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

Luis Badesa
Department of Electrical and Electronic Engineering, Imperial College London
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](https://great-britain-blackout-aug-2019))
How to optimally procure the ancillary services needed because of low inertia?

Frequency ancillary services ("insurance to prevent blackouts")

Described by differential equations (timescale of seconds)

Economic Optimisation

Based on algebraic equations (timescale of min/hours)

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

\[
\min \sum_{n \in N} \pi(n) \sum_{g \in G} C_g(n)
\]

subject to
- RoCoF constraint
- Nadir constraint
- Steady State constraint

(and other typical constraints)
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**.

More info [here](#).
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](#)

![Graph showing cost of frequency services and reduction in CO₂ emissions](#)

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

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

£900m/year savings for a high-wind system

Part-loading becomes very beneficial for a largest loss of 1.8GW
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](#)
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
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:**

\[
\frac{\lambda_2}{\sqrt{\Delta f_{\text{max}}}} - (\mu - \lambda_1) \frac{T_1 + T_{\text{del,1}}}{4\Delta f_{\text{max}}}
\]

**Price for slow FR services:**

\[
(\mu + \lambda_1) \frac{1}{T_2} + (\mu - \lambda_1) \frac{T_{\text{del,2}}/T_2}{4\Delta f_{\text{max}}} - \lambda_2 \frac{T_{\text{del,2}}/T_2}{\sqrt{\Delta f_{\text{max}}}}
\]
**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](#)
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.