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Application of a Continuous Particle Swarm Optimization (CPSO) for the Optimal Coordination of Overcurrent Relays Considering a Penalty Method

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Abstract: In an electrical power system, the coordination of the overcurrent relays plays an important role in protecting the electrical system by providing primary as well as backup protection. To reduce power outages, the coordination between these relays should be kept at the optimum value to minimize the total operating time and ensure that the least damage occurs under fault conditions. It is also imperative to ensure that the relay setting does not create an unintentional operation and consecutive sympathy trips. In a power system protection coordination problem, the objective function to be optimized is the sum of the total operating time of all main relays. In this paper, the coordination of overcurrent relays in a ring fed distribution system is formulated as an optimization problem. Coordination is performed using proposed continuous particle swarm optimization. In order to enhance and improve the quality of this solution a local search algorithm (LSA) is implanted into the original particle swarm algorithm (PSO) and, in addition to the constraints, these are amalgamated into the fitness function via the penalty method. The results achieved from the continuous particle swarm optimization algorithm (CPSO) are compared with other evolutionary optimization algorithms (EA) and this comparison showed that the proposed scheme is competent in dealing with the relevant problems. From further analyzing the obtained results, it was found that the continuous particle swarm approach provides the most globally optimum solution.

Keywords: continuous particle swarm optimization (CPSO); overcurrent relay coordination (OCR); time multiplier setting (TMS); power system protection

1. Introduction

In an electric power system, the overcurrent relays provide both primary and backup protection to maintain the system reliable and healthy, and to ensure minimum exposure to the healthy portion of the system. In a transmission system, sometimes this type of relay is used as backup protection when deploying distance protection as the primary protection. The overcurrent relays are a useful choice for telecommunication networks, industries, and consumers in terms of offering fast protection and from an economic point of view. Once the overcurrent relays fulfil the requirements of reliability, sensitivity, and selectivity they can operate quickly and without mal-operating issues by isolating the faulty portion of the system with the help of circuit breakers [1]. The main aim for the coordination of relays is to set the relays so that the whole system receives both the primary and backup protection if the level of load and fault current are known. Therefore, accurate coordination of the overcurrent relays is necessary. Coordination amongst these OCRs should be maintained at the optimum value to reduce the overall operating time and ensure that the minimum number of power outages occur during fault conditions. Hence, the coordination of OCRs is formulated as a minimization problem [2,3]. In the research undertaken by [4], a technical survey was presented for the optimal coordination of time overcurrent relays. In the past, different optimization algorithms have been investigated in order to deal with the problem of optimum coordination of relays. A linear programming technique was applied in the study by [5]. In experiments described in [6], a random search method was used. In [7], an evolutionary algorithm was applied for the first time to deal with the relay coordination problem. In various papers [8–13], different versions of a genetic algorithm have been applied to improve the convergence characteristics of genetic algorithms overall. A different version of the particle swarm optimization technique has also been suggested in order to achieve the optimum values for relay coordination [14–19]. In the research of [20], five different versions of the Modified Differential Evolution Algorithm (MDE) were proposed to solve the coordination problem in order to figure out the best performance of the MDE with respect to other algorithms. The artificial bee colony technique was utilized in research by [21]. In [22], a hybrid evolutionary algorithm based on tabu search was used for optimum relay coordination. Reference [23] suggested that the coordination of the overcurrent relay is formulated as a mixed integer nonlinear program by employing a population-based heuristic search algorithm, which regards optimization process as a search of optimal solution by a seeker population. In [24], to improve and enhance the quality of solution the chaos theory is incorporated to the conventional firefly algorithm to figure out the coordination problem. The coordination problem is solved using different metaheuristic method is [25]. Reference [26] suggests that the coordination of the overcurrent relay is formulated as a nonlinear program by employing a group search optimization algorithm. In the paper by [27], the hybridized symbiotic organism search method is used to deal with the directional overcurrent relay problem. The authors found the optimal coordination of directional overcurrent relays by using a firefly algorithm [28]. In the paper by [29], distributed system protection coordination is investigated based on directional overcurrent protection with an inverse time characteristic. Reference [30] designed a protection scheme for a distribution system considering different modes of operation. In [31], a robust optimization strategy was proposed for the protection of micro-grids using microprocessor-based relays. The major deficiency of the previously proposed methods, including both the mathematical and evolutionary approaches, is the possibility of convergence to values which may not be a global optimum but rather are stuck at a local optimum. To solve this issue, a continuous particle swarm optimization (CPSO) is examined in this study for the optimum coordination of overcurrent relays, and is compared with continuous genetic algorithms (CGA), genetic algorithms (GA), the dual and two phase simplex methods (DSM, TPSM), fire fly algorithms (FA), and chaotic firefly algorithms (CFA).

This paper proposes that a continuous particle swarm optimization (CPSO), using the penalty method, can achieve the optimum coordination of overcurrent relays. To enhance and improve the quality of the solutions the CPSO scheme is assimilated, thereby preventing the search from becoming stuck in local minima. The proposed algorithm has a high search capability and convergence speed as compared to other evolutionary techniques, and these characteristics make the population member of the CPSO more discriminative in finding the optimal solution than other evolutionary techniques. To the best of the authors' knowledge the CPSO has not previously been implemented for the optimization of the overcurrent relay coordination problem, investigation into which is presented in this paper. The main aim of this paper is to find the optimal values of the Time Multiplier Setting (TMS) to minimize the operating time of overcurrent relays under several constraints, such as relay setting and backup constraints.

2. Formulation of the Overcurrent Relay Problem

In a multi- or single-source loop system the coordination of the directional overcurrent relays is formulated as an optimization problem. However, the coordination problem has an objective function and constraints that should satisfy the distinct constraints:

$$minf = \sum_{j=1}^{n} w_j T_{j,k} \tag{1}$$

where the parameters w_i and T_i are the weight and operation of the relays. For all the relays the value $w_i = 1$. Therefore, the characteristic curve for the operating relay R_i can be selected from the IEC standards and could be defined as follows:

$$T_{op} = TMS_i\left(\frac{\alpha}{(\frac{If_j}{Ip_j})^k - 1}\right) \tag{2}$$

where α and k are constant parameters which define the relay characteristic and are assumed as $\alpha = 0.14$ and $k = 0.02$ for a normal inverse type relay. The variables TMS_i and Ip_j are the Time Multiplier Setting and pickup current of the ith relay, while If_i is the fault current flowing through relay R_i:

$$PSM = \frac{I_{fj}}{Ip_j} \tag{3}$$

where Ip_j is the primary pickup current and PSM stands for the Plug Setting Multiplier:

$$T_{op} = TMS_i\left(\frac{\alpha}{(PSM)^k - 1}\right) \tag{4}$$

The above problem, as represented in Equation (4), is a nonlinear problem in nature. By taking the plug setting of the relay as fixed, and the operating time of the relays, and a linear function of the TMS, the coordination can be expressed as linear programming. In linear programming only the TMS is continuous while the rest of the parameters are constant, so Equation (4) becomes:

$$T_{op} = a_\rho(TMS_i) \tag{5}$$

where:

$$a_\rho = \frac{\alpha}{(PSM)^k - 1} \tag{6}$$

Hence the objective function can be formulated as:

$$minf = \sum_{i=1}^{n} a_\rho(TMS_i) \tag{7}$$

Constraints

The objective of minimizing the total operating times of the relays should be achieved under two types of constraints; the constraints of the relay setting parameters and coordination constraints.

The first type consists of the boundaries of the TMS, whereas the second type is pertinent to the coordination of the primary and backup relays. The boundary on the relay setting parameters imposes constraints (8) on the choice of relay parameters:

$$TMS_i^{min} \leq TMS_i \leq TMS_i^{max} \tag{8}$$

The second type of constraint is pertinent to the adjustment of the operating time of the primary and backup relays. Since the fault would be sensed by both the primary and the backup relays simultaneously, in order to avoid mal-operation the coordination time interval (CTI) should be taken into account in the tripping action. The CTI includes the sum of the operating time of the circuit breaker (CB) associated with the primary relay, the overshoot time of the backup relay, and an appropriate safety margin. Therefore, according to Figure 1, the backup relay R_j should operate later than the primary relay R_i [32]. This is critical for satisfying the requirement for selectivity of the primary and backup relays. The coordination constraint is defined as follows:

$$T_j \geq T_i + \text{CTI} \tag{9}$$

where T_i and T_j are the operating times of the primary and backup relays, respectively, for a fault occurring in front of the primary relay. The value of the CTI could vary from 0.2 to 0.5 s, depending upon different circumstances and factors.

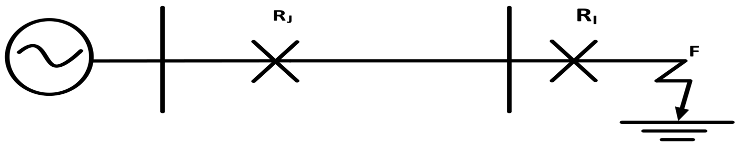

Figure 1. A single end radial distribution system.

3. Continuous Particle Swarm Optimization

PSO is one of the EA techniques that is, in basic terms, inspired by the swarm behavior associated with fish schooling and bird flocking [33–37]. The task of the PSO algorithm is to control the agents or particle population, and these agents or particles are called a "swarm". Each particle serves as the possible result of the objective function under consideration. The particles in the population can memorize the current position with respect to the objective function, and the best position and velocity as visited during its fish flying tour or bird flocking tour in the group will be referred to as the "personal best position" (p_{best}). The tour will find the best position among all the possible solutions and this is referred to as the "global best position" (g_{best}). Some features of the continuous particle swarm optimization are found in the literature [38–40]. In the literature survey, PSO in its standard form has been widely used for unconstrained optimization projects. In this paper two modifications have been added to the authentic PSO algorithm; the penalty method and the initialization of PSO with a local search. As CPSO basically solves the unconstrained optimization problem, to convert the relay coordination problem into an unconstrained optimization problem a new objective function is defined via the penalty method. It is probable that the PSO executes such a bearded exploration that it generates immature results, which is an insufficient solution. To produce a more satisfactory solution, it is necessary to insert a local search algorithm into the original PSO. In this paper, the author inserted a local search alongside the global best position vector. The CPSO method proposed for the coordination of the overcurrent relay problem deals with each particle position on three key vectors; velocity (v_i), position (x_i) and open facility (y_i), where v_i expresses the ith velocity vector in the swarm, x_i represents the ith position vector in swarm, and y_i expresses the opening facilities determined based on the position vector (x_i). For N number of facility problems, each particle contains N number of dimensions so the position vector x_i approaches the continuous value for N facilities, $x_i = [x_{i1}, x_{i2}, \ldots, x_{in}]$, although it does not describe a candidate solution to calculate the total cost. To create a candidate solution, the position vector is reciprocated to a binary variable, $y_i \leftarrow x_i$. Specifically, a discrete set is formed from the continuous set for generating a candidate solution. The fitness of the ith particle is calculated with the help of the open facility vector (y_i). The personal best fitness value of the ith particle p_i is expressed by fi^{bp}. At the beginning the personal best vector is computerized with the position vector ($p_i = x_i$), where p_i is the position vector and the fitness values of the personal bests are equal to the fitness of the positions, $fi^k = f(x_i^k)$. Then, the best particle in the whole swarm with respect to the fitness value is selected with the named global best and expressed as g_i. The global best, $fb^k = f(y \leftarrow g)$ can be achieved by finding the best of the personal bests over the whole swarm, $fi^k = min\{f(x_i^k)\}$, with its corresponding position vector xg which is to be used for $g = xg$ and $yg = y$ where yg express the y_i vector of the global best. Then, the velocity of the individual particle is updated based on its personal best and the global best in the following way (10):

$$v_{ik}^{(t+1)} = (w.v_{ik}^t + c_1 r_1 (p_{ik}^t - x_{ik}^t) + c_2 r_2 (g_k^t - x_{ik}^t)) \tag{10}$$

where w, c_1 and c_2 are the inertia weight and learning factors, also known as the social and cognitive parameters respectively, while r_1 and r_2 are random numbers with limits between [0, 1]. The job of w is to control the influence of the preceding velocity on the present one. The next step is to update the positions that are given as follows:

$$x_{ik}^{(t+1)} = x_{ik}^t + v_{ik}^{t+1} \tag{11}$$

Algorithm 1 scale equations to the same size as the rest of the text

1. Set parameter w_{min}, w_{max}, c_1, c_2 and r_1, r_2 of PSO
2. Initialize population of particles as having positions X and velocities V
3. Set iteration $k = 1$
4. Calculate fitness of particles $F_i^k = f(x_i^k)$ $\forall i$ and find the index of the best particle b
5. Select $Pbest_i^k = x_i^k, \forall i$ and $Gbest^k = x_b^k$
6. $w = w_{max} - k \times (w_{max} - w_{min})$/Maxite
7. Update velocity and position of particles

$v_{ik}^{(t+1)} = (w.v_{ik}^t + c_1 r_1 (p_{ik}^t - x_{ik}^t) + c_2 r_2 (g_k^t - x_{ik}^t))$ $x_{ik}^{(t+1)} = x_{ik}^t + v_{ik}^{t+1}$

8. Update $Pbest$ population
9. If $F_i^{k+1} < F_i^k$ then $Pbest_i^{k+1} = x_i^{k+1}$

Or else

$Pbest_i^{k+1} = Pbest_i^k$

10. If $Fb_{b1}^{k+1} < F_b^k$ then

$Gbestb^{k+1} = Pbest_{b1}^{k+1}$ and set $b = b1$

Or else

$Gbestb^{k+1} = Pbest^k$

11. If K < Maxite then $K = K + 1$ and go to step 6
12. End while
13. End PSO-LS

Or go to step 14

14. Display optimum solution as $Gbest^k$

After getting the updated position values of all the particles, if the prearranged meeting condition is not fulfilled the corresponding open facility vectors are resolved with their fitness values to start a new repetition, as the PSO produces a premature and unsatisfactory solution as a result of a rough search. In this regard there is a need to implant a local search algorithm (LSA) into the PSO to produce more satisfactory solutions. At the end of each iteration of the PSO the global best that is found is adopted as the initial solution by the LSA. The Flow chart of CPSO is shown in Figure 2, and the pseudocode of the proposed algorithm (CPSO) is also given above in algorithm 1 [39–41].

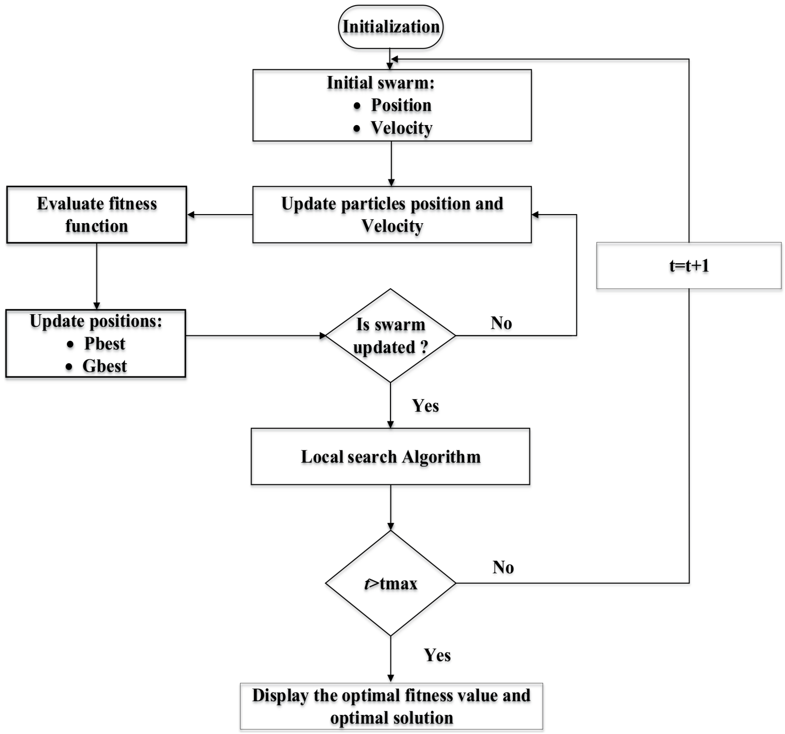

Figure 2. Flow chart of continuous particle swarm optimization (CPSO).

4. Results and Discussion

To study the continuous particle swarm optimization algorithm, four case studies have been considered. The system details of all case studies can be found in earlier works [9,24,42,43].

4.1. Case I

In this case a single end fed system with four overcurrent relay is used, as shown in Figure 3. The relays R_1 and R_4 are non-directional while relays R_2 and R_3 have a directional feature. Two faults are taken into consideration: A and B. At bus 2 the maximum load current, including overload, is 600 A. The current transformer (CT) and plug setting ratio for each relay is 300:1 and 1, respectively. The maximum fault current is 4000 A. For each relay the minimum operating time (MOP) is 0.1 s. The primary and backup relation of the relays is shown in Table 1. Table 2 provides the detail of the a_ρ constant and current seen by the relays for different fault points. In this case the total number of constraints is six; four constraints emerge as a result of the boundaries of the relay operation and two constraints emerge as a result of the coordination condition. The TMS range is 0.025–1.2. The CTI is 0.3 s. The TMSs of all four relays are x_1–x_4. The optimal operations of the relays obtained by the proposed algorithm are given in Table 3, which also provides the comparative results of the proposed algorithm with a previously published algorithm described in the literature. According to Table 3, the proposed algorithm is a better solution for the current case.

Table 1. Primary and backup relationships of the relays for Case I.

Fault Point	Primary Relay	Backup Relay
A	2	4
B	3	1

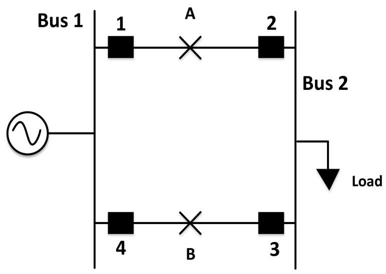

Figure 3. A single end system with parallel feeders.

Table 2. a_ρ Constants and relay currents for Case I.

Fault Point		1	2	3	4
A	I_{relay}	10	3.33	-	3.33
	a_ρ	2.97	5.749	-	5.749
B	I_{relay}	3.33	-	3.33	10
	a_ρ	5.749	-	5.749	2.97

- Indicates the fault is not seen by the relay.

The objective function for minimization can be stated as:

$$z = 8.764x_1 + 5.749x_2 + 5.749x_3 + 8.764x_4 \tag{12}$$

The constraints that emerge because of the MOPs of the relays are:

$$2.97x_1 \geq 0.1 \tag{13}$$

$$5.749x_2 \geq 0.1 \tag{14}$$

$$5.749x_3 \geq 0.1 \tag{15}$$

$$2.97x_4 \geq 0.1 \tag{16}$$

The constraints explained by Equations (14) and (15) violate the constraints of the minimum value of the TMS. The minimum limit on the TMS is 0.025. Hence, these constraints are rewritten as:

$$x_2 \geq 0.025 \tag{17}$$

$$x_3 \geq 0.025 \tag{18}$$

The constraints that emerge because of coordination are:

$$5.749x_4 - 5.749x_2 \geq 0.3 \tag{19}$$

$$5.749x_1 - 5.749x_3 \geq 0.3 \tag{20}$$

The objective function was solved using a continuous particle swarm algorithm. In each case study the number of iterations and population size are both taken to be 300, the minimum and maximum inertia weights are 0.4 and 0.9, and the acceleration factor (c_1, c_2) is 2. In addition, r_1 and r_2 are between [0, 1]. As can be seen in Table 3, the proposed method works and it performs better as compared to other evolutionary techniques. The proposed algorithm gives an optimal solution and lower total operating time ($\sum T_{op}$) and can solve the overcurrent relay problem faster and in a superior way. The values of the TMSs obtained are found to satisfy all the constraints. They give the minimum operating time of the relays for any fault location and also ensure proper coordination. Figure 4 depicts the graphical representation of the optimized Time Multiplier Setting in the literature.

Table 3. Comparison of the optimized TMS by the proposed method with the literature for Case I.

TMS	GA 1 [42]	GA 2 [42]	SM [42]	DSM [43]	CPSO
TMS 1	0.081	0.168	0.07718	0.15	0.078
TMS 2	0.025	0.0250	0.0250	0.041	0.0250
TMS 3	0.025	0.0250	0.0250	0.041	0.0250
TMS 4	0.081	0.168	0.07718	0.15	0.078
T_{op} z (s)	**1.70**	**3.23**	**1.64**	**3.09**	**1.65**

GA 1: Solution 1 using GA; GA 2: Solution 2 using GA.

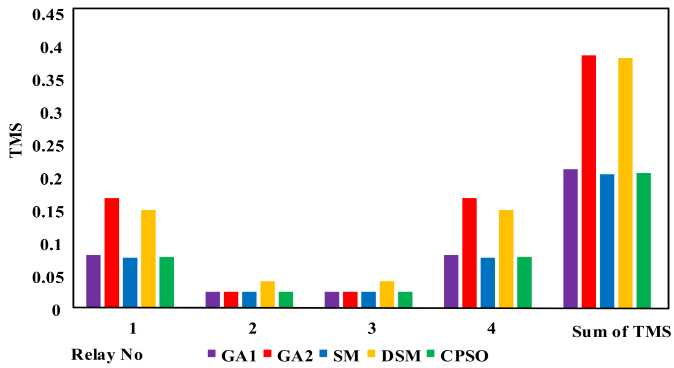

Figure 4. Graphical representation of the optimized TMS compared with the literature for Case I.

The convergence characteristic graph for the total operating time (TOP) obtained for Case 1 during the simulation is shown in Figure 5, demonstrating that the convergence is faster and achieved a better value for the objective function (z) in fewer iterations. The total net gain in time achieved by the proposed algorithm is shown in Table 4, which demonstrates the superiority and advantages of CPSO over the techniques mentioned in the literature.

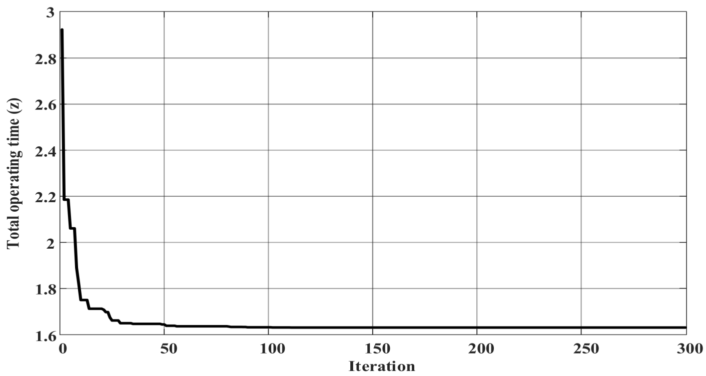

Figure 5. Convergence characteristic graph for Case I.

Table 4. Comparison of the total net gain in time achieved by the proposed algorithm with the literature for Case I.

Net Gain	CPSO/GA	CPSO/GA	CPSO/DSM
$\sum\Delta(t)s$	0.05	1.58	1.44

4.2. Case II

In this case a parallel distribution system that is fed from a single end with five overcurrent relays is shown in Figure 6. Five different fault points were considered with a negligible load current as compared to the fault current. The primary and backup relation of the relays for five different fault points are given in Table 5. The plug setting and CT ratios are illustrated in Table 6. The a_ρ constants and current seen by the relays for the different fault locations are given in Table 7. In this case there are nine constraints in total; five of these constraints arise as a result of boundaries of the relay operation and the other four constraints emerge as a result of the coordination condition. The MOP of each relay is 0.1 s and the CTI is 0.2 s. The TMSs of all the relays is x_1–x_5.

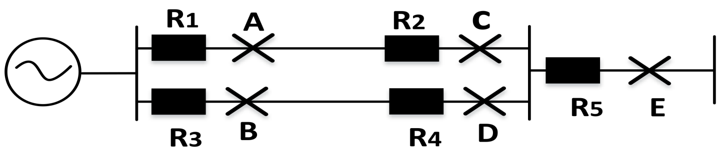

Figure 6. A single end fed parallel feeder distribution system.

Table 5. Primary and backup relationships of the relays for Case II.

Fault Point	Primary Relay	Backup Relay
A	1	-
B	3	-
C	1, 2	-, 3
D	3, 4	-, 1
E	5	1, 3

- Indicates no back up relay.

Table 6. CT ratios and plug settings of the relays for Case II.

Relay	CT Ratio	Plug Setting
1	300/1	1
2	300/1	1
3	300/1	1
4	300/1	1
5	100/1	1

Table 7. a_ρ Constants and relay currents for Case II.

Fault Point		Relay				
		1	2	3	4	5
A	I_{relay}	42.34	-	-	-	-
	a_ρ	1.799	-	-	-	-
B	I_{relay}	-	42.34	-	-	-
	a_ρ	-	1.799	-	-	-
C	I_{relay}	4.876	4.876	4.876	-	-
	a_ρ	4.348	4.348	4.348	-	-
D	I_{relay}	4.876	-	4.876	4.876	-
	a_ρ	4.348	-	4.348	4.348	-
E	I_{relay}	4.876	-	4.876	-	29.25
	a_ρ	4.348	-	4.348	-	2.004

- Indicates the fault is not seen by the relay.

The optimization problem can be stated as:

$$z = 14.843x_1 + 6.147x_2 + 13.044x_3 + 4.348x_4 + 2.004x_5 \quad (21)$$

The constraints that emerge because of the MOP of the relays are:

$$1.799x_1 \geq 0.1 \quad (22)$$

$$4.348x_2 \geq 0.1 \quad (23)$$

$$1.799x_3 \geq 0.1 \quad (24)$$

$$4.348x_4 \geq 0.1 \quad (25)$$

$$2.004x_5 \geq 0.1 \quad (26)$$

The constraints that emerge because of coordination are:

$$4.348x_3 - 4.348x_2 \geq 0.2 \quad (27)$$

$$4.348x_1 - 4.348x_4 \geq 0.2 \quad (28)$$

$$4.348x_1 - 2.004x_5 \geq 0.2 \quad (29)$$

$$4.348x_3 - 2.004x_5 \geq 0.2 \quad (30)$$

The objective function was solved using the proposed algorithm and keeping the same parameters. Table 8 provides the results of the proposed method for this case and a comparison with previous works, respectively. In this case no miscoordination or violations were found. All the relays will initiate operation at a minimum operating time while maintaining coordination. The time required by the relay R_1 to initiate its operation is lowest for a fault at point A (0.214 s) and will require extra time for a fault at point D (0.43 s) and E (0.3 s). Hence, at fault point A the relay R_1 will operate first while at fault points D and E, relays R_4 and R_5 should operate first. If the expected relay fails to activate, then relay R_1 should take over the tripping action. The graphical representation of the optimized TMS is shown in Figure 7, and demonstrates that the TMS is optimized up to the optimum value. Figure 8 shows the convergence characteristic graph obtained during the simulation. According to Tables 8 and 9, the proposed method finds a better solution for this case.

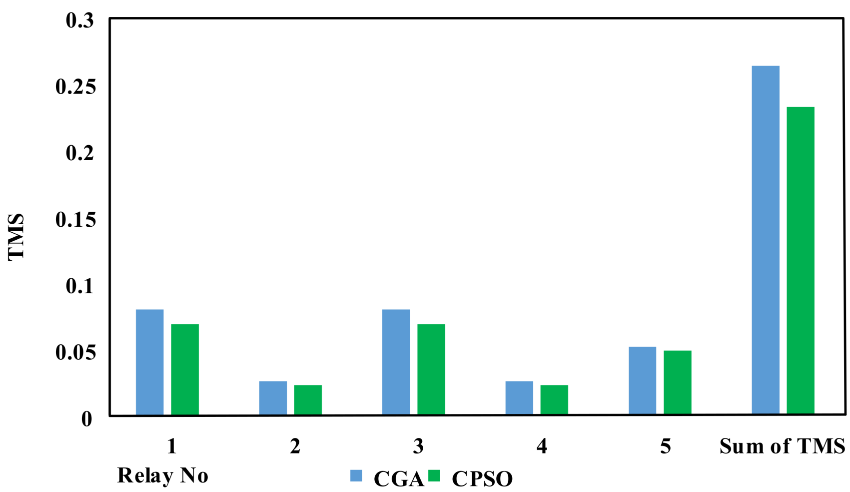

Figure 7. Graphical representation of the optimized TMS compared with the literature for Case II.

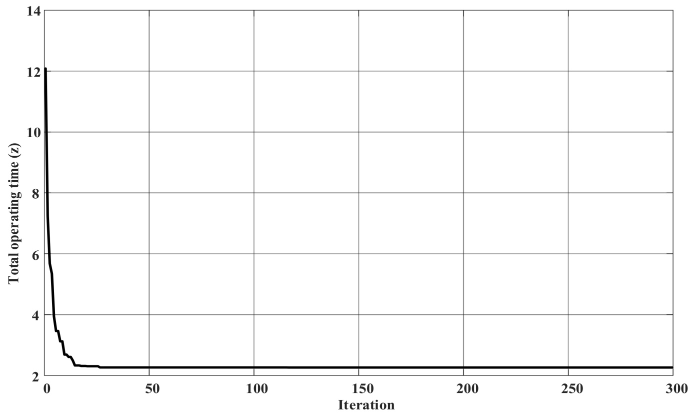

Figure 8. Convergence characteristic graph for Case II.

Table 8. Comparison of the proposed method with the literature for Case II.

TMS	CGA [9]	CPSO
TMS 1	0.08	0.0690
TMS 2	0.026	0.0230
TMS 3	0.08	0.0690
TMS 4	0.026	0.0230
TMS 5	0.052	0.0499
T_{op} (z)	**2.52**	**2.21**

Table 9. Total net gain in time achieved by the proposed algorithm compared with the literature for Case II.

Net Gain	$\sum\Delta(t)s$
CPSO/CGA	0.31

4.3. Case III

A parallel distribution system that is fed from a single end with five overcurrent relays is shown in Figure 9. The current transfer ratio and plug setting of the relays are assumed to be 300:1 and 1, respectively. Two fault currents are imposed in the middle of the lines, i.e., A and B. For the fault at A backup protection will be provided by relay R_3 to relay R_2 while for the fault at B the backup will be provided by relay R_1 to R_4, and for the fault at C back up will be provided by R_1, R_3 to R_5. In this case, the total number of constraints is nine; five constraints arise as a result of the boundaries of the relay operation and four constraints emerge as a result of the coordination condition. The MOP of each relay is 0.1 s. The CTI is 0.2 s. The TMSs of all the relays is x_1–x_5. The currents seen by the relays and a_ρ constants for different fault locations are given in Table 10.

Table 10. a_ρ Constants and relay currents for Case II.

Fault Point		Relay				
		1	2	3	4	5
A	I_{relay}	9.059	3.019	3.019	-	-
	a_ρ	3.106	6.265	6.265	-	-
B	I_{relay}	3.019	-	9.059	3.019	-
	a_ρ	6.265	-	3.106	6.265	-
C	I_{relay}	4.875	-	4.875	-	29.25
	a_ρ	4.348	-	4.348	-	2.004

- Indicates no fault current seen by the relay.

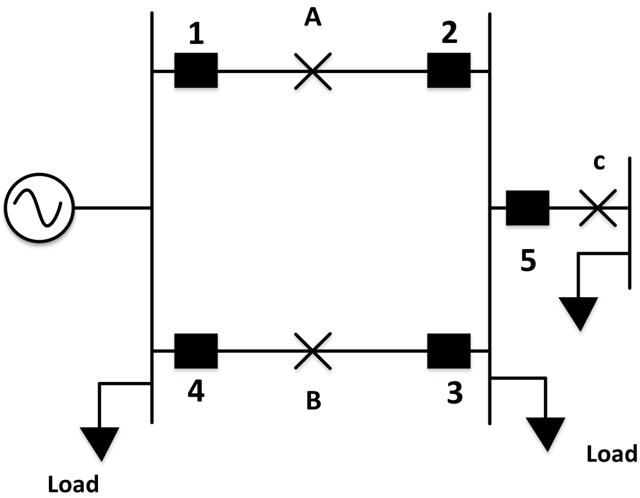

Figure 9. A single end parallel feeder distribution system.

In this case two optimization problems are derived from Table 10 for comparison with the other published techniques mentioned in the literature and can be stated as:

$$\min z = 13.719x_1 + 6.265x_2 + 13.719x_3 + 6.265x_4 \ + 2.004x_5 \quad (31)$$

$$\min z = 3.106x_1 + 6.265x_2 + 3.106x_3 + 6.265x_4 \ + 2.004x_5 \quad (32)$$

The constraints that emerge because of the MOP of the relays are:

$$3.106x_1 \geq 0.1 \quad (33)$$

$$6.265x_2 \geq 0.1 \quad (34)$$

$$3.106x_3 \geq 0.1 \quad (35)$$

$$6.265x_4 \geq 0.1 \quad (36)$$

$$2.004x_5 \geq 0.1 \quad (37)$$

The constraints that emerge because of coordination are:

$$6.265x_3 - 6.265x_2 \geq 0.2 \quad (38)$$

$$6.265x_1 - 6.265x_4 \geq 0.2 \quad (39)$$

$$4.348x_1 - 2.004x_5 \geq 0.2 \quad (40)$$

$$4.348x_3 - 2.004x_5 \geq 0.2 \quad (41)$$

The problem was solved using the CPSO algorithm. The optimized graphical representation and convergence characteristic graph for this case is shown in Figures 10–12, which demonstrate that the proposed method yields a faster convergence and a better solution for the objective function "z". Table 11 provides the comparative results of the proposed algorithm with a previous optimization algorithm explained in the literature, which ensures that for the fault at point A, relay R_1 is first to operate, whereas for the fault at point B relay R_4 will operate, and for the fault at point C the relay R_5 should get the first chance to operate. The total net gain in time achieved by the proposed algorithm is tabulated in Table 12.

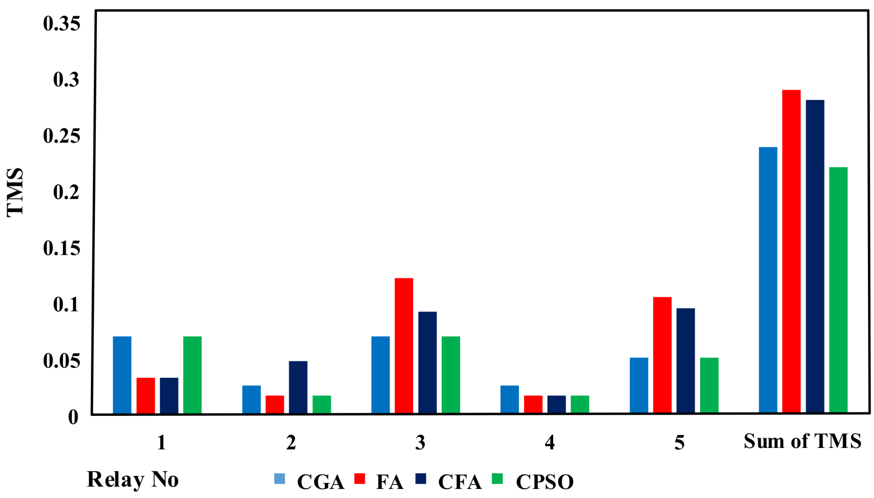

Figure 10. Graphical representation of the optimized TMS compared with the literature for Case III.

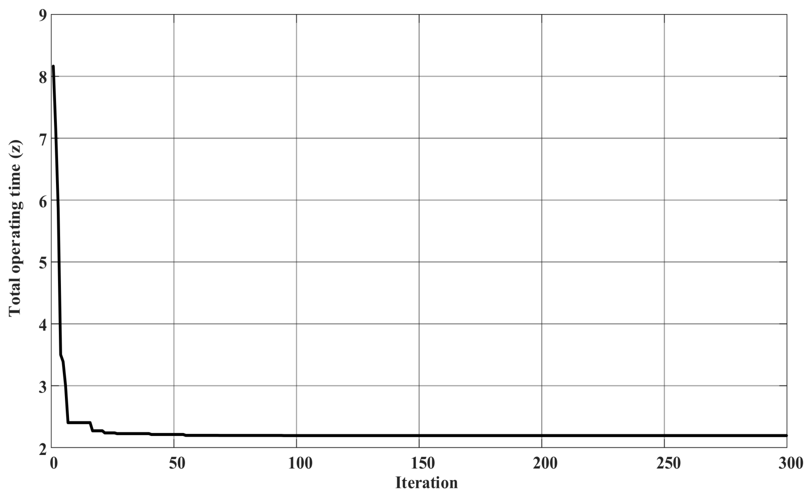

Figure 11. Convergence characteristic graph of the objective function *z* (31) for Case III.

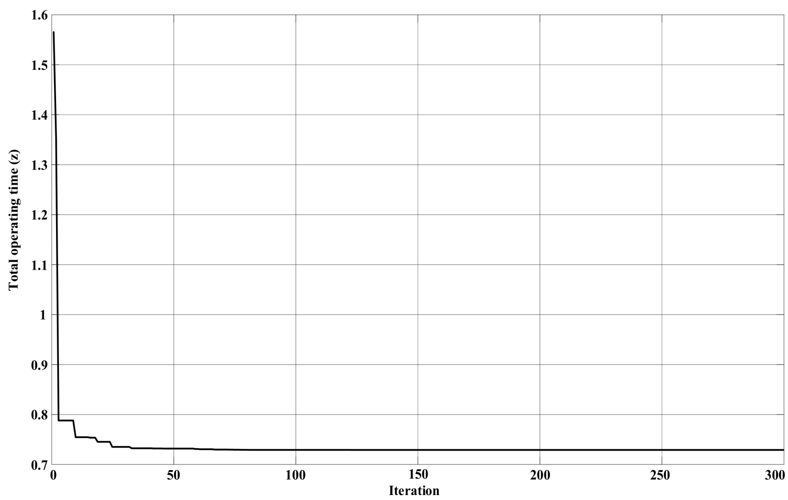

Figure 12. Convergence characteristic graph of the objective function *z* (32) for Case III.

Table 11. Comparison of the optimized TMS with the literature for Case III.

TMS	TPSM [44]	CPSO [1]	FA [24]	CFA [24]	CPSO [2]
TMS 1	0.069	0.069	0.032	0.032	0.069
TMS 2	0.025	0.0160	0.0160	0.047	0.0160
TMS 3	0.069	0.069	0.121	0.091	0.069
TMS 4	0.025	0.0160	0.0160	0.0160	0.0160
TMS 5	0.0499	0.0499	0.104	0.094	0.0499
$T_{op}\ z$ **(s)**	**2.27**	**2.17**	**1.73**	**1.63**	**0.7291**

[1] For the objective function mentioned in Equation (31); [2] for the objective function mentioned in Equation (32).

Table 12. Comparison of the total net gain in time achieved by the proposed algorithm compared with the literature for Case III.

Net Gain	$\sum\Delta(t)s$
CPSO [1]/TPSM	0.10
CPSO [2]/FA	1.01
CPSO [2]/CFA	0.91

[1] For the objective function mentioned in Equation (31); [2] for the objective function mentioned in Equation (32).

4.4. Case IV

In this case, a multi-loop system with six overcurrent relays and with negligible line charging admittances is considered, as shown in Figure 13. A set of various primary and backup relays are designed which are subject to the locations of the various faults. These configurations are contingent on the path of the fault current in the different feeders. The line data of the system are shown in Table 13. Four different fault positions are considered. The primary and backup relationships of the relays for the four fault points are given in Table 14. The CT ratios and plug setting are illustrated in Table 15. The a_p constants currents seen by the relays for the different fault locations are given in Table 16. In this case study the total number of constraints is eleven; six constraints emerge as a result of the boundaries of the relay operation and five constraints emerge as a result of the coordination condition. The MOP of each relay is 0.1, while the range of the TMS is 0.025–1.2, except x_1 which is 0.027. The CTI is 0.3 s. The TMSs of all six relays are x_1–x_6. The optimal operation of the relays as achieved by the proposed algorithm is given in Table 17, which also provides the comparative results of the proposed algorithm with a previous optimization algorithm explained in the literature. According to Table 18, the proposed algorithm achieves a better solution for this case.

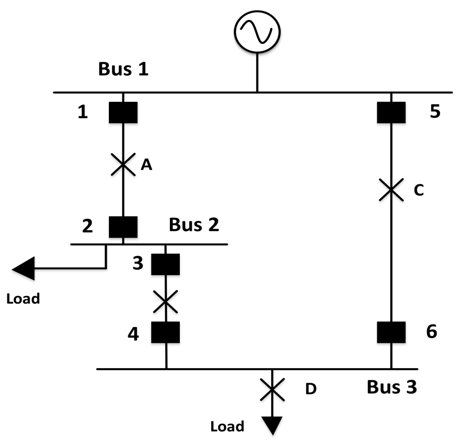

Figure 13. A multi-loop distribution system.

Table 13. Line data for Case IV.

Line	Impedance (Ω)
1-2	0.08j1
2-3	0.08 + j1
1-3	0.16 + j2

Table 14. Primary and backup relationships of the relays for Case IV.

Fault Point	Primary Relay	Backup Relay
A	1, 2	-, 4
B	3, 4	1, 5
C	5, 6	-, 3
D	3, 5	1, -

- Indicates no back up relay.

Table 15. CT ratios and plug settings of the relays for Case IV.

Relay	CT Ratio	Plug Setting
1	1000/1	1
2	300/1	1
3	1000/1	1
4	600/1	1
5	600/1	1
6	600/1	1

Table 16. a_ρ Constants and relay currents for Case IV.

Fault Point		Relay					
		1	2	3	4	5	6
A	I_{relay}	6.579	3.13	-	1.565	1.565	-
	a_ρ	3.646	6.065	-	15.55	15.55	-
B	I_{relay}	2.193	-	2.193	2.193	2.193	-
	a_ρ	8.844	-	8.844	8.844	8.844	-
C	I_{relay}	1.096	-	1.096	-	5.482	1.827
	a_ρ	75.91	-	75.91	-	4.044	11.539
D	I_{relay}	1.644	-	1.644	-	2.741	-
	a_ρ	13.99	-	13.99	-	6.872	-

- Indicates the fault is not seen by the relay.

Table 17. Comparison of the optimized TMS by the proposed method with the literature for Case IV.

TMS	CGA [9]	FA [24]	CFA [24]	CPSO
TMS 1	0.0765	0.027	0.027	0.0589
TMS 2	0.034	0.130	0.221	0.0250
TMS 3	0.0339	0.025	0.025	0.0250
TMS 4	0.036	0.025	0.025	0.0290
TMS 5	0.0711	0.489	0.363	0.0630
TMS 6	0.0294	0.0285	0.029	0.0250
T_{op} z (s)	15.88	16.25	14.39	11.87

Table 18. Comparison of the proposed method results with the literature for Case IV.

Method	Objective Function
CGA [9]	15.88
FA [21]	16.25
CFA [21]	14.69
Proposed CPSO	11.87

The objective function for minimization can be defined as:

$$z = 102.4x_1 + 6.06x_2 + 98.75x_3 + 24.4x_4 + 35.31x_5 + 11.53x_6 \quad (42)$$

The constraints that emerge because of the MOP of the relays are:

$$3.646x_1 \geq 0.1 \quad (43)$$

$$6.055x_2 \geq 0.1 \quad (44)$$

$$8.844x_3 \geq 0.1 \quad (45)$$

$$8.844x_4 \geq 0.1 \quad (46)$$

$$4.044x_5 \geq 0.1 \quad (47)$$

$$11.539x_6 \geq 0.1 \quad (48)$$

The constraints explained by Equations (44)–(48) violate the constraints of the minimum value of the Time Multiplier Setting (TMS). All the TMSs should be greater than 0.025. Hence, these constraints are rewritten as:

$$x_2 \geq 0.025 \quad (49)$$

$$x_3 \geq 0.025 \quad (50)$$

$$x_4 \geq 0.025 \quad (51)$$

$$x_5 \geq 0.025 \quad (52)$$

$$x_6 \geq 0.025 \quad (53)$$

The constraints that emerge as a result of coordination are:

$$15.55x_4 - 6.065x_2 \geq 0.3 \quad (54)$$

$$8.844x_1 - 8.844x_3 \geq 0.3 \quad (55)$$

$$8.844x_5 - 8.844x_4 \geq 0.3 \quad (56)$$

$$75.91x_3 - 11.53x_6 \geq 0.3 \quad (57)$$

$$13.998x_1 - 13.998x_3 \geq 0.3 \quad (58)$$

The objective function was solved using a continuous particle swarm algorithm. As can be seen in Tables 17 and 18, the proposed method achieves a satisfactory solution as compared to other methods. The values shown in Table 17 prove that the relays will operate in the minimum possible time for a fault at any point in the system, and will also maintain coordination. The time taken by relay 1 to operate is the minimum possible time for the fault at point A, while it will take maximum time for the fault at point C. This is desirable, because for the fault at point A, relay 1 is the first to operate, whereas for the fault at point C, relay 6 should be the first to operate. If relay 6 fails to operate then relay 3 should take over the tripping action, and if relay 3 also fails to operate only then should relay 1 take over the tripping action. The proposed algorithm gives an optimal solution and optimized total operating time up to the optimum value. Figure 14 depicts a graphical representation of the optimized Time Multiplier Setting compared with the literature. The convergence characteristic for the total operating time obtained for Case IV during the simulation is shown in Figure 15, which demonstrates that the convergence is faster and achieved a better value for the objective function in fewer iterations. The total net gain in time achieved by the proposed algorithm is shown in Table 19, demonstrating the superiority and advantages of CPSO over the techniques mentioned in the literature.

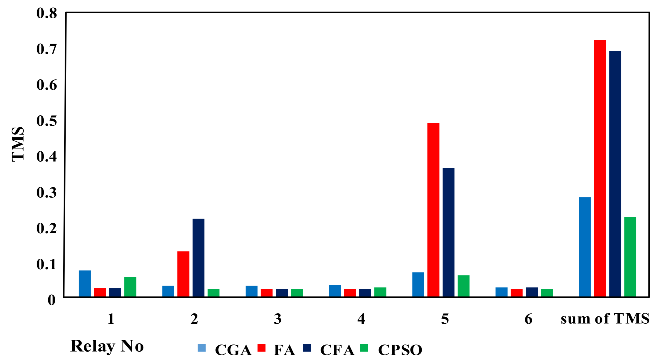

Figure 14. Graphical representation of the optimized TMS compared with the literature for Case IV.

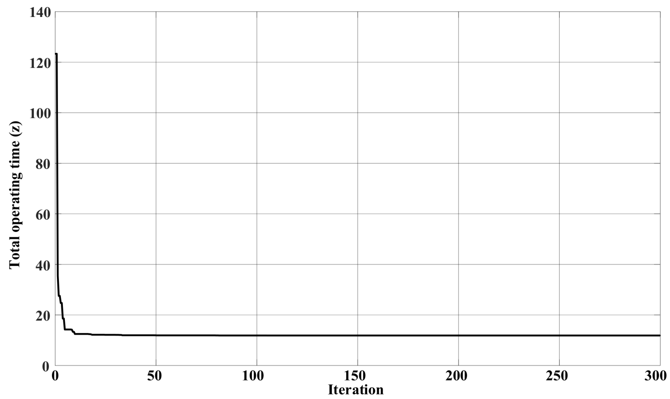

Figure 15. Convergence characteristic graph for Case IV.

Table 19. Comparison of the total net gain in time achieved by the proposed algorithm compared with the literature for Case IV.

Net Gain	$\sum\Delta(t)s$
CPSO/CGA	3.242
CPSO/FA	4.348
CPSO/CFA	2.82

5. Discussion

The CPSO algorithm was used to evaluate the overcurrent relay coordination problem. The proposed algorithm has a high search capability and convergence speed as compared to other optimization techniques, and these characteristics make the population member of the CPSO more discriminative in finding the optimal solution than that of other optimization techniques. The case studies presented in this paper have also been evaluated by GA, CGA, FA, CFA, DSM, SM, and TPSM optimization algorithms, with several different initial conditions and parameter values as shown in the literature, and an improved optimal solution was observed from the proposed CPSO algorithm compared to these other algorithm options. The optimum relay coordination problem is basically a highly constrained optimization problem. As CPSO can solve constrained and unconstrained optimization problems, the relay coordination problem has been converted into an unconstrained optimization problem by defining a new objective function (using the penalty method) and by using the boundaries on the TMS (and boundaries on the relay operating time) as the limits of the variables. A systematic procedure for converting a relay coordination problem into an optimization problem has been developed in this paper. A program has been developed in MATLAB for finding the optimum time coordination of relays using the CPSO method. The program can be used for setting the optimum time coordination of relays in a system with any number of relays and any number of primary-backup relationships. The TMS and total operating time of relays obtained for all case studies by the proposed CPSO algorithm ensured that the relays will activate in the minimum possible amount of time for a fault at any point in the system. However, if the number of relays is increased the nature of the highly constrained problem becomes more distinct. Therefore, an accurate optimum relay coordination minimizes the total operating time as well as reduces and limits the damage produced by the fault. Unwanted tripping of the circuit breaker can also be bypassed by this method. The convergence characteristic graphs obtained during simulations show that the convergence is faster and obtains a superior solution for the fitness function "z" in fewer iterations. The CPSO algorithm is superior to the GA, DSM, TPSM, FA, CFA, and CGA algorithms, as shown in Tables 4, 9, 12 and 19. The CPSO algorithm gains 1.58 s and 1.44 s over the GA and DSM algorithms in Case I, and although this may appear insufficient it should be noted that it is a very small system. In Case II the CPSO algorithm gains 31 ms over the CGA algorithm. In Case III the CPSO gives an advantage of 1 ms over the TPSM and 1.01 s and 0.91 s over the FA and CFA algorithms, respectively. In Case IV the CPSO algorithm gives an advantage of 3.24 s, 4.34 s, and 2.82 s over the CGA, FA and CFA algorithms. For Case IV this advantage is sufficient given that it is a very small system, as it can be clearly seen from Tables 4, 9, 12 and 19, and from Figure 5, Figure 8, Figure 11, Figure 12, and Figure 14 that the proposed method is superior to the recent published techniques mentioned in the literature in term of the quality of the solution, convergence, and minimizing the objective function to the optimum value. The proposed method additionally addressed the weaknesses of the previous methods.

6. Conclusions

This paper proposed a CPSO algorithm based on inspirited swarm behavior associated with fish schooling and bird flocking. The overcurrent relay coordination problem was pursued using the CPSO algorithm for the various test systems. The prolificacy of the CPSO algorithm has been determined and tested on various single end multi-loop distribution systems, by analyzing its superiority compared with GA, SM, DSM, TPSM, CGA, FA, and CFA published techniques. The simulation results of the CPSO algorithm efficiently minimize all four models of the problem. The efficiency of the CPSO can be observed from the minimum function evaluations required by the algorithm to reach the optimum as compared to the CGA, FA, CFA, GA, and TPSM algorithms. The CPSO contributes a new approach for clarification as one of its distinctions is the generous field of research considering the characterization of fish schooling and bird flocking. The simulation results acknowledge the supremacy of the proposed CPSO algorithm in solving the overcurrent relay coordination problem. In future work, this algorithm can be extended to solve overcurrent relay problems of higher buses and complex power systems.

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