Opportunities and Limitations of Stochastic Control of Flexible Resources

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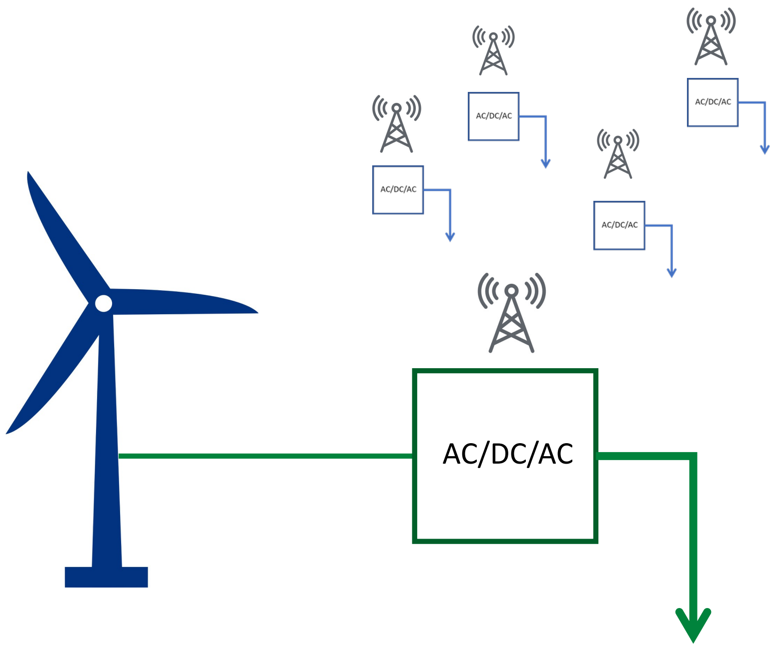
Super Session: Trends in Changing Power System Dynamics

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)

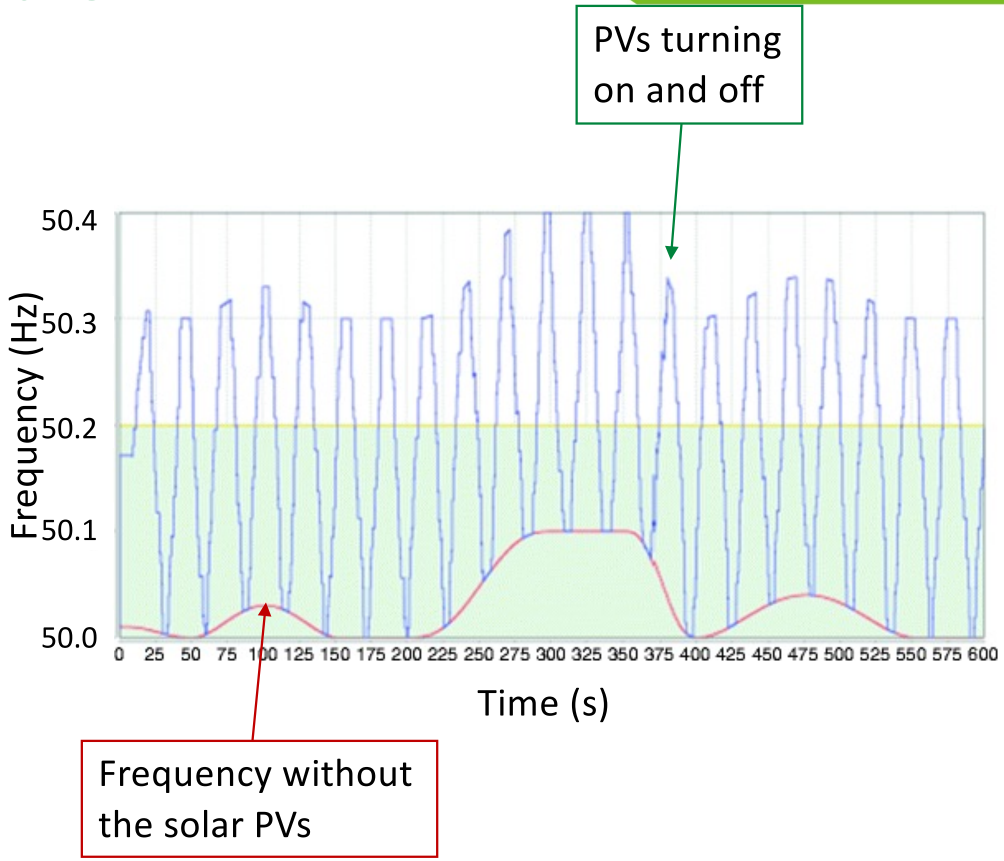


Figure from H. Hermanns, H. Wiechmann, Demand-Response Management for Dependable Power Grids, in Embedded Systems for Smart Appliances and Energy Management, 2012

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)

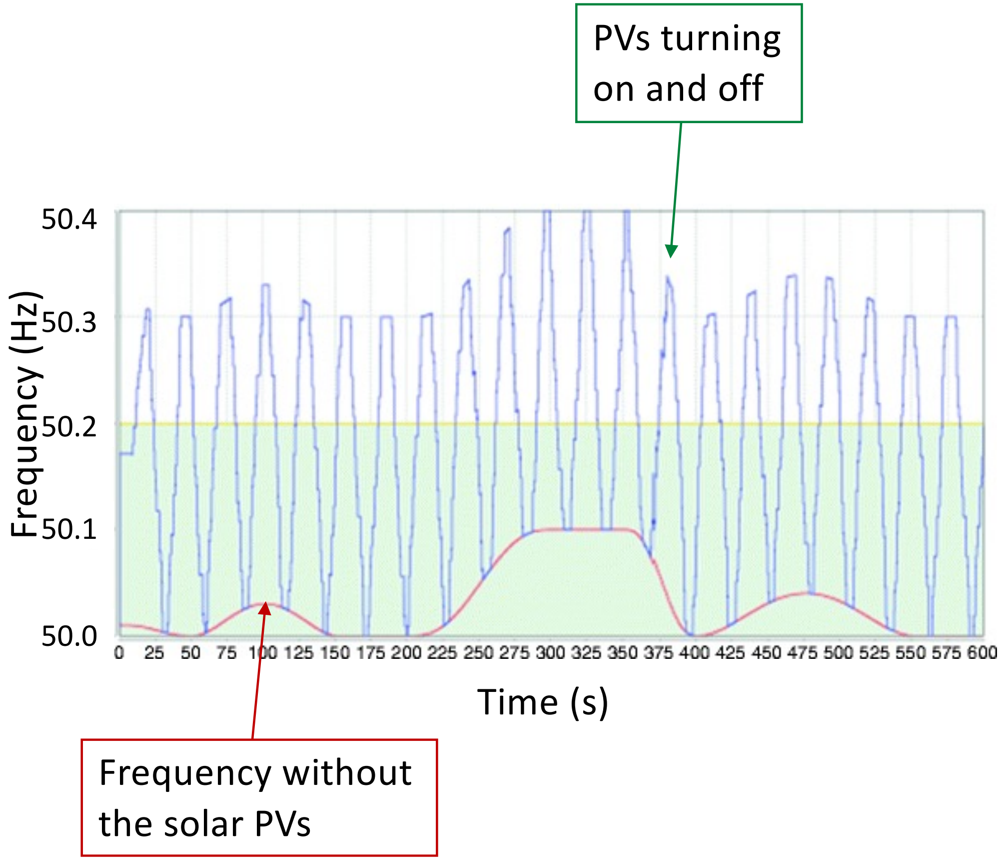


Figure from H. Hermanns, H. Wiechmann, Demand-Response Management for Dependable Power Grids, in Embedded Systems for Smart Appliances and Energy Management, 2012

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…

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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

Thermostatically Controlled Loads
(periodic loads)

TCL - 1

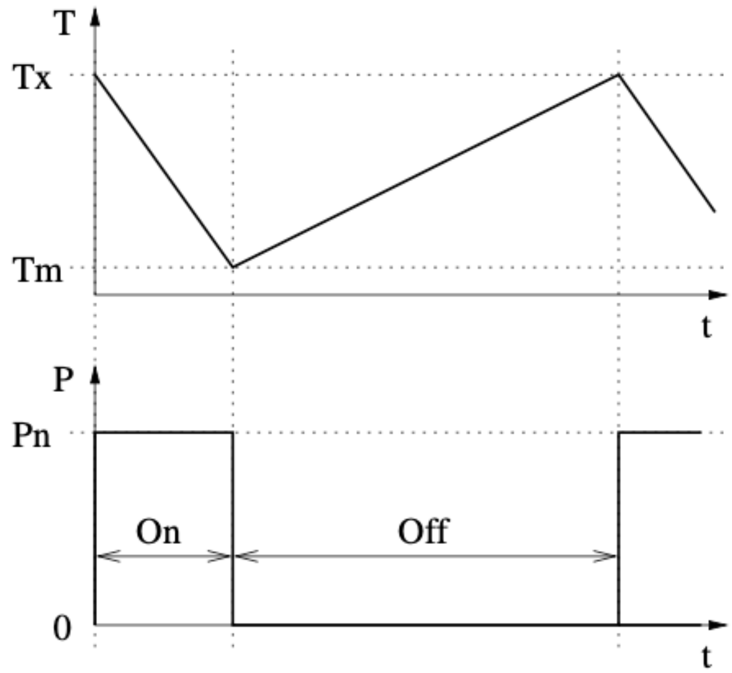
Assumptions

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:

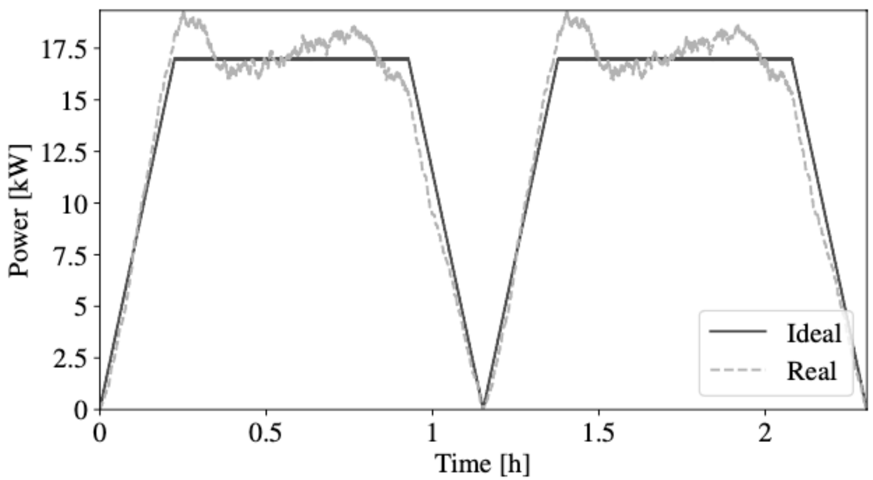
$$P_T(t) = NdP_{n,i} + \frac{P_{n,i}}{k\pi} \sum_{k}^{\infty} \sum_{i}^{N} [a_{k,i} \sin(\omega_k t) + b_{k,i} \cos(\omega_k t)]$$

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

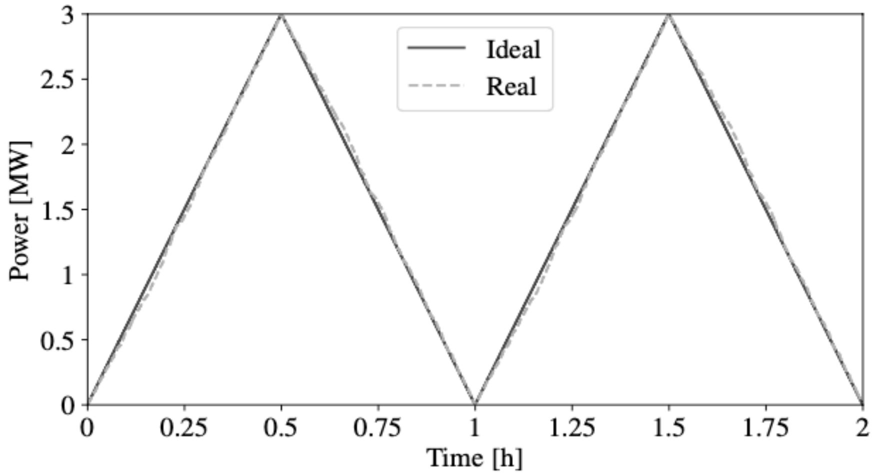
TCL - 3

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

d = 20%



d = 50%



Case Study 2

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 (Δ*t*) 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* ≤ *q*, the load will switch on, and switch off otherwise.
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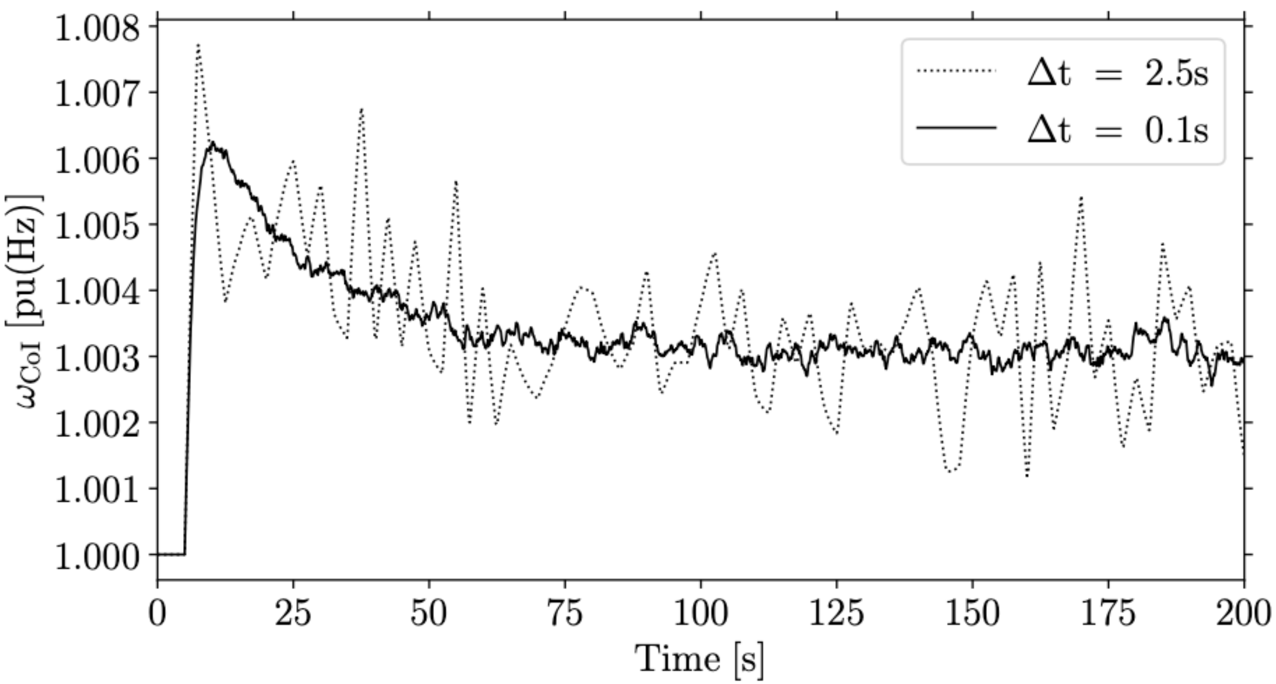
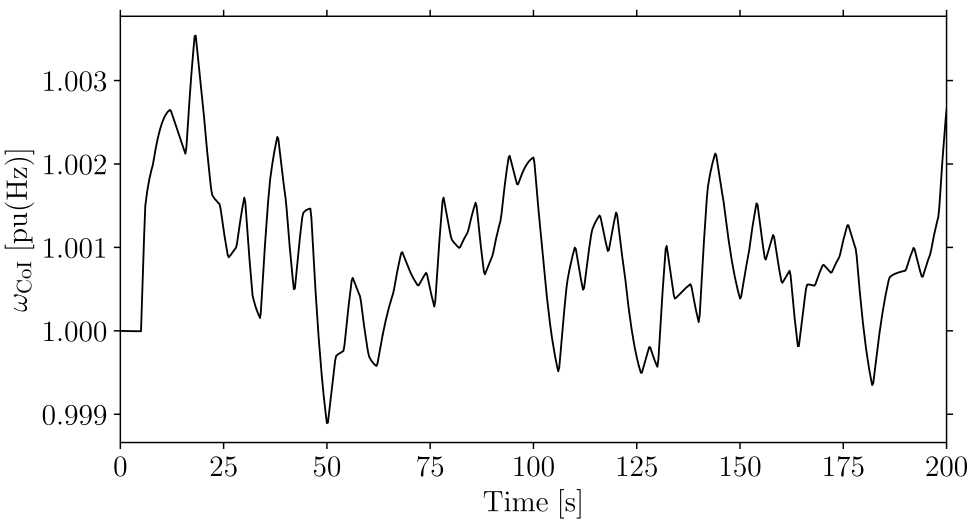
Flexible Loads - 2

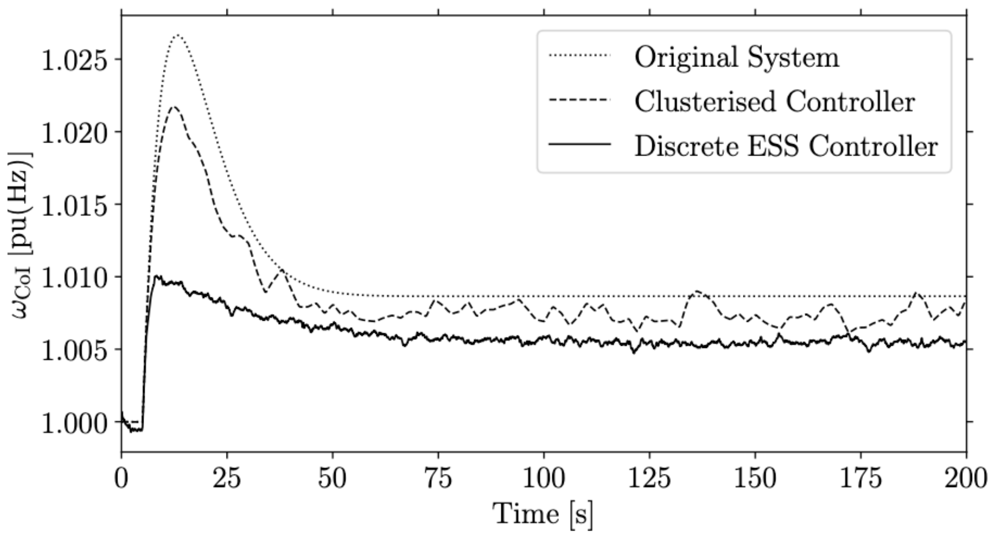
Impact of time discretization



Flexible Loads - 3

Impact of power discretization





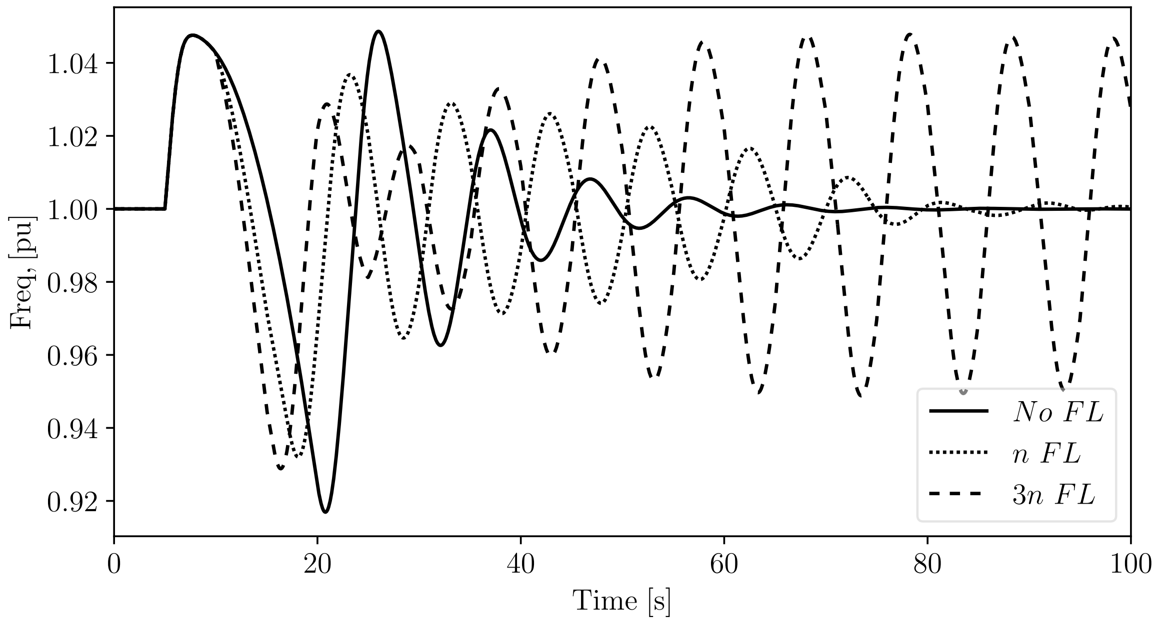
Case Study 3

Can stochastic control go wrong?

Challenges of stochastic control - 1

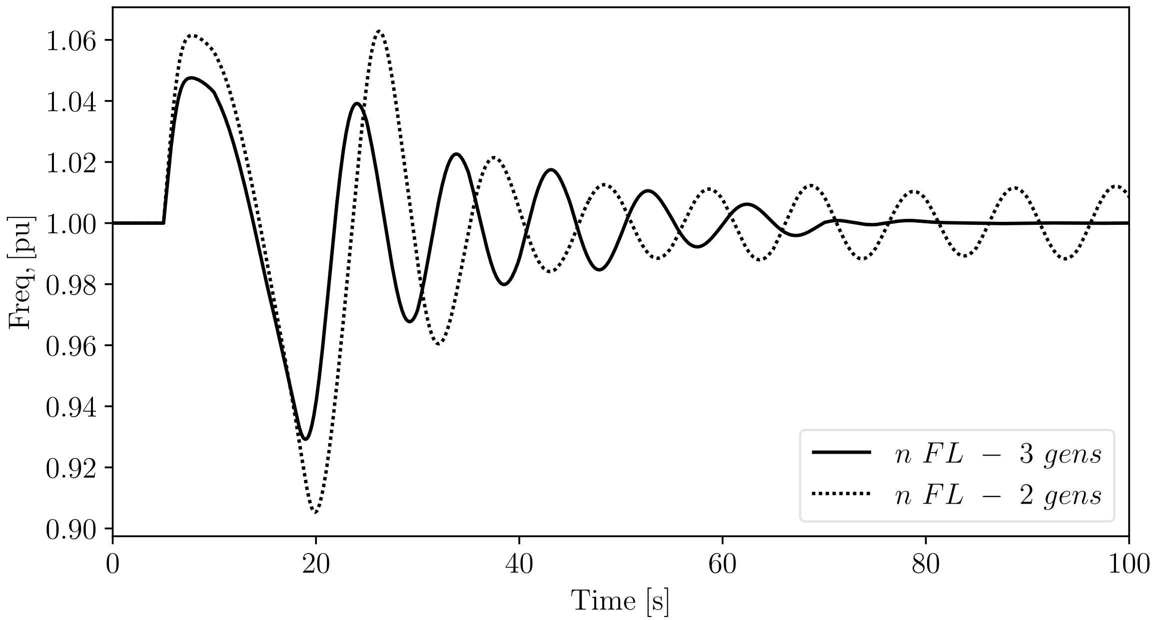
Flexible loads

Effect of increasing the number of flexible loads:



Flexible loads

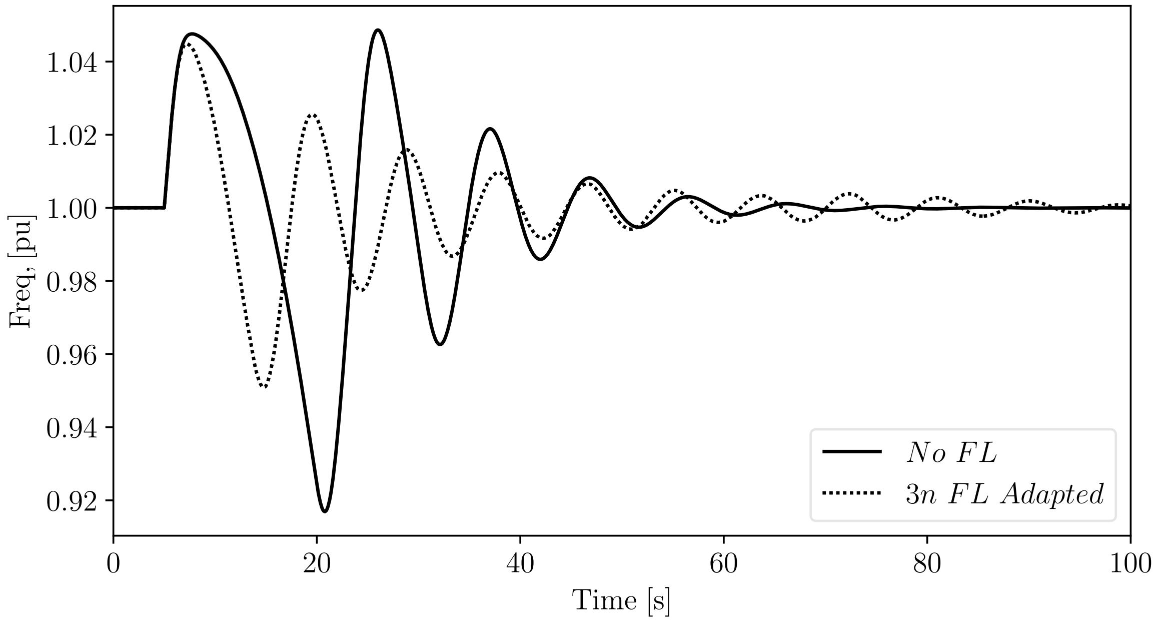
Impact on stochastic control of decreasing the inertia of the system:



Challenges of stochastic control - 3

Flexible loads

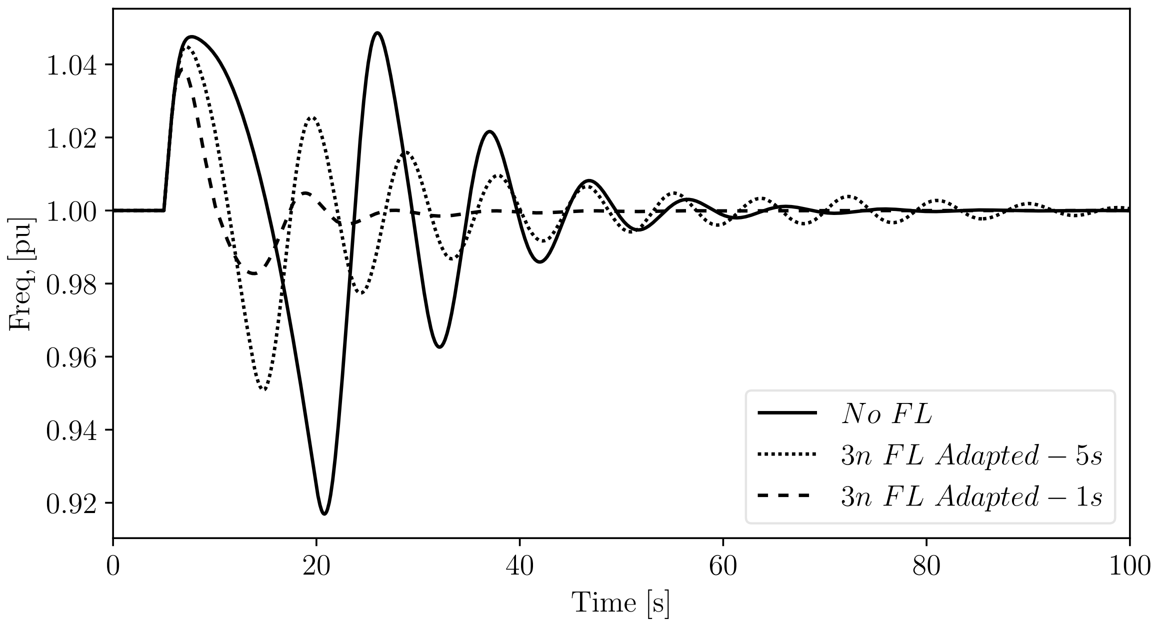
A solution can be to give up decentralized control and send to the load information on the number of loads and on the inertia (this can be done, e.g., every 15 minutes)



Challenges of stochastic control - 4

Flexible loads

Moreover, increasing the number of times the load change its status improves the effectiveness of the stochastic control



Case Study 4

Stationarity of Stochastic Control

Challenges of stochastic control - 5

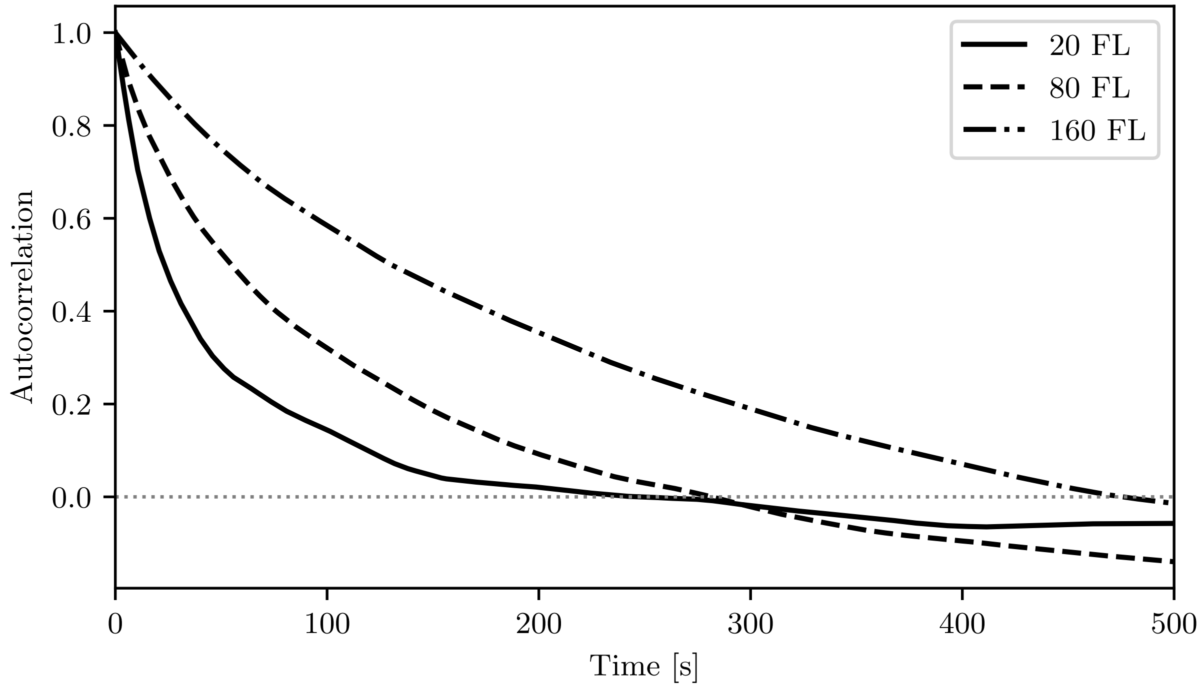
Flexible loads

- An issue of stochastic control is that some loads can contribute to the control more than others.
- The control is “fair” only when the stochastic process following the stochastic control is stationary.
- But… **a stochastic process takes time to reach stationarity**

Challenges of stochastic control - 6

Flexible loads

The more the loads, the longer it takes to reach stationarity



Concluding Remarks

Takeaways - 1

Modelling Challenges

- Move from continuous to discrete models (hard to define stability)
- Include stochastic processes and probabilistic control

Takeaways - 2

Control Challenges

- The number of devices and the parameters of the system (inertia) matter as they affect the stability of the stochastic control and of the system. Full decentralization might not be an option.

- The dynamics of the stochastic processes arising from the stochastic control matter as they affect the fairness of the control. Clustering of loads can be a solution.

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Thank you!

Questions?

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