ADAPTIVE PROTECTION COORDINATION STRATEGY FOR INVERTER-DOMINATED RADIAL DISTRIBUTION SYSTEMS WITH BIDIRECTIONAL POWER FLOW

Amit Kumar Singh[1], Dr. Imran Khan[2]

[1]*Master of Technology, Electrical Engineering (Power System), Azad Institute of Engineering and Technology, Lucknow, India*
[2]*Professor, Department Electrical Engineering (Power System), Azad Institute of Engineering and Technology, Lucknow, India*

---***---

Abstract - *The increasing penetration of inverter-based distributed energy resources (DERs) in modern power distribution systems has significantly altered network characteristics, particularly in radial configurations. Traditional protection coordination schemes, primarily designed for unidirectional power flow and high fault current levels, face major challenges under inverter-dominated conditions. These challenges include reduced and controlled fault currents, bidirectional power flow, relay miscoordination, false tripping, and protection failure. This paper proposes an adaptive protection coordination strategy to address these issues in inverter-dominated radial distribution systems. A standard IEEE 33-bus test system is modeled with varying levels of distributed generation, and detailed simulations are performed using MATLAB/Simulink. The proposed approach dynamically adjusts relay settings, including pickup current and time dial settings, based on real-time system parameters such as voltage magnitude, fault current level, power flow direction, and distributed generation status. Various fault scenarios and operating conditions are analyzed to evaluate system performance. The results demonstrate that the adaptive protection scheme significantly improves relay sensitivity, reduces operating time, and maintains proper coordination compared to conventional protection methods. Additionally, the scheme effectively mitigates issues such as relay blinding and coordination time interval violations under dynamic conditions. The proposed strategy enhances the reliability, selectivity, and efficiency of protection systems, making it suitable for modern smart grid applications with high renewable energy penetration.*

Key Words: **Adaptive Protection, Inverter-Based Resources, Distributed Generation, Bidirectional Power Flow, Relay Coordination**

1. INTRODUCTION

The modern power distribution landscape is undergoing a significant transformation due to the rapid integration of distributed energy resources (DERs), particularly renewable energy sources. Traditional distribution systems were designed as passive networks with predictable operating conditions and unidirectional power flow from centralized generation to loads. However, the emergence of inverter-based technologies and decentralized generation has introduced dynamic and complex operational characteristics. These changes have profound implications for system protection, stability, and control. As a result, conventional protection schemes are increasingly becoming inadequate, necessitating the development of advanced and adaptive protection strategies that can ensure reliable and efficient operation under evolving grid conditions (Lopes et al., 2007; Conti, 2009).

1.1 Background

The evolution of power distribution systems from passive to active networks represents a paradigm shift in the operation and control of modern electrical grids. In conventional systems, power flow was unidirectional, originating from large centralized generation units and delivered to consumers through hierarchical transmission and distribution networks. Protection schemes such as overcurrent relays were designed based on these predictable conditions, relying on high fault current levels and fixed coordination settings.

With the increasing penetration of renewable energy sources such as solar photovoltaic and wind systems, distribution networks have become active in nature. These sources are typically connected through power electronic interfaces, known as inverters, which fundamentally alter system behavior. Unlike synchronous generators, inverter-based distributed generation (DG) provides limited and controlled fault current, significantly affecting fault detection and relay operation. Additionally, the integration of DG introduces bidirectional power flow, where power can flow from consumers back to the grid depending on generation and load conditions. This transition challenges the assumptions of traditional protection schemes and requires more flexible and intelligent protection mechanisms (Ustun et al., 2011).

1.2 Problem Statement

The transformation of distribution systems has exposed critical limitations in conventional overcurrent protection schemes. These schemes rely heavily on high fault current magnitudes and predefined time-current characteristics to ensure proper coordination between primary and backup protection devices. However, in inverter-dominated systems, fault current levels are significantly reduced due to inverter current limiting, making it difficult for relays to distinguish between normal and fault conditions.

One of the major issues arising from this scenario is relay blinding, where upstream relays fail to detect faults because distributed generation supplies a portion of the fault current locally. This reduces the current seen by the relay, leading to non-operation or delayed operation. Another critical issue is false tripping, which occurs when relays incorrectly interpret reverse power flow or transient conditions as faults, resulting in unnecessary disconnection of healthy network sections. Furthermore, relay miscoordination becomes prevalent due to variations in fault current magnitude and direction, disrupting the coordination time interval (CTI) between protective devices. These challenges compromise system reliability, selectivity, and protection performance (Girgis and Brahma, 2001).

1.3 Research Motivation

The increasing penetration of renewable energy sources is one of the primary drivers motivating research in adaptive protection strategies. Governments and utilities worldwide are actively promoting clean energy integration to reduce carbon emissions and enhance sustainability. However, this transition introduces variability and uncertainty in power system operation, necessitating advanced protection solutions capable of handling dynamic conditions.

In addition, the development of smart grid technologies has enabled real-time monitoring and control of power systems through advanced measurement devices such as phasor measurement units (PMUs) and intelligent electronic devices (IEDs). These technologies provide a foundation for implementing adaptive protection schemes that can dynamically adjust relay settings based on real-time system conditions.

Another key motivation is the growing demand for high reliability and stability in modern power systems. The presence of distributed generation, fluctuating renewable output, and bidirectional power flow increases the complexity of system operation, making it essential to ensure fast, accurate, and selective fault detection. These factors collectively drive the need for innovative protection strategies that can enhance system resilience and operational efficiency (Laaksonen, 2010).

1.4 Objectives of the Study

The primary objective of this study is to investigate the impact of inverter-based distributed generation on the fault characteristics of radial distribution systems. This includes analyzing changes in fault current magnitude, direction, and system response under various operating conditions. Understanding these changes is essential for evaluating the performance of existing protection schemes.

Another key objective is to develop an adaptive relay coordination strategy that can dynamically adjust protection settings based on real-time system parameters. This involves designing an algorithm that considers factors such as voltage levels, fault current, power flow direction, and the operational status of distributed generation units to ensure proper coordination between relays.

Finally, the study aims to evaluate the overall system performance by comparing conventional and adaptive protection schemes under different scenarios. Performance metrics such as relay operating time, coordination time interval, and fault detection accuracy are analyzed to demonstrate the effectiveness of the proposed approach. The ultimate goal is to enhance the reliability, selectivity, and efficiency of protection systems in inverter-dominated distribution networks.

2. LITERATURE REVIEW

The rapid transformation of distribution systems due to the integration of distributed generation and inverter-based resources has attracted extensive research attention in recent years. Traditional protection philosophies, originally designed for passive and predictable networks, are increasingly being challenged by dynamic operating conditions such as bidirectional power flow and reduced fault current levels. This section reviews existing literature on conventional protection schemes, the impact of distributed generation, inverter characteristics, emerging protection challenges, and adaptive protection techniques, while also identifying key research gaps that motivate this study.

2.1 Conventional Protection Schemes

Conventional protection schemes have long been the foundation of distribution system protection, particularly in radial networks. Overcurrent protection using Inverse Definite Minimum Time (IDMT) relays is widely adopted due to its simplicity, cost-effectiveness, and ease of coordination. These relays operate based on the magnitude of current, where higher fault currents result in faster operation, enabling selective fault isolation through time grading. Proper coordination between primary and backup relays is achieved by adjusting pickup current and time dial settings, ensuring that the relay closest to the fault operates first.

In addition to overcurrent protection, distance and differential protection schemes are also employed in certain applications. Distance protection operates by measuring the impedance between the relay and the fault location, making it suitable for transmission systems. Differential protection, on the other hand, compares currents at both ends of a protected zone and provides high sensitivity and fast operation. However, these schemes require complex communication infrastructure and are less commonly used in distribution networks due to cost and implementation challenges (Horowitz and Phadke, 2008).

2.2 Impact of Distributed Generation

The integration of distributed generation (DG), particularly renewable energy sources, has significantly altered the operational characteristics of distribution systems. One of the most notable impacts is the variation in fault current levels. Unlike conventional synchronous generators, inverter-based DG contributes limited fault current, leading to reduced overall fault current magnitude in the system. This reduction affects the sensitivity and reliability of protection devices that rely on current magnitude for fault detection.

Another critical impact is the introduction of bidirectional power flow. In traditional systems, power flows unidirectionally from the substation to the loads. However, with DG integration, excess generation can cause reverse power flow toward the grid. This change disrupts the operation of protection devices that are configured for a fixed current direction, leading to incorrect fault detection and coordination issues. These challenges necessitate the re-evaluation of existing protection strategies in modern distribution systems (Brahma and Girgis, 2004).

2.3 Inverter-Based Resource Characteristics

Inverter-based resources (IBRs) exhibit distinct characteristics that differentiate them from conventional generation sources. One of the most important features is their limited fault current contribution, typically restricted to 1.2 to 2 per unit of rated current. This limitation is imposed by the control strategies and thermal constraints of power electronic devices, resulting in lower and more controlled fault currents compared to synchronous generators.

Additionally, inverter operation can be categorized into grid-following and grid-forming modes. Grid-following inverters rely on the existing grid voltage for synchronization and inject current accordingly, making them dependent on a strong grid. In contrast, grid-forming inverters can establish voltage and frequency references independently, supporting system stability in weak or islanded conditions. These operational differences significantly influence system behavior during faults and must be considered in protection design. The controlled and dynamic nature of inverter response complicates fault detection and reduces the effectiveness of traditional protection schemes (IEEE PES, 2020).

2.4 Protection Challenges

The integration of inverter-based distributed generation introduces several complex challenges in protection coordination. Relay miscoordination is a major issue, arising from variations in fault current magnitude and direction. In conventional systems, coordination is achieved through fixed time grading; however, in dynamic environments, this coordination can be disrupted, leading to improper relay operation.

False tripping and relay blinding are also critical concerns. False tripping occurs when relays operate unnecessarily due to reverse power flow or transient disturbances, while relay blinding occurs when reduced fault current prevents relays from detecting faults. Both issues compromise system reliability and can result in unnecessary outages or failure to isolate faults.

Furthermore, dynamic topology changes and islanding conditions add complexity to protection design. The frequent connection and disconnection of distributed generation units alter system configuration, requiring continuous adjustment of relay settings. Islanding, where a portion of the network operates independently from the main grid, poses additional challenges in fault detection and system stability (Laaksonen, 2010).

2.5 Existing Adaptive Protection Techniques

To address the limitations of conventional protection schemes, various adaptive protection techniques have been proposed in the literature. Communication-assisted protection utilizes real-time data exchange between protection devices through advanced communication networks. Technologies such as Phasor Measurement Units (PMUs) and Intelligent Electronic Devices (IEDs) enable synchronized measurements, improving fault detection accuracy and coordination.

Optimization-based relay coordination methods employ algorithms such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) to determine optimal relay settings under varying system conditions. These techniques are effective in handling complex and nonlinear coordination problems, ensuring improved protection performance.

Real-time adaptive relaying represents a more advanced approach, where relay settings are continuously updated based on real-time system parameters. This dynamic adjustment allows protection systems to respond instantly to changes in load, generation, and network topology, enhancing reliability and selectivity in inverter-dominated systems (Zamani et al., 2011).

2.6 Research Gaps

Despite significant advancements in adaptive protection, several research gaps remain. One of the major limitations is the lack of fully developed real-time adaptive frameworks capable of responding to rapid system changes without relying heavily on centralized control. Many existing methods are either partially adaptive or operate under predefined scenarios, limiting their effectiveness in highly dynamic environments.

Another gap is the limited consideration of inverter dynamics in protection design. Most studies assume simplified inverter models and do not fully account for different control modes, such as grid-forming and grid-following behavior, which significantly influence fault characteristics.

Additionally, many adaptive protection schemes depend heavily on communication infrastructure, making them vulnerable to delays, failures, and cyber-security threats. This dependency raises concerns regarding the practical implementation and reliability of such systems in real-world applications. Addressing these gaps is essential for developing robust, efficient, and scalable protection strategies for modern power distribution networks.

3. SYSTEM MODELING AND METHODOLOGY

This section presents the systematic framework adopted to model, simulate, and evaluate the proposed adaptive protection coordination strategy for inverter-dominated radial distribution systems. The methodology integrates power system modeling, fault analysis, relay coordination, and adaptive control to ensure accurate and reproducible results under dynamic operating conditions.

3.1 Overall Research Framework

The overall research framework follows a structured step-by-step approach consisting of system modeling, simulation, analysis, and validation. Initially, a standard radial distribution network is developed to represent real-world operating conditions. Inverter-based distributed generation is then integrated into the system to simulate modern grid scenarios characterized by bidirectional power flow. Load flow analysis is performed to determine voltage profiles and power flow directions under different conditions. Subsequently, fault simulations are carried out to analyze system response and relay performance. Conventional protection coordination is implemented to establish a baseline for comparison. An adaptive protection strategy is then developed and applied, followed by a comprehensive performance evaluation. This sequential methodology ensures logical progression and accurate assessment of the proposed approach (Monticelli, 1999).

3.2 Test System Description

The study utilizes standard IEEE radial distribution test systems, such as the IEEE 33-bus or IEEE 69-bus network, which are widely accepted benchmarks in distribution system research. These systems provide a realistic representation of radial feeders with multiple buses and branches, making them suitable for analyzing protection coordination issues. The network parameters include bus voltage levels, load demands, and line impedance values (resistance and reactance). Assumptions such as balanced loading conditions, steady-state operation, and per-unit system representation are considered to simplify analysis while maintaining accuracy. The use of standardized test systems ensures comparability and validation of results with existing studies (Baran and Wu, 1989).

3.3 Modeling of Inverter-Based Distributed Generation

The modeling of inverter-based distributed generation (DG) is a critical component of this research. A solar photovoltaic (PV) system is considered as the primary DG source, consisting of a PV array, DC-DC converter, and voltage source inverter (VSI). The inverter operates under a grid-following control strategy, synchronizing with grid voltage using a phase-locked loop and injecting controlled current into the network. During fault conditions, the inverter limits its current output to protect semiconductor devices, typically within 1.2–2 per unit of rated current.

The placement of DG units is carried out at selected buses, such as mid-feeder and remote-end locations, to evaluate their impact on system performance. Different penetration levels (e.g., 20%, 40%, and 60% of total load) are considered to simulate varying degrees of renewable integration. This modeling approach captures the dynamic behavior of inverter-based resources and their influence on protection coordination (Blaabjerg et al., 2006).

3.4 Load Flow Analysis

Load flow analysis is performed to determine the steady-state operating condition of the distribution system. The Backward/Forward Sweep (BFS) method is employed due to its computational efficiency and suitability for radial networks with high R/X ratios. In the backward sweep, branch currents are calculated from load nodes toward the source, while in the forward sweep, bus voltages are updated from the source to the end nodes.

Three operating scenarios are considered: the base case without distributed generation, where power flow is unidirectional; the DG-integrated case, where local generation modifies voltage profiles and introduces mixed power flow; and the high penetration case, where reverse power flow occurs due to excess generation. These scenarios provide a comprehensive understanding of system behavior under different operating conditions (Teng, 2003).

3.5 Fault Modeling

Fault modeling is conducted to analyze system behavior under abnormal conditions and evaluate protection performance. Various types of faults are considered, including single line-to-ground (SLG), line-to-line (LL), double line-to-ground (LLG), and three-phase faults. These fault types represent common disturbances in distribution systems and provide a comprehensive basis for analysis.

Faults are applied at different locations along the feeder, including near the source, mid-feeder, and remote-end buses, to assess the impact of fault location on current magnitude and relay operation. Key fault parameters such as fault resistance and fault inception time are varied to simulate realistic conditions. Higher fault resistance results in lower fault current, making detection more challenging, while variation in inception time affects transient response. This detailed fault modeling ensures accurate evaluation of protection schemes (Anderson, 1999).

3.6 Conventional Protection Scheme

The conventional protection scheme is based on overcurrent relays using Inverse Definite Minimum Time (IDMT) characteristics. These relays operate according to a predefined time-current relationship, where higher fault currents lead to faster operation. Key parameters such as pickup current and Time Dial Setting (TDS) are configured to achieve coordination between primary and backup relays.

Relay coordination is achieved through time grading, ensuring that the relay closest to the fault operates first, followed by upstream relays with a time delay. However, in the presence of distributed generation, this coordination is adversely affected due to reduced fault current levels and bidirectional power flow. As a result, issues such as delayed operation, miscoordination, and false tripping are observed, highlighting the limitations of conventional schemes in modern distribution systems (Gers and Holmes, 2004).

3.7 Proposed Adaptive Protection Strategy

The proposed adaptive protection strategy aims to overcome the limitations of conventional schemes by dynamically adjusting relay settings based on real-time system conditions. Adaptive relaying enables continuous monitoring and updating of protection parameters to maintain sensitivity, selectivity, and coordination under varying operating scenarios.

Key input parameters for the adaptive scheme include bus voltage magnitude, fault current level, power flow direction, and the operational status of distributed generation units. These parameters provide critical information about system conditions and are used to modify relay settings accordingly. By incorporating these inputs, the adaptive strategy ensures accurate fault detection and reliable coordination even in the presence of inverter-based generation and bidirectional power flow (Horowitz and Phadke, 2008).

3.8 Adaptive Algorithm Development

The adaptive protection algorithm is designed to adjust relay parameters such as pickup current and Time Dial Setting (TDS) in real time. The relay setting adjustment logic is based on predefined rules and system conditions, ensuring optimal performance under both normal and fault scenarios. A flowchart representation of the adaptive mechanism is developed to illustrate the sequence of operations, including data acquisition, condition evaluation, and parameter updating.

Mathematically, the relay operating time is determined using the IDMT equation, where TDS and pickup current are dynamically updated based on system inputs. The algorithm ensures that coordination time intervals are maintained while minimizing relay operating time. This combination of logical decision-making and mathematical formulation enables the adaptive scheme to respond effectively to dynamic system behavior, improving overall protection performance (Blackburn and Domin, 2014).

4. RESULTS AND DISCUSSION

This section presents a comprehensive analysis of the simulation results obtained for the inverter-dominated radial distribution system. The performance of the system is evaluated under different operating conditions, including the base case without distributed generation (DG), DG-integrated scenarios, and the application of both conventional and adaptive protection schemes. Key parameters such as voltage profile, fault current levels, relay operating time, and coordination performance are analyzed to assess the effectiveness of the proposed adaptive protection strategy.

4.1 Base Case Performance (Without DG)

Under the base case condition, the distribution system operates as a conventional radial network with unidirectional power flow from the source to the loads. The voltage profile exhibits a gradual decline from the substation to the remote-end buses due to line impedance and load demand. This behavior is typical of radial systems and reflects stable operating conditions.

Fault current levels in the base case are relatively high, as they are primarily supplied by the main grid supported by synchronous generators. These high fault currents enable protective relays to clearly distinguish between normal and fault conditions, ensuring reliable operation. As a result, proper relay coordination is achieved through predefined settings, with primary relays operating quickly and backup relays responding with appropriate time delays. The coordination time interval (CTI) remains within acceptable limits, confirming effective protection performance in traditional operating conditions.

4.2 System Performance with Distributed Generation (DG)

The integration of inverter-based distributed generation significantly alters system performance. One of the key observations is the improvement in the voltage profile across the network. DG units supply power locally, reducing voltage drops along the feeder and enhancing voltage stability, particularly at buses located farther from the source.

However, the presence of DG introduces bidirectional power flow, especially when local generation exceeds load demand. In such cases, power flows from the DG units toward the upstream network, reversing the traditional flow direction. This reversal complicates the operation of protection devices that are designed based on fixed current direction assumptions.

Additionally, fault current levels are reduced due to the current-limiting behavior of inverter-based sources. Unlike conventional generators, inverters contribute limited fault current, resulting in lower overall fault current magnitude throughout the system. This reduction directly impacts the sensitivity and effectiveness of protection devices, making fault detection more challenging.

4.3 Performance of Conventional Protection Scheme

The performance of the conventional protection scheme deteriorates significantly in the presence of distributed generation. One of the primary issues observed is the increase in relay operating time. Due to reduced fault current levels, inverse-time overcurrent relays take longer to operate, leading to delayed fault clearance and increased system vulnerability.

Coordination Time Interval (CTI) violations are also observed under DG conditions. Variations in fault current magnitude and direction disrupt the predefined coordination between primary and backup relays, causing the CTI to fall below acceptable limits. This results in improper sequencing of relay operations and potential failure of backup protection.

Furthermore, several protection-related issues are identified, including relay miscoordination, false tripping, and relay blinding. Miscoordination occurs when relays do not operate in the intended order, while false tripping results from incorrect interpretation of reverse power flow as fault conditions. Relay blinding occurs when reduced fault current prevents upstream relays from detecting faults. These issues collectively highlight the inadequacy of conventional protection schemes in modern distribution systems.

4.4 Proposed Adaptive Protection Results

The proposed adaptive protection strategy demonstrates significant improvements in system performance by dynamically adjusting relay settings based on real-time conditions. One of the key advantages of this approach is the ability to modify parameters such as pickup current and Time Dial Setting (TDS) in response to changes in fault current levels, voltage, and power flow direction.

As a result of dynamic relay setting adjustment, the protection system achieves faster fault detection and reduced relay operating time across all locations in the network. This ensures timely fault isolation and minimizes the risk of equipment damage and system instability.

In addition, the adaptive scheme effectively maintains proper coordination between relays by preserving the Coordination Time Interval within acceptable limits. Unlike the conventional scheme, no miscoordination or CTI violations are observed under varying operating conditions. The adaptive approach also eliminates issues such as false tripping and relay blinding, ensuring reliable and selective protection. Overall, the results confirm that the proposed adaptive protection strategy significantly enhances the efficiency, reliability, and robustness of protection systems in inverter-dominated distribution networks.

5. CONCLUSION

This research investigated the challenges associated with protection coordination in inverter-dominated radial distribution systems with bidirectional power flow and proposed an adaptive protection coordination strategy to address these issues. The study demonstrated that conventional protection schemes, designed for unidirectional power flow and high fault current levels, become ineffective in modern distribution networks due to the integration of inverter-based distributed generation. Key issues such as reduced fault current magnitude, relay blinding, false tripping, increased relay operating time, and coordination time interval (CTI) violations were observed under distributed generation conditions.

To overcome these limitations, an adaptive protection strategy was developed that dynamically adjusts relay settings based on real-time system parameters, including voltage magnitude, fault current level, power flow direction, and distributed generation status. The simulation results confirmed that the proposed method significantly improves relay performance by reducing operating time, enhancing sensitivity under low fault current conditions, and maintaining proper coordination between primary and backup relays. The adaptive scheme effectively mitigates miscoordination and eliminates false tripping, thereby ensuring reliable and selective fault detection.

Overall, the proposed adaptive protection coordination strategy enhances the reliability, efficiency, and robustness of distribution system protection. It provides a practical and scalable solution for modern power systems with high penetration of renewable energy sources and supports the transition toward smart grid operation.

5.1. Future Scope of Research

Future research can focus on extending the proposed adaptive protection strategy to more complex network configurations, such as meshed and interconnected distribution systems. Incorporating communication delays, cyber-security concerns, and real-time data uncertainties will improve the practical applicability of the method. The integration of artificial intelligence and machine learning techniques can further enhance adaptive decision-making and predictive fault detection capabilities. Additionally, investigating the impact of advanced inverter control strategies, including grid-forming and hybrid control modes, will provide deeper insights into protection coordination. Hardware implementation using real-time digital simulators or field testing can be conducted to validate the proposed approach under practical conditions. Developing decentralized or communication-independent adaptive protection schemes may also improve system resilience and reliability in future smart grid environments.

REFERENCES

1. Anderson, P.M., 1999. Power System Protection. New York: IEEE Press.
2. Baran, M.E. and Wu, F.F., 1989. Optimal capacitor placement on radial distribution systems. IEEE Transactions on Power Delivery, 4(1), pp.725–734.
3. Blackburn, J.L. and Domin, T.J., 2014. Protective Relaying: Principles and Applications. 4th ed. Boca Raton: CRC Press.
4. Blaabjerg, F., Teodorescu, R., Liserre, M. and Timbus, A.V., 2006. Overview of control and grid synchronization for distributed power generation systems. IEEE Transactions on Industrial Electronics, 53(5), pp.1398–1409.
5. Brahma, S.M. and Girgis, A.A., 2004. Development of adaptive protection scheme for distribution systems with high penetration of distributed generation. IEEE Transactions on Power Delivery, 19(1), pp.56–63.
6. Conti, S., 2009. Analysis of distribution network protection issues in presence of distributed generation. Electric Power Systems Research, 79(1), pp.49–56.
7. Gers, J.M. and Holmes, E.J., 2004. Protection of Electricity Distribution Networks. 2nd ed. London: IET.
8. Girgis, A.A. and Brahma, S.M., 2001. Effect of distributed generation on protective device coordination in distribution system. In: Proceedings of IEEE Power Engineering Society Winter Meeting, pp.115–119.
9. Horowitz, S.H. and Phadke, A.G., 2008. Power System Relaying. 3rd ed. Singapore: Wiley.
10. IEEE PES, 2020. IEEE Guide for Protection of Inverter-Based Resources. IEEE Power & Energy Society.
11. Laaksonen, H., 2010. Protection principles for future microgrids. IEEE Transactions on Power Delivery, 25(4), pp.2910–2918.
12. Lopes, J.A.P., Hatziargyriou, N., Mutale, J., Djapic, P. and Jenkins, N., 2007. Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities. Electric Power Systems Research, 77(9), pp.1189–1203.
13. Monticelli, A., 1999. State Estimation in Electric Power Systems: A Generalized Approach. Boston: Kluwer Academic Publishers.
14. Teng, J.H., 2003. A direct approach for distribution system load flow solutions. IEEE Transactions on Power Delivery, 18(3), pp.882–887.
15. Ustun, T.S., Ozansoy, C. and Zayegh, A., 2011. Recent developments in microgrids and example cases around the world—A review. Renewable and Sustainable Energy Reviews, 15(8), pp.4030–4041.
16. Zamani, M.A., Sidhu, T.S. and Yazdani, A., 2011. A protection strategy and microprocessor-based relay for low-voltage microgrids. IEEE Transactions on Power Delivery, 26(3), pp.1873–1883.