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Solving Directional Overcurrent Relay Coordination Problem Using Artificial Bees Colony

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***Abstract*—**This paper presents the implementation of Artificial Bees Colony (ABC) algorithm in solving Directional OverCurrent Relays (DOCRs) coordination problem for near-end faults occurring in fixed network topology. The coordination optimization of DOCRs is formulated as linear programming (LP) problem. The objective function is introduced to minimize the operating time of the associated relay which depends on the time multiplier setting. The proposed technique is to taken as a technique for comparison purpose in order to highlight its superiority. The proposed algorithms have been tested successfully on 8 bus test system. The simulation results demonstrated that the ABC algorithm which has been proved to have good search ability is capable in dealing with constraint optimization problems.

***Keywords*—**Artificial bees colony, directional overcurrent relay coordination problem, relay settings, time multiplier setting.

I. Introduction

CONTINUOUS electricity needs to be maintained securely to the customer so as to ensure economic activities operational. Thus, power system protection becomes significantly important. Basically, power system protection tasks are minimizing damage and maintain continuity of supply. In power system protection, protective relay is considered as an important apparatus to sense abnormal conditions such as faults, overvoltage and overcurrent.

One of the most commonly used protective relay for overcurrent protection is the overcurrent relay which is placed at the secondary side of the current transformer. Overcurrent relays are used for primary and backup protection in meshed distribution and multi-source power network [1]. This relay has two settings known as time setting and plug setting. To secure protection for the entire DOCRs system, the operators must set time multiplier setting (TMS) and pickup current (I_p) values according to the coordination of primary/backup relay pairs.

Relays must be coordinated properly to avoid mal-operation and unnecessary downtime in other parts of the system [2]. Initially, DOCRs was performed manually and it was very time consuming. With the increasing of electricity demand, huge networking of power systems having multi source and loops will become more complex to handle by using conventional approach. Thus, optimization techniques are more effective for this kind of system.

Birla et al. in [3], categorized the coordination of DOCRs into three methods i.e. curve fitting technique, graph theoretical technique and optimization technique. Among these three methods, optimization method eliminates the need to find the set of breakpoints that are required in curve fitting technique and graph theoretical technique [4]. Furthermore, TMS and I_p obtained from graph and curve theoretical approach are not optimal [4].

To overcome these approaches, linear optimization techniques such as Simplex, dual Simplex and two-phase Simplex are applied for DOCRs problem. Ezzedine et. al in [5] did stress that although these techniques are simple and easy to converge but only the values of TMS can be optimized while I_p settings are assumed to be known. This is not optimum answer to the solution since these techniques may be trapped in local minimum. Some researchers used non linear programming technique but this method is very complex and time consuming [6]. In [7], [8], A.J. Urdaneta et. al and A.S. Noghabi et al. formulated the DOCRs problem as mixed integer non linear programming (MINLP) and was solved by using General Algebraic Modeling System (GAMS) software. However, the use of binary variables for I_p increases the complexity of the coordination problem [6], [9]. Due to this, many researchers proposed Artificial Intelligence (AI) and Nature Inspired Algorithms (NIA) to solve DOCRs problem.

AI methods such as Genetic Algorithm (GA), Evolutionary Programming (EP) and Differential Evolution (DE) are applied for the last two decades. GA discovered two problems; miscoordination between each relay pairs and discrete TMS [10], [11], EP also introduces two problems same as GA except that discrete TMS changed to continuous [11] while DE required large population size and large convergence time to avoid premature convergence [12]. Then, researchers turn attention to meta-heuristic based on NIA. PSO has been used in [13], [14] but sometimes suffers major drawback such as converge to a local optimum. Honey Bee Algorithm (HBA) also have been used but required some parameters to be tuned [15] that lead to larger time to converge.

This paper proposes meta-heuristic algorithms called Artificial Bees Colony (ABC) to overcome the mentioned drawbacks for directional overcurrent relay coordination studies. The operating time of the relays are minimized accordingly with an optimal TMS or Time Dial Setting (TDS) with a given values of I_p. The proposed ABC technique which

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has been implemented on 8 bus test system indicates that the technique performed much better than PSO.

II. Problem Formulation

The coordination studies of DOCRs is to find an optimal TMS or TDS, objective function, considering linear or non-linear relay characteristic, relay type, primary and backup relay constraints and coordination constraints [16]. All of these mentioned requirements should be satisfied properly.

A. Objective Function

In this paper, the objective of the coordination problem is to minimize the total operating time of primary relays with an optimized values of TSM's, for near-end fault respectively. The objective function [10], [14], [16] used in this paper is given as follows.

$$OF = \min\left(\alpha_1 \sum_{i=1}^{N} t_i^{\,2} + \alpha_2 \sum_{j=1}^{P} (\Delta t_{pb} - \beta_2(\Delta t_{pb} - |\Delta t_{pb}|))^2\right) \quad (1)$$

where

t_i	the i^{th} relay operating time for near-end fault of the i^{th} relay
Δt_{pb}	the operation time difference for relay pairs
N	the number of relays
P	the number of primary/backup relay pairs
i	represents each relay and varies to N
α_1	control the weight of $\sum_{i=1}^{N} t_i^{\,2}$
α_2	control the weight of $\sum_{j=1}^{P} (\Delta t_{pb} - \beta_2(\Delta t_{pb} - \lvert\Delta t_{pb}\rvert))^2$
β_2	the parameter to consider miscoordination

B. Relay Characteristic

Non linear relay characteristics based on ANSI/IEEE C37.112-1996 is considered. The operating time of this relay characteristic is represented as follows:

$$t_i = \left[\frac{K}{(M_i)^{\alpha} - 1} + L\right] TMS_i \quad (2)$$

where M_i is the ratio of relay short circuit current or fault current to the pickup current setting of the i-th relay $M_i = \frac{I_{sc\,i}}{I_{pickup\,i}}$. TMS$_i$ is the time multiplier setting of the i-th relay and the range is from 0 to 1. The constant K, α and L are the scalar quantities and are determined according to extremely inverse characteristics. These values are tabulated in Table I.

TABLE I
Characteristic of Overcurrent Relays

Type of characteristic	K factor	α factor	L factor
Extremely Inverse	28.2	2	0.1217

C. Coordination Constraints

Coordination constraints are related with primary and backup relays. The time margin or time interval that must allowed between two adjacent relays for correct discrimination purpose is known as time grading margin (TGM). The grading margin depends on several factors such as relay timing errors, the overshoot time of the relay, Current Transformer (CT) error and fault current interrupting time of the Circuit Breaker (CB). In general, the coordination constraints are indicated as follows:

$$\Delta t_{pb} = t_b - t_p - TGM \quad (3)$$

where

t_b is the operating time of the backup relay due to near-end fault

t_p is the operating time of the primary relay due to near-end fault

TGM is the coordination time interval varies from 0.1 – 0.4s under different condition

According to authors in [17], TGM's relay to relay values of 0.3 to 0.4 are for electromagnetic relays while 0.1 to 0.2 represent for microprocessor relays. TGM is depending on relay technology. In this study, TGM of 0.2 was chosen.

III. Artificial Bees Colony

Artificial Bees Colony (ABC) [18], [19] was developed by Karagoba for optimizing numerical problems. The algorithm simulates the intelligent foreaging behavior of honey bee swarms [18], [20]. In ABC, the colony of artificial bees consists of three groups of bees called as employed bees and unemployed bees. Unemployed bees are divided into two parts commonly known as onlooker bees and scout bees. Employed bees are the ones going to the food source and onlooker bees are making a decision to choose a food source visited by it before. The other one, scout bees, search for discovering new sources. The position of a food source represents a possible solution to the optimization problem and the nectar amount (fitness value) of a food source corresponds to the fitness of the associated solution, calculated by [18], [19].

$$fit_i = \begin{cases} \dfrac{1}{1 + f_i} & f_i \geq 0 \\ 1 + abs(f_i) & f_i < 0 \end{cases} \quad (4)$$

where fit_i is the fitness of the associated solution, f_i is the fitness of the population.

Firstly, ABC generates randomly distributed initial population *P(C=0)* of *SN* solution (food source positions). *SN* represents the population size. Each solution, x_i *(i=1, 2, ... ,SN)* is a D-dimensional vector where D is the number of optimization parameters [18], [19]. After initialization, the population of solutions is subjected to repeated cycles, *(C=1, 2, ... ,MCN)* of the search processes of the employed bees, onlooker bees and scout bees [18], [19].

An employed bee produces a modification on the solution in its memory depending on the local information and the fitness value of the new solution (new source) is tested. If the fitness value of the new one is higher than the previous one, the bees memorizes the new position (solution) and forgets the previous one. Otherwise, it keeps the position of the previous one in its memory. After all the employed bees complete the search process, these bees share the nectar (fitness) information of the food source and their position (solution) information with the onlooker bees on the dance area. Then, the onlooker bees evaluate the fitness information taken from all employed bees and chooses a food source with a probability related to its nectar amount (fitness value).

An onlooker bee chooses a food source depending on the probability value associated with that food source, P_i calculated by the following expression [18], [19]:

$$P_i = \frac{fit_i}{\sum_{n=1}^{SN} fit_n} \quad (5)$$

where *SN* is the number of food sources equal to the number of employed bees and fit_i is the fitness of the solution given in (4).

In order to produce a candidate food position from the previous one in memory, the ABC algorithm uses the following expression [18], [19]:

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

where $k \in \{1,2,..., SN\}$ and $j \in \{1,2,..., D\}$ are randomly chosen indexes. Although *k* is determined randomly, it should not be similar to *i* while ϕ_{ij} is a random number between -1 and 1. It controls the production of neighbor food sources around x_{ij} and represents the comparison of two food positions visible to the bees [18], [19].

The food source which fitness is abandoned by the bees is replaced with a new food source by the scout bee. The value of predetermined number of cycles is an important parameter in ABC algorithm, known as "limit" for abandonment. Assumed that the abandoned source is x_i and $j \in \{1,2,..., D\}$, then the scout bee discovers a new food source to be replaced with x_i. This operation can be defined as in (7) below in matlab code:

$$x_{ij} = x_{j\min} + rand\,(0,1)(x_{j\max} - x_{j\min}) \quad (7)$$

After source position of each candidate vij has been produced and evaluated by the artificial bee, its performance is compared with the previous one. A greedy selection is employed as the selection operation between the previous and candidate one. Greedy selection is used to make a selection between the source position in their memory and the new source position [20]. In ABC, there are the number of food sources which are equaled to the number of employed or onlooker bees (*SN*), the value of *limit* and the maximum number cycle (*MCN*). While onlookers and employed bees carry out the exploitation process in search space, the scouts bee control the exploration process.

The basic steps of the ABC algorithm can be summarized as the pseudo code which depicted in Fig. 1.

```
ABC algorithm
Generate initial population of rounded xi (i=1, 2, … ,SN)
Evaluate the fitness (fi) of the population
Set iteration to 1
Repeat
For each employed bee {
        Produce new solution vi by using (6)
        Calculate the value of fi
        Apply greedy selection process}
Calculate the probability values Pi for the solutions (xi) by using (5)
For each onlooker bee {
        Select a solution xi depending on Pi
        Produce new solution vi
        Calculate the value fi
        Apply greedy selection process}
If there is abandoned solution for the scout
Then replace it with new solution which will be randomly produced by (7)
Memorize the best solution so far
Cycle=Cycle+1
Until Cycle=MCN
```

Fig. 1 Pseudo code of the ABC

IV. Results and Discussion

An optimization engine was developed in MATLAB to implement ABC technique. Both techniques were executed on Intel Core i5 2.53 GHz with 4 GB RAM. The study revealed the feasibility of ABC algorithm to solve DOCRs problem. The proposed method has been tested on 8 bus test system and was compared with PSO algorithm. The control parameters of ABC algorithm are listed in Table II. The single line diagram of the test system is depicted in Fig. 2. The test system comprises of 8 buses, 7 lines, 2 transformers, 2 generators and 14 DOCRs.

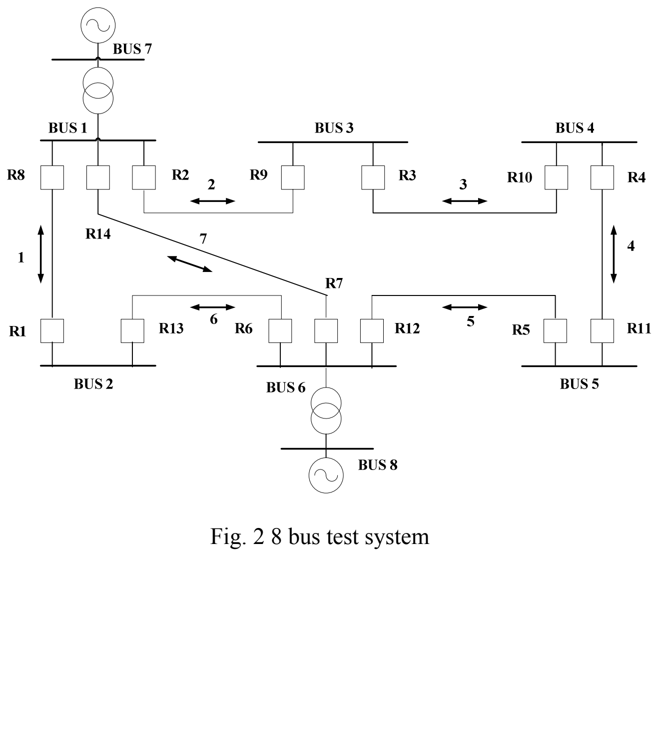

Fig. 2 8 bus test system

TABLE II
ABC CONTROL PARAMETERS

Parameters	Value
Number of food source (*SN*)	100
Number of iteration (*MCN*)	500
Limit	1400

The network information which consists of line characteristic, generator data and transformer data are given in reference [21]. The values of α1, α2 and β2 are listed in Table III. After implemented exhaustive experiment, the values listed are considered as the best values in this study. The determination of parameters α1, α2 and β2 is important for evaluating the objective function as well as testing the effectiveness of ABC algorithm.

TABLE III
PARAMETERS VALUES

Parameters	α_1	α_2	β_2
Values	1	1	100

Table IV tabulates the primary relay and backup relay short circuit current corresponding to near-end fault for the test system. The occurrence of fault in a transmission lines is symmetrical balanced three phase fault. There are 20 inequality constraints corresponding to each relay pairs. The units for both primary and backup relays current are in Amperes. The relevant information on pickup current settings for the relays is given in Table V.

TABLE IV
PRIMARY AND BACKUP RELAY SHORT CIRCUIT CURRENT EXTRACTED FROM [22]

Primary Relay	Backup Relay	Primary Short Circuit Current	Secondary Short Circuit Current
8	9	6080	1160
8	7	6080	1880
2	7	5910	1880
2	1	5910	993
3	2	3550	3550
4	3	3780	2240
5	4	2400	2400
6	5	6100	1200
6	14	6100	1870
14	1	5190	993
14	9	5190	1160
1	6	3230	3230
9	10	2480	2480
10	11	3880	2340
11	12	3700	3700
12	14	5890	1870
12	13	5890	985
13	8	2980	2980
7	5	5210	1200
7	13	5210	985

TABLE V
PICKUP CURRENT SETTINGS EXTRACTED FROM [23]

Relay	Pickup Current (I_p)
1	600
2	800
3	500
4	800
5	600
6	500
7	600
8	500
9	600
10	500
11	600
12	500
13	600
14	800

The DOCRs coordination problem in this paper is formulated as a LP problem. Table VI tabulates the results for TMS values and 14 DOCRs value. The best result of ABC technique is compared with those obtained using PSO. By applying ABC with the selected values, the results for TMS's are obtained. It can be observed that the values of TMS's for ABC are in the range between 0.01 and 0.53s. For PSO, the values of TMS's are in the range between 0.01 and 0.55s. The results of ABC technique are considered as the best results among 20 runs with the 300 iteration as compared to PSO. In terms of total TSM's, ABC technique exhibits shorter time, i.e. 2.17s compare to PSO, i.e. 2.25s. From Table VI also, it indicates that the total operating time of primary relay for ABC technique is only 1.1922 s which is 0.0355s faster than PSO. The reduction in the DOCRs operating time demonstrates that the ABC method can be implemented for determining optimum settings DOCRs.

TABLE VI
TIME MULTIPLIER SETTING AND RELAY OPERATING TIME

Time Multiplier Setting (TMS)			Relay Operating Time for near-end fault (t_i)		
Parameters	[weight: α_1=1, α_2=1, β_2=100]		Parameters	[weight: α_1=1, α_2=1, β_2=100]	
Techniques / TMS No	ABC	PSO	Techniques / t_i	ABC	PSO
TMS_1	0.03	0.04	t_1	0.0339	0.0452
TMS_2	0.22	0.24	t_2	0.1426	0.1555
TMS_3	0.20	0.19	t_3	0.1385	0.1316
TMS_4	0.07	0.07	t_4	0.1011	0.1011
TMS_5	0.01	0.01	t_5	0.0200	0.0200
TMS_6	0.31	0.34	t_6	0.0969	0.1062
TMS_7	0.11	0.11	t_7	0.0551	0.0551
TMS_8	0.26	0.27	t_8	0.0816	0.0847
TMS_9	0.01	0.01	t_9	0.0187	0.0187
TMS_{10}	0.17	0.17	t_{10}	0.1016	0.1016
TMS_{11}	0.16	0.15	t_{11}	0.1413	0.1325
TMS_{12}	0.53	0.55	t_{12}	0.1730	0.1795
TMS_{13}	0.03	0.03	t_{13}	0.0394	0.0394
TMS_{14}	0.06	0.07	t_{14}	0.0485	0.0566
Iteration			300		
total time setting multiplier (s)	2.17	2.25	total operating time of primary relays (s)	**1.1922**	**1.2277**

Table VII shows the DOCRs coordination time and it is discovered that ABC technique performed much better than PSO. Some values of Δt_{pb} are zero such as the coordination time between relays 8 and 9. This is due to the relay 8 is connected to a generator-transformer bus. In such case, there is no need to study the coordination time [10]. Other primary relays with Δt_{pb} equal to zero are also connected to generator-transformer buses.

ABC technique exhibits shorter time for objective function, i.e. 0.3125s as compared to PSO, 0.5030s. This indicates that the selection of α_1, α_2 and β_2 is correct in ensuring miscoordination of relay is avoided. Although PSO computational time, i.e. 140.6535s is slightly faster than ABC but in terms of minimum fitness function, ABC technique is much better. Hence, the ABC produces better results than PSO. Fig. 3 displays that ABC nearly reached global optimum after 292 iterations while PSO reached at 252 iterations. It can be seen that ABC results in better fitness function values than PSO technique.

TABLE VII
DOCRS COORDINATION TIME

Relay Coordination Time for each relay pairs, Δt_{pb}		
Parameters	[weight: α_1=1, α_2=1, β_2=100]	
Techniques / Δt_{pb}	ABC	PSO
Δt_{89}	0	0
Δt_{87}	0.0836	0.0805
Δt_{27}	0.0226	0.0096
Δt_{21}	0.1476	0.2980
Δt_{32}	0.0202	0.0597
Δt_{43}	0.0190	0.0030
Δt_{54}	0.0353	0.0353
Δt_{65}	0	0
$\Delta t_{6,14}$	0.0895	0.1445
$\Delta t_{14,1}$	0.2416	0.3969
$\Delta t_{14,9}$	0	0
Δt_{16}	0.0185	0.0316
$\Delta t_{9,10}$	0.0051	0.0051
$\Delta t_{10,11}$	0.0354	0.0143
$\Delta t_{11,12}$	0.0012	0.0229
$\Delta t_{12,14}$	0.0134	0.0712
$\Delta t_{12,13}$	0.1298	0.1232
$\Delta t_{13,8}$	0.0046	0.0140
Δt_{75}	0	0
$\Delta t_{7,13}$	0.2477	0.2477
Iteration	300	
Computation time (s)	**140.8325**	**140.6535**
Fitness Function (s)	**0.3125**	**0.5030**

V. CONCLUSION

Artificial Bees Colony technique has been presented to solve DOCRs problem. The effectiveness of ABC was demonstrated and tested on the 8 bus test system. From the results, it can be revealed that the proposed ABC technique gave best result to solve DOCRs coordination problem and to avoid miscoordination in relay operation compared to PSO. The proposed technique is feasible to be implemented in a larger system which in turn helps the power system operator to perform such protection scheme.

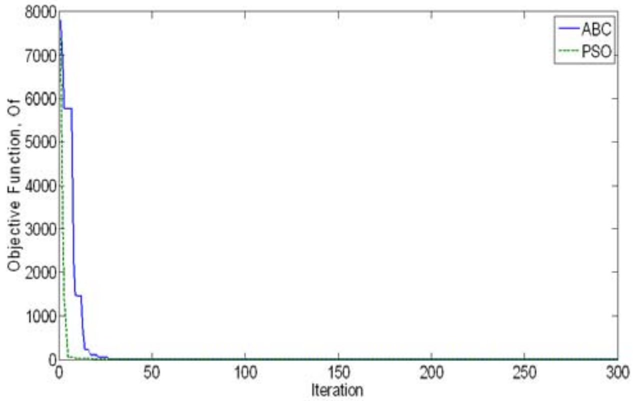

Fig. 3 Convergence of ABC and PSO to the optimal solution for 8 bus test system

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