Overcurrent Coordination by Eel Swarm Optimization Algorithm

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***Abstract*-- In recent years, the complexity of modern distribution systems has increased due to the integration of dispersed generation resources. Coordinating directional overcurrent relays (DOCR) for protecting these systems poses a challenging optimization problem. This study introduces the Eel Swarm Optimization Algorithm (ESOA) to address this issue. Inspired by eels' hunting behavior, ESOA effectively explores the solution space. Testing on various error scenarios in 3-bus and 15-bus systems demonstrates ESOA's superior performance in reducing primary relay performance time compared to other optimization algorithms. The algorithm demonstrates proficiency in ensuring synchronization between primary relay pairs and backup relays, reducing the time difference in coordination.**

***Index Terms*-- Directional Overcurrent Relays (DOCRs), Relay Coordination, Eel Swarm Algorithm**

I. INTRODUCTION

Directional Overcurrent Relays (DOCRs), in conjunction with circuit breakers, recloses, and fuses, are commonly employed to protect radial distribution systems. The increasing presence of dispersed generators (DGs) in recent times offers technical advantages but necessitates a shift from radial to mesh structures with bidirectional power flow. The magnitude of short-circuit currents influences DG selection, prompting the preference for DOCRs over simpler OCRs for effective protection in intricate networks. Ensuring the accurate coordination of DOCRs is crucial for improving the effectiveness of the protection system. Two key factors that impact the response time of a DOCR are the pickup setting (PS) and the time multiplier setting (TMS). The primary role of a DOCR is to swiftly identify faults within its designated operational area, serving as primary protection. In instances where primary protection fails to clear a fault due to relay or circuit breaker issues, backup protection becomes necessary to address the fault. Backup protection acts as an additional safeguard for a specific section, activating only after a deliberate time delay following primary protection failure. The goal of DOCR coordination is to determine the optimal values for PS and TMS for each relay, taking into account specific constraints to minimize the overall operation time of primary relays and ensure alignment between primary relay pairs and backups. Numerous approaches to DOCR coordination have been detailed in research. Conventional trial-and-error techniques for DOCR coordination in radial distribution networks typically require numerous iterations and exhibit slow convergence rates. As a result, optimal DOCR coordination utilizing topological analysis was introduced, providing a more streamlined method with reduced iteration requirements. However, while topology-based methods can lead to suitable solutions more quickly than trial-and-error approaches, they may not always guarantee the global optimum values for PS and TMS of DOCRs. Additionally, innovative algorithms inspired by nature, such as the firefly algorithm [1], have been proposed to enhance relay synchronization in distribution systems, including scenarios involving solar panel integration [3].

In [4], the use of Renewable energy resources is explored by coordinating relays, while in [5], the BBO algorithm is utilized to enhance relay coordination. Additionally, [6] investigates the impact of electric vehicles being present in the network simultaneously with overcurrent relays, and [7] examines the utilization of the marine elite hunter's algorithm for synchronizing the construction of overcurrent relays. Dual simplex [8] is known for its speed and simplicity, but it is limited to TMS optimization due to the linear relationship between DOCR running time and TMS. To address the nonlinear nature of DOCR coordination and overcome the constraints of LP-based techniques, various nonlinear programming methods such as sequential quadratic programming [9], random search, and gradient search [10] have been proposed in the literature. These NLP-based optimization techniques involve optimizing both PS and TMS DOCRs together and have demonstrated superior performance in solving the DOCR coordination problem compared to LP techniques.

Nevertheless, traditional optimization techniques may become stuck in local minima and struggle to achieve the global maximum. Additionally, these methods tend to exhibit slow convergence rates as the system size increases. In recent times, a variety of innovative and nature-inspired algorithms have emerged to tackle these challenges effectively. These include Genetic Algorithm (GA) [11], GA-NLP [12], Search Algorithm (SA) [13], Learning-Based Optimization [14], Informative differential evolution [15], perturbed differential evolution [16], artificial bee colony [17], biogeography-based optimization [18], genetic algorithm with non-dominant sorting-II [19], combined gravitational search algorithm and programming consecutive quadratic [20], Cuckoo Search Algorithm [21], Gravity Optimization Hybrid Particle Swarm Search Algorithm [22], Symbiotic Organism Search [23],

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Modified Electromagnetic Field Optimization [24], Fuzzy-Genetics [25], Improved IGWO Gray Wolf Optimizer [26], Ant-lion optimization [27], Firefly algorithm [28], [29], HWOA hybrid whale optimization algorithm [30], MILP mixed integer linear programming [31], [32], Modified water cycle algorithm [33], and Jaya's adversarial algorithm [34]. These methods have proven successful in addressing optimal coordination challenges related to Directional Overcurrent Relays (DOCRs).

These heuristic and evolutionary optimization techniques are superior in terms of achieving the global optimum compared to the traditional performance method [39]. In the following, after introducing the proposed objective function and the kingfisher algorithm, the effectiveness of the new algorithm is evaluated against four significant algorithms previously documented: SA [13], IGWO [26], HWOA [30], and MILP [39], with a focus on achieving the shortest overall performance time. The arrangement of relays is then compared to the existing algorithms throughout the remainder of the article. In Section 2, the coordination problem of DOCRs is formulated using the fish-eating chicken algorithm. Results and discussions are presented in Section 3. Finally, in Section 4 we present the conclusion.

TABLE I
Comparison of Proposed Method With Previous Methods

Reference	Algorithm	Technic
[11]	Genetic Algorithm	modification of the existing objective function of GA
[12	GA-NLP	determination of optimum values of TMS and PS of OCRs
[13]	Search Algorithm	mixed-integer nonlinear programming problem
[14]	Learning-Based Optimization	optimal coordination of DOCR relays in a looped power system.
[15]	Informative differential evolution	DOCRs coordination
[16]	perturbed differential evolution	OCDE1 and OCDE2
[17]	artificial bee colony	comparison purpose in order to highlight its superiority.
[18]	biogeography-based optimization	the performance of ten types of constraint-handling techniques
[19]	genetic algorithm with non-dominant sorting-II	reduce the discrimination time of the primary and backup relays
[20]	combined gravitational search algorithm and programming consecutive quadratic	minimize the sum of operating times of all the primary relays

2-The formulation of the Relay Coordination Problem involves expressing it as either a linear or nonlinear function. When considering a linear function, the PS (Pickup Setting) remains constant within the minimum and maximum current limit, while the TMS (Time Multiplier Setting) is optimized. On the other hand, in the case of a nonlinear function, both PS and TMS are simultaneously optimized. Furthermore, the discrete nature of relay settings introduces added complexity to the coordination problem. To solve the DOCR coordination problem, two primary objectives need to be addressed. The primary goal is to reduce the overall operation time of all relays within the system to swiftly clear faults. The secondary objective is to uphold the coordination between primary relays and their backup counterparts. The characteristics of relays can be mathematically expressed as outlined in reference [14]:

$$T_{ik} = \frac{TMS_i}{\left(\frac{I_{R_i,k}}{PS_i}\right)^{\alpha} - 1} \quad (1)$$

Within this scenario, Tik signifies the response time of relay Ri to a fault at location kth, IRi,k represents the fault current detected by relay Ri for a fault at location k, PSi denotes the threshold setting at which relay Ri triggers its operation, and TMSi indicates the time multiplier setting of relay Ri. The constants α and β are variables that differ based on the characteristics of the relay. For an Inverse Definite Minimum Time (IDMT) relay, α and β values are set at 0.02 and 0.14, respectively. The main objective of the DOCR coordination challenge is to determine the best values for PS and TMS to reduce the total weighted sum of operation times for all primary relays in their designated zones. Hence, the objective function (OF) can be formulated as follows:

$$\min(OF) = \sum_{i=1}^{n} \sum_{k=1}^{l} w_{ik} * T_{ik} \quad T_{ik}^{min} \leq T_{ik} \leq T_{ik}^{max}, \; i=1,2,3,\ldots m \quad (2)$$

In this context, n represents the total number of relays, while l signifies the fault location. The parameter wik denotes the likelihood of a fault occurring within any protection zone. The sum of all weight coefficients in equation (2) is set to 1 [18], indicating uniform error probability across all buses. The secondary objective is to ensure coordination between primary and backup relays. In the event that the primary relay is unable to successfully clear a fault within its specified zone, the backup relays must be triggered to resolve the problem.

The time delay before the backup relay engages, in cases where the primary relay fails to act, is referred to as the CTI coordination time interval, expressed as follows [10]:

$$CTI \geq T_{jk} - T_{ik}, \quad i = 1,2,3, \ldots CTI \geq T_{jk} - T_{ik}, \quad i = 1,2,3, \ldots m \quad (3)$$

Tjk represents the response time of relay j, potentially serving as the initial backup relay for the fault at location k. Electromechanical relays commonly utilize a CTI ranging from 0.3 to 0.4 seconds, whereas microprocessor-based numerical relays typically operate with a CTI between 0.1 and 0.2 seconds [7].

1-2-Relay coordination restrictions:

It is essential to adhere to specific constraints regarding the relay's operating time to ensure its proper functionality. PS and TMS need to be restricted to operate within specified boundaries.

2-2-Inscription of performance time:

The response time of a relay is influenced by factors such as PS, TMS, and the fault current detected by the relay. The operating time is established based on the relay's specific characteristics, either calculated using an analytical formula or standard inverse curves. Consequently, the constraint on the relay's operational duration can be articulated in the following manner.

$$T_{ik}^{min} \leq T_{ik} \leq T_{ik}^{max},\ \ i = 1,2,3, \dots m \tag{4}$$

minimum and maximum working time of the ith relay at the kth location, Tik min and Tik max, respectively, should be adjusted to ensure the relay remains inactive during peak load flow through the feeder and activates only for faults generating a minimal fault current. To achieve these criteria, the setting boundaries for relay plug I can be defined as per reference [15].

$$max\left(PS_i^{min}, I_{load_i}^{max}\right) \leq PS_i \leq min\left(PS_i^{max}, I_{fault_i}^{min}\right)\ i = 1,2,3, \dots m \tag{5}$$

PSi min represents the minimum setting available for the relay plug, while Iload max i denotes the maximum current that can pass through it. On the other hand, PSi max indicates the maximum setting for the relay plug, and Ifault min i signifies the minimum fault current that the relay will encounter.

2-3- The limitations of setting the time factor:

Establishing the time parameters comes with specific requirements to ensure the relay operates quickly and accurately. The relay must comply with the designated time limits, operating within the set minimum and maximum thresholds. Hence, the TMS boundary configuration for the relay can be phrased as such:

$$TMS_i^{min} \leq TMS_i \leq TMS_i^{max},\ \ i = 1,2,3, \dots m \tag{6}$$

TMSi min and TMSi max represent the lower and upper limits of TMS values for the relay. This study considers TMS values ranging from 0.1 to 1.1.

3- Fish-eating chicken algorithm:

Drawn from the patience of the snow owl and the boldness of the snowy plover, ESOA integrates the strengths of both strategies and establishes a corresponding mathematical model to quantify these behaviors. As illustrated in Fig. (1), ESOA is a parallel algorithm consisting of three key elements: the patient approach, the aggressive approach, and specific conditions. Within a team of egrets, egret A leads the front line, while egrets B and C employ random walking and circling mechanisms, respectively. Each component is further elaborated below. Fig. (1) depicts the hunting behavior of ospreys. In this context, considering the osprey's hunting experience and the prey's subsequent actions, it must identify the optimal location. The variable Dh, i signifies the adjustment to determine the best location for the team, while Dg, i represents the optimal location for all available teams.

$$d_{h,i} = \frac{X_{ibest} - X_i}{|X_{ibest} - X_i|} \cdot \frac{f_{ibest} - f_i}{|X_{ibest} - X_i|} + d_{ibest} \tag{7}$$

Egret B It tends to randomly search for prey and its behavior can be shown as follows:

$$x_{a,i} = x_i + \tan\left(r_{b,i}\right).hop/(1) + t \tag{8}$$

$$y_{b,i} = f\left(x_{b,i}\right) \tag{9}$$

Where rb,i is a random number between (-π/2, π/2) and xb, i is the next position of B and yb, i is the corresponding objective function. Egret C prefers to chase the prey aggressively, so the encirclement mechanism is used as a method of updating its position.

$$D_h = X_{ibest} - x_i,$$
$$D_g = X_{gbest} - x_i,$$
$$x_{c,i} = \left(1 - r_i - r_g\right).x_i + r_h.D_h + r_g.D_g \tag{10}$$

$$y_{b,i} = f\left(x_{b,i}\right) \tag{11}$$

Dh is the gap matrix between the current location and the best location of this egret platoon while Dg is compared to the best location among all egret platoons. Xc;i is the next place expected from minnow C. rh and rg are random numbers in the interval [0; 0:5. After each member of the chicken team decides on their plan, the team chooses the optimal option and acts together. Xs;i is the solution matrix of the ith chicken team:

$$x_{s,i} = \left[x_{a,i}\ \ x_{b,i}\ \ \ x_{c,i}\right], \tag{12}$$

$$y_{s,i} = \left[y_{a,i}\ \ y_{b,i}\ \ \ y_{c,i}\right], \tag{13}$$

$$c_i = argmin\left(y_{s,i}\right), \tag{14}$$

$$x_i = \begin{cases} x_{s,i}| \ if\ Y_{s,i} < y_i \quad r < .3 \\ \quad x_i \ \ else \end{cases} \tag{15}$$

If the minimum value of ys,i was better than the current value of yi, this team is selected as the better team, or if the random number r2 (0; 1) is less than 0.3, which means that there is a 30% chance of accepting the worse plan. You can see the flowchart of the fish-eating chicken algorithm in Fig. 1.

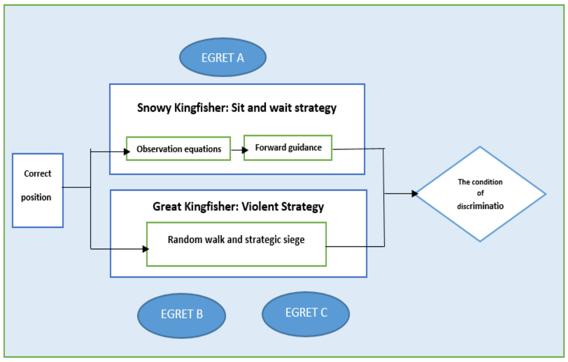

Fig. 1. Diagram of the fish-eating chicken algorithm

In solving the relay coordination problem with the proposed algorithm, the problem variable can be formulated as X= [TMS1, PSC2..., TMS n, PCS n]. To solve the proposed economic load distribution problem with the fish-eating chicken algorithm, the following steps are performed in order:

Step 1: Define the search space for each relay between TMS min and TMS max and PCS min and PCS max

Step 2: Calculate the value of the objective function for each droplet

Step 3: Ranking the chicken-eating chicken teams and identifying the best

Step 4: Carrying out the strategy of sitting and waiting and the strategy of violence and attack simultaneously on the new situation and generating situations Xa, Xb, Xc according to the existing relationships.

Step 5: Update the new position with the formula Xs=[Xa Xb Xc]

Step 6: Calculate the objective function for the new position and rank them

Step 7: Repeat steps 3 to 6 until the convergence condition is reached

Step 8: Stop and extract results

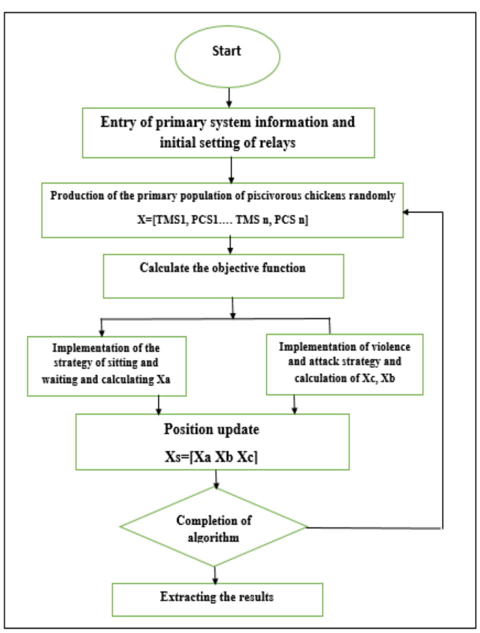

Fig. 2. Flowchart of solving the problem of coordination of relays with ESOA algorithm

4-Simulation and Results

The newly developed algorithm underwent testing on two distinct test systems, comprising a 3-bus and a 15-bus configuration, to assess the effectiveness of the optimization method. The feasibility of the proposed optimization technique in addressing the DOCR coordination challenge was verified and juxtaposed against the findings from a recent study utilizing SCA [13]. IGWO [26], HWOA [30], and SBB [31] were utilized to evaluate the effectiveness of the proposed approach. A three-phase voltage drop fault was induced at the midpoint of line 3 in the 3-bus test system and line 9 in the 15-bus test system to assess performance. The simulation was conducted using MATLAB and DigSilent software on a system equipped with an i-7 processor, 1.8 GHz clock speed, and 16 GB of RAM. The algorithm was implemented in the MATLAB environment, while the network and objective function were coded in the DPL environment of DigSilent software.

1-4- Simulation on the 3-buss Test System

A 3-bus test system B1 to B3 has three generators G1 to G3 and six DOCRs, R1 to R6 as shown in Fig. 3.

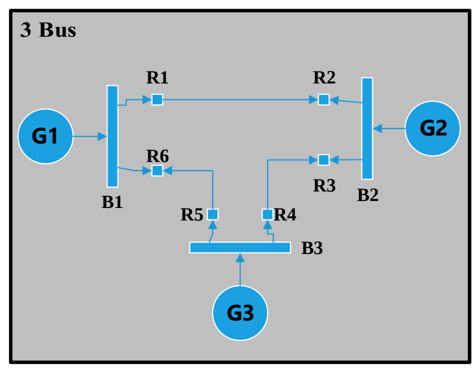

Fig. 3. 3-bus test system diagram

The network component information was obtained from [4]. Using the standard data provided, we determined the three-phase fault current at every bus in case of a three-phase fault happening at the midpoint of the line, as detailed in Table I. The CT current transformer ratio for each relay and tap transformer setting can be found in Table II. To rectify the discrepancies identified in Table I, we performed a comparative analysis using the ESOA algorithm to determine the optimal values of PS and TMS for each error scenario. The results from the ESOA algorithm were compared with three other recent methods, namely SCA [13], IGWO [13], and HWOA [30], and the comparison outcomes are presented in Table III.

Based on the information provided in the table, it is clear that the new algorithm completes the operation of primary relays in 0.9034 seconds, demonstrating a quicker performance compared to existing methods. This suggests that the new algorithm surpasses current techniques. Table IV illustrates the coordination limits, showing that all relays operate within these boundaries, with the CTI value consistently exceeding 0.3 seconds [13]. Additionally, the CTI margin has been fine-tuned and typically remains under 0.50 seconds in most scenarios. The convergence diagram for the 3-bus test system is depicted in Fig. 4.

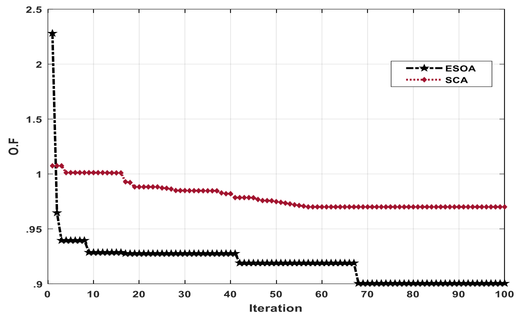

Fig. 4. Convergence diagram of ESOA algorithm compared to SCA

TABLE I
Observed Fault Current During a three-phase Fault in the Middle of the line

Primary relay	Current Fault(A)	Secondary relay	Current Fault(A)
1	400.70	5	2075.0
2	700.64	4	1621.7
3	760.17	1	1779.6
4	622.65	6	1911.5
5	558.13	3	1588.5
6	380.70	2	1855.4

TABLE II
Current Transformer Information and Setting Relays

Relay Number	CT Ratio	Tap setting
1	300/5	5
2	200/5	1.5
3	200/5	5
4	300/5	4
5	200/5	2
6	400/5	2.5

TABLE III
The Results of Different Algorithms in Determining the Optimal TMS, and PS for a 3-bus Network

Relay no.	ESOA		SCA [13]		IGWO [26]		HWOA [30]	
	TMS	PS	TMS	PS	TMS	PS	TMS	PS
1	0.1000	2.0	0.1070	2.5	0.1000	1.5000	0.0500	1.250
2	0.1061	2.5	2.0	0.1000	0.0500	1.250	0.1061	2.5
3	0.1000	2.5	3.0	0.1001	0.0500	1.250	0.1000	2.5
4	0.1000	2.0	2.5	0.1000	0.0500	1.250	0.1000	2.0
5	0.1000	1.0	2.5	0.1000	0.0612	1.756	0.1000	1.0
6	0.1000	2.0	1.5	0.1000	0.8065	1.250	0.1000	2.0
Total time	0.9034		1.4419		1.5990		1.4789	

TABLE IV
Coordination of Operation Time of Primary and Secondary Relays

Relay Number	CTI	Secondary relay operation time			Primary relay operation time		
		T_{op}	PS	TMS	T_{op}	PS	TMS
1	0.3096	0.2386	2.0	0.1000	0.5482	2.5	**0.1292**
2	0.4248	0.2592	2.5	0.1061	0.6840	2.5	**0.1324**
3	0.4324	0.2362	2.5	0.1000	0.6686	2.5	**0.1671**
4	0.3367	0.2459	2.0	0.1000	0.5826	2.5	**0.1303**
5	0.3141	0.1832	1.0	0.1000	0.4973	2.5	**0.1000**
6	0.4754	0.2786	2.0	0.1000	0.7541	2.0	**0.1484**

2-4-Simulation on the 15-bus Test System

The experimental system of 15- buses (B1 to (B15) includes seven DGs, twenty-one lines, and forty-two DOCRs, as shown in Fig. 5.

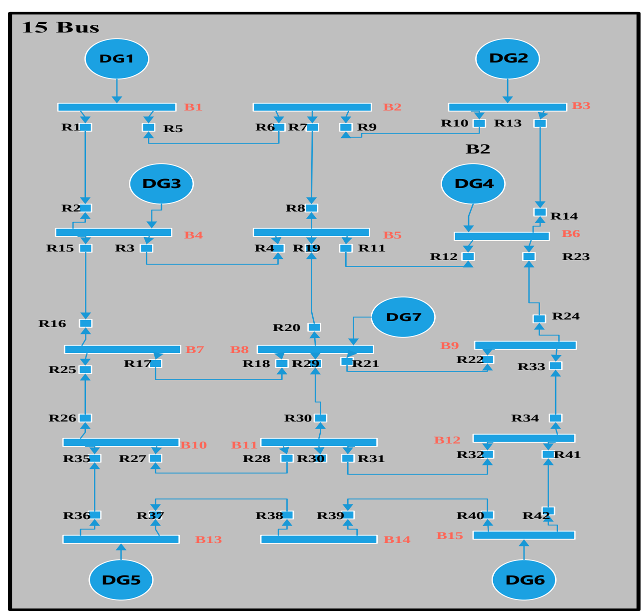

Fig. 5-15 bus Test system diagram

The DG connected in Fig. 5, the capacity is 200 MVA [13]. The system parameters and CT ratio for every relay align with the specifications outlined in the reference [13]. The relay plug settings vary from 0.5 to 2.5 in increments of 0.5 [13]. Table V displays the optimal values of TMS and PS, as identified by the ESOA algorithm for the 15-bus test system. A comparative analysis with IGWO [26], SCA [13], and SBB [30] is included. The proposed algorithm significantly reduces the overall operation time of primary relays compared to existing methods, highlighting the efficacy of the ESOA algorithm. CTI limits are confirmed in Table VI, with a CTI threshold of 0.3 seconds [13]. It should be highlighted that all relays stay within the specified limits, with the backup relay consistently activating at least 0.3 seconds following the primary relay's action. The convergence chart for the 15-bus test system can be observed in Fig. 6, showcasing the rapid convergence rate of ESOA, achieving convergence in 38% of the total iterations. The proposed algorithm achieves convergence in 1.943 seconds for the 15-bus test system.

The article provided highlights the technical specifications and performance of the proposed algorithm in the context of relay protection systems for a power distribution network. The short-circuit capacity of the DG connected in Fig. 5 is stated to be 200 MVA, with system parameters and CT ratios aligning with specified references. The relay plug settings range from 0.5 to 2.5 in increments of 0.5, as outlined in reference [13]. Table V presents optimal values of TMS and PS determined by the ESOA algorithm for the 15-bus test system, with a comparative analysis against other methods such as IGWO, SCA, and SBB.

TABLE V

Results for the 15-bus Test System

Relay no.	**ESOA**		**SCA [13]**		**IGWO [26]**		**SBB [30]**	
	TMS	PS	TMS	PS	TMS	PS	TMS	**PS**
1	0.1000	2.5	0.1001	2.8114	0.118	1.0	2.5	**0.100**
2	0.1158	1.5	0.1000	1.5104	0.101	1.0	1.5	**0.100**
3	0.1685	0.5	0.1048	1.7950	0.105	2.0	2.0	**0.124**
4	0.1000	2.0	0.1002	3.0701	0.115	1.0	1.5	**0.119**
5	0.1000	2.5	0.1003	1.5191	0.109	2.0	1.5	**0.152**
6	0.1000	2.5	0.1004	1.5367	0.108	2.0	0.5	**0.227**
7	0.1000	1.5	0.1000	2.4252	0.106	2.0	1.5	**0.152**
8	0.1248	1.5	0.1012	2.3699	0.108	1.5	2.0	**0.102**
9	0.1000	0.5	0.1030	2.0256	0.106	2.0	2.5	**0.117**
10	0.2143	0.5	0.1000	1.5244	0.112	1.5	2.5	**0.100**
11	0.1000	0.5	0.1002	2.5299	0.100	1.5	1.5	**0.111**
12	0.1568	2.0	0.1008	2.8068	0.100	1.5	0.5	**0.211**
13	0.1000	2.5	0.1004	2.4412	0.107	2.0	0.5	**0.259**
14	0.1130	1.0	0.1001	1.6608	0.111	1.0	1.5	**0.100**
15	0.1000	1.0	0.1000	1.5666	0.103	1.0	0.5	**0.207**
16	0.1432	0.5	0.1001	1.7755	0.100	1.5	0.5	**0.198**
17	0.1294	0.5	0.1008	1.5505	0.100	2.0	2.5	**0.100**
18	0.1620	0.5	0.1130	1.6783	0.105	1.0	1.5	**0.100**
19	0.1000	0.5	0.1003	2.1283	0.102	2.0	0.5	**0.218**
20	0.1341	2.5	0.1040	1.5726	0.100	1.5	2.0	**0.100**
21	0.1000	0.5	0.1002	2.0357	0.166	0.5	0.5	**0.189**
22	0.1500	1.0	0.1001	1.5461	0.109	1.5	2.0	**0.100**
23	0.1362	2.5	0.1000	1.5502	0.109	1.0	0.5	**0.188**
24	0.1000	0.5	0.1002	1.6656	0.100	1.5	2.5	**0.100**
25	0.1000	2.5	0.1002	1.5019	0.103	2.0	0.5	**0.258**
26	0.1000	2.5	0.1002	2.9163	0.112	1.5	2.5	**0.100**
27	0.1000	0.5	0.1002	2.1045	0.104	2.0	1.0	**0.185**
28	0.1414	0.5	0.1002	1.5029	0.105	2.5	2.0	**0.136**
29	0.1000	0.5	0.1017	1.6389	0.104	1.5	2.0	**0.100**
30	0.1000	0.5	0.1006	2.1199	0.101	2.0	0.5	**0.217**

31	0.1000	0.5	0.1000	2.0376	0.100	2.0	1.5	**0.138**
32	0.1000	2.5	0.1008	3.0167	0.105	1.5	2.0	**0.100**
33	0.1000	0.5	0.1012	1.5459	0.100	2.5	2.0	**0.137**
34	0.1154	2.0	0.1006	1.5149	0.107	2.5	1.0	**0.196**
35	0.1519	2.5	0.1002	1.9585	0.103	2.0	2.5	**0.109**
36	0.1374	1.5	0.1002	3.3271	0.100	2.0	1.0	**0.183**
37	0.1125	2.5	0.1016	1.7971	0.103	2.5	1.0	**0.213**
38	0.1000	1.0	0.1002	2.5855	0.106	2.5	1.0	**0.214**
39	0.1000	1.0	0.1004	2.7681	0.103	2.5	1.0	**0.198**
40	0.1000	0.5	0.1010	2.5714	0.104	2.5	2.0	**0.152**
41	0.1000	2.5	0.1003	1.7723	0.104	2.5	2.0	**0.146**
42	0.1000	1.5	0.1001	3.4527	0.104	1.5	1.0	**0.160**
Total time (sec)	**465111.**		**9535.11**		**12.227**		**15.335**	

TABLE VI

Coordination of Operation Time of Primary and Secondary Relays

Relay no	**CTI**	**Secondary relay operation time**			**Primary relay operation time**		
		T_{op}	PS	TMS	T_{op}	PS	**TMS**
1	0.7029	0.3108	2.5	0.1000	1.0137	2.5	**0.1105**
2	0.4184	0.3102	1.5	0.1158	0.7286	1.0	**0.1420**
3	0.3194	0.2902	0.5	0.1685	0.6096	2.5	**0.1120**
4	0.4605	0.3096	2.0	0.1000	0.7701	2.5	**0.1000**
5	0.3220	0.3238	2.5	0.1000	0.6458	2.0	**0.1380**
6	0.3124	0.3145	2.5	0.1000	0.6269	2.0	**0.1490**
7	0.3228	0.2592	1.5	0.1000	0.5820	2.5	**0.1103**
8	0.5771	0.3315	1.5	0.1248	0.9086	2.5	**0.1242**
9	0.3515	0.1729	0.5	0.1000	0.5244	1.5	**0.1314**
10	0.3774	0.3802	0.5	0.2143	0.7576	2.5	**0.1106**
11	0.3698	0.1881	0.5	0.1000	0.5580	1.0	**0.1474**
12	0.3647	0.4954	2.0	0.1568	0.8601	2.5	**0.1105**
13	0.3275	0.3201	2.5	0.1000	0.6476	2.5	**0.1241**
14	0.7746	0.2599	1.0	0.1130	1.0345	2.5	**0.1000**
15	0.3099	0.2282	1.0	0.1000	0.5381	1.0	**0.1088**
16	0.4889	0.2675	0.5	0.1432	0.7564	2.0	**0.1235**
17	0.4047	0.2265	0.5	0.1294	0.6312	2.5	**0.1000**
18	0.3227	0.2749	0.5	0.1620	0.5976	1.0	**0.1227**
19	0.5252	0.1721	0.5	0.1000	0.6973	2.5	**0.1243**
20	0.5582	0.4061	2.5	0.1341	0.9644	2.5	**0.1132**
21	0.7840	0.1699	0.5	0.1000	0.9540	2.0	**0.1000**
22	0.2938	0.3184	1.0	0.1500	0.6122	2.5	**0.1032**
23	0.7768	0.4441	2.5	0.1362	1.2209	2.0	**0.1252**
24	0.4735	0.1852	0.5	0.1000	0.6586	1.5	**0.1366**
25	0.3259	0.3375	2.5	0.1000	0.6635	2.5	**0.1056**
26	0.3843	0.3367	2.5	0.1000	0.7210	2.5	**0.1150**
27	0.3212	0.1924	0.5	0.1000	0.5136	2.0	**0.1091**
28	0.3431	0.2549	0.5	0.1414	0.5980	2.5	**0.1195**
29	0.3655	0.1701	0.5	0.1000	0.5356	1.0	**0.1357**
30	0.4319	0.1787	0.5	0.1000	0.6106	1.0	**0.1908**
31	0.5245	0.1741	0.5	0.1000	0.6986	2.5	**0.1000**
32	0.4785	0.3555	2.5	0.1000	0.8340	2.0	**0.1284**
33	0.3901	0.1849	0.5	0.1000	0.5750	1.0	**0.1908**
34	0.3679	0.3328	2.0	0.1154	0.7006	1.5	**0.2136**
35	1.0024	0.5365	2.5	0.1519	1.5389	2.5	**0.2467**

36	0.3144	0.3581	1.5	0.1374	0.6726	2.0	**0.1209**
37	1.2616	0.3654	2.5	0.1125	1.6270	2.5	**0.3006**
38	0.3221	0.2375	1.0	0.1000	0.5596	2.5	**0.1204**
39	0.2945	0.2356	1.0	0.1000	0.5301	1.5	**0.1553**
40	0.3089	0.1838	0.5	0.1000	0.4927	1.5	**0.1265**
41	0.3209	0.2990	2.5	0.1000	0.6199	2.5	**0.1180**
42	0.5877	0.2603	1.5	0.1000	0.8481	2.5	**0.1000**

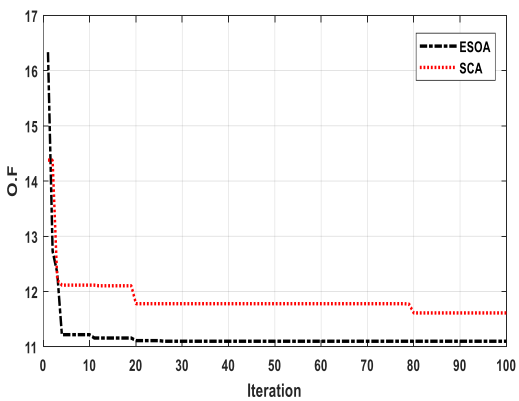

Fig. 6. ESOA algorithm convergence curve for 15-bus test system

5-Conclusions

In this paper, the study presents a novel approach to enhancing the coordination of protective relays in complex ring distribution systems with distributed DG generation resources. The method utilizes ESOA to determine the optimal settings for DOCRs, specifically PS and TMS values. Notably, the ESOA demonstrates rapid convergence and effective avoidance of local optima. The proposed technique is evaluated on 3 and 15-bus test systems and compared against several recent optimization algorithms (SCA [13], IGWO [17], HWOA [21], SBB [38]). The findings suggest that the new method surpasses current methods by reducing the time needed for coordination among primary relays and enhancing the coordination interval between primary and backup relay pairs. By adopting this algorithm, superior solutions can be achieved more efficiently compared to current methods. Future research may explore further enhancements by integrating SCA with other advanced optimization techniques for complex system structures.

II. Conflict of Interest

Professor Zahra Moravej, the corresponding author of this paper is the Assistant Editor of Journal of Modeling & Simulation in Electrical & Electronics Engineering but she has no involvement in the peer review process used to assess this work submitted to the Journal. This paper was assessed, and the corresponding peer review managed by Prof. Nima Amjady, an Editor-in-Chief in Journal of Modeling & Simulation in Electrical & Electronics Engineering.

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