Application of Artificial Bee Colony Algorithm for Optimal Overcurrent Relay Coordination for Power System Including DGs

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Abstract: This paper presents a new approach for optimal simultaneous coordinated tuning of overcurrent relay for a power delivery system (PDS) including distribution generations (DGs). In the suggested scheme, instead of changing in protection system structure or using new elements, solving of relay coordination problem is done with revising of relays setting in presence of DGs. For this, the relay coordination problem is formulated as the optimization problem by considering two strategies: minimizing the relays operation time and minimizing the number of changes in relays setting. Also, an efficient hybrid algorithm based on Artificial Bee Colony (ABC) and linear programming (LP) is introduced for solving complex and non-convex optimization problem. To evaluate the efficiency and ability of the proposed method, a 30-bus IEEE test system is considered for simulation studies. Also, three scenarios are examined to evaluate the effectiveness of the proposed approach to solve the directional overcurrent relay coordination problem for a PDS with DGs. Simulation result show the efficiency of proposed method.
[Mostafa Azimi Dehaghani, Mehdi Soltani, Sayed Mohsen Ahmadi, Payam Ghaebi Panah. **Application of Artificial Bee Colony Algorithm for Optimal Overcurrent Relay Coordination for Power System Including DGs.** *Life Sci J* 2012;9(4):5135-5142] (ISSN:1097-8135). http://www.lifesciencesite.com. 765

Keywords: Directional overcurrent relay coordination, distributed generation, looped power delivery system, short-circuit analysis, Artificial Bee Colony, linear programming.

1. Introduction

Directional overcurrent relays (DOCRs) are good technical and economic alternative for the protection of interconnected subtransmission systems and back-up protection of transmission systems. These relays are coordinated to provide a reliable redundant protection scheme while minimizing load interruption. DOCRs have two types of settings: pickup current setting and time multiplier setting (TMS). Basically, to determine these settings, two different approaches are used; conventional approach, and optimization techniques. Several optimization techniques have been proposed to solve the overcurrent relay coordination problem. For example in [1-5], genetic algorithm (GA), evolutionary algorithm (EA), and particle swarm optimization (PSO) algorithms are used to calculate the optimal solution for relay settings. In [6] a novel hybrid GA method is developed. The hybrid GA method is designed to improve the convergence of conventional GA using a local LP optimizer.

Introducing DG into the PDS has both positive and negative impacts on system design and operation. One of the negative effects of DGs is system protection, especially the disturbance caused to the existing relay coordination [7-9]. This disturbance is caused by the change in value and direction of both the system's power flow under normal operation and short-circuits current under fault conditions due to DG implementation. Solving the identified relay coordination problem for PDS with DG is still under development. In[10] disconnecting of DGs in fault duration is recommended, so that before operation of relays in the event of fault the source of change in current and disturbance of the relay coordination's is removed. But disconnecting of DGs confines their benefits and on the other hand the problem of synchronization must be considered. In [11] authors suggested the implementation of a fault current limiter (FCL) to locally limit the DG fault current and thus restore the original relay coordination. This approach requires FCL design. Implementation of an advanced protection scheme based on automation and communication channels is another approach. This approach has many advantages but is costly [12].

In this paper, solving of relay coordination problem for PDS with DGs is performed with revising of relays setting. Actually instead of changing in protection system structure or using new elements, setting of current relays is changed. In this work, the revising relays setting in presence of DGs is done using the optimization framework suggested in [6]. For this aim, the relay coordination problem is formulated as the optimization problem and two strategies are recommended. Firstly, optimization the relays operation time and secondly, minimizing the number of changes in relays setting. Also, an efficient hybrid algorithm based on Artificial Bee Colony (ABC) and linear programming (LP), which is called ABC-LP algorithm, is used for solving complex and non-convex optimization problem. artificial bee colony is a new metaheuristic optimization method imitating the music improvisation process where musicians improvise their instruments' pitches searching for a perfect state of harmony [13], such as during jazz improvisation.

In the proposed hybrid approach, the ABC and LP are used as global and local optimizers, respectively. These cause a decrease in the search space which results in time consuming and computational efficiency in finding the optimum solutions. To investigate the ability of the proposed method, the numerical results are presented on a 30-bus IEEE test system. Two scenarios are examined to evaluate the effectiveness of the proposed approach to solve the directional overcurrent relay coordination problem for a PDS with DGs. Moreover, to validate the results obtained by ABC-LP algorithm, the hybrid approach based on Genetic Algorithm (GA) and LP algorithm (GA-LP) is adopted from [6] and applied for comparison. Simulation results show the efficiency and superiority of the ABC-LP algorithm over the GA-LP algorithm.

The paper is organized as follows. In the next section an overview on the directional overcurrent relay coordination problem is presented. The basic concept of ABC briefly is explained in section 3. The normal coordination procedures and the hybrid method proposed to solve the relay coordination problem for a PDS with DGs are discussed in section 4. Section 5 provides the PDS understudy and several operating scenarios. Simulation results to evaluate the proposed method are provided in section 6 and some conclusions are drawn in section 7.

2. Relay Coordination Problem

The coordination problem of DOCRs is one of the most important problems to be solved in the operation and protection of a power system. The primary objective of the relay coordination problem is to determine the time multiplier setting and pickup current setting of each relay which would minimize the time of operation of the primary relays, while satisfying certain coordination constraints [1-10].

The optimal coordination problem of DOCRs, can be formulated as an optimization problem, where consists of minimizing an objective function (performance function) subject to limits on problem variables and certain coordination constraints. In [14], an overview on the objective functions formed by researchers to solve the relay coordination problem has been presented recently. In this work, the total time objective function, for primary relay near-end-fault, is considered as (1) by including the constraints aiming to avoid the sympathy trips. These constraints are relay setting constraints and backup-primary relay constraints that presented in the next subsections.

$$\min J = \sum_{i=1}^{n} w_i t_i \qquad (1)$$

In (1), n is the number of relays. Also, t_i is the operation time of i^{th} relay for near-end fault and W_i is the correspondent weighting factor and depends upon the probability of a given fault occurring in each protection zone. Commonly these weighting factors set to one. Figure 1 shows the concepts of near-end fault (F_1) and far-end fault (F_2).

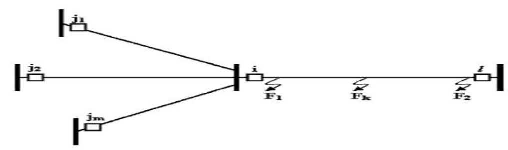


Figure 1. The concepts of near-end and far-end faults for i^{th} relay [6].

2.1 Relay Characteristics

There are various linear and nonlinear overcurrent relay characteristics reported in the literature. In this work, relays were assumed identical and with characteristic functions approximated by the following nonlinear characteristics function based on IEC standard:

$$t_i = TDS_i\{\frac{A}{M_i^c - 1} + B\} \quad , \quad M_i = \frac{I_{fi}}{I_{pi}} \qquad (2)$$

Where TDS_i stand for the time multiplier setting, and also, I_{pi} and I_{fi} are pickup current setting of the i^{th} relay the fault current passing through i^{th} relay, respectively.

2.2 Primary -Backup Relay Constraints

In the relay coordination problem, to ensure the relay coordination, it is necessary that the operating time of the backup relay be greater than that of the primary relay for the same fault location by a coordination time interval (CTI). For this, the coordination constraints between the primary i^{th} relay and its/their backup relay(s) for the near-end and the far-end faults are considered as follows:

$$\begin{aligned} t_j^{F1} - t_i^{F1} &\geq CTI \\ t_j^{F2} - t_i^{F2} &\geq CTI \end{aligned} \qquad (3)$$

Where t_i^{F1} is the operating time of i^{th} primary relay for the near-end fault. Also, t_j^{F1} is defined in the j^{th} backup relay. Moreover, CTI is the minimum interval that permits the backup relay to clear a fault in its operating zone. In the other words, the *CTI* is the time lag in operation between the primary and its backup relay. It includes many factors, such as the breaker operating time and a safety margin. The value of *CTI* is usually chosen between 0.2 and 0.5 s.

2.3 Bounds on the Relay Settings

The limits on the relay parameters can be written as following inequalities:

$$TDS^{k}_{min} < TDS^{k} < TDS^{k}_{max} \quad (4)$$

$$Ip^{k}_{min} < Ip^{k} < Ip^{k}_{max} \quad (5)$$

3. Artificial Bee Colony Algorithm

Over the last decades there has been a growing concern in algorithms inspired by the observation of natural phenomenon. It has been shown by many researches that these algorithms are good alternative tools to solve complex computational problems.

Artificial Bee Colony (ABC) algorithm, proposed for real parameter optimization, is a recently introduced optimization algorithm and simulates the foraging behavior of bee colony [15] for unconstrained optimization problems [16]. For solving constrained optimization problems, a constraint handling method was incorporated with the algorithm [17]. In a real bee colony, there are some tasks performed by specialized individuals. These specialized bees try to maximize the nectar amount stored in the hive by performing efficient division of labor and self-organization. The minimal model of swarm-intelligent forage selection in a honey bee colony, that ABC algorithm adopts, consists of three kinds of bees: employed bees, onlooker bees, and scout bees. Half of the colony comprises employed bees and the other half includes the onlooker bees. Employed bees are responsible from exploiting the nectar sources explored before and giving information to the other waiting bees (onlooker bees) in the hive about the quality of the food source site which they are exploiting. Onlooker bees wait in the hive and decide a food source to exploit depending on the information shared by the employed bees. Scouts randomly search the environment in order to find a new food source depending on an internal motivation or possible external clues or randomly. Main steps of the ABC algorithm simulating these behaviors are given below:

Step 1. Initialize the food source positions.
Step 2. Each employed bee produces a new food source in her food source site and exploits the better source.
Step 3. Each onlooker bee selects a source depending on the quality of her solution, produces a new food source in selected food source site and exploits the better source.
Step 4. Determine the source to be abandoned and allocate its employed bee as scout for searching new food sources.
Step 5. Memorize the best food source found so far.
Step 6. Repeat steps 2-5 until the stopping criterion is met.

In first step of the algorithm, $x_i (i = 1,..., SN)$ solutions are randomly produced in the range of parameters where SN is the number of the food sources. In the second step of the algorithm, for each employed bee, whose total number equals to the half of the number of food sources, a new source is produced by (6):

$$v_{ij} = x_{ij} + \varphi_{ij}(x_{ij} - x_{kj}) \quad (6)$$

Where φ_{ij} is a uniformly distributed real random number within the range [-1, 1], k is the index of the solution chosen randomly from the colony (k=int (rand * SN) + 1), where j = 1, . . ,D and D is the dimension of the problem. After producing $\vec{v_i}$, this new solution is compared to x_i solution and the employed bee exploits the better source. In the third step of the algorithm, an onlooker bee chooses a food source with the probability (7) and produces a new source in selected food source site by (6). As for employed bee, the better source is decided to be exploited.

$$p_i = \frac{fit_i}{\sum_{j=1}^{SN} fit_j} \quad (7)$$

Where fit_i is the fitness of the solution x_i. After all onlookers are distributed to the sources, sources are checked whether they are to be abandoned. If the number of cycles that a source cannot be improved is greater than a predetermined limit, the source is considered to be exhausted. The employed bee associated with the exhausted source becomes a scout and makes a random search in problem domain by (8). General principle of ABC algorithm is shown in Figure 2.

$$x_{ij} = x_j^{min} + (x_j^{max} - x_j^{min}) * rand \quad (8)$$

4. Proposed Approach to Solve Relay Coordination Problem

There are two approaches for solving the relay coordination problem in presence of DGs: First, revising the protection system by optimization the relays operation time and second, revising the protection system by minimizing the number of changes in relays setting. The first approach is explained in section2. In this approach, the fitness value is defined based on the objective function in (1) which is the overall operating time of primary relays.

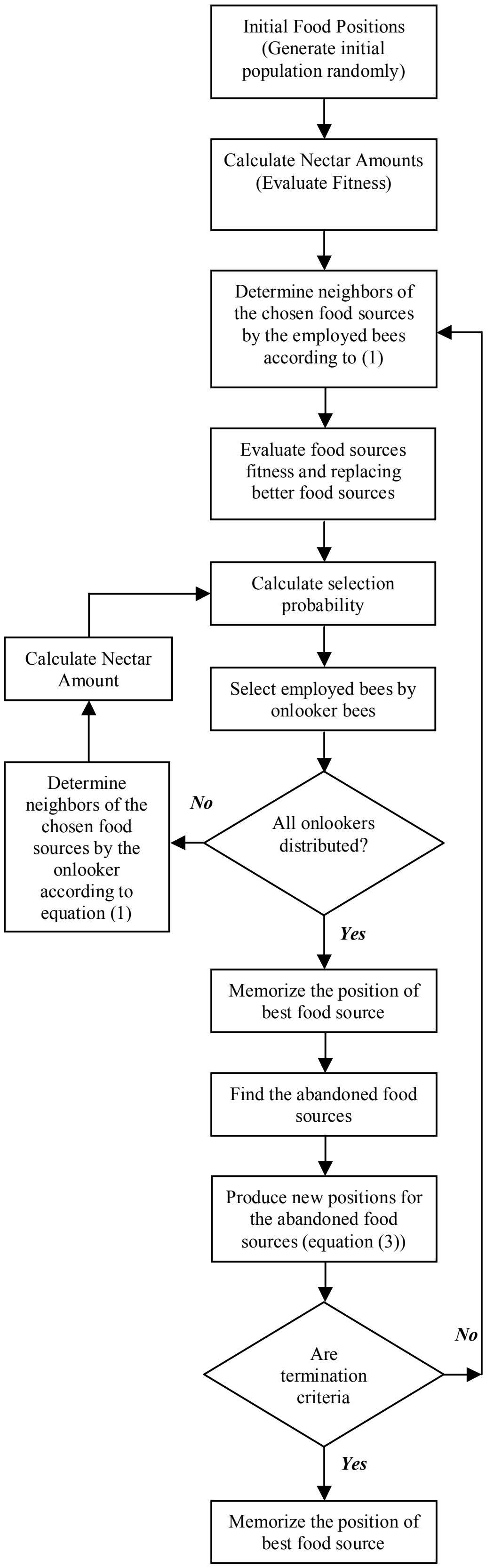


Figure 2. The general principle of ABC algorithm

In the second approach, the fitness function is defined as follow.

$$\text{Fitness} = \frac{1}{1+\text{noc}} \qquad (9)$$

In (10), noc represents the number of relays that their setting is changed. In this paper a hybrid approach based on ABC and LP algorithms is employed to solve the optimization problem.

Here, the optimization framework suggested in [6] is adopted to develop a hybrid method based on ABC and LP algorithms for solving this complex and non convex optimization problem.

In the proposed hybrid approach, the ABC and LP are used as global and local optimizers, respectively. For this, the LP algorithm is employed as a local optimizer to improve the convergence of ABC algorithm and the ABC is used to solve the first sub problem [i.e., the nonlinear part of optimization problem (1)], in order to determine the I_{pi} variables.

By extracting the candid solution information, the DOCRs coordination problem is converted to a Linear Programming problem. Therefore to evaluate the fitness value for each solution, the standard LP is solved to determine the corresponding *TMS* variables. The flowchart of the proposed hybrid method is shown in Figure. 3.

As can be seen from Figure 3, the LP sub problem is the main part of fitness function evaluation which is called several times by the ABC. To compute the fitness value for each solution, firstly, the values of the I_{pi} variables are extracted by decoding the solution information. Based on the fixed values of the variables, the nonlinear DOCRS coordination problem is converted to a LP problem. Then, by solving this LP problem the corresponding fitness value and the *TMS* variables are computed. This causes a decrease in the search space which results in time consuming and computational efficiency in finding the optimum solutions.

For some individuals according to the values of the variables, the LP sub problem is not converged. In these cases, some of the inequality coordination constraints are violated. To decrease the chance of these solutions in the next process, their fitness values are penalized. The amount of penalty is composed of a fixed value and a variable value in proportion to the number of violated constraints. Whole approach can be summarizing as following steps: 1) Extracting of relays pickup current by decoding each solution. 2) Determination of *TMS* variables by solving LP problem. The objective function in LP sub problem is defined based on (1). 3) Comparison between the result of each iteration and current relays setting and calculating fitness value for each solution based on (10).

5. Case Study

5.1 The PDS under Study

In order to show the effectiveness of the proposed method, some numerical results are presented on a 30-bus IEEE test system [12]. The considered PDS system is modeled with all of its detailed parameters (synchronous condensers with their generation limits, shunt reactors, distribution transformers taking into consideration their turn's ratio, and aggregated loads represented by constant power models). This study system is illustrated in Figure 4. The considered PDS is fed from three primary distribution substations (132/33 kV) at buses 10, 12, and 27. Each primary distribution feeder is protected by two directional overcurrent relays, one relay at each end. The PDS is assumed to have 29 existing directional overcurrent relays and the system is originally well coordinated. It is assumed that all relays are identical and have the standard IEEE moderately inverse relay curves with the following constants 0.0515, 0.114, and 0.02 for A, B, and C, respectively [12]. Also, the *TMS* values can range continuously from 0.1 to 1.3; while seven available discrete pickup tap settings (0.5, 0.6, 0.8, 1.0, 1.5, 2.0 and 2.5) are considered [12].The ratios of the current transformers (CTs) are indicated in Table. I and the CTI is assumed to be 0.3 s for each backup-primary relay pair.

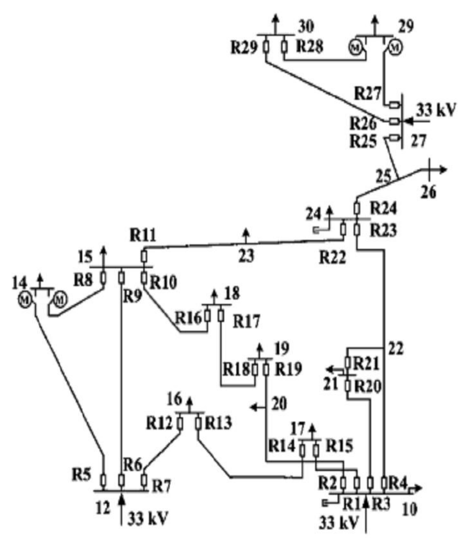


Figure 4. The 30-bus IEEE test system schematic.

Moreover, two CDGLs are considered which consist: PDS substation bus 12, and PDS load bus 19. The selected DG technology is a synchronous type, 10 MVA capacity, operating nominally at 0.9 lagging power factor, and 0.15 p.u. transient reactance based on its capacity. The DG is practically connected to the PDS bus through a transformer which is assumed to have 10 MVA capacity and 0.05 p.u. reactance based on its capacity. The DG is simulated with its required active power and constrained by the minimum and maximum reactive power that can be produced in normal operating conditions. In this work, the maximum individual DG capacity is assumed to be around 10% of the maximum PDS active power loading (115 MVA at 0.9 lagging power factor).

Table 1. The Ratios of The Current Transformers (CTs)

Relay Number.	CT	Relay Number.	CT
1	200/5	16	200/5
2	300/5	17	100/5
3	600/5	18	100/5
4	300/5	19	200/5
5	300/5	20	600/5
6	600/5	21	100/5
7	300/5	22	100/5
8	50/5	23	200/5
9	600/5	24	100/5
10	200/5	25	200/5
11	200/5	26	200/5
12	300/5	27	200/5
13	100/5	28	100/5
14	100/5	29	300/5
15	200/5		

5.2 Scenarios under Study

There are three scenarios are to be considered to investigate the proposed method.

Scenario A: It is considered as the base case with well established relay coordination, in which there is no DG installed on the PDS.

Scenario B: DG as a power source is installed on the PDS territories.

Scenario C: Revising relays setting in presence of DG.

In this paper, revising relays setting is considered with two explained approaches and the results are compared. Furthermore, in order to validate the results obtained by ABC-LP algorithm, the hybrid approach based on Genetic Algorithm (GA) and LP algorithm (GA-LP) is adopted from [6] and applied for comparison.

6. Analysis and Results

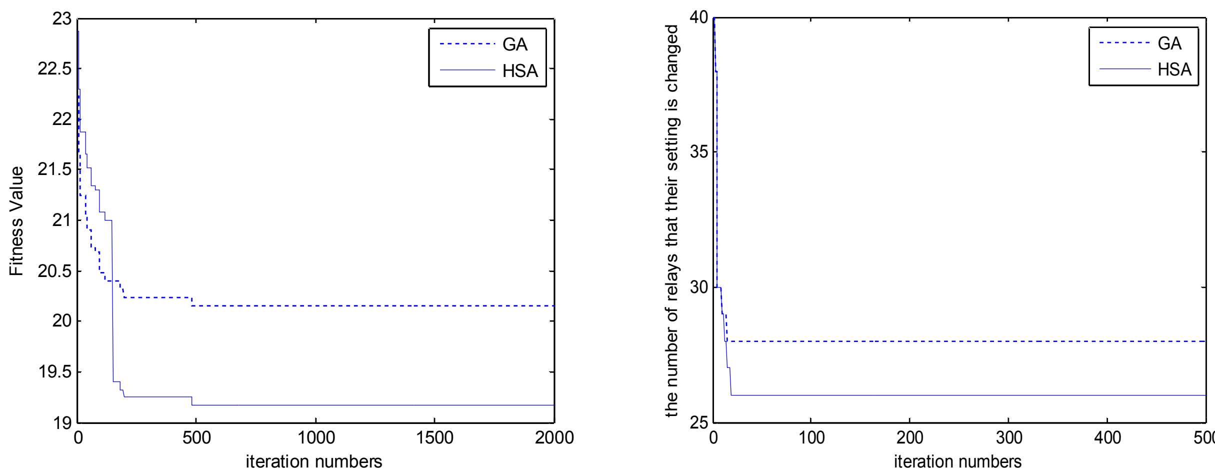
6.1 Scenario A: Relay Coordination for the Original PDS

This scenario is considered as a base PDS case without DGs. To evaluate the optimal tuned relay settings, the DOCRs coordination problem is solved using the proposed hybrid method. In this work, stopping criterion is set to be 2000 improvisations or iterations.

To validate the obtained result by ABC-LP, a GA-LP method is applied. The number of chromosomes in the population is set to be 100. One point crossover is applied with the crossover probability $p_c = 0.9$ and the mutation probability is selected to be $p_m = 0.01$. Also, the number of iterations is considered to be 2000, which is the stopping criteria used in ABC.

To find the best value for the solution, the algorithms are run for 10 independent runs under different random seeds. The average best-so-far of each run are recorded and averaged over 10 independent runs. To have a better clarity, the convergence characteristics in finding the best values is given in Figure 5, where shows ABC performs better than GA at early iterations.

The optimal values of the decision parameters (i.e., pickup tap settings and TMS variables) are shown in Table. 2. Also, the final optimal total time obtained is 14.22s. Moreover, Table. 3 shows a sample of backup-primary relay pair short circuit currents, operating times



(a) (b)

Figure 5. a) Convergence characteristics of ABC and GA on the average best-so-far cost function. (Fitness function is based on Eq. (1)). b) Convergence characteristics of ABC and GA (approach 2).

Table 2. Pick up Tap Settings And TMS Variables

Relay No.	ABC		GA		Relay No.	ABC		GA	
	Pikup Tap	TDS	Pickup Tap	TDS		Pickup Tap	TDS	Pickup Tap	TDS
1	2	0.907	2.5	0.9507	16	2.5	0.1212	2.5	0.2308
2	2	0.6656	2.5	0.6198	17	2	0.2489	2.5	0.6076
3	2.5	0.4312	2.5	0.4667	18	2	0.7502	2	0.7690
4	2	0.3367	2.5	0.1711	19	2.5	0.1	2.5	0.1879
5	2.5	0.1215	2.5	0.1	20	1	0.13	0.8	0.1
6	2.5	0.3337	2.5	0.4031	21	1.5	1.3201	2	0.9469
7	2.5	0.7694	2.5	0.8881	22	1.5	0.5726	2.5	0.7006
8	2	0.5126	2.5	0.4174	23	2.5	0.3234	2.5	0.3485
9	1.5	0.1	2	0.1	24	1	0.5568	2	0.4901
10	2	0.603	2.5	0.7363	25	1	0.5785	2.5	0.3214
11	1.5	0.3423	2.5	0.4082	26	1.5	0.26	1.5	0.2505
12	2.5	0.1346	2.5	0.1684	27	2	0.2159	2	0.1582
13	1	1.2046	2.5	0.0309	28	1.5	0.1	1	0.1
14	2	0.5517	2.5	0.6927	29	0.8	0.1	0.6	0.1
15	2	0.3741	2.5	0.4228					

Table 3. Sample of Backup-Primary Relay Pair (For ABC Results)

Relay unit	Relay current(Amp.)	Operating time (sec.)	CTI
R1	6180	1.0232	-
R19,1	627	1.3506	0.3274
R23,1	880	1.3916	0.3684

6.2. Scenario B: Relay Coordination in Presence of DG

The presence of DG will change the normal power flow as well as the short-circuit current all over the PDS, which is not restricted to the DG connected bus. Table 4 shows the primary/backup (P/B) relay pairs and corresponding fault currents passing through them in presence of the DG at buses 12 and 19 (each at a time). Based on the reported results shown in Table 3, the PDS will face relay miss-coordination. For the DG at bus 12, three relay pair mis-coordinations, based on CTI threshold (0.3s). Similarly, six relay pair mis-coordinations are reported for a DG installed at bus 19 and different fault locations.

Table 4. Primary/Backup (P/B) Relay Pairs In Presence Of The DG At Bus 19

Primary relay		Backup relay		
Relay No.	Realy current (Amp.)	Relay No.	Realy current (Amp.)	CTI
1	6754	19	1104	0.0388
3	7316	19	1104	-0.262
4	7511	19	1104	0.1852
6	6452	12	1256	0.2547
7	6463	9	279	0.0602
1	1536	31	1368	0.2142

5. Conclusion

This paper presents a new approach for simultaneous coordinated tuning of overcurrent relay for a power delivery system (PDS) including distribution generations (DGs). In the proposed scheme, solving of relay coordination problem is done with revising of relays setting in presence of DGs. For this aim, two approaches introduced. First, revising the protection system by optimization the relays operation time and second, revising the protection system by minimizing the number of changes in relays setting. For this, the relay coordination problem is formulated as the optimization problem and solved by an efficient hybrid algorithm based on artificial bee colony (ABC) and linear programming (LP). To investigate the ability of the proposed method, a 30-bus IEEE test system is considered with three scenarios. Moreover, to validate the results obtained by ABC - LP algorithm, the hybrid approach based on Genetic Algorithm (GA) and LP algorithm (GA-LP) is adopted from [6] and applied for comparison. Simulation results show the efficiency of the proposed approach in three scenarios.

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