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Optimal Coordination of Directional Overcurrent Relays Using PSO-TVAC

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Abstract

This paper presents an efficient variant of particle swarm optimization (PSO) algorithm named Time Varying Acceleration Coefficients (PSO-TVAC) to solve the optimal coordination of directional overcurrent relays (DOCRs) in a practical power system, considering the optimum pickup current (Ip) as discrete parameter and time dial setting (TDS) as continuous parameter, in order to obtain minimum operating time for the relays, while satisfying various boundary constraints. Comparison results with the standard global optimization methods such as GA using Matlab toolbox, PSO and to other techniques showed the efficiency of the proposed variant and confirmed its potential to enhance the solution of optimal coordination of directional overcurrent replays.
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Keywords: Directional overcurrent relay coordination, Particle swarm optimization (PSO), Time Varying Acceleration Coefficients (TVAC), Power system protection,

1. Introduction

Due to the requirement of power systems security, the protective relays must be well coordinated with each other. The problem of coordinating protective relay in electric power systems consists of selecting their suitable settings such that their fundamental protective function is met under the requirements of sensitivity, selectivity, reliability, and speed [1-4]. The coordination between overcurrent relays is performed, in order to remove the faults, by disconnecting the least possible part of the network [5]. In the relay coordination problem, the objective is to minimize a well-known objective function which is the total summation operating time of primary relay. Therefore is the process of determining the exact relay settings (Time Dial Setting (TDS) and the pickup current (Ip) setting or pickup tap setting (PTS) for directional over-current relays) such that the relay primary closes to the fault would

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operates faster than other relays secondly. In this problem considering various constraints, such as boundary limits and coordination time interval (CTI), in order to ensure correct sequential operation of these relays [1-5].

Several conventional methods have been proposed for the coordination of overcurrent relays, Urdaneta et al [1] was the first researchers describing the application of the optimization theory in the coordination of directional overcurrent relay using linear programming (LP) techniques. The drawback of these optimization techniques is that they are based on an initial guess and may be trapped in the local minimum values [7–10]. Authors in [6] present a review of the major contributions in this area. Recently, in order to solve the relay coordination problem, as a complex and non-convex optimization problem, intelligence based optimization methods have been developed [10].

The applications of evolutionary techniques have been used in optimal coordination of directional overcurrent relays. In [3] the problem of determining the optimum settings of DOCRs is formulated as a Nonlinear Programming Problem (NLPP), and hybrid GA approach is proposed to find the optimum solution. Authors in [2] proposed a hybrid GA considering different network topologies, in [4] author proposed a seeker algorithm for coordination of directional overcurrent relays, in [5] an analytic approach adapted and applied for optimal coordination of overcurrent relays.

Particle swarm optimization (PSO) algorithm introduced by Kennedy and Eberhart [7, 8] is one of the most power full method applied with success to solve many problems related to power system protection coordination. To improve the convergence characteristic and solution quality of the standard PSO, various variants and modified versions based PSO are proposed for solving the relays coordination problem. Variants named modified particle swarm optimization (MPSO) proposed for solving the optimal coordination of directional overcurrent and distance relays considering series compensation [12-16]. Recently a new variant based PSO named time varying acceleration coefficient (PSO-TVAC) proposed by authors in [17] to solving the economic dispatch considering non-convex generators constraints [18].

In this paper the problem of determining the optimum values of TDS (continuous parameter) and PTS (discrete parameter) of DOCRs is formulated as a nonlinear programming problem (NLPP) and is solved by PSO-TVAC algorithm. The proposed method is validated on a practical 8_Bus test system.

2. Problem Formulation

In the relay coordination problem of DOCRs, the main objective is to minimize the total time of operation of primary relays, through two types of tap settings, namely the time dial setting TDS and pickup tap setting PTS. The objective function can be defined as follows [3]:

$$\min J = \sum_{i=1}^{n} w_i t_i \tag{1}$$

Where n is the number of relays and w_i depends upon the probability of a given fault occurring in each protection zone and is usually set to one and t_i is the operating time of the i *th* relay.

2.1. Relay characteristics

The operating time of the operating time of the over current relay is non-linear function of pickup current setting (Ip) and time dial setting TDS. Various equations have been applied for overcurrent relays characteristics simulation. In this work we will use approximate mathematical formula for a relay characteristic suggested in References [2-3] given by:

$$T_{ik} = TDS_i \frac{0.14}{\left(\frac{I_i}{Ip_i}\right)^{0.02} - 1} \tag{2}$$

Where TDS_i and Ip_i are time dial setting and primary pickup current setting of the i-*th* relay respectively and I_i is the fault current passing through i-*th* relay The concept of relay pickup tap setting (PTS) could be formulated by [4]:

$$PTS_i = Ip_i / RC_i \tag{3}$$

Where RC_i is the stands for the CT ratio.

2.2. Constraint

The coordination problem has two types of constraints, firstly is the constraint of the relay characteristic and secondly is coordination constraint. Relay constraints include limits of relay operating time and settings. Coordination constraints are related to the coordination of primary and backup relays [3-4].

A.1 Constraint of operating time and Bounds on the relay settings

- *The bounds on operating time:* The limits are expressed by:

$$T_{ik}^{\min} \le T_{ik} \le T_{ik}^{\max}, \qquad i = 1, \ldots, m \tag{3}$$

Where $T_{ik}^{\min}$ and $T_{ik}^{\max}$ are the minimum and maximum operating times of the *i-th* relay at the *k-th* location.

- *The constraint of Time and Current Settings*: The limits on TDS and Ip_i are expressed by:

$$TDS_i^{\min} \le TDS_i \le TDS_i^{\max}, \qquad i = 1, \ldots, m \tag{4}$$

$$PTS_i^{\min} \le PTS_i \le PTS_i^{\max}, \qquad i = 1, \ldots, m \tag{5}$$

Where $TDS_i^{\min}, PTS_i^{\min}$ $TDS_i^{\max}, PTS_i^{\max}$ are the minimum and maximum value of TDS_i and PTS_i of the relay *i-th* location.

A.2 Coordination criteria

The coordination of directional overcurrent relays involvers a choice of relay settings such that for every fault in the system, there is a specified minimum coordination interval or time delay between the operation of the primary relay and that of the backup relay, this interval ensures that the backup relay operates only when the primary relay fails to perform its assigned task [2].The value time coordination interval (CTI) is usually selected between 0.2 and 0.5 s. In this work the CTI is taken as 0.3 s.

$$T_{ik} \geq T_{jk} + CTI; \quad CTI = 0.3 \tag{6}$$

Where T_{jk} operating time of the primary relay R_j for fault at *k-th* location. T_{ik} operating time of the backup relay R_i , for the same fault at *k-th* location.

$$error = (T_{op-jk} - (T_{op-ik} + CTI)) \tag{8}$$

Where $error$ violation in the coordination criteria, T_{op-ik} , T_{op-jk} are the operating time of the primary relay and backup relay respectively.

3. Optimization algorithm

3.1. Standard PSO

Particle Swarm Optimization, firstly introduced by Kennedy and Eberhart 1995 [7, 8], is relatively a modern heuristic search method motivated from the simulation of the behavior of social systems. The motivation behind this concept is to well balance the exploration and exploitation capability for attaining better convergence to the optimal solution. In the standard PSO, a population of particles is initialized with random positions marked by $\mathrm{x}(t)$ vectors and random velocities $\mathrm{v}(t)$. The modified velocity and position of each particle can be calculated using the current velocity and the distance from $Pbest_i, Gbest_i$ shown in the following formulas general:

$$\begin{cases} \mathrm{v}(t+1) = w * \mathrm{v}(t) + c_1 rand_1 * (Pbest_i - x(t)) + c_2 rand_2 * (Gbest_i - x(t)) \\ \mathrm{x}(t+1) = x(t) + (t+1) \end{cases} \tag{9}$$

where $\mathrm{v}(t+1), v(t)$ is the current and modified velocity respectively , $rand_1, rand_2$ are the random numbers between 0 and 1, $Pbest_i, Gbest_i$ is the best values found by particle i and the best found in the group respectively, $\mathrm{v}(t+1), v(t)$ is the current and modified position, c_1, c_2 are cognitive and social coefficients..

3.2. PSO based Time Varying Acceleration Coefficients (PSO-TVAC)

The idea behind TVAC is to enhance the global search in the early part of the optimization and to encourage the particles to converge towards the global optima at the end of the search [17]. This is achieved by changing the acceleration coefficients c_1 and c_2 with time in such a manner that the cognitive component is reduced while the social component is increased as the search proceeds. The acceleration coefficients are expressed as:

$$\begin{cases} c_1 = (c_{1f} - c_{1i})\dfrac{iter}{iter_{\max}} + c_{1i} \\ c_2 = (c_{2f} - c_{2i})\dfrac{iter}{iter_{\max}} + c_{2i} \end{cases} \tag{10}$$

Were c_{1f}, c_{1i}, c_{2f} and c_{2i} are social acceleration factors and initial and final values of cognitive respectively. The value of this coefficients taken from Ref [18-19] reports 2.5 each for c_{1i} and c_{2f} and 0.5 each for c_{2i} and c_{1f} as the most effective values. The concept of time varying inertial weight was introduced in [17] is suggested to decrease linearly from 0.9 to 0.4 during execution. The inertial weight formulated as:

$$w = (w_{\max} - w_{\min}) * \frac{(iter_{\max} - iter)}{iter_{\max}} + w_{\min} \tag{11}$$

Where $iter$ is the current iteration number while $iter_{\max}$ is the maximum number of iterations.

4. Simulation Results

4.1. Case Studies

Three test cases are considered:

1- The first test consists in applying the genetic algorithm toolbox (GATOOL).

2- The second test is by applying the PSO-TVAC original to solve the relay coordination problem (PSO-TVAC 1).

3- The DOCRs coordination problem is solved using the (PSO-TVAC modified) by fixing the initial population found from (PSO-TVAC 1). The parameters setting of the three algorithms are depicted in Table 1.

Table. 1. Parameters setting of the three algorithms.

GA Toolbox	PSO-TVAC 1	PSO-TVAC 2
Population size 200	Population size 200	Population size 200
Max- generations 4000	Max- generations 1000	Max- generations 1000
Selection, Crossover and Mutation.(Gatool:)	C1f=0.2, C1i=2.5 C2f=2.2, C2i=0.2 Wmin=0.4, Wmax=0.9	C1f=0.2, C1i=2.5 C2f=2.2, C2i=0.2 Wmin=0.4, Wmax=0.9

4.2. Test System (8_Bus)

The proposed algorithm is applied to an 8-bus network; the single line diagram of this test system is shown in Fig 1. In this paper the coordination time interval CTI is taken equal 0.3s, and the TDS values can range continuously from 0.1 to 1.1, while seven available discrete pickup tap setting PTS (0.5, 0.6, 0.8, 1.0, 1.5, 2.0, and 2.5) [2]. The ratio current transformers of relay (1, 2, 4, 5, 6, 8, 10, 11, 12, and 13) and (3, 7, 9, 14) are assumed as 240 and 160 respectively. The short-circuit current for near-end 3-ph short–circuit faults is given in table 2 [3]. Details technical data can be retrieved from [4].

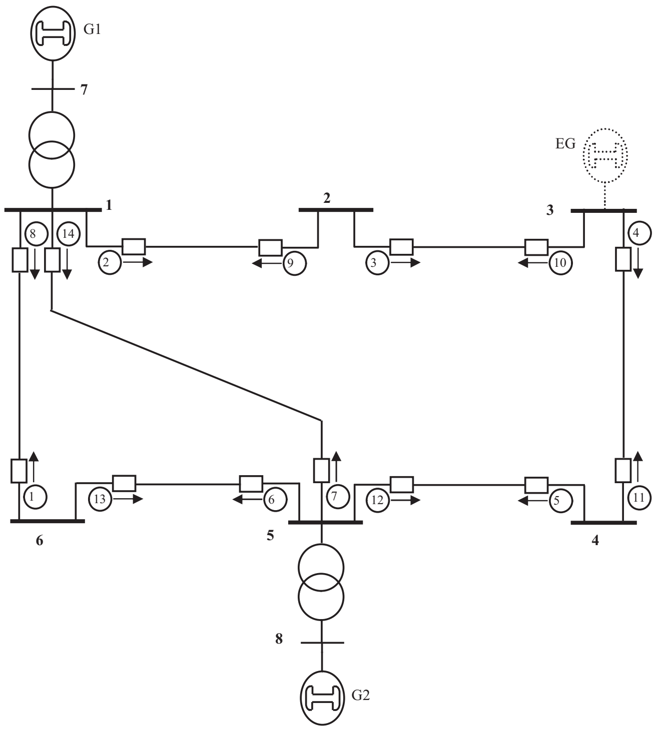

Fig. 1 Single line diagram of 8-bus system.

Table. 2 Near-End 3-phase short circuit results, 8-Bus system

	Primary Relay	Fault Current(A)	Backup relay	Fault Current(A)		Primary Relay	Fault Current(A)	Backup relay	Fault Current(A)
1	1	3232	6	3232	11	8	6093	7	1890
2	2	5924	1	996	12	8	6093	9	1165
3	2	5924	7	1890	13	9	2484	10	2484
4	3	3556	2	3556	14	10	3883	11	2344
5	4	3783	3	2244	15	11	3707	12	3707
6	5	2401	4	2401	16	12	5899	13	987
7	6	6109	5	1197	17	12	5899	14	1874
8	6	6109	14	1874	18	13	2991	8	2991
9	7	5223	5	1197	19	14	5199	1	996
10	7	5223	13	987	20	14	5199	9	1165

Fig 2 shows the convergence characteristic of the GA based Matlab toolbox, Fig 3 shows the convergence characteristic of the proposed variant named PSO-TVAC2. The results obtained as well depicted in Table 3 clearly prove the efficiency of the proposed variant. It can be seen that PSO_TVAC 2 gives better result (8.5112 s) compared to PSO-TVAC 1 (8.8423 s) and to GA (10.8893 s). As well illustrated in Table 4 the execution time taken by PSO-TVAC2 to achieve the optimal value is 12.4822 s which is better than the execution time required using GA-Toolbox (293.8489 s).

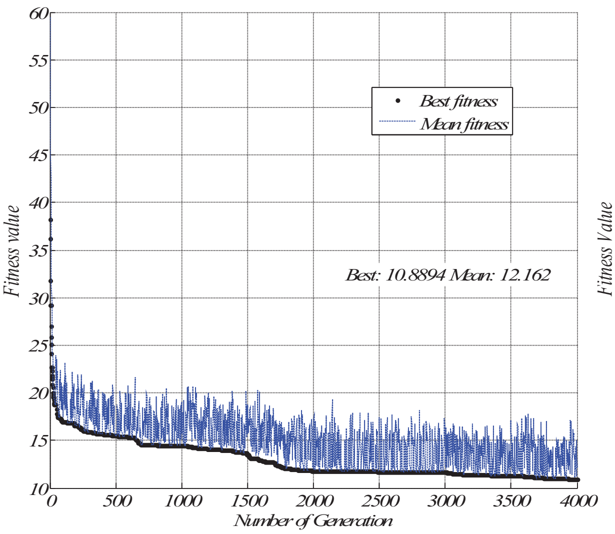

Fig. 2. Convergence characteristic of the GA Toolbox

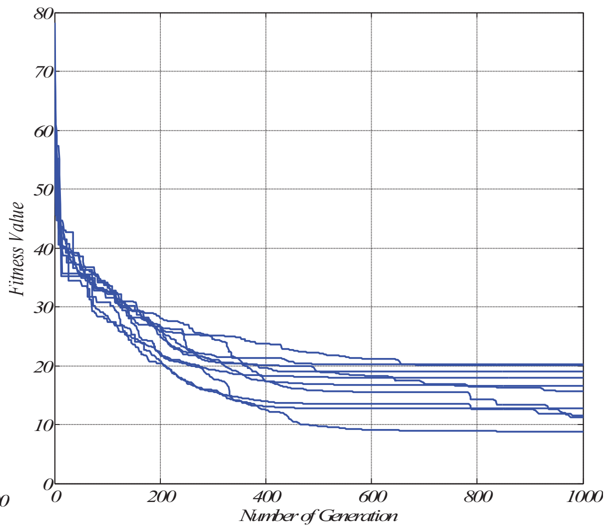

Fig. 4 Convergence characteristic of PSO_TVAC1 variant

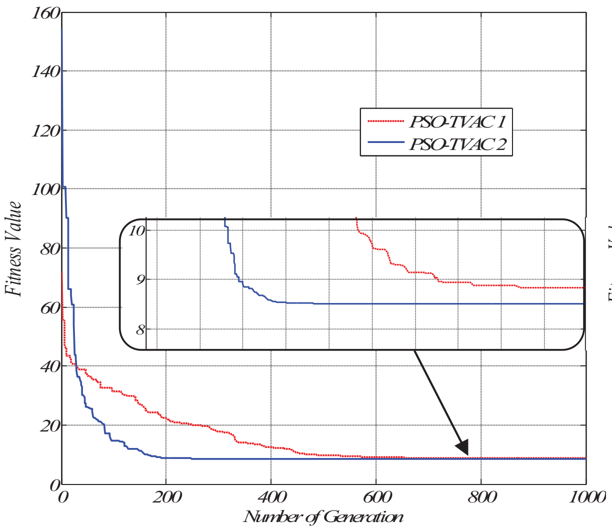

Fig. 3. Convergence characteristic of the PSO-TVAC1 and PSO-TVAC2 variants

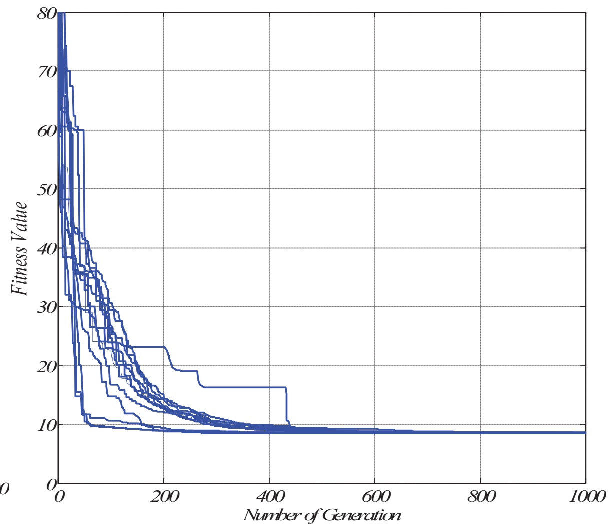

Fig. 5. Convergence characteristic of PSO_TVAC2 variant

Due to the stochastic aspect of global optimization method, the best solutions are obtained by experiencing many trails. Figs. 4, 5 show the convergence characteristic of PSO-TVAC1 and PSO-TVAC2 for 10 trails. It can be observed that PSO-TVAC2 provide better results it converges in less than 500 iterations, also the mean value is 8.5845 s which is better than mean values obtained using PSPO-TVAC1 and GA toolbox as well shown in Table 5. In order to verify the robustness of the proposed variant, a comparative study for constraints violations is shown in table 4, the negative values indicate the degree of constraints violation. From Table 4 we can see a superior performance of the proposed variant named PSO-TVAC2 compared to other techniques.

Table. 3. Optimal settings of the 8-Bus system

Relay No	GA [2]		Hybrid GA-IP [2]		GA-Toolbox		PSO-TVAC 1		PSO-TVAC 2	
	TDS	TPS	TDS	TPS	TDS	TPS	TDS	TPS	TDS	TPS
1	0.29	1.0	0.3043	1.0	0.1837	1.5000	0.1000	2.5000	0.1000	2.5000
2	0.31	2.5	0.2917	2.5	0.3491	2.0000	0.2602	2.5000	0.2602	2.5000
3	0.26	2.5	0.2543	2.5	0.3543	1.5000	0.2251	2.5000	0.2251	2.5000
4	0.19	2.5	0.1851	2.5	0.3782	0.6000	0.1603	2.5000	0.1603	2.5000
5	0.18	1.5	0.1700	1.5	0.1436	2.0000	0.1000	2.5000	0.1000	2.5000
6	0.26	2.5	0.2711	2.5	0.2425	2.0000	0.3447	0.5000	0.3447	0.5000
7	0.54	0.5	0.5316	0.5	0.3224	2.0000	0.2428	2.5000	0.2428	2.5000
8	0.24	2.5	0.2387	2.5	0.2709	2.0000	0.1700	2.5000	0.1700	2.5000
9	0.17	2.0	0.1856	2.0	0.1721	2.5000	0.1535	2.5000	0.1473	2.5000
10	0.19	2.5	0.1895	2.5	0.4041	0.6000	0.3917	0.5000	0.1759	2.5000
11	0.21	2.5	0.2014	2.5	0.3115	1.5000	0.2095	2.5000	0.1869	2.5000
12	0.30	2.5	0.2890	2.5	0.3635	2.0000	0.2890	2.5000	0.2664	2.5000
13	0.23	1.5	0.2297	1.5	0.2652	1.0000	0.1000	2.5000	0.1000	2.5000
14	0.51	0.5	0.5278	0.5	0.3327	2.0000	0.2611	2.5000	0.2459	2.5000
Obj-	11.001		10.9499		10.8893		**8.8423**		**8.5112**	

Table. 4. Comparative study: verification of constraints violation

Primary Relay	Backup relay	GA [2]	Hybrid GA-IP [2]	GA Toolbox	PSO-TVAC 1	PSO-TVAC 2
1	6	0.0021	0.0100	0.0001	0.0001	0.0001
2	1	0.1801	0.3041	0.0026	0.2968	0.2968
2	**7**	**-0.0682**	**-0.0315**	0.0001	0.0002	0.0002
3	2	0.0830	0.0301	0.0006	**-0.0001**	**-0.0001**
4	3	0.0282	0.0237	0.0011	**-0.0002**	**-0.0002**
5	**4**	**-0.0056**	0.0062	0.0002	0.0002	0.0002
6	**5**	**-0.0301**	**-0.1203**	0.1395	0.1164	0.1164
6	14	0.0304	0.0360	0.3440	0.2751	0.2073
7	**5**	**-0.1311**	**-0.1752**	0.0042	0.0619	0.0619
7	13	0.4130	0.4244	0.2086	0.4547	0.4547
8	7	0.1498	0.1356	0.2208	0.2760	0.2760
8	**9**	**-0.0990**	**-0.0118**	0.0875	0.1929	0.1527
9	10	0.0541	**-0.0006**	0.0176	0.0000	0.0001
10	11	0.0651	0.0234	0.0116	0.0001	**-0.0001**
11	12	0.0397	0.0306	0.0060	0.0001	0.0001
12	13	0.3823	0.4132	0.0053	0.2343	0.3020
12	**14**	**-0.1013**	**-0.0301**	0.0054	0.0003	0.0001
13	**8**	**-0.0153**	**-0.0199**	0.0002	0.0001	0.0001
14	1	0.2862	0.3269	0.1385	0.3797	0.4201
14	**9**	**-0.2110**	**-0.1562**	0.0026	**-0.0001**	0.0002

Table. 5. Comparison of simulation results

	GA Toolbox	PSO-TVAC 1	PSO-TVAC 2
The Best	10.8893	8.8423	**8.5112**
The Mean	12.2875	15.8014	8.5854
The Max	12.3581	22.5068	8.7960
Time (s)	293.8489	12.6322	**12.4822**

5. Conclusion

In this paper, an efficient strategy based PSO-TVAC is adapted and applied successfully for solving the IDMT overcurrent relays coordination problem. In this variant based PSO the cognitive and social factors aren't constant but they are adjusted dynamically to explore most all the positions space research to eliminate the local minima. The main objective of the proposed optimization strategy is the minimization of total operation time of the associated relays installed at specified locations in the power system to enhance the performance of power system protection. The robustness of the proposed variant named based PSO-TVAC is validated on a practical 8-Bus test system. Simulation results compared to GA and to the standard PSO clearly confirm the efficiency and robustness of the proposed variant in term of solution quality and convergence characteristic.

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