GAMS-based Efficient Approach for Coordination of Directional Overcurrent Relays in Distribution System

Abu Bakar Waqas[1], Muhammad Bilal Raza[1], Muhammad Mansoor Ashraf[1], Muhammad Waseem[2,3], Fabiano Pallonetto[2,3], Farzana Kulsoom[4]

[1]*Electrical Engineering Department, University of Engineering and Technology, Taxila, Pakistan*

[2]*International Renewable and Energy Systems Integration Research Group (IRESI), Department of Electronics Engineering, Maynooth University, Co., Kildare, Ireland*

[3]*Lero - Science Foundation Ireland Research Centre for Software, School of Business, Innovation Value Institute (IVI), Maynooth University, Co., Kildare, Ireland*

[4]*Telecommunication Engineering Department, University of Engineering and Technology, Taxila, Pakistan*

abubakar.waqas@uettaxila.edu.pk, 22MS-EE-7@students.uettaxila.edu.pk, mansoor.ashraf@uettaxila.edu.pk, mwaseem148@yahoo.com, fabiano.pallonetto@mu.ie, farzana.kulsoom@uettaxila.edu.pk

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***Abstract*—In designing a power system, efficacious synchronization of directional over-current relays (DOCRs) plays a pivotal role in guaranteeing the system's stability and ensuring continuous power flow, even in the event of disturbance. However, attaining this optimized strategy pertains to the persistence of solving extremely constrained and nonlinear optimized complications. The main intention is to formulate an optimized coordination strategy to optimize the overall operational time (OT) of DOCRs. This involves featuring optimized values of decision variables, specifically the relay plug settings (PS) and time dial settings (TDS). The designed formulation for DOCRs is employed on various IEEE bus networks like the 8, 9, and 15 bus systems. Comparative evaluation of obtained results is accomplished with numerous algorithms that showcase the competency of the GAMS-driven optimization strategy. The results depict that there is an improvement of 1.8-23% in the total operational time of relays depending upon the test system under consideration.**

***Index Terms*—General Algebraic Modelling System, Directional Over-current Relays, Time multiplier setting, Plug Setting, Coordination time Interval.**

I. Introduction

The dynamic advancement in power systems has elevated concerns regarding system stability and security, making them crucial challenges for system operation [1]. Protective relays serve the purpose of identifying and isolating the malfunctioning section of the power system while safeguarding the operational integrity of the system's healthy segments.

Power system network comprises of regions and zones safeguarded by their respective protection relays, that result in operational interference among them [2]. So, it is imperative to execute a well-coordinated strategy for protection relays, allowing them to promptly detect and isolate faulty segments with minimal time delay [3].

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Conventional electric grids feature a radial configuration with a central power source at one end so the single over-current relay is sufficient for protection. This coordination becomes more challenging for the multi-loop compared to single-loop distribution systems [4].

DOCRs comprise the directional element that indicates the direction of the faulty current and are employed for ensuring system protection in the ring or mesh-type networks and the distribution systems fed by various sources.These relays function as the main defense to secure distribution and sub-transmission systems, or they act as secondary backup protection for localized transmission systems [5].

A directional over-current relay normally consists of an instantaneous element and a time delay element. The optimal adjustment of the over-current relay involves the parametric settings that outline the necessary time/current characteristics of both the instantaneous and time delay units. The modeling parameters for the time delay element of definite-time relays and inverse-time relays are PS and TDS [5].

The main objective of optimal coordination is to determine the suitable relay settings that results in minimal operating time, while adhering to coordination constraints. The purpose is to tackle the faulty segment, particularly using the appropriate primary relays. If a misoperation occurs, the adjusted backup relay activates within the designated Coordination Time Interval (CTI) to ensure the system operates stably [6].

Addressing the coordination challenges associated with the DOCRs being characterized by the complex optimization problem comprised of numerous constraints, functional non-linearity, and non-convexity. The optimized strategy to solve this issue is through Linear Programming (LP), which includes the TDS being modeled as the decision variable, while the PS is considered as the constant value constrained within the predefined boundaries [7]. The non-linear problem (NLP) formulation involves modeling both TDS and PS as control variables, which can take on either continuous or discrete values.

Optimization has become a widely researched field and a cost-effective approach for tackling complex real-time challenges. Due to the increasing complexity of power systems and the need for reliable and efficient protection system operation, researchers are increasingly employing optimization techniques to address coordination issues related to DOCRs.Numerous optimization strategies are being modeled to address the coordination challenges.

In the past, various approaches have been employed by power system engineers for optimal coordination of DOCRs. A trial-and-error method is used to find the optimal relay configurations, it involves numerous cycles of trial runs and adjustments to relay parameter settings, which proved to be a time-intensive process [8]. The issue of achieving optimal coordination for DOCRs was tackled in [9], where the ideal time dial configurations for effective DOCR coordination were identified through the application of a genetic algorithm (GA). In [10], diverse forms of PSO algorithm were utilized to achieve optimal relay coordination.

L. Ma et al. in [11] present a hierarchical clustering approach using the cuckoo search algorithm (HCSA), aimed at improving the efficiency and efficacy of addressing coordination issues. In [12], optimal relay settings and coordination challenges were addressed using the grey wolf optimizer (GWO). To increase the exploration potentiality of search agents across a broad search space, referred to as the Improved Grey Wolf Optimizer (IGWO), as illustrated in [13].

In exploring the most effective relay configurations for DOCRs across varied power grid structures, in [14], the author utilizes the Adaptive Fuzzy Directional Bat Algorithm (AFDBA), which is capable of dynamically adjusting its settings to identify optimal relay settings, abolishing the need for manual fine-tuning of initial parameters.

Meanwhile, in [15], a hybrid approach integrating a firefly-genetic algorithm (FA-GA) is utilized to reduce the overall operating time of DOCRs by identifying the optimized values of control variables.To enhance coordination of DOCRs, a variety of heuristic and meta-heuristic optimization algorithms have been employed. The key contribution of this study involves employing GAMS-based optimization to achieve optimal TDS and PS for all DOCRs.

The goal is to minimize the total sum of operating time for all primary relays. This optimization strategy is evaluated on the IEEE 8-bus, 9-bus, and 15-bus systems. Comparative analysis with other meta-heuristic optimization techniques from existing literature demonstrates the superior performance of the proposed method.

The remaining sections are organized as below: Section II delineates the mathematical formulation regarding DOCR coordination. Section III offers a concise overview of GAMS-based optimization, succeeded by the presentation and discussion of results in Section IV. The paper is rounded off with a summary in Section V.

II. Mathematical Formulation

A. Objective function

The sequential activation of DOCRs commences upon detecting current measurements. Once the measurements exceed the predetermined pickup current values set for activating the protective relay, the primary relay must promptly remove the faulty segment. If the primary relay malfunctions, the backup relay in the adjacent zone must address the defective condition within a predetermined coordination margin time.

Modeling DOCR coordination involves framing it as an NLP problem focused on determining particular relay configurations to minimize the overall operating time for all primary relays. The subsequent equation formulates the objective function of the DOCRs [16].

$$\text{Minimize} \qquad OF = \sum_{i=1}^{n} W_i \times T_{ik}, \tag{1}$$

where W_i serves as a weighting factor signifying the probability of a specific faulty condition occurring within each protection zone, typically adjust at one.Consequently, the likelihood of a fault transpiring in each protection zone is assumed to be equally probable. T_{ik} signifies the operating time for the i^{th} relay reacting to fault k, where, n represents the total count of relays within the protective system.

According to the IEC Standard 60255-151 [17], the time-current curves commonly and extensively used for DOCRs can be expressed as:

$$T_{ik} = \frac{\alpha \times TDS_i}{(\frac{I_{Fi}}{I_{Pi}})^{\beta} - \gamma}, \qquad i = 1, 2, 3, \ldots, n \tag{2}$$

where TDS_i denotes the time delay configuration for the i^{th} relaying agent, and I_{Fi} corresponds to the fault current associated with a protective relay responding to the specified fault in the designated region, and I_{Pi} is used to represent the pickup current for the i^{th} relay. The constants α, β, and γ are defined as 0.14, 0.02, and 1.0, respectively [18].

The pickup current refers to the minimal level of current required to activate the signal to the circuit breaker, when it exceeds this threshold and flows through the protective relay's coil. The aforementioned equation, based on the NLP formulation for optimizing coordination problems, is employed in the modeling process, where I_{Pi} takes on continuous values.

Furthermore, the articulation of the coordination problem formulation utilizing mixed-integer non-linear programming (MINLP) is modelled as belows:

$$T_{ik} = \frac{\alpha \times TDS_i}{(\frac{I_{Fi}}{PTS_i \times CT_i})^{\beta} - \gamma}, \qquad i = 1, 2, \ldots, n \tag{3}$$

where Pickup tap setting $(PTS)_i$ represents the pickup configuration for protective relay R_i with discrete values while CT_i pertains to current transformer ratio (CTR) linked to the i^{th} relay.

B. Objective Function Constraints

The constraints required to achieve optimal coordination of DOCRs are outlined as follows:

1) Pickup Current Constraints: The equations describing the load flow and functioning as equality constraints can be articulated as follows:

$$I_{pi}^{min} \leq I_{pi} \leq I_{pi}^{max}, \tag{4}$$

where I_{pi}^{min} denotes the minimum pickup current, exceeding the load current, while I_{pi}^{max} indicates the upper bound of the minimum fault current $(I)_F$, which is below $\frac{2}{3}$.

The following equations express the bounds on the pickup current settings [19]:

$$I_{pi,min} = \max\left[\frac{\text{OLF} \times I_{Li}}{CT_i}, \text{min tap setting}\right], \tag{5}$$

$$I_{pi,max} = \min\left[\frac{2 \times I_{fi,min}}{3 \times CT_i}, \text{max tap setting}\right], \tag{6}$$

where OLF represents the overload factor, with a specified value of 1.25. Moreover, I_{Li}, $I_{fi,min}$, and CT_i denote the maximum load current, the minimum fault current, and the current transformer ratio for relay R_i, respectively.

2) Time Delay Setting Constraints: These limitations are formulated in the following manner:

$$TDS_{pi}^{min} \leq TDS_{pi} \leq TDS_{pi}^{max}, \tag{7}$$

where TDS_{pi}^{min} and TDS_{pi}^{max} indicate the minimum and maximum boundary limits of TDS_{pi} for a specific relay. These constraints are found to fluctuate between 0.1 and 1.1 seconds, contingent on the manufacturing specifications of the protective relay [18].

3) Pickup tap setting Constraints: The constraints governing the pickup tap setting can be articulated in the following manner:

$$PTS_{pi}^{min} \leq PTS_{pi} \leq PTS_{pi}^{max}, \tag{8}$$

where PTS_{pi}^{min} and PTS_{PI}^{max} denote the minimum and maximum limits for the pickup tap settings of i^{th} relay, respectively.

4) Constraints on Relay Operational Time: The limitations on the operational time of the relay are outlined as follows:

$$T_{pi}^{min} \leq T_{pi} \leq T_{pi}^{max}, \tag{9}$$

where T_{pi}^{min} and T_{pi}^{max} are lower and upper permissible bounds for the operating times, respectively.

5) Coordination Time Interval Constraints: The CTI commonly referred to as the time margin, is crucial for ensuring accurate sequential operation among pairs of relays. It can be expressed as follows:

$$T_{sec} - T_{pri} \geq CTI, \tag{10}$$

where T_{sec} and T_{pri} denote the operational time for the secondary and primary relays, respectively.

The CTI varies based on the protection relay type, with digital microprocessor relays typically having a CTI range of [0.1:0.2] seconds and electromechanical relays having a range of [0.3:0.4] seconds. The characteristics of these values are shaped by elements such as the operational velocity of the circuit breaker, the permissible margin for CTR inaccuracies, discrepancies in relay timing, and the duration of overshooting in relay operations [19].

III. GAMS-Driven DOCRs Coordination Strategy

GAMS serves as the high-level modeling language, that offers a specialized environment to perform optimized computations, equipped with a range of solvers employing diverse algorithms [20], [21].

A. Step-Wise Methodology for DOCRs Coordination

- Acquiring Network and Relay Data: Gather pertinent data related to the power system being examined, encompassing details on the network topology, line parameters, and relay configurations.
- Modeling the Power System Network: Formulate a mathematical representation of the power system network using GAMS which incorporates electrical characteristics, component parameters, and relay settings.
- Embedding Directional Overcurrent Relay Model: Insert a comprehensive model of DOCRs into the GAMS framework, encompassing characteristics such as directional elements, time-current characteristics, and coordination settings.
- Formulation of Objective Function: Model an objective function in the GAMS model that outlines coordination goals, such as minimizing relay operating times or maximizing selectivity.
- Integration of Constraints: Ensure relay coordination aligns with operational and protection requirements by including pertinent constraints in the GAMS model.
- Optimization Procedure: Execute optimization calculations using GAMS solvers to identify effective coordination and ensure selective operation during faults by avoiding unnecessary tripping.
- Analysis of Coordination Outcomes: Evaluate the results obtained from the GAMS optimization process, examining the settings of relay coordination, time-current curves, and any modifications made to achieve optimal coordination.
- Documentation and Reporting: Record the optimized relay coordination settings and outcomes for future reference. Generate reports summarizing the GAMS-driven coordination process, encapsulating significant findings and recommendations.

Fig. 1 shows the methodical approach that outlines the systematic utilization of GAMS for coordinating DOCRs, thereby ensuring efficient and discerning protection within a power system.

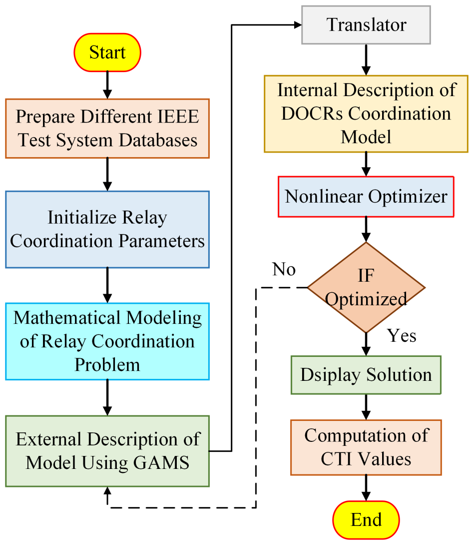

Fig. 1. GAMS-based DOCR Coordination

IV. Numerical Results And Discussion

To assess and verify the efficacy of the DOCR coordination using the GAMS-based approach, the framework is tested on various IEEE bus systems along with the conduction of comparative assessment with other algorithms.

A. Test Case-I: IEEE 8-Bus System

The IEEE 8-bus system is employed as the initial test case for evaluating the competency of the proposed algorithm in minimizing the operational time of the DOCRs. The system characteristics such as the CTR along with the short circuit current measurements for relays, are taken from [22]. Additionally, the TDS range is defined with a minimum of 0.05 and a maximum of 1.1, whereas the PS varies from 0.5 to 2.0.

TABLE I
Optimized Relay Parameters - IEEE 8-Bus Network

Relay	TDS	PS
1	0.071338	2.00000
2	0.233886	2.00000
3	0.181319	2.00000
4	0.076161	2.00000
5	0.050000	1.12968
6	0.146098	2.00000
7	0.218459	2.00000
8	0.143088	2.00000
9	0.050000	1.69403
10	0.079585	2.00000
11	0.148059	2.00000
12	0.234590	2.00000
13	0.071615	2.00000
14	0.219024	2.00000
$OF = 6.069997$		

In the formulation of DOCR coordination using Mixed-Integer Nonlinear Programming (MINLP), the decision variables include TDS and PS as given in Table I. Furthermore, Table II displays the operating times (OT) for both primary and backup relays, along with the corresponding CTI values. Table III displays the optimal solution obtained, along with the comparative analysis demonstrating the effectiveness of the GAMS-based optimization, including 8.03% more optimized values compared to the Modified Electromagnetic field optimization (MEFO) algorithm.

TABLE II
Relays Operating Time and CTI-IEEE 8-Bus System

Primary Relay	OT (s)	Backup Relay	OT (s)	CTI
1	0.286267	6	0.586267	0.3000
2	0.661497	1	0.961497	0.3000
2	0.661497	7	0.961497	0.3000
3	0.529562	2	0.829562	0.3000
4	0.343108	3	0.643108	0.3000
5	0.216149	4	0.516149	0.3000
6	0.427198	5	0.876232	0.4490
6	0.427198	14	0.963372	0.5362
7	0.576232	5	0.876232	0.3000
7	0.576232	13	0.963372	0.3871
8	0.418463	7	0.961497	0.5430
8	0.418463	9	0.877787	0.4593
9	0.207775	10	0.507775	0.3000
10	0.348678	11	0.648678	0.3000
11	0.513312	12	0.813312	0.3000
12	0.663372	13	0.963372	0.3000
12	0.663372	14	0.963372	0.3000
13	0.300597	8	0.600597	0.3000
14	0.577787	1	0.961497	0.3837
14	0.577787	9	0.877787	0.3000

TABLE III
Comparative Analysis - IEEE 8-bus Network

Operating Time	GAMS	MEFO [22]	DE [22]	BBO [22]
OF	6.0699	6.5997	6.9012	8.099

B. Test Case-II: IEEE 9-bus System

The study analyzes the IEEE 9-bus network, which comprises one power generator, 9 buses, 12 branches, and 24 DOCRs. In this scenario, each relay is considered a numerical relay, which turns the network into an NLP problem.

The three-phase short circuit current values, encompassing all key system characteristics, are sourced from [15]. Table IV presents the optimal relay settings, whereas Table VI provides the CTI values for the corresponding relay pairs. Furthermore, Table V provides a comparative analysis of the proposed method, showing an effective performance improvement of 1.79%.

C. Test Case-III: IEEE 15-bus System

The distribution network configurations along parametric settings for DOCRs, are taken from [15]. All relays in this scenario are considered numerical. Consequently, the network is modeled as an NLP. The continuous controlling variables, PS and TDS, range from 0.5 to 2.5 and 0.1 to 1.2, respectively. A CTI value of 0.2 seconds is applied. Table VII shows the optimized relay parametric settings that results in the minimal relay's cumulative operating time. Moreover, the comparative analysis in Table VIII indicates that the GAMS-based optimization attains a remarkable 23.18% improvement

TABLE IV
OPTIMIZED RELAY PARAMETERS - IEEE 9-BUS NETWORK

Relay	**TDS**	**Plug Setting**
1	0.1	0.712485
2	0.1	0.5
3	0.1	0.639730
4	0.1	0.61533
5	0.1	0.5
6	0.1	0.65024
7	0.1	0.65024
8	0.1	0.5
9	0.1	0.61533
10	0.1	0.63973
11	0.1	0.5
12	0.1	0.5
13	0.1	0.50563
14	0.1	0.60368
15	0.1	0.60368
16	0.1	0.50563
17	0.1	0.57956
18	0.1	0.5
19	0.1	0.56391
20	0.1	0.5
21	0.1	0.61887
22	0.1	0.5
23	0.1	0.60538
24	0.1	0.5
$OF = 6.90495$		

TABLE V
COMPARATIVE ANALYSIS - IEEE 9-BUS NETWORK

Operating Time	**GAMS**	**FA-GA** [15]	**GA** [15]	**MFA** [15]
OF	6.90495	7.03106	7.08666	10.23700

over the FA-GA algorithm, and Table IX displays the CTI values for the corresponding pairs of relays.

V. CONCLUSION

This research introduces an optimization strategy employing GAMS for resolving the issues related to coordinating DOCRs, specifically crafted to determine the optimized relay parametric settings. Comprehensive testing on various IEEE test systems demonstrates that GAMS-based optimization achieves minimal operating time with efficient relay coordination. A comparative analysis with modern methods like the MEFO and hybrid FA-GA demonstrates the proposed approach's efficiency. Future potential avenues may include standardizing GAMS-based methods by conducting case studies or simulations that demonstrate the translation of acquired results into practical scenarios using simplified models or real-world data where available, and exploring non-standard relay characteristics for enhanced coordination.

TABLE VI
CTI VALUES FOR PAIR OF RELAYS - IEEE 9-BUS SYSTEM

Sr. No.	CTI	Sr. No.	CTI
1	0.249392	19	0.2312
2	0.2	20	0.2
3	0.2	21	0.2312
4	0.2	22	0.2
5	0.2	23	0.20652
6	0.2	24	0.41115
7	0.4003	25	-
8	0.2	26	0.2
9	0.4003	27	0.2
10	0.2	28	-
11	0.2	29	0.2
12	0.2	30	0.411154
13	0.288197	31	-
14	0.2	32	0.2
15	0.2279	33	0.2
16	0.2	34	-
17	0.46707	35	0.300404
18	0.227984	36	0.300404

TABLE VII
OPTIMIZED RELAY PARAMETERS - IEEE 15-BUS NETWORK

Relay	**TDS**	**PS**	**Relay**	**TDS**	**PS**
1	0.1	1.2435	22	0.1	1.68865
2	0.1	0.9741	23	0.1	1.12319
3	0.1	2.0596	24	0.1	1.45145
4	0.1	1.2408	25	0.1	2.00448
5	0.1	2.17085	26	0.1	1.7237
6	0.1	2.10321	27	0.1	1.99805
7	0.1	2.06386	28	0.104122	2.5
8	0.1	1.58103	29	0.1	1.569751
9	0.1	2.11345	30	0.1	1.73923
10	0.1	1.70933	31	0.1	1.87205
11	0.1	1.27865	32	0.1	1.596088
12	0.1	1.4106	33	0.10644	2.4917
13	0.1	2.17285	34	0.1	2.5
14	0.1	1.11303	35	0.1	2.06659
15	0.1	1.02532	36	0.10207	1.84632
16	0.1	1.44419	37	0.10408	2.5
17	0.1	1.5755	38	0.10119	2.5
18	0.1	1.04754	39	0.10288	2.5
19	0.1	1.80434	40	0.103247	2.5
20	0.1	1.30751	41	0.1	2.5
21	0.1	0.5	42	0.1	1.5741
$OF = 11.69916$					

TABLE VIII
COMPARATIVE ANALYSIS - IEEE 15-BUS NETWORK

Operating Time	**GAMS**	**FA-GA** [15]	**MFA** [15]	**GA** [15]
OF	11.69916	15.2292	16.0694	17.2657

VI. ACKNOWLEDGMENTS

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REFERENCES

[1] M. F. Rezaei and S. Ghobadpour, "Reconfiguration of the real distribution network and providing a new resilience index, considering the uncertainty of renewable energy sources and digital protection devices in order to improve the resilience," *Electric Power Systems Research*, vol. 228, p. 110012, 2024.

[2] M. M. Ashraf and T. N. Malik, "A novel optimization framework for the least cost generation expansion planning in the presence of renewable energy sources considering regional connectivity," *Arabian Journal for Science and Engineering*, vol. 45, no. 8, pp. 6423–6451, 2020.

TABLE IX
IEEE 15-BUS SYSTEM - CTI VALUES FOR RELAY PAIRS

Relay Pair	CTI Value	Relay Pair	CTI Value
1	0.2	42	0.2
2	0.2021119	43	0.2722406
3	0.2458512	44	0.2722406
4	0.2	45	0.2639088
5	0.2	46	0.2796642
6	0.2060067	47	0.20922609
7	0.21792817	48	0.2046427
8	0.21792817	49	0.23691158
9	0.2	50	7.539944
10	0.2	51	0.2
11	0.2050837	52	0.2
12	0.2	53	0.2
13	0.2	54	0.2374139
14	0.2	55	0.2385235
15	0.2	56	0.2
16	0.2	57	0.2
17	0.217370	58	0.2
18	0.212286	59	0.2
19	0.2	60	0.2
20	0.214081	61	0.2
21	0.202159	62	0.2
22	0.214081	63	0.2
23	0.2	64	0.264524
24	0.2	65	0.202463
25	0.2	66	0.266988
26	0.2	67	0.221509
27	0.232268	68	0.2521607
28	0.2437393	69	7.468655
29	0.2	70	0.2
30	0.2364470	71	0.2
31	0.2	72	0.2
32	0.251402	73	0.2011096
33	0.214955	74	0.2
34	0.231973	75	0.2
35	0.2319733	76	0.2
36	0.223641	77	0.2
37	0.211921	78	0.2
38	0.2	79	0.2
39	0.211921	80	0.2306508
40	0.208331	81	0.2
41	0.208331	82	0.2

[3] S. Kamel, A. Korashy, A.-R. Youssef, and F. Jurado, "Development and application of an efficient optimizer for optimal coordination of directional overcurrent relays," *Neural Computing and Applications*, vol. 32, pp. 8561–8583, 2020.

[4] A. Wadood, S. Gholami Farkoush, T. Khurshaid, C.-H. Kim, J. Yu, Z. W. Geem, and S.-B. Rhee, "An optimized protection coordination scheme for the optimal coordination of overcurrent relays using a nature-inspired root tree algorithm," *Applied Sciences*, vol. 8, no. 9, p. 1664, 2018.

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

[6] P. Alaee and T. Amraee, "Optimal coordination of directional overcurrent relays in meshed active distribution network using imperialistic competition algorithm," *Journal of modern power systems and clean energy*, vol. 9, no. 2, pp. 416–422, 2020.

[7] Y. Damchi, M. Dolatabadi, H. R. Mashhadi, and J. Sadeh, "Milp approach for optimal coordination of directional overcurrent relays in interconnected power systems," *Electric Power Systems Research*, vol. 158, pp. 267–274, 2018.

[8] S. P. Ramli, H. Mokhlis, W. R. Wong, M. A. Muhammad, N. N. Mansor, and M. H. Hussain, "Optimal coordination of directional overcurrent relay based on combination ofimproved particle swarm optimization and linear programming consideringmultiple characteristics curve," *Turkish Journal of Electrical Engineering and Computer Sciences*, vol. 29, no. 3, pp. 1765–1780, 2021.

[9] M. Al TalaqÃ and M. Al-MuhainiÃ, "Optimal coordination of time delay overcurrent relays for power systems with integrated renewable energy sources," *Power System Protection in Future Smart Grids: Achieving Reliable Operation with Renewable Energy, Electric Vehicles, and Distributed Generation*, p. 81, 2023.

[10] D. Vyas, P. Bhatt, and V. Shukla, "Coordination of directional overcurrent relays for distribution system using particle swarm optimization," *Int. J. Smart Grid Clean Energy*, vol. 9, no. 2, pp. 290–297, 2020.

[11] L. Ma and J. Yu, "Hierarchical clustering cuckoo search optimization implemented in optimal setting of directional overcurrent relays," *Mathematical Problems in Engineering*, vol. 2022, no. 1, p. 8966149, 2022.

[12] A. Korashy, S. Kamel, A.-R. Youssef, and F. Jurado, "Solving optimal coordination of direction overcurrent relays problem using grey wolf optimization (gwo) algorithm," in *2018 Twentieth International Middle East Power Systems Conference (MEPCON)*. IEEE, 2018, pp. 621–625.

[13] N. Z. Jamal, M. H. Sulaiman, O. Aliman, and Z. Mustaffa, "Optimal overcurrent relays coordination using an improved grey wolf optimizer," *International Journal of Advanced Computer Science and Applications*, vol. 9, no. 11, 2018.

[14] F. C. Sampaio, F. L. Tofoli, L. S. Melo, G. C. Barroso, R. F. Sampaio, and R. P. S. Leão, "Adaptive fuzzy directional bat algorithm for the optimal coordination of protection systems based on directional overcurrent relays," *Electric Power Systems Research*, vol. 211, p. 108619, 2022.

[15] T. Foqha, M. Khammash, S. Alsadi, O. Omari, S. S. Refaat, K. Al-Qawasmi, and A. Elrashidi, "Optimal coordination of directional overcurrent relays using hybrid firefly–genetic algorithm," *Energies*, vol. 16, no. 14, p. 5328, 2023.

[16] J. Yu, C.-H. Kim, and S.-B. Rhee, "Oppositional jaya algorithm with distance-adaptive coefficient in solving directional over current relays coordination problem," *IEEE Access*, vol. 7, pp. 150 729–150 742, 2019.

[17] R. Tiwari, R. K. Singh, and N. K. Choudhary, "Optimal coordination of dual setting directional over current relays in microgrid with different standard relay characteristics," in *2020 IEEE 9th Power India International Conference (PIICON)*. IEEE, 2020, pp. 1–6.

[18] A. Draz, M. M. Elkholy, and A. A. El-Fergany, "Slime mould algorithm constrained by the relay operating time for optimal coordination of directional overcurrent relays using multiple standardized tripping curves," *Neural Computing and Applications*, vol. 33, pp. 11 875–11 887, 2021.

[19] V. N. Rajput, F. Adelnia, and K. S. Pandya, "Optimal coordination of directional overcurrent relays using improved mathematical formulation," *IET Generation, Transmission & Distribution*, vol. 12, no. 9, pp. 2086–2094, 2018.

[20] A. Haseeb, M. M. Ashraf, U. Waleed, and T. Hussain, "Gams-based harmonics estimation technique for reliable harmonics analysis of power signals," in *2023 North American Power Symposium (NAPS)*. IEEE, 2023, pp. 1–6.

[21] A. Haseeb, M. M. Ashraf, and A. Arshad, "Emission constrained generation expansion planning considering site-dependent renewable energy sources of pakistan," in *2023 International Conference on Emerging Power Technologies (ICEPT)*. IEEE, 2023, pp. 1–6.

[22] H. Bouchekara, M. Zellagui, and M. A. Abido, "Optimal coordination of directional overcurrent relays using a modified electromagnetic field optimization algorithm," *Applied Soft Computing*, vol. 54, pp. 267–283, 2017.