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Optimal Provision of Frequency Services in Low-Carbon Grids

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Introduction

1. Frequency Stability

2. Frequency-Security Constraints

3. Optimisation of Power System's Operation

4. Relevance of this work

Intro: from Dynamics to Optimisation

Deduce **dynamic-security rules** to implement them in an optimisation routine

Power System Dynamics

Economic Optimisation

Described by differential equations

Based on algebraic equations

Goal: achieve minimum cost while keeping the system stable

My work focuses on **frequency dynamics**

- Why is it important? **Low inertia** in decarbonised grids. Risk of frequency instability has increased

Demand   *Generation*

1) Inertia
2) Frequency Response
3) Load Damping

time (seconds)

Frequency (Hz)
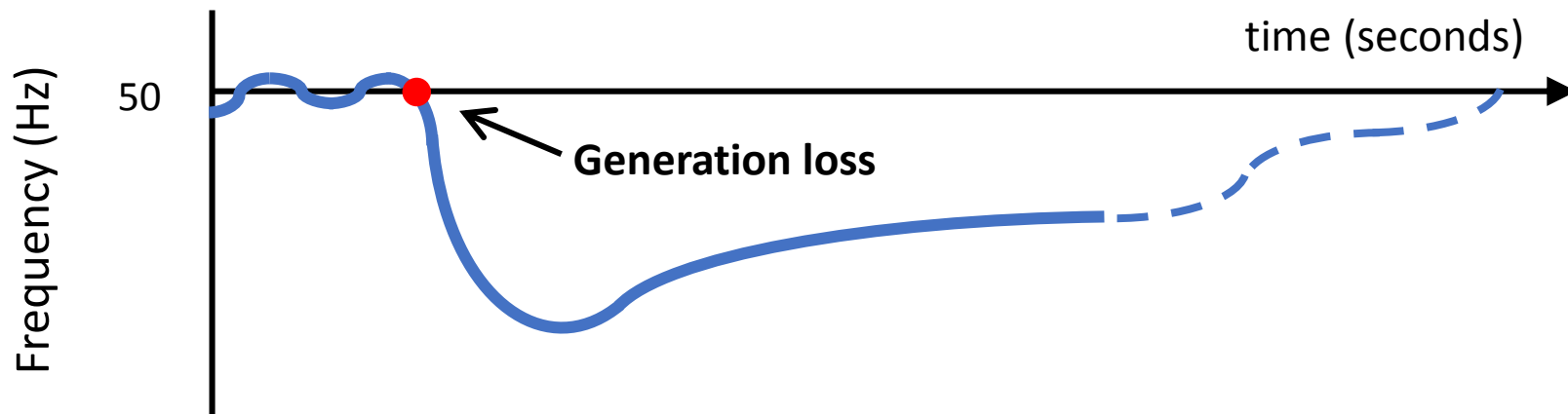
50

Generation loss
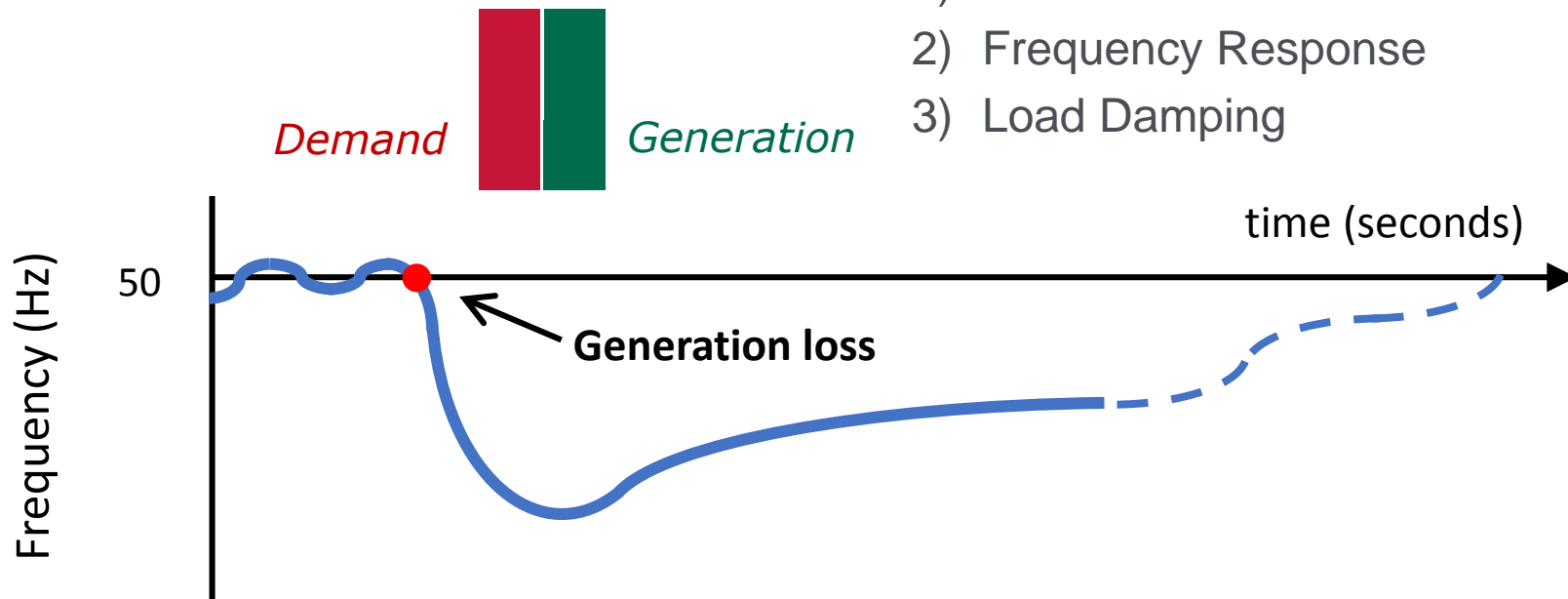
1. Frequency Stability

How to study frequency-stability conditions?

Options:

➢ Dynamic simulations of the system
  - Advantage: represents well the system dynamics
  - Disadvantage: computationally slow

➢ Analytical methods (swing equation)
  - Disadvantage: difficult to obtain closed-form solutions
  - Advantage: computationally fast and transparent information

Swing equation:

$$2H\frac{\mathrm{d}\Delta f(t)}{\mathrm{d}t} + \mathrm{D}\cdot\mathrm{P_D}\cdot\Delta f(t) = -\mathrm{P_{Loss}^{max}} + \sum\mathrm{FR}(t)$$

Loss of largest power infeed (N-1 requirement)
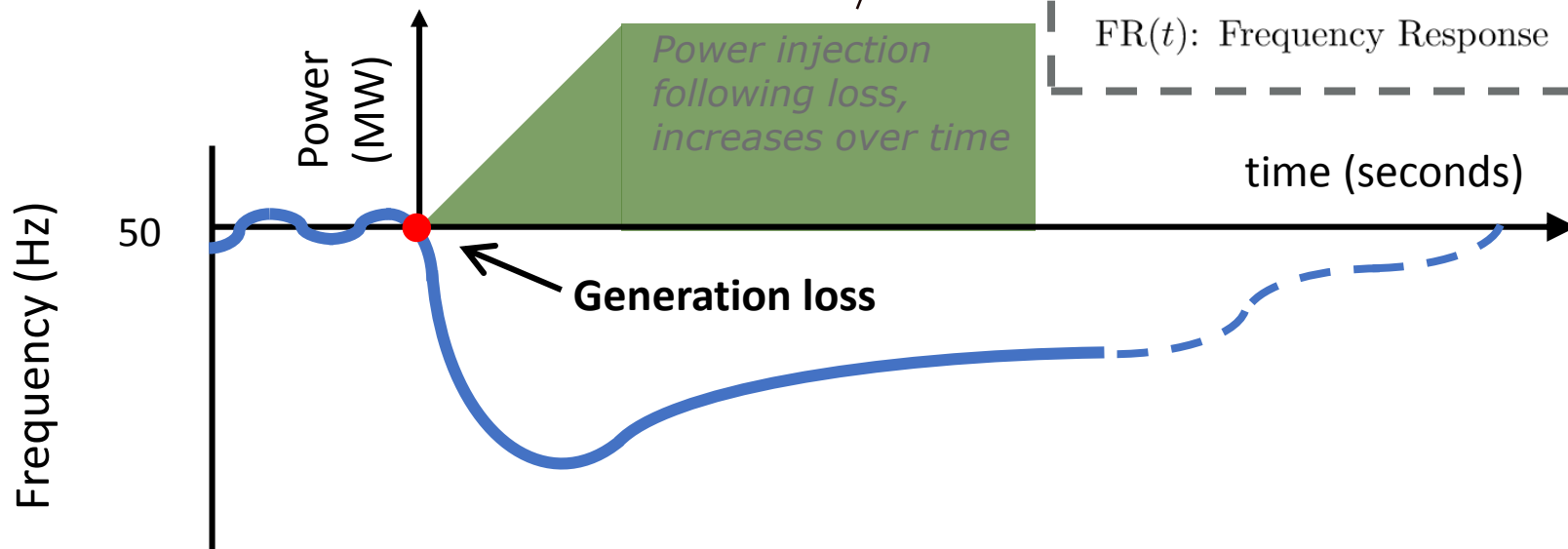
Nomenclature

H: System's inertia

D: Load damping factor

$\mathrm{P_D}$: System's demand

$\mathrm{P_{Loss}^{max}}$: Largest possible power loss in the system

$\mathrm{FR}(t)$: Frequency Response

Power (MW)

Power injection following loss, increases over time

time (seconds)

Frequency (Hz)

50

Generation loss

1. Frequency Stability

Swing equation:

Loss of largest power infeed (N-1 requirement)

$$2H\frac{d\Delta f(t)}{dt} + D \cdot P_D \cdot \Delta f(t) = -P_{Loss}^{max} + \sum FR(t)$$

Power injection following loss, increases over time

Nomenclature
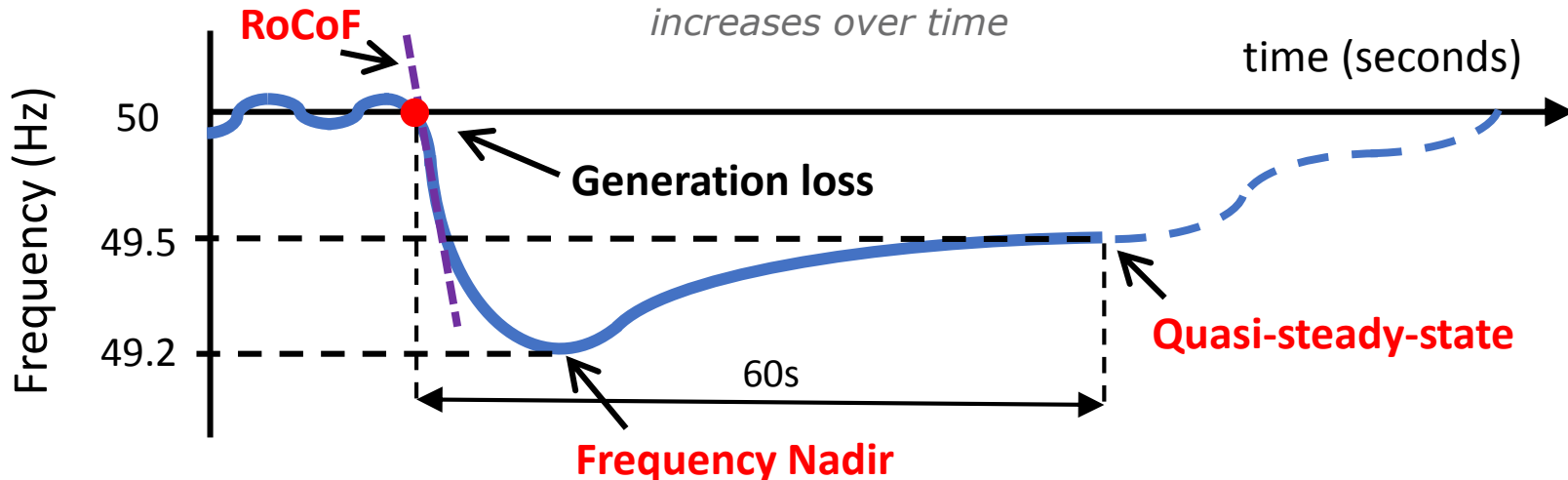
H: System's inertia

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P_{Loss}^{max}: Largest possible power loss in the system

$FR(t)$: Frequency Response

RoCoF

time (seconds)

Frequency (Hz)

50

49.5

49.2

Generation loss

Quasi-steady-state

60s

Frequency Nadir

7

From the swing equation, deduce the 3 security rules:

- **RoCoF** $\longrightarrow$ $f(H, P_{loss}^{max})$
- Frequency **nadir** $\longrightarrow$ $f(H, P_{Loss}^{max}, D, FR)$
- Frequency **quasi-steady-state**
  $\longrightarrow$ $f(P_{Loss}^{max}, D, FR)$

> **Nomenclature**
>
> H: System's inertia
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> D: Load damping factor
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> P_D: System's demand
>
> P_{Loss}^{max}: Largest possible power loss in the system
>
> $FR(t)$: Frequency Response

*These are the **frequency services**, system's variables that allow to comply with frequency security rules*

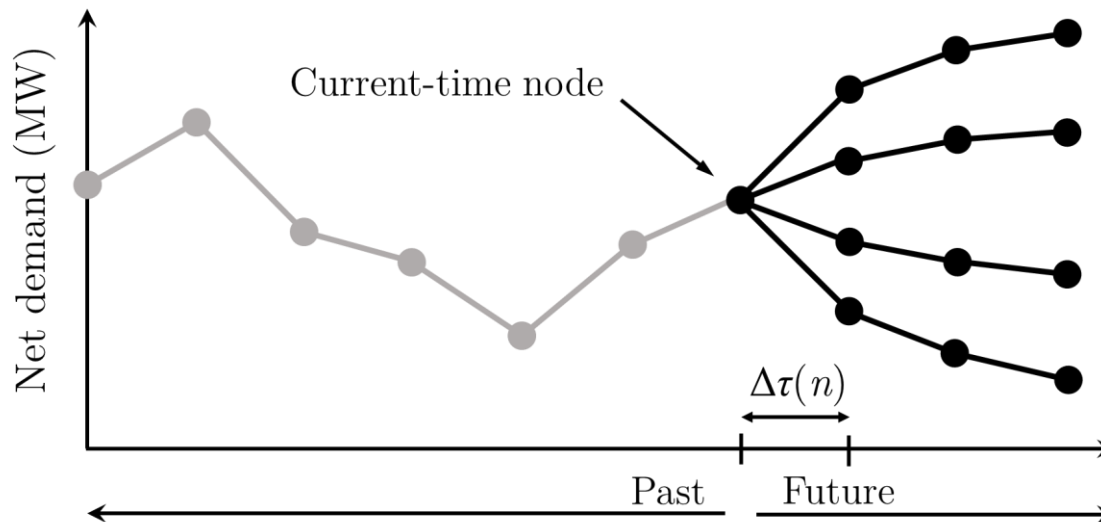Still one big problem: nadir is a nonlinear constraint (even nonconvex in some cases)

These security rules can be applied to:

1. Optimal Power Flow and **Unit Commitment**
    - We use Stochastic Unit Commitment, to model uncertainty from renewables

$$\min \quad \sum_{n \in \mathcal{N}} \pi(n) \sum_{g \in \mathcal{G}} C_g(n)$$

subject to   RoCoF constraint

Nadir constraint

SteadyState constraint

(and other typical constraints)

4. Relevance of this work

Applied to a **current power system**:

- Allows to optimally operate the system, for example dynamically reducing the largest power infeed. Particularly valuable for systems with high renewable penetration

Applied to **potential future scenarios** of generation mix or market structure:

- Allows to study the value of different technologies (fast power injections from battery storage, flexibility from thermal units, etc.)