Evaluating a Novel Protection Coordination Method Based on a Hybrid SSO/CS/FF Algorithm for Directional Overcurrent Relays in a Distribution Network

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ABSTRACT

To reduce mal-operations of backup Overcurrent (OC) relays, loss of relay selectivity, and inaccuracy of protection coordination, setting parameters of OC relays in a Distribution Network (DN) must be adequately and effectively determined, which is a non-linear and non-convex optimization problem with multiple constraints. The purpose of this optimization problem is to find optimal relay parameters, including Time Multiplier Setting (TMS) and pickup current values for OC relays, in such a way that the total operating time of relays is minimized and, at the same time, the mal-operation of relays can be avoided, whereas relay selectivity and protection coordination can be improved. Hence, this paper proposes a hybrid protection coordination method based on Simplified Swarm Optimization (SSO), Cuckoo Search (CS), and Firefly (FF) algorithms, called the SSO-CS-FF approach, for Directional Overcurrent (DOC) relays in a DN. The obtained results demonstrate that the hybrid optimization algorithm of SSO-CS-FF can obtain a feasible and globally optimal solution with a small deviation in results and improve the minimization of relay coordination time of the DOC relays for this complex problem with multiple constraints. Moreover, the results of the proposed hybrid method are also compared with standard SSO, Particle Swarm Optimization (PSO), CS, and FF methods, hybrid algorithms of SSO-PSO, SSO-CS, and SSO-FF, and others to highlight its advantages. Specifically,

numerical simulation results from MATLAB software of a standard IEEE 8-bus system have been used to validate the effectiveness and accuracy of the proposed hybrid protection coordination algorithm. The total operating time of the coordination function for the IEEE 8-bus DN is 7.879 s by the proposed hybrid SSO-CS-FF approach, which is reduced by 57.2% from PSO (18.434 s), 56.7% from SSO (18.217 s), 22.7% from the SSO-PSO method (10.188 s), 19.9% from the SSO-FF algorithm (9.839 s), 6.1% from the SSO-CS algorithm (8.392 s), and 1.9% from the hybrid CS-FF algorithm (8.028 s). Furthermore, the proposed algorithm exhibits a standard deviation of approximately 0.052 s, which is notably lower than the 0.1413 s of the standard CS method and comparable to the 0.053 s of the conventional FF method. This deviation is nearly equivalent to that observed in the SSO-CS and SSO-FF methods.

Keywords-constrained optimization; Cuckoo Search Algorithm (CSA); Directional Overcurrent (DOC) relays; Distribution Network (DN); Firefly Algorithm (FFA); Particle Swarm Optimization (PSO); protection coordination; Simplified Swarm Optimization (SSO)

I. INTRODUCTION

Overcurrent (OC) protection is one of the main protection methodologies used in a Distribution Network (DN) to not only prevent the distribution system from damage due to fault events but also to enhance the reliability and efficiency of electrical networks [1]. OC or Directional Overcurrent (DOC) relays are more economical and, therefore, commonly used in DNs. These OC (DOC) relays can operate without support from communication systems, as required by distance and differential protection relays. In a meshed DN, the use of DOC relays is necessary for ensuring operational safety, performance reliability, and efficiency of the power system. The DOC relay observes the current direction in the circuit for protection purposes. If the short-circuit current flows in a certain direction and exceeds its setpoint, then the DOC relay will send a tripping signal to the circuit breaker to isolate the faulty section of the network [2]. Economically, DOC relays are mainly used to design primary and backup protection systems in a DN, which are more reliable and efficient than traditional protection schemes. DOC relays can significantly reduce the number of relays required for protection, the need for communication systems, as well as equipment and installation costs [3].

Proper relay coordination is essential for effective power system protection, typically for DOC relays in DNs, ensuring an optimal relay operating sequence for quick fault clearing [4]. This can be achieved by using various coordination techniques, such as time (or current)-based coordination, or a combination of both time and current. The time-based coordination method is used to adjust the tripping time of relays according to their placement in the network. A parameter called the Coordination Time Interval (CTI) is defined as the difference in operating time between two subsequent relays, i.e. between the primary and backup relays, in the protection system. The time-based coordination typically uses intentional time delays for selectivity, allowing downstream protective devices to trip first, with upstream devices providing backup. While simple, this approach can slow down fault clearing and increase equipment stress. In contrast, current-based coordination depends largely on differing pickup current thresholds. Consequently, the downstream device becomes more sensitive, being activated for faults that the upstream device does not detect, which facilitates quicker operation. However, this demands a clear demarcation between load/inrush currents and fault currents to prevent spurious trips or a loss of selectivity. In practical applications, a combined time–current approach is commonly adopted in power systems. This method involves setting appropriate pickup currents and coordinating time–current curves, such that the downstream curve appears "below and to the left" of the upstream curve. This design ensures robust selectivity for a wide range of fault sizes and allows for quick clearing of high-current faults.

The coordination problem of DOC relays can be tackled using different optimization techniques. Previously, power system engineers used a trial-and-error approach to find the best DOC relay settings for a power system. This calculation process often took a long time due to numerous trial run iterations and adjustments to relay settings [5]. Recently, the coordination of time-overcurrent relays by meta-heuristic algorithms has been well-reviewed in [6-8]. Typically, a Linear Programming (LP) technique was applied for adaptive protection in [9]. Random search was utilized in the study referenced in [10]. Relay coordination was successfully achieved in [11] using Genetic Algorithms (GAs). In [12], the Particle Swarm Optimization (PSO) algorithm was utilized. In addition, the relay coordination problem was addressed using the Artificial Bee Colony algorithm [13], a hybrid evolutionary algorithm that integrates Tabu search [14], and the Seeker algorithm [15]. A Mixed Integer Nonlinear Programming (MINLP) problem was used in [16] to represent the coordination problem in a distribution system with distributed energy resources, and the Differential Evolution (DE) algorithm was employed for its optimal solution. Authors in [17] utilized several DE variations to establish the optimal relay setting. A modified DE algorithm with an information exchange strategy, named informative differential evolution, was developed in [18] for relay setting optimization. Authors in [19] implemented the Biogeography-Based Optimization (BBO) algorithm to solve the optimal coordination problem of DOC relays. An oppositional Jaya algorithm with a Distance-Adaptive Coefficient (DAC) was utilized in [3] to solve the optimal relay coordination problem. Optimal relay settings and coordination issues were addressed using the Grey Wolf Optimizer (GWO) in [20]. An Improved Grey Wolf Optimizer (IGWO) was developed in [21] to enhance the search capabilities of grey wolves over a broad search area. The Teaching–Learning-Based Optimization (TLBO) algorithm was used in [22] to achieve the best coordination of DOC relays in looped power systems. At the same time, a new TLBO algorithm variant, MATLBO, was proposed in [23] to solve the DOC relay problem. In [24], the Transit Search Optimization (TSO) algorithm, used for relay coordination, proved more effective than the conventional PSO, reducing the relay operating time by 33.19%. In [25], a comparative analysis was performed on OC relay coordination optimization for a 33-bus radial distribution system, employing GA, Black Hole Algorithm (BHA), and League Championship Algorithm (LCA). The findings indicated that the LCA provided quicker convergence and superior relay coordination accuracy. In [26], five meta-heuristic algorithms (Zebra Optimization Algorithm (ZOA), African Vultures Optimization Algorithm (AVOA), TSO, Nutcracker Optimization Algorithm (NOA), and Artificial Rabbits Optimization (ARO)) were used for minimizing the total primary relay operating time in the IEEE 3-, 8-, and 15-bus test systems. In the IEEE 3-bus and 8-bus systems, ARO demonstrates the lowest total primary relay operating time; however, NOA is superior in the 15-bus system.

Based on available literature, hybrid algorithms typically provide better outcomes than conventional or meta-heuristic optimization. A hybrid approach combining PSO and DE was employed in [27]. PSO-DE offers both a globally optimal solution and accelerated convergence. Authors in [28] presented a combined optimization method, the Immune Algorithm and PSO (IA-PSO), to optimally coordinate DOC relays in meshed power systems. By integrating immune information processing and PSO, this algorithm improves global solution quality while lowering computational demands.

As a popular method in swarm intelligence optimization, the Firefly Algorithm (FFA) draws inspiration from the way fireflies flash in nature. The operational success of the FFA is, however, diminished by a stochastic value following a Gaussian distribution, thereby inducing slow convergence and susceptibility to local optimization plateaus [29]. In the standard FFA, each firefly is drawn to any other firefly possessing superior fitness. The iterative standard FFA is susceptible to population optimal value oscillations due to an excess of attractions, and prolonged fitness comparisons can consequently increase computational time complexity. Authors in [30] presented an adaptive, modified version of the FFA, designed to determine the optimal coordination of DOC relays through systematic exploration of the search space, thereby improving the convergence rate. As outlined in [31], the FFA benefits from an additional improvement: a self-adaptive weight that modifies the propensity to converge on the superior solution and to disregard the inferior one. Additionally, a learning strategy based on the experience of other solutions is employed to enhance the flashing mechanism and increase the exploration of the algorithm. In this paper, a Firefly (FF) optimization approach combined with a Simplified Swarm Optimization (SSO) is proposed. This approach, called SSO-FF, effectively coordinates the DOC relays. Compared to the standard FFA, the SSO-FF hybrid algorithm can obtain a global solution and achieve a good convergence rate.

The SSO was proposed by authors in [32] in 2009. The concept of particles in the SSO was inspired by the PSO, which was proposed by scholars to model the foraging behavior of birds. Yet the continuous, velocity-driven updates of PSO are restricted when solving discrete problems, often causing premature convergence and suboptimal performance. Hence, the SSO addresses these constraints through a step-function update, enabling varied parameter configurations and updating rules for distinct problem types, thereby compensating for PSO's weaknesses in handling discrete problems. Furthermore, the SSO is easy to use and can be applied to both discrete and continuous problems [33]. Many studies have demonstrated that the SSO is more efficient than the traditional PSO method and GA in terms of solution speed, and its easy-to-understand update mechanism makes it easier to use. The update mechanism of the SSO has four probabilistic scenarios: keeping the current value, taking the personal best, choosing the global best, or a random replacement. Random assignments diversify solutions, avoiding local optima and guiding convergence to global optima. Hence, the proposed SSO-FF hybrid algorithm can further enhance the optimization process and achieve better solutions while maintaining a balance between global and local search.

In [34], the authors effectively adjusted the Cuckoo Search Algorithm (CSA)'s parameters to find the best global solution for the DOC relay coordination challenge. The study showed a modification in the randomly generated step size, which was between 0 and 1. Nevertheless, this metric demonstrated a poor response to environmental shifts throughout the iterative process. Therefore, authors in [35] presented a hierarchical clustering method with CSA to boost the efficiency and effectiveness of addressing the coordination issue. In [36], a hybrid CSA-FFA method is successfully applied to solve the DOC relay coordination problem including highly nonlinear constraints. The global optimal solution is achieved in FFA by using the initial optimal values from CSA as an upper bound. The hybrid CSA-FFA demonstrates its ability to reach an optimal global solution with minimal deviation and enhanced computational speed. In [37], to optimize the coordinated protection of DOC relays in microgrids and determine the optimal fault current limiter value at the point of common coupling, the CSA and LP are integrated. In this paper, the Cuckoo Search (CS) optimization approach will be combined with the SSO, called SSO-CS, to effectively coordinate the DOC relays in the DN. Due to the advantages and simplicity of the SSO, this combination aims to overcome the typical CSA's issues of premature convergence and being trapped in local optima on complex multimodal functions, particularly when population diversity diminishes quickly. Additionally, the hybrid SSO-CS approach accommodates constraints in discrete and combinatorial challenges, often through penalty functions that vary with the protection coordination problem.

Last but not least, this paper also proposes a new hybrid protection coordination method based on the SSO, CS, and FF algorithms, called the SSO-CS-FF approach, for DOC relays in a DN. At each iteration, the local and global optimal values of the Time Multiplier Setting (TMS) coefficient TMS and pickup current I_p, obtained by the SSO-CS algorithm, are employed as an upper boundary in the SSO-FF algorithm in order to achieve the global optimal solution. Numerical simulation results from MATLAB software for an IEEE 8-bus system show that the hybrid SSO-CS-FF algorithm can reach a global optimal solution, marked by low deviation and high computational effectiveness without violating constraints. To the authors' current knowledge, optimization of the hybrid

SSO-CS-FF algorithm for the DOC relay coordination problem has not yet been studied.

In light of the DOC relay protection coordination, the main contributions of this paper are summarized as follows:

- To overcome the drawbacks of conventional FFA, the combination of SSO and FFA, called the SSO-FF method, has been proposed. Similarly, the SSO-CS method is also developed in this paper. Then, the DOC relay coordination problem can be solved more effectively with the development of the hybrid SSO-CS-FF algorithm. Consequently, the minimum deviation in the fitness value is observed with better computational efficiency. With a standard deviation approximating 0.052 s, the proposed algorithm presents a marked improvement over the standard CSA method's 0.1413 s, while remaining competitive with the conventional FFA method's 0.053 s. In addition, this deviation is nearly equivalent to that observed in the SSO-CS and SSO-FF methods.
- The performance of the new SSO-CS-FF algorithm is assessed by implementing it on the standard IEEE 8-bus test network. It will be illustrated that the proposed hybrid SSO-CS-FF algorithm converges to optimal solutions faster and produces better results. The total operating time of the protection coordination function is 7.879 s using the proposed approach.
- The proposed SSO-CS-FF optimization technique is verified by comparing it to the SSO algorithm, the PSO algorithm, the SSO-PSO algorithm, the SSO-FF algorithm, the SSO-CS algorithm, and other up-to-date optimization algorithms that have been utilized to address the DOC relay coordination problem in the DN.

II. OPTIMAL COORDINATION PROBLEM OF DOC RELAYS IN A DISTRIBUTION NETWORK

The protection coordination issue of DOC relays in ring-fed distribution systems can be formulated as an optimization problem, in which the total operating time of primary relays throughout the system corresponding to various fault locations is minimized [6]:

$$\min Z = \sum_{i=1}^{m} W_i t_{i,k} \tag{1}$$

where m represents the number of relays in the system, whereas $t_{i,k}$ denotes the operating time of primary relay R_i for a fault occurring in the zone k. Additionally, W_i refers to the weight assigned to the operating time of relay R_i. To reduce the sum of operating times of the relays, only far-end faults are considered in the system.

In a distribution system, since the lines are short and have approximately equal lengths, an equal weight of 1 is assigned for the operating times of all relays. The goal of minimizing the total operating time of the relays is subject to three sets of inequality constraints, which are described in the following subsections.

According to the IEC standard [38], OC relay curves are given by:

$$t_{op} = \frac{A \times TMS}{\left(\frac{I_f}{I_p}\right)^B - 1} + C \tag{2}$$

where I_f is the fault current detected by DOC relays; I_p is the pickup current; t_{op} is the operating time of relay; and TMS is the TMS coefficient of the relay. The DOC relays can be properly classified into three groups: Standard Inverse (SI), Very Inverse (VI), and Extremely Inverse (EI). In this study, the SI characteristics of OC relays will be considered, with A, B, and C coefficients selected to 0.14, 0.02, and 0, respectively.

A. *Constraints on Time Coordination*

A fault can be simultaneously detected by both primary and secondary relays in the DN. The backup relay should only take over tripping if the primary relay malfunctions. If R_j is the primary relay for a fault occurring at location k, and R_i serves as the backup relay for the same fault, then the coordination constraint can be expressed as:

$$t_{i,k} - t_{j,k} \geq \Delta t \tag{3}$$

where $t_{j,k}$ represents the operating time of primary relay R_j for a fault at location k, whereas $t_{i,k}$ denotes the operating time of backup relay R_i for the same fault; and Δt refers to the CTI. The CTI is contingent upon circuit breaker operating time, relay types, safety margin, and relay error. The minimum value of CTI normally falls within the range of 0.2 to 0.5 s.

B. *Constraints on Relay Settings and Operating Time*

For optimal TMS setting results, determining the upper and lower bounds is essential. The boundaries of the TMS's range are established by the specifications issued by protection relay manufacturers. Generally, the limitations of the TMS can be defined as follows:

$$TMS_{i,\min} \leq TMS_i \leq TMS_{i,\max} \tag{4}$$

where $TMS_{i,\min}$ is the minimum value of the TMS for relay R_i, and $TMS_{i,\max}$ is the maximum value of the TMS for the same relay. The values of $TMS_{i,\min}$ and $TMS_{i,\max}$ are commonly taken as 0.1 and 1.1, respectively [11].

In addition, the constraint imposed due to the limitation on the operating time of relays can be mathematically expressed as follows:

$$t_{i,\min} \leq t_{i,k} \leq t_{i,\max} \tag{5}$$

where $t_{i,\min}$ denotes the minimum operating time of the relay at i for a fault at any point, whereas $t_{i,\max}$ represents the maximum operating time of the relay at i for a fault at any point. The upper time boundary is dictated by the critical clearing time and the permissible thermal threshold of the component under protection; conversely, the lower boundary is determined by the relay manufacturer, normally selected as 0.2 s [39].

Equation (6) can be utilized to establish the boundaries of the pickup current for each relay. The value I_p is influenced by the full load current and the short-circuit level of the system, and it can be defined as follows [40]:

$$I_{i,p,\min} \le I_{i,p} \le I_{i,p,\max} \quad (6)$$

where $I_{i,p,\min}$ and $I_{i,p,\max}$ are the minimum and maximum values of the pickup current of the *i*-th relay, respectively. The protection relay's proper operation is contingent upon setting the lower limit $I_{i,p,\min}$ at or above the maximum overload current. This establishes the necessary sensitivity to detect and react to fault conditions where current levels exceed the maximum overload. Setting the upper limit $I_{i,p,\max}$ to be equal to or less than the minimum fault current $I_{f,\min}$ is crucial for the relay to activate and initiate protection when fault currents exceed the set threshold. These boundaries of the *i*-th relay can be obtained as follows:

$$I_{i,p,\min} = \frac{k_{OLF} \times I_{i,\text{Load},\max}}{CTR_i} \quad (7)$$

$$I_{i,p,\max} = \frac{2 \times I_{i,f,\min}}{3CTR_i} \quad (8)$$

where k_{OLF} is the overload factor depending on the specific protected element, $I_{i,\text{Load},\max}$ is the maximum load current, and $I_{i,f,\min}$ is the minimum fault current, both of which must be detected by the *i*-th same relay. Additionally, the current transformer ratio (CTR_i) for the *i*-th relay can be considered when the relay pickup current is defined in terms of the secondary current of the current transformer in (2).

C. Constraint Handling Technique

The optimization process might violate the coordination constraint in (3). To solve this problem, the penalty method is applied for constraint management in optimization. A penalty term is included in the objective function to punish solutions that fail to satisfy the constraints [3]. Larger constraint violations result in a bigger penalty term, motivating the optimizer to achieve solutions that adhere to the constraints.

Penalty functions are a popular choice because other approaches can be difficult to model or require derivations. For the coordination problem, the penalty method combines the relay coordination constraints and relay characteristic constraints within the objective function, as presented in (9).

$$\min Z = \sum_{i=1}^{m} W_i t_{i,k} + \sum_{l=1}^{k} P_{pen}(l) \quad (9)$$

$$P_{pen}(l) = \begin{cases} 0, & \text{if } (t_j - t_i) \ge CTI \\ r_p & \text{otherwise} \end{cases} \quad (10)$$

If a constraint is violated, a penalty value is incorporated into the objective function. Because the objective function seeks to minimize, a high penalty factor r_p is used. With (10), the penalty function values range from 1 to k entries, where k denotes the relay pairs that are involved. When all pairs adhere to the constraints outlined in (10), the penalty function from (9) results in zero, and r_p represents a large value assigned to the solutions that violate the constraints. In general, the function yields a zero result when the boundaries are respected. For optimal minimization, the penalty function's value must also be zero.

III. A NEW SSO-CS-FF ALGORITHM PROPOSED FOR DIRECTIONAL OVERCURRENT RELAY COORDINATION PROBLEM

In this section, different hybrid optimization algorithms, namely, the SSO-CS, the SSO-FF, the SSO-PSO, and the new SSO-CS-FF approaches, will be discussed in detail for solving the DOC relay coordination problem.

A. A Hybrid SSO-CS Optimization Method

The CSA is a meta-heuristic approach that draws inspiration from the brood parasitic behavior observed in certain cuckoo species, characterized by their practice of depositing eggs in the nests of different avian species. Cuckoos exhibit random flight patterns in nature to locate optimal spots for nesting and egg-laying. The CSA's modeling of a cuckoo, according to [41], is based on three key principles, typically: i) the cuckoo lays one egg in a randomly selected nest before incubation; ii) from the randomly chosen nests, those of superior quality are selected for the next generation's propagation; iii) given a fixed number of nesting sites, there is a defined probability $p_a \in [0,1]$, that the nest's original owner will identify the misplaced cuckoo egg. If this happens, the nest owner can either throw out the egg or build a new nest. The following formulas detail the cuckoo bird's updated location and path for finding a host nest, based on the aforementioned three rules:

$$x_i^{(t+1)} = x_i^{(t)} + \alpha \otimes L(s,\lambda) \quad (11)$$

$$\alpha = \alpha_0 \left(x_i^{(t)} - x_{\text{best}}^{(t)} \right) \quad (12)$$

where $x_i^{(t)}$ denotes the position of the *i*-th bird's nest at the *t*-th iteration; α represents the step factor (or step size) that controls the cuckoo's moving step size; α_0 is normally taken as 0.01; $x_{\text{best}}^{(t)}$ is the best individual of the *t*-th generation. $L(s,\lambda)$ is a Lévy flight function, calculated by the following equations:

$$L(s,\lambda) = \frac{\lambda \Gamma(\lambda) \sin\left(\frac{\pi\lambda}{2}\right)}{\pi} \left(\frac{1}{s^{1+\lambda}} \right) \quad (13)$$

$$s = \frac{u}{|\nu|^{1/\lambda}};\ \text{with } u \sim N\left(0,\sigma_u^2\right);\ \nu \sim N\left(0,\sigma_\nu^2\right) \qquad (14)$$

$$\begin{cases} \sigma_u = \left[\dfrac{\Gamma(1+\lambda)\sin\left(\dfrac{\pi\lambda}{2}\right)}{\Gamma\left(\dfrac{1+\lambda}{2}\right)\lambda 2^{\left(\frac{\lambda-1}{2}\right)}} \right]^{1/\lambda} \\ \sigma_\nu = 1 \end{cases} \qquad (15)$$

where $\Gamma(\cdot)$ stands for the Gamma distribution operation; λ $(1<\lambda<3)$ denotes the power factor; s represents the step size expressed as in (14); u and ν are two randomly generated numbers conforming to a normal distribution, where parameters σ_u and σ_ν are defined as in (15).

Next, if other birds find the cuckoo's eggs in their nest, they might abandon it with a certain probability p_a and then build a new nest using a random wandering approach, as shown in (16).

$$x_i^{(t+1)} = \begin{cases} x_i^{(t)} + r_1 \cdot \left(x_m^{(t)} - x_n^{(t)}\right), & r_2 > p_a \\ x_i^{(t)} & \text{, otherwise} \end{cases} \qquad (16)$$

where $x_m^{(t)}$ and $x_n^{(t)}$ represent two distinct solutions randomly selected in the population, and r_1, r_2 are two random numbers following the uniform distribution.

On the other hand, suitable for continuous problems, the PSO algorithm has a very simple step [42]. The solution is shown in the form of particles. Particles are updated using their individual best-found solutions and the collective best solution. Considering a group of particles, $X^{(t)} = \left\{x_1^{(t)},\ldots,x_i^{(t)},\ldots,x_N^{(t)}\right\}$, each particle i at the $(t+1)$-th iteration, $x_i^{(t+1)}$, is updated as follows:

$$\begin{aligned} v_i^{(t+1)} = w \cdot v_i^{(t)} &+ r_1 \cdot c_1 \cdot \left(x_{i,Lbest} - x_i^{(t)}\right) \\ &+ r_2 \cdot c_2 \cdot \left(x_{Gbest} - x_i^{(t)}\right) \end{aligned} \qquad (17)$$

$$x_i^{(t+1)} = x_i^{(t)} + v_i^{(t+1)} \qquad (18)$$

where $x_{i,Lbest}$ is the best position of the i-th particle, x_{Gbest} is the global best position; w is the inertia weight controlling the influence of the previous velocity $v_i^{(t)}$, selected within 0 and 1; c_1 and c_2 are learning rates adjusting the influence of the particle's local best and global best, respectively, selected within the range of 1–4; finally, r_1 and r_2 are random numbers between 0 and 1, which maintain diversity among particles' positions.

A subsequent study has put forth an improved version of the PSO algorithm, called the SSO algorithm, due to its limitations [32]. The key distinction between SSO and PSO lies in their particle update formulas. The SSO algorithm utilizes the following updating formula in (19), rather than the PSO algorithm's update formulas as in (17) and (18).

$$x_i^{(t+1)} = \begin{cases} x_i^{(t)}, & \rho_{N(0,1)} \in \left[0, c_w\right) \\ x_{i,Lbest}, & \rho_{N(0,1)} \in \left[c_w, c_p\right) \\ x_{Gbest}, & \rho_{N(0,1)} \in \left[c_p, c_g\right) \\ x, & \rho_{N(0,1)} \in \left[c_g, 1\right) \end{cases} \qquad (19)$$

where $\rho_{N(0,1)}$ is a uniform random number in the range $[0,1]$, x represents the new value for the particle in every dimension, which is randomly generated from the random function $rand()$ within the feasible region, c_w, c_p, and c_g are parameter settings with respect to $0 \le c_w \le c_p \le c_g \le 1$, $k = k+1$ represents the best local solution of the *i*-th particle at the *t*-th iteration, whereas x_{Gbest} is the global best position of the *t*-th iteration.

As a novel contribution of this study, a hybrid SSO-CS algorithm is implemented as in Algorithm 1. This SSO-enhanced CSA is designed to tackle the common problems of premature convergence and local optima in complex multimodal functions, especially when population diversity rapidly decreases. Moreover, the hybrid SSO-CS method handles limitations in discrete and combinatorial problems, frequently by using penalty functions that adapt to the protection coordination problem.

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Algorithm 1. Hybrid SSO-CS optimization method
Input: Population size: $N_{sol}$, dimension: $D$, selection probability: $p_a$, maximum iteration number: $k_{\max}$, parameter settings from the SSO: $c_w$, $c_p$, $c_g$; $k=0$
Output: The best solution found by the SSO-CS algorithm
Generate an initial population of $N_{sol}$ nests, $x_i^0$, $i=1,2,...,N_{sol}$ based on the lower and upper boundaries of all variables of the particle
Get all fitness values $F_i = F(x_i)$
Find the best solution in $F(x_i)$ as the global best $x_{Gbest}$ and $x_{i,Lbest}$ with $i=1,2,...,N_{sol}$
while $k < k_{\max}$
  Update a new solution $x_i^{t+1}$ by (11) and (12)
  Get its fitness $F_i^{t+1} = F(x_i^{t+1})$
  If $F_i^{t+1} < F_i^t$ then
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$$x_i^{(t+1)} = \begin{cases} x_i^{(t)} + \left(\alpha_0\left(x_i^{(t)} - x_{Gbest}^{(t)}\right)\right) \otimes L(s,\lambda), & \rho_{N(0,1)} \in [0, c_w) \\ x_{i,Lbest}^{(t)} + \left(\alpha_0\left(x_i^{(t)} - x_{i,Lbest}^{(t)}\right)\right) \otimes L(s,\lambda), & \rho_{N(0,1)} \in [c_w, c_p) \\ x_i^{(t)} + \left(\alpha_0\left(x_{Gbest}^{(t)} - x_{i,Lbest}^{(t)}\right)\right) \otimes L(s,\lambda), & \rho_{N(0,1)} \in [c_p, c_g) \\ L_b + (U_b - L_b)\left(\alpha_0\left(x_{Gbest}^{(t)} - x_{i,Lbest}^{(t)}\right)\right) \otimes L(s,\lambda), & \rho_{N(0,1)} \in [c_g, 1) \end{cases}$$

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    where $L_b$ and $U_b$ are the lower and
    upper boundaries of the variables of
    the particle
8.  If $F^{t+1}\left(x_i^{(t+1)}\right) < F^t\left(x_{i,Lbest}^{(t)}\right)$ then $x_{i,Lbest}^{(t+1)} = x_i^{(t+1)}$;
    if not, keep it unchanged
9.  If $F^{t+1}\left(x_i^{(t+1)}\right) < F^t\left(x_{Gbest}^{(t)}\right)$ then $x_{Gbest}^{(t+1)} = x_i^{(t+1)}$;
    if not, keep it unchanged
10. end if
11. Release the probability $p_a$ of worse
    nests
12. Generate new solutions by (16)
13. If $F^{t+1}\left(x_i^{(t+1)}\right) < F^t\left(x_{i,Lbest}^{(t)}\right)$then $x_{i,Lbest}^{(t+1)} = x_i^{(t+1)}$;
    if not, keep it unchanged
14. If $F^{t+1}\left(x_i^{(t+1)}\right) < F^t\left(x_{Gbest}^{(t)}\right)$then $x_{Gbest}^{(t+1)} = x_i^{(t+1)}$; if
    not, remaining it to be unchanged
15. Gain the best available option
16. $k = k + 1$
17. end while
18. Get the best (global optimal solution)
```

B. A Hybrid SSO-FF Optimization Method

The FFA is a swarm intelligence method that mimics the flashing flight patterns of fireflies [43]. Among fireflies, gender is irrelevant, as they only approach individuals emitting greater light. The FFA consists of two main elements: brightness and attractiveness. The firefly's movement direction is dictated by how bright it is and where it's located, whereas the movement distance is dictated by the attraction. Objective optimization is possible through continuous adjustments to brightness and attractiveness. The fundamental principle of FFA is that less luminous fireflies gravitate towards more luminous ones, and then adjusting their positions accordingly. Fireflies' brightness is determined by the objective function's fitness value. When two adjacent fireflies exhibit equal brightness, their movements become random. The firefly attraction index β is determined by the firefly brightness, and thus is represented by:

$$\beta = \beta_0 \cdot e^{-\gamma r^2} \tag{20}$$

where r represents the Euclidean distance between two individuals; when $r = 0$, the value β is maximum. The parameter γ, typically set at 1, indicates the light absorption coefficient. Mathematically, the Euclidean distance r_{ij} between two fireflies x_i and x_j can be represented as follows:

$$r_{ij} = \left\|x_i - x_j\right\| = \sqrt{\sum_{d=1}^{D}(x_{id} - x_{jd})^2} \tag{21}$$

where x_{id} and x_{jd} are the *d*-th dimension values of two fireflies x_i and x_j, respectively, and D is the number of dimensions of the particle.

Suppose there are two fireflies x_i, x_j with $j = 1,...N, j \neq i$. Meanwhile, if x_j is brighter than x_i, x_i will move toward x_j. The movement formula for x_i is defined as follows:

$$x_i^{(t+1)} = x_i^{(t)} + \beta_0 \cdot e^{-\gamma r_{ij}^2} \cdot \left(x_j^{(t)} - x_i^{(t)}\right) + alpha \cdot \varepsilon \tag{22}$$

where $alpha$ is the step length factor, which is a random value in the range $[0,1]$; ε also represents another random value in the range $[-0.5, 0.5]$; and t is the *t*-th iteration order of the algorithm.

To improve the performance of the FFA, this paper introduces the SSO-FF, a novel approach that merges FFA optimization with SSO, designed for effective coordination of DOC relays. Different from the standard FFA, the SSO-FF hybrid algorithm achieves a global solution and offers a good convergence rate. This hybrid methodology facilitates an improved equilibrium between exploration and exploitation compared to individual techniques; SSO is characterized by rapid global searches and uncomplicated swarm updates with minimal parameters, whereas the FFA incorporates a distance-dependent attraction component that enhances local refinement of viable solutions. Consequently, this often leads to faster convergence, higher solution accuracy for multimodal/nonlinear problems, and reduced risk of premature convergence. The SSO-FF hybrid algorithm is briefly shown in Algorithm 2. It is considered for the minimization coordination problem, $F(x_i) > F(x_j)$ indicates that the firefly x_j is brighter than x_i (i.e. the fitness value of x_j is better than x_i), with $\forall i, j \in 1,...,N_{sol}$.

```
Algorithm 2. Hybrid SSO-FF optimization
method
Begin
1. Initialize population randomly and
   generate $N$ fireflies (solutions) $x_i$,
   $i \in 1,...,N_{sol}$; the dimension $D$; the maximum
   iteration number $k_{\max}$; and parameter
   settings from the SSO $c_w$, $c_p$, $c_g$; $k = 0$
2. Calculate the brightness (fitness value)
   of each firefly
3. Find the best solution in $F(x_i)$ as the
   global best $x_{Gbest}$ and $x_{i,Lbest}$ with
   $i = 1, 2, ..., N_{sol}$
4. while $k < k_{\max}$
```

```
  $k = k + 1$
  for $i = 1 \rightarrow N_{sol}$ do
    for $j = 1 \rightarrow N_{sol}$ do
      if $F(x_j) < F(x_i)$ then
        Move $x_i$ toward $x_j$ according to:
        $x_i^{(t+1)} = \begin{cases} x_i^{(t)} + \beta_0 \cdot e^{-\gamma r_{ij}^2} \cdot \left(x_j^{(t)} - x_i^{(t)}\right) + alpha \cdot \varepsilon, & \rho_{N(0,1)} \in \left[0, c_w\right) \\ x_{i,Lbest}^{(t)} + \beta_0 \cdot e^{-\gamma r_{ij}^2} \cdot \left(x_j^{(t)} - x_i^{(t)}\right) + alpha \cdot \varepsilon, & \rho_{N(0,1)} \in \left[c_w, c_p\right) \\ x_{Gbest}^{(t)} + \beta_0 \cdot e^{-\gamma r_{ij}^2} \cdot \left(x_j^{(t)} - x_i^{(t)}\right) + alpha \cdot \varepsilon, & \rho_{N(0,1)} \in \left[c_p, c_g\right) \\ L_b + (U_b - L_b) \otimes rand(1, D), & \rho_{N(0,1)} \in \left[c_g, 1\right) \end{cases}$
        Calculate the fitness value of the new solution $x_i^{(t+1)}$
        If $F^{t+1}\left(x_i^{(t+1)}\right) < F^t\left(x_{i,Lbest}^{(t)}\right)$ then $x_{i,Lbest}^{(t+1)} = x_i^{(t+1)}$; if not, keep it unchanged
        If $F^{t+1}\left(x_i^{(t+1)}\right) < F^t\left(x_{Gbest}^{(t)}\right)$ then $x_{Gbest}^{(t+1)} = x_i^{(t+1)}$; if not, remaining it to be unchanged
      end if
    end for
  end for
end while
End
Output: Get the best (global optimal solution)
```

C. A Hybrid SSO-PSO Optimization Method

In this study, the hybrid SSO-PSO optimization method is also proposed for the DOC relay coordination problem, which will be compared to the aforementioned SSO-CS and SSO-FF methods. Algorithm 3 briefly describes this SSO-PSO hybrid approach.

```
Algorithm 3. Hybrid SSO-PSO optimization method
Begin
Set parameters $w$, $c_1$, $c_2$ and $r_1$, $r_2$ of PSO, as mentioned in (17); the dimension $D$; the maximum iteration number $k_{\max}$; and parameter settings from the SSO $c_w$, $c_p$, $c_g$; $k = 0$
Initialize a population of particles with positions $x_i$ and velocities $v_i$
Calculate fitness of particles $F(x_i), \forall i = 1, \ldots, N_{sol}$ and find the global best $x_{Gbest}$ and the local best $x_{i,Lbest}$
while $k < k_{\max}$
  $k = k + 1$
  Update velocity and position of particles:
  $x_i^{(t+1)} = \begin{cases} x_i^{(t)} + w \cdot v_i^{(t)} + r_1 \cdot c_1 \cdot \left(x_{i,Lbest}^{(t)} - x_i^{(t)}\right) + r_2 \cdot c_2 \cdot \left(x_{Gbest}^{(t)} - x_i^{(t)}\right) & \rho_{N(0,1)} \in \left[0, c_w\right) \\ x_{i,Lbest}^{(t)} + w \cdot v_i^{(t)} + r_1 \cdot c_1 \cdot \left(x_{i,Lbest}^{(t)} - x_i^{(t)}\right) + r_2 \cdot c_2 \cdot \left(x_{Gbest}^{(t)} - x_i^{(t)}\right) & \rho_{N(0,1)} \in \left[c_w, c_p\right) \\ x_{Gbest}^{(t)} + w \cdot v_i^{(t)} + r_1 \cdot c_1 \cdot \left(x_{i,Lbest}^{(t)} - x_i^{(t)}\right) + r_2 \cdot c_2 \cdot \left(x_{Gbest}^{(t)} - x_i^{(t)}\right) & \rho_{N(0,1)} \in \left[c_p, c_g\right) \\ L_b + (U_b - L_b) \otimes rand(1, D), & \rho_{N(0,1)} \in \left[c_g, 1\right) \end{cases}$
  If $F^{t+1}\left(x_i^{(t+1)}\right) < F^t\left(x_{i,Lbest}^{(t)}\right)$ then $x_{i,Lbest}^{(t+1)} = x_i^{(t+1)}$; if not, keep it unchanged
  If $F^{t+1}\left(x_i^{(t+1)}\right) < F^t\left(x_{Gbest}^{(t)}\right)$ then $x_{Gbest}^{(t+1)} = x_i^{(t+1)}$; if not, remaining it to be unchanged
end while
End
Output: Get the best (global optimal solution)
```

D. A New Hybrid SSO-CS-FF Optimization Method

As mentioned in [36], the FFA achieves the global optimal solution by employing the initial optimal values derived from the CSA as an upper bound. The hybrid CSA-FFA model can achieve an optimal global solution with reduced deviation and increased computational efficiency. From the above combination, in this paper, a novel protection coordination method based on hybrid algorithms of SSO, CS, and FF, called the SSO-CS-FF approach, has been developed for DOC relays in a DN. Typically, the optimal results obtained from the hybrid SSO-CS method are used as an upper bound in the hybrid SSO-FF method, to achieve the realizable and global best solution with a small deviation and improve the coordination-time minimization of the DOC relays with multiple inequality constraints. Figure 1 shows the flowchart of the new hybrid SSO-CS-FF optimization method. The position update of each Cuckoo particle and each firefly particle by the global and local search from the CSA and FFA approaches, respectively, is performed by the SSO algorithm. Moreover, it is worth noting that the upper bounds of TMS and I_p in the FFA are set up based on the optimal result of the CSA. We empirically determined the algorithm-specific parameters as follows. For the SSO, parameters c_w, c_p, and c_g are selected as 0.35, 0.75 and 0.95, respectively. For the FFA, parameters $alpha$, β_0, and γ are selected as 0.001, 0.2, and 2, respectively. For the CSA, the parameters p_a and a_0 are selected as 0.25 and 0.01, respectively.

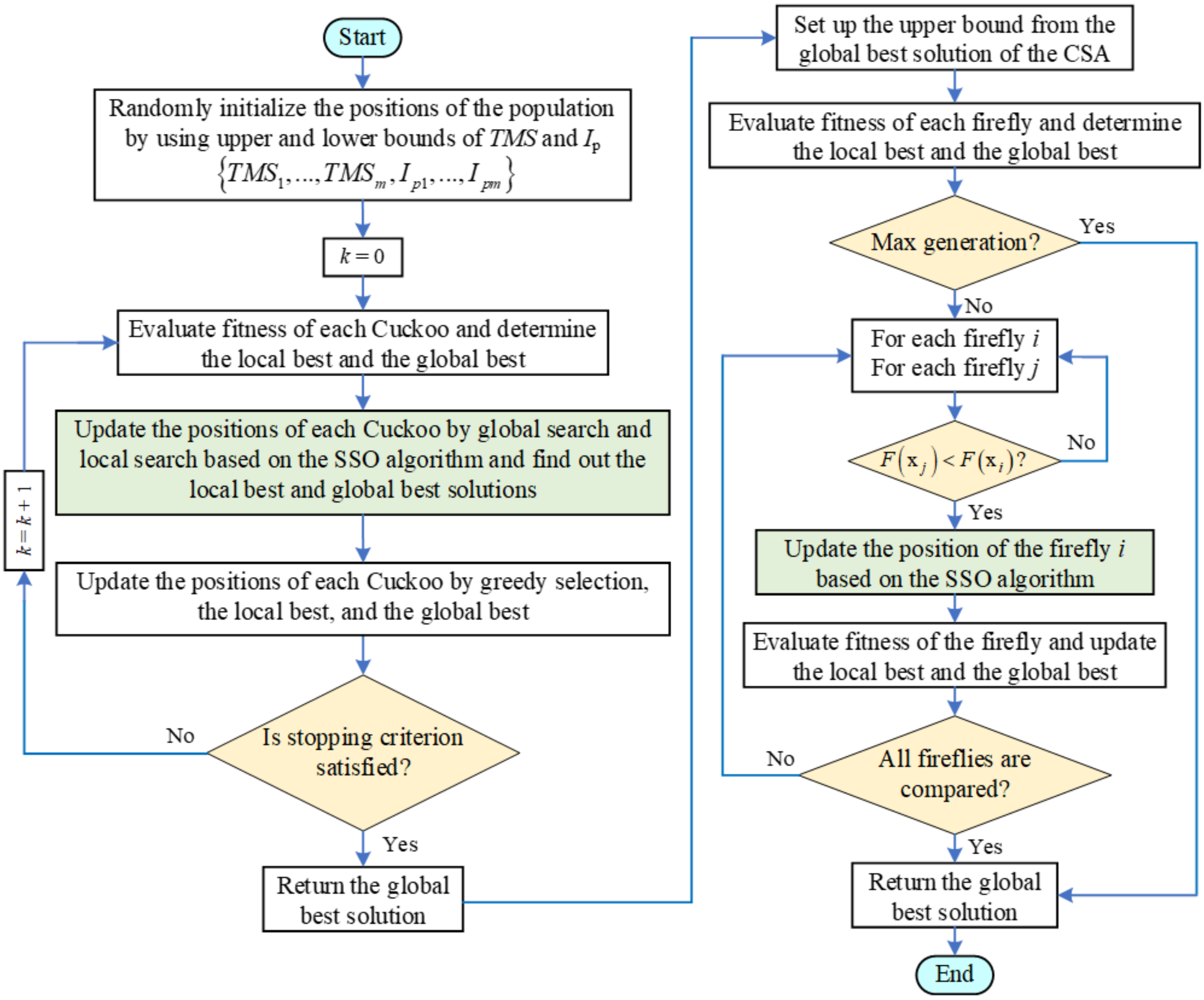


Fig. 1. Flowchart of the new hybrid SSO-CS-FF optimization method.

IV. NUMERICAL AND SIMULATION RESULTS OF THE PROPOSED HYBRID SSO/CS/FF ALGORITHMS

The simulation was performed using a test model of the IEEE 8-bus system [44]. These results were generated through the utilization of MATLAB R2024a. The network consists of eight buses, two generating units, one external grid connection, two transformers, and fourteen DOC relays. The test system at Bus-4 is linked to an external grid (EG) with a short-circuit capacity rated at 400 MVA. Concurrently, the two generator units are rated identically at 150 MVA, 10 kV, and possess a reactance of 15%. Additionally, all transformer units are rated at 150 MVA and 10 kV, featuring a reactance of 4%. The relay coordination scheme is evaluated for three-phase faults occurring at seven different locations. Figure 2 presents a single-line schematic of the 8-bus test system. Table I displays the current transformer (CT) ratios, fault current magnitudes, and applicable relays.

A. *Problem Formulation*

The minimum operating time for each relay and the CTI are chosen as 0.2 s and 0.3 s, respectively, as noted in (3). The objective function (OF) from (1) can be rewritten as in (23).

$$\begin{aligned}\min Z &= \sum_{i=1}^{m} W_i t_{i,k} = \sum_{i=1}^{14} \frac{0.14\times TMS_i}{\left(I_{f,i}/I_{i,p}\right)^{0.02}-1} \\ &= \sum_{i=1}^{14} \frac{0.14x_i}{\left(I_{f,i}/x_{i+14}\right)^{0.02}-1}, \forall k=1,\dots,7\end{aligned} \qquad (23)$$

where $I_{f,i}$ is the maximum fault current seen by the i-th primary relay with respect to the k-th faulted location; $\forall k=1,\dots,7$; and each particle $x=\{x_1,\dots,x_{28}\}$ has 28 variables. Specifically, $\{x_1,\dots,x_{14}\}$ represent $\{TMS_1,\dots,TMS_{14}\}$, whereas $\{x_{15},\dots,x_{28}\}$ represent $\{I_{1,p},\dots,I_{14,p}\}$. The values of $TMS_{i,\min}$ and $TMS_{i,\max}$ are commonly taken as 0.1 and 1.1. The values of $I_{i,p,\min}$ and $I_{i,p,\max}$ of the pickup current for each i-th relay are selected as 200 A and 600 A, respectively, from the primary side of the current transformer [44].

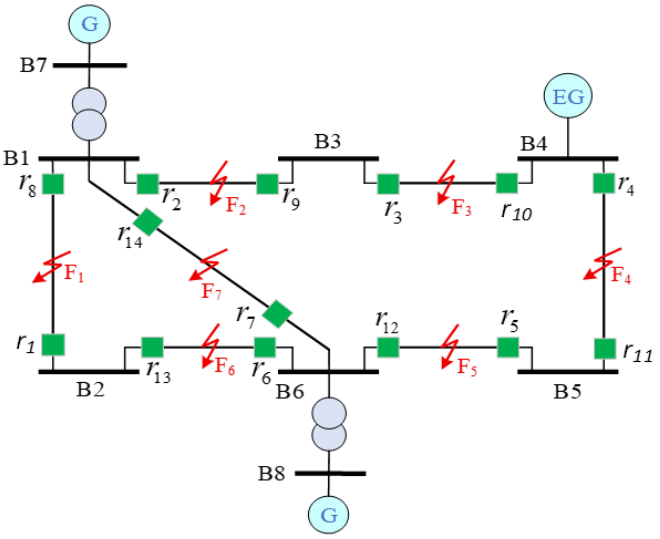


Fig. 2. Single-line diagram of an IEEE 8-bus system.

TABLE I. FAULT CURRENT DATA, CT RATIOS, AND PRIMARY-BACKUP RELAYS

Fault locations	Primary relay	CT ratio	Fault current (A) seen by primary relay	Backup relay	Fault current (A) seen by backup relay
F1	R1	1,200:5	3,232	R6	3,232
F2	R2	1,200:5	5,924	R1	996
				R7	1,890
F3	R3	800:5	3,556	R2	3,556
F4	R4	1,200:5	3,783	R3	2,244
F5	R5	1,200:5	2,401	R4	2,401
F6	R6	1,200:5	6,109	R5	1,197
				R14	1,874
F7	R7	800:5	5,223	R5	1,197
				R13	987
F1	R8	1,200:5	6,093	R7	1,890
				R9	1,165
F2	R9	800:5	2,484	R10	2,484
F3	R10	1,200:5	3,883	R11	2,344
F4	R11	1,200:5	3,707	R12	3,707
F5	R12	1,200:5	5,899	R13	987
				R14	1,874
F6	R13	1,200:5	2,991	R8	2,991
F7	R14	800:5	5,199	R1	996

In the hybrid SSO-CS method, the bounds on TMS are handled by setting the lower and upper limits for variables x_1 to x_{14}, whereas the bounds on I_p are managed by setting the lower and upper limits for variables x_{15} to x_{28}. The OF value is determined by adding the operating time of every relay for faults in its primary protection area. The optimal values of TMS and I_p are found by using the SSO-CS method to minimize the operating time of DOC relays; then these values are used as the upper bound of TMS and I_p in the hybrid SSO-FF method, which results in global best solution for the given relay coordination problem.

B. Results and Discussion on the Hybrid Algorithms of SSO-CS and SSO-FF

Tables II and III display the outcomes for optimizing the TMS, I_p, and OF values, calculated by the conventional CSA and FFA algorithms as well as the hybrid algorithms of SSO-CS and SSO-FF. The obtained value of CTI of Primary/Backup (P/B) relay pairs by these hybrid methods is shown in Table IV. The CTI value is kept at nearly 0.3 s for most P/B relay pairs in the SSO-CS and the SSO-FF algorithms, but it is also higher for the CSA and FFA. The operating times of the relays, minimized by the above combined methods, are shown in Table V, all of which are above 0.2 s.

TABLE II. OPTIMIZED RELAY SETTINGS FOR THE STANDARD CSA AND THE SSO-CS METHODS

Relays	CSA		SSO-CS	
	TMS	I_p	***TMS***	I_p
R1	0.1000	598.49	0.1000	534.56
R2	0.4651	241.00	0.3529	307.96
R3	0.2263	538.50	0.1812	574.10
R4	0.2221	519.76	0.1685	566.63
R5	0.1403	549.01	0.1000	596.78
R6	0.1922	550.80	0.1723	569.36
R7	0.2373	600.00	0.2318	487.29
R8	0.2561	420.32	0.1718	567.41
R9	0.1334	552.21	0.1029	599.89
R10	0.3402	200.00	0.1685	581.70
R11	0.2476	543.97	0.2292	415.92
R12	0.3286	591.02	0.3021	484.69
R13	0.1399	522.90	0.1000	549.49
R14	0.3455	356.57	0.2493	444.89
OF	**10.274 s**		**8.392 s**	

TABLE III. OPTIMIZED RELAY SETTINGS FOR THE STANDARD FFA AND THE SSO-FF METHODS

Relays	FFA		SSO-FF	
	TMS	I_p	***TMS***	I_p
R1	0.3221	384.55	0.2853	215.12
R2	0.5058	367.42	0.4562	232.89
R3	0.3375	516.51	0.2744	356.52
R4	0.3057	588.55	0.3057	211.07
R5	0.1840	581.14	0.1094	600.00
R6	0.6349	250.16	0.3479	314.93
R7	0.3609	517.76	0.2174	573.17
R8	0.4740	423.15	0.3212	208.46
R9	0.1605	597.84	0.1117	546.40
R10	0.3494	271.73	0.2450	311.53
R11	0.2756	505.32	0.1901	600.00
R12	0.6153	230.07	0.3446	366.02
R13	0.3403	310.30	0.1521	393.16
R14	0.3902	461.70	0.3012	306.67
OF	**15.162 s**		**9.839 s**	

TABLE IV. OPTIMIZED VALUES OF CTI FROM THE HYBRID SSO-CS AND SSO-FF METHODS

Primary relay	Backup relay	CTI (s)	
		SSO-CS	SSO-FF
R1	R6	0.3004	0.3044
R2	R1	0.3073	0.3279
	R7	0.3698	0.3053
R3	R2	0.3021	0.3239
R4	R3	0.3085	0.3048
R5	R4	0.3091	0.3140
R6	R5	0.5027	0.3045
	R14	0.7001	0.3470
R7	R5	0.3311	0.4279
	R13	0.5204	0.4723
R8	R7	0.6862	0.6167
	R9	0.5839	0.3808
R9	R10	0.3006	0.3007
R10	R11	0.3024	0.3003
R11	R12	0.3009	0.3004
R12	R13	0.3631	0.3023
	R14	0.3712	0.3003
R13	R8	0.4718	0.3920
R14	R1	0.4256	0.5590
	R9	0.3858	0.3005

TABLE V. OPTIMIZED RELAY OPERATING TIMES FOR THE HYBRID SSO-CS AND SSO-FF METHODS

Relays	SSO-CS (s)	SSO-FF (s)
R1	0.3822	0.7172
R2	0.8109	0.9553
R3	0.6831	0.8161
R4	0.6095	0.7202
R5	0.4960	0.5448
R6	0.4963	0.7971
R7	0.6679	0.6737
R8	0.4946	0.6439
R9	0.5000	0.5084
R10	0.6095	0.6629
R11	0.7175	0.7174
R12	0.8252	0.8437
R13	0.4062	0.5141
R14	0.6926	0.7241

As seen in Table II, the OF value of the standard CSA method is 10.274 s, whereas the hybrid SSO-CS method achieves 8.292 s for the total operating time for all primary relays, i.e., resulting in a reduction of 19.3% compared to the standalone CSA method. Additionally, the results presented in Figures 3 and 4, following 30 simulations, indicate that the CSA method's mean OF value is 11.824 s and its standard deviation is 0.1413 s. These metrics are greater than those obtained from the SSO-CS method, which were 9.528 s and 0.068 s. Therefore, it can be concluded that the hybrid SSO-CS method is better than the conventional CSA method. The standard deviation of the SSO-CS method is significantly improved by a reduction of 51.9%. Table III shows that the standard FFA method's OF is 15.162 s, whereas the hybrid SSO-FF method achieves 9.839 s for the entire operating time of all primary relays, with a significant reduction of 35.1%. Furthermore, after conducting 30 simulations, the data displayed in Figures 5 and 6 demonstrates that the FFA method yields a mean OF value of 16.892 s, with a standard deviation of 0.053 s. The metrics here exceed those from the SSO-FF method, which were 11.721 s and 0.046 s. To elaborate, a significant reduction of 30.6% has been observed in the mean OF value, along with a 13.2% decrease in the standard deviation of the attained outcomes. Consequently, the hybrid SSO-FF method outperforms the conventional FFA method.

C. Results and Discussion on the New Hybrid SSO-CS-FF Algorithm

Table VI shows the simulation results of the new hybrid SSO-CS-FF algorithm. The standard IEEE 8-bus test network is used to implement and assess the performance of the new SSO-CS-FF algorithm. It will be demonstrated that the proposed hybrid SSO-CS-FF algorithm converges to optimal solutions with increased speed and delivers improved results. In addition, the SSO-CS-FF optimization technique's performance was validated by contrasting it with the SSO algorithm, PSO algorithm, SSO-PSO algorithm, SSO-FF algorithm, SSO-CS algorithm as shown in Table VI, and other contemporary optimization algorithms that have been used for the DOC relay coordination problem in the DN, as shown in Table VII.

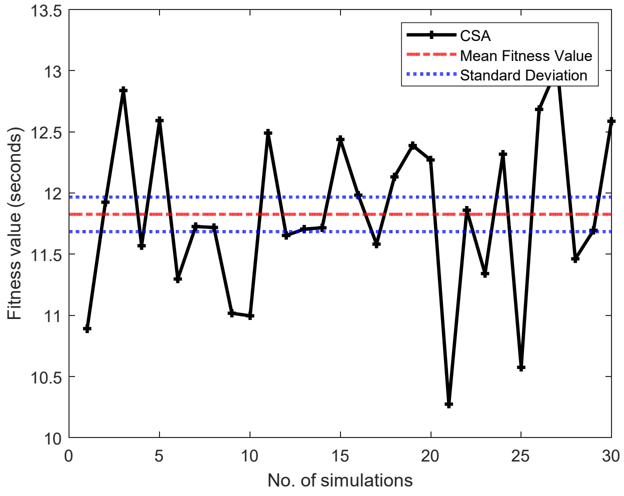


Fig. 3. Fitness values from 30 simulations of the standard CSA.

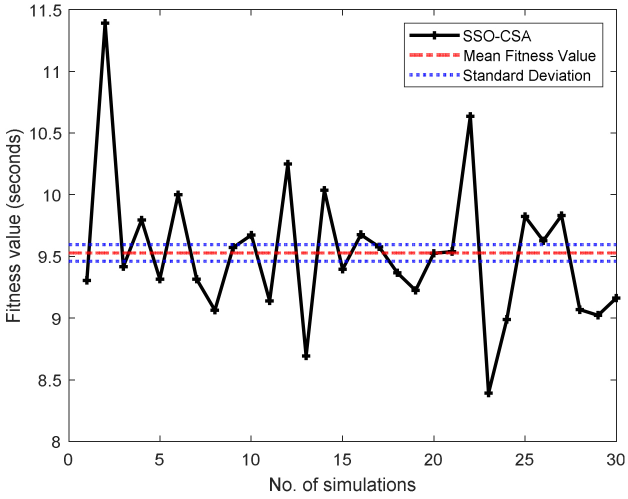


Fig. 4. Fitness values from 30 simulations of the hybrid SSO-CS method.

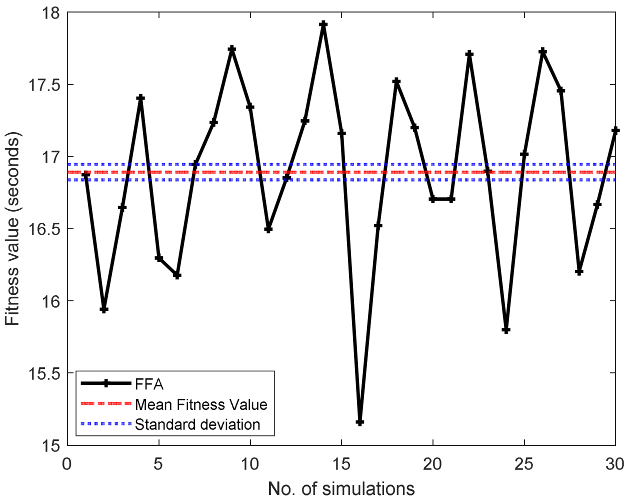


Fig. 5. Fitness values from 30 simulations of the standard FFA method.

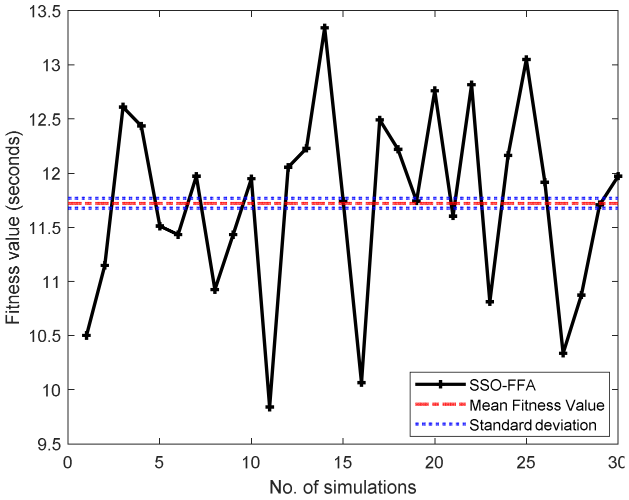


Fig. 6. Fitness values from 30 simulations of the hybrid SSO-FF method.

TABLE VI. OPTIMIZED RELAY SETTINGS FOR THE HYBRID SSO-CS-FF ALGORITHM

Relays	**SSO**		**PSO**		**SSO-PSO**		**CSA-FFA [36]**		**SSO-CS-FF**	
	TMS	I_p	***TMS***	I_p	***TMS***	I_p	***TMS***	I_p	***TMS***	I_p
R1	0.2774	373.34	0.4153	368.39	0.1002	599.19	0.1000	516.15	0.1000	516.89
R2	0.7667	225.50	0.5726	373.13	0.3467	535.83	0.2538	599.57	0.2578	556.91
R3	0.6527	201.98	0.3482	402.83	0.2935	438.34	0.2052	449.98	0.1750	567.34
R4	0.6551	202.94	0.3526	424.35	0.3690	272.24	0.1553	599.83	0.1603	566.57
R5	0.3399	260.82	0.3671	216.62	0.2412	296.78	0.1000	559.26	0.1002	544.86
R6	0.5821	201.44	0.3924	600.00	0.2227	389.07	0.1651	599.71	0.1770	534.36
R7	0.4689	344.69	0.4722	280.81	0.2530	480.31	0.2201	449.85	0.2001	503.40
R8	0.6540	210.85	0.5332	200.00	0.2031	523.97	0.1614	599.66	0.1769	576.53
R9	0.5695	202.44	0.4841	222.04	0.2002	413.34	0.1262	450.00	0.1000	523.02
R10	0.4628	446.38	0.6274	295.98	0.4198	355.44	0.1663	599.99	0.1823	458.65
R11	0.5687	260.66	0.5643	413.89	0.4098	454.72	0.1798	599.98	0.1860	548.67
R12	0.7735	200.06	0.5314	600.00	0.6948	203.95	0.2596	597.82	0.2898	475.33
R13	0.2903	336.12	0.3173	399.95	0.1202	599.79	0.1000	517.12	0.1096	489.51
R14	0.6519	200.38	0.3977	541.39	0.3246	516.65	0.2223	449.95	0.1790	598.43
OF value	**18.217 s**		**18.434 s**		**10.188 s**		**8.028 s**		**7.879 s**	

TABLE VII. COMPARISON OF THE TOTAL OPERATION TIME OF THE PROPOSED ALGORITHM WITH OTHER METHODES

Method	**OF value (s)**
Linear method [45]	11.065
GA [11]	11.001
Hybrid GA-LP [11]	10.950
BBO algorithm [19]	10.550
Jaya algorithm [3]	10.232
Simulated Annealing [46]	9.848
Harmony search algorithm [47]	9.769
Moth flame optimization algorithm [48]	9.545
BBO-LP [19]	8.756
Fractional order derivative MFO [48]	8.657
PSO with time-varying acceleration coefficients [49]	8.511
Seeker algorithm [15]	8.427
Imperialistic Competition Algorithm (ICA) [50]	8.209
Modified African vultures optimization algorithm [51]	8.090
Walrus Optimization Algorithm (WOA) [52]	8.029
Hybrid SSO-CS-FF algorithm (proposed)	7.879

Specifically, the SSO-CS-FF optimization method, as presented in Table VI, achieved an OF value of roughly 7.879 s, which is superior to SSO (18.217 s), PSO (18.434 s), SSO-PSO (10.188 s), and CSA-FFA (8.028 s) [36]. When considering percentage-based enhancements, the hybrid SSO-CS-FF methodology achieves a significant reduction of 56.7% compared to SSO, 57.2% compared to PSO, 22.7% compared to SSO-PSO, and 1.9% compared to CSA-FFA. When the SSO algorithm is integrated with the hybrid CS-FF method, it can greatly enhance the coordination outcomes for DOC relays within a DN.

Figure 7 shows the fitness values of the DOC relay coordination after running 30 simulations. It is shown that the standard deviation is very small in the case of the new SSO-CS-FF method (0.052 s) with a mean OF value of 8.5782 s, as compared to the standard CSA with a reduction of 63.2% (0.1413 s as seen in Figure 3), and the conventional FFA with a slight improvement of 1.9% (0.053 s as depicted in Figure 5). Moreover, the standard deviation of the new SSO-CS-FF method is similar to that of the SSO-CS and the SSO-FF methods, as described in Figures 4 and 6, respectively.

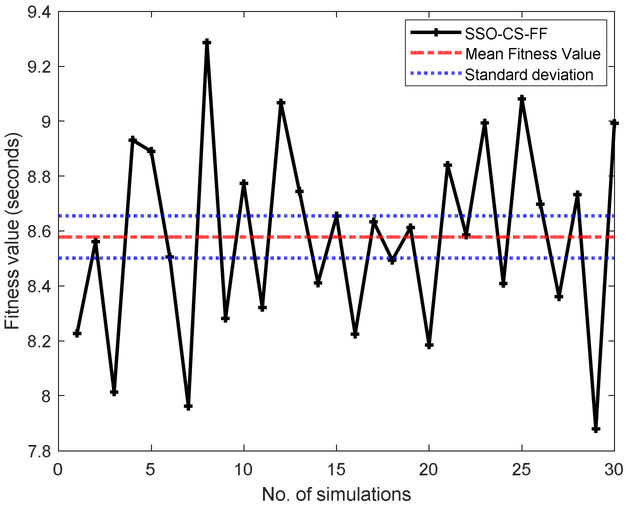
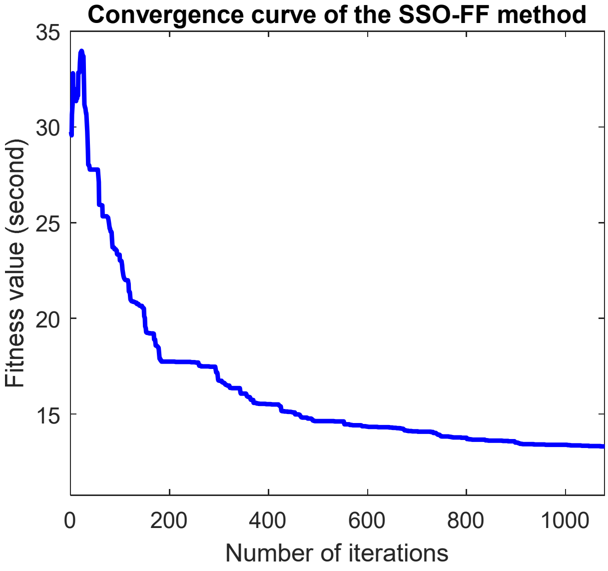


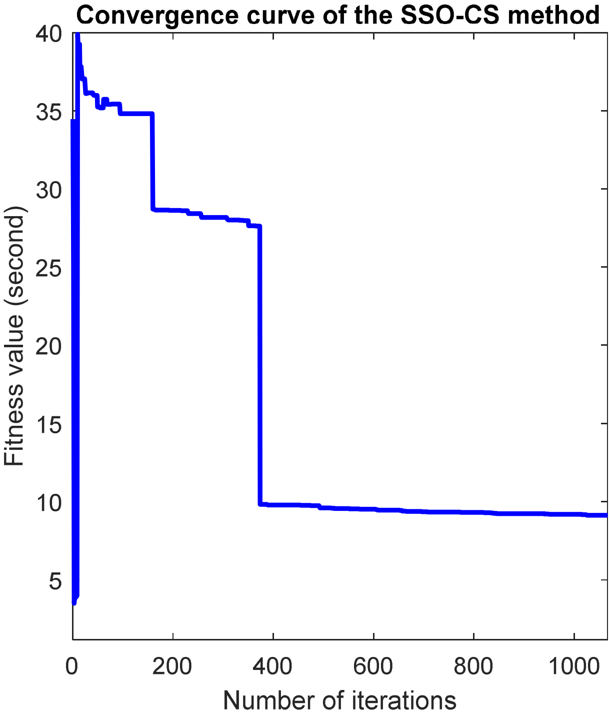
Fig. 7. Fitness values from 30 simulations of the proposed hybrid SSO-CS-FF method.

Figure 8 compares the convergence curves (fitness value over iterations) of the hybrid SSO-CS-FF method to the SSO-FF and SSO-CS methods. In terms of convergence time, the proposed algorithm aligns with the SSO-CS, while demonstrating superior performance over the SSO-FF.

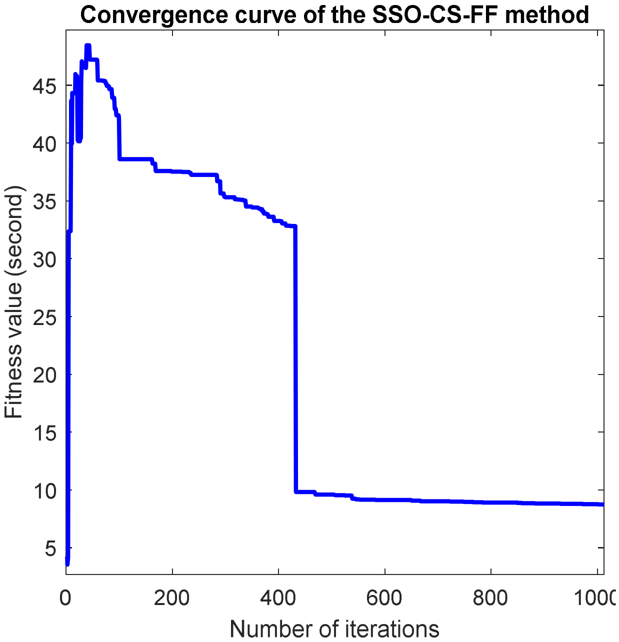
In addition, a comparison of the minimum operation times achieved by the proposed SSO-CS-FF method and other algorithms is presented in Table VII. The results show that the proposed algorithm finds more optimal solutions for the coordination problem of DOC relays than other algorithms, regardless of slightly different objective functions with more or fewer constraints. The proposed algorithm achieves a better OF value of 7.879 s, outperforming recent algorithms like the imperialistic competition algorithm, modified African vultures optimization algorithm, and walrus optimization algorithm, which achieve around 8 s.



(a)



(b)



(c)

Fig. 8. Convergence curves of: (a) the SSO-FF method, (b) the SSO-CS method, and (c) the hybrid SSO-CS-FF method.

Table VIII displays the CTI values for P/B relay pairs as determined by the hybrid SSO-CS-FF method. This combined algorithm maintains a CTI value close to 0.3 s for the majority of P/B relay pairs. Two significant advantages of the proposed algorithm are the fast convergence due to the SSO and the reliability in finding the best solution due to the combination of both CSA and FFA.

TABLE VIII. CTI VALUES FOR PRIMARY/BACKUP RELAY PAIRS DETERMINED BY THE HYBRID SSO-CS-FF METHOD

Primary relay	**Backup relay**	**CTI (s)**		
		SSO-CS	**SSO-FF**	**SSO-CS-FF**
R1	R6	0.3004	0.3044	0.3012
R2	R1	0.3073	0.3279	0.3150
	R7	0.3698	0.3053	0.3000
R3	R2	0.3021	0.3239	0.3001
R4	R3	0.3085	0.3048	0.3000
R5	R4	0.3091	0.3140	0.3000
R6	R5	0.5027	0.3045	0.3875
	R14	0.7001	0.3470	0.5891
R7	R5	0.3311	0.4279	0.3000
	R13	0.5204	0.4723	0.5020
R8	R7	0.6862	0.6167	0.5316
	R9	0.5839	0.3808	0.3542
R9	R10	0.3006	0.3007	0.3001
R10	R11	0.3024	0.3003	0.3000
R11	R12	0.3009	0.3004	0.3000
R12	R13	0.3631	0.3023	0.3013
	R14	0.3712	0.3003	0.3000
R13	R8	0.4718	0.3920	0.3556
R14	R1	0.4256	0.5590	0.4930
	R9	0.3858	0.3005	0.3000

V. CONCLUSION AND FUTURE WORK

The hybrid Simplified Swarm Optimization (SSO)–Cuckoo Search (CS)–Firefly (FF) approach presented in this paper effectively resolves the Directional Overcurrent (DOC) relay coordination issue, encompassing complex nonlinear constraints. This new SSO-CS-FF algorithm's performance was successfully evaluated through its implementation on the standard IEEE 8-bus test network. The suggested hybrid SSO-CS-FF algorithm demonstrates its capacity to achieve a global best solution with minimal result deviation and enhanced computational performance. According to simulation results obtained using MATLAB software, the hybrid SSO-CS-FF approach provides satisfactory results without violating any constraints. For the IEEE 8-bus Distribution Network (DN), the total operating time for the protection coordination function is 7.879 s, representing a reduction compared to the SSO-FF algorithm's 9.839 s (19.9% reduction), the SSO-CS algorithm's 8.392 s (6.1% reduction), and the hybrid CS-FF algorithm's 8.028 s (1.9% reduction). In fact, this hybrid optimization methodology achieves a better balance between exploration and exploitation compared to standalone methods. The SSO algorithm exhibits rapid global search capabilities and simple swarm updates with few parameters, whereas the CSA and FFA include a distance-dependent attraction mechanism that aids in the localized refinement of practical solutions. This, in turn, often leads to faster convergence, higher accuracy in multimodal optimization problems, and a reduced probability of premature convergence. Therefore, the proposed approach serves as an effective method for DOC relay coordination and optimization due to its ability to identify optimal solutions.

While the results are promising, this study has some limitations. Only worst-case conditions, such as three-phase faults, were considered. The analysis did not explicitly address phase-to-ground or high-impedance faults in the relay coordination problem. Hardware-in-the-loop testing and real-network validation with numerical relays are still required to further verify the proposed algorithm. Additionally, this study focuses on minimizing the total operating time of primary relays rather than comparing the computational time of the proposed algorithm with individual methods. Further research can focus on protection challenges in networks with distributed generators [53], large dynamic load variations, and network reconfiguration scenarios, as well as the broader applicability of hybrid optimization methods in power system protection problems.

DECLARATION OF COMPETING INTERESTS

The authors state that they have no financial or personal conflicts of interest that could have compromised the integrity of the reported research.

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DATA AVAILABILITY

All data generated or analyzed during this study are included in this published article.

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