Locating Control-Induced and Electromechanical Oscillations in a Modern Power System: Case Studies from India Grid

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***Abstract*—The rapid integration of inverter-based resources (IBRs) presents stability challenges for modern power systems. This paper analyzes recent oscillation events in the Indian grid, characterizing natural and forced oscillations using a unified methodology of dissipating energy flow for source localization and the matrix pencil method for modal analysis on synchrophasor data. The study examines a 2000 MW renewable generation loss and a 150 MW hydro unit trip, which excited poorly-damped natural inter-area modes at 0.45 Hz and 0.21 Hz, respectively. It also investigates high-frequency forced oscillations ($\approx 3.8Hz$) originating from Northern solar plants, caused by control interactions in STATCOMs and communication delays in IBR outer loops. The DEF method successfully pinpointed the precise source locations for all events, while modal analysis confirmed the distinct oscillation modes and their damping characteristics. Key insights reveal the vulnerability of IBR-heavy grids to controller-induced oscillations and the long-distance propagation of natural modes due to weak damping. While existing controls like power system stabilizers remain effective for synchronous generator-related oscillations, the evolving grid landscape demands refined monitoring, adaptive IBR control strategies, and standardized real-time energy analysis to mitigate escalating oscillation risks and ensure future grid resilience amidst growing renewable penetration.**

***Index Terms*—Forced oscillations, inverter-based resources, natural oscillations, phasor measurement unit, STATCOM**

I. Introduction

The increasing integration of inverter-based resources (IBRs) and high-voltage direct current (HVDC) systems has intensified challenges in monitoring and mitigating oscillatory phenomena in modern power grids, including India. These phenomena include forced oscillations (FOs), driven by external periodic disturbances such as malfunctioning power plants, generators, loads, or IBRs, and poorly damped natural oscillations (PDNOs), which arise from low damping of inherent grid modes following disturbances like faults or major generation loss [1]. Historical events, including the 2005 Western North American resonance and the 2010 WECC oscillations caused by a faulty plant, illustrate the severe risks posed by both oscillation types, with FOs capable of exciting resonant inter-area modes and PDNOs amplifying system stress [2]. These concerns are increasingly relevant for India, where large renewable installations such as the 2,245 MW Bhadla Solar Park and widespread HVDC links elevate stability challenges and demand enhanced oscillation monitoring.

India operates a power grid with more than 11,000 buses at 132 kV and above, including 990 buses at 400 kV and higher, making it vulnerable to oscillation-driven security risks [3]. The unified real-time dynamic state measurement (URTDSM) project, under the National Smart Grid Mission, has deployed around 1,700 phasor measurement units (PMUs) within a wide-area monitoring system (WAMS) to improve observability [4]. These synchronized measurements support real-time detection of both FOs and PDNOs. Phase II, guided by optimized PMU placement criteria issued in 2025, reflects the need for efficient monitoring of grids with high IBR penetration. This need was highlighted by the 2025 Iberian Peninsula blackout, where oscillations preceded a voltage-driven cascade. The infrastructure also enables analysis of recent Indian events, including FOs on 14 February 2024 and 30 September 2024 due to an IBR controller, and PDNOs triggered by a 1,500 MW loss in southern India and a 150 MW loss following a short-circuit fault.

Oscillation source location (OSL) methodologies are central to addressing both FOs and PDNOs. Energy-based methods, especially the dissipating energy flow (DEF) approach, are widely applied due to their effectiveness in identifying source buses using PMU-derived power, frequency, and voltage measurements. DEF also locates insufficiently damped areas contributing to PDNOs, informing mitigation such as power system stabilizer retuning [3]. For recent Indian events, combining energy based method with the matrix pencil method for modal analysis has shown strong capability under high IBR penetration. Complementary OSL techniques include model-based, data-driven, and signal processing methods. Model-based approaches, such as transfer function alignment, depend on linearized system models and degrade with model inaccuracies [5]. Data-driven methods, including robust principal component analysis, separate resonance from local FO sources and identify PDNO-related correlated modes [6]. Machine learning methods using deep neural networks, dynamic time warping, or impulse response estimation enable rapid localization with PMU data [7]. Signal processing tools such as Prony analysis and cross-correlation support high-resolution modal estimation and noise-robust localization, particularly in weak-grid regions with low short circuit ratios (SCRs), which are prone to voltage oscillations [3].

This paper examines four recent oscillation events in India: two FOs caused by a STATCOM controller and an IBR controller issue, and two PDNOs triggered by a 1,500 MW

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loss in the Southern Region and a 150 MW loss following a short-circuit event. The coordinated use of DEF and the matrix pencil method proved effective in determining oscillation sources and modes, providing actionable insights for secure operation under rising IBR penetration. The 2025 Iberian blackout reinforces the need for real-time monitoring to avoid cascading failures [8]. Continued advances in analytical algorithms, monitoring infrastructure, and research into IBR-related oscillations will be essential to maintain system resilience amid expanding renewable and HVDC integration.

II. India Power Grid and WAMS Architecture

India power grid expanded rapidly, with installed capacity rising from 248 GW (2014) to 446 GW (2024); coal grew from 139 GW to 210 GW, and renewables from 75 GW to 195 GW. The network comprises 195,181 ckm of lines, 730 GVA transformation capacity, and 82 GW inter-regional transfer capability. On 4 August 2024, frequency peaked at 50.39 Hz due to underdrawal during high solar output, with IBRs supplying 29% of demand as shown in Fig. 1. Increasing IBR penetration introduces frequent, harder-to-localize FOs, often indicating equipment malfunctions.

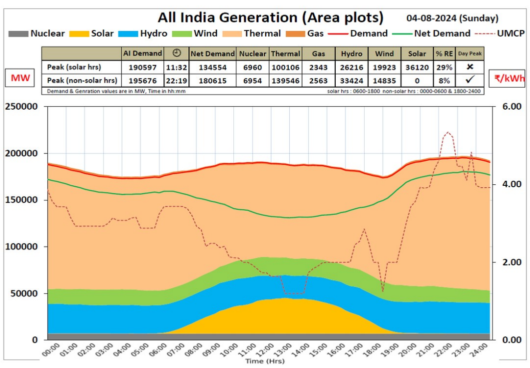

Fig. 1: All India generation on 4 August 2024.

A. WAMS Architecture in India

India wide-area monitoring system employs a hierarchical structure for phasor acquisition and processing at substation, state, regional, and national levels. PMU data are transmitted from substations to SLDC PDCs for synchronization and alignment, then forwarded to the five regional PDCs shown in Fig. 2, and finally aggregated at NLDC for nationwide situational awareness. WAMS mode-metering applications extract real-time oscillation parameters and archive events for operational analysis. Over 100 oscillatory events have been detected recently, spanning both natural and forced types, with typical modes in the 0-2 Hz range posing risks to transmission performance and protection systems [9].

III. Oscillation Source Identification

This section summarizes two methods for oscillation source identification in power systems: the matrix pencil method (MPM) for extracting modal parameters from time-domain measurements, and the DEF method for locating oscillation sources using modal energy flow.

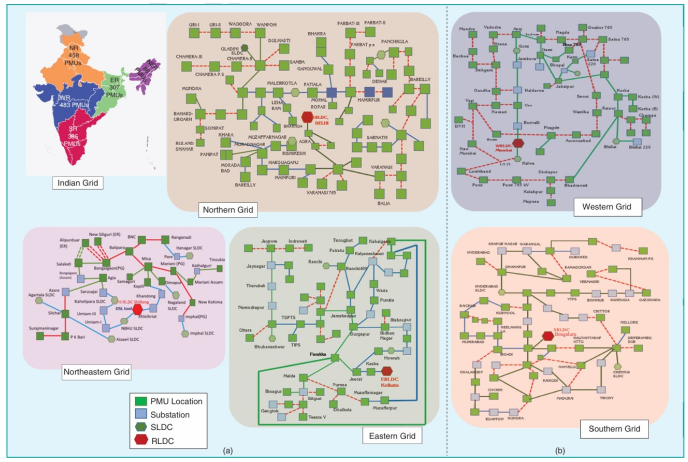

Fig. 2: WAMS architecture in India.

A. Matrix Pencil Method

MPM approximates a sampled oscillatory signal $y[n]$ as a sum of complex exponentials:

$$y[n] = \sum_{k=1}^{K} c_k z_k^n, \qquad z_k = e^{(\sigma_k + j\Omega_k)T_s}, \tag{1}$$

where σ_k and Ω_k denote modal damping and angular frequency. A Hankel matrix $\mathbf{H}$ is constructed from $y[n]$, from which two submatrices $\mathbf{H}_1$ and $\mathbf{H}_2$ are formed by removing the last and first columns, respectively. The generalized eigenvalues of $(\mathbf{H}_1, \mathbf{H}_2)$ yield z_k, from which σ_k and Ω_k are computed. The complex amplitudes c_k are obtained via least squares [10].

B. Dissipating Energy Flow Method

For a mode with angular frequency Ω_m, the oscillatory energy transferred on branch (m, n) is

$$E_{mn} = \int \big(P_{mn}\, 2\pi \Delta\nu_m \, dt + Q_{mn}\, d(\ln V_m)\big), \tag{2}$$

where P_{mn} and Q_{mn} are branch powers, V_m is the bus voltage magnitude, and $\Delta\nu_m$ is the frequency deviation. Net maximum positive injection at a bus indicates the oscillation source [11].

IV. Analysis of Recent Oscillation Event of India Grid

A. Natural Oscillation case of 2000 MW Generation Loss on September 24, 2025

On 24 September 2025, the Southern Region (SR) of the Indian power grid, particularly Tamil Nadu (TN), experienced two major generation-loss events at 11:04 hrs and 11:32 hrs, leading to rapid frequency deviations and oscillatory behavior that exposed the vulnerability of an IBR-dominated system.

The first event at 11:04 hrs, verbally reported by TN as a 600 MW loss, was shown by SRLDC PMU data to be far larger. TN deviation increased from −328 MW at 11:04 hrs to 2251 MW at 11:05 hrs, indicating an actual renewable energy loss of roughly 2500 MW. A substantial portion of this loss resulted from solar and wind plants tripping due to

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LVRT non-compliance [12]. The contingency caused an all-India frequency drop from 50.054 Hz to a nadir of 49.892 Hz (a 0.162 Hz decline) within 10.72 s. The quasi-steady-state frequency settled at 50.029 Hz after 36 s, corresponding to an all-India FRC of about 40,000 MW/Hz. The nadir breached the ±0.03 Hz dead band, though the quasi-steady-state frequency remained within it. A rapid frequency reversal then crossed both the initial value and 50 Hz, preventing deeper under-frequency load shedding.

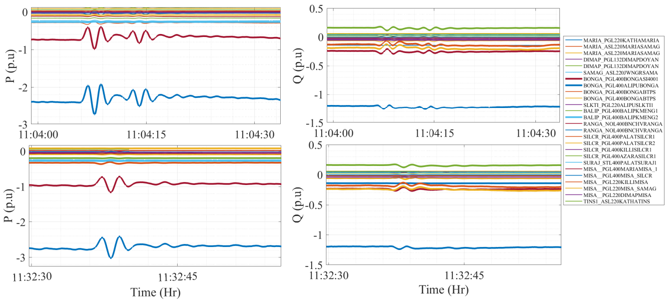

Fig. 3: Active power oscillations at different buses of the NER.

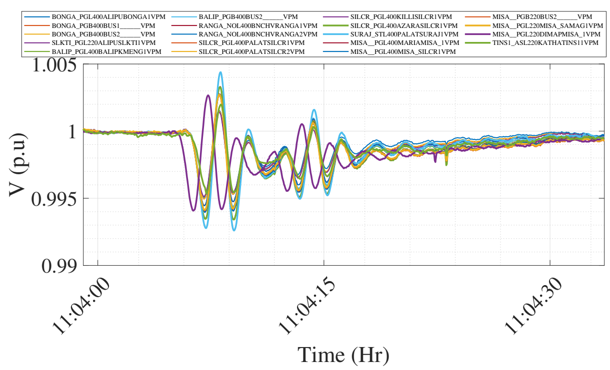

Fig. 4: Voltage oscillations at different buses of the NER.

The second event at 11:32 hrs followed the tripping of the 400 kV Kanarpatty–Tirunelveli line. To avoid overloading the 230 kV network at Kayathar, TN manually curtailed renewable generation. Although the exact curtailment was not provided, PMU data showed an increase in TN deviation of approximately 1400 MW at 11:31 hrs. This manual reduction, potentially under FRC action, triggered another frequency excursion: frequency fell from 50.057 Hz to a nadir of 49.930 Hz (0.127 Hz drop) within 9.56 s, then stabilised at 50.053 Hz after 33 s, yielding a higher FRC of about 250,000 MW/Hz. As in the first event, the nadir crossed the dead band, and rapid reversal again brought the system above 50 Hz.

The abrupt generation imbalances excited inter-area oscillatory modes that propagated across the Southern Region, influencing national frequency stability. Figures 3 and 4 show the resulting active power, reactive power, and voltage oscillations in the North Eastern region.

1) Source Identification: Source is identified using the DEF method and modal analysis (matrix pencil) on PMU data. Modal analysis extracted a dominant 0.45 Hz inter-area mode with low damping ($\zeta \approx 5\%$), confirming a poorly damped natural oscillation (PDNO) from the RE loss. The DEF method quantified the energy dissipation using NER PMU data. The DEF localized positive dissipation to the Bongaigaon-Siliguri bus, identifying it as the source (Fig. 5), later verified by the system operator.

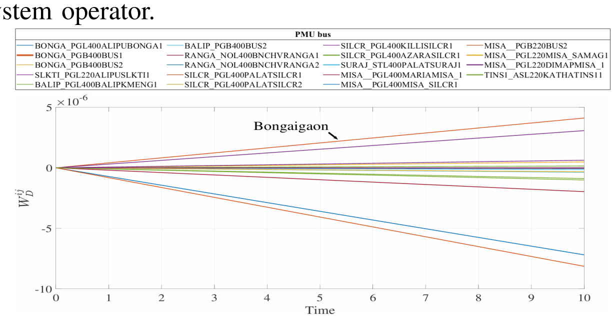

Fig. 5: Energy flow of the generators in the NER grid.

2) Key Insights: The FRC (≈250,000 MW/Hz) in the second event shows manual curtailment is effective but needs regional coordination. Further, quick frequency reversal averted UFLS, but nadirs outside the dead band signal eroding inertia from RE dominance. The DEF-matrix pencil synergy proved effective for PDNO source attribution in partially-observed grids. These events mirror precursors to the 2025 Iberian cascade, reinforcing the need for advanced WAMS.

B. Natural Oscillation case of 150 MW Generation Loss on November 07, 2025

On November 07, 2025, at 22:56 Hrs IST, a natural oscillation event disrupted the NER power system due to the tripping of Kameng Unit 2, triggered by a 95% stator earth fault. This incident resulted in a sudden generation imbalance of 150 MW, significantly affecting the supply and demand balance of the NER grid. The loss of this hydroelectric generating unit introduced a transient disturbance that excited the system's inherent natural modes, leading to oscillatory behavior observable in active and reactive power across the region as shown in Fig. 6. According to the provided analysis, the NER's inherent system mode was identified at 0.21 Hz, and the oscillation was effectively damped by the PSS in place, indicating a stable response to the disturbance.

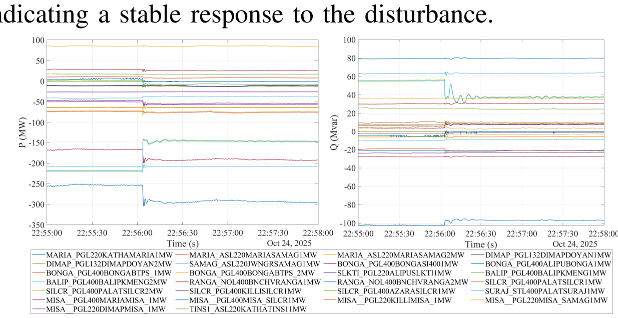

Fig. 6: Active and reactive power oscillations at different NER PMU buses.

1) Source Identification: Source identification used DEF and matrix pencil methods. Modal analysis identified the dominant 0.21 Hz mode with positive damping. The DEF method then localized the source. Analysis showed positive W_D^{ij} at the Kameng Unit 2 bus (Fig. 7), consistent with the 150 MW loss, while adjacent buses absorbed the energy.

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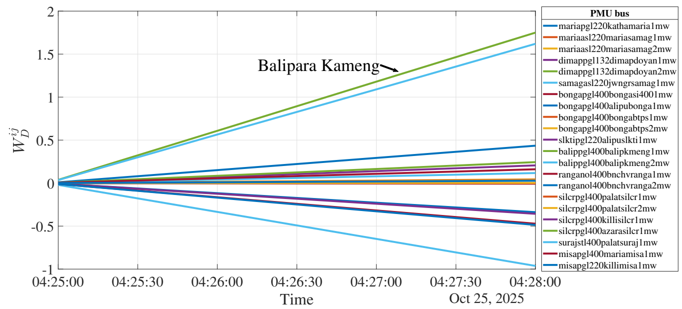

Fig. 7: Energy flow of the generators in the NER India grid.

2) Key Insights: Analysis of the 07 November 2025 natural oscillation event highlights key aspects of NER system behaviour and stability. The 0.21 Hz inherent mode with effective PSS damping confirms small-signal stability, with synchronous generation such as Kameng Unit 2 providing adequate inertia and damping. The stable response under this contingency underscores the continued importance of synchronous units as IBR penetration increases.

C. Forced Oscillation Event on September 23, 2025

On Sep 23, 2025 (11:51 Hrs), a 3.83 Hz forced oscillation, originating in the northern region, propagated to the NER. As per system operator, this was control-induced FO from dynamic interactions in a multi-IBR system under low SCR, where STATCOMs amplified instability. The FO manifested in P and Q data is shown for one of the buses in Fig. 8. The root cause involved phase lags from slow gain adjustments in the STATCOM controller. Mitigation was achieved by switching the STATCOM to fixed reactive power (Q) mode [13], [14].

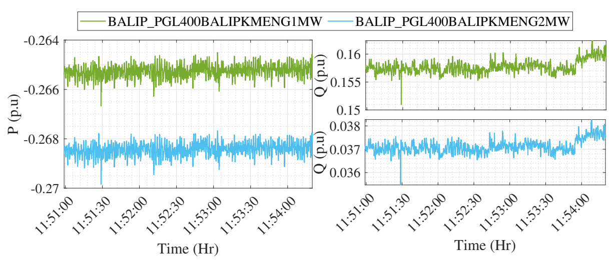

Fig. 8: Active and reactive power oscillations at Balipara PMU bus.

1) Source Identification: Source identification employed DEF and Matrix Pencil. Modal analysis extracted the 3.83 Hz mode with 0.02% damping, confirming an FO [10]. DEF-based energy flow revealed a positive energy slope at northern solar pockets, propagating via the 400 kV Balipara-Kameng tie line—identifying it as the oscillation source in NER.

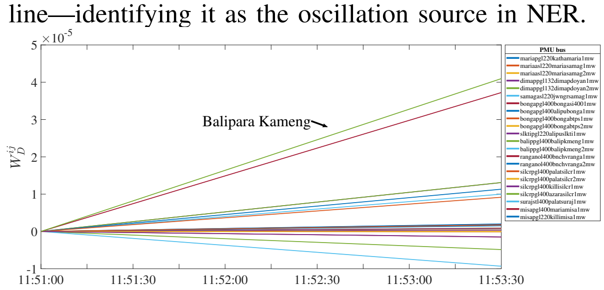

Fig. 9: Energy flow of the generators in the NER India grid.

2) Key Insights: The 3.83 Hz frequency, far above traditional modes, shows how IBR controls create unique high-frequency profiles. The low damping highlights risks of control delays (e.g., 70 ms STATCOM gain lag). Propagation to NER reveals geographic vulnerabilities with source outside the region confirmed using DEF method. Further, mitigation via fixed Q mode demonstrates an effective fail-safe but exposes voltage control limitations under weak grid conditions. This stresses the need for adaptive controls and real-time energy flow monitoring.

D. Forced Oscillation Event on May 17, 2025

On May 17, 2025 (15:20 Hrs), a similar 3.81 Hz FO propagated from the northern region to the NER. This was also a control-induced FO from IBR dynamics under low SCR. The cause was communication delays as per system operator in the IBR's outer control loop [13], creating destabilizing phase lags that amplified voltage fluctuations (Fig. 10). The issue involved high volt/var sensitivity at high power export levels, exacerbated by the control delay.

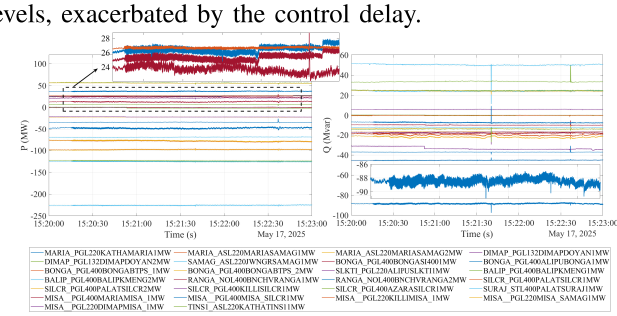

Fig. 10: Active and reactive power oscillations at different NER PMU buses.

1) Root-cause analysis: In IBR systems, control is organized hierarchically through plant-level and inverter-level controllers deployed across multiple parallel units. This architecture regulates voltage and reactive power at the PCC but becomes vulnerable when many inverters operate in parallel. Each inverter's outer control loop measures the PCC voltage, computes the reactive power reference Q^*, and generates the current references I_d^* and I_q^* for the inner current-control loops. Communication delays between PCC sensing and reference generation, typically 50–100 ms due to measurement, processing, and transmission latencies, can destabilize this loop. These delays led to the forced oscillations observed on 17 May 2025, shown in Fig. 10.

The plant-level controller measures V_{pcc} and compares it with the reference V_{ref} (typically 1.0–1.05 p.u. with 3–5% droop). The voltage error $\Delta V = V_{ref} - V_{pcc}$ drives the outer-loop adjustment of reactive power $\Delta Q^* = -K_{droop}\Delta V$, which is converted to I_q^* for var regulation, while I_d^* is determined through MPPT for active-power control. These references are transmitted to all inverter-level controllers, whose inner loops produce the corresponding PWM commands. Although scalable, this distributed architecture accumulates delay: PCC sensing, centralized computation, and communication to numerous dispersed inverters collectively increase latency. Such delays introduce destabilizing phase shifts in the voltage-control loop. A delay $\tau \approx$ 70–100 ms

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imposes a phase lag $\phi = -\omega\tau$, which becomes significant at the 3.81 Hz oscillation frequency, resulting in $\phi \approx -80^\circ$ to -140°. This reduction in phase margin increases oscillations. A drop in V_{pcc} triggers an increase in I_q^* to inject reactive power, but with delay, the corrective action often arrives after V_{pcc} has already recovered, leading to over-injection. Similarly, voltage rises yield delayed under-correction. These misaligned responses inject out-of-phase reactive power and create a self-reinforcing cycle. In large plants, variations in delay across inverters further desynchronize their behaviour, with some units damping while others amplify, producing net positive feedback.

High volt/var sensitivity $\frac{dV}{dQ} \approx 0.01$–$0.05$ p.u./Mvar, especially during high export conditions, magnifies the impact of small reactive-power errors and intensifies voltage deviation. As a result, oscillations manifest primarily in voltage and reactive power, whereas active power is less affected due to the weaker coupling between MPPT and voltage-driven dynamics.

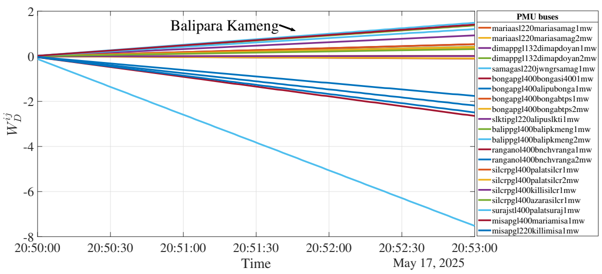

Fig. 11: Energy flow of the generators in the NER India grid.

2) Source Identification: Source localization is performed using DEF and matrix pencil. Modal analysis extracted the 3.81 Hz mode with 0.02% damping. DEF analysis revealed positive energy slopes in northern IBR clusters, with peak dissipation traced to buses behind the 400 kV Balipara-Kameng tie line (Fig. 11), confirming source outside NER. This oscillation is attributed to outer loop communication delays in IBR plants, as observed by the system operator during the May 17, 2025 event. However, direct parametric evidence linking the measured delay to the 3.81 Hz mode remains unavailable due to lack of access to proprietary IBR control gains and time-stamped delay logs.

3) Key Insights: The 3.81 Hz frequency highlights high-frequency profiles created by IBR outer loop communication delays. Propagation to NER again shows interconnection vulnerabilities. Furhter, the event underscores that control delays in volt-var feedback drive instability. This necessitates optimizing IBR outer loops for minimal delay and using PMU data to parameterize sensitivities.

V. Conclusion

This analysis of recent oscillatory events in the Indian power system demonstrates the capability of combining DEF and matrix pencil methods for reliable source localization, while also underscoring emerging challenges in a rapidly evolving grid. The study identifies two distinct oscillation categories: naturally occurring low-frequency modes (0.21–0.45 Hz) triggered by generation losses, which remain effectively damped by existing controls, and high-frequency forced oscillations (~ 3.8 Hz) arising from malfunctioning controllers in inverter-based resources and STATCOMs. Owing to their frequency characteristics, these forced oscillations propagate widely across the network and expose the growing sensitivity of renewable-heavy systems to control-induced disturbances. The successful mitigation of such events through measures like switching STATCOMs to fixed Q-mode highlights the value of operational safeguards and timely corrective actions. Overall, the findings emphasize the need for strengthened monitoring frameworks, adaptive and grid-forming control strategies for renewable plants, and coordinated approaches to address both benign natural modes and high-frequency forced oscillations as power system transitions toward higher renewable penetration.

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