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OPTIMAL COORDINATION FOR DIRECTIONAL OVERCURRENT RELAYS INCORPORATING DISTRIBUTION GENERATORS: A COMPARATIVE STUDY

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Abstract

The integration of renewable energy-based distributed energy resources (DER) into distribution networks has increased due to rising load demand and growing concerns about global warming. The integration of DERs has transformed the operation of distribution networks from a passive to an active nature. As a result, a bidirectional flow of current occurs in the distribution networks. The protection of such systems is generally performed using directional overcurrent relays (DOCRs). However, optimal coordination of the DOCRs is necessary to ensure safe operation. Therefore, this paper aims to develop the optimal coordination of DOCRs using two nature-inspired techniques: Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). The developed algorithms are tested on IEEE 6-Bus and IEEE 15-Bus test systems in the MATLAB R2022b environment. To validate the effectiveness of the methods, the obtained results are compared with various up-to-date algorithms. The comparison shows that the GA outperformed all the algorithms in minimizing the relay operation time for optimum coordination of overcurrent relays.

Keywords: directional overcurrent relay, optimal coordination, genetic algorithm, particle swarm optimization.

List of Symbols/Acronyms

ABC – Artificial Bee Colony;
BSA – Backtracking Search Algorithm;
CHIO – Coronavirus Herd Immunity Optimizer;
CTI – Coordination Time Interval;
CTR – Current Transformer Ratio;
DE – Differential Evaluation;
DER – Distributed Energy Resources;
DG – Distribution Generators;
DOCR – Directional Overcurrent Relay;
EEO – Enhanced Equilibrium Optimization;
EEO – Enhanced Equilibrium Optimization;
FA – Firefly Algorithm;
GA – Genetic Algorithm;
GSO – Group Search Optimization;
GWO – Grey Wolf Optimizer;
IA – Immune Algorithm;
IFA – Improved Firefly Algorithm;
LP – Linear Programming;
MEFO – Modified Electromagnetic Field Optimization;
MFA – Modified Firefly Algorithm;
NLP – Non-Linear Programming;
OCR–Overcurrent Relay;
PS – Plug Setting;
PSO – Particle Swarm Optimization;
TLBO –Teacher Learning Based Optimization;
TMS – Time Multiplier Setting;
Top – Operation Time of Relay;

1. INTRODUCTION

Traditionally, distribution networks have a radial structure in which electrical power is transmitted from the substation towards the load [1-2]. Overcurrent relays (OCR) have always been considered an economical and efficient approach to protect such systems [3-5]. However, recent trends in the energy sector, driven by the growing adoption of renewable energy sources, have led to a shift towards more complex distribution networks. These modern networks incorporate DERs at the distribution level and provides various economic and technical advantages. Consequently, traditional power distribution networks have been transformed from regular radial networks to more complex looped networks. Although these developments increase the flexibility and reliability of the power system, they also cause new protection issues. Therefore, the protection based on OCR, which was initially developed for radial networks, seems inadequate for the reliable protection of these bidirectional looped networks containing DGs [6].

To address these problems, DOCRs have emerged as a promising solution to protect DER-integrated ring/looped distribution networks [7]. DOCRs offer a more adaptable and cost-effective solution by considering the direction of power flow,

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which is crucial in systems with multiple generation sources and complex network topologies.

The primary relay is very important in electrical protection, and its main function is to isolate the faulty section as soon as a fault is detected, ensuring that no other parts of the system are affected. However, there are cases where the primary relay does not operate [8-9]. In such cases, the backup relay comes into effect and set to open the faulty section after a time determined by the fault, ensuring that the faulty section is cleared even if the main protection fails. The settings in DOCRs are adjusted so that they can act as both primary and backup protection.

The fault has three levels of coordination criteria, such as near-end faults or faults that are located in the middle point or far-end fault as shown in Fig 1. In this paper, the all scenarios for our study were taken on near-end faults.

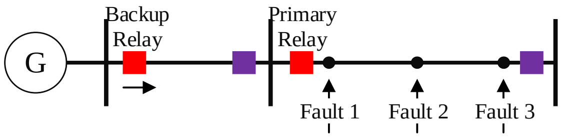

Fig. 1. Fault levels

DOCRs are constructed using two primary settings: the plug setting (PS) and the time multiplier setting (TMS). These settings define the operation time of each relay, which aids in the proper coordination among primary and backup relays. Therefore, obtaining optimal PS and TMS values is crucial [10].

Numerous DOCR coordination methods have been developed and discussed by researchers, Fig. 2 show classification of various DOCR coordination methods. These methods can be broadly categorized into two main groups:

1. conventional methods;
2. computational intelligence methods.

The conventional methods of DOCR coordination include the use of topological analysis [11], graph-theoretical techniques [12], curve-fitting techniques [13], and trial-and-error techniques [14]. Although these techniques are simple, they have a very slow convergence rate and do not guarantee an optimal solution.

To overcome the limitations of conventional methods, computational intelligence techniques have been employed. Linear programming (LP) is used for DOCR coordination, which is simple to implement and fast [15-16]. However, LP-based methods can only obtain TMS due to its linear relation in the objective function. To optimally obtain both TMS and PS, nonlinear quadratic programming-based methods were developed. However, these methods also have slow convergence and cannot guarantee a global optimum solution.

Nowadays, advanced metaheuristic and nature-inspired approaches are increasingly employed to solve the optimization problem of DOCR coordination.

Metaheuristic-based DOCR coordination methods include differential evolution [17], artificial bee colony (ABC) [18], evolutionary algorithms [19], teaching-learning-based optimization [20], Firefly Algorithm [21], genetic algorithms [4], chaotic differential evolution [22], biogeography-based optimization [23], improved group search optimization [24], modified electromagnetic field optimization [25], and symbiotic organism search [26]. These techniques generally produce high-quality global optimization solutions than LP and NLP methods but face challenges related to computational space, time, and early convergence. Some of the latest developments in DOCR coordination include hybrid particle swarm optimization [27], Harris Hawk optimization [28], the JAYA algorithm [29], and the whale optimization algorithm [30]. Another noteworthy method is the bio-inspired rooted tree algorithm developed for the optimal coordination of DOCRs [31]. Particle Swarm Optimization solution is used to constrained single-objective IDMT directional over current relay coordination network with Wind Energy Farms [32]. Slime Mould Algorithm used in [33] to allocate several Photovoltaic Distributed Generation units with a multi-objective function to minimize voltage deviation, power loss and operation time. In this paper [34] examines multiple algorithms for optimal relay coordination honeybee, ABC, GA, employing NLP and LP models for DOCRs.

Another algorithm for coordinating directional overcurrent and distance relays with exploration balancing exploitation for finding optimal settings Enhanced Equilibrium Optimization (EEO) algorithm [35]. Monte Carlo optimization of directional overcurrent protections for transient scenarios and fault locations [36].

To increase efficiency and effectiveness in solving the coordination problem, a cuckoo search algorithm-based hierarchical clustering mechanism was proposed [37]. The grey wolf optimizer was deployed to identify the best relay configuration and solve coordination issues [38]. Coronavirus Herd Immunity Optimizer (CHIO) was applied for directional overcurrent relay coordination in [39].

In general, hybrid algorithms are considered to generate improved solutions compared to standard or metaheuristic optimization procedures. A combined method of PSO with differential evolution (DE), called PSO-DE, provided better solutions in a shorter time [40]. Another proposed method modified the conventional AI-embedded firefly algorithm using LP to improve performance [41]. A novel technique for optimal DOCR coordination based on a hybrid optimization technique, namely an immune algorithm (IA) and PSO, was introduced [42]. This technique combines the PSO algorithm with the immune (IA) information processing mechanism using historical information to enhance PSO's searching capabilities.

This paper aims to develop an optimal coordination of DOCRs in the presence of distributed generators in distribution networks using two nature-inspired techniques. In comparison with the research referred to [43] research gives information regarding two different protection types overcurrent and distance relays. We focused on one type of relay and thus explored the challenges of directional overcurrent protection with distributed generators in a larger power distribution system with more buses and higher operational complexity. Besides, our work focused on comparing well-known nature-inspired algorithms for relay setting Optimization namely Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). With this broader application scope and focused methodological comparison, the proposed method reveals more advanced protection schemes and provides a solid basis for further improvements in directional overcurrent relay coordination.

The developed algorithms are tested on IEEE 6-Bus system and IEEE 15-Bus system within the MATLAB R2022b environment. To validate the efficacy of these methods, the obtained results are rigorously compared with a range of contemporary algorithms. The comparison reveals that GA consistently outperforms other methods in minimizing relay operating time, thereby achieving superior optimal overcurrent relay coordination. Additionally, this study explores the robustness of both GA and PSO, highlighting their respective strengths and potential areas for improvement. The findings suggest that GA offers a more reliable and efficient solution for complex power system protection schemes, ensuring rapid and accurate relay operations, which is critical for maintaining system stability and preventing widespread outages.

2. PROBLEM FORMULATION

The coordination of DOCRs is a fundamental aspect of power system protection. Effective relay coordination ensures that the correct relay operates in response to a fault, minimizing the impact on the system and preventing unnecessary outages. The primary goal is to determine the optimal settings for TMS and PS to reduce the overall relay operating time while adhering to all the necessary constraints.

2.1. Objective Function

The goal of the DOCR coordination problem is to minimize the overall operating time of all relays within the system. This can be mathematically represented as [8]:

$$OF = \sum_{i=1}^{N} T_{op,i} \tag{1}$$

Where *OF* is the objective function, *N* represents the total of relays in a system, and $T_{op,i}$ denotes the operating time of relay *i*. The operating time of each relay is obtained by its characteristic curve and it's the theoretical operating time derived independently for a relay, which is influenced by the TMS and PS. The operating time can be computed by:

$$T_{op,i} = TMS_i \cdot \frac{\alpha}{(\frac{I_f}{PS_i * CTR})^{\beta} - 1} \tag{2}$$

Here, TMS_i is the time multiplier settings of relay *I*, I_f is the fault current seen by the relay, PS_i is the plug settings, CTR is the current transformer ratio, and α and β are the relay constant. In this study, the IEC standard inverse time characteristics of the relay are applied, where α and β are 0.14 and 0.02, respectively [44-45].

The TMS of each relay should be within specific bounds to ensure practical and feasible settings:

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

where TMS_{min} and TMS_{max} are the lower and upper limits of the TMS for the i^{th} relay, respectively. Similarly, The PS of each relay should also lie within specific bounds.

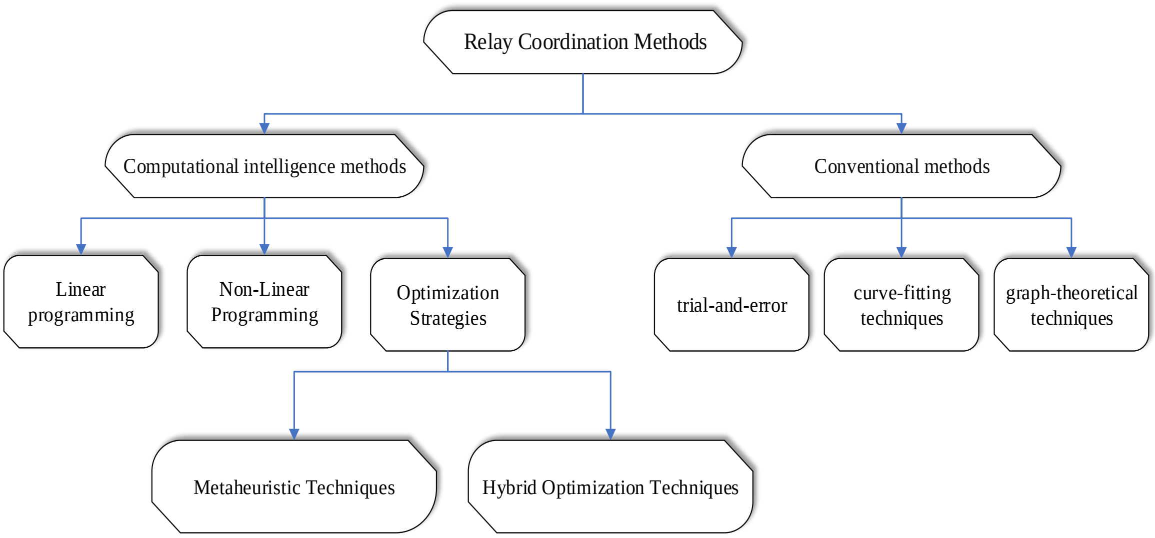

Fig. 2. coordination methods

$$PS_{min} \leq PS_i \leq PS_{max} \quad (4)$$

where PS_{min} and PS_{max} are the minimum and maximum boundaries of the PS for the i^{th} relay, respectively.

The operating time of each relay should be within the specific range.

$$T_{op,\ min} \leq T_{op,\ i} \leq T_{op,\ max} \quad (5)$$

The upper operating time limit is set by the thermal limit of the component being protected, whereas the lower operating time limit is specified by the relay manufacturer (7).

2.2. Coordination Time Interval

The coordination constraint is essential to warrant that the backup and primary relay trip with no unwanted or uncoordinated tripping. Effective coordination mandates that the backup relay's operational time must exceed that of the primary relay by a predetermined constant. These coordination demands mean that the backup relay operating time should be greater than that of the primary relay by a specific Coordination Time Interval (CTI), which can be expressed as:

$$T_{j,k} - T_{i,k} \geq CTI \quad (6)$$

Here, $T_{j,k}$, and $T_{i,k}$ operation times of the backup relay j and primary relay i respectively, for a fault occurring at location k. And it is important to note, $T_{j,k}$, and $T_{i,k}$ show the optimized operating time under specific fault scenarios, taking coordination into account and the constraints while minimizing total relay operating times.

3. GENETIC ALGORITHM

GA was originally developed by Holland in the 1960s and extensively studied by Goldberg in 1989 [4]. It is an optimization technique rooted in the concepts of natural evolution and selection, inspired by the "survival of the fittest" principle. For DOCR coordination, the goal is to reduce the total relay operation time while guaranteeing all constraints are met. The steps involved in the DOCR coordination using GA are as follows:

3.1. Initialization of Population

The initialization of the population is a crucial step in GA. In the DOCR coordination problem, the initial population for TMS and PS is randomly generated within their upper and lower bounds. This diversity in the initial population ensures a wide exploration of the solution space, which is essential for the efficiency of the GA. GA can better avoid local optima and improve the chances of finding the global optimum by starting with a varied set of potential solutions.

3.2. Tournament Selection

In GA, after the generation of the initial population, the next step is the selection of parents for reproduction in the population. In this study, tournament selection is used, and the individual with the best fitness among the selected candidates is chosen as a parent for reproduction. This is done sequentially until the required number of parents is selected. This method is also efficient in terms of computations and hence can be used in optimization problems of many kinds. Tournament selection helps maintain diversity and prevents premature convergence by ensuring that even less fit individuals have a chance to be selected.

3.3. Crossover

Crossover is one of the basic operators in GA that is responsible for mating two parents to produce new offspring. This mimics the biological reproduction process, where the progeny inherits characteristics from both parents. Crossover is used effectively in GA to ensure population diversity, as it allows different individuals to exchange the better qualities they possess.

In this study, blend crossover is used because it is best for continuous optimization problems. The equation for blend crossover is as follows:

$$C = P_1 + \alpha(P_2 - P_1) + \beta(P_1 - P_2) \quad (7)$$

Where C is a child; P_1 and P_2 are the parents and α and β are the crossover coefficients. In this study, α and β are selected as 0.3 and 0.5 respectively.

Crossover ensures that the offspring have a balanced mix of the characteristics of their parents. This promotes genetic diversity and improves the search for optimal solutions.

3.4. Mutation

Mutation is another critical operator in GA, as it introduces variation into the population by randomly altering individual genes. This process is similar to natural mutation in biological evolution and permits the algorithm to discover unvisited parts of the solution space. The primary role of mutation is to maintain population diversity, hence preventing hasty convergence to a local minimum and make the search process more effective.

This study utilized random mutation, where an individual within the population is randomly selected, and its value is changed to a random value. This helps prevent the algorithm from getting stuck in local optima and aids in exploring the search space more thoroughly.

3.5. Elitism

In elitism, some of the best solutions from the current generation are transferred directly to the next generation without any changes. This strategy is useful in sustaining the quality of the solutions as it preserves the best candidates, thus avoids their elimination during crossover and mutation steps. The algorithm can accelerate convergence to the optimal solution and maintain high-quality solutions throughout the generations by retaining elite individuals. This ensures that the best solutions are not lost and continue to contribute to the overall population fitness.

3.6. Genetic Algorithm for DOCR Coordination

The flowchart of GA for DOCR coordination is shown in Fig.3. It is clear from the figure the algorithm starts with creation of initial population of solutions for PS and TMS randomly. Afterward, tournament selection is applied to obtain a set of parents for mating to generate a new population. This involves comparing individuals at random and then choosing the best ones to be the parents of the next generation. Next, the selected parents go through blend crossover to create offspring.

This operation combines the genes of the parents to produce new individuals, which inherit features from both parents but also contain variations. Then, mutation is applied to the offspring by making small random changes in the genes inherited from the parent generation. This step helps avoid stagnation of the algorithm at local optima and achieve better genetic diversity. The high performers of the current generation are carried over to the next without degradation. This ensures the best solutions are retained and not diluted by less optimal individuals.

The constraints are then applied to all members of the population to check for feasible solutions. This guarantees that all individuals maintain the required operational constraints. Moreover, the total operating time for each population is computed. Finally, termination conditions are checked. If they have been fulfilled, the results are displayed, and the algorithm is terminated. Otherwise, the algorithm applies tournament selection, crossover, and mutation to the new population, and continue the search for the optimal solution. This iterative process ensures continuous improvement of the solution quality until the best possible coordination of DOCRs is achieved. Fig.3. shown the flowchart of iterative process for DOCR coordination.

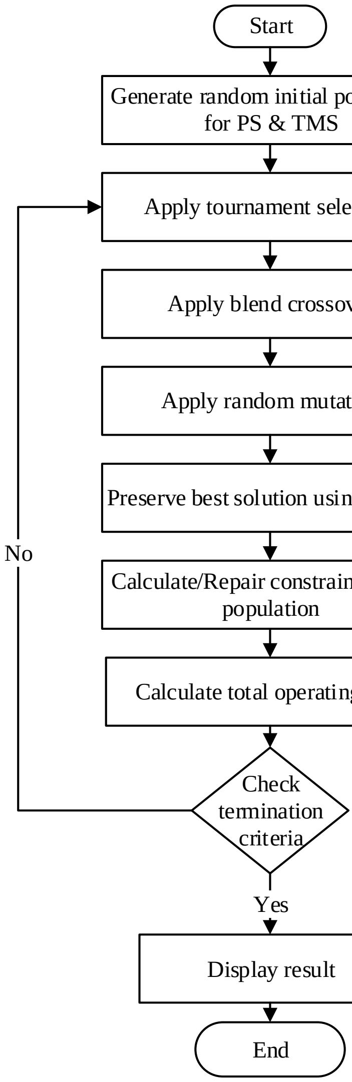

Fig. 3. GA Flowchart for DOCR Coordination

4. PARTICLE SWARM OPTIMIZATION

PSO is an evolutionary computation technique inspired by the social behaviours observed in nature. It was introduced by Kennedy and Eberhart in 1995. PSO is extensively used to solve various optimization problems due to its simplicity and efficiency [40]. PSO operates by maintaining a population of candidate solutions, known as particles, that explore the search space of the optimization problem. Each particle adjusts its position based on its own experience as well as the collective experience of neighbouring particles. The algorithm iteratively improves the quality of the solutions through these adjustments.

The key components of PSO include particles, position, velocity, personal best, and global best. Each particle has a velocity and position, which represent a potential solution and the rate of change in its position, respectively. The personal best is the best solution that a particle has discovered, while the global best is the best solution found by the entire swarm. The collective behaviour of particles guarantees an equilibrium between investigation and utilization and allows the algorithm to search through complex solution spaces efficiently.

The PSO algorithm begins with the initialization of particles in the search space randomly, followed by fitness assessment and setting personal and global bests. The diversity in initial positions helps in covering a wide area of the search space, enhancing the chances of finding the global optimum.

The velocity and position of each particle are updated iteratively. The mathematical expression to update the velocity is as follows [27,40]:

$$v_i(t+1) = w \cdot v_i(t) + c_1 \cdot r_1 \cdot (p_{best,i} - x_i(t)) + c_2 \cdot r_2 \cdot (g_{best} - x_i(t)), \quad (8)$$

Here, $v_i(t)$ is the velocity of particle i at time t, w is the inertia weight, $c1$ and $c2$ are cognitive and social coefficients, and $r1$ and $r2$ are random numbers between 0 and 1.

The position of each particle after following the velocity update, is adjusted as follows:

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (9)$$

The velocities and positions of the particles are updated iteratively, and the fitness is evaluated again to update the personal best and the global bests until a stop criterion, such as a certain number of iterations or the attainment of an acceptable fitness level, is reached. The iterative process ensures continuous refinement of the solutions. The strength of PSO lies in its simplicity and flexibility. It is easy to implement with several adjustable factors, making it applicable to both continuous and discrete optimization problems

The inertia weight balances the exploration of new areas and the exploitation of known solutions, while the cognitive and social components guide the direction of particles within the solution space. However, PSO might encounter some problems, such as premature convergence to a local solution. Strategies like adaptive parameter tuning and hybrid methods can mitigate these issues and enhance robustness of PSO.

The process begins by initializing the variables, including the PS and the TMS, with random values. Next, the algorithm calculates the total operating time for the particles within the PSO. The PSO flow chart for DOCR coordination is shown in Fig. 4.

This step involves evaluating the fitness of each particle based on the objective function. This is followed by updating the velocity and positions of the particles based on their global best and personal best positions found so far. The algorithm then repairs any constraints that may be violated by the particles, to ensure feasible solutions. After this, it determines the global best and personal best positions of the particles, updating these values based on the current fitness evaluations. The process continues iteratively until a termination condition is satisfied, at which point the final result is displayed, and the algorithm ends. The iterative nature of PSO ensures that the solutions improve progressively, leading to optimal or near-optimal DOCR settings.

The optimization process benefits from the ability of PSO to navigate complex search spaces efficiently. The collective intelligence of the swarm enhances the capability to find high-quality solutions, ensuring effective and reliable power system protection.

5. SIMULATION RESULTS

In this section, the results obtained for the DOCR coordination by employing the GA and PSO algorithms are presented, The GA was configured with a population size of 100 and 5,000 generations, utilizing Blend Crossover ($a = 0.5$) and an 8% mutation rate. And PSO employed 150 particles over 5,000 iterations, with inertia weight (w = 0.12) and cognitive (C1 = 1.5) and social (C2 = 2.0) coefficients. Both algorithms maintained a Coordination Time Interval (CTI) of at least 0.2 seconds and minimized relay operating times.

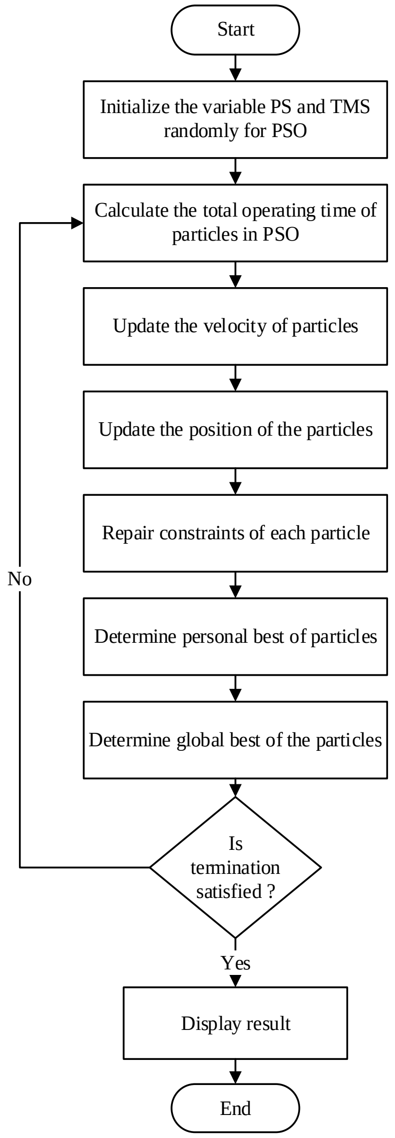

Fig. 4. PSO Flow chart for DOCR coordination

The competence of the algorithms is established by comparing the results with those of other optimization methods. The effectiveness of both algorithms is validated and tested on IEEE 6-bus system and 15-bus system. The program was utilized to perform simulation is MATLAB software version 2022b.

Additionally, the reliability and robustness of the proposed methods are highlighted through rigorous testing and comparison, showcasing their superiority in minimizing relay operating times and ensuring optimal coordination.

The proposed methodology is valid on IEEE 30-bus test system network application. This study model and algorithms are designed to handle distributed generation and coordination in complex distribution systems. Though simulations were performed on smaller test systems, scalability of proposed methods allows compatibility with larger networks such as the 30-bus system. Further studies could directly verify this on the IEEE 30-bus network under different fault and load conditions.

The proposed methods may be applied experimentally to check their real-world performance. The necessary hardware setup and facilities to test and validate the methods under practice may require future work.

In applying the proposed methods in simulations some challenges were encountered and solved. First, instability of the algorithm was detected during simulations with high fault currents caused by DGs. Hence this issue was solved by adding constraints in the algorithm that reduced the effect of reverse fault currents on system stability. Second, long computation times were a problem especially for modelling large and complex systems. This was minimized by using parallel programming techniques and optimizing the code structure, which significantly accelerated the simulation without losing result accuracy. These solutions enabled the application and testing of proposed methods in different scenarios.

5.1. IEEE 6-Bus System

The one-line diagram of the IEEE 6-bus system is shown in Fig. 5. It has seven branches, four generators, and fourteen relays. In this system, a three-phase near-end bolted fault was applied and measured for analysis. The data of this system and the fault currents for backup and primary relay pairs, shown in Table 1, were sourced from reference [46], while the corresponding CTRs are presented in Table 2.

The Coordination CTI for this system is 0.2 seconds. The TMS and PS are continuous and bounded by the ranges of [0.1, 1.1] and [1.5, 5.0], respectively. The system incorporates a total of 76 constraints, which consist of 14 inequalities for minimum operating times, 14 inequalities for maximum operating times, 20 constraints related to selectivity criteria, 14 side constraints for PS, and 14 side constraints for TMS.

Table 1. Input data for 6 Bus System

Fault location	Primary Relay	Short-Circuit Current (kA)	Backup Relay	Short-Circuit Current (kA)
F1	1	18.172	13	0.6010
F2	2	4.8030	3	1.3650
F3	3	30.547	4	0.5528
F4	4	5.1860	12	3.4220
F4	4	5.1860	14	1.7640
F5	5	2.8380	11	1.0740
F5	5	2.8380	14	1.7640
F6	6	18.338	8	0.7670
F7	7	4.4960	11	1.0740
F7	7	4.4960	12	3.4220
F8	8	2.3510	2	0.8690
F8	8	2.3510	7	1.4830
F9	9	6.0720	1	4.5890
F9	9	6.0720	7	1.4830
F10	10	4.0770	9	0.6390
F11	11	30.939	10	0.9455
F12	12	17.705	6	0.8610
F13	13	17.821	5	0.9770
F14	14	5.4570	1	4.5890
F14	14	5.4570	2	0.8680

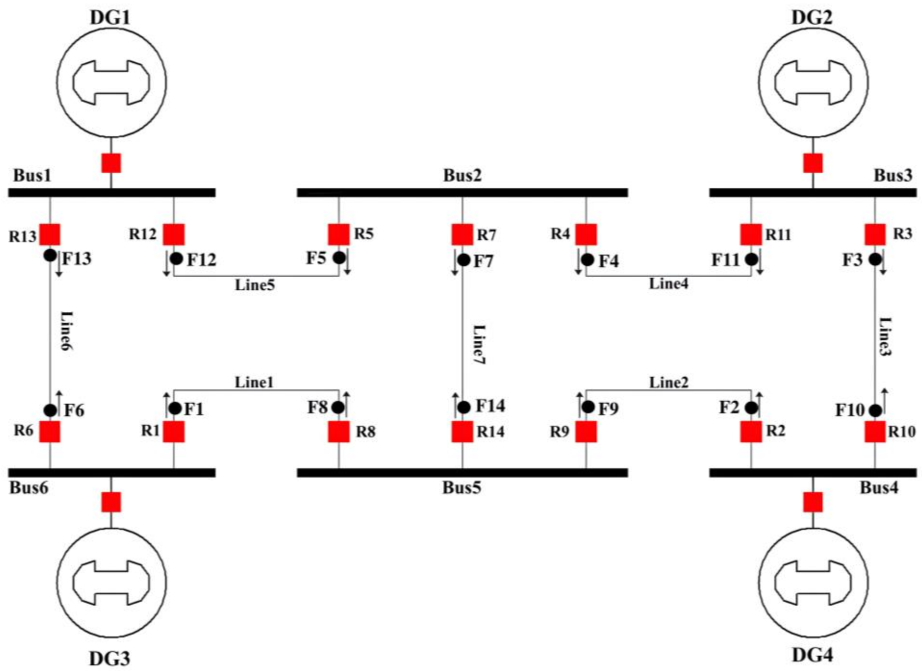

Fig. 5. IEEE 6-Bus system

The optimal PS and TMS values derived by employing the GA and PSO are detailed in Table 3. The table clearly depict that the GA delivers better results compared to the PSO. Fig. 6 illustrates the total net time savings achieved through the two methods relative to other algorithms, including Firefly algorithm (FA) [21], and improved Firefly algorithm (IFA) [41], TLBO [20], PSO-DE [40]. Table 4, show the iterations of each algorithm.

Table 2. CTR of Relays for IEEE 6 Bus

Relay Number	CTR
10	600/5
2, 3, 4, 5, 7, 8, 9, 11, 12, 14	800/5
1,6,13	1200/5

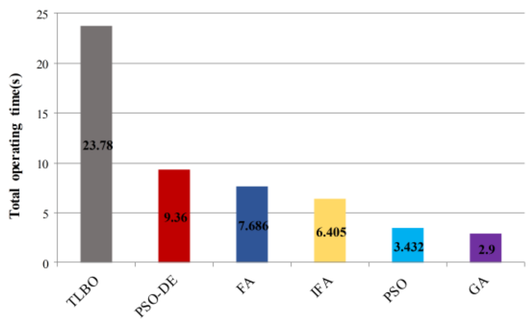

Fig. 6. Comparison of the proposed methods with other method for IEEE-6 Bus system

Table 3. TMS and PS obtained from GA and PSO

Relay Number	GA		PSO	
	TMS	PS	TMS	PS
1	0.1753	1.4942	0.2781	0.6223
2	0.1024	1.2092	0.1596	0.7383
3	0.1065	1.4661	0.1584	1.0219
4	0.1039	0.5245	0.1000	0.9400
5	0.1042	0.7659	0.1096	0.8508
6	0.1027	0.8243	0.1020	0.9882
7	0.1143	1.4667	0.1463	1.0167
8	0.1030	0.6421	0.1034	0.7269
9	0.1065	0.6400	0.1065	0.8181
10	0.1026	1.0266	0.1360	0.7775
11	0.1027	1.4648	0.1440	0.9655
12	0.1806	1.4990	0.2354	0.9320
13	0.1042	0.5958	0.1007	1.1329
14	0.1240	1.4945	0.1942	0.6439
Total Operating time	2.90 s		3.43 s	

Results indicate that the GA shows superior performance for the IEEE 6-bus test system. These results indicate that when compared to other methods, the GA offers a significant net time savings advantage, thereby signifying both enhanced and acceptable performance. Additionally, the improved results highlight the potential of GA and PSO in optimizing the coordination of DOCRs, ensuring more efficient and reliable power system protection.

Table 4. Algorithmic parameters

algorithm	iterations
TLBO [20]	not mentioned
PSO-DE [40]	100
FA [21]	1000
IFA [41]	100

The Operation time of relay pairs of each relay pair, as calculated by the two algorithms, is illustrated in Fig. 7 and Fig. 8. The figure clearly reveals that all CTI values exceed the minimum threshold of 0.2 seconds.

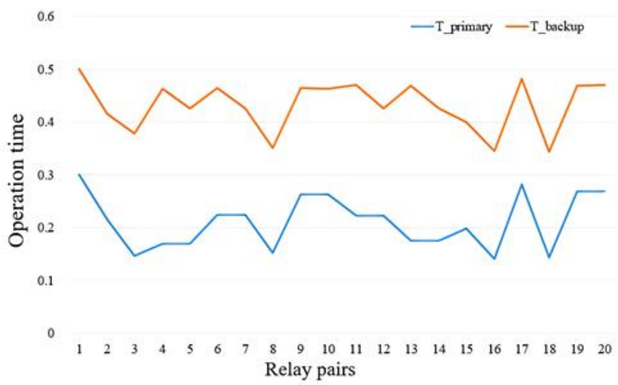

Fig. 7. Operation time of relay pairs obtained by GA

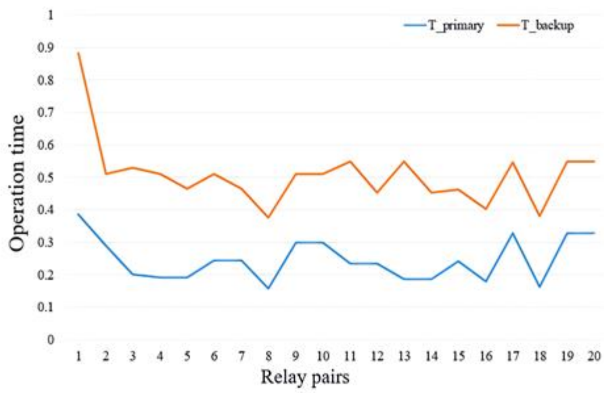

Fig. 8. Operation time of relay pairs obtained by PSO

This indicates that the two methods effectively ensure the desired sequential operation of relay pairs, thereby fulfilling the objective of optimal relay settings. These results confirm the efficacy of the GA algorithm in achieving reliable and coordinated protection for the power system. Fig. 9. Show the convergence comparison between the two proposed methods PSO and GA.

5.2. IEEE 15-Bus System

The other system used here consists of 42 relays on 21 lines and 15 buses, as depicted in Fig. 10. In

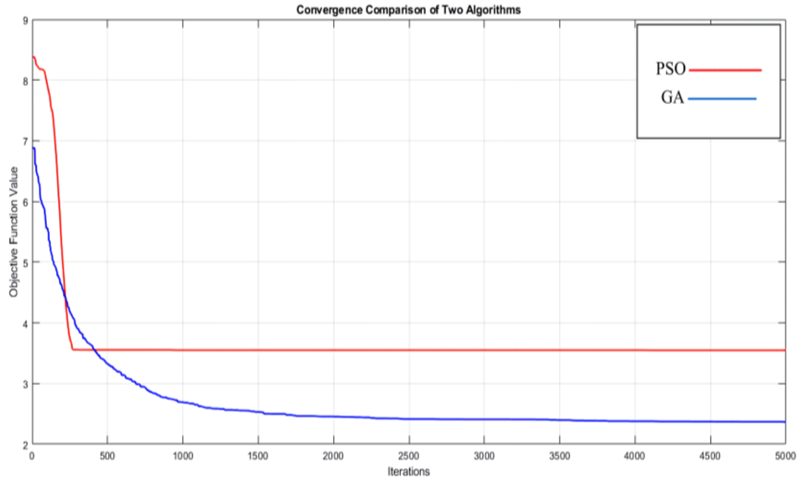

Fig. 9. Convergence Comparison between PSO and GA

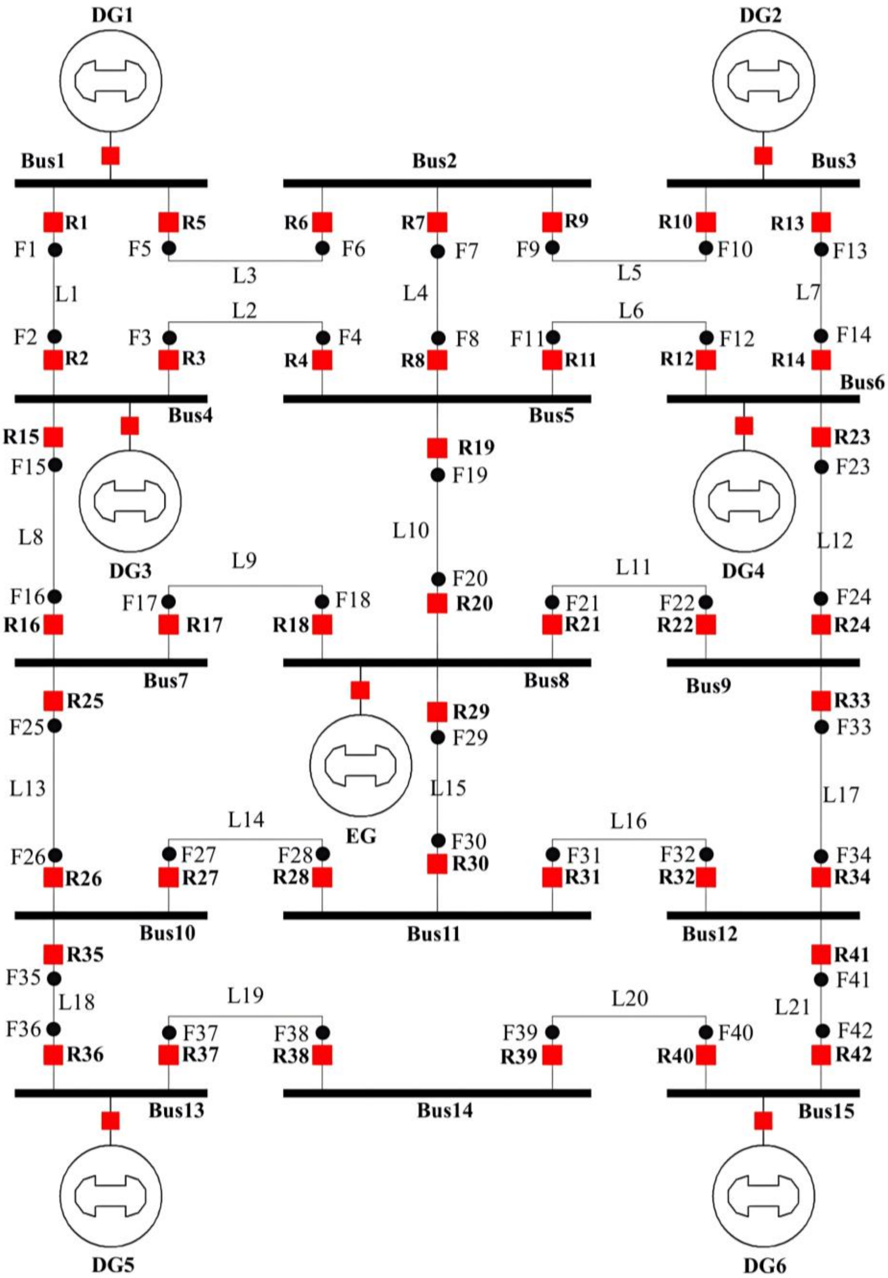

Fig. 10. IEEE 15-Bus System

this system, a three-phase bolted fault at the near-end was applied and measured for analysis. The fault currents observed at both backup and primary relays, detailed in Table 5, were sourced from reference [46], whereas Table 6 provides the Current Transformer Ratios (CTRs) for the DOCRs.
This scenario describes a distribution network with a high level of distributed generation (DG), as shown in Fig. 10. Each generator has a synchronous reactance of 15% and is rated at 15 MVA and 20 kV. The external grid has a short-circuit capacity of 200 MVA. The impedance per kilometre for each line section is defined as $Z = 0.19 + j0.46\ \Omega/km$ [47]

All relays in this scenario are considered numerical relays. The continuous variables TMS and PS have values between [0.5, 2.5] for PS and [0.1, 1.2] for TMS. A CTI of 0.2 seconds is applied to ensure proper relay coordination and system protection.

The coordination problem involves a total of 250 constraints, which include 82 constraints on inequality for selectivity requirements, 42 constraints on maximum acceptable operating times, 42 constraints on minimum acceptable operating times, and 42 additional constraints for both PS and TMS. These constraints are essential to achieve optimal relay settings, thereby improving the reliability and stability of the power distribution network.

Table 5. Input data for 15 Bus System

Primary Relay	Short-Circuit Current (A)	Backup Relay	Short-Circuit Current (A)	Primary Relay	Short-Circuit Current (A)	Backup Relay	Short-Circuit Current (A)	Primary Relay	Short-Circuit Current (A)	Backup Relay	Short-Circuit Current (A)
1	3621	6	1233	15	4712	1	853	26	2300	36	1109
2	4597	4	1477	15	4712	4	1477	27	2011	25	903
2	4597	16	743	16	2225	18	1320	27	2011	36	1109
3	3984	1	853	16	2225	26	905	28	2525	29	1828
3	3984	16	743	17	1875	15	969	28	2525	32	697
4	4382	7	1111	17	1875	26	905	29	8346	17	599
4	4382	12	1463	18	8426	19	1372	29	8346	19	1372
4	4382	20	1808	18	8426	22	642	29	8346	22	642
5	3319	2	922	18	8426	30	681	30	1736	27	1039
6	2647	8	1548	19	3998	3	1424	30	1736	32	697
6	2647	10	1100	19	3998	7	1111	31	2867	27	697
7	2497	5	1397	19	3998	12	1463	31	2867	29	1828
7	2497	10	1100	20	7662	17	599	32	2069	33	1162
8	4695	3	1424	20	7662	22	642	32	2069	42	907
8	4695	12	1463	20	7662	30	681	33	2305	21	1326
8	4695	20	1808	21	8384	17	599	33	2305	23	979
9	2943	5	1397	21	8384	19	1372	34	1715	31	809
9	2943	8	1548	21	8384	30	681	34	1715	42	907
10	3568	14	1175	22	1950	23	979	35	2095	25	903
11	4342	3	1424	22	1950	34	970	35	2095	28	1192
11	4342	7	1111	23	4910	11	1475	36	3283	38	882
11	4342	20	1808	23	4910	13	1053	37	3301	35	910
12	4195	13	1503	24	2296	21	1326	38	1403	40	1403
12	4195	24	753	24	2296	34	970	39	1434	37	1434
13	3402	9	1009	25	2289	15	969	40	3140	41	1434
14	4606	11	1475	25	2289	18	1320	41	1971	31	809
14	4606	24	753	26	2300	28	1192	41	1971	33	1162
								42	3295	39	896

Table 6. CTR of Relays for IEEE 15 Bus

Relay Number	CTR
2, 4, 8, 11, 12, 14, 15, 23	1200/5
1, 3, 5, 10, 13, 19, 36, 37, 40, 42	800/5
18, 20, 21, 29	1600/5
6, 7, 9, 16, 24, 25, 26, 27, 28, 31, 32, 33, 35	600/5
17, 22, 30, 34, 38, 39, 41	400/5

Table 7. Algorithmic parameters

algorithm	iterations
BSA [44]	400 iterations
GSO [24]	1000 iterations
MFA [45]	100 iterations
MEFO [25]	5000 iterations

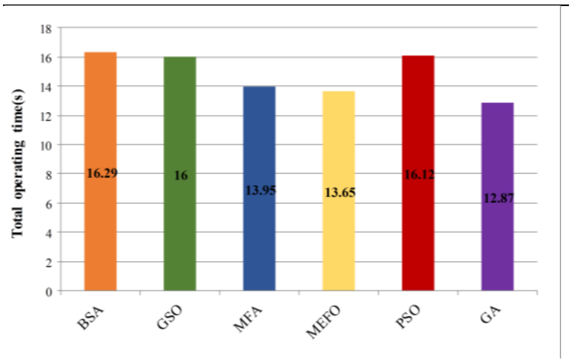

Fig. 11. Comparison of the proposed methods with other method for IEEE-15 Bus system

The superior performance of the GA is evident from the comparative analysis of the total operating time. The GA not only surpasses the PSO but also outperforms other known optimization techniques. This highlights the robustness and reliability of the GA in optimizing relay settings, ensuring efficient and effective coordination among the relays.

The Operation time for each relay pair as determined by the proposed algorithms is shown in Fig. 12 and Fig. 13. The figures clearly reveal that all CTI values exceed the minimum threshold of 0.2 seconds.

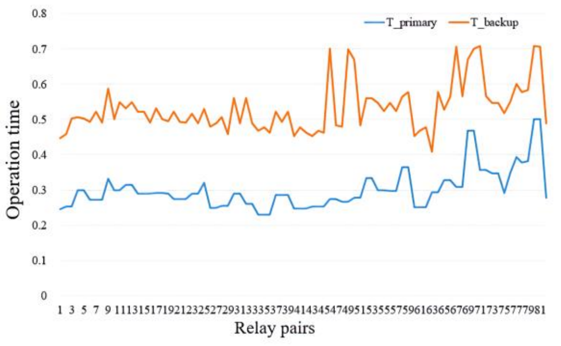

Fig. 12. Operation time of relay pairs obtained by GA

Table 8. TMS and PS for IEEE 15 Bus

Relay Number	GA		PSO	
	TMS	PS	TMS	PS
1	0.1028	1.3161	0.1138	1.4584
2	0.1063	1.0992	0.1000	1.4961
3	0.1066	2.1731	0.1732	1.1636
4	0.1089	1.1975	0.1205	1.1843
5	0.1131	2.0072	0.1596	1.5494
6	0.1041	2.0585	0.1520	1.3079
7	0.1044	2.1492	0.1550	1.4931
8	0.1128	1.3676	0.1340	1.4965
9	0.1035	2.1801	0.1859	1.1578
10	0.1077	1.7695	0.1477	1.3481
11	0.1022	1.4153	0.1733	0.7752
12	0.1010	1.6032	0.1444	1.0897
13	0.1029	2.3686	0.2026	0.8431
14	0.1027	1.1699	0.1000	1.8862
15	0.1108	1.0302	0.1003	1.7479
16	0.1105	1.3626	0.1672	0.9070
17	0.1035	1.5523	0.1374	1.4034
18	0.1080	1.0892	0.1093	1.3240
19	0.1167	1.5433	0.1364	1.6269
20	0.1076	1.2473	0.1196	1.3741
21	0.1121	1.3005	0.1077	1.7118
22	0.1068	1.7211	0.1541	1.2326
23	0.1031	1.4693	0.1475	1.2059
24	0.1069	1.3901	0.1392	1.1902
25	0.1185	1.6862	0.1825	1.1751
26	0.1057	1.7038	0.1383	1.5125
27	0.1069	1.4311	0.1337	1.3533
28	0.1215	2.1434	0.2383	0.8917
29	0.1015	1.6500	0.1475	1.4194
30	0.1121	1.6060	0.1119	1.8219
31	0.1137	2.2186	0.1492	2.0245
32	0.1064	1.6266	0.1518	1.3858
33	0.1418	2.4173	0.2353	1.4703
34	0.1152	2.3517	0.2171	0.9062
35	0.1156	1.7778	0.1660	1.4495
36	0.1057	1.7229	0.1345	1.4627
37	0.1084	2.4542	0.1896	1.3179
38	0.1124	2.4750	0.2037	0.9522
39	0.1170	2.1535	0.1888	1.0865
40	0.1255	2.0772	0.2111	1.0941
41	0.1710	2.3923	0.2800	1.2477
42	0.1049	1.5747	0.1243	1.6178
Total Oper. time	12.87 s		16.10 s	

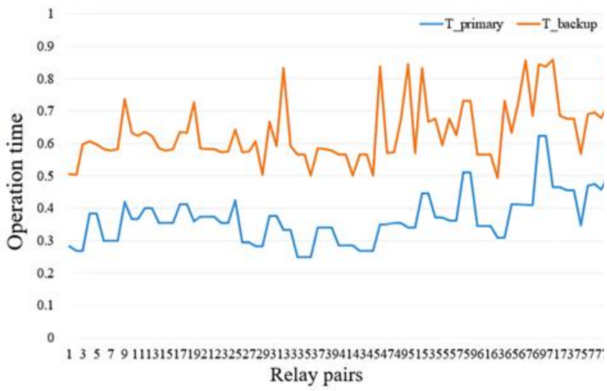

Fig.13.Operation time of relay pairs obtained by PSO

This indicates that the suggested techniques effectively ensure that desired sequential operation for relay pairs. Consequently, primary relays will trip before backup relays if the coordination time margin has been violated.

This demonstrates that the proposed methods fulfil the objective of optimal relay settings, thereby enhancing the overall protection scheme of the system. Fig. 14. Show the time-current curve for relays 1 and 6 when relay1 act as primary relay and relay6 act as backup It is clear from the figure that if the main relay fails to operate for any reason, the backup relay will operate for a time not exceeding 0.2. Additionally, the consistency in maintaining the CTI above the threshold signifies the reliability of the proposed algorithms in real-world applications, ensuring the system's stability and integrity under fault conditions. The data of IEEE 15-Bus system shown in Table 9.

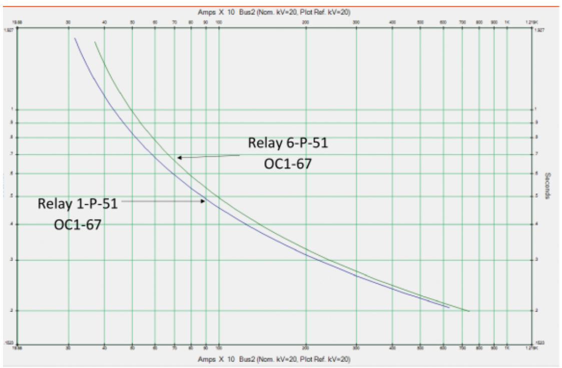

Fig. 14. Curves of time-current for relays 1 and 6

6. CONCLUSION

The incorporation of renewable energy-based DG in the distribution system has completely changed the dynamics of the distribution system from a passive to an active one which has led to two-way flow of current. Hence proper tuning of DOCRs that are applied for safe operation of mentioned systems is mandatory. To alleviate this problem, this paper implemented two nature-inspired metaheuristic techniques, which are genetic algorithm and particle swarm optimization. The algorithms were implemented by using the MATLAB R2022b on IEEE 6-Bus and IEEE 15-Bus test systems.

Table 9. Parameters of IEEE 15 Bus [47]

Parameters	Value
Synchronous reactance of all generators	15%
Rated at	15 MVA and 20 kV
Short-circuit capacity of external grid	200 MVA
Impedance per kilometre for each line	$Z = 0.19 + j0.46\ \Omega/km$
Length of each Line	
L1	20 km
L2	10 km
L3	10 km
L4	10 km
L5	15 km
L6	10 km
L7	15 km
L8	20 km
L9	15 km
L10	15 km
L11	10 km
L12	20 km
L13	15 km
L14	10 km
L15	10 km
L16	20 km
L17	10 km
L18	15 km
L19	10 km
L20	10 km
L21	20 km

In this paper highlights how to find the best coordination settings between directional protection relays in distribution networks. Improper coordination between protection devices may lead to faults or failure of protection relays, which puts equipment at risk and endangers the safety of peoples.

To justify the utility of the proposed methods, the outcomes of these tests were compared with other current algorithms. It was observed that the GA provided significantly less relay operating time, indicating better efficiency of the technique in obtaining the best coordination of the overcurrent relays.

future work will focus on hardware implementation of proposed algorithms on FPGA or microcontrollers to enable fast real time applications and computational efficiency. Also, the methods will be validated in the field with large scale test cases under real world conditions to confirm their reliability, practicality and robustness in dynamic power system environments.

The results of the study shown the suggested. GA can identify optimal settings of PS and TMS. Which gave a safe coordination margin and reduced the total tripping time in collecting all the primary relays and eliminated the miscoordination of the relays.

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