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Impact of Market Reforms on Deterministic Frequency Deviations in the European Power Grid

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ABSTRACT Deterministic frequency deviations (DFDs) are systematic and predictable excursions of grid frequency that arise from synchronized generation ramps induced by electricity market scheduling. In this paper, we analyze the impact of the European day-ahead market reform of 1 October 2025, which replaced hourly trading blocks with quarter-hourly blocks, on DFDs in the Central European synchronous area. Using publicly available frequency measurements, we compare periods before and after the reform based on daily frequency profiles, indicators characterizing frequency deviations, principal component analysis, Fourier-based functional data analysis, and power spectral density analysis. We show that the reform substantially reduces characteristic hourly frequency deviations and suppresses dominant spectral components at hourly and half-hourly time scales, while quarter-hourly structures gain relative importance. While the likelihood of large frequency deviations decreases overall, reductions for extreme events are less clear and depend on the metric used. Our results demonstrate that market-design reforms can effectively mitigate systematic frequency deviations, but also highlight that complementary technical and regulatory measures are required to further reduce large frequency excursions in low-inertia power systems.

INDEX TERMS Frequency stability, electricity market design, power system stability.

I. INTRODUCTION

THE ongoing energy transition poses fundamental challenges to the operation and stability of electric power systems. An increasing share of renewable generation is connected to the grid via power electronic inverters, which provide little or no intrinsic rotational inertia. As a result, the aggregate system inertia is declining, and frequency stability is becoming increasingly at risk [1].

Deterministic frequency deviations (DFDs) are predictable and repeatable departures of the system frequency from its nominal value, caused by systematic imbalances between power generation and load. The mechanism underlying DFDs in the Central European power system was summarized in [2] and is illustrated in Fig. 1. Electricity trading is organized in hourly or quarter-hourly blocks, which induces strong generation ramps at the boundaries of the trading intervals. The resulting temporary overgeneration (or scarcity) leads to a rapid increase (or decrease) in system frequency before the imbalance is compensated by the load–frequency control system.

DFDs have been identified by the European Network of Transmission System Operators for Electricity (ENTSO-E), the official representative of the European transmission system operators, as a major challenge to system operation, leading to the publication of a comprehensive assessment report in 2020 [3]. The report highlights that DFDs can systematically activate frequency containment reserves, induce unscheduled power flows, and reduce effective damping margins, thereby weakening system operation even in the absence of major contingencies. These effects make DFDs a relevant operational concern and motivate the need for targeted mitigation measures.

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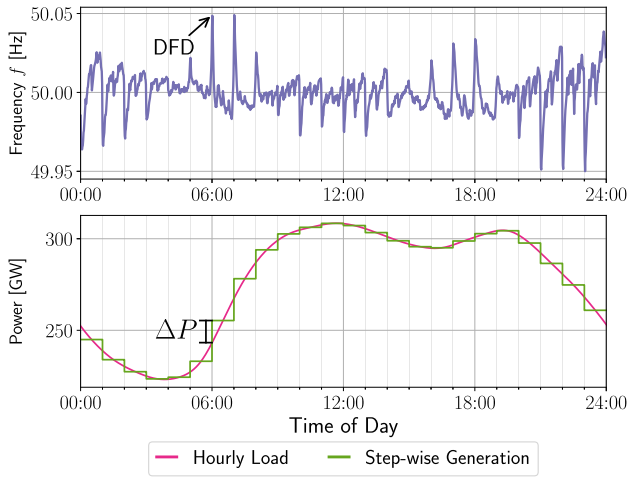

FIGURE 1. Emergence of hourly deterministic frequency deviations (DFDs) due to electricity trading. Upper panel: The daily profile of the grid frequency in the Continental European synchronous area shows characteristic peaks at the beginning of every hour. Lower panel: These DFDs can be understood from the design of European electricity markets. Load evolves continuously, while generation is traded in blocks. At the beginning of each block, generation is adjusted in an approximately stepwise manner, leading to a power imbalance ΔP and thus to DFDs. Until 1 October 2025, electricity was mainly traded in hourly blocks, resulting in pronounced hourly DFDs. The figure shows the daily profile of the load as a continuous curve, while generation is depicted as a step function for illustrative purposes. The illustration uses data from 2019.

The design of the European electricity market plays a central role in the emergence of DFDs. Traditionally, the day-ahead market was organized in hourly trading blocks, leading to pronounced generation ramps at the beginning of each hour, particularly during morning and evening periods (see Fig. 1). Intraday electricity trading in Germany was introduced in the early 2010s and further developed with the introduction of quarter-hourly intraday auctions in 2014, enabling smaller, more frequent generation adjustments. Indeed, modest deviations at half-hourly and quarter-hourly intervals can already be observed in the daily frequency profile shown in Fig. 1. However, due to its significantly lower trading volume [4], the intraday market could not fully mitigate the hourly DFDs. The day-ahead market was revised in 2025 [5], replacing hourly blocks with quarter-hourly blocks and thereby directly addressing one of the structural causes of strong hourly DFDs. The market reform took effect on 30 September 2025 for delivery day 1 October 2025.

Improving grid balancing and frequency quality was one major objective of the market reform [3], [6], but the magnitude of its impact under real-world operating conditions remained largely unknown. The reform thus provides a unique opportunity to quantify the effect of shorter market time units directly from measurements. In this article, we investigate the impact of the transition from hourly to quarter-hourly day-ahead trading on DFDs in the Continental European power system. We compare frequency time series before and after the reform using stability indicators and hourly and quarter-hourly patterns. Beyond confirming the expected reduction of DFDs, the analysis reveals how deterministic frequency patterns are redistributed across time scales and which structures persist after the reform.

This article is organized as follows. We review the scientific literature on DFDs in Sec. II. The methods used for the analysis of frequency time series are described in Sec. III. The results are presented in Sec. IV and discussed in Sec. V.

II. BACKGROUND AND LITERATURE

The origins of market-induced DFDs in the Continental European synchronous area, as sketched in Fig. 1, were summarized by Weissbach and Welfonder in [2]. The authors identify block-based market scheduling as a key driver of synchronized generator ramps and propose quarter-hourly trading intervals as a countermeasure, with a more detailed analysis of generator ramps given in [7]. Borsche et al. extended this to control signals and proposed a battery-based reserve framework [8]. The fundamental explanation of DFDs was refined in [9], showing that slowly ramping generation, such as solar, mitigates DFDs and is therefore excluded from the ramps illustrated in Fig. 1. The ENTSO-E Report on Deterministic Frequency Deviations confirms this empirically, attributing DFDs primarily to market scheduling and ramping behavior, and evaluating a range of technical and market-based countermeasures through simulations and national case studies [3]. Beyond documenting the phenomenon, the report establishes operational performance targets, monitoring approaches, and a policy-relevant framework for assessing trade-offs between market-design reforms and reserve-based mitigation strategies.

In general, market design and institutional factors strongly shape balancing needs and frequency control efforts, sometimes more than the rise in variable renewable generation [10]. For DFDs, the central mechanism is the use of block-based market time units, which can trigger synchronized schedule changes and amplified system-wide ramping [11]. Coarse temporal resolution in market schedules therefore increases reserve needs and operational stress, motivating reforms toward finer market time units [12]. In principle, finer market time units weaken this synchronization and mitigate deterministic imbalances. Empirical evidence supports this: the introduction of quarter-hourly intraday products and tighter balance-responsibility rules in Germany substantially reduced deterministic imbalances and frequency restoration reserve demand, although residual effects persist [13]. Furthermore, Schäfer et al. show that shorter trading intervals reduce the likelihood of large frequency deviations [14]. Motte-Cortés and Eising document a Europe-wide shift toward finer, closer-to-real-time operation driven by renewable penetration [15], and ter Borg et al. argue that

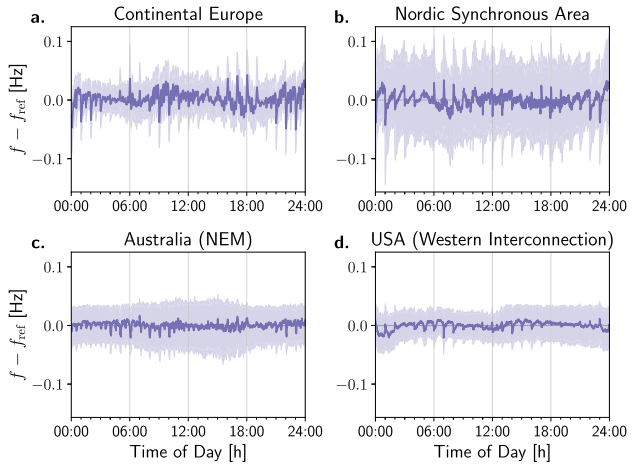

FIGURE 2. Comparison of daily frequency profiles for different grids. Panels a, b, c, and d show the daily profiles for Continental Europe, the Nordic grid, Australia (NEM) and the USA (Western Interconnection), respectively. The data were recorded between 17 January and 17 July 2024. The solid line shows the average of the frequency for the respective time of day, while the shaded areas show the region between the 5% and 95% quantiles.

moving to five-minute intervals could considerably decrease systematic imbalances in future high-renewable systems, albeit with higher complexity for market participants [16]. Together, these studies indicate that while finer market time units are a promising lever to mitigate DFDs, how they interact with system inertia, control reserves, and frequency dynamics remains an open question.

General aspects of frequency dynamics and control in future low-inertia grids have been reviewed in [1]. The impact of reduced rotational inertia and increasing inverter-based generation on frequency dynamics following disturbances using large-scale dynamic simulations were analyzed in [17] and [18]. Data-driven analyses based on explainable machine learning identified rapid generation ramps as key drivers of deterministic frequency dynamics [19], with hydropower and other highly flexible resources shaping rate of change of frequency patterns. This suggests that the physical flexibility of the generation portfolio influences how market schedules translate into observable frequency patterns. A physics-informed machine learning model predicting both DFDs and ambient frequency fluctuations was presented in [20]. Notably, other recurrent grid-frequency patterns not driven by market mechanisms exist at shorter periods [21], [22].

A broader international comparison shows that deterministic frequency deviations are not unique to the Continental European synchronous area but depend strongly on market organization and balancing practices. To illustrate this, Fig. 2 compares average daily frequency profiles across several major synchronous areas, based on a common observation period in 2024, for which data from all systems were available.

The Nordic synchronous area exhibits daily patterns that qualitatively resemble those observed in Continental Europe, including positive frequency excursions during the morning hours and negative excursions in the late evening. This similarity is consistent with the close integration of the Nordic and Continental European electricity markets. However, deterministic peaks are less pronounced, while the overall frequency variability is higher. These differences may be related to the smaller size of the Nordic synchronous area, which typically increases overall frequency variability [23], the use of ramping restrictions to mitigate deterministic frequency deviations [24], and distinct balancing practices [25].

The Western Interconnection in North America shows only weak deterministic frequency patterns. Small but recurring hourly-scale structures can be identified, with negative frequency deviations during the morning and afternoon, and positive deviations during nighttime. Notably, the sign of these patterns is opposite to that typically observed in European systems. North American electricity markets generally employ centralized real-time dispatch processes with substantially finer temporal resolution than in Europe, in addition to day-ahead scheduling. For example, CAISO combines hourly day-ahead scheduling with 15-minute market clearing and 5-minute real-time dispatch [26]. Notably, no clear structures are visible at periods of 15 minutes or 5 minutes.

Among the systems considered here, the Australian National Electricity Market (NEM) exhibits the weakest daily profile. Only small negative frequency deviations are visible during morning hours, and weak positive deviations during the evening. This observation is consistent with the comparatively fine temporal resolution of the Australian market design, which was reduced to 5 minutes in 2021 [27], [28]. Overall, the comparison highlights the strong influence of market design on deterministic frequency deviations.

III. METHODS

We analyze frequency time series $f(t)$ from the Central European power system before and after the market reform on 1 October 2025. We compare the power spectral density, the daily frequency profile, and indicators characterizing frequency deviations, such as the rate of change of frequency (RoCoF), as defined in Sec. III-D below. Finally, we quantify the contribution of quarter-hourly and hourly patterns in the time series via principal component analysis (PCA) and Fourier-based functional data analysis (FDA).

A. FREQUENCY DATA

Frequency data for the Continental European synchronous area are publicly available at [29], for the Nordic synchronous area at [30] and for the Australian power system at [31]. Frequency in the Western Interconnection has been measured at the distribution level as described in [32] and published in [22]. For the analysis, we center the frequency around the reference value, $\tilde{f}(t) = f(t) - f_{\mathrm{ref}}$ with $f_{\mathrm{ref}} = 50\,\mathrm{Hz}$

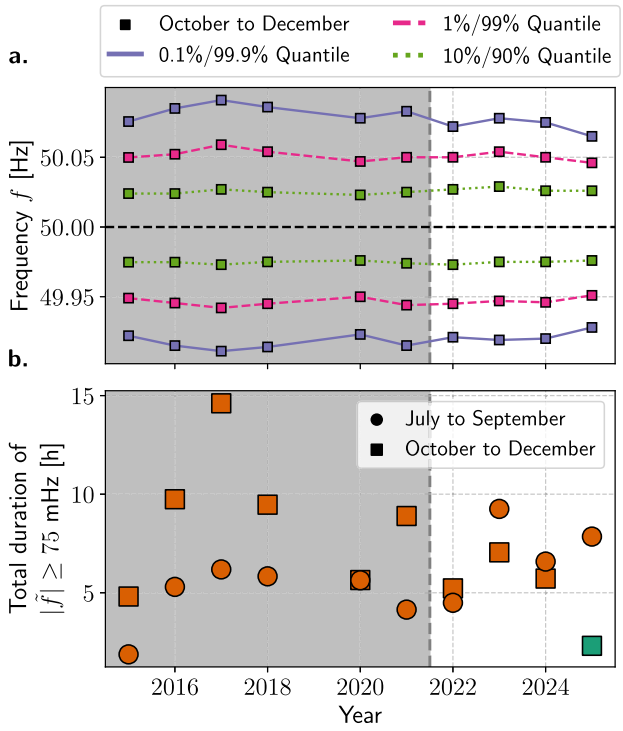

FIGURE 3. Long-term trends of frequency deviations. Upper panel: Evolution of selected quantiles of the frequency distribution during the months October–December from 2015 to 2025. Lower panel: Total duration of periods with large frequency deviations $|\tilde{f}(t)| \geq 75$ mHz. We provide data for the months October–December as well as July–September for comparison. The gray shading indicates that data publication changed in June 2022 (see Sec. III-A).

or $f_{\mathrm{ref}} = 60\,\mathrm{Hz}$, for the European/Australian grids and the Western Interconnection, respectively.

Throughout the paper, we compare data for three months before and after the market reform. Specifically, we consider the period from 1 October 2025 at 00:00 to 31 December 2025 at 00:00 and the respective period in 2024, to exclude seasonal effects as much as possible. For selected analyses, additional data from earlier years are included to place the observed changes in a longer-term context (cf. Fig. 3).

We note that data handling and publication procedures at the Netztransparenz platform [29] changed in June 2022, as indicated by the gray shading in Fig. 3. Frequency data prior to 2022 frequently exhibit quality issues, including missing values and inconsistencies. To mitigate these effects, we follow the postprocessing procedure of [33] and remove values with either an unrealistically large deviation from the reference frequency or an unrealistically large difference to previous values. After postprocessing, the data for 2019 have more than 10% missing values and are therefore excluded from the analysis.

We remark that regional differences in the grid frequency are typically small and damped out in seconds [23], [34], such that the results derived from this data are representative for the entire synchronous area.

B. POWER SPECTRAL DENSITY

To analyze the spectral properties of the grid frequency $f(t)$, we compute the power spectral density (PSD) $S(\nu)$, where $\nu = 1/T$ denotes the spectral frequency corresponding to the period T. The PSD quantifies how the variance of $f(t)$ is distributed across different spectral frequencies. Comparing $S(\nu)$ before and after the market reform reveals spectral changes across all time scales.

We estimate $S(\nu)$ using Welch's method [35] implemented in SciPy [36]. The signal is detrended and split into overlapping segments, and a Hann window is applied to each segment to improve the distinction of neighboring peaks. Subsequently, each segment is transformed via the discrete Fourier transform, and the spectra of segments are averaged to obtain a good estimate of the power spectral density.

C. THE DAILY PROFILE

The daily profile of the grid frequency allows for a straightforward visual analysis of recurrent patterns. Splitting time t into the day index d and the time of day t', the daily profile is defined as

$$f_{\mathrm{dp}}(t') = \frac{1}{N_d} \sum_{d} f(d, t'), \tag{1}$$

where the sum is taken over all days in the respective period and N_d denotes the number of available days.

In addition to the mean profile, we analyze the empirical 5% and 95% quantiles at each time of day t'. These quantiles are defined as the values below which 5% and 95% of the frequency observations at the same time of day across all days are located, and they characterize the variability and asymmetry of recurrent frequency deviations.

D. INDICATORS OF FREQUENCY DEVIATIONS

We consider four indicators characterizing frequency deviations for every hourly interval, following [19]. The intervals are denoted as I_h, starting at time t_h. These indicators quantify the magnitude, persistence, and temporal structure of frequency deviations during normal system operation and are thus used in the analysis of recurrent DFDs.

The nadir is defined as the largest frequency deviation from the reference value within the interval I_h,

$$\mathrm{Nadir}(h) = \max_{t \in I_h} |\tilde{f}(t)|\,. \tag{2}$$

For simplicity, we use the term nadir for the largest absolute frequency deviation, irrespective of whether the excursion is toward lower or higher frequencies. The mean square deviation (MSD) quantifies the primary control effort in the respective interval [37],

$$\mathrm{MSD}(h) = \frac{1}{|I_h|} \sum_{t \in I_h} \tilde{f}^2(t). \tag{3}$$

The integrated frequency deviation is defined as

$$\text{Integral}(h) = \tau \sum_{t \in I_h} \tilde{f}(t) \tag{4}$$

and indicates a systematic imbalance between generation and load. Finally, we consider the RoCoF at the beginning of the respective interval. We estimate the derivative $\frac{df}{dt}$ at time t by smoothing the increments $\delta f(t') = [f(t') - f(t'-\tau)]/\tau$ over an interval $[t-L, t+L]$. We then consider the steepest slope of the derivative within a window $W_h = [t_h - T, t_h + T]$ around t_h,

$$\text{RoCoF}(h) = \max_{t \in W_h} \left| \frac{df}{dt}(t) \right| .$$

We choose $L = T = 60\,\text{s}$ following [19]. Notably, we consider only the magnitude of the nadir and the RoCoF in the following, i.e., we do not distinguish positive and negative frequency deviations in the statistical analysis.

E. PRINCIPAL COMPONENT ANALYSIS

To identify and characterize recurrent patterns in the grid frequency beyond simple averages, we apply principal component analysis (PCA) to hourly segments of the frequency time series. PCA is a standard dimensionality-reduction technique that represents a set of time-dependent signals as a weighted superposition of orthogonal modes, ordered by the amount of variance they explain [38].

As before, we divide the frequency time series into hourly segments and denote the frequency trajectory within hour h by $f_h(s)$, where $s = 1, \ldots, 3600$ indexes the seconds within the hour. We center the data by subtracting the mean across all segments at each second$s$ $\hat{f}_h(s)$. PCA yields a decomposition of the form

$$\hat{f}_h(s) = \sum_{n=1}^{3600} a_{h,n}\, v_n(s), \tag{5}$$

where $v_n(s)$ are the orthonormal principal components (modes) and $a_{h,n}$ are the corresponding coefficients for hour h. The components $v_n(s)$ are empirically obtained from the data and represent orthogonal intra-hour frequency patterns, ordered by the fraction of total variance they explain, while the coefficients $a_{h,n}$ quantify how strongly these patterns are expressed in individual hours.

By comparing the leading components and their coefficients before and after the market-design reform, we assess how characteristic market-induced frequency patterns change in structure and importance. We note that each principal component is defined only up to an overall sign. Consequently, a given component can represent both positive and negative frequency excursions, depending on the sign of the corresponding coefficient $a_{h,n}$.

F. FOURIER-BASED DATA ANALYSIS

To quantify the relative importance of intra-hour temporal patterns at specific time scales, we complement the PCA-based analysis with a Fourier-based functional data analysis. As above, the frequency time series is partitioned into hourly segments, each treated as a functional observation.

Within each segment h, the centered frequency signal $\tilde{f}_h(s)$ is represented by a truncated Fourier expansion,

$$\tilde{f}_h(s) = c_{h,0} + \sum_{k \in \mathcal{K}} \left[c_{h,k} \cos\left(\frac{2\pi k s}{T}\right) + b_{h,k} \sin\left(\frac{2\pi k s}{T}\right) \right] + \varepsilon_h(s), \tag{6}$$

where $T = 1$ hour in our analysis, $\mathcal{K}$ denotes a predefined set of harmonics, $\varepsilon_h(s)$ captures residual fluctuations, and $c_{h,0}$ is the segment mean. Subtracting the segment mean before the decomposition removes constant offsets and suppresses leakage from very low-frequency components.

In contrast to principal component analysis, which extracts data-driven basis functions, the Fourier representation employs a fixed orthogonal basis, allowing individual harmonics to be directly associated with specific intra-hour time scales. The coefficients $(b_{h,k}, c_{h,k})$ are calculated independently for each segment and quantify the amplitude of oscillatory patterns at harmonic k.

For each harmonic k, we define the oscillatory energy as

$$E_{h,k} = \frac{b_{h,k}^2 + c_{h,k}^2}{2} \quad \text{for} \quad k > 0. \tag{7}$$

Variability on the hourly scale corresponds to the fundamental mode $k = 1$, while variability on the quarter-hourly scale corresponds to the harmonic $k = 4$, i.e., four oscillation cycles per hour. Hence, the most relevant question is how $E_{h,1}$ and $E_{h,4}$ change after the market reform.

G. GENERATION AND RESERVE DATA

Aggregated generation data for reservoir hydropower in Germany per market interval were downloaded from the ENTSO-E Transparency Platform [39]. Reservoir hydropower is a highly flexible generation technology that has previously been identified as an important driver of RoCoF patterns and deterministic frequency deviations [19]. To characterize changes in generation schedules, we compute the dispatch change as the difference between two consecutive quarter-hourly generation values. Dispatch changes are related to, but not identical to, physical generation ramps, which additionally depend on the ramping capabilities and operating constraints of individual units. The dispatch change can thus be interpreted as the time integral of the underlying physical ramp.

Data on Automatic Frequency Restoration Reserve (aFRR) activation were obtained from the Netztransparenz platform [40]. We use the second-by-second aFRR setpoint signal (*Sekündlicher SRL-Sollwert*), which represents the sum of the activation signal sent to German aFRR providers. Data on activated reserve volumes are also available, but only at quarter-hourly resolution, and are thus not considered here.

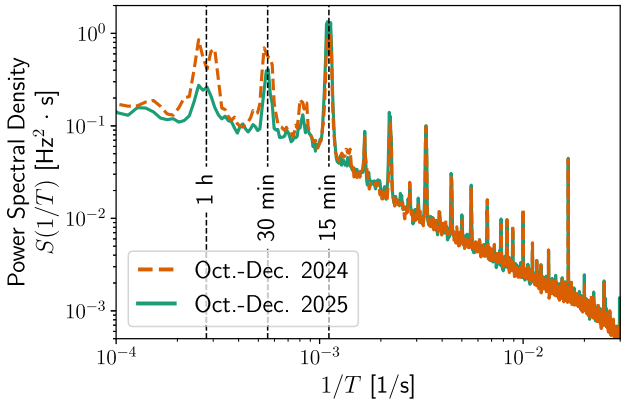

FIGURE 4. **Power spectral density $S(1/T)$ of the grid frequency time series before (orange dashed line) and after (green solid line) the market reform. We plot S versus $1/T$, where T denotes the period. The characteristic peaks corresponding to oscillations with hourly and half-hourly periods appear suppressed after the market change in 2025.**

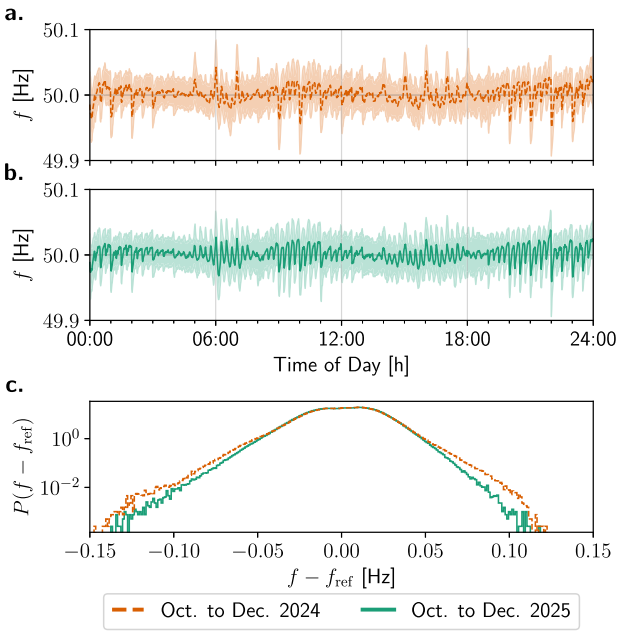

FIGURE 5. **Impact of the market reform on the global statistical properties of the grid frequency. (a,b) Daily profiles of the grid frequency $f(t)$ before (orange) and after (green) the market reform on 1 October 2025 (see Sec. III-C for details). Large deterministic frequency deviations are substantially reduced after the market reform. The shaded areas show the region between the 5% and 95% quantiles of the grid frequency at the time of day. (c) Histogram of the frequency deviation $\tilde{f}(t) = f(t) - f_{\text{ref}}$ before (orange) and after (green) the market reform. The likelihood of frequency deviations exceeding 50 mHz is strongly reduced.**

IV. RESULTS

A. POWER SPECTRAL DENSITY OF THE FREQUENCY TIME SERIES

To highlight the change in characteristic oscillations in the grid frequency, we calculate its power spectral density as described in Sec. III-B. This provides a global frequency-domain characterization of variability across all time scales.

Figure 4 shows the power spectral density of the grid frequency before and after the market reform. Prior to the reform, pronounced spectral peaks are observed at periods of $T = 1$ h and $T = 30$ min, reflecting strong systematic hourly and half-hourly variability. After the reform, these peaks are substantially reduced, indicating a marked suppression of market-induced frequency fluctuations on these time scales. In contrast, the spectral peak at $T = 15$ min increases, consistent with the growing importance of quarter-hourly structures following the introduction of quarter-hourly trading in the day-ahead market. Further strong peaks emerge at lower periods due to control actions [21], [22].

B. DAILY PROFILE, HISTOGRAM AND LONG-TERM TRENDS

The daily frequency profiles shown in Fig. 5 (a,b) indicate that the market reform on 1 October 2025 has substantially reduced large deterministic frequency deviations in the Central European synchronous area. In particular, the pronounced positive spikes observed in the morning and early evening before the reform are strongly diminished. Negative deviations are also reduced significantly, although they remain clearly visible at certain times of the day. Moreover, hourly and quarter-hourly features appear to be of comparable magnitude in the post-reform period, consistent with the transition from hourly to quarter-hourly trading blocks in the day-ahead market.

A notable exception occurs at 22:00, where a pronounced negative frequency deviation persists even after the market reform. A plausible explanation for this feature is the shutdown or throttling of wind turbines to comply with nighttime noise regulations. In Germany, for example, stricter noise limits apply during the nighttime period between 22:00 and 6:00 [41]. A comparison of such regulations across European countries is provided in [42]. This suggests that the remaining spike at 22:00 is at least partly driven by regulatory constraints on wind generation and is therefore largely unaffected by the market reform.

These observations are corroborated by the histogram of the frequency deviations shown in Fig. 5(c). The likelihood of large frequency deviations is substantially reduced after the market reform, particularly for positive deviations. ENTSO-E defines 75 mHz as the maximum acceptable magnitude of deterministic frequency deviations [3]. Using this threshold, the cumulative duration of intervals with $\tilde{f} \geq 75$ mHz decreased from 2.23 hours to 0.61 hours (−72.70%) over the considered three-month period. Likewise, the cumulative duration of intervals with $\tilde{f} \leq -75$ mHz decreased from 3.49 hours to 1.70 hours (−51.27%).

To place these short-term observations into a longer-term perspective, Fig. 3(a) shows selected quantiles of the

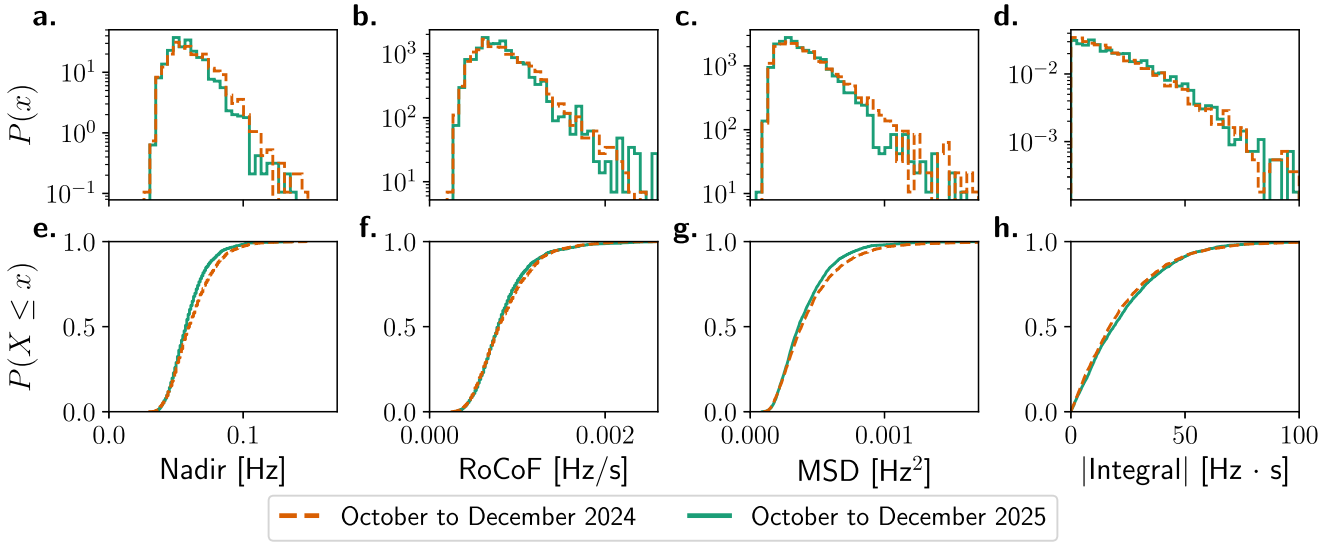

FIGURE 6. Distributions of stability indicators before and after the market reform on 1 October 2025. We show the probability density $P(x)$ and the cumulative distribution function in the top row and bottom row, respectively. The definition of the indicators is summarized in Sec. III-D.

frequency deviation histogram for the period from 2015 to 2025, focusing on the months October to December in each year. The extreme quantiles (1% and 99%), as well as the even rarer tails (0.1% and 99.9%), are shifted toward the mean in 2025 compared to 2024, consistent with the reduction of large frequency deviations observed above. Notably, these quantiles attain their smallest absolute values in 2025 among all years under consideration, indicating that extreme frequency deviations during the period of interest are less pronounced than in any previous year since 2015. This finding supports the conclusion that the market reform was effective in mitigating large deterministic frequency deviations. At the same time, we note that reductions of comparable magnitude were also observed in earlier years, for instance, between 2017 and 2018, highlighting that year-to-year variability can be substantial.

As a complementary long-term indicator, we analyze the cumulative duration of periods with $|\tilde{f}(t)| \geq 75\,\text{mHz}$ in Fig. 3(b). During the period October to December 2025, the cumulative duration above this threshold amounts to 2.31 hours, which is substantially lower than in the corresponding periods of all years since 2015. The largest value is observed in 2017, exceeding 14 hours. For comparison, we also show the same metric for the months July to September. In contrast to the October–December period, the year 2025 exhibits a comparatively high cumulative duration of frequency deviations exceeding 75 mHz, amounting to slightly less than 8 hours for the July–September period. This suggests that the pronounced reduction observed in the period of interest is unlikely to be driven by longer-term trends or structural changes unrelated to the market reform.

In summary, the long-term analysis indicates that the market reform effectively reduced the occurrence of deterministic frequency deviations exceeding the critical threshold of 75 mHz during the months following its implementation.

C. INDICATORS OF FREQUENCY DEVIATIONS

We now analyze the indicators characterizing frequency deviations, introduced in Sec. III-D. Results are shown in Fig. 6. The most pronounced changes are observed for the nadir. The likelihood of large nadir values is clearly reduced after the market reform. In particular, the total number of hours in which the absolute nadir exceeds 75 mHz decreases from 458 to 288 (−37.12%), while the number of hours with nadir values exceeding 100 mHz decreases from 62 to 39 (−37.10%). Consistent with the histogram of the raw frequency time series seen in Fig. 5, the reduction of frequency deviations can be seen to affect nadir values above around 40 mHz, suggesting that the market reform was effective in mitigating frequency deviations of intermediate magnitudes, while its impact on small and rare events is more limited.

Changes in the RoCoF are also clearly visible but less pronounced. This is noteworthy, as the RoCoF is directly related to power imbalances through the aggregated swing equation [17]. The most significant differences are observed for RoCoF values between approximately 0.8 mHz/s and 1.5 mHz/s, corresponding to large but not extreme events. This indicates that the market reform was successful in mitigating ordinary large RoCoF excursions, whereas very large RoCoF events persist. A plausible explanation is that such extreme events are not primarily driven by typical market-induced imbalances but by other disturbances.

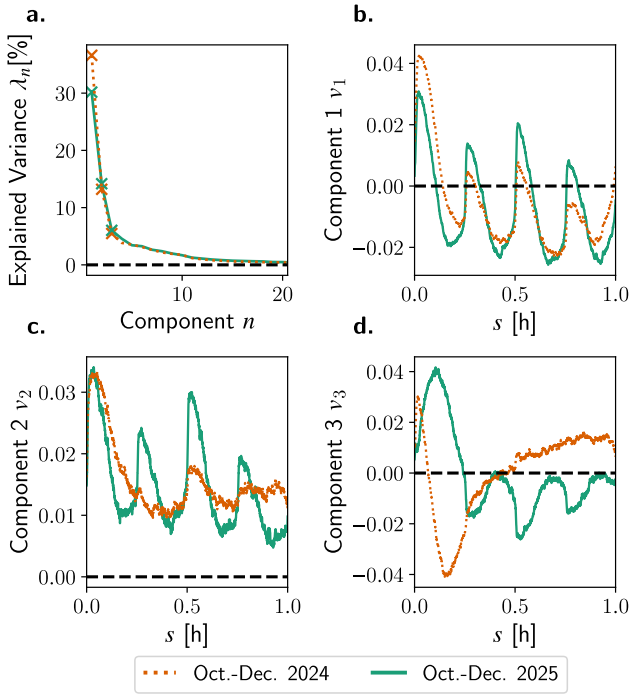

FIGURE 7. Principal component analysis of the frequency time series $\tilde{f}(t)$ before (orange dotted line) and after (green solid line) the market reform. (a) Explained variance λ_n per principal component. The contribution of the first component has decreased from approx. 36.60 % to 30.18 %. (b-d) Shape of the three leading components $v_n(s)$, i.e., $n = 1, 2, 3$, over the time s within the hourly segments.

The mean square deviation (MSD), which reflects the total primary control effort and thus operational costs [37], exhibits a modest reduction of large values after the market reform. This points to a slight decrease in the average activation of primary control.

By contrast, no significant change is observed for the integrated frequency deviation. This is consistent with the fact that the integral primarily captures persistent power imbalances rather than rapid ramps. Such imbalances can arise from forecasting errors or slow solar power ramps [19], which are largely independent of the market design.

D. PRINCIPAL COMPONENT ANALYSIS

The principal component analysis reveals pronounced changes in the structure of systematic intra-hour frequency variations following the market reform. Figure 7 shows the shape of the three leading principal components $v_n(s)$, $n = 1, 2, 3$ and the share of explained variance.

The leading principal component $v_1(s)$ directly mirrors the characteristic shape of deterministic frequency deviations (DFDs). The frequency rapidly increases at the beginning of each quarter hour and relaxes slowly afterward. We emphasize that this component describes both positive and negative DFDs, depending on the sign of the corresponding coefficient $a_{h,1}$ in Eq. (5). Comparing data from 2024 and 2025 reveals a striking difference. The size of the peaks at 15, 30, and 45 minutes has increased substantially, while the spike at the beginning of the full hour has diminished, fully consistent with the growing importance of quarter-hourly electricity trading. At the same time, the fraction of variance explained by this component has decreased, indicating that the dominant intra-hour pattern is less pronounced and that a richer substructure of frequency variations contributes to the overall dynamics. This observation is consistent with smaller market-design-induced generation ramps at the beginning of the full hour.

The second principal component $v_2(s)$ encodes persistent frequency imbalances and their correlation with DFDs. The function $v_2(s)$ is positive throughout the hour, such that $a_{h,2}v_2(s)$ describes a continuing positive or negative offset of the frequency, depending on the sign of $a_{h,2}$. Notably, the sign of the offset is positively correlated with the sign of the DFD spikes. Interestingly, this correlation has changed substantially from 2024 to 2025. Prior to the market reform, $v_2(s)$ was primarily associated with the DFD occurring at the beginning of the full hour. After the reform, the component contains four comparable spikes at the beginning of each quarter-hour, reflecting the redistribution of deterministic frequency variations from hourly to quarter-hourly time scales.

The third principal component $v_3(s)$ encodes two different effects before and after the market reform. Prior to the reform, $v_3(s)$ was characterized by a ramp at the beginning of the hour, followed by a single spike, with almost no quarter-hourly substructure. This component encoded temporal shifts of the dominant frequency spike at the beginning of the full hour. Specifically, if the amplitudes $a_{h,1}$ and $a_{h,3}$ have the same (opposite) sign, the dominant spike shifts toward earlier (later) times. After the reform, $v_3(s)$ features four spikes with opposite signs. This shape can describe differences in the relative importance of the DFD spikes at the beginning of the full hour with respect to the spikes at 15, 30, and 45 minutes. If the amplitudes $a_{h,1}$ and $a_{h,3}$ have the same (opposite) sign, the relative importance of the hourly spike increases (decreases). This aligns with the observation that some hourly peaks, especially the one at 22:00, are still very pronounced, while others have been strongly reduced.

Overall, these findings are consistent with the growing importance of quarter-hourly trading in shaping systematic frequency variations after the reform. In particular, the third component is no longer associated with the timing of the dominant DFD spike but instead describes shifts between hourly- and quarter-hourly-dominated frequency patterns.

E. FOURIER-BASED FUNCTIONAL DATA ANALYSIS

For a more detailed, scale-resolved analysis, we turn to the Fourier-based functional data analysis described in Sec. III-F. Each hourly segment of the centered frequency time series $\tilde{f}_h(s)$ is decomposed into Fourier components according to Eq. 6. In contrast to the principal component analysis, which extracts data-driven modes, this approach

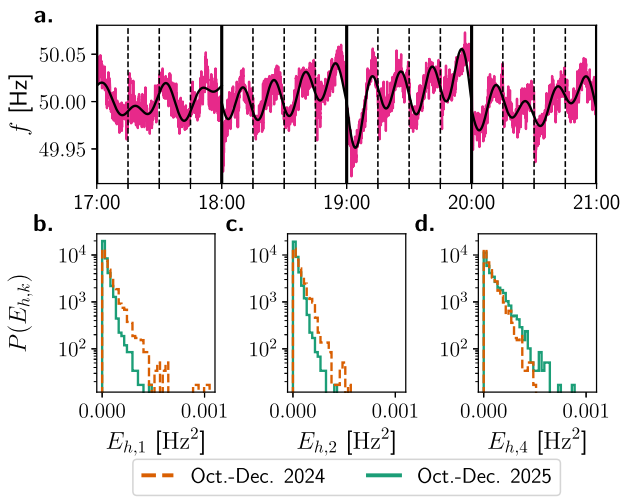

FIGURE 8. Fourier-based functional data analysis. (a) Expansion of hourly frequency time series into Fourier modes up to $k = 4$, shown as a solid line, with the frequency time series behind it. (b-d) Histogram of the energy $E_{h,k}$ in the modes $k = 1, 2, 4$ capturing variations on the time scale of hours, half-hours and quarter-hours, respectively.

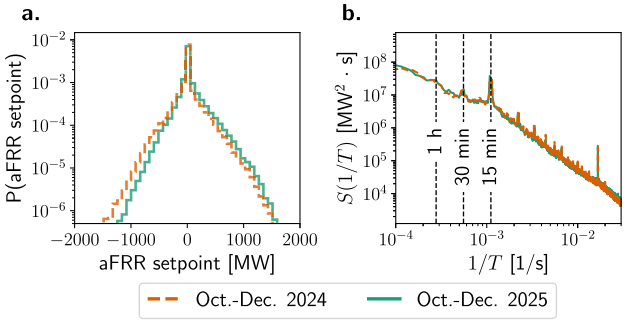

FIGURE 9. Statistics of *Automatic Frequency Restoration Reserve* (aFRR) setpoints in Germany from October to December in 2024 and 2025.

employs a fixed set of sine and cosine basis functions, allowing individual temporal scales to be analyzed directly.

Figure 8 illustrates the Fourier expansion. Retaining Fourier modes up to order $k = 4$ captures slow intra-hour variations of the frequency and is therefore well suited to describe the dominant temporal structure associated with deterministic frequency deviations.

The lower panels of Fig. 8 show the distributions of the oscillatory energy $E_{h,k}$ in the modes $k = 1$, $k = 2$, and $k = 4$ across all hourly intervals. We observe that the energy associated with the hourly ($k = 1$) and half-hourly ($k = 2$) modes is substantially reduced after the market reform. Notably, the reduction is particularly pronounced for large values of $E_{h,1}$, indicating a strong suppression of large hourly-scale frequency variations. This is highlighted by evaluating the 90-percent quantile $q_{90\%}$ for $E_{h,1}$ and $E_{h,2}$. While $q_{90\%}$ was around 175.76 mHz^2 for $E_{h,1}$ and 154.38 mHz^2 for $E_{h,2}$ before the market change, these values decreased to 92.33 mHz^2 and 90.11 mHz^2, respectively, for the time interval after the market change.

At the same time, the energy of the quarter-hourly mode ($k = 4$) increases, consistent with the shift from hourly to quarter-hourly trading intervals. The 90-percent quantile rises from 179.42 mHz^2 to 233.47 mHz^2. These findings are consistent with the daily profiles and principal component analysis: hourly variability is strongly reduced, while quarter-hourly variability gains importance. However, they cannot be directly linked to extreme nadir values, which are sensitive to faster fluctuations and higher Fourier modes. Together with the spectral analysis in Sec. IV-A, these results provide further evidence for a shift from hourly- to quarter-hourly-dominated frequency variability after the reform.

F. IMPLICATIONS FOR RESERVE ACTIVATION

The reduction of deterministic frequency deviations is expected to affect the activation of control reserves. Since different reserve products operate on different time scales and are activated according to different control principles, the impact is not necessarily uniform across reserve types.

Frequency Containment Reserve (FCR), the ENTSO-E implementation of primary frequency control, is activated locally and proportionally to the frequency deviation once the frequency leaves the deadband ±10 mHz [43]. Consequently, a reduction in the magnitude and occurrence of deterministic frequency deviations directly translates into a reduced need for FCR activation. This effect is particularly relevant because battery energy storage systems are a significant and growing source of FCR in the German market [44], [45]. Reduced FCR activation may therefore lower battery cycling requirements.

To assess the impact on secondary control, we analyze the Automatic Frequency Restoration Reserve (aFRR). We observe small changes in the distribution of the aggregated German aFRR setpoint signal shown in Fig. 9. Large negative setpoint values have become less frequent, whereas large positive values have become slightly more frequent. The distribution remains noticeably asymmetric toward positive setpoint values both before and after the reform, with this asymmetry becoming slightly more pronounced in 2025. The power spectral density of the aFRR signal remains largely unchanged across all time scales.

These observations suggest that the market reform had no major impact on the aFRR setpoint signal. This finding is plausible because aFRR primarily compensates sustained power imbalances, whereas deterministic frequency deviations are characterized by short-lived frequency excursions that are predominantly addressed by FCR. Hence, the main operational benefit of the market reform is expected to arise from reduced activation of primary frequency control rather than secondary control.

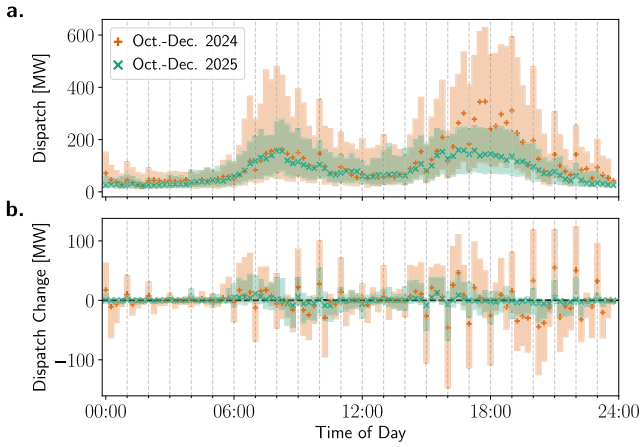

FIGURE 10. The daily profiles of the dispatch and dispatch change for *Hydro Water Reservoir* in the bidding zone of DE-LU, i.e. the zone that is comprised of Germany and Luxembourg, are shown in the top and bottom panels, respectively. The medians are shown as different symbols for the two time intervals, while shaded areas show the region between the 0.25 and 0.75 quantiles.

G. HYDROPOWER DISPATCH

To further assess the role of physical flexibility constraints, we analyze quarter-hourly dispatch changes derived from ENTSO-E Transparency Platform data. We focus on reservoir hydropower in Germany, for which we find pronounced changes after the market reform. Reservoir hydropower provides some of the fastest generation ramps in the system and has previously been identified as an important driver of RoCoF and deterministic frequency deviations [19].

In 2024, reservoir hydropower exhibited pronounced dispatch changes at the beginning of the hour, often with opposite sign compared to the dispatch changes at 15, 30, and 45 minutes, especially during the evening hours (Fig. 10). Notably, the dispatch changes at the beginning of the full hour often opposed the overall dispatch trend, suggesting that reservoir hydropower was used to mitigate large dispatch changes at that point and shift them to subsequent quarter-hourly intervals via intraday trading. In 2025, this qualitative pattern remains visible, but with substantially reduced magnitude, consistent with a reduced need for intra-hour smoothing after the introduction of quarter-hourly day-ahead trading. However, the lower overall reservoir-hydro dispatch in 2025 should be taken into account.

These findings suggest that part of the flexibility previously provided through intraday market adjustments shifted to the day-ahead market after the reform. Consequently, the characteristic compensating reservoir-hydropower dispatch changes observed in 2024 are much weaker in 2025.

V. CONCLUSION AND OUTLOOK

In this paper, we analyzed the impact of the European day-ahead market reform, which took effect on 30 September 2025 for delivery day 1 October 2025, on deterministic frequency deviations (DFDs) in the Central European power system. By comparing frequency measurements before and after the reform, we combined time-domain indicators, daily frequency profiles, principal component analysis, Fourier-based functional data analysis, and power spectral density analysis to assess changes in characteristic intra-hour frequency patterns. This multi-perspective approach allowed us to quantify both global and scale-specific changes in frequency deviations associated with the market reform.

Our results show that the market reform was largely successful in mitigating deterministic frequency deviations, in particular the characteristic deviations occurring at the beginning of each full hour. Hourly-scale variability is substantially reduced across all analyses, while quarter-hourly structures gain relative importance, consistent with the transition to quarter-hourly trading intervals. However, market-induced DFDs are not the sole contributors to large frequency deviations, and several effects remain largely unchanged. Notably, the pronounced frequency dip around 22:00 persists after the reform, plausibly linked to regulatory constraints such as nighttime noise limits for wind generation. In addition, long-lasting power imbalances related to forecasting errors are largely unaffected. As a result, while frequency quality has improved overall, large deviations are not fully eliminated, which is reflected in the statistics of the hourly nadir.

These findings are consistent with recent observations from the European day-ahead market following the transition to 15-minute trading intervals [46]. Pronounced intra-hour price variability has emerged, characterized by recurring sawtooth patterns and persistently high intra-hour price spreads that were previously mainly observed in intraday trading. These price signatures indicate that physical flexibility at the 15-minute level remains limited. Furthermore, a considerable share of block orders continues to follow hourly structures despite the finer market resolution [46]. These observations suggest that interactions between bidding behavior, market liquidity, and physical constraints can sustain synchronized ramps and residual DFDs.

The additional analyses presented in this work further suggest that the impact of shorter market time units depends strongly on the balancing product and the available flexibility resources. While deterministic frequency deviations and thus frequency containment reserve activation are reduced, we observe no major change in the aFRR setpoint signal in Germany. This finding indicates that the expectation that shorter trading intervals generally reduce balancing needs is overly simplistic and that different balancing products are affected differently.

Furthermore, strong differences in the quarter-hourly dispatch changes are observed for reservoir hydropower in Germany. Prior to the reform, these units exhibited characteristic quarter-hourly dispatch change patterns consistent with the use of intraday trading to compensate for hourly day-ahead schedules. After the reform, these patterns

become substantially weaker, suggesting that part of the required flexibility shifted from the intraday market to the day-ahead market. This interpretation is consistent with the observed reduction of DFDs and highlights that market design primarily changes how flexibility is scheduled rather than the underlying need for flexibility.

Looking ahead, frequency control and frequency performance remain critical challenges during the ongoing transition toward renewable-dominated power systems with low rotational inertia [1]. Past events have shown that particularly critical situations can arise when DFDs coincide with contingencies. For example, in January 2019, a technical error in the load-frequency control system, combined with a pronounced DFD, led to an exceptionally large frequency deviation and ultimately to load shedding of approximately 1.5 GW in the Continental European synchronous area [47]. Even more severe risks emerge when DFDs coincide with major contingencies, underscoring the need for continued research on synthetic inertia, advanced converter control, and fast-acting frequency support from power-electronic devices. Beyond these technical measures, our results highlight that economic regulations and market design strongly influence power system operation and must therefore be considered an integral part of future frequency-control strategies.

REFERENCES

[1] F. Milano, F. Dörfler, G. Hug, D. J. Hill, and G. Verbič, "Foundations and challenges of low-inertia systems," in *Proc. Power Syst. Comput. Conf. (PSCC)*, Jun. 2018, pp. 1–25.

[2] T. Weissbach and E. Welfonder, "High frequency deviations within the European power system: Origins and proposals for improvement," in *Proc. IEEE/PES Power Syst. Conf. Expo.*, Mar. 2009, pp. 1–6.

[3] European Network of Transmission System Operators for Electricity. (2020). *Report on Deterministic Frequency Deviations*. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/Publications/SOC/Report_Deterministic_Frequency_Deviations_final_version.pdf

[4] C. Han et al., "Complexity and persistence of price time series of the European electricity spot market," *PRX Energy*, vol. 1, no. 1, Apr. 2022, Art. no. 013002.

[5] Directorate-General for Energy. (2025). *EU Electricity Trading in the Day-Ahead Markets Becomes More Dynamic*. [Online]. Available: https://energy.ec.europa.eu/news/eu-electricity-trading-day-ahead-markets-becomes-more-dynamic-2025-10-01_en

[6] European Union. (2019). *Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the Internal Market for Electricity*. Accessed: Jun. 22, 2026. [Online]. Available: https://data.europa.eu/eli/reg/2019/943/oj

[7] T. Weissbach and E. Welfonder, "Improvement of the performance of scheduled stepwise power programme changes within the European power system," *IFAC Proc. Volumes*, vol. 41, no. 2, pp. 11972–11977, 2008.

[8] T. Borsche, A. Ulbig, and G. Andersson, "A new frequency control reserve framework based on energy-constrained units," in *Proc. Power Syst. Comput. Conf.*, Aug. 2014, pp. 1–7.

[9] J. Kruse, B. Schäfer, and D. Witthaut, "Exploring deterministic frequency deviations with explainable AI," in *Proc. IEEE Int. Conf. Commun., Control, Comput. Technol. Smart Grids (SmartGridComm)*, Oct. 2021, pp. 133–139.

[10] L. Hirth and I. Ziegenhagen, "Balancing power and variable renewables: A glimpse at German data,", in*SSRN Electronic Journal*, 2013, doi: 10.2139/ssrn.2371752.

[11] L.Meeus, *The Evolution of Electricity Markets in Europe*. Cheltenham, U.K.: Edward Elgar Publishing, 2020, doi: 10.4337/9781789905472.

[12] K. Neuhoff, S. Ruester, and S. Schwenen, "Power market design beyond 2020: Time to revisit key elements?" Tech. Rep., 2015, doi: 10.2139/ssrn.2576693.

[13] T. Weißbach, S. Remppis, and H. Lens, "Impact of current market developments in Europe on deterministic grid frequency deviations and frequency restauration reserve demand," in *Proc. 15th Int. Conf. Eur. Energy Market (EEM)*, Jun. 2018, pp. 1–6.

[14] B. Schafer, M. Timme, and D. Witthaut, "Isolating the impact of trading on grid frequency fluctuations," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Eur. (ISGT-Europe)*, Oct. 2018, pp. 1–5.

[15] A. Motte-Cortés and M. Eising, "Assessment of balancing market designs in the context of European coordination," in *Proc. 16th Int. Conf. Eur. Energy Market (EEM)*, Sep. 2019, pp. 1–7.

[16] B. T. Borg et al., "(When) should we go for a 5-minute temporal granularity in European intraday markets?" in *Proc. 20th Int. Conf. Eur. Energy Market (EEM)*, Jun. 2024, pp. 1–4.

[17] A. Ulbig, T. S. Borsche, and G. Andersson, "Impact of low rotational inertia on power system stability and operation," *IFAC Proc. Volumes*, vol. 47, no. 3, pp. 7290–7297, 2014.

[18] V. Gevorgian, Y. Zhang, and E. Ela, "Investigating the impacts of wind generation participation in interconnection frequency response," *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 1004–1012, Jul. 2015.

[19] J. Kruse, B. Schäfer, and D. Witthaut, "Revealing drivers and risks for power grid frequency stability with explainable AI," *Patterns*, vol. 2, no. 11, Nov. 2021, Art. no. 100365.

[20] J. Kruse, E. Cramer, B. Schäfer, and D. Witthaut, "Physics-informed machine learning for power grid frequency modeling," *PRX Energy*, vol. 2, no. 4, Oct. 2023, Art. no. 043003.

[21] C. Mishra, L. Vanfretti, J. Delaree, T. J. Purcell, and K. D. Jones, "Understanding the inception of 14.7 Hz oscillations emerging from a data center," *Sustain. Energy, Grids Netw.*, vol. 43, Sep. 2025, Art. no. 101735.

[22] C. Hartmann et al., "Cyber-physical systems on the megawatt scale: The impact of battery control on grid frequency stability," 2025,*arXiv:2510.09862*.

[23] L. Rydin Gorjão et al., "Open database analysis of scaling and spatio-temporal properties of power grid frequencies," *Nature Commun.*, vol. 11, no. 1, p. 6362, Dec. 2020.

[24] Nordic TSOs. (2023). *Amended Nordic LFC Block Methodology for Ramping Restrictions for Active Power Output*. [Online]. Available: https://consultations.entsoe.eu/system-operations/nordic-tsos-methodology-for-ramping-restrictions-f/supporting_documents/230130%20Methodology%20Ramping%20restrictions%20for%20active%20power%20output%20amended%20for%20public%20consultation.pdf

[25] J. Janssen, A. Zocca, B. Zwart, and J. Kazempour, "Dynamic dimensioning of frequency containment reserves: The case of the Nordic grid," *IEEE Trans. Power Syst.*, vol. 41, no. 3, pp. 1744–1755, May 2026.

[26] California Independent System Operator. (2026). *Business Practice Manual for Market Operations*. Accessed: Jun. 22, 2026. [Online]. Available: https://bpmcm.caiso.com/BPM%20Document%20Library/Market%20Operations/BPM_for_Market%20Operations_V104_Clean.doc

[27] Australian Energy Market Commission. (2017). *Five Minute Settlement*. [Online]. Available: https://www.aemc.gov.au/rule-changes/five-minute-settlement

[28] Australian Energy Market Operator. *Five Minute Settlement Program*. Accessed: Jun. 22, 2026. [Online]. Available: https://aemo.com.au/initiatives/major-programs/nem-five-minute-settlement–program-and-global-settlement

[29] Netztransparenz. *Frequency Data for the CE Grid*. Accessed: Jun.22, 2026. [Online]. Available: https://www.netztransparenz.de/de-de/Regelenergie/Daten-Regelreserve/

[30] Fingrid. *Frequency Data for the Nordic Grid*. Accessed: Jun. 22, 2026. [Online]. Available: https://data.fingrid.fi/en/datasets/339

[31] AEMO. *Frequency Data for the NEM Grid in Australia*. Accessed: Jun. 10, 2026. [Online]. Available: https://www.aemo.com.au/energy-systems/electricity/national-electricity-market-nem/system-operations/ancillary-services/frequency-and-time-deviation-monitoring

[32] R. Jumar, A. Erdmann, H. Maaß, U. Kühnapfel, and V. Hagenmeyer, "Open source 3-phase function generator for smart grid experiments and monitoring device testing," in *Proc. 2nd Int. Colloq. Smart Grid Metrology (SMAGRIMET)*, Apr. 2019, pp. 1–7.

[33] J. Kruse, B. Schäfer, and D. Witthaut, "Predictability of power grid frequency," *IEEE Access*, vol. 8, pp. 149435–149446, 2020.

[34] L. Rydin Gorjão, L. Vanfretti, D. Witthaut, C. Beck, and B. Schäfer, "Phase and amplitude synchronization in power-grid frequency fluctuations in the Nordic grid," *IEEE Access*, vol. 10, pp. 18065–18073, 2022.
[35] P. Welch, "The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms," *IEEE Trans. Audio Electroacoustics*, vol. AE-15, no. 2, pp. 70–73, Jun. 1967.
[36] P. Virtanen et al., "SciPy 1.0: Fundamental algorithms for scientific computing in Python," *Nature Methods*, vol. 17, pp. 261–272, Jul. 2020.
[37] M. Tyloo and P. Jacquod, "Primary control effort under fluctuating power generation in realistic high-voltage power networks," *IEEE Control Syst. Lett.*, vol. 5, no. 3, pp. 929–934, Jul. 2021.
[38] I. T. Jolliffe and J. Cadima, *Principal Component Analysis*, 3rd ed., Cham, Switzerland: Springer, 2016.
[39] European Network of Transmission System Operators for Electricity. (2026). *ENTSO-E Transparency Platform*. Accessed: Jun. 15, 2026. [Online]. Available: https://transparency.entsoe.eu/
[40] Netztransparenz. *Regelenergie—Daten Regelreserve—Sekündliche Daten*. Accessed: Jun.22, 2026. [Online]. Available: https://www.netztransparenz.de/de-de/Regelenergie/Daten-Regelreserve/SekC3BCndliche-Daten
[41] Bundesministeriums Umwelt, Naturschutz, Bau und Reaktorsicherheit. (1998). *Sechste Allgemeine Verwaltungsvorschrift Zum Bundes-Immissionsschutzgesetz (Technische Anleitung Zum Schutz Gegen Lärm-TA Lärm*). [Online]. Available: https://www.verwaltungsvorschriften-im-internet.de/bsvwvbund_26081998_IG19980826.htm
[42] E. Nieuwenhuizen and M. Köhl, "Differences in noise regulations for wind turbines in four European countries," in *Proc. Euronoise*, 2015, pp. 333–338.
[43] UCTE Operations Handbook. (2009). *P1—Policy 1: Load-Frequency Control and Performance*. Accessed: Jun. 22, 2026. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/entsoe/Operation_Handbook/Policy_1_final.pdf
[44] 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH.*Präqualifizierte Leistungen in Deutschland, Stand: 01.01.2026. (in German)*. Accessed: Sep.10, 2026. [Online]. Available: https://www.regelleistung.net/xsppproxy/api/staticfiles/regelleistung/01_startseite/dateien/2026-01-01%20pr%C3%A4qualifizierte%20leistung%20in%20deutschland.pdf
[45] J.Fleer et al., "Techno-economic evaluation of battery energy storage systems on the primary control reserve market under consideration of price trends and bidding strategies," *J. Energy Storage*, vol. 17, pp. 345–356, Jun.2018.
[46] F. Rewald and J. Breuing. (Oct. 2025). *SDAC 15 Min MTU Go-Live: Insights From the First Week(s)*. [Online]. Available: https://web.archive.org/web/20260211030250/https://www.strommarkttreffen.org/wp-content/uploads/2025/10/2.-Julia-Breuing_day-ahead-15min.pdf
[47] European Network of Transmission System Operators for Electricity. (2019). *Continental Europe Significant Frequency Deviations—January 2019*. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/news/2019/190522_SOC_TOP_11.6_Task%20Force%20Significant%20Frequency%20Deviations_External%20Report.pdf



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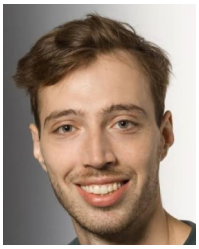

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