Dynamical Model for Power Grid Frequency Fluctuations: Application to Islands with High Penetration of Renewables

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As the transition towards a sustainable energy system accelerates, conventional power plants are progressively replaced by variable renewable energy sources (VRES). This reduces the overall flexibility of the grid, requiring additional control strategies to ensure stable operation.

We propose a model for the high-voltage grid including conventional and variable renewable generation, as well as demand variations [1]. By assimilating load and generation data, our model reproduces frequency fluctuations with the current power mix with a high degree of accuracy. Moreover, it allows to simulate the frequency dynamics for different scenarios with a very high penetration of renewable energy. As a case study, we analyze the power grids of Gran Canaria and the Balearic Islands. We characterize the frequency fluctuations and propose a method to estimate the control needed to keep frequency deviations within statutory limits (50 ± 0.15 Hz).

The model takes the demand and each plant's scheduled generation as input [2], and it gives the frequency and generation at each site. In Figure 1, we compare simulations to actual frequency measurements [3]. We see that the model correctly captures frequency deviations in accordance to power ramps, and it reproduces the frequency time series and the main statistical properties with reasonable accuracy. The discrepancies are mainly associated with the lack of power data with finer temporal and spatial resolution, as well as unknown power plant characteristics.

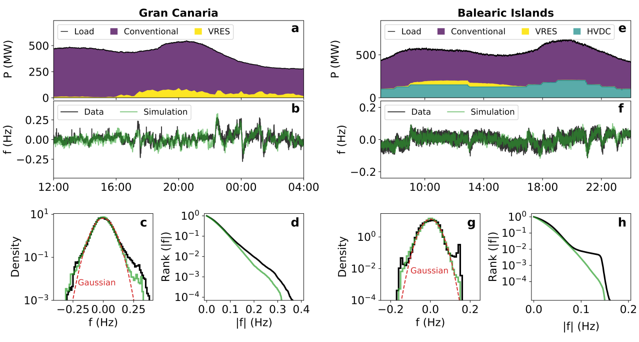

Fig. 1. Model validation. (a,e) Demand-generation balance. (b,f) Frequency-time series, (c,g) probability density, and (d,h) rank-size distribution of frequency fluctuations given by the model in comparison to the data.

Our model can be used as a test bench to study the power grid under different scenarios. In this work, we focus on the effects of a high penetration of VRES. Accordingly, we perform simulations for increasing amounts of VRES in the system. We take 2019 (Gran Canaria) and 2020 (Balearic Islands) as the reference cases, where VRES generation covers a small fraction of the demand, and frequency deviations stay close to the statutory limits.

For Gran Canaria, we increase wind capacity because it is a major resource in the island. As wind power ramps are magnified, frequency deviations become larger, except for the time windows where the wind generation exceeds the demand. In these cases, we only introduce in the grid the demanded amount and the excess power is simply discarded. This is known as curtailment, which serves as another control mechanism showing benefits to some extent.

In Figure 2b, we show that increasing secondary control reduces the size of all frequency deviations. In [1], we estimated the control needs in winter and summer using a numerical and an analytical approach. As expected, the control needs increase with wind penetration. Up to a certain point, there is a linear relationship between the secondary control gain parameter κ and the installed wind power. However, for larger fractions of installed wind power, there is a plateau due to the curtailment. We obtained a good agreement between the analytical approach and the numerical simulation results for scenarios with up to 4 times the current wind capacity.

For the Balearic Islands, we increase solar photovoltaics, as wind is not viable. The Balearic grid has the peculiarity that it is connected to mainland via a high voltage direct current (HVDC) link. The link provides threshold-like frequency control when the frequency reaches its legal limits [4], leading to characteristic features in the shape of the frequency fluctuations. In scenarios with increasing solar generation, where all conventional power plants are completely disconnected from the grid, the control provided by the link is enough to keep the frequency deviations within the statutory limits [5]. Nonetheless, fluctuations are very fast in the control dead band due to lack of inertia. Having inertia or keeping one conventional plant operating at a minimum power to provide frequency regulation reduces this volatility (Figure 2d).

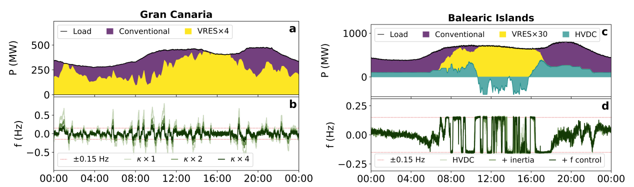

Fig. 2. Increasing VRES. (a,c) Demand-generation balance. (b,d) Frequency-time series for different control scenarios.

[1] M. Martínez-Barbeito, D. Gomila, P. Colet, *IEEE Trans. Sustain. Energy* (2023). Published online. DOI: 10.1109/TSTE.2022.3231975

[2] https://demanda.ree.es/visiona/home

[3] https://power-grid-frequency.org

[4] M. Martínez-Barbeito, D. Gomila, P. Colet, *ENERGY Int. Conf. Smart Grids, Green Commun. IT Energy-aware Technol.* (2021).

[5] M. Martínez-Barbeito, D. Gomila, P. Colet. *Submitted* (2023).