

HYBRID STATE ESTIMATION TECHNIQUE INTEGRATING SCADA AND SYNCHROPHASOR DATA FOR IMPROVED OBSERVABILITY IN ACTIVE DISTRIBUTION NETWORKS

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Abstract - The rapid transformation of conventional power systems into Active Distribution Networks (ADNs) with high penetration of Distributed Energy Resources (DERs) has introduced significant challenges in system monitoring, observability, and operational reliability. Traditional Supervisory Control and Data Acquisition (SCADA)-based state estimation techniques suffer from low sampling rates, lack of time synchronization, and limited measurement coverage, resulting in reduced estimation accuracy. Conversely, Phasor Measurement Units (PMUs) provide high-speed, time-synchronized measurements with superior accuracy, but their widespread deployment is constrained by high installation and communication costs. To address these limitations, this paper proposes a hybrid state estimation (HSE) technique that integrates SCADA and synchrophasor data within a unified Weighted Least Squares (WLS) framework. The proposed method combines nonlinear SCADA measurements with linear PMU data to enhance system observability and improve estimation accuracy. The approach is validated on standard IEEE 33-bus distribution system under realistic operating conditions, including load variability and measurement noise. Simulation results demonstrate that the proposed HSE significantly improves observability from approximately 65–75% to 95–100% and reduces voltage magnitude and angle estimation errors compared to conventional methods. Furthermore, the hybrid approach achieves faster convergence with moderate implementation cost, making it a practical and scalable solution for modern smart grid applications.

Key Words: Hybrid State Estimation, SCADA, Phasor Measurement Unit (PMU), Active Distribution Network, Observability, Weighted Least Squares (WLS)

1. INTRODUCTION

The modern electric power system is undergoing a structural transformation driven by the integration of distributed generation, renewable energy sources, and advanced control technologies. This transition has significantly increased system complexity, particularly at the distribution level, where traditional monitoring and control approaches are no longer sufficient. Accurate and reliable state estimation has become a critical requirement for

ensuring system stability, efficient operation, and enhanced situational awareness. In this context, hybrid state estimation techniques that integrate multiple data sources have emerged as a promising solution to address the limitations of conventional methods.

1.1 Background

The motivation for this research arises from the rapid evolution of distribution networks and the growing need for advanced monitoring frameworks capable of handling dynamic and uncertain system conditions.

1.1.1 Evolution from Passive to Active Distribution Systems

Traditionally, distribution networks were designed as passive systems characterized by unidirectional power flow from centralized generation to end consumers. These systems had predictable load patterns and limited operational complexity, allowing conventional monitoring tools to function effectively. However, with the advent of Active Distribution Networks (ADNs), the operational paradigm has shifted significantly. Modern distribution systems now incorporate distributed generation, bidirectional power flows, and dynamic load behavior. This transformation introduces increased uncertainty, variability, and complexity, making accurate system monitoring and state estimation more challenging and essential for reliable operation.

1.1.2 Impact of Distributed Energy Resources (DERs)

The widespread integration of Distributed Energy Resources (DERs), such as solar photovoltaic systems, wind turbines, and electric vehicles (EVs), has further intensified the complexity of distribution networks. These resources are inherently intermittent and stochastic in nature, leading to rapid fluctuations in voltage levels and power flows. Electric vehicles add an additional layer of variability due to their unpredictable charging patterns. As a result, the traditional assumption of steady-state operation is no longer valid, and system operators require high-resolution, real-time data to

maintain system stability, optimize performance, and ensure efficient energy management.

1.1.3 Need for Real-Time Monitoring and Accurate Estimation

Given the dynamic behavior of modern distribution networks, real-time monitoring and precise state estimation have become indispensable. Accurate estimation of system states, such as voltage magnitudes and phase angles, enables effective decision-making for voltage regulation, fault detection, load balancing, and integration of renewable energy sources. Conventional monitoring systems, however, are often unable to capture fast system dynamics due to their inherent limitations. Therefore, there is a strong need for advanced estimation techniques that can process high-frequency data, handle uncertainties, and provide reliable system visibility in real time.

1.2 Limitations of Existing Monitoring Systems

Despite advancements in measurement technologies, existing monitoring systems—primarily SCADA and PMU-based frameworks—exhibit several limitations when applied independently in active distribution networks.

1.2.1 SCADA Limitations

Supervisory Control and Data Acquisition (SCADA) systems have been the backbone of power system monitoring for decades. However, their effectiveness is increasingly constrained in modern distribution environments.

1.2.1.1 Low Sampling Rate

SCADA systems typically operate with sampling intervals ranging from 2 to 10 seconds, which is insufficient for capturing fast transient events and dynamic variations introduced by renewable energy sources. This low temporal resolution limits the ability to accurately track system changes in real time.

1.2.1.2 Non-Synchronized Data

Another major limitation of SCADA systems is the lack of time synchronization among measurements collected from different network locations. Since data is not aligned to a common time reference, inconsistencies arise, leading to inaccuracies in state estimation, especially under rapidly changing operating conditions.

1.2.1.3 Sparse Measurements

SCADA infrastructure is often sparsely deployed in distribution networks due to economic and practical constraints. As a result, only a limited number of measurement points are available, leading to poor system observability. This insufficiency of data makes it difficult to

accurately estimate all system states, thereby reducing the reliability of monitoring and control operations.

1.2.2 PMU Limitations

Phasor Measurement Units (PMUs) provide high-speed, time-synchronized measurements and have significantly improved monitoring capabilities. However, their independent application also presents certain challenges.

1.2.2.1 High Cost

The installation of PMUs involves substantial capital investment, including costs associated with hardware, communication infrastructure, and maintenance. This high cost limits their widespread deployment, particularly in large-scale distribution networks.

1.2.2.2 Limited Deployment

Due to economic constraints, PMUs are typically installed at selected critical locations rather than across the entire network. This partial deployment restricts full system observability when relying solely on PMU-based estimation, thereby limiting its effectiveness as a standalone solution.

1.3 Research Gap

Although both SCADA and PMU technologies have been extensively studied, several critical gaps remain in their integration and application for distribution system state estimation.

1.3.1 Lack of Efficient SCADA-PMU Data Fusion

Existing research has explored hybrid state estimation; however, efficient integration of heterogeneous data sources remains a challenge. SCADA and PMU measurements differ significantly in terms of sampling rates, accuracy, and mathematical representation. Developing a unified framework that effectively combines these datasets while maintaining computational efficiency is still an open research problem.

1.3.2 Multi-Rate Synchronization Handling

A major technical challenge in hybrid estimation is the handling of multi-rate data. SCADA provides low-frequency measurements, whereas PMUs generate high-frequency synchronized data streams. Aligning these datasets temporally and ensuring consistency in the estimation process requires advanced synchronization and data processing techniques, which are not fully addressed in existing methods.

1.3.3 Lack of Distribution-Specific Hybrid Frameworks

Most existing hybrid state estimation techniques are designed for transmission systems and do not adequately account for the unique characteristics of distribution networks, such as radial topology, high resistance-to-reactance ratios, and unbalanced operation. Consequently, there is a need for a robust, distribution-specific hybrid state estimation framework that can address these challenges while improving observability, accuracy, and computational performance in active distribution networks.

2. LITERATURE REVIEW

This section synthesizes prior work on state estimation methodologies in power systems, with emphasis on their applicability to Active Distribution Networks (ADNs). It critically evaluates conventional SCADA-based approaches, synchrophasor-driven methods, and emerging hybrid frameworks, and identifies persistent gaps that motivate the proposed research.

2.1 Conventional State Estimation

Conventional state estimation has historically relied on SCADA measurements and nonlinear optimization techniques, most notably the Weighted Least Squares (WLS) method.

2.1.1 WLS-Based SCADA Estimation

The WLS estimator formulates state estimation as an optimization problem that minimizes the weighted residual between measured and calculated quantities. Measurements typically include active/reactive power injections, line flows, and bus voltage magnitudes. The nonlinear relationship between these measurements and system states necessitates iterative solution techniques, such as the Newton-Raphson method, with the Jacobian matrix updated at each iteration. This framework has been widely adopted in transmission systems due to adequate measurement redundancy and relatively stable operating conditions.

2.1.2 Limitations in Active Distribution Networks (ADNs)

When applied to ADNs, SCADA-based WLS estimation exhibits notable deficiencies. Low sampling rates (seconds-level) fail to capture fast dynamics introduced by DERs, while lack of time synchronization degrades temporal consistency across measurements. Moreover, sparse measurement placement in distribution feeders leads to poor observability and ill-conditioned estimation problems. High resistance-to-reactance (R/X) ratios further exacerbate numerical instability, resulting in reduced accuracy and convergence reliability under dynamic conditions.

2.2 PMU-Based State Estimation

The advent of Phasor Measurement Units (PMUs) has enabled high-fidelity, time-synchronized monitoring, prompting a shift toward synchrophasor-based estimation.

2.2.1 Advantages: Accuracy and Synchronization

PMUs provide direct measurements of voltage and current phasors with precise time stamping via GPS, typically at 30–60 samples per second. This high temporal resolution allows accurate tracking of fast system dynamics and reduces model nonlinearity since phasor measurements are linearly related to state variables. Consequently, PMU-based estimators exhibit improved numerical conditioning, faster convergence, and superior accuracy compared to SCADA-only approaches.

2.2.2 Deployment Constraints

Despite their technical advantages, PMUs face practical limitations. High capital and operational expenditures—including device cost, communication infrastructure, and data management—restrict large-scale deployment. In distribution systems, PMUs are typically installed at a limited number of strategic buses, leading to incomplete observability when used in isolation. This economic constraint motivates hybrid approaches that leverage existing SCADA infrastructure.

2.3 Distribution System State Estimation (DSSE)

DSSE extends classical state estimation to distribution networks, which differ fundamentally from transmission systems in structure and operation.

2.3.1 Differences from Transmission Systems

Transmission networks are generally meshed, balanced, and well-instrumented, enabling robust estimation with ample measurement redundancy. In contrast, distribution systems are predominantly radial or weakly meshed, often unbalanced, and sparsely monitored. The lack of redundancy and presence of phase asymmetry require tailored modeling and estimation strategies distinct from transmission-level formulations.

2.3.2 Challenges: Radial Topology and High R/X Ratio

Radial topology limits alternative measurement paths, making observability highly sensitive to meter placement. Additionally, high R/X ratios in distribution lines degrade the effectiveness of conventional Jacobian-based methods, leading to poor numerical conditioning. The presence of DERs introduces variability and bidirectional power flow, further complicating DSSE. These factors necessitate specialized algorithms capable of handling limited data, unbalance, and dynamic behavior.

2.4 Hybrid State Estimation Techniques

Hybrid state estimation integrates SCADA and PMU data within a unified framework to exploit complementary strengths.

2.4.1 Existing SCADA-PMU Integration Methods

Prior studies have proposed WLS-based hybrid estimators that combine nonlinear SCADA measurements with linear PMU phasors. Approaches include augmented measurement vectors, modified Jacobian formulations, and sequential/decoupled estimators. Some works incorporate pseudo-measurements and employ robust estimators (e.g., LAV) to mitigate bad data. Multi-area and distributed formulations have also been explored to improve scalability.

2.4.2 Reported Performance Improvements

Empirical results consistently demonstrate that hybrid methods enhance estimation accuracy and convergence characteristics. Reported benefits include significant reductions in voltage magnitude and angle errors, improved numerical conditioning, and faster convergence (often 20–35% reduction in iterations). Critically, hybrid integration achieves near-complete observability with partial PMU deployment, offering a cost-performance balance suitable for ADNs.

3. SYSTEM MODELING AND PROBLEM FORMULATION

This section establishes the mathematical and simulation framework used to represent the active distribution network (ADN) and formulate the state estimation problem. Accurate system modeling is essential to ensure that the proposed hybrid estimation technique reflects real-world operating conditions, including distributed generation, load variability, and network constraints.

3.1 Active Distribution Network Modeling

The modeling of the ADN provides the structural and electrical foundation required for implementing the state estimation algorithm.

3.1.1 IEEE 33-Bus / 69-Bus System

Standard IEEE test systems, such as the 33-bus and 69-bus distribution networks, are widely adopted for validating state estimation techniques due to their realistic representation of practical systems. These systems include detailed bus, line, and load data, enabling consistent benchmarking and comparison with existing studies. The IEEE 33-bus system represents a medium-scale network with moderate complexity, while the 69-bus system offers a larger and more complex topology, making it suitable for scalability analysis. Their standardized structure ensures reproducibility and credibility of simulation results.

3.1.2 Radial Topology Characteristics

Distribution networks are predominantly radial in nature, meaning that each load is supplied through a single path from the source. This topology simplifies protection schemes but introduces challenges for state estimation due to limited measurement redundancy. Unlike meshed transmission systems, radial networks have fewer alternative paths for power flow, making observability highly dependent on measurement placement. Additionally, radial systems often exhibit high resistance-to-reactance (R/X) ratios, which affect numerical stability and require specialized modeling approaches for accurate estimation.

3.2 DER Integration Modeling

To emulate modern active distribution networks, the integration of Distributed Energy Resources (DERs) is incorporated into the system model.

3.2.1 Solar PV and Battery Energy Storage Systems (BESS)

Solar photovoltaic (PV) systems are modeled as distributed generation units connected at selected buses, contributing active power based on irradiance conditions. Battery Energy Storage Systems (BESS) are included to provide energy balancing, peak shaving, and voltage support. These components introduce bidirectional power flow and dynamic behavior into the network, reflecting real-world smart grid conditions. The presence of DERs significantly increases system variability and necessitates robust estimation techniques.

3.2.2 Penetration Levels (20–40%)

The penetration level of DERs is typically assumed to be within the range of 20–40% of the total system load, which aligns with contemporary distribution network scenarios. At these levels, DERs have a substantial impact on system operation, influencing voltage profiles, power flows, and network stability. Modeling such penetration levels allows the evaluation of the proposed method under realistic and challenging operating conditions.

3.3 Load Modeling

Load representation is a critical aspect of system modeling, as it directly influences power flow and state estimation accuracy.

3.3.1 PQ Load Model

In this study, loads are modeled using the constant power (PQ) model, where active (P) and reactive (Q) power demands are specified at each bus. This is a widely used approximation in power system analysis due to its simplicity and effectiveness in steady-state studies. The PQ model

assumes that load consumption remains constant regardless of voltage variations, providing a baseline for estimation.

3.3.2 Time-Varying Demand

To enhance realism, load profiles are modeled as time-varying, reflecting daily or hourly fluctuations in demand. Variations in load are typically considered within a range of $\pm 10\text{--}20\%$, simulating peak and off-peak conditions. This dynamic behavior introduces variability into the system, allowing the evaluation of the estimation algorithm under changing operating scenarios.

4. MEASUREMENT MODELING

Measurement modeling defines how system data is acquired, represented, and incorporated into the state estimation framework. In hybrid state estimation, both SCADA and PMU measurements are utilized, each with distinct characteristics.

4.1 SCADA Measurement Model

SCADA measurements form the conventional data source for state estimation and are modeled as nonlinear functions of system states.

4.1.1 Power Injections, Flows, and Voltage Magnitude

SCADA systems provide measurements such as active and reactive power injections at buses, power flows along transmission lines, and voltage magnitudes. These measurements are derived from physical sensors and transmitted to control centers via communication networks. They offer wide coverage but limited temporal resolution.

4.1.2 Nonlinear Measurement Equations

The relationship between SCADA measurements and system states (voltage magnitude and phase angle) is inherently nonlinear, governed by power flow equations. As a result, the estimation problem requires iterative numerical techniques, such as the Newton–Raphson method, to solve the nonlinear equations. The Jacobian matrix plays a key role in linearizing the system during each iteration.

4.1.3 Error Characteristics ($\pm 1\text{--}3\%$)

SCADA measurements are subject to relatively higher uncertainty due to sensor inaccuracies, communication delays, and lack of synchronization. Measurement errors are typically assumed to lie within $\pm 1\%$ to $\pm 3\%$. These errors are incorporated into the estimation framework through weighting factors, which influence the contribution of each measurement in the solution.

4.2 PMU Measurement Model

PMU measurements provide high-precision, time-synchronized data and significantly enhance the estimation process.

4.2.1 Voltage and Current Phasors

PMUs directly measure voltage and current phasors, including both magnitude and phase angle, at specific buses. These measurements provide real-time insight into system conditions and are particularly useful for capturing dynamic behavior.

4.2.2 Linear Representation

Unlike SCADA measurements, PMU data has a linear relationship with system state variables, which simplifies the estimation problem. This linearity reduces computational complexity and improves convergence characteristics when integrated into the estimation algorithm.

4.2.3 High Sampling Rate (30–60 Samples/sec)

PMUs operate at high sampling rates, typically between 30 and 60 samples per second, enabling real-time monitoring of fast system dynamics. This high temporal resolution allows the detection of disturbances and rapid changes that cannot be captured by SCADA systems.

4.3 Measurement Noise Modeling

Accurate representation of measurement uncertainty is essential for realistic state estimation.

4.3.1 Gaussian Noise Assumption

Measurement noise in both SCADA and PMU data is commonly modeled as a Gaussian (normal) distribution with zero mean and specified variance. This assumption reflects practical measurement errors and is widely used in estimation theory. SCADA measurements are assigned higher variance, while PMU measurements have lower variance due to their higher accuracy.

4.3.2 Weight Assignment in WLS

In the Weighted Least Squares (WLS) framework, each measurement is assigned a weight inversely proportional to its variance. Measurements with lower noise (PMUs) are given higher weights, thereby having a greater influence on the estimated states. Conversely, SCADA measurements with higher uncertainty are assigned lower weights. This weighting mechanism ensures that the estimation process prioritizes more reliable data, leading to improved accuracy and robustness.

5. PROPOSED HYBRID STATE ESTIMATION METHOD

This section presents the formulation and implementation of the proposed Hybrid State Estimation (HSE) technique, which integrates SCADA and PMU measurements within a unified mathematical framework. The objective is to enhance estimation accuracy, improve observability, and achieve faster convergence in active distribution networks.

5.1 State Variable Definition

The state variables represent the unknown electrical quantities that must be estimated to describe the operating condition of the power system.

5.1.1 Voltage Magnitude and Phase Angle

In this study, the system state vector is defined in terms of bus voltage magnitudes and phase angles. These variables fully characterize the steady-state behavior of the network. Each bus in the system is associated with two state variables: voltage magnitude ($|V|$) and phase angle (θ). The slack bus angle is typically taken as a reference (zero), reducing the number of independent variables. Accurate estimation of these states is essential for system monitoring, control, and stability analysis.

5.2 Hybrid Measurement Integration

The hybrid approach combines measurements from SCADA and PMUs to leverage their complementary advantages.

5.2.1 Combined Measurement Vector

In hybrid state estimation, all available measurements are combined into a single measurement vector, denoted as z . This vector includes nonlinear SCADA measurements (power injections, flows, voltage magnitudes) and linear PMU measurements (voltage and current phasors). By integrating both data types, the estimator utilizes wide-area coverage from SCADA and high-accuracy data from PMUs.

5.2.2 Multi-Rate Data Alignment

A key challenge in hybrid estimation is handling the difference in sampling rates between SCADA (low frequency) and PMU (high frequency) data. To address this, PMU data is synchronized and aligned with SCADA timestamps using appropriate data processing techniques such as time-window averaging or interpolation. This ensures consistency in the measurement set and enables effective integration within the estimation framework.

5.3 WLS-Based Formulation

The estimation problem is formulated using the Weighted Least Squares (WLS) method, which minimizes the discrepancy between measured and estimated values.

5.4 Jacobian Matrix Development

The Jacobian matrix represents the sensitivity of measurements with respect to state variables and is essential for iterative solution methods.

5.4.1 Combined SCADA + PMU Structure

In the hybrid framework, the Jacobian matrix is constructed by combining partial derivatives of both SCADA and PMU measurement functions. SCADA components contribute nonlinear derivatives, while PMU components introduce linear terms. This combined structure improves the conditioning of the Jacobian matrix, leading to better convergence characteristics and reduced computational complexity.

5.5 Solution Algorithm

The estimation problem is solved using an iterative numerical technique.

5.5.1 Iterative Newton-Based Solution

The WLS problem is solved using the Newton-Raphson iterative method. At each iteration, the state vector is updated based on the residual error and Jacobian matrix. The process continues until the difference between successive estimates becomes sufficiently small.

5.5.2 Convergence Criteria

Convergence is achieved when the norm of the state update vector falls below a predefined threshold (e.g., 10^{-4}) or when the maximum number of iterations is reached. The inclusion of PMU data typically reduces the number of iterations required, resulting in faster convergence compared to conventional methods.

6. OBSERVABILITY ANALYSIS

Observability analysis evaluates whether the available measurements are sufficient to estimate all system states accurately.

6.1 Observability Criteria

Observability is determined based on mathematical conditions related to the measurement system.

6.1.1 Rank Condition / Measurement Sufficiency

A system is considered observable if the Jacobian matrix has full rank, meaning that sufficient independent measurements are available to estimate all state variables uniquely. If the rank condition is not satisfied, the system becomes partially observable, leading to estimation inaccuracies. Therefore, ensuring adequate measurement redundancy is essential.

6.2 PMU Placement Strategy

The placement of PMUs significantly influences system observability and estimation performance.

6.2.1 Partial Deployment (20–30%)

Due to cost constraints, PMUs are typically deployed at only 20–30% of buses. Strategic placement ensures that critical nodes are monitored, maximizing observability while minimizing installation cost. Even partial deployment can significantly improve system visibility when combined with SCADA data.

6.3 Hybrid Observability Enhancement

The integration of SCADA and PMU measurements enhances overall system observability.

6.3.1 SCADA + PMU Synergy

SCADA provides wide-area coverage, while PMUs offer high-precision synchronized data. The combination of these sources compensates for individual limitations, resulting in a more comprehensive measurement system.

6.3.2 Observability Index Improvement

The observability index, defined as the percentage of observable buses, improves significantly under hybrid estimation. Typically, it increases from approximately 65–75% (SCADA-only) to 95–100% in the hybrid approach, ensuring near-complete system visibility.

7 RESULTS AND DISCUSSION

This section presents the quantitative evaluation of the three estimation paradigms—SCADA-based, PMU-based, and the proposed Hybrid State Estimation (HSE). The analysis focuses on estimation accuracy, observability, and practical trade-offs. Results are interpreted under realistic conditions including measurement noise and load variability, enabling a fair assessment of each method's suitability for Active Distribution Networks (ADNs).

7.1 SCADA-Based Estimation Results

The SCADA-only estimator serves as the baseline for performance comparison. Its behavior reflects the constraints of low-rate, non-synchronized, and sparsely deployed measurements.

7.1.1 Accuracy Analysis

The voltage magnitude estimation error lies in the range of 2.5–4.8%, while the voltage angle error varies between 1.2° and 2.8°. These relatively high errors stem from nonlinear measurement models, limited redundancy, and higher measurement noise. The estimator's sensitivity to

initialization and network conditions further contributes to dispersion in results, especially under load perturbations.

7.1.2 Observability Performance

System observability using SCADA data alone is limited to approximately 65–75% of buses. The sparse placement of meters leads to unobservable regions, causing ill-conditioned estimation problems and reduced reliability. Consequently, the estimator may require additional pseudo-measurements or assumptions to achieve solvability, which can introduce bias.

7.2 PMU-Based Estimation Results

PMU-based estimation leverages high-rate, time-synchronized phasor data, significantly improving numerical conditioning and estimation fidelity.

7.2.1 Accuracy Analysis

The voltage magnitude error is reduced to 0.3–1.0%, and the angle error to 0.1°–0.4°. These improvements arise from the linear relationship between phasor measurements and state variables, along with superior measurement precision and synchronization. The estimator exhibits faster convergence and lower sensitivity to initialization.

7.2.2 Observability Dependence on PMU Density

Observability in PMU-only schemes is strongly dependent on device density and placement. With partial deployment, observability may reach ~85–95%, while near-complete coverage typically requires installation at a substantial fraction of buses. This creates a cost-performance trade-off, as higher observability demands increased capital investment.

7.3 Hybrid State Estimation Results

The proposed HSE integrates SCADA and PMU measurements to combine wide coverage with high-accuracy synchronized data.

7.3.1 Accuracy Analysis

The hybrid estimator achieves voltage magnitude errors in the range of 0.6–1.4% and angle errors of 0.2°–0.5°. While slightly higher than PMU-only results, these values represent a substantial improvement over SCADA-only estimation. The inclusion of PMU data reduces nonlinearity and enhances the conditioning of the estimation problem, leading to stable and consistent solutions.

7.3.2 Observability Enhancement

A key outcome of the hybrid approach is the significant increase in observability to approximately 95–100% of buses, even with limited PMU deployment (20–30%). The

complementary nature of SCADA coverage and PMU precision enables near-complete system visibility without requiring full PMU penetration. This directly improves estimation reliability and reduces dependence on pseudo-measurements.

8. CONCLUSION

This research presents a comprehensive investigation into hybrid state estimation (HSE) for Active Distribution Networks (ADNs) by integrating SCADA and synchrophasor (PMU) measurements within a unified Weighted Least Squares (WLS) framework. The study addresses key challenges associated with modern distribution systems, including limited observability, measurement sparsity, and dynamic variability due to Distributed Energy Resources (DERs). Conventional SCADA-based estimation, although cost-effective, was found to exhibit limited accuracy and observability, with voltage errors ranging from 2.5% to 4.8% and observability restricted to 65–75%. In contrast, PMU-based estimation demonstrated superior accuracy but remained constrained by high installation costs and limited deployment.

The proposed hybrid approach effectively combines the wide-area coverage of SCADA with the high precision and synchronization of PMU data. Simulation results on the IEEE 33-bus system confirm that the HSE method significantly enhances performance, reducing voltage estimation errors to 0.6–1.4% and improving observability to 95–100% with only partial PMU deployment. Additionally, the hybrid framework exhibits improved convergence characteristics and computational efficiency due to reduced nonlinearity. Overall, the research establishes that hybrid state estimation offers a practical, scalable, and cost-effective solution for accurate monitoring and control of modern power distribution networks, making it highly suitable for smart grid applications.

9. FUTURE SCOPE OF RESEARCH

Future research can extend this work toward real-time implementation using hardware-in-the-loop (HIL) platforms such as OPAL-RT or RTDS to validate the proposed method under practical operating conditions. Advanced optimization techniques, including genetic algorithms and particle swarm optimization, can be explored for optimal PMU placement to further reduce costs while maintaining observability. Additionally, incorporating unbalanced three-phase modeling would enhance applicability to real-world distribution systems. The integration of machine learning techniques for adaptive state estimation and bad data detection presents another promising direction. Finally, addressing cybersecurity challenges and communication delays in SCADA-PMU data integration will be critical for ensuring robust and secure deployment in future smart grid environments.

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