Optimal Coordination of Directional Overcurrent Relays in Interconnected Networks Using an Improved Multi-Strategy Coati Optimization Algorithm

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The proper coordination of directional overcurrent relays (DOCRs) in interconnected power systems is essential for selective and time-efficient protection. This study introduces a Tuned Non-inertial T-distribution based Weighted Coati Optimization Algorithm (TNTWCOA) to solve the challenging, highly constrained DOCR coordination problem. The proposed method optimizes time dial settings (TDS) and plug settings (PS) to minimize relay operating times while maintaining selectivity. Coordination is critical for both primary and backup protection devices to prevent fault currents from rising to dangerously high levels too quickly. TNTWCOA uses a chaotic sequence mechanism for better population initialization, a nonlinear inertia weight to balance exploration and exploitation, an adaptive T-distribution strategy to increase diversity and avoid local optima, and an alert update mechanism to improve search adaptability. The algorithm was tested on IEEE 3-bus and 15-bus networks, considering both mid and near-end faults with a normal inverse relay characteristic. A comparative analysis with other advanced metaheuristics shows that TNTWCOA outperforms classical and recent optimization methods by reducing total relay operation time. The results confirm that TNTWCOA helps prevent premature convergence and boosts search efficiency, making it a highly effective solution for DOCR coordination in modern power systems.

Keywords: Optimal coordination, Directional overcurrent relays, Power System Protection, Relay Settings, Coati Optimization Algorithm

Introduction:

The synthesis of overcurrent relays (OCR) with directional units leads to the creation of directional overcurrent relays (DOCRs). Coordinating these relays is a highly non-linear and challenging problem in complex networks, and it becomes even more difficult to solve using analytical techniques as the number of relays and the presence of external grids or distributed generators (DG) increase [1], [2]. The key to DOCR coordination is isolating faults by targeting the smallest possible network zone, which ensures optimal overcurrent protection by minimizing the total operating time of the main relays. This process involves determining the appropriate Time Dial Settings (TDS) and Plug Settings (PS) for relays, ensuring that any fault is isolated quickly by the corresponding main relay. Coordination with adjacent zone relays further complicates the process [3]. In the late 1980s, traditional approaches like curve fitting [4] and analytical methods were explored, along with graph theory-based techniques.

These tactical mathematical methods aimed to achieve optimal results. The introduction of linear programming (LP) techniques provided a way to address the coordination problem in a linear framework [5]. Linear programming treats TDS as a decision variable while keeping the PS of all relays fixed. As a result, LP optimizes TDS with fixed PS values, but it is limited in reaching global optima. Nonlinear Programming (NLP) treats both TDS and PS as decision variables. In [6], an interior point method was used to optimize TDS and PS, aiming to minimize operating time and ensure relay coordination. The optimal coordination problem of DOCRs can be formulated as a Mixed-Integer Nonlinear Programming (MINLP) problem, where TDS is continuous, and PS is discrete. In [7], a MILP formulation using discrete PS values by converting bilinear variables into linear inequalities was proposed. Metaheuristic methods, such as the teaching-learning-based optimization algorithm [8], modified differential evolution (MDE) [9], adaptive fuzzy directional bat algorithm [10], and swarm-based techniques like modified particle swarm optimization (PSO) [11], have also been used to solve this problem. The Gorilla Troops Optimizer (GTO) [12] has been applied as well. Additionally, an elite marine predator algorithm was recently proposed for DOCR coordination, where the elite vector enhanced the global exploitation of the original marine predators algorithm [1]. These are among the state-of-the-art techniques contributing to solving the coordination problem.

In this article, the problem of DOCR coordination in complex networks is addressed using an improved coati optimization algorithm, named TNTWCOA, which is tested on the IEEE 3-bus and 15-bus benchmark systems. The decision variables, PS and TDS, are optimized to minimize the total operating time of primary relays, ensuring effective isolation of faulty lines while satisfying the necessary constraints. The article is structured as follows: Section II presents the mathematical formulation of the problem, Section III explains the improved coati optimization algorithm, Section IV presents the statistical results and graphs from the simulations, Section V concludes the study, and Section VI includes the acknowledgments. In this paper, near-end and mid-point faults for the 3-bus and 15-bus networks have been considered for short-circuit analysis. Both decision variables, TDS and PS, are treated as continuous variables, making the study a case study of an NLP-type problem configuration.

Objectives:

This study focuses on enhancing the coordination of Directional Overcurrent Relays (DOCRs) in interconnected power systems using an improved optimization technique. An advanced multi-strategy Coati Optimization Algorithm (TNTWCOA) is proposed to address the nonlinear and constrained nature of the DOCR coordination problem. The approach is validated through simulations on standard IEEE test systems under various fault conditions. Objectives of the Study are:

1. To develop a mathematical model for the coordination of Directional Overcurrent Relays (DOCRs) in interconnected and meshed power systems.

2. To implement the proposed multi-strategy Coati Optimization Algorithm (TNTWCOA) in the MATLAB environment for solving the nonlinear DOCR coordination problem, using Time Dial Setting (TDS) and Plug Setting (PS) as decision variables.
3. To evaluate the performance of TNTWCOA under mid-point and near-end fault scenarios for IEEE 3-bus and 15-bus test systems respectively.
4. To validate the effectiveness of the proposed approach by comparing its relay operating time minimization performance against existing optimization techniques.

Novelty Statement:

This paper introduces a novel multi-strategy Coati Optimization Algorithm shorted as TNTWCOA that integrates chaotic initialization, nonlinear inertia weight, adaptive T-distribution variation, and an alert update mechanism collectively enhancing exploration, diversity, and convergence—for the optimal coordination of directional overcurrent relays (DOCRs). Unlike existing methods, TNTWCOA demonstrates superior performance across multiple IEEE test systems, effectively minimizing relay operating times and overcoming common issues like premature convergence.

Problem Formulation:

Objective Function (OF):

The coordination issue of DOCRs is formulated as an optimization problem aimed at minimizing the total operating time of all primary relays in a complex system for various fault points. This is achieved by determining the settings (TDS, PS) to prevent fault currents from rising quickly to potentially hazardous levels [1]. Mathematically, the objective function (OF) can be expressed as shown in Eq. (1), where the operating times are minimized as the net sum of the main relays embedded throughout the system, with coordination as the primary goal:

$$OF = min\ Ъ_{opr} = \sum_{\varphi=1}^{\varepsilon} (\omega_{\varphi} \cdot Ъ_{\varphi,pri}) \qquad (1)$$

Where, $Ъ_{opr}$ represents the total operating time, ε indicates the total number of primary relays, and $Ъ_{\varphi,pri}$ represents the trip time at fault for the R_{φ}, the φ^{th} primary relay. The value of ω is set to 1. The IEC and ANSI/IEEE standard inverse time characteristics are used to formulate the operating time of the relays:

$$Ъ_{\varphi,\partial} = \frac{TDS_{\varphi}(\theta_{\varphi})}{\left(\frac{I_{sc,f_{\partial}}}{PS_{\varphi}}\right)^{\gamma_{\varphi}} - \mu} + \Lambda; (\forall \varphi, \partial \in N; I_{sc,f_{\partial}} \in \mathbb{R}) \qquad (2)$$

Where,$\{\forall\ TDS_{\varphi}, PS_{\varphi} \in \mathbb{Q}^{+}\}$, representing the TDS and PS of the φ^{th} primary relay. $I_{sc,f_{\partial}}$is the magnitude of the short-circuit current observed by the φ^{th} relay when a fault (f) occurs at the ∂^{th} location. Additionally, γ, μ, Λ and θ are constants. For a normal inverse curve, the values of For normally inverse curve, the values of γ, μ, Λ, and θ are 0.02, 1, 0, and 0.14 respectively. Moreover, CTR_{φ} is the current transformer ratio for the φ^{th} relay, which is related to Eq. (2) through the following expressions:

$$\frac{I_{\varphi}^{P}}{CTR_{\varphi}} = PS_{\varphi}; (\forall \varphi \in N, CTR \in \mathbb{Q}^{+}) \qquad (3)$$

$$\left\{I_{\varphi}^{P} \mid I^{P^{min}} \leq I_{\varphi}^{P} \leq 66.67\% \times I_{sc,f_{\partial}}\right\}; (\forall \varphi, \partial \in N) \qquad (4)$$

Where I_{φ}^{P} is the pickup current value for the φ^{th} primary unit, with $I^{P^{min}}$ as the lower bound, which is greater than the load current. Essentially, this equation illustrates how the plug setting is calculated for each relay based on the current transformer ratio and the pickup current.

Constrainsts of Objective Function:

The objective function must satisfy constraints based on the variable settings. Both PS and TDS must remain within the specified range for each relay, as defined by Eq. (5) and (6). Typically, TDS ranges from 0.05 to 1.1, and PS ranges from 0.1 to 5, as referenced in [1].

- $TDS_{\varphi}^{min} \le TDS_{\varphi} \le TDS_{\varphi}^{max};\ (\forall \varphi \in N)$ (5)
- $PS_{\varphi}^{min} \le PS_{\varphi} \le PS_{\varphi}^{max};\ (\forall \varphi \in N)$ (6)
- $Ʊ_{\varphi}^{min} \le Ʊ_{\varphi} \le Ʊ_{\varphi}^{max};\ (\forall \varphi \in N)$ (7)
- $Ʊ_{\varphi}^{bu} - Ʊ_{\varphi}^{pri} \ge CTI; (\forall \varphi \in N, CTI \in \mathbb{Q})$ (8)

Where $Ʊ_{\varphi}^{min}$ is the relay's minimum active time (0.05–0.2 s), which which corresponds to 2.5 to 10 cycles in a 50 Hz system. This relationship arises because one electrical cycle at 50 Hz lasts 0.02 seconds, so ratio of the time interval to the cycle duration gives the number of cycles. These short-duration responses are critical for ensuring prompt fault detection. This value is manufacturer-dependent. $Ʊ_{\varphi}^{max}$ typically ranges from 1 to 2 seconds. Backup relays handle the issue after a coordination delay, ensuring proper coordination with the primary relay through the coordination time interval (CTI), as shown in Eq. (8). The CTI for digital relays typically falls within the range [0.3, 0.4], but in systems with high inertia due to external grids or DG penetration, longer CTI values may occur [1].

Penalized Objective Function:

Optimizing coordination limits involves adding penalty factor components to the objective function to discourage impractical solutions. This is a common approach to ensure a practically feasible solution set for a constrained objective function, as shown in Eq. (9).

$$OF = min\left(\sum_{\varphi=1}^{\varepsilon} Ʊ_{\varphi,pri} + \left(\sum_{\sigma=1}^{\beta} Penalty(\sigma)\right)\right) \quad (9)$$

Where β denotes tandem relay pairs and $Penalty(\sigma)$ is given by expression in Eq. (10)

$$Penalty(\sigma) = \begin{cases} 0, & (Ʊ_{\varphi}^{bu} - Ʊ_{\varphi}^{pri} \ge CTI) \\ \Delta, & (otherwise) \end{cases} \quad (10)$$

Where Δ is the penalty factor in the penalized objective function, which increases the objective function's contribution during the minimization process. During implementation, whenever the conditions in Eq. (10) are violated, a penalty is added to the solution, making it infeasible.

To ensure effective coordination and constraint compliance in DOCR optimization, the selection of an appropriate optimization framework becomes crucial. While the penalized objective function defines the mathematical foundation for evaluating solutions, the performance of the optimization heavily depends on the method used to explore the solution space. In this context, the following section introduces the Multi-Strategy Coati Optimization Algorithm (TNTWCOA), specifically tailored to address the complex, nonlinear, and constrained nature of relay coordination problems.

Multi-Strategy Coati Optimization Algorithm:

This study presents an enhanced version of the Coati Optimization Algorithm, called the Tuned Non-inertial T-distribution based Weighted Coati Optimization Algorithm (TNTWCOA) [13], introduced by Qi et al. in 2024. Inspired by the hunting and escape behaviors of coatis, TNTWCOA strikes a balance between exploration and exploitation phases. These natural behaviors of coatis are carefully simulated to form the foundation of TNTWCOA's design, which optimizes relay operation times while fine-tuning towards a global optimum within constraints such as TDS, PS, and CTI. Figure 1 illustrates the algorithm's flowchart.

$$\mu_{\zeta}:\ \Gamma_{\zeta,\alpha} = lb_{\alpha} + \psi_{\alpha}(ub_{\alpha} - lb_{\alpha}),\ \ \zeta = 1,2,\ldots,\upsilon, \alpha = 1,2,\ldots,k \quad (11)$$

$\mu_\zeta$is location of ζ^{th}coati in the search space, and $\Gamma_{\zeta,\alpha}$ is the value of the α^{th}decision variable for the ζ^{th} coati. lb_α and ub_α denote the lower and upper bounds for the α^{th} decision variable, respectively. The index ζ ranges from 1 to υ (the total number of coatis), and α ranges from 1 to k (the total number of decision variables).

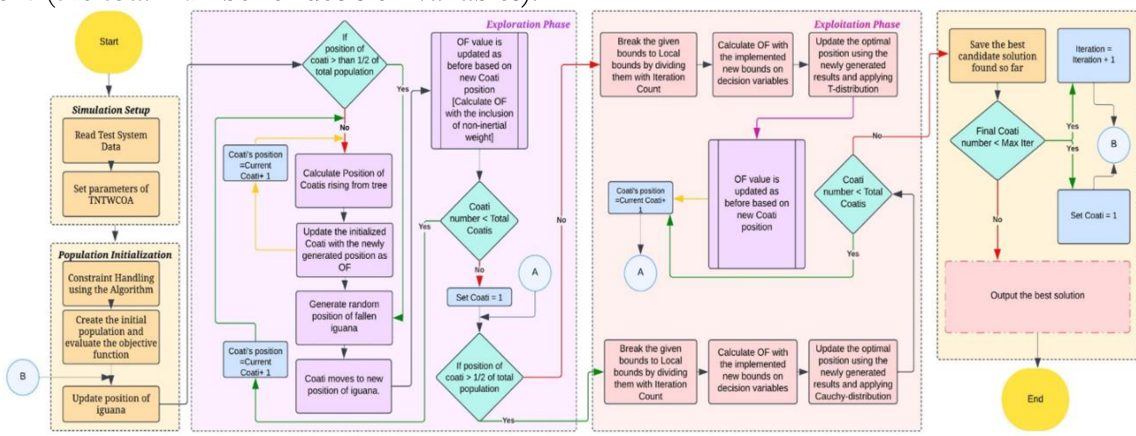

Figure 1. Flowchart of the TNTWCOA for optimal coordination of DOCRs

Phase 1: Exploration (Hunting and Attacking Strategy):

In the first phase, the position of the best member is considered as the iguana's position. This is achieved using a tent chaotic initialization sequence. To ensure even distribution of search agents (coatis) across both the ground and trees in the search space for global exploration, a non-inertial weight factor ($\acute{\omega}$) is introduced. This weight factor is initialized with random values at the beginning phase during the pre-iteration run. The random numbers are drawn from the range $\psi(0,1)$, as described in Eq. (15) and Eq. (16).

$$\mu_\zeta^{p1}: \Gamma_{\zeta,\alpha}^{p1} = \acute{\omega} \cdot \Gamma_{\zeta,\alpha} + \psi\left(iguana_\alpha - \Theta \cdot \Gamma_{\zeta,\alpha}\right), \qquad \zeta = 1,2,\dots,\left\lfloor \frac{\upsilon}{2} \right\rfloor, \alpha = 1,2,\dots,k. \quad (15)$$

$$iguana^g: iguana_\alpha^g = lb_\alpha + \psi(ub_\alpha - lb_\alpha), \qquad \text{for } \alpha = 1,2,\dots,k \quad (16)$$

$$\mu_\zeta^{p1}: \begin{cases} \acute{\omega} \cdot \Gamma_{\zeta,\alpha} + \psi\left(iguana_\alpha^g - \Theta \cdot \Gamma_{\zeta,\alpha}\right), \ \Omega_n > \Omega_\zeta \\ \quad \acute{\omega} \cdot \Gamma_{\zeta,\alpha} + \psi\left(\Gamma_{\zeta,\alpha} - iguana_\alpha^g\right), else \end{cases} \quad (17)$$

The new position μ_ζ^{p1} for the ζ^{th} coati is represented by $\Gamma_{\zeta,\alpha}^{p1}$, which corresponds to its α^{th} dimension. Ω_ζ^{p1} represents its objective function value. The iguana corresponds to the best position, and Θ is an integer selected from {1, 2}. $iguana_\alpha^g$ is the randomly generated iguana's position, as its α^{th} dimension, and $\Omega_{iguana^g} = \Omega_n$ is its objective function value.

The position of the coati is updated only if it improves the objective function; otherwise, it remains unchanged. This applies for $\zeta = 1,2,\dots,\upsilon$, as shown in Eq. (18).

$$\mu_\zeta = \begin{cases} \mu_\zeta^{p1}, & \Omega_\zeta^{p1} < \Omega_\zeta \\ \mu_\zeta, & otherwise \end{cases} \quad (18)$$

Phase 2: Exploitation (Escaping predator Strategy):

When threatened, a coati swiftly moves to a nearby safe spot, demonstrating TNTWCOA's capacity to refine local searches, as shown in Eqs. (19) to (24). The term $\Gamma_{\zeta,\alpha}^{p2}$ takes values from sub-equations (20) and (21) based on specified conditions. Equation (22) represents the adaptive T-distribution element.

$$lb_\alpha^{loc} = \frac{lb_\alpha}{\aleph}, ub_\alpha^{loc} = \frac{ub_\alpha}{\aleph}, \qquad \aleph = 1,2,\dots,e \quad (19)$$

Where $\aleph$ is the iteration index. The local bounds lb_α^{loc} and ub_α^{loc} are derived from the global bounds lb_α and ub_α, respectively.

The second half involves a method called the sparrow alert mechanism, where coatis in the middle move randomly to get closer to others in the group, as described by:

$$\Gamma^{p2}_{\zeta,\alpha} = iguana_{\alpha} + iguana_{\alpha} * f(t), \Omega^{p2}_{\zeta} > \Omega_{AVG} \quad (20)$$

$$\mu^{p2}_{\zeta}: \Gamma^{p2}_{\zeta,\alpha} = \Gamma_{\zeta,\alpha} + (1-2\psi)\cdot(lb^{loc}_{\alpha} + \psi(ub^{loc}_{\alpha} - lb^{loc}_{\alpha})) \quad (21)$$

In this context, μ^{p2}_{ζ} represents the updated position of the ζ^{th}coati in the second phase of COA. $\Gamma^{p2}_{\zeta,\alpha}$ is its α^{th} dimension, Ω^{p2}_{ζ} denotes its objective function value.

$$f(n,t) = \frac{\Gamma\left(\frac{n+1}{2}\right)}{\sqrt{(\pi n)}\Gamma\left(\frac{n}{2}\right)} \times \left(\frac{t^2}{n}+1\right)^{-\frac{n+1}{2}}, -\infty < t < \infty \quad (22)$$

Where 't' is the degree of freedom parameter, 'n' is the degree of freedom, and $\Gamma(\,)$. As, N(0,1) t(n⟶∞)=N(0,1) (Gaussian); for, t(n⟶1) = C(0,1) (Cauchy). In TNTWCOA, coati positions are adjusted with t-distribution mutation, defined as:

$$t(x) = x \oplus xf(n,t) \quad (23)$$

A new position is valid if it enhances the objective function. This is demonstrated in Eq. (24).

$$\mu_{\zeta} = \begin{cases} \mu^{p2}_{\zeta}, & \Omega^{p2}_{\zeta} < \Omega_{\zeta} \\ \mu_{\zeta}, & otherwise \end{cases} \quad (24)$$

Results:

This section evaluates the TNTWCOA on two IEEE test systems: the 3-bus and 15-bus networks, to assess its effectiveness in relay coordination with the MATLAB simulated results. Each test system is subjected to coordination with results from the algorithm reflected in optimal relay settings, tendencies of times of primary/backup pairs and CTI. While algorithm's robustness is showcased by convergence curves and performance over mutually exclusive runs and fixed iteration bound.

IEEE 3-Bus Test System:

As shown in Figure 2, the IEEE 3-bus test system consists of three generators, three lines, six DOCRs (R1-R6), and six primary/backup relay pairs. The optimal settings for these six relays were determined by adjusting the 12 control variables (TDS1 to TDS6 and PS1 to PS6) to their ideal values. The TDS values range from [0.05 to 1.1], while PS values range from [0.1 to 5], with a CTImin of 0.2s chosen. Table 1 presents the optimized TDS, PS, and operation times of the primary relays. Table II shows the primary and backup operating times and lists the CTI of the relay pairs. Table V, presented in section-VII compares the results produced by TNTWCOA with state-of-the-art techniques from the literature, highlighting improvements in operating times. Figure 3 shows the convergence curve of the Objective Function (OF), while Figure 4 illustrates the OF variations across 30 runs, presenting the minimum, maximum, and mean results graphically. Additionally, Figure 5 and Figure 6 show the trends in operating times and CTI of the relay pairs involved in the coordination issue. The results are highly precise and well-coordinated, with violations of no constraints.

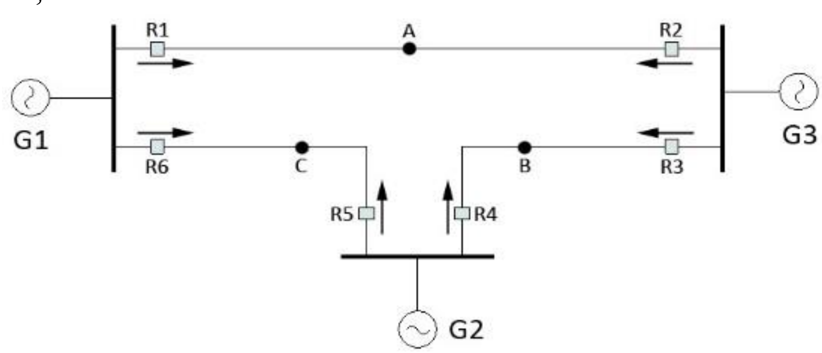

Figure 2. IEEE 3-bus system

Table 1. Optimal relay settings for 3-bus system

Relay No.	$\mho_{\varphi,pri}$ (s)	TDS	PS
1	0.1556	0.05	3.6553
2	0.1014	0.05	1.3564
3	0.1316	0.05	3.1546
4	0.1464	0.05	2.9272
5	0.1110	0.05	1.7617
6	0.1466	0.05	2.1440
$\sum \mho_{\varphi,pri}$	**0.79267**		

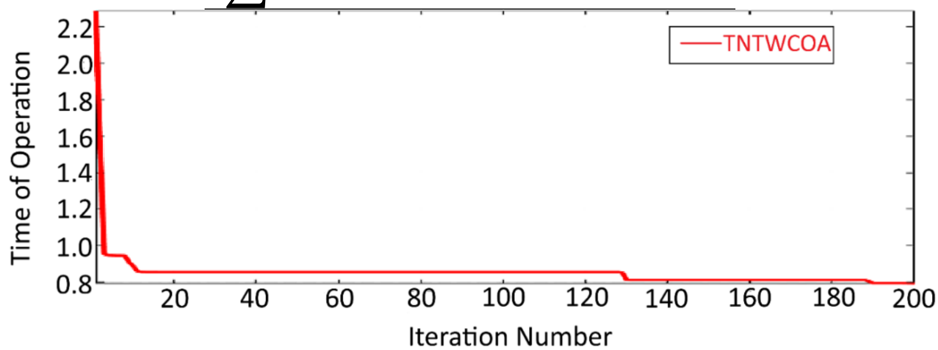

Figure 3. Convergence Curve for the OF of IEEE 3-bus system

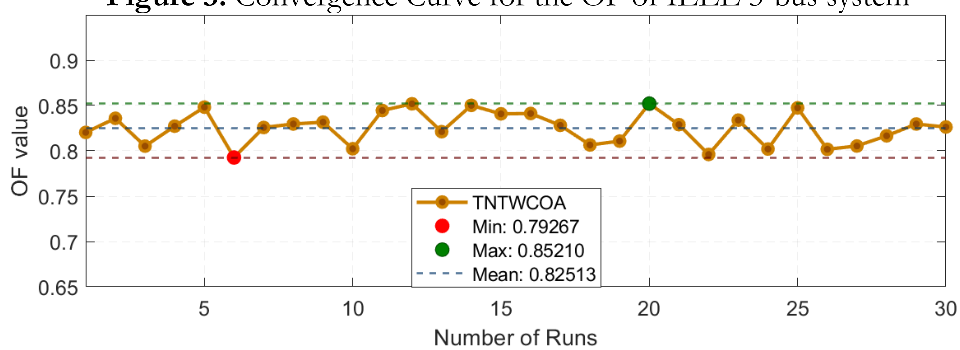

Figure 4. OF variation along 30 runs for IEEE 3-bus system

Table 2. operating times for pri-bu relay pairs and cti for IEEE 3-bus system

Relay Pairs		$\mho_{pri}$	$\mho_{bc}$	CTI (s)
R_{pr}	R_{bc}			
1	**5**	0.1556	0.3813	0.2257
2	**4**	0.1014	0.3056	0.2042
3	**1**	0.1316	0.3348	0.2032
4	**6**	0.1464	0.3466	0.2002
5	**3**	0.1110	0.3110	0.2000
6	**2**	0.1466	0.3517	0.2051

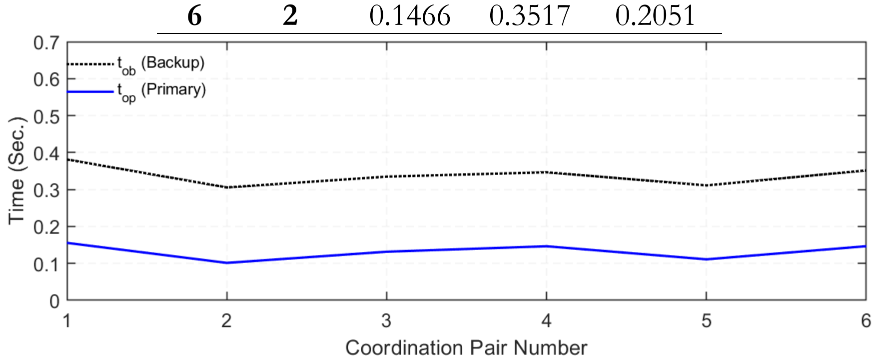

Figure 5. Tendencies of times for all P/B relay pairs of the IEEE 3-bus system

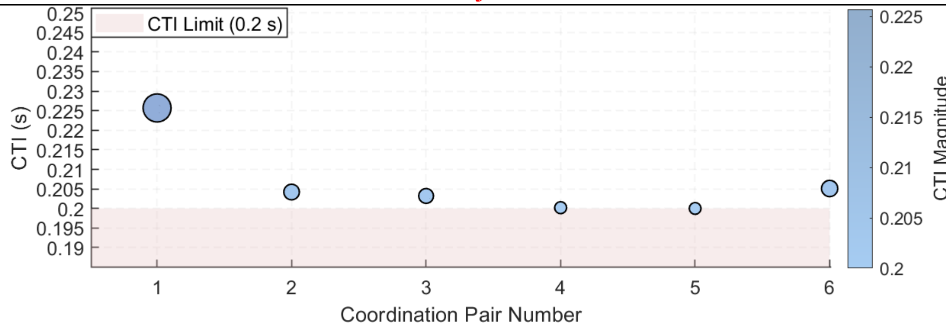

Figure 6. CTI tendencies for 3 bus system

IEEE 15-Bus Test System:

Figure 7 presents the single-line diagram of the 15-bus test system, which includes the placement of relays (R1-R42), external grids, and distributed generators (DGs). Each generator is rated at 15 MVA and 20 kV. The network consists of 21 lines and 42 relays. A 3-phase near-end short circuit at each relay location is considered for fault current calculations in the short-circuit analysis. The TDS and PS values are set within the ranges [0.05:1.1] and [0.1:5], respectively, with a CTImin of 0.2 seconds. There are 84 variables and 164 constraints in the system. Table IV shows the optimal TDS, PS, and operation time values for the DOCRs, as determined by the proposed technique, where the total minimized time reaches 10.3815s for all the main relays in the system. Table V lists the operating times for each primary-backup pair along with their respective CTIs. The proposed system ensures that no coordination constraints or relay setting bounds are violated. Table VI highlights the improvements in results produced by TNTWCOA compared to other robust methods published in the literature, showing net time gains. Figure 8 illustrates the convergence curve of TNTWCOA, while Figure 9 shows the variations of the objective function (OF) across 30 independent runs, presenting the mean, maximum, and minimum values. Figure 10 and Figure 11 display the graphical and bubble chart representations of the tendencies in primary and backup relay times, as well as the CTI magnitudes across coordinating relay pairs. It is important to note that, while the method successfully reduces relay operating times, there is a trade-off where backup relay response times extend beyond 3 to 5 seconds to maintain selectivity. This trend, observed in the results optimized by the proposed algorithm, aligns with findings in related studies. Despite this trade-off, the results confirm that TNTWCOA effectively mitigates premature convergence through its multi-strategy framework, making it a highly efficient approach for DOCR optimization.

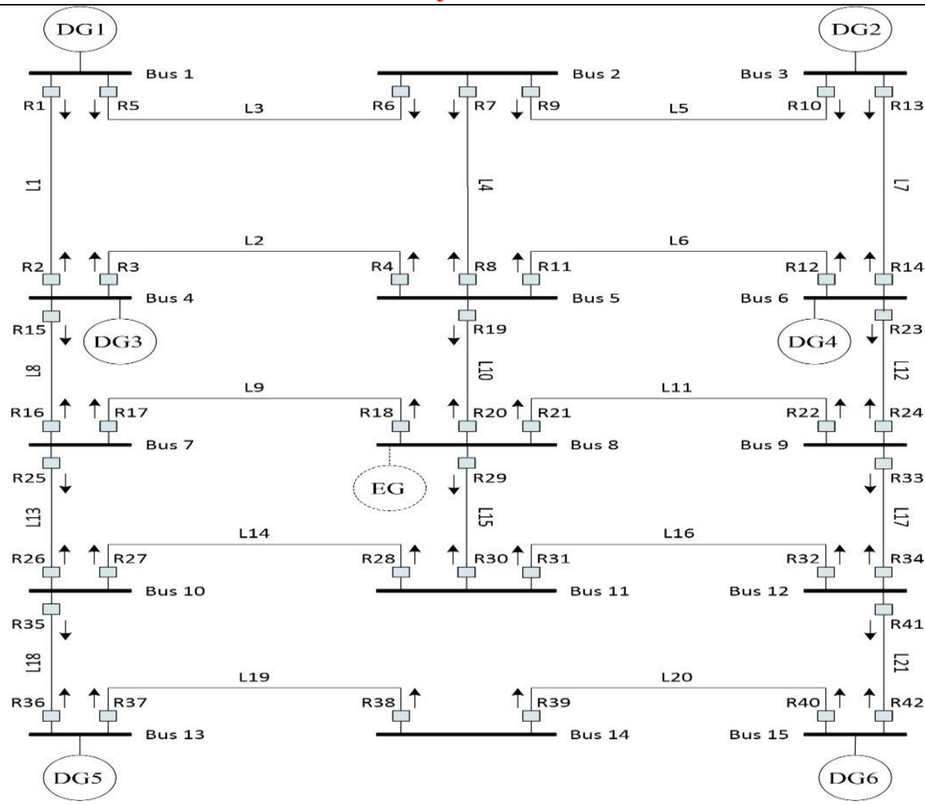

Figure 7. IEEE 15-bus system

Table 3. Optimal relay settings for 15-bus system

Relay No.	$T_{\varphi,pri}$ (s)	TDS	PS
1	0.2158	0.050012	4.5842
2	0.2399	0.05	4.5469
3	0.1989	0.05	4.4179
4	0.2408	0.05	4.3561
5	0.2424	0.05	4.9981
6	0.2247	0.05	4.7593
7	0.2354	0.050006	4.8077
8	0.1968	0.05	4.4083
9	0.2000	0.05	4.3929
10	0.2002	0.05	4.0672
11	0.2351	0.05	4.1715
12	0.2281	0.05	3.8560
13	0.2322	0.05	4.8154
14	0.2362	0.05	4.4571
15	0.2287	0.05	4.348
16	0.2635	0.05	4.9981
17	0.2222	0.05002	4.9662
18	0.2007	0.05	4.7436
19	0.2069	0.05	4.7325
20	0.2083	0.05	4.5874
21	0.1752	0.050685	3.5985
22	0.2083	0.05	4.6672
23	0.2443	0.05	4.9818
24	0.7254	0.05	4.1458
25	0.2531	0.05	4.8747

26	0.2335	0.05	4.3779
27	0.2857	0.05	4.9958
28	0.2242	0.050972	4.3921
29	0.2447	0.1178	1.0000
30	0.1954	0.05	3.7327
31	0.2202	0.05	4.9954
32	0.2577	0.050005	4.5139
33	0.2389	0.05	4.5337
34	0.5671	0.12135	4.9009
35	0.2104	0.05	3.3992
36	0.2139	0.05	4.1016
37	0.2194	0.05	4.2906
38	0.2711	0.050024	4.8990
39	0.2704	0.05	4.9981
40	0.2421	0.05	4.7179
41	0.2056	0.050488	4.4551
42	0.2159	0.05	4.9981
$\sum$ Ʈ$_{\varphi,pri}$	**10.3815**		

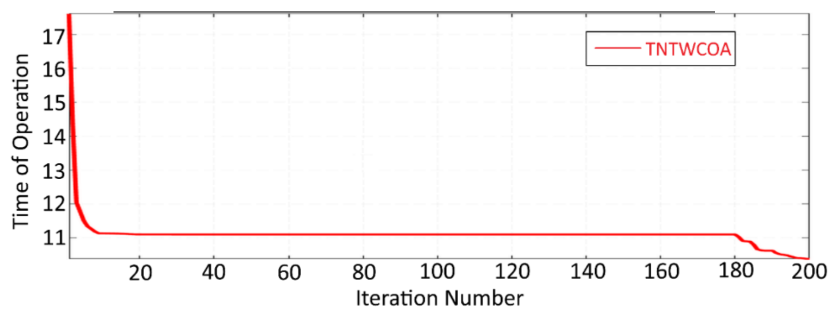

Figure 8. Convergence curve for the OF of IEEE 15-bus system

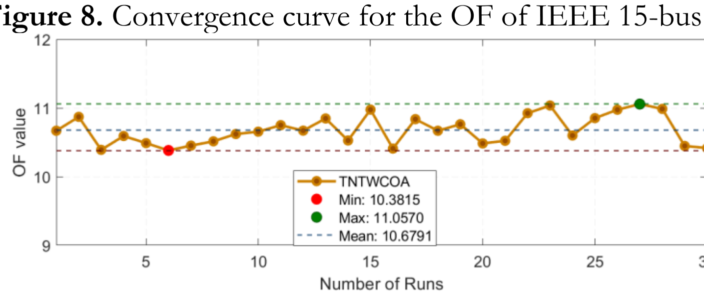

Figure 9. OF variation along 30 runs for IEEE 15-bus system

Table 4. Operating times for pri-bu relay pairs and cti for 15-bus system

Relay Pairs		Ʈ$_{pri}$	Ʈ$_{bc}$	**CTI (s)**
R_{pr}	**R_{bc}**			
1	**6**	0.2158	0.4513	0.2355
2	**4**	0.2399	1.0094	0.7695
2	**16**	0.2399	1.6309	1.3910
3	**1**	0.1989	2.3153	2.1164
3	**16**	0.1989	1.6309	1.4320
4	**7**	0.2408	0.5307	0.2899
4	**12**	0.2408	0.7607	0.5199
4	**20**	0.2408	1.6765	1.4357
5	**2**	0.2424	2.0802	1.8378
6	**8**	0.2247	0.5452	0.3205

6	**10**	0.2247	0.6633	0.4386
7	**5**	0.2354	0.6239	0.3885
7	**10**	0.2354	0.6633	0.4279
8	**3**	0.1968	0.4962	0.2994
8	**12**	0.1968	0.7607	0.5639
8	**20**	0.1968	1.6765	1.4797
9	**5**	0.2000	0.6239	0.4239
9	**8**	0.2000	0.5452	0.3452
10	**14**	0.2022	0.7242	0.5220
11	**3**	0.2351	0.4962	0.2611
11	**7**	0.2351	0.7607	0.5256
11	**20**	0.2351	1.6765	1.4414
12	**13**	0.2281	0.6239	0.3958
12	**24**	0.2281	0.5452	0.3171
13	**9**	0.2322	0.5356	0.3034
14	**11**	0.2362	0.8997	0.6635
14	**24**	0.2362	0.8410	0.6048
15	**1**	0.2287	2.3153	2.0866
15	**4**	0.2287	1.0094	0.7807
16	**18**	0.2635	2.5083	2.2448
16	**26**	0.2635	0.6400	0.3765
17	**15**	0.2222	0.7270	0.5048
17	**26**	0.2222	0.6400	0.4178
18	**19**	0.2007	0.5853	0.3846
18	**22**	0.2007	0.6423	0.4416
18	**30**	0.2007	0.4211	0.2204
19	**3**	0.2069	0.4962	0.2893
19	**9**	0.2069	0.5307	0.3238
19	**12**	0.3069	0.7607	0.4538
20	**17**	0.2083	0.8493	0.6410
20	**22**	0.2083	0.6423	0.4340
20	**30**	0.2083	0.4211	0.2128
21	**17**	0.1752	0.8493	0.6741
21	**19**	0.1752	0.5853	0.4101
21	**30**	0.1752	0.4211	0.2459
22	**23**	0.2083	1.7543	1.5460
22	**34**	0.2083	0.9292	0.7209
23	**11**	0.2443	0.8997	0.6554
23	**13**	0.2443	1.1169	0.8726
24	**21**	0.7254	0.9919	0.2665
24	**34**	0.7254	0.9292	0.2038
25	**15**	0.2531	0.7270	0.4739
25	**18**	0.2531	2.5083	2.2552
26	**28**	0.2335	0.4337	0.2002
26	**36**	0.2335	0.6636	0.4301
27	**25**	0.2857	0.8026	0.5169
27	**36**	0.2857	0.6636	0.3779
28	**29**	0.2242	0.4650	0.2408
28	**32**	0.2442	1.3849	1.1407
29	**17**	0.2447	0.8493	0.6046

29	**19**	0.2447	0.5853	0.3406
29	**22**	0.2447	0.6423	0.3976
30	**27**	0.1954	0.6330	0.4376
30	**32**	0.1954	1.3849	1.1895
31	**27**	0.2202	0.6330	0.4128
31	**29**	0.2202	0.4650	0.2448
32	**33**	0.2577	0.4577	0.2000
32	**42**	0.2577	2.7762	2.5185
33	**21**	0.2389	2.5133	2.2744
33	**23**	0.2389	1.7543	1.5154
34	**31**	0.5671	1.1640	0.5969
34	**42**	0.5671	2.7762	2.2091
35	**25**	0.2104	0.8026	0.5922
35	**28**	0.2104	0.4337	0.2233
36	**38**	0.2139	0.4282	0.2143
37	**35**	0.2194	0.4327	0.2133
38	**40**	0.2711	0.5612	0.2901
39	**37**	0.2706	0.4716	0.2010
40	**41**	0.2421	0.4892	0.2471
41	**31**	0.2056	1.1640	0.9584
41	**33**	0.2056	0.4577	0.2521
42	**39**	0.2159	0.4303	0.2144

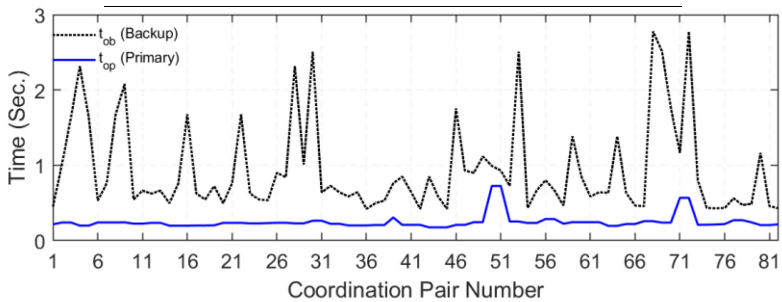

Figure 10. Tendencies of times for all P/B relay pairs of the IEEE 15-bus

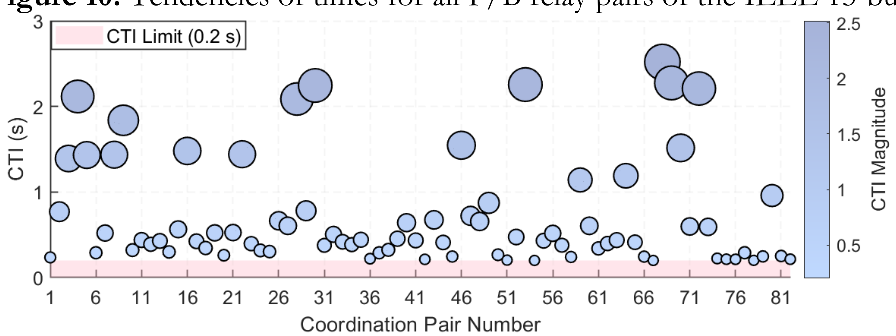

Figure 11. CTI Tendencies for IEEE 15-bus system

Discussion:

The proposed TNTWCOA method outperformed several established techniques across both small and large test systems. In the 3-bus case, a 3-phase bolted short circuit at the center of the lines (shown in Figure 2 as A, B, and C) was considered. The CTR of relays and additional system data can be found in [1]. As, tabulated in Table V, and Figure 12(A) provides the graphical representation of comparative analysis as the algorithm achieved net gains in total relay operation times of up to 4.54 seconds (a 85.2% improvement) when compared to TLBO [8], 3.99 seconds (a 83.4% improvement) over MDE [9], 1.74 seconds (a 68.8% improvement) over AFDBA [10], 1.13 seconds (a 58.8% improvement) over MPSO [10], 0.81 seconds (a 50.6%

improvement) over GTO [12], and 0.59 seconds (a 42.8% improvement) over EMPA [1]. These improvements demonstrate the algorithm's strong capability to optimize protection settings efficiently in smaller systems, where fast fault clearance is critical and coordination windows are tighter. In the 15-bus case, which involved a significantly larger solution space and a higher number of constraints, the power system parameters, including short-circuit current values, provided in [14]. As, tabulated in Table VI, Figure 12(B) provides the graphical representation of comparative analysis as TNTWCOA achieved a minimized total primary relay operating time of 10.3815 seconds, securing gains of 19.52 seconds (a 65.3% improvement) over MPA [1], 8.52 seconds (a 45.0% improvement) over GA [12], 1.73 seconds (a 14.3% improvement) over IHSA [15], 1.40 seconds (a 11.9% improvement) over VNS [1], 1.29 seconds (a 11.0% improvement) over IHSA-NLP [15], 0.89 seconds (a 7.9% improvement) over WOA [16], and 0.58 seconds (a 5.3% improvement) over EMPA [1].

However, while achieving these reductions in primary operating times, a trade-off was observed as some backup relays exhibited response delays of 3 to 5 seconds to preserve proper selectivity. This behavior, which the objective function (OF) was designed to accommodate, is consistent with trends reported in related studies. Yet, in comparative terms, backup relay times have also been effectively compressed relative to other methods, reducing the risk of selectivity-related miscoordination or runaway timings. The algorithm's parameters were intelligently fine-tuned, including the number of search agents, with a deliberately chosen stopping criterion of 200 iterations. This relatively low, self-imposed limit serves as an additional measure of computational rigor, contrasting with other metaheuristics that typically require 500 to 20,000 iterations across independent runs to approach near-optimal solutions. Despite this inherent balance between speed and protection margin, the results confirm that TNTWCOA's multi-strategy optimization framework successfully mitigates premature convergence and delivers highly coordinated, robust, and constraint-compliant DOCR settings across varying system complexities.

Table 5. Comparison of results for 3-bus system

Method	OF (s)	$\sum \Delta T_{\varphi,pri}\,(s)$
TLBO [7]	5.3349	4.54223
MDE [8]	4.7806	3.98793
AFDBA [9]	2.5287	1.73603
MPSO [10]	1.9258	1.13313
GTO [11]	1.5990	0.80633
EMPA [1]	1.3792	0.58653
TNTWCOA	**0.79267**	

Table 6. Comparison of results for IEEE 15-bus system

Method	OF (s)	$\sum \Delta T_{\varphi,pri}\,(s)$
MPA [1]	29.89717	19.51567
GA [12]	18.9033	8.5218
IHSA [13]	12.1122	1.7307
VNS [1]	11.7790	1.3975
IHSA-NLP [13]	11.6699	1.2884
WOA [14]	11.2670	0.8855
EMPA [1]	10.9610	0.5795
TNTWCOA	**10.3815**	

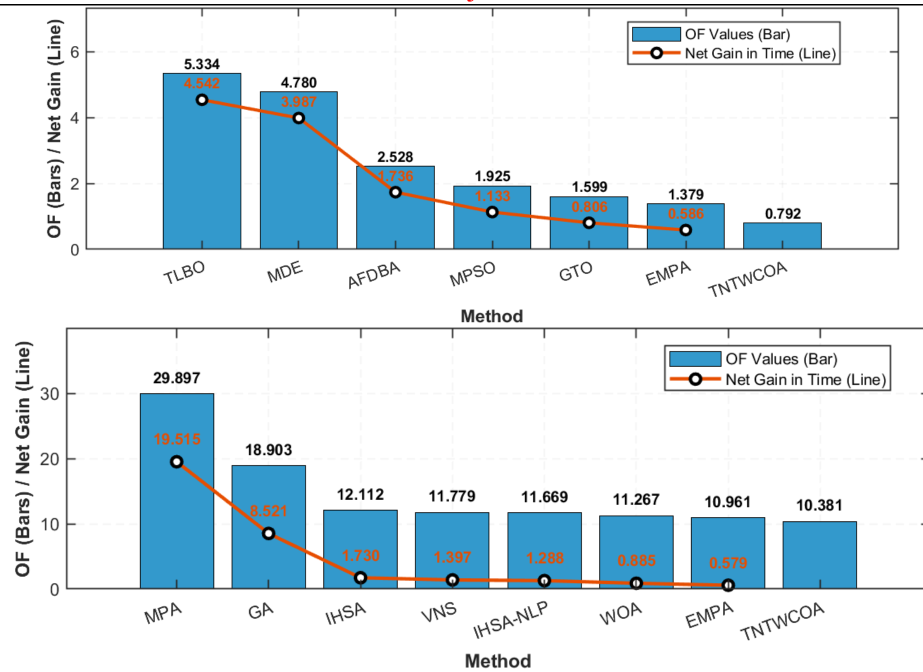

Figure 12. Graphical Representation of Comparison of Results of TNTWCOA for IEEE 3-bus (A) and 15-bus test systems (B)

Conclusion:

This study enhances DOCR coordination in interconnected power networks using TNTWCOA (Tuned Non-inertial T-distribution based Weighted Coati Optimization Algorithm). By integrating chaotic initialization, nonlinear inertia, adaptive T-distribution, and an alert update mechanism, TNTWCOA addresses challenges such as premature convergence and diversity loss. Applied to optimize TDS and PS for near-end and mid-faults with normal inverse characteristics, TNTWCOA outperforms both classical and modern optimization methods on the IEEE 3- and 15-bus systems, achieving superior relay operation times.

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The authors hereby confirm that the manuscript has not been published previously, nor is it under consideration for publication elsewhere. All authors contributed equally to the research and preparation of this manuscript and are in full agreement with its content.

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