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OPTIMAL COORDINATION OF DIRECTIONAL OVERCURRENT RELAYS CONSIDERING NON-STANDARD CURVES AND MULTIPLE NETWORK TOPOLOGIES USING TLBO-LP

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Abstract. In this article, Directional Over-current Relay (DOCR) Coordination was performed considering various network topologies and the non-standard curve for the overcurrent relay. In practice, usually the network topology changes by switching lines and the overcurrent relay coordination might be removed. The purpose of this article is to maintain relay coordination while the network topology is changed and to get the best setting and reduce the operating time of relays. For coordinating and setting overcurrent relays, a hybrid TLBO method was used which combined Teaching-Learning Based Optimization (TLBO) and LP. Four variables were used to set overcurrent relays and the algorithm obtained specific settings for each relay. The proposed algorithm was also compared with the conventional methods. The results show that the TLBO-LP method and using non-standard curve will improve the operating time of overcurrent relay, increase coordination between them and maintain the DOCR coordination by changing the network topology and switching lines.

Keywords: DOCR, TLBO, Multiple Network Topologies, Coordination, Optimization

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1. INTRODUCTION

The main part of the power system protection is protection relays, hence, researching on these devices can be beneficial for power system protection (Abdelmoumene, 2014). Overcurrent relays are the most inexpensive and the most widely used protective relays in the distribution and sub-transmission networks. The main task of relays is to identify and remove short-circuit faults in the shortest time. There are two variables to set usual DOCRs: pickup current setting (I_{Set}) and time multiplier setting (TMS). With the advent of digital relays (Istrate, 2009), non-standard curves with additional variables can also be used .

In power system protection issues traditional, optimization and intelligent methods (Yadav, 2016) can be used for solve protection problems. In radial networks or in relays with only one variable, traditional methods can be used for solve coordination problem of DOCRs .In (Kida, 2016) LP method is used to set DOCRs where is considered as the only adjustable variable. In complex large power grids, relay coordination problem is facing difficult settings (Wang, 2015). Hence, Traditional methods cannot be used and optimization methods are commonly used to coordinate DOCRs for better results. Different optimization methods are used for DOCR coordination using two variables (TMS and I_{Set}) for relay setting: Particle Swarm Optimization (PSO) (Srivastava, 2016), Genetic Algorithm (GA) (Marcolino, 2015), Ant Colony Optimization (ACO) (Shih, 2015), Teaching Learning Based Optimization (TLBO) (Singh, 2013), Backtracking Search Algorithm (Bouchekara, 2016) and Biogeography Based Optimization (BBO) (Albasri, 2015) .In (Saleh, 2015) the impact of bus bar voltages is also considered in the DOCR setting and 3 variables are used to set relays which reduce the operating time of the relays. The results of optimization methods can be improve by increasing the number of variables, in (Salazar, 2015) five variables are used to set relays which reduce the operating time and increase relay coordination. Yet, by increasing the number of variables, the optimization time will increase and the probability of convergence will decrease. Hence, one of purposes of this paper is decreasing the variables of TLBO using combining of TLBO with LP .

For DOCR coordination, the network topology is usually assumed to be fixed but in real networks, one or more lines might be cut off at any time which changes the short circuit levels, thus relay coordination is changed. Also, presence of DGs can cause voltage sage (Mbuli, 2016) and change the short circuit level, therefore the increasing short circuit level can miscoordinate the DOCRs. These changes might increase relay miscoordination. In (Noghabi, 2010) changes in the network topology are also considered and the ILP method is used to optimize DOCRs. In this method, considering the changes in switching lines, maximum and minimum currents passing through each relay are also considered for DOCR coordination. Yet, the operation time of DOCRs is an important issue, hence, one of the aim of this paper is maintaining the coordination of DOCRs during variation of network topology and decrease the operation time of DOCRs .

In this article, DOCR coordination is performed by the TLBO-LP algorithm considering different network topologies and the non-standard curve. For optimization, the linear part was optimized by LP and the nonlinear part by TLBO. In optimization, in addition to TMS and I_{Set}, two other variables are also used for relay setting. In real networks, topology usually changes by switching lines, and overcurrent relay coordination might be eliminated .

The purpose of this article is to maintain relay coordination while changing the network topology and to obtain the best setting and reduce the operating time of relays. While changing the topology, all possible cases in the network are considered and the worst case is considered for relay current coordination. Through selecting different curves of the relays, the proposed method improves the coordination among the relays while changing network topology. Meanwhile, the use of TLBO-LP method reduces optimization computational time and improves the coordination among DOCRs. On the other hand, a new fitness function introduced for relay coordination problem. The benefit of the proposed algorithm compared with conventional algorithms is explained and the overcurrent relay coordination is maintained during switching lines by using the proposed algorithm.

2. OVERCURRENT RELAY COORDINATION

The main objective of relay setting is to maintain relay coordination and reduce the operating time of relays, so that backup relays work after the main relays with a certain time delay under all circumstances. This specific time is represented by the Coordination Time Interval (CTI). The value of CTI is usually between 0.2 and 0.5 seconds. The

DOCR operating time equation according to the IEEE C37.112-1996 is as Equation 1.

$$t = \frac{A}{(\frac{I_{SC}}{I_{Set}})^{B} - 1} TMS \quad (1)$$

Where I_{sc} is short-circuit current passing through the relay, *t* is the operating time of the relay, TMS is time multiplier setting, I_{set} is pickup current setting, and A and B are adjustable fixed of the relay.

Usually the two variables, TMS and I_{set} are used for DOCR coordination, but cases may occur in which the relay coordination cannot be held by the two variables or the operating time of relays might be excessive. Therefore, 4 variables (TMS, A, B and I_{set}) can be used for DOCR coordination. With the advent of digital relays, instead of assuming A and B to be fixed, one can set them specifically for each relay and create different curves for the relay which increases the probability of obtaining the desired operating time. Moreover, in overcurrent relay coordination, one can reduce the relay operating time and establish constraints.

The aim of DOCR coordination is to minimize the operating time and establish constraints. An effective objective function is needed for DOCR coordination problem (Shih, 2017). The proposed objective function is as Equation 2.

$$f = \alpha T_m + \beta \sum t_p^2 + \lambda \sum t_b^2 + \omega \sum (\mathrm{t}_p - t_b + K) \quad (2)$$

Where α,β,λ and ω are weighting factors, T_m is the number of miscoordinations, t_p and t_b are operation time of primary and backup relays, respectively. K is penalty factor which if the value of t_p-t_b was more than CTI, the value of k will be zero, and if the value of t_p-t_b was less than CTI, the value of k will be a large number. Constraints for the coordination of the i-th main relay and the j-th backup relay for faults close to the main relay are as Equation 3.

$$t_j - t_i \geq CTI \quad (3)$$

Where, in this article CTI=0.3. All variables have limitations in relay coordination. The value of *A* is considered between 0.01 and 1, the value of B between 0.02 and 5 and the value of TMS between 0.05 and 2. The range of I_{set} is as Equation 4.

$$\max(I_{Load}^{\max}, I_{Set}^{\min}) \leq I_{Set} \leq \min(I_{fault}^{\min}, I_{Set}^{\max}) \quad (4)$$

Where $I_{load}^{\max}$ is the maximum load current, $I_{set}^{\min}$ is the minimum adjustment current, $I_{fault}^{\min}$ and $I_{set}^{\max}$ are the minimum short-circuit current and the maximum adjustment current of the relay, respectively.

3. MULTIPLE NETWORK TOPOLOGY

DOCR coordination is usually performed when the network topology is fixed but in practice the network topology changes by switching lines, and this change will increase or decrease the short-circuit levels which may cause miscoordination between relays. To determine DOCR coordination with changes in topology, due to the increased number of constraints and occurrence of cases in the network where DOCR coordination is not possible, using 4 variables can increase flexibility which reduces miscoordination between relays.

In relay coordination, the worst case of relay coordination is when the current passing through the backup relay is maximum for the fault in front of the main relay and the current passing through the main relay is minimum. This is expressed by the Equation 5.

$$t_j^{\max} - t_i^{\min} \geq CTI \quad (5)$$

Where $t_j^{\max}$ is the operating time related to maximum current of the operating time related to backup relay and $t_i^{\min}$ is the minimum current of the main relay.

As equation 5 shows, the use of critical currents (maximum current of the backup relay and minimum current of the main relay) for adjusting and coordinating relays establishes coordination among the relays in other network topologies. Figure 1 shows that the operating time difference of the main and backup relays, Δt , reduces with the fault current of the main relay, R_p, reducing from I_4 to I_3, and Δt reduces with the fault current of the backup relay, R_b, increasing from I_1 to I_2.

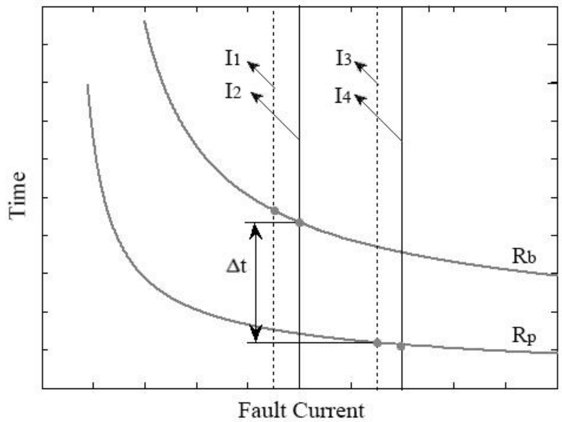


Figure. 1. the use of critical currents

4. TLBO

TLBO based optimization is a new optimization method which has been applied in different optimization problems (Vanithasri , 2016; Mandal, 2013). This method is based on how a teacher affects students and it is a population based method. Population is considered as a group of students to whom a teacher tries to increase their score through training. Since a teacher cannot raise students to their own level, thus it is tried to increase average score of the class. From mathematical point of view, first a population is defined randomly and they are all compared using objective function and sum of variables with best score is considered as the teacher. This method has two phases: teacher and student.

4.1 Teacher phase

In each step, average of class is defined by M_i and the teacher tries to increase this value. In each iteration, student with best score is considered as the teacher which is described with $M_{teacher}$. Difference of these values is defined as Equation 6.

$$D_i = r(M_{teacher} - TM_i) \tag{6}$$

Value of r is a random number between 0 and 1 and teacher parameter or T is 1 or 2 randomly. Variables are updated as Equation 7.

$$M_{New,i} = M_{old,i} + D_i \tag{7}$$

4.2 Student Phase

Students can either learn from the teacher or from other students. In this phase, student j is also considered in addition to student I, where student with higher score trains students with lower score. If student j has a better grade, then student i is defined as Equation 8.

$$M_{i,\text{new}} = M_{i,old} + r(M_j - M_{i,old}) \tag{8}$$

If new score is better than previous score, previous score is replaced with new score. In TLBO method, number of fitness evaluation is calculated as Equation 9 (Jordehi, 2015).

$$NFE = (1+2N_p)t_{\max} \tag{9}$$

Where N_p is population and t_{max} is maximum number of iterations.

5. HYBRID TLBO-LP METHOD

To improve the performance of the TLBO method, TLBO can be combined with LP. In this paper, the TLBO-LP method is used for relay coordination. In this method, TLBO is used for optimizing nonlinear variables and the LP method for finding linear variables. Since TLBO variables are reduced, the calculation time and the search space are also reduced. In this paper, the TMS variable is linear and the other three variables are nonlinear.

The flowchart of the TLBO-LP method is shown in Figure 2. It is clear from the flowchart that, LP is a sub-problem in the fitness function.

In the first step, the initial population is created randomly and the fitness value is determined. The objective function is to minimize the operating time of the main relays. To obtain optimal values, TLBO selects multiple scores for students according to the fitness function value in order to use them in the next update.

The LP sub-problem is placed in the fitness function of the TLBO. First, the values of non-linear variables are calculated by the TLBO, the DOCR optimization problem becomes a linear problem and the linear variable can be calculated by LP. Cases may occur in which the algorithm becomes divergent, that is why we penalized the fitness function.

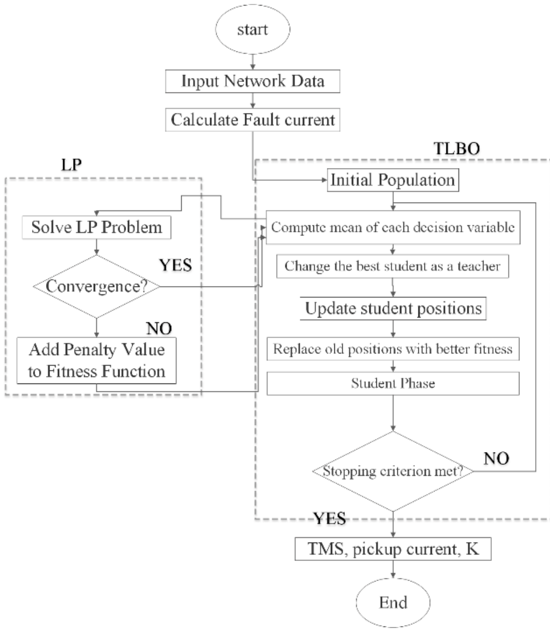


Figure 2. flowchart of TLBO-LP method

6. SIMULATION AND RESULTS

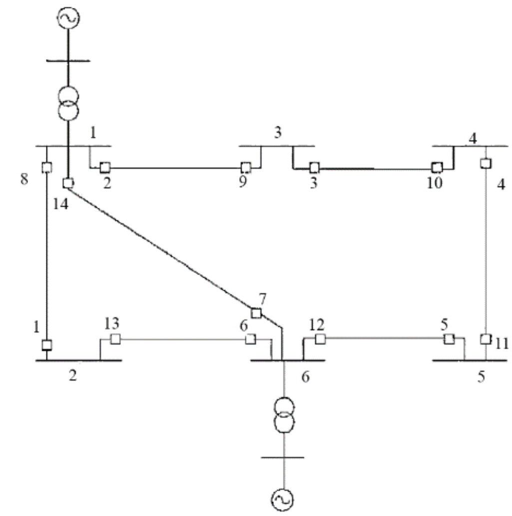
The proposed method has been applied on an 8-bus network in Figure 3. The network information is given in (Zeineldin, 2006). The network has 14 relays, as shown in Figure 3. In Table 1, the range of pickup current settings for each relay are shown. The value of pickup current settings for each relay is between these values. The network is examined in two ways (fixed network topology and Multiple Network Topology) and both GA and TLBO-LP algorithms are applied to both network topologies and the results are compared. The effect of using non-standard curves in each case is also investigated.

Figure 2. single line diagram for 8-bus network

Table 1. Range of pickup current seting value for each relay

Relays	**Minimum I_{set}**	**Maximum I_{set}**
1,5,6,8,10,12,13	120	600
2,4	120	800
3,9	80	600
7	80	650
11	120	650
14	80	800

6.1 Fixed network topology



In this section, the network topology is assumed to be fixed and the DOCR coordination is performed by both GA and TLBO-LP methods considering the standard and non-standard curves.

Due to the difference between GA and TLBO-LP, the calculation time, size of the initial population and generation of the two methods for obtaining optimal values are different. In optimizing by the TLBO-LP, the optimization speed is much higher. Table 2 shows the time for the optimization methods with 4 variables. As shown in Table 2, the calculation time for TLBO-LP is much lower than GA.

Table 2. Calculation time for TLBO-LP and GA

	TLBO-LP	GA
Elapsed time	92seconds	589 seconds.

Normally optimization is performed with 2 variables (TMS and I_{set}). In this case, the TMS value is calculated by LP and the I_{set} value is calculated by TLBO. Table 3 shows the settings for this case for 14 relays. Table 4 shows the constraints for each pair of relays in both methods. As it is clear from Table 4, the fitness function or the operating time of the main relays in TLBO-LP is lower than GA. The constraints are as Equation 10.

$$\text{Constraint}=t_j - t_i - CTI \qquad (10)$$

Table 3. the relay settings for standrad curves in fixed network topology

Relay	TLBO-LP			GA
	TMS	**I_{set}**	**TMS**	**I_{set}**
1	0.0654	499.9524	0.2765	234.709
2	0.258	373.26	0.4004	216.172
3	0.2127	191.7707	0.2537	365.566
4	0.05	682.7994	0.207	200.076
5	0.05	259.5302	0.0869	329.679
6	0.1903	271.3579	0.5515	137.506
7	0.1302	596.3377	0.331	498.11
8	0.1297	502.5564	0.6684	137.624
9	0.05	248.4196	0.1473	217.996
10	0.1237	258.9877	0.257	180
11	0.1268	649.7529	0.3353	273.44
12	0.258	403.0874	0.6208	156.2
13	0.0562	554.2247	0.5009	150.174
14	0.1138	598.8109	0.4816	200.633

Table 4. constraints of relay pairs for fixed network topology and standard curve

Backup Relay	Primary Relay	TLBO-LP constraints	GA constraints
7	8	0.277	0.4947
7	2	0.000	1.2084
1	2	0.000	0.7174
2	3	0.000	0.0554
3	4	0.000	0.0774
4	5	0.003	0.0190
14	6	0.100	0.2914
1	14	0.286	0.1968
6	1	0.000	0.1859
10	9	0.000	0.0109
11	10	0.000	0.0870
12	11	0.000	0.1578
14	12	0.000	0.1406
13	12	0.070	0.5673
8	13	0.000	0.0559
13	7	0.000	0.5037
9	8	0.004	1.0587
5	6	0.003	1.4151
9	14	0.0061	0.2693
5	7	0.0183	1.5216
Sum of DOCR Operation times		2.5943	11.83

Table 5. Relay settings for non-standrad curves in fixed network topology

Relay	TLBO-LP			
	TMS	I_{set}	A	B
1	1.99	289	1.00	1.56
2	1.89	375	0.83	0.76
3	1.64	590	0.75	0.92
4	0.34	326	0.86	0.46
5	1.88	227	0.99	2.45
6	1.95	183	0.17	0.24
7	2.00	386	0.86	1.07
8	1.95	460	0.88	1.08
9	2.00	182	1.00	2.30
10	1.64	340	0.99	1.26
11	1.25	557	0.94	0.88
12	1.93	526	0.99	0.76
13	1.65	531	0.73	2.38
14	1.99	752	0.96	1.89

Table 6. constraints of relay pairs for fixed network topology and non-standard curve

Backup Relay	Primary Relay	TLBO-LP constraints	GA constraints
7	8	0.06	0.00
7	2	0.00	0.04
1	2	0.00	0.00
2	3	0.00	0.00
3	4	0.00	0.00
4	5	0.00	0.00
14	6	0.12	0.00
1	14	0.14	0.29
6	1	0.00	0.00
10	9	0.00	0.00
11	10	0.00	0.00
12	11	0.00	0.00
14	12	0.00	0.17
13	12	0.03	0.00
8	13	0.00	0.00
13	7	0.00	0.10
9	8	0.05	0.00
5	6	0.00	0.00
9	14	0.00	0.17
5	7	0.14	0.46
Sum of DOCR Operation times		0.57	2.07

The constraint values should be close to zero. If the constraints are negative, it means that there is miscoordination between the i-th main relay and the j-th backup relay.

By increasing the number of variables and using non-standard curves for each relay, one can achieve smaller values for operating time. In this case, 4 variables (TMS, A, B and I_{set}) are used for each relay. Table 5 shows settings for relays. Table 6 shows constraints and the fitness function for each method. As it can be seen from Table 6, the operating time of relays has been largely reduced in comparison with using standard curves. In this case, optimization of operating time is also lower than GA.

As it can be seen from tables 4 and 6, all constraints are positive in both GA and TLBO-LP for both standard and non-standard curves that is coordination between all the relay pairs is done properly. In this case, if the network topology changes, videlicet, the line between buses 1 and 2 is disconnected and, coordination between relays might be eliminated due to changes in the short-circuit levels. For this reason all network topologies should be considered.

6.2 Multiple Network Topologies

In this section, the network topology is assumed to be variable so that when the topology changes, no miscoordination occurs in the relays. The miscoordination between relays is done by TLBO-LP for non-standard curves. Then, the line between buses 1-2 and 1-6 are disconnected for evaluation of the proposed method.

First, all cases of switching lines must be considered and short-circuit calculations for these cases must be performed. For each pair of relays, minimum and maximum short-circuit currents passing through them are considered for near-end fault.

Table 7. Relay setting for non-standrad curves in multiple network topology

Relay		**TLBO-LP**		
	TMS	**I_{set}**	**A**	**B**
1	0.8680	203.4157	0.9992	0.2960
2	1.9961	479.8957	0.7199	0.4835
3	1.7489	241.1605	0.8924	0.5110
4	1.9845	728.3456	1.0000	1.5271
5	1.6172	184.1468	0.9922	0.5965
6	1.7305	367.3504	0.9993	0.4874
7	2.0000	403.4507	0.7804	0.5419
8	1.9986	501.3445	0.7737	0.4490
9	1.6627	125.9048	0.5301	0.2700
10	1.9375	167.9230	0.8213	0.3757
11	1.9192	272.0658	0.9483	0.3930
12	1.9997	376.2518	0.9428	0.3804
13	1.9986	163.7206	0.7758	0.3126
14	1.6473	607.3513	0.9272	0.5955

Table 7 shows the setting of relays for non-standard curves via TLBO-LP algorithm. When the relays are tuned, the constraints relating to three topologies from the network, such as main topology, elimination of line 1-2, and elimination of line 1-6 might be seen in Table 8. When a line is eliminated, certain pairs of relays in that line are lost. The constraints pertaining to them are denoted by "--" in the table. It can be deduced from Table 8 that the coordination of the relays is maintained in certain topologies of the network where the lines are eliminated, in addition to preserving the coordination of the relays in the main topology. In other words, the coordination among the relays is kept when the topology is changed. The coordination of the relays is robust against network variations.

Table 8. constraints of relay pairs for multiple network topology and non-standard curve

Backup Relay	**Primary Relay**	**Main topology**	**Line 1-2 outage**	**Line 1-6 outage**
7	8	0.32	--	--
7	2	0.60	0.19	--
1	2	0.85	--	0.00
2	3	0.00	0.01	0.09
3	4	0.00	0.00	0.00
4	5	0.26	0.14	0.00
14	6	1.11	0.48	--
1	14	0.74	--	--
6	1	0.00	--	0.00
10	9	0.03	0.02	0.00
11	10	0.12	0.12	0.13
12	11	0.06	0.06	0.07
14	12	0.70	0.00	--
13	12	1.02	--	0.00
8	13	0.01	--	0.00
13	7	1.47	--	--
9	8	1.61	--	0.00
5	6	1.63	0.76	0.00
9	14	1.36	0.65	--
5	7	1.74	0.69	--

7. CONCLUSION

A new method is presented for the coordination of the relays considering non-standard curves and changes in the network topology. This paper aims to put forward a method for improving relay operation time in addition to maintaining the coordination of the relays. Considering topology changes, number of constraints pertaining to optimization becomes excessive. Only the important constraints for maintaining relay coordination are taken into account. Moreover, in terms of the non-standard curves and increased settings of the relays, the miscoordination between the relays eliminated and relay operation time is decreased. Furthermore, because of applying TLBO-LP algorithm and the decreased number of variables for TLBO, the time and results of the calculations are improved. Using the proposed approach while changing the network topology, DOCR coordination is maintained which proves the robust method of the proposed approach.

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