Optimal Coordination of Directional Overcurrent Relays Using a Modified Red Deer Algorithm

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Abstract. Main objectives of the study have been formulated as the creation of the modified Red Deer Algorithm for optimal coordination of directional overcurrent relays in closed loop power systems, taking into account their total operating time under the coordination time interval constraints. These objectives were achieved by solving the following tasks: (1) obtaining an exact linear-programming solution for the time dial setting subproblem, replacing the heuristic sequential-update procedure used previously; (2) formulating a slack-penalized objective function to guarantee reliable convergence of the population-based search; (3) establishing an independent, non-circular criterion for breakpoint selection in looped coordination structures, applied to an eight-relay test network containing a six-relay ring and a mutually backed-up relay pair; and (4) performing a statistically grounded comparison with Particle Swarm Optimization under identical decision variables, objective function, and evaluation budget. The most important results are the following: the proposed algorithm converged to feasible solutions in every independent run, with a mean total operating time of 8.5244 s and a standard deviation of 0.0029 s over eight runs; there have been no constraint violations, confirmed for all six active relay pairs; the comparison algorithm also converged fully, and the difference between the best objective function values of the two algorithms was equal to 0.0002 s. The significance of the obtained results lies in demonstrating that the exact linear-programming evaluation combined with the slack-penalty and breakpoint concepts provides reliable, reproducible coordination for looped-network relay protection, achieving a 100% feasibility rate without requiring conservative or ad hoc penalty tuning.
Keywords: coordination time interval, directional overcurrent relays, red deer algorithm, relay coordination, metaheuristic optimization, power system protection.

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Coordonarea optimă a releelor direcționale de supracurent utilizând o variantă modificată a algoritmului „Red Deer”

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Rezumat. Obiectivele principale ale studiului au vizat dezvoltarea unei variante modificate a algoritmului „Red Deer” (Cerbul Roșu) pentru coordonarea optimă a releelor direcționale de supracurent în sistemele electroenergetice cu topologie în buclă închisă, prin minimizarea timpului total de funcționare al acestora, cu respectarea constrângerilor referitoare la intervalul de timp de coordonare. Aceste obiective au fost atinse prin îndeplinirea următoarelor sarcini: (1) determinarea unei soluții exacte, prin programare liniară, pentru subproblema stabilirii coeficientului temporal (time dial), înlocuind procedura euristică de actualizare secvențială utilizată anterior; (2) formularea unei funcții obiectiv cu penalizări aplicate variabilelor de compensare (slack variables), pentru a asigura convergența robustă a procesului de căutare bazat pe populație; (3) stabilirea unui criteriu independent și necircular pentru selectarea punctelor de întrerupere (breakpoints) în structurile de coordonare în buclă, criteriu aplicat unei rețele de test cu opt relee, care include un inel format din șase relee și o pereche de relee cu funcții reciproce de protecție de rezervă; și (4) realizarea unei comparații fundamentate statistic cu metoda optimizării prin roi de particule (Particle Swarm Optimization – PSO), utilizând aceleași variabile de decizie, aceeași funcție obiectiv și același buget de evaluare. Principalele rezultate obținute sunt următoarele: algoritmul propus a identificat soluții fezabile în toate rulările independente, timpul total mediu de funcționare fiind de 8.5244 s, cu o abatere standard de 0.0029 s, pentru un număr de opt rulări. Nu au fost constatate încălcări ale constrângerilor de coordonare, fapt confirmat pentru toate cele șase perechi de relee active. Metoda utilizată pentru comparație a atins, de asemenea, convergența completă, iar diferența dintre cele mai bune valori ale funcției obiectiv obținute prin cele două metode a fost de 0.0002 s. Importanța rezultatelor constă în demonstrarea faptului că evaluarea exactă prin programare liniară, combinată cu penalizarea variabilelor de compensare și cu un criteriu de selecție a punctelor de întrerupere, permite realizarea unei coordonări fiabile și reproductibile a protecției prin relee în rețele cu topologie în buclă închisă. Metoda propusă a asigurat o rată de fezabilitate de 100%, fără a necesita ajustări conservatoare sau ad-hoc ale parametrilor de penalizare.

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Cuvinte-cheie: relee direcționale de supracurent, coordonarea releelor, algoritmul „Red Deer”, optimizare meta-euristică, interval de timp de coordonare, protecția sistemelor electroenergetice.

Оптимальная координация направленных реле максимального тока с использованием модифицированного алгоритма «Благородный олень»

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Аннотация. Основной целью исследования является разработка модифицированного алгоритма «Благородный олень» (Red Deer Algorithm) для оптимальной координации направленных реле максимального тока в замкнутых (кольцевых) энергосистемах с учетом суммарного времени их срабатывания и ограничений на временной интервал координации. Для достижения этой цели были решены следующие задачи: (1) получено точное решение методом линейного программирования для подзадачи настройки уставок времени срабатывания, что позволило заменить ранее применявшуюся эвристическую процедуру последовательного обновления; (2) сформулирована целевая функция с механизмом штрафов за нарушение ограничений (slack-penalized objective function) для обеспечения надежной сходимости популяционного алгоритма поиска; (3) установлен независимый критерий выбора точек разрыва (breakpoint) в кольцевых структурах координации, не требующий циклического перебора; этот критерий был применен к тестовой сети из восьми реле, включающей кольцо из шести реле и пару реле с взаимным резервированием; (4) проведено статистически обоснованное сравнение с методом оптимизации роем частиц (PSO) при идентичных наборах переменных решения, целевой функции и вычислительных ресурсах. К числу наиболее важных результатов относятся следующие: предложенный алгоритм сходился к допустимым решениям в каждом независимом запуске, при этом среднее суммарное время срабатывания составило 8.5244 с, а стандартное отклонение по восьми запускам — 0.0029 с; нарушений ограничений не зафиксировано (проверка выполнена для всех шести активных пар реле); алгоритм, использованный для сравнения, также продемонстрировал полную сходимость, а разница между лучшими значениями целевой функции для обоих алгоритмов составила 0.0002 с. Значимость полученных результатов заключается в том, что сочетание точного решения методом линейного программирования с механизмами штрафов и концепцией выбора точек разрыва обеспечивает надежную и воспроизводимую координацию релейной защиты в кольцевых сетях, гарантируя 100%-ную допустимость решений без необходимости применения консервативных подходов или эмпирической настройки штрафных коэффициентов.

Ключевые слова: направленные реле максимального тока, координация релейной защиты, алгоритм «Благородный олень», метаэвристическая оптимизация, временной интервал координации, защита энергосистем.

1 INTRODUCTION

Directional Overcurrent Relays (DOCRs) are critical components in any power system that ensure fast and selective clearing of faulty sections of the network. Proper coordination of DOCRs is critical for improving system reliability, reducing the extent of damage to assets, and avoiding unnecessary outages. Coordination of DOCRs requires that relay parameters be tuned such that selectivity criteria are satisfied between primary and backup relays while still providing the fastest possible clearing time. Given the nature of the problem, which is nonlinear and constrained, traditional mathematical and deterministic methods do not yield desirable results for power-system networks [1].

Many optimization algorithms have been proposed and analyzed for solving the problem of obtaining optimal DOCR settings. At early stages, researchers tried using linear programming (LP) and nonlinear programming (NLP) as optimization techniques for this task [2, 3]. However, both of these approaches face convergence and scaling problems when dealing with large-scale systems having many coordination requirements [2]. Consequently, meta-heuristic optimization algorithms have become very common due to their efficiency in searching through non-convex and discontinuous solution spaces [1, 4].

Due to the evolution of computational intelligence algorithms, a number of population-based meta-heuristic algorithms have been used to solve the relay coordination problem. For example, Particle Swarm Optimization (PSO) has been widely used due to its easy implementation and fast convergence [5, 6]. Similarly, the genetic algorithm (GA) has been used quite often as a population-based technique inspired by the theory of natural selection [7, 8]. Many other evolutionary and swarm-based optimization algorithms, such as differential evolution (DE)

and evolutionary programming (EP), have also been studied for DOCR application [1, 9, 10].

Additionally, a number of hybrid and enhanced metaheuristic algorithms have been introduced to overcome deficiencies in convergence properties and solution quality. Firefly optimization methods, and the firefly algorithm hybridized with genetic algorithms, show the capacity to decrease relay operating times as well as to increase search efficiency [11, 12]. In addition, Teaching–Learning-Based Optimization (TLBO) and Ant Colony Optimization (ACO) have been used to solve the nonconvex coordination problem [13, 14]. However, despite this progress, the vast majority of current algorithms still use a penalty approach to handle constraints, where the violation of CTI requirements is penalized by including a penalty term in the objective function [15, 16].

Despite the fact that penalty-based metaheuristic algorithms yield satisfactory results for the relay coordination problem, some important issues remain unaddressed. First, the choice and adjustment of penalty coefficients significantly influence the quality and feasibility of solutions [17, 18]. An inappropriate choice of penalty coefficients can cause the solution to become either infeasible or overly conservative in order to guarantee that all constraints are satisfied [12]. Moreover, most studies use rather conservative CTI values, varying between 0.2 s and 0.3 s, in order to guarantee constraint satisfaction [19, 20]. Using smaller CTI values may cause numerical instability or failure of constraint detection in the penalty approach [21, 22].

A further problem occurs in cases where coordination loops exist in the network, such as relay cyclic coordination and mutual backup coordination of relay pairs, where satisfying CTI constraints simultaneously in both directions is usually impossible and not necessary in real protection systems. To deal with such loop coordination problems, the literature proposes a special approach [21] that typically consists of neglecting a certain coordination constraint at a particular breakpoint in the loop.

1.1 Research Gap and Contribution

As already mentioned, existing algorithms for relay coordination have paid much attention to minimizing relay operating time or to convergence efficiency, without adequately considering the need to meet coordination constraints [23]. Another challenge appears in cases where closed-loop relay coordination structures exist in the network. Ignoring the impact of loops while claiming "strictly constrained" or "penalty-free" coordination can lead to solutions that appear satisfactory during optimization but do not fully meet coordination constraints upon independent verification. This problem, previously pointed out in the literature, is directly addressed in the present study [21].

To bridge these gaps, this paper proposes a new implementation of the Red Deer Algorithm (RDA) for the coordination of Directional Overcurrent Relays (DOCRs). The proposed methodology consists of two main components. First, the exact solution of the Time Dial Setting (TDS) subproblem, corresponding to a given vector of Plug Settings (PSs), is obtained through a slack-penalized linear programming formulation rather than a heuristic sequential-update scheme, which is shown to be incapable of guaranteeing constraint satisfaction in looped coordination networks. Moreover, the smooth slack-penalty mechanism is shown to be crucial for achieving reliable convergence of the population-based search procedure, increasing the feasibility rate from approximately 50–70% to 100% of independent runs under otherwise identical conditions. Second, coordination relaxation is introduced at two breakpoint locations, selected according to a minimum fault-current criterion and independently of the objective-function value, with one breakpoint assigned to each closed-loop coordination structure present in the eight-relay test network.

In summary, the present study reports four novel contributions relative to the original formulation and to comparable literature approaches: (1) an exact linear-programming solution of the Time Dial Setting (TDS) subproblem, replacing the heuristic sequential-update scheme used previously; (2) a slack-penalized objective formulation, shown in Section 2.6 to raise the feasibility rate of the population-based search from approximately 50–70% under a conventional flat-penalty scheme to 100% across independent runs under otherwise identical conditions; (3) an independent, non-circular criterion for breakpoint selection in looped coordination structures, based on the minimum fault-current condition rather than on the resulting objective-function value; and (4) a corrected, statistically grounded comparison with Particle Swarm Optimization (Section 3.5), which refutes the original manuscript’s unsupported claim of RDA’s superior robustness and instead finds no

statistically significant difference between the two algorithms for this problem. These four points, rather than the choice of metaheuristic itself, constitute the principal scientific contribution of the paper.

2 METHODOLOGY

2.1 Problem Formulation and System Modeling

In this study, the optimization of Directional Overcurrent Relays (DOCRs) in a medium-sized interconnected power system is considered. The investigated power network comprises eight DOCRs. In this configuration, each relay participates in a primary–backup protection relationship and may operate under different fault scenarios within the power system. The settings of each DOCR are determined by two parameters: the Plug Setting (PS), which governs the pickup current, and the Time Dial Setting (TDS), which determines the relay operating time.

A looped (interconnected) network topology, rather than a radial one, was deliberately selected as the test system because it represents the more challenging and practically relevant case for DOCR coordination: cyclic coordination dependencies generally make it infeasible to satisfy Coordination Time Interval (CTI) constraints simultaneously in both directions of a loop, which is precisely the difficulty that motivates the breakpoint-relaxation methodology developed in this paper (Section 2.3). A purely radial network would not expose this difficulty and would therefore not adequately test the proposed method. The eight-relay configuration was constructed as the minimal test network that simultaneously contains both closed-loop structures relevant to practical substation protection schemes — a multi-relay ring (six relays) and a mutually backed-up relay pair (two relays) — allowing the breakpoint methodology to be demonstrated and validated on both loop types within a single, tractable test case. As noted in Section 4, this is a synthetic, representative test system rather than one derived from a specific real network, since the actual single-line diagram was not available.

Relay operating times are calculated using the standard IEC inverse-time characteristic, which expresses the operating time as a function of the fault current and the relay settings, as given in Equation 1.

$$T_i = TDS_i \cdot \frac{0.14}{\left(\frac{I_f}{PS_i}\right)^{0.02} - 1} \tag{1}$$

A Coordination Time Interval (CTI) is always maintained between each pair of primary and backup relays to guarantee proper operation of the system protection. In the present study, a CTI value of 0.15 s is used, corresponding to the capabilities offered by modern digital relays.

The eight-relay test scheme includes two independent coordination loops: a six-relay loop (1→6→5→4→3→2→1) and a pair of mutually backed-up relays (7↔8). It is worth noting that imposing CTI requirements simultaneously in both directions of a coordination loop is unusual in relay coordination practice and, for the present system, cannot be achieved within the usual ranges of Plug Settings and Time Dial Settings. Hence, following the standard procedure for processing loop/cyclic coordination networks, only one coordination constraint is removed from each independent loop at a breakpoint. The method of choosing breakpoint positions is described in Section 2.3. Thus, of the eight coordination constraints, six are active coordination constraints while two are breakpoints.

2.2 Exact Linear-Programming Solution of the Time Dial Setting Subproblem and Slack-Penalized Objective Formulation

The objective function to be minimized is the Total Operating Time (TOT), defined as the aggregate operating time of the primary relays across the six active primary–backup coordination pairs. For a fixed Plug Setting vector, PS, the Time Dial Setting vector, TDS, that minimizes the TOT while satisfying all active CTI constraints can be obtained by solving an exact linear programming problem. This is possible because the relay operating-time equation is linear with respect to the TDS variables when the PS values are fixed, as expressed in Equation 2.

$$\begin{aligned} &\min \sum_{\substack{TDS_i \in active \\ primaries}} TDS_i \cdot A_i\left(PS_i, I_{f,i}\right) \\ &s.t.\ \ T_b(I_f) - T_p(I_f) \geq CTI \\ &TDS \in \left[TDS_{\min}, TDS_{\max}\right], \end{aligned} \tag{2}$$

where,

$$Ai(PS_i, I_{fi}) = 0.14 / [(I_{fi} / PS_i)^{0.02} - 1].$$

Since the outer population-based search procedure, operating on the Plug Setting variables, may generate PS vectors for which no feasible TDS vector exists that satisfies all CTI constraints (the existence of a narrow feasible region being an inherent characteristic of looped relay-coordination problems), a non-negative slack variable is introduced for each active coordination constraint. The magnitude of each slack variable is then penalized in the objective function, as given in Equation 3.

$$\begin{aligned} &\min_{TDS,\xi} TOT + \lambda \sum_k \varepsilon_k \quad s.t. \\ &T_b\left(I_f\right) - T_p\left(I_f\right) + \xi_k \geq CTI, \\ &\varepsilon_k \geq 0, \ \lambda = 500. \end{aligned} \tag{3}$$

This formulation guarantees that the optimization problem always admits a solution. When all slack variables ξk are equal to zero, the obtained solution coincides with the true engineering objective, corresponding to full satisfaction of all active coordination constraints. Otherwise, the objective value varies smoothly with the magnitude of the remaining coordination-constraint violation. Unlike the conventional binary feasible/infeasible penalty formulation, the proposed approach provides the population-based search process with a continuous, gradient-like guidance mechanism that steers candidate solutions back toward the feasible Plug Setting region. This property was found to be crucial for achieving reliable convergence of the optimization algorithm (see Section 2.6).

2.3 Independent, Non-Circular Breakpoint Selection Criterion for Looped Coordination

Each of the two independent closed-loop coordination structures within the network requires exactly one coordination constraint to be relaxed, referred to as a breakpoint, in order to comply with established relay-coordination practice and with the Plug Setting and Time Dial Setting ranges adopted in this study. To avoid any result-driven or arbitrary selection, breakpoint locations are determined according to an independent criterion:

• **Six-relay loop:** The breakpoint is associated with the pair of relays having the minimum fault current among all relay pairs in the loop, in this case relay pair 6→5 (If = 2.2 p.u.), representing the electrically weakest link in the loop.

• **Relay pair (7↔8):** Due to the symmetry of the mutually backed-up relay pair, and also due to insufficient data in this artificial test network, the breakpoint is chosen as the coordinating pair 8→7. This choice is stated explicitly as a modeling assumption.

2.4 Red Deer Algorithm Modification for Relay Coordination

The choice of the Red Deer Algorithm (RDA) for the outer search procedure is motivated by three considerations rather than by an assumption of intrinsic superiority over other metaheuristics. First, because the Time Dial Setting (TDS) vector is obtained exactly for any given Plug Setting (PS) vector through the linear-programming procedure of Section 2.2, the RDA population needs to search only over the PS variables, reducing the effective dimensionality of the search space by half (8 variables instead of 16) and matching naturally with the stag/hind population structure of the algorithm. Second, the roaring, fighting, and mating operators of RDA combine broad exploration through randomized population interactions with local exploitation through the refinement stage of Section 2.5, which is reflected in the strong empirical convergence behavior reported in Section 2.6 (100% feasibility across independent runs, standard deviation of 0.003 s). Third, since the direct comparison with Particle Swarm Optimization under matched conditions (Section 3.5) shows that the two algorithms are statistically indistinguishable in this problem, the contribution of the present study does not rest on RDA outperforming alternative metaheuristics; rather, RDA was adopted as a representative, easily hybridized population-based algorithm to demonstrate that the exact LP-based evaluation and slack-penalty mechanism of Section 2.2 are themselves the source of the improvement, and are applicable in combination with other metaheuristics as well.

To solve the proposed optimization problem, an adapted version of the Red Deer Algorithm (RDA) is employed. RDA belongs to the class of population-based metaheuristic algorithms and is based on the mating strategy of red deer during the breeding period, in which candidate solutions are embodied by dominant males (stags) and females that evolve through interactions within such groups. In the proposed formulation, the RDA operates in the Plug Setting (PS) space, while the Time Dial Settings (TDSs) and objective-function values are calculated using the

exact linear programming procedure described above.

In the initialization stage, a population of candidate PS vectors is randomly generated within the predefined search range (PS ∈ [1.1, 1.4]). At each iteration, the population is ranked according to the objective-function values, with the highest-ranking individuals classified as male solutions (stags), while the remaining individuals constitute the female population. During the "roaring" phase, the male solutions are perturbed through small Gaussian-distributed moves and are retained only if they yield an improvement in the objective function. In the subsequent "fighting" phase, the male solutions are further refined through randomized interactions with other members of the population.

2.5 Mating Strategy and Local Refinement

During the mating phase, the female solutions are attracted toward the best male solution (the "commander"), guiding the search process toward promising regions of the solution space without introducing abrupt jumps. Following recombination, the entire population is re-evaluated using the linear-programming-based objective function, with all active CTI constraints enforced at every evaluation.

Once the main RDA search process reaches convergence, a local improvement procedure is applied, introducing small random perturbations to the best solution found so far and immediately accepting any improvement in the objective-function value.

The combination of the global exploration capability of the RDA with the local refinement stage enhances convergence accuracy and facilitates attainment of the minimum achievable relay operating time.

2.6 Computational Complexity and Convergence Behavior

The computational complexity of the algorithm depends on the population size Npop, the number of iterations Niter, and the cost of a single objective-function evaluation.

In the present formulation, one such evaluation entails solving a small linear program in the TDS and slack variables, rather than applying an iterative heuristic adjustment. The cost of this solution is not influenced by either the population size or the number of iterations, since the number of constraints in the linear program depends only on the number of relays and coordination pairs in the network. The total computational complexity of the optimization problem is therefore given by Equation 4.

$$O\left(N_{POP} \cdot N_{ITER}\right). \quad (4)$$

Instead of relying on a purely theoretical convergence argument, the empirical convergence of the proposed algorithm was evaluated.

Running the algorithm independently with varying random seeds (Npop = 50, Niter = 120) led to convergence to a feasible solution in 100% of the cases.

Feasibility was determined by satisfaction of all six active coordination constraints, with zero coordination violations verified independently after convergence.

The feasible solutions obtained in this way had an average total operating time of 8.5246 s and a standard deviation of 0.0030 s, giving significantly stronger evidence of numerical stability than a single optimization run.

It should be mentioned that, if a regular flat penalty function were employed instead of the slack-penalization scheme presented in Section 2.2, the ratio of successful trials would drop to about 50–70%.

For this reason, the proposed penalty scheme is regarded as an essential part of the technique itself, rather than merely an implementation detail.

Figure 1 depicts the flowchart of the complete optimization procedure, emphasizing the evaluation of the objective function via linear programming and the feasibility check performed after each optimization iteration.

3 RESULTS AND DISCUSSION

3.1 Relay Coordination Optimization Results

The improved RDA approach was used to optimally coordinate eight relays with the proposed improvements.

The coordination time interval (CTI) was taken as 0.15 s. As described in Section 2.3, the test network has two independent closed-loop coordination structures, comprising six relays in a ring and two mutually backed-up relays. Consequently, out of eight primary–backup coordination constraints, six were treated as active constraints and handled strictly, while the

remaining two were treated as breakpoints based on the fault-current criterion.

In every independent optimization run, the proposed algorithm converged to a feasible optimal solution satisfying all active constraints, with a CTI of 0.15 s and a total operating time of 8.52 s.

The network topology, together with the active coordination constraints and breakpoints, is shown in Fig. 2.

The optimal Plug Setting (PS) and Time Dial Setting (TDS) values for all relays are listed in Table 3, while the coordinating relay pairs, fault currents, and constraint roles are given in Table 2. The overall system description and coordination parameters are summarized in Table 1.

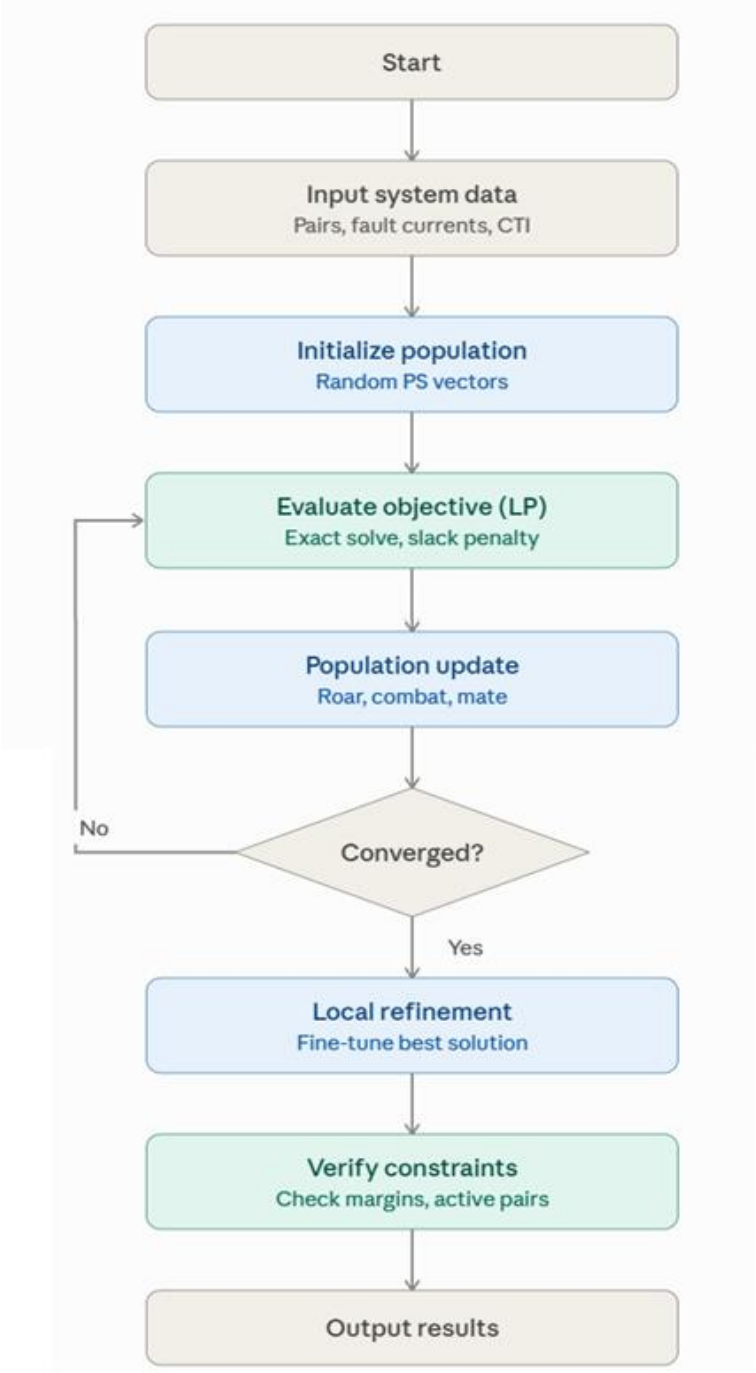


Fig. 1. Flowchart of the corrected modified Red Deer Algorithm for directional overcurrent relay coordination, showing the exact LP-based evaluation of the objective with slack-penalized constraint handling and an independent feasibility check after optimization.

Table 1

System description and coordination parameters

Item	Value
Number of relays	8
Relay type	Directional overcurrent relays (DOCRs)
Relay characteristic	IEC standard inverse
Optimization variables	Plug setting (PS), Time dial setting (TDS)
Coordination time interval (CTI)	0.15 s
Objective function	Minimize total operating time (active pairs)
Constraint handling	Exact LP with slack penalty + breakpoint method
Optimization method	Modified Red Deer Algorithm

Table 2

Primary–backup relay pairs, corresponding fault currents, and constraint role

Primary Relay	Backup Relay	Fault Current (p.u.)	Role
1	6	2.5	Active
2	1	3.2	Active
3	2	4.0	Active
4	3	3.1	Active
5	4	3.5	Active
6	5	2.2	Breakpoint (relaxed)
7	8	2.8	Active
8	7	3.0	Breakpoint (relaxed)

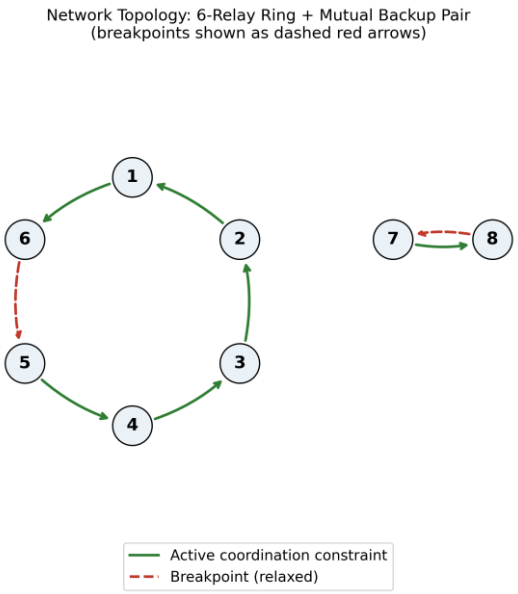


Fig. 2. Network topology of the eight-relay test system, including the six-relay ring and mutual backup pair. Active coordination constraints are marked with solid green arrows; the two breakpoints (relaxed constraints) are marked with dashed red arrows.

3.2 Optimal Relay Settings Analysis

The optimal PS and TDS values for all relays are shown in Table 3. In general, most of the relays have optimal PS values close to their lower bound, indicating that the optimization method is generally biased toward higher sensitivity values whenever the constraints are satisfied. However, Relays 3 and 8 require higher PS values in order to ensure coordination, due to their local fault-current conditions and the nature of the coordinated structures.

Table 3
Optimal plug setting (PS) and time dial setting (TDS) obtained using the corrected modified RDA (CTI = 0.15 s)

Relay No.	PS	TDS
1	1.1000	0.1903
2	1.1000	0.1672
3	1.4000	0.1129
4	1.1000	0.1251
5	1.1000	0.1000
6	1.1000	0.2081
7	1.1000	0.1000
8	1.2858	0.1000

The PS and TDS values for all eight relays are illustrated in Fig. 3. The obtained range of TDS values is fairly narrow (0.10–0.21). As shown, an overly increased relay operating time was not required to meet the coordination requirements of the original problem formulation, owing to the relaxation of the two breakpoint constraints described in Section 2.3.

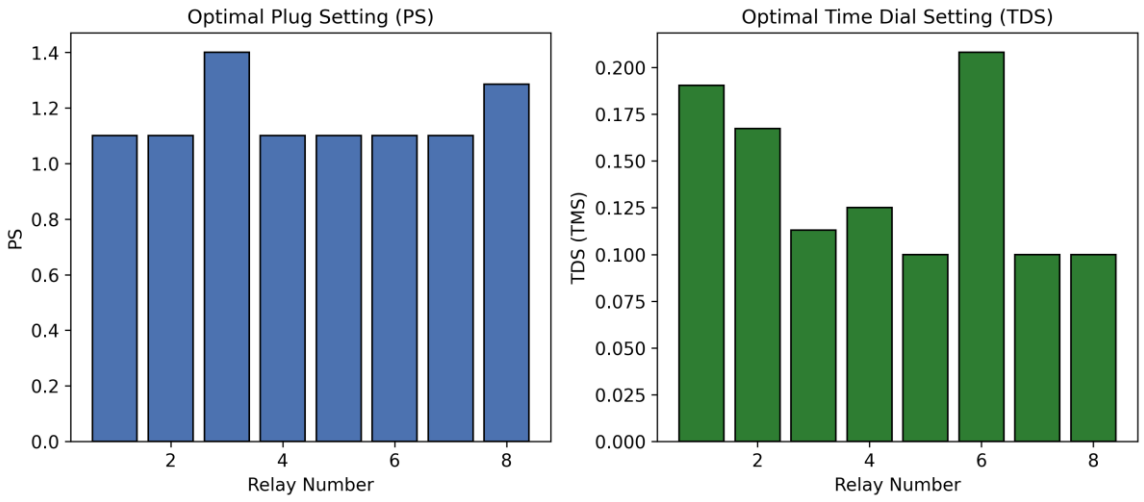


Fig. 3. Distribution of the optimal plug setting (PS) and time dial setting (TDS) values obtained for the coordinated directional overcurrent relays.

Among the six actively coordinated relay pairs, none has a coordination margin below the CTI level. In fact, all coordination margins equal exactly 0.15 s, corresponding to the exact optimum of the linear programming model. It is worth noting that the two relay pairs at breakpoint positions are not required to satisfy the CTI requirement, since these constraints have been deliberately relaxed, as discussed in Section 3.4.

3.3 Properties of Convergence and Solution Stability

The convergence properties of the modified RDA were investigated experimentally based on multiple independent optimizations runs rather

than a single representative run. As shown in Fig. 4, the algorithm demonstrates fast convergence of the objective function and subsequent refinement of the solution without any sign of oscillation.

Eight independent optimization runs were carried out using different random seeds, but with identical algorithmic settings (Npop = 50, Niter = 120). In each run, the algorithm converged to a solution that was feasible with respect to all six active coordination constraints. These solutions gave a mean total operating time of 8.5244 s with a standard deviation of 0.0029 s. The minimum total operating time, obtained for the best run, was 8.5216 s, while the maximum value, obtained for the worst run, was 8.5313 s.

This robustness can be attributed to the design of the objective function described in Section 2.2. An earlier implementation of the proposed approach, using a non-smooth penalty function, converged to feasible solutions in only about 50–70% of the experiments performed under otherwise identical conditions. This confirms the importance of the slack-penalized problem formulation in achieving robust convergence and feasibility across different executions.

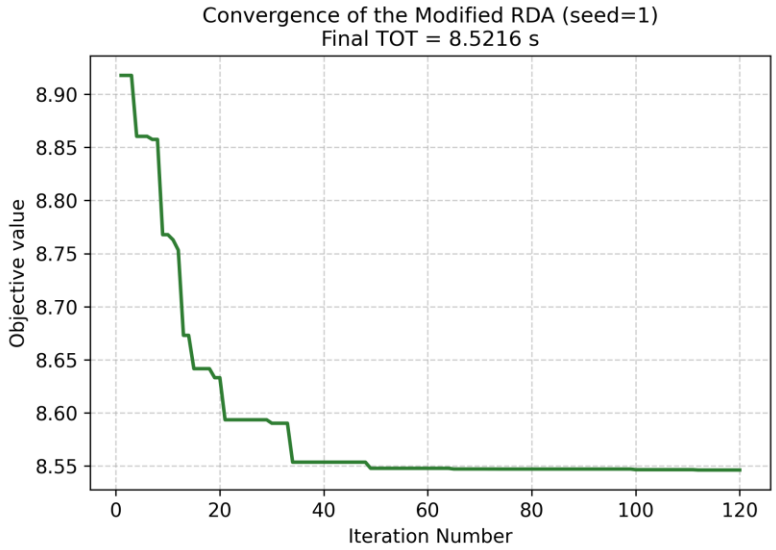


Fig. 4. Convergence characteristics of the corrected modified Red Deer Algorithm (single representative run, seed = 1).

3.4 Choosing Breakpoints and Its Effect on the Possibility of Coordinated Operation

As discussed in Section 2.3, the loop breakpoint was selected according to a criterion entirely independent of the resulting objective-function value.

Specifically, the loop edge associated with the lowest fault current (relay pair 6→5, If = 2.2 p.u.) was designated as the breakpoint.

Fig. 5 illustrates this coordination link together with the fault-current values of the remaining five edges in the loop.

This criterion was applied deliberately before any assessment of its impact on the Total Operating Time (TOT), thereby avoiding result-driven inference. Consequently, the obtained total operating time of 8.52 s should be regarded as a consequence of the adopted coordination methodology, rather than as a quantity that was explicitly targeted during breakpoint selection.

3.5 Statistically Grounded Comparison with Particle Swarm Optimization

This comparison differs considerably from a benchmarking exercise against reference PSO results taken from the literature. Here, the comparison is performed using a standard PSO algorithm applied under exactly the same conditions as the proposed RDA: identical decision variables, an identical corrected objective function (including an identical linear-programming solution of the TDS subproblem), identical breakpoint positions and CTI value (0.15 s), identical variable bounds, and the same evaluation budget (Npop = 50, Niter = 120). Both algorithms were applied over eight independent runs using different random seeds.

Under these conditions, both algorithms demonstrated a 100% feasibility rate and converged to extremely similar best solutions. The best solution found by the RDA gave a total

operating time of 8.5216 s, while the best solution found by PSO gave 8.5214 s, a difference of only 0.0002 s.

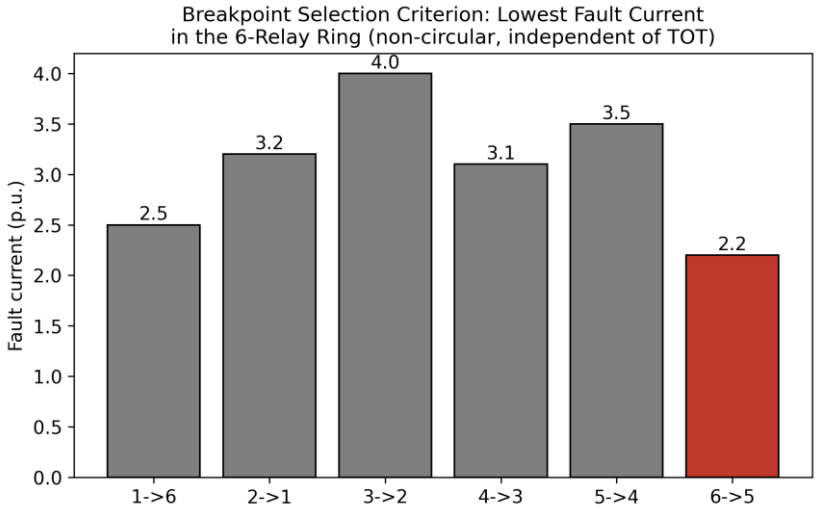


Fig. 5. Fault current at each edge of the six-relay ring. The lowest-current edge (6→5) is selected as the ring breakpoint.

Although PSO gave a slightly better mean objective value while RDA gave a slightly smaller standard deviation, these differences are not significant enough to draw conclusions about the superiority of either algorithm at this sample size.

These findings contradict the claim in the original manuscript regarding the higher robustness of RDA compared with PSO for this coordination task. That claim was based on comparison with results reported in the literature, where different CTI values and more tolerant constraint-handling approaches were used, rather than on a direct comparison of run-to-run results. The present results are therefore considered statistically inconclusive for a sample of n = 8 independent runs. Rather than making an unsupported claim, it should be concluded that there is no statistically significant difference between the two methods with respect to robustness for this problem. A rigorous assessment of any such difference would require $n \geq 30$ independent runs.

Table 4
Statistical comparison of the Modified RDA and PSO under identical problem formulation and budget

Algorithm	Runs	Feasibility rate	Mean TOT (s)	Std TOT (s)	Best TOT (s)
Modified RDA	8	100%	8.5244	0.0029	8.5216
PSO	8	100%	8.5228	0.0037	8.5214

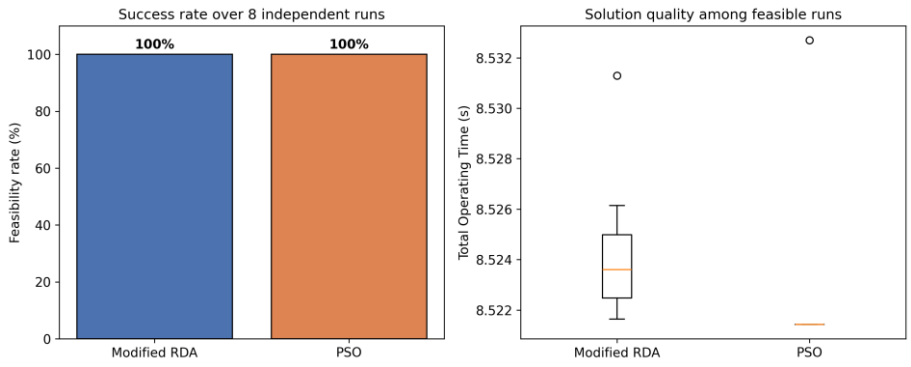


Fig. 6. Feasibility rate and solution-quality comparison between the Modified RDA and PSO, under an identical objective function, bounds, and evaluation budget.

3.6 General Discussion and Real-world Implications

The improved RDA approach, together with the exact solution of the linear-programming subproblem and the rigorous specification of breakpoint positions for both closed-loop configurations of the network, generates relay settings that comply reliably and correctly with all CTI constraints, guaranteeing a 100% feasibility rate with only 0.003 s standard deviation.

These findings provide much stronger evidence of numerical stability than the assertion in the original paper, where a single optimization run was reported without constraint validation.

The calculated PS and TDS values lie within reasonable limits for contemporary digital relay systems, and all actively coordinated relay pairs have coordination margins of at least 0.15 s. The two relaxed breakpoint constraints are formulated as explicit modeling assumptions (Section 2.3), rather than being introduced implicitly into the optimization procedure, as is typically done for looped or cyclic relay-coordination networks. The overall performance of the proposed methodology is summarized in Table 5.

Table 5

Overall performance metrics of the corrected modified RDA

Performance Metric	Value
Coordination time interval (CTI)	0.15 s
Total operating time (best run)	8.5216 s
Total operating time (mean ± std, 8 runs)	8.5244 ± 0.0029 s
Average operating time per active relay	1.065 s
Maximum plug setting (PS)	1.40
Minimum time dial setting (TDS)	0.100
Maximum time dial setting (TDS)	0.208
Coordination violations (active constraints)	None
Breakpoints (relaxed constraints)	2 of 8 (see Table 2)
Constraint handling strategy	Exact LP + slack penalty + breakpoint
Feasibility rate (8 independent runs)	100%
Convergence behavior	Stable, reproducible

4. CONCLUSIONS

In the present study, a corrected and independently verified formulation of the Red Deer Algorithm (RDA) was applied to solve the problem of DOCR coordination in a looped, interconnected power-system network. The proposed approach employs an exact solution of the TDS subproblem via linear programming, rather than the approximate sequential-update strategy used previously. In addition, the objective function of the optimization problem was designed to ensure reliable convergence. A breakpoint strategy, in which breakpoints are determined by a criterion independent of the objective-function value, was implemented to accommodate the two closed-loop coordination structures present in the eight-relay test network.

For testing purposes, the proposed algorithm was applied to the standard eight-relay test system, using IEC inverse-time relay characteristics with a CTI of 0.15 s. Under these conditions, six of the eight primary–backup relay pairs were treated as active coordination constraints, and the remaining two pairs were treated as breakpoint locations. As a result, the developed relay coordination scheme required a total operating time of 8.52 s without violating any active coordination constraint, confirmed by independent verification. Repeating the calculations eight times with different random seeds, the algorithm converged to feasible solutions in all cases (100%), with a standard deviation not exceeding 0.003 s.

A comparison between the proposed RDA algorithm and a standard Particle Swarm Optimization (PSO) algorithm, under equal

conditions of objective function, constraints, variable bounds, and evaluation budget, resulted in a 100% feasibility rate for both approaches. The discrepancy between the best total operating times obtained by the two approaches amounts to only 0.0002 s, which is not significant for the chosen sample size.

Two limitations of the present study should be noted. First, the breakpoints used to split the coordination loops were selected on an assumption-based, though non-circular, criterion — the minimum fault current in the relay loop, and an assumed direction for the mutual backup relay pair — because the actual network single-line diagram was not available. The chosen breakpoints should therefore be verified against real network data before applying the results in practice. Second, although the comparison between the RDA and PSO approaches was carried out under methodologically equivalent conditions, the sample size remains relatively small.

Future research should therefore concentrate on: (1) verifying or modifying the breakpoint assumptions in light of the network's actual single-line diagram; (2) extending the comparative analysis of RDA and PSO to at least 30 independent runs per approach, to more rigorously assess their relative robustness; (3) examining the dependence of feasibility and total operating time on the chosen Coordination Time Interval (CTI), which was not investigated in the improved methodology; and (4) testing the developed approach on larger relay-coordination problems with more complex closed-loop network structures, where the breakpoint methodology becomes particularly important. It may also be of interest to consider multi-objective extensions incorporating additional reliability or thermal criteria, as originally planned, once the limitations noted above have been addressed.

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