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Optimal Placement of μPMUs in Distribution Networks with Adaptive Topology Changes

Khaoula Hassini [1,2,3], Ahmed Fakhfakh [2,3] and Faouzi Derbel [1,*]

[1] Department of Electrical Engineering and Information Technology, Leipzig University of Applied Sciences, 04277 Leipzig, Germany; khaoula.hassini@htwk-leipzig.de
[2] Laboratory of Signals, Systems, Artificial Intelligence and Networks (SM@RTS), Digital Research Center of Sfax, Sfax 3018, Tunisia; ahmed.fakhfakh@enetcom.usf.tn
[3] National School of Electronics and Telecommunications of Sfax, Technopole of Sfax, Sfax 3018, Tunisia
* Correspondence: faouzi.derbel@htwk-leipzig.de

Abstract: With the increasing integration of energy sources and the growing complexity of distribution networks, it is crucial to monitor and early detection of topological changes to ensure grid stability and resilience. Current methods, for optimizing the placement of micro Phasor Measurement Units (μPMUs) focus on achieving observability and efficient monitoring. These algorithms aim to minimize the number of μPMUs needed while maintaining system observability or meeting criteria for observability. However, they may not consider all real-world constraints and uncertainties. In this study, we introduce a strategy for placing μPMUs with the objective of enhancing observability and monitoring capabilities. Our proposed algorithm employs a technique that makes optimal decisions at each step to approximate the global optimum. To determine the locations for μPMUs our algorithm takes into account parameters such as network structure, key nodes, and system stability. One distinguishing feature is its adaptability to distribution networks, including changes, in topology or potential device failures. Unlike classical approaches, our algorithm can continuously provide optimal placement solutions even in evolving network conditions. We have demonstrated that our suggested method achieves better results in terms of observability value and the required number of μPMUs compared to the state-of-the-art. By strategically placing μPMUs, operators can improve system observability, quickly detect and locate faults, and make informed decisions for effective network operations. This research helps improve optimal placement strategies for μPMUs by providing practical and effective solutions to improve distribution network reliability, resilience, and performance in the face of changing dynamics.

Keywords: micro phasor measurement unit; distribution networks; optimal placement; dynamic network; device failures

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1. Introduction

The integration of Phasor Measurement Units (PMUs) in transmission networks brings significant advantages to system control and operation [1]. PMUs provide synchronized measurements of voltage and current phasors across the network, offering a real-time view of the system's dynamic behavior. This synchronized data enables precise monitoring and control of the transmission network, facilitating efficient grid management and decision-making [2,3]. By integrating PMUs, operators gain a comprehensive understanding of system conditions, including voltage stability, phase angles, and power flows. This information empowers operators to detect and respond swiftly to any abnormal conditions or disturbances, such as voltage fluctuations, oscillations, or line overloads [4,5]. With PMUs providing high-resolution data in real time, operators can accurately assess system stability, implement corrective actions promptly, and maintain the reliability and security of the transmission network [6]. Additionally, PMUs enable advanced applications like wide-area monitoring and control systems, enabling system-wide coordination and optimization [7].

Overall, the integration of PMUs in transmission networks offers enhanced control capabilities, improved situational awareness, and better grid reliability, leading to efficient and secure operation of the transmission infrastructure [8,9].

Distribution networks are highly complex and dynamic systems due to the increasing integration of renewable energy sources, the adoption of electric vehicles, and the growing demand for electricity. The presence of distributed energy resources, varying loads, and intermittent renewable generation introduce fluctuations and uncertainties in the system. As a result, accurate monitoring becomes essential to ensure the stability, reliability, and resilience of the distribution network [10,11]. DNs face several challenges and exhibit distinct characteristics compared to transmission networks. DNs typically have a significantly larger number of nodes compared to transmission networks. This is due to the extensive distribution infrastructure required to supply electricity to residential, commercial, and industrial consumers. The large number of nodes poses challenges in terms of network management, control, and coordination [12].

Monitoring the distribution network provides real-time visibility into the system's operational status, allowing operators to detect and address issues promptly. By continuously measuring and analyzing parameters such as voltage, current, power factor, and frequency, operators can identify potential faults, voltage violations, and abnormal operating conditions. Moreover, monitoring enables better load management, optimal utilization of resources, and improved energy efficiency. It allows operators to balance supply and demand, adjust power flows, and optimize energy distribution across the network [13]. This, in turn, reduces losses, enhances power quality, and mitigates the risk of power outages. With the distribution network being a critical link between the transmission grid and end-users, effective monitoring is essential for maintaining a stable and resilient power supply. μPMUs play a crucial role in this context by providing synchronized, high-resolution data that enables advanced monitoring, grid control, and fault detection [14]. The need for online or real-time operation depends on the specific goals of the μPMU placement, the level of automation and adaptability required, and the operational characteristics of the power grid being monitored. In many cases, a combination of offline planning and periodic online adaptation suffices to maintain an effective and efficient placement of μPMUs while ensuring observability and reliability in the power grid. The choice between offline and online placement depends on the specific requirements and characteristics of the grid being monitored.

The PMUs, located within the Distribution Networks (DNs) highlight their smaller scale and localized monitoring capabilities. They are valuable assets in distribution networks [15]. The deployment of μPMUs brings significant advantages to grid monitoring and control at the distribution level. μPMUs offer real-time and synchronized measurements of voltage and current phasors, enabling operators to gain a comprehensive understanding of the network's dynamic behavior [16]. By incorporating PMUs, operators can precisely monitor key parameters such as voltage magnitude, phase angles, frequency, and power quality at different locations within the distribution grid. This real-time visibility allows for rapid detection of voltage fluctuations, power imbalances, harmonics, and other disturbances that may impact the grid's performance and reliability. With μPMUs providing high-resolution data, operators can quickly assess the network's condition, identify potential issues, and implement appropriate corrective measures [17]. μPMUs also facilitate fault detection, localization, and isolation, contributing to faster restoration times and improved overall grid resilience. Furthermore, the integration of PMUs supports advanced grid control applications, such as volt/VAR optimization, power flow analysis, and demand response management, enabling more efficient utilization of resources and enhanced system operation. Overall, μPMUs in distribution networks offer improved monitoring, control, and optimization capabilities, leading to a more reliable and resilient distribution grid [9,18].

Given a large number of nodes in distribution networks, it becomes essential to determine an optimal placement strategy for a limited number of μPMUs. The objective is to strategically position the PMUs in a way that ensures effective monitoring and observability of the network while minimizing the number of PMUs required. The optimal placement of μPMUs helps overcome the challenge of limited resources by maximizing the coverage and observability of the network with a minimal number of PMUs. This approach enables operators to monitor key points in the distribution network, detect abnormalities, and make informed decisions for efficient system operation, fault detection, and quick restoration. Additionally, the optimal placement of μPMUs facilitates cost-effective deployment by minimizing the investment required for μPMUs and their associated communication infrastructure. It ensures that the limited number of μPMUs are strategically positioned to provide the maximum benefit in terms of network monitoring and control.

Existing algorithms for the optimal placement of μPMUs in distribution networks have made significant contributions to enhancing system observability and fault detection [19]. These algorithms utilize various optimization techniques, such as heuristic algorithms [20], mathematical programming [21], and machine learning to identify the optimal locations for μPMU placement. They consider factors like load characteristics, fault history, and system observability requirements. However, these algorithms have certain limitations. They often rely on simplified network models, which may not accurately represent the complexity of real-world distribution networks. Additionally, some algorithms focus solely on minimizing the number of PMUs without considering other important factors, such as cost, communication infrastructure, and cybersecurity. Furthermore, the existing algorithms may not adequately account for dynamic changes in the network, such as variations in load patterns, distributed generation integration, or device failure. Thus, there is a need for advanced algorithms that can address these limitations and provide more robust and adaptive solutions for the optimal placement of μPMUs in distribution networks [18].

In this context, our algorithm for the optimal placement of μPMUs in distribution networks will take into account topology changes in the network and the possibility of device failure. Unlike existing algorithms, which may overlook these factors, our algorithm aims to provide a more comprehensive and adaptive solution. By considering both dynamic changes and device failure, our algorithm will provide a more robust and adaptive solution for the optimal placement of μPMUs in distribution networks. This will result in enhanced monitoring, control, and reliability of the network, enabling efficient operation and effective response to system changes and potential failures. Distribution systems in power grids often contain various switches that can change the system's structure dynamically. These switches are used for the purpose of reconfiguring the distribution network, managing faults, optimizing performance, and ensuring the reliability of electricity supply to end-users. When a switch is open, it may isolate certain parts of the distribution network, creating new branches or altering the topology. This dynamic nature of the network due to switch status changes can significantly impact the observability of the system. Our algorithm takes these topology changes into account and performs a thorough evaluation to determine the most optimal placement of μPMUs considering the network's current configuration. The combined consideration of open switches and device failure allows our algorithm to dynamically adapt to changing network conditions and uncertainties. It continuously evaluates and adjusts the placement of devices, ensuring optimal observability and monitoring capabilities even in the presence of topology changes and potential device failures. By addressing both open switches and device failure, our algorithm provides a more comprehensive and robust approach to optimize the placement of devices in distribution networks. This feature distinguishes our method from conventional approaches, making it well-suited for real-world applications where network dynamics and uncertainties are critical factors in the decision-making process.

Our optimal placement algorithm for μPMUs stands out for its adaptive approach, adjusting PMU locations to accommodate changing network topologies caused by device failures and open switches. This algorithm prioritizes grid observability under diverse conditions. Its robustness is evident in its consideration of worst-case scenarios.

Addressing communication security issues and noise interference is essential for maintaining the reliability and trustworthiness of μPMU measurements and, by extension, the effectiveness of the power grid monitoring system [22,23]. Robust security measures and data quality assurance techniques are critical components of a resilient and accurate monitoring infrastructure [24,25]. The algorithm identifies candidate locations for μPMUs based on network observability objectives. Thus, these locations provide good network coverage while minimizing the impact of noise interference. At each step of the greedy algorithm, the location of the next μPMU is determined based on the scoring function. The algorithm prioritizes sites with the highest scores, indicating better data quality and less noise interference. Additionally, the algorithm adds redundancy to the placement by placing multiple μPMUs in critical areas, such that the μPMUs are strategically distributed to maximize data quality and redundancy.

This paper presents the results and analysis of the proposed algorithm using the IEEE 7-bus, 9-bus, 13-bus, 34-bus, 37-bus, and 123-bus standard systems. To account for topology changes, our algorithm takes into consideration the presence of open switches in the network. By considering the state of these switches, we ensure an accurate representation of the network's dynamic topology. A comparison of the proposed method with previous methods shows that our approach allows us to obtain a higher System Observed Repeat Index (SORI), which indicates the effectiveness of the μPMUs in providing complete observability of the power system, with a minimal number of μPMUs.

The rest of this article is organized as follows. Following the Section 1, in Section 2, we define and explain the micro phasor measurement unit. Then, the Section 3 introduces the state of the art of optimal placement. Moving forward, in Section 4, parameters and challenges of placement algorithms are presented. After that, in the Sections 5 and 6 the proposed algorithm and results are described. Important observations from this work are summarized in the Section 7.

2. Micro Phasor Measurement Unit in Distribution Networks

It should be emphasized that the integration of renewable energy sources can pose challenges to power quality. However, these challenges can be successfully addressed through careful planning and implementation of advanced control strategies. By utilizing advanced technologies, energy storage systems, and smart grid solutions, the adverse effects of renewable energy on power quality can be mitigated, resulting in a dependable and consistent power supply [26,27].

To ensure the reliable and efficient delivery of electricity to end consumers there are some requirements that need to be achieved: Refs. [28–31].

- **Proper Voltage:** Ensuring stable voltage levels at consumers' terminals is essential for the proper functioning of electrical devices and equipment. Voltage variations should remain within acceptable limits, typically ±6% of the rated voltage. This minimizes the risk of equipment damage and malfunction due to voltage fluctuations.
- **Availability of Power on Demand:** The distribution network should be designed to meet consumers' varying power demands promptly. Whether consumers need a small amount of power or a larger supply, the network should be capable of delivering it without interruption.
- **Reliability:** The dependence of various industries and services on electrical power underscores the importance of a reliable distribution network. Interruptions in power supply can lead to production halts, loss of revenue, and inconvenience to consumers. A reliable network is crucial to prevent such disruptions and maintain consistent service.

In this context comes the μPMU is a device used in power systems to measure electrical quantities with high accuracy based on time synchronization. It provides real-time data on voltage, current, phase angles, and frequency, enabling detailed monitoring and analysis of power system behavior (see Figure 1). It has an accuracy angle of 0.01°, total vector error allowance of ±0.05% (precision), angle resolution of 0.002°, and magnitude resolution of

±0.0002%. Its sampling rate is adjustable in the range (of 10–120) samples per second for a 60 Hz system [32,33].

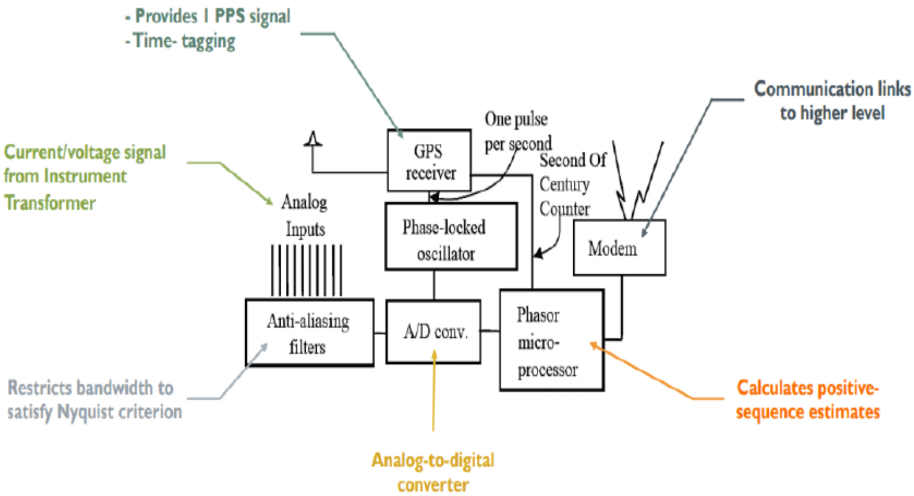

Figure 1. Functional block diagram of PMU.

μPMUs are used for multiple control and diagnostic applications. Data from multiple μPMUs can help us observe, analyze, and understand events. If the data is of sufficient quality, the operator can locate the source of the events [26,34].

3. State of the Art of Optimal Placement

Given the large number of nodes in power networks, it becomes essential to determine an optimal placement strategy for a limited number of PMUs [35]. The objective is to strategically position the PMUs in a way that ensures effective monitoring and observability of the network while minimizing the number of PMUs required [34].

Placement algorithms can be classified into three groups, namely: the heuristic method, the meta-heuristic method, and the deterministic method [36].

The heuristic method, commonly known as an approximation algorithm, is a type of mathematical optimization technique for locating the optimal solution using optimal computing time and memory space. Heuristic methods are often used to speed up the process of finding a reasonable solution when an exhaustive search is impractical [37]. Examples of heuristic methods include the depth-first algorithm, the domination set, etc. [32,36].

The meta-heuristic Method, which is an improvement of the Heuristic Method, involves smart search processes that can treat discrete variables and non-continuous cost functions. Fundamentally, it combines a randomized algorithm and a local optimization algorithm to solve the optimization problem. Two types of Meta-Heuristic Methods that were applied to the OPP problem were the Genetic Algorithm and Particle Swarm Optimisation Method. A deterministic algorithm can be defined as an algorithm capable of predicting behavior. In other words, given a particular input parameter, the system will generate the predicted output. Deterministic algorithms are by far the most studied and familiar type of algorithm, and they can be effectively measured on the TOMLAB Optimization Toolbox [38].

Recursive Quadratic Programming (RQP) is used for optimizing PMU placement in power systems. It allows for a systematic and efficient approach to finding the optimal locations for PMUs, taking into account both observability and controllability objectives while adhering to various constraints. This approach helps enhance the monitoring and control capabilities of the power grid, ultimately contributing to its stability and reliability [1].

The Generalized Pattern Search (GPS) algorithm is a numerical optimization method used to find the minimum (or maximum) of a scalar objective function in a multidimensional space. Adapting GPS for PMU placement allows you to systematically explore the space of potential PMU locations, optimize observability and controllability objectives, and consider cost constraints. It provides a structured approach to solving the complex optimization problem associated with PMU placement in power systems, ultimately enhancing the grid's monitoring and control capabilities [39].

PMU placement algorithms are essential for the efficient and cost-effective deployment of PMUs in power systems. They enable operators to ensure complete observability, enhance system monitoring, detect and locate faults accurately, and support various applications such as state estimation, stability analysis, and control. The choice of the algorithm depends on factors such as system size, complexity, available data, computational resources, and specific requirements of the power system operator [40,41].

Our algorithm for optimal placement of μPMUs based on topology change can be related to existing placement algorithms by considering the dynamic nature of the network. It can incorporate the concept of topology change, which involves adjusting the placement of μPMUs in response to changes in the network configuration. By considering dynamic network conditions and topology changes, our algorithm can provide an innovative and adaptive approach to PMU placement, ensuring effective monitoring and control in a changing power system environment.

4. Placement Algorithms: Parameters and Challenges

For real-time measurements using measuring devices, it is unfeasible to place the devices on every node of a network for the following reasons:

- High cost of measuring devices.
- High implementation costs of the communication infrastructure.

Otherwise, it is possible to calculate the voltage phasors of the nodes without measuring devices installed. It is sufficient that one of its surrounding nodes contains a device installed. This way, if the line impedance is known, it is possible to calculate the voltages of these nodes using Ohm's law. This theory is demonstrated with a simple network of 4 nodes (see Figure 2).

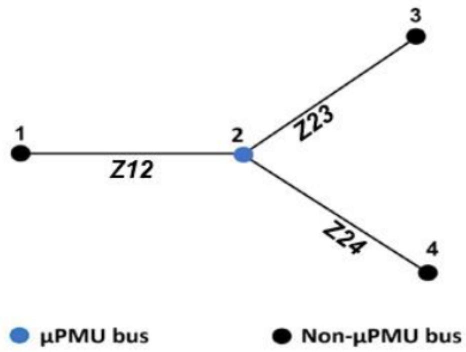

Figure 2. Placement in a 4-Node Network.

A μPMU is only placed on node 2, which is surrounded by nodes 1, 3, and 4, and presents the impedance values of the incident lines at node 2. The μPMU will measure the voltage value V2 of node 2 and the current values of the incident lines. Using (1)–(3), the voltage values, and of nodes 1, 2, and 3 could be calculated.

$$V_3 - V_2 = Z_{23} * I_{23} \tag{1}$$

$$V_4 - V_2 = Z_{24} * I_{24} \tag{2}$$

$$V_1 - V_2 = Z_{21} * I_{21} \tag{3}$$

1. **Key Parameters**
   - Observability
     The optimization method attempts to find out the places with the highest observation. Observability is defined as the ability to uniquely estimate the states of a bus in a power system using certain measurements. Observability analysis is necessary for deciding on the location of the device in order to maintain the solvability of the observation equations under different conditions. An observability constraint vector is used to store information about the observability of the network. Observability can be classified into Numerical Observability and Topological Observability. Observability is evaluated by the Bus Observability Index BOI (β_i) which presents the number of devices that are able to observe a given bus. A bus is said to be observable if its voltage and branch currents are measurable. Consequently, the maximum bus observability index is limited to the maximum connectivity (mc_i) of a bus plus one as presented in (4).

$$\beta_i = mc_i + 1 \quad (4)$$

     where mc is the maximum connectivity and i is the number of the bus.
   - Number of placed devices
     One of the criteria that must be considered in the placement problem is the number of placed devices. The goal of a placement problem is to accomplish this task with as few devices as possible [42].
   - System Observability Redundancy Index (SORI)
     SORI is the total count of observability of a bus by different measuring devices either directly or indirectly. It refers to the number of buses, which achieve observability. Increasing the SORI value helps reduce the uncertainty in measurements. When multiple measurements corroborate each other, it enhances the confidence in the accuracy and reliability of the data, contributing to better observability [42]. The System Observability Redundancy Index β_i for all the busses of a system is presented in (5).

$$\gamma = \sum \beta_i \quad (5)$$

     When the SORI value is higher, it indicates that more of the system will remain visible and more reliable in the event of a device failure [15].

2. **Distribution Network Challenges**
   Many of the placement algorithms have been previously used for transmission systems. Because of the clear difference between transmission and distribution systems in terms of topology and the number of nodes, these algorithms would not lead to optimal results in distribution systems because they did not take into consideration the specifications of distribution networks. In addition, the distribution network is a dynamic system due to the existence of switches in it, which makes the network topology changeable. The placement algorithms of the distribution network should be improved for the following three reasons:
   - Computing time: Distribution systems contain more nodes than transmission systems, resulting in higher compute time in the network.
   - Topology: A radial network is a common configuration in electrical power distribution.
   - Switches: Distribution systems contain switches that make the system structure subject to change.

   Placement algorithms should be optimized by making them consider these characteristics of the distribution system, in order to solve its complexities [38].

5. Proposed Solution

A group of approaches has considered the placement problem as a special case of the maximum coverage problem. In these approaches, the problem is formulated so that a greedy algorithm can produce near-optimal results with approximation boundaries. A greedy algorithm is an algorithmic paradigm that follows the problem-solving heuristic of making the locally optimal choice at each stage with the hope of finding a global optimum. In fact, a greedy algorithm always makes the choice that seems to be the best only at a particular moment. It is a simple, intuitive algorithm that is used in optimization problems. In many problems, a greedy strategy does not usually lead to an optimal solution. The key is to know which problems will work with this approach and which will not. Generally, the problems that could be solved by the greedy technique must exhibit two properties, which are the greedy choice property and optimal substructure. Greedy algorithms are used to solve optimization problems, where local optimal decisions may be used to build a globally optimal solution in a reasonable amount of time [42].

The state of the art in the placement of μPMUs has witnessed significant progress, with advanced methodologies and optimization techniques emerging to enhance the performance of these methods. Traditional placement methods focused on placing μPMUs at strategic locations, such as key substations or transmission lines, to achieve system observability. However, recent research has embraced more sophisticated approaches, leveraging advanced algorithms and computational techniques to optimize PMU placement for enhanced observability and analysis of the power grid. These methods take into account factors such as grid complexity, load variations, and critical system components to determine the optimal locations for μPMUs. They employ optimization algorithms, including convex optimization, genetic algorithms, and particle swarm optimization, to solve the placement problem and find the optimal set of PMU locations. The performance of these state-of-the-art placement methods has demonstrated substantial improvements in system observability, accuracy of state estimation, fault detection, and overall grid resilience [43]. These advancements contribute to a more efficient and effective operation of power systems, enabling enhanced situational awareness, faster fault identification, and improved response to grid events. The new contributions in the placement of μPMUs highlight the potential to optimize the grid monitoring infrastructure and support the transition towards smarter, more reliable power systems.

The key novelty of our method lies in its unique ability to account for both topology changes and device failures in the optimal placement of μPMUs in distribution networks. Unlike traditional approaches that often overlook these dynamic factors, our method offers a comprehensive solution that considers the impact of topology changes and potential device failures on the observability and stability of the grid.

Our algorithm for PMU placement is based on a greedy approach. By utilizing a greedy algorithm for PMU placement, our approach can prioritize the immediate benefits and optimize the placement of PMUs while considering specific criteria or constraints. The proposed optimal placement solution for μPMUs introduces a novel approach that brings new advancements to the field. This solution leverages innovative algorithms, advanced data analytics, and sophisticated optimization techniques to address the challenges associated with PMU placement. What sets this solution apart is its ability to consider multiple factors simultaneously, including system observability, measurement redundancy, cost considerations, and operational constraints, to determine the optimal locations for PMU deployment. By incorporating these factors into the optimization process, the proposed solution aims to achieve enhanced grid observability, more accurate state estimation, efficient fault detection and localization, and improved grid operation. The introduction of this new approach represents a significant contribution to the field of optimal PMU placement, as it offers a comprehensive and effective methodology for the strategic positioning of PMUs within the power grid.

Even though greedy algorithm may find local solutions rather than global ones, there are several merits and considerations specific to the context of µPMU placement in a power system:

- Greedy algorithms are relatively simple to implement and computationally efficient. They often have low time complexity, which is essential for solving optimization problems in large-scale power systems with real-time requirements.
- While greedy algorithms do not guarantee finding the global optimum, they can often find solutions that are near-optimal or good enough for practical purposes. In many cases, near-optimal solutions are sufficient to improve the observability and control of the power system.
- The placement of μPMUs can be a combinatorial optimization problem, which can be computationally intensive. Greedy algorithms can reduce the combinatorial complexity by making incremental decisions based on a local criterion. This can significantly speed up the solution process compared to exhaustive search methods.
- Greedy algorithms can be adapted to incorporate different criteria and constraints, allowing for flexibility in addressing specific power system objectives. For example, we can modify the greedy algorithm to consider cost constraints or communication network limitations.
- The nature of µPMU placement problems may make greedy strategies particularly effective. Depending on the specific problem formulation and objectives, a greedy algorithm may produce solutions that meet the power system's observability and control requirements.

1. **Assumptions**

   The proposed algorithm was developed based on several assumptions concerning both the distribution network and the μPhasor Measurement Units. These assumptions serve as foundational principles for the algorithm's design:

   - The distribution networks under consideration are balanced and are modeled as single-phase power systems.
   - Each μPMU is equipped with multiple channels, enabling them to be connected to all the incident lines. This configuration enables a μPMU to measure the voltage phasor of its own node and the current phasors of the lines connected to it.
   - The impedances of the lines in the distribution network are known. This knowledge of line impedances facilitates the calculation of voltage values for nodes that are not equipped with μPMUs, ensuring a comprehensive understanding of the entire network.

   Modeling distribution networks as balanced and single-phase power systems is indeed more suitable for certain types of applications, particularly residential areas where loads are predominantly single-phase and relatively small. It may be particularly well-suited for apartment buildings or blocks of flats where individual apartments are typically supplied with single-phase electricity. μPMUs can have applications in various settings, including apartment buildings or blocks of flats, although their deployment in such environments may differ from larger-scale power systems. μPMUs can monitor the voltage quality within apartment buildings. They can detect issues such as voltage sags, swells, or harmonics, which can affect the operation of sensitive electronic equipment in residential units. In addition, in areas with distributed energy resources like rooftop solar panels, μPMUs can help assess the stability of the local grid and ensure that energy generation and consumption are balanced.

   These assumptions provide a structured framework upon which the proposed algorithm is built, allowing it to effectively optimize the placement of μPMUs while accounting for the distribution network's characteristics and the capabilities of the measurement units themselves.

2. **Objectives**
   The developed algorithm aims to achieve the following objectives:
   - Achieving full network observability: full network observability entails the installation of μPMUs strategically throughout the distribution network. This strategic placement ensures the measurement and observation of all voltage and current values across the network, resulting in a comprehensive monitoring system. This approach facilitates the accurate analysis and understanding of the behavior of voltage and current quantities at every node within the network.
   - Minimize the number of μPMUs: optimize the deployment of μPMUs in such a way that the total count of these units utilized is minimized. This objective seeks to ensure an efficient and cost-effective solution by strategically selecting only the essential locations for installing μPMUs across the distribution network. By achieving this objective, the monitoring system can effectively capture critical data points while keeping the infrastructure investment and operational costs to a minimum.
   - Achieve a high redundancy index: as indicated by the System Overall Redundancy Index value, this emphasis on SORI underscores the importance of enhancing system reliability and robustness. By attaining a high SORI value, the distribution network becomes better equipped to handle potential failures, ensuring uninterrupted operation even in the presence of disturbances or faults.
3. **Considerations**
   In order to face the real challenges of the distribution network, certain constraints have been taken into account in this algorithm, they are listed below:
   - Topology Change: The existence of switches in the distribution network makes the network dynamic by switching their status from open to close or vice versa. This fact makes the topology of the distribution network changeable, that some nodes of the network could be totally disconnected from the rest of the nodes. This challenge affects directly the placement problem. In fact, μPMUs need to be placed in such a way that complete observability is achieved regardless of the switch (es) status.
   - Devices Failure: Device failure is a possible event that could occur at μPMUs placed on the distribution network for technical or environmental reasons. This event could also affect the complete observability of the system. The goal is to find a location, which has the minimum number of unobserved nodes in the event of a device failure. The key parameter that depends on the number of unobserved nodes in the event of a device failure is the SORI value. The higher the SORI value, the fewer unobserved nodes are reached in the event of a device failure. Taking this constraint into account improves the reliability of the system.
4. **Functioning of the Algorithm**
   The proposed algorithm has the connectivity matrix of the network as input. To consider the topology change of the network, this matrix is built with all switches set to "open" status, which is the worst case.

   To avoid the manual creation of the connectivity matrix, a user interface is used to draw the graph of the desired network and an algorithm would automatically generate the connectivity matrix into an Excel file. This Excel file will be the input of the algorithm.

   The algorithm is composed of a pre-processing step and a greedy algorithm followed by three configurations. The result of this algorithm is the placement of the μPMUs on the network graph as well as the number of, the SORI values, and the nodes where the μPMUs have been optimally placed. The algorithm also detects the location of switches on the network. The block diagram of this algorithm is presented in Figure 3.

A greedy algorithm, by nature, focuses on making locally optimal decisions at each step of a problem-solving process without considering the global consequences. While it may not inherently prioritize data quality assurance. Consider adding redundancy to the placement by placing multiple μPMUs in critical areas. The greedy algorithm can distribute μPMUs strategically to maximize both data quality and redundancy. In each step of the greedy algorithm, select the next µPMU location based on the scoring function. The algorithm should prioritize locations with the highest scores, indicating better data quality and lower noise interference.

Connectivity Matrix

The connectivity matrix is the binary admittance matrix of a power system network and essentially shows which buses are connected to one another (see Algorithm 1). Usually gets the variable A, and its mathematical definition is defined in (6).

$$A(i;j) = \begin{cases} 1, \text{ if } i = j \\ 1, \text{ if bus } i \text{ and bus } j \text{ are connected} \\ 0, \text{ otherwise} \end{cases} \tag{6}$$

Algorithm 1: Connectivity Matrix

```
Result: Connectivity Matrix
Variable: int i,j,N; Matrix A;
for i ← 1 to N do
    for j ← 1 to N do
        if i = j then
            A[i, j] ← 1;
        else
            if i and j are connected then
                A[i, j] ← 1;
            else
                A[i, j] ← 0;
            end
        end
    end
end
```

Pre-processing

The aim of this step is to place μPMUs on nodes connected to the final nodes and eliminate the placement on the end nodes because a μPMU placed on an end node could observe only two nodes and a failure of a device, in this case, increase the number of unobserved nodes.

Otherwise, a μPMU placed on nodes connected to an end node would observe three or more nodes. This step improves the SORI value and reduces the search space of the network to provide a faster search for the next steps (see Algorithm 2). As the connectivity matrix is the input of this step, end-nodes and nodes connected to end-nodes must be identified from it.

Greedy Algorithm

Once the μPMUs have been placed on the nodes connected to the end nodes, the greedy algorithm runs.

In the first step of the greedy algorithm, the number of observed nodes of each node except fixed and end nodes is determined. Then the results are presented in the observability matrix O. The fixed and end-nodes get the number 0 in this matrix because no μPMU would be placed on them. The greedy algorithm always takes the first best solution it encounters. The algorithm will therefore place a μPMU on this node then the observability will be tested using the matrix T presented in (7). If the observability is reached, the results will be saved and the greedy algorithm stops here. Otherwise, the algorithm will continue to place on the other nodes that have the greatest number of nodes observed in the matrix O as in Algorithm 3.

$$T(i;j) = \begin{cases} \text{A(i;j), if a } \mu\text{PMU is placed at node j} \\ \text{0, otherwise} \end{cases} \tag{7}$$

After placing the μPMU on the node and calculating the matrix T, the complete observability of the system can be easily tested by following these steps:

- Verification of each row of matrix T.
- Calculate the number of 1 in each row.
- If the number of 1s in each row equals at least 1, then the system is completely observable. The μPMUs placed from the greedy algorithm are unfixed μPMUs and could change their placement in the following steps.

Algorithm 2: Preprocessing

```
Result: μPMUs in nodes connected to End Node
Variable: int x,y,N,l,g,count,t; Matrix A; Table C, output,output1;
for x ← 1 to N do
    for y ← 1 to N do
        if A[x][y] == 1 then
            count ← count + 1;
            C[t] ← y;
            t ← t + 1;
            ;
        end
    end
    t ← 0;
    if count == 2 then
        output1[l] ← x;
        if C[0] ≠ x then
            output[l] ← C[0];
            l ← l + 1;
        else
            output[l] ← C[1];
            l ← l + 1;
        end
    end
    count ← 0;
end
```

Configuration steps

After performing the pre-processing and greedy algorithm, placement is done and observability is obtained. Otherwise, this is not enough, as other key parameters such as the number of μPMU and the SORI value have not yet achieved their best results, compared to the results of other algorithms [35–37]. The configuration steps are performed in order to improve these parameters by achieving the minimum number of μPMUs as possible and the highest value of SORI possible to ensure system workability and minimize implementation costs see Algorithm 4.

- Configuration 1
  The objective of this configuration is to reduce the number of μPMUs installed without affecting the complete observability of the network.
- Configuration 2
  The goal of this configuration is to improve the system observability redundancy

index (SORI) value. This step gives priority to free nodes that have a higher degree than nodes with unfixed μPMUs because a node with a higher degree can observe more nodes and as a result, the SORI value will increase.

- Configuration 3
  This configuration search also for a placement situation where it is possible to remove a μPMU without affecting the complete observability of the system.

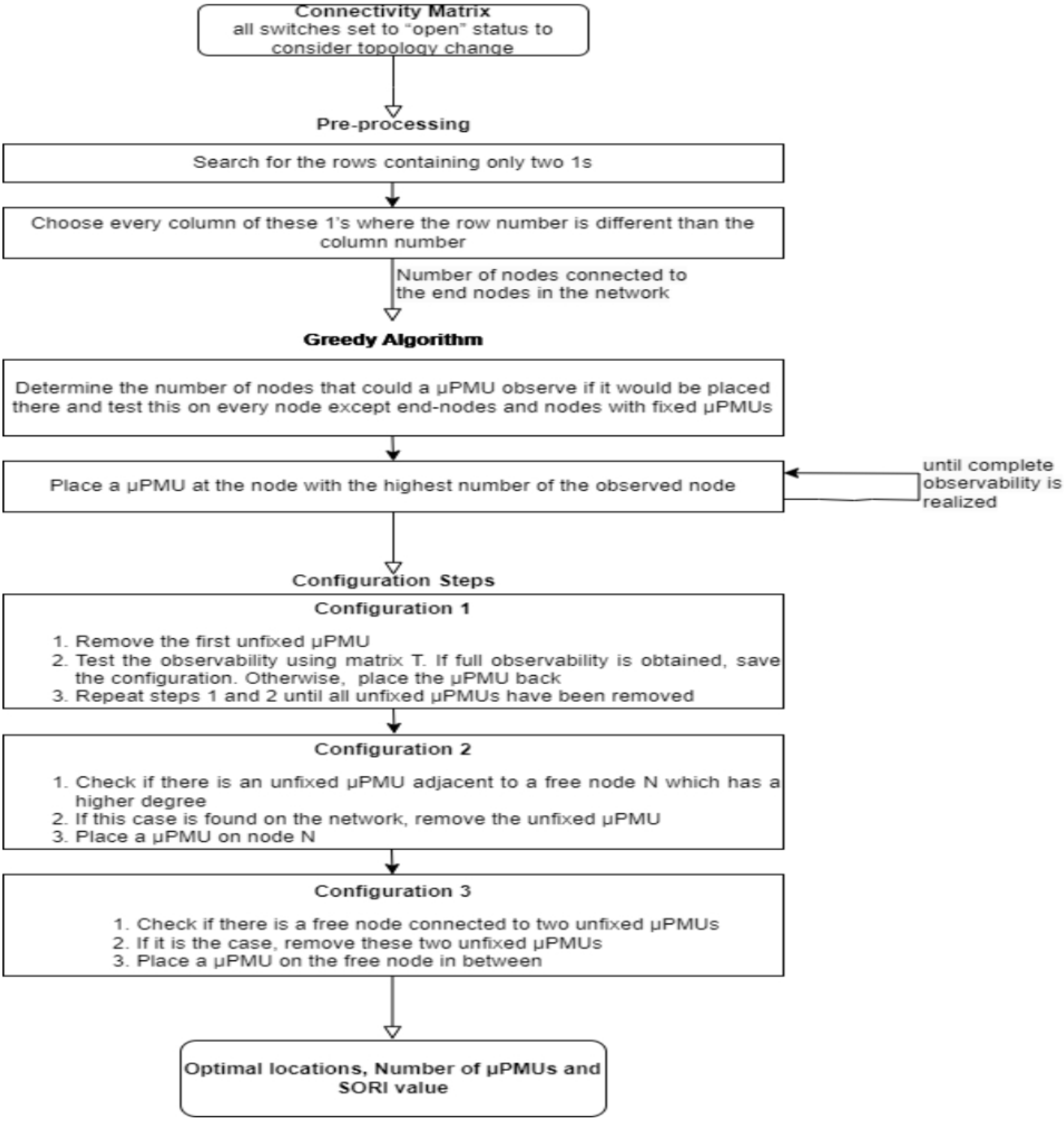

Figure 3. Block diagram of the proposed algorithm.

Algorithm 3: Greedy

```
Result: Unfixed μPMUs
Variable: int x,y,N,l,m; Matrix A,T; Table pmu,output1; boolean Observability;
while observability == False do
    for x ← 1 to N do
        O[x] ← 0;
        if xnotinoutput and fnotinoutput1 then
            for y ← 1 to N do
                if A[x][y] == 1 then
                    m ← m + 1;
                end
            end
        end
        O[x] ← m;
        m ← 0;
    end
    for x ← 2 to N do
        max ← O[1];
        if O[x] > max then
            max ← O[x];
            pmu[l] ← f;
            l ← l + 1;
        end
    end
    for x ← 1 to N do
        for y ← 1 to N do
            if y ≠ pmu[1] or y ∉noutput1 then
                T[x][y] ← A[x][y];
            end
            T[x][y] ← 0
        end
    end
    for x ← 1 to N do
        for y ← 1 to N do
            if T[x][y] == 1 then
                m ← m + 1;
                if m >1 then
                    m ← 0;
                    Observability ← True break;
                else
                    Observability ← False
                end
            end
        end
        if Observability == False then
            break;
        end
    end
end
```

Algorithm 4: Configuration

```
Result: Optimal locations, SORI
Variable: int x,y,N,L,l; Matrix T,T1; Table pmu; boolean Observability;
for l ← 1 to L do
    for x ← 1 to N do
        for y ← 1 to N do
            T1[x][y] ← T[x][y];
        end
        T1[x][pmu[l]] ← 0;
    end
    Check observability ;
    if observability == True then
        T[x][pmu[l]] ← T1[x][pmu[l]];
    end
end
if unfixed μPMU adjacent to a free node N then
    μPMU on node N;
end
if free node connected to 2 unfixed μPMUs then
    μPMU on the free node in-between;
end
```

5. Applications

The proposed method for optimal placement of μPMUs in distribution networks has several practical applications in real-world power system operations and management.

Enhanced Fault Detection and Localization: By strategically placing μPMUs in critical locations, the proposed method improves the observability of the distribution network. This enables rapid detection and precise localization of faults when they occur. With accurate fault information, utilities can quickly dispatch crews to the affected areas, reducing outage durations and improving overall system reliability.

Grid Stability and Resilience: The proposed method ensures better observability of the distribution system, which is crucial for maintaining grid stability and resilience. With the number of μPMUs strategically placed, operators can detect voltage fluctuations, frequency deviations, and other system dynamics promptly, enabling them to take corrective actions to prevent instability or cascading failures.

Distribution Network Planning and Expansion: The placement results obtained from the proposed algorithm can be used for long-term distribution network planning. Utilities can use this information to identify areas with inadequate observability and plan for future expansions or upgrades to ensure grid reliability as the demand for electricity and distributed generation resources increases.

Integration of Renewable Energy Sources: As renewable energy sources (e.g., solar, wind) are integrated into distribution networks, their intermittent nature poses challenges for grid management. The proposed method optimizes the placement of μPMUs to monitor the impact of renewable energy generation, enabling utilities to balance supply and demand efficiently and maintain power quality.

Grid Restoration and Blackout Prevention: In the event of a major grid disruption or blackout, the high observability provided by the optimal placement of μPMUs allows for faster restoration and post-event analysis. Utilities can identify affected areas and assess the system's response during the event, aiding in grid restoration and learning from such incidents for future grid resilience.

6. Results and Analysis

The algorithm has been tested on IEEE 7-Node, IEEE 9-Node, IEEE 13-Node, IEEE 34-Node, IEEE 37-Node Networks. A graphical representation of each network is plotted with the locations of the μPMUs colored in red.

6.1. IEEE 7-Node Network

The IEEE 7-Node network consists of 7 nodes and a switch. One node is a generator bus and the others are load buses. The network includes loads and generators connected to different buses. The loads represent the power consumption at each bus, while the generators represent the power generation (see Figure 4).

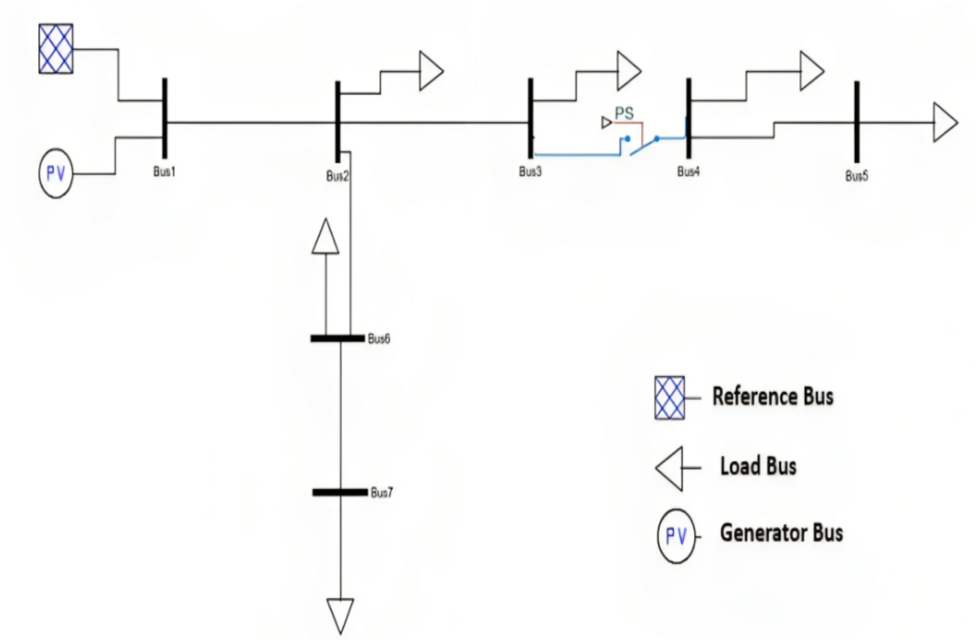

Figure 4. IEEE 7-Node Network design on PSAT Toolbox.

The IEEE 7-Node Network is used as a test case for various power system analysis and optimization problems. Researchers often apply algorithms, such as optimal power flow, state estimation, and observability analysis, to evaluate and validate their performance on this test network. The status of open switches in the distribution network is considered to optimize the placement of devices. Open switches represent the locations where switches are not connected, allowing the network to be reconfigured for different operational scenarios. By analyzing the status of these open switches, we can identify potential locations where μPMUs can be strategically installed to enhance observability and monitoring capabilities. The simulation output can be seen in Figure 5. The algorithm runs on the assumption that the switch is still open so as not to let the change in topology influence the placement results.

The algorithm achieves Observability, the switch is shown in node 4. 3 μPMUs are integrated into nodes 2, 4, and 6 with a SORI value equal to 9.

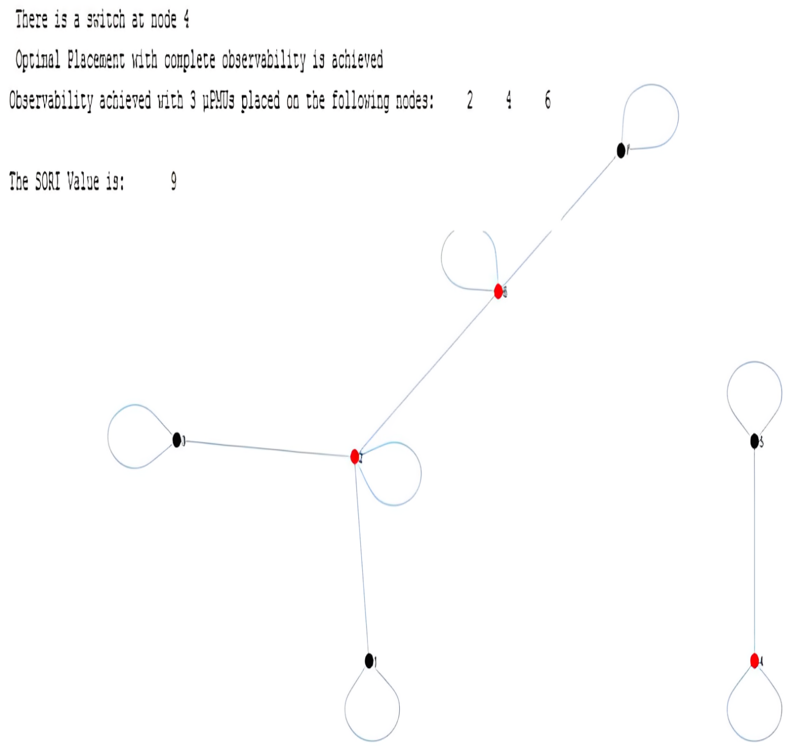

Figure 5. Simulation results on 7-Node Network.

6.2. IEEE 9-Node Network

The IEEE 9-Node Network is comprised of 9 nodes and no switches. One node is a generator bus and the others are load (see Figure 6). The IEEE 9-Node Test System provides a more realistic representation of distribution systems compared to the IEEE 7-Node Network. It includes additional nodes, meshed connections, and distributed generation, making it more suitable for studying various power system analysis and optimization problems specific to distribution networks.

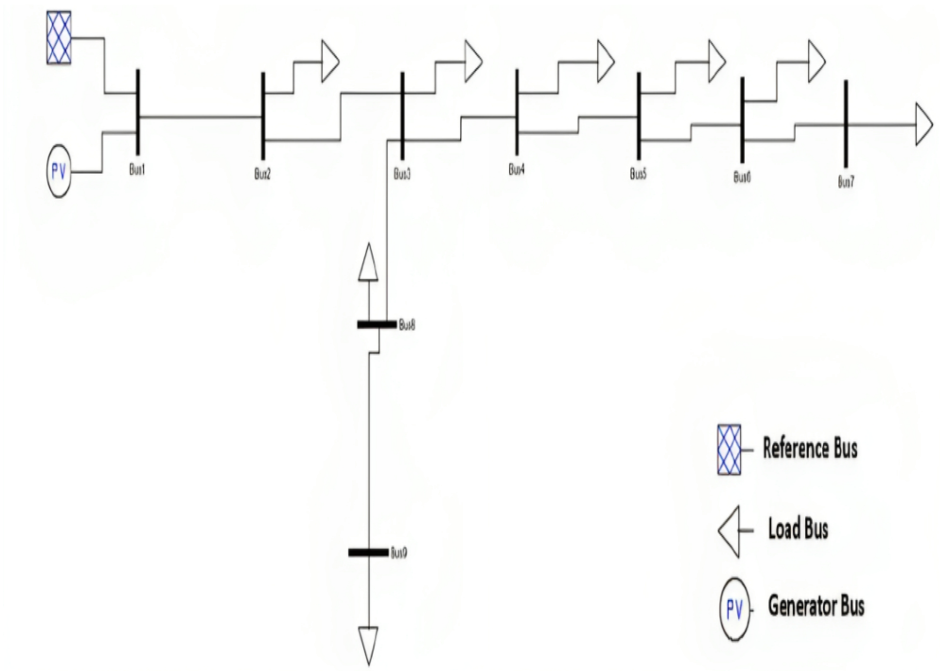

Figure 6. IEEE 9-Node Network design on PSAT Toolbox.

As the goal is also to find a location, which has the minimum number of unobserved nodes in the event of a device failure. So the higher the SORI value, the fewer unobserved nodes are reached in the event of a device failure. In this case, the SORI is equal to 13. And 4 μPMUs are installed in nodes 2, 3, 6, and 8 (see Figure 7).

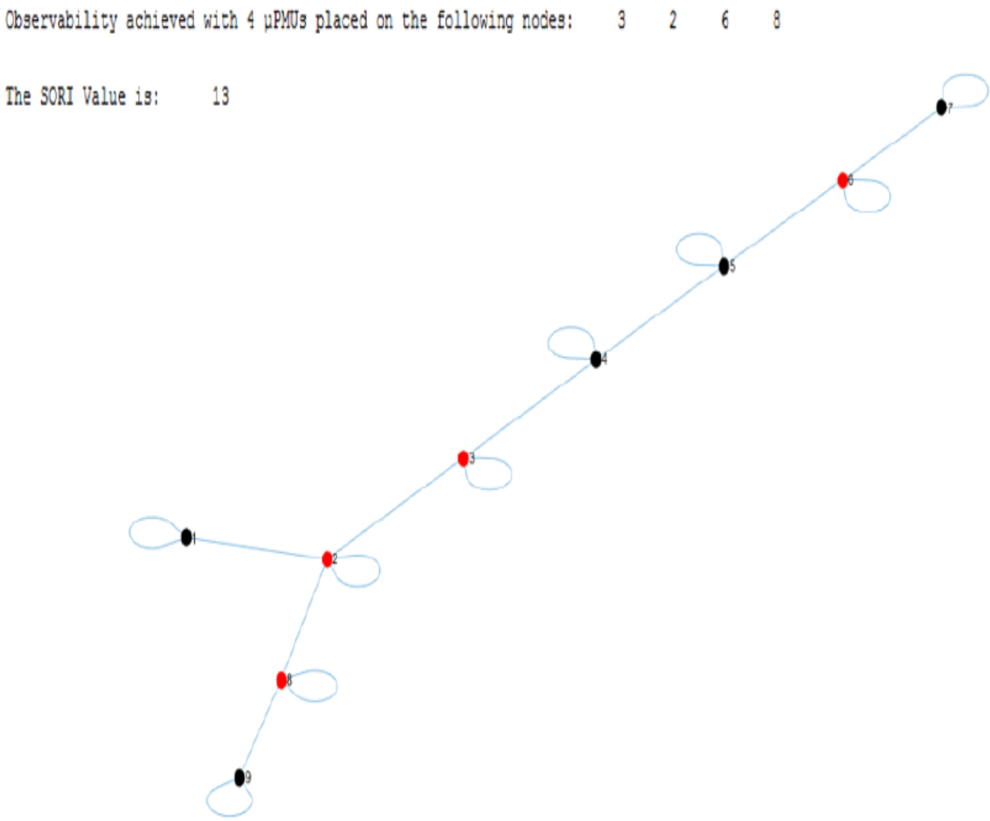

Figure 7. Simulation results on 9-Node Network.

If a device in node 8 malfunctions, 8 nodes are still observed, so more than 88% of the network is observable. Only if the device, which is installed in node 6, malfunctions so 6 nodes are still observed, 66% of the network is observable.

IEEE 13-Node Network

The IEEE 13-Node Network is comprised of 13 nodes and one switch. One node is a generator bus and the others are load buses (Figure 8). The IEEE 13-Node Test Feeder is a widely used benchmark system in the field of distribution system analysis and optimization. It is designed to represent a small-scale distribution network and is commonly used to evaluate the performance of various algorithms and methodologies for distribution system studies. The nodes are connected by distribution lines, forming a radial configuration. Radial distribution networks have power flowing in one direction, from the substation to the loads. The IEEE 13-Node Test Feeder is often used to evaluate various aspects of distribution systems, such as power flow, voltage regulation, fault analysis, and optimization of distributed energy resources.

The output of the simulation can be seen in Figure 9. The algorithm reaches the observability and produces the implementation of 6 μPMUs in nodes 3, 4, 5, 8, 9, and 10, with a SORI value of 20.

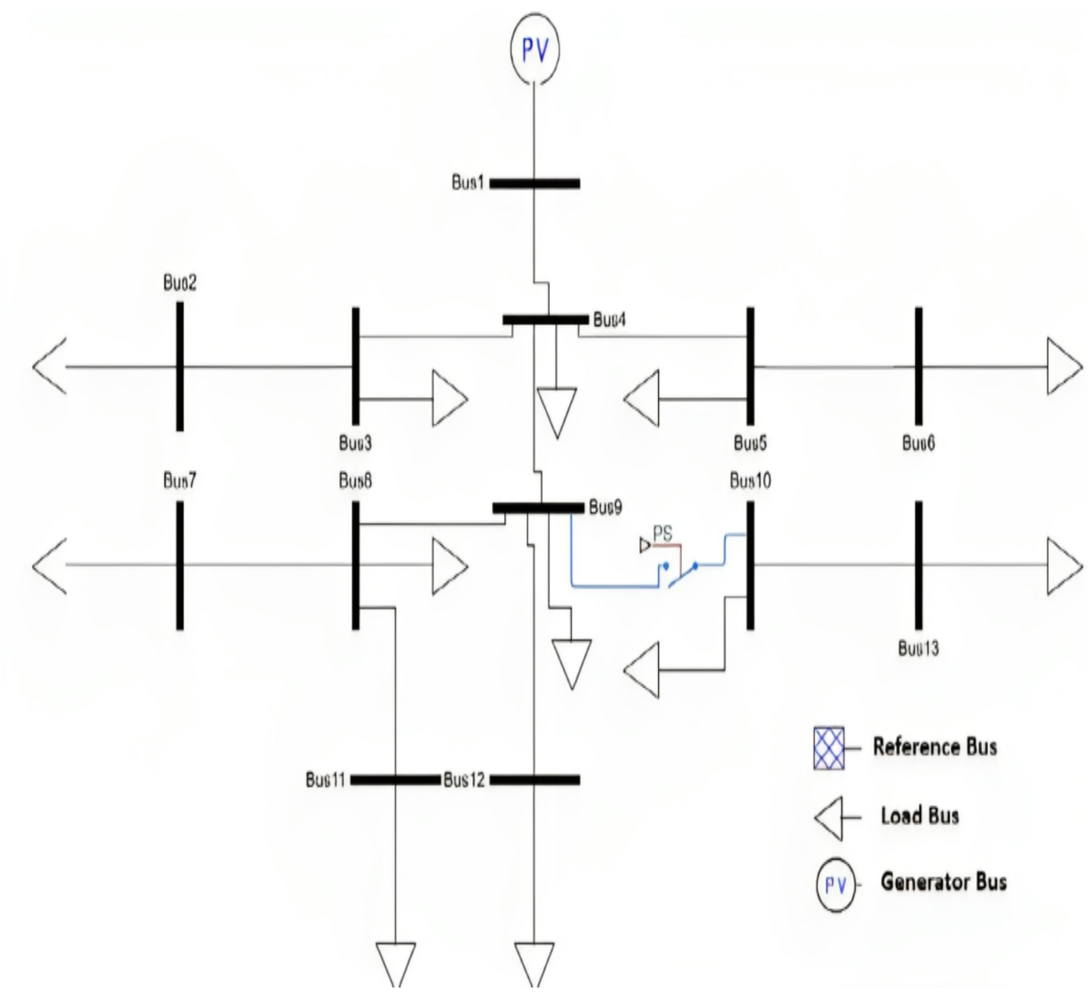

Figure 8. IEEE 13-Node Network design on PSAT Toolbox.

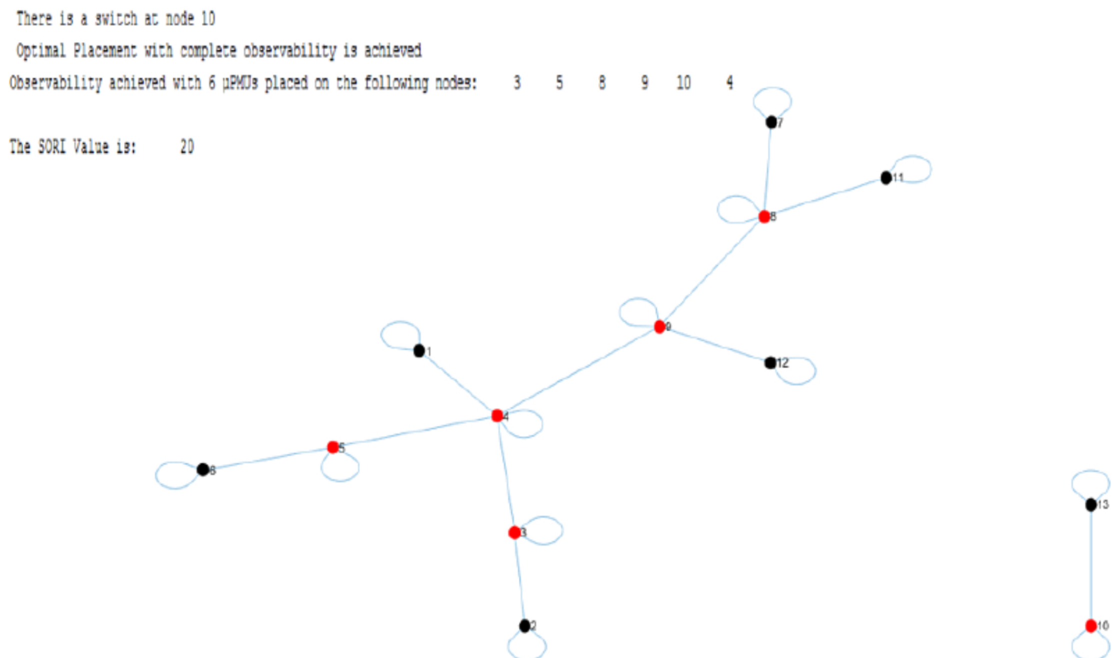

Figure 9. Simulation results on 13-Node Network.

6.3. IEEE 34-Node Network

The IEEE 34-Node Network is comprised of 34 nodes and no switches. One node is a generator bus and the others are load buses (Figure 10). The IEEE 34-Node Test Feeder is another commonly used benchmark system in the field of distribution system analysis and optimization. It is designed to represent a medium-scale distribution network and provides a more complex and challenging test case compared to smaller test feeders like the IEEE 13-Node Test Feeder.

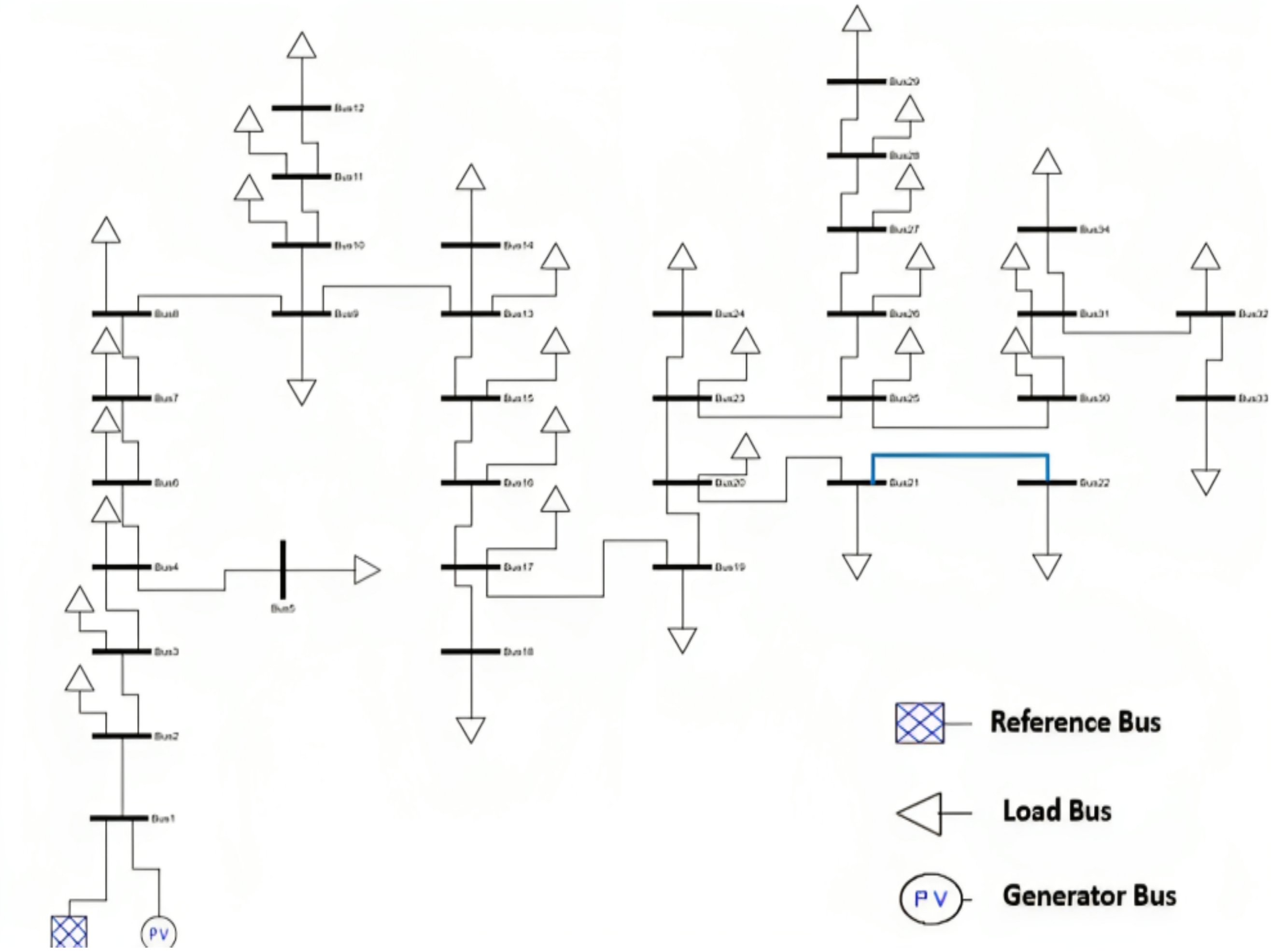

Figure 10. IEEE 34-Node Network design on PSAT Toolbox.

Also in this case, our algorithm takes into consideration both the status of open switches and the possibility of device failure in the distribution network to optimize the placement of devices. The algorithm accounts for the possibility of device failure in the network. Devices, including μPMUs, can experience failures due to various reasons, such as equipment malfunctions or external factors. By factoring in the likelihood of device failures, the algorithm can assess the robustness and reliability of the placement strategy. Only 12 μPMUs are put in nodes 25, 7, 2, 4, 11, 13, 17, 21, 23, 28, 32, and 31, with a SORI value of 42 reached. The simulation output can be seen in Figure 11.

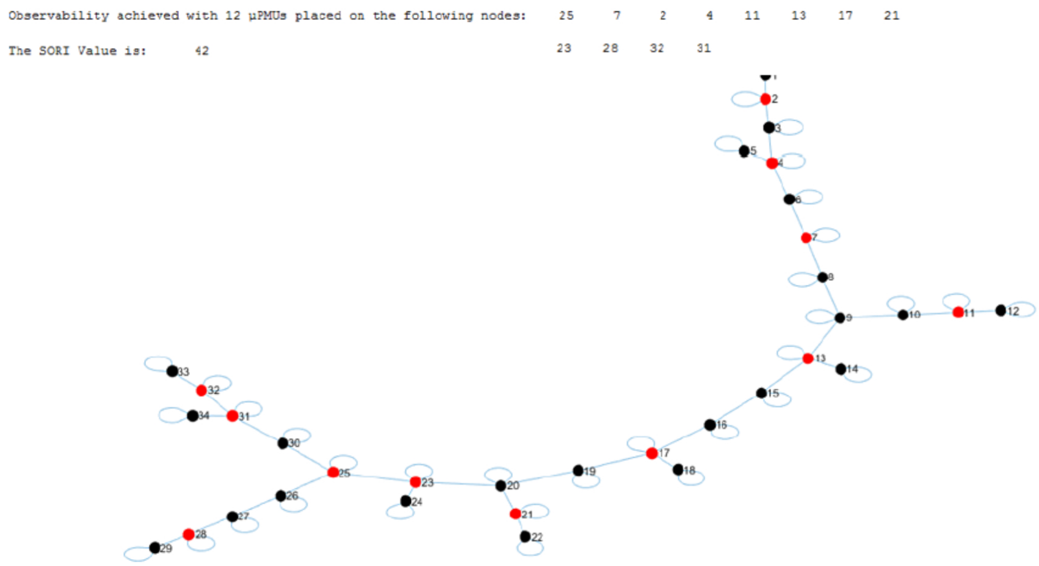

Figure 11. Simulation results on 34-Node Network.

IEEE 37-Node Network

The IEEE 37-Node Network is comprised of 37 nodes and one switch. One node is a generator bus and the others are load buses (Figure 12).

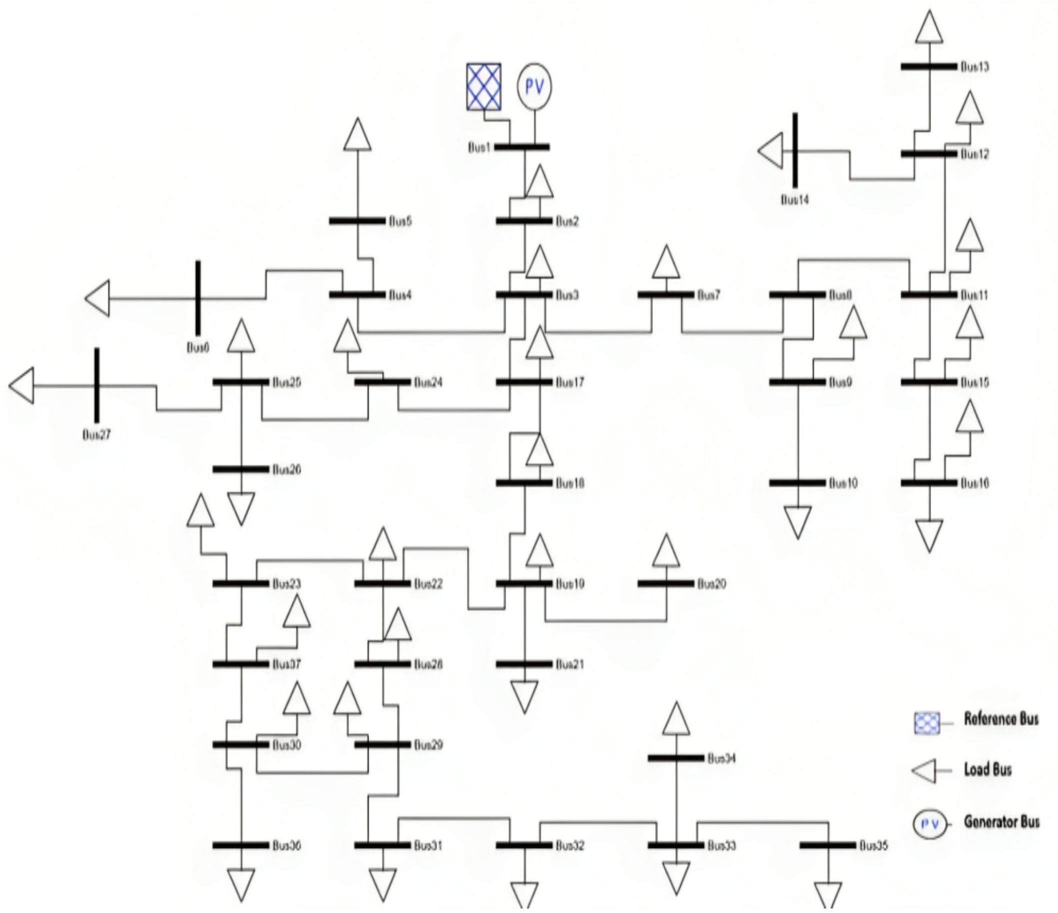

Figure 12. IEEE 37-Node Network design on PSAT Toolbox.

The algorithm reaches the observability and it gives 12 μPMUs implemented in nodes 3, 29, 2, 4, 9, 12, 15, 19, 22, 25, 33, 30. SORI is equal to 46. It accounts for the possibility of device failure in the network. If a device crashes always more than 90% will be observable.

The simulation output can be seen in Figure 13.

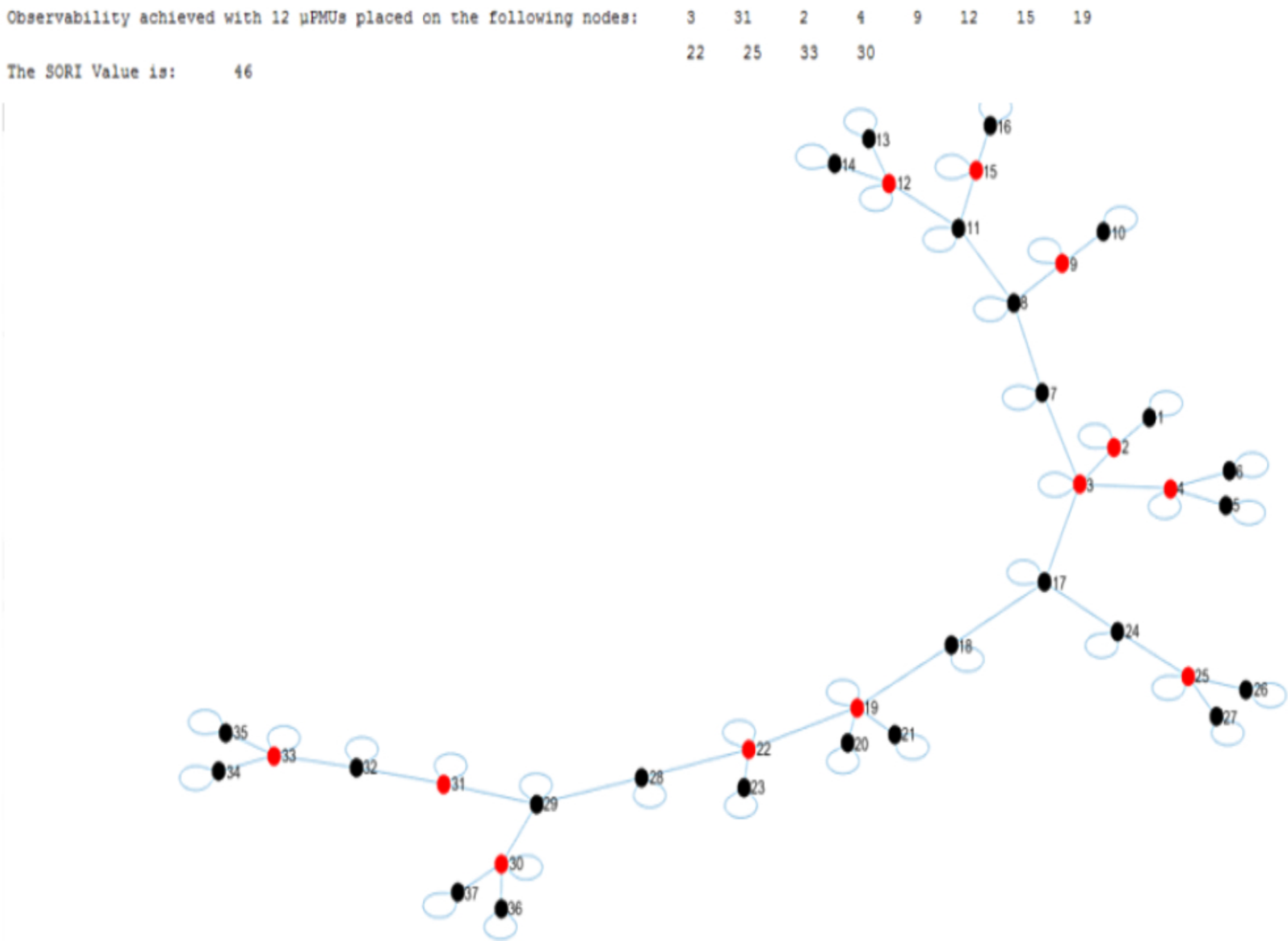

Figure 13. Simulation results on 37-Node Network.

6.4. IEEE 123-Node Network

The IEEE 123-Node Network is comprised of 123 nodes. The feeder includes a variety of loads and distributed generation sources connected to different nodes. Loads represent the power consumption at various locations, while distributed generation represents power generation sources integrated into the distribution system. Its larger size and increased complexity provide a more realistic representation of modern distribution systems, enabling more comprehensive and in-depth studies. The μPMU placement results can be seen in Figure 14, where 48 μPMUs have been used to achieve full observability.

The algorithm outputs give the following results:

- Observability: Achieved
- Number of μPMUs: 48
- Locations of μPMUs: 18, 25, 72, 63, 98, 1, 3, 5, 14, 8, 15, 19, 21, 23, 31, 27, 36, 38, 40, 42, 45, 47, 55, 58, 60, 65, 70, 74, 78, 82, 84, 87, 89, 91, 93, 95, 103, 106, 110, 113, 30, 52, 35, 51, 108, 67, 100, 101
- SORI value: 171

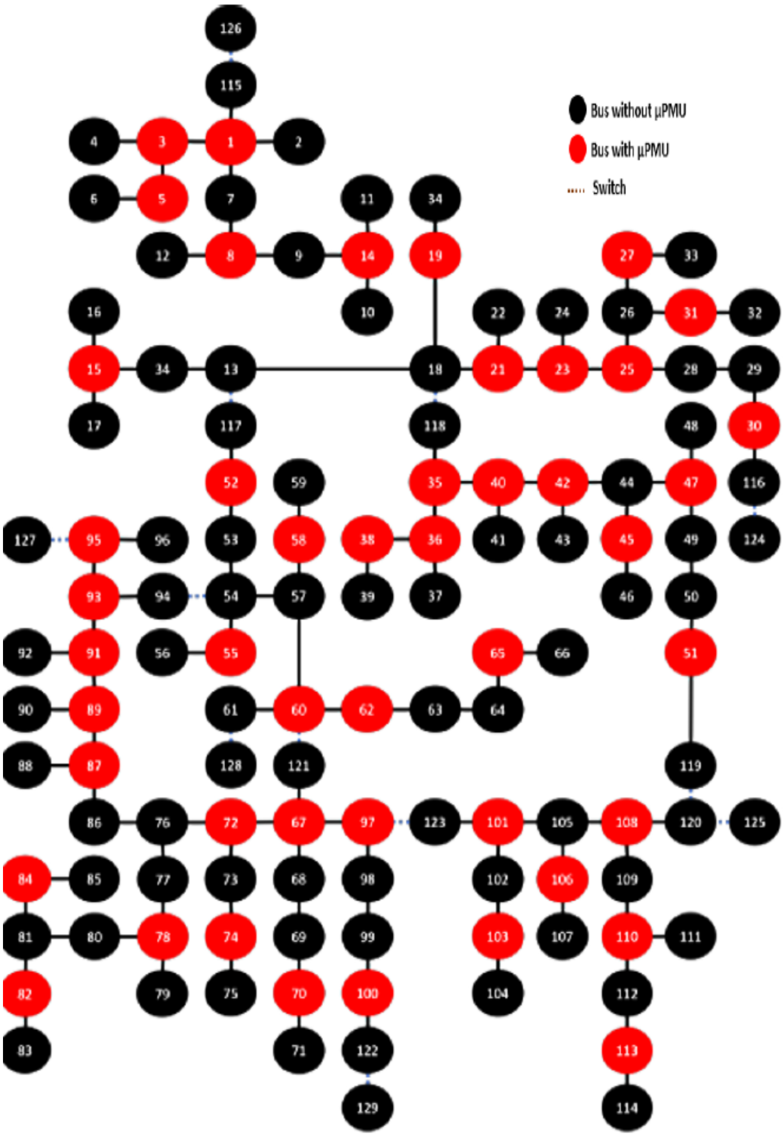

Figure 14. Simulation results on 123-Node Network.

6.5. Comparison with Previous Algorithms

The comparison of our algorithm with other existing approaches was conducted based on a review of the literature in the field of optimal μPMUs placement for distribution networks. We identified and collected relevant research papers, journal articles, conference papers, and technical reports that proposed various μPMU placement algorithms. All the previous algorithms have been tested on a limited number of test feeders. Tables 1 and 2 compare the proposed greedy algorithm with the other algorithms in terms of μPMUs number and SORI value. Our algorithm yields a minimal number of devices with a high SORI value compared to the existing algorithms.

The proposed algorithm demonstrates its superiority over previous works by achieving comparable or improved results in terms of SORI value and the number of μPMUs required. What sets this algorithm apart is its unique capability to consistently achieve optimal results in the majority of tested networks. Unlike other algorithms, it goes beyond relying solely on the connectivity matrix as an input. It takes into account the dynamic nature of the network and considers the effect of topology changes, which has not been addressed by other algorithms. By incorporating the impact of topology changes, the algorithm provides optimal placement solutions. This distinguishing feature makes the algorithm highly valuable, offering enhanced performance and addressing a critical aspect that has been overlooked in previous methods.

Table 1. Comparison in terms of μPMUs number.

Algorithm	13-Node Network	34-Node Network	37-Node Network	123-Node Network
Integer Programming [19,44]	6	13	-	47
Simulated Annealing [41]	5	12	12	-
Graph Theory [40,43]	5	12	12	-
Proposed Algorithm	6	12	12	48

Table 2. Comparison in terms of SORI value.

Algorithm	13-Node Network	34-Node Network	37-Node Network	123-Node Network
Integer Programming [19,44]	16	40	-	147
Simulated Annealing [41]	20	42	47	-
Graph Theory [40,43]	20	42	47	-
Proposed Algorithm	20	42	46	171

The algorithm's performance improves as the number of nodes in a network increases, it aligns with the expectation that larger networks often benefit from more extensive monitoring and optimization efforts. This can be especially valuable for distribution networks, which can be quite extensive and complex in practice.

The placement of μPMUs plays a crucial role in accurately monitoring and analyzing the dynamic behavior of power systems. The results indicate that the chosen placement method has a significant impact on the quality and comprehensiveness of the measurements obtained. By strategically positioning the μPMUs, the method allows for capturing critical information from key points within the power system. This leads to improved observability as in Table 2 and a better understanding of the system's dynamics, enabling more accurate analysis and control. Additionally, the results shed light on the optimal number of PMUs required for achieving desired system observability, striking a balance between the cost of deployment and the accuracy of measurements. The analysis of the results provides valuable insights for power system operators and planners in determining the optimal placement of μPMUs to enhance the monitoring and control of the power grid.

7. Conclusions

In conclusion, this paper presents an optimal placement algorithm for μPhasor Measurement Units in distribution networks. The algorithm addresses the important problem of determining the strategic locations for deploying μPMUs to achieve maximum observability while minimizing the number of units required.

Through extensive testing and analysis, the algorithm demonstrates its superiority over previous approaches. It consistently delivers comparable or better results in terms of the SORI value and the number of μPMUs needed. What makes this algorithm stand out is its consideration of the dynamic nature of the network, particularly the effect of topology changes. Unlike other algorithms, it goes beyond simply relying on the connectivity matrix as an input. By factoring in topology changes, the algorithm ensures optimal results even in evolving network conditions.

The findings of this paper have significant implications for the effective monitoring and control of distribution networks. By strategically placing μPMUs, operators can enhance situational awareness, detect faults promptly, and make informed decisions for efficient system operation. The proposed algorithm's ability to achieve optimal results in most tested networks, while considering topology changes, establishes it as a valuable contribution to the field. This work opens up new possibilities for improving the reliability, resilience, and performance of distribution networks through the optimal placement of μPMUs.

Our future work aims to enhance the robustness, security, and adaptability of μPMU placement algorithms in dynamic distribution networks, and accommodate a wider range of network topologies with different impedance conditions. By integrating continuous noise monitoring, strengthening data security measures, and quantifying cybersecurity metrics, we seek to ensure the reliability of critical power system data. Real-time adaptability to changing communication conditions and delays, combined with the use of hybrid algorithms that balance placement optimality and robustness, will further advance the effectiveness of our approach. As we embrace the evolving landscape of distribution network management, these advancements will contribute to safer and more resilient electrical grids, ultimately benefiting both utilities and consumers.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

μPMU	μPhasor Measuring Unit
REG	Renewable Energy-based Generator
DNs	Distribution Networks
DER	Distributed Energy Resource
SORI	System Observed Repeat Index
LV	Low Voltage
MV	Medium Voltage
PQ	Power Quality
RES	Renewable Energy Sources
EVs	Electric Vehicle
RES	Renewable Energy Sources
ADC	Analog-to-Digital Converter
DSP	Digital Signal Processor
DG	Distributed Generator
SPI	Serial Peripheral Interface
RQP	Recursive Quadratic Programming
GPS	Generalized Pattern Search

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