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Adaptive protection scheme for optimally coordinated relay setting using modified PSO algorithm

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Abstract

With growing power demand and heightened concern about the use of fossil fuels in conventional power plants, the integration of distributed energy resources into power networks is gaining attention due to their ability to cater for localized energy needs, putting the concept of the Smart grid center stage. Network protection systems, faced with a gradual increase in complexity, will have to develop responses to the changes brought about by ever greater penetration by distributed generation and sophisticated network topologies. The main goal of this paper is to provide optimal relay coordination of an adaptive protection scheme. Designed software based on a Modified Particle Swarm Optimization (MPSO) algorithm is implemented to solve the relay coordination problem. In this study, the 14 IEEE bus system is tested across a range of power system scenarios to validate the suggested technique. The results obtained show that optimal relay settings are achieved by the proposed algorithm regardless of the prevailing network topology.

Keywords: Adaptive protection scheme; modified particle swarm optimization; overcurrent relay coordination

1. Introduction

Recently, the addition of active distributed energy resources in medium and low voltage distribution systems as well as the possible introduction of several sophisticated network topologies have contributed to a large variation in network impedances and fault current levels of power networks. Distribution utilities are usually protected by overcurrent relays (OCRs). The relays are designed to operate at a fixed fault current level. Whenever the magnitude of short circuit current changes, power networks may experience maloperation of protective devices that could result in the OCRs having inappropriate settings, and the selectivity of protection systems may be degraded [1]. Therefore, the relay settings have to be permanently adapted to the current operating status, introducing the concept of “Adaptive Protection scheme” [2]. Adaptive protection is an "online procedure that automatically adjusts the relay settings whenever the grid operating conditions alter, in order to guarantee selective operation in all possible network topologies". The implementation of the adaptive protection technique could be achieved in two phases. In phase 1, the optimum setting groups are calculated by robust power engineering software for all possible network topologies and stored in the relays in an offline manner. In phase 2, a central controller monitors the grid operating state and uses the calculated settings to configure the relays, properly based on the existing power system scenario [3]. The offline analysis of adaptive protection scheme is almost based on the determination of optimal relay setting groups in each network topology, following a set of meaningful constraints to ensure reliable operation of the system. The setting of optimal relay parameters in a meshed network system is considered a very challenging task. Many artificial intelligence techniques have been developed to devise an efficient way to compute optimum relay settings that deliver good coordination among the protective devices. In [4] and [5], the coordination of directional OCRs is solved using methods based on Genetic Algorithm (GA). In [4], GA is applied to calculate current and time settings, considering peak and off-peak loading conditions. In [5], a hybrid method based on GA and linear programming (LP) is suggested by J. Sadeh et al., to find the global optimum points for relay settings. In the proposed methodology, GA is used to compute the pickup current settings for OCRs, then time settings are solved in each iteration using the linear programming technique. In [6], an adaptive protection scheme based on the Ant Colony optimization (ACO) technique is presented to solve the relay coordination problem, and the results are compared to GA for several case studies. The results obtained show that ACO achieved better results than

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GA. In [7], V. Telukunta et al., proposed an overcurrent relay coordination approach based on the differential evolution (DE) algorithm, which utilizes an adaptive fuzzy technique to select optimal relay settings. In [8] and [9], the authors presented a Modified Particle Swarm Optimization (PSO) algorithm to calculate optimal relay parameters. The modification includes the initialization of PSO particles and a repair algorithm is added to help PSO satisfy the coordination constraints [9]. In this paper, a Modified PSO algorithm is suggested for the optimization of relay settings, which employs a linear programming method to calculate the initial positions, in order to hold all particles in a feasible solution. A software program is designed to implement the suggested approach, via different power system scenarios to validate the concept of an adaptive protection scheme.

2. Relay Coordination Problem

2.1. Theory

Each power system element is safeguarded by two lines of defense, known as primary and backup protection. Primary protection should react to a fault as soon as possible, so that the faulty parts can be isolated from the healthy parts, thereby reducing the possibility of an unwanted power outage. Whenever the primary relay fails to operate, backup protection should kick in so as to eliminate the fault after a predetermined time delay—known as the coordination time interval [10]. Therefore, good coordination should be maintained among the protective devices in order to fulfill the requirements of fast, reliable and secure power system protection.

2.2. Proposed Relay Settings

A typical inverse time overcurrent relay consists of two setting values: pickup current (I_p) and Time Dial Setting (TDS). The pickup current is the minimum current value at which the relay begins to operate. TDS adjusts the inverse characteristics of the overcurrent device, and hence controls the time-delay before a relay starts to operates if the fault current reaches a value equal to or greater than the pickup current [11]. The characteristic of an inverse time overcurrent relay can be expressed by the following equation, in accordance with IEC 60255 [12]:

$$t_{op} = TDS \frac{A}{(I_F/I_p)^{B-1}} \tag{1}$$

Where (t_{op}) is the relay operating time, (TDS) is the relay time dial setting, (I_p) is the pickup current setting, (I_F) is the fault current, (A) is the constant for relay characteristics, and (B) is the constant representing inverse time type.

3. Problem Formulation

The coordination of OCRs is formulated as a Nonlinear Optimization Problem (NLP) since the relay operating time is a nonlinear function of TDS and I_p as shown in equation 1.

3.1. Objective Function

In the coordination of OCRs, the main aim is to determine the optimum relay parameters including the TDS and I_p settings so as to minimize the total operation time of all protective devices. Therefore, the main objective function can be stated as the summation of the operating times of all relays, which needs to be minimized. The general form of the objective function is expressed as follows:

$$min\sum_{k=1}^{n}(t_{op,k}) \tag{2}$$

Where, n is the number of relays in the system and ($t_{op,k}$) is the operating time of the relay R_k.

3.2. Constraints

The objective function defined above is subjected to the following set of constraints.

3.2.1. Selectivity Constraint:

The requirement of selectivity dictates that when a fault occurs, only the primary relay should operate to trip the fault. If the main relay fails to cure the fault, the backup relay should clear the fault after a pre-arranged delay time. It is normally set at between 0.2 s and 0.5 s. In order to satisfy this requirement, the following constraint must be added:

$$T_{backup} - T_{main} \leq CTI \tag{3}$$

Where, T_{main} and T_{backup} are the main and backup operation times, respectively. The Coordination Time Interval (CTI) is the minimum time gap in operation between the primary and backup relay.

3.2.2. Limit Constraints:

There is always a range for each relay setting, from which feasible solutions are encountered. Therefore, other constraints should be considered on the limits of relay parameters, including TDS and I_p settings, which can be expressed in the following equations:

$$TDS_{min} \leq TDS \leq TDS_{max} \tag{4}$$

$$I_{p,min} \leq I_p \leq I_{p,max} \tag{5}$$

Where TDS_{min} and TDS_{ma}, $I_{p,min}$ and $I_{p,max}$, are the minimum and maximum limits of Time Dial Setting (TDS), and pickup current (I_p) settings, respectively. The minimum pickup current setting of the relay usually depends on the maximum load current passing through it, while the maximum pickup current setting can be chosen based on the minimum fault current passing inside the coil of the relay.

4. Proposed PSO Algorithm

4.1. Typical PSO Algorithm

PSO was developed by Eberhart and Kennedy in 1995 [13]. It is a population based stochastic optimization algorithm inspired by social and cooperative behavior of various species to meet their needs in the search space. In the standard form of PSO, every particle is associated with a certain velocity and intends to move to its best position P_{best}, and the best location of the group G_{best}. In each iteration, the particles move through the search space, adjusting their positions based on their current velocities and the distance from P_{best} and G_{best} according to equations 6 and 7, seeking the global optimum solution.

$$\begin{aligned} v_i^{k+1} &= w \cdot v_i^k + c_1 \cdot rand_1 \cdot (P_{best,i} - X_i) \\ &+ c_2 \cdot rand_2 \cdot (G_{best,i} - X_i) \end{aligned} \tag{6}$$

$$X_i^{k+1} = X_i^k + v_i^{k+1} \tag{7}$$

$$w = \frac{(w_{max} - w_{min})}{iter_{max}} * iter \tag{8}$$

Where:

w—the inertia weight of the particle that can be calculated using equation (8), where w_{max} is 0.9, w_{min} is 0.4.

$iter_{max}$—the maximum number of iterations

$iter$—the current iteration

v_i^k—the velocity of particle (i) for iteration (k)

$c_1.c_2$—acceleration rates that pull each particle towards P_{best} and G_{best} positions

$rand_1 \cdot rand_2$—random numbers from 0 to 1

P_{best}—best position for particle (i) based on its own position

G_{best}—best position achieved by all particles in the swarm

X_i—position of particle (i)

4.2. Modified PSO Algorithm

In conventional PSO, the generation of initial positions is based on a population of random solutions. This by consequence will not assure that all initial particles will be selected from the feasible search space. Moreover, the resultant swarm positions during the updating procedures could not satisfy all the constraints specified by the relay coordination problem. In order to overcome these problems, two modifications were added to the original PSO, including the initialization and updating of swarm positions.

4.2.1. Initial position generation

In the proposed Modified PSO, the initial solutions were calculated using the "Interior-point Method", which is based on a linear programming subroutine. This is done by initializing the pickup current settings randomly between minimum and maximum boundaries, thus the problem becomes linear, and the TDS settings are then computed using linear programming. The main aim of this modification is to hold all particles in a feasible search space.

4.2.2. Updating of swarm positions

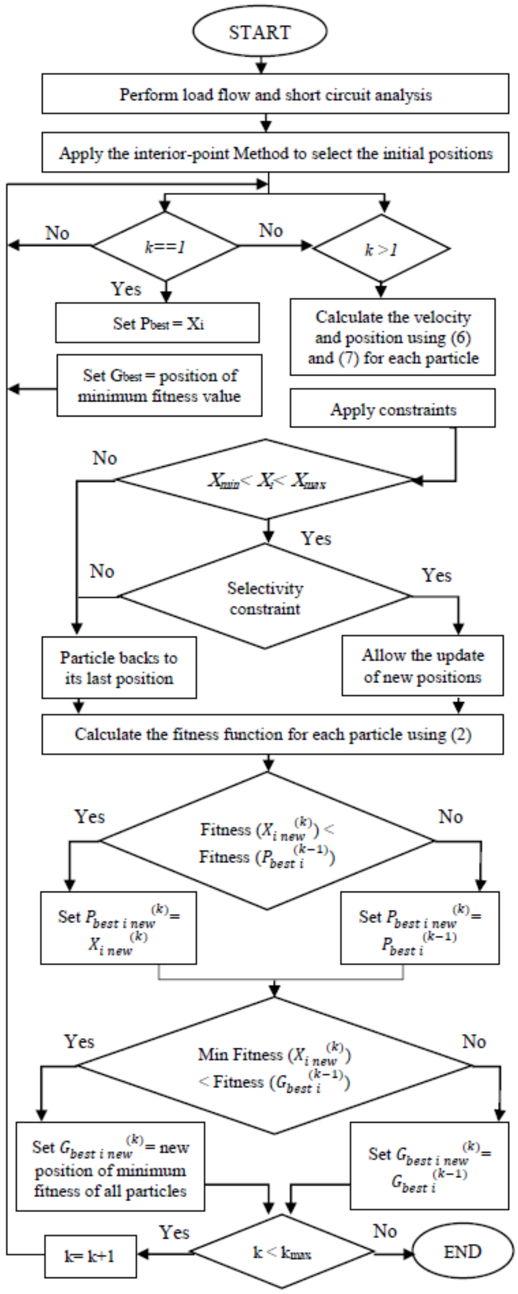

Figure 1: The suggested MPSO flowchart

Another modification concerning the updating process is applied to the traditional PSO in order to ensure that all particles will be maintained in feasible solution. In the suggested technique, particles are updated one after another in the entire swarm using 6, then each one will be subjected to constraint check including limitation and selectivity constraint. If the resultant population is still within the feasible search space, then accept the updated position, otherwise, particle backs to its previous position [8]. The proposed algorithm steps are illustrated in Fig 1.

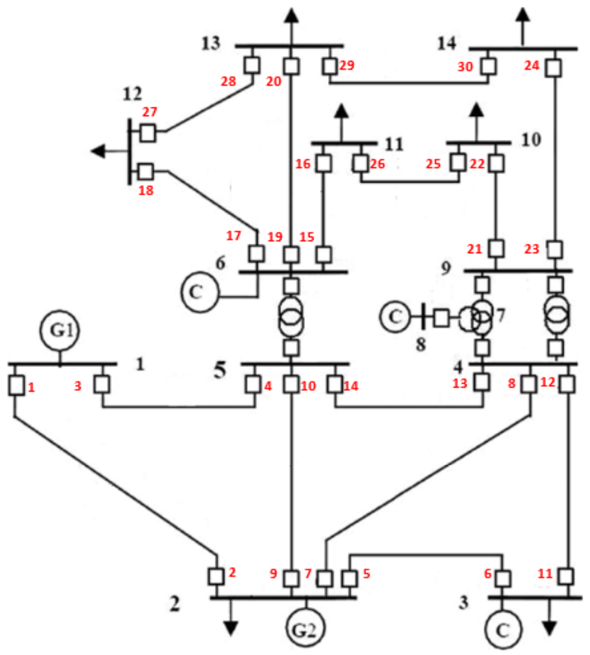

Figure 2: The 14 IEEE bus test system

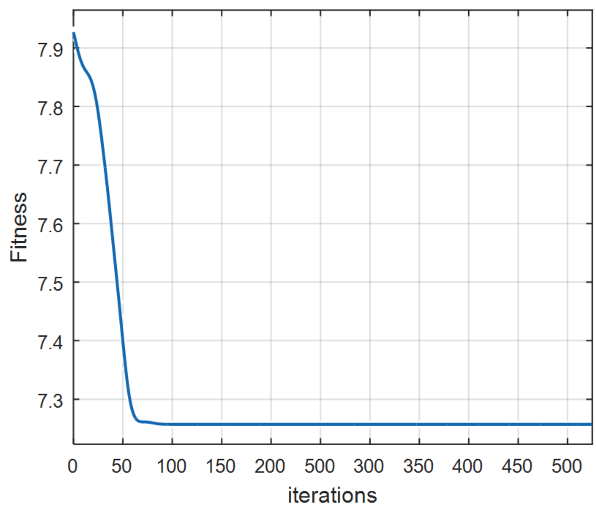

Figure 3: The convergence of fitness function for power system scenario 1

Table 1: Proposal of Power System Scenarios

Power System Scenario	G1	G2	Line 1–2	Line 2–3	Line 2–5	Line 12–13
Scenario 1	ON	ON	ON	ON	ON	ON
Scenario 2	ON	OFF	ON	ON	ON	ON
Scenario 3-1	ON	ON	OFF	ON	ON	ON
Scenario 3-2	ON	ON	ON	OFF	ON	ON
Scenario 3-3	ON	ON	ON	ON	OFF	ON
Scenario 3-4	ON	ON	ON	ON	ON	OFF

5. Test Case System

In order to evaluate the proposed method and the effectiveness of Modified-Particle Swarm Optimization (MPSO) technique, the IEEE 14-bus system was selected and tested for multiple power system scenarios. The system consists of 30 phase relays, and 5 synchronous machines located at buses 1, 2, 3, 8, 6 as illustrated in Fig 2. The machines located at buses 1 and 2 are used as generation units G1 and G2. G1 is considered as the main grid while G2 is used as a distributed generation source. The three others remaining are considered as synchronous compensators used only for reactive power support [14]. All relays are assumed to be overcurrent relays with IEEE standard inverse type characteristic curves.

Three different power system scenarios are used to validate the robustness of adaptive protection technique, as described in Table 1. The first and second scenarios depend on the status of G1 and G2. If ON, it means that the generation unit is operated in service, while OFF is used for out of service operation. The third topology represent the system if a “Single-line-outage” occurs. Four transmission lines are chosen to be disconnected each one in a single case as illustrated in Table 1.

For each scenario, a load flow and short circuit analysis should be performed in order to achieve optimum relay setting using the suggested optimization algorithm. A deep explanation for each power system scenario will be included in next sections.

5.1. Power System Scenario 1

In this topology, the main network was simulated when both generation units G1, G2 are assumed to be operated in parallel together to supply the corresponding loads. G1 is considered as the main grid, while G2 is used as a distributed generation (DG) unit operating in grid-connected mode. The upper and lower limits for the pickup current setting of each relay should be calculated in order to satisfy the boundaries constraints. The pickup current setting should lie between the full load current and the minimum short circuit current passing through the relay. Therefore, a load flow analysis is carried out to compute the relays full load currents, while the minimum short circuit current is estimated by assuming a phase-phase fault occurring at the far-end of each circuit breaker.

In order to obtain optimum settings, the primary/backup (P/B) relay pairs should be identified first, then, the maximum short circuit currents passing through the relays are calculated, by applying a three-phase fault at the near-end of each relay in order to represent the worst case fault for each protective device. Table 2 shows 50 P/B relay pairs found and their corresponding near-end fault currents for both main and backup overcurrent relays. The pickup current (I_p) and Time Dial settings (TDS) for all the overcurrent relays are optimized using MPSO algorithm based on a swarm size of 50, and the time settings are selected between maximum and minimum bounds of 0.1 and 1.1 s respectively.

The obtained results for I_p and TDS are listed and given in Table 3. Fig 3 shows the convergence of the fitness function for the power system scenario 1, which illustrates that MPSO reaches the best solution after approximately 100 iterations.

Table 2: Primary/Backup relay pairs and Near-End fault currents of 14 IEEE bus system for power system scenario 1

P/B pairs P/B No.	Primary Relay	Backup Relay	Near-End Fault currents Primary Current, kA	Backup Current, kA	P/B No	Primary Relay	P/B pairs Backup Relay	Near-End Fault currents Primary Current, kA	Backup Current, kA
1	R1	R4	67.73	1.323	26	R13	R11	4.885	1.603
2	R2	R10	44.12	1.115	27	R14	R3	4.955	1.954
3	R2	R8	44.12	1.054	28	R14	R9	4.955	2.243
4	R2	R6	44.12	1.205	29	R15	R18	1.432	0.021
5	R3	R2	72.38	6.097	30	R15	R20	1.432	0.0816
6	R4	R6	6.156	2.243	31	R16	R25	0.281	0.281
7	R4	R13	6.156	3.121	32	R17	R16	1.567	0.158
8	R5	R1	49.19	6.644	33	R17	R20	1.567	0.816
9	R5	R10	49.19	1.115	34	R18	R28	0.235	0.235
10	R5	R8	49.19	1.054	35	R19	R16	1.506	0.158
11	R6	R12	4.941	1.681	36	R19	R18	1.506	0.021
12	R7	R1	49.33	6.644	37	R20	R27	0.268	0.136
13	R7	R10	49.33	1.115	38	R20	R30	0.268	0.144
14	R7	R6	49.33	1.205	39	R21	R24	0.851	0.123
15	R8	R14	5.843	3.161	40	R22	R26	0.258	0.245
16	R8	R11	5.843	1.603	41	R23	R22	0.921	0.194
17	R9	R1	49.27	6.644	42	R24	R29	0.212	0.212
18	R9	R8	49.27	1.054	43	R25	R21	0.539	0.539
19	R9	R6	49.27	1.205	44	R26	R15	0.433	0.433
20	R10	R3	5.861	1.954	45	R27	R17	0.339	0.339
21	R10	R13	5.861	3.121	46	R28	R19	0.675	0.541
22	R11	R5	5.320	2.070	47	R28	R30	0.675	0.144
23	R12	R14	6.409	3.161	48	R29	R27	0.666	0.136
24	R12	R7	6.409	2.206	49	R29	R19	0.666	0.541
25	R13	R7	4.855	2.206	50	R30	R23	0.293	0.293

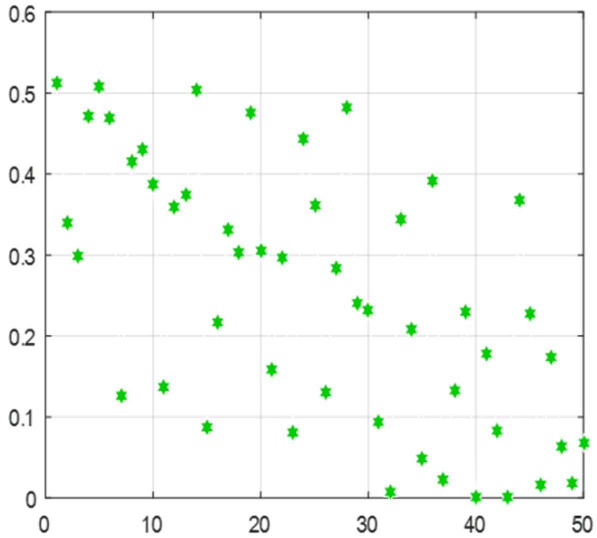

Figure 4: The coordination time interval points for all P/B relay pairs of power system scenario 1

Table 3: TDS and pickup current settings for power system scenario 1

Relay No.	TDS	I_p, A	Relay No.	TDS	I_p, A
R1	0.1	1965.4	R16	0.1	8.7
R2	0.1134	1805.9	R17	0.1	77.4
R3	0.1001	547.7	R18	0.1	6.3
R4	0.1	493.7	R19	0.1	39.4
R5	0.1	590.0	R20	0.1	24.2
R6	0.1	454.9	R21	0.1	26.6
R7	0.1412	522.8	R22	0.1001	34.9
R8	0.1	292.7	R23	0.1001	44.2
R9	0.162	496.7	R24	0.1001	24.4
R10	0.1	339.0	R25	0.1	26.3
R11	0.1054	312.9	R26	0.1342	17.1
R12	0.1026	318.4	R27	0.1517	4.8
R13	0.1	550.5	R28	0.1	41.3
R14	0.1001	356.6	R29	0.1061	34.2
R15	0.1236	116.4	R30	0.1	27.6

It should be noted that the convergence of fitness function shows the response of PSO algorithm after the optimization of initial generation for a population size of 50 particles using Interior-point-method that reaches approximately 7.9 sec total operating time of all relays as best solution for the initial condition, then minimized to 7.2569 sec after 100 iterations of PSO algorithm. The coordination time intervals between primary and backup relay pairs are also presented in Fig 4. It should be noted that all the coordination intervals points are maintained between 0 and 0.5 sec which means that MPSO has reached the minimum operating time of all relays while satisfying no more than the predefined selectivity constraint for relay coordination problem.

5.2. Power System Scenario 2

In this topology, the distributed generation source (G2) is assumed to be disconnected and the main grid (G1) is used to supply the whole system. This will affect the short circuit level of the network and hence new optimized relay settings must be computed again in order to cope with such change in topology. Table 4 shows the coordination time intervals (CTI) of relay settings calculated in power system scenario 1 if tested on scenario 2. The highlighted sections in the table return negative coordination time intervals which indicate the miscoordination that has been occurred between relay pairs R2 and R6, R2 and R8, R2 and R10, R3 and R2, R22 and R26 respectively, as illustrated in Table 4. This miscoordination will be eliminated by re-optimization of relay settings in offline mode to adapt the new change in network topology. The new optimized relay setting for power system scenario 2 are calculated and reported in Table 5.

Table 4: Coordination time intervals for power system scenario 2 using old relay settings

P/ B relays		CTI	P/B relays		CTI
R1	R4	1.519	R13	R11	0.137
R2	R10	-0.75	R14	R3	0.278
R2	R8	-0.79	R14	R9	0.737
R2	R6	-0.61	R15	R18	0.257
R3	R2	-14.1	R15	R20	0.249
R4	R9	0.716	R16	R25	0.096
R4	R13	0.152	R17	R16	0.009
R5	R1	0.313	R17	R20	0.360
R5	R10	0.330	R18	R28	0.210
R5	R8	0.289	R19	R16	0.051
R6	R12	0.177	R19	R18	0.409
R7	R1	0.226	R20	R27	0.021
R7	R10	0.243	R20	R30	0.137
R7	R6	0.377	R21	R24	0.233
R8	R14	0.105	R22	R26	-0.01
R8	R11	0.249	R23	R22	0.180
R9	R1	0.181	R24	R29	0.083
R9	R8	0.157	R25	R21	0.001
R9	R6	0.333	R26	R15	0.368
R10	R3	0.308	R27	R17	0.229
R10	R13	0.202	R28	R19	0.017
R11	R5	0.458	R28	R30	0.178
R12	R14	0.092	R29	R27	0.064
R12	R7	0.701	R29	R19	0.018
R13	R7	0.603	R30	R23	0.075

5.3. Power System Scenario 3

The third scenario is based on simulating the system in case that a single line goes out of service. This by consequence will affect the short circuit level of the network and hence new optimized relay settings must be computed in order to cope with such change in topology. Four different cases of single-lines out have been applied and tested in order to demonstrate the effectiveness of adaptive protection technique.

- Case 1: refers that line 1–2 is disconnected
- Case 2: refers that line 2–3 is disconnected
- Case 3: refers that line 2–5 is disconnected
- Case 4: refers that line 12–13 is disconnected

For each case, the upper and lower limits for relay pairs, and the short circuit currents for near and far end faults are recalculated again, and new relay settings are optimized to adapt the change in each test case. The computed relay settings for the four cases are listed and given in Table 5. The convergence of fitness function for the four topologies of power system scenario 3 are combined and illustrated in Fig. 5 showing that MPSO has achieved minimum operating time for all relays.

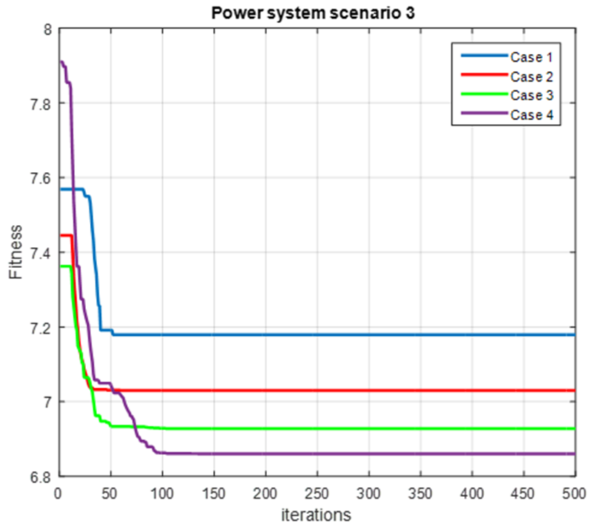

Figure 5: the convergence of fitness functions for case 1, 2, 3 and 4 for power system scenario 3

6. Conclusions

In this paper, the MPSO algorithm was proposed to solve the relay coordination problem. The modification added to the typical PSO technique helped to keep all particles in a feasible solution. The 14 IEEE bus network was tested in various power system scenarios to validate the idea of an adaptive protection scheme. The selected case studies introduced the effect of DG penetration and line outage on the distribution networks. The results obtained demonstrated the effectiveness of the suggested approach in achieving optimum relay setting groups according to each network topology, minimizing the total operation time while maintaining the selectivity constraints among all protective devices.

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Table 5: TDS and pickup current settings for power system scenarios 2 and power system scenario 3

Relay No.	Power system scenario 2		Power system scenario 3 cases: Case 1		Case 2		Case 3		Case 4	
	TDS	I_p, A	TDS	I_p, A	TDS	I_p, A	TDS	I_p, A	TDS	I_p, A
R1	0.1328	1595	-	-	0.1	1803.56	0.1	1612.44	0.1	1169.59
R2	0.1008	498.14	-	-	0.1	1213.28	0.1	849.139	0.1	1652.79
R3	0.1008	602.11	0.1	803.11	0.1	532.65	0.1	554.029	0.1	558.538
R4	0.1005	283.85	0.1	473.50	0.1	418.95	0.1002	372.817	0.1	342.43
R5	0.1	462.50	0.1	488.48	-	-	0.1	645.203	0.1	599.88
R6	0.1	466.08	0.1	336.73	-	-	0.1	375.508	0.1001	372.21
R7	0.1001	438.42	0.1553	322.69	0.1	724.02	0.1001	624.696	0.1	567.68
R8	0.1	279.79	0.1004	313.54	0.1	382.39	0.1	429.065	0.1	305.76
R9	0.1220	363.93	0.1002	511.99	0.1	589.88	-	-	0.1	498.29
R10	0.1004	326.90	0.1006	418.08	0.1	335.08	-	-	0.1	322.812
R11	0.1013	343.99	0.1	479.43	0.1	435.32	0.1001	518.908	0.1	335.71
R12	0.1008	289.37	0.1001	491.89	0.1005	471.36	0.1001	480.105	0.1009	468.93
R13	0.1006	515.55	0.1	1155.68	0.1	909.28	0.1	299.238	0.1	692.96
R14	0.1006	648.58	0.1002	874.09	0.1	914.18	0.1	408.657	0.1004	661.36
R15	0.15	64.98	0.1	130.89	0.1	49.74	0.1	73.3514	0.1473	12.82
R16	0.1005	28.23	0.1005	18.85	0.1001	25.64	0.1	16.967	0.1	8.559
R17	0.1	37.11	0.1	37.39	0.13	55.78	0.1001	14.44	0.1	55.318
R18	0.1002	5.98	0.1	6.346	0.1	6.95	0.1	6.037	0.1	45.701
R19	0.1413	121.00	0.1007	68.06	0.1	101.44	0.1	117.76	0.1	61.994
R20	0.1009	21.96	0.1	24.59	0.1	24.314	0.1001	20.944	0.1	24.093
R21	0.1018	81.02	0.1	93.43	0.1	55.328	0.1001	69.398	0.1214	6.352
R22	0.1002	30.57	0.1024	18.07	0.1	14.205	0.1	19.19	0.1	33.515
R23	0.1008	32.55	0.1002	85.80	0.1	67.195	0.1005	76.27	0.1	74.796
R24	0.1	33.76	0.1	17.45	0.1	30.328	0.1	34.74	0.1	30.827
R25	0.1	29.48	0.1	29.56	0.1	32.706	0.1	34.30	0.1008	10.735
R26	0.106	27.59	0.1014	25.69	0.1398	5.9095	0.2201	2.5056	0.1215	22.068
R27	0.1	35.66	0.1010	12.25	0.1406	8.416	0.1536	2.915	-	-
R28	0.1041	5.212	0.1002	25.50	0.1	58.174	0.1	56.07	-	-
R29	0.1998	9.311	0.1003	48.10	0.1001	54.067	0.1006	46.39	0.1	61.99
R30	0.1	12.94	0.1	27.19	0.1		0.1604	5.96	0.1731	6.77

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