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Review On Machine Learning-Based Adaptive Protection Scheme For Distribution Side Relay Coordination

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ABSTRACT
The increasing penetration of distributed energy resources, renewable energy systems, electric vehicles, and intelligent loads has significantly increased the complexity of modern power distribution networks. Consequently, conventional relay coordination techniques based on fixed settings face challenges in maintaining reliable, selective, and fast protection under varying operating conditions. Recent advances in Artificial Intelligence (AI) and Machine Learning (ML) have introduced adaptive protection strategies capable of improving fault detection, classification, and relay coordination performance. This review paper presents a comprehensive analysis of machine learning-based adaptive protection schemes for distribution-side relay coordination, with particular emphasis on Artificial Neural Networks (ANN) and Support Vector Machines (SVM). Various fault classification techniques, including single line-to-ground (SLG), line-to-line (LL), double line-to-ground (DLG), and three-phase (LLL) faults, are reviewed using electrical parameters such as voltage, current, impedance, and fault location as input features.
Keywords- MG (micro grid), Support Vector Machines and Artificial Neural Networks

I. INTRODUCTION
Conventional power plants, despite their undeniable contributions to electricity generation, carry a multitude of drawbacks that cast a shadow on their presence.1,2 Global warming, limited fossil fuel sources, and exorbitant construction costs stand as formidable adversaries to their sustained existence.3–5 Furthermore, as the physical distance between power plants and load centers widens, the losses incurred in transmission lines grow exponentially, exacerbating the inefficiencies of the system. In response to these pressing concerns, a paradigm shift has occurred, manifesting in the remarkable growth and utilization of DGs within distribution networks over the past few decades.6–8 DGs play a pivotal role by supplying ample power to meet local demand and serving as an auxiliary support to the main grid during 9,10 times of high-power withdrawal [1].

II. TRANSMISSION AND DISTRIBUTION SYSTEM
The power system is an interconnected network designed to generate electricity, transmit it efficiently, and deliver it to load centers for consumer use. For electricity generation and transmission to be effective and economical, the system is divided into three primary subsystems: generation, transmission, and distribution [11]. At generating stations, primary energy sources are transformed into electrical energy, and the generated voltage is increased to transmission levels using step-up transformers. The transmission system carries the power closer to load centers, forming part of the distribution network, where voltage is reduced to

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stepped down for residential, commercial, or industrial applications [2]. Figure 1 illustrates the block diagram of a traditional power system. Electricity is generated as a three-phase supply and is stepped up to high voltage at the power substation. This high-voltage energy is transmitted over long distances via transmission lines. At the distribution substation, the voltage is stepped down to a level suitable for consumption. Transformers facilitate the process of stepping up and stepping down the voltage, after which the electrical power is distributed to various consumers [3].

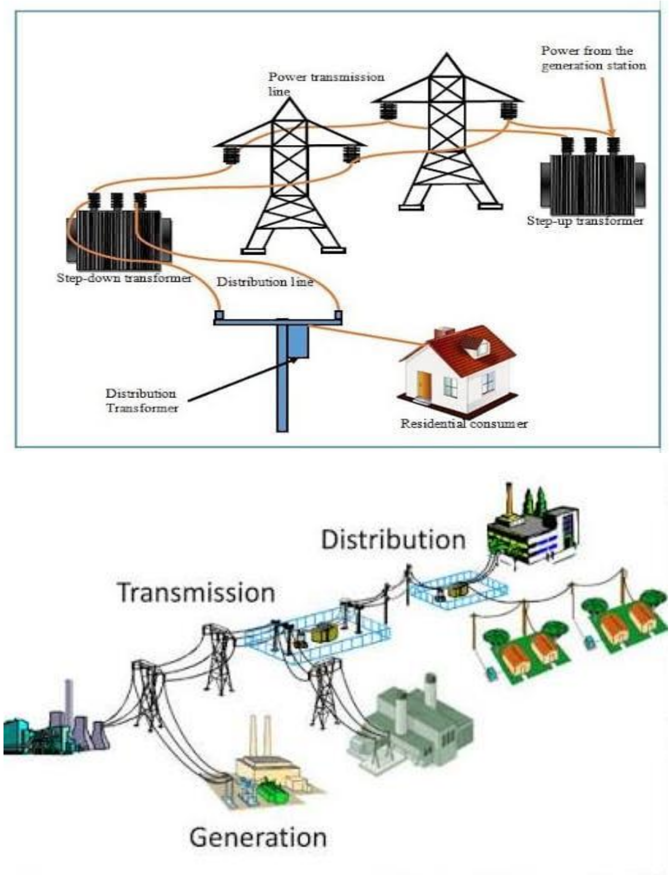

Fig. 1. Transmission and distribution system

III. PROTECTION SCHEMES BASED ON TRADITIONAL PROTECTION PRINCIPLES

This section reviews the MG protection schemes for both grid-connected and islanded modes of operation, which are developed based on the traditional protection principles. Due to the protection challenges as discussed in Section I, the conventional protection schemes are required to be re-designed for MG. The relay protection settings would be different and depends on the operating mode of MG. There are also adaptive protection schemes which are suitable for both grid connected and islanded operating modes [4]. These protection challenges in a MG are addressed through the following protection schemes. The schematics of a grid-connected MG with different components is presented in Fig.2.

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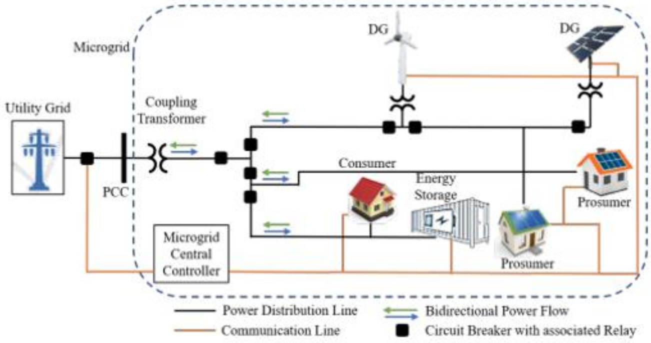

Fig.2. Protection schemes

A. Protection Schemes for Grid-connected Microgrid

1) Current-based Protection Schemes: Current-based protection schemes include overcurrent, differential, current-only directional principles. An adaptive phase current-based protection method is proposed in [5]. The effect of high penetration of DGs on relay coordination is explored first. Subsequently, fault detection is performed using the current contribution information from all the sources, including the main grid. The faulted section is identified by the pre-calculation of Thevenin equivalent impedance of each source for different fault types. A protection strategy is presented in [6] where the MG is not disconnected from the main grid in case of a MG fault. The overcurrent relay performs correctly and selectively clears the fault due to the large fault current supplied by the grid. For a fault on the grid side, the MG gets disconnected and operates in an islanded mode. In case, if a fault occurs within the MG in islanded mode, it is considered as a second fault, resulting in the disconnection of the MG DGs (after a certain time delay) to avoid any undesirable situation. In grid-connected mode, directional overcurrent relay distinguishes the forward and reverse direction faults. For proper coordination, a definite time delay is added in the reverse mode. The negative sequence component of current is incorporated in the directional unit to detect unbalanced faults in MG [7].

2) Voltage-based Protection Schemes:

The three-phase balanced faults do not contain negative and zero-sequence components and thus an undervoltage relay accompanied with a directional element can be used for the protection during the balanced fault [6]. Also, a definite time delay is utilized for coordinated operation in forward and reverse direction of fault [8].

3) Both Voltage and Current based Protection Schemes:

Protection principles based on impedance, reactance, and the directional unit use both voltage and current for the protection decision. Usually, impedance-based protection schemes are deployed for transmission level, but being free from fault calculations, they also find applications in MG protection. An impedance-based protection scheme for MG is discussed in [7]. However, it's performance in a system with multiple tapped feeders is not reliable due to current in-feed.

B. Protection Schemes for Grid-disconnected (Islanded) Microgrid

The subsection discusses the protection schemes where the MG is islanded from the main grid due to any reason. A comprehensive digital protection scheme is proposed in [9] for MGs operating in both grid-connected and islanded modes. The current differential technique is used for line protection. While, overcurrent, undervoltage, negative sequencebased protection functions are used for DG and point of common coupling (PCC) protection. A dynamic adaptive overcurrent relay is presented in [10] for the protection of MG in islanded mode. The relay changes the pickup current settings by using the DG status. A symmetrical component-based protection scheme is proposed in [6], where the fault is detected by obtaining the positive-sequence impedance of the line. Thereafter, the correct faulted section is identified by comparing the upstream and downstream positive sequence impedance during fault and pre-fault conditions. An integrated impedance angle (computed from positive sequence voltage and current phasors) based protection scheme is presented in [7] for MGs in islanded operation. An internal fault is confirmed when the angle is in the range of −5 ◦ to −90◦ ; otherwise, it is treated as an external fault. The rate of change of voltage phase angle of a bus with respect to PCC is used for fault detection in [8]. The method uses a phasor measurement unit (PMU) with IEEE C37.118.1 standard for angle estimation and the rate of angle difference between two buses is an indicator of fault identification. The sum of the phase and neutral currents are used in [9] to detect the fault in MG, where the entire MG is divided into several protection zones, and a circuit breaker is connected between the zones to isolate the minimum part during a fault.

IV. PROBLEM IDENTIFICATION

Modern power distribution systems are becoming increasingly complex due to the integration of distributed generation, renewable energy resources, electric vehicles, microgrids, and dynamically varying loads. These developments have significantly altered power flow patterns and fault characteristics, making conventional relay coordination methods less effective. Traditional protection schemes rely on fixed relay settings determined during system planning, which are unable to adapt to changing network operating conditions. As a result, relay miscoordination, delayed fault clearance, false tripping, and unnecessary outages may occur, reducing the overall reliability and stability of the power distribution system.

Another major challenge is the accurate identification and classification of different fault types, including single line-to-ground (SLG), line-to-line (LL), double line-to-ground (DLG), and three-phase (LLL) faults, under varying load conditions. Conventional overcurrent and distance relays primarily depend on predefined threshold values and deterministic algorithms, which often fail to maintain high accuracy when network topology or operating conditions change. The increasing penetration of inverter-based distributed energy resources further complicates fault detection because fault current magnitudes and directions differ significantly from those in traditional radial distribution systems. Recent studies have demonstrated the potential of Artificial Intelligence (AI) and Machine Learning (ML) techniques for intelligent power system protection. However, most existing research focuses on a single machine learning algorithm or specific fault scenarios, with limited emphasis on adaptive relay coordination under real-time operating conditions. Many reported methods are evaluated using simplified test systems and do not comprehensively compare different ML techniques, such as Artificial Neural Networks (ANN) and Support Vector Machines (SVM), in terms of classification accuracy, relay operating time, selectivity, sensitivity, computational efficiency, and robustness.

Furthermore, the practical implementation of adaptive relay coordination remains a significant challenge due to issues such as feature selection, training data availability, communication delays, computational complexity, and the absence of standardized validation frameworks. There is also a lack of comprehensive MATLAB-based studies that integrate intelligent fault classification with adaptive relay decision-making and evaluate their performance against conventional protection schemes under diverse fault and loading conditions. Therefore, there is a need to develop an intelligent, adaptive, and reliable relay coordination framework capable of accurately detecting and classifying faults, dynamically adjusting relay settings, minimizing relay operating time, improving selectivity and sensitivity, and enhancing the overall reliability of modern distribution systems. Machine learning techniques, particularly Artificial Neural Networks (ANN) and Support Vector Machines (SVM), offer promising solutions to address these challenges by enabling data-driven, real-time protection strategies for next-generation smart distribution networks.

V. RESEARCH MOTIVATION

The rapid transformation of conventional power distribution systems into intelligent smart grids has introduced significant challenges in power system protection. The widespread integration of distributed energy resources (DERs), renewable energy sources, electric vehicles, microgrids, and bidirectional power flow has changed the operating characteristics of distribution networks. These developments have reduced the effectiveness of conventional relay coordination schemes that rely on fixed protection settings and predefined operating conditions. Conventional protection methods are often unable to respond efficiently to dynamic changes in network topology, load variation, and fault characteristics. Relay miscoordination, delayed fault isolation, false tripping, and reduced system reliability have become increasingly common in modern distribution systems. These limitations motivate the need for intelligent protection schemes that can adapt automatically to changing system conditions while maintaining high fault detection accuracy and fast relay operation. Recent advances in Artificial Intelligence (AI) and Machine Learning (ML) have demonstrated significant potential for improving power system protection. Algorithms such as Artificial Neural Networks (ANN) and Support Vector Machines (SVM) are capable of learning complex nonlinear relationships from historical and real-time electrical data, enabling accurate fault detection, classification, and adaptive relay decision-making. Unlike traditional methods, machine learning models can continuously improve their performance through training and can generalize to different operating scenarios without requiring frequent manual adjustment of relay settings.

VI. LITERATURE REVIEW

Sheta et al. [1] proposed a machine learning-based adaptive setting methodology for directional overcurrent relays (DOCRs) with double-inverse characteristics to improve the protection performance of microgrids. The primary objective of the study was to dynamically adjust relay settings according to changing operating conditions caused by distributed energy resources and varying fault levels. Machine learning algorithms were employed to estimate optimal relay parameters while maintaining coordination among protection devices. Simulation results demonstrated improved relay coordination accuracy, reduced operating time, and enhanced system stability compared with conventional fixed-setting approaches. The study concluded that machine learning-based adaptive relay settings significantly improve the reliability and flexibility of modern microgrid protection systems.

Al-Bhadely and Inan [2] proposed an online adaptive relay coordination framework using Deep Neural Networks (DNN) integrated with a hybrid Genetic Algorithm–Sequential Quadratic Programming (GA-SQP) optimization technique. The primary objective was to optimize relay settings in real time under varying operating conditions in distribution systems. The DNN predicted relay parameters, while the GA-SQP algorithm refined coordination settings for minimum operating time and proper relay selectivity. Experimental results showed improved coordination performance, faster fault clearance, and better adaptability than conventional optimization methods. The study concluded that combining deep learning with hybrid optimization provides an efficient solution for adaptive relay coordination.

Elhaffar et al. [3] proposed an adaptive clustering and optimization framework for overcurrent relay protection in power distribution networks with Hardware-in-the-Loop (HIL) validation. The study aimed to improve relay coordination by dynamically grouping network sections and optimizing relay settings under changing system conditions. The proposed method was validated using real-time HIL implementation, demonstrating improved relay response, enhanced selectivity, and reliable fault isolation. The authors concluded that adaptive clustering combined with optimization techniques provides a practical and scalable solution for intelligent distribution system protection.

Chen and Zhang [4] presented a comprehensive review of the communication-oriented evolution of power system relay protection, focusing on emerging communication technologies and intelligent protection architectures. The study examined the role of high-speed communication networks, digital substations, Internet of Things (IoT), and artificial intelligence in modern relay protection systems. The authors identified challenges related to communication latency, cybersecurity, interoperability, and real-time data exchange. The study concluded that future relay protection systems will increasingly depend on communication-assisted intelligent protection strategies to improve system reliability and operational efficiency.

Rahman [5] proposed a Federated Deep Reinforcement Learning (FDRL)-based cooperative relay protection framework for resilient cascade mitigation in smart grids. The primary objective was to enhance relay coordination while preserving data privacy across multiple substations. The proposed federated learning architecture enabled distributed model training without sharing sensitive operational data. Simulation results demonstrated improved resilience against cascading failures, enhanced relay coordination, and better privacy preservation compared to centralized learning methods. The study concluded that federated deep reinforcement learning represents a promising direction for next-generation intelligent smart grid protection.

Ruiyi et al. [6] investigated an IoT-based multi-agent relay protection system with cooperative control strategies for modern power systems. The primary objective was to improve relay coordination through distributed intelligent agents capable of exchanging real-time information using IoT communication infrastructure. The proposed cooperative framework enabled faster fault identification, coordinated decision-making, and improved system reliability. Experimental analysis demonstrated enhanced protection performance and reduced fault-clearing time. The study concluded that IoT-enabled multi-agent systems offer an effective solution for distributed intelligent relay protection.

Mayangsari and Khayam [7] conducted a systematic literature review on Artificial Intelligence-driven relay coordination for distribution networks with multiple Distributed Energy Resources (DERs). The review analyzed recent developments in machine learning, deep learning, reinforcement learning, and optimization techniques applied to adaptive relay coordination. The authors highlighted research trends, implementation challenges, and existing limitations, including communication delays, insufficient real-time validation, and cybersecurity concerns. The study concluded that AI-based adaptive protection has significant potential but requires further practical implementation and standardized evaluation.

Wu et al. [8] proposed an adaptive protection scheme based on Proximal Policy Optimization (PPO) reinforcement learning for modern distribution networks. The primary objective was to enable relay protection systems to continuously learn optimal protection policies under dynamic network conditions. The reinforcement learning model adjusted relay operating strategies according to real-time system conditions and fault characteristics. Simulation results indicated improved adaptability, reduced relay operating time, and enhanced fault discrimination accuracy. The authors concluded that reinforcement learning offers an effective approach for intelligent adaptive protection in future smart distribution systems.

Prasad et al. [9] proposed a robust centralized protection scheme incorporating AI-based fault diagnosis for graph-structured AC microgrids. The study aimed to improve fault detection accuracy and relay coordination using artificial intelligence techniques capable of identifying complex fault patterns. The proposed centralized protection architecture achieved accurate fault classification and reliable protection under different operating conditions. Simulation results demonstrated superior protection performance and reduced fault-clearing time compared to conventional methods. The authors concluded that AI-assisted centralized protection significantly enhances the reliability of AC microgrid protection systems.

Alamshah et al. [10] presented a comprehensive review of directional overcurrent relay coordination in ring distribution networks based on hybrid optimization techniques. The study analyzed recent optimization algorithms, including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Grey Wolf Optimizer (GWO), and other hybrid methods for relay coordination. The review compared various optimization approaches based on coordination time, computational efficiency, convergence speed, and protection reliability. The authors concluded that hybrid optimization techniques significantly improve relay coordination performance and provide promising solutions for complex modern distribution networks.

Drul [11] presented a comprehensive state-of-the-art review on the application of Reinforcement Learning (RL), Demand Response (DR), and intelligent protection techniques in active distribution networks. The primary objective of the study was to examine recent advancements in AI-driven power system operation, adaptive protection, and energy management. The review discussed the integration of reinforcement learning with demand response programs to enhance grid flexibility, fault resilience, and protection coordination. Furthermore, the study highlighted existing challenges such as computational complexity, communication delays, cybersecurity threats, and limited real-world implementation. The author concluded that reinforcement learning-based adaptive protection and demand response strategies are promising solutions for improving the reliability, efficiency, and resilience of future smart distribution networks.

Yazdaninejadi et al. [12] proposed an advanced deep learning-based local current-only protection scheme for microgrids. The primary objective of the study was to develop a protection method capable of accurately identifying faults using only local current measurements without requiring communication between protection devices. A deep learning model was trained to classify different fault conditions and determine appropriate relay actions under various operating scenarios. Simulation results demonstrated high fault detection accuracy, fast relay response, and improved robustness against network topology changes compared with conventional protection methods. The study concluded that deep learning-based local protection provides an effective and communication-independent solution for modern microgrid protection.

Fu et al. [13] proposed a machine learning-based adaptive relay protection control strategy for smart grids. The primary objective was to improve relay protection performance by dynamically adjusting protection parameters according to real-time system operating conditions. Machine learning algorithms were employed to analyze electrical parameters, identify fault characteristics, and optimize relay control decisions. Experimental analysis demonstrated enhanced fault recognition accuracy, reduced relay operating time, and improved adaptability compared with traditional fixed-setting protection schemes. The authors concluded that machine learning techniques significantly enhance the intelligence and reliability of smart grid relay protection systems.

Uddin et al. [14] proposed a hybrid machine learning-based intelligent distance protection and control scheme for grid-connected wind farms. The primary objective was to improve fault detection, fault classification, and protection zone identification under varying wind generation conditions. The proposed hybrid machine learning model accurately classified fault types and determined the corresponding protection zones using electrical measurements obtained from the transmission system. Simulation results demonstrated higher fault classification accuracy, improved zone discrimination, and faster relay operation compared with conventional distance protection methods. The study concluded that hybrid machine learning techniques can significantly improve the reliability and adaptability of protection systems for renewable energy-integrated power networks.

Al-Saadi et al. [15] presented a comprehensive survey of reinforcement learning-based intelligent control strategies for optimal power management in advanced power distribution systems. The primary objective of the study was to review recent reinforcement learning algorithms applied to distributed energy resource management, voltage regulation, energy optimization, and intelligent control of smart grids. The survey compared various reinforcement learning techniques based on learning capability, computational efficiency, adaptability, and practical implementation. The authors also discussed current research challenges, including data availability, training complexity, cybersecurity, and real-time deployment. The study concluded that reinforcement learning offers significant potential for developing autonomous and adaptive control and protection systems in future intelligent power distribution networks.

VII. CONCLUSION

The reviewed literature indicates that Artificial Intelligence (AI) and Machine Learning (ML) techniques have significantly improved relay coordination and power system protection by enhancing fault detection accuracy, reducing relay operating time, and enabling adaptive decision-making. Techniques such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), Deep Neural Networks (DNN), Deep Learning (DL), Reinforcement Learning (RL), and hybrid optimization algorithms have demonstrated superior performance over conventional protection methods. However, most existing studies focus on individual AI techniques, specific network configurations, or limited fault scenarios, with insufficient emphasis on integrated adaptive relay coordination under diverse operating conditions. Therefore, there remains a need to develop a comprehensive ML-based adaptive relay protection framework that combines accurate fault classification with real-time relay coordination to improve the reliability, selectivity, and resilience of modern power distribution systems.

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