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Wide-Area Monitoring Using PMU Technology for Real-Time Stability Assessment of Saudi Arabia's Smart Energy Grid

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Abstract-** Saudi Arabia is transitioning toward a more diversified electricity mix, integrating large-scale solar, wind, storage, digital substations, and advanced control alongside a substantial synchronous generation fleet. This evolution increases the importance of measurements capable of capturing grid dynamics at the time scale of electromechanical disturbances, rather than relying solely on the slower operating state observed by conventional supervisory control and data acquisition (SCADA) systems. This review assesses the role of phasor measurement unit (PMU)-based wide-area monitoring systems (WAMS) for live stability assessment in Saudi Arabia's smart energy grid. Rather than presenting an implementation report, the study uses a structured review of literature published from 2020 to 2025, synthesizing evidence across synchrophasor architecture, frequency and inertia monitoring, transient and angular stability, voltage regulation, oscillation detection, event analytics, data engineering, and renewable-rich grid operation. The review is motivated by Saudi-specific concerns identified in recent studies, particularly the sensitivity of frequency response to increasing inverter-based generation and the necessity to maintain reliability as renewable capacity expands. The evidence demonstrates that PMU-based monitoring is most effective when implemented as an operational decision-support layer that supplements SCADA, includes strong data-quality controls, and translates synchronized measurements into interpretableindicators such as frequency nadir, rate of change of frequency, inter-area angle separation, damping ratio, voltage recovery, and event location. A Saudi-oriented architecture is proposed, linking geographically distributed PMUs to redundant phasor data concentrators, streaming analytics, historian services, and control-room applications. The review further identifies research gaps in public PMU deployment information, low-inertia thresholds, hybrid SCADA-PMU system estimation, cybersecurity, and validation by Saudi disturbance records. A staged research agenda is recommended to progress from observability studies and offline replay toward operator-validated real-time stability assessment.

***Keywords:** wide-area monitoring system, phasor measurement unit, synchrophasor, Saudi Arabia, smart grid, real-time stability, frequency stability, voltage stability, oscillation monitoring, renewable integration*

I. INTRODUCTION

Electrical power systems are undergoing major transformation due to the rapid expansion of renewable generation, converter-interfaced resources, energy storage, digital protection, and data-centric operational approaches. While these developments improve system flexibility and decarbonization potential, they also alter the physical dynamics upon which system operators have traditionally depended. In grids dominated by synchronous machines, the rotating mass inherently provides inertial response to sudden differences between generation and demand. However, as inverter-based solar and wind resources replace portions of synchronous generation, frequency changes can occur more rapidly, and local voltage or oscillatory effects may become increasingly sensitive to network strength and converter controls. Denholm et al. [2] argue that inertia should be considered as one component within a wider frequency-response capability, rather than as an isolated parameter. Recent research on synchrophasor-enabled monitoring additionally demonstrates that dynamic observability is critical when operating networks closer to stability boundaries [1,3,4].

This challenge is especially pertinent to Saudi Arabia, where the electricity sector is undergoing a substantial transition toward renewables, gas, storage, and digitalized grid infrastructure. Alqahtani et al. [6] found that high penetration of inverter-fed renewable energy can worsen post-disturbance frequency behavior, especially under light-load conditions with fewer synchronous units online. Their scenarios demonstrated that declining equivalent inertia increases both the rate and depth of frequency deviation following significant generation loss. Conversely, recent reliability analyses of Saudi renewable projects indicate that renewable expansion may improve adequacy when projects are properly integrated and planned [7]. These outcomes are complementary, as aadequacy and dynamic stability represent distinct dimensions of reliability.

Phasor measurement units provide a practical measurement foundation for that faster layer. PMUs estimate synchronized voltage and current phasors and normally report frequency and rate of change of frequency using a common time reference. Wide-area monitoring systems combine PMUs, communications, phasor data concentrators, data-quality logic, storage, analytics, and operator interfaces. Compared with conventional SCADA, which is optimized for steady-state supervision and control, WAMS can capture system-wide electromechanical behavior at much higher reporting rates. The recent Colombian operational case documented by Bustamante et al. [1] demonstrates how a national control center can use synchrophasors for frequency, RoCoF, angle, oscillation, and voltage-profile monitoring while retaining SCADA as a complementary source.

A key problem in the Saudi context is that public literature provides strong evidence about renewable-integration challenges but does not provide a complete, current, openly documented map of PMU coverage, communication paths, data concentration, or operational WAMS applications across the national transmission system. This review therefore does not claim that a specific national PMU architecture is already deployed. Instead, it asks what a technically defensible Saudi-oriented WAMS should monitor, how it should process data, and which stability indicators ought to be prioritized if the objective is real-time assessment.

The aim of this study is to develop an evidence-based framework for using PMU technology to strengthen real-time stability assessment in Saudi Arabia's evolving smart energy grid. The study has four objectives. First, it integrates recent developments in WAMS and synchrophasor applications published between 2020 and 2025, with emphasis on methods that have been tested using operational or realistic large-system data. Second, it evaluates the principal stability functions that are relevant to a renewable-rich Saudi grid: frequency and inertia awareness, transient and angular stability, short-term voltage behavior, oscillation detection, and disturbance analytics. Third, it examines the data-engineering requirements that determine whether PMU measurements can be trusted and acted upon in a control room, including synchronization, latency, data quality, redundancy, storage, and hybrid SCADA-PMU integration. Fourth, it identifies Saudi-specific implementation priorities and a research agenda that can guide pilot studies, validation, and eventual operational deployment.

This contribution is distinct from broader smart-grid and WAMS reviews [3-5,24] by explicitly focusing regarding real-time stability assessment for Saudi Arabia and directly linking monitoring functions to the Kingdom's renewable and storage transition.

II. REVIEW METHODOLOGY

A structured narrative review protocol was used because the topic spans measurement standards, power-system dynamics, wide-area monitoring, machine learning, operational analytics, and Saudi energy-transition studies. The review window was limited to 2020-2025 to satisfy the need for recent evidence and to capture the rapid development of inverter-rich grid operation. Searches were organized around combinations of the terms "phasor measurement unit," "synchrophasor," "wide-area monitoring system," "WAMS," "real-time stability," "frequency stability," "RoCoF," "electrical voltage stability," "transient stability," "oscillation monitoring," "event detection," "big data," "SCADA-PMU fusion," and "Saudi grid." Peer-reviewed journal articles, peer-reviewed conference papers, authoritative technical reports, and current standards were considered. A recent operational WAMS article was also used as a structural reference because it offers a clear link between infrastructure, data processing, monitoring applications, and future needs [1].

Eligibility was based on five criteria. A source had to be published from 2020 through 2025; address PMU/WAMS measurement, dynamic stability, data analytics, or a directly relevant Saudi grid challenge;

provide sufficient methodological detail to support technical interpretation; be available through a traceable publisher, professional society, standardization body, or government source; and contribute a non-duplicative insight to the synthesis. Studies limited to unrelated distribution applications, purely economic market analysis, or pre-2020 methods were excluded even when historically influential. Older concepts such as classical synchrophasor theory are acknowledged indirectly through recent sources, but they were not used as references because the requested citation window is 2020-2025.

The final evidence base comprises 30 references. The literature was categorized into six themes: WAMS architecture and observability; frequency, RoCoF, and inertia; transient and angular stability; voltage and oscillatory stability; event analytics and data engineering; and Saudi renewable-integration requirements. This thematic structure corresponds to the manner in which control centers process information. Operators respond not to the presence of a PMU itself, but to analyses such as accelerating frequency decline, increasing inter-area angle, poorly damped oscillation, delayed voltage recovery, or event signatures suggestive of credible contingencies. Consequently, each reviewed method was evaluated based on measurement requirements, time scale, computing burden, interpretability, data-quality sensitivity, and possible operational actions.

The synthesis differentiates between demonstrated capabilities and proposed applications. Operational WAMS applications are established for frequency, RoCoF, angle, oscillation, and voltage monitoring [1], while many predictive methods are primarily certified through simulations or recorded datasets [10,11,13-16]. Saudi studies identify pertinent renewable-driven stability problems [6-8], but do not document current use of these analytics by Saudi operators. A method is considered suitable for Saudi evaluation if its underlying physical problem is relevant and its measurements are compatible with PMU data.

Quality appraisal emphasized repeatability and operational relevance. Greater weight was given to studies using real PMU records, substantial datasets, utility-scale architectures, transparent indicators, or explicit data-quality handling. IEEE C37.118.2-2024 was included for interoperability [29], and Saudi policy context was anchored to the Ministry of Energy's 2025 storage update [30]. Because systems, disturbances, sampling rates, labels, and metrics are heterogeneous, the method is an evidence-weighted review rather than a statistical meta-analysis.

III. PMU-WAMS ARCHITECTURE FOR A SAUDI REAL-TIME STABILITY LAYER

A WAMS for live stability assessment should be designed as a layered information system rather than a collection of isolated PMUs. At the field layer, PMUs measure synchronized voltage and current phasors and provide frequency-related quantities at selected buses, generating plants, renewable connection points, major transmission corridors, and electrically strategic interfaces. At the aggregation layer, phasor data concentrators align time-stamped frames from multiple locations, check completeness, and forward coherent streams to redundant control-center services. At the analytical layer, high-speed processing calculates indicators, detects events, estimates modal behavior, and associates measurements with network areas. At the presentation layer, control-room displays translate these calculations into warnings, trends, security regions, and event summaries. The operational Colombian architecture described by Bustamante et al. [1] illustrates this separation of acquisition, concentration, data management, analytics, and visualization.

For Saudi Arabia, PMU placement should be driven by dynamic observability. Full numerical coverage of every substation is neither required nor economically efficient for the first stages of a program. Priority locations would include interfaces between major operating regions, buses with high transfer sensitivity, large conventional generation sites, large renewable plants, grid-scale battery facilities, and nodes whose voltage angles provide strong separation among coherent areas. Ortiz et al. [25] show that power-system dynamics can still be monitored under incomplete PMU observability if the architecture and estimation problem are designed around available measurements. Cheng et al. [26] further demonstrate the importance of combining multiple measurement sources, including PMU and SCADA, within modern state-estimation frameworks. These conclusions support a staged Saudi deployment in which a stability-focused PMU layer supplements rather than duplicates the existing telemetry estate.

The communication and concentration layer must be engineered for deterministic performance, redundancy, and cybersecurity. Giraldo-Gomez et al. [27] reported scalability testing of a wide-area synchrophasor communication network, highlighting that network architecture becomes a technical constraint as PMU counts and subscriptions grow. IEEE C37.118.2-2024 defines standardized synchrophasor data transfer and is still essential for interoperable data exchange [29]. A Saudi architecture should therefore use redundant PDC paths, quality flags, disciplined time synchronization, bandwidth engineering, segmentation from business networks, and failover behavior that is tested under packet loss and device outage. Real-time stability analytics should degrade gracefully: if one PMU becomes invalid, a prioritized alternative should be selected where possible, and the interface should make measurement uncertainty visible rather than silently presenting stale or corrupted values.

Data historians are important because each disturbance can improve later monitoring. High-rate phasor streams create storage and query demands past conventional SCADA archives. Big-data WAMS functions, dataset preparation, and parallel PMU querying are addressed in recent studies [21,24,28]. A Saudi historian should support synchronized replay, disturbance labeling, model validation, operator training, and governed research access, creating a loop in which archived events develop future alarm logic. Table 1 summarizes how SCADA and PMU-WAMS capabilities differ for Saudi real-time stability functions.

Table 1. Functional comparison of SCADA and PMU/WAMS for Saudi real-time stability assessment.

Parameter	Conventional SCADA	PMU/WAMS	Relevance to Saudi stability assessment
Temporal resolution	Typically, seconds; optimized for steady-state supervision	High-rate synchronized reporting, commonly tens of frames per second	Captures fast frequency, angle, voltage, and oscillatory trajectories
Synchronization	Measurements need not share a precise common time base	Common UTC-referenced time alignment across locations	Enables credible inter-area comparison and disturbance propagation analysis
Core variables	Analog magnitudes, status, breaker and control information	Voltage/current phasor magnitude and angle, frequency, RoCoF, status flags	Supports low-inertia monitoring, angular separation, event analysis, and recovery metrics
Primary role	Routine monitoring, dispatch, topology, alarms, and supervisory control	Dynamic situational awareness and high-speed post-event analysis	Complements rather than replaces the existing telemetry and control environment
Data challenge	Moderate volume and mature historian workflows	High volume, strict time quality, continuous streams	Requires PDC redundancy, fast historian queries, quality logic, and cybersecurity
Deployment logic	Broad operational coverage	Selective dynamic observability can deliver high value	Prioritize regional interfaces, renewable hubs, BESS, generation, and weak areas

Figure 1 presents the proposed Saudi-oriented stability-monitoring architecture synthesized from the reviewed evidence.

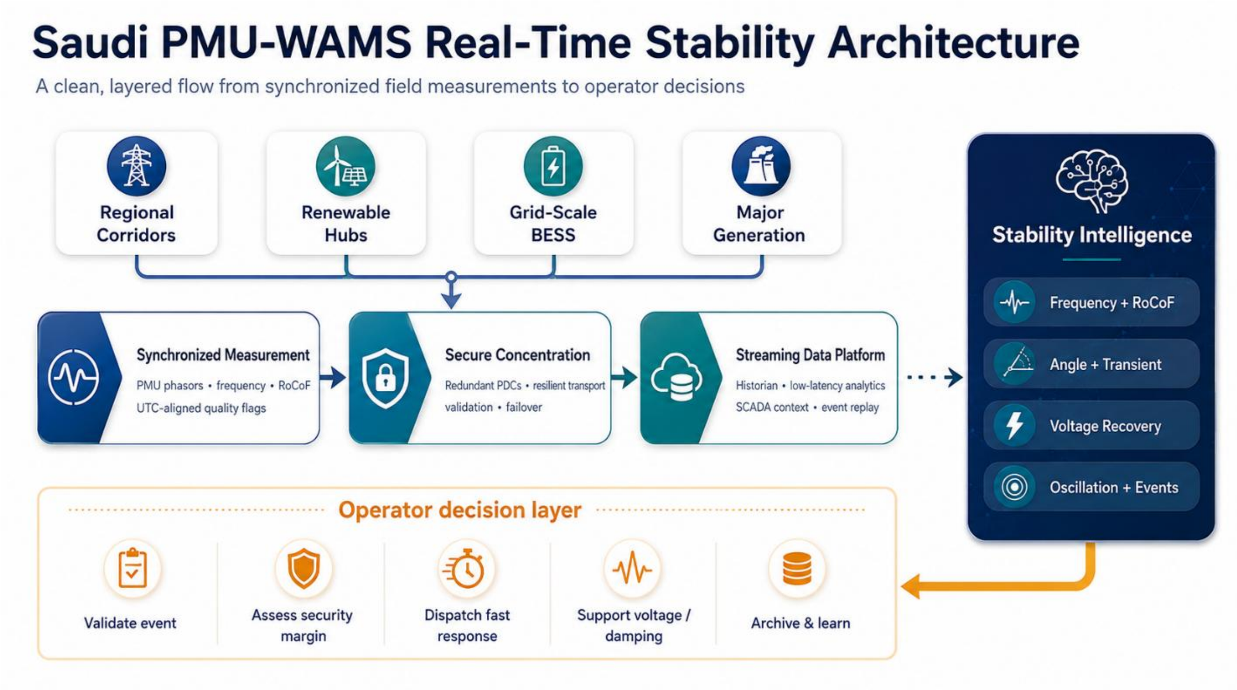

Figure 1. Proposed Saudi-oriented PMU/WAMS architecture for instant stability intelligence. Original synthesis based on the reviewed evidence [1,21,24,27-29].

IV. REAL-TIME STABILITY ASSESSMENT FUNCTIONS

4.1. Frequency, RoCoF, and Inertia Awareness

Frequency is the most immediate system-wide indicator of active-power imbalance. In a high-inertia grid, the initial decline after generation loss is moderated by stored kinetic energy in synchronous machines. As inverter-based resources displace part of the synchronous fleet, the same contingency can produce a steeper RoCoF and a lower frequency nadir unless alternative fast-frequency resources respond. Denholm et al. [2] emphasize that frequency security depends on the combined response of inertia, primary response, fast controls, load behavior, and reserves. Saudi-specific simulations by Alqahtani et al. [6] show why this matters for the Kingdom: the worst frequency performance appears under high renewable penetration and base-load conditions, when equivalent synchronous inertia is reduced.

PMUs enable frequency assessment at multiple locations using synchronized timestamps, which makes it possible to distinguish local measurement noise from coherent system operation. A practical Saudi application should display nominal frequency, selected regional measurements, RoCoF, event start time, nadir or zenith, recovery time, and measurement quality. RoCoF is especially useful because it provides early information about the severity of an imbalance before slower regulation acts. However, raw derivatives amplify noise; therefore, window length, filtering, reporting rate, and bad-data logic must be configured carefully. Kerdphol et al. [19] review inertia assessment from transient measurements in Japanese WAMS practice, while Lakshmanan and Swarup [18] summarize constant challenges in real-time inertia monitoring, including disturbance identification, parameter uncertainty, and varying resource behavior.

The operational objective should not be to produce an inertia number for its own sake. Instead, PMU measurements should support actionable security logic. Examples include identifying intervals of unusually high negative RoCoF, recognizing when frequency nadir approaches load-shedding thresholds, comparing responses across operating regions, and evaluating whether battery or fast-frequency services performed as expected. Saudi Arabia's expanding storage portfolio makes this coupling particularly relevant. The Ministry of Energy has identified battery storage as a key part of renewable integration, and its 2025 update reported large storage procurement ambitions [30]. A WAMS historian can verify the delivered response of storage during real disturbances and help tune future reserve requirements.

4.2. Transient and Angular Stability

Transient stability matters the ability of synchronous machines and interconnected areas to remain in synchronism after severe disturbances such as faults, line trips, or major generation loss. PMU voltage angles provide a direct wide-area view of how electrical separation develops. Acosta et al. [10] used measurement-based singular-value decomposition used to estimate critical clearing time, showing how synchronized measurements can support transient-security assessment. Chrashekhar and Srivani [11] investigated regression-based online transient-stability prediction using wide-area information. Although such methods call for careful validation before operational use, they show the direction of travel from post-event angle inspection toward predictive security assessment.

For a Saudi WAMS, the first operational step should be transparent angle monitoring rather than an opaque classifier. Operators can monitor angle differences between selected regional reference buses and major transfer corridors, with limits derived from offline security studies. A rising angle difference does not by itself prove instability; it can reflect normal power transfer, topology, or changing dispatch. Therefore, limits should be state-dependent and linked to contingency studies. The value of synchronized angles is that they let operators see whether areas are separating in a coherent pattern immediately after a disturbance. When combined with topology and power-flow context, this supports early warning, event confirmation, and targeted remedial action.

Machine-learning prediction ought to follow creation of a strong labeled event library. PMU-based detection methods can identify disturbances using data-driven or strong strategies [14-16], but functional reliability depends on representative training data and transparent confidence. Saudi disturbance records, renewable operating points, protection behavior, and regional characteristics should form the validation basis. Foreign models are best treated as transferable algorithms, not transferable thresholds.

4.3. Voltage Steadiness and Recovery

Voltage regulation is becoming more important as power-electronic generation, reactive-power controls, long transmission corridors, and changing load characteristics alter post-disturbance voltage behavior. PMU voltage magnitude provides fast visibility, while synchronized angle and current measurements add context for estimating network stress. Zhu et al. [12] demonstrated spatial-temporal feature learning for short-term voltage-stability assessment, and Li et al. [13] later applied Transformer-based deep learning to short-term voltage stability facing class imbalance. These methods show that multi-location time series contain useful precursors, but they also illustrate the dependence of advanced models on labeled, system-specific data.

A Saudi operational application should begin with indicators that are physically interpretable. These include minimum retained voltage, time below an operational threshold, recovery slope, recovery time, regional voltage dispersion, reactive reserve context, and repeated sag propagation across nearby PMUs. Elkhidir et al. [8] show, in a renewable-integrated microgrid setting, how reactive compensation and coordinated controls can improve transient response and voltage regulation. At transmission scale, the same principle applies: measurement is most useful when it points to the resource or control action capable of supporting voltage, such as generator excitation, synchronous condensers, STATCOMs, storage inverters, or grid-forming controls.

Because voltage instability can be spatially uneven, PMUs should cover weak areas, renewable hubs, major load centers, and interfaces where poor recovery could propagate. Complementary disturbance records continue to be necessary for very fast electromagnetic dynamics. WAMS is therefore a dynamic supervisory layer, not a replacement for protection relays or fault

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recorders; its strength is showing how regional measurements evolve together across the network.

4.4. Oscillation Detection and Disturbance Analytics
Low-frequency oscillations can limit transfer capability and, if poorly damped, threaten secure operation. PMUs are well suited to oscillation monitoring because they provide synchronized active-power, angle, and frequency measurements throughout geographically separated areas. Negi et al. [9] proposed PMU-data methods for detecting oscillatory events and identifying associated variables. The Colombian operational experience uses WAMS for instant oscillation detection and assessment [1]. A Saudi implementation would be especially useful across long transmission paths and between areas with changing generation composition, where inter-area modes may shift as renewable output and dispatch change.

The monitoring workflow should estimate dominant mode frequency, damping, amplitude, participating locations, and persistence. Alarms should not be based solely on amplitude because a small but negatively damped mode can be more concerning than a large disturbance that decays rapidly. Mode estimates should be cross-validated across several PMUs to reduce false alarms caused by regional noise. When oscillations are detected, the historian should automatically preserve the event window and operating state so engineers can compare the behavior with power-system-stabilizer settings, inverter controls, topology, and transfer levels. This creates a direct link between practical monitoring and model validation.

Disturbance analytics go beyond oscillations. da Silva et al. [17] used WAMS infrastructure to monitor systemic dynamic effects following HVDC-related disturbances, and Katariya et al. [22] describe a data-driven event-analytics framework for disturbance characterization and source localization in the Indian grid. Large-scale event analytics are relevant to Saudi Arabia because rapid interpretation can shorten the time between alarm and operator understanding. The system should answer four questions after an event: what happened, where did it originate, how did it propagate, and is the system returning to a secure state? PMU time alignment makes those questions easier to address than with asynchronous records.

Table 2 and Figure 2 connect representative analytical methods with the operator decisions they are intended to support.

Table 2. Synthesis of recent PMU/WAMS stability methods and their relevance to Saudi grid operation.

Domain	Representative evidence (2020-2025)	Operational output	Saudi-oriented use	Main limitation
Frequency / inertia	Alqahtani et al. [6]; Lakshmanan and Swarup [18]; Kerdphol et al. [19]	Frequency, RoCoF, nadir, recovery time, inertia indicators	Identify low-inertia operating conditions and verify fast-frequency response	Filtering, disturbance-size uncertainty, resource-dependent response
Transient / angle	Acosta et al. [10]; Chrashekhar and Srivani [11]	Angle separation, criticality indicators, stability prediction	Monitor major regional interfaces and severe post-fault separation	Thresholds depend on topology and operating point
Voltage stability	Zhu et al. [12]; Li et al. [13]; Elkhidir et al. [8]	Retained voltage, recovery time, classification, spatial-temporal features	Assess renewable hubs, weak nodes, and post-disturbance voltage recovery	Advanced models require labeled Saudi data
Event detection	Liu et al. [14]; Shaw and Jena [15]; Lopes et al. [16]	Event flag, class, timestamp, confidence	Accelerate disturbance interpretation and event triage	False alarms and class imbalance can affect trust

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Oscillation analytics	Negi et al. [9]; Bustamante et al. [1]	Mode frequency, amplitude, damping, participation	Track inter-area modes as dispatch and renewable output vary	Estimation windows create speed-versus-confidence tradeoffs
Data engineering	Chintakindi and Mitra [21,23]; Hart et al. [24]; Pinzón et al. [28]	Clean synchronized streams, historian replay, scalable queries	Build an auditable event library and analytics pipeline	Missing data, configuration changes, labels, storage, latency
Hybrid observability	Ortiz et al. [25]; Cheng et al. [26]	SCADA-PMU state and dynamic context	Use existing topology with targeted PMU deployment	Fusion models must handle different rates and uncertainty
National transition context	Almutairi and Alhamed [7]; Saudi Ministry of Energy [30]	Planning and policy context for renewables/storage	Link WAMS priorities to renewable expansion and BESS services	Public PMU deployment detail remains limited

Figure 2. Five-stage PMU analytics pathway from disturbance measurement to an operator decision, with core stability views for frequency, angle, voltage, oscillations, and event propagation.

V. DATA ENGINEERING, ANALYTICS, AND CONTROL-ROOM USABILITY

A technically advanced stability algorithm has little operational value if its input data are incomplete, delayed, or poorly labeled. PMU quality management should therefore be treated as part of the stability method. IEEE synchrophasor messages provide status information that can be used to detect synchronization and data-validity problems [29]. A real-time platform should combine these flags with plausibility checks, duplicate-source comparison, time-skew detection, and rules for substituting a redundant measurement. The operator display should indicate when an application is operating in degraded mode. This is preferable to hiding uncertainty behind a visually clean interface.

Data fusion offers another route toward the resilience. SCADA continues to be valuable for breaker status, topology, slower analogs, schedules, and many measurements not economically duplicated by PMUs. Cheng et al. [26] review power state estimation using PMU, SCADA, advanced metering, and other sources, while Ortiz et al. [25] address monitoring under incomplete synchrophasor observability. For Saudi Arabia, hybrid applications can combine SCADA topology with PMU dynamics, enabling state-aware angle limits, event localization, and post-disturbance reconstruction. This also reduces the risk of designing a WAMS as a parallel information silo.

Machine learning should be positioned after, not before, data governance. Hart et al. [24] evaluated the "machine-learning readiness" of large synchrophasor datasets and found that high data volume does not automatically translate into high analytical value. Missing data, inconsistent labels, changing device configurations, event imbalance, and uncertain ground truth is able to undermine training. Liu et al. [14], Shaw and Jena [15], and Lopes et al. [16] provide useful examples of event detection, but a Saudi deployment ought to maintain an auditable chain from raw data to model output. Each model should have version control, training-data documentation, drift monitoring, and a fallback rule when confidence is insufficient.

Control-room usability is a separate engineering discipline. The operational WAMS model reported by Bustamante et al. [1] emphasizesvisualization and event-specific alerts rather than dense numerical dashboards [1]. For Saudi operators, the interface should be hierarchical. The first level can show system frequency, RoCoF, regional angle separation, oscillation status, and voltage-recovery alarms. The second level can provide regional drill-down with PMU trends, topology, and quality status. The third level can expose analytical detail for engineers and post-event investigators. This layered design lessens alarm fatigue and keeps the main display oriented toward decisions rather than measurement abundance. Latency should be measured end to end. A nominal PMU reporting rate does not guarantee timely situational awareness if communication, concentration, analytics, database queries, or visualization add delay. Each application needs a latency budget based on its purpose. Frequency and RoCoF alerts require very low processing delay; oscillation damping can tolerate a somewhat longer estimation window; post-event classification may trade speed for confidence. Chintakindi and Mitra [21,23] identify data and implementation challenges that arise as WAMS scale increases, while Pinzon et al. [28] demonstrate the role of parallel processing in decreasing query time. Saudi pilot projects should therefore publish internal performance measures such as data availability, packet loss, synchronization failures, median and worst latency, and false-alarm rates.

VI. Saudi-Specific Implementation Priorities

The most important Saudi design principle is to connect WAMS investment to the changing generation mix. Alqahtani et al. [6] show that frequency vulnerability can increase when renewable penetration is high and system inertia is low. Almutairi and Alhamed [7] show that renewable expansion can improve adequacy and reliability indices when evaluated at planning scale. Together, these studies imply that a secure transition requires both adequate capacity and dynamic observability. PMU applications should therefore be prioritized around conditions that are likely to evolve as solar, wind, storage, and new transmission projects are added.

A first priority is regional frequency and RoCoF observability. Saudi Arabia's geographically large interconnected system can benefit from synchronized comparison of frequency behavior throughout operating regions following major events. The objective is not to create different regional frequencies in a synchronized system, but to detect propagation, measurement anomalies, and coherent response. A second priority is monitoring of inter-area angles across critical transmission interfaces, particularly where large renewable injections change transfer patterns. A third is voltage recovery around renewable hubs and load centers. A fourth is oscillation monitoring across long transmission paths. A fifth is event analytics that automatically associates a disturbance with topology, generation mix, and storage response.

Energy storage creates a particularly useful validation case. The Ministry of Energy's 2025 update identifies large-scale battery storage as central to renewable integration [30]. PMU measurements can quantify whether a battery delivers expected fast-frequency response, how quickly power injection affects RoCoF and nadir, and whether local voltage support improves recovery. This converts storage performance from a contractual or model-based expectation into an observed dynamic service. Over time, recorded events can support better reserve sizing and location decisions.

Cybersecurity and governance must be addressed from the beginning because WAMS links substations, communications, control-center servers, historians, and analytics. Segmentation, authentication, least-privilege access, configuration control, and incident logging are essential. Historical research access should use curated or de-identified datasets so dynamic signatures can be studied without exposing sensitive network details.

Implementation should proceed in stages. Stage one is an observability and use-case study that pinpoints critical buses, corridors, renewable hubs, and existing telemetry gaps. Stage two is a limited pilot with redundant PMUs and PDCs, focused on frequency, RoCoF, angle, and data quality. Stage three adds historian integration, event replay, oscillation analysis, and voltage-recovery metrics. Stage four introduces hybrid SCADA-PMU analytics and carefully validated machine learning. Stage five moves selected applications into formal operating procedures with alarm thresholds linked to contingency studies and operator actions. This sequence reduces technological risk because each stage produces evidence needed to justify the next.

VII. RESEARCH GAPS AND FUTURE AGENDA

The first research gap is empirical. Public studies describe Saudi frequency-stability scenarios and renewable reliability, but there is limited openly available evidence on nationwide PMU measurements, actual disturbance signatures, or operational WAMS performance. Subsequent research should therefore create reference datasets from controlled pilots or de-identified events. Such datasets would allow Saudi-specific testing of RoCoF filters, angle thresholds, oscillation estimators, voltage-recovery metrics, and machine-learning classifiers.

The second gap is the definition of dynamic security thresholds under future operating conditions. Thresholds derived from a synchronous-dominated grid may not stay appropriate when grid-forming inverters, batteries, flexible demand, and new interconnections provide fast response. Research should couple PMU replay with dynamic simulations so that measured behavior continuously improves models. The third gap is uncertainty-aware analytics. Rather than reporting a single predicted stability class, future applications should show confidence, data-quality status, and sensitivity to missing PMUs.

A fourth gap is coordinated control. Most WAMS studies focus on monitoring, while the extended value lies in moving from awareness to validated remedial action. Cepeda et al. [20] describe wide-area monitoring, protection, and control as a route to improved security and dependability in an operational national context. Saudi research can examine how PMU indicators might trigger or recommend actions involving batteries, reactive-power devices, generation redispatch, controlled islanding, or renewable-plant controls. Such work should begin with advisory decision support before any closed-loop action is considered.

Finally, human factors deserve greater attention. A WAMS can generate many mathematically valid indicators while still failing operators if alarms are poorly prioritized. Future Saudi pilots should evaluate display comprehension, alarm response time, false-alarm tolerance, and training requirements.

VIII. CONCLUSION

PMU-based wide-area monitoring offers a strong technical foundation for instant stability assessment in Saudi Arabia's renewable-rich smart grid, but its value depends on system design rather than device count. Recent evidence supports synchronized monitoring of frequency, RoCoF, phase angle, oscillations, and voltage recovery, complemented by solid data quality, high-speed storage, hybrid SCADA integration, and operator-centered visualization. Saudi studies already show why low-inertia frequency behavior, renewable integration, and storage performance require closer dynamic observation [6,7,30]. The next step is therefore not to assume a finished national WAMS, but to build a staged, evidence-driven program: identify dynamic observability needs, deploy targeted PMUs, validate indicators using Saudi events, and progressively integrate trusted analytics into control-room procedures. In this form, WAMS becomes a practical bridge between Vision 2030 energy transformation and the real-time security discipline required to operate a increasingly dynamic power system.

REFERENCES

[1] Bustamante, S.; Pinzón, J.D.; Giraldo-Gómez, D. Evolution of Real-Time Dynamics Monitoring of Colombian Power Grid Using Wide-Area Monitoring System and High-Speed Big Data Analytics. Sustainability 2025, 17, 3848. https://doi.org/10.3390/su17093848.

[2] Denholm et al., P.; Mai, T.; Kenyon, R.W.; Kroposki, B.; O'Malley, M. Inertia and the Power Grid: A Guide Without the Spin. Technical Report NREL/TP-6A20-73856; National Renewable Energy Laboratory: Golden, CO, USA, 2020.

[3] Maheswari, M.; Suthanthira Vanitha, N.; Loganathan, N. Wide-Area Measurement Systems and Phasor Measurement Units. In Wide Area Power Systems Stability, Protection, and Security; Haes Alhelou, H.; Abdelaziz, A.Y.; Siano, P., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 105-126.

[4] Zamani, R.; Panahi, H.; Abyaz, A.; Haes Alhelou, H. Introduction to WAMS and Its Applications for Future Power System. In Wide Area Power Systems Stability, Protection, and Security; Haes Alhelou, H.; Abdelaziz, A.Y.; Siano, P., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 45-69.

[5] Alotaibi, I.; Abido, M.A.; Khalid, M.; Savkin, A.V. A Comprehensive Review of Recent Advances in Smart Grids: A Sustainable Future with Renewable Energy Resources. Energies 2020, 13, 6269. https://doi.org/10.3390/en13236269.

[6] Alqahtani, S.; Shaher, A.; Garada, A.; Cipcigan, L. Impact of the High Penetration of Renewable Energy Sources on the Frequency Stability of the Saudi Grid. Electronics 2023, 12, 1470. https://doi.org/10.3390/electronics12061470.

[7] Almutairi, A.; Alhamed, Y. Sustainability and Grid Reliability of Renewable Energy Expansion Projects in Saudi Arabia by 2030. Sustainability 2025, 17, 4493. https://doi.org/10.3390/su17104493.

[8] Elkhidir, L.; Khan, K.; Al-Muhaini, M.; Khalid, M. Enhancing Transient Response and Voltage Stability of Renewable Integrated Microgrids. Sustainability 2022, 14, 3710. https://doi.org/10.3390/su14073710.

[9] Negi, S.S.; Kishor, N.; Singh, A. PMUs data based detection of oscillatory events and identification of their associated variable: Estimation of information measures approach. Sustainable Energy, Grids and Networks 2024, 39, 101457. https://doi.org/10.1016/j.segan.2024.101457

[10] Acosta, M.N.; Gómez, E.; Gonzalez-Longatt, F.; Andrade, M.A.; Vázquez, E.; Barocio, E. Single Value Decomposition to Estimate Critical Clearing Time of a Power System Using Measurements. IEEE Access 2021, 9, 125999-126010. https://doi.org/10.1109/ACCESS.2021.3111006

[11] Chandrashekhar, P.K.; Srivani, S.G., P.K.; Srivani, S.G. Wide Area Based Online Transient Stability Prediction Using Regression Model. In Proceedings of the 2022 IEEE 7th International Conference on Recent Advances and Innovations in Engineering (ICRAIE), Mangalore, India, 1-3 December 2022; pp. 433-437. 10. DOI: 1109/ICRAIE56454.2022.10054249

[12] Zhu, L.; Lu, C.; Kamwa, I.; Zeng, H. Spatial-Temporal Feature Learning in Smart Grids: A Case Study on Short-Term Voltage Stability Assessment. IEEE Transactions on Industrial Informatics 2020, 16, 1470-1482. https://doi.org/10.1109/TII.2018.2873605

[13] Li, Y.; Cao, J.; Xu, Y.; Zhu, L.; Dong, Z.Y. Deep learning based on Transformer architecture for power system short-term voltage stability assessment with class imbalance. Renewable and Sustainable Energy Reviews 2024, 189, 113913. https://doi.org/10.1016/j.rser.2023.113913

[14] Liu, S.; Zhao, Y.; Lin, Z.; Liu, Y.; Ding, Y.; Yang, L.; Yi, S. Data-Driven Event Detection of Power Systems Based on Unequal-Interval Reduction of PMU Data and Local Outlier Factor. IEEE Transactions on Smart Grid 2020, 11, 1630-1643. https://doi.org/10.1109/TSG.2019.2941565

[15] Shaw, P.; Kumar Jena, M. A Novel Event Detection and Classification Scheme Using Wide-Area Frequency Measurements. IEEE Transactions on Smart Grid 2021, 12, 2320-2330. https://doi.org/10.1109/TSG.2020.3039274

[16] Lopes, G.V.d.S.; Moraes, G.R.; Issicaba, D.; Dotta, D. WAMS-based two-level robust detection methodology of power system events. Sustainable Energy, Grids and Networks 2022, 31, 100689. https://doi.org/10.1016/j.segan.2022.100689

[17] da Silva, D.S.; Moraes, G.R.; Penna, L.D.; Decker, I.C.; Aquino, A.F.; Issicaba, D. Monitoring systemic dynamic effects following disturbances affecting HVDC power transmission in the BIPS using WAMS infrastructure. Electric Power Systems Research 2024, 235, 110821. https://doi.org/10.1016/j.epsr.2024.110821

[18] Lakshmanan, L.; Swarup, K. Inertia monitoring in power systems: Critical features, challenges, and framework. Renewable and Sustainable Energy Reviews 2024, 190, 114076. https://doi.org/10.1016/j.rser.2023.114076

[19] Kerdphol, T.; Watanabe, M.; Mitani, Y.; Ngamroo, I. Inertia Assessment from Transient Measurements: Recent Perspective from Japanese WAMS. IEEE Access 2022, 10, 66332-66344. https://doi.org/10.1109/ACCESS.2022.3185056

[20] Cepeda, J.C.; Echeverría, D.E.; Chamba, M.S.; Kamwa, I.; Rueda-Torres, J. Wide-Area Monitoring Protection and Control Supported Operation and Planning in the Ecuadorian Power System: Improving Security and Reliability. IEEE Power & Energy Magazine 2025, 23, 59-68. https://doi.org/10.1109/MPE.2024.3435811

[21] Chintakindi, R.; Mitra, A. Execution of Real-time Wide Area Monitoring System with Big Data Functions and Practices. In Proceedings of the 2020 IEEE 9th Power India International Conference (PIICON), Sonepat, India, 28 February-1 March 2020; pp. 1-6. https://doi.org/10.1109/PIICON49524.2020.9113070

[22] Katariya, K.V.; Yadav, R.; Kumar, S.; Pradhan, A.K.; Kamwa, I. Wide-Area-Measurement-System-Based Event Analytics in the Power System: A Data-Driven Framework for Disturbance Characterization and Source Localization in the Indian Grid. IEEE Power & Energy Magazine 2025, 23, 35-46. https://doi.org/10.1109/MPE.2024.3446737

[23] Chintakindi, R.; Mitra, A. WAMS challenges and limitations in load modeling, voltage stability improvement, and controlled island protection-A review. Energy Reports 2022, 8, 699-709. https://doi.org/10.1016/j.egyr.2021.11.217

[24] Hart, P.; He, L.; Wang, T.; Kumar, V.S.; Aggour, K.; Subramanian, A.; Yan, W. Application of Big Data Analytics and Machine Learning to Large-Scale Synchrophasor Datasets: Evaluation of Dataset 'Machine Learning-Readiness'. IEEE Open Access Journal of Power and Energy 2022, 9, 386-397. https://doi.org/10.1109/OAJPE.2022.3197553

[25] Ortiz, G.; Rehtanz, C.; Colomé, G. Monitoring of power system dynamics under incomplete PMU observability condition. IET Generation, Transmission & Distribution 2021, 15, 1435-1450. https://doi.org/10.1049/gtd2.12111

[26] Cheng, G.; Lin, Y.; Abur, A.; Gómez-Expósito, A.; Wu, W. A Survey of Power System State Estimation Using Multiple Data Sources: PMUs, SCADA, AMI, and Beyond. IEEE Transactions on Smart Grid 2024, 15(1), 1129–1151. DOI: 10.1109/TSG.2023.3286401..

[27] Giraldo-Gómez, D.; Arboleda, B.; Viana-Villa, P.; Quintero-Zuluaga, F.; Villegas, D.; Sánchez,

M.; Tóbon, Á.; Gómez, J.; Duque, N. Towards a Colombian Power System Fully Supervised with PMU: Scalability Test of the iSAACnet Communications Network. In Proceedings of the 2020 IEEE PES Transmission & Distribution Conference and Exhibition-Latin America, Montevideo, Uruguay, 28 September-2 October 2020; pp. 1-6. https://doi.org/10.1109/TDLA47668.2020.9326229

[28] Pinzón, J.D.; Santamaria, F.; Espinel, A. Parallel Computing-Based PMU Measurements Big Data Query Tool to Analyze the Colombian Power System Dynamic Performance. In Proceedings of the 2023 IEEE PES Innovative Smart Grid Technologies Latin America (ISGT-LA), San Juan, PR, USA, 6-9 November 2023; pp. 25-29.

[29] IEEE Standard C37.118.2-2024. IEEE Standard for Synchrophasor Data Transfer for Power Systems. IEEE: Piscataway, NJ, USA, 2024.

[30] Saudi Ministry of Energy. Saudi Arabia Ranks Among World's Top 10 Energy Storage Markets, Advancing Leadership in Renewable Energy. Ministry of Energy, Riyadh, Saudi Arabia, 13 February 2025.