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An Algorithm for Effective Coordination of Directional Overcurrent Relays Based on Enhanced ABC Optimizer

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ABSTRACT: In this paper, An Enhanced Artificial Bee Colony (EABC) optimization algorithm have been developed by logically integrating a newly developed optimizer with the conventional ABC algorithm, to form a highly efficient and reliable DOCR setting optimization algorithm with guaranteed rate of convergence. A variety of DOCR settings optimization simulation scenarios (case 1 to 4) have been carried out using the IEEE 3-Bus, 4-Bus, 6-Bus, and 8-Bus networks, in order to investigate and demonstrate the effectiveness of the developed models and algorithms. The obtained results are further compared with the available best in literature; and the proposed EABC based approach demonstrated an outstanding performance over the existing best DOCR optimization algorithms in literature so far.

KEYWORDS: Directional Overcurrent Relay, Enhanced Artificial Bee Colony, Optimization Algorithm, Relay, Settings

I. INTRODUCTION

Directional Over Current Relay (DOCR) coordination is a highly complex optimization problem comprising of a non-linear function characterizing the behaviour of the DOCR and the need to minimize the operation time of such device. Firstly, the need to represents the DOCR operation using characteristic equation arises. Secondly, a powerful optimization technique is required to optimally select the most appropriate operating parameter setting that could result in a minimal total operating time for a fault to be cleared. Improper setting of such relays may result into Severe damage to a part or the entire network under consideration [1].

The improper outage of any part in the protectedelectrical systems will affect its reliable operation. Definitely,each portion in the protected zones has a primary protectionand backup protection for providing a high level of security for the electrical network systems [2]. Protection devicesshould be coordinated such that: primary protection willprovide the first defence to clear the faulty section, and if itfails the backup protection should operate after a predefinedtime interval called time margin [3], [4].

Researchers have conducted several investigative and/or demonstrative works in the area of DOCR setting optimization, some of which arereviewedand summarised as follows.

[5], formulated DOCR coordination as a Mixed Integer Nonlinear Programming (MINLP) problem and solved it using Particle Swarm Optimization (PSO) technique. [6], presented a Modified Particle Swarm Optimization (MPSO) based technique that made use of improved inertia weights, and used it in solving DOCR coordination problem. [7], presented an approach for protecting low voltage grid-connected and islanded microgrid using programmable microprocessor-based relays with directional elements. However, the approach relies less on the communication link and fault currents.

[8], presented a DOCR coordination strategy using the conventional artificial bee colony (ABC) algorithm, and further carryout a comparative analysis with a PSO based approach. [9], developed a modified time-current and voltage based characteristics equation for DOCRs, and test it in the presence/absence of DG using the IEEE-14 and 30-bus networks, in order to investigate its effectiveness. [10], developed a teaching learning based optimization (TLBO) techniques for finding the optimal peak-up settings (PS) and time dial settings (TDS) of DOCRs and apply it to solve coordination problem using the Western System coordinating council (WSCC) 9-bus system. [11] formulated an approach of optimally coordinating fault current limiters (FCL) based on a hybridized

heuristic algorithm comprising of PSO and Cuckoo search optimizer (CSO).

[12] developed an optimization technique called Backtracking Search Algorithm (BSA) and applied to solve a DOCRs coordination problem on a 15-bus network in order to demonstrate its effectiveness. [13], presented an adaptive protection strategy for a distribution system with DG integration. The proposed strategy considers both grid-connected and islanded operating modes. [14], presented a DOCR coordination algorithm based on Genetic Algorithm (GA). The different topology and operating modes of a micro-grid were considering to demonstrate its effectiveness. [15], developed a continuous genetic algorithm (CGA) technique for optimum coordination of DOCR in a ring fed distribution system.

[16], presented Cascade Forward Neural Network (CFNN) strategy for modelling DOCR network loops. The CFNN made use of the DOCR coordination data acquired over several network protection operations. [17], presented a DOCR coordination analysis using Dig-SILENT Software. The data collected from the software were deployed to MATLAB simulation environment and analysed. [18], presented Grey wolf optimizer (GWO) algorithm for optimal coordination of DOCRs. The algorithm was compared with traditional GA and PSO based algorithm to ascertain its effectiveness. [19], developed a Simulink model of the IEEE 13-bus standard system and carried out several scenarios of DOCR coordination optimization using MATLAB Software package. [20], presented a DOCR coordination strategy for a distribution network with Inverter Interfaced Integration (IIG). The scheme sub-divided the relay operating zone based on Positive Sequence Fault Components (PSFC), by considering sensitive highly-sensitive, less-sensitive and insensitive areas.

[21], Presented an approach for optimal coordination of DOCRs, using hybridized simulated annealing and linear programming (SA-LP) algorithm. The algorithm was tested on five test-systems (IEEE-3, IEEE-6, IEEE-8, IEEE-15 and IEEE-30 bus). [22], Presented an ETAP Software based simulation strategy for coordinating DOCRs in a microgrid in the presence of distributed generation (DG). [23] Presents a non-standard relay characteristic based optimal DOCR coordination using genetic algorithm (GA). The technique was tested on the IEC microgrid with 15-relays. [24] presented a smart-grid based centralized protection control system called quaternary protection scheme that uses dual-DOCRs. The presence/absence of DGs in the network were also considered.

With respect to the similar works reviewed so far, it could be established that, several aspects regarding power system protection using directional overcurrent relays (DOCRs) have been dealt with in different fashions. However, a solution to one problem might result into another. Furthermore, as the network size increases in terms of number of DOCRs and/or topological complexity, the complexity of the solution search process exponentially increases, thereby requiring the use of highly efficient and reliable approaches and algorithm with high rate of convergence to the true optimum solution.

This research work, seek to develop an Enhanced Artificial Bee Colony (EABC) algorithm by integrating a newly developed optimizer with the conventional artificial bee colony (ABC) optimizer, resulting into an enhanced algorithm with a guaranteed rate of convergence and that can be redly deployed for solving DOCR optimization problems. Finally, the following set of steps are adopted in this work.

- Formulation of DOCR setting optimization problem based on two types of objective function (Type-1 and 2), and a modified objective function, which considers a set of constraints as mathematical functions.
- Development of an Enhanced Artificial Bee Colony (EABC) optimization algorithm by logically integrating a newly developed optimizer (Algorithm-X) with the conventional artificial bee colony (ABC) optimization technique.
- Obtaining the DOCR settings optimization problem data for 6 test network systems, comprising of the IEEE 3-Bus, 4-Bus, 6-Bus and 8-Bus networks.
- Investigating the performance of the developed EABC based DOCR settings optimization algorithm, by simulating four cases (Case 1 to 4) of DOCR setting optimization problem solution using the 6 test systems.

This section presents a general over view of network protection coordination strategies based on DOCR settings optimization, the relevant works carried out so far and the proposed step by step approach towards the development of an improved solution strategy. The rest of the sections are organised as follows: The formulation of DOCR coordination problem is presented in sections II to IV. The optimization constraints are presented in sections V to IX. The proposed Enhanced Artificial Bee Colony (EABC) optimizer is presented in section X. The case study system networks are presented in section XI. Section XII presents the simulation setups. The results and discussions are presented in sections XIII to XVI. Performance analysis of the proposed EABC is presented in section XVII.

II. DOCR COORDINATION PROBLEM FORMULATION

The main aim of DOCR problem formulation is to determine the optimum Time-Dial Setting (TDS) and Peak-up current Setting (PS) of the Primary relays, which are usually located closest to the point of fault occurrence. In the event of a Primary relay coordination failure, one or more of the other relays can act as Back-up to prevent the fault current from propagating itself to the other part of the network. Primary relays fault coordination is often further classified into the close-in and the far-bus fault coordination. This is often used in literature to model a suitable relay coordination objective function as will be seen later in this work. However, this imposes constraint that, a Primary relay must always operate before its corresponding Back-up counterpart. Due to the non-convexity of DOCR problem an Enhanced Artificial Bee Colony (EABC) is developed for optimal DOCR setting for reliable network protection coordination.

III. DOCR OPERATION CHARACTERISTICS

A DOCR is designed to operate only when the input current in the pre-set direction becomes greater than the product of its PS and the Current Transformation Ratio (CTR). The current transformer in a DOCR enables the use of the same type of DOCR with varying current transformer sizes to protect different part of a network. The most common DOCRs are of the inverse definite minimum time (IDMT) type. The International Electro-Technical Commission (IEC) proposed equation (1) for calculating the operational time of DOCR with IDMT characteristic [25].

$$T_{i,j} = \frac{0.14 \times TDS_i}{\left(\left(\frac{I_{SC,j}}{CTR_i \times PS_i}\right)^{0.02} - 1\right)} \quad (1)$$

IV. DOCR OBJECTIVE FUNCTION

The Objective Function (OF) commonly used for DOCR problem solution optimization is formulated as to minimize the overall sum of the relays operational time (when they are functioning as primary relays). However, other objective functions also exist. One of such objective function that combines the summation of both the near (primary) and far (backup) relays operational time is also considered in this work. DOCRs are expected to operate as fast as possible to prevent the effect of a phenomenon called “built-up current”, while still ensuring constraints satisfaction. The first kind of objective function (Type-1) used in this work is represented by equation (2). Whereas, the second kind (Type-2) is given by equation (3). These two kinds of objective function are deployed to demonstrate the effectiveness of the proposed DOCR coordination strategy irrespective of the objective function used. The Type-1 or Type-2 objective are usable depending on the available network and fault data. Equation (2) presents the Type-1 objective function [25].

$$OF^{Type-1} = \sum_{i=1}^{N_{DOCR}} T_{i,j}^{pri.} \quad (2)$$

where N_{DOCR} represents the total number of DOCR in the network, $T_{i,j}^{pri.}$ represents the operational time of **i**th primary relay when it coordinates the **j**th fault. The Type-2 objective function is also given in equation (3) [26].

$$OF^{Type-2} = \sum_{i=1}^{N_{cl}} T_{i,j}^{pri\_cl\_in.} + \sum_{k=1}^{N_{far}} T_{k,j}^{pri\_far\_bus.} \quad (3)$$

where N_{cl} is the total number of relay responding to close-in fault, N_{cl} is the total number of relay responding to far-bus fault, $T_{i,j}^{pri\_cl\_in.}$ is the operational time of **i**th primary relay during a jth close-in fault, $T_{k,j}^{pri\_far\_bus.}$ is the operational time of **k**th primary relay during a jth far-bus fault. Unlike $T_{i,j}^{pri.}$ which can be calculated using equation (1) or (3.2), $T_{i,j}^{pri\_cl\_in.}$ and $T_{k,j}^{pri\_far\_bus.}$ are computed using equations (4) and (5) respectively [26].

$$T_{i,j}^{pri\_cl\_in.} = \frac{0.14 \times TDS_i}{\left(\frac{a_i}{PS_i \times b_i} - 1\right)} \quad (4)$$

and

$$T_{k,j}^{pri\_far\_bus.} = \frac{0.14 \times TDS_k}{\left(\frac{c_k}{PS_k \times d_k} - 1 \right)} \quad (5)$$

where $a_i\ b_i\ c_k$ and d_k represents the **i**th and **k**th primary close-in and far-bus relay tripping coefficients respectively. The aforementioned objective functions are usually minimized in an attempt to optimize the DOCR settings to achieve optimal network protection coordination. However, optimum DOCR coordination cannot be achieved without satisfying a set of predefined constraints. These constraints are described in the following.

V. DOCR OPTIMIZATION CONSTRAINTS

In this work, the proposed DOCR optimization is designed to satisfy 4 major constraints. Conventionally, these constraints are usually integrated into a selected optimizer algorithm (that would be used to predict the TDS and PS that could generate the optimal relay settings) to prevent it from generating infeasible solutions. However, this may greatly reduce the rate in which solutions are found, thereby decreasing the rate of convergence, and possibly resulting in a premature convergence. In order to avert the aforementioned drawback, the constraints are formulated and integrated into the conventional objective function to form a Modified Objective Function (MOF). The MOF can be generalized using equation (6).

$$MOF^{Type-n} = OF^{Type-n} + N_{DOCR}\left(\sum_{C=1}^{4} F_C \right) (6)$$

where n is the index of the objective function type, F_C is the constraints cost function of the **C**th constraint evaluated over the entire network. Furthermore, the second part of the right hand side of equation (6) is designed to disappear if and only if, the entire DOCR optimization constraints are satisfied. The proposed constraints cost functions are developed as follows.

VI. OPERATIONAL TIME CONSTRAINT

The DOCR operational time of each (m) primary relay is subjected to a constraint that bounds it between a certain minimum and maximum. In this work, the minimum and maximum DOCR operational time are set to 0.05s and 1.00s respectively. In order to ease integrating this constraint into the objective function, the DOCR operational time constraints cost function (F_1) is developed as represented by equation (7).

$$F_1 = \sum_{m=1}^{N_{DOCR}} \begin{cases} T_{m,j}^{pri} - 1 & T_{m,j}^{pri} > 1 \\ 0 & 0.05 \le T_{m,j}^{pri} \le 1 \\ 0.05 - T_{m,j}^{pri} & T_{m,j}^{pri} < 0.05 \end{cases} (7)$$

VII. TIME DIAL SETTING (TDS) CONSTRAINT

The TDS of each (m) primary relay is also subjected to a constraint that bounds it between a certain minimum (TDS^{Min}) and maximum (TDS^{Max}). In order to ease integrating this constraint into the objective function, the DOCR TDS constraints cost function (F_2) is developed as represented by equation (8).

$$F_2 = \sum_{m=1}^{N_{DOCR}} \begin{cases} TDS_m - TDS^{Max} & TDS_m > TDS^{Max} \\ 0 & TDS^{Min} \le TDS_m \le TDS^{Max} \\ TDS^{Min} - TDS_m & TDS_m < TDS^{Min} \end{cases} \quad (8)$$

VIII. PEAK-UP SETTING (PS) CONSTRAINT

The PS of each (m) primary relay is also subjected to a constraint that bounds it between a certain minimum (PS^{Min}) and maximum (PS^{Max}). In order to ease integrating this constraint into the objective function, the DOCR PS constraints cost function (F_3) is developed as represented by equation (9).

$$F_3 = \sum_{m=1}^{N_{DOCR}} \begin{cases} PS_m - PS^{Max} & PS_m > TDS^{Max} \\ 0 & PS^{Min} \le PS_m \le PS^{Max} \\ PS^{Min} - PS_m & PS_m < PS^{Min} \end{cases} (9)$$

IX. COORDINATION TIME INTERVAL CONSTRAINT

The Coordination Time Interval (CTI) is another important parameter in DOCR optimization that ensures network protection and maximize the proximity of fault detection and isolation. As previously stated, it represents the minimum time delay between a primary relay operation ant its corresponding backup relay counterparts. The CTI constraint is computed over a set of predefined primary-backup (P/B) relay pair [m, n] of fault detection and isolation operations. The CTI constraint is one of the most critical and default constraint to satisfy. The minimum allowable coordination time interval (CTI^{Min}) can be used to formulate a suitable cost to amount for this constraint. In order to ease integrating this constraint into the objective function, the CTI constraints cost function (F_4) is developed as represented by equation (10).

$$F_2 = \sum_{m=1}^{N_{[m,n]}} \begin{cases} CTI^{Min} - T^{bac}_{n,j} + T^{pri}_{m,j} & T^{bac}_{n,j} - T^{pri}_{m,j} < CTI^{Min} \\ 0 & otherwise \end{cases} \tag{10}$$

For objective function of Type-1, $T^{bac}_{n,j}$ and $T^{pri}_{m,j}$ are evaluated using the $T_{i,j}$ formula presented in either equation (1). However for Type-2 objective function, equations (11) and (12) are used for calculating $T^{bac}_{n,j}$ and $T^{pri}_{m,j}$ respectively. This backup and primary operational time are computed using [26]:

$$T^{bac.}_{p,j} = \frac{0.14 \times TDS_p}{\left(\dfrac{e_p}{PS_p \times f_p} - 1 \right)} \tag{11}$$

and

$$T^{pri.}_{m,j} = \frac{0.14 \times TDS_q}{\left(\dfrac{e_q}{PS_q \times f_q} - 1 \right)} \tag{12}$$

where e_p f_p g_p and h_p represents the **p**th backup relay tripping/operational time ($T^{bac.}_{p,j}$) coefficients, with **n = p**. Whereas, e_q f_q g_q and h_q represents the **q**th primary relay tripping/operational time ($T^{bac.}_{q,j}$) coefficients, with **m = q**. In general, for the Type-2 objective function, a table of the aforementioned coefficients is required. These coefficients are often represented/labelled with a, b, c, d, e, f, g, h, p, and q; as can be noticed in Tables 3.3 and 3.4, for the IEEE 4-Bus bench marked DOCR coordination test network. The same coefficients for the IEEE 6-Bus bench marked network are provided in Tables 3.5 and 3.6.

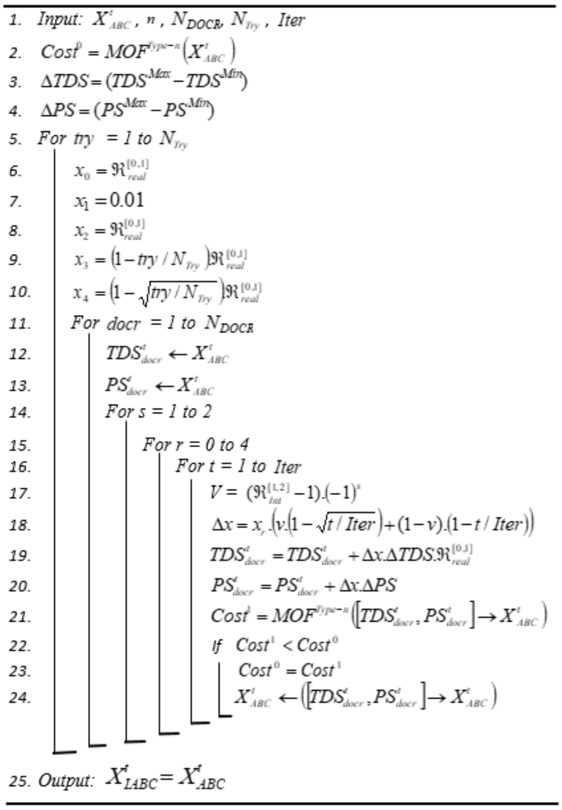
X. ENHANCED ARTIFICIAL BEES COLONY (EABC) ALGORITHM

The proposed Enhanced Artificial Bees Colony (EABC) optimization algorithm is a modified form of the conventional ABC algorithm with enhance solution search capability. However, the enhancement is achieved by logically integrating ABC with a new solution search procedure (Algorithm-X) that further explore the solution search space, in order to improve the rate of convergence of the standard ABC algorithm. Algorithm-X attempt to achieve optimization by randomly searching the entire boundaries around the current solution set. Consider an ABC optimizer based solution candidate set generated at the **t**th stage as represented by equation (13).

$$X^t_{ABC} = \{TDS^t_1 \quad TDS^t_2 \quad \ldots \quad TDS^t_{N_{DOC}} \quad PS^t_1 \quad PS^t_2 \quad \ldots \quad PS^t_{N_{DOC}}\} \tag{13}$$

The proposed EABC is achieved by improving every X^t_{ABC} by shifting its elements to a new and better solution search space given rise to a new solution candidate set X^t_{IABC} using Algorithm-X.

In Algorithm-X, an ABC based candidate solution X^t_{ABC} (represented by equation 13) ; the choice of objective function n ; the total number of DOCRs N_{DOCR} ; the maximum number of optimization trials N_{Try} ; and the maximum number of optimization iteration for a particular DOCR $Iter$ are all taken as input. Whereas, the output is the improved solution X^t_{IABC}. The algorithm begins by evaluating the fitness of the original solution using step 2. A range of random real numbers are generated between steps 6 and 10. These numbers are gradually used to modify the solution using steps 19 and 20. The algorithm obtain and temporary store a DOCR settings using steps 12 and 13. These settings are respectively modified using steps 19 and 20. The algorithm then evaluate the fitness of a new solution formed by modifying the settings of the current relay using step 21. Finally, the original solution is replaced by the new solution if the later has a lower fitness value using steps 23 and 24. Otherwise, the new solution is discarded. Steps 16, 15, 14, 11 and 5 are respectively completed one after the order, and then step 25 is finally carried out. In Algorithm-X, $\Re_{real}^{[a,b]}$ is used to represent a random real number (N) generated within the closed interval $a \le N \le b$; whereas, $\Re_{Int}^{[c,d]}$ represents a random Integer (N) generated within the closed interval $c \le N \le d$; whereas,



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1.  Input: $X^t_{ABC}$ , $n$ , $N_{DOCR}$, $N_{Try}$ , $Iter$
2.  $Cost^0 = MOF^{Type-n}(X^t_{ABC})$
3.  $\Delta TDS = (TDS^{Max} - TDS^{Min})$
4.  $\Delta PS = (PS^{Max} - PS^{Min})$
5.  For $try$ = 1 to $N_{Try}$
6.      $x_0 = \Re_{real}^{[0,1]}$
7.      $x_1 = 0.01$
8.      $x_2 = \Re_{real}^{[0,1]}$
9.      $x_3 = (1 - try / N_{Try})\Re_{real}^{[0,1]}$
10.     $x_4 = (1 - \sqrt{try / N_{Try}})\Re_{real}^{[0,1]}$
11.     For $docr$ = 1 to $N_{DOCR}$
12.         $TDS^t_{docr} \leftarrow X^t_{ABC}$
13.         $PS^t_{docr} \leftarrow X^t_{ABC}$
14.         For $s$ = 1 to 2
15.             For $r$ = 0 to 4
16.                 For $t$ = 1 to $Iter$
17.                     $V = (\Re_{Int}^{[1,2]} - 1).(-1)^s$
18.                     $\Delta x = x_r.(v.(1 - \sqrt{t / Iter}) + (1 - v).(1 - t / Iter))$
19.                     $TDS^t_{docr} = TDS^t_{docr} + \Delta x.\Delta TDS.\Re_{real}^{[0,1]}$
20.                     $PS^t_{docr} = PS^t_{docr} + \Delta x.\Delta PS$
21.                     $Cost^1 = MOF^{Type-n}([TDS^t_{docr}, PS^t_{docr}] \rightarrow X^t_{ABC})$
22.                     If $Cost^1 < Cost^0$
23.                         $Cost^0 = Cost^1$
24.                         $X^t_{ABC} \leftarrow ([TDS^t_{docr}, PS^t_{docr}] \rightarrow X^t_{ABC})$
25. Output: $X^t_{IABC} = X^t_{ABC}$
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In Algorithm-X, the number of '**For**' loops are 5, and the product of the upper limits (N_{Try} N_{DOCR} , 2 , 4, and $Iter$) of the '**For**' loops give rise to the Number of Function Evaluation (**NFE**). The NFE defines the number of times the objective function of any given optimization problem is evaluated during the solution search procedure. Therefore, the NFE of Algorithm-X can be calculated as in equation (14).

$$NFE_{Algorithm-1} = 8.N_{DOCR}.N_{Try}.Iter \quad (14)$$

The conventional ABC algorithm can be generalized as an optimization technique comprising of four major stages which includes: Initialization, Employee Bees, Onlooker Bees, and Scout Bees. A random candidate solution generated at the initialization stage is passed through the other three stages to perform a single generation of artificial bee optimization trial. Therefore, for N_{gen} optimization trials, each bee must have at least pass through $3N_{gen} + 1$ optimization stages. Let N_{Bees}, represents the number of artificial bees (population size) optimized in parallel. The number of parameters in a DOCR optimization problem is $2N_{DOCR}$. The proposed EABC is achieved by execution Algorithm-X after every (of the $3N_{gen} + 1$) stages in the ABC optimization. However, if the 0th generation exist, the $3N_{gen} + 1$ generation can be replaced by $3N_{gen}$. Therefore, the EABC can be achieved using the flowchart shown in Figure 1. The proposed EABC algorithm is designed to have a guaranteed rate of convergence, and as such, need only a few (at most 10) generations to converge. Furthermore, the total NFE in EABC is the product of $NFE_{Algorithm-1}$ and the total number of stages in EABC. This can be calculated using equation (15). The EABC is designed to have a minimum ($N_{gen} = 1$) number of function evaluation of $4.NFE_{Algorithm-1}$.

$$NFE_{IABC} = 8.N_{DOCR}.N_{Try}.Iter.(3N_{gen} + 1) \quad (15)$$

Another parameter of the DOCR settings optimization is the Number of Function Evaluation Before Convergence (NFEBC). This parameter is used to describe the algorithm performance based on its speed of convergence. The NFEBC is calculated by substituting the value of the generation (N_{gen}) at which an optimization converges to its optimum value.

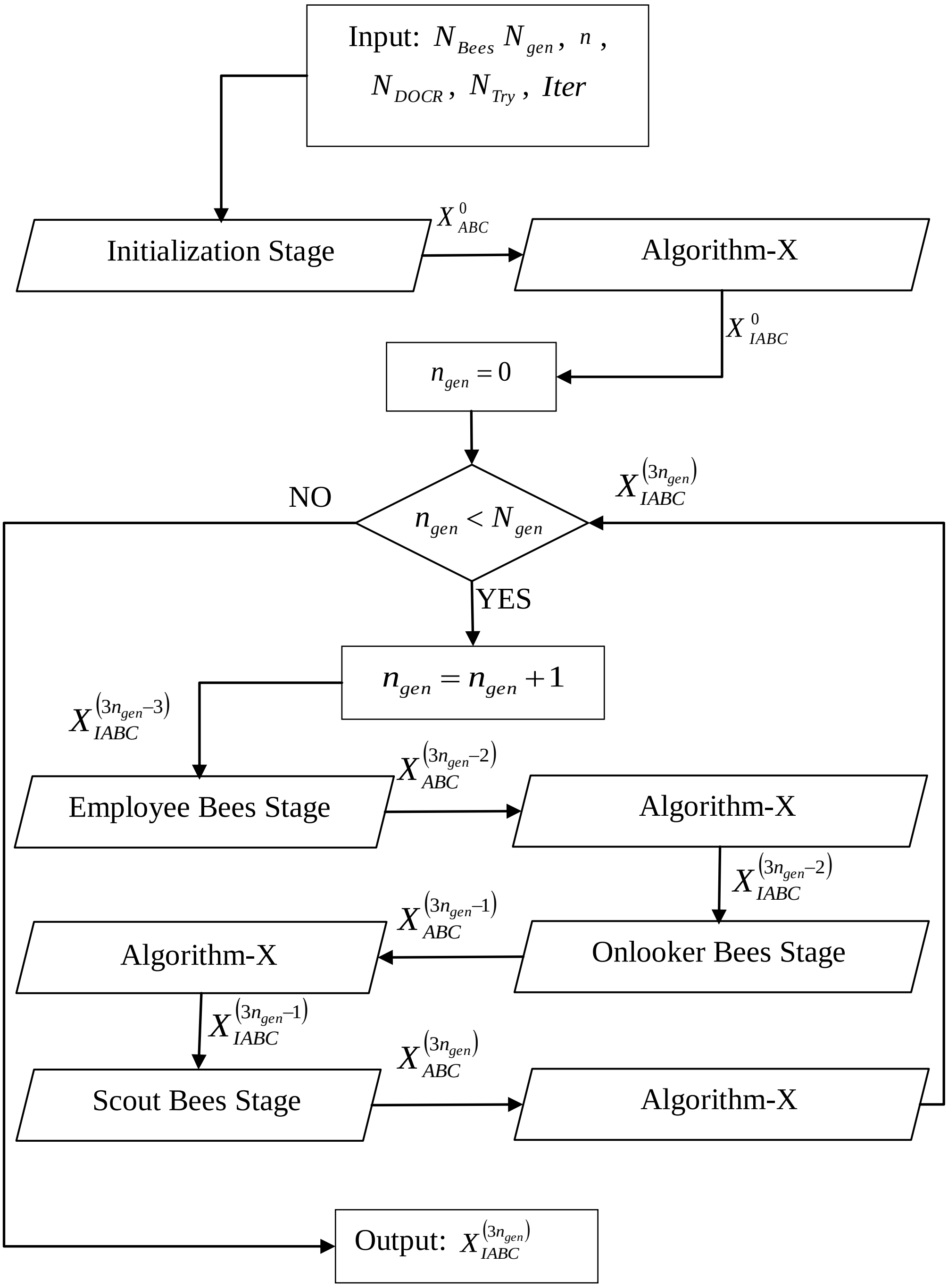

Figure 1: Flow Chart for the Proposed EABC Algorithm.

XI. CASE-STUDY/TEST SYSTEMS

In this work, four test system were employed to investigate and demonstrated the performance of the proposed EABC based DOCR settings optimization approach. These systems include: the IEEE 3, 4, 6, 8, 15, and 30-Bus meshed networks. These test systems give rise to a DOCR settings optimization problem of a network with 6, 8. 14, 14, 42, and 68 DOCRs respectively. The upper and lower bounds of the DOCR settings for various test systems are presented in Table 1. The minimum coordination time interval (CTI^{Min}) and the allowable incremental value of PS are also provided in column 6 and 7 of Table 1, for each of the test systems. Finally, the necessary data required to replicate all the simulations carried out in this work, are provided in Tables 2 to 7. The single-line network diagrams of the aforementioned IEEE test systems are also shown in Figures 2 to 5 respectively.

Table 1: DOCR Constraints Data for IEEE 3-Bus Test Systems[27].

IEEE-Bus	TDS^{min}	TDS^{max}	PS^{min} (A)	PS^{max} (A)	CTI^{Min} (Sec)	Change in PS /Step size (A)
3	0.1	1.1	1.5	5	0.2	0.5
4	0.05	1.1	1.25	1.5	0.3	0.0001
6	0.05	1.1	1.25	1.5	0.2	0.0001
8	0.1	1.1	0.5	2.5	0.3	0.5
15	0.1	1.1	0.5	2.5	0.2	0.5
30	0.1	1	1.5	5	0.3	0.5

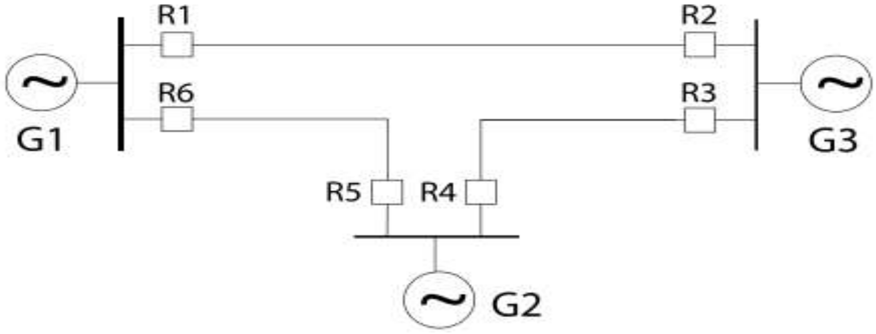

Figure 2. Single-line diagram of the IEEE 3-bus system [27]

Table 2: IEEE 3-Bus Primary/Back-up Short Circuit Currents (Isc)[25]

Relay		Normal Isc (A)		Transient Isc (A)		CTR
Primary	Back-Up	Primary	Back-Up	Primary	Back-Up	Primary
1	5	1979	175	2075	400.7	60
2	4	1526	545	1622	700.6	40
3	1	1684	617.2	1780	760.2	40
4	6	1815	466.2	1912	622.7	60
5	3	1500	384	1589	558.1	40
6	2	1766	145.3	1855	380.7	80

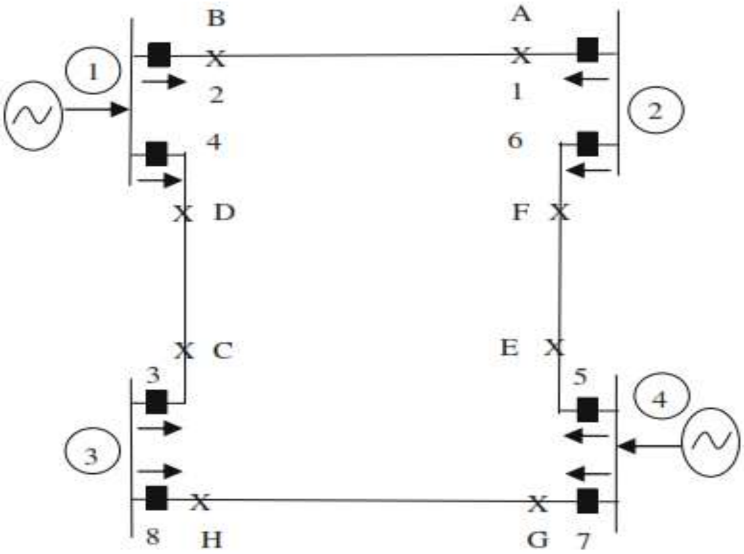

Figure 3. A typical IEEE 4-bus DOCR coordination problem model [26].

Table 3: IEEE 4-Bus Tripping Time Constant Data [26]

pri_cl_in			pri_far_bus		
Relay i	a	b	Relay j	a	b
1	20.32	0.48	2	23.75	0.48
2	88.85	0.48	1	12.48	0.48
3	13.61	1.179	4	31.92	1.179
4	116.8	1.179	3	10.38	1.179
5	116.7	1.526	6	12.07	1.526
6	16.67	1.526	5	31.92	1.526
7	71.7	1.202	8	11	1.202
8	19.27	1.202	7	18.91	1.202

Table 4: IEEE 4-Bus Primary/Backup Time Constant Data [26]

Back-up			Primary		
p	e	f	q	g	h
5	20.32	1.526	1	20.32	0.48
5	12.48	1.526	1	12.48	0.48
7	13.61	1.202	3	13.61	1.179
7	10.38	1.202	3	10.38	1.179
1	1.16	0.48	4	116.8	1.179
2	12.07	0.48	6	12.07	1.179
2	16.67	0.48	6	16.67	1.526
4	11	1.179	8	11	1.202
4	19.27	1.179	8	19.27	1.202

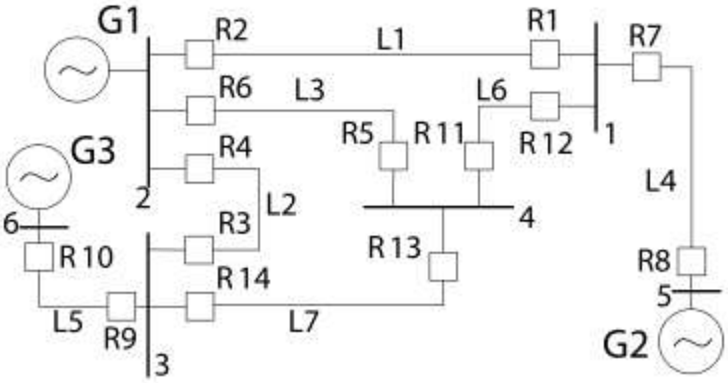

Figure 4. Single-line diagram of the IEEE 6-bus system [27].

Table 5: IEEE 6-Bus Tripping Time Constant Data [26]

pri_cl_in			pri_far_bus		
Relay i	a	b	Relay j	a	b
1	2.531	0.259	2	5.95	0.259
2	2.738	0.259	1	5.375	0.259
3	2.972	0.486	4	6.664	0.486
4	4.148	0.486	3	4.59	0.486
5	1.955	0.714	6	6.235	0.714
6	2.768	0.714	5	4.257	0.714
7	3.842	1.746	8	6.369	1.746
8	5.618	1.746	7	4.178	1.746
9	4.654	1.042	10	3.87	1.042
10	3.526	1.042	9	5.27	1.042
11	2.584	0.773	12	6.114	0.773
12	3.801	0.773	11	3.901	0.773
13	2.414	0.588	14	2.901	0.588
14	5.354	0.588	13	4.335	0.588

Table 6: IEEE 6-Bus Primary/Backup Time Constant Data[26]

Back-up			Primary			Back-up			Primary		
p	e	f	q	g	h	p	e	f	q	g	h
8	4.0909	1.746	1	5.375	0.259	13	1.832	0.588	9	5.2696	1.0424
11	1.2886	0.773	1	5.375	0.259	4	3.439	0.486	9	5.2696	1.0424
8	2.9323	1.746	1	2.531	0.259	13	1.618	0.588	9	4.6538	1.0424
3	0.6213	0.486	2	2.738	0.259	4	3.037	0.486	9	4.6538	1.0424
3	1.6658	0.486	2	5.95	0.259	14	2.087	0.588	11	3.9005	0.7729
10	0.0923	1.042	3	4.59	0.486	6	1.814	0.714	11	3.9005	0.7729
10	2.561	1.042	3	2.972	0.486	14	1.474	0.588	11	2.584	0.7729
13	1.4995	0.588	3	4.59	0.486	6	1.11	0.714	11	2.584	0.7729
1	0.8869	0.259	4	4.148	0.486	8	3.329	1.746	12	3.8006	0.7729
1	1.5243	0.259	4	6.664	0.486	2	0.473	0.259	12	3.8006	0.7729
12	2.5444	0.773	5	4.257	0.714	8	4.574	1.746	12	6.1144	0.7729
12	1.4549	0.773	5	1.955	0.714	2	1.543	0.259	12	6.1144	0.7729
14	1.7142	0.588	5	4.257	0.714	12	2.727	0.773	13	4.335	0.5879
3	1.4658	0.486	6	6.235	0.714	6	1.609	0.714	13	4.335	0.5879
3	1.1231	0.259	6	6.235	0.714	12	1.836	0.773	13	2.4143	0.5879
11	2.1436	0.773	7	4.178	1.746	10	2.026	1.042	14	2.9011	0.5879
2	2.0355	0.259	7	4.178	1.746	4	0.876	0.486	14	2.9011	0.5879
11	1.9712	0.773	7	3.842	1.746	10	2.778	1.042	14	5.3541	0.5879
2	1.8718	0.259	7	3.842	1.746	4	2.582	0.486	14	5.3541	0.5879

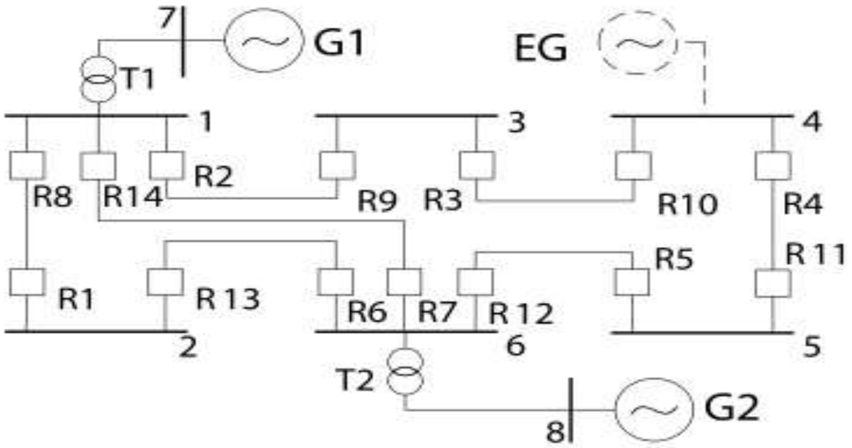

Figure 5. Single-line diagram of the IEEE 8-bus system [27].

Table 7: IEEE 8-Bus Primary/Back-up Short Circuit Currents (Isc) & Current Transformer Ratio (CTR) [25]

Relay		Normal Isc (A)		CTR	Relay		Normal Isc (A)		CTR
Primary	Back-Up	Primary	Back-Up	Primary	Primary	Back-Up	Primary	Back-Up	Primary
1	6	3232	3232	240	8	7	6093	1890	240
2	1	5924	996	240	8	9	6093	1165	240
2	7	5924	1890	240	9	10	2482	2484	160
3	2	3556	3556	160	10	11	3883	2344	240
4	3	3783	2244	240	11	12	3707	3707	240
5	4	2401	2401	240	12	13	5899	987	240
6	5	6109	1197	240	12	14	5899	1874	240
6	14	6109	1874	240	13	8	2991	2991	240
7	5	5223	1197	160	14	1	5199	996	160
7	13	5223	987	160	14	9	5199	1165	160

XII. SIMULATION SETUP

The entire simulation was carried out in MATLAB 2019-A Software environment on an 8GB, 2.7GHz, 5-cores based Laptop computer. All algorithms, codes and programming were achieved using the aforementioned simulation environment. Four simulation cases (Case 1 to 4) of DOCR settings optimization are performed in this work. The EABC optimization parameter settings and other relevant setups for the various cases are shown in Table 8. furthermore, the DOCR settings optimization problem data, the DOCR constraints data, and all other data required for the DOCR problem formulations in all the four scenarios (Case 1 to 4) are presented in chapter three (Tables 1 to 7). Finally, the test systems used in case 1 to 4 are the IEEE standard test networks, as such all the problem data are obtained from other similar literatures as indicated via the references provided in chapter three.

XIII. CASE 1

This simulation scenario is comprised of a DOCR settings optimization for the IEEE 3-bus network presented in Chapter 3. The simulation was carried out using the developed EABC optimization algorithm. The simulation parameter settings provided in Table 8, under Case 1 were using for optimization. The optimal TDS and PS for the 3-bus network were determined and presented in Table 9. The resulting operational time $(T_{i,j})$ and the coordination time interval (CTI) were also computed and presented in the same table. It was found that the entire constraints were satisfied and the EABC was able to minimize the objective function (OF) to 1.3818s. This can be verified by summing the entire operation time provided in column 4 of Table 9. The modified objective function (MOF) was found to have the same value as OF, due to the total constraints satisfaction. A comparative analysis of the simulation result was also presented as in Table 10. It can be observed that the developed EABC algorithm has the least OF and therefore, outperforms the existing algorithms.

XIV. CASE 2

This scenario consists of the IEEE 4-Bus DOCR settings optimization using the developed EABC algorithm. Similarly, the simulation parameter settings for this scenario are as presented in Table 8. Here, the EABC was able to optimize the OF to 3.6403s. Table 11 presents the resulting optimal DOCR settings and their corresponding operational and coordination time. In this scenario, the EABC algorithm was also able to satisfy all the DOCR operational constraints and ensures that the MOF and OF becomes equal. Other details of the obtained results can be easily observed from Table 10. Furthermore, the result is compared with the 6 Differential Evolution (DE) based methods presented in [26] as presented in Table 12. The developed EABC algorithm can be observed to outperform all the approaches presented in [26].

XV. CASE 3

So far, the DOCR settings optimization problems in Cases 1 and 2 can be considered as small DOCR optimization problems. This is because, less than 10 relays are involved with only 6 and 9 P/B relay pairs coordination constraints respectively. In small DOCR problems, the computational complexity is greatly reduced and as such, most improved/modified algorithms can be readily deployed for solution. However, as the number of relay increases, together with the number of P/B constraint, the computational complexity rapidly increases. This simulation case involves the IEEE 6-bus network having 14 DOCRs with 38 P/B relay pairs condition constraints. This may be considered as a medium DOCR optimization problem. Just like the aforementioned cases, the proposed EABC algorithm was able to predict optimal DOCR settings for the 6-bus network with higher performance that the existing algorithm. A total operational time (OF) of 10.0147s was obtained using the developed EABC algorithm. Detailed simulation results of this case are also presented in Table 13. A comparison of the results obtained with those of other literatures is also carried out based on OF minimization. This is presented in Table 14. This scenario further emphasizes the effectiveness of the proposed EABC based DOCR settings optimization.

XVI. CASE 4

This scenario involves a DOCR settings optimization of the IEEE 8-Bus network. The network data are as presented in chapter 3. This can also be considered as a medium DOCR optimization problem (with 14 DOCRs and 20 P/B pair constraints), even though it's of less complexity than that in case 3. The total operational time of the primary DOCRs (OF) was minimized to 8.2079s. Detailed results of this scenario are also presented in Table 15. The results of this scenario shows that the DOCRs have a district TDS setting, unlike those of case 3. The algorithm was not restricted by the boundary conditions of TDS. However, most of the PSs are the same (bounded by the upper limit of the PS constraints). This results in a slowly varying operational time that ranges between 0.407s and 0.796s. Table 16 also presents the comparison of the DOCR results for the 8-Bus network in which the proposed EABC algorithm still remains the most effective approach.

XVII. PERFORMANCE ANALYSIS OF EABC ALGORITHM

The integration of Algorithm-X into the conventional ABC algorithm to form the proposed EABC have greatly improved the performance of the resulting algorithm. The simulation scenarios presented so far has demonstrated the effectiveness of EABC over its counterparts. Table 17 presents a result summary of the simulation cases presented in this chapter, and the best objective function values reported in relevant literatures. Finally, the developed EABC algorithm has demonstrated a guaranteed convergence rate over a considerably low simulation time, as such, the proposed models can be readily deployed in real-time network protection scenarios

Table 8: The Optimization Parameter Settings & Scenario (Cases 1 to 7) Setups

Case No.	Number of IEEE Network Buses	N_{bees}	N_{gen}	n	N_{DOCR}	N_{Try}	$Iter$	Number (P/B) Relay Pair	Operational Time Equation
1	3	12	100	1	6	6	10	6	(3.1)
2	4	16	100	2	8	8	10	9	(3.8)
3	6	28	100	2	14	14	10	36	(3.8)
4	8	28	100	1	14	14	10	20	(3.1)
5	15	84	100	1	42	42	10	82	(3.1)
6	30	136	100	1	68	68	10	122	(3.1)

7	8	16	100	1	8	8	10	20	(3.2)

Table 9: DOCR Settings Optimization Results for IEEE 3-Bus Network (Case 1)

n_{docr}	DOCR Settings		$T_{i,j}$	P/B Relay Pair		
	TDS	PS		Primary	Backup	CTI
1	0.1004	2	0.244	1	5	0.403
2	0.1	1.5	0.209	2	4	0.2
3	0.1	2	0.223	3	1	0.2
4	0.107	1.5	0.242	4	6	0.267
5	0.1	1.5	0.211	5	3	0.229
6	0.1	1.5	0.253	6	2	0.531

Table 10: Comparison of the IEEE 3-Bus Result

	PSO [6]	SOA [25]	BBO-LP [28]	SA-LP [27]	**EABC**
OF(s)	1.926	1.599	1.5987	1.5987	**1.3818**

Table 11: DOCR Settings Optimization Results for IEEE 4-Bus Network (Case 2)

n_{docr}	DOCR Settings		$T_{i,j}$	P/B Relay Pair		
	TDS	PS		Primary	Backup	CTI
1	0.05	1.262	0.502	1	5	0.3
2	0.2099	1.499	0.403	1	5	0.394
3	0.05	1.25	0.506	3	7	0.3
4	0.1499	1.498	0.416	3	7	0.344
5	0.1248	1.498	0.4	4	1	0.3
6	0.05	1.25	0.481	6	2	0.344
7	0.1324	1.498	0.415	6	2	0.3
8	0.05	1.25	0.519	8	4	0.391
				8	4	0.3

Table 12: Comparison of the IEEE 4-Bus Result

	DE[26]	MDE1 [26]	MDE2 [26]	MDE3 [26]	MDE4 [26]	MDE5 [26]	EABC
OF(s)	3.677	3.6694	3.673	3.6692	3.6674	3.6694	3.6403

Table 13: DOCR Settings Optimization Results for IEEE 6-Bus Network (Case 3)

n	DOCR Settings		$T_{i,j}$	P/B Relay Pair			P/B Relay Pair			P/B Relay Pair		
	TDS	PS		Primary	Backup	CTI	Primary	Backup	CTI	Primary	Backup	CTI
1	0.0982	1.499	0.818	1	8	0.299	6	3	0.33729	12	2	6.12904
2	0.1841	1.499	0.901	1	11	3.983	7	11	0.2	12	8	0.26467
3	0.0925	1.276	0.712	1	8	0.822	7	2	0.22854	12	2	0.71466
4	0.0991	1.482	0.707	2	3	411.3	7	11	0.22545	13	12	0.2
5	0.05	1.25	0.627	2	3	0.2	7	2	0.2	13	6	0.48011
6	0.05	1.35	0.55	3	10	0.2	9	13	0.2	13	12	0.4077

		8	1									2
7	0.05	1.25	0.939	3	10	0.2	9	4	0.2	14	10	0.59968
8	0.05	1.25	0.902	3	13	0.268	9	13	0.24722	14	4	3.15228
9	0.05	1.25	0.619	4	1	0.434	9	4	0.20391	14	10	0.26032
10	0.05	1.371	0.631	4	1	0.2	11	14	0.2	14	4	0.27373
11	0.0641	1.5	0.76	5	12	0.212	11	6	0.2	-	-	-
12	0.05	1.475	0.653	5	12	0.99	11	14	0.37824	-	-	-
13	0.05	1.408	0.724	5	14	0.501	11	6	2.03157	-	-	-
14	0.069	1.499	0.471	6	3	0.562	12	8	0.53851	-	-	-

Table 14: Comparison of the IEEE 6-Bus Result

	GA [29]	BIP [30]	MDE5 [26]	OCDE2 [31]	ADE [32]	SA-LP [27]	**EABC**
OF(s)	10.73	10.538	10.35	10.3286	10.2664	10.1512	10.0147

Table 15: DOCR Settings Optimization Results for IEEE 8-Bus Network (Case 4)

n_{docr}	DOCR Settings		$T_{i,j}$	P/B Pair		CTI	P/B Pair		CTI
	TDS	PS		Primary	Backup	CTI	Primary	Backup	CTI
1	0.1103	2.0000	0.3972	1	6	0.3000	11	12	0.3000
2	0.2542	2.5000	0.7594	2	1	0.3000	12	13	0.3000
3	0.2208	2.5000	0.6920	2	7	0.3000	12	14	0.3000
4	0.1583	2.5000	0.5908	3	2	0.3000	13	8	0.3000
5	0.1000	2.5000	0.4978	4	3	0.3000	14	1	0.4172
6	0.1682	2.5000	0.4957	5	4	0.3000	14	9	0.3000
7	0.2365	2.5000	0.6279	6	5	0.5109	-	-	-
8	0.1641	2.5000	0.4842	6	14	0.5661	-	-	-
9	0.1425	2.5000	0.5366	7	5	0.3787	-	-	-
10	0.1702	2.5000	0.6261	7	13	0.4335	-	-	-
11	0.1808	2.5000	0.6824	8	7	0.5655	-	-	-
12	0.2577	2.5000	0.7713	8	9	0.4390	-	-	-
13	0.1101	2.0000	0.4136	9	10	0.3000	-	-	-
14	0.2379	2.5000	0.6328	10	11	0.3000	-	-	-

Table 16: Comparison of the IEEE 8-Bus Result

	MPSO [6]	GA [33]	GA-LP [33]	BBO-LP [28]	BIP [30]	SOA [25]	SA-LP [27]	EABC
OF(s)	17.33	11.001	10.949	8.7556	8.6944	8.4271	8.4271	8.2024

Table 17: Result Summary of the Simulation Scenarios and Comparison

Case No.	Number of IEEE Network Buses	N_{DOCR}	CPU Time (s)	NFEBC	OF (s) EABC	Best OF in Literature
1	3	6	0.0357	28800	1.3818	1.5987s SA-LP [27]
2	4	8	0.0635	51200	3.6403	3.6694sMDE5 [26]
3	6	14	0.3946	456800	10.0147	10.1512sSA-LP [27]
4	8	14	0.0685	156800	8.2079	8.4271sSA-LP [27]
5	15	42	0.5432	987840	12.1868	12.1868sSA-LP [27]
6	30	68	0.9899	1479680	20.3894	22.3936s SA-LP [27]

XVIII. CONCLUSION

Directional over-current relay (DOCR) coordination, is a frequently arising problem in the field of electrical engineering, which can be formulated as an optimization problem. The mathematical model of the problem is highly complex and non- linear in nature, subject to various constraints, and requires sophisticated optimization techniques for its solution. In general, this work has presented a concise overview on the existing works on the coordination of DOCR, its fundamentals, its problem mathematical formulation strategy, and solution strategies presented in relevant literatures.

At first, a DOCR setting optimization problem was formulated using two types of objective function (Type-1 and 2), and a modified objective function, which considers four sets of constraints as mathematical functions that must be minimized to zero during optimization.

Secondly, a new DOCR operational time characteristic equation, which considers both load voltage and current ratios as additional parameters to those in the conventional equation was proposed to demonstrate flexibility in DOCR optimization problem formulation.

Thirdly, an Improved Artificial Bee Colony (EABC) optimization algorithm is formed by logically integrating a novel optimizer (Algorithm-X) with the conventional artificial bee colony (ABC) optimization technique. This resulted in a highly efficient and reliable optimization technique that can be rapidly deployed for DOCR settings optimization under any kind of condition.

Fourthly, DOCR settings optimization problem data for 6 test network systems, comprising of the IEEE 3-Bus, 4-Bus, 6-Bus, 8-Bus, 15-Bus, and 30-Bus networks were obtained and presented.

Fifthly, the performance of the developed EABC based DOCR settings optimization algorithm is demonstrated, by simulating four cases (Case 1 to 4) of DOCR setting optimization problem solution using the 6 test systems.

Finally, extensive simulation of DOCR setting optimization (case 7) based on the new DOCR operational time equation is carried out to investigate the variability of the solution convergence with changes in either the load current (M_I) or voltage ratio (M_V). The proposed EABC based DOCR setting optimization strategy have been found to demonstrate superiority over the existing algorithms and therefore can serve as a reliable approach for real-time DOCR coordination.

IXX. SIGNIFICANT CONTRIBUTION TO KNOWLEDGE

Some of the significant contribution this work to the existing body of knowledge are as follows:

- An Enhanced Artificial Bee Colony (EABC) optimization algorithm have been developed by logically integrating a newly developed optimizer with the conventional ABC algorithm, to form a highly efficient and reliable DOCR setting optimization algorithm with guaranteed rate of convergence.
- A variety of DOCR settings optimization simulation scenarios (case 1 to 4) have been carried out using the IEEE 3-Bus, 4-Bus, 6-Bus, 8-Bus, 15-Bus, and 30-Bus networks, in order to investigate and demonstrate the effectiveness of the developed models and algorithms by comparing the obtained results with the available best in literature, and the proposed EABC based approach have shown

to outperform the existing algorithms in literature so far.

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