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TOPICAL REVIEW

Optimization Techniques for Directional Overcurrent Relay Coordination: A Comprehensive Review

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ABSTRACT This paper provides a comprehensive review of optimization techniques for coordinating directional overcurrent relays in power systems. It covers a wide range of techniques, including conventional and deterministic methods, metaheuristic algorithms, and hybrid approaches. The paper discusses the objective functions utilized in formulating relay coordination problem and presents the development of optimization methods for solving this problem. Furthermore, it examines the criteria for comparing different algorithms for coordination problem and includes a case study to demonstrate the practical application of these criteria. It also presents simulation software employed for examining and validating results obtained from optimization algorithms. Future trends and challenges regarding optimal coordination of directional overcurrent relays are also discussed. The paper concludes that there is no single "best" optimization technique for the coordination problem. The best technique for a particular application will depend on the specific characteristics of the power system and the constraints of the coordination problem.

INDEX TERMS Distributed power generation, microgrids, optimization methods, particle swarm optimization, power distribution networks, power system faults, power system protection, relays, short-circuit currents, transmission lines.

NOMENCLATURE

VARIABLES AND CONSTANTS

TM	Time multiplier.
CSM	Current setting multiplier.
t_u	Operating time of the upstream relay.
t_d	Operating time of the downstream relay.
t_{op}	Primary relay operational time.
λ & γ	Tripping curve constants defined by ANSI/IEEE and IEC standards.
T_{ik}	Operating time of ith relay for a fault in zone k.
W_i'	Probability of the occurrence of the fault on a line.
$T^i_{pri,near}$	Operating time of ith primary relay for near-end fault.
$T^j_{pri,far}$	Operating time of jthprimary relay for far-end fault.
t_i	The ith relay operating time for a fault close to the circuit breaker (CB) of the ith relay.
t_m	Operating time of the main relay for a fault exactly close to the CB of the ith relay.
t_b	Operating time of the backup relays for a fault exactly close to the CB of the ith relay.
T^m_i, t_{n+1}, t_j, T_b, t_b	Operational time of the backup relay.
T^b_j, t_n, t_i, T_p, t_m	Operational time of the primary relay.

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TGM	Time grading margin.
Δt_{mb}	Difference of operating time between backup and primary relay.
Δt_{pbk}	Operating time difference with CTI between kth relays pair.
$t^{p}_{fw\_cij}$	The primary relay i operating time, in the forward direction, for fault at j for configuration c.
$t^{bk}_{rv\_cij}$	The backup relay i operating time, in the reverse direction, for fault at j for configuration c.
t_{z2i}	Time defined for the second zone of distance relay.
NV	Number of violations of coordination constraints.
NCP	The number of coordination pairs.
t_{p-a}	The primary operation time of relay a.
t_{b-a}	The backup operation time of relay b.
E_{CTIL}	the CTI error of Lth coordination pair.
α, β, δ and w	weighting factors.
PS	Plug setting.
Ip	Pickup current.
TMS	Time multiplier setting.
TDS	Time dial setting.
CTI	Coordination time interval.
CTR	Current transformer ratio.
BC	Broken constraints.

ABBREVIATIONS

DOCR	Directional Overcurrent Relay.
WoS	Web of Science.
OF	Objective Function.
TCCC	Time-Current Characteristic Curve.
ENS	Energy Not Supplied.
P/B	Primary/Backup.
GUI	Graphical User Interface.
CAPE	Computer Aided Protection Engineering.
LP	Linear Programming.
NLP	Non-Linear Programming.
MILP	Mixed Integer Linear Programming.
MINLP	Mixed Integer Non-Linear Programming.
RST	Random Search Technique.
GAMS	General Algebraic Modelling System.
SQP	Sequential Quadratic Programming.
RTO	Rooted Tree Optimisation.
AA	Analytic Method.
DG	Distributed Generating.
GA	Genetic Algorithm.
NSFA-II	Non-Dominated Sorting Ga.
PSO	Particle Swarm Optimization.
DE	Differential Evolution.
MDE	Modified Version Of Differential Evolution.
TLBO	Teaching Learning Based Optimization.
LSA	Local Search Algorithm.
GSA	Gravitational Search Algorithm.
FA	Firefly Algorithm.
MFA	Modified Firefly Algorithm.
AMFA	Adaptive Modified Firefly Algorithm.
CPSO	Continuous Particle Swarm Optimization.
LIPSOL	Linear Interior Point Solver algorithm.
CGA	Continuous Genetic Algorithm.
ABC	Artificial Bee Colony.
MDE	Modified Differential Evolution.
LNS	Local Neighbourhood Search.
GMDE	Gaussian Modified Differential Evolution.
CMDE	Cauchy Modified Differential Evolution.
LMDE	Laplace Modified Differential Evolution.
ADE	Adaptive Differential Evolution.
SQP	Sequential Quadratic Programming.
OBL	Opposition Based Learning.
OCDE	Opposition Based Chaotic Differential Evolution.
HAS	Harmony Search Algorithm.
SM	Simplex Method.
DSM	Dual Simplex Method.
IHSA	Improvised Harmony Search Algorithm.
BMHS	Box-Muller Harmony Search.
SOMA	Self-Organizing Migrating Algorithm.
SOMGA	Self-Organizing Migrating Genetic Algorithm.
SOA	Seeker Optimization Algorithm.
FCL	Fault Current Limiter.
CFA	Chaotic Firefly Algorithm.
MATLBO	Modified Adaptive Teaching Learning Based Optimization.
WOA	Whale Optimization Algorithm.
MPSO	Modified Particle Swarm Optimization.
BBO	Biogeography-Based Optimization.
ILP	Interval Linear Programming.
BH	Black Hole.
CS	Cuckoo Search Algorithm.
HCS	Hierarchical Clustering Step Size.
ACO	Ant Colony Optimization.
ALO	Ant Lion Optimization.
AIS	Artificial Immune System.
BSA	Backtracking Search Algorithm.
EBSA	Enhanced Backtracking Search Algorithm.
MEFO	Modified Electromagnetic Field Optimization.
EM	Electromagnetism-Like Mechanism.
HHO	Harris Hawk Optimization.
CSA	Crow Search Algorithm.
ICA	Imperialist Competitive Algorithm.
FPA	Flower Pollination Algorithm.

WCA	Water Cycle Algorithm.
MWCA	Modified Water Cycle Algorithm.
ERWCA	Evaporation-Rate Based Water Cycle Algorithm.
MERWCA	Modified Evaporation-Rate Based Water Cycle Algorithm.
GWO	Grey Wolf Optimizer.
IGWO	Improvised Grey Wolf Optimizer.
EGWO	Enhanced Grey Wolf Optimizer.
RW-GWO	Random Walk Grey Wolf Optimizer.
MOGWO	Multi-Objective Grey Wolf Optimizer.
MHHO	Modified Harris Hawk Optimization.
GSO	Group Search Optimization.
SBB	Standard Branch-And-Bound.
PO	Political Optimization.
SOS	Symbiotic Organism Search Technique.
MECPSO	Multiple Embedded Crossover Particle Swarm Optimization.
MAPSO	Modified Adaptive Particle Swarm Optimization.
WOA	Whale Optimization Algorithm.
SCA	Sine Cosine Algorithm.
DC-HSS	Discrete And Continuous Hyper-Sphere Search.
BO	Bonobo Algorithm.
OJaya	Oppositional Jaya.
DAC	Distance Adaptive Coefficient.
OL	Oppositional Learning.
mGWO	Improved Grey Wolf Optimizer.
wGWO	Weighted Grey Wolf Optimizer.
SSA	Salp Swarm Algorithm.
cSSA	Chaotic Salp Swarm Algorithm.
EHA	Efficient Heuristic Algorithm.
NM	Nelder-Mead Simplex Search Method.
TVAC	Time Varying Acceleration Coefficients.
SA	Simulated Annealing.
MFO	Moth-Flame Optimization.
GBO	Gradient-Based Optimizer.
LSHADE	Memory-Based Linear Population Size Reduction Technique of Success-History-Based Adaptive Differential Evolution.
IWO	Invasive Weed Optimization.
IIWO	Improved Invasive Weed Optimization.
PT	Potential Transformer.

I. INTRODUCTION

Power system protection is an essential branch of electrical engineering that deals with the protection of electrical power systems from faults by disconnecting faulty components from the rest of the network [1]. Fast identification and isolation of faulty components are the main objectives of power system protection, minimizing the negative impact of the fault on the rest of the system [2].

Protection from faults is a basic necessity in the planning and designing of distribution systems. Electrical distribution networks include protection devices such as fuses, reclosers, relays, and circuit breakers. These devices play an essential role in protecting the network from faults by isolating the faulty section of the network from the rest. However, one limitation of these devices is their inability to accurately determine the current direction [3]. Directional overcurrent relays (DOCRs) are utilized for power system protection to ensure safe, reliable, and efficient operation of the power system [4].

The DOCR observes the current flow in the circuit that requires protection. If the short-circuit current flow in a certain direction exceeds the setpoint, the relay generates a trip signal that is transmitted to the circuit breaker, which isolates the faulty section of the network [5]. DOCRs have been used to design economical alternatives for primary and backup power system protection, providing reliable and efficient protection compared to traditional protection schemes. Consequently, by using DOCRs, it is possible to reduce the number of relays required for protection, which can significantly decrease the protection equipment and installation costs [6].

DOCRs can be classified according to their operating characteristics, which determine the time taken by the relay to operate under different fault conditions. Instantaneous relays operate without any time delay and trip the circuit breaker immediately when the current exceeds a predetermined value [7]. Definite time relays operate with a fixed time delay before tripping the breaker, regardless of the magnitude of the fault current [8]. Inverse time relays have a time-current characteristic that varies inversely with the magnitude of the fault current, resulting in faster operation rates for higher fault currents [9]. Inverse definite minimum time (IDMT) relays provide a combination of the inverse and definite time characteristics. The operating time of the relay is also inversely proportional to the fault current magnitude, but it also has a minimum time delay to prevent nuisance tripping for low fault currents [7]. The inverse time and IDMT characteristics are commonly used to optimize the coordination problem in power system protection schemes. They achieve a balance between the quick response to high fault currents and the minimal delay for low fault currents, preventing unnecessary tripping and reduce power system disruptions.

Relay coordination is an important stage in designing the protection system for an electrical power system. It ensures that the protective relays operate in the optimal sequence when a fault occurs [10]. It can be achieved using various techniques, including time-based coordination, current-based coordination, or a combination of both.

Time-based coordination involves adjusting the tripping time of relays based on their location in the power system. The difference in operating time between two subsequent relays is the Coordination Time Interval (CTI). This coordination system benefits from being simple and providing its own backup [8]. However, it falls short in networks where the fault current varies based on the fault location [7]. On the other hand, current-based coordination is suitable for circuits where there is a large difference in the ratio of fault current to rated current in sections of the network [11]. In such a situation, relays are configured to pick up gradually at greater current levels in the direction of the power source, and the current setting of the relays is decreased as one moves from the load to the power source. This ensures that the relay nearest to the fault will always trip first. The benefit of this method relative to the first method is that it requires less operating time when in close proximity to the power source. However, accurate relay discrimination is not achievable with this approach, as the fault current may not necessarily change with the location. To overcome the limitations of these individual techniques, a combination of time-based coordination and current-based coordination is often employed. In this approach, IDMT relays are used, and time and current settings are available for these relays. The current setting of the relays is set according to the short circuit current level of the specific zone that requires protection. The relays are configured to gradually pick up greater current levels in the direction of the power source. Additionally, the time setting is described in progressively higher order away from the source, ensuring accurate relay discrimination [9]. This approach is considered the most common method used for the coordination of DOCRs in power systems [7].

For any fault occurring on a line, protection relays are classified as primary relays and backup relays. Primary relays are the first line of defense against faults, and they recognize these faults as "in-zone" faults. Backup relays recognize the faults as "out-zone" faults, and they merely operate if the primary relays exceed the allowable time delay, which is the CTI [12], [13].

Proper relay coordination involves selecting the appropriate relay settings to ensure that backup protection in the protected zone is coordinated with the primary protection. This coordination ensures that, in the event of a fault, the appropriate relay will isolate the fault and protect the remaining power system components. In addition, if the primary relays fail to operate, the corresponding backup relays will operate after a specified time period, which is the CTI [14]. The relays must be properly coordinated to prevent maloperation. This will also help to avoid unnecessary tripping of breakers and the isolation of sections of the power system that are not faulted. This may be accomplished by appropriately determining the operating time of the relays [15], [16]. There are two main settings for the overcurrent relays: plug setting (PS) or pickup current (I_P) and time multiplier setting (TMS) or time dial setting (TDS). The operating time of each relay is determined by these two settings and the relay characteristic curve [17]. To minimize power network interruptions, the total operating time of DOCRs should be minimized while maintaining the specified CTI between the primary and backup protections to ensure the validity of the selectivity study [18]. However, the coordination problem can be formulated as an optimization problem with the purpose of minimizing the total operating times of the DOCRs while taking into account different constraints and boundary limits such as relay settings and selectivity constraints [19], [20].

The coordination problem is considered as a highly constrained, nonlinear, and non-convex optimization problem. It can be expressed as a linear programming problem by designating the time multiplier setting of the relays as a design variable, while the plug setting is considered as a fixed value within relay boundaries [21]. Alternatively, it can be formulated as a nonlinear programming problem by designating the time multiplier setting and plug setting as decision variables, which can either be continuous or discrete. For electromechanical and static relays, the time multiplier setting is continuous, and the plug setting is taken as a discrete variable. On the other hand, for microprocessor-based relays, both the time multiplier setting and plug setting are considered as continuous variables [10]. However, the discrete nature of the settings adds more complexity to the coordination problem as it limits the number of possible solutions that can be considered [22].

The purpose of the time multiplier setting is to adjust the time delay of the relay to ensure proper coordination with other relays in the system. By providing a family of curves, two or more relays, recognizing the same fault, can operate at different times. The plug setting, on the other hand, determines the level of current at which the relay will trip. Its value is adjusted to ensure that the relay operates only for faults within its designated protection zone and does not interfere with the operation of other protective devices in the system. The plug setting of the relay remains bounded between the upper and lower values at which all faults in the line section are visible. It should be above the largest possible load current and below the minimum short-circuit current, with a safety margin. Therefore, the main objective of the coordination problem is to find the optimal time multiplier setting and plug setting with a minimum operating time of DOCRs and under different network configurations and conditions [23], [24].

The integration of distributed generating (DG) units has introduced some complexity in protecting the distribution systems. This is attributed to the fact that DG units are mostly predicated on the bidirectional power flow smart grid scheme, which can make it difficult to ensure that relays are coordinated properly. DG units can also affect short-circuit levels, leading to relay coordination failure, nuisance fuse tripping, and other problems [25].

In recent years, optimization has become a popular research field and an economical way to find an optimal solution to complex problems. They have been widely applied by researchers for solving DOCRs coordination problem due to the increasing complexity of power systems and the need to ensure reliable and efficient operation of protection systems. Till today, the optimal relay coordination difficulties of DOCRs have received a lot of attention from researchers.

Almost always, the main goal is to minimize the overall operating time of the relays by optimizing the relay settings. However, the problem of coordination between relays remain unaddressed to this day [26], [27].

To optimize DOCRs coordination, it is necessary to satisfy three main requirements. Firstly, coordination between all relays should be maintained while minimizing the total operating time. Secondly, the plug settings and time multiplier settings should be robust enough to handle all possible operational and topological scenarios. Thirdly, it is essential to find the near-global optimal settings for effective optimization [23]. The gap that most scholars intended to fill is the improvement of the third requirement while also considering the first and second requirements.

There are various optimization techniques available to address the coordination problem of DOCRs. These techniques can be broadly classified into three categories: conventional and deterministic optimization methods [21], [22], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], metaheuristic methods [2], [6], [14], [15], [18], [19], [23], [26], [27], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114], [115], [116], [117], [118], [119], and hybrid methods [17], [20], [29], [120], [121], [122], [123], [124], [125], [126], [127], [128], [129], [130], [131], [132], [133], [134], [135], [136], [137]. Conventional and deterministic optimization, including linear programming (LP) such as simplex, dual simplex, two-phase simplex and Big-M methods [36], [37], [40], [138], [139], [140], non-linear programming (NLP) such as sequential quadratic programming (SQP) [30], interior point-based method [22], Random Search Technique (RST) [31], and gradient search-based method [32], Mixed Integer Linear Programming (MILP) [21], Analytical method (AA) [33], [34], and Local Fit method [35]. Metaheuristic methods, including Genetic Algorithm (GA) [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [119], Particle Swarm Optimization (PSO) [54], [55], [56], [57], [58], [59], [60], Rao-1 optimization algorithm [61], Honey bee algorithm [62], Artificial Bee Colony (ABC) [63], [64], [65], Differential Evolution (DE) [66], [67], [68], [69], [70], [71], [72], Harmony Search Algorithm (HSA) [73], [74], [75], Seeker Optimization Algorithm (SOA) [23], Biogeography-based optimization (BBO) [17], Firefly Algorithm (FA) [76], [77], [78], [79], [80], [81], [82], [83], Teaching Learning Based Optimization (TLBO) [84], [85], Cuckoo Search Algorithm (CS) [86], [87], [88], Ant Colony Optimization (ACO) [89], Ant Lion Optimization (ALO) [90], Backtracking Search Algorithm (BSA) [91], [92], Modified Electromagnetic Field Optimization (MEFO) [93], Rooted Tree Optimisation (RTO) [94], [95], Crow Search Algorithm (CSA) [96], Flower Pollination Algorithm (FPA) [18], [19], Gravitational Search Algorithm (GSA) [97], [98], [99], Water Cycle Algorithm (WCA) [100], [101], [102], [103], [104], [105], Grey Wolf Optimizer (GWO) [14], [106], [107], [108], [109], Harris Hawk Optimization (HHO) [27], [110], Group Search Optimization (GSO) [111], Imperialist Competitive Algorithm (ICA) [112], [113], Political Optimization (PO) [114], Symbiotic Organism Search Technique (SOS) [115], Whale Optimization Algorithm (WOA) [116], Sine Cosine Algorithm (SCA) [26], Discrete and Continuous Hyper-Sphere Search (DC-HSS) [2], Bonobo Algorithm (BO) [117], JAYA [6], [15], [118], and Improved Invasive Weed Optimization algorithm (IIWO) [130]. Hybrid methods, including GA-LP [131], GA-NLP [141], GA-EHA [132], PSO-LP [133], NM-PSO [135], [136], [137], PSO-TVAC [120], PSO-DE [121], PSO-GA [122], PSO-LSA [123], [142], PSO-SA [124], ABC-LP [125], BBO-LP [17], FA-LP [29], FA-GA [3], WOA-SA [126], HHO-SQP [20], HS-SA [127], SA-LP [143], WCMF [144], GBO and LSHADE [128], HWGO [129], and IIWO-SQP [130]. Fig. 1 shows the optimization techniques used to optimize DOCRs settings and reviewed in this paper.

Fig. 2 shows the increased trend of optimization studies in the field of solving the coordination problem of DOCRs within the last 5 years. The authors verified the number of publications available in the Web of Science (WoS) database for the period of 2018-2022. The number of articles that included references to the concept of optimization of the DOCRs coordination problem was 220. The set of generated data contained articles, conference papers, books, and book chapters. A bibliometric visualization of the keywords used in previous studies conducted in the past 5 years related to optimal coordination of directional overcurrent relays has been made via the VOS viewer software and depicted in Fig. 3. These figures have shown a great interest of research community in applying optimization techniques for DOCRs coordination problem.

This research comprises a review of 272 publications, including various journals and conferences from various reputable international and national publishers such as IEEE, Elsevier, Springer, Hindawi, etc.

The existing literature has extensively examined the coordination problem of DOCRs from various perspectives. In [145], the authors discussed the evolution of computer methods for coordination implementation, including adaptive, traditional, and optimization techniques. In [146], the focus was on the application of different optimization techniques proposed for solving the coordination problem, including conventional, metaheuristic, and hybrid approaches. The advantages and disadvantages of each technique were also discussed. Additionally, authors of [147] provided a review of optimizing overcurrent protection settings, including Artificial Intelligence and Nature-Inspired Algorithms, along with conventional approaches. Authors of [148] specifically addressed protection coordination techniques in distribution systems, considering the presence and absence of distributed energy resources. The paper delved into the challenges associated with protection coordination in both scenarios, examining factors such as the impact of distributed energy resources integration on fault levels, coordination failures, nuisance tripping, and relay performance. Furthermore, authors of [149] reviewed various approaches employed for DOCR coordination, including conventional methods, deterministic approaches, metaheuristic algorithms, and hybrid methods. The review explored the objective functions utilized in formulating the coordination problem. In [150], authors focused specifically on optimization techniques proposed for DOCR coordination in distribution systems for microgrids. In [151], the authors provided a comprehensive review of nonstandard characteristics for DOCRs. Lastly, authors of [152] provided a review of metaheuristic-based algorithms for optimal relay coordination.

Existing literature review papers have not yet comprehensively examined the optimization techniques used for DOCRs coordination. This gap motivates the present review to provide a comprehensive overview of the different optimization techniques that have been used to address the DOCR coordination problem. It discusses the objective functions, constraints, and development of each optimization method, as well as the performance criteria for comparing different algorithms. The simulation software used to validate the results obtained from the optimization algorithms are also presented. Finally, future trends and challenges regarding optimal coordination of DOCRs are discussed.

Research scholars will be able to better comprehend how the field has developed through time and how it arrived at the current state-of-the-art by understanding how these algorithms were developed. This can assist scholars to identify areas where further development and improvements are needed, as well as opportunities for innovation and new approaches. Furthermore, the review article can be a useful reference for researchers who need to choose the most suitable optimization algorithm for their specific coordination problem. By comprehensively covering the range of optimization algorithms that have been applied to coordination problems and highlighting their strengths and weaknesses, researchers can gain a deeper understanding of which algorithms are likely to be the most effective for their particular problem. This can lead to better-informed decisions and ultimately, more successful results. To this end, the main contributions of this review are summarized as follows:

- A description and summarization of the objective functions used in formulating the relay coordination problems are provided.
- A thorough summary of the techniques used to handle the constraints of the relay optimization problem are captured.
- The development of each of the optimization method for solving the relay coordination problem is provided.
- The performance criteria for comparing different algorithms for solving the coordination problem are discussed. The Firefly algorithm and Particle Swarm Optimization algorithm are used to demonstrate these criteria on the 3-bus test system.
- The simulation software used to examine and validate the results obtained from the optimization algorithms are presented.
- Future trends and challenges regarding optimal coordination of directional overcurrent relays are also discussed.

The rest of this paper is organized as follows. Section II discusses the formulation of the DOCRs coordination problem. Section III reviews the optimization techniques and challenges in optimization techniques for the coordination problem of DOCRs. Section IV provides the criteria used for comparison between the optimization algorithms. Section V discusses the simulation software utilized for verifying the optimization results. Finally, Section VI concludes the paper with some future research directions.

II. PROBLEM FORMULATION

The general steps that taken for the optimum coordination of the DOCRs are illustrated in Fig. 4. The first step is to collect the necessary data regarding the given power network. The necessary data are shown in Fig. 5. This involves gathering information about the specifications of each component of the power network, including generators, transformers, transmission lines, loads, and protective devices. The network type refers to the topological arrangement of the power system, which can be radial, loop or interconnected. The network type determines the possible fault paths and the complexity of the protection scheme required to ensure selective and reliable operation of the relays. Determining the network topology, whether fixed or dynamic, is an essential step in optimizing the coordination of DOCRs. It helps to identify the requirements for protection and the most appropriate protection scheme to ensure that the relays operate reliably and selectively under different network conditions. In a fixed network topology, the protection scheme can be designed based on the known fault paths, as the physical configuration of the power system remains constant. However, in a dynamic network topology, due to various factors such as switching operations, outages, and installation of new equipment, the physical configuration of the power system is prone to change. The power flow in a dynamic network is more difficult to predict, and the coordination of DOCRs must be adaptable to these changes. There are different types of faults that can occur in a power system, including symmetrical faults and unsymmetrical faults. Each type of fault has different characteristics and requires specific protection schemes. Coordination of protective relays can be significantly impacted by the location of the fault, whether it is near-end or far-end.

In the event of a near-end fault, the fault current reaches the protective relays quickly, necessitating the rapid operation of the relays closest to the fault to isolate the faulted section of

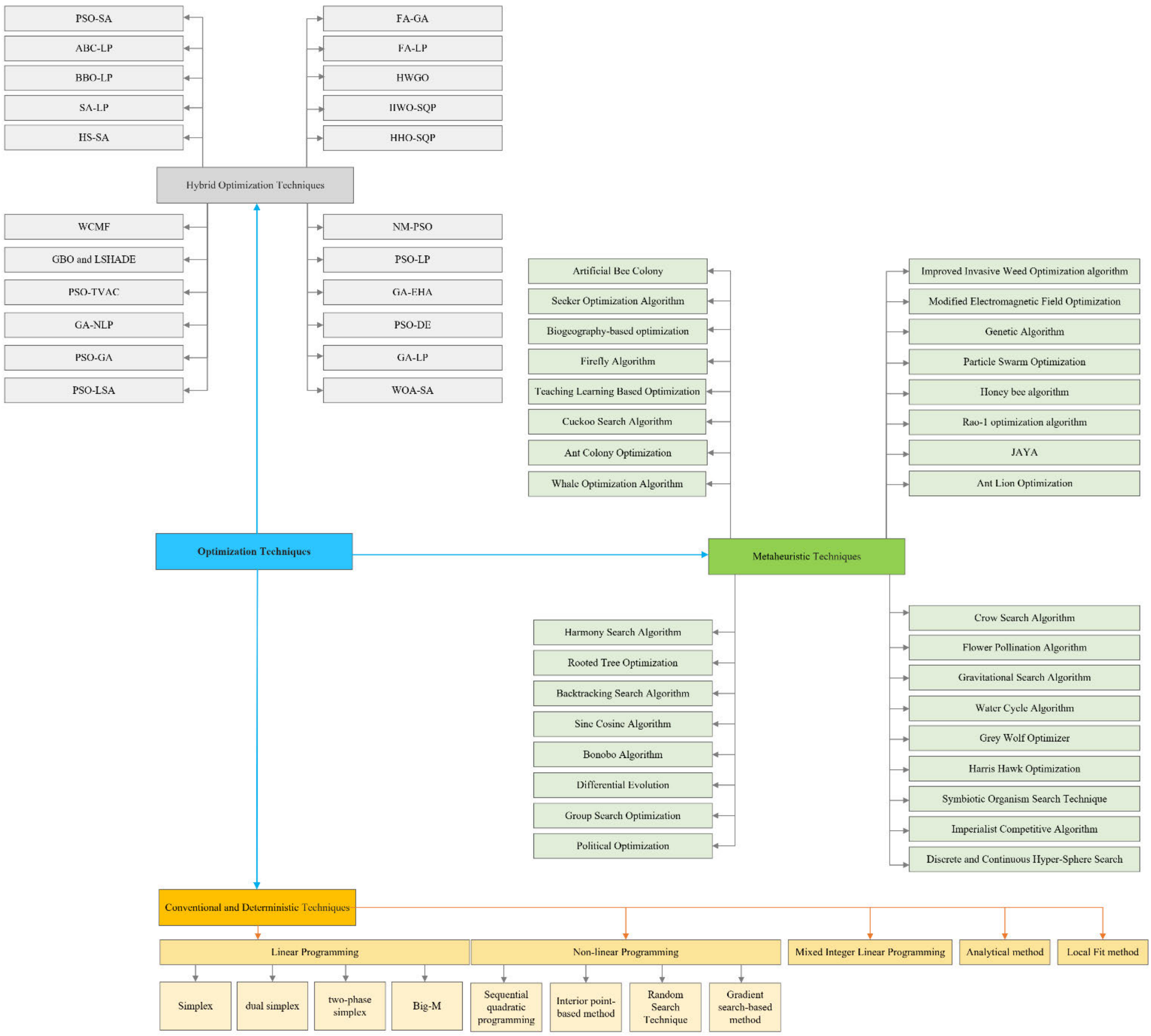

FIGURE 1. **Optimization algorithms reviewed in this paper for solving DOCRs coordination problem.**

the power system. This is considered the worst-case scenario because the protective relays have limited time to operate before the fault current reaches them. Thus, if the DOCRs are correctly coordinated for the near-end fault scenario, they will likely be coordinated for other fault scenarios. In contrast, faults at the far-end of the protected zone are less critical for coordination purposes as the protective relays have more time to operate before the fault current reaches them. This is correct only in the case if one unified relay characteristic is used for all DOCRs. This phenomenon can be graphically explained by Fig. 6 [153].

The second step is carrying out the load flow analysis to determine the maximum load current that can be carried by the protected zone, which represents the minimum value of the plug setting of each relay. Load flow analysis is also needed since the results of computed short-circuit currents are influenced by the fault type and by the pre-fault load flow [154].

To ensure proper and sequential selectivity among relay groups, it is necessary to identify all relay pairs involved in the coordination process. Consequently, if a fault occurs in any zone, a set of primary relays should be activated first. If any relay malfunctions or exceeds the assigned chance, backup protection relays should activate immediately. Each of these backup relays will also function as the primary relay for a different set of relays. Thus, identifying the primary/backup (P/B) relay pairs of all DOCRs is an essential step for solving the coordination problem.

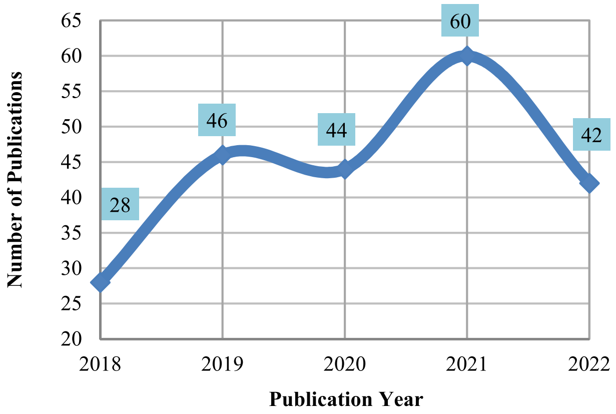

FIGURE 2. Number of publications indexed in the Web of Science database and referring to the concept of coordination of directional overcurrent relays in the past 5 years.

An effective protection design should be able to detect both the largest overload current and the smallest severe faults, which are reflected in the plug setting's permissible limits. Therefore, it is necessary to conduct a short-circuit analysis on the given network before starting the process of optimal relay coordination. Load flow analysis and short circuit analysis can be performed using different software such as ETAP, PowerWorld Simulator, DIgSILENT Power Factory and others. The last stage, which applies the optimization method to determine the optimum relay settings, can then be initiated.

The coordination problem of DOCRs is a complex optimization issue that involves dealing with multiple linear and nonlinear inequality constraints. Formulation of the DOCRs coordination problem can be divided into four main categories as shown in Fig. 7. These include the mathematical formulation of the objective function, the constraints related to relay settings, the constraints related to selectivity between relays, and the techniques used to handle the constraints. The following sections discuss how to express the coordination problem as an optimization problem.

A. OBJECTIVE FUNCTION

The DOCR system should quickly identify a fault and isolate the affected area of the power network while ensuring that the healthy zone of the network is not affected by any fault occurrences [27]. The coordination problem of DOCRs is stated as an optimization problem that is to be minimized [110]. The different types of objective functions, related to DOCRs coordination problem are shown in Table 1. It presents the objective functions' mathematical formulation along with their description and purposes. The different types of objective functions presented in Table 1 provide different ways for optimizing the coordination of DOCRs, depending on the specific criteria that need to be considered. One of the objective functions mentioned in Table 1 is presented in [3], [6], [19], [29], [33], [46], [48], [52], [69], [73], [74], [77], [78], [81], [88], [91], [93], [94], [96], [101], [102], [105], [106], [107], [108], [110], [114], [117], [120], [123], [124], [128], [129], [138], [140], [142], [155], [156], [157], [158], [159], [160], [161], [162], [163], [164], [165], [166], [167], [168], [169], and [170], which aims to minimize the overall operating time of all relays in the system, while taking into account the CTI requirement between the backup and primary relays. However, this objective function only minimizes the operating time of the primary relay, resulting in a longer discrimination time between the primary and backup relays. To address this limitation, other objective functions have been proposed, such as the one presented in [14] and [22], which aims to minimize the operating time of both primary and backup relays simultaneously. By using this objective function, the selectivity between the primary and backup relays can be improved, as it ensures shorter operating times for the relays under all operating conditions.

In [171], authors proposed an objective function that aims to minimize both of the operating time of the relays and the number of miscoordinations occurrences. However, it is observed that the penalty magnitude for miscoordination is low for smaller Δt values, potentially insufficient to effectively avoid miscoordination and guide the optimization process. Additionally, increasing the weighting factor, β, may prevent optimization algorithms from converging. To overcome these drawbacks, authors in [172] proposed an objective function with a relatively high and constant penalty factor. This forces the optimization algorithm to prevent the accumulation of negative Δt values, addressing the issue of lower-value discrimination times. Although the penalty factor varies for different primary/backup pair relays, it remains the same for different magnitudes of discrimination times. However, it does not enforce any specific behavior regarding positive discrimination times of relays. It primarily focuses on addressing the issue of lower-value discrimination times by increasing the penalty for negative Δt values. Therefore, authors of [173] proposed an objective function utilizes an exponential penalty term inspired by previous objective functions to guide the solutions towards the desired operating region. The penalty term varies with different discrimination times, remains independent of network topology, and effectively leads the variables towards the optimal solutions.

Other objective functions are presented in Table 1, including the minimization of the summation of relay operating times for near-end faults. It aims to reduce the overall time of the protection system when dealing with faults that occur close to the relay location [15], [17], [18], [21], [23], [26], [27], [36], [37], [41], [42], [48], [51], [55], [57], [59], [61], [64], [66], [70], [76], [79], [80], [86], [87], [92], [95], [97], [98], [99], [100], [103], [104], [111], [113], [116], [118], [125], [126], [127], [131], [132], [133], [134], [135], [136], [138], [141], [143], [144], [174], [175], [176], [177], [178], [179]. Additionally, it includes the minimization of the total operating time of all primary relays for both near-end and far-end faults. This objective function takes into account the fact that faults can occur at different locations from the relay and aims involved in protecting the system [31], [60], [67], [68],

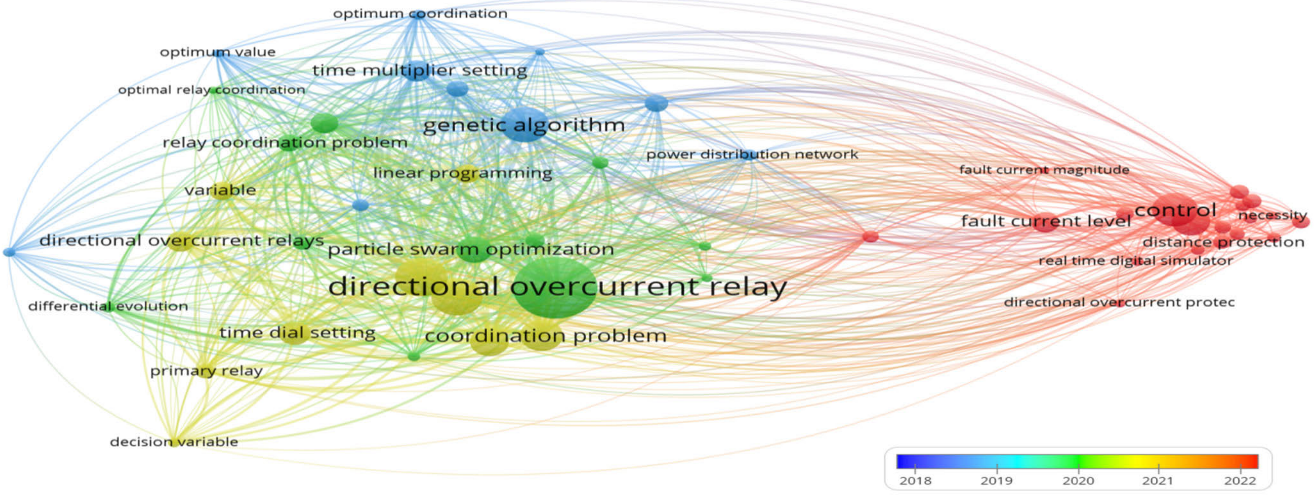

FIGURE 3. Bibliometric visualization for the author-supplied keywords, created with VOS viewer software.

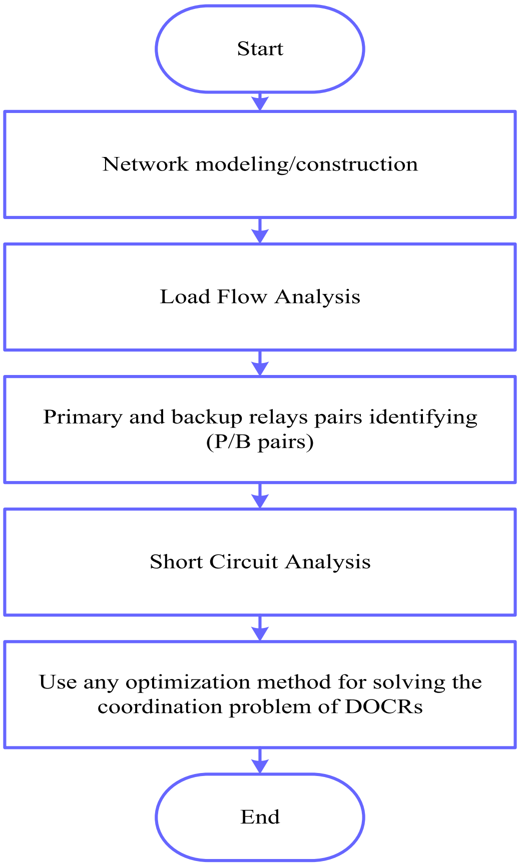

FIGURE 4. Flowchart of the general procedures for achieving optimal coordination of DOCRs.

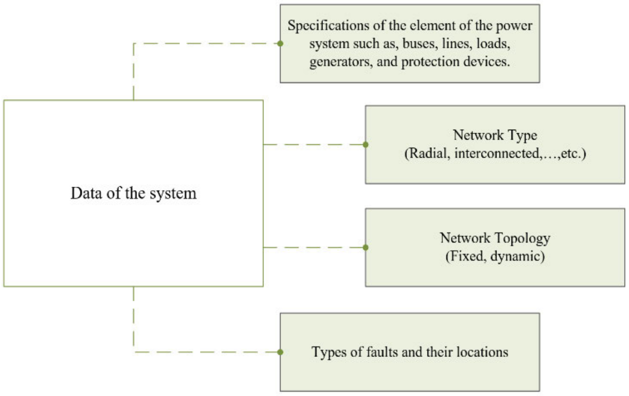

FIGURE 5. Information required for modeling the power system.

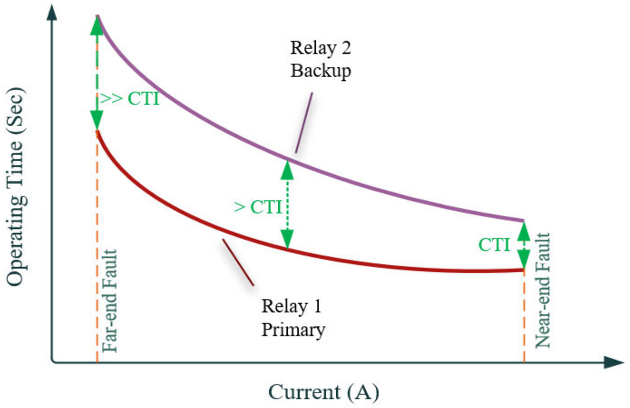

FIGURE 6. Discrimination margin between primary and backup DOCRs.

[71], [75], [84], [90], [115], [121], [137], [180], [181], [182], [183], [184]. It also includes the minimization of the summation of the operating time of all primary and backup relays. It aims to enhance the speed and effectiveness of the protection system in responding to faults, thereby minimizing damage and reducing system downtime [56], [60], [85], [123], [130], [185], [186], [187], [188]. Another objective is to minimize

TABLE 1. Summary of objective functions used in DOCRs coordination, including mathematical formulations and main aims. Objective functions used for DOCRs coordination problem mathematical formulation.

Reference	Objective function/ Description	Aim
[119]	$OF = \chi \sum relay\ operating\ time + \beta \sum (relay\ TM - user\ preferred\ TM)^2 + \alpha \sum (relay\ CSM - user\ preferred\ CSM)^2 + \delta \sum (timing\ difference\ of\ t_u\ and\ t_d - 0.4)^2$ Where χ is used to control the weighting on operating time minimization, β is used to control the weighting of time grading, TM is the time multiplier, α is used to control the weighting of current grading, CSM is the current setting multiplier, δ is a constant to provide a contribution on the amount of the mismatch of the grading margins. t_u is the operating time of the upstream relay and t_d is the operating time of the downstream relay.	To minimize the summation of all relays operating time considering the contribution of the required relay TM and CSM settings, as well as the mismatch of the grading margins
[3], [6], [19], [29], [33], [46], [48], [52], [69], [73], [74], [77], [78], [81], [88], [91], [93], [94], [96], [101], [102], [105]–[108], [110], [114], [117], [120], [123], [124], [128], [129], [138], [140], [142], [155]–[170]	$\min Z = \sum_{i=1}^{m} \alpha_i\,(TMS)_i = \sum_{i=1}^{m} t_{op}$ $\alpha = \frac{\lambda}{(PSM)^{\gamma} - 1}$ Where TMS is the time multiplier setting, t_{op} is the primary relay operational time, m is representing the number of relays in the power system and λ and γ are tripping curve constants defined by ANSI/IEEE and IEC standards.	To reduce the overall operating time of all relays in the power network, considering the CTI requirement between the backup and primary relays. The primary limitation of this OF is that it only decreases the operating time of the primary relay, which could lead to a longer discrimination time between the primary and backup relays.
[15], [17], [18], [21], [23], [26], [27], [36], [37], [41], [42], [48], [51], [55], [57], [59], [61], [64], [66], [70], [76], [79], [80], [86], [87], [92], [95], [97]–[100], [103], [104], [111], [113], [116], [118], [125]–[127], [131]–[136], [138], [141], [143], [144], [174]–[179]	$min \sum W_i'\ T_{ik}$ Where T_{ik} the operating time of i-th relay for a fault in zone k and W_i' is a coefficient that represents the probability of the occurrence of the fault on a line.	To reduce the sum of operating times of the relays in the system, for near end fault is to be minimized. This OF has two drawbacks. First, it is miscoordination. Second, is insensibility to avoid having large discrimination times in addition to CTI.
[58], [82]	$min \sum_{i=1}^{n} TDS_i$ Where n is the number of the relays to be set.	To reduce the time dial setting of all relays connected to the power network.
[56], [60], [85], [123], [130], [185]–[188].	$OF = \sum_{i=1}^{N_m} T_i^m + \sum_{j=1}^{N_b} T_j^b$ Where Nm and Nb state the number of main relays and backup ones, respectively, and T_i^m and T_j^b are the operation times of main and backup DOCRs, respectively.	To minimize the summation of operating time of all primary and backup relays, which ensures proper coordination between them. It may lead to longer CTI if the focus is primarily on reducing the total operating time of all relays.
[31], [60], [67], [68], [71], [75], [84], [90], [115], [121], [137], [180]–[184]	$\sum_{i=1}^{N_{near}} T^i_{pri,near} + \sum_{j=1}^{N_{far}} T^j_{pri,far}$ Where N_{near} is the total primary relays operating for near-end fault; N_{far} is the total primary relays operating for far-end fault; $T^i_{pri,near}$ is the operating time of ith primary relay for near-end fault; $T^j_{pri,far}$ is the operating time of jth primary relay for far-end fault..	To reduce the total operating time of all primary relays for both near-end and far-end faults, with no consideration for optimizing the operating time of the backup relays. This could result in a delayed operation of the backup relays and excessively high values for the OF.
[193]	$\sum_{i=1}^{n} t_i + \sum_{j=1}^{m} t_{z2i}$ Where t_i is the operating time of the primary DOCR i and t_{z2i} is the time defined for the second zone of each distance relay.	To minimizing the total operation time (ti) of the DOCRs and the total time of second zone (T_{Z2}) for distance relays.

TABLE 1. ***(Continued.)*** **Summary of objective functions used in DOCRs coordination, including mathematical formulations and main aims. Objective functions used for DOCRs coordination problem mathematical formulation.**

[190]–[192]	$\sum_{c=1}^{C}\sum_{i=1}^{N}\sum_{j=1}^{M}(\mathrm{t}_{\mathrm{fw\_cij}}^{\mathrm{p}} + \sum_{k=1}^{K}\mathrm{t}_{\mathrm{rv\_cij}}^{\mathrm{bk}})$ Where c is the configuration identifier, and it takes a value of 1 for the grid connected configuration and 2 for the islanded configuration. N is the total number of relays. M is the total number of fault locations. $t_{fw\_cij}^{p}$ is the primary relay i operating time, in the forward direction, for fault at j for configuration c. $t_{rv\_cij}^{bk}$ is the backup relay i operating time, in the reverse direction, for fault at j for configuration c. The identifier k denotes the total number of backup relay for a fault at j.	To minimize the total relay operating times for both primary and backup operation considering both modes of microgrid operation: grid- connected and islanded configuration.
[14], [22]	$OF = \beta_1 \sum (t_i)^2 + \beta_2 \sum (t_b - CTI)^2$ Where β_1 and β_2 are the positive weights corresponding to primary and backup relays, and $\beta_1 + \beta_2 = 1$. The values of weighting factors β_1 and β_2 provide a conciliation between the operating times of backup and primary relays.	To minimize the operating time of both primary and backup relays, as well as incorporating the CTI requirement. This results in improved selectivity and faster operating times for both types of relays, ensuring proper protection for the power system. it may lead to more complex and computationally intensive optimization procedures.
[171]	$OF = \alpha_1 \sum (t_i)^2 + \alpha_2 \sum (t_b - t_m - CTI)^2$ Where α_1 is used to control the weighting of $\sum(t_i)^2$, t_i is the ith relay operating time for a fault close to the circuit breaker (CB) of the ith relay, α_2 is used is used to control the weighting of $\sum(t_b - t_m - CTI)^2$, t_m and t_b are the operating times of the main and backup relays for a fault exactly close to the CB of the ith relay.	The main advantage of this OF is the incorporating the CTI in OF which will minimize the value of the OF.
[2], [34], [44], [45], [54], [62], [63], [65], [83], [112], [122].	$OF = w_1 \sum_{i=1}^{n} t_i^2 + w_2 \sum_{j \in FC} [\Delta t_{mb} - w_3(\Delta t_{mb} - \lvert \Delta t_{mb} \rvert)]^2$ $\Delta t_{mb} = t_b(F_i) - t_m(F_i) - TGM \geq 0, i \in FC$ Where $t_b(F_i)$ is the operational time of the backup relay due to fault F_i, $t_m(F_i)$ is the operating time of the primary relay due to fault F_i, TGM is the time grading margin, FC denotes a set of fault cases, Δt_{mb} is difference of operating time between backup and primary relay, t_i refers to the ith relay operational time for a fault near to the circuit breaker of the ith relay, $w_1, w_2, w_3$are the weighting factor and n is the total number of relays.	To minimize the total operating time of primary relays and total relay coordination time. The results produced do not have any miscoordination or only the miscoordination that is inherent in the network configuration and imposed on the protection system, and therefore it cannot be eliminated. In the case of positive values of Δt_{mb}, besides reduction of t_b, increasing of t_m is a probable cause of reduction of the Δt_{mb}.
[47]	$OF = \alpha_1 \sum_{i=1}^{n} t_i^2 + \alpha_2 \sum_{k=1}^{N} (\lvert \Delta t_{pbk} - \lvert \Delta t_{pbk} \rvert \rvert t_{pk}^2 + (\Delta t_{pbk} + \lvert \Delta t_{pbk} \rvert) t_{bk}^2)$ $\Delta t_{pbk} = t_{bk} - t_{pk} - CTI$ Where Δt_{pbk} is the operating time difference with CTI between kth relays pair, t_{pk} and t_{bk} are the operating times of the P/B relays, respectively, N is the number of P/B relay pairs, and k represents each P/B relay pair and varies from 1 to N.	The program aims to further decrease the t_b and therefore avoids the unwanted increase of the operating time of the primary relay.
[20], [257]	OF= $\alpha_1 \sum_{i=1}^{n} t_i^2 + \alpha_2 \sum_{k=1}^{N} (\lvert \Delta t_{pbk} - \lvert \Delta t_{pbk} \rvert \left\lvert \frac{t_{pk}^2}{t_{bk}^2} + (\Delta t_{pbk} + \lvert \Delta t_{pbk} \rvert) t_{bk}^2 \right)$	The OF eliminates the issue of miscoordination between the primary and backup relays. It minimizes the operating time of the backup relays for larger positive values of Δt_{pbk}. This feature of the objective function reduces the operating time of the relays while keeping the discrimination time at the desired level.
[72]	$OF = \left(\frac{NV}{NCP}\right) + \left(\frac{\sum_{NCP}^{a=1} t_{p-a}}{NCP}\right) * \alpha + \left(\frac{\sum_{NCP}^{b=1} t_{b-a}}{NCP}\right) * \beta + \left(\sum_{L}^{NCP} E_{CTIL}\right) * \delta$ Where NV is the number of violations of coordination constraints, NCP is the number of coordination pairs, t_{p-a} is the primary operation time of relay a, t_{b-a} is the backup operation time of relay b, E_{CTIL} is the CTI error of Lth coordination pair and α, β and δ are weighting factors tuned based on improving relaying protection performance.	To reduce the operating time of both primary and backup relays while maintaining their selectivity.

TABLE 1. ***(Continued.)*** **Summary of objective functions used in DOCRs coordination, including mathematical formulations and main aims. Objective functions used for DOCRs coordination problem mathematical formulation.**

[172]	$OF = \alpha_1 \sum_{i=1}^{n} t_i^2 + \sum_{k=1}^{N} \beta_k \, x \, BC_k$ $BC_k = \begin{cases} 0, & \Delta t_{k,d} \geq \epsilon \cong 0 \\ 1, & \Delta t_{k,d} < \epsilon \cong 0 \end{cases}$ Where β is the weight to consider the miscoordination, α_1 is used to control the weightings of $\sum_{i=1}^{n} t_i^2$, and BC is a binary variable whose status is determined through the evaluation of Δt with ε, which is determined as the threshold value.	The first part of the OF is the summation of relays operating times for faults close to the circuit breaker of the main relays. The second expression (also existing in previous methods) is used to satisfy coordination constraints.
[173]	$OF = \sum_{d \in D} \left[\alpha \sum_{i \in 1} (t_{i,d})^2 + \beta \sum_{k \in K} B\,C_{k,d} + \gamma_1 \sum_{k \epsilon K} e^{\gamma_2 [\Delta t_{k,d}]} \right]$ $BC_{k,d} = \begin{cases} 0, & \Delta t_{k,d} \geq \epsilon \cong 0 \\ 1, & \Delta t_{k,d} < \epsilon \cong 0 \end{cases}$ Where γ_1 and γ_2 are weighting factors. d is the indices of fault points and D represents the set of fault points.	To minimize the overall operation time of relaying task. As well, effective penalty factors are integrated to the main objective to steer the optimization towards the desired regions.
[189]	$OF1 = \alpha_1 \sum (t_i)^2 + \alpha_2 \sum (\Delta t_{mb}^{F1} - \beta_2 (\Delta t_{mb\,m}^{F1} - \lvert \Delta t_{mb}^{F1} \rvert)^2 + \alpha_3 \sum (\Delta t_{mb}^{F2} - \beta_3 (\Delta t_{mb\,m}^{F2} - \lvert \Delta t_{mb}^{F2} \rvert)^2 + \lambda\,((t_i - CTI_i) + \lvert (t_i - CTI_i) \rvert$ Where α_1, α_2 and α_3 are weighting factors. β_2 and β_3 are parameters for avoiding interactions of relays. λ is the penalty factor for considering transient stability constraint, and F1 and F2 are fault location in near-end and far-end of primary relays protection zone, respectively.	The operation time of primary and backup relays for near-end and far-end of protection zone of each primary relay is considered simultaneously.
[30], [32], [109]	$OF1 = \sum_{k=1}^{E} T_{pk} + \sum_{k=1}^{R} T_{bk}$ $OF2 = Max(T_b - T_p - CTI)$ Where T_{pk} is the operating time of primary relay, E is the number of primary relays in the system, T_{bk} is the operating time of backup relay, and R is the number of backup relays.	To reduce the overall operating time of both primary and backup relays, while also minimizing the coordination margin between relay pairs, and maintaining the proper sequential operation between relay pairs. However, implementing this objective function may require a more complex optimization algorithm and may result in higher computational costs.
[53]	$OF1 = \sum_{i=1}^{m} t_i$ $OF2 = \sum_{j=1}^{n} t_j$ Where t_i and t_j are the operational times of the primary and backup relays, respectively, m is the number of relays and n is the number of P/B relay pairs.	To reduce the discrimination time of P/B relays, the t_j are minimized separately as one of the OFs. Increasing of t_i does not lead the program to lower values of OF. Also, the problems of calculating suitable weighting factors are eliminated inherently.
[50]	$OF1 = Min\,(t_{n+1} - t_n)$ $OF2 = Min\,(TD_{n+1})$ Where t_{n+1} denotes the operational time of the backup relay and t_n denotes the operational time of the primary relay.	The first objective function is to minimize the time delay setting between the main protective relay and the backup protection relay to ensure that the main protective relay trips first and to prevent miscoordination. Secondly, the TD setting of the backup overcurrent relay is optimized as some vendors have restrictions on the range of TD settings.
[194]	$OF_{ENS} = 90\,x \left(\sum_{h=1}^{h_{max}} ENS_h \right)$ $ENS_h = \sum_{fl=1}^{fl_{max}} ENS_{h\,fl}$ $ENS_{h\,fl} = \lambda_{fl}\,x\,r_{fl}\,x\,(L_p + P_F\,x\,L_b)$ Where $ENS_{h\,fl}$ is the ENS value for a specific location of fault in h-th hour, ENS_h is the ENS value in h-th hour, fl_{max} is the total number of considered fault locations, h_{max} is the total number of time segments that is equal to 96 h. λ_{fl} represents the number of faults within fl-th location per year, r_{fl} is the repair times in hours for faults in fl-th location, L_p is the Total interrupted loads in kilowatt, if corresponded switch to the primary DOCR operates correctly, P_F is the probability of unsuccessful operation for corresponded switch to primary DOCR, and L_b is the additional interrupted loads due to unsuccessful operation of corresponded switch to primary DOCR.	To minimize the energy not supplied and improve overall reliability.

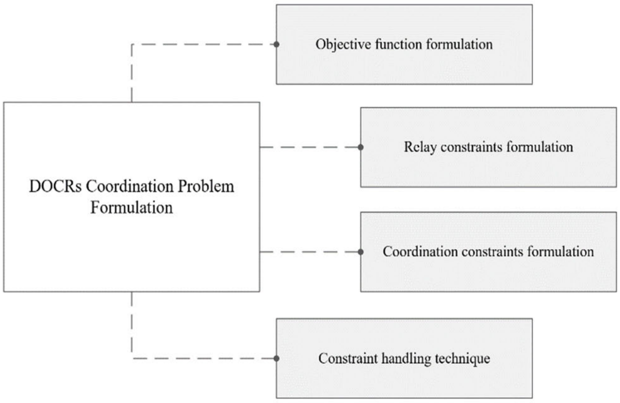

FIGURE 7. Stages involved in the formulation of the coordination problem for DOCRs.

the total operating time of primary relays and relay coordination time. It aims to strike a balance between reducing the time taken for the protection system to operate and ensuring proper coordination between relays [2], [34], [44], [45], [54], [62], [63], [65], [83], [112], [122]. In [189], authors proposed an objective function that considers the transient stability. In [190], [191], and [192], authors proposed an objective function aims to minimize the total relay operating times for both the primary and backup operation considering both modes of microgrid operation. Authors of [193] proposed an objective function considering the primary operating times of the DOCRs and the tripping times for zone 2 of the distance relays.

In addition to these single-objective functions, there are also multi-objective functions that can be used to optimize DOCR coordination. A multi-objective function aims to simultaneously minimize the total operating time of both primary and backup relays while also minimizing the coordination margin between relay pairs. This objective function is designed to strike a balance between enhancing the reliability of the protection system and ensuring efficient coordination among the relays [30], [32], [109]. Moreover, minimizing the total operating time of the primary and backup relays separately can significantly enhance the reliability and efficiency of the protection system. By optimizing the operating time of both types of relays individually, the system can effectively and promptly respond to faults, thereby minimizing the damage caused by the fault and reducing system downtime [53].

DG voltage protection plays a significant role in determining DG contribution in fault response. Traditional objective functions that solely consider relay operating times may not effectively account for DG voltage protection. To address this challenge, alternative objective functions, such as minimizing Energy Not Supplied (ENS), have been proposed in [194]. These functions consider the interactions between DOCR coordination and DG voltage protection, ensuring that DGs can contribute to enhancing system reliability during fault conditions.

All the objective functions mentioned rely on determining the operating time of the overcurrent relays are determined using (1), which is defined by both IEC/BS and ANSI/IEEE standards for a known short-circuit current (I_{sc}) and pickup current (I_P) [157].

$$t_{op} = TMS\left[\frac{\beta}{(\frac{I_{sc}}{PS})^{\alpha} - 1} + \gamma\right] \tag{1}$$

$$PS = \frac{Ip}{CTR} \tag{2}$$

where, α, β and γ are scalar quantities, and they vary based on the type of the characteristics used for DOCRs as stated in Table 2. In general, the plug setting represents the ratio of the pickup current (I_P) to the current transformer ratio (CTR).

TABLE 2. Standard european and north american time-current characteristic curves.

Type of Curve	Standard	α	β	γ
Moderately Inverse	IEEE	0.02	0.05150	0.11400
Very Inverse	IEEE	2.00	19.6100	0.49100
Extremely Inverse	IEEE	2.00	28.2000	0.12170
Inverse	CO8	2.00	5.96000	0.18000
Short-Time Inverse	CO2	0.02	0.02394	0.01694
Standard Inverse	IEC	0.02	0.14000	0
Very Inverse	IEC	1.00	13.5000	0
Extremely Inverse	IEC	2.00	80.0000	0
Long-Time Inverse	AREVA/UK	1.00	120.000	0
Short-Time Inverse	AREVA	0.04	0.05000	0

B. RELAY SETTING CONSTRAINTS

The objective function minimization is bounded by several sets of constraints. The first set of constraints refers to the setting of the relay. It includes the upper and lower limits of TMS and PS, which are defined in (3) and (4). Protection relays manufacturers offer their products with some specifications. One of these specifications is about the lower and upper limits of TMS [180].

$$TMS_{i,min} \leq TMS_i \leq TMS_{i,max} \tag{3}$$

where $TMS_{i,min}$ and $TMS_{i,max}$ are the minimum and maximum values of TMS of the *i*-th relay, respectively. Setting TMS too high may result in delayed or ineffective operation during fault conditions, while $TMS_{i,min}$ signifies the minimum acceptable value that can be set for the relay. Setting TMS too low may lead to unnecessary tripping or improper coordination with upstream relays [22], [180].

The bounds of the plug setting of each relay are provided by (4). The PS value is dependent on the system's short circuit level and full load current; it is given by the following relationship.

$$PS_{i,min} \leq PS_i \leq PS_{i,max} \tag{4}$$

where, $PS_{i,min}$ and $PS_{i,max}$ are the minimum and the maximum value of PS of the i-th relay, respectively. The lower limit ($PS_{i,min}$) should be set equal to or greater than the maximum overload current. This ensures that the relay is sensitive enough to detect and respond to fault conditions where the current exceeds the maximum overload level. Similarly, the upper limit ($PS_{i,max}$) should be set equal to or less than the minimum fault current. This ensures that the relay will be activates and then initiate the appropriate protection measures whenever a fault current exceeds the specified threshold. Setting the maximum value lower than the minimum fault current may result in the relay failing to detect and respond to lower magnitude faults, potentially leading to inadequate protection. On the other hand, setting the maximum value lower than the minimum fault current may cause false tripping and unnecessary interruptions in normal operation [17], [195]. For the sake of clarity, the following practical calculation can be used to determine these two bounds [17], [156]:

$$PS_{i,min} = max\left\{\frac{OLF * I_{i-L,max}}{CTR_i}, \frac{I_{i-f,min}}{3CTR_i}\right\} \tag{5}$$

$$PS_{i,max} = \frac{2I_{i-f,min}}{3CTR_i} \tag{6}$$

where OLF is the overload factor, which depends on the element being protected, $I_{i-L,max}$ is the max load current, $I_{i-f,min}$ is the minimum fault current that must be detected by that relay and CTR_i is the current transformer ratio of the i-th relay.

The time bound for the minimum ($t_{op,i,min}$) and maximum ($t_{op,i,max}$) operational time of DOCRs is presented as follows:

$$t_{op,i,min} \leq t_{op,i} \leq t_{op,i,max} \tag{7}$$

where the critical clearing time and the allowable thermal limit of the protected component determine the maximum time, and the minimum time is based on the manufacture of the relay [196].

C. COORDINATION CONSTRAINTS (SELECTIVITY CONSTRAINTS)

During abnormal conditions, both primary and backup relays will sense the fault simultaneously. Therefore, it is a universal practice to adjust the backup relay's operating time such that it is only activated when the primary relay fails to operate. CTI should be considered in the tripping action to prevent any malfunction. The CTI includes an appropriate safety margin, the overshoot time of the backup relay, and the operating time of the circuit breaker connected to the primary relay. This is essential for ensuring that the primary and backup relays meet the requirement for selectivity. The coordination constraint is defined as follows [158]:

$$t_{op,j,k} - t_{op,i,k} \geq CTI \tag{8}$$

where, $t_{op,j,k}$ and $t_{op,i,k}$ are the operating times of backup relay (R_j) and primary relay (R_i), respectively, for a fault at k, and CTI is the coordination time interval given to the *i*-th primary relay which is also the minimum allowable discrimination margin between R_i and R_j.

D. OTHER CONSTRAINTS

Many authors used other constraints such as the thermal limits for the electrical equipment, which limit time delay settings based on electrical equipment withstand ratings, and to consider the maximum allowable time delay setting for relays, as in [50] and [197]. This improved the system's reliability by lowering the risk of equipment failures. However, this also increases the coordination complexity as it becomes more difficult to guarantee that all relays are appropriately coordinated.

Variable network topology constraints can be also included in relay coordination studies as described in [137]. This means that changes in the network topology, such as the addition or removal of any element of the power system, can be accounted for in the coordination analysis. However, if the network topology changes, the original coordination settings of DOCRs may no longer be suitable for the new configuration, which could lead to miscoordination. Therefore, it is necessary to investigate new sets of coordination constraints that correspond to the various network topologies that may occur. Incorporating such constraints can improve the accuracy and effectiveness of relay coordination studies by ensuring that the coordination settings are optimized for the specific network topology. However, it can also add complexity to the analysis, as different network topologies may require different coordination settings.

In [189], the authors proposed a new methodology for relay coordination that considers transient stability as a constraint. The authors emphasized that traditional relay coordination methods do not consider the impact of relay settings on transient stability, which can lead to cascading outages. Their proposed method uses a two-phase procedure to optimize the relay settings while ensuring transient stability. The proposed method provides a more comprehensive approach to relay coordination that considers the impact of relay settings on transient stability. This is a critical consideration for ensuring the reliable operation of distribution networks.

Due to low inertia time constant of synchronous-based DGs, they are more prone to instability during faults. Thus, the transient stability of active distribution networks should be considered while designing protection schemes. A tripping time of relays must be lower than the critical clearing times of synchronous-based distributed generators. Authors in [191] proposed a novel approach for coordinating DOCRs in meshed active distribution networks while considering transient stability constraints. However, it may lead to increased computational complexity in the optimization process.

Authors of [198] combined the stability of DGs with the CTI of the DOCRs. Both CTIs and DGs stability criteria were used as constraints in the optimal protection coordination problem. This improved the coordination of DOCRs while maintaining the stability of DGs during fault clearing time. However, this approach resulted in improved DOCR coordination while maintaining DG stability during fault clearing.

However, there are potential drawbacks associated with this method, such as increased complexity of the optimization problem and limited applicability to certain power systems.

In [186], the fault current direction constraint was incorporated into the optimal coordination formulation for DOCRs. This was done to ensure that each DOCR in the backup scheme only operates for faults within its forward zone, and will be excluded if it cannot do so. This constraint helps to ensure that only the relays that are effective at detecting and clearing faults in their designated zones are included in the backup protection scheme. However, there are also some drawbacks associated with this constraint. It can increase the complexity of the problem and the computational time required to solve it. Additionally, if a DOCR cannot detect the fault current in its forward zone due to the direction of the fault current, it will be excluded from the coordination scheme, which may reduce the effectiveness of the backup protection scheme.

The method described in [187] takes into account the future growth and changes in the size of the DGs that may be added to the distribution system. Instead of creating separate relay settings for each size of the DG units, the method uses a single set of relay settings that work for all sizes of DGs. This approach saves time and effort in the planning process and ensures that the system is prepared for future changes. To achieve this, the method considers all the constraints related to different sizes of DGs and processes them simultaneously while setting up the relays. This ensures that the relay settings are robust and can handle any changes in the distribution system's topology or size.

The auxiliary variable is defined as the difference between the time settings of the DOCRs and the distance relays. It is added to the objective function of the optimization problem, and it helps to ensure that the relays operate in a coordinated manner. In [199], authors presented a technique for determining the optimal time setting for the second zone of distance relays when used in a mixed protection scheme with DOCRs. This technique considers the coordination requirement associated with the auxiliary variable. By incorporating the auxiliary variable as a new constraint in the optimization problem, this ensures that the time settings of the distance relays are coordinated with the time settings of the DOCRs.

In [173], the auxiliary variable was used to modify the time-current characteristics of the DOCRs. The modification helps to improve the coordination between the DOCRs and the distance relays, and it also makes the DOCRs more robust to faults that occur near the protected line. Furthermore, the auxiliary variable was integrated into the objective function as a penalty term in [28]. By minimizing the auxiliary variable, the objective function seeks to achieve optimized coordination among the DOCRs, ultimately improving the overall performance of the protection system. However, the inclusion of the auxiliary variable may make the optimization problem more difficult to solve. This could lead to longer computational times.

Authors in [194] presented a method for coordinating DOCRs while considering voltage protection requirements and DG voltage support. These requirements were used as constraints in the optimization problem. It was formulated to minimize the ENS while ensuring that the voltage protection requirements and DG voltage support requirements are satisfied. The ENS is the amount of energy that is not supplied to the load due to a fault.

The problem of coordinating distance relays and DOCRs is complex and involves numerous constraints. This is due to the different operating principles of distance relays and DOCRs, requiring careful coordination to ensure proper operation during faults. In [193], two new constraints were proposed. The first constraint states that the coordination margin between relay pairs must be greater than a minimum value to ensure proper coordination and prevent unnecessary operation of backup relays. The second constraint emphasizes that the operating time of distance relays should be shorter than the operating time of DOCRs to prevent misoperation of the protection system.

E. CONSTRAINTS HANDLING TECHNIQUES

During the optimization process, it is possible for the coordination constraint described in (8) to be violated. To ensure that no relay go out of bounds and defined constraints, a constraint handling technique is added to the objective function of the algorithm [110]. One common approach is the use of penalty methods [2], [3], [6], [14], [15], [18], [19], [20], [22], [23], [25], [32], [34], [41], [44], [45], [46], [47], [48], [53], [54], [57], [62], [63], [65], [66], [69], [70], [72], [75], [76], [78], [81], [83], [84], [86], [88], [91], [92], [93], [94], [98], [100], [102], [103], [106], [110], [111], [112], [118], [122], [125], [128], [129], [130], [131], [132], [141], [142], [161], [167], [171], [172], [173], [179], [181], [182], [183], [188], [189], [193]. In this technique, a penalty term is added to the objective function whenever a constraint is violated. The penalty term increases the objective function value and ensures that the optimizer finds a solution that satisfies the constraints. The penalty parameter is usually chosen carefully to balance the need for constraint satisfaction with the desire for optimization performance [6]. Another approach is the use of repair methods [58], [59], [67], [68], [71], [135], [136], [137]. In repair methods, the solutions that violate the constraints are repaired or modified to bring them back within the feasible region. This can involve making small adjustments to the solution variables or applying specific rules or algorithms to ensure constraint satisfaction. Repair methods are often used in combination with other optimization techniques to iteratively improve the solution until all constraints are satisfied. The Karush-Kuhn-Tucker (KKT) approach [175], is also utilized to handle constraints in the coordination problem. By incorporating the KKT conditions into the optimization algorithm, the coordination problem can be solved while satisfying the constraints. The KKT conditions introduce Lagrange multipliers, which act as weights to balance the objective function and the constraints.

An approach for addressing the constraints violation problem is by formulating the constraints as simultaneous equations using KKT conditions to the Lagrangian of the optimization problem. The first step is to define the Lagrangian function, which combines the objective function and the constraints utilizing Lagrange multipliers. Then, the KKT conditions can be implemented to derive a set of equations that connect the Lagrange multipliers to the variables in the problem. These equations involve complementary slackness conditions that guarantee that the Lagrange multipliers and slack variables are non-negative. Solving these equations provides the optimal settings of the DOCRs that meet the constraints [141], [200].

Repair methods involve modifying the solution generated by the optimization algorithm to ensure that any violated constraints are satisfied. This can involve adjusting one or more decision variables in the solution or performing additional computations. As in [58], the repair algorithm was used to force the violating particle to return to the feasible region if a violation was detected. This was achieved by modifying the position and velocity of the particle to satisfy the constraints while minimizing the objective function.

Because the other approaches need derivations or are difficult to model, the penalty methods are frequently utilized [17]. In [110], the authors modified the objective function to include the penalty function to ensure that no relay go out of bounds and defined constraints as shown in the following equations.

$$OF = min \sum_{i=1}^{n} Wt_{op,i} + \sum_{j=1}^{k} penalty \tag{9}$$

$$penalty = \begin{cases} 0, & if\ (t_{op,b} - t_{op,p}) \geq CTI \\ \delta, & Otherwise \end{cases} \tag{10}$$

where the penalty function value varies from 1 to ‘k’ entries, which indicates the relay pairs. When the condition given by (10) is met, the penalty function in (9) returns zero, and δ is the big value for solutions that violate the constraints. The function returns a result of zero if the boundaries are obeyed, and for optimal minimization, the value of the penalty function must also be zero.

Authors of [17] focused on using the exterior penalty function methods and the classical random search method, which is classified as one of the direct search methods. The performance of the conventional BBO was evaluated with respect to the constraint-handling techniques used, based on 50 Monte Carlo simulations. The results showed that the binary static penalty technique outperformed the others. The adaptive and self-adaptive penalties demonstrated competitive results, but their speed performance, which is an important factor in protective relaying, was unsatisfactory.

Table 3 presents the constraint handling techniques used with the optimization algorithms in the reviewed references. Unfortunately, there is a shortage of information in the available literature concerning this essential aspect. In many research papers, this problem is either not mentioned at all, or no sufficient information is provided. Therefore, it is imperative to conduct further research in this area because it directly affects the optimization algorithm's performance in terms of the overall cost and convergence rate [201].

TABLE 3. Constraint handling techniques used in the revised papers.

Reference	Constraint Handling Technique
[26]–[31], [36], [37], [42], [49]–[52], [55], [56], [60], [61], [64], [71], [73], [74], [77], [79], [80], [82], [85], [87], [89], [90], [95]–[97], [99], [101], [104], [105], [107]–[109], [113]–[117], [126], [127], [133], [134], [138], [143], [144], [155]–[160], [162]–[166], [168]–[170], [174], [176]–[178], [180], [185]–[187], [190]–[192], [196]	Undefined
[2], [3], [6], [14], [15], [18]–[20], [22], [23], [25], [32], [34], [41], [44]–[48], [53], [54], [57], [62], [63], [65], [66], [69], [70], [72], [75], [76], [78], [81], [83], [84], [86], [88], [91]–[94], [98], [100], [102], [103], [106], [110]–[112], [118], [122], [125], [128]–[132], [141], [142], [161], [167], [171]–[173], [179], [181]–[183], [188], [189], [193]	Penalty Methods
[58], [59], [67], [68], [71], [135]–[137]	Repair methods
[175]	KKT

The coordination of DOCRs is essential to ensure that protective devices within a power network operate reliably and selectively. The optimization process involves several steps, including data collection, load flow analysis, primary/backup relay identification, and short-circuit analysis. The coordination problem is formulated as an optimization problem with objective functions and constraints. The objective functions aim to optimize the coordination of DOCRs in terms of different criteria, such as minimizing the total operating time of relays or maximizing the selectivity between the primary and backup relays. The constraints ensure that the relays meet the required operating criteria and that the coordination is effective. The constraint handling techniques discussed in this section are used to ensure that the relays satisfy the defined constraints. These techniques include penalty methods, KKT conditions, and repair methods. This section provides a general overview of the DOCR coordination problem formulation, including the objective functions, constraints, and constraints handling techniques. Researchers can use this information to guide their own studies of DOCR coordination. The next step is to apply optimization algorithms, which will be discussed in the next section.

III. OPTIMIZATION ALGORITHMS FOR DOCRS COORDINATION PROBLEM

Different approaches have been proposed in the past few decades to solve the DOCRs coordination problem. These methods can be divided into five categories: The first category is the dual setting protection scheme, which enables the relay to be configured with two distinct operating characteristics - one for primary protection in the forward direction, and another for backup protection in the reverse direction. This feature allows the relay to function independently in either direction, thereby enhancing coordination and flexibility in protection schemes. Dual setting protection schemes can be applied to both operating modes of the microgrid [10], [190], [192]. Although, the scheme with dual setting DOCRs provide faster operation in clearing faults, but using these kind of relays needs to assist communication links to guarantee a proper protection scheme [173]. To address the challenge of achieving feasible coordination while minimizing relay operating time, the authors of [202] proposed a novel dual-setting DOCR characteristic as an alternative to the conventional characteristic. They evaluated the proposed characteristic on both the IEEE 14-bus and 24-bus systems, considering multiple fault locations across each feeder. The results demonstrated that employing the dual-setting characteristic instead of the conventional one resulted in a significant reduction in overall DOCR operating time while maintaining feasibility. To further validate the effectiveness of the dual-setting DOCR scheme, the authors of [10] applied it to microgrid protection and conducted a comparative analysis of relay coordination for 7-bus and 18-bus microgrid systems. They evaluated the performance of dual-setting and conventional relays under both operating modes of the microgrid, considering different relay characteristics. The results demonstrated that the total primary relay operating time using the dual-setting DOCR was lower than that of the conventional DOCR, with no violations observed. This shows the superior performance of the dual-setting DOCR scheme in achieving efficient and reliable microgrid protection.

The second category is the utilization of new constraints to achieve optimal coordination. These constraints may include thermal limits for electrical equipment [50], [197], variable network topology [137], constraints related with DGs [187], and others. By incorporating these constraints, the optimization algorithm can ensure that the protection scheme operates within safe and reliable parameters and improves the overall performance of the network.

The third category is the use of the non-standard characteristics, non-standard features are those not described neither in IEEE nor in IEC standards. It can provide several advantages and disadvantages. While non-standard characteristics can improve coordination, flexibility, accuracy, and fault detection, they can also introduce complexity, increased cost, and compatibility issues [159], [160], [161]. Non-standard characteristics can offer significant benefits in certain applications, particularly where traditional coordination methods face challenges. The four main groups of non-standard approaches are:

- Approaches that include electrical magnitudes: These approaches incorporate additional electrical parameters, such as voltage, current derivative, or frequency, into the relay characteristic to achieve better coordination or protection performance.
- Approaches that use different coefficients apart from the standard characteristics: These approaches modify the coefficients used in the standard inverse or definite time characteristics to achieve desired protection performance, such as faster fault clearance or improved coordination with other relays.
- Mathematical approaches: These approaches employ mathematical techniques to design non-standard characteristics with specific properties, such as improved selectivity or sensitivity.
- Other approaches: This category includes various non-traditional methods for constructing non-standard characteristics. These methods can involve unconventional techniques or incorporate additional factors beyond fault currents and operating times, such as maximum allowable conductor temperature, fault current directionality, or look-up tables [151].

The fourth category is the coordination strategy that considers utilizing user defined characteristics for the inverse time overcurrent relays. The coordination problem is formulated such that the relay will have five settings. The conventional time dial setting and pick up current are used, along with three new settings, α, β, and γ, which control the time/current relation of the relay. This allows the relays to be coordinated more effectively, with increased flexibility and improved reliability [203], [204]. In [205], the authors introduced a novel user-defined adaptive relay coordination strategy for both near-end and far-end faults in a power line. The proposed scheme employs user-defined four-setting numerical DOCRs for grid-connected microgrid operation on IEEE 6, modified 14-bus, and IEEE 30-bus test systems. Computational results demonstrate the significant potential of the user-defined approach in minimizing the overall operating time of Numerical-based DOCRs. This demonstrates its effectiveness and reliability, particularly in meshed distribution systems incorporating distributed generation units.

Finally, the last category relates to the application of optimization techniques for solving the coordination problem, which constitutes the core of this study. The optimization techniques used to solve the coordination problem of the DOCRs are discussed in this study. Relay coordination is characterized as an optimization problem that can be resolved by employing optimization techniques, including conventional and deterministic optimization techniques, metaheuristic techniques, and hybrid optimization techniques. A summary of the advantages and disadvantages of each approach is provided in Table 4.

TABLE 4. Summary of the advantages and disadvantages of approaches used for DOCRs coordination problem.

Approach	Main Advantage/s	Main Disadvantage/s
Dual setting protection scheme	• Enhances coordination and flexibility. • Applicable to both operating modes of the microgrid and to distribution systems.	• Requires communication links for proper operation.
Utilization of new constraints	• Ensures safe and reliable operation. • Applicable to systems with thermal limits, systems with variable network topology, systems with DGs.	• Can increase complexity of the protection scheme.
Using non-standard characteristics	• Provides improved coordination, flexibility, accuracy, and fault detection. • Applicable to systems with complex protection requirements, and systems with high reliability requirements.	• Can introduce complexity, increased cost, and compatibility issues.
Using user defined characteristics	• Allows for more effective coordination with increased flexibility and improved reliability. • Applicable to systems with unique protection requirements, such as distribution systems with DGs.	• Requires additional settings and may not be compatible with all relays.
Application of optimization techniques	• Can find optimal settings that consider multiple factors and conditions. • Applicable for all systems.	• Can be computationally expensive and may not always converge to a solution.

A. CONVENTIONAL AND DETERMINISTIC OPTIMIZATION TECHNIQUES

The conventional techniques involve trial and error, and topological techniques [162]. Power system engineers have previously used a trial and error approach to determine the best relay settings. However, the rate of convergence for this methodology is slow due to the several iterations required to find a suitable relay setting, and it may not always produce acceptable relay settings [94], [126], [162], [163], [193]. A solution to the issue of slow convergence and difficulty in finding acceptable relay settings is to employ a technique known as "breakpoint," which breaks all the loops, and to identify the starting relays at these points. The breakpoint technique can help to reduce the number of iterations required to find suitable relay settings and can also improve the accuracy of the settings [70], [149]. The break points are determined using topological methods based on graph theory and functional dependency to decrease the number of iterations needed for the relay coordination process [14], [33], [84]. The solutions obtained from the topological methods are among the best of all feasible solutions, but they are not optimal. In other words, the relays' time multiplier settings are quite large that may damage electrical equipment or reduce their life span [58], [84], [97], [164]. Nevertheless, these techniques are not effective for complex networks and high penetration of DG. Thus, the coordination problem in such complex networks was solved using a computer with a graphical user interface. In [38], the coordination problem of the IDMT relays was solved using Computer Aided Protection Engineering (CAPE). The graphical user interface of CAPE is useful since it enables protection engineers to make any required adjustments, revisions, or even upgrades to the current setting to ensure good coordination with the network system. MATLAB Graphical User Interface (MATLAB-GUI) was implemented to solve the inverse-time and instantaneous overcurrent relays coordination problems as presented in [39]. MATLAB-GUI contains curves of various standardizations that can generate coordination graphs by adjusting the slopes of inverse-time curves and the adjustment parameters of instantaneous and timed overcurrent functions. However, the computer-aided approach is not optimal enough when multi-miscoordination occurs.

Deterministic optimization techniques, which are also referred to as mathematically based optimization techniques, are commonly utilized in solving coordination problems for DOCRs. These techniques can be categorized into linear programming (LP), non-linear programming (NLP), mixed integer nonlinear programming (MINLP), and mixed integer linear programming (MILP) [20], [206].

To coordinate the DOCRs, linear programming such as simplex, dual simplex, and two-phase simplex techniques were occasionally utilized [36], [37], [138], [139], [140]. It has some benefits such as fast computational time and simplicity to resolve, but it needs expertise to set the initial guess for plug settings and may get stuck in local minima [39], [102]. The Big-M method, in which the plug settings are considered to be known and fixed, was proposed in [40] to obtain the optimum value of time multiplier settings of DOCRs for both radial and ring main systems. The results of the Big-M method for the radial system were comparable to those obtained through the two-phase simplex method, but with fewer iterations, indicating that the Big-M method was an efficient and potentially faster alternative. The algorithm was also tested on the ring main system, with satisfactory results, indicating that the Big-M method can be applied to different power system configurations to obtain satisfactory results. However, The Big-M method may not always converge to the optimal solution, particularly if the value of M is chosen incorrectly. In addition, it requires the plug settings to be known and fixed, which may not always be the case in real-world power systems.

In [41], various methods, including revised simplex, dual simplex, two-phase simplex, and Big-M, were employed to obtain optimal values of time multiplier setting for DOCRs in a single-end-fed distribution system. The results indicated that the dual simplex method was able to efficiently find the optimal solution with a relatively small number of calculations compared to the other methods.

Interval arithmetic is a method for bounding errors in mathematical computations and rounding errors in measurements. This approach combines interval arithmetic with analytical estimation techniques to find the sharpest interval solution set that encompasses the true solution set. In this approach, instead of computing exact values for the decision variables, the computations are performed on intervals that contain the possible values of the variables. This results in a solution set that is possesses a range of possible values instead of a single point value [207].

The linear programming techniques were modified and implemented with intervals where the computations were conducted using interval arithmetic that it allows for a more robust and reliable solution. However, the use of intervals can lead to increased computational complexity, as the interval arithmetic operations are more computationally intensive than traditional arithmetic operations. In [42], Interval Simplex, Interval Two Phase Simplex and Interval Revised Simplex methods were applied to solve the coordination problem for the IEEE 3-bus and 6-bus systems. The optimal relay settings were determined with a minimum operating time and within specified bounds, without any miscoordination. It was demonstrated that the revised simplex technique is the fastest approach, as it requires fewer iterations to reach the optimal values compared to other method. In [43], the coordination problem of DOCRs was solved using a primal-dual interior point linear programming approach, taking into account definite time backup relays. The results of the pre-solving study reduced the complexity and size of the linear programming problem and expedited the total solution time. On other hand, many scholars have expressed the coordination problem as a NLP problem and it was observed that it is complex and time-consuming [28]. The DOCRs problem was formulated as a NLP problem, with the time multiplier setting and plug setting designated as decision variables. This allows for a more efficient and effective solution to the problem [29]. In [30], the coordination problem of a sample 6-bus and IEEE 30-bus systems was solved using nonlinear optimization techniques based on General Algebraic Modeling System (GAMS) and Sequential Quadratic Programming (SQP). In [22], the authors employed an interior point-based method, which generated both TMS and PS simultaneously using a new objective function. The aim was to minimize the operating time while ensuring that the coordination of the backup primary relay pair was not violated. Authors of [31] used non-linear Random Search Technique (RST) to obtain proper coordination with acceptable speed of primary protection by introducing criteria to relax selectivity constraints. Relay coordination problems for mid line faults were successfully optimized using a gradient search-based method in [32]. The relay coordination problem was formulated as MINLP problem and solved using GAMS software. However, due to the discrete nature of the plug setting, incorporating binary variables led to an increase in the complexity of the coordination problem. As a result of the coordination problem's non-linearity and non-convexity, NLP and MINLP techniques are likely to become trapped in local minima. Therefore, a formulation based on MILP has been proposed for DOCRs coordination in [21] to overcome these problems. The problems have been solved using the branch and bound approach. Therefore, the proposed formulation transforms the nonlinear and nonconvex coordination problem into a linear and convex one at each branch. This matter guarantees convergence to global optimal settings and makes the problem easier to solve.

The main drawback of these methods is that they are highly dimensional, and in order to solve the coordination problem, they require a lot of computational time and computer memory [206]. The problem of a minimum solution plagues conventional methods, especially in the case of large-scale systems, even though they provide a considerable contribution to the problem's solution. Convergence is also difficult to achieve [20].

In [33], an analytical method (AA) proposed to solve the optimal overcurrent protection coordination problem. The proposed numerical technique converges to the global optimal values, which are independent by the relay setting order and initial values. To accurately determine the critical fault point to coordinate DOCRs, authors in [34] presented an analytical method for calculating the network's impedance matrix in a fault condition. These techniques often use a lot of iterations to calculate the relay settings and fall short of determining the optimal relay setting for an interconnected power network. However, for radial systems, analytical methods are very effective.

In [35], the authors introduced the Local Fit method, which efficiently solves the coordination of DOCRs in meshed systems. It provides intuitive results in less time by defining reference marks based on relay characteristics and operating parameters. The method allows for a focused analysis on each individual relay, minimizing the need for extensive testing between primary and backup relay pairs. This method utilizes the linear weighted logarithmic integral algorithm for analysis and coordination of relays, ensuring fast and effective protection. It was successfully applied to the Brazilian transmission network and the 8-bus test system, demonstrating superior performance compared to other methods such as LP [208], NLP [208], Ezzeddine method [208], and

TABLE 5. **Comparison of advantages and disadvantages between conventional and deterministic optimization methods.**

Method	Main Advantage/s	Main Disadvantage/s
Trial and Error	• Easy and good for simple networks.	• Yields slow convergence rate because it needs many iterations to achieve an optimized condition. • Obtain larger TMS settings of the relay.
Topological methods	• Require fewer iterations to reach at a satisfactory solution than the trial and error approaches.	• Global optimum value of PS and TMS of DOCRs may not be guaranteed.
LP	• Fast and simple.	• Requires experts for setting the initial values of PS • Are only helpful in optimizing the TMS settings • It may not yield an optimal solution.
NLP	• Give better performance than LP. • Both the PS and TMS of DOCRs are optimized together.	• The rate of convergence is slow with the increase of the system size. • It is possible to get stuck at local minima and fail to reach the global maxima.
MINLP	• The avoidance of the possibility of getting trapped in a local optimal solution. • Generates better solutions than the LP.	• Complex. • The success of the method is very dependent to initial starting point.
MILP	• PS is discretized into a fixed number of steps, and TMS is optimally found by formulating MILP. • Easier for solving the problem due to optimization process is not trapped in local minima and access to global optimal settings is guarantee.	• Increases the running time of the program.
Analytical Method	• The global solution can be achieved regardless of the starting solution. • Fast convergence and less running time.	• It may experience a slow rate of convergence and lack optimality when dealing with highly interconnected and complex networks.
Local Fit Method	• Simple and efficient. • Has short computing time. • Provides intuitive results.	• More sensitive to errors in the relay settings or to changes in the system conditions. • May not be able to account for all the factors that can affect the coordination of DOCRs.

AA [33]. Table 5 presents the main advantages and disadvantages of conventional and deterministic optimization methods in solving the coordination problem.

B. METAHEURISTIC OPTIMIZATION TECHNIQUES

Recently, various metaheuristic optimization algorithms have been utilized to obtain solutions to electrical engineering problems, such as the optimum settings of DOCRs coordination [81], [126], [150]. Metaheuristic methods have attracted a lot of interest for their ability to optimize DOCR settings [23], [62], [84], [96], [124], [133], [172]. They populate several solutions to start the optimization process rather of starting with just one, as in conventional ones. Additionally, for complex tasks, their gradient independence can increase their flexibility [128]. The speed of protective relay can be improved by choosing the appropriate characteristics for modern DOCRs, though. Metaheuristic methods that take into account the tripping characteristics of the relay as an optimization parameter together with TMS and PS can help achieve this [209]. Relay coordination has been solved by metaheuristic methods in terms of a constrained objective function to optimize coordination [49]. The following sections discuss the development of each of the metaheuristic optimization algorithms used to solve the coordination problem of DOCRs.

1) GENETIC ALGORITHM (GA)

The GA is an Artificial Intelligence technique that is based on Darwin’s natural selection theory to find solutions to optimization problems [52]. It is a search method that mimics the biological process of natural evolution and the idea of the “survival of the fittest”. Starting with a population of randomly created solutions, the solutions with better fitness are more likely to be chosen as a parent to produce new solutions (offsprings) for the next generation [48]. GA and its modified variations were utilized to find the optimal settings for the appropriate coordination of DOCRs. In [119], GA was applied to solve the DOCRs coordination problem of a 6-bus ring network. The GA implementation in [44] and [45] used a special objective function that is able to handle discrete and continuous TMS and PS problems as well as the miscoordination problem. The algorithm was applied to two different power system networks, and it was evident from the results that the new proposed method failed to maintain the coordination criteria in some cases. Authors in [46], included the constraints in the OF using the penalty method, and the optimal DOCR coordination problem was solved using the GA. In contrast, authors in [47] introduced a new problem formulation that not only obtained the optimal relay settings but also significantly reduced the operating times of the primary and backup relays. The effects of both near and far-end faults were considered. The program was capable of choosing the best characteristic for each relay to achieve better coordination and less operating times. The GA was used as an optimization tool.

In [48], the Continuous Genetic Algorithm (CGA) was tested for various test systems, including multi-loop systems, and it was found that the proposed algorithm provided satisfactory results in all cases. In [49], a new approach was proposed for optimizing DOCR coordination in power distribution systems by using GA, including transformer protection. The relay coordination problem was resolved by using an efficient objective function with constraints that considers both the current setting multiplier and the time setting. In the simulation, several relay curves, the transformer damage curve, and the limitation on the short circuit current in the system and others are considered.

Power flow and short circuit levels change as renewable energy sources are introduced in the transmission and distribution systems. To adapt to changes in the power system, the protection system must be updated. Authors in [50] proposed a method used to evaluate the effect of integrating renewable energy sources on exiting the overcurrent setting, and provided new settings without the need to replace existing protection devices when the short circuit was within equipment thermal limits. The ultimate minimum time dial for overcurrent protection considering high renewable energy source penetration was investigated, and GA optimization was provided to ensure proper coordination between the relays, considering the high penetration. The proposed method included the identification of the minimum time delay overcurrent settings and integration of IEEE and IEC time-current curves in the optimization. The constraints for the time settings were the minimum allowable setting based on the IEEE Buff Book requirement and the maximum permissible overcurrent time delay setting considers the thermal limits of all electrical equipment. Different decimals for the time dial settings were considered based on three different vendors. In [51], optimization-based adaptive coordination protection of DOCRs using GA in a radial network under presence of DGs was described for different scenarios. In [52], a methodology based on the GA with the purpose of coordinating a protection system involving distance relays and DOCRs was presented. Nine photovoltaic systems were integrated in the feeder intended to apply the methodology.

The Non-Dominated Sorting Genetic Algorithm (NSGA-II) is a powerful decision space exploration engine based on GA for solving multi-objective optimization problems [210]. In [53], a new approach based on NSGA-II were proposed for optimum coordination of DOCRs. With this technique, a multi-objective function can be converted into a single objective function equivalent without the need for weighting factors. Different relay characteristics and both near and far-end faults were considered in the proposed method. Three different power system networks, including 3-bus, 8-bus and IEEE 30-bus networks were used to test the proposed method. The results were compared with algorithms proposed in [44] and [47], and conventional GA. It was revealed that the new approach was more accurate, flexible, and efficient. Table 6 shows the development on the GA for solving the DOCRs coordination problem.

2) PARTICLE SWARM OPTIMIZATION ALGORITHM (PSO)

The PSO is a population-based optimization technique developed by Eberhart and Kennedy in 1995. It is originally inspired by the sociological behavior associated with bird flocking and fish schooling. It was used to solve a wide variety of optimization problems, and function minimization. In [54], standard PSO was applied to an 8-bus test system and compared with GA that suggested in [44]. It was shown that PSO demonstrated 44% lesser time of primary relays as compared to GA. This implies that PSO is superior to GA. In [55], standard PSO was employed to optimize the coordination of DOCRs for the protection of internal faults all over transmission lines in radial networks. The coordination of DOCRs based on PSO was proposed in [56] taking into account the direction of fault current constraint.

The PSO algorithm has limitation in terms that, during the updating process, where each particle modifies its position, the resultant particle position could be outside the feasible search space. This lowers the chance of discovering a solution that is either optimal or near-optimal [59]. PSO has a few attractive features when contrasted with GA. It has memory which enables all particles to retain knowledge of good solutions, whereas in GA, any prior knowledge of the problem is lost once the population changes [57]. PSO in its standard form is not capable of dealing with the coordination of DOCR, which is a constrained optimization problem. Therefore, modifications on the standard PSO were introduced to dealing with the coordination problem as in [57], [58], [59], and [60]. The authors of [57] utilized the interior point method to obtain the initial feasible solutions initially. This was done by initializing the pickup currents randomly, thus the problem becomes linear and the TDS values are calculated using the interior point method. The initial feasible solutions are then applied to the PSO algorithm. To prevent the occurrence of infeasible particles, a significant modification was made to the standard PSO algorithm. Instead of updating particle positions, particle feasibility was updated. The coordination problem was first solved using the conventional problem formulation and then the new proposed MINLP formulation was applied to verify the importance of the new problem formulation. In contrast, authors in [58] proposed two modifications on the standard PSO. The first modification was the repair algorithm that gives the PSO algorithm the capability of tackling the coordination constraints imposed on the relays, while searching for an optimal setting. In addition, another technique for initializing PSO, rather than the random initialization, was proposed. As in [58], authors of [59] modified the standard PSO with the repair algorithm, where the pickup currents were randomly initialized, and the TDS values were calculated using the

TABLE 6. Development of the GA in solving the DOCR coordination problem, highlighting significant contributions, test case applications, comparative analyses, and observations.

Ref	Method	Contribution	Test case/s	Compared with	Remark/s
[119]	GA	• Application of GA for solving the coordination problem.	33kV ring circuit	None	• Able to identify the optimal relay settings, which cannot be accomplished through the conventional methods.
[44] [45]	GA	• Improvement of GA by adding a new expression to the objective function to solve miscoordination problems. In addition, the new algorithm can handle both continues and discrete TSM's or TDS's.	8-bus sample distribution network, and 8-bus test system	None	• The proposed algorithm resulted in infeasible solutions (Miscoordination).
[46]	GA	• Incorporating the constraints in the OF using penalty method.	Single end fed, multi loop distribution system	None	• The proposed algorithm provided satisfactory results in all test cases.
[47]	GA	• Improvement of the objective function to obtain optimal relay settings and significantly reduce the operating times of primary and backup relays.	IEEE 9-bus and 30-bus distribution systems	• Evolutionary Algorithm [258] • GA [44] • GA [45]	• The proposed objective function was more precise, adaptable, and effective than other compared objective functions and was successful in minimizing the miscoordination and operating times of the primary and backup relays.
[48]	CGA	• Application of CGA for solving the coordination problem rather than using GA since CGA is inherently faster. Additionally, CGA has the benefit of requiring less storage than binary GA.	A single-end-fed multi-loop distribution system, A single-end-fed, distribution system with parallel-feeders	None	• The proposed algorithm gives satisfactory results in all the cases.
[49]	GA	• Inclusion of transformer protection in the relay coordination problem in power distribution systems using GA optimization.	Industrial radial system, Ring type power distribution system	• Trained engineer using a computer-aid software package	• GA can be adopted to implement DOCR coordination considering not only different relay curves but also the curves of other components, such as transformers and the limitation on the short circuit current in the system and others to optimize possible constraints. • Better results within less time and at lower cost.
[50]	GA	• Integration of both IEC and IEEE TCC when determining the optimal time delay setting to limit time delay settings between the IEEE Buff Book and thermal limits for electrical devices.	IEEE 42-bus	None	• It can provide new settings without the need to replace existing protection devices when the short circuit is within equipment thermal limits.
[51]	GA	• Proposing adaptive coordination scheme to obtain optimal protection coordination with different system configuration.	Radial network with DG	• Conventional algorithm	• Better results than the compared algorithm.
[52]	GA	• Analyze the influence of the DGs insertion, based on the addition of the photovoltaic system in the test, by using GA to coordinate DOCRs.	IEEE 13-Node Test Feeder	None	• GA successfully minimized the objective function and the constraints were satisfied for all cases (with and without DG).

TABLE 7. Advancements of the PSO in addressing the DOCR coordination problem, highlighting key contributions, test case applications, comparative analyses, and observations.

Ref	Method	Contribution	Test case/s	Compared with	Remark/s
[54]	PSO	• The application of standard PSO for solving the coordination problem.	8-bus test system	• GA [44].	• Infeasible solution (Many violations)
[55]	PSO	• Optimization of DOCRs coordination for internal faults protection over transmission lines using PSO.	IEEE 15-node radial system	None	• The obtained settings of each relay showed the effectiveness of the standard PSO technique in terms of accuracy and speed.
[56]	PSO	• Coordination of DOCR based on PSO algorithm with consider of fault current direction restriction constraint.	IEEE 30-bus system	None	• Misoperation of some relays due to reverse direction of midpoint faults
[57]	Modified PSO	• Proposing a modified version of PSO to deal with the coordination problem by modifying the initialization and the updating processes of the standard PSO algorithm.	8-bus test system, IEEE 14-bus network.	• Standard PSO • CONOPT & DICOPT solvers in GAMS	• Formulating the problem as an MINLP problem prevented the possibility of obtaining infeasible settings and guarantees a better optimal setting for the relays other than the predetermined pickup settings. • Modified PSO succeeded in finding a close to optimal solution for the coordination problem as compared with the standard PSO. • Modified PSO capable of finding a better feasible solution than the GAMS solver with less number of iterations.
[58]	Modified PSO	• Adding the repair algorithm and modifying the initialization process to the standard PSO.	3-, 6- and 8-bus power systems	• Simplex • Linear Interior Point Solver algorithm (LIPSOL)	• Proposed PSO gives better results with feasible settings. • Proposed PSO outperformed the standard PSO in terms of computational speed and memory requirements.
[59]	Modified PSO	• Adding the repair algorithm and modifying the initialization process to the standard PSO.	6-bus power system	None	• Modified PSO capable of finding a close to global solution for the coordination problem.
[60]	Modified PSO	• Proposing PSO based on constriction factor approach for optimal coordination of DOCRs.	3-, 4- and 6-bus power systems	• RST [31] • MDE [67] • chaotic DE [71] • TLBO [84] • Modified real coded GA [181]	• Obtained optimized settings of DOCRs produced much better results with all valid constraints satisfied as compared to other methods.

interior point method. The initial feasible solutions were then applied to the PSO algorithm.

The application of a constriction factor into PSO is a useful technique to ensure convergence of the PSO algorithm [211]. In [60], the aim was to decrease the operating time of all primary DOCRs while taking both a far-end and a near-end fault approach into account. The optimization was performed with PSO based on the constriction factor approach for standard test systems of 3-bus, 4-bus, and 6-bus. Table 7 presents the development on the PSO for solving the DOCRs coordination problem.

3) RAO-1 OPTIMIZATION ALGORITHM

The Rao-1 algorithm is a metaphor-less heuristic search technique used for solving optimization problems that can be either constrained or unconstrained. The technique does not require any algorithm-specific control assumptions and solely utilizes algebraic operations [212]. In [61], Rao-1 was used

TABLE 8. Evolution of the ABC algorithm in solving the DOCR coordination problem, with emphasis on key contributions, test case applications, comparative analyses, and observations.

Ref	Contribution	Test case/s	Compared with	Remark/s
[63]	The implementation of ABC algorithm for solving the optimal coordination of DOCRs.	WSCC 9 bus test system.	Quasi-Newton PSO	The Quasi-Newton can converge towards the better solution, but it is imprecise when compared to other approaches in terms of standard deviation. In comparison to other methods, ABC provided accurate and convergence results with slightly faster computational time.
[64]		IEEE 3-bus, 4-bus, and 6-bus systems.	Simplex [175] PSO [58]	ABC outperformed the LP and PSO.
[65]	Application of Neighborhood search-based ABC for determining the optimal electromechanical-based overcurrent relays settings.	8-bus test case and IEEE 14-bus distribution system.	GA PSO	The proposed ABC given fitness function better than the result obtained from PSO and GA optimization algorithms.

to find the optimal settings of the DOCRs in the presence and absence of distributed generators for a 4-bus distribution system. The results were compared to PSO [57], GSA [97], FA [79], [94], MFA [79], AMFA [80], RTO [94], CPSO [94], and CGA [94]. It was found that the Rao-1 approach produced superior results than other algorithms and had a convergence rate that was significantly faster than the other algorithms.

4) HONEY BEE ALGORITHM

The Honey bee algorithm is a multi-objective optimization technique inspired from the foraging behavior of honey bees [213]. The algorithm performs both an exploitative neighborhood search combined with random explorative search [214]. For the relay coordination problem, authors in [62] used the Honey Bee algorithm for solving the optimization problem as LP for the 8-bus test system.

5) ARTIFICIAL BEE COLONY (ABC)

The ABC algorithm is very simple and efficient nature-inspired algorithm with very fewer parameters. D. Karaboga introduced ABC algorithm in 2005 that mimics the foraging conduct of real honey bees. This algorithm is simulated by the activities of honey bees while looking for an eminent food source [215]. In [63], ABC was proposed to solve the coordination problem for WSCC 9-bus test system. Whereas in [64], 3-bus, 6-bus, and 8-bus test systems were employed to show the ABC algorithm's efficacy in solving the coordination problem. Since the exploitation method in classical ABC appears to be adaptive, the standard approach tends to exhibit a bias towards exploration rather than exploitation. To address this issue and improve the search strategy, authors in [65] introduced a neighborhood search-based exploitation scheme that leverages Cauchy and Gaussian mutation strategies. Furthermore, authors used the modified problem formulation proposed in [47] to optimize the relay setting. Table 8 presents the development on the ABC algorithm for solving the DOCRs coordination problem.

6) DIFFERENTIAL EVOLUTION ALGORITHM (DE)

The DE is one of the most popular evolutionary algorithm inspired by Darwin's theory of evolution and has been studied extensively to solve different areas of optimization and engineering applications [216]. In 1995, Storn and Price introduced this approach to minimize continuous functions that are potentially nonlinear and non-differentiable [217]. DE is like other evolutionary algorithms, particularly GA, in that it uses the same evolutionary operators, such as selection, recombination, and mutation. The mutation operator, which differs from the crossover operator in GA, plays a significant role in the working of DE [67]. The optimal coordination problem of DOCRs in a sample distribution system with distributed generators was expressed as a MINLP problem and solved using the DE algorithm in [66].

DE, like many other population-based stochastic search techniques, does not always perform up to expectations and can suffer from issues such as premature convergence and population stagnation. DE schemes require only one control parameter i.e., the crossover rate, whereas most of the other techniques have more than one control parameters, which are to be fine-tuned for the successful performance of an algorithm. Authors in [67] proposed five modified versions of DE (MDE1 – MDE5) to solve the coordination problem for various IEEE test systems. The algorithms differ from the basic DE algorithm in the phase of generating the mutant vector.

The basic DE algorithm was enhanced in [68] with the introduction of three variants: Gaussian Mutated Differential Evolution (GMDE), Cauchy Mutated Differential Evolution (CMDE), and Laplace Mutated Differential Evolution (LMDE). These variants incorporate the "Local Neighborhood Search" (LNS) operator as a means of mutation to accelerate the DE algorithm by providing information about potential candidates near the best candidate in the population. Moreover, a constraint handling technique was implemented using repair methods to handle the constraints in these DE variants.

The basic DE has its own drawbacks because of the necessity of tuning the DE control parameters. A new adaptive strategy in mutation operation was introduced in [69]. In the adaptive DE (ADE), each individual in the population (or search point in the hyperspace) has its own unique set of control parameters. The control parameters being space-varying, contribute to the exploration capabilities of the proposed ADE algorithm. This prevents stalling of the decision variables to a local optimum. Otherwise, stalling will occur as any discrete feasible search point in the hyperspace is densely surrounded by infeasible solutions in the relay coordination problem. One of the significant advantages is that the proposed ADE avoids the requirement of tuning the mutation control parameters, making it more robust. Robustness and feasibility of the proposed technique was demonstrated on three different model test systems and compared with different algorithms.

DE has a balancing between the explorative and exploitative power, but in some cases the exploitative nature leads to a premature convergence or trapping to a local optimum in a complicated and multimodal search space. In [70], a modified DE algorithm with an information exchange strategy was developed. Several subpopulations, which enhance the explorative power of the algorithm, were used. This may overcome the trapping into a local optimum. The total population was subdivided using the K-means clustering algorithm and throughout the iterations, the number of subpopulations was changed in a self-adaptive way to balance the exploration and exploitation. Additionally, a local search technique for better tuning near a suspected optimum was applied. A fitness feedback scheme to vary the subpopulation number was used. Both continuous as well as discrete versions of the informative DE algorithm were applied for optimizing the relay setting. Proper combinations of backup relays for each primary relay were identified by using the LINKNET graph theory approach.

Opposition based learning (OBL) and chaotic scale factor DE techniques were proposed in [71]. The main concept of OBL involves simultaneously considering an estimate and its opposite estimate to attain a more accurate approximation of the current candidate solution. To maintain the diversity of DE and improve its performance in preventing the premature convergence to local minima, chaotic sequences instead of random sequences was applied. The two algorithms, OCDE1 and OCDE2, which have been suggested, are simple extensions of the fundamental DE algorithm. They only vary in two respects: how the initial population is generated and the selection of the scale factor. The proposed algorithms were simulated over four test cases.

The level of difficulty in interconnected networks is several times greater than in radial networks, and the complexity increases exponentially as the system becomes larger and more interconnected. Coordination can lead to undesired relay operation times and violations of coordination constraints. In order to tackle this, the authors in [72] developed an enhanced DE to coordinate the highly interconnected IEEE 14-bus and 57-bus systems. They assessed the effectiveness of different mutation versions of DE algorithms, including binomial and exponential crossover, in solving the coordination problem. The performance of different DE family was tested and compared on the IEEE 14-bus test system for the coordination of DOCR. The best results were achieved with the trigonometric mutation DE with binomial crossover. This method was then improved in four aspects and successfully coordinated the highly interconnected IEEE 57-bus system with good results and without violating any coordination constraints. Table 9 summarizes the development of DE algorithm for addressing the coordination problem.

7) HARMONY SEARCH ALGORITHM (HSA)

The Honey bee algorithm is a multi-objective optimization HSA is a recently developed metaheuristic in the last decade. The algorithm is inspired by the behavior of musicians who produce a perfect harmony, and it has been successfully applied to a wide range of real-life optimization problems due to its easy implementation compared to other metaheuristics [218]. The authors in [73] applied HSA to determine the optimal settings of DOCRs in different distribution power systems. In [74], HSA was introduced for coordinating DOCRs in a looped distribution system. To enhance the fine tuning and convergence rate of HSA, the authors developed a new algorithm called Improvised Harmony Search Algorithm (IHSA). The advantages of the proposed IHSA algorithm include its ability to improve the convergence rate and solution quality of the HSA algorithm and it is computationally efficient and does not require prior knowledge of the system parameters.

In [75], a new effective and reliable approach that employs a constrained HSA and integrates the Box-Muller harmony search (BMHS) algorithm was suggested to address the coordination problem. This technique was proposed to obtain optimal results. The results demonstrated that the proposed approach achieves better coordination performance in terms of speed, accuracy, and convergence compared to other methods. Table 10 outlines the progress of the HSA in addressing the coordination problem of DOCRs.

8) SEEKER OPTIMIZATION ALGORITHM (SOA)

The SOA is a computational search algorithm inspired by the behavior of human memory consideration, experience gained, uncertainty reasoning, and social learning [219]. In [23], the coordination of DOCRs was stated as a MINLP problem, and then resolved using the SOA. A simple fuzzy rule was used to evaluate seekers step length. The proposed method was implemented in three different test cases. The obtained results were compared with the simplex method

TABLE 9. Development of the DE algorithm in addressing the DOCR coordination problem, highlighting key contributions, test case applications, comparative analyses, and observations.

Ref	Method	Contribution	Test case/s	Compared with	Remark/s
[66]	Basic DE	• The application of the basic DE for solving the coordination problem of DOCRs in a distribution system with DG.	Sample distribution system	None	• Efficient
[67]	Modified DE (MDE1 – MDE5)	• The development of five versions of the basic DE (MDE). • The utilization of the modified DE versions (MDE1 – MDE5) for solving the coordination problem.	IEEE 3-, 4- and 6-bus systems	• RST [31] • GA [259] • SOMA [259] • SOMGA [259] • LX-POL [260] • LX-PM [260]	• MDE4 and MDE5 algorithms performed better than other algorithms for IEEE 3-bus and 6-bus models, respectively. • In case of 4-bus model, LX-POL gave better performance than other algorithms. • For IEEE 6-bus model, GA and SOMA gave the worst performance.
[68]	Improved DE	• The development of enhanced DE that use the LNS concept with the aid of the probability distributions Laplace (LMDE), Cauchy (CMDE) and Gaussian (GMDE) to solve the coordination problem.	IEEE 3- and 4-bus systems	• GA [259] • SOMA [259] • SOMGA [259] • LX-POL [260] • LX-PM [260] • MDE1-MDE5 [67]	• The superior performance of the proposed approach for both the IEEE bus systems.
[69]	Adaptive DE	• An adaptive DE algorithm is proposed as an effective approach for solving the coordination problem, which eliminates the need for time-consuming tuning and prevents convergence to local optima.	IEEE 3-, 4- and 6-bus systems	• LP [208] • NLP [208] • Ezzeddine Method [208] • RST [31] • SOMGA [259] • DE [67] • MDE1-MDE5 [67]	• Adaptive DE algorithm given better optimal operating time of relay without miscoordination when compared with other algorithms.
[70]	Informative DE	• The settings of the DOCRs are optimized using developed informative DE algorithm (IDA) with self-adaptive re-clustering technique. • The combination of backup relays for each primary relay is determined using a LINKNET graph theory approach.	9-bus and IEEE 30-bus distribution systems	• GA-NLP [141] • SQP [30]	• Overall operating time of all primary DOCRs is successfully minimized and the constraint violations are also eliminated with proposed Informative DE optimization algorithm and given better performance as compared with other algorithms.
[71]	Opposition based chaotic DE	• Two algorithms, called opposition-based chaotic differential evolution (OCDE1 and OCDE2), were developed, and utilized to address the coordination problem.	IEEE 3-, 4-, 6- and 14-bus systems	• GA [259] • SOMA [259] • SOMGA [259] • RST [31] • MDE4-MDE5 [67] • PSO-W [182] • LXPSO-W [182] • PSO-C [182] • LXPSO-C [182]	• In terms of number of function of evaluations and CPU time also, the proposed variants outperform the other algorithms taken in this study.
[72]	Enhanced DE	• An analysis of performance evaluations and comparisons between various mutation versions of the DE algorithm using two crossover schemes (binomial and exponential) is conducted. • The DE algorithm is specifically improved for addressing the coordination problem. • The enhanced DE algorithm can achieve near-global optimal results in a shorter execution time. • The enhanced DE algorithm operates efficiently even when analyzing larger systems.	IEEE 14 and 57 bus systems	None	• The DE algorithm with binomial crossover, specifically designed for trigonometric functions, was found to be the most effective. • It was further improved in four different ways and was able to successfully coordinate the highly interconnected IEEE 57 bus system with excellent outcomes and no coordination constraints violations.

TABLE 10. Advancements of the HSA in solving the DOCR coordination problem, with emphasis on key contributions, test case applications, comparative analyses, and observations.

Ref	Method	Contribution	Test case/s	Compared with	Remark/s
[73]	HSA	• Application of the HSA to obtain the optimum settings of the DOCRs for coordination problem.	A single-ended power system with parallel feeders and single-ended multi-loop distribution power system	• GA [232] • SM [232] • DSM [140]	• HSA minimizes overall operating time better than other algorithms. • HSA required fewer function evaluations than other algorithms, making it a more efficient option.
[74]	IHSA	• The development of the Improvised HSA to solve the coordination problem.	IEEE 30-bus system	• LP • GA	• HSA and IHSA lead to better solution than GA and LP. • IHSA has high quality solutions, stable convergence characteristic and desirable computational speed and efficiency than HSA.
[75]	BMHSA	• Proposing a new variation of HSA based on the Box-Muller transform.	IEEE 3-, and 4-bus systems	• RST [31] • GA [259] • SOMA [259] • SOMGA [259] • Different versions of PSO [183] • LP	• BMHS method is fast and reaches the optimal solution with a relatively low number of iterations. • The proposed method shows better performance than the other algorithms.

[175] and PSO [58]. It was found that the proposed SOA can find superior relay settings in linear and nonlinear models.

In [156], five meta-heuristic optimization techniques (GA, PSO, DE, HS and SOA) were utilized to determine the optimal settings for DOCRs. The performance of these algorithms was tested on various power system networks of varying sizes. The results showed that DE performed the best among the five algorithms studied.

9) FIREFLY ALGORITHM (FA)

The FA is a swarm-based metaheuristic algorithm, which was introduced by Xin-She Yang in 2008. The algorithm mimics how fireflies interact using their flashing lights [220]. Unlike PSO, FA does not depend on either the historical best or the global best. This helps to reduce the chance to trap the potential solutions in premature convergence. This is because FA does not need to be concerned about the initialization of velocity, especially at high velocities that are relatively unstable to control [221]. It was frequently used by researchers to solve the coordination problem with DOCRs. In [76], FA was used to obtain the optimal settings of DOCRs for single-ended power system with parallel feeders.

The effect of an inductive fault current limiter (FCL) on fault current values lowers the fault current that is seen by the relays, while the location of the Inductive FCL within the power system has a significant impact on its effectiveness. The installation of Inductive FCL in the power system has a great impact on the CTI and thus a new setting of the relays is required. Authors in [77] included the impact of the Inductive FCL on DOCRs coordination problem.

The insertion of series compensation to the line will change its impedance, as well as the short circuit currents, and could lead to loss of coordination between the relays. Consequently, the DOCR setting must be adjusted considering the new effective impedance of the line. To overcome this technical problem, authors in [78] proposed intelligent overcurrent relays coordination in the presence of series compensation using FA.

In [79], the standard FA was modified to eliminate its weakness by improving randomness of the fireflies because it influences the fireflies in exploration of the optimal solution. The modified Firefly Algorithm (MFA) reduced the randomness of fireflies by modifying the randomization parameter. The proposed algorithm was simulated in a radial network under the presence of a distributed generator.

The effectiveness of the FA algorithm in optimization is affected by a Gaussian distribution random value, which causes convergence and traps the solution in the local slow optimization point. To address this, the authors of [80] introduced a new and fast adaptive modified version of FA called (AMFA), which aims to find the optimal coordination of DOCRs by exploring the search space and increasing the convergence rate. The proposed algorithm was tested on the same system in [79].

Another method to improve the quality of the solution using FA is to incorporate the chaos theory to prevent the search process from being trapped in a local minima. Chaos theory is introduced by modifying the concept of random movement factor. Authors in [81] developed the Chaotic Firefly algorithm (CFA) for optimal coordination of DOCRs. It was found that CFA yielded better results than the standard FA on the points of quality of solution, speed of convergence and number of iterations taken to obtain the best solution. Furthermore, the CFA was superior to the standard FA irrespective of the initialization value of the random movement factor.

In [82], a self-adaptive weight was employed to adjust the propensity of moving toward the best solution and neglecting the worst one. To enhance the flashing mechanism and so rise the capacity for exploration, a learning strategy based on the experience of other solutions was also established. All of which contributes to the development of Improved FA.

The main issue with using FA to solve a multi-objective coordination problem for DOCRs is that it can easily get trapped at a local optima, hence, in [83], a modified FA was developed to overcome this problem and improve the performance and efficiency of FA. Table 11 demonstrates the progress made on the application of FA to solve the DOCRs coordination problem.

10) TEACHING LEARNING BASED OPTIMIZATION (TLBO)

The TLBO algorithm, similar to other nature-inspired algorithms, is a population-based approach that advances to the global solution from a population of solutions. The population is considered as a group or a class of learners. This approach is based on the effect of the influence of a teacher on the output of learners in a class [222]. In [84], TLBO algorithm was utilized to achieve optimal coordination of DOCRs in looped power systems. The Far vector of the LINKNET structure was used to determine the combination of primary and backup relays. The results were then compared with those of MDE [67], indicating that the total primary operating time of relays was greater when TLBO was utilized. However, TLBO resulted in a decrease in the number of miscoordination pairs. This indicates that the algorithm was successful in achieving better coordination among the relays.

In [85], a Modified Adaptive Teaching Learning Based Optimization (MATLBO) algorithm was proposed to improve the search capability and the probability of finding better feasible solutions. One of the advantages of the MATLBO algorithm is that it uses an advanced set of population that helps in generating better solutions. This approach increases the efficiency of the algorithm in finding optimal solutions. An advance set of population was generated with a maximum value of TMS available from the earlier solution. MATLBO algorithm was evaluated on different networks and was found more effective. For one of the case studies, the effect of distributed generators and application of superconducting FCL to mitigate DG impact was presented. In this case study, the near end relays were replaced by digital relays with adaptive settings, and the FCL was used to restore protection coordination of far end relays. This approach appeared to have been successful in mitigating the impact of distributed generators and restoring protection coordination.

In [185], a comparison between the application of the PSO and TLBO for determining the optimal settings of DOCRs for coordination in loop-based interconnected power systems was presented. It was shown that TLBO produced better results than PSO in terms of the total operating times of relays and reliable coordination margin. Table 12 illustrates the advancement of the TLBO algorithm in addressing the DOCRs coordination problem.

11) CUCKOO SEARCH ALGORITHM (CS)

Yang and Deb developed the CS algorithm, which is based on swarm intelligence and inspired by the natural behavior of certain cuckoo species, which exhibit obligate brood parasitism by laying their eggs in the nests of other host birds [223]. CS algorithm can be enhanced by using Lévy flights instead of using simple random walks. The Lévy flights are a type of random walk in which the steps are defined in terms of the step-lengths that follow a certain probability distribution in which the directions of the steps must be isotropic and random [224]. When Lévy flights is generating new solutions, the search will mostly stay around the best solution obtained so far, which speeds up the local search [225]. Authors in [86] used the Lévy flights CS algorithm for optimal time coordination of DOCRs.

In [87], the CS parameters were successfully fine-tuned to achieve the best global solution for the DOCRs coordination problem. The results showed that modifying the randomly generated value for step size within [0, 1], which cannot adapt to the environmental changes as the iteration goes on. Thus, the authors of [88] incorporated a hierarchical clustering mechanism with CS (HCS) to replace the fixed CS parameters could lead to a more efficient and effective solution of this coordination problem. Standard CS is suffering difficulties in achieving high-quality solutions and fast convergence speeds due to the value of step size instead of an adaptive hierarchical clustering step size. Table 13 presents the development on the CS algorithm for solving the coordination problem.

12) ANT COLONY OPTIMIZATION (ACO)

The ACO is a metaheuristic algorithm inspired from the foraging behavior of real ant colonies [226]. Authors in [174] used ACO technique to coordinate DOCRs. IEEE 3-bus and 8-bus systems were used to test the proposed algorithm. The results illustrated that ACO not only can assume various classes of decision variables robustly but, more important, finding high-quality solutions. In [89], a comparison of ACO and FA for coordination problem solving showed that FA outperformed ACO in terms of optimal solution.

13) ANT LION OPTIMIZER (ALO)

The ALO is a nature-inspired optimization algorithm based on the hunting strategy of antlions [227]. In [90], ALO was used to solve the DOCRs coordination problem for IEEE 30-bus distribution system and practical 11-bus distribution system. Results were compared with Artificial Immune System (AIS) and PSO. ALO exhibited superior accuracy, shorter computation time, and greater stability than PSO and AIS, establishing its efficiency and reliability.

14) BACKTRACKING SEARCH ALGORITHM (BSA)

The BSA is one of the metaheuristic algorithms, which was developed by Civicioglu [273]. The remarkable features of BSA are that it has a very simple structure and only needs the essential parameters [228]. Authors in [91] implemented

TABLE 11. **Development of the FA in addressing the DOCR coordination problem, highlighting key contributions, test case applications, comparative analyses, and observations.**

Ref	Method	Contribution	Test case/s	Compared with	Remark/s
[76]	FA	• The application of the FA for optimal time coordination of DOCRs.	Radial distribution system and single-ended power system with parallel feeders	• LP • GA	• The coordination problem was formulated as LP problem. • The TMS values obtained by FA are better than obtained from LP and GA.
[77]	FA	• Solving the coordination problem using FA considering the impact of the Inductive Fault Current Limiter on the relays.	8-bus power test systems	None	• All relays are well coordinated for all scenarios.
[78]	FA	• Application of FA for Optimal Coordination of DOCRs in presence of series compensation.	8-bus power test systems	• LP [261] • GA [131] • GA-LP [131] • PSO-LP [133] • SOA [23]	• The obtained settings provide a well relays coordination in the presence of series compensation.
[79]	MFA	• Development of MFA to enhance the performance of the FA for solving the coordination problem.	Radial network with distributed generators	• FA	• MFA can greatly reduce the operating time of the relays. It was faster to reach the global optimum than FA convergence.
[80]	AMFA	• Proposing a new fast adaptive modified FA to find an optimal coordination of DOCRs.	Radial network with distributed generators	• FA [79] • MFA [79] • PSO	• The results demonstrate that the proposed AMFA can achieve the optimized coordination of DOCRs in all test cases with significant improvement in time reduction with faster convergence rate.
[81]	CFA	• Application of a tent map initiated Chaotic FA for optimal DOCRs coordination.	A parallel feeder system and a multi-loop distribution system	• FA	• The CFA yields better results than the standard FA on the points of quality of solution, speed of convergence and number of iterations taken to obtain the best solution. • It is better to use chaos than random initialization while using evolutionary algorithms for relay coordination.
[82]	IFA	• Proposing an improved FA by adding the self-adaptive weight and experience-based learning strategy to the standard FA.	IEEE 6-, 9- and 30-bus systems.	• FA • WOA • MPSO [58] • GA [141], [170] • TLBO [84] • PSO-DE [121] • PSO [184] • BBO [17] • ILP [262], [263] • MDE4-MDE5 [67] • OCDE-1-OCDE-2 [71] • IDE [85] • BH [93] • NLP [141]	• Self-adaptive weight was presented in IFA to get the best solution and removing the worst solution during simulation procedure. • Experience-based learning strategy was added to improve the convergence rate and enhances the exploitation ability of the algorithm. • The proposed IFA is efficient and robust as compared with the other techniques.
[83]	Modified FA	• Proposing Modified FA for multi-objective DOCRs problem.	8-bus power test system	• ABC	• Modified FA results outperformed ABC approach in terms of fitness function values and computation time.

TABLE 12. Evolution of the TLBO algorithm in solving the DOCR coordination problem, with emphasis on key contributions, test case applications, comparative analyses, and observations.

Ref	method	Contribution	Test case/s	Compared with	Remark/s
[84]	TLBO	• Application of TLBO algorithm for optimal coordination of DOCR relays in a looped power system.	IEEE 3, 4 and 6 bus systems	• MDE [67]	• Compared to MDE, the proposed TLBO algorithm provides a higher total sum of primary relay operating time and eliminates miscoordination pairs.
[85]	MATLBO	• Proposing a modified adaptive teaching learning-based optimization algorithm to find the optimum solution for the DOCRs settings.	IEEE 6-bus system, 8-bus, 9-bus meshed distribution systems and15-bus meshed distribution system	• TLBO [84] • PSO [57] • MPSO [57] • GA [131] • GA-LP [131] • SOA [23] • MINLP [23] • IDE [70]	• The proposed MATLBO algorithm overcomes the weakness of TLBO algorithm and capable to find superior TMS and PS settings as compared to other optimization algorithms. • In case of existence of distributed generators and application of fault current limiter to mitigate distributed generators impact, to restore protection coordination of far end FCL was used and for near end relays Adaptive Relaying was used.

TABLE 13. Development of the CS algorithm in solving the DOCR coordination problem, highlighting key contributions, test case applications, comparative analyses, and observations.

Ref	method	Contribution	Test case/s	Compared with	Remark/s
[86]	CS	• The application of Levy flight CS algorithm for determining the TMS for DOCRs.	A parallel feeder system and a practical distribution system	• LP	• CS algorithm gives total operating time which is less compared to that obtained by LP method.
[87]	Tuned CS	• Proposing tuned CS to solve DOCRs coordination problem effectively.	8-bus power test system	• GA [141] • GA-NLP [141]	• Tuned CS gives minimum OF value for relay coordination problem without violation in CTI.
[88]	HCS	• Proposing HCS with a hierarchical clustering step size in place of the step size that is randomly generated. Moreover, the superiority of HCS is verified by solving the DOCRs optimal setting problem.	IEEE 3- and 8-bus systems	• Simplex [175] • LP [58] • SOA [23] • OJAYA [6] • EFO [93] • MEFO [93] • DE [93] • PSO [93], [58] • BH [93] • EM [93] • BBO [93] • HS [93] • JAYA [264] • HHO [264]	• In aspects of convergence rate, solution quality, and robustness, HCS behaves much better than CS. • HCS was more effective than other techniques in reducing the value of the objective function and maintaining its robustness

and applied BSA to the optimal coordination of DOCRs. To have very effective exploration and exploitation capabilities of BSA, authors in [92] proposed enhanced BSA (EBSA) that contains two new crossover and mutation operators. Moreover, the EBSA technique had a memory to obtain the advantage of experiences from previous generations during creation of a new generation. The proposed EBSA technique for optimal DOCR coordination was implemented and tested effectively on three different distribution systems with different complexities. The progress of the BSA algorithm in solving the coordination problem of DOCRs is demonstrated in Table 14.

15) MODIFIED ELECTROMAGNETIC FIELD OPTIMIZATION (MEFO)

EFO is one of the relatively new physics-inspired metaheuristic algorithms, which is first proposed by Abedinpourshotorban et al. It simulates the behavior of electromagnets with different polarities and takes advantage of a nature-inspired ratio, known as the golden ratio [229]. A notable characteristic of EFO is the collaboration of multiple particles to create a novel electromagnetic particle, and it was demonstrated that EFO exhibits superior performance when compared to other optimization algorithms [230]. Authors in [93] applied two simple modifications on the algorithm by changing the uniformly distributed random generation procedure (used in the search equation) to the normal distributed random generation and boundary check procedure of the electromagnets. The optimal coordination of DOCRs for 8-bus, 9-bus, and 15-bus test systems was identified using the proposed Modified Electromagnetic Field Optimization (MEFO) algorithm. The results showed that MEFO is a reliable and effective tool for DOCR coordination, and it outperformed EFO, DE, PSO, BH, EM, BBO, and HS optimization techniques in terms of the quality of results obtained.

16) ROOT TREE OPTIMIZATION (RTO)

The RTO is a well-known and reliable bio-inspired algorithm for solving linear, nonlinear, constrained optimization problems. It mimics the behavior of desert plants where the water resources are lacked [231]. In [94], RTO has been utilized to search for the global optimum, in order to find the optimal solution of the coordination problem of DOCRs for different case studies. The proposed technique was compared with the other mathematical and evolutionary techniques such as the FA [76], CFA [81], GA [46], CGA [48], SM [232], and CPSO [142]. The simulation results of the RTO algorithm efficiently minimize all models of the problem better than the other methods. Authors in [95] applied the RTO algorithm for solving the coordination problem for the IEEE-8 bus system. Compare to LP [33], NLP [33], GA [131], GA-LP [141] and SOA [23], the proposed algorithm given an optimal solution and lower total operating time and was capable of solving directional overcurrent relay problem in a fast and better way.

17) CROW SEARCH ALGORITHM (CSA)

CSA is a nature-inspired metaheuristic optimization algorithm developed in 2014 by Yang and Deb. The algorithm is based on the intelligent foraging behavior of crows, where crows hide and retrieve food in a group while communicating with each other [233]. Authors in [96] successfully applied the CSA algorithm for the optimal relay coordination problem of DOCRs for different power system networks and the results were compared with FA [76], CFA [81], GA [46], CGA [48], SM [232], and RTO [94] techniques and found that CSA outperformed these techniques in terms of solution quality, achieving minimized objective function values. The faster convergence rate of CSA also indicates its potential to reduce the computational time required for optimization. These advantages make CSA a promising optimization technique for solving real-world problems in power systems.

18) FLOWER POLLINATION ALGORITHM (FPA)

The FPA is a highly efficient metaheuristic optimization algorithm that is inspired by the pollination process of flowering species. FPA is characterized by simplicity in its formulation and high computational performance [234]. In [19], the coordination problem was formulated as LP problem and then solved using FPA for a parallel feeder distribution system. The results obtained using FPA was better than LP technique. Whereas in [18], author integrated simultaneously the relay coordination study to the arc-flash assessment. The FPA was applied for 8-bus transmission network and 15-bus meshed network to minimize the hazard of the arc-flash and to realize the optimal settings of relays. The results were compared with other algorithms and it was shown that the FPA succeeded in finding a close to optimal solution for the relay selectivity problem.

19) GRAVITATIONAL SEARCH ALGORITHM (GSA)

The GSA is a nature-inspired algorithm based on the mathematical modelling of the Newton's law of gravity and motion [235]. In [97], GSA was developed for obtaining optimal coordination of DOCRs for a radial system considering the DG penetration. The results of this method were compared with PSO algorithm and found to be superior to it. In [98], GSA was employed for optimum coordination of DOCRs using standard and user defined relay characteristics. In [99], the opposition learning scheme was merged with basic GSA to accelerate the performance of convergence of the proposed optimization towards the optimum solution. The progress of the GSA algorithm in solving the coordination problem of DOCRs is demonstrated in Table 15.

20) WATER CYCLE ALGORITHM (WCA)

WCA is one of the novel metaheuristic optimization algorithms that was introduced by Tizhoosh and Muezzinoglu in 2017. It mimics the flow of rivers and streams toward the sea and was derived by observing the water cycle process [236]. Good exploitation and exploration capabilities have made the WCA a good alternative for solving large scale optimization problems [237]. For this reason, authors in [100] was successfully employed WCA to address the DOCRs coordination problem in a several interconnected mesh systems. The proposed method showed it was flexible and adequate for dealing with a large power system. Authors in [101] expressed the coordination problem as a LP problem and then resolved successfully using WCA on a distribution system.

The performance of the WCA algorithm can be enhanced by balancing the capability of the exploitation and exploration to find the global optimal solution and reduce the search space. This can be achieved according to the value of parameter C. Authors in [102] proposed a modified version of the WCA (MWCA) to search for the global optimal solution by increasing the C-value exponential over the course of iterations instead of being chosen as a constant value.

TABLE 14. **Advancements of the BSA in addressing the DOCR coordination problem, with emphasis on key contributions, test case applications, comparative analyses, and observations.**

Ref	Method	Contribution	Test case/s	Compared with	Remark/s
[91]	BSA	• Development of BSA for the optimal coordination of DOCRs.	6-bus, 8-bus, and 15-bus test systems	• DE • PSO • BH • EM • BBO • HS	• Superior other compared algorithms.
[92]	EBSA	• Proposing enhancement BSA that can find global optimized solutions with an efficient procedure for optimization of DOCR parameters.	3-bus, 8-bus, and 15-bus test systems	• PSO [58] • SOA [23] • NLP [58] • ICA [265]	• The mutation process uses only one individual from a previous population and its crossover process is more advanced than in others; • EBSA is a dual-population algorithm that uses both the current and historical population to take advantage of the experiences from previous generations. • The effectiveness of the proposed EBSA-based approach in solving the optimal coordination problem.

TABLE 15. **Development of the GSA algorithm in solving the DOCR coordination problem, highlighting key contributions, test case applications, comparative analyses, and observations.**

Ref	Method	Contribution	Test case/s	Compared with	Remark/s
[97]	GSA	• Application of GSA for coordination of DOCRs for a system containing DG.	Single source 4-bus radial system	• PSO	• GSA technique is giving superior results than PSO.
[98]	GSA	• The optimal coordination of DOCRs was achieved using the GSA by incorporating a user-defined characteristic for inverse-time overcurrent relays in addition to the standard characteristic. By adjusting the constant values, the shape of the relay characteristic was controlled, resulting in optimal DOCR coordination.	8-bus, 15-bus, and IEEE 30-bus systems.	• SOA [23] • IDE [70] • BBO [17] • PSO-LP [177]	• GSA exhibits superior performance in terms of solution quality when compared to other evolutionary algorithms. • The primary concern with the proposed technique is its high computational requirement, as each iteration involves multiple computations in contrast to other evolutionary algorithms.
[99]	OLGSA	• Integration of opposition learning concept with GSA to find optimum TDS setting and minimum operating time of DOCRs.	Single end multi parallel feeder system, multi loop single end fed system and single loop distribution system	• FA [76] • CFA[81] • CGA [69] • RTO [94] • WCA [101] • Simplex [141]	• In terms of objective function value, the proposed OLGSA outperforms other algorithms.

The proposed algorithm was tested using four standard test systems to find the optimal settings of the DOCRs.

Microgrids experience significant short-circuit level fluctuations due to frequent changes in their operating modes (grid-connected and islanded modes). Consequently, these changes can impact the overcurrent protection scheme. To address this issue, researchers in [103] developed a constrained optimization formulation for the coordination problem of DOCR schemes in microgrids, which was then solved using WCA and PSO to optimize the objective function. The proposed optimization process was shown to yield improved solutions for the coordination problem, with the fitness function of WCA converging to a better minimum operational time while satisfying all constraints compared to PSO. Moreover, WCA converged to the best solution in a minimum number of iterations than PSO.

In [104], the WCA was enhanced by introducing an evaporation-rate-based mechanism, known as ERWCA, which leads to a wider gap between the exploitation and exploration phases as compared to WCA. Moreover, the convergence rate towards a global solution was accelerated, resulting in superior performance when compared to WCA.

TABLE 16. **Evolution of the WCA in addressing the DOCR coordination problem, with emphasis on key contributions, test case applications, comparative analyses, and observations.**

Ref	Method	Contribution	Test case/s	Compared with	Remark/s
[100]	WCA	• Application of WCA to optimally deal with coordination problem of DOCRs.	15-bus transmission network and IEEE 30-bus system	• GA • SFSA [188] • FPA [18] • MINLP [23] • SA [23]	• WCA superior other algorithms in terms of high convergence speed and its proper design.
[102]	MWCA	• Development of WCA for solving the coordination problem by updating the C-value according to iteration number instead of constant value.	8-bus, 9-bus, 15- bus, and IEEE-30 bus systems	• AFA [80] • SOA [23] • HSA [167] • BBO [17] • GA [178] • BH [[266] • EFO [230] • MEFO [121] • GSA [267] • GA-NLP [141] • BSA [91] • GSA-SQP [196]	• The modified algorithm converges to the global minimum faster than the traditional WCA • MWCA able to find the best relay setting, satisfy coordination margin, and minimize the total operating time of all primary relays.
[104]	ERWCA	• Development of Improvised version of WCA to get a better distribution between the exploitation and exploration phases as compared to WCA and a faster convergence to a global solution with accurate results than WCA in solving the DOCRs coordination problem.	IEC microgrid benchmark system	• WCA [103] • PSO [103]	• The performance of the proposed ERWCA is outstanding over WCA and PSO in terms of the number of population the requirements of iterations and the overall operating time.
[105]	MERWCA	• Proposing a modified version of ERWCA to improve its performance and use it for solving DOCRs coordination problem for both conventional and non-conventional characteristics curves.	IEEE 39-bus network	• GA [178] • TLBO [84] • FFA [268] • SMA [269] • AEO [270] • PSO [57] • GWO [106]	• The obtained results prove the superiority of the MERWCA to solve the coordination problem.

The proposed ERWCA algorithm was evaluated on the standard IEC microgrid benchmark in [103].

To enhance the search ability and the balance between the explorations to the exploitation of the original ERWCA, a modified ERWCA (MERWCA) was proposed in [105]. Different strategies such as Lévy flight and OBL were applied to the original ERWCA, to avoid falling on the local optimal. MERWCA was used to obtain the optimal DOCRs settings for the IEEE 39-bus network. Both of MERWCA and ERWCA were assessed on the case of conventional and non-conventional characteristics curves. The advancements in the WCA algorithm to solve the coordination problem of DOCRs are displayed in Table 16.

21) GREY WOLF OPTIMIZER (GWO)

The GWO is a popular algorithm in the field of metaheuristics algorithm that was introduced by Mirjalili et al. in 2014. The algorithm is inspired by the social hierarchy and hunting behavior of grey wolves in nature. The GWO algorithm is known for its simplicity, fast convergence speed, and strong exploitation ability, which makes it an effective tool for solving various optimization problems [238]. It mimics the leadership hierarchy and hunting mechanism of grey wolves in nature. GWO was implemented in [106] to get the proper relay setting and solve the coordination problem. The GWO algorithm tends to fall into local optimum, leading to imbalance between exploitation and exploration. Meanwhile, the diversity of the population may be poor relying on the greedily optimization process [238]. In [107], improved GWO (IGWO) algorithm was proposed to solve the coordination problem in which the omega considered as a searching agent instead of obliged to follow the first three best candidates to improve the search ability of the grey wolves in a wide range of search space. In [108], the authors introduced an improved version of the GWO called the Enhanced Grey Wolf Optimizer (EGWO), which strikes a suitable balance between the exploration and exploitation phases to enhance convergence characteristics and computation time. This was achieved by exponentially decreasing the control parameter during the iterative process. The proposed EGWO was effectively applied to solve the coordination problem of DOCRs for various power systems.

In [14], the authors presented a solution to overcome the limitations of local optima and premature convergence in conventional GWO when dealing with nonlinear and complex optimization problems. They proposed a Random Walk GWO (RW-GWO) algorithm to find the best settings for the directional overcurrent relay coordination problem.

The multi-objective optimization problems can be solved based on weighting factors or Pareto front. Authors of [109] proposed a novel multi-objective optimization algorithm called multi-objective GWO (MOGWO) proposed to solve the coordination problem of DOCRs. It works based on the Pareto front. An archive and a leader selection mechanism are added to the conventional GWO to solve the multi-objective optimization problem. Different optimal solutions were obtained using the MOGWO algorithm, and then fuzzy logic decision-making was used to obtain the best compromise solution from these solutions. Table 17 demonstrates the advancements made in utilizing the GWO algorithm to solve the problem of coordinating DOCRs.

22) HARRIS HAWK OPTIMIZATION (HHO)

The HHO is a population-based metaheuristic algorithm, inspired by the hunting strategy and cooperative behavior of Harris hawks [239]. HHO has been leveraged for many applications and engineering problems due to its optimization features and competitive performance [240], [241]. In [27], the optimal settings for DOCRs were found by HHO deployed in a multi-loop power systems. Unlike other optimization methods, HHO is designed to dynamically adapt to different prey behavior patterns during the exploitation phase, which increases its exploration capability. These unique qualities of the HHO algorithm enable search agents to better seek out optimal solutions. The HHO algorithm's distinct hunting and sieging capabilities have been found to be effective in identifying global optimum values with enhanced robustness and improved convergence compared to other algorithms.

Modifications of crowding distance and roulette wheel selection to improve the ability to converge towards better solution while maintaining diversity, to the HHO was developed in [110]. The modified HHO (MHHO) was proposed to address the coordination and optimization problem of DOCRs. It was compared to various algorithms and it was demonstrated that the enhanced results obtained by MHHO indicated its superiority and reliability as a valuable optimization tool. Table 18 illustrates the progress made in using the HHO algorithm to address the issue of coordinating DOCRs.

23) GROUP SEARCH OPTIMIZATION (GSO)

GSO is a nature-inspired optimization algorithm that was introduced by He et al. in 2009. It mimics animal search behavior in the natural world, and has been successfully applied to a range of optimization problems. The GSO algorithm is known for its simplicity, adaptability, and ease of implementation, making it a versatile tool for solving various optimization problems when compared to other algorithm [242]. The conventional GSO often converges to the local optima and for most cases, it has low convergence speed. Hence, in [111], some modifications were applied to the original GSO in order to improve its ability in finding the optimal solution for the coordination problem. The modified GSO was developed to select the optimal values of time dial setting and pickup current setting to minimize operating time of DOCRs. Four test cases and some benchmark functions with lots of local minima were utilized to confirm the efficiency of the proposed method. Comparison between earlier reported results and the proposed algorithm results indicated that, applied modifications have improved convergence performance of the proposed method.

24) IMPERIALIST COMPETITIVE ALGORITHM (ICA)

The ICA is a metaheuristic algorithm introduced by Atashpaz-Gargari and Lucas [274], was inspired by socio-political behaviors [243]. This algorithm is a strong means of solving many optimization problems [244]. It was used in [112] to solve the coordination problem for a 6-bus test system using ICA. The performance of the ICA was compared with GA in terms of the mean of convergence speed, mean of convergence time, convergence reliability, and the tolerance of convergence speed to reach the optimum point. It was proved that ICA is much more powerful than GA in finding the approximate location of the optimum point. However, in the proximity of the optimum point, where the absolute optimum point should be accurately located, GA operates more powerfully. It was also proved that in the first stage of optimization, convergence speed, convergence time, and convergence reliability was better in ICA. It was also shown that the tolerance of convergence speed is better in GA than in ICA. Authors in [113] used the same algorithm in [112] to obtain the optimal settings of DOCRs for 3-bus, 8-bus and 15-bus test systems. Different relay characteristics were used in the formulation of the objective function for the coordination problem. The results were compared with GA [141], GA-LP [141], SOA [58], and SBB algorithms. It was revealed that the proposed algorithm demonstrated significant advantages in terms of fast convergence and its reliable ability to find the best solution.

25) POLITICAL OPTIMIZATION ALGORITHM (PO)

The PO is a global optimization algorithm which inspired by the multi-phased process of politics. PO is the mathematical mapping of all the major phases of politics such as constituency allocation, party switching, election campaign, inter-party election, and parliamentary affairs. It has an excellent convergence speed with good exploration capability in early iterations [245]. In [114], PO was applied efficiently to coordinate the DOCRs for 8-bus, 9-bus and 15-bus test systems.

26) SYMBIOTIC ORGANISM SEARCH TECHNIQUE (SOS)

The SOS is a recently developed robust and powerful metaheuristic algorithm applied to numerical optimization and engineering design problems. It has received wide

TABLE 17. Development of the GWO algorithm in solving the DOCR coordination problem, highlighting key contributions, test case applications, comparative analyses, and observations.

Ref	Method	Contribution	Test case/s	Compared with	Remark/s
[106]	GWO	• Proposing the GWO to obtain the optimal relay setting of the DOCRs and solve the coordination problem.	15-Bus meshed distribution system	• BH [93] • BBO [93] • GA [93] • FA [17] • MEFO [93]	• GWO minimize the objective function and satisfies all the constraints of relays setting. • GWO algorithm gives the least objective function compared to other algorithms, which indicates the high quality and robustness of the GWO algorithm.
[107]	IGWO	• Modification on the conventional GWO to enhance the candidate's exploration ability.	8-Bus and 15-bus test systems	• MPSO [58] • MINLP [23] • SOA [23] • GA-NLP [141] • CSA [87] • GWO	• The optimization of DOCRs coordination problem exhibits enhanced convergence performance with the application of IGWO. • Proposed modification has counteracted the argument of randomness exploration activity.
[108]	EGWO	• Improvement on the conventional GWO technique performance by choosing a proper balance between exploration and exploitation phases to obtain the optimum global minima solution in the search space.	8-bus, 9-bus, 15-bus, and 30-bus	• MEFO [93] • DE [156] • PSO [156] • GA [156] • HS [167] • MWCA [102] • EWCA [252] • GA-NLP [141] • GSA-SQP [98] • BBO-LP [17] • CSA [87] • BSA [91] • EBSA [92] • GSO [111] • FA [271]	• A significant reduction in the overall operational time of all primary relays is accomplished while ensuring sequential operation between relay pairs. • The results obtained demonstrate that the proposed EGWO algorithm is more effective and superior in solving the DOCRs coordination problem, in comparison to conventional GWO and other optimization techniques.
[14]	RW-GWO	• The RW-GWO algorithm is introduced to enhance the search capability of dominant wolves in the conventional GWO algorithm and address the problems of being stuck in local optima and experiencing premature convergence when tackling complex and nonlinear optimization problems. • Testing the RW-GWO algorithm for three different modes as: 1. Grid-connected mode. 2. Islanded mode and 3. Disconnection of distributed generators to find the optimal DOCRs setting.	4-bus distribution network.	• GWO • mGWO • EEGWO • wGWO • SSA • cSSA • SCA	• In RW-GWO, the search agents are, on average, closer to each other than in classical GWO, indicating a better balance between exploration and exploitation. • The primary search agents, which are enhanced through random walk in RW-GWO, offer better guidance compared to those in classical GWO, resulting in improved problem solutions. • Compared to other methods, the RW-GWO algorithm achieved better solution accuracy in solving the coordination problem.
[109]	MOGWO	• Proposing a new objective function to minimize the coordination time between relay pairs. • Developing a MOGWO algorithm to solve the multi-objective coordination problem by adding archive and a leader selection mechanism to the conventional GWO. Then the fuzzy logic decision-making is utilized to obtain the best compromise solution from these solutions.	8-bus test system and IEEE 30-bus test system.	• GWO • WCA • EFO • GSA-SQP • NSGA-II	• In contrast to GWO, which concentrates on enhancing and retaining its improved three solutions, MOGWO explores a group of archive members to identify potential alternatives. • Significant reduction in the combined operational time of all primary and backup relays, as well as the time taken to distinguish between pairs of relays. • The results obtained demonstrate the superiority of the proposed MOGWO algorithm in solving the coordination problem compared to other optimization techniques.

TABLE 18. **Advancements of the HHO algorithm in solving the DOCR coordination problem, with emphasis on key contributions, test case applications, comparative analyses, and observations.**

Ref	Method	Contribution	Test case/s	Compared with	Remark/s
[27]	HHO	• Application of HHO for solving the network relay coordination and optimization problem.	IEEE-9, 15 and 14-bus systems.	• PSO [156] • GA [141] • NLP [141] • IDE [85] • HS [156][93] • BBO [17] • MTLBO [85] • SA[23] • MINLP [23][82] • AA [33] • DE [156] • BSA [91] • IGSO [111] • MEFO [93] • GA-LP [21] • MECPSO [272] • MAPSO [272]	• Compared to other metaheuristic algorithms, HHO offers a greater capacity for exploration. • The essential factor of the proposed HHO is selecting the best TDS and PS estimates to reduce the operating time of DOCRs regarding reinforcement and hand-off setting limitations. • In comparison to other state-of-the-art algorithms, the HHO's unique sieging and hunting capacity was demonstrated to be efficient in locating the global optimum values with robustness and better convergence.
[110]	MHHO	• Development of HHO to enhance the solution space diversity and selection ability by made modifications of crowding distance and roulette wheel selection.	IEEE 8 and 15-bus systems	• HHO [179] • SA [131] • GA-LP [17] • BBO-LP [17] • JAYA [6] • MINLP [131] • AA [33] • DE [156] • HS [156] • BSA [91] • MTLBO [85] • IGSO [111] • MEFO [93]	• To improve the optimization capability, crowding distance and roulette wheel selection were changed. These changes increased the diversity of the general search space and the ability to identify the best minimized settings for the DOCR problem. • As a result of the modifications, MHHO demonstrates greater improvements in results than baseline HHO.

acceptance in recent years from researchers in continuous and discrete optimization domains. Like most population-based metaheuristic algorithms. The SOS differs from other population-based algorithms in that it uses few control parameters and requires no parameter fine-tuning. These characteristics are considered as the advantages which the SOS have over other similar algorithms [246]. SOS algorithm was adopted in [115] as an optimization tool to test DOCR coordination in loop-based IEEE 6-bus and WSCC 9-bus systems. The SOS algorithm was compared with other optimization algorithms, including PSO and TLBO, in terms of their ability to find a solution that satisfies the coordination constraints while minimizing the total relay operating times and maintaining a reliable coordination margin. The study found that the SOS algorithm gave superior results compared to PSO and TLBO, with better coordination margin and lower total relay operating times. The SOS algorithm was able to find an optimal solution that satisfied the coordination constraints and maintained a reliable coordination margin, while also minimizing the total relay operating times. However, it was observed that the SSO required more computation time in comparison to other optimization algorithms.

27) WHALE OPTIMIZATION ALGORITHM (WOA)

The WOA is a swarm-based metaheuristic algorithm that is based on the bubble-net hunting maneuver technique—of humpback whales—for solving the complex optimization problems. It has been a widely accepted swarm intelligence technique in various engineering fields due to its simple structure, less required operator, fast convergence speed and better balancing capability between the exploration and exploitation phases [247]. Owing to its optimal performance and efficiency, authors in [116] used WOA to obtain the optimal settings of the DOCRs for IEEE 3-bus, 8-bus, 9-bus, 14-bus, 15-bus, and 30-bus test systems. The results achieved validated that the suggested WOA is an effective and reliable tool for the coordination of DOCRs. Moreover, the results obtained utilizing WOA were better than those obtained using a number of well-known and up-to-date algorithms such as GA, PSO, DE, HS, SOA [156], BBO-LP [17], and GSO [111].

28) SINE COSINE ALGORITHM (SCA)

The SCA is a recently proposed population-based algorithm introduced by Mirjalili in 2016 for dealing with highly nonlinear optimization problems. The SCA generates various initial random solutions and asks them to shift towards the best solution using a mathematical model based on sine and cosine functions [248]. In [26], SCA was applied for optimal coordination of DOCRs on 3-bus, 8-bus, 15-bus and 30-bus test power systems. The performance of the proposed algorithm was compared with other algorithms such as SA

[23], IGWO [107], HWOA [126], MILP [21], [165], DE [156] and HS [156]. It was found to be superior in achieving a minimum overall operating time of relays with less execution time compared to the other algorithms.

29) DISCRETE AND CONTINUOUS HYPER-SPHERE SEARCH (DC-HSS)

The Hyper-Sphere Search algorithm is a metaheuristic algorithm inspired by a space search mechanism and causes the particles to converge to the global minimum of the cost function [249]. The DC-HSS is a combination of the continuous and discrete HSS. Each particle contains discrete and continuous variables. In [2], DC-HSS algorithm was adapted to relays coordination problems by adding a new discrete part to the continuous HSS which enables the user to select the relay characteristics to improve the protection coordination. The proposed method was simulated on a 6-bus network. To show the effectiveness of the DC-HSS in the protection coordination, the results were compared with the GA. In addition, to show the effect of considering relay characteristics as an optimization variable, two different cases were studied. It was obvious that by considering relay characteristics as variable, the coordination was improved. It can be then concluded that the DC-HSS leads to better results in the optimization of relay coordination problems.

30) BONOBO ALGORITHM (BO)

The BO is an intelligent and adaptive metaheuristic optimization algorithm inspired from the social behavior and reproductive strategies of bonobos [250]. The algorithm has a simple implementation process and a fast computational time [251]. In order to further enhance its performance, an Improved Bonobo algorithm (IBO) was developed in [117] by incorporating the Levy flight distribution and three leaders selection. Two solvers for the optimal coordination of DOCRs were developed using BO and IBO. The effectiveness of BO and IBO in reducing the overall operating time of relays while meeting the operational constraints was validated using the 15-bus and 30-bus test systems. The results obtained confirmed the superiority of the proposed IBO algorithm over BO and various other well-known optimization algorithms, including GA [166], PSO [137], [185] SOA [156], DE [72], BBO [17], HS [167], GSA [196], SQP [196], GSA-SQP [196], EFO [20], MEFO [20], WCA [252], and MWCA [252]. The IBO algorithm demonstrated exceptional performance in minimizing the total operating time of relays for the optimal coordination of DOCRs.

31) JAYA ALGORITHM

The JAYA algorithm is proposed by Rao in 2016 and gained a considerable interest from a wide variety of research communities due to its impressive characteristics. It is simple in concepts and easy-to-use. It has no derivative information in the initial search. It is a parameter-less algorithm. It is adaptable, flexible, and sound-and-complete [253]. Based on these distinctive attributes, JAYA algorithm was proposed in [118] to find the optimal coordination of DOCR for a single-loop and multi-loop distribution systems. When the relay coordination problem was approached using the Jaya technique, it was found that some candidate solutions' adjusted values for few variables did not always follow the lower or upper bound. In this case, the algorithm deviates from the optimal solution and fails to provide a feasible solution. This issue was solved by proposing a modified JAYA algorithm in [15].

An oppositional Jaya (OJaya) algorithm with distance-adaptive coefficient (DAC) was suggested in [6] to solve the optimal coordination problem of DOCRs. Compared with standard Jaya, there are two improvements in OJaya. First, the searching space was expanded and its population's diversity was strengthened through oppositional learning (OL). Second, the population's tendency to escape the worst position and move to the best position was accelerated with the aid of DAC, which was based on the best and worst positions in Jaya. Table 19 presents the development on the JAYA algorithm for solving the DOCRs coordination problem.

C. HYBRID OPTIMIZATION TECHNIQUES

Many researchers have observed that most of the deterministic optimization methods suffer from notable drawbacks such as premature convergence, extended search times, and susceptibility to initial solution conditions. Additionally, these techniques differ significantly in their computational speed, storage requirements, and implementation complexity. In contrast, metaheuristic algorithms may struggle to find appropriate global minima and may not always converge to a viable solution. There is always a possibility of convergence to a local minima because no specific algorithm can be successful in solving all different types of optimization tasks [20], [29], [101], [124], [128]. Hybrid optimization methods have been developed to address these issues by integrating multiple optimization techniques, which can enhance the accuracy and efficiency of the overall solution beyond what individual techniques can achieve [20], [124], [128], [168].

The network topology frequently changes due to various operating conditions and occurring system contingencies. The protective system may operate without selectivity because of these changes in the network topology. DOCR coordination problem was solved in [131] using hybrid GA-LP, considering the effects of the different network topologies. It was designed to enhance the convergence of conventional GA using a local LP optimizer. The PS settings of all relays were coded into genetic string as discrete variables. Whereas, the LP was utilized to calculate the optimal TMS of relays as continuous variables for each genetic string.

GA has the shortcoming of sometimes converging to values that are not optimal, whereas NLP approaches have the shortcoming of converging to local optimum values if the initial choice is closer to local optimum. GA searches a vast solution space because it is a multipoint search method rather than the conventional single point search methods. In [141], authors effectively combined the features of GA with NLP to find

TABLE 19. **Development of the JAYA algorithm in solving the DOCR coordination problem, highlighting key contributions, test case applications, comparative analyses, and observations.**

Ref	Method	Contribution	Test case/s	Compared with	Remark/s
[118]	JAYA	• Application of JAYA algorithm in solving the coordination problem of DOCRs.	Single end-loop, multi-loop, and parallel single end feeder distribution systems.	• GA [46] • CGA [48] • CPSO [142] • RTO [94] • FA [81] • CFA [81] • TPSM [139]	• When considering the overall time gain, the JAYA algorithm surpasses the CGA, FA, CFA, GA, TPSM, and RTO algorithms. However, in comparison to the CPSO algorithm, while the JAYA algorithm requires a longer execution time, it achieves a similar optimal result.
[15]	Modified JAYA	• Proposing Modified JAYA algorithm by adding a new step to algorithm for ensuring that all candidates move to the optimum solution and give feasible solution.	Parallel feeder, single-end-fed system	• GA • simplex methods	• Modified Jaya algorithm outperforms the GA technique and all simplex algorithms in terms of the objective function value, and time required to reach to the optimum solution.
[6]	OJAYA	• Proposing an OJAYA algorithm with DAC, to effectively solve the DOCRs coordination problem.	3-bus, 8-bus, 9-bus, and 15-bus test systems	• JAYA • DJAYA • Simplex [175] • LP [58] • PSO [58] [156] • Seeker [23] • IGSO [111] • Analytic [33] • SBB [23] • BBO-LP [17] • GA-LP [131] • NLP [141] • GA-NLP [141] • DE [156] • SOA [156] • MINLP [23] • GA [156] [131] • HS [156]	• Through oppositional learning, Jaya's search area is increased and its population diversity is strengthened. • DAC accelerates the population's trends to move to the optimal position and away from the worst position. • The superiority of OJaya in solving DOCRs coordination problems compared with standard JAYA and other algorithms in aspects of convergence rate, objective function value, robustness and computation efficiency is indicated from the obtained results.

the optimal DOCRs settings. GA was used to determine the initial value of TMS and PS of DOCRs. These values were then used as initial choice in the NLP method, which gave the global optimal solution.

A combination between GA with an efficient heuristic algorithm (EHA) was proposed in [132] to solve the coordination problem in radial distribution networks. The GA was responsible for solving the nonlinear optimization problem, which determines the PS, relay types and curve types. Through this approach it is possible to find the optimum TDS, including these variables. The problem of finding its optimal values is now considered as LP problem, which was solved using the EHA. Because of TDS, which are not encoded in the chromosome of the GA, its search space was greatly reduced. The hybrid algorithm also ensures the selectivity for multiple fault levels.

The convergence rate of PSO is slow, and optimization problems with constraints cannot be solved effectively. In order to improve the convergence of PSO, authors of [133] proposed a hybrid PSO-LP technique to solve the coordination problem. The optimal plug setting of each relay was determined using PSO, and the time multiplier setting of each relay was obtained using the LP approach. The same hybridization was used in [134] to coordinate DOCRs in a microgrid system.

The PSO algorithm has been widely recognized as a powerful tool for solving both linear and nonlinear optimization problems, particularly in the context of power system protection and coordination. With a limited runtime period, the standard PSO considers the optimal solution as the final solution, and an early convergence of PSO results in decreased overall performance and an increase in the risk of mistaking local optima for global optima. Therefore, authors in [135] and [136] introduced a hybrid optimization algorithm, the NM-PSO, which combines the Nelder-Mead simplex search method with particle swarm optimization (PSO) to efficiently solve the DOCR coordination optimization problem. PSO was the primary optimizer, while the Nelder-Mead simplex search method was utilized to improve the efficiency of PSO by enabling faster convergence. In addition to [135] and [136], the various network topologies have been successfully included in [137].

TABLE 20. **Hybrid optimization methods applied to the coordination problem, detailing method features and observations.**

Ref	Method	Features	Remark/s
[131]	GA-LP	• GA is used to determine PS of relays. Thus, each chromosome in the genetic population was used to represent PS of relays. With this chromosome information the DOCR coordination problem gets converted to LP problem, which is solved using standard LP method to determine the TMS of relay. This significantly reduced the GA's search space.	• The hybrid GA-LP method utilizes the GA algorithm to determine only the PS setting, while the TMS variables are calculated efficiently by the local LP optimizer. This approach significantly reduces the search space of GA, leading to notable improvements in computational time and iteration numbers.
[141]	GA-NLP	• The proposed approach utilizes the strengths of both GA and NLP by using GA to find the initial solution of the problem, which is then passed on to the NLP method to obtain the global optimal solution, effectively overcoming the limitations of both methods.	• The proposed hybrid GA-NLP method reduces the time required to achieve the global optimum solution to a large extent, as compared to that using hybrid GA-LP method.
[132]	GA-EHA	• The proposed method combines EHA and GA to reduce the problem's dimension and decrease the search space of GA. The EHA is used to calculate the optimum TDS, and this information is utilized by GA.	• The consideration of the relays and curves types as decision variables, result in a wide range of curves shapes that can be chosen. This flexibility improved the coordination of OCR. • EHA showed to be a superior technique to LP in finding the optimum TDS in radial distribution networks.
[133], [134]	PSO-LP	• Quantizing PS parameter is considered as a part of optimization producer in PSO iterations. After that, optimum TMS is calculated with LP at the end of each iteration of PSO optimization algorithm.	• The benefits of the proposed method are the way to meet the discrete value in optimization problem and its simplicity.
[135]–[137]	NM-PSO	• The PSO algorithm can avoid being trapped in local optima, but it can be slow due to the need for many particles. On the other hand, the Nelder-Mead simplex search method is fast but can easily get stuck in local optima. Combining both algorithms, along with gradient-based repair methods, allows for feasible optimal solutions that meet the constraints to be found, improving the efficiency, and avoiding local optima. • The PSO algorithm used to update all particles, in contrast to the original PSO calculation method that only updates the remaining particles.	• The NM-PSO technique addresses the limitations of slow convergence, high particle requirements, and the inability to handle constraints, resulting in accurate and optimal solutions. • The proposed algorithm exhibits superior performance to PSO in computation speed, convergence rate, and objective function value.
[120]	PSO-TVAC	• To improve global search during the early stages of optimization and to guide the particles to converge towards the global optimum by regulating the acceleration coefficients towards the end of the search.	• The variant-based PSO dynamically adjusts the cognitive and social factors, which are not fixed but vary, to explore a broad range of positions in the search space and avoid local minima.
[121]	PSO-DE	• High-dimensional problems often cause the PSO algorithm to get trapped in local optima, which leads to low optimization accuracy or failure. To overcome this, the proposed methodology involves using the PSO algorithm for the first 30% of the iterations, and then using the mutation and crossover operators of DE during the remaining 70% of the iterations. • This approach can identify optimal TDS and PS that result in the minimum operating time of the relays and the minimum CTI.	• It offers a faster convergence speed while also delivering the globally optimal solution. • It is not robust.
[122]	PSO-GA	• Proposed a method in which not only the miscoordination is omitted but also operation times of the relays are the smallest. • The results would be more optimized when the coefficients are optimized by the proposed algorithm.	• The coefficients of the objective function are calculated based on the optimization technique. • The results show the flexibility of the technique and the best reliability because of the smallest $\sum$TMS and $\sum\Delta t_{mb}$ compared to the conventional coordination methods.

TABLE 20. *(Continued.)* **Hybrid optimization methods applied to the coordination problem, detailing method features and observations.**

[124]	PSO-SA	• The high search capability and fast convergence of the proposed technique allow the PSO-SA swarm agents to be more selective in their search for the best solution.	• In terms of the quality of the solution, convergence, and minimization of the objective function to the optimum value, the proposed hybrid method outperforms the other compared methods.
[123] [142]	PSO-LSA	• The proposed method has a lot of relaxation to its simplicity of implementation, modesty, and robustness.	• High search capability, less execution time and better rate of convergence.
[125]	ABC-LP	• The ABC and LP are used as global and local optimizers, respectively. These lead to a reduction in the search space, which reduces the amount of time needed to determine the best solution and increases computing efficiency.	• Simulation results show the efficiency and superiority of the ABC-LP algorithm over the GA-LP algorithm.
[17]	BBO-LP	• To increase BBO's accuracy and convergence speed.	• The hybridization demonstrates that the required number of populations and generations has greatly decreased with better fitness optimization and lower CPU time requirements.
[29]	FA-LP	• The FA initially achieves the optimum PSC value before TMS, and the LP is used to determine the relay operating times. The search space of FA is hence greatly reduced.	• The proposed hybrid FA has improved computing efficiency by reducing the search space and utilizing LP as a mathematical technique. Additionally, the proposed technique handles fewer constraints, resulting in a faster search for feasible solutions while ensuring constraints are not violated.
[3]	FA-GA	• The hybrid algorithm combines the modified firefly algorithm with the genetic algorithm to improve the optimization process and achieve better solutions. The solution obtained from the modified firefly algorithm is used as the initial population for the genetic algorithm. The genetic algorithm then performs crossover and mutation operations to generate new solutions. This hybrid algorithm can balance the global and local search, which helps to prevent the algorithm from getting trapped in local optima.	• The results indicate that the proposed methods outperform the previous approaches in achieving a minimal total operating time for primary relays and ensuring proper coordination between the primary and backup relay pairs. The algorithm achieves a better solution with fewer objective function evaluations than the standard genetic algorithm.
[126]	WOA-SA	• Incorporating the SA algorithm into the WOA algorithm improves the algorithm's ability to exploit solutions by searching for the best solution about both a randomly preferred solution and the best-known solution, then replacing the original solution with the new one. In this methodology, the SA algorithm acts as an operator within the WOA algorithm.	• The WOA-SA algorithm provides improved and satisfactory results while also saving time compared to both the WOA algorithm and other techniques.
[20]	HHO-SQP	• The HHO algorithm is executed normally, and in each iteration, the best fitness is chosen, and the corresponding agent is used as the initial values for the variables in the SQP algorithm. The SQP algorithm is then run, resulting in an improved fitness value compared to the HHO algorithm alone. As a result, the hybrid method can provide a globally optimum solution.	• By utilizing the global search capability of HHO and the precise local search of SQP, the proposed method can achieve the benefits of both techniques. • The obtained results demonstrate that the hybrid HHO-SQP technique is effective in finding robust and satisfactory solutions that do not violate coordination constraints.
[127]	HS-SA	• SA introduces diversification in the search process and allows the HS to escape from locally optimal solutions.	• HS-SA was the metaheuristic with the best performance in terms of quality of the objective function.
[143]	SA-LP	• SA-LP method provided solutions of high quality, fast computational processing times, and good convergence towards the optimum solution, thus offering an advantage over adaptive coordination tendency. By improving monitoring, communication capabilities, and grid control, the SA-LP method proved to be effective. • Reliable and robust.	• The SA-LP method was able to identify the best solutions, and in some cases, even better solutions, without any coordination errors.

TABLE 20. *(Continued.)* **Hybrid optimization methods applied to the coordination problem, detailing method features and observations.**

Ref	Method	Features	Remark/s
[144]	WCMF	• The WCMF algorithm is easy to implement and requires only a few control parameters, less computational time, fewer iterations, and has fast convergence characteristics. Additionally, it consistently provides accurate results for different objective functions, even after several attempts using the same parameter settings.	• The complex optimization problem was successfully solved using the WCMF algorithm, which combines the benefits of the WCA and MFO algorithms to explore and exploit the solution space.
[128]	GB-LSHADE	• Enhance the search capabilities by exploring new areas of the search space, which can increase the likelihood of achieving the global minimum and avoiding local optima.	• GB-LSHADE produced adapted optimal settings that resulted in complete coordination of the protection without any violations.

In [120], an efficient variant of the PSO algorithm known as the Time Varying Acceleration Coefficient (PSO-TVAC) was developed to determine the optimal settings for DOCRs. TVAC's goal was to improve the global search and encourage particles to converge on the global optima at the end of the search. A hybrid particle swarm optimization based differential evolution technique (PSO-DE) was performed in [121]. This technique yields the most globally optimal solution at a faster convergence rate. Authors in [122] proposed a hybrid PSO-GA to solve the optimization problem. The initial population of GA was assigned by the solution of the PSO to obtain better results.

The standard PSO yields immature results that fail to reach the global optimum as well converge to a local minima. This can be avoided by combining the original PSO with the local search algorithm (LSA). The LSA can tackle the coordination constraints established on the relays while researching for an optimal solution. The global best value obtained at the end of iteration was adopted as an initial value to the LSA which provided the optimum solution. A position check was carried out after updating the position of each agent, to make it clear that none of the agent was moved outside from search space bounds or violated the constraints, so that all the solutions are feasible. In [123], authors combined the standard PSO with the LSA to improve the solution quality. Whereas, in [142], two modifications were added to the standard PSO algorithm; the penalty method and the initialization of PSO with a local search. The authors inserted a local search alongside the global best position vector to produce a more satisfactory solution.

SA is a metaheuristic algorithm known for its ability to efficiently search for local optima, which makes it a good candidate for being combined with swarm-based optimization algorithms. In [124], the authors used a hybrid PSO-SA approach to solve the coordination problem of a multi-loop power system. They introduced SA into the original PSO algorithm to avoid getting stuck at a local optima and to enable the search for a global optimum solution.

In [125], hybrid ABC with LP was proposed to improve the conventional ABC algorithm performance, which decreased the search space, resulting in time consuming and computational efficiency in determining the optimum solutions.

Biogeography-based optimization (BBO) algorithm was presented by Dan Simon in 2008 as a new evolutionary algorithm and proved to be a very competitive and fast method compared to the other algorithms. Authors in [17] applied BBO to solve the optimal coordination problem of DOCRs. In addition, to improve convergence speed and accuracy, a hybrid BBO with LP was developed, and the hybridization demonstrated that the needed number of populations and generations has been greatly reduced with better optimized fitness and required lower CPU time.

Several research papers have shown that combining FA with conventional optimization methods is beneficial in terms of enhancing the convergence rate of FA and improving its computational efficiency. In [29], a hybrid FA and LP (FA-LP) was introduced to attain the coordination problem. The technique involved using FA to identify PS, which was then used in the second stage to solve the relay characteristic operating time equation. LP was then applied to the linearized equation to determine the TMS. By linearizing the DOCRs coordination problem, the search space was relaxed and the solution quality and convergence rate of the FA were improved. This approach prevented the FA from getting stuck at a local optima.

In [3], the authors proposed a modified firefly optimization approach (MFA) for an effective DOCR coordination. The MFA controls the attractiveness and randomized movement parameters to achieve a global solution and good convergence. To further enhance the optimization process and achieve better solutions while maintaining a balance between global and local search, the authors proposed a hybrid approach called FA-GA that combines the MFA with the GA. This hybrid approach helps to prevent the solution from being trapped at a local optima and offers improved performance.

The authors in [126] used a hybrid approach of the WOA algorithm, combining it with the SA technique to improve the optimal solution found in each iteration and increase exploitation by focusing on the most promising regions identified by the WOA algorithm. This resulted in a globally optimal solution for the coordination problem.

The HHO algorithm's search agent may not present a global search, and there is no guarantee that it will find the global optimum in complex problems, which can lead to local optima issues. Additionally, HHO only uses the fitness function to find the best solution, making it a blind optimizer. These issues can be addressed by combining HHO with local search methods. In [20], the authors proposed a hybrid HHO-SQP approach to obtain a globally optimum solution for a highly constrained coordination problem. This approach combined the global search capability of HHO with the precise local search capability of SQP to minimize the total operating time for primary relays while maximizing the backup relays' operating time.

In the HS algorithm, a collection of plausible solutions is generated randomly. A new candidate solution is produced using all available solutions in the harmony memory. If this new generated solution is better than the worst current solution in the harmony memory, the worst solution is substituted by this one. In [127], hybrid HS-SA algorithm proposed for optimal coordination of DOCRs in modern distribution systems with a high concentration of DG units. SA introduced diversification in the search process and allowed the HS to escape from locally optimal solutions.

The SA-LP algorithm, introduced in [143], is a combined approach that merges the SA meta-heuristic with LP to optimize the coordination of DOCRs in meshed systems. The SA algorithm was used to optimize the plug settings as decision variables, while LP solver was utilized to optimize the time dial settings. This combined approach showed significant computational performance and convergence, making it a suitable candidate for online adaptive protection schemes.

The main feature of the WCA is its exploration rate, however it does not perform well enough during the exploitation stage. Contrary, the Moth-Flame Optimization (MFO) performs well in the exploitation phase but is often stuck at the local optimum point. In [144], a hybrid algorithm called water cycle and moth flame (WCMF) was developed by the authors to enhance the exploitation potential in the solution area of the WCA. The position of the stream was updated using a Levy flight function to increase randomization in the original WCA.

The gradient-based optimizer (GBO) is an effective metaheuristic optimization algorithm that was established based on the gradient-based Newton's rules [254]. The GBO algorithm has certain limitations. Although it has good local exploration capabilities with few control parameters that are easy to manage, it can still suffer from premature convergence and may get trapped at a local optima when dealing with complex and large-scale optimization problems. The memory-based linear population size reduction technique of Success-History-based Adaptive Differential Evolution (LSHADE) algorithm acquires a strong global mining capability. Therefore, an efficient combination of GBO and LSHADE algorithm was presented in [128] to develop a novel hybrid optimization model called GB-LSHADE. The GBO was used to explore potential regions of the search space, while the LSHADE algorithm was utilized as a local search scheme to improve the diversity of solutions and avoid premature convergence.

Authors in [129] employed a hybrid approach using the WOA and GWO algorithms (referred to as HWGO) to optimize the coordination of DOCRs. The GWO leadership hierarchy was incorporated into the WOA bubble-net attack strategy to improve convergence and enhance the exploitation phase, resulting in the identification of the optimal solution.

Invasive weed metaheuristic algorithm (IWO) is a population-based optimization algorithm and an effective probabilistic that finds the general optimum of a mathematical function through imitating compatibility and randomness of weeds colony [255]. This algorithm yields slower convergence when solving large dimensional problems. Therefore, by tuning the algorithm through adjusting the standard deviation, the IWO was modified in [130] to run faster and prevent good weeds from being eliminated, achieving better solutions faster than IWO. Moreover, a hybrid approach was proposed which was obtained by fusing IIWO with SQP technique to improve the computational efficiency. The proposed techniques were tested on both the 9-bus test system and IEEE 30-bus systems, producing effective and reliable results. Table 20 summarizes the hybrid optimization algorithm used for solving the DOCRs coordination problem.

In this section, various optimization algorithms, including conventional and deterministic methods, metaheuristic techniques, and hybrid approaches, were explored to address the coordination problem of DOCRs. The development of each algorithm in solving the coordination problem was discussed, showing the field's evolution over time. This section assists future researchers in identifying suitable optimization algorithms for their specific coordination problems. The strengths and weaknesses of each algorithm are highlighted, enabling researchers to make informed decisions on the most effective approaches.

IV. PERFORMANCE COMPARISON BETWEEN THE OPTIMIZATION ALGORITHMS FOR SOLVING THE DOCRS PROBLEM

To evaluate the effectiveness and the performance of the optimization algorithms in solving DOCRs coordination problem, test systems should be used to validate the proposed algorithm. They offer a standardized platform for evaluating the algorithm's performance and facilitate comparisons among different algorithms to identify the most effective one. Test systems also provide a benchmark for evaluating the algorithm's performance and detecting any potential issues that need to be resolved. Additionally, test systems offer a means for verifying the algorithm's effectiveness in real-world situations by assessing its performance on various systems and in different scenarios. Numerous studies on the IEEE power systems were conducted for these purposes such as 3-bus, 8-bus, 9-bus, 15-bus, and 30-bus test systems. All optimization algorithms were coded using MATLAB software.

The performance criteria for comparison between the optimization algorithms used for the coordination of DOCRs can be broadly stated as solution quality, convergence rate, number of objective function evaluation, solution feasibility, and robustness. Further discussion on these criteria, along with a case study, is presented below for clarity.

A. SOLUTION QUALITY

The main objective of optimization is to minimize the total operating time of the DOCRs in the tested system. Therefore, the algorithm with a lower OF value is regarded as being superior. It measures how close the solution obtained by an algorithm is to the true optimal solution. Algorithms that produce higher quality solutions are generally preferred.

The overall net time gain achieved by the proposed technique can be utilized to demonstrate its superiority to the other compared methods. It represents the difference between the OF value obtained by the suggested algorithm and the compared algorithm. As this value increases, it is considered that the algorithm has outperformed the compared algorithm in terms of the OF value. The comparative analysis in Fig. 8 indicates that the objective function value achieved by using ERWCA is superior to that of other optimization methods, thus confirming its superiority [104].

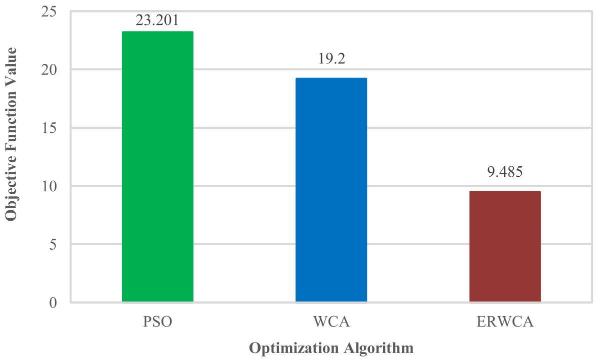

FIGURE 8. Comparison of objective function value with different optimization techniques for the tested IEC standard microgrid benchmark in [104].

Authors of [126] evaluated the proposed HWOA algorithm against other algorithms in terms of total net gain of the operating time, which is depicted in Fig. 9. The results showed that the proposed HWOA algorithm outperformed other techniques in terms of net gain in time and produced improved and satisfactory results.

B. CONVERGENCE RATE

To evaluate the improvements in efficiency and robustness of a proposed optimization algorithm, convergence curve is used. It shows the value of the objective function versus the computational time during the minimization process. It shows which algorithm converges faster than the others. This is important for real-time optimization applications. Authors in [90] compared the convergence performance among PSO, AIS and ALO as shown in Fig. 10.

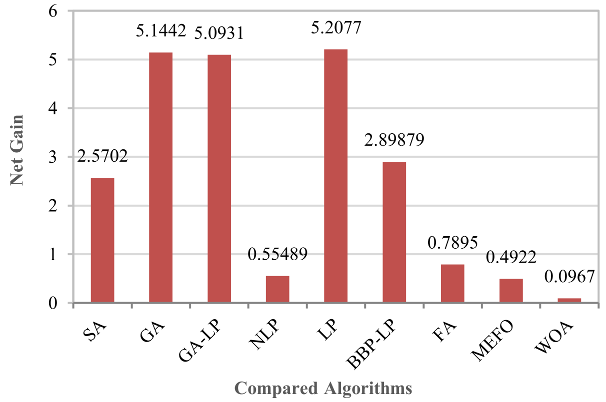

FIGURE 9. Net gain achieved by the proposed HWOA algorithm against other algorithms for the 8-bus test system.

As illustrated from Fig. 10, the value of the objective function in case of ALO algorithm decreases very fast to the minimum value than the other two techniques, which implies that the ALO can converge to the global optimum faster.

C. NUMBER OF OBJECTIVE FUNCTION EVALUATION (NFE)

NFE refers to the total number of times the objective function is evaluated during the optimization process. The objective function is typically evaluated multiple times during the optimization algorithm as it searches for the optimal solution. Algorithms that require fewer function evaluations are generally more efficient and may converge to a solution faster.

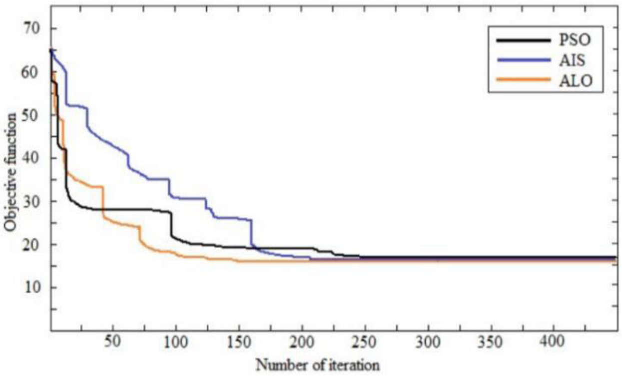

FIGURE 10. Convergence of the objective function for a practical 11-bus distribution system [90].

Authors of [67] used this criteria to compare between the DE algorithm with its modified versions (MDE1-MDE5) as shown in Fig. 11. It was demonstrated that the performance of MDE5 is significantly better than all the other algorithms. MDE5 required only 38,250 NFE to achieve the optimal solution, which is almost 50% less than the NFE required by other variants. On the other hand, MDE3 had the worst

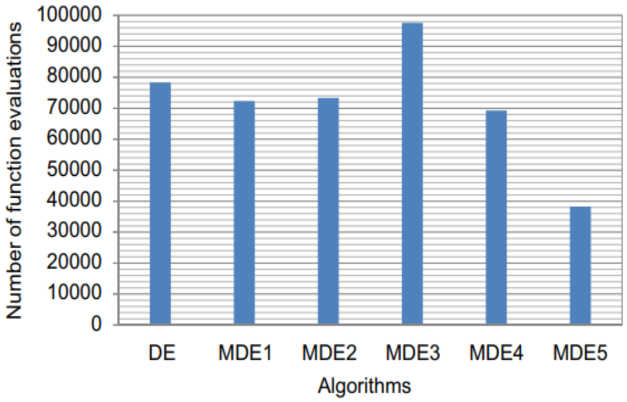

FIGURE 11. Comparison of DE and modified DE algorithms in term of number of function evaluations: IEEE 3-bus model [67].

performance in terms of NFE, which means that it required more NFE to converge to the optimal solution compared to other variants.

D. SOLUTION FEASIBILITY

The feasibility of the solution obtained from the optimization algorithm can be checked based on the number of selectivity constraints violations. The algorithm with no violations achieved feasible solutions.

Fig. 12 shows the CTI value of 20 back-up and primary relay pairs for the 8-bus test system [29]. The shaded area of the graph demonstrates that the CTI, which was set at 0.3 seconds, is consistently exceeded by the range of relay pair delays. As a result of these settings, all relays managed to coordinate in proper manner. Whereas, in [67] the MDE algorithm failed to achieve a feasible solution as there are some cases of selectivity constraints violations.

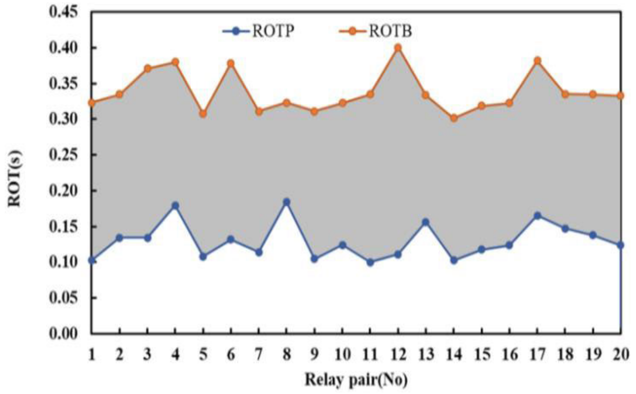

FIGURE 12. Coordination time interval for 20 relay pair for 8-bus system [29].

E. ROBUSTNESS

It determines the ability of the optimization algorithm to perform well in different system conditions. This is important for ensuring a reliable protection coordination. In [131], the authors investigated the optimization problem of DOCRs coordination, taking into account the impact of various network topologies in the optimization problem. GA and hybrid GA-LP were used to solve the coordination problem. The GA method exhibited poor convergence with violated coordination constraints due to the increasing number of coordination constraints. After about 100000 iterations, the fitness value for the conventional GA reached to 112.43 seconds while hybrid GA-LP was converged to the optimal and feasible solution in less than 50 iterations with a fitness value of 19.3476 and all the constraints were satisfied. This indicated the robustness of the hybrid GA-LP over the conventional GA.

These performance criteria were used to compare and evaluate different optimization algorithms performance for the coordination of DOCRs, and to determine which algorithm outperforms another algorithm. Table 21 provides a comparison of the performance criteria used to evaluate optimization algorithms for solving the coordination problem. The table lists each performance criterion, the method for evaluating it, an interpretation of the criterion, and a discussion of how it can be used to compare algorithms. To illustrate the comparison between two different algorithms in solving the coordination of DOCR using these criteria, the 3-bus test system is employed and optimized using the Particle Swarm Optimization algorithm and Firefly algorithm.

For this case, we utilized the procedures described in Section II to optimize the 3-bus test system. The system consists of 3 buses, 3 power generators, 3 branches, and 6 DOCRs, as depicted in Fig. 13. The 3-bus system is a widely used test system in optimal relay coordination problems and was first introduced in a paper published in 1988 [175]. The necessary data for optimization, such as CTR, P/B relay pairs, and fault currents for three-phase faults at the middle of each line, are obtained from [126].

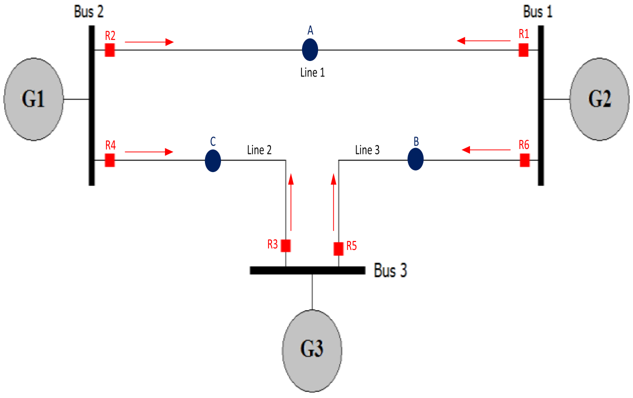

FIGURE 13. 3-bus test system single-line diagram.

In this optimization problem, we utilized the objective function employed in [3], [6], [19], [29], [33], [46], [48], [52], [69], [73], [74], [77], [78], [81], [88], [91], [93], [94], [96], [101], [102], [105], [106], [107], [108], [110], [114],

TABLE 21. Performance criteria used to compare between optimization algorithms applied to solve the coordination problem.

Performance Criteria	Evaluation Method	Interpretation	Remark/s
Solution Quality	The value of the function being optimized by the algorithm.	Lower is better.	• It compares the objective function value obtained by the different algorithms. • It indicates that the algorithm can obtain better coordinated relay settings other the compared one.
Convergence Rate	The rate at which the algorithm converges to a solution.	Lower is better.	• It compares the speed of the different algorithms (number of iterations and the required computational time) in reaching an acceptable solution. • It indicates that the algorithm can converge to a solution quickly and efficiently, reducing the computational time required to obtain a solution.
Number Of Objective Function Evaluation	The number of times the objective function is evaluated by the optimization algorithm.	Lower is better.	• It compares the number of times each algorithm evaluates the objective function to find the optimal or satisfactory solution. • It indicates the computational efficiency of an optimization algorithm.
Solution Feasibility	The extent to which the algorithm satisfies the problem's constraints.	Feasible/Infeasible.	• It compares the ability of the algorithms to deliver solutions that satisfy the operating constraints of optimization problem. • It indicates that the algorithm can produce feasible coordination solutions that satisfy the coordination requirements and constraints
Robustness	Capability of the algorithm to deliver satisfactory results despite variations and uncertainties in the system conditions.	Higher is better.	• It compares the ability of the algorithms to perform well under different system conditions. • It indicates that the algorithm can produce good coordination solutions under different system conditions. A robust algorithm can provide reliable coordination even in the presence of uncertainties and variations in the system.

[117], [120], [123], [124], [128], [129], [138], [140], [142], [155], [156], [157], [158], [159], [160], [161], [162], [163], [164], [165], [166], [167], [168], [169], and [170]. A detailed description and discussion of this objective function can be found in Table 1. The values of the constants α, β, and γ in the operating time equation are obtained from Table 2, where the IEC standard inverse time characteristic is applied.

The coordination problem is formulated as a nonlinear programming problem. The continuous decision variables PS and TMS have ranges between 1.5 and 5.0, and 0.1 and 1.1, respectively. These ranges are necessary for formulating the constraints in (3) and (4). The values for $t_{\mathrm{op,min}}$ and $t_{\mathrm{op,max}}$ are 0.1 and 1.1 seconds, respectively, which are used to formulate the constraint in (7). Additionally, a coordination interval of 0.2 seconds is considered, which is needed for formulating the constraint in (8). A penalty method is used to handle the constraints as described in Section II-D.

The computations conducted for this case study were executed on a computer system equipped with a 1.8 GHz Intel Core i3 processor and 8 GB of RAM. The authors developed the source code using MATLAB, version 2021a.

The optimal settings for the decision variables TMS and PS for both algorithms are presented in Table 22. FA outperforms PSO, resulting in an overall net gain in operating time of 0.0855 seconds, representing an improvement of 5.558%. These results highlight the superiority and advantage of PSO over FA in terms of solution quality.

Fig. 14 illustrates the convergence behavior of the fitness value for the best individual in the population over the number of generations for both the FA and PSO algorithms. It demonstrates that the PSO algorithm converges faster than FA, reaching its best fitness value in 826 iterations, while FA requires 879 iterations to achieve convergence.

TABLE 22. Optimal settings of DOCRs for the 3-bus test system.

Variables	FA	PSO	Variables	FA	PSO
TMS1	0.1000	0.12296	PS1	2.2157	1.5371
TMS2	0.1000	0.10497	PS2	1.5576	1.5174
TMS3	0.1000	0.11562	PS3	2.6923	1.6996
TMS4	0.1000	0.11486	PS4	2.5719	1.7665
TMS5	0.1000	0.10611	PS5	1.5000	1.8005
TMS6	0.1000	0.11214	PS6	1.5000	1.5672
OF Value	FA	1.4528	PSO	1.5383	

Based on Table 23, which shows the coordination time interval for the 3-bus test system, it can be observed that for the FA, there are no violations in the constraints. Similarly, for the PSO algorithm, there are also no violations. This indicates that both the FA and PSO algorithms successfully satisfy the

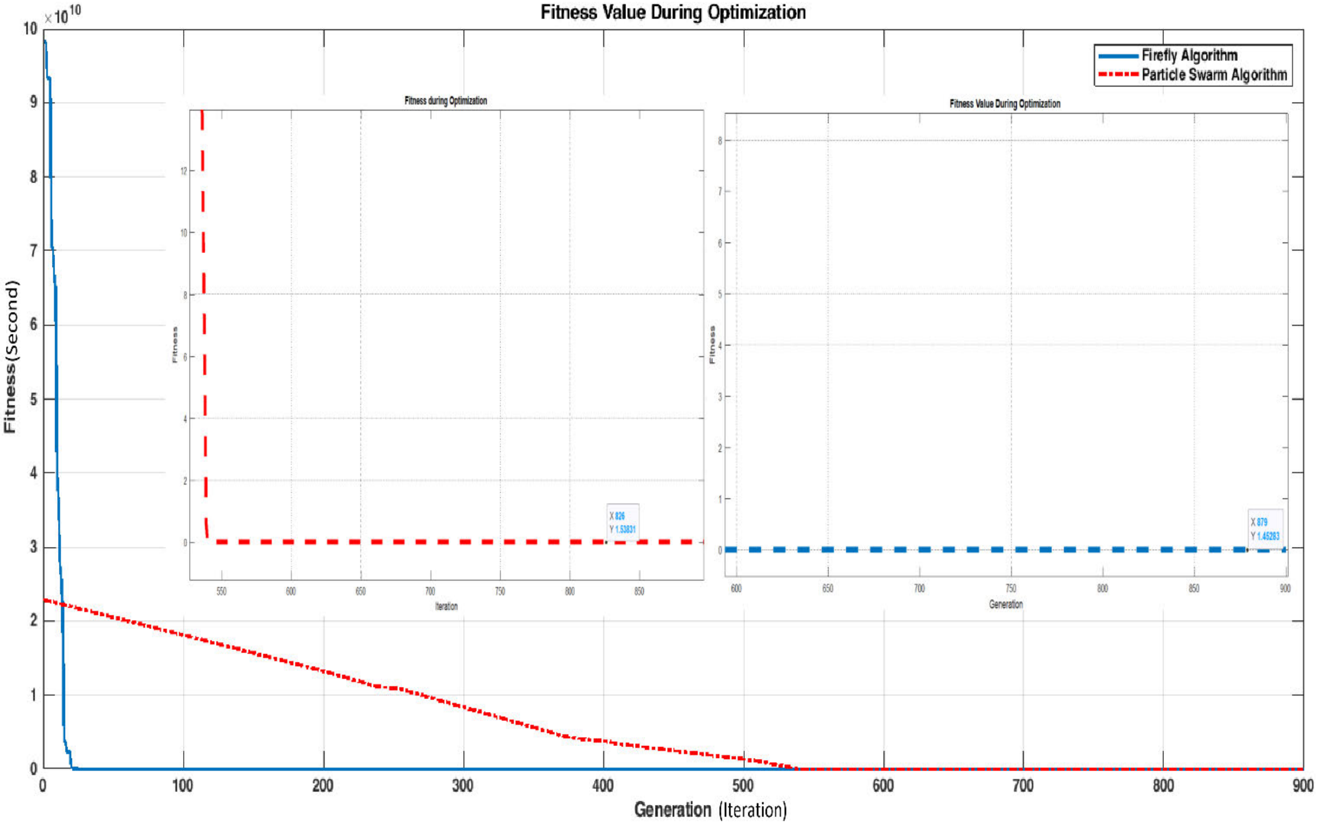

FIGURE 14. Convergence Characteristics for the proposed tested algorithms.

constraints imposed on the coordination time interval for the 3-bus test system.

TABLE 23. Coordination time interval for the 3-bus test system.

Primary	Backup	FA	PSO
R1	R5	0.39467	0.57202
R2	R4	0.33584	0.27562
R3	R1	0.20133	0.20534
R4	R6	0.23183	0.31998
R5	R3	0.33306	0.23085
R6	R2	0.56604	0.55418
Number of violations		0	0

In a comparative analysis of computational time between algorithms, both the FA and PSO algorithms were tested with a fixed number of iterations of 900. The results revealed that the FA algorithm took 99.47 seconds to complete the computation, whereas the PSO algorithm finished in 91.72 seconds. This indicates that the PSO algorithm outperformed the FA algorithm in terms of computational time, demonstrating faster execution. The PSO algorithm is faster than the FA algorithm because it requires fewer calculations, which FA involves additional attractiveness and distance computations.

The original code used a fixed maximum number of iterations as the stopping criterion. However, to compare the algorithms based on the number of objective function evaluations, a dynamic stopping criterion based on stagnation detection was implemented. This modification involved tracking the number of iterations without improvement in the global best cost. After each iteration, the algorithms checked if there was an improvement compared to the previous iteration. If there was an improvement, the stagnation counter was reset to zero. Otherwise, the counter was incremented by one. The algorithms continued iterating until the stagnation counter reached a specified limit, indicating a stagnation point where no significant improvement was observed. This allows the algorithms to automatically terminate when further iterations are unlikely to yield significant improvements. The results demonstrate that the FA required 690 iterations and 13,820 NFE, achieving an objective function value of 1.4409. In contrast, the PSO algorithm converged in 551 iterations with 11,020 NFE, yielding an objective function value of 1.5456. The performance of PSO was significantly better than FA, requiring 20.26% fewer NFE to achieve the optimal solution.

The transient configuration refers to a situation where the primary relay has opened the circuit breaker at one end of the line. This condition is discussed in detail in [256]. After the circuit breaker operation, there are changes in the short circuit currents at various locations in the power system. The updated values of the short circuit currents for this scenario can be found in [23]. The transient changes are taken into account in the problem formulation, as described in [169]. This case is implemented to demonstrate the robustness of both algorithms. Table 24 presents the coordination time interval for the 3-bus system under the transient configuration condition. The cases where miscoordination occurred are indicated. The increase in violations is a result of the growing number of coordination constraints. In this case, the PSO algorithm exhibits one violation, while the FA algorithm has four violations. This indicates that the PSO algorithm is more robust than FA in handling this case.

TABLE 24. Coordination time interval for the 3-bus test system incorporating the transient configuration condition.

Primary	Backup	FA	PSO
R1	R5	**-6.40480**	1.30070
R2	R4	3.26320	0.41561
R3	R1	1.63930	0.28450
R4	R6	**-0.82076**	0.40451
R5	R3	0.52924	0.34411
R6	R2	2.71710	0.94397
R1'	R5'	**-0.13515**	0.29186
R2'	R4'	2.58470	0.31272
R3'	R1'	1.40940	0.22406
R4'	R6'	**-0.98920**	0.25998
R5'	R3'	0.33053	0.21823
R6'	R2'	0.27396	**0.19634**
Number of violations		4	1

V. OPTIMIZATION RESULTS VERIFICATION

Different simulation tools can be used to verify the results and the effectiveness of a suggested algorithm for solving the coordination problem.

ETAP is a power system software extensively used in the industry and can perform a thorough analysis of power systems. One of the main features offered by ETAP is the STAR ETAP package, which is employed to verify the coordination settings of DOCRs. Furthermore, ETAP provides models of all industry-used DOCRs, and it is also viable to design a customized relay. Authors in [29] used ETAP to verify the results obtained from FA-LP algorithm for the IEEE 8, 15 and 30-bus test systems.

Verification of the optimized results can be done through using the Digsilent Power Factory simulation software. This software contains pre-designed models of potential transformers (PT), current transformers (CT), and various overcurrent relays having distinctive inverse characteristics. Authors in [70], [84], [105], and [108] used Digsilent power factory to validate the results obtained from the developed algorithms.

A simulation was conducted using the ETAP software to verify the results obtained in Table 22. All data needed to simulate the system are taken from [169]. The time-current characteristic for the 3-bus system is depicted in Fig. 15 and 16, representing the PSO algorithm and FA, respectively. In the coordination process, the backup relay R4 successfully

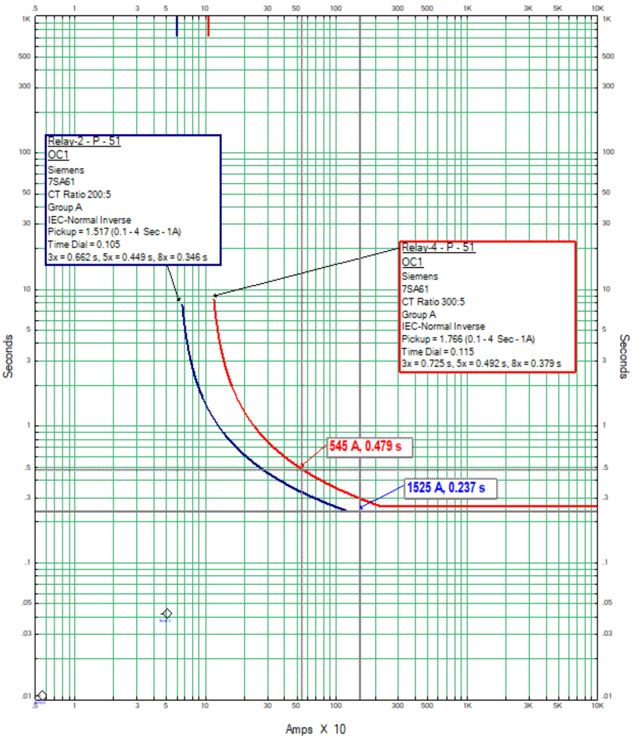

FIGURE 15. Coordination between R2 and R4 in 3-Bus test system achieved using PSO algorithm through ETAP.

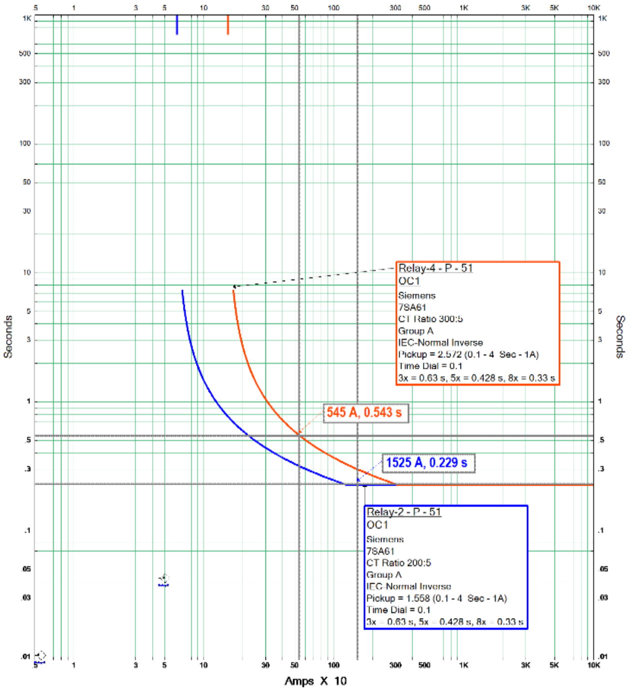

FIGURE 16. Coordination between R2 and R4 in 3-Bus test system achieved using FA through ETAP.

tripped with a time delay exceeding 0.2 seconds, while maintaining the appropriate tripping sequence.

VI. CONCLUSION AND FUTURE DIRECTIONS

This paper provided a comprehensive review of the application of optimization techniques for optimal DOCRs coordination. The review has highlighted the growing importance of optimization algorithms in addressing the challenges of DOCRs coordination and has presented a detailed overview of the various optimization methods that have been proposed in the literature. The performance of these methods has been evaluated using a variety of performance criteria, and the results have shown that optimization algorithms can be an effective tool for solving the DOCRs coordination problem. The study also identified several important findings and concerns related to the use of optimization algorithms for DOCRs coordination. Key findings include:

- Optimization techniques can be used to significantly improve the coordination of DOCRs, leading to faster fault clearance times and improved system reliability.
- Different optimization techniques have been proposed in the literature, each with its own advantages and disadvantages.
- Hybrid optimization techniques, which combine two or more optimization techniques, can often outperform individual techniques.
- The optimization problem of DOCRs coordination is complex and there is no single algorithm that will always provide the best solution.
- Optimization algorithms can be computationally expensive, especially for large and complex power systems.
- The difficulty of tuning the parameters of optimization algorithms for different power systems.
- The lack of robust optimization algorithms that can handle uncertain and dynamic system conditions.

Based on these findings, the study also identified several potential future directions for research:

- Identify new optimization algorithms: There are many new optimization algorithms being developed all the time. It is important to identify new algorithms that have the potential to outperform existing algorithms for DOCRs coordination.
- Improved initialization techniques: To ensure that the metaheuristic search converges to a global optimum, improved initialization methods, such as chaos initialization or opposition-based initialization, can be used.
- Use of multi-objective optimization algorithms: This could allow the optimization algorithms to consider multiple conflicting objectives.
- Hybrid algorithms: It is possible to achieve better optimization results by integrating various optimization techniques.
- The development of more reliable and robust optimization techniques: This is essential to ensure consistent and accurate results in the case of changing system conditions.
- Increased use of simulations and testing: Relay coordination approaches results can be verified using simulations and testing, which can also guarantee proper operation in practical settings.
- Integration with the smart grid: The integration of DOCRs with smart grid technologies, such as distributed energy resources, and demand response can lead to more efficient and effective protection coordination.
- Incorporate the coordination of DOCRs with the presence of electric vehicles: This is important to address the impact of electric vehicles on the power grid.

The optimization problem of DOCRs coordination is a rapidly evolving field, and there are many exciting opportunities for future research. The techniques discussed in this paper provide a solid foundation for future work, and it is likely that optimization algorithms will play an increasingly important role in the coordination of DOCRs in the years to come. The optimization problem of DOCRs coordination is a challenging one, but it is also a very rewarding one. The development of effective optimization algorithms for this problem can have a significant impact on the reliability and efficiency of power systems.

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