COORDINATION OF DIRECTIONAL OVERCURRENT RELAYS USING ARTIFICIAL BEE COLONY

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ABSTRACT

This paper proposes to solve the coordination of directional overcurrent relays problem (DOCR) using Artificial Bee Colony optimization (ABC) which is robust and easily implemented. Three case studies were evaluated and implemented on looped 3-bus, 6-bus, and 8-bus systems. The obtained results from the proposed ABC algorithm is compared to those using Linear Programming (LP) and Particle Swarm Optimization (PSO) techniques to demonstrate the effectiveness of the ABC in such problems that are highly constrained. Finally, conclusions are reported and discussed.

INTRODUCTION

Power systems' faults are hazardous to people and equipments and must be removed by separating the faulty part. The purpose of power system protection is to minimize the consequences resulting from faults as soon as possible. Therefore, a backup protective scheme is provided to operate in case of a failure in the primary protection with a proper coordination. To achieve such coordination, an optimal protective relay setting, i.e pick-up current and Time Dial Setting (*TDS*) that satisfy a certain Coordination Time Interval (*CTI*). A lot of efforts have been dedicated to get the optimum setting of directional overcurrent relays (DOCR) in interconnected power systems using digital computers to achieve the best coordination between relays.

Traditionally, to solve such problem the trial and error approach was used, but it suffered a slow rate of convergence. A technique called "break points" was used to break all the loops and locate the starting relays at these points (where the coordination process starts). Topological methods, including graph theory and functional dependency, were used to determine the break points [1]. The solution obtained by these topological methods is the best of the alternative settings considered, but not the optimal one. In [2], the coordination of DOCR in the frame of the optimization theory was reported. The values of the TDS have been calculated using LP (simplex method) for a given values of the pick-up currents (I_P). Genetic algorithm [3], evolutionary algorithm [4], and Particle Swarm Optimization (PSO) [5] have been used to find an optimal setting of the protective relays as well.

A new Evolutionary Computation (EC) technique was proposed in [6], which is called Artificial Bee Colony (ABC), motivated by the intelligent behavior of honey bees. It is as simple as PSO and Differential Evolution algorithms, and uses only common control parameters such as colony size and maximum cycle number. ABC as an optimization tool provides a population-based search procedure in which individuals called foods positions are modified by the artificial bees with time and the bee's aim is to discover the places of food sources with high nectar amount and finally the one with the highest nectar. ABC system combines local search methods, carried out by employed and onlooker bees, with global search methods, carried out by scouts.

This paper presents the solution of the coordination problem of DOCR using a proposed ABC technique. The development and implementation of the proposed algorithm on three case studies are given.

THE COORDINATION PROBLEM

The coordination problem of DOCR can be stated as an optimization problem. The objective function is developed to minimize the sum of the operating times of the primary relays connected to the system as in (1).

$$\min \sum_i \sum_j T_{ij_{primary}} \tag{1}$$

where,

$T_{ij_{primary}}$ is the operating time of the primary relay *i* for a fault *j*

Subject to the following constraints [2]:

$$h(T) \le 0 \qquad \text{(Coordination criteria)} \tag{2}$$

$$T = f(S) \qquad \text{(Relay characteristics)} \tag{3}$$

$$S_{i\min} \le S_i \le S_{i\max} \qquad \text{(Bounds on relay settings)} \tag{4}$$

1) **COORDINATION CRITERIA***:* to achieve a reliable protective system, a backup protection scheme is used with primary protection. They should be coordinated together, i.e. a predefined *CTI* should elapse before the backup scheme comes into action. This *CTI* depends upon the type of the relays (electromechanical or microprocessor based), speed of the circuit breakers, and

other system parameters. The above situation can be described by:

$$T_{backup} - T_{primary} \geq CTI \quad (5)$$

where,

T_{backup} is the operating time of the backup relay
$T_{primary}$ is the operating time of the primary relay

In some cases, it is important to consider the dynamic changes in the network topology that occurs during the transient conditions. Such transient configurations take place when only one relay of the protective zone operates, while the other one is still inoperative [2]. The transient situation can be described mathematically by:

$$T'_{backup} - T'_{primary} \geq CTI' \quad (6)$$

Where; the superscript ($'$) indicates transient quantities.

2) **RELAY OPERATIONAL CHARACTERISTICS***:* typically, the inverse time overcurrent relay (OCR) has two values to be set, I_P and *TDS*. The pickup value is the minimum current value for which the relay operates, and the *TDS* defines the relay operating time (*T*) for each current value. The characteristics of the OCR are given as a curve of *T* vs. *M*, where *M* (multiple of pickup current) is the ratio of the relay current, *I*, to the I_P value.

$$M = \frac{I}{I_P} \quad (7)$$

In this work, equations (8)-(11) are used to approximately represent the inverse OCR characteristics [7]:

$$T = K_1 \frac{TDS}{M^{K_2} + K_3} \quad (8)$$

$$T = (PTDS)(PI_P) \quad (9)$$

$$PTDS = b_0 + b_1(TDS) + b_2(TDS)^2 + b_3(TDS)^3 \quad (10)$$

$$PI_P = a_0 + \frac{a_1}{(M-1)} + \frac{a_2}{(M-1)^2} + \frac{a_3}{(M-1)^3} + \frac{a_4}{(M-1)^4} \quad (11)$$

Where; K_1, K_2, K_3, a_0, a_1, a_2, a_3, a_4, b_1, b_2, and b_3 are constants depending on the type of the relay simulated.

3) **BOUNDS ON RELAY SETTINGS***:* the essence of the DOCR coordination study is the calculation of its *TDS* and I_P. Formulating the above constraints gives:

$$TDS_{i_{min}} \leq TDS_i \leq TDS_{i_{max}} \quad (12)$$

$$I_{P_{i_{min}}} \leq I_{P_i} \leq I_{P_{i_{max}}} \quad (13)$$

In order to determine the operating time of the relay for a given fault, there are two variables to be set (TDS- continuous value and IP- discrete value). To solve such problem, one variable is optimized assuming that the other one is predefined. Accordingly, there are two methods to solve the DOCR coordination problem:

1) **FINDING *TDS* FOR A PREDEFINED I_P***:* equation (8) is reduced to:

$$T = a * TDS \quad (14)$$

$$a = \frac{K_1}{M^{K_2} + K_3} \quad (15)$$

and the problem is reduced to a LP problem.

It is worthy to mention that even if (9) is used to represent the characteristics of the relays, the coordination problem can still be stated as a LP one. In this case, the problem is solved in terms of the variables *PTDS*, then the corresponding *TDS* can be calculated by finding the roots of the polynomial defined by (10) using the optimum values of *PTDS* calculated.

2) **FINDING I_P FOR A PREDEFINED *TDS***: in this case, using (8) converts the problem to a non-linear optimization one, whose variables are the I_P of the relays. If the relays are represented by the characteristic equation indicated by (9), then the problem can still be considered as a LP one if it is solved in terms of PI_P's. The values obtained for PI_P's in conjunction with the relay current (*I*) would be used to compute the I_P*'s* using (11).

In this paper, ABC is used to solve a LP problem of finding TDS of the relays for a previously set I_P.

ARTIFICIAL BEE COLONY

A bee swarm algorithm called artificial bee colony algorithm for numerical optimization problems is introduced in [6]. ABC has been employed by several researchers to solve various problems in different research areas [8]. It simulates the intelligent behavior of honey bee swarms. ABC contains three groups: employed bee, onlooker bee and scout. The bee going to the food source which is visited previously is an employed bee. The bee waiting on the dance area for making decision to choose a food source is onlooker bee. The bee carrying out random search is scout bee. The onlooker bee with scout also called unemployed bee In the ABC algorithm, the collective intelligence searching model consists of three essential components: employed, unemployed foraging bees, and food sources. The employed and unemployed bees search for the rich food sources, which close to the bee's hive. The employed bees store the food source information and share the information with onlooker bees. The number of employed bees is equal to the number of food sources and also equal to the amount of onlooker bees. Employed bees whose solutions cannot be improved through a predetermined number of trials, specified by the user of the ABC algorithm and called "limit", become scouts and their solutions are abandoned. The model also defines two leading modes of behavior which are necessary for self-organizing and collective intelligence: recruitment of foragers to rich food sources resulting in positive feedback and abandonment of poor sources by scout causing negative feedback.

1) **INITIAL PHASE**

The food sources, whose population size is SN, are randomly generated by scout bees. The number of Artificial Bee is NP. Each food source X_{ij} is a vector to the optimization problem, X_{ij} has D variables and D is the dimension of searching space of the objective function to be optimized. The initiation food sources are randomly produced via the following formula.

$$X_{ij} = X_{minj} + rand(0,1)(X_{maxj} - X_{minj}) \quad (16)$$

where X_{max} and X_{min} are the upper and lower bound of the solution space of objective function, rand (0,1) is a random number within the range [0,1].

2) **EMPLOYED BEES PHASE**

They fly to a food source and find a new food source within the neighborhood of the food source. The higher quantity food source will be selected. The food source information stored by employed bee will be shared with onlooker bees. A neighbor food source V_{ij} is determined and calculated by the following formula.

$$V_{ij} - X_{ij} + \varnothing(X_{mi} - X_{ki}) \quad (17)$$

where X_k is a randomly selected food source, i is a randomly chosen parameter index, φ is a random number within the range [-1,1]. The range of this parameter can make an appropriate adjustment on specific issues. To simulate the information sharing by employed bees in the dance area, probability values are calculated for the solutions by means of their fitness values using the following equation. The fitness values might be calculated using the below definition as in (19).

$$Pf_i = \frac{fit_i}{\sum_{j=1}^{n} fit_i} \quad (18)$$

$$fit_i = \begin{cases} \frac{1}{1+f_i} & f_i \geq 0 \\ 1 + abs(f_i) & f_i < 0 \end{cases} \quad (19)$$

3) **ONLOOKER BEES PHASE**

Onlookers are placed onto the food source sites by using a fitness based selection technique.

4) **SCOUT BEES PHASE**

Every bee swarm has scouts that are the swarm's explorers. The explorers do not have any guidance while looking for food. In case of artificial bees, the artificial scouts might have the fast discovery of the group of feasible solutions. In the searching algorithm, the artificial employed bee whose food source nectar has been exhausted or the profitability of the food source drops under a certain threshold level is selected and classified as the artificial scout. The classification is controlled by "abandonment criteria" or "limit". If a solution representing a food source position is not improved until a predetermined number of trials, then that solution is abandoned by its employed bee and the employed bee becomes a scout.

IMPLEMENTATION

To use ABC algorithm for solving relay coordination problems, a MATLAB computer program is developed. The ABC's parameters used during simulation are; Number of bee is 100, Food number is 50, and the limit and number of iterations are 200. The proposed ABC algorithm is used to coordinate three different systems adopted from previous literature. The simulation results are compared to those of LP obtained using MATLAB optimization toolbox and PSO algorithm.

Case study-1: 3-bus system

ABC is applied to the 3-bus system shown in Figure 1. This system has been previously adopted to illustrate the usage of the LP and PSO in calculating the setting of DOCR [2] and [5], and is used here for the sake of comparison. All relays are identical, having inverse time characteristic that can be approximated by (8), where $K_1 = 0.14$, $K_2 = 0.02$, $K_3 = -1$. The *TDS* ranges are from 0.1 to 1.1. *CTI* of 0.2 sec. is adopted. Three-phase faults at the middle of the transmission lines are considered as the relevant faults. During the formulation of the coordination constraints, the transient changes in the network topology are taken into account. The results of the proposed method compared to those of the Simplex method in [2] and PSO in [5] are given in Table I.

The obtained results show that the ABC algorithm successfully converges to the same optimal relay settings reached by the classical LP methods and PSO algorithm. The ABC convergence rate is about 45 iterations.

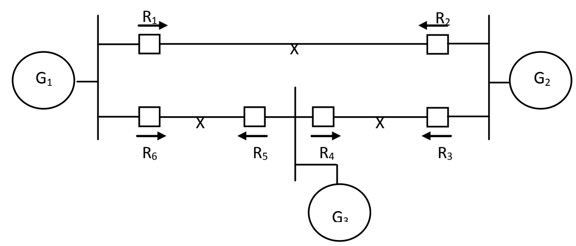

Fig. 1. System-1: 3-bus system

TABLE I
TDS SIMULATION RESULTS OF THE 3-BUS SYSTEM

Relay No.	Simplex method [2]	LP using MATLAB[5]	PSO [5]	ABC
1	0.1000	0.1000	0.1000	0.1000
2	0.1364	0.1364	0.1364	0.1364
3	0.1000	0.1000	0.1000	0.1000
4	0.1000	0.1000	0.1000	0.1000
5	0.1298	0.1298	0.1298	0.1298
6	0.1000	0.1000	0.1000	0.1000
∑ *TDS*	1.9258	1.9258	1.9258	1.9258

Case study-2: 6-bus system

In Figure 2, three-phase faults are applied at the near-end of each relay (close in faults). The relays used in the network are the Westinghouse Co-9 that can be modeled by (9). The coefficients of (10) and (11) required to calculate the operating times of the relays using (9) are given in Table II. The *TDS* are assumed to vary between a minimum value of 0.5 and maximum value of 11, and *CTI* of 0.2 sec., while the transient changes in the network topology are not considered. A sample of the *PTDS* values obtained from the simulation is given in Table III.

This case study shows that ABC and PSO succeeded to find an optimum solution while the LP using MATLAB failed to converge to any solution. The reason for such failure is caused by effect of the residuals of the function that are neither growing nor shrinking as per [**5**]. Also this case study shows that ABC can find more optimum results than the results obtained using PSO.

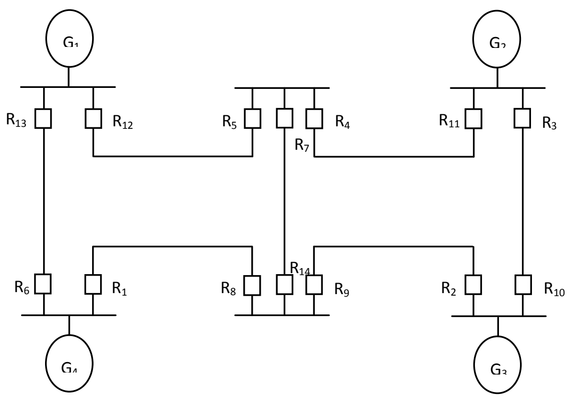

Fig. 2. System-2: 6-bus system

TABLE II
COEFFICIENTS OF EQUATIONS (6) & (7)

b_0	b_1	b_2	b_3
1.86007e-2	5.607555e-2	3.012819e-3	1.23400e-8

a_0	a_1	a_2	a_3	a_4
0.9296478	6.792136	14.03259	-8.430325	2.679891

TABLE III
SAMPLE of *PTDS* VALUES OF THE 6-BUS SYSTEM

Relay No.	Polynomial *PTDS*		
	LP using MATLAB [5]	PSO [5]	ABC
1	No Convergence to a feasible solution	0.0889	0.0889
2		0.0474	0.0474
…		…	…
13		0.0474	0.0474
14		0.0474	0.0474
∑ *PTDS*		0.7084	0.7051

Case study-3: 8-bus system

The proposed ABC was also applied on a 8-bus system. The obtained results showed same conclusion obtained from the 6-bus system.

CONCLUSION

The coordination problem in this paper is solved using ABC, which is a new optimization technique that still unpopular in the power engineering community. ABC will gain more popularity in the upcoming years for its robustness and easiness. As shown in the simulation results, ABC algorithm succeeds to converge to the same optimal setting found by the Simplex method and PSO, as in the first case study. Moreover ABC and PSO are capable of finding a feasible setting while the LP using MATLAB failed to, as in the second case study. Also the robustness of ABC over PSO has been shown as ABC always converges to the optimal solution, as in the third case study. Therefore, ABC can be considered as a potential alternative suitable for solving the *DOCR* coordination problem in the future.

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