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Optimal Overcurrent Relay Protection Coordination in Distribution Network Based on a Simulated Annealing Inertia Weight Particle Swarm Optimization Technique

Mohammed Kabir
Department. of Electrical Engineering
Kaduna Polytechnic
Kaduna, Nigeria
kabirjb@gmail.com

Aliyu D. Usman
Dept. of Communications Engineering
ABU Zaria
Kaduna, Nigeria
adusman@abu.edu.ng

Boyi Jimoh
Department of Electrical Engineering
ABU Zaria
Kaduna, Nigeria
jboyi@abu.edu.ng

ABSTRACT— The coordination of overcurrent relays in a power system is to ensure that only the faulted section of the system is isolated when an abnormal operating state occurs. Large numbers of relay tripping and mis-coordination are due to improper or inadequate settings rather than to genuine faults. A Modified Particle Swarm Optimization (MPSO) techniques which is based on an adaptive simulated annealing inertia weight was used to solve the problem of overcurrent relay coordination. The objective function is the minimization of the operation time of the protective relays in the IEEE 15 and 30 bus networks. The Time of Operation (T_{op}) and Coordination Time Interval (CTI) were used as the performance metrics of the research. The obtained operating time of the IEEE 15 bus is 23.22 seconds. The simulation time of the 15 bus network is 11.22 seconds. Relay no. 11 and 21 with CTI values of 0.0863 seconds and 0.0940 seconds violated the CTI constraints. The result obtained for the IEEE 15 bus was validated and an improvement of 11.3288% was observed in terms of reduction in the operating time of the relays in the system. The obtained T_{op} and CTI settings of the relays in the system show the effectiveness of the proposed MPSO technique.

KEYWORDS - Relays, Optimal Coordination, Plug Setting, Time Multiplier Setting, Coordination Time Interval.

INTRODUCTION

This The primary objective of all power systems is to maintain a very high level of continuity of service, and when intolerable conditions occur, to minimize the extent and time of the outage. However, because it is impossible, as well as impractical, to avoid the consequences of natural events, physical accidents or equipment failure owing to human error, many of these will result in faults [1, 2].

Since 1960s, a great effort has been devoted for solving this problem by computational tools [3]. The methods, which are used for performing this task can be classified into three classes: trial and error method, topological analysis method, and Heuristic optimization method [3, 4]. Furthermore, due to the complexity of the power system network, trial and error approach and topological analysis are time consuming and not optimal [5].

Several optimization techniques and artificial intelligence methods have been deployed in solving relay coordination problem, methods such as Harmony Search Algorithm (IHSA) to solve relay coordination problem with three different cases on IEEE 14-bus and IEEE 30-bus systems [6], Cuckoo Search Algorithm [7]. Variants of PSO and its hybrids have also been deployed in optimal relay coordination [8-12].

The optimal coordination of over current relays poses serious problems in the modern complex power system networks, which are interconnected, because of that, they are protected by directional over current relays, which are standalone devices and strategically placed throughout the system [4, 5].

According to statistical evidence, a large number of relay tripping and mis-coordination are due to improper or inadequate settings rather than to genuine faults [5]. Overcurrent relay coordination has been worked upon by many researchers and the challenge was mainly on how to design an optimal relay coordination system. The relay coordination is not an exact science, but in fact an Art that involves some degree of uncertainty due to its complexity and nonlinearity [5, 6], hence it is difficult to claim that a global optimal result has been yielded

Thus, this work seeks to improve the solution of the coordination problem by using a modified particle swarm optimization technique for reaching the global optimum value with less computational time. Simulated Annealing Inertia Weight is used to modify the conventional PSO to develop an efficient model for solving the relay coordination problem was based on the outcome of experiments where several inertia weight strategies were subjected to optimization test functions. The Simulated Annealing Inertia Weight strategy gave an outstanding performance when the average error, average number of iteration and minimum error were used as the criteria for comparison.

COORDINATION PROBLEM FORMULATION

The coordination problem and constraints for optimum relay coordination are formulated in this section.

A. *Objective Function (OF) Formulation*

First, The objective function of the optimization problem is therefore, the minimization of the operation time of the associated relays. After considering all these criteria, the objective function (OF) can be formulated mathematically as given in equation 1.

$$\mathrm{OF} = \min \sum_{i=1}^{n} w_1 \times T_{op_i} \quad (1)$$

Where n is the number of relays in the network, is a coefficient usually set to 1, it indicates the probability of the occurrence of a fault and is the operating time of relay.

All relays are assumed to be identical and have IDMT characteristic, the operating time is given by equation 2 [1, 3, 5, 7, 9, 11-13].

$$T_{op} = \frac{\lambda \times TMS}{\left(\frac{I_f}{PS \times CT}\right)^{\eta} - 1} + L \quad (2)$$

Where TMS is the Time Multiplier Setting, PS is the Plug Setting, I_f is the fault current, CT is the current transformer ratio and $i = 1, 2, \ldots n$.

There are several characteristics of overcurrent relays as shown in Table I. The standard Inverse overcurrent relay is the relay of choice for this paper.

Table I: Characteristics of DOCRs [6]

Type of Characteristic	K	A	L
Short Time Inverse	0.05	0.04	0
Standard Inverse	0.14	0.02	0
Very Inverse	13.5	1	0
Extremely Inverse	80	2	0
Long Time Inverse	120	1	0
Moderately Inverse	0.0515	0.02	0.114
Very Inverse	19.61	2	0.491
Extremely Inverse	28.2	2	0.1217

In equation (3), λ, η and L are the characteristic constants of the relays while I_f is the fault current through the relay operating coil. For standard inverse definite minimum time (IDMT) relays λ = 0.14, η = 0.02 and L = 0 [4, 7, 8, 10, 11-13].

$$T_{op,i} = \frac{0.14 \times TMS_i}{\left(\frac{I_{f,i}}{PS_i \times CT}\right)^{0.02} - 1} \quad (3)$$

B. Constraints Formulation

For the objectives of optimum relay coordination to be achieved, the coordination and boundary constraints must be satisfied. The lower and upper bounds of TMS and PS of each DOCR are given by equations 4

$$TMS_{i_{\min}} \le TMS_i \le TMS_{i_{\max}}$$
$$PS_{i_{\min}} \le PS_i \le PS_{i_{\max}} \quad (4)$$

Based on the Standard Inverse relay characteristic used in this work, the TMS and PS are the decision variables of the optimization problem, their limits are outlined in equations (5), (6) and (7). The values of the limit are adopted from [9] for the purpose of validation.

$$0.1 \le TMS \le 1.1 \quad (5)$$

$$0.5 \le PS \le 2.5 \quad (6)$$

$$0.1 \le T_{op} \le 4s \quad (7)$$

I. C. Coordination Time Interval (CTI)

Coordination time interval (CTI) is the criteria to be considered for coordination. It’s a predefined time delay and it depends on the type of relays. For electromagnetic relays, CTI has a minimum value of 0.2 s, while for a microprocessor based relay, it is of the order of 0.1 to 0.2 s [9, 15]. The sample network of two directional overcurrent relays is shown in Figure 1, where R_b and R_p are in order of backup and primary relays for close in fault to R_p at location *F* [6, 8, 13, 15].

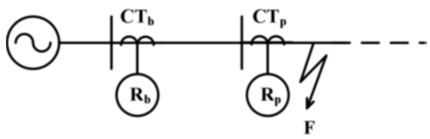

Figure 1: Illustrative diagram for P/B relay pair [6, 13]

In this case, R_p should trip as quickly as possible, whereas R_b should operate after time period required for preserving selectivity between P/B protections known as CTIexpressed by 8.

$$T_b - T_p \geq CTI \quad (8)$$

Where T_b and T_p are operating time of backup relay (R_b) and primary relay (R_p) respectively. The *CTI* depends on the types of relays, circuit breaker operating time, relay error and safety margin [9, 14].

II. SIMULATED ANNEALING INERTIA WEIGHT PARTICLE SWARM OPTIMIZATION

This research work employed an adaptive behavior based simulated annealing inertial weight for selecting the appropriate inertia weight for the PSO as the algorithm swarm towards the optimum solution. This is given in equation (9)

$$w_k = w_{\min} + \left(w_{\max} - w_{\min}\right) \times \lambda^{(k-1)} \quad (9)$$

Where w_k is the inertial weight at current generation, w_{min} is a randomly generated number within an interval of 0 and 1, w_{max} is a randomly generated number within an interval of 0 and 1, k is the current iteration number.

In this work, the value of lambda shall be determined using equation (10)

$$\lambda = \left(\frac{ITR\max - ITR}{ITR\max} \right)^n \qquad (10)$$

Where ITR_{max} is the maximum value of iteration which is defined by the user, ITR is the current value of iteration, n is the total number of particle defined by the user.

The lambda in equation (10) serves as the dynamic parameter for the inertia weight which is selected adaptively during the optimization process. Figure 2 shows the flowchart modified PSO. The shaded portion in the flowchart indicates the application of the simulated annealing inertia weight.

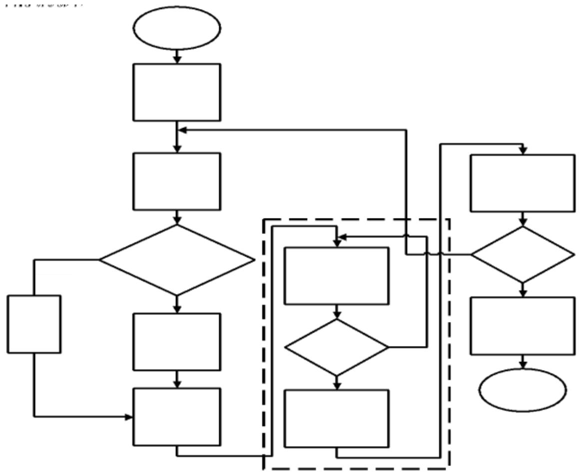

Figure 2: PSO flowchart showing the Simulated Annealing Inertia Weight

III. IEEE 15-BUS SYSTEM

The IEEE 15 bus radial test system is used in this work to validate the performance of the proposed solution. The data and parameters used are based on the work of [9]. The test system is shown in Figure 3. The system is widely used as a case for conducting various studies such as relay coordination, interconnected grid problems etc.

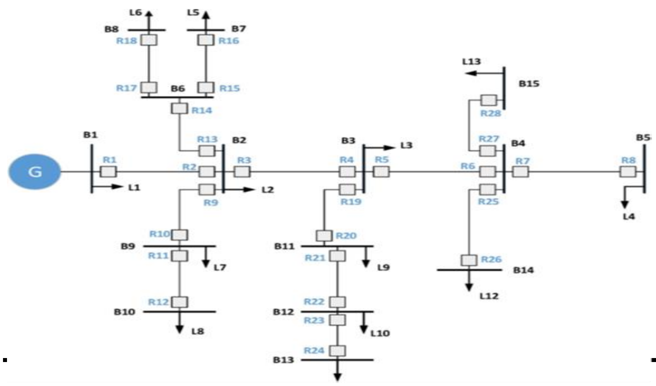

Figure 3: IEEE 15-Bus Radial network

All the relays in the network are considered Directional Overcurrent Relays (DOCR) with standard Inverse Definite Minimum Time (IDMT) characteristics and have their tripping direction away from the bus. The fault currents values given in Table II are based on International Electrotechnical Commission standard for the IEEE 15 bus 3-ϕ bolted faults simulated at the near end.

Table II: Fault Current Values of the Relays for IEEE 15-Bus Radial System

Relay No.	Fault Currents (A)	Relay No.	Fault Currents (A)
1	22778	15	7710
2	11532	16	5790
3	11509	17	7700
4	7710	18	5790
5	7700	19	7700
6	5790	20	5790
7	5785	21	5785
8	4636	22	4636
9	11509	23	4632
10	7710	24	3866
11	7700	25	5785
12	5790	26	4636
13	11509	27	5785
14	7710	28	4636

IV. SIMULATION

V. A. MATLAB Simulation Software

The professional software package MATLAB software is used to develop the optimal relay coordination model. For the purpose of this research MATLAB version R2017a was used. When the program is run, the Matlab Graphical User Interface prompts the user to select which of models will be evaluated, either 1 or 2 (1 = the developed algorithm; 2 = the standard PSO). MATLAB's flexibility and user-friendly environment made it a choice for this research.

B. Computer System

All the simulations carried out in this research were done on an Acer laptop computer system. The specification of the computer is given in Table III.

Table III: Computer Specification

Items	Specification
Operating System	Windows 8 Professional
RAM	4.00GB
System Type	64-bit Operating System
Processor	Core i5-243M @ 2.40GHz
Rating	4.0
Video Graphics	32MB

C. PSO Parameters

A set of initialization parameters has to be declared for the PSO algorithm to work effectively. The values in Table 4 were selected based on [9] for ease of validation. Subsequently, the N_{pop} and number of iterations will be varied in order to see their effect on the optimality of the decision variables.

Table 4: PSO Parameters Settings

Initialization Parameters	Values
Learning coefficient C_1&C_2	2.0
Maximum inertia weight (w_{max})	0.9
Minimum inertia weight (w_{min})	0.4
Damping Ratio	0.99
Number of population (N_{pop})	60
Number of iterations	100

VI. VI. RESULTS AND DISCUSSION

In this section, the performance of the optimal relay coordination using the MPSO is evaluated. The operating time of the IEEE 15 bus test system is presented.

A. Convergence on the IEEE 15-Bus System

After the developed MPSO is run for 100 iteration using the IEEE 15 data, the plot in Figure 4 is obtained. The figure shows the fitness evolution in the developed model.

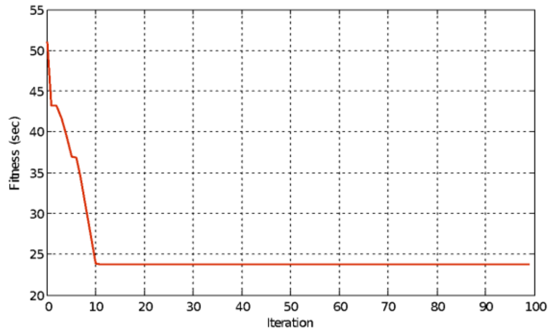

Figure 4: Fitness function evolution of the IEEE 15 Bus using MPSO

It is observed from Figure 4 that the optimal operating time of the relays in the system converged at 23.2221secs after 10 iterations, the optimal time remained constant through the 100^{th} iteration.

B. Simulation Result on IEEE 15-Bus System

The optimal values of the Time Multiplier Settings (TMS) and Plug Settings of the IEEE 15 bus test system is shown in Table 5, the table also shows the optimal operating times of the relays in the network. The results in Table 5 are obtained using the set of 28 fault currents values given in chapter three. A fixed CT Ratio of 500:1 in used for the simulation.

The results of the optimized TMS, PS and T_{op} of the entire primary relays obtained by the MPSO is shown in Table 5. The objective function value obtained is $\sum T_{op} = 23.2221\text{secs}$ and is the summation of the individual operating time of the relays in the system. This value represents optimal operating time of the relays in the network and is obtained after the algorithm determines the set of optimal values of TMS and PS which it used to compute the time of operation of the relay.

Table 5: Optimized PS, TMS and T_{op} for the IEEE 15-bus

Relay No.	PS	TMS	T_{op}
1	0.6612	0.6612	1.3223
2	0.4307	0.4307	0.8189
3	0.3987	0.3987	0.8181
4	0.3126	0.3126	0.5220
5	0.5566	0.5566	1.4473
6	0.1948	0.1948	0.4960
7	0.2042	0.2042	0.5036
8	0.4567	0.4567	1.0909
9	0.3409	0.3409	0.7582
10	0.2350	0.2350	0.5055
11	0.2263	0.2263	0.4546
12	0.2103	0.2103	0.5405
13	0.7773	0.7773	1.4967
14	0.4189	0.4189	0.9242
15	0.4749	0.4749	0.9402
16	0.462	0.462	0.7627
17	0.4087	0.4087	0.9459
18	0.2597	0.2597	0.6271
19	0.2512	0.2512	0.5581
20	0.1709	0.1709	0.3883
21	0.5222	0.5222	1.2783
22	0.2441	0.2441	0.5792
23	0.5544	0.5544	1.4856
24	0.2053	0.2053	0.4712
25	0.4069	0.4069	0.9957
26	0.2420	0.2420	0.6885
27	0.3541	0.3541	0.8744
28	0.3694	0.3694	0.9281

VALIDATION

To validate the result of the research, the result obtained using the proposed model is compared with that obtained in [9] which is the base research work used.

Table 7: Comparison of Results for the IEEE 15-Bus

A. Comparison of the TMS, PS and T_{op}

The summation of the optimized time of operation of the individual relays in the IEEE 15 bus system which is equal to the objective function value is compared as shown in Table 7.

Relay No.	Proposed			[9]		
	PS	**TMS**	T_{op}	**PS**	**TMS**	T_{op}
1	0.8136	0.3126	0.5220	0.5499	0.7439	1.1277
2	0.6609	0.4307	0.8189	1.2551	0.3222	0.7523
3	0.7812	0.6612	1.3223	1.5153	0.3416	0.8552
4	0.5686	0.3987	0.8181	2.4141	0.5525	2.0470
5	0.7974	0.2053	0.4712	0.6086	0.3634	0.7622
6	0.7596	0.1948	0.4960	1.0805	0.4309	1.2418
7	0.7318	0.2042	0.5036	1.2611	0.1119	0.3456
8	0.5375	0.4567	1.0909	1.8220	0.2726	1.1538
9	0.7927	0.2263	0.4546	1.1148	0.4539	1.0181
10	0.6592	0.2350	0.5055	1.3933	0.1536	0.4366
11	0.7277	0.3409	0.7582	0.5009	0.3213	0.6344
12	0.8165	0.2103	0.5405	2.4727	0.2642	1.1793
13	0.6887	0.7773	1.4967	1.9075	0.3209	0.8796
14	0.7113	0.4189	0.9242	2.1497	0.7389	2.5740
15	0.5057	0.4749	0.9402	0.7922	0.4263	0.9762
16	0.5319	0.3462	0.7627	0.6784	0.5439	1.3043
17	0.8170	0.4087	0.9459	0.6199	0.2179	0.4598
18	0.6917	0.2597	0.6271	1.1896	0.1204	0.3619
19	0.7255	0.2512	0.5581	0.6667	0.3199	0.6912
20	0.5826	0.1709	0.3883	1.1323	0.5657	1.6638
21	0.7172	0.5222	1.2783	0.6075	0.2638	0.6083
22	0.5276	0.2441	0.5792	1.8741	0.1431	0.6167
23	0.7260	0.5544	1.4856	0.7978	0.1249	0.3481
24	0.5617	0.5566	1.4473	1.3848	0.5530	2.2124
25	0.7166	0.4069	0.9957	0.6553	0.2225	0.5271
26	0.8396	0.2420	0.6885	1.6316	0.2904	1.1498
27	0.7342	0.3541	0.8744	0.7789	0.1347	0.3401
28	0.6161	0.3694	0.9281	2.4925	0.1028	0.5404
			$\sum T_{op}$=23.222s		$\sum T_{op}$=23.222s	

The objective function value of the developed MPSO is 23.2221s, while that obtained by [9] is 26.189s as shown in Table 7. This shows that the total operating time of the relays in the IEEE 15 bus has reduced significantly by 2.967s which translate to a reduction of 11.3288%.

B. Conergence Response Comparison

The developed MPSO and that of the work of [9] are run using the same set of parameters, i.e. iterations, number of particles and same boundary conditions, both are then plotted on the same figure. Figure 6 shows the fitness evolution of both developed algorithms.

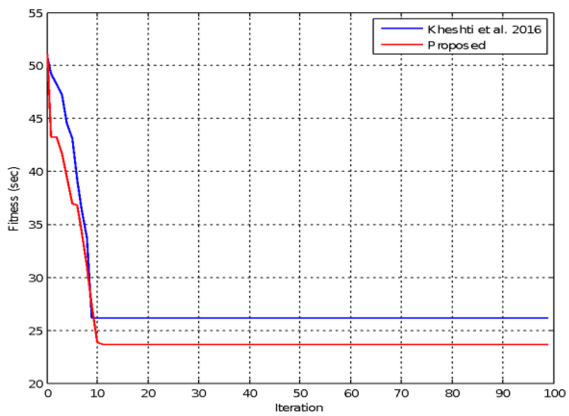

Figure 6: Fitness function evolution comparison of MPSO and [10]

It is observed from Figure 6 that the fitness function of the MPSO converges at 23.222s, while that of [9] converges at 26.189s. MPSO converges after 10 iterations while [9] converges before the 10^{th} iteration. This shows that the minimal operating time of the relays in the IEEE 15 bus network is achieved using the MPSO.

CONCLUSION

The research developed an Optimal Overcurrent Protection Relay Coordination for distribution system using a Modified Particle Swarm Optimization Technique. The modification is based on a Simulated Annealing Inertia Weigh. The objective function is the minimization of the operation time of the protective relays. The optimality and Coordination Time Interval (CTI) were used as the performance metrics of the research. The result obtained an optimum solution with a good convergence when implemented on IEEE 15-bus network. When the result of the research was validated with that of [9], an improvement of 11.3288% is observed in terms of optimality and the CTI violations was reduced to two when compared to five recorded in [9]. The effectual result obtained for the relay coordination problem shows that the method is a viable one.

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