Pairwise Consistency of Co-Located PMU Frequency Streams

Casi Setianingsih
Department of Electric Power Engineering
Budapest University of Technology and Economics
Budapest, Hungary
setianingsihcasi@edu.bme.hu

Bálint Hartmann
Department of Electric Power Engineering
Budapest University of Technology and Economics
Budapest, Hungary
hartmann.balint@vik.bme.hu

***Abstract*— Co-located phasor measurement unit frequency streams are often treated as practically interchangeable because they represent the same local operating conditions. However, very high agreement over a long observation period does not necessarily imply negligible disagreement during short event-sensitive intervals. This paper evaluates the practical interchangeability of two co-located synchronized frequency streams, anonymized as Station A and Station B, using approximately one month of measurements from the Hungarian transmission grid in February 2025. A direct pairwise framework is applied to aligned frequency and frequency-deviation records using correlation, root mean square error, mean absolute error, bias, robust spread, quantiles, and the timestamps of the largest mismatches. The full-month results show extremely strong agreement under ordinary operating conditions, with raw frequency and frequency-deviation correlations of 0.99997. At the same time, the mismatch distribution shows a pronounced upper tail, and the largest discrepancies are concentrated in a short anomalous burst rather than being distributed across the month. To interpret this behavior, the pair is examined through ordinary, off-nominal, and anomalous operating classes. Strong agreement is preserved in the ordinary and off-nominal classes, whereas the anomalous class shows a sharp breakdown of practical interchangeability. The results show that co-located PMU streams should be validated explicitly rather than treated as automatically interchangeable on the basis of bulk agreement alone.**

Keywords—PMU, co-located measurements, pairwise consistency, practical interchangeability.

I. Introduction

Power systems are increasingly monitored through synchronized measurements that support wide-area observation of dynamic behavior and improve the visibility of grid conditions during ordinary operation as well as during disturbances [1]–[3]. Among these measurements, frequency-related signals are especially important because they reflect system-wide dynamic response and are widely used in monitoring and event interpretation [4], [5]. In practical applications, however, the usefulness of such measurements depends not only on synchronization and availability, but also on the consistency and reliability of the recorded streams [6].

When two frequency measurement streams are obtained from the same location or from closely related monitoring points, they are often treated as practically interchangeable. This assumption is attractive because it can simplify data handling and downstream analysis workflows [7]. However, practical interchangeability should not be assumed without verification, especially when the measurements are used for event-sensitive tasks, anomaly screening, or correlation-based summaries, where short but severe disagreement may matter more than bulk similarity [8]–[10].

This question is particularly relevant in the present case study, which examines two co-located frequency streams, here anonymized as Station A and Station B. The two measurement points are associated with separate feeders connected to cross-border 400 kV interconnection corridors, which makes the pair operationally meaningful in an interconnected-system setting [11]. From a measurement perspective, their co-located nature suggests that their recorded frequency behavior should be very similar. At the same time, if disagreement appears, it is important to determine whether it remains negligible across the full operating range or becomes concentrated in specific non-ordinary regimes. In interconnected power systems, frequency quality and short-time-scale deviations are themselves operationally meaningful and therefore require dedicated analysis rather than being considered only through long-window aggregates [12].

The objective of this paper is to evaluate the practical interchangeability of the two co-located streams using a direct pairwise framework. The analysis first quantifies full-month agreement through standard pairwise consistency metrics. It then examines mismatch distribution and temporal concentration in order to distinguish typical behavior from rare severe disagreement. Finally, it interprets the pair through three operating classes, namely ordinary, off-nominal, and anomalous conditions. A short supporting sensitivity check is also included to determine whether the choice of station representation materially affects selected downstream correlation summaries.

II. Data and Method

A. Data Source and Study Period

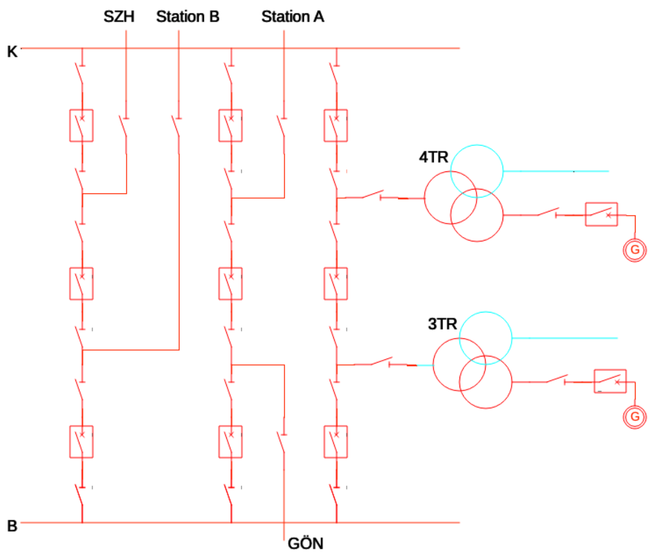

Fig. 1. 400 kV substation single-line diagram with the feeders of Station A and Station B indicated.

The analysis uses synchronized measurements collected from the Hungarian transmission grid during February 2025. These data are obtained from the MAVIR wide-area synchronized measurement system, referred to internally as the Phase Angle Measurement System (Fázisszögmérő Rendszer, FMR). The system uses phasor measurement units (PMUs) installed at different points of the transmission network to collect synchronized measurements of grid frequency, voltage, current, and phase angle, thereby supporting continuous monitoring of dynamic system behavior. Following a major reconstruction program launched in 2020, the system supports higher-resolution acquisition, including 20 ms time resolution. The present case study focuses on two co-located synchronized streams associated with different feeders within the same substation measurement environment, here anonymized as Station A and Station B.

The study focuses on two channels: the measured grid frequency, denoted by FREQ, and the corresponding frequency-deviation signal, denoted by DFREQ, where DFREQ represents deviation from the nominal 50 Hz level. The broader data environment, the high-resolution Hungarian grid-frequency context, and the use of correlation-oriented temporal analysis are consistent with earlier work by the authors and with related measurement-based studies on the same grid context [13], [14].

B. *Pair Extraction and Timeline Alignment*

Both streams are evaluated on a common aligned timestamp axis. Missing observations are preserved as NaN rather than removed, so that the shared timeline remains intact and pairwise comparisons are performed only on valid overlapping samples. This choice avoids artificial continuity and preserves the temporal structure of the measurement record. Such preprocessing is consistent with the broader need for quality-aware handling of streaming PMU-type data, especially when anomalous or incomplete observations may affect downstream interpretation [15].

The paired dataset used in this study contains 24,155,126 valid overlapping FREQ samples. While the overwhelming majority of the record remains within ordinary operating ranges, a very small number of raw points exhibit clearly extreme values. This contrast motivates the use of a class-based interpretation in the present paper. Rather than relying only on a single full-month aggregate summary, the analysis separates ordinary operation, broader off-nominal but still plausible behavior, and clearly anomalous episodes.

C. *Pairwise Agreement Metrics*

To assess full-month pairwise consistency, the paper uses Pearson correlation, RMSE, MAE, mean bias, median bias, and a robust spread descriptor. These metrics are used jointly to provide a broader description of pairwise agreement than any single metric alone. In particular, correlation reflects similarity in overall variation, whereas absolute and squared-error measures emphasize mismatch magnitude in different ways [16], [17]. Pairwise mismatch is further analyzed through the difference defined as

$$\Delta DFREQ = DFREQ_A - DFREQ_B \quad (1)$$

together with quantiles, exceedance behavior, and top mismatch timestamps.

D. *Frequency-Based Operating Classes*

To interpret pairwise behavior under different operating conditions, the analysis distinguishes three frequency-based classes. A sample is treated as ordinary when both streams remain within 49.95–50.05 Hz, consistent with the narrow ENTSO-E frequency-deviation context used for monitoring significant steady-state deviations around the nominal 50 Hz level [18]. A sample is treated as off-nominal when both streams remain within the broader 49.0–51.0 Hz range but at least one leaves the ordinary band. This broader interval is consistent with ENTSO-E grid-connection requirements that specify the frequency range in which generating units in Continental Europe shall remain connected for unlimited operation [19]. A sample is treated as anomalous when either stream falls outside 47.5–51.5 Hz. This outer boundary is consistent with ENTSO-E Continental Europe frequency-stability criteria, which state that once frequency exceeds the range bounded by 47.5 Hz and 51.5 Hz, blackout conditions can hardly be avoided [20].

TABLE I. FULL-MONTH PAIRWISE AGREEMENT SUMMARY FOR STATION A AND STATION B.

Class	Bound	Meaning	Role
Ordinary	49.95–50.05 Hz	Narrow ordinary band	Reference operating window
Off-nominal	49.0–51.0 Hz, excluding ordinary	Plausible non-ordinary behavior	Window selection and persistence check
Anomalous	Outside 47.5–51.5 Hz	Extreme / non-physical behavior	Burst identification

These classes are used in the present study as practical analysis categories for separating ordinary behavior, broader but still plausible non-ordinary behavior, and clearly extreme or non-physical episodes. Representative windows are then selected from these classes in order to expose operating contexts that may not be visible from monthly aggregate summaries alone.

III. RESULTS

A. *Full-Month Pairwise Agreement*

Table II summarizes the main full-month agreement statistics between Station A and Station B. For the raw DFREQ signal, agreement is extremely high, with a correlation of 0.99997, an RMSE of 4.450, and an MAE of 0.0366. For the raw FREQ signal, the correlation also reaches 0.99997, while the MAE remains very small at 0.0116. When the comparison is restricted to the plausible frequency range, agreement becomes even tighter in practical terms: the plausible-range FREQ comparison yields a correlation of 0.99845, an RMSE of 0.00121, and an MAE of 0.00088. Taken together, these results show that the two co-located streams remain extremely close under ordinary operating conditions.

TABLE II. FULL-MONTH PAIRWISE AGREEMENT SUMMARY FOR STATION A AND STATION B.

Model	N valid	Corr.	RMSE	MAE
DFREQ raw	24.16 M	0.99997	4.450	0.0366
FREQ raw	24.16 M	0.99997	4.593	0.0116
FREQ plausible	24.15 M	0.99845	0.00121	0.00088

Table III complements this picture by showing bias, spread, and tail-sensitive statistics. For the raw DFREQ comparison, the mean bias remains close to zero, the median bias is exactly 0, and the robust spread is only 0.02. A similar pattern is observed for FREQ, where bias remains very small in both the raw and plausible-range comparisons. However, the tail-sensitive statistics also show that rare extreme mismatch is still present. In particular, the raw DFREQ comparison reaches a 99th-percentile absolute mismatch of 0.09 and a maximum absolute mismatch of 3096, while the raw FREQ comparison reaches a maximum absolute mismatch of 3024. Thus, the full-month results indicate two coexisting features: extremely strong typical agreement and a very small number of severe outlying episodes.

TABLE III. BIAS, SPREAD, AND TAIL STATISTICS FOR THE FULL-MONTH PAIRWISE COMPARISON.

Model	Mean bias	Med. bias	Robust spread	P99 |Δ|	Max |Δ|
DFREQ raw	0.00061	0	0.02	0.09	3096
FREQ raw	0.00161	0	0.001	0.003	3024
FREQ plausible	0	0	0.001	0.003	0.117

B. Pairwise Mismatch Distribution and Temporal Concentration

Although the typical mismatch is very small, the distribution of $|\Delta DFREQ|$ shows a pronounced upper tail. The median absolute mismatch is 0.02, the 95th percentile is 0.07, and the 99th percentile is 0.09, confirming that ordinary disagreement is generally minor. At the same time, the maximum absolute mismatch reaches 3096, showing that rare extreme episodes dominate the upper end of the distribution.

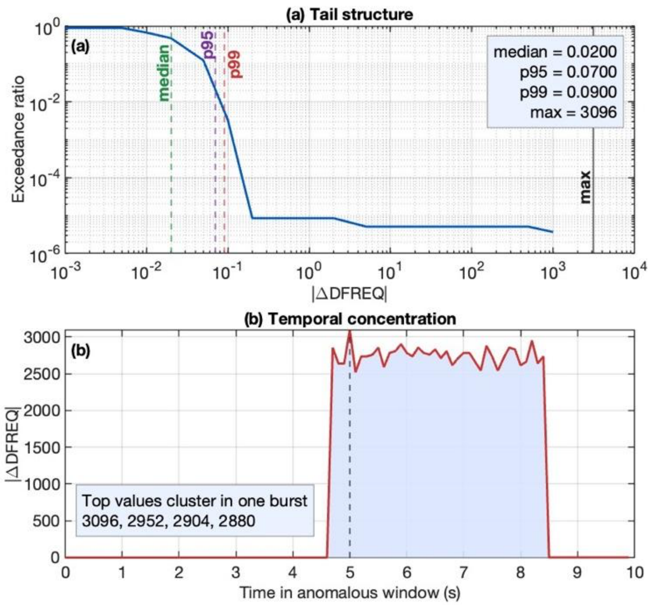

Fig. 2. Mismatch tail and temporal concentration for Station A and Station B.

This contrast between very small typical mismatch and very large maximum mismatch shows that bulk monthly agreement does not eliminate the presence of short but severe disagreement. In other words, correlation and average-error metrics alone do not fully describe the structure of pairwise inconsistency when anomalous episodes are present. The strongest disagreement is not distributed uniformly across the month, but is instead highly concentrated in time.

The largest mismatches are clustered around 2025-02-25 09:59. The top-ranked mismatch occurs at 2025-02-25 09:59:14.300, where the two streams differ by 3096 in DFREQ. The next-ranked mismatches appear within the same short interval, with absolute differences of 2952, 2904, and 2880. This confirms that the most severe disagreement is concentrated in a brief burst rather than spread over long periods.

In the present co-located PMU analysis, the disagreement between the two streams is generally limited, but a small number of episodes produce disproportionately large mismatch values. This indicates that the empirical mismatch distribution is shaped not only by routine small deviations but also by rare extreme events. Similar statistical features have been reported in earlier power-system studies. For empirical Hungarian grid-frequency data, q-Gaussian distributions were found to provide a better fit than simple Gaussian assumptions, and the frequency spectrum showed spatio-temporally correlated noise [20]. In empirical outage studies, outage-energy and outage-duration statistics exhibited strong tail behavior over selected ranges [21]. In reinforcement studies of the Hungarian high-voltage grid, cascade simulations showed fat-tailed cascade-time distributions at intermediate coupling strengths [22]. Although these earlier studies address different quantities, they support the broader interpretation that rare-event-dominated statistical behavior can naturally arise in power-system data.

C. Representative Operating Classes

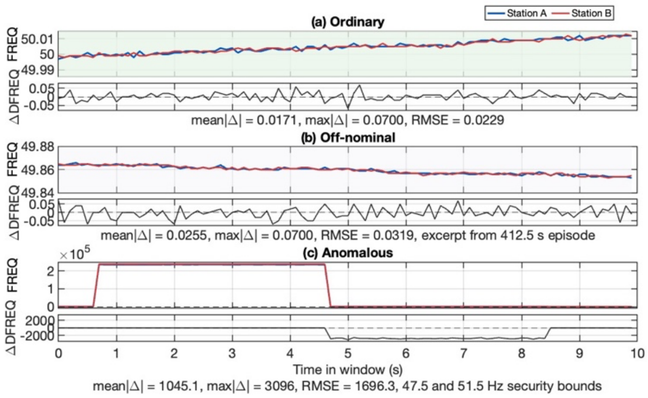

Fig. 3. Representative ordinary, off-nominal, and anomalous windows for Station A and Station B.

To expose operating context hidden behind aggregate monthly summaries, the pair is examined through three representative classes: ordinary, off-nominal, and anomalous.

In the ordinary class, the representative 10-second window selected over the full month is 2025-02-06 07:55:50.700 to 2025-02-06 07:56:00.600. In this interval, the two traces remain very closely aligned. The mean absolute DFREQ mismatch is only 0.0171, the maximum absolute mismatch is 0.07, and the RMSE is 0.0229. The corresponding frequency values remain within the narrow ordinary band, confirming that ordinary operating conditions are associated with near-overlapping pairwise behavior.

In the off-nominal class, the representative 10-second window selected over the full month is 2025-02-18 08:01:36.000 to 2025-02-18 08:01:45.900. In this interval, the pair remains outside the narrow ordinary band while still staying within the broader ENTSO-E-consistent plausible range. The mean absolute DFREQ mismatch remains small at 0.0255, the maximum absolute mismatch is 0.07, and the RMSE is 0.0319. However, this 10-second window is not an isolated short event. It lies within a much longer contiguous off-nominal episode extending from 2025-02-18 07:59:47.800 to 2025-02-18 08:06:40.300, with a total duration of 412.5 s and a maximum deviation from nominal of approximately 0.147 Hz. Thus, the importance of the off-nominal class in the present dataset comes not from extreme instantaneous magnitude, but from sustained departure from the narrow ordinary band while pairwise agreement remains strong [12]. This sustained off-nominal behavior may also be consistent with periods of larger system imbalance, although the present pairwise analysis does not identify the underlying operational cause.

This interpretation is also supported by the full-month class statistics. Out of 24,155,126 valid paired FREQ samples, 23,572,545 (97.59%) fall in the ordinary class, 582,118 (2.41%) fall in the off-nominal class, and only 463 (0.0019%) fall in the anomalous class. Therefore, the off-nominal class is not negligible in occurrence, even though its amplitude remains moderate relative to the broader ENTSO-E-derived bounds.

In the anomalous class, the representative 10-second window is anchored at the global top-mismatch event and spans 2025-02-25 09:59:09.300 to 2025-02-25 09:59:19.200. In this interval, the mean absolute DFREQ mismatch rises to 1045.0862, the maximum mismatch reaches 3096, and the RMSE increases to 1696.3148. At the same time, the raw frequency values jump to clearly extreme levels, far beyond the broader ENTSO-E security boundary. This window therefore represents a sharp breakdown of practical interchangeability and should be interpreted separately from both ordinary and off-nominal operation [23].

A short supporting PMU-choice sensitivity check indicates that the selected downstream correlation summaries remain highly stable with respect to whether Station A or Station B is used as the site representative. For the monthly comparison, both lag-1 and peak-correlation differences remain very small, and no monthly best-lag change is observed across the 15 site-to-network pairs. The weekday results are similarly stable, while the weekend peak-lag analysis shows only two best-lag changes, again under very small correlation differences. Thus, despite the presence of short local anomalous disagreement, the selected monthly and regime-level network summaries remain largely stable under PMU choice [8].

IV. Discussion

The results show that practical interchangeability between the two co-located streams is condition-dependent. Under ordinary operating conditions, the pair remains extremely close in both DFREQ and FREQ, so the monthly statistics strongly support practical equivalence. This conclusion applies to the dominant portion of the examined period: 23,572,545 out of 24,155,126 valid paired FREQ samples, corresponding to 97.59%, fall in the ordinary class. However, this conclusion does not hold uniformly across all operating contexts [24].

The main limitation of a bulk-only interpretation is that extremely high monthly agreement can coexist with short but severe disagreement. In the present case, the strongest inconsistency is concentrated in a brief anomalous burst rather than distributed across the month. Thus, strong aggregate agreement does not guarantee negligible event-level disagreement [25].

The off-nominal class adds a different type of limitation. Its importance does not come from extreme instantaneous magnitude, but from persistence outside the narrow ordinary band. In the present dataset, the representative off-nominal window lies within a much longer contiguous episode lasting 412.5 s, showing that sustained non-ordinary behavior can remain relevant even when pairwise mismatch stays small. At the same time, the full-month class statistics show that the off-nominal class accounts for 582,118 samples, or 2.41% of the valid paired record, so this regime is not negligible in occurrence.

A short supporting sensitivity check shows that the selected monthly and regime-level summaries remain highly stable with respect to PMU choice. Thus, the main message is not that the two streams produce materially different network-level results, but that bulk stability and local interchangeability are not identical concepts [26].

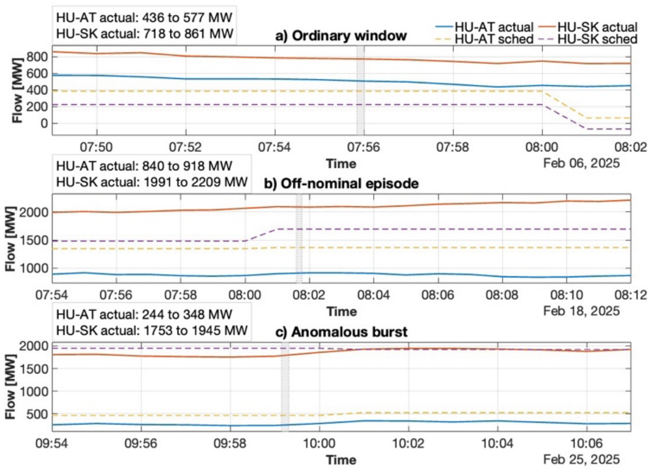

Fig. 4. Cross-border flow time series for the representative ordinary, off-nominal, and anomalous windows on the HU-AT and HU-SK interconnections.

Station A is connected to the cross-border corridor HU-SK, while Station B is connected to the cross-border corridor HU-AT. Accordingly, the representative PMU windows in Fig. 3 are examined together with the corresponding cross-border conditions in Fig. 4 through the difference between the actual and scheduled corridor flows.

For the ordinary window, Fig. 3(a) shows that Station A and Station B remain nearly overlapping, with only very small mismatch. At the same time, Fig. 4(a) indicates differences between actual and scheduled corridor flows of about 50.68–390.00 MW on HU-AT and 494.73–790.87 MW on HU-SK. Thus, very strong pairwise PMU agreement is observed even under visible corridor-level flow imbalance, particularly on HU-SK.

For the off-nominal window, Fig. 3(b) shows that Station A and Station B remain highly consistent even though the frequency lies outside the narrow ordinary band. Over the same interval, Fig. 4(b) shows sustained differences between actual and scheduled corridor flows, with HU-AT at about 428.89–526.27 MW and HU-SK at about 390.90–582.93

MW. Therefore, the off-nominal PMU regime occurs under persistent and clearly off-schedule corridor conditions, yet the co-located pair still preserves strong agreement.

The anomalous window in Fig. 3(c) is qualitatively different. Here, Station A and Station B show a severe mismatch burst and the clearest breakdown of practical interchangeability. However, in Fig. 4(c) the differences between actual and scheduled corridor flows are not the largest among the three cases, remaining at about 177.61–244.90 MW on HU-AT and 3.52–193.37 MW on HU-SK. Thus, the strongest PMU anomaly does not coincide with the largest corridor-flow differences. The most severe event signature is concentrated in the co-located PMU pair itself, while the cross-border flow differences remain much smaller in magnitude.

V. Conclusion

This paper examined the practical interchangeability of two co-located frequency measurement streams, anonymized as Station A and Station B, using a direct pairwise framework. The full-month results show extremely strong agreement under ordinary operating conditions. At the same time, the mismatch distribution shows a pronounced upper tail, and the largest disagreement is concentrated in a short anomalous episode rather than distributed across the month.

The results therefore show that practical interchangeability is not absolute. It is strongly supported under ordinary operation, remains stable in sustained off-nominal but plausible conditions, and breaks down sharply during short anomalous bursts. Co-located PMU streams should therefore be validated explicitly rather than treated as automatically interchangeable on the basis of bulk agreement alone. Future work should examine the abnormal intervals using additional operational context and event-level information in order to better understand the source of these short disagreement bursts.

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