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Towards a Cost-Effective Operation of Low-Inertia Power Systems

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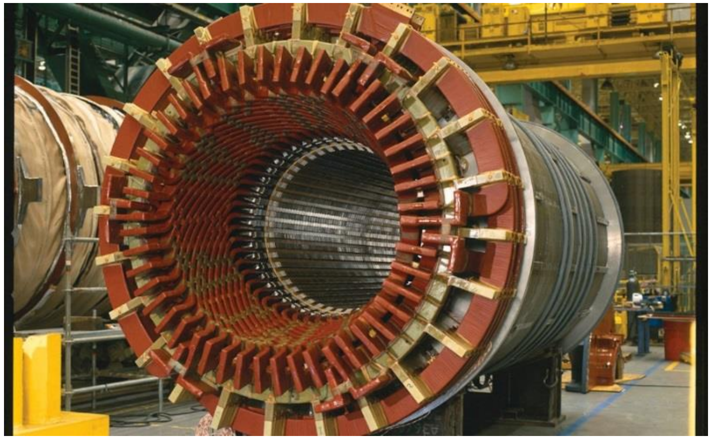
Motivation: lower inertia on the road to lower emissions

"Inertia" means physical inertia, a **rotating mass**

Thermal generators (nuclear, gas, coal…):



Most renewables: no inertia

Inertia stores kinetic energy:
this energy gave us time to contain a sudden generation-demand imbalance
But now the risk of instability has increased (e.g. Great Britain blackout Aug 2019)

My research question

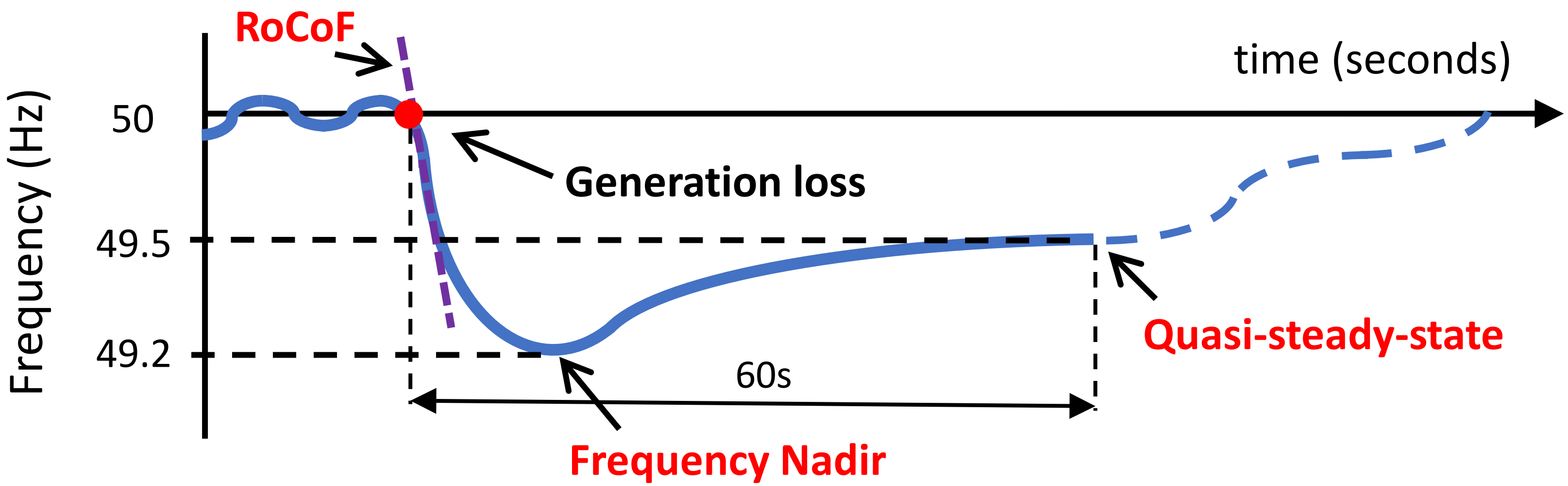
How to optimally procure the ancillary services needed because of low inertia?

Described by ***differential equations*** *(timescale of seconds)*

Based on ***algebraic equations*** *(timescale of min/hours)*

Goal: Achieve **minimum cost** while keeping the **system stable**

Why is frequency important?



After a generation outage, the electric frequency of the grid drops.

Devices can be damaged if frequency falls too low: protection mechanisms disconnect generators and loads if they detect low frequencies.

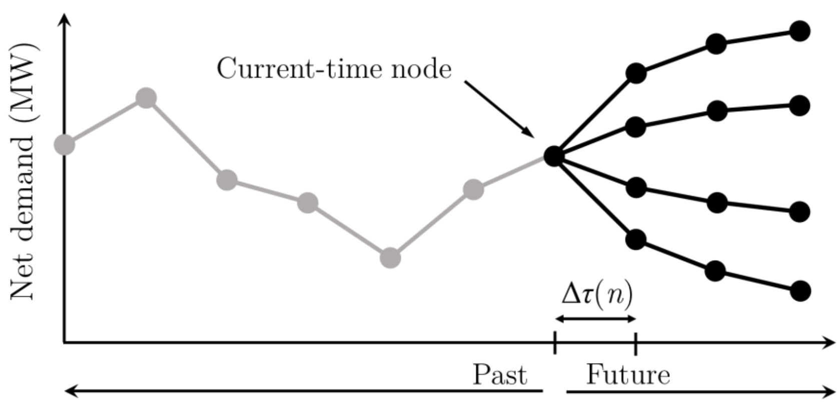
These disconnections, although necessary, **could lead to an eventual blackout**.

Key to keep frequency within safe limits to avoid demand disconnection!

Scheduling and markets for energy and ancillary services

Analysis conducted with our **frequency-secured Stochastic Unit Commitment** model

1. Considers uncertainty from RES generation
2. Guarantees frequency stability

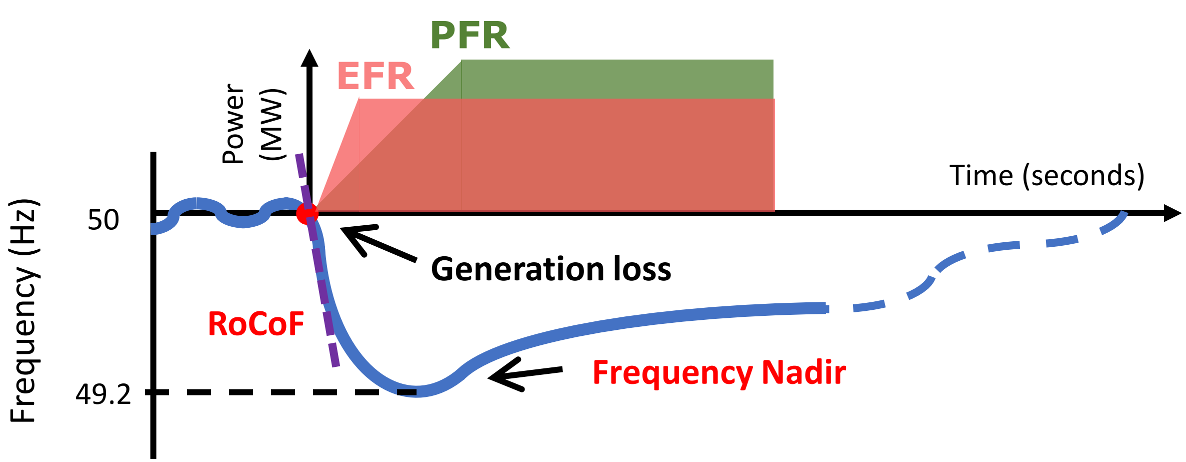


Operating costs: fuel costs, start-ups, etc.

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

subject to RoCoF constraint
Nadir constraint
SteadyState constraint

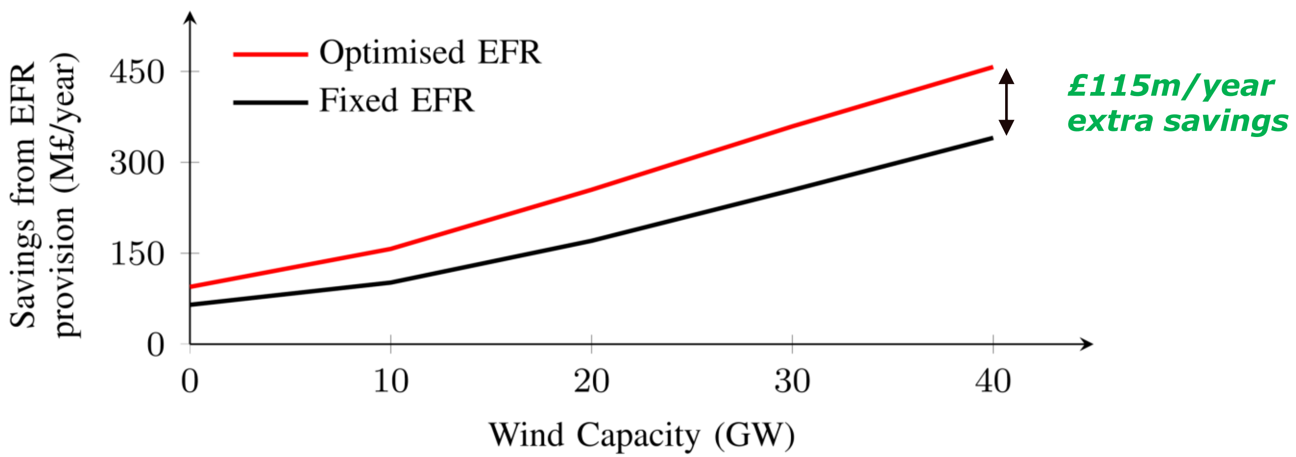
(and other typical constraints)



Co-optimisation of multiple frequency services

Our models demonstrate the importance of co-optimising inertia and frequency response procurement. For example, **Enhanced Frequency Response (EFR) is not always needed**: it only becomes significantly more valuable than PFR when inertia is low

Instead of procuring a fixed-amount of 200MW of EFR at all times (current approach in GB), **co-optimising EFR procurement** can achieve **savings of up to £115m/year**



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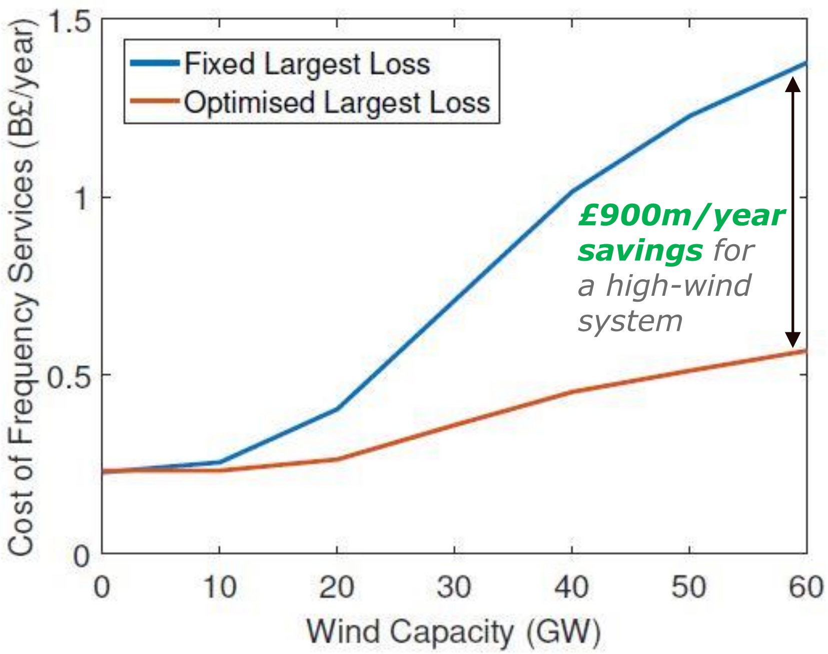
Part-loading large nuclear to reduce the largest loss

Reducing the power output of large nuclear units **when it is optimal because it reduces the need for ancillary services**:

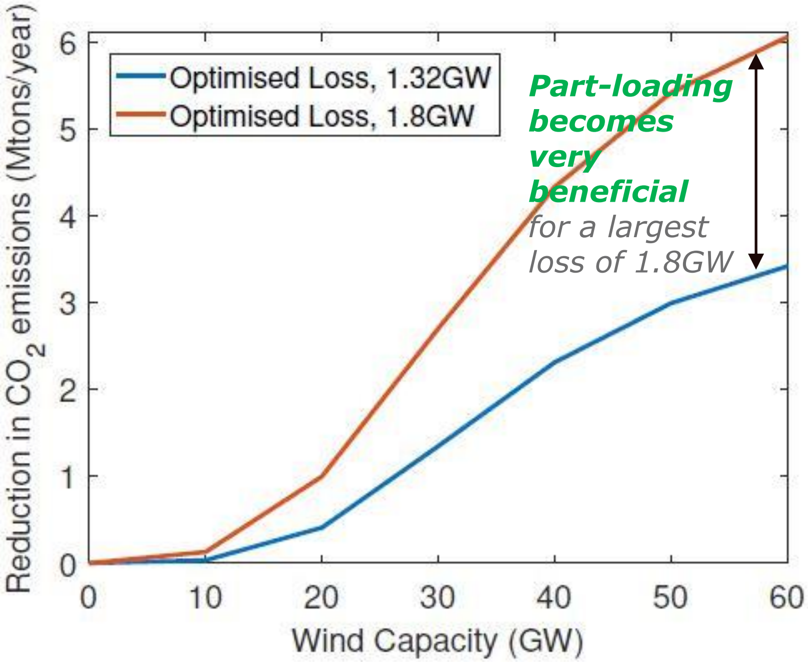
- Low-wind conditions: nuclear at full output
- High-wind conditions: nuclear part-loaded to reduce the largest loss

Part-loading large nuclear plants can reduce overall carbon emissions! More info here

Current largest nuclear in Great Britain: **1.32GW**



Planned largest nuclear in Great Britain: **1.8GW**



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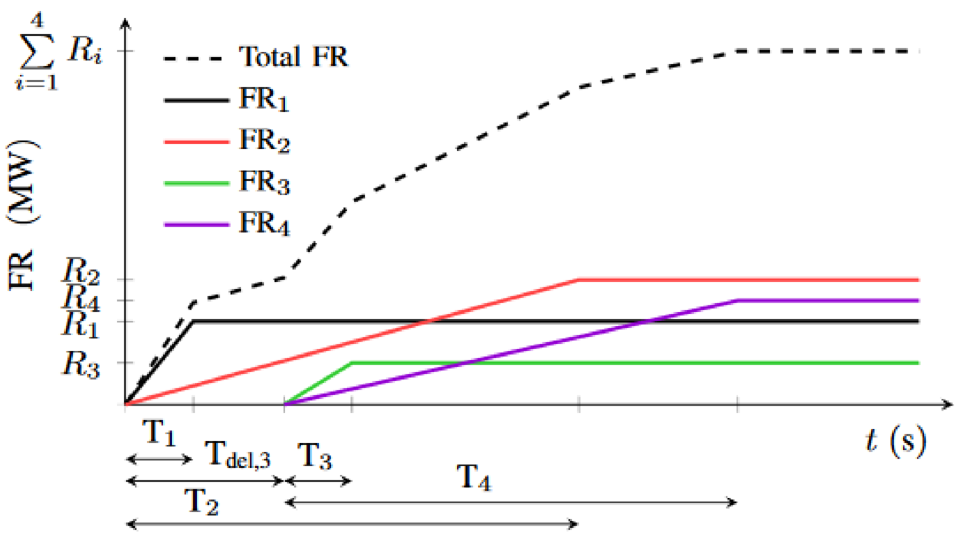
Optimal portfolio of multi-speed frequency response

We have developed an optimisation framework that allows to consider any combination of different frequency-response speeds and activation delays:



This formulation allows to **fully extract the value of the different assets** in a power system, **putting in place the right incentives** for those assets to provide the fastest frequency response possible.

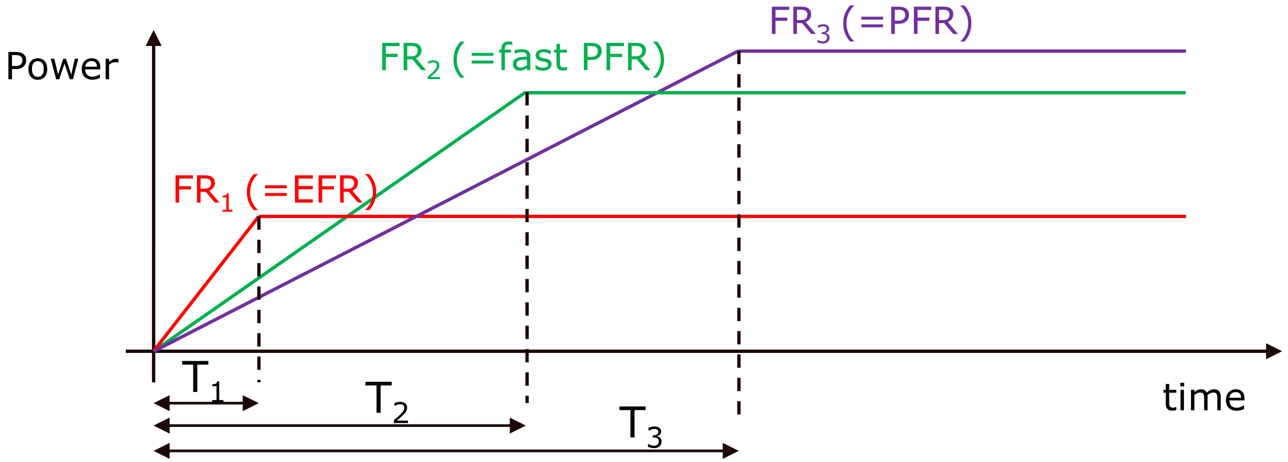
More info here

Value of recognising different response speeds

Beyond the EFR-PFR duo: *is there value in creating new FR services, that are faster than PFR, but slower than EFR?*

We have shown that **there is value in 'fast PFR'**

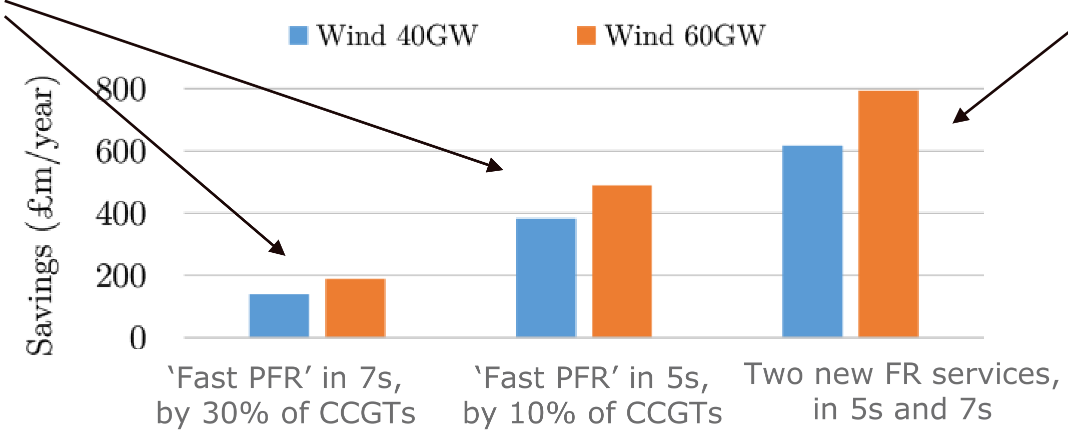
- But it is important to understand the capabilities of the system assets before defining new services: new services increase market complexity and in some cases do not bring great benefits. More info here



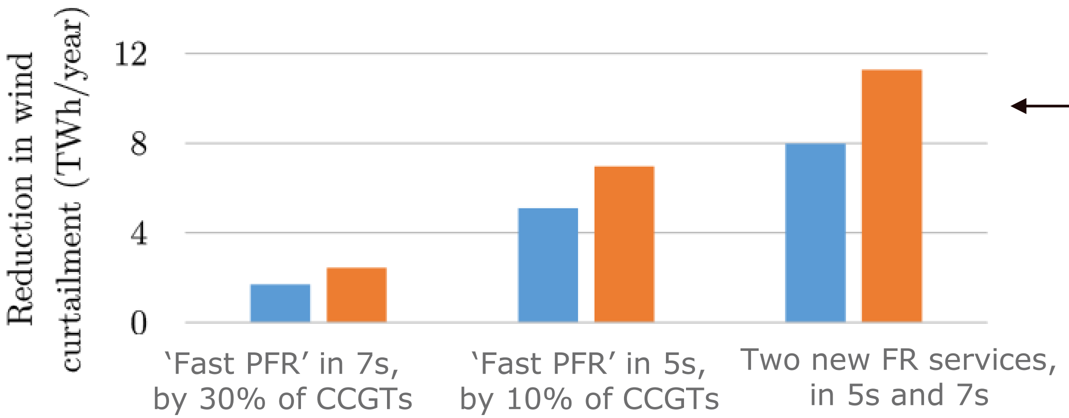
Value of recognising different response speeds

Benefits compared to simply considering EFR+PFR in Great Britain:

Important to analyse the system thoroughly before defining a new service: 10% of CCGTs providing FR in 5s achieve higher savings than 30% providing FR in 7s



Defining new FR services can further increase savings, although market complexity increases



Faster FR services imply a lower overall volume of FR needed, therefore less thermal plants are needed online and more wind can be accommodated

More info here

Marginal-pricing mechanism for frequency services

Taking advantage of a convex Second-Order Cone formulation we developed, we propose a **pricing scheme** using **duality theory**:

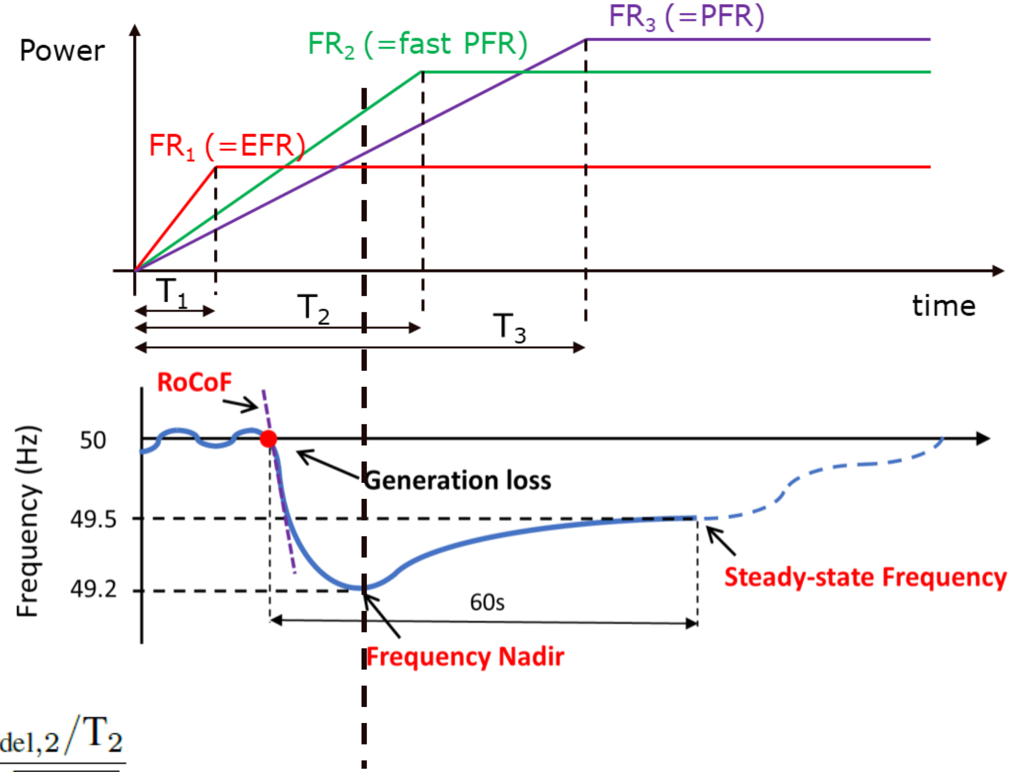
More info here

Price for fast FR services:

$$\frac{\lambda_2}{\sqrt{\Delta f_{\max}}} - (\mu - \lambda_1)\frac{\mathrm{T}_1 + \mathrm{T}_{\mathrm{del},1}}{4\Delta f_{\max}}$$

Price for slow FR services:

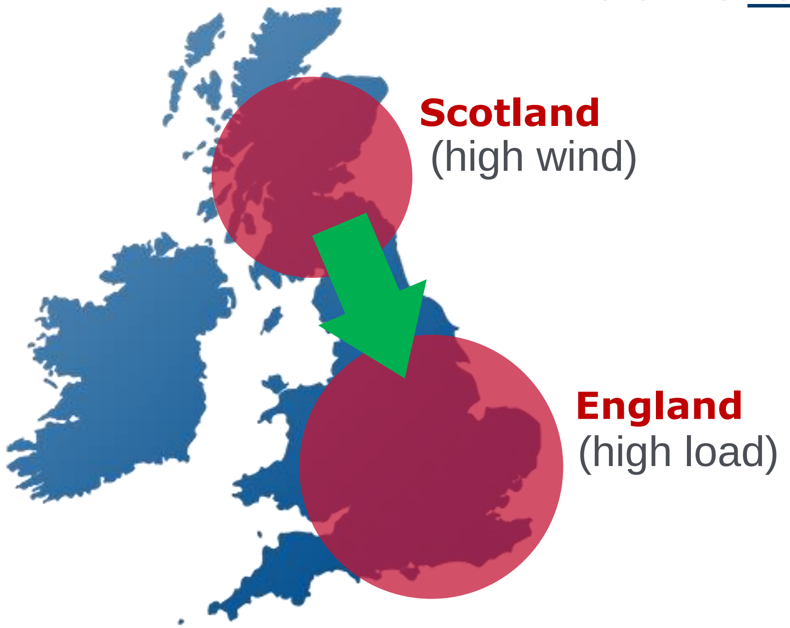
$$(\mu + \lambda_1)\frac{1}{\mathrm{T}_2} + (\mu - \lambda_1)\frac{\mathrm{T}^2_{\mathrm{del},2}/\mathrm{T}_2}{4\Delta f_{\max}} - \lambda_2\frac{\mathrm{T}_{\mathrm{del},2}/\mathrm{T}_2}{\sqrt{\Delta f_{\max}}}$$

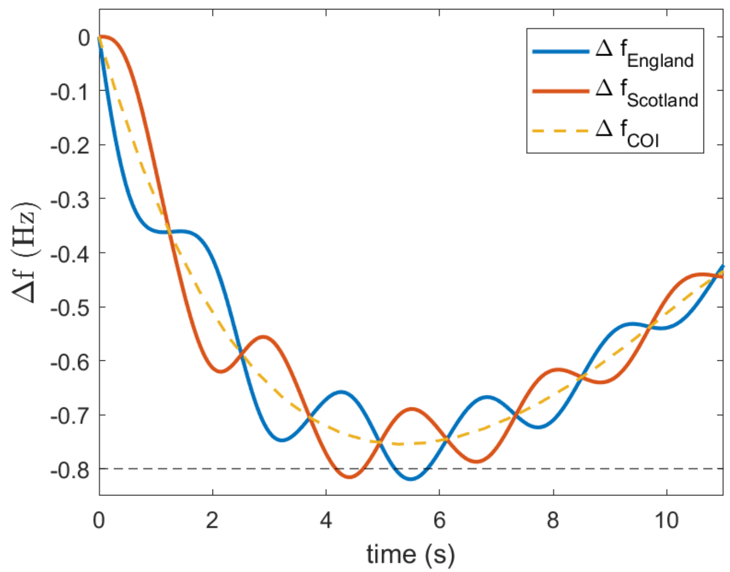


Conditions for regional frequency stability

- **Inter-area frequency oscillations** around the Centre Of Inertia (COI) appear when **inertia is not evenly distributed in the grid** (e.g. high wind capacity in Scotland but most of the electric demand located in England).
- **Ignoring inter-area oscillations could be dangerous**: higher RoCoFs and lower frequency nadirs than the COI could lead to unexpected blackouts.
- We have, for the first time, **deduced stability conditions for regional frequency**, and studied their implications in the Great Britain system.

More info here and here





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Summary of contributions

For **current power systems**:

- Allows to optimally operate the system, for example optimally part-loading large nuclear plants to reduce the largest possible loss. Particularly valuable for systems with high renewable penetration.
- Allows to inform market design for energy and ancillary services, putting in place the right incentives for providers of inertia and frequency response.

For **potential future scenarios** of generation mix or market structure:

- Allows to study the value of different technologies (e.g. fast power injections from battery storage, flexibility from thermal units).
- Where in the network to place ancillary services, guaranteeing regional frequency stability in a cost-effective manner.