Robust Protective Relay Setting and Coordination Using Modified Differential Evolution Considering Different Network Topologies

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Abstract. In real power system, the system may be subjected to operate in different network topologies due to single line outage contingencies, network reconfiguration and maintenance. These changes in the network would lead to operational inconsistency of directional overcurrent relays. To overcome this problem, a set of new coordination constraints corresponding to each network topology needs to be formulated. Directional Overcurrent Relays (ODCRs) problem can be formulated as a nonlinear optimization problem and also in addition to nonlinearity, the optimization problem encounter a large number of coordination constraints. This paper presents a modified Differential Evolution (DE) algorithm to handle such type of Optimal Directional Overcurrent Relays problem. Modified DE computes the optimal time dial setting and pickup current setting in terms of discrete values which collectively minimize the total operating time of the relays. To verify the performance of the proposed method, similar evolutionary computation methods such as the Genetic Algorithm (GA) approaches are also implemented using the same database. The proposed method has been verified on 8-bus test system. The results indicate that the proposed method can obtain better results than the method compared in terms of total operating time and convergence performance for both fixed and changed network topologies.

Keywords: Differential Evolution Algorithm, Directional overcurrent relays, Relay coordination, Pickup current settings, Time dial settings, Time multiplier settings.

1 Introduction

One of the fundamental tasks in a power system protection is to disconnect the faulty section from the network at a minimum time when any type of fault occurs. Directional Overcurrent Relays is commonly used for the protection of interconnected networks and looped distribution network [1]-[3]. Selecting suitable settings (TDS & Ip) ensures the effective coordination between primary relays and backup relays even in case of different fault conditions [1].

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Several optimization algorithms have been proposed and applied for the coordination of DOCRs. The coordination problem can be formulated as Linear Programming Problem (LPP), in which pickup current settings are assumed to be known and operating time of relay is a linear function of TDS. After the problem formulation as LPP, it can be solved by linear programming techniques such simplex [1], [4], [5] two-phase simplex [6] and dual simplex methods [7]. The use of conventional techniques leads to the introduction of slack or surplus variables for each inequality constraint which would result in undesirable increase in the number of variables handled. Hence, only fewer constraints can be considered in conventional techniques. In [8]-[10], Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Modified PSO are proposed to determine the optimal settings of the relay.

A network topology may change due to system contingencies, maintenance activities and network reconfiguration. The change in the network topology could cause the variation in the fault current which lead to incoordination of directional overcurrent because the parameters set for each relay was for fixed network. A new coordination constraint is formed by considering the coordination constraints for each topology to the main coordination problem of the fixed network [11]. In [11], a hybrid GA is proposed to solve the coordination problem considering the effects of the different network topologies and also at the same it improves the convergence of the conventional GA. In this method, the pickup current settings are coded into genetic strings as discrete variables and to determine the optimal TDS as continuous variables for each genetic string, LP is used. In [12], the DOCR problem is formulated as an interval linear programming (ILP) problem. The obtained ILP problem, which has no equality constraints corresponding to each relay pair, is converted to standard linear programming (IP) thereby, reducing the number constraints in new formulation.

In this paper, a modified Differential Evolution is developed to determine the optimal discrete value of TDS and Ip, satisfying the set of inequality coordination constraints which are related to different network topologies. Modified DE also improves the convergence performance. In conventional DE the scaling factor may get stuck to local optimum as the parameters are tuned constant value and not tailored for handling discrete variables. The proposed method is applied to 8 bus test system and the results show robust coordination against topological uncertainty.

The paper is organized as follows. In Section 2, the coordination problem in fixed network topology and different network topologies is presented. In Section 3, describes about the modified differential evolutionary algorithm which has been applied to solve the problem. In Section 4, the proposed method is tested on 8 bus model test systems and the results are discussed by comparing with the existing techniques. Finally, conclusions are summarized in Section 5.

2 Overcurrent Relay Coordination Problem

In the coordination problem of directional overcurrent relays (DOCRs), the target is determine the optimal TDS and Ip for each relay so that the overall operating times of primary relays are minimized without violating any coordination constraints. The relay coordination problem for both fixed and different network topologies are presented in this section. The transient network during partial fault clearance can be ignored in this study since the relays operate based on the local current measurements available to them and the transient currents decay very soon for large networks considered in such studies.

2.1 Problem Formulation for Main Network Topology

Mathematically, for a fixed network topology the DOCRs problem can be formulated as non-linear optimization problem as follows:

$$Minimize\ \ J = \sum_{i=1}^{n} T^{i}_{pri\_Near} \tag{1}$$

where n is the number of relays and $T^{i}_{pri\_Near}$ is the operating time of the i^{th} relay for near end fault.

2.1.1 Relay Characteristics

The operating time of i^{th} overcurrent relay is a function of Time Dial Setting (TDS_i), Pickup Current Setting (I_{p_i}) and the fault current passing through the relay (I_{f_i}). The relay characteristics are given by constants a and b.

$$T_i = F_i\left(TDS_i, I_{p_i}, I_{f_i}\right) = \frac{\left(a \times TDS_i\right)}{\left(I_{f_i} / I_{p_i}\right)^b - 1} \tag{2}$$

2.1.2 Limits on the Relay Settings

The bounds on the relay settings can be represented as

$$I_{p_i}^{\min} < I_{p_i} < I_{p_i}^{\max} \tag{3}$$

$$TDS_i^{\min} < TDS_i < TDS_i^{\max} \tag{4}$$

Overcurrent relay coordination involves the appropriate settings of TDS_i (discrete) and I_{p_i} (discrete). The lower limit of I_{p_i} is the minimum tap available. The upper limit of I_{p_i} is the maximum tap available. Similarly TDS_i has also lower and upper limit values based on the relay current-time characteristic.

2.1.3 Coordination Criteria

Coordination constraint between the primary and backup relays is illustrated as,

$$T_{backup} - T_{primary} \geq CTI \tag{5}$$

where, T_{backup} is the operating time of backup relay and $T_{primary}$ is the operating time of the primary relay. The Coordination Time Interval (*CTI*) ensures that the operating time of the backup relay must be greater than the corresponding primary relay for all the faults considered (all fault types, normal and single-contingency conditions). The value of *CTI* is normally selected between 0.2 to 0.5 s.

2.2 Problem Formulation of Changed Network Topologies

The fault current passing through the relays changes when the network topology is changed. Owing to the changed fault current, the operating time of primary and backup relays will also change and this change in the operating time leads to the incoordination. To overcome this problem, a new set of coordination constraints is added to the coordination constraints of main topology. Considering the different network topologies due to single line outage contingencies, the coordination constraint is reformulated as follows:

$$T^{s}{}_{backup} - T^{s}{}_{primary} \geq CTI \text{ , } s \in S \tag{6}$$

where $T^{s}{}_{backup}$ and $T^{s}{}_{primary}$ are the operating time of backup and primary relays for the s^{th} network topology. S is the set of all topologies which have been obtained under single line outages contingencies of the main topology.

3 Modified Differential Evolution (DE)

The differential evolution (DE) algorithm inspired evolutionary computing, proposed by Storn and Price [13], is a stochastic, population based optimization method. DE has been successfully applied in many engineering fields such as power systems [14], mechanical engineering [14], pattern recognition [14] etc. due to its simplicity in implementation, robustness and fast convergence. The modified algorithm customized for the problem at hand is as follows.

3.1 Initialization

It begins with randomly initiated population of N D–dimensional parameter vectors, which represents the potential solutions of the global optimum. The total number of iterations or generations is represented by G. Each i^{th} vector at g^{th} iteration is produced using corresponding minimum and maximum limits, using a uniformly distributed random variable. This causes the initial solutions to be spread over the search space without any bias. For all equations of the algorithm, integers $i \in [1, N]$, $j \in [1, D]$ and $g \in [1, G]$.

$$X_i^g = \left[x_{(i,1)}^g, x_{(i,2)}^g, \ldots, x_{(i,j)}^g, \ldots, x_{(i,D-1)}^g, x_{(i,D)}^g\right] \tag{7}$$

Each element in the candidate vector has lower and upper numerical bounds, which are characteristic of the system being optimized.

$$X_i^{lower} = \left[x_1^{lower}, x_2^{lower}, \ldots, x_j^{lower}, \ldots, x_{(D-1)}^{lower}, x_D^{lower}\right] \tag{8}$$

$$X_i^{upper} = \left[x_1^{upper}, x_2^{upper}, \ldots, x_j^{upper}, \ldots, x_{(D-1)}^{upper}, x_D^{upper}\right] \tag{9}$$

$$x_{(i,j)}^1 = x_j^{lower} \times \left(1 - rand_{(i,j)}\right) + x_j^{upper} \times rand_{(i,j)} \tag{10}$$

It is notable that the optimization here contains physically dissimilar variables; the candidate vector is represented as a concatenation of those variables.

$$X_i^g = \left[TDS_{(i,1)}^g, TDS_{(i,2)}^g, \ldots, TDS_{(i,n)}^g, Ip_{(i,1)}^g, Ip_{(i,2)}^g, \ldots, Ip_{(i,n)}^g\right] \tag{11}$$

3.2 Mutation

This step modifies the potential vectors to be tested against the rest of the current vectors, going through a sorting process to ensure that only the best is transferred to the next iteration. It can be done through one of the many ways shown using mutually exclusive random indices a, b, c, d, e and index of the best vector.

1) "DE/rand/1":

$$M_i^g = X_a^g + \lambda\left(X_b^g - X_c^g\right) \tag{12}$$

2) "DE/best/1":

$$M_i^g = X_{best}^g + \lambda\left(X_a^g - X_b^g\right) \tag{13}$$

3) "DE/rand-to-best/1":

$$M_i^g = X_i^g + \lambda\left(X_{best}^g - X_i^g\right) + \gamma\left(X_a^g - X_b^g\right) \tag{14}$$

4) "DE/best/2":

$$M_i^g = X_{best}^g + \lambda\left(X_a^g - X_b^g\right) + \gamma\left(X_c^g - X_d^g\right) \tag{15}$$

5) "DE/rand/2":

$$M_i^g = X_a^g + \lambda\left(X_b^g - X_c^g\right) + \gamma\left(X_d^g - X_e^g\right) \tag{16}$$

Obtaining the modified vector M_i^g is dependent on the control parameters λ and γ, which can be intelligently modified to handle discrete variables. Instead of using them as just multipliers, in this algorithm they are treated as operators on the differential vectors which can multiply adaptive weights and also discretize the differential vectors operated upon.

$$\lambda(\theta)=\left\{\overline{\overline{(\theta\times\Lambda)}}\,\middle|\,\Lambda=\Lambda_0+\delta\right\} \tag{17}$$

$$\gamma(\theta)=\left\{\overline{\overline{(\theta\times\Omega)}}\,\middle|\,\Omega=\Omega_0+\delta\right\} \tag{18}$$

The double-bar operator represents discretization of the variable to the nearest possible state as allowed for TDS or Ip values. θ represents a generic multi-dimensional matrix of real numbers. Λ and Ω are multipliers which start with Λ_0 and Ω_0 values respectively, but are modified by a Gaussian random variable δ, which has standard deviation of unity over a mean value (μ^g) given by the normalized mean of the current population's objective values. If the mean of objective values are relatively small, larger is the perturbation, leading to higher explorative capabilities. As the iteration progresses, the mean value becomes relatively higher and the probability of smaller perturbations becomes high, leading to more exploitative capabilities of the population.

$$F^g=\left[f\left(X_1^g\right),f\left(X_2^g\right),\ldots,f\left(X_i^g\right),\ldots,f\left(X_{(N-1)}^g\right),f\left(X_N^g\right)\right]^T \tag{19}$$

$$\mu^g=\left(\frac{\min\left(F^g\right)-N^{-1}\sum_{i=1}^{N}f\left(X_i^g\right)}{\max\left(F^g\right)}\right) \tag{20}$$

where F^g is the column vector containing the objective values of the current population. The values of μ^g are reasonable for mutation operation only if all values in F^g are non-negative. Since the objective of the problem studied is total operating time, this criterion is satisfied automatically.

3.3 Crossover

It determines the intermixing of the mutant population with the original population. Depending on *Cr*, either mutant element or the original population is selected to a crossed population as shown below.

$$c_{(i,j)}^g=\left\{\begin{matrix} m_{(i,j)}^g & if\,(rand_{(i,j)}\le Cr) \quad or \quad j=j_{rand} \\ x_{(i,j)}^g & otherwise \end{matrix}\right\} \tag{21}$$

where $c^g_{(i,j)}$ is the j^{th} element of the vector C^g_i, $m^g_{(i,j)}$ is the j^{th} element of the vector M^g_i and $x^g_{(i,j)}$ is the j^{th} element of the vector X^g_i. The value j_{rand} is a random integer generated such that $j_{rand} \in [1, D]$. The value of $Cr \in (0,1)$ is generally taken high such that the crossed population would have higher probability of having larger percentage of mutated portions.

3.4 Selection

From the crossed population and the current population, candidate vectors are selected for the next generation, purely based on merit (or objective function value). *N* vectors giving the best objective values when both populations combined are selected.

$$X_i^{g+1} = \begin{Bmatrix} C_i^g & if \quad f\left(C_i^g\right) \leq f\left(X_i^g\right) \\ X_i^g & otherwise \end{Bmatrix} \tag{22}$$

The procedure is repeated till specific criteria for termination is reached.

4 Case Study

In order to assess the proposed method, the developed modified DE is applied to 8-bus test-system shown in Fig.1. The system data is given in [9]. **:** The overcurrent relays having IEC standard inverse-type characteristics is considered for research work. The network consists of 14 relays shown in Fig 1. The TDS can vary from 0.05 to 1.1 with a step of 0.01 and the Ip can vary from 0.5 to 2.5 with a step of 0.25. The ratios of the CTs are shown in Table 1. CTI is assumed to be 0.3, a=0.14 and b=0.02. The primary/backup relay pairs and the corresponding fault current are shown in Table 2.

The proposed modified DE is capable of solving discrete non-linear optimization problems. The DOCRs coordination is solved for fixed network topology using the GA and modified DE and was coded in MATLAB with total number of variables 28 and population size of 20 individuals. The maximum number of generation count used is 1000. The modified DE performs best with the last strategy in DE. The scaling factor Λ_0 *and* Ω_0 are taken to be as 0.5 and 0.3 respectively after many trials. The crossover rate used is 0.8. In GA, its own individual best performance for this problem is found empirically when the probability of selection, crossover and mutation are taken as 0.6, 0.5 and 0.02 respectively. The optimal time dial setting and pick up current setting of each overcurrent relay are computed for two cases.

Case 1) Coordination problem considering fixed network topology
Case 2) Coordination problem considering changed network topology

Table 1. CT ratio for 8 bus system

Relay no	CT ratio	Relay no	CT ratio
1	1200/5	8	1200/5
2	1200/5	9	800/5
3	800/5	10	1200/5
4	1200/5	11	1200/5
5	1200/5	12	1200/5
6	1200/5	13	1200/5
7	800/5	14	800/5

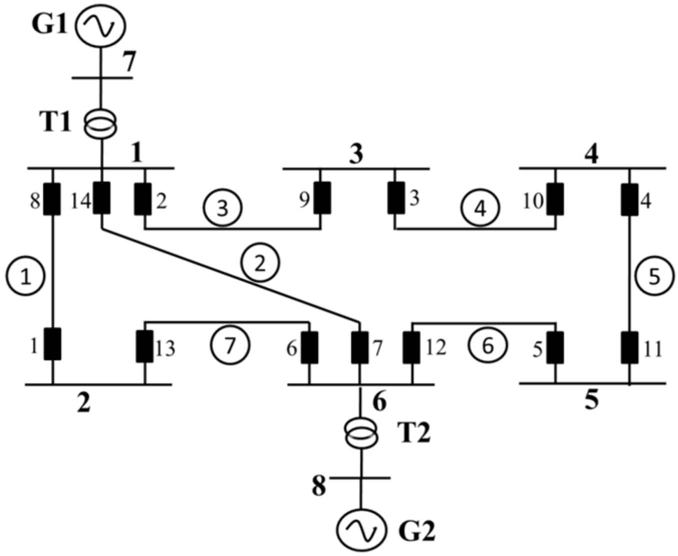

Fig. 1. 8-bus test-system, 14 relay pairs (Nodes, branches and relays are labelled. Node labels are in bold and branch labels are circled. Line outage numbers and branch labels are the same.)

The optimal values are shown in Table 3. From the results obtained by developing GA and modified DE, it shows the latter gave better optimal solution than GA for both the cases. Table 4 shows the coordination constraints number, number of incoordination and percentage of incoordination for fixed network and changed in the network topology due to single line outages contingencies. The parameters already set for fixed network topology would no longer make the system operate without any incoordination when there is a changed in the network topology because of the fault current variations. Table 5 shows the obtained optimal settings for fixed network and after consideration of different network topologies.

Table 2. Primary/Backup Relay Pairs and Fault Currents in Fixed Network Topology

Primary/Backup pairs		Near-End Fault Current	
Primary Relay No	Backup Relay No	Primary Relay (KA)	Backup Relay (KA)
1	6	2.6671	2.6671
2	1	5.2841	1.5791
2	7	5.698	2.0258
3	2	3.6274	3.6274
4	3	2.4216	2.4216
5	4	1.3651	1.3651
6	5	4.5068	0.7049
6	14	5.2354	1.4855
7	5	4.0438	0.2404
7	13	4.188	0.3959
8	7	5.1201	1.402
8	9	4.4388	0.6668
9	10	1.43	1.43
10	11	2.5382	2.5382
11	12	3.789	3.789
12	13	5.3675	1.6259
12	14	5.7953	2.086
13	8	2.4943	2.4943
14	1	4.188	0.3959
14	9	3.8957	2.0271

To verify the robustness of the modified DE, the results of the cases 1 and 2 are compared for an arbitrary relay pair. The operating time of primary and backup pairs are shown in Table 6 for every single line outage contingency.

Table 3. Optimal Settings of Relays for 8-Bus Test-System for Fixed Network Topology

Relay Number	Genetic Algorithm, GA		Proposed DE Algorithm	
	TDS	Ip	TDS	Ip
1	0.23	1.25	0.36	0.5
2	0.58	1	0.26	2.5
3	0.52	0.5	0.2	2
4	0.35	0.5	0.14	1.75
5	0.18	0.5	0.18	0.5
6	0.49	0.5	0.35	1.25
7	0.59	0.75	0.23	2.25
8	0.51	0.75	0.26	2
9	0.13	1	0.25	0.5
10	0.13	1.7	0.21	1.25
11	0.41	0.5	0.46	0.5
12	0.59	0.5	0.42	1.5
13	0.41	0.5	0.29	0.75
14	0.55	0.75	0.37	1.5
Objective Function Value (s)	11.9424		10.2864	

Table 4. Number of incoordination Constraints due to Single line Outage

Line Outage No	Coordination Constraints No.	Incoordination Constraints No.	Percentage of Incoordination
1	12	3	25
2	12	4	33
3	10	1	10
4	11	4	36.4
5	11	2	18.2
6	10	2	20
7	12	3	25

Table 5. Optimal Settings of Relays for 8-Bus Test-System

Relay Number	DE, Case 1		DE, Case 2	
	TDS	Ip	TDS	Ip
1	0.36	0.5	0.55	0.75
2	0.26	2.5	0.6	1.25
3	0.2	2	0.4	1.75
4	0.14	1.75	0.3	1.75
5	0.18	0.5	0.45	0.5
6	0.35	1.25	0.5	1.5
7	0.23	2.25	0.5	1.75
8	0.26	2	0.5	2
9	0.25	0.5	0.7	0.75
10	0.21	1.25	0.45	1.75
11	0.46	0.5	0.45	2.5
12	0.42	1.5	0.55	2.5
13	0.29	0.75	0.65	0.75
14	0.37	1.5	0.5	2.25
Objective Function Value (s)	10.2864		20.4	

Column 1 of Table 6 shows the line outage number and zero indicates the fixed network topology i.e. without any line outage. Columns 2 and 3 represents the operating time for backup and primary relays for case 1 and the incoordination constraint value is shown in column 4 for case 1. Columns 5, 6 and 7 show the operating time for backup relays, primary relays and incoordination constraint value for case 2. Near-end fault is created in line no. 3 (Relay 2 will act as primary and relay 7 as back for relay 2).

By employing the setting obtained from the case 1, the violation of four coordination constraints is caused by single line outage. It is seen from the Table 6, that setting obtained from case 2 removed all the violation constraints, thereby making solution robust against the single line outage even though the values of TDS and Ip are increased in multiple network topology. The objective function value shown in the Table 7 shows the advantage of proposed method over the GA.

Table 6. Operating Time of Primary/Backup Relay (2, 7) due to Single Line Outage Contingencies (for near-end faults)

Line Outage No.	Case 1			Case 2		
	Primary Operating Time	Backup Operating Time	Incoordination (CTI= 0.3)	Primary Operating Time	Backup Operating Time	Incoordination (CTI=0.3)
0	0.7766	0.3416	0.34	1.3662	0.6939	0.69
1	0.7908	0.9167	**0.1259**	1.3854	0.3497	0.3
2	-	-	-	-	-	-
3	-	-	**-**	-	-	-
4	0.7362	0.9133	**0.1771**	1.3106	0.419	0.42
5	0.7362	1.1182	0.38	1.3106	0.7495	0.75
6	0.7362	0.9133	**0.1771**	1.3106	0.419	0.4
7	0.7905	0.9159	**0.1254**	1.385	1.7339	0.3

Table 7. Optimal Settings of Relays for 8-Bus Test-System after Considering the Different Network Topologies

Relay Number	Genetic Algorithm, GA		Proposed DE Algorithm	
	TDS	Ip	TDS	Ip
1	0.490	1	0.55	0.75
2	0.62	1.5	0.6	1.25
3	0.62	0.75	0.4	1.75
4	0.39	1	0.3	1.75
5	0.44	0.5	0.45	0.5
6	0.48	1.5	0.5	1.5
7	0.74	1	0.5	1.75
8	0.69	1.25	0.5	2
9	0.96	0.5	0.7	0.75
10	0.52	1.75	0.45	1.75
11	0.91	0.75	0.45	2.5
12	0.67	2.5	0.55	2.5
13	0.67	1	0.65	0.75
14	0.65	1.75	0.5	2.25
Objective Function Value (s)	22.71		20.08	
No. of Function Evaluation	12000		9000	

5 Conclusion

This paper presents the reformulation of DOCRs coordination problem considering different network topologies. DOCRs can be formulated as a complex non-linear optimization problem .The proposed modified DE is applied to find the optimal settings of the DOCR without violating any of the coordination constraints. The algorithm is tailored for handling discrete variables and exhibit adaptive mutation as the state of the population changes. The proposed method provides the system robustness against network uncertainties caused through line outages.

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