

Coordination of directional overcurrent relays for distribution system using particle swarm optimization

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Abstract

The protection of electrical distribution network with multiple loops and bidirectional power flow needs optimal coordination of directional overcurrent relays (DOCRs). The DOCRs coordination is highly non-linear and largely constrained optimization problem where plug settings (PS) and time dial settings (TDS) of DOCRs are set as control variables. The objective function in this paper is based on minimizing the operating time of all primary DOCRs considering far-end and near-end fault approach. The optimization is performed with particle swarm optimization (PSO) for standard test systems of 3-bus, 4-bus and 6-bus and the results are compared with the existing methods of relay coordination reported in literature. The optimized PS and TDS for DOCRs has resulted in the least value of objective function along with proper coordination time interval for all test systems.

Keywords: Directional overcurrent relay coordination, coordination time interval, optimization, particle swarm optimization

1. Introduction

Directional overcurrent relays (DOCRs) are required for the protection of feeders at sub-transmission and distribution level which carry bidirectional power flow. The relaying system must be selective, sensitive, reliable and fast in its operation to isolate the faulty section of electrical network. Selectivity of relaying systems identifies the primary and backup relays. Backup relays will operate only in case of failure of primary relay with proper coordination time interval. The problem of relay coordination requires the knowledge of maximum possible load and fault current for each possible fault location to cover whole network with primary and backup overcurrent protection. The optimal relay coordination guarantees the correct relay operating sequence with the least fault clearing time for each fault location.

DOCRs coordination has been obtained by various optimization techniques in literature. Linear programming (LP) is one of the popular techniques to solve this problem. LP formulates the problem in linear form and solved with the help of simplex methods [1-3]. In LP technique, PS requires to be assumed while allowing TDS as a linear function which will determine time of operation (TOP) for each relay. In [4], Random Search Technique (RST) is applied to achieve optimal relay settings. To optimize both TDS and PS, Sequential Quadratic Programming was proposed in [5-6]. Relay coordination is formulated by Mixed integer nonlinear programming problem and optimized by different variants of PSO in [7-11]. Various evolutionary methods such as Differential Evolutionary (DE) algorithm and its modified variants [12-15], Seeker algorithm [16], Teaching Learning Based Optimization (TLBO) [17-18], Ant colony algorithm [19], Group search optimization method [20], Chaotic firefly algorithm [21] and real coded genetic algorithm (RGA) with bounded exponential cross over and power mutation [22] have been reported to solve this highly constrained optimization problem of DOCRs coordination. Hybrid methods which are the combination of two or more methods such as GA-LP [23], GA-NLP [24], Gravitational Search Algorithm (GSA)-SQP [25], PSO-GSA [26], Biogeography-Based Optimization

algorithm-LP [27] have also been reported for this problem.

It is observed through the literature survey that the researchers have applied different optimization techniques to solve the relay coordination problem by using different objective functions. These objective functions are mainly dependent on the minimizing the operating time of primary relays. The ‘near-end fault’ approach [5-6], [21], [24-25] and ‘near-end and far-end fault’ approach [4-5], [12], [16-17], [22] have been implemented for relay coordination. The optimization obtained with ‘near-end fault’ approach sometimes results in mis-coordination of relay operation [5]. In this paper, comparative results for both approaches have been presented. PSO based on constriction factor approach is used for optimal coordination of DOCRs for standard 3 bus, 4 bus and 6 bus test systems. The optimized values of TDS and PS of DOCRs are obtained which meets all required constraints. The obtained results are also compared with the existing methods available for DOCRs coordination. It is shown that even simple PSO is capable to find the optimal set of PS and TDS of DOCRs coordination.

2. Problem Formulation for Relay Coordination

2.1. Formulation of objective function

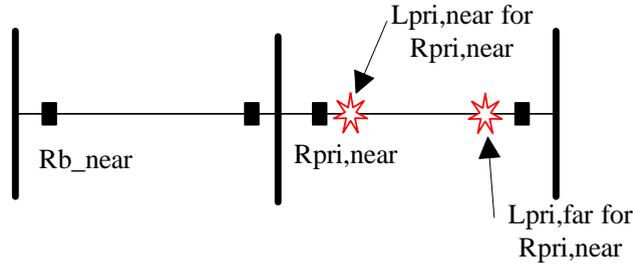


Fig. 1. Problem formulation for ‘near-end and far-end fault’

The problem of relay coordination of DOCRs has been formulated for ‘near-end and far-end fault’ approach as can be viewed from Fig. 1. For Relay $R_{pri,near}$ in Fig. 1, the fault occurs at location $L_{pri,near}$ i.e. very close to primary relay $R_{pri,near}$ is defined as near end fault. Similarly, the fault occurs at location $L_{pri, far}$ is defined as far-end fault for relay $R_{pri,near}$. In Fig. 1, R_b is a backup relay for relay $R_{pri,near}$ for both near-end and far-end fault. Hence, relay R_b must be coordinated with relay $R_{pri,near}$ for both the faults and should operate only after pre-defined coordination time interval in case of failure of $R_{pri,near}$. The objective function for ‘near-end and far-end’ is given in (1). While optimizing (1), the running sum of coordination constraints violations discussed in Section 2.2.4 is also added to the evaluated objective function.

$$Z_{near_far} = \sum_{i=1}^{N_{near}} T_{pri,near}^i + \sum_{j=1}^{N_{far}} T_{pri, far}^j \quad (1)$$

where N_{near} = total primary relays operating for near-end fault; N_{far} = total primary relays operating for far-end fault ; $T_{pri,near}^i$ = operating time of i^{th} primary relay for near-end fault; $T_{pri, far}^j$ = operating time of j^{th} primary relay for far-end fault.

$$T_{pri,near}^i = \frac{TDS_{pri,near}^i \times 0.14}{\left(\frac{I_f^i}{(PS_{pri,near}^i \times CTR_{pri,near}^i)} \right)^{0.02}} - 1 \quad (2)$$

$$T_{pri, far}^j = \frac{TDS_{pri, far}^j \times 0.14}{\left(\frac{I_f^j}{(PS_{pri, far}^j \times CTR_{pri, far}^j)} \right)^{0.02}} - 1 \quad (3)$$

2.2. Formulation of constraints

2.2.1. Limits on time dial settings (TDS) of DOCRs

TDS of DOCRs are set as control variables and are bounded in the range given by (4). The upper limit and lower limit for TDS are set as 1.1 and 0.05, respectively.

$$TDS_{lower}^i \leq TDS_i \leq TDS_{upper}^i, \quad i = 1, 2, \dots, N \text{ (Total relays in network)} \quad (4)$$

2.2.2. Limits on plug setting (PS) of DOCRs

PS of DOCRs are also set as control variables and are bounded in the range given by (5). Lower and upper limits for PS are set as 1.2 and 1.5, respectively.

$$PS_{lower}^i \leq PS_i \leq PS_{upper}^i, \quad i = 1, 2, \dots, N \text{ (Total relays in network)} \quad (5)$$

2.2.3. Limits on operating time of relays

The operating time of relay in (1) should be limited by the constraints otherwise relays will operate either too fast or too slow. Higher limit of 1 sec and lower limit of 0.05 sec are set for the relay operating time.

2.2.4. Coordination time interval (CTI)

In case of failure of primary relay, backup relay will respond after some time interval. If the backup relay will operate earlier than primary relay, then larger portion of the network will be disconnected. Hence, selectivity constraints as given in (6) are used. In this work, CTI is set as 0.3 sec for 3-bus test system and 0.2 sec for 4-bus and 6-bus test systems.

$$ToP_{backup} - ToP_{primary} \geq CTI \quad (6)$$

3. Primary-Backup (P/B) Relay Pairs, Fault Current and CT Ratings

In this work, three standard test systems of 3-bus, 4-bus and 6 bus as shown in Figs. 2-4 have been used for the DOCRs coordination. In Figs. 2-4, the DOCRs are also shown along with their assigned direction of operation. The P/B relay pairs are determined using LINKNET structure [28]. Table 1, 2 and 3 list P/B relay pairs, fault current and CT rating for 3-bus, 4-bus and 6 bus test systems, respectively. In Tables 1-3, it can be observed that some of the primary relays don't get backup protection due to network topology, hence, their corresponding constraints related to coordination time interval are relaxed during optimization. Selectively constraint is further relaxed if the fault current for any relay drops below its pick up current.

Table 1. P/B relay pairs, fault currents and CT ratings for 3-bus test system

Primary relay	CT ratings	I_f (near)	I_f (far)	Backup relay	CT ratings	I_f (near)	I_f (far)
R1	2.06	9.46	14.08	R5	0.8	9.46	14.08
R2	2.06	26.91	100.63	-	-	-	-
R3	2.23	8.81	12.07	R6	0.8	8.81	12.07
R4	2.23	37.68	136.23	-	-	-	-
R5	0.8	17.93	25.9	R2	2.06	17.93	25.9
R6	0.8	14.35	19.2	R4	2.23	14.35	19.2

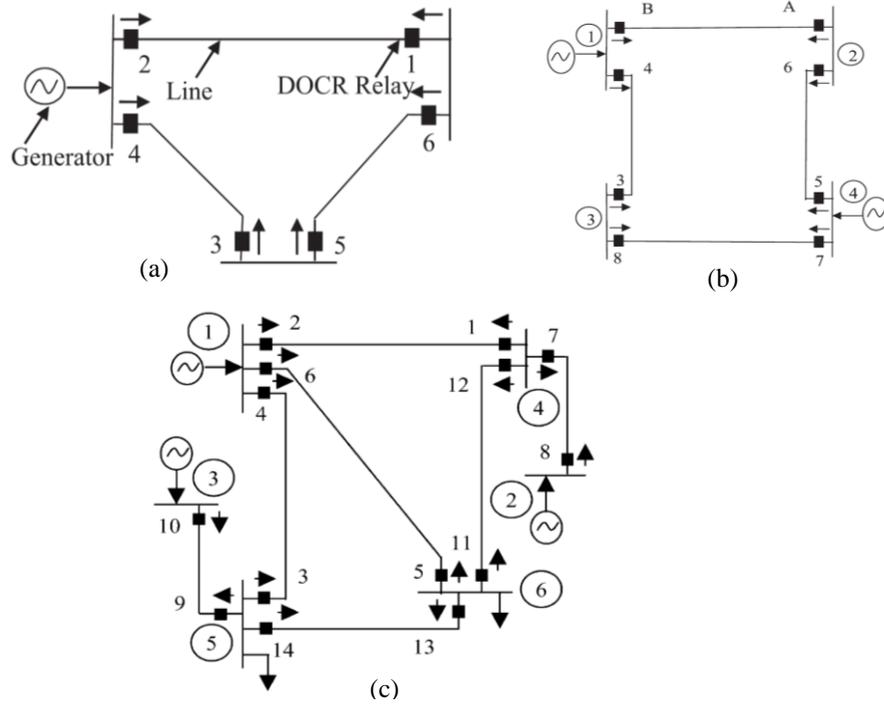


Fig. 2. IEEE test bus system: (a) 3-bus system (b) 4-bus system and (c) 6-bus system

Table 2. P/B relay pairs, fault currents and CT ratings for 4-bus test system

Primary relay	CT ratings	I_f (near)	I_f (far)	Backup relay	CT ratings	I_f (near)	I_f (far)
R1	0.48	20.32	12.48	R5	1.5259	20.32	12.48
R2	0.48	88.85	23.75	-	-	-	-
R3	1.1789	1.789	10.38	R7	1.2018	1.789	10.38
R4	1.1789	116.81	31.92	R1	0.48	116.81	31.92
R5	1.5259	116.79	31.92	-	-	-	-
R6	1.5259	16.67	12.07	R2	0.48	16.67	12.07
R7	1.2018	71.7	18.91	-	-	-	-
R8	1.2018	19.27	11	R4	1.1789	19.27	11

Table 3. P/B relay pairs, fault currents and CT ratings for 6-bus test system

Primary relay	CT ratings	I_f (near)	I_f (far)	Backup relay	CT ratings	I_f (near)	I_f (far)	Backup relay	CT ratings	I_f (near)	I_f (far)
R1	0.258	2.531	5.375	R8	1.746	2.932	4.090	R11	0.772	1.288	-
R2	0.258	2.737	5.949	R3	0.486	0.621	1.665	-	-	-	-
R3	0.486	2.972	4.589	R10	1.042	2.561	-	R13	0.587	-	1.499
R4	0.486	4.147	6.664	R1	0.258	0.886	1.524	-	-	-	-
R5	0.713	1.954	4.257	R12	0.772	1.454	2.544	R14	0.587	-	1.714
R6	0.713	2.767	6.234	R1	0.258	1.465	1.123	R3	0.486	-	-
R7	1.746	3.842	4.178	R11	0.772	1.971	2.143	R2	0.258	1.871	2.035
R8	1.746	5.618	6.369	-	-	-	-	-	-	-	-
R9	1.042	4.653	5.269	R4	0.486	3.036	3.438	R13	0.587	1.61	1.832
R10	1.042	3.526	3.87	-	-	-	-	-	-	-	-
R11	0.772	2.584	3.900	R6	0.713	1.109	1.813	R14	0.587	1.474	2.087
R12	0.772	3.800	6.114	R2	0.258	0.473	1.543	R8	1.746	3.322	4.573
R13	0.587	2.414	4.335	R6	0.713	1.836	1.608	R12	0.772	-	1.608
R14	0.587	5.354	2.901	R10	1.042	2.778	2.026	R4	0.486	2.582	0.845

4. Particle Swarm Optimization (PSO)

PSO was proposed by Eberhart and Kennedy in [29] and has been widely reported in literature for handling constrained optimization problems due to its superiority over other evolutionary techniques. It relies on simple computational steps and requires less memory and shorter solution time. The PSO equations modified with constriction factor approach is followed from [30] and explained in brief. The velocity and position update on are as per (7) and (8), respectively.

$$v_j^{p+1} = CF \times v_j^p + \left(c_1 \times r_1 \times p_{best,j} - x_j^p \right) + \left(c_2 \times r_2 \times g_{best,j} - x_j^p \right) \quad (7)$$

$$x_j^{p+1} = x_j^p + v_j^{p+1} \quad (8)$$

$$CF = \frac{2 \times K}{\left| 2 - \varphi - \sqrt{\varphi^2 - 4\varphi} \right|}, \quad \varphi = \varphi_1 + \varphi_2, \quad \varphi_1 = \varphi_2 = 2.05, \quad K = 1 \quad (9)$$

$$c_1 = CF \times \varphi_1 \quad \text{and} \quad c_2 = CF \times \varphi_2 \quad (10)$$

where v_j^p = velocity of j^{th} particle at iteration p ; r_1 and r_2 are random numbers in range of 0-1; x_j^p = position of j^{th} particle at iteration p ; c_1 and c_2 are acceleration co-efficient; $P_{best,j}$ and $g_{best,j}$ are personal and global best of particle.

5. Simulation Results

The PSO algorithm is applied for DOCRs coordination for standard 3, 4 and 6 bus systems. The fault currents are determined by creating three phase solid fault on each bus ends. Occurrence of fault near a bus and gets clearance by the relay placed on the same bus is treated as near-end fault. If the same fault gets clearance by the relay placed on other end of line, then it is treated as far end fault. The objectives are to minimize (1) and (2) subjected to the constraints satisfaction listed in Section 2. In each line of test systems, two DOCRs are placed. For each DOCR, there are two control variables, namely PS and TDS. Thus, there are 12, 16 and 28 control variables to be optimized for 3-bus, 4-bus and 6-bus test systems, respectively. Total constraints related to coordination time interval for the 3-bus, 4-bus and 6-bus were 8, 9 and 48, respectively. Depending upon the assumptions of fault current less than pick up current of the relay, these constraints are reduced to 38 for 6-bus test system. The coordination constraints for 3-bus and 4-bus test system remain unchanged.

Tables 4-5 list the optimized values of PS and TDS for DOCRs obtained with PSO for all test systems along with the minimized value of objective functions. Similarly, Tables 6-7 list the time of operation of P/B relay pairs and their corresponding CTI for all three systems under consideration. Table 8 compares the optimized values of objective function obtained with PSO to other methods reported in literature. For 3-bus and 4-bus test system, only RST [4], TLBO and modified TLBO [15], BEX-PM [22] and PSO-CFA can produce feasible solution. BEX-PM [22] reported recently is far better compared to RST [4] and TLBO [15] but PSO-CFA has resulted slightly better result than BEX-PM method. The results obtained with DE and its variants reported in [13], [15] are comparable, but they did not satisfy all valid constraints. For 6-bus test system, except BEX-PM and proposed PSO-CFA, all methods result in infeasible solution. TLBO not only result in infeasible solution, its optimized values is very high as compared to BEX-PM and PSO-CFA. For relatively larger test system of 6-bus, PSO-CFA gives better result compared to BEX-PM.

Table 4. list the optimized values of PS and TDS for DOCRs obtained with PSO for 3 and 4 bus test system

3-bus test system			4-bus test system		
Relay	TDS	PS	Relay	TDS	PS
R1	0.05	1.2	R1	0.05	1.2
R2	0.2097	1.3267	R2	0.1766	1.2111
R3	0.05	1.2	R3	0.05	1.2984
R4	0.2158	1.4045	R4	0.1202	1.3766
R5	0.1885	1.3293	R5	0.104	1.2003
R6	0.1786	1.4987	R6	0.05	1.2195
			R7	0.1165	1.2114
			R8	0.05	1.2026

Table 5. list the optimized values of PS and TDS for DOCRs obtained with PSO for 6 bus test system

Relay	TDS	PS	Relay	TDS	PS
R1	0.1028	1.5	R8	0.05	1.2
R2	0.1768	1.5	R9	0.05	1.2
R3	0.097	1.2	R10	0.0513	1.5
R4	0.1135	1.2	R11	0.0622	1.5
R5	0.05	1.2	R12	0.0557	1.4335
R6	0.05	1.4215	R13	0.0605	1.2
R7	0.05	1.2	R14	0.0727	1.4292

Table 6. list the time of operation of P/B relay pairs and their corresponding CTI for 3 and 4bus test system

3-bus test system					4-bus test system				
Primary Relay	Backup relay	TOB	TOP	CTI	Primary relay	Backup relay	TOB	TOP	CTI
1	5	0.4977	0.1977	0.3	1	5	0.2952	0.0948	0.2004
1	5	0.5906	0.2573	0.3333	1	5	0.372	0.1103	0.2617
3	6	0.5289	0.2289	0.3	3	7	0.3567	0.1567	0.2
3	6	0.6143	0.2902	0.324	3	7	0.407	0.1794	0.2276
5	4	0.7002	0.4002	0.3	4	1	0.4965	0.1885	0.308
5	4	0.851	0.454	0.397	6	2	0.3954	0.1837	0.2117
6	2	0.8705	0.4911	0.3793	6	2	0.3562	0.1562	0.2
6	2	0.7383	0.4383	0.3	8	4	0.4313	0.169	0.2624
					8	4	0.3317	0.1317	0.2001

Table 7. list the time of operation of P/B relay pairs and their corresponding CTI for 6 bus test system

Primary relay	Backup relay	TOB	TOP	CTI	Primary relay	Backup relay	TOB	TOP	CTI
1	8	0.5196	0.2664	0.2531	9	13	0.4399	0.2399	0.2
1	11	4.1121	0.2664	3.8457	9	4	0.4399	0.2399	0.2
1	8	1.0377	0.3763	0.6615	9	13	0.5064	0.2629	0.2435
2	3	10.8334	0.6208	10.2126	9	4	0.4736	0.2629	0.2107
2	3	0.6409	0.4409	0.2	11	14	0.5543	0.3543	0.2
3	10	0.5227	0.3226	0.2	11	6	0.5991	0.3543	0.2448
3	10	0.7237	0.4105	0.3132	11	14	0.9	0.5385	0.3615
3	13	0.5579	0.3226	0.2353	11	6	3.899	0.5385	3.3605

4	1	0.8622	0.3971	0.4651	12	8	0.7526	0.3126	0.44
4	1	0.5183	0.3183	0.2	12	2	6.1874	0.3126	5.8748
5	12	0.4653	0.2148	0.2505	12	8	0.4449	0.2245	0.2203
5	12	1.428	0.4208	1.0073	12	2	0.8835	0.2245	0.659
5	14	0.7087	0.2148	0.4939	13	12	0.4292	0.2292	0.2
6	3	0.7308	0.1893	0.5415	13	6	0.7562	0.2292	0.527
6	1	0.6692	0.1893	0.4799	13	12	0.7685	0.3403	0.4282
7	11	0.7036	0.5036	0.2	14	10	1.3816	0.4056	0.9759
7	2	0.7339	0.5036	0.2304	14	4	1.9489	0.4056	1.5433
7	11	0.8154	0.5737	0.2417	14	10	0.6206	0.2698	0.3509
7	2	0.7737	0.5737	0.2	14	4	0.5261	0.2698	0.2564

Table 8. Comparison of optimized objective function with other optimization techniques

Optimization Technique	3-bus	4-bus	6-bus
RST [4]	4.8354	3.7050	-
Basic DE [13]	4.8422*	3.6774*	10.6272*
MDE1 [13]	4.8070*	3.6694*	10.5067*
MDE2 [13]	4.7873*	3.6734*	10.6238*
MDE3 [13]	4.7822*	3.6692*	10.4370*
MDE4 [13]	4.7806*	3.6674*	10.3812*
MDE5 [13]	4.7806*	3.6694*	10.3514*
OCDE1 [15]	4.7806*	3.6674*	10.3479*
OCDE2 [15]	4.4806*	3.6674*	10.3286*
TLBO [17]	5.3349	5.5890	23.7878*
TLBO-MOF [17]	6.9720*	8.7088	24.3900*
BEX-PM [22]	4.7899	3.6957	10.4056
PSO-CFA	4.7555	3.2973	10.0707

6. Conclusion

The problem of coordination of DOCRs has been solved using PSO based on constriction factor approach. The objective function is based on minimizing the operating time of primary relay for both near-end and far-end fault. The objective function is also modified by adding the running sum of coordination constraints violations in order to satisfy all valid constraints. For all three systems, the obtained optimized values of PS and TDS of DOCRs produced much better results with all valid constraints satisfied as compared to other methods reported in literature. The better solution of objective function leads to faster operation of primary relay and satisfaction of all valid constraints achieves the selectivity of protective relaying.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Mr. Deepak Vyas and Dr. Praghnes Bhatt conducted the research; Dr. Praghnes Bhatt and Mr. Vipin Shukla analysed the data; Mr. Deepak Vyas wrote the paper. All authors have approved the final version.

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