to a smoother response

- Stressing the **need for careful tuning**

Going beyond randomness: Exploiting prior knowledge





- Exploiting the knowledge about the system, local measurements, and the communication infrastructure can deliver simple and much more effective control strategies

Conclusions and Main Takeaways

- Challenges arising from the granular control of millions of devices
  - Move to discrete models
  - Include stochastic behavior and probabilistic control
  - Need to consider time delays (in measurements, communication, and control)
- Randomness: both a challenge and an opportunity
- Stochastic Controllers offer benefits. But there are barriers for their adoption: operators need to trust them
- Population size does matter: the more controllable devices, the more predictable their stochastic behavior
- Appropriate parameterization of equivalent models is key

Where does this lead us? [1/2]

1. We need to develop better **models**: discrete, stochastic, consider time delays. And invent computationally efficient ways to simulate them.

2. We need to design **simulation approaches** that can handle the sheer complexity of large systems, e.g. full T&D models.
   - Co-simulation? Parallel computing? Quantum computing?

3. We need to design suitable ways to accurately **parameterize** the equivalent models
   - Data-driven? First principles? Physics-informed machine learning?

Where does this lead us? [2/2]

4. **Make the controllable devices trustworthy**: We need to design control approaches that can handle stochasticity
   - Can we go beyond control approaches that work well "in expectation"?

5. We need to design **markets**:
   - That can deal with the stochastic availability of flexible resources (e.g. reliability-aware markets?)
   - That can provide consumers with the right incentives to offer grid services

6. We need to develop and take advantage of the **IoT infrastructure**
   - Coordinated control helps. Can it scale?
   - What about data privacy? What about cybersecurity?

Thank you!

Micro-Flexibility:
Challenges for Power System Modelling and Control

Presented by:

- *Spyros Chatzivasileiadis,* [*spchatz@dtu.dk*](mailto:spchatz@dtu.dk)
- *Federico Milano,* [*federico.Milano@ucd.ie*](mailto:federico.Milano@ucd.ie)
- *Petros Aristidou,* [*petros.aristidou@cut.ac.cy*](mailto:petros.aristidou@cut.ac.cy)

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[1] Technical Univ. of Denmark (DTU), [2] Cyprus Univ. of Technology,
[3] University College Dublin, [4] Univ. of Chile, [5] EPRI

All authors contributed equally