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Hybrid Mixed-Integer Non-Linear Programming Approach for Directional Over-Current Relay Coordination

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Abstract

This paper proposes the optimal coordination problem of protective relays within a hybrid optimization framework which is presented based on integer coded genetic algorithm (ICGA) and non-linear programming (NLP). The optimal coordination problem of directional overcurrent relays (DOCRs) is implemented while aimed at finding the optimal plug setting multiplier (PSM) and time dial setting (TDS). In this respect, PSM is a function of the current transformer (CT) size and the tap of the relay which is discrete in nature. TDS is a function of the operating time of the relay for different short-circuit currents at different locations of the system. In this paper, the variables of the problem are decomposed into continuous and discrete variables. The first stage of the problem uses the ICGA to determine the size of CTs considering the permitted tap of relays while the second stage utilizes the NLP method to evaluate the feasibility and optimality. The presented framework is then simulated on a 8-bus test system. The obtained results verify the effectiveness and the applicability of the optimization technique to find the optimal settings of DOCRs.

1 Introduction

Using overcurrent relays are of the most primary methods to detect and isolate the faulty areas in power systems. In interconnected power systems, doubly-fed power systems, and the power systems with parallel lines, directional overcurrent relays (DOCRs) must be used to precisely determine the fault location and isolate the faulty areas. Such relays use the current and voltage signals, simultaneously to specify the magnitude and the direction of short-circuit currents. However, optimal coordination of DOCRs regarding the clearance time of the primary and backup relays is a challenging issue in power systems. In general, the optimal coordination of DOCRs is done to find the optimal settings of relays including the time dial setting (TDS) and plug setting multiplier (PSM). It is noteworthy that a coordination time interval (CTI) should be considered to omit the overlap between the operation of the primary and backup relays for a given fault. Many researches have investigated the optimal coordination problem of DOCRs and various optimization techniques have been presented to find the optimal settings. PSM is obtained experimentally with respect to the load current and the fault current in linear programming techniques. In such methods, TDS is the only variable which its optimal value is derived with respect to the coordination constraints of the primary and backup relays, i.e. CTI [1-6]. Determining the two variables, simultaneously, turns the optimization model into a mixed-integer non-linear programming (MINLP) model which is difficult to solve. In this regard, authors in[7] have employed an enhanced particle swarm optimization (PSO) algorithm while the repair method and non-random approach for initialization have been presented to modify the original algorithm. An evolutionary PSO (EPSO) has been employed in [8] to solve similar optimization problem. Researchers in [9] have proposed an optimization framework using leaching-learning based optimization (TLBO) in which LINKNET configuration (utilizing merely far vector) is employed to diagnose the backup pairs for every primary protective relay. Besides, Ref. [10] presented a modified adaptive TLBO (MATLBO) and firefly algorithm (FA) has been proposed in Ref. [11]. The effect of fault current limiter (FCL) on the coordination of DOCRs has been discussed in [12]. Authors of [13, 14] also utilized a chaotic FA (CFA) and a modified swarm FA (MSFA), respectively. Additionally, Ref. [15] presented the artificial bee colony (ABC) method while Ref. [16] solved the mentioned problem using improved group search optimization algorithm (IGSOA). Informative differential evolution (IDE) [17], and seeker algorithm [18] are used to find the optimum relay settings. The application of modified differential evolution algorithms [19], opposition based chaotic differential evolution algorithm [20], PSO [21] and modified PSO (MPSO) [22] algorithms are also presented by the researchers to find the optimal settings for TMS and PSM. The capability of dual setting relays is evaluated in [23] for the optimum coordination of DOCRs. Besides, an adaptive protection scheme is presented in [24] to mitigate impact of distributed generation. Meanwhile, some research works have utilized hybrid techniques to solve the coordination problem of DOCRs. For instance, Ref. [25] has utilized Genetic Algorithm (GA) together with linear programming (LP) known as GA-LP and Ref. [26] has adopted GA along with non-linear programming known as GA-NLP to solve the coordination problem of DOCRs. An optimization framework has been developed in [27] using biogeography based optimization (BBO) together with a novel hybrid BBO combined with LP known as BBO-LP to solve the coordination problem of DOCRs. However, it should be noted that none of the obtained solutions are global optimum. Each research work has considered different assumptions to obtain the optimal settings of DOCRs. In this regard, the input data including the short-circuit currents and the fault location (for near-end, far-end or at the mid-point of the feeder) should be verified and the problem assumptions are the same. The research work in [28] proposes a comprehensive review on the assumptions made in different research works for the optimal coordination of DOCRs.

This paper proposes the optimal coordination problem of DOCRs for the 8-bus test system taking into account different assumptions made so far in research works. The hybrid ICGA-NLP optimization technique is used to solve the problem. The remainder of the paper is categorized as follows. Section 2 provides the mathematical modelling of the optimal coordination problem of DOCRs. The hybrid optimization approach is presented in section 3. Section 4 includes the simulation results while accurately investigates the short-circuit currents and the protection settings. Finally, section 5 draws some relevant conclusions.

2 DOCRs Coordination Problem

The coordination problem of DOCRs has been presented in the MINLP framework while the objective function is defined as the minimization of fault clearing time of primary relays, TP_i.

$$Min \ \sum_{i=1}^{N} TP_i \tag{1}$$

where

$$TP_i = \frac{0.14 \times TDS_i}{\left(M_i\right)^{0.02} - 1}, \ i = 1, 2, ..., N \tag{2}$$

Subject to:

$$TB_{j,i} = \frac{0.14 \times TDS_j}{\left(M_j\right)^{0.02} - 1}, \ j = 1, 2, ..., N \tag{3}$$

$$M_i = \frac{I_i^F}{PSM_i \times CTR_i}, M_j = \frac{I_i^F}{PSM_j \times CTR_j} \tag{4}$$

$$PSM_i^{Min} \le PSM_i \le PSM_i^{Max} \tag{5}$$

$$TDS_i^{Min} \le TDS_i \le TDS_i^{Max} \tag{6}$$

$$TB_{j,i} - TP_i \ge CTI \tag{7}$$

where, *TP* and *TB* show the clearing time of primary and backup relays, respectively. In this respect, Eq. (2) and Eq. (3) are used to obtain *TP* and *TB*, respectively. The characteristic curve used for the DOCRs is the IEC standard inverse characteristic. Besides, *TB* is derived taking into account the current seen by the primary relay. This parameter is used to specify the time needed so that the backup relay operates and sends the tripping command. In (2)-(3), M_i and M_j denote the effective currents for primary and backup DOCRs, respectively. The *PSM* and *TDS* should be selected from the permissible values for the *i*-th DOCR. The PSM can be either continuous or discrete and should be selected from the acceptable range of relays as stated in (5). It should be noted that the relay's clearing time should be in the allowed range. Furthermore, as inequality (6) states, TDS should be also in the allowed range. However, as stated in (7), the conflicting conditions regarding the operation of the primary and the backup relay must be omitted. To this end, a CTI is considered. It is noteworthy that the ICGA determines the integer values related to PSM and TDS is obtained according to the PSMs of each relay.

3 Hybrid ICGA-NLP Algorithm

Decomposition of the problem and the variables into two parts is a common technique in solving MINLP problems. In this respect, one part is devoted to solving the mixed-integer programming (MIP) problem and the other one is devoted to solving the NLP problem. Using the suggested technique, the integer variables of the problem are obtained as the remaining NLP problem is solved faster which overall improves the solution time compared to MINLP. In this respect, the ICGA is employed to determine the current setting (PSM) of the relay which is an optimization problem with discrete variables. The NLP method is also utilized to obtain the TDS of the relay. The detailed descriptions of the ICGA method and the decomposition technique are described in the following.

3.1 Integer Coded Genetic Algorithm

There are several significant factors that should be accurately considered in the GA. These factors are the crossover, mutation as well as other operators defined for each problem and they should be determined in a way imposing the minimum computational burden. To this end, an effective representation of the GA has been utilized in the paper while its solution configuration is an ordered structure of integer numbers with dimension, N, showing the total number of DOCRs. The integer variables are presented to describe the controllers, as assigned to the vector elements indicated by the DOCRs through implementing a mapping procedure. In the proposed mapping strategy, the discrete setting multiples of DOCRs will be determined as shown in Fig.1.

Number of DOCRs	1	2	3	…	N-1	N
Integer Selection	1	8	4	…	6	2
PSM of DOCRs	0.5	5.0	2.0	…	3.0	1.0

Fig. 1: Representation of an Individual's Chromosome and Mapping Procedure

So far, various techniques have been suggested to tackle the constraints of the problem in GA, while the most widely used one is to assign penalty functions to the problem. [29], [30].

In this respect, this method is implemented using a penalty to avoid the infeasible solutions by decreasing the related fitness values proportionally to the extent of the violation. This technique would highly depend upon the value considered for the penalty parameter. In this paper, the proposed GA incorporates an NLP sub-problem to evaluate the feasibility and optimality of the suggested settings from GA.
The procedure of the proposed GA is as follows:

1- Initialize by producing the population of K various solutions built at random while the size of the initial population is indicated by K. In this respect, every initial solution is produced by randomly allocating a PSM for corresponding DOCRs.
2- Decoding the structure of the solution to derive the value of the fitness computed based on a fitness function. Generally, the obtained objective function from the NLP sub-problem must be considered. However, the method suggested in [31] is used in this paper to replace the method based on assigning the penalty function to the problem.
3- Using the binary tournament to select each parent by randomly selecting two players and afterwards, selecting the most desired individual among that sets as a parent (smaller fitness value) [32]. The child is also selected using two binary tournaments to generate a parent.
4- Mating random pairs. By taking the crossover operators presented in the literature [33], [34], a uniform one on the basis of a random mask is utilized in this paper. In this respect, a crossover between two parents would have a single child while the gene of the child solution is generated by duplicating the equivalent gene from one of the other parent, selected based on a random binary number generator. Ref. [35] provides the comprehensive information.
5- The next step after the crossover is the mutation process generated by selecting a gene $p \in \{1, . . . , N\}$ at random. After that, the value would be replaced by a randomly generated integer number, PSM, chosen uniformly from $\{1, . . . , S\}$ so that the compatibility constraints are satisfied.
6- Substituting an individual in the population with the child solution, i.e., mutated child. Once the mutated child is feasible with a lower value of fitness, the individual with the highest fitness would be replaced provided that the population includes the entire solutions which are feasible, otherwise, no replacement. By using this technique, the infeasible solutions of the population would be rejected. Moreover, a copied child which is described as a solution with the similar structure to other solution structures available in the population would not be permitted to get into the population. This is due to that fact that in case of occurrence of such a thing, the population will probably include all identical solutions which highly restricts the capability of the algorithm for producing new solutions. This phenomenon is in line with the principle that we desire to obtain the best solutions from the feasible space.
7- Redoing the steps 3 to 6 for pre-defined iterations excluding any replacement in the existing population. It is worth-mentioning that numerous solutions can be produced since it is desired to produce different settings to attain the best results.

3.2. Coordination of DOCRs using hybrid ICGA-NLP

The decision variables of the optimal coordination of DOCRs are TDS and PMS of relays. Accordingly, the presented optimization problem has two degrees of freedom. The PSM and TDS are determined using ICGA and NLP, respectively. It should be noted that TDS is a positive variable. The problem with one degree of freedom would be solved to find the TDS for the values of PSM obtained from the ICGA method. Besides, the operating time of the relay is calculated with respect to the characteristic curve chosen for the relay. This characteristic curve is selected proportionally to the short-circuit current seen by the current transformer (CT) and the relay. It is worth-mentioning that appropriately choosing the characteristic curve of relays impacts the optimal coordination of primary and backup relays. Thus, the coordination constraint may not be satisfied in the NLP sub-problem. To this end, the NLP objective function and the CTI must be reconsidered. Accordingly, the objective function would be as (8) and the primary and backup protection coordination time constraint would be as inequality (9).

$$Min \quad \sum_{i=1}^{N} TP_i + \sum_{i=1}^{N} Penalty \times SL_i \tag{8}$$

$$TB_{j,i} - TP_i + SL_i \geq CTI \tag{9}$$

$$SL_i \geq 0 \tag{10}$$

where SL_i is a slack positive variable used to avoid not meeting constraint (9). However, a penalty is applied to the objective function to consider this constraint with a penalty factor. Therefore, the problem of optimal coordination of DOCRs would be tractable.

4 Simulation Results

A standard test system i.e. the 8-bus test system has been considered to evaluate the proposed protection coordination framework. The test system has been used in the literature to validate the models and optimization methods. However, the results for the short-circuit currents and the assumptions on the load and network modeling as well as selecting protection settings are different. This paper has studied the mentioned problem taking into consideration different conditions considered in the literature.
The proposed framework is implemented on the standard 8-bus test system using data of protective relays, current CTs, generating units, the external grid as well as the load demand data reported in [22].

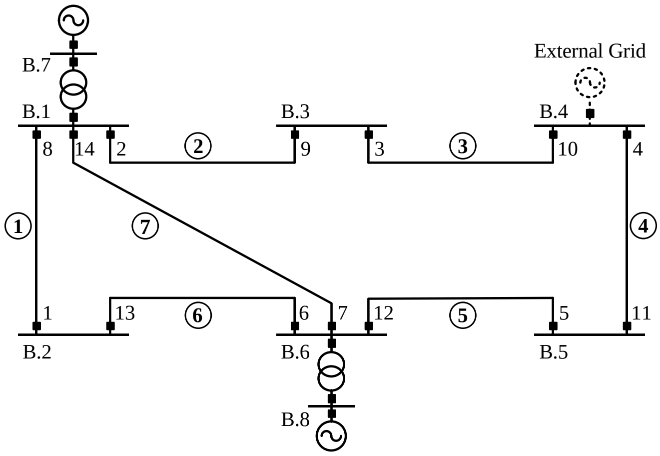

Fig. 2 Single line diagram of 8-bus test system [18]

Fig. 2 demonstrates the single-line diagram of the test system. Different short-circuit currents have been reported in the literature while in some cases, the external grid has not been modeled and the impact of the pre-fault load currents have not been taken into consideration. Hence, the protection settings have been differently reported. Besides, different values have been proposed for similar short-circuit currents. For instance, Table 1 represents the short-circuit currents while the pre-fault currents have been neglected and by considering the impact of the external grid with the short-circuit level equal to 400 MVA as well as exclusion of the external grid. These results are similar to those reported in [18] and [36] for these scenarios, respectively.

	Including Ext. Grid		**Excluding Ext. Grid**	
(P:B)	**Primary**	**Back up**	**Primary**	**Back up**
(1:6)	3233	3233	2703	2703
(2:1)	5924	996	5391	812
(2:7)	5924	1889	5391	1540
(3:2)	3556	3556	3347	3347
(4:3)	3782	2243	2243	2243
(5:4)	2401	2401	1361	1361
(6:5)	6109	1198	4995	416
(6:14)	6109	1873	4995	1540
(7:5)	5223	1198	4267	416
(7:13)	5223	987	4267	812
(8:7)	6092	1889	4995	1540
(8:9)	6092	1165	4995	416
(9:10)	2484	2484	1453	1453
(10:11)	3884	2345	2345	2345
(11:12)	3708	3708	3495	3495
(12:13)	5899	987	5391	812
(12:14)	5899	1873	5391	1540
(13:8)	2990	2990	2507	2507
(14:1)	5199	996	4267	812
(14:9)	5199	1165	4267	416

Table 1. Short-circuit currents for different network topology

Relay	**Including Ext. Grid**		**Excluding Ext. Grid**	
	TDS	**PSM**	**TDS**	**PSM**
1	0.113	2.0	0.100	2.0
2	0.260	2.5	0.226	2.5
3	0.225	2.5	0.187	2.5
4	0.160	2.5	0.100	2.0
5	0.100	2.5	0.100	0.8
6	0.173	2.5	0.152	2.5
7	0.243	2.5	0.196	2.5
8	0.170	2.5	0.148	2.5
9	0.147	2.5	0.120	1.0
10	0.176	2.5	0.108	2.0
11	0.187	2.5	0.151	2.5
12	0.266	2.5	0.228	2.5
13	0.114	2.0	0.100	2.0
14	0.246	2.5	0.198	2.5
Obj. (Sec.)	**8.426493**		**7.172135**	

Table 2. Optimal settings of DOCRs for different network topology

	Including Ext. Grid	**Excluding Ext. Grid**
Ref. [25]	11.0010	N/A
Ref. [25]	10.9499	N/A
Ref. [27]	10.5495	N/A
Ref. [27]	8.7556	N/A
Ref. [37]	8.6944	N/A
Ref. [18]	8.4270	N/A
Ref. [36]	N/A	8.8425
ICGA-NLP	8.426493	7.172135

Table 3. Comparison of results for different network topology

CTI	**TDS^{min}**	**Including Ext. Grid**	**Excluding Ext. Grid**
0.2	**0.05**	**5.338080**	**4.199777**
0.2	**0.10**	**6.106033**	**5.513823**
0.3	**0.05**	**8.001712**	**5.728200**
0.3	**0.10**	**8.426493**	**7.172135**

Table 4. Optimal settings of DOCRs for different network topology

TDS is assumed to be in [0.1-1.1] in this paper for base case. However, seven discrete setting multiples are taken into consideration to draw a comparison as (0.5, 0.6, 0.8, 1.0, 1.5, 2.0, and 2.5) Beside the current transform ratios of the DOCRs (1, 2, 4, 5, 6, 8, 10, 11, 12, 13) and (3, 7, 9, 14) are (1200:5) and (800:5), respectively [18].

Table 2 represents the results obtained for the optimal settings of the relays installed in the 8-bus test system both by including and excluding the external grid connected to bus 4. It should be noted that the simulation has been done for *CTI*=0.3 seconds and TDS^{min}=0.1 seconds. In this respect, the results obtained by considering the external grid are exactly the same as the ones reported in Ref. [18]. Table 3 illustrates the comparison made between the obtained results and those reported by other methods. Moreover, Table 4 includes the simulation results derived for different *CTIs* and different values of TDS^{min}.

The simulation results show that the operating time of the relay increases with the increase in the short-circuit current which is due to including the external grid. By decreasing the *CTI* and TDS^{min}, the operating time has reduced which is true for both network topologies. DIgSILENT Powerfactory has been used to calculate the short-circuit currents and the ICGA algorithm has been implemented in MATLAB software. Also, the NLP sub-problem has been solved using CONOPT in GAMS. The number of iterations is 200 and the population size is 100. Furthermore, the number of variables, N, is 14, the variation range of integer variable, S, is equivalent to seven different PSMs and the penalty factor equivalent to the slack variable has been considered 1000.

5 Conclusion

This paper investigated the optimal coordination problem of directional overcurrent relays (DOCRs) using a hybrid optimization technique. In this respect, the hybrid optimization method included the integer coded genetic algorithm (ICGA) and non-linear programming (NLP) technique. First, the short-circuit currents were obtained using DIgSILENT PowerFactory for different network topologies, i.e. by both including and excluding the external grid with short-circuit current level 400 MVA at bus 4. Afterwards, these results were fed into the optimization problem of optimal coordination of DOCRs as the inputs. Since different assumptions were made for the values of coordination time interval (*CTI*) and the minimum Time dial setting (TDS^{min}), different cases were simulated for the sake of comparison. The simulation results verified that the proposed optimization technique is capable of finding acceptable solutions with respect to the mentioned assumptions. It should be also noted that as the short-circuit currents reported in some references for these two scenarios are different or the number of states of plug setting multiplier (PSM) are different, it was not possible to compare the results.

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