Controlling the Grid Edge

Can Randomness be the Solution to achieve Stability?

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Panel Session: Future electricity systems How to handle millions of power electronic-based devices and other emerging technologies

Micro-Flexibility

Challenges for Power System Modelling and Control

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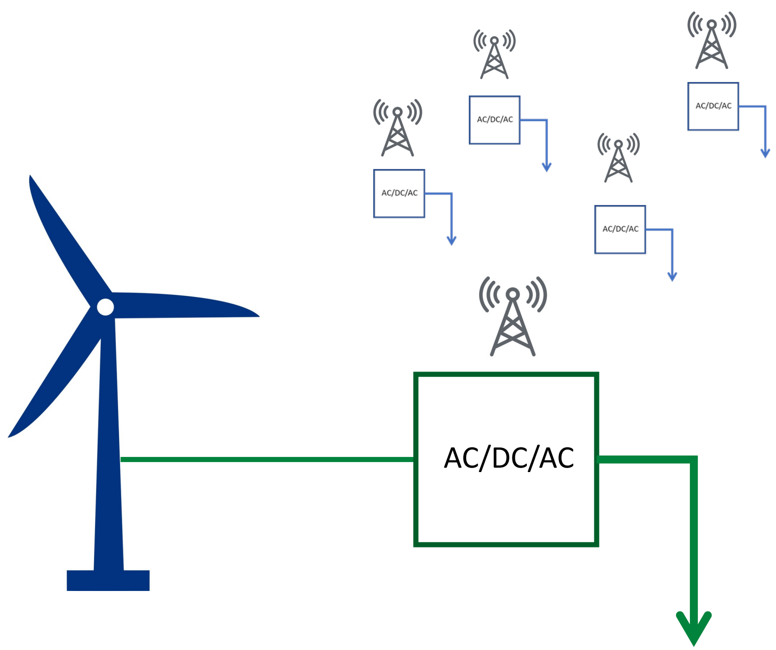
Motivation

Millions of Controllable Devices

How can we properly coordinate them?



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

The German 50.2 Hz Problem

Flapping phenomenon

- 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?

  "Flapping"

(also showing in many other systems, e.g., traffic jams)

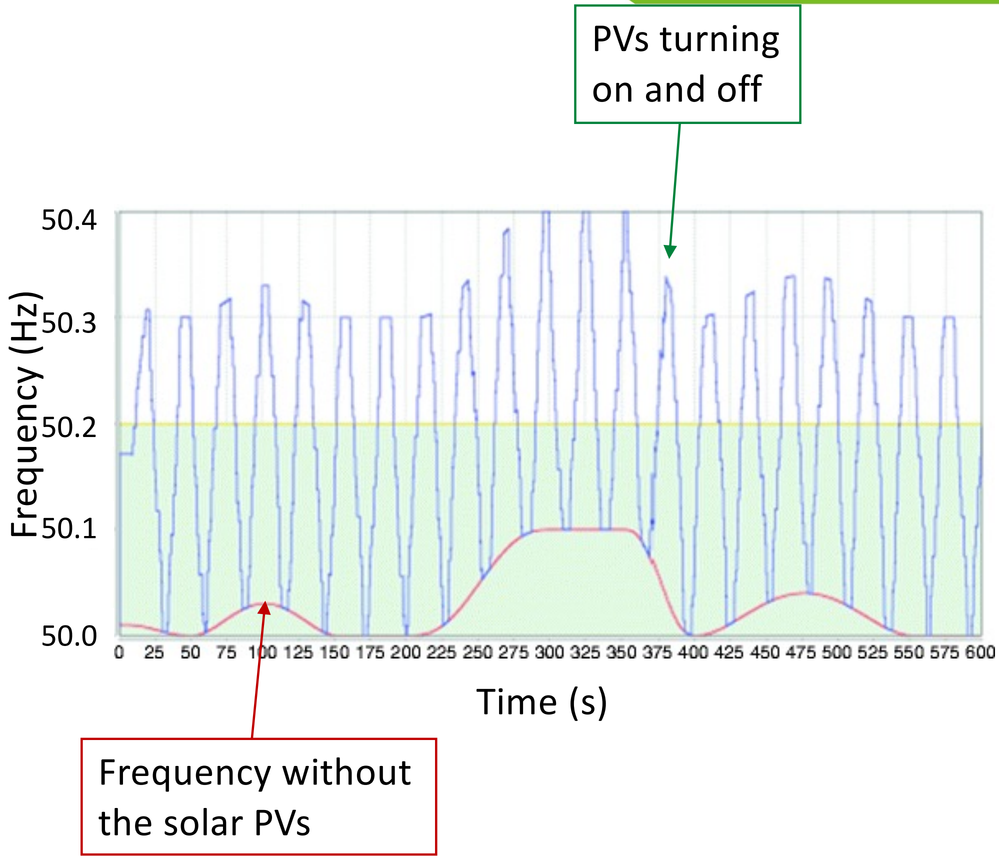


Figure from H. Hermanns, H. Wiechmann, Demand-Response Management for Dependable Power Grids, in Embedded Systems for Smart Appliances and Energy Management, 2012

The German 50.2 Hz Problem

Flapping phenomenon

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)

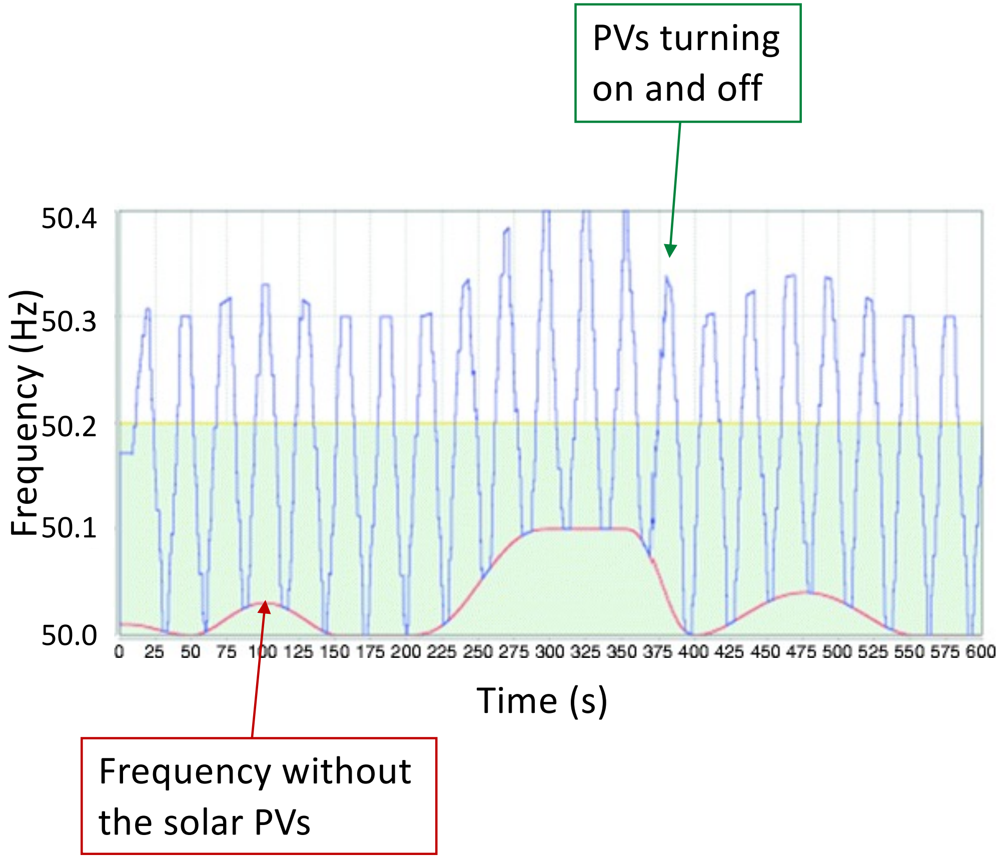


Figure from H. Hermanns, H. Wiechmann, Demand-Response Management for Dependable Power Grids, in Embedded Systems for Smart Appliances and Energy Management, 2012

Million of Devices

Issues

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)

Battery Storage

Electric Vehicles

Solar PV

Heat Pumps

Electric Drives

and many others...

Modelling

Hybrid-Stochastic Differential-Algebraic Equations

Conventional Power System Models

Are they still adequate?

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

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

Structural changes

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

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

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

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

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**)

3. Need to capture **time delays**

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** to address stochasticity → **lose the added information** from discrete variables and noise
- Time delays make the modeling and numerical solution much more complicated

Stochasticity and Randomness

Opportunities

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**

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")

Stochasticity and Randomness

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 → **interconnection requirements shall be control-agnostic**

Case Study 1

Flexible Loads

Flexible Loads - 1

Assumptions

- A given number of loads (*N*) switches on and off based on frequency measurements to provide frequency control to the system
- The controller is decentralized i.e., each load switches based on a local frequency measurement and is independent from the activity of all other loads within the system.
- A probability *q* is utilised at every time step (Δt) to decide if a load switches on or off.

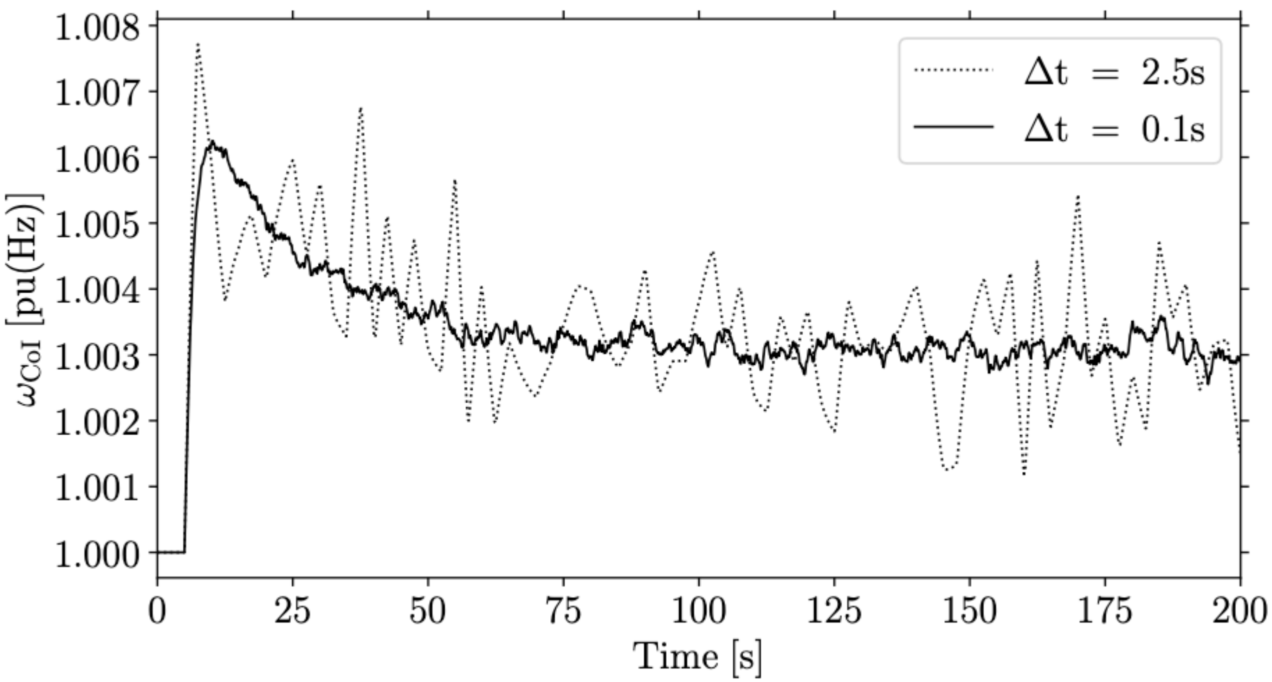
$$q(t) = \begin{cases} 0 & \text{if } \tilde{q}(t) \leq 0, \\ 1 & \text{if } \tilde{q}(t) \geq 1, \\ \tilde{q}(t) & \text{otherwise.} \end{cases}$$

$$\tilde{q}(t) = \frac{\Delta f(t) + \Delta f_{\max}}{2\Delta f_{\max}}$$

- Once the value of q is determined, each load independently generates a random number, *u*, between 1 and 0 using a uniform distribution. If $u \leq q$, the load will switch on, and switch off otherwise.
-

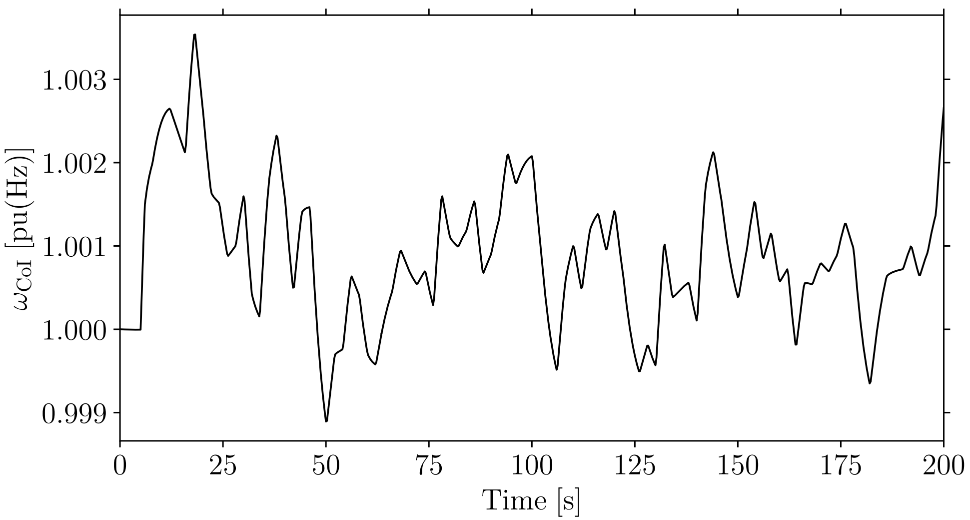
Flexible Loads - 2

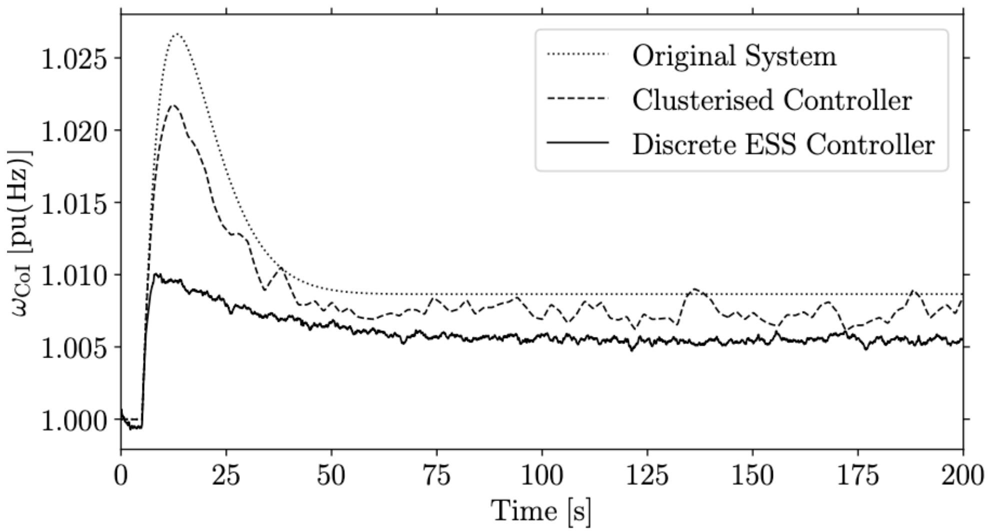
Impact of time discretization



Flexible Loads - 3

Impact of power discretization





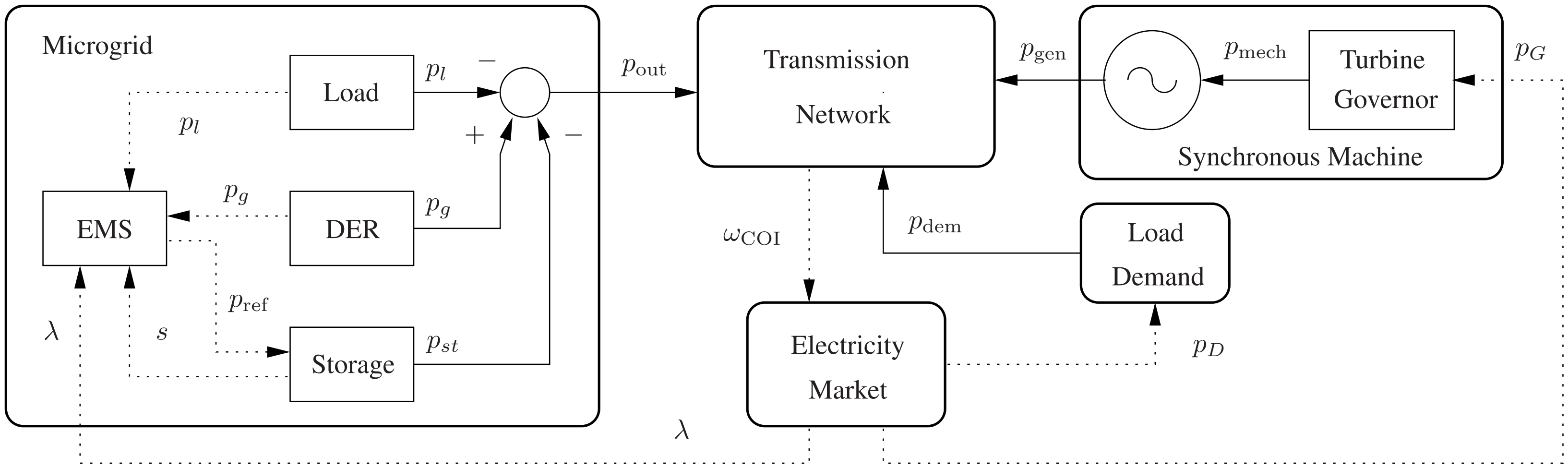
Case Study 2

Microgrids

Microgrids - 1

Assumptions

- Let assume that microgrids include a stochastic load, a DER and a storage system.
- Microgrids are fully decentralized and decide to connect to or disconnect from the system based on the market price (which can vary in a short unit of time)
- The original EMS does not include a frequency control



Microgrids - 2

AIMD Algorithm

The AIMD algorithm has been widely employed in the Internet congestion control problem.

An individual agent (e.g., a computer sending packets) gently increases its transmission rate, during the Additive Increase (AI) phase, until a packet loss signal is received.

Upon detecting congestion, the agents instantaneously decrease their transmission rate in a multiplicative fashion. This is the Multiplicative Decrease (MD) phase of the algorithm.

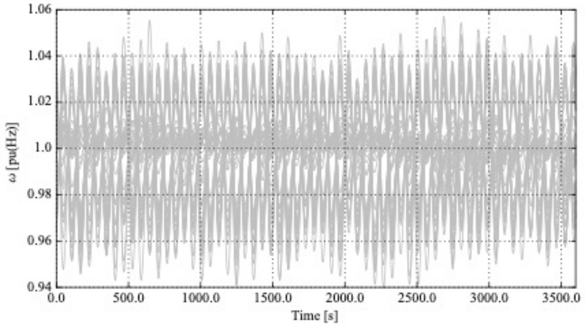
This algorithm does not require users to communicate among themselves, e.g., to know how many users are currently connected to the Internet.

Algorithm 2 Decentralized AIMD Algorithm

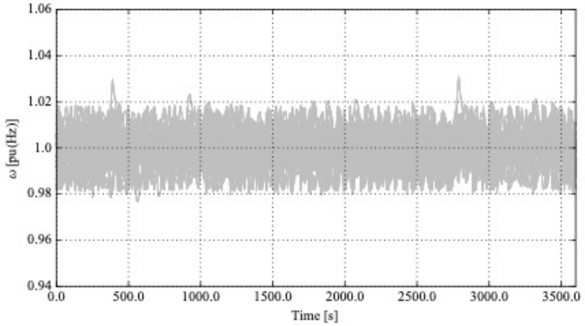
Initialization: $k = 1$, $P_{s_i} = 0$;
Broadcast the parameter Γ to the entire network;
while $k < k_{\text{simulation}}$ **do**
    if $|\omega_{B_i} - \omega_0| \leq M\overline{\omega}_m$ **then**
        $P_{si}(k+1) = P_{si}(k) + \alpha$
    else if $\text{rand}(1) \leq \pi_i(k) = \Gamma \frac{f_i'(\overline{P_{si}}(k))}{\overline{P_{si}}(k)}$ **then**
        $P_{s_i}(k+1) = \beta P_{s_i}(k)$
    $k = k + 1$

Microgrids - 3

Controller performance and effect of the size of the ESS



(a) No controller



(c) Decentralized Controller

Discharge Time s	Storage Capacity pu(MWh)	σ_ω pu(Hz)	$\bar{R}(t)$ pu($)
0	0	0.022	0.679
360	0.1	0.015	0.712
720	0.2	0.013	0.847
980	0.3	0.006	0.888
1340	0.4	0.006	0.902
1800	0.5	0.006	0.945
2160	0.6	0.006	0.989
2520	0.7	0.006	1.000
2880	0.8	0.006	1.000
3240	0.9	0.006	1.000
3600	1.0	0.006	1.000

Case Study 3

Thermostatically Controlled Loads

TCL - 1

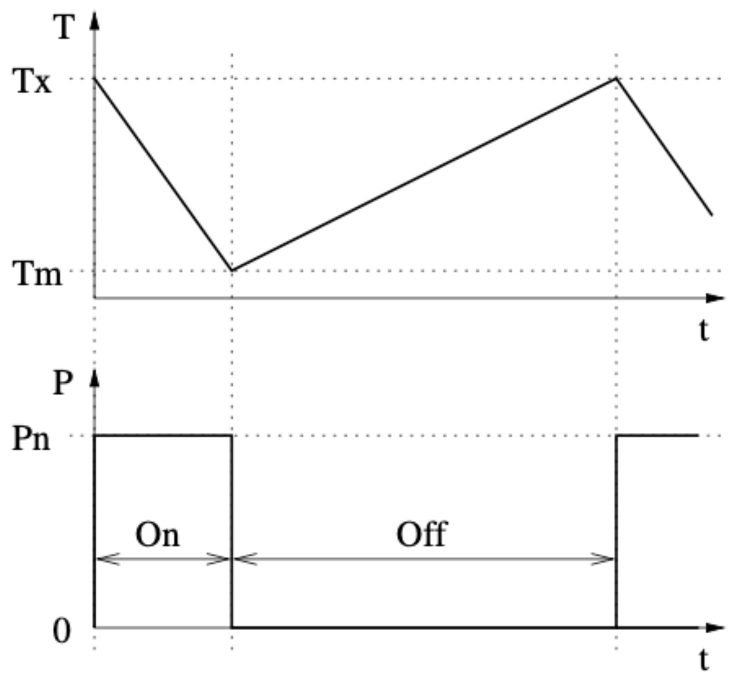
Assumptions

TCLs operate between two given thresh- old temperatures, say Tmin and Tmax.

In case of cooling devices, if the temperature of the device reaches Tmin, the load will switch off while if temperature of device reaches Tmax, the load will switch on.

For heating devices, the switching logic is the other way around.

Thermal capacity has been utilized to provide frequency control and flexibility.



TCL - 2

Modelling of the Duty Cycle

Let us focus on the duty cycle of the TCLs.

Using Fourier, one can rewrite the TCL duty-cycle as:

$$P_i(t) = dP_{n,i} + \frac{P_{n,i}}{k\pi} \sum_{k}^{\infty} [a_k \sin(\omega_k t) + b_k \cos(\omega_k t)]$$

And, assuming the duty cycles of all TCLs of the same kind have same period:

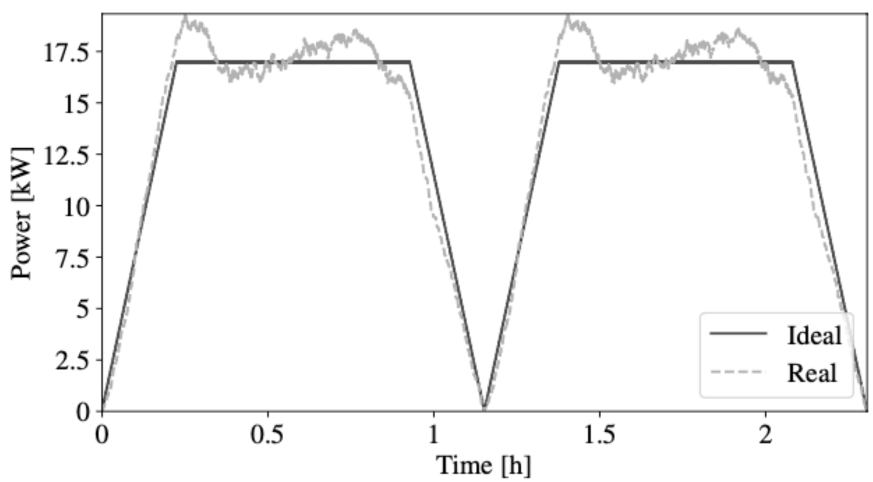
$$P_T(t) = NdP_{n,i} + \frac{P_{n,i}}{k\pi} \sum_{k}^{\infty} \sum_{i}^{N} [a_{k,i} \sin(\omega_k t) + b_{k,i} \cos(\omega_k t)]$$

$$= NdP_{n,i} + \frac{P_{n,i}}{k\pi} \sum_{k}^{\infty} A_k [a_k \sin(\omega_k t + \phi_k) + b_k \cos(\omega_k t + \phi_k)]$$

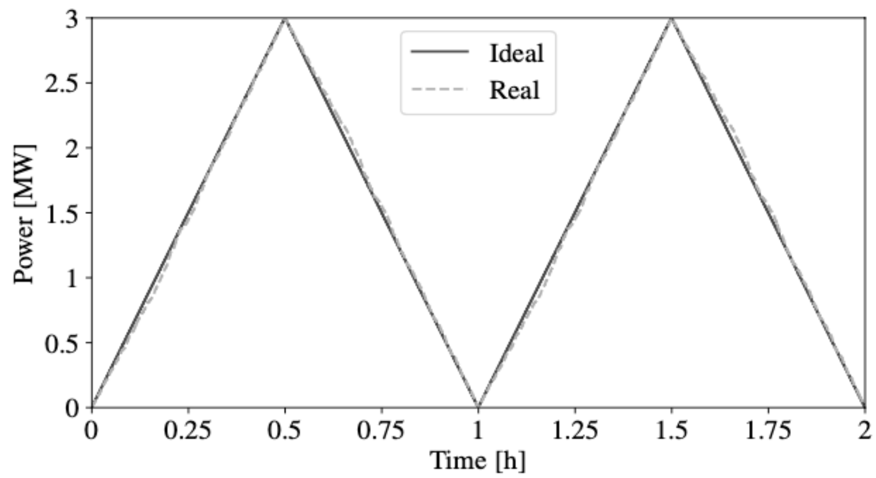
TCL - 3

The sum of all TCL is a periodic function! (even if one takes into account noise)

d = 20%



d = 50%



Concluding Remarks

Main Takeaways

Challenges and Opportunities

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)

There is need for families of new models, suitable for different time scales and granularity

Stochastic Controllers offer benefits. But there are barriers for their adoption: operators need to trust them

Despite complexity, population size matters: the more controllable devices, the more predictable their stochastic behavior

Appropriate parameterization of equivalent models is key: exploit both physics and data

Future Directions

Modelling & Control

- We need to develop better **models**: discrete, stochastic, consider time delays.
  - For different time-scales and granularity
  - And invent computationally efficient ways to simulate them.
- **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"?

References

- P. Ferraro, E. Crisostomi, R. Shorten, F. Milano, **Stochastic Frequency Control of Grid-connected Microgrids**, IEEE Transactions on Power Systems, vol. 33, no. 5, pp. 5704-5713, September 2018.

- J. McMahon, T. Kërçi, F. Milano, **Combining Flexible Loads with Energy Storage Systems to provide Frequency Control**, IEEE PES ISGT Asia, Brisbane, Australia, hybrid conference, 5-8 December 2021.

- S. Chatzivasileiadis, P. Aristidou, I. Dassios, T. Dragicevic, D. Gebbran, F. Milano, C. Rahmann, D. Ramasubramanian, **Micro-Flexibility: Challenges for Power System Modelling and Control**, Electric Power Systems Research, Elsevier, vol. 216, 109002, March 2023.

Thank you!

Questions?