Relay Coordination in Resilient and Sustainable Power Systems: Review on Optimization Techniques and Future Directions

Anu Kuriakose, Balamurugan S.*, and Lekshmi R. R.
Department of Electrical and Electronics Engineering, Amrita School of Engineering, Coimbatore,
Amrita Vishwa Vidyapeetham, India
Email: k_anu@cb.students.amrita.edu (A.K.), s_balamurugan@cb.amrita.edu (B.S.), rr_lekshmi@cb.amrita.edu (L.R.R.)

Manuscript received March 1, 2025; May 7, 2025; accepted May 21, 2025
*Corresponding author

***Abstract*—This article presents a technical review of advanced relay coordination techniques in modern power systems. Focusing on directional overcurrent relays, the study examines optimization-based methods for tuning key relay parameters, which include the pickup current and the time multiplier setting, to minimize the total relay operating times and ensure reliable protection. Both deterministic and metaheuristic approaches, including various hybrid algorithms, are analyzed in terms of their ability to formulate and solve different objective functions subjected to coordination time intervals and other operational constraints. Various solutions proposed by researchers employing diverse techniques have been validated using multiple test systems and tools and comprehensively discussed. The review also highlights emerging trends in real-time adaptive protection and cybersecurity integration, providing a roadmap for enhancing the robustness of protection schemes in increasingly complex and dynamic power networks.**

***Index Terms*—intelligent power systems, protection, directional overcurrent relay, relay coordination, optimization**

NOMENCLATURE

ADNs:	Active Distribution Networks
COA:	Cuckoo Optimization Algorithm
CTI:	Coordination Time Interval
DE:	Differential Evolution
DG:	Distributed Generation
DN:	Distribution Network
DOCRs:	Directional Overcurrent Relays
DS-ROCOV:	Dual-Setting Rate-Of-Change-Of-Voltage
GA:	Genetic Algorithm
GSA-SQP:	Gravitational Search Algorithm-Sequential Quadratic Programming
I_p:	pickup current setting
LP:	Linear Programming
OCR:	Over Current Relays
PS:	Plug Setting
PSM:	Plug Setting Multiplier
PSO:	Particle Swarm Optimization
TCCs:	Time Current Characteristics
TDS:	Time Dial Setting
TMS:	Time Multiplier Setting

I. INTRODUCTION

The effective operation of electrical power systems crucially depends on the coordination and protection of various components, among which relays play a pivotal role [1]. These protective relays identify and isolate faulty components to avoid large disturbances and damage [2]. However, the dependability, balanced selectivity, and proper coordination in interconnected electric grids associated with numerous operating situations are challenging [3]. The need to make sure that the protective relays function quickly and selectively to isolate faults while limiting the effect on the rest of the system gives rise to the relay coordination problem [4, 5]. This coordination depends on the electrical system's stability, dependability, and safety. Poor coordination of relays causes cascade failures, blackouts, and equipment damage, and even puts human lives at risk [6]. Relay coordination has become more important in recent decades due to increased power systems' complexity, scale, and technological improvements [7]. The coordination becomes increasingly difficult when power systems develop to include Distributed Generation (DG), renewable energy sources, and smart grid technology [8–10]. Relay coordination schemes become more complicated due to integrating these new components, which also brings new complications such as bidirectional power flows, voltage variations, and quick system reconfigurations [11]. Engineers and academicians have created various approaches, algorithms, and tools to efficiently handle the relay coordination challenges. Engineers and academicians have created various approaches, algorithms, and tools to efficiently handle the relay coordination challenges [12]. These methods seek to improve the power system's overall performance and reliability by figuring out coordination schemes and relay settings [13]. On the other hand, attaining optimal relay coordination requires a thorough understanding of fault characteristics, relay characteristics, system dynamics, and operational limitations [14, 15].

Overcurrent Relays (OCRs) must be coordinated to locate and dissociate faults in a power system network.

Two essential factors that significantly affect OCR coordination are the pickup current setting (I_p) and the Time Multiplier Setting (TMS) [16]. The lowest and highest current level values are the main factors that define the I_p. Different types of objective functions, the addition of new constraints, and non-standard and user-defined relay characteristics are used as several optimization strategies for coordinated protection in an electrical system. These methods aim to guarantee the safety and dependability of protection devices in the electrical system by coordinating their operations [17]. Coordination of Directional Overcurrent Relays (DOCRs) has historically been accomplished via a blend of analytical and graphical methods. On the contrary, constrained optimization methods streamline intricate topological analysis programs by eliminating the need to ascertain breakpoints [18, 19]. The primary aim is to develop a mathematical objective function that represents the protection coordination problem for the system considered. Generally, researchers have constructed the objective function by incorporating the operation time of the primary relays. This formulation faces limitations of selectivity and sensitivity. In addition, while solving the optimization problem, the suggested objective function seeks to determine the optimal value of the TMS to minimize the total tripping time. Several authors have put forth diverse recommendations to enhance the efficacy of DOCR coordination [19–23].

This article explores and analyses the advancements and challenges in relay coordination, including the formulations of objective functions and constraints, the test systems, software, and optimization techniques deployed. Furthermore, it highlights the potential areas for future research to address existing limitations.

The rest of the paper is organized as follows: Section II briefly describes the philosophy of DOCR coordination. Section III includes the various contributions and challenges in relay coordination. Section IV discusses formulation, diagnostics, and techniques adopted in different literatures to perform relay coordination. Recent innovative solutions are presented in Section V. Section VI points out the prospects in relay coordination, followed by conclusions.

II. Philosophy of Directional Overcurrent Relay Coordination

Relay coordination refers to selecting and setting protective relays for a particular fault in an electrical power system. A relay should isolate faults quickly and selectively to minimize the impact of faults, thereby ensuring continuity of power supply. This is accomplished with the deployment of DOCRs that are configured based on TMS and I_p. As specified in IEC 60255, the formula for the time–current (t–I) characteristic of a DOCR is given in Eq. (1).

$$t = \text{TMS}\frac{A}{(I/I_p)^B - 1} \tag{1}$$

where A denotes the relay characteristic constant and B signifies the inverse time type constant. A and B can possess fixed standard values according to the relay characteristic types: normal inverse, very inverse, or extremely inverse, and are tabulated in Table I.

TABLE I: PARAMETERS FOR INVERSE TIME CHARACTERISTICS CURVES

Relay Characteristic Type	*A*	*B*
Normal Inverse	0.14	0.02
Very Inverse	13.5	1
Extremely Inverse	80	2

For an IEC normal inverse relay, Eq. (1) can be written as per Eq. (2).

$$t = \text{TMS}\frac{0.14}{(I/I_p)^{0.02} - 1} \tag{2}$$

The ratio of the actual fault current to I_p given in Eq. (2) refers to the Plug Setting Multiplier (PSM). The relation between PSM and the operating time of the relay can be graphically represented through Time Current Characteristics (TCCs) and is shown in Fig. 1.

The primary relay detects and initiates protective actions in response to faults or abnormal conditions in the power system. If the primary fails or malfunctions, the backup relay acts as the secondary. The CTI (Coordination Time Interval) shown in Fig. 1 refers to the interval at which the backup relay must operate while the primary relay fails to clear the fault. TCCs of primary and backup relays, along with CTI, play a crucial role in coordinating the operation of protective relays. Selective fault protection, minimizing system downtime, and maximizing reliability are the challenges in relay coordination.

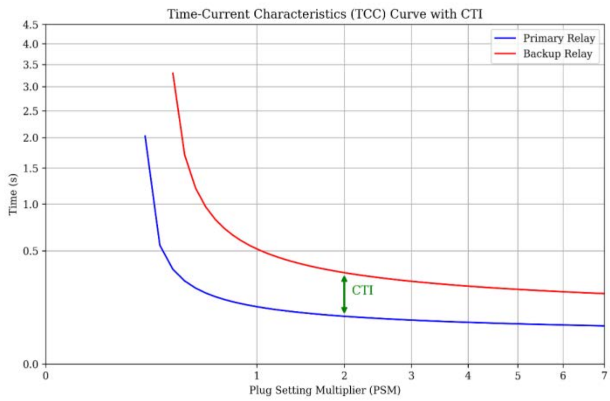

Fig. 1. Time-current characteristics curve of OCR.

III. Relay Coordination: Challenges and Contributions

Integrating DG units and renewable energy sources has introduced significant complexity to traditional OCR coordination, particularly in microgrids and Active Distribution Networks (ADNs). Fluctuating fault current levels, bidirectional power flows, and varying network topologies challenge conventional protection schemes that often rely on static settings. Existing methods struggle to maintain selectivity, sensitivity, and reliability under dynamic operating conditions, such as grid-connected and islanded modes. Advanced techniques, including optimization algorithms and adaptive relay settings, have been proposed to address these limitations, enhancing protection scheme performance. However, practical implementation faces challenges such as computational complexity, real-time adaptability, and integration with legacy systems. Furthermore, renewable energy sources such as photovoltaic systems introduce additional challenges, including high-impedance fault detection and handling capability of transient faults. Addressing these issues requires innovative relay coordination strategies that ensure robust, scalable, and efficient protection for modern power systems. This section explores the contributions that have shaped relay coordination and challenges that need to be overcome in meeting the demands of future power systems. By addressing these challenges, the pivotal role of relay coordination in enhancing grid resilience and operational efficiency can be ensured.

Zeineldin *et al*. [20, 21] suggested dual configurations to achieve the most effective coordination of DOCRs in a multi-loop Distribution Network (DN). Dual setting relays were proposed for micro-grids with grid-connected and islanded capabilities, addressing the failure of backup schemes to operate in a coordinated manner in grid-connected DG systems in [22] and [23]. A dual-setting rate-of-change-of-voltage (DS-ROCOV) based protection coordination scheme was proposed in [24], offering two different primary and backup protection settings, ensuring sensitivity to high resistance faults. Furthermore, researchers have proposed novel time-current-voltage attributes for IEEE-14 and IEEE-30 bus systems [25]. Birla *et al*. [26] has explored the optimal coordination of directional OCRs for near-end faults, and Saleh *et al*. [27] has developed methods for detecting multiple fault locations. Kuriakose and Balamurugan [28] and [29] explained the relay coordination in the 5-bus radial system and the 9-bus single-loop system. Adaptive relay coordination for the IEEE 5-bus system under different loop configurations was described in [30].

Modifications in the objective function and additional constraints are deployed for the best coordination of OCRs. For example, Purwar *et al*. [31] proposed a novel constraint considering a DG system's varying operational conditions. Additional limitations regarding transient stability, fault current direction, and OCR coordination employing distance protection schemes have been suggested in [32–34]. *N*–1 contingency constraints, fault ride-through requirements for transmission-level interconnected wind parks in [35], and various network topologies in [36] were suggested for enhanced coordination. Numerous studies have proposed user-defined and non-standard characteristics for improving the coordination of OCRs. In contrast, to employ a phase over-current element to safeguard against DN, Elneweihi *et al*. [37] has suggested the application of the negative-sequence element. Double-inverse over-current relays have been proposed to enhance the stability of DG operation [38]. To improve the coordination of distance protection schemes and acquire new values for standard inverse OCR, many researchers have put forth user-defined characteristics in [39–43]. In addition, certain authors have utilized metaheuristic optimization algorithms, including gravitational search algorithms, to coordinate OCR systems according to user-defined attributes [44]. The efficacy of various objective functions for all possible short-circuit contributions to optimize OCR coordination was analyzed in the IEEE 30-bus system [29, 45–46]. The major contributions in relay coordination are provided in Table II.

In summary, relay coordination challenges in microgrids and the ADNs are multifaceted and involve computational complexity, operational variability, and system reliability. Addressing these challenges requires a paradigm shift toward advanced optimization techniques, adaptive protection schemes, and innovative relay coordination strategies to ensure safe and reliable operation under diverse conditions.

TABLE II: CONTRIBUTIONS TO RELAY COORDINATION

Ref. No.	Contributions
[20]	Dual configurations are proposed for the effective coordination of DOCRs in a multi-loop DN.
[21]	Dual configurations for multi-loop DN coordination of DOCRs.
[22]	Dual-setting relays are proposed for microgrids with grid-connected and islanded capabilities.
[23]	Addressed backup scheme failures in grid-connected DG systems.
[24]	DS-ROCOV-based protection coordination with dual primary and backup settings for sensitivity to high-resistance faults.
[25]	Proposed novel time-current-voltage attributes for IEEE-14 and IEEE-30 bus systems.
[26]	Explored optimal coordination of directional OCRs for near-end faults.
[27]	Developed methods for detecting multiple fault locations.
[28]	Described relay coordination in a 5-bus radial system and a 9-bus single-loop system.
[29]	Analyzed IEEE 5-bus system coordination for different single-loop configurations.
[30]	Relay coordination for IEEE 5-bus systems in various configurations.
[31]	Proposed novel constraints considering DG systems' varying operational conditions.
[32–34]	Suggested constraints for transient stability, fault current direction, and OCR coordination using distance protection.
[35]	*N*-1 contingency constraints and Fault Ride-Through Requirements for Transmission Level Wind Parks.
[36]	Suggested various network topologies for enhanced coordination.
[37]	Replaced phase overcurrent elements with negative-sequence elements for DN protection.
[38]	Proposed double-inverse OCRs for enhancing DG stability.
[39–43]	Proposed user-defined characteristics to improve the coordination of distance protection schemes.
[44]	Utilized metaheuristic optimization algorithms (e.g., gravitational search algorithms) for OCR coordination.
[45]	Assessed the efficacy of various objective functions using the IEEE 30-bus system.
[46]	Considered all possible short-circuit contributions when optimizing OCR coordination.

IV. RELAY COORDINATION: FORMULATION, DIAGNOSTICS, AND TECHNIQUES

This section provides an overview of the mathematical formulations, practical validation methods, and innovative strategies driving advancements in relay coordination. Subsection A focuses on optimization techniques, covering conventional and metaheuristic approaches and advanced hybrid methods. These techniques address challenges such as computational complexity, non-linearity, and the need for adaptive coordination in dynamic systems. Subsection B highlights the development of objective functions, which aim to minimize relay operation times or deviations in settings, subject to constraints such as Time Dial Setting (TDS), I_p, and CTI. Finally, Subsection C discusses diverse test systems, which include well-known IEEE bus configurations and simulation tools like DIgSILENT, MATLAB, and PSCAD for evaluating relay coordination methods.

A. Relay Coordination Technique: A Focus on Optimization

In addition to effective coordination, OCRs must operate swiftly. The prolonged duration of the fault increases observable damage inside the system. Consequently, it is essential to reduce the operational duration of the OCRs. Numerous evolutionary strategies and algorithms have been devised to optimize operational efficiency. Optimization approaches may be broadly categorized into conventional and non-conventional.

In traditional methods, the optimization of a function starts with an initial estimate, and with each iteration, the solution progresses toward the ideal value. These approaches are categorized as direct, indirect, and gradient search techniques [47]. Instances of direct search, indirect search, and gradient search methodologies are patternsearch [48], surrogateopt, and fmincon [49, 50], respectively. Various common strategies exist for optimizing the operational duration of OCRs. Vijayachandran *et al*. [51, 52] developed a relaying strategy using the curve-fitting approach. Chung *et al*. [53] presented a fixed-point coordination curve to eliminate crossings of coordination curves. The drawbacks of these strategies include an increased number of iterations and a restriction to certain types of goal functions. To address these limitations, researchers transitioned to other optimization techniques, mostly population-based approaches, which provide a dependable and global optimal value.

The unconventional methods include deterministic, metaheuristic, and hybrid approaches. The innovations for function optimization have transitioned to deterministic approaches for the optimum coordination of OCRs. Authors have used techniques such as Linear Programming (LP) [54, 55], whereby either the PSM or I_p value was predetermined, making the relay's running duration a linear function of TMS, which was then optimized to get the ideal TMS values. While microprocessor-based relays allow quasi-continuous adjustment of PSM and TMS, several studies, including [56, 57], have treated them as discrete variables for practical and computational reasons. A mixed-integer nonlinear programming approach was used [56], and binary integer programming was applied [57], both considering the discrete nature of available setting steps in real relays. This reflects field constraints where TMS and PSM were typically selected from a finite set of manufacturer-defined values. Papaspiliotopoulos *et al.* [58] reconstructed the non-linear issue into an analogous restricted quadratic problem. This paradigm mitigates the complexity of the issue; yet, these deterministic solutions include several drawbacks [59]:

1) The ultimate resolution of the function is more contingent upon the original estimate.
2) These strategies can provide a local solution. A strong and dependable solution is not guaranteed.
3) The convergence rate of these approaches is sluggish.

The metaheuristic approaches were devised to address these limitations. These techniques include nature-inspired algorithms, whereby problem-solving strategies were taken from natural processes. Prominent techniques include Genetic Algorithm (GA) [60] and non-dominated sorting GA [61], Particle Swarm Optimization (PSO) [62–64], Differential Evolution (DE) [65], Modified DE [66], Adaptive DE [67], Informative DE [68], Artificial bees Colony [69], Biogeography based optimization [70], Simulated Annealing [71], Grey Wolf Optimization [72], Water Cycle Algorithm [72], Firefly Algorithm [71] and others. Advantages of metaheuristic approaches over deterministic methods include:

1) These methods often provide global solutions that are independent of the starting estimate.
2) These methods can optimize functions by exhibiting discontinuities.
3) These algorithms may also enhance multimodal functionality.
4) The convergence rate is somewhat expedited.

Researchers continue to discover innovative applications of these algorithms, creating hybrid algorithms by amalgamating two unconventional algorithms and comparing the outcomes with those derived from metaheuristic approaches. A synthesis of many algorithms leverages the strengths of each to enhance the function, yielding superior outcomes. Examples of hybrid algorithms that were suggested by the authors to optimize relay operating time were Hybrid GA-Nonlinear Programming [73], Hybrid GA-LP [74], and Biogeography-Based Optimization mixed with Linear Programming. Hybrid PSO and LP [75], Cuckoo Linear Programming Hybrid Algorithm, Hybrid Gravitational Search Algorithm-Sequential Quadratic Programming (GSA-SQP) [76], an approach using GSA and SQP was proposed for the optimum coordination of DOCRs. Additional instances encompass the hybridization of disparate metaheuristic methodologies, including GA-PSO [77], Cuckoo-Search Algorithm combined with Firefly Algorithm [13], Biogeography-Based Optimization – DE [78], and Hybrid Water Cycle Moth Flame Optimization [79], among others.

The frequency of usage of algorithms in the works of literature considered for this paper is shown in Fig. 2. The optimization techniques used for relay coordination are tabulated in Table III. Numerous authors have used various metaheuristic and hybrid algorithms to optimize the operation time of the relays and have compared these methods with prior techniques. These methods were used for the objective function to determine the ideal relay settings, which include TMS, I_p, A, and B.

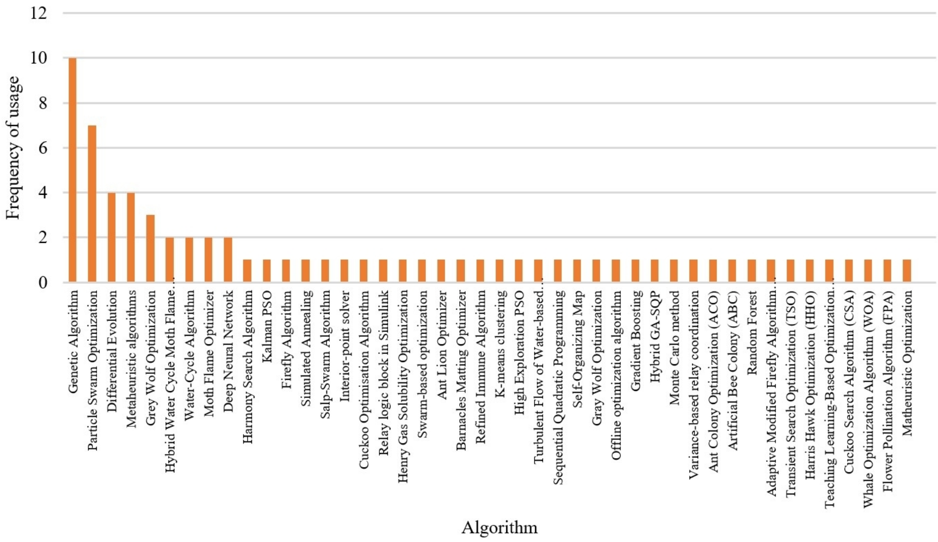

Fig. 2. Frequency of usage of algorithms in relay coordination for the last 10 years (2015–2025).

Authors of [80] have used GA to ascertain the ideal configurations for TMS, PSM, and A. In [81], the authors used the interior point solver approach to determine the best configurations (TMS and PSM) for both grid-connected and islanded modes. Researchers have used PSO [63, 64] and Kalman PSO [64] to enhance operational efficiency. These strategies have been used for both standard and non-standard relay characteristic curves to determine optimum values of A and B, in conjunction with TMS and PSM. Researchers have opted for hybrid algorithms and created new algorithms due to increased computing time, reduced likelihood of achieving a global solution, and slower convergence rates. The Hybrid Water Cycle Moth Flame Optimization approach was used in [82] to determine optimum values based on the Standard and Non-Standard Characteristics curves of relays. A hybrid consists of two metaheuristic methods [83, 84] or a metaheuristic combined with classical techniques [84, 85]. Researchers in [84] have used a GA combined with PSO (GA-PSO) to ascertain the parameters. Certain writers have linearized the objective function from its non-linear form by pre-determining the values of PSM or I_p, hence simplifying the optimization process. If the PSM value is unoptimized, the function becomes linear. Authors in [85] have proposed the Cuckoo Optimization Algorithm (COA) in conjunction with LP. The COA was used to ascertain the best value of I_p that renders the function linear. Linear programming was used to ascertain the best value of TMS. In reference [84], an analogous methodology was suggested for a radial DN. In [86], the authors have rendered PSM unoptimized, making the goal function linear and only dependent on TMS. Operating time was enhanced using GA and Simulated Annealing. Authors in [87] have used DE to get the best I_p values. Additionally, several studies establish a maximum threshold for PSM [82, 88], beyond which optimizing TMS yields the least operational duration for the OCRs. Researchers in [82] have employed an evolutionary method to enhance PSM fiftyfold, optimizing TMS. A similar methodology was used in [88] when coordination occurred in two segments: one where PSM is less important and another where PSM is more relevant.

In [89], DOCRs implemented as logic blocks in MATLAB Simulink, optimize coordination for radial and hybrid systems, ensuring the minimal relay operation times and hardware validation to confirm effectiveness in handling various faults. Ref. [90] deployed improved PSO through hybrid approaches such as Henry Gas Solubility Optimization and DE, where DE demonstrated superior computational efficiency and convergence speed. Metaheuristic algorithms, including GA and PSO, have also been utilized for relay coordination, transforming constrained problems into unconstrained forms to optimize TMS and improve selectivity and sensitivity [91]. Several nature-inspired algorithms, such as Ant Lion Optimizer, Moth Flame Optimizer, Grey Wolf Optimizer, and Barnacles Matting Optimizer, have been evaluated on IEEE test systems. The best performances of Moth Flame Optimization in small-scale systems and Grey Wolf Optimizer in mesh power DN were highlighted in [92]. The use of a refined immune algorithm along with an auto-tuning reproductive mechanism is a promising technique in reducing overall operation time and improving relay coordination after DG integration [93]. Machine learning techniques have been applied in [94], with K-means clustering to optimize relay settings in IEEE 14-bus systems, forming network clusters based on time-dependent attributes. High Exploration PSO and Turbulent Flow of Water-based Optimization algorithms have been employed in [95] to discretize relay settings and enhance performance in IEEE 14-bus and 30-bus systems. To improve fault detection capabilities of Digital DOCRs, optimization using GA and clustering using Self-Organizing Map was deployed in [96]. Additionally, relay coordination was investigated under varying DG penetration levels, with dual-setting DOCRs outperforming conventional methods and operating efficiently without communication channels [97]. Fault location detection was improved using hybrid methods, including an offline optimization algorithm combining GA and SQP, alongside a Deep Neural Network for identifying faults in dynamic conditions [98]. Reference [99] applied Monte Carlo methods for fault location selection, demonstrating near-perfect selectivity index values and allowing parallel computing applications for optimization. In [100], a novel fault detection algorithm for low-voltage DC microgrids was proposed, leveraging variance-based relay coordination to enhance immunity against noise while ensuring reliable fault detection across different microgrid topologies.

Ant Colony Optimization (ACO) and Artificial Bee Colony (ABC), inspired by the foraging behaviours of ants and bees, respectively, have been applied to determine optimal relay settings in constrained power systems [101]. Machine learning techniques such as Gradient Boosting [98] and Random Forest [102] have demonstrated high accuracy and robustness in optimizing relay coordination by learning complex, nonlinear fault-setting relationships. Additionally, Deep Neural Networks (DNNs) have enabled real-time fault detection and adaptive protection strategies in modern grids [98]. Nature-inspired metaheuristic algorithms such as the Adaptive Modified Firefly Algorithm (AMFA) [103], Transient Search Optimization (TSO), and Harris Hawk Optimization (HHO) have proven effective in minimizing operating times and enhancing relay coordination under conditions like distributed generation and electric vehicle integration [104–106]. Hybrid approaches, including the Genetic Algorithm–Sequential Quadratic Programming (GA-SQP) technique, offer improved coordination by combining global search with local refinement capabilities [98]. Further notable algorithms include Teaching Learning-Based Optimization (TLBO), Cuckoo Search Algorithm (CSA), Whale Optimization Algorithm (WOA), Flower Pollination Algorithm (FPA), and Matheuristic Optimization, each contributing uniquely to solving multi-objective, nonlinear relay coordination problems [107–110]. Together, these algorithms reflect a shift toward intelligent, adaptive, and hybrid techniques that are better suited to the complexity of modern smart grid and microgrid environments.

TABLE III: OPTIMIZATION TECHNIQUES FOR RELAY COORDINATION

Algorithm	Ref. No.	Corresponding Year
GA	[63, 80, 83, 86, 91, 93–97]	[2022, 2022, 2023, 2022, 2025, 2024, 2024, 2024, 2025, 2024]
PSO	[63, 64, 83, 90–92, 95]	[2022, 2021, 2023, 2024, 2025, 2025, 2024]
DE	[63, 78, 87, 90]	[2022, 2019, 2022, 2024]
Metaheuristic algorithms	[84, 88, 91,107]	[2021, 2021, 2025, 2018]
Grey Wolf Optimization	[71, 92, 97]	[2021, 2025, 2024]
Hybrid Water Cycle Moth Flame Optimization	[79, 82]	[2021, 2022]
Water-Cycle Algorithm	[71, 79]	[2021, 2021]
Moth Flame Optimizer	[79, 92]	[2021, 2025]
Deep Neural Network	[98, 105]	[2024, 2024]
Harmony Search Algorithm	[63]	[2022]
Kalman PSO	[64]	[2021]
Firefly Algorithm	[71]	[2021]
Simulated Annealing	[71]	[2021]
Salp-Swarm Algorithm	[80]	[2022]
Interior-point solver	[81]	[2023]
Cuckoo Optimization Algorithm	[85]	[2018]
Relay logic block in Simulink	[89]	[2024]
Henry Gas Solubility Optimization	[90]	[2024]
Swarm-based optimization	[91]	[2025]
Ant Lion Optimizer	[92]	[2025]
Barnacles Matting Optimizer	[92]	[2025]
Refined Immune Algorithm	[93]	[2024]
K-means clustering	[94]	[2024]
High Exploration PSO	[95]	[2024]
Turbulent Flow of Water-based Optimization	[95]	[2024]
Sequential Quadratic Programming	[95]	[2024]
Self-Organizing Map	[96]	[2025]
Gray Wolf Optimization	[97]	[2024]
Offline optimization algorithm	[98]	[2024]
Gradient Boosting	[98]	[2024]
Hybrid GA-SQP	[98]	[2024]
Monte Carlo method	[99]	[2024]
Variance-based relay coordination	[100]	[2024]
Ant Colony Optimization (ACO)	[101]	[2021]
Artificial Bee Colony (ABC)	[101]	[2021]
Random Forest	[102]	[2023]
Adaptive Modified Firefly Algorithm (AMFA)	[103]	[2023]
Transient Search Optimization (TSO)	[104]	[2023]
Harris Hawk Optimization (HHO)	[105]	[2024]

Teaching Learning-Based Optimization (TLBO)	[106]	[2023]
Cuckoo Search Algorithm (CSA)	[107]	[2018]
Whale Optimization Algorithm (WOA)	[108]	[2022]
Flower Pollination Algorithm (FPA)	[109]	[2015]
Matheuristic Optimization	[110]	[2017]

B. Formulation: Objective Functions and Constraints

The objective functions in the various literature aim to optimize the coordination of protective relays by minimizing operation times or deviations in relay parameters, subject to specific constraints. Commonly, the objective function can be generalized as minimizing a sum of weighted 'w_i' relay times or settings [91–93] as in Eq. (3).

$$\text{Objective Function: Min } \sum_{i=1}^{n} w_i t_i \tag{3}$$

Minimizing deviations from target values was also considered as the objective function [95, 97]. Constraints across the references typically enforce bounds on TDS [90, 93, 95] as in Eq. (4), CTI [92, 94, 96] based on primary relay operating time (t_p) and its backup relay operating time (t_b) as in Eq. (5) and limits for I_p [91, 98] as in Eq. (6).

$$\text{Inequality Constraint 1: } \mathrm{TDS_{min}} \leq \mathrm{TDS} \leq \mathrm{TDS_{max}} \tag{4}$$

$$\text{Inequality Constraint 2: } t_b - t_p \geq \mathrm{CTI} \tag{5}$$

$$\text{Inequality Constraint 3: } \mathrm{PS_{min}} \leq \mathrm{PS} \leq \mathrm{PS_{max}} \tag{6}$$

The different objective functions and constraints considered for relay coordination are consolidated and presented in Table IV for comparison.

TABLE IV: OBJECTIVE FUNCTIONS AND CONSTRAINTS

Ref. No.	Objective function	Constraints
[90]	minimize $t_{i,j} = \sum_{i=1}^{n} \sum_{j=1}^{m} \left(t_{p_{i,j}} + \sum t_{b_{i,j}} \right)$	$t_b - t_p \geq \mathrm{CTI}$ $\mathrm{TDS_{min}} \leq \mathrm{TDS} \leq \mathrm{TDS_{max}}$ $\mathrm{TDS_{min}} = 0.015$, $\mathrm{TDS_{max}} = 1.0$ $I_{P\mathrm{min}} \leq I_P \leq I_{P\mathrm{max}}$ $I_{P\mathrm{min}}$ is 1.5 times the maximum load current $I_{P\mathrm{max}}$ is the minimum fault current $T_{\mathrm{min}} \leq T \leq T_{\mathrm{max}}$ $T_{\mathrm{min}} = 0.1\ s$ T_{max} depends on the critical clearing time (CCT)
[91]	$\mathrm{OF} = \mathrm{f(x)} = \min\left(\sum_{i=1}^{n} W_i * T_{i_P}\right)$	$T_{i_P} \geq R_{i_{\mathrm{TDT}}}$ $R_{i_{\mathrm{TDT}}}$ is the relay trip delay time (TDT) obtained from real-time measurements $\mathrm{TMS}_i^{\mathrm{max}} \leq \mathrm{TMS}_i \leq \mathrm{TMS}_i^{\mathrm{min}}$ TMS maximum value is 0.2 TMS minimum value is 0.05 $T_{\mathrm{(backup)P}} - T_{\mathrm{(main)P}} \geq \mathrm{CTI_{(main)}}$ CTI is the sum of the real-time TDTs of the OCRs and the contact opening delay time of the CBs $I_{\mathrm{pu},i}^{\mathrm{max}} \geq I_{\mathrm{pu},i} \geq I_{\mathrm{pu},i}^{\mathrm{min}}$ I_p is set to 1.25 times the nominal load current
[92]	minimize: $\mathrm{OF} = \sum_{i=1}^{n} \delta_i T_i$	$\mathrm{PS}_i^{\mathrm{min}} \leq \mathrm{PS}_i \leq \mathrm{PS}_i^{\mathrm{max}}$ $\mathrm{PS}_i^{\mathrm{min}} = 1.25 \times I_n$, $\mathrm{PS}_i^{\mathrm{max}} = \frac{2}{3} \times I_{f\,\mathrm{min}}$ $\mathrm{TMS}_i^{\mathrm{min}} \leq \mathrm{TMS}_i \leq \mathrm{TMS}_i^{\mathrm{max}}$ $\mathrm{TMS}_i^{\mathrm{min}} = 0.1$ and $\mathrm{TMS}_i^{\mathrm{max}} = 1.1$ $\mathrm{CTI} = T_{\mathrm{bc}} - T_{\mathrm{pr}}$ $\mathrm{CTI}_i^{\mathrm{min}} \leq \mathrm{CTI}_i \leq \mathrm{CTI}_i^{\mathrm{max}}$ $0.2\mathrm{s} \leq \mathrm{CTI}_i \leq 0.5\mathrm{s}$
[93]	minize $\mathrm{Obj}_F = \sum_{k=1}^{\mathrm{TP}} \sum_{j=1}^{\mathrm{FN}} \sum_{i=1}^{\mathrm{RN}} W_{i,j}^k \times \mathrm{TMS}_i$	$\mathrm{CTI}_{x,j}^k = t_{i_b,j}^k - t_{i_p,j}^k$ $\mathrm{CTI^{min}} \leq \mathrm{CTI}_{x,j}^k \leq \mathrm{CTI^{max}}$ $\mathrm{TMS^{min}} \leq \mathrm{TMS}_i^k \leq \mathrm{TMS^{max}}$ $\mathrm{PCS^{min}} \leq \mathrm{PCS}_i^k \leq \mathrm{PCS^{max}}$ $\mathrm{CTI^{min}}$: The lower CTI bound is set to 0.2s. $\mathrm{CTI^{max}}$: The upper CTI bound is set to 0.35s. $\mathrm{TMS^{min}}$: The lower TMS bound is set to 0.05. $\mathrm{TMS^{max}}$: The upper TMS bound is set to 1.0. $\mathrm{PCS^{min}}$: The lower PCS bound is set to 0.05. $\mathrm{PCS^{max}}$: The upper PCS bound is set to 5.0.
[94]	$\mathrm{O.F.} = \sum t_p;\ p = 1,2,3,\ldots,16$	$0.05 \leq \mathrm{TMS}_p \leq 1.1;\ p = 1,2,3,\ldots,16$ $I_{P\mathrm{min},p} = 1.5\ I_{L_p};\ p = 1,2,3,\ldots,16$ $I_{P\mathrm{max},p} = 2/3\ I_{\mathrm{SC}_p};\ p = 1,2,3,\ldots,16$ $I_{P\mathrm{min},p} \leq I_{P_p} \leq I_{P\mathrm{max},p};\ p = 1,2,3,\ldots,16$ $t_{b_i} - t_{p_i} \geq 0.2;\ i = 1,2,3,\ldots,22$ $0.05 \leq t_p \leq 1;\ p = 1,2,3,\ldots,16$
[95]	$\mathrm{OF} = \sum_{i=1}^{n} t_{p_i}$	$t_{b_j} - t_{p_i} - \mathrm{CTI} \geq 0$

	$\mathrm{OF} = \alpha_1 \sum_{i=1}^{n} t_{p_i}^2 + \alpha_2 \sum_{j=1}^{m} \left(\Delta t_{\mathrm{bp}_j} - \beta \left(\Delta t_{\mathrm{bp}_j} - \left\lvert \Delta t_{\mathrm{bp}_j} \right\rvert \right)\right)^2$ $\Delta t_{\mathrm{bp}} = t_b - t_p - \mathrm{CTI}$	$\mathrm{TDS}_{\min} \le \mathrm{TDS} \le \mathrm{TDS}_{\max}$ $I_{\mathrm{load,max}} \le I_p \le I_{f,\min}$ $I_p = \mathrm{CTR} \times \mathrm{PTS}$ $\mathrm{PTS}_{\min} \le \mathrm{PTS} \le \mathrm{PTS}_{\max}$
[96]	$\text{minimize} \Longrightarrow T_{\mathrm{O,ax}} = \sum_{f=1}^{f_m} \left(\sum_{\rho=1}^{N_P} \left(t^{\mathbb{P}}_{r_{\mathrm{ax},f,\rho}} + \sum_{\kappa=1}^{N_B} t^{\mathbb{B}}_{r_{\mathrm{ax},f,\rho,\kappa}} \right)\right)$	$t_{r_{\mathrm{ax}}} = \mathrm{TDS}_{\mathrm{ax}} \frac{A_{\mathrm{ax}}}{\left(\frac{I_{\mathrm{fc}}}{I_{\mathrm{ps_{ax}}}}\right)^{B_{\mathrm{ax}}} - 1} + T_{\mathrm{shift_{ax}}}$ $t^{\mathbb{B}}_{r_{\mathrm{ax},f,\rho,\kappa}} - t^{\mathbb{P}}_{r_{\mathrm{ax},f,\rho}} \ge \mathrm{CTI}$ $\mathrm{TDS}_{\mathrm{LB}} \le \mathrm{TDS}_{\mathrm{ax}} \le \mathrm{TDS}_{\mathrm{UB}}$ $A_{\min} \le A_{\mathrm{ax}} \le A_{\max}$ $B_{\min} \le B_{\mathrm{ax}} \le B_{\max}$ $T_{\mathrm{shift_{min}}} \le T_{\mathrm{shift_{ax}}} \le T_{\mathrm{shift_{max}}}$ $1.1 \cdot I_\ell \le I_{\mathrm{ps_{ax}}} \le 0.6 \cdot I_{\mathrm{fc_{min}}}$ $t^{\mathbb{P}}_{r_{\mathrm{ax},f,\rho}} \le \mathrm{CCT}_f - \tau_{\mathrm{CB}}$ $A_{\min} = 0.14; A_{\max} = 80$ $B_{\min} = 0.02; B_{\max} = 2$ $T_{\mathrm{shift_{min}}} = -10; T_{\mathrm{shift_{max}}} = 10$
[97]	$\mathrm{OF} = \min\left(A_1 \sum_{i=1}^{m} \left(t^i_{\mathrm{op,fow}} - \mathrm{CTI}\right)^2 + A_2 \sum_{j=1}^{n} \left(t^j_{\mathrm{op,rev}} - \mathrm{CTI}\right)^2 + \sum_{p=1}^{m} t^j_{\mathrm{op,z2}}\right)$ $t^i_{\mathrm{op,fow}} = \frac{\alpha^i_{\mathrm{fow}} \times \mathrm{TMS}^i_{\mathrm{fow}}}{\left[\frac{I^i_f}{\mathrm{PS}^i_{\mathrm{fow}} \times \mathrm{CTR}^i}\right]^{\beta^i_{\mathrm{fow}}} - 1}$ $t^j_{\mathrm{op,rev}} = \frac{\alpha^j_{\mathrm{rev}} \times \mathrm{TMS}^j_{\mathrm{fow}}}{\left[\frac{I^j_f}{\mathrm{PS}^j_{\mathrm{rev}} \times \mathrm{CTR}^j}\right]^{\beta^j_{\mathrm{rev}}} - 1}$	$t^j_{\mathrm{op,z2}} - t^i_{\mathrm{op,fow}} \ge \mathrm{CTI}'$ $t^j_{\mathrm{op,rev}} - t^i_{\mathrm{op,fow}} \ge \mathrm{CTI}$ $\mathrm{TMS}^i_{\mathrm{min,fow}} \le \mathrm{TMS}^i_{\mathrm{fow}} \le \mathrm{TMS}^i_{\mathrm{max,fow}}$ $\mathrm{TMS}^j_{\mathrm{min,rev}} \le \mathrm{TMS}^j_{\mathrm{fow}} \le \mathrm{TMS}^j_{\mathrm{max,rev}}$ $\mathrm{PS}^i_{\mathrm{min,fow}} \le \mathrm{PS}^i_{\mathrm{fow}} \le \mathrm{PS}^i_{\mathrm{max,fow}}$ $\mathrm{PS}^j_{\mathrm{min,rev}} \le \mathrm{PS}^j_{\mathrm{fow}} \le \mathrm{PS}^j_{\mathrm{max,rev}}$ $\alpha^i_{\mathrm{min,fow}} \le \alpha^i_{\mathrm{fow}} \le \alpha^i_{\mathrm{max,fow}}$ $\alpha^j_{\mathrm{min,rev}} \le \alpha^j_{\mathrm{fow}} \le \alpha^j_{\mathrm{max,rev}}$ $\beta^i_{\mathrm{min,fow}} \le \beta^i_{\mathrm{fow}} \le \beta^i_{\mathrm{max,fow}}$ $\beta^j_{\mathrm{min,rev}} \le \beta^j_{\mathrm{fow}} \le \beta^j_{\mathrm{max,rev}}$ $t^j_{\mathrm{z2,min}} \le t^j_{\mathrm{z2}} \le t^j_{\mathrm{z2,max}}$ $\mathrm{TMS}^i_{\mathrm{min,fow}} = \mathrm{TMS}^j_{\mathrm{min,rev}} = 0.1$ $\mathrm{TMS}^i_{\mathrm{max,fow}} = \mathrm{TMS}^j_{\mathrm{max,rev}} = 1.1$ $\mathrm{PS}^i_{\mathrm{min,fow}} = \mathrm{PS}^j_{\mathrm{min,rev}} = 0.5$ $\mathrm{PS}^i_{\mathrm{max,fow}} = \mathrm{PS}^j_{\mathrm{max,rev}} = 2.0$ $\alpha^i_{\mathrm{min,fow}} = \alpha^j_{\mathrm{min,rev}} = 0.14$ $\alpha^i_{\mathrm{max,fow}} = \alpha^j_{\mathrm{max,rev}} = 80$ $\beta^i_{\mathrm{min,fow}} = \beta^j_{\mathrm{min,rev}} = 0.02$ $\beta^i_{\mathrm{max,fow}} = \beta^j_{\mathrm{max,rev}} = 2.0$ $t^{\mathrm{DR}}_{\mathrm{z2,min}} = 0.3\mathrm{s}; t^{\mathrm{DR}}_{\mathrm{z2,max}} = 0.9\mathrm{s}$ $t^{\mathrm{DOCR}}_{\mathrm{op,min}} = 0.1\mathrm{s}; t^{\mathrm{DOCR}}_{\mathrm{op,max}} = 4.0\mathrm{s}$
[98]	$\mathrm{OF} = \min \sum_{i=1}^{m} t_{\mathrm{op},i}$ $\min_{\mathrm{PS}_i, \mathrm{TMS}_i} \mathrm{OF} = \sum_{i=1}^{N} \sum_k T_{ik} + \alpha_1 \sum_{i=1}^{N} \mathrm{Penalty}^2$ $\mathrm{Penalty} = \alpha_2 \sum_{p=1}^{N_p} \left(\left\lvert \Delta T_{N_{\mathrm{bp}}} < 0 \right\rvert + \beta \lvert \sum_{p=1}^{N_p} T_{N_{\mathrm{bp}}} < 0.2 \rvert \right)$ $\Delta T_{N_{\mathrm{bp}}} = T_{jk} - T_{ik} - \mathrm{CTI}$	$t_{\mathrm{ob},j} - t_{\mathrm{op},i} \ge \mathrm{CTI}$; CTI is set to 0.2s. $\mathrm{TMS}_{i,\min} \le \mathrm{TMS}_i \le \mathrm{TMS}_{i,\max}$ $\mathrm{TMS}_{i,\min} = 0.01; \mathrm{TM}S_{i,\max} = 1.1$ $\mathrm{PS}_{i,\min} \le \mathrm{PS}_i \le \mathrm{PS}_{i,\max}$ $\mathrm{PS}_{i,\min} \ge I^{\max}_{\mathrm{OL}}$ $I^{\max}_{\mathrm{OL}} = \mathrm{OLF} \times I^{\max}_L$; OLF is set between 1.25 and 1.5. $\mathrm{PS}_{i,\max} = \frac{2}{3} \times I^{\min}_f$ $t_{i,\min} \le t_{\mathrm{op},i} \le t_{i,\max}$

C. Diagnostic Framework: Test System and Software

The test systems considered across the studies include several well-known IEEE bus systems such as the IEEE 6-bus system [78, 90], IEEE 8-bus system [80], IEEE 9-bus system [64, 90], IEEE 14-bus system [94, 95, 98], IEEE 15-bus system [78], IEEE 37-bus system [93], IEEE 42-bus system [78], IEEE 30-bus system [95, 98], IEEE 33-bus system [96] and WSCC 9-bus system [90]. Additionally, power system models were simulated in software like DIgSILENT [80, 94, 96], ETAP [63, 83–84, 86], MATLAB [83–84, 86, 89, 93, 94] and POWER WORLD simulator [90] for various optimization and fault detection studies. Microgrid systems, such as the IEC benchmark microgrid system, were used for evaluating protection coordination in DG scenarios [63, 82, 86], while modified versions of the IEEE 33-bus system were also considered in [96]. Hardware-in-loop simulations validate performance in [81]. Furthermore, simulations using PSCAD/EMTDC were conducted for low-voltage direct current microgrids to evaluate relay coordination and fault detection algorithms [100]. These diverse test systems presented in Table V are instrumental in validating the proposed relay coordination methods and optimization techniques.

TABLE V: TEST SYSTEMS AND SOFTWARE

Ref. No.	Test Systems and Software
[78, 90]	IEEE 6-bus system
[80]	IEEE 8-bus system
[64, 90]	IEEE 9-bus system

[94, 95, 98]	IEEE 14-bus system
[78]	IEEE 15-bus system
[93]	IEEE 37-bus system
[78]	IEEE 42-bus system
[95, 98]	IEEE 30-bus system
[96]	IEEE 33-bus system
[90]	WSCC 9-bus system
[80, 94, 96]	DIgSILENT
[63, 83, 84, 86]	ETAP
[83, 84, 86, 89, 93, 94]	MATLAB
[90]	POWER WORLD simulator
[63, 82, 86]	IEC benchmark microgrid system
[96]	Modified IEEE 33-bus system
[81]	Hardware-in-loop simulations
[100]	PSCAD/EMTDC

V. Relay Coordination: Emerging Trends for Smart Grids

The transition to smart grids, characterized by high penetration of DG and RES, has transformed traditional power systems. Relay coordination, a critical aspect of power system protection, must adapt to the evolving dynamics of bidirectional flows, variability in generation, and increasing complexity. This section reviews the strengths and weaknesses of modern optimization techniques, details the challenges posed by RES and DG, and discusses state-of-the-art solutions and technologies applicable in smart grid environments.

A. Strengths and Weaknesses of Optimization Techniques

Relay coordination in smart grids benefits significantly from the use of user-defined relay characteristics, which improve performance by allowing custom settings for Plug Setting (PS), Time Multiplier Setting (TMS), and relay characteristic coefficients [111]. Advanced metaheuristic algorithms such as Grey Wolf Optimization (GWO) and Particle Swarm Optimization (PSO) enhance coordination under a variety of conditions, leading to more robust relay settings and greater overall system reliability [112]. Optimization techniques also facilitate adaptability to DG operating conditions, particularly by dynamically adjusting to bidirectional power flows [113]. However, these techniques are not without limitations. Their implementation introduces complexity and cost, primarily due to the necessity of directional elements and communication infrastructure [11]. Additionally, the inherently variable operating conditions associated with DG can result in coordination issues or failures in fault isolation, complicating protection strategies [63, 31]. Further, the presence of multiple DGs significantly increases the number of constraints in the optimization problem, necessitating more advanced techniques to ensure timely and accurate protection [114].

B. Challenges and Solutions in Relay Coordination

Integrating RES and DG into smart grids introduces challenges such as variable fault currents, dynamic operating topologies, and complex microgrid protection. The variability of fault currents caused by fluctuating DG output undermines the reliability of traditional protection schemes [113, 115]. Changing topologies and inconsistent DG connections further compromise coordination strategies [31, 114]. In islanded microgrid configurations, protection becomes even more challenging due to bi-directional fault currents with low magnitudes [116]. In response, adaptive protection schemes have been developed to dynamically update relay settings in real-time using digital signal processing (DSP) and machine learning [115]. Another notable development is the constraint-reduction approach, which simplifies the optimization problem and thereby improves both efficiency and accuracy [114]. Communication-based methods, which leverage data exchange among relays and controllers, enhance relay coordination across grid-connected and islanded modes [116]. Lastly, improved coordination between Transmission System Operators (TSOs) and Distribution System Operators (DSOs) in decentralized frameworks has shown promise in reducing computational and communication burdens, leading to more reliable protection schemes [117].

C. Optimization Techniques for Dynamic Networks

Relay coordination in dynamic smart grid scenarios necessitates advanced techniques to cope with frequent changes in topology and power flows. Voltage-based relay coordination schemes are more resilient to fluctuations in grid conditions compared to current-based methods, making them particularly effective in DG-dominated systems [118]. Modified Particle Swarm Optimization (MPSO) has demonstrated success in dynamically adapting relay settings for systems with varying network configurations, as validated on the IEEE 14-bus system [119]. Additionally, high-set relay coordination strategies using genetic algorithms provide faster fault clearance times and improve the reliability of protection schemes [120]. For more advanced grid control, Model Predictive Control (MPC) facilitates real-time integration of distributed energy resources, storage, and load flow optimization by accounting for economic, technical, and environmental constraints [121]. Adaptive critic designs also support continuous system optimization through real-time monitoring and rapid reconfiguration, which is critical for maintaining grid stability under high RES penetration [122].

D. Role of Emerging Technologies

Machine Learning (ML), cybersecurity, and clustering techniques have introduced transformative capabilities in relay coordination. ML algorithms, such as Gradient Boosting, enhance the precision and efficiency in coordinating Inverse Definite Minimum Time (IDMT) overcurrent and earth fault relays, achieving high accuracy and generalizability [102]. ML is also instrumental in cybersecurity, where models like Random Forest classifiers effectively detect and mitigate malicious alterations in relay settings [123, 124]. In terms of protection, the integration of DG and RES has increased the cyber-attack surface, necessitating advanced defense strategies involving AI-driven automation, blockchain, and quantum-resistant cryptography [125, 126]. The Distributed Energy Resource Cybersecurity Framework (DER-CF) provides a structured method for evaluating and addressing these risks [127]. Clustering algorithms combined with Multi-

Agent Systems (MAS) enable decentralized, adaptive protection by allowing intelligent relay agents to communicate and make local decisions. This approach supports real-time fault detection, predictive maintenance, and load balancing in dynamic grid environments [128, 129].

The increasing penetration of DG and RES into smart grids necessitates a shift toward more adaptive, intelligent, and cost-effective relay coordination strategies. While optimization techniques such as GA, PSO, MPSO, and MPC have significantly advanced the capabilities of protection systems, their success depends on proper constraint management and real-time adaptability. Emerging technologies, including ML, clustering, and cybersecurity frameworks, provide complementary support by enhancing responsiveness and resilience against evolving operational and security threats. As smart grids continue to evolve, future research must focus on scalable, interoperable, and standardized solutions that address both technical and infrastructural challenges in modern power systems. Recent works [130, 131] underscore the critical importance of such scalable frameworks and resilient architectures in contemporary grid environments.

VI. Opportunities and Future Trends

This article explores various optimization methods, objective functions, and constraints that allow researchers and engineers to investigate the relay coordination challenges effectively. To ensure validation, different systems are analyzed. The literature offers numerous solutions for addressing protection coordination issues in smart microgrid systems.

The reviewed studies collectively showcase significant advancements in relay coordination through optimization techniques, real-time methodologies, and adaptive strategies. Future work focuses on:

- Enhancing the scalability and efficiency of algorithms for larger power networks.
- Integrating renewable energy sources and dynamic load conditions.
- Developing hybrid methods combining machine learning with optimization for real-time applications.
- Addressing cybersecurity challenges in smart grid relay coordination.

These directions ensure continued progress in relay coordination, supporting the evolution of resilient and intelligent power systems.

VII. Conclusion

Distributed generation, renewable energy integration, and smart grid technologies have significantly increased the challenges associated with relay coordination in modern power systems. Directional Overcurrent Relays and Overcurrent Relays ensure the system's protection, reliability, and stability. This article discusses various methodologies, optimization techniques, and constraints explored by researchers and engineers to effectively address the relay coordination problem. The review highlights the advancements in optimization techniques using innovative hybrid and metaheuristic algorithms. The performance improvement has been demonstrated through minimized tripping times and ensured selectivity under different operational scenarios. To enhance the coordination schemes during high penetration of renewable energy and dynamic network configurations, user-defined relay characteristics, adaptive settings, and novel objective functions have been deployed. To ensure resilient power systems, emerging technologies such as machine learning, clustering algorithms, and deep neural networks present promising solutions to address the variability of fault current contributions, bidirectional power flows, and real-time adaptive protection. Future research expects enhancement of interoperability in protection systems, scalability of algorithms to larger networks, and cybersecurity in smart grids.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Ms. Anu Kuriakose conducted the literature survey and wrote the review article. Dr. Balamurugan S. and Dr. Lekshmi R. R. gave guidance for the survey and also modified the article. All authors approved the final version.

Acknowledgment

The authors would like to thank the editors and anonymous reviewers for providing insightful suggestions and comments to improve the quality of the research paper.

References

[1] H. Zayandehroodi, A. Mohamed, H. Shareef, and M. Mohammadjafari, "A comprehensive review of protection coordination methods in power distribution systems in the presence of DG," *Przeglad Elektrotechniczny*, vol. 87, no. 8, pp. 142–148, 2011.

[2] R. Haron, A. Mohamed, and H. Shareef, "A review on protection schemes and coordination techniques in microgrid system," *Journal of Applied Sciences*, vol. 12, no. 2, pp. 101–112, Jan. 2012.

[3] M. H. Hussain, S. R. A. Rahim, and I. Musirin, "Optimal overcurrent relay coordination: A review," *Procedia Engineering*, 2013, pp. 332–336. doi: 10.1016/j.proeng.2013.02.043

[4] M. Singh, "Protection coordination in distribution systems with and without distributed energy resources—A review," *Protection and Control of Modern Power Systems*, vol. 2, no. 1, Dec. 2017, doi: 10.1186/s41601-017-0061-1

[5] L. R. Chandran, K. Ilango, M. G. Nair, and G. S. Sunil, "Wireless communication assisted over current protection of radial distribution system," in *Proc. the 5th Int. Conf. on Trends in Electronics and Informatics*, Jun. 2021. doi: 10.1109/ICOEI51242.2021.9453089

[6] X. Kang, C. E. K. Nuworklo, B. S. Tekpeti, and M. Kheshti, "Protection of micro-grid systems: a comprehensive survey," *The Journal of Engineering*, vol. 2017, no. 13, pp. 1515–1518, Jan. 2017.

[7] J. S. Farkhani, M. Zareein, A. Najafi, R. Melicio, and E. M. G. Rodrigues, "The power system and microgrid protection—A review," *MDPI AG*, 2020. doi: 10.3390/app10228271

[8] E. Amer, E. A. A. Gouda, and A. Elmitwally, "An overview in

protection coordination methods for mitigation DGs penetration in distribution system. (Dept. E)," *Mansoura Engineering Journal*, vol. 46, no. 4, pp. 53–64, Dec. 2021.
[9] M. Ghotbi-Maleki, R. Mohammadi Chabanloo, H. Askarian Abyaneh, and M. Zamani, "Considering transient short-circuit currents of wind farms in overcurrent relays coordination using binary linear programming," *International Journal of Electrical Power & Energy Systems*, vol. 131, Oct. 2021. doi: 10.1016/J.IJEPES.2021.107086
[10] M. Ghotbi-Maleki, R. Mohammadi Chabanloo, M. R. Taheri, and H. H. Zeineldin, "Coordination of non-directional overcurrent relays and fuses in active distribution networks considering reverse short-circuit currents of DGs," *IET Generation, Transmission and Distribution*, vol. 15, no. 18, pp. 2539–2553, Sep. 2021.
[11] A. M. Agwa and A. A. El-Fergany, "Protective relaying coordination in power systems comprising renewable sources: challenges and future insights," *Sustainability*, vol. 15, no. 9, p. 7279, Apr. 2023. doi: 10.3390/su15097279
[12] W. M. Hamanah, M. I. Hossain, M. Shafiullah, and M. A. Abido, "AC microgrid protection schemes: A comprehensive review," *IEEE Access*, vol. 11, pp. 76842–76868, 2023.
[13] V. S. Kamble, P. Khampariya, and A. A. Kalage, "A survey on the development of real-time overcurrent relay coordination using an optimization algorithm," *International Journal of Intelligent Systems and Applications in Engineering*, vol. 11, no. 3s, pp. 104–114, 2023.
[14] G. Mhagama, N. Y. Hamisi, and S. Naiman, "Review on coordination of time overcurrent relays in electrical distribution network," *Acta Technica Jaurinensis*, vol. 17, no. 3, pp. 143–151, Jun. 2024.
[15] M. R. Taheri, R. Mohammadi, and M. Ghotbi-Maleki, "Optimal cable size selection in distribution network considering damage curve with variable fault clearing time of overcurrent relay," *Electric Power Systems Research*, vol. 225, Dec. 2023. doi: 10.1016/J.EPSR.2023.109812
[16] L. R. Chandran, V. S. Anju Parvathy, K. Ilango, and M. G. Nair, "Adaptive over current relay protection in a PV penetrated radial distribution system with fuzzy GA optimisation," in *Proc. 2022 IEEE 19th India Council Int. Conf.*, 2022. doi: 10.1109/INDICON56171.2022.10040021
[17] G. Antonova, M. Nardi, A. Scott, and M. Pesin, "Distributed generation and its impact on power grids and microgrids protection," in *Proc. 2012 65th Annual Conf. for Protective Relay Engineers*, 2012. doi: 10.1109/CPRE.2012.6201229
[18] M. Ghotbi-Maleki, R. M. Chabanloo, M. A. Ebadi, and M. Savaghebi, "Determination of optimal breakpoint set of overcurrent relays using modified depth-first search and mixed-integer linear programming," *IET Generation, Transmission and Distribution*, vol. 14, no. 23, pp. 5607–5616, Dec. 2020.
[19] M. N. Alam, B. Das, and V. Pant, "An interior point method based protection coordination scheme for directional overcurrent relays in meshed networks," *International Journal of Electrical Power & Energy Systems*, vol. 81, pp. 153–164, Oct. 2016.
[20] H. H. Zeineldin, H. M. Sharaf, D. K. Ibrahim, and E. E. D. A. El-Zahab, "Optimal protection coordination for meshed distribution systems with DG using dual setting directional over-current relays," *IEEE Trans Smart Grid*, vol. 6, no. 1, pp. 115–123, Jan. 2015.
[21] A. Yazdaninejadi, S. Golshannavaz, D. Nazarpour *et al.*, "Dual-setting directional overcurrent relays for protecting automated distribution networks," *IEEE Trans. Industr. Inform.*, vol. 15, no. 2, pp. 730–740, Feb. 2019.
[22] K. Singh, S. Sarangi, A. K. Singh, and S. R. Mohanty, "Coordination of dual-setting overcurrent and distance relays for meshed distribution networks with distributed generations and dynamic voltage restorer," *Smart Science*, vol. 11, no. 1, pp. 135–153, 2023.
[23] R. Tiwari, R. K. Singh, and N. Kumar Choudhary, "Optimal coordination of dual setting directional over current relays in microgrid with different standard relay characteristics," in *Proc. 2020 IEEE 9th Power India Int. Conf. (PIICON)*, Feb. 2020. doi: 10.1109/PIICON49524.2020.9112883
[24] P. K. Gupta, P. Niranjan, N. K. Choudhary, N. K. Singh, and N. Kumar, "A novel protection coordination scheme based on dual-setting rate of change of voltage based relays," in *Proc. 5th Int. Conf. on Energy, Power, and Environment: Towards Flexible Green Energy Technologies*, 2023. doi: 10.1109/ICEPE57949.2023.10201612
[25] K. A. Saleh, H. H. Zeineldin, A. Al-Hinai, and E. F. El-Saadany, "Optimal coordination of directional overcurrent relays using a new time-current-voltage characteristic," *IEEE Trans. on Power Delivery*, vol. 30, no. 2, pp. 537–544, Apr. 2015.
[26] D. Birla, R. P. Maheshwari, and H. O. Gupta, "A new nonlinear directional overcurrent relay coordination technique, and banes and boons of near-end faults based approach," *IEEE Trans. on Power Delivery*, vol. 21, no. 3, pp. 1176–1182, Jul. 2006.
[27] K. A. Saleh, H. H. Zeineldin, A. Al-Hinai, and E. F. El-Saadany, "Dual-setting characteristic for directional overcurrent relays considering multiple fault locations," *IET Generation, Transmission and Distribution*, vol. 9, no. 12, pp. 1332–1340, Sep. 2015.
[28] A. Kuriakose and S. Balamurugan, "Optimum overcurrent relay coordination in radial system using particle swarm optimization," in *Proc. 2023 IEEE 7th Conf. on Information and Communication Technology (CICT)*, pp. 1–4, Dec. 2023. doi: 10.1109/cict59886.2023.10455379
[29] A. Kuriakose and S. Balamurugan, "Optimum overcurrent relay coordination using genetic algorithm with time multiplier setting and pick-up current setting as variables," *International Review on Modelling and Simulations (IREMOS)*, vol. 16, no. 5, p. 324, Oct. 2023. doi: 10.15866/iremos.v16i5.23645
[30] A. Kuriakose and S. Balamurugan, "Optimum overcurrent relay coordination in scaled-down IEEE 5-bus system for changing network configuration," *International Review of Electrical Engineering (IREE)*, vol. 19, no. 1, p. 31, Feb. 2024. doi: 10.15866/iree.v19i1.23915
[31] Purwar, D. N. Vishwakarma, and S. P. Singh, "A novel constraints reduction-based optimal relay coordination method considering variable operational status of distribution system with DGs," *IEEE Trans Smart Grid*, vol. 10, no. 1, pp. 889–898, Jan. 2019.
[32] T. S. Aghdam, H. Kazemi Karegar, and H. H. Zeineldin, "Transient stability constrained protection coordination for distribution systems with DG," *IEEE Trans Smart Grid*, vol. 9, no. 6, pp. 5733–5741, Nov. 2018.
[33] Y. Damchi, J. Sadeh, and H. R. Mashhadi, "Optimal coordination of distance and overcurrent relays considering a non-standard tripping characteristic for distance relays," *IET Generation, Transmission and Distribution*, vol. 10, no. 6, pp. 1448–1457, Apr. 2016.
[34] M. Singh, T. Vishnuvardhan, and S. G. Srivani, "Adaptive protection coordination scheme for power networks under penetration of distributed energy resources," *IET Generation, Transmission and Distribution*, vol. 10, no. 15, pp. 3919–3929, Nov. 2016.
[35] K. A. Saleh, M. S. El Moursi, and H. H. Zeineldin, "A new protection scheme considering fault ride through requirements for transmission level interconnected wind parks," *IEEE Trans. Industr. Inform.*, vol. 11, no. 6, pp. 1324–1333, Dec. 2015.
[36] S. Noghabi, J. Sadeh, and H. R. Mashhadi, "Considering different network topologies in optimal overcurrent relay coordination using a hybrid GA," *IEEE Trans. on Power Delivery*, vol. 24, no. 4, pp. 1857–1863, 2009.
[37] A. F. Elneweihi, E. O. Schweitzer, M. W. Feltis, "Negative-sequence overcurrent element application and coordination in distribution protection," *IEEE Trans. on Power Delivery*, vol. 8, no. 3, pp. 915-924, 1993.
[38] T. S. Aghdam, H. K. Karegar, and H. H. Zeineldin, "Optimal coordination of double-inverse overcurrent relays for stable operation of DGs," *IEEE Trans. Industr. Inform.*, vol. 15, no. 1, pp. 183–192, Jan. 2019.
[39] A. Castillo Salazar, A. Conde Enríquez, and S. E. Schaeffer, "Directional overcurrent relay coordination considering non-standardized time curves," *Electric Power Systems Research*, vol. 122, pp. 42–49, May 2015.
[40] M. Sharaf, H. H. Zeineldin, D. K. Ibrahim, and E. E. D. A. El-Zahab, "A proposed coordination strategy for meshed distribution systems with DG considering user-defined characteristics of directional inverse time overcurrent relays," *International Journal of Electrical Power & Energy Systems*, vol. 65, pp. 49–58, Feb. 2015.
[41] C. Kiliçkiran, H. Akdemir, I. Şengör, B. Kekezoğlu, and N. G. Paterakis, "A non-standard characteristic based protection scheme

for distribution networks," *Energies (Basel)*, vol. 11, no. 5, 2018. doi: 10.3390/en11051241

[42] M. Singh, V. Telukunta, and S. G. Srivani, "Enhanced real time coordination of distance and user defined over current relays," *International Journal of Electrical Power & Energy Systems*, vol. 98, pp. 430–441, Jun. 2018.

[43] A. Castillo, A. Conde, and E. Fernandez, "Mitigation of DOCR miscoordination through distance relays and non-standard overcurrent curves," *Electric Power Systems Research*, vol. 163, pp. 242–251, Oct. 2018.

[44] Chawla, B. R. Bhalja, B. K. Panigrahi, and M. Singh, "Gravitational search based algorithm for optimal coordination of directional overcurrent relays using user defined characteristic," *Electric Power Components and Systems*, vol. 46, no. 1, pp. 43–55, Jan. 2018.

[45] Shah, N. Khristi, V. N. Rajput, and K. S. Pandya, "A comparative study based on objective functions for optimum coordination of overcurrent relays," in *Proc. 2017 7th Int. Conf. on Power Systems*, Dec. 2017, pp. 7–12. doi: 10.1109/ICPES.2017.8387260

[46] J. Ehrenberger and J. Švec, "Directional overcurrent relays coordination problems in distributed generation systems," *Energies (Basel)*, vol. 10, no. 10, Oct. 2017. doi: 10.3390/en10101452

[47] J. Nocedal and S. J. Wright, *Numerical Optimization*, 2nd Edition, New York: Springer, 2006. doi: 10.1007/978-0-387-40065-5

[48] S. M. A. Mosavi, T. A. Kejani, and H. Javadi, "Optimal setting of directional over-current relays in distribution networks considering transient stability," *International Trans. on Electrical Energy Systems*, vol. 26, no. 1, pp. 122–133, Jan. 2016.

[49] E. Purwar, D. N. Vishwakarma, and S. P. Singh, "Optimal relay coordination for grid connected variable size DG," in *Proc. 2016 IEEE 6th Int. Conf. on Power Systems*, Mar. 2016. doi: 10.1109/ICPES.2016.7584147

[50] M. K. Afifi, H. M. Sharaf, M. M. Sayed, and D. K. Ibrahim, "Comparative study between single-objective and multi-objective optimization approaches for directional overcurrent relays coordination considering different fault locations," in *Proc. 2019 IEEE Milan PowerTech*, Jun. 2019. doi: 10.1109/PTC.2019.8810815

[51] V. Vijayachandran and U. J. Shenoy, "Design and implementation of an adaptive relay based on curve-fitting technique for micro-grid protection," *International Journal of Emerging Electric Power Systems*, vol. 23, no. 4, pp. 621–631, Aug. 2022.

[52] IEEE, "Computer representation of overcurrent relay characteristics," *IEEE Trans. on Power Delivery*, vol. 4, no. 3, pp. 1659–1667, Jul. 1989.

[53] L. Chung, Y. Lu, W. S. Kao, and C. J. Chou, "Study of solving the coordination curve intersection of inverse-time overcurrent relays in subtransmission systems," *IEEE Trans. on Power Delivery*, vol. 23, no. 4, pp. 1780–1788, 2008.

[54] S. Noghabi, H. R. Mashhadi, and J. Sadeh, "Optimal coordination of directional overcurrent relays considering different network topologies using interval linear programming," *IEEE Trans. on Power Delivery*, vol. 25, no. 3, pp. 1348–1354, Jul. 2010.

[55] J. Urdaneta and H. Restrepo, "Coordination of directional overcurrent relay timing using linear programming," *IEEE Trans. on Power Delivery*, vol. 11, no. 1, pp. 122-129, 1996.

[56] J. Urdaneta, R. Nadira, and L. G. P. Jimenez, "Optimal coordination of directional overcurrent relays in interconnected power systems," *IEEE Trans. on Power Delivery*, vol. 3, no. 3, pp. 903–911, Jul. 1988.

[57] R. Corrêa, G. Cardoso, O. C. B. D. Araújo, and L. Mariotto, "Online coordination of directional overcurrent relays using binary integer programming," *Electric Power Systems Research*, vol. 127, pp. 118–125, Oct. 2015.

[58] V. A. Papaspiliotopoulos, G. N. Korres, and N. G. Maratos, "A novel quadratically constrained quadratic programming method for optimal coordination of directional overcurrent relays," *IEEE Trans. on Power Delivery*, vol. 32, no. 1, pp. 3–10, Feb. 2017.

[59] V. N. Rajput, K. S. Pandya, and K. Joshi, "Optimal coordination of directional overcurrent relays using hybrid CSA-FFA method," in *Proc. 2015 12th Int. Conf. on Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology*, Jun. 2015. doi: 10.1109/ECTICon.2015.7207044

[60] P. Niranjan, P. K. Gupta, P. Ahmad, N. K. Choudhary, N. Singh, and R. K. Singh, "Protection coordination scheme in microgrid with common optimal settings of user-defined dual-setting overcurrent relays," in *Proc. 5th Int. Conf. on Energy, Power, and Environment: Towards Flexible Green Energy Technologies*, 2023. doi: 10.1109/ICEPE57949.2023.10201516

[61] Z. Moravej, F. Adelnia, and F. Abbasi, "Optimal coordination of directional overcurrent relays using NSGA-II," *Electric Power Systems Research*, vol. 119, pp. 228–236, Feb. 2015.

[62] H. H. Zeineldin, E. F. El-Saadany, and M. M. A. Salama, "Optimal coordination of overcurrent relays using a modified particle swarm optimization," *Electric Power Systems Research*, vol. 76, no. 11, pp. 988–995, Jul. 2006.

[63] M. Senapati, P. K. Panigrahi, P. K. Ray, and A. Mohanty, "Optimal relay coordination and optimization in distributed generation based power system," in *Proc. 2022 IEEE 2nd Int. Symp. on Sustainable Energy, Signal Processing and Cyber Security*, 2022. doi: 10.1109/iSSSC56467.2022.10051512

[64] F. Alasali, A. Al-Hayajneh, E. Zarour, and O. Alsmadi, "Optimal protection coordination scheme of overcurrent relays for microgrid system," in *Proc. 10th IEEE Int. Conf. on Renewable Energy Research and Applications*, 2021, pp. 88–93.

[65] H. Yang, F. Wen, and G. Ledwich, "Optimal coordination of overcurrent relays in distribution systems with distributed generators based on differential evolution algorithm," *International Trans. on Electrical Energy Systems*, vol. 23, no. 1, pp. 1–12, Jan. 2013.

[66] M. Ezzeddine, R. Kaczmarek, and M. U. Iftikhar, "Coordination of directional overcurrent relays using a novel method to select their settings," *IET Generation, Transmission & Distribution*, vol. 5, no. 7, pp. 743–750, Jul. 2011.

[67] J. Moirangthem, K. R. Krishnanand, S. S. Dash, and R. Ramaswami, "Adaptive differential evolution algorithm for solving non-linear coordination problem of directional overcurrent relays," *IET Generation, Transmission and Distribution*, vol. 7, no. 4, pp. 329–336, 2013.

[68] M. Singh, B. K. Panigrahi, A. R. Abhyankar, and S. Das, "Optimal coordination of directional over-current relays using informative differential evolution algorithm," *J. Comput. Sci.*, vol. 5, no. 2, pp. 269–276, Mar. 2014.

[69] M. H. Hussain, A. Farid Abidin, S. Rafidah, and A. Rahim, "Solving directional overcurrent relay coordination problem using artificial bees colony," *International Journal of Electrical and Computer Engineering*, vol. 8, no. 5, pp. 773–778, 2014.

[70] A. Albasri, A. R. Alroomi, and J. H. Talaq, "Optimal coordination of directional overcurrent relays using biogeography-based optimization algorithms," *IEEE Trans. on Power Delivery*, vol. 30, no. 4, pp. 1810–1820, Aug. 2015.

[71] R. Tiwari, R. K. Singh, and N. K. Choudhary, "A comparative analysis of optimal relay coordination for different network configuration," in *Proc. 2021 1st Int. Conf. on Power Electronics and Energy*, Jan. 2021. doi: 10.1109/ICPEE50452.2021.9358719

[72] R. Tiwari, R. K. Singh, and N. K. Choudhary, "A comparative analysis of optimal coordination of distance and overcurrent relays with standard relay characteristics using GA, GWO and WCA," in *Proc. 2020 IEEE Students Conf. on Engineering & Systems*, Jul. 2020. doi: 10.1109/SCES50439.2020.9236743

[73] P. Bedekar and S. R. Bhide, "Optimum coordination of directional overcurrent relays using the hybrid GA-NLP approach," *IEEE Trans. on Power Delivery*, vol. 26, no. 1, pp. 109–119, Jan. 2011.

[74] J. Sadeh, V. Aminotojari, and M. Bashir, "Optimal coordination of overcurrent and distance relays with hybrid genetic algorithm," in *Proc. 2011 10th Int. Conf. on Environment and Electrical Engineering*, May 2011. doi: 10.1109/EEEIC.2011.5874690

[75] V. A. Papaspiliotopoulos, T. A. Kurashvili, and G. N. Korres, "Optimal coordination of directional overcurrent relays in distribution systems with distributed generation based on a hybrid PSO-LP algorithm," in *Proc. MedPower 2014*, 2014. doi: 10.1049/cp.2014.1697

[76] J. Radosavljević and M. Jevtić, "Hybrid GSA-SQP algorithm for optimal coordination of directional overcurrent relays," *IET Generation, Transmission and Distribution*, vol. 10, no. 8, pp. 1928–1937, May 2016.

[77] M. Bashir, M. Taghizadeh, J. Sadeh, and H. R. Mashhadi, "A new hybrid particle swarm optimization for optimal coordination of over current relay," in *Proc. 2010 Int. Conf. on Power System Technology*, 2010. doi: 10.1109/POWERCON.2010.5666600

[78] R. Al-Roomi and M. E. El-Hawary, "Optimal coordination of

double primary directional overcurrent relays using a new combinational BBO/DE algorithm," *Canadian Journal of Electrical and Computer Engineering*, vol. 42, no. 3, pp. 135–147, Jun. 2019.

[79] D. Sarkar and S. Kudkelwar, "Optimal over current relay coordination in Microgrid using a novel hybrid Water Cycle-Moth Flame algorithm," *International Journal of System Assurance Engineering and Management*, vol. 12, no. 3, pp. 553–564, Jun. 2021.

[80] H. Ataee-Kachoee, H. Hashemi-Dezaki, and A. Ketabi, "Optimal protective coordination of microgrids considering N-1 contingency using dual characteristics directional overcurrent relays," in *Proc. the 16th Int. Conf. on Protection and Automation of Power Systems*, 2022. doi: 10.1109/IPAPS55380.2022.9763257

[81] K. Soni, A. Kumar, R. K. Panda, A. Mohapatra, and S. N. Singh, "Adaptive coordination of relays in AC microgrid considering operational and topological changes," *IEEE Syst. J.*, vol. 17, no. 2, pp. 3071–3082, Jun. 2023.

[82] S. Abeid, Y. Hu, and N. El-Naily, "Optimal overcurrent relay coordination based on hybrid water cycle moth flame optimization (HWCMFO) algorithm considering standard and non-standard characteristics of microgrids," *IET Conf. Proc.*, vol. 2022, no. 2, pp. 433–438, May 2022. doi: 10.1049/icp.2022.0978

[83] M. G. A. Elsamahy, E. Beshr, and K. El Bahrawy, "Optimal overcurrent relay coordination for small scale microgrid," in *Proc. the 2023 5th Int. Youth Conf. on Radio Electronics, Electrical and Power Engineering*, 2023. doi: 10.1109/REEPE57272.2023.10086772

[84] M. Usama, M. Moghavvemi, H. Mokhlis, N. N. Mansor, H. Farooq, and A. Pourdaryaei, "Optimal protection coordination scheme for radial distribution network considering on/off-grid," *IEEE Access*, vol. 9, pp. 34921–34937, 2021.

[85] E. Dehghanpour, H. Kazemi Karegar, R. Kheirollahi, and T. Soleymani, "Optimal coordination of directional overcurrent relays in microgrids by using cuckoo-linear optimization algorithm and fault current limiter," *IEEE Trans Smart Grid*, vol. 9, no. 2, pp. 1365–1375, 2018.

[86] H. El-Hamrawy, A. A. M. Ebrahiem, and A. I. Megahed, "Improved adaptive protection scheme based combined centralized/decentralized communications for power systems equipped with distributed generation," *IEEE Access*, vol. 10, pp. 97061–97074, 2022.

[87] S. Ashfaq, D. Zhang, M. O. Dioha, and T. N. Malik, "A novel protection coordination scheme for regionalized microgrid at islanded mode," in *Proc. 2022 IEEE PES Gen., Transm. and Distri. Conf. and Expo. - Latin America*, 2022. doi: 10.1109/IEEEPESGTDLatinAmeri53482.2022.10038301

[88] S. M. Saad, F. Alasali, N. El Naily, A. Elhaffar, T. Hussein, and F. A. Mohamed, "Coordination of mixed overcurrent and voltage-restrained overcurrent relays to avoid miscoordination problems considering IEC time-current curve limitations," in *Proc. 2021 12th Int. Renewable Energy Congress*, 2021. doi: 10.1109/IREC52758.2021.9624932

[89] Y. N. Bhosale, R. P. Hasabe, and A. Kshirsagar, "Real time relay coordination in radial and hybrid distribution system," in *Proc. 2024 IEEE 4th Int. Conf. on Sustainable Energy and Future Electric Transportation*, 2024. doi: 10.1109/SEFET61574.2024.10718025

[90] R. Nidhi, Kumar Saha Roy, D. Saha, and M. Mukherjee, "Performance comparison of PSO, HGSO, and DE optimization techniques for computation of directional overcurrent relay coordination in power systems," *Engineering Review*, vol. 44, no. 2, 2024. doi: 10.30765/er.2429

[91] A. Unluturk and I. Ozer, "Optimization based control of overcurrent relays in distribution network considering real-time measurements: A case study," *Appl. Energy*, vol. 377, Jan. 2025. doi: 10.1016/j.apenergy.2024.124439

[92] N. Z. Jamal, M. H. Sulaiman, A. Nasir, and W. A. Jabbar, "Optimal overcurrent relay solutions for protection coordination using metaheuristics approaches with penalty function method," *Journal of Advanced Research in Applied Sciences and Engineering Technology*, vol. 49, no. 1, pp. 245–271, Jul. 2025.

[93] T. S. Zhan, Y. Der Lee, and J. L. Jiang, "Optimal OCR coordination in a high penetration distribution power system using a refined immune algorithm with an auto-tuning reproductive mechanism," *AIMS Energy*, vol. 12, no. 6, pp. 1225–1263, 2024.

[94] J. Sarvaiya and T. Pandya, "Optimal coordination of multiple setting group type overcurrent relays," *Journal of Electrical Systems*, vol. 20, no. 5s, pp. 126–132, Apr. 2024.

[95] A. Bayazidi, A. Abdali, and J. C. Vasquez, "Optimal coordination of directional overcurrent relays in power energy systems with emphasis on the discreteness of variables: Comprehensive comparisons," *Heliyon*, vol. 10, no. 19, Oct. 2024. doi: 10.1016/j.heliyon.2024.e37972

[96] N. Sheta, B. E. Sedhom, A. Pal, M. S. El Moursi, and A. A. Eladl, "Machine-learning-based adaptive settings of directional overcurrent relays with double-inverse characteristics for stable operation of microgrids," *IEEE Trans. Industr. Inform.*, vol. 21, no. 1, pp. 584–593, Jan. 2025.

[97] R. Tiwari, R. K. Singh, and N. K. Choudhary, "Effect of DG penetration on hybrid relay coordination using user-defined dual-setting directional overcurrent relays and distance relays," *Smart Science*, 2024. doi: 10.1080/23080477.2024.2403257

[98] Al-Bhadely and A. İnan, "An innovative approach for enhancing relay coordination in distribution systems through online adaptive strategies utilizing DNN machine learning and a hybrid GA-SQP framework," *Arab. J. Sci. Eng.*, Dec. 2024. doi: 10.1007/s13369-024-09291-0

[99] M. De Oliveira-De Jesus and E. Sorrentino, "A Monte Carlo method to solve the optimal coordination of directional overcurrent protections considering all the possible fault locations," *Electric Power Systems Research*, vol. 236, Nov. 2024. doi: 10.1016/j.epsr.2024.110974

[100] Bhalla and B. R. Bhalja, "A new fault detection and relay coordination technique for low voltage DC microgrid," *Electric Power Systems Research*, vol. 236, Nov. 2024. doi: 10.1016/j.epsr.2024.110907

[101] M. B. Atsever, O. Karacasu, and M. H. Hocaoglu, "Performance analysis of different optimization algorithms on overcurrent relay coordination problem in distribution systems," in *Proc. 2021 11th Smart Grid Conf. (SGC)*, Dec. 2021. doi: 10.1109/sgc54087.2021.9664218

[102] S. U. Khan, M. Shazzad Hossain, and I. Sultan, "Machine learning based coordination for IDMT overcurrent and earth fault relays," in *Proc. 2023 33rd Australasian Universities Power Engineering Conf. (AUPEC)*, Sep. 2023. doi: 10.1109/aupec59354.2023.10502775

[103] O. Seng, M. Pujiantara, A. Priyadi, and V. R. Mahindara, "Enhancement of overcurrent relay coordination in modern industrial distribution system using adaptive modified firefly algorithm," in *Proc. 2023 Int. Seminar on Intelligent Technology and Its Applications*, Jul. 2023, pp. 534–539.

[104] N. Kumar and D. K. Jain, "A novel transient search optimization for optimal directional over current relay coordination for multi-technology microgrid protection," *International Journal on Recent and Innovation Trends in Computing and Communication*, vol. 11, no. 9, pp. 1553–1562, Nov. 2023.

[105] S. Ganji, J. N. Manohar, and G. Yesuratnam, "Adaptive overcurrent coordination scheme to improve relay sensitivity in smart grid with DGs and EV charging stations using harris hawk optimization," in *Proc. 2024 IEEE 4th Int. Conf. on Sustainable Energy and Future Electric Transportation (SEFET)*, Jul. 2024. doi: 10.1109/sefet61574.2024.10718136

[106] P. Kumar, O. AlZaabi, K. Al Jaafari, P. Kumar, K. Al Hosani, and U. R. Muduli, "Comparative assessment of optimization techniques employed for coordination of directional overcurrent relays," in *Proc. 2023 IEEE IAS Global Conf. on Renewable Energy and Hydrogen Technologies (GlobConHT)*, Mar. 2023. doi: 10.1109/globconht56829.2023. 10087487

[107] S. Ralhan, R. Goswami, and S. Ray, "Comparative study of optimal overcurrent relay coordination using metaheuristic techniques," *Computational Intelligence in Data Mining*, pp. 333–344, Jul. 2018. doi: 10.1007/978-981-10-8055-5_30

[108] A. Korashy, S. Kamel, H. Shahinzadeh, E. Kabalci, and F. Jurado, "Different optimization techniques for solving the coordination problem of DOCRs," in *Proc. 2022 4th Global Power, Energy and Communication Conf. (GPECOM)*, Jun. 2022, pp. 499–505.

[109] I. N. Trivedi, S. V. Purani, and P. K. Jangir, "Optimized over-current relay coordination using flower pollination algorithm," in *Proc. 2015 IEEE Int. Advance Computing Conf. (IACC)*, Jun. 2015, pp. 72–77.

[110] M. H. Costa, R. R. Saldanha, M. G. Ravetti, and E. G. Carrano,

"Robust coordination of directional overcurrent relays using a matheuristic algorithm," *IET Generation, Transmission & Distribution*, vol. 11, no. 2, pp. 464–474, Jan. 2017.

[111] R. Tiwari, R. K. Singh, and N. K. Choudhary, "Optimal relay coordination for DG-based power system using standard and user-defined relay characteristics," *International Journal of Engineering and Technology Innovation*, vol. 12, no. 3, pp. 207–224, Mar. 2022.

[112] S. S. Rath, G. Panda, P. K. Ray, and A. Mohanty, "Optimal relay coordination in solar PV integrated power system using grey wolf optimization," *Sustainable Energy and Technological Advancements*, pp. 665–674, 2023. doi: 10.1007/978-981-99-4175-9_53

[113] P. Niranjan, A. Anand, N. Singh, and N. K. Choudhary, "Comparative study of optimal relay coordination with current and voltage-based relay in distributed generation systems," in *Proc. 2022 IEEE Students Conf. on Engineering and Systems (SCES)*, Jul. 2022. doi: 10.1109/sces55490.2022.9887749

[114] E. Purwar, S. P. Singh, and D. N. Vishwakarma, "A robust and fast solving approach to improve relays coordination considering variable sizes of DGs and their outages," in *Proc. 2022 IEEE Int. Conf. on Power Electronics, Smart Grid, and Renewable Energy*, Jan. 2022. doi: 10.1109/pesgre52268.2022.9715950

[115] A. Alipour and M. Pacis, "Optimal coordination of Directional Overcurrent Relays (DOCR) in a ring distribution network with Distributed Generation (DG) using genetic algorithm," in *Proc. 2016 IEEE Region 10 Conf. (TENCON)*, Nov. 2016, pp. 3109–3112.

[116] S. T. P. Srinivas and K. S. Swarup, "Optimal relay coordination and communication based protection for microgrid," in *Proc. 2017 IEEE Region 10 Symposium (TENSYMP)*, Jul. 2017. doi: 10.1109/tenconspring.2017.8070034

[117] T. Alazemi, M. Darwish, and M. Radi, "TSO/DSO coordination for RES integration: A systematic literature review," *Energies*, vol. 15, no. 19, p. 7312, Oct. 2022. doi: 10.3390/en15197312

[118] P. Niranjan, A. Anand, N. Singh, and N. K. Choudhary, "Comparative study of optimal relay coordination with current and voltage-based relay in distributed generation systems," in *Proc. 2022 IEEE Students Conf. on Engineering and Systems (SCES)*, Jul. 2022. doi: 10.1109/sces55490.2022.9887749

[119] A. I. Atteya, A. M. El Zonkoly, and Hamdy. A. Ashour, "Optimal relay coordination of an adaptive protection scheme using modified PSO algorithm," in *Proc. 2017 Nineteenth Int. Middle East Power Systems Conf. (MEPCON)*, Dec. 2017, pp. 689–694. doi: 10.1109/mepcon.2017.8301256

[120] A. H. Ataee‐Kachoee, H. Hashemi-Dezaki, and A. Ketabi, "Optimal adaptive protection of smart grids using high-set relays and smart selection of relay tripping characteristics considering different network configurations and operation modes," *IET Generation, Transmission & Distribution*, vol. 16, no. 24, pp. 5084–5116, Nov. 2022. doi: 10.1049/gtd2.12659

[121] A. Bonfiglio, F. Delfino, R. Minciardi, R. Procopio, and M. Robba, "A dynamic decision model for Smart Grid real time optimal control," in *Proc. 2012 IEEE Int. Energy Conf. and Exhibition (ENERGYCON)*, Sep. 2012, pp. 587–592. doi: 10.1109/energycon.2012.6348221

[122] G. K. Venayagamoorthy, "A dynamic optimization method for a smart grid," in *Proc. IEEE PES General Meeting*, Jul. 2010. doi: 10.1109/pes.2010.5589824

[123] S. R. J. Varghese, A. Venu, K. R. M. Vijaya Chandrakala, T. Gireesh Kumar, and V. K. Arun Shankar, "Enhancing power grid security by detecting relay setting manipulation attacks with machine learning," in *Proc. 2024 3rd Int. Conf. on Artificial Intelligence for Internet of Things (AIIoT)*, May 2024. doi: 10.1109/aiiot58432.2024.10574573

[124] A. N. Sheta, M. I. El-Afifi, B. E. Sedhom, and A. A. Eladl, "Machine learning-enhanced security for distance relays against cyber-attacks," in *Proc. 2024 25th Int. Middle East Power System Conf.* 2024. doi: 10.1109/mepcon63025.2024.10850182

[125] M. Cavus, "Integration smart grids, distributed generation, and cybersecurity: strategies for securing and optimizing future energy systems," Oct. 2024. doi: 10.20944/preprints202410.1225.v1

[126] O. Dzobo, L. Tivani, and L. Mbatha, "A review on cybersecurity for distributed energy resources: Opportunities for South Africa," *Journal of Infrastructure, Policy and Development*, vol. 8, no. 15, p. 8631, Dec. 2024. doi: 10.24294/jipd8631

[127] S. McFly, J. Peterson, and T. Reynolds, "Distributed energy resource cybersecurity framework and cyber range integration," U.S. Department of Energy Office of Scientific and Technical Information (OSTI), May 2022. doi: 10.2172/1868050

[128] A. A. Shobole and M. Abafogi, "Adaptive protection in smart distribution networks: coordination demonstration of multi-agent systems," in *Proc. 2023 5th Global Power, Energy and Communication Conf. (GPECOM)*, Jun. 2023, pp. 483–488.

[129] P. Biswas, A. Rashid, A. Al Masum *et al.*, "An extensive and methodical review of smart grids for sustainable energy management-addressing challenges with AI, renewable energy integration and leading-edge technologies," *IEEE Access*, pp. 1–1, 2025. doi: 10.1109/access.2025.3537651

[130] A. Dayoub, "Integrating security, privacy, and advanced cyber technologies for resilient urban, IoT, and AI systems," *World Journal of Advanced Engineering Technology and Sciences*, vol. 13, no. 1, pp. 85–99, Sep. 2024.

[131] L. Garza, P. Mandal, and G. Ravikumar, "Mitigation of cyber attacks in DER-integrated distribution grid using deep generative models," in *Proc. 2024 IEEE Power & Energy Society General Meeting (PESGM)*, Jul. 2024. doi: 10.1109/pesgm51994.2024.10689021

Anu Kuriakose received her bachelor of technology in electrical and electronics engineering (2009) from Mahatma Gandhi University, Kottayam, Kerala, India, and her master of engineering in power systems (2012) from Anna University, Chennai, Tamil Nadu, India. She worked as an assistant professor in reputed institutions in Kerala. She is a full-time Ph.D. scholar in the Department of Electrical and Electronics Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India. Her research interests include smart grid, power system relay coordination, and ai applications in power system protection.

S. Balamurugan was born at Nagapattinam, Tamil Nadu, India, in 1980. He got a B.E. in electrical and electronics engineering and an M.E. in power systems from Annamalai University, Tamil Nadu, India. He also obtained his Ph.D. from Anna University, Chennai, Tamil Nadu, India. He is the chairperson & professor, Department of Electrical and Electronics Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India. He has published over 31 International Journal publications and 55 conference publications. His area of interest is power system operation and control, deregulated power system, smart grid, power electronics applications to power systems, soft computing, and gas turbine control.

Lekshmi R. R. was born in Kollam, India in 1985. She received her B.Tech. Degree in electrical and electronics engineering from Cochin University of Science and Technology, Kerala, India, in 2006, M.E. Degree in power systems engineering from Anna University, Tamil Nadu, India, in 2008, and Ph.D. degree from Amrita Vishwa Vidyapeetham, Tamil Nadu, India, in 2018. Her research interest includes operation and control in deregulated power systems, soft computing, energy management techniques, machine learning, and deep learning. Dr. Lekshmi R. R. has received the Outstanding Women Researcher award from Venus International Foundation, the Best Young Researcher International Award, and the Best Paper Award.