Data Analysis of Frequency Fluctuations in the Balearic Grid Before and After Coal Closure

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***Abstract*—In 2019, the most polluting power station in the Balearic Islands was partially closed down, marking the end of coal as the main energy source in the territory. In this work, we analyze the differences in the statistics of fluctuations of the electrical frequency before and after the closure.**

***Keywords*—frequency fluctuations; power grid analysis; frequency-dependent control; coal generation; decarbonization.**

I. Introduction

Stable power grid operation is based on the continuous balance between supply and demand. This balance is not trivial due to the lack of large-scale storage capacity and the intrinsic fluctuations of (part of) the demand. If demand exceeds generation, the grid frequency reduces, while if generation exceeds demand, it increases. Thus, studying frequency fluctuations is a good proxy to analyze the power grid stability.

Nowadays, balance is achieved by adapting in real time the generated power to the demand, which can only be achieved using controllable energy sources. Besides being controllable, conventional power plants play a key role in grid stability. They provide primary and secondary control, which compensate frequency deviations from the reference frequency, and they incorporate large inertia to the grid, which damps fast fluctuations.

The need to urgently address the effects of climate change and the dependency of the energy sector on hydrocarbon resources is accelerating the transition towards sustainable and renewable energies. A first step in this transition implies the progressive closure of the most contaminating power plants, such as those based on coal, whose role is taken over by cleaner conventional energy sources, e.g., natural gas. Subsequent steps imply a progressive reliance on variable renewable energy sources to generate electricity, together with a larger degree of electrification of the industrial, commercial, transportation and domestic sectors [1].

The energy transition is particularly pressing on islands, whose energy supply typically depends on imported fossil fuels and submarine connections to mainland or nearby islands, which increases generation costs [2]. Given their typically small size and limited inter-connectivity, islands have less robust power grids compared to the mainland. In turn, they are prone to more frequent failures. Moreover, many islands rely on tourism as their main economic activity, thus they are subject to seasonal changes of population and large demand variations. Therefore, replacing conventional with renewable generation in these territories requires specific analysis of their operational challenges [3]. In the case of the Balearic Islands, the energy transition has led to the partial close down of its coal fired power plant. We base our analysis on the grid frequency statistics, as has been considered for several locations [4]. Here, we focus on the effect that the replacement of coal has had on this statistics.

The paper is structured as follows. Section II introduces the Balearic grid as our case study. Section III presents the two data sets which will be used. Sections IV and V analyze frequency fluctuations in the absence and presence of coal generation, respectively. Section VI discusses the presence of threshold-like frequency control. Finally, Section VII, summarises the concluding remarks of our study.

II. The Balearic grid

The Balearic Islands are a Spanish archipelago located in the Mediterranean Sea, near the eastern coast of the Iberian Peninsula. Their high-voltage power grid can be mapped down to substation level as a network of 61 nodes and 88 links distributed across its four largest islands, i.e., Mallorca, Menorca, Ibiza, and Formentera [5]. This includes 6 conventional power plants, which we summarize in Table I, and the 3 Alternating Current (AC) submarine interconnections of Menorca-Mallorca, Mallorca-Ibiza, and Ibiza-Formentera. Moreover, Mallorca has a High Voltage Direct Current (HVDC) submarine connection to mainland that provides around 30% of the total demand [6].

The AC connections among the different islands ensure the synchronous operation of the Balearic grid. Since the line with mainland is DC, the Balearic grid operates asynchronously with respect to European continental grid.

Although islands only account for a small fraction of global greenhouse gas emissions, they are one of the most vulnerable territories to the effects of climate change. The Balearic Islands are no exception. For this reason, in 2019, the electric utility company Endesa, the Balearic and the Spanish Government reached an agreement to close down 2 out of the 4 coal generating units of Es Murterar [7], the most polluting power station in Mallorca.

Besides the close down, they also limited the amount of operation time of the two remaining units to 1500 hours

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TABLE I. INSTALLED POWER AT EACH CONVENTIONAL POWER PLANT OF THE BALEARIC GRID BEFORE THE PARTIAL CLOSE DOWN OF ES MURTERAR [8]. CCGT STANDS FOR COMBINED CYCLE GAS TURBINE.

Power plant	Generation type	Installed capacity (MW)
Mahón (Menorca)	gas turbine + ancillary	171.7 32.7
	diesel engine (ancillary)	40.8
Es Murterar (Mallorca)	coal	241.2
	gas turbine	65.4
Son Reus (Mallorca)	CCGT	394
	gas turbine	134.8
Cas Tresorer (Mallorca)	CCGT	429
Ibiza	gas turbine + ancillary	119 68
	diesel engine + ancillary	69.6 29
Formentera	gas turbine (ancillary)	11.5

per year until 2021. After that, the number of hours will be reduced to 500 per year until the complete close down of the power plant, which will coincide with the activation of a new connection to mainland. These measures were taken in order to decrease emissions, as a step in the decarbonization agenda [8]. Nowadays, the main technology types in the archilepago are combined cycle, gas turbines, and diesel engines.

III. DATA

Frequency data measured every second is obtained from the open database [9] [4]. The database includes measurements from October 2019 until December 2020, except the months of August and October 2020. The data was taken at a single location in the island of Mallorca, and we assume that the grid frequency is the same in the other islands.

We also make use of data publicly available on the web site of Red Eléctrica de España (REE) [10], the Spanish grid operator, who is responsible for maintaining the demand-supply balance under specific power quality conditions. In particular, for the case of the Balearic Islands, they provide the overall demand and generated power averaged over 10 minutes, as well as the power arriving from mainland Spain through the HVDC line. Generation is disaggregated by power plant technology.

IV. ANALYSIS OF FREQUENCY FLUCTUATIONS

Frequency fluctuations illustrate supply-demand unbalances, which are a result of the unpredictable load changes. According to Spanish legislation [11], the reference frequency for the power grid is 50 Hz and the statutory operational limits are between 49.85 and 50.15 Hz.

Since we have access to both frequency and power data, the first step in our study is to simply compare these two data sets. In Figure 1, we show the comparison for one day in January 2020, when there was no coal generation. In the upper panel, we have the 10-minute power data for demand and generation disaggregated by technology, and in the lower panel, we have the 1-second frequency data.

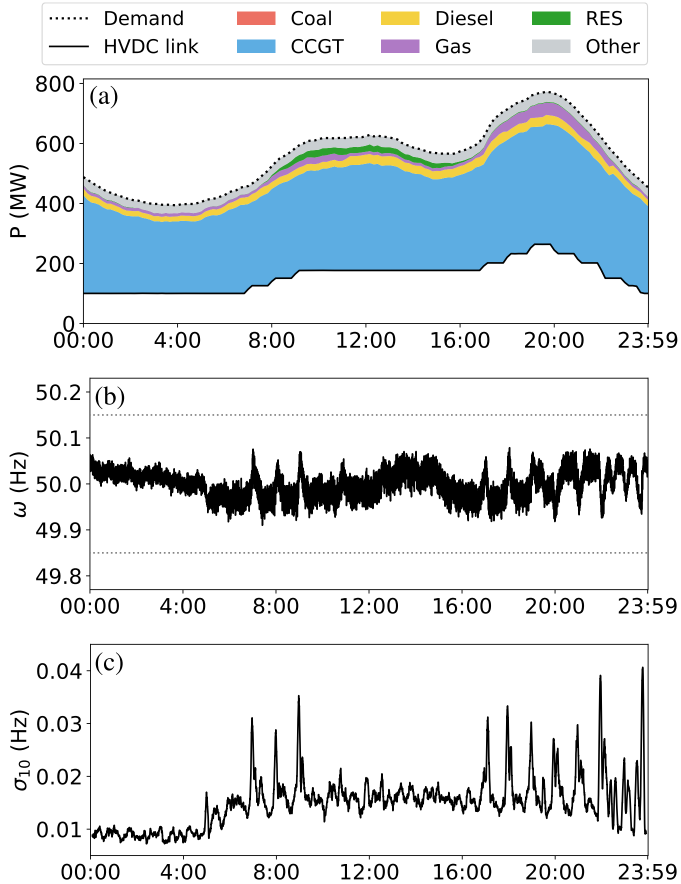

Figure 1. Time evolution of the demand and generation (a) and frequency fluctuations (b) on January 26, 2020, a day in which there was no coal generation. On panel (a), generation is disaggregated by power plant technology, including the HVDC connection to mainland. On panel (b), the dotted lines indicate the statutory operational limits, i.e., (50.00 ± 0.15) Hz. Panel (c) shows the moving standard deviation of the frequency calculated using a 10 minute sliding window.

The first point that we notice is the overall behavior of the frequency, which follows the daily pattern of the demand. During the first hours of the day, the frequency is above 50 Hz indicating an excess of generation. Since the demand is decreasing, so is the generation. However, the generation runs a bit behind because it is a response to the changes in the demand, hence the excess.

Early in the morning, the decrease rate of the demand slows down, which brings the frequency near its nominal value. In other words, the generation closely matches the demand. However, at some point, the demand starts increasing, which causes a lack of generation and makes the frequency drop below 50 Hz. Then, we could follow the same reasoning throughout the rest of the day to see how the slow changes in power are linked to the grid frequency.

Nonetheless, there are also fast power variations, which are naturally responsible for the fast frequency fluctuations. We are referring to the stochastic changes in the demand caused by consumers. Although these changes are not recorded in the 10-minute power data, they can be seen in the frequency data by

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looking at the thickness of the curve. This is further evidenced in panel (c) which shows the frequency volatility measured by the moving standard deviation σ_{10} evaluated using a sliding time window of duration 10 minutes. As expected, we notice the difference between daytime and nighttime, when there is less frequency volatility because consumers are asleep.

Besides the random fluctuations of the demand, there can also be large deterministic events. These can be both demand or generation power changes induced by a unique and sometimes anomalous cause. In Figure 1, we can see that this is the case of the step-like changes in the power provided by the HVDC connection between Mallorca and mainland Spain, which cause large frequency changes visible in panel (b), also reflected as large peaks in the moving standard deviation σ_{10} (panel (c)). In fact, most of the large frequency changes in that day can be identified with changes in this power line. The size of these large frequency shifts depends, of course, on the power imbalance, but it also depends on the amount of control available in the power plants operating at that particular moment. It should be noted that during low load hours the system is more susceptible due to the decrease in conventional generation, which affects the inertial response. Therefore, a HVDC power change in the morning can have a different impact on the system than if the same variation happened at night.

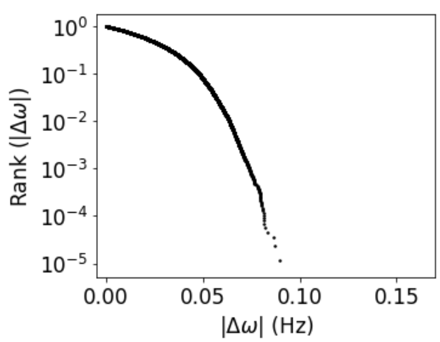

Figure 2. Rank distribution of the absolute value of the frequency fluctuations on January 26, 2020, when there was no coal generation and the energy mix was dominated by CCGT.

In order to characterize the frequency fluctuations, we can use the rank size distribution. We evaluate $\Delta\omega_k \equiv \omega_k - \omega_R$, where ω_R is the reference frequency (50 Hz), reorder the set of values $|\Delta\omega_k|$ from the smallest to the largest value, and finally estimate the complementary cumulative distribution of the deviations as $R(|\Delta\omega_i|) = 1-(i-1)/(M-1)$, where M is the number of data points. $R(|\Delta\omega|)$ measures the probability to have a frequency fluctuation of size larger than $|\Delta\omega|$. In Figure 2, we plot the result. We see that frequency variations from the nominal value stay below 0.1 Hz, which we could already see in Figure 1b. Moreover, the shape of the curve shows a smooth decay in the probability of having large fluctuations. In other words, the frequency tends to stay close to its nominal value, and large deviations are highly unlikely.

V. Coal generation and frequency fluctuations

As we indicated in Section II, the year 2019 marked the end of coal as the main source of power generation in the Balearic Islands. In Figure 3, we plot the daily average power generated from coal (panel a) and from CCGT (panel b) in 2019 and 2020.

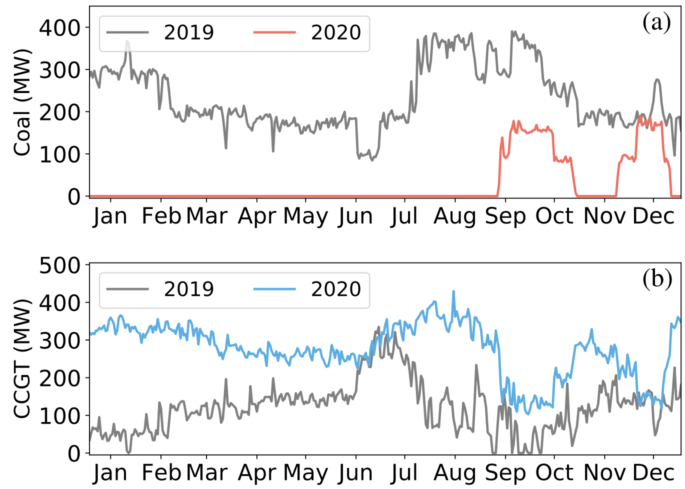

Figure 3. (a) Coal generation daily average in 2019 (gray) and 2020 (red). (b) CCGT generation daily average in 2019 (gray) and 2020 (blue).

To better appreciate the changes in the energy mix disregarding the seasonal variations in demand, we plot in Figure 4 the percentage of generation covered by the different generation technologies in 2019 (panel a) and 2020 (panel b). We can see that coal generation has been replaced by natural gas (combined cycle), which is a less polluting fossil fuel. However, during certain periods of 2020, coal was still used for electricity generation. In fact, it represents a very substantial part of the energy mix on these periods.

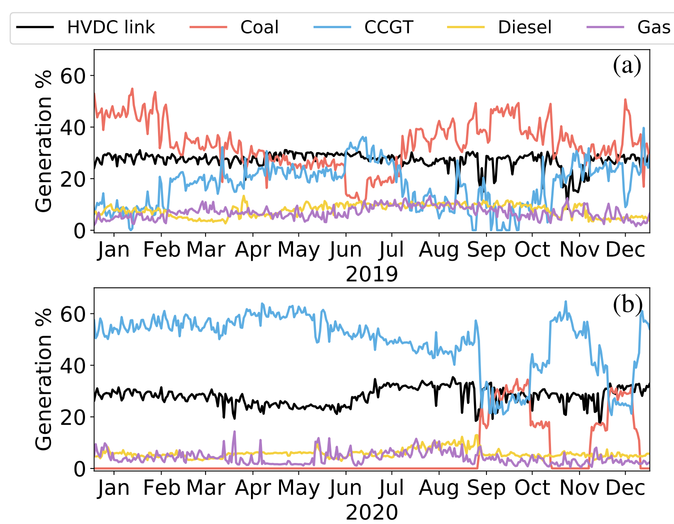

Figure 4. Percentage of the generation covered by different power plant technologies in (a) 2019 and (b) 2020.

In Figure 5, we plot the demand and generation disaggregated by power plant technology (panel a), the grid frequency (panel b), and the frequency volatility (panel c) for a typical day in 2019, when there were no restrictions to coal generation. Looking at panel (b), we observe large frequency deviations, specially compared to those in Figure 1b. In fact, it is clear that the frequency reaches the statutory limits of ± 0.15 Hz on several occasions. The frequency volatility, as indicated by the standard deviation σ_{10}, is also much larger when coal generation dominates the energy mix, as shown in panel (c) (compare this panel with that of Figure 1). Altogether, this is an indication that the overall control capacity of the Balearic grid is significantly smaller than the case shown in Figure 1. We believe that this is simply because combined cycle power plants have a faster and more powerful control response.

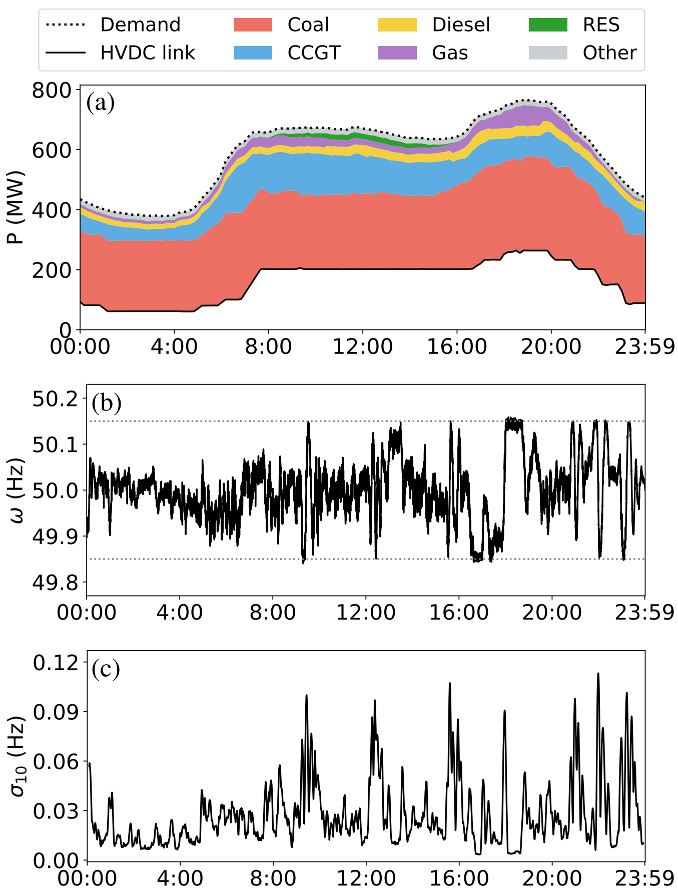

Figure 5. Time evolution of the demand and generation (a) and frequency fluctuations (b) on December 18, 2019, a day in which coal was the main source in the energy mix. On panel (a), generation is disaggregated by power plant technology, including the HVDC connection to mainland. On panel (b), the dotted lines indicate the statutory operational limits, i.e., (50.00 ± 0.15) Hz. Panel (c) shows the frequency volatility σ_{10}.

We also computed the rank distribution of frequency fluctuations for this case, which we show in Figure 6. Comparing it with Figure 2, we can confirm the difference in terms of fluctuation sizes, but also in the shape of the distribution. The smooth parabolic decay that we saw in Figure 2 is not present

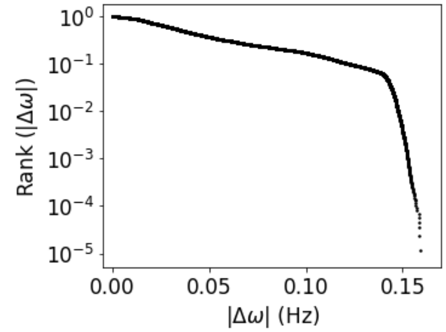

Figure 6. Rank distribution of the absolute value of the frequency fluctuations on December 18, 2019, when coal was the main energy source.

in Figure 6. Instead, we see a much slower linear decay of frequency deviations up to 0.15 Hz, which is followed by a very steep drop. This indicates that the probability to have frequency fluctuations up to 0.15 Hz is significantly larger than in the case considered in Figure 2. Nevertheless, the probability to have frequency fluctuations beyond the statutory limits ± 0.15 Hz is very small.

VI. Discussion on threshold-like frequency control

The behavior of the frequency fluctuations displayed in Figure 5b and Figure 6 is very peculiar. The sharp cut of the frequency deviations at the statutory limit of 0.15 Hz is not observed in the analysis of other power grids [4]. Besides the cut of the frequency deviations at ± 0.15 Hz, we can also see that when the frequency reaches that value, it may remain clamped at that value for a relatively long period of time (tens of minutes or even more than one hour). For instance, this is what happens around 6 PM in Figure 5, when the frequency is kept at its upper limit for 45 minutes.

The typical control mechanisms present in conventional power plants tend to restore the frequency back to its nominal value and act proportionally to the frequency deviation or depending on a smooth function of the frequency deviation. The existence of a threshold-like value beyond which the damping of the fluctuations is much stronger is not the natural response of these mechanisms. For these reasons, we conclude that there must be an additional control which is activated when the frequency deviation reaches the statutory limits ± 0.15 Hz.

The effect of this threshold-like frequency control is more noticeable in periods of coal generation, when there are larger frequency fluctuations. However, we have found that it can also be seen when combined cycle is the main generating technology, although in this case it happens seldomly. This is illustrated in Figure 7 for January 30, 2020. Although there was no coal generation, during the first hours of the day the frequency reached 50.15 Hz and it stayed around that value for 2 hours. As a consequence, in this day the rank distribution of the frequency fluctuations has a sharp drop at $|\Delta\omega| = 0.15$ Hz, as shown in Figure 8.

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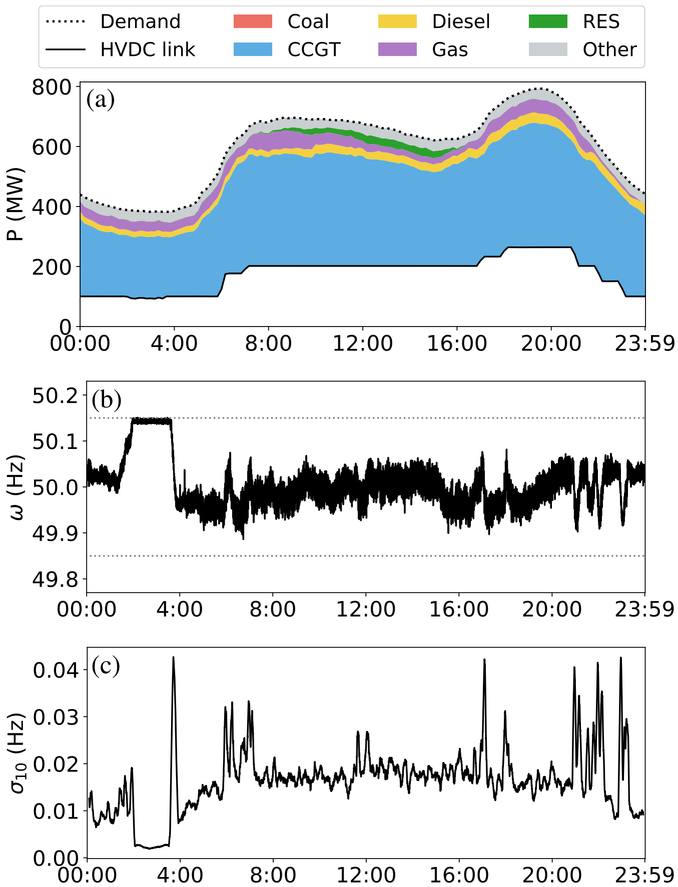

Figure 7. Time evolution of the demand and generation (a) and frequency fluctuations (b) on January 30, 2020. On panel (a), generation is disaggregated by power plant technology, including the HVDC connection to mainland. On panel (b), the dotted lines indicate the statutory operational limits, i.e., (50.00 ± 0.15) Hz. Panel (c) shows the frequency volatility σ_{10}.

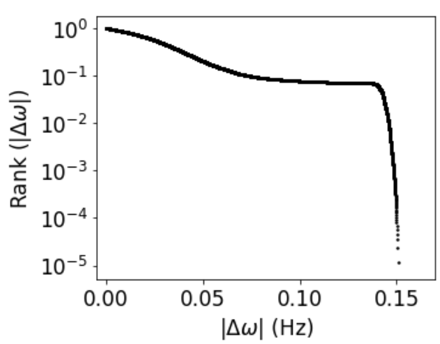

Figure 8. Rank distribution of the absolute value of the frequency fluctuations on January 30, 2020, when the threshold-like frequency control was activated despite not having coal generation.

VII. Conclusions

We have analyzed the frequency fluctuations recorded in the Balearic power grid. We have seen that the partial close down of its coal fired power plant in 2019, being replaced by CCGT, has lead to significant reduction of the frequency fluctuations. Nowadays, CCGT is the main generating technology during large part of the year. However, coal can still be used for electricity generation. On the periods of time in which this is the case, the frequency is more volatile and has larger fluctuations.

In Figure 9, we compare the rank size distribution of frequency variations for a three-months period in which coal was the main energy source (red) with a similar period where it was replaced by CCGT (blue). There is a clear difference between the two scenarios. When there is coal generation, we observe a similar shape to that in Figure 6, with a roughly power-law decay up to 0.15 Hz followed by a sharp decrease all the way down to cumulative probabilities of the order of 10^{-6}. This sharp decay is associated to the activation of threshold-like frequency control, which happens quite frequently for periods of time in which coal is the main component of the energy mix. The sharp decay is followed by another power-law decay for fluctuations larger than 0.2 Hz, which was not visible on Figure 6 since it is associated to very rare events not present on the particular day of the figure.

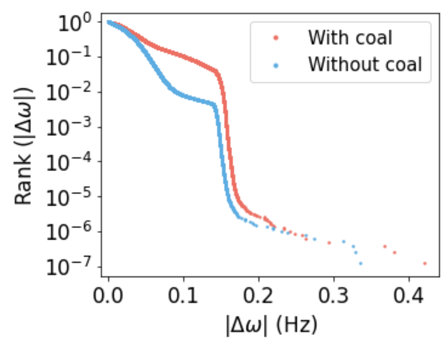

Figure 9. Rank distribution of frequency deviations measured from October to December 2019 (red), and from January to March 2020 (blue).

When there is no coal generation, the shape of the distribution decays faster than power law for $|\Delta\omega| < 0.10$ Hz. This fast decay is followed by a practically horizontal plateau up to 0.15 Hz which indicates that there are very few fluctuations of that size. This is what we saw in Figure 8, and it has to do with the fact that the frequency stays within $(49.9, 50.1)$ Hz most of the time. However, larger frequency variations can occur as illustrated in Figure 7b, where the frequency goes up to 50.15 Hz and, after some time, it jumps back down to a point closer to its nominal value. The point is that it spends very little time in the range $(50.10, 50.15)$ Hz, which is why the size distribution is flat around those values. Once the frequency fluctuations reach 0.15, the threshold-like mechanism is activated, albeit this happens seldomly when there is no coal generation and the energy mix is dominated by CCGT, leading to a sharp decay in the rank distribution. Finally, the power-law tail associated to fluctuations larger than 0.2 Hz is still present but its probability is lower than in the case of coal-dominated generation mix.

To further illustrate the differences in the frequency statistics when coal or CCGT are the main generation source, in Figure 10, we plot the probability density function for the daily time series that we have analyzed in Figures 1, 5, and 7. Table

II shows the mean, variance, skewness, and kurtosis of these data sets. The data set in Figure 1 has the mean closest to 50 Hz, and the smallest variance, indicating that frequency fluctuations are smaller than for the other cases. This data set has also the most symmetric distribution (smallest skewness). Nonetheless, as we can see in Figure 10 and with a skewness of 0.09, the data in Figure 5 can also be considered symmetric. In contrast, the data set in Figure 7 is highly skewed to the right. This is due to the fact that the frequency fluctuates around its reference value for most of the time, except during the two hours where it stays in the limit 50.15 Hz. For the kurtosis, we have to compare it to that of the normal distribution, i.e., 3. We see that Figure 1 is platykurtic (less than 3) and Figure 7 is leptokurtic (greater than 3). Therefore, in the former, the probability of large events is smaller than in the Gaussian distribution, while it is larger in the latter.

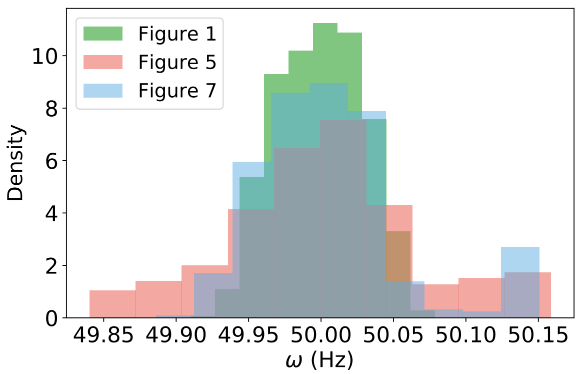

Figure 10. Probability density function of the daily frequency time series shown in Figures 1, 5, and 7. The histogram is normalized so that the total area is 1, as it corresponds for a probability density function.

TABLE II. MEAN, VARIANCE, SKEWNESS, AND KURTOSIS OF THE FREQUENCY TIME SERIES SHOWN IN FIGURES 1, 5, AND 7.

Measure	**Figure 1 2020-01-30**	**Figure 5 2019-12-18**	**Figure 7 2020-01-30**
Mean	49.999	50.002	50.006
Variance	0.03	0.06	0.05
Skewness	-0.03	0.09	1.17
Kurtosis	2.19	3.04	4.50

Moreover, we plot in Figure 11 the probability density function of the frequency fluctuations obtained from sampling the frequency every second during a three-months measurement period. The probability distribution for the coal-dominated period (red) shows a much longer tail than the one for the CCGT-dominated period. As a consequence, while frequency deviations between 0.10 and 0.15 Hz are quite probable for the former case, they are very rare for the last one.

Finally, we have also seen that there is clear evidence of a threshold-like frequency control in addition to the typical control mechanisms operating in conventional power plants. This additional control is activated when the frequency deviation reaches the statutory limits ± 0.15 Hz, strongly damping deviations beyond this threshold. Its effect can be seen in the frequency time series (Figure 5 and Figure 7), and also as a steep cut in the rank size distribution (Figure 9).

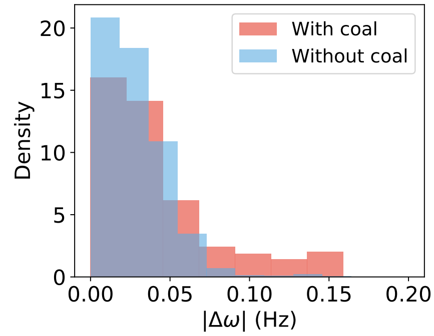

Figure 11. Probability density function of frequency deviations measured from October to December 2019 (red), and from January to March 2020 (blue). The histogram is normalized so that the total area is 1, as it corresponds for a probability density function.

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