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The Plant Propagation Algorithm for the Optimal Operation of Directional Over-Current Relays in Electrical Engineering

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ABSTRACT

In modern and large scale power distribution topologies, directional relays play an important role in the operation of an electrical system. These relays must be coordinated optimally so that their overall operating time is reduced to a minimum. They are sensor protection devices for the power systems and must be coordinated properly. The present work uses a metaheuristic optimization technique known as the Plant Propagation Algorithm (PPA) in order to suggest improved solutions for the optimization problem of coordination of directional overcurrent relays (DOCRs). We have obtained comparatively better solutions for the overall operating times taken by relays fitted on important positions in the system. Our findings are useful in isolating the faulty lines efficiently and in keeping the continuity of power supply. The difference in response times taken in coordination between primary relays and corresponding backup relays is minimized. The output of our experiments is compared with various algorithms and classical optimization techniques, which are found in the literature. Moreover, graphical analyses are presented for each problem to further clarify the results.

KEYWORDS: **Nature-Inspired Algorithms, Constraint Optimization, Sensors, Engineering Optimization Problems, Directional over-current relays, Plant Propagation Algorithm.**

1. INTRODUCTION

Power systems consist of different transmission systems [1], which are interconnected to other sub-transmission systems. Ideal protection for such transmission systems can be achieved by placing sensing devices like DOCRs in appropriate positions. Furthermore, these devices must be good in terms of cost and technicality. The function of DOCRs is to separate the faulty lines in the event of any fault in the system. They serve as logical units and they trip the line if a fault occurs in the neighborhood of relays fitted on both ends of the line. The coordination of these devices is always a challenging optimization problem

for engineers and scientists. These problems are about to determine the specific relays to be operated for a fault in that location. This selection of a set of relays is based on the topology of the network, characteristic of relays and protection procedures.

The problem of DOCRs involves two types of decision variables: one for Plug Setting (PS) and the other for Time Dial Setting (TDS). By finding

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suitable values for these variables, one can guarantee the efficient and proper coordination of the DOCRs to maintain power supply through healthy lines and avoid disruption.

The classical approach to solve the optimal coordination of DOCRs is the hit and trails approach [2]. The main drawback of classical approaches was slow convergence and hence an increased number of iterations to reach the best solution. In the beginning, Urdeneta *et al.* [3] implemented the optimization theory to solve this problem. They modeled the situation as a non-linear, non-convex objective function subject to several design constraints. They suggested a technique to consider the dynamic variations in the network's structure for the coordination of DOCRs using linear programming. A linear programming interior point algorithm is proposed for the solution of the problem of coordinating directional overcurrent relays in interconnected power systems considering definite time backup relaying [2, 3].

Yazdaninejadi *et al.* [4] presented a non-linear programming approach that is tackled based on genetic algorithm (GA) to solve the problem of minimizing the overall operating time of primary and backup relays. Moreover, many researchers have suggested optimization techniques to get a better solution of DOCRs problem, like, real coded genetic algorithm [5], Teaching Learning-Based Optimization (TLBO) algorithm [6], a multiple embedded crossover PSO (Particle Swarm Optimization) [7], opposition based chaotic differential evolution algorithm [8], interior point method [9], PSO-TVAC (Time Variant Acceleration Coefficients) based on Series Compensation [10], modified electromagnetic field optimization algorithm [11], Hybridised SA-SOS (Simulated Annealing based Symbiotic Organism Search) algorithm [12] and improved firefly algorithm [13].

In this paper, we have successfully implemented PPA [14-24], for the solution of standard IEEE (3, 4, and 6 bus) test systems. The two types of decision variables were PS and TDS and the sum of operating times taken by all main relays which were needed to operate for clarity of fault(s) in their respective sections. They were estimated along with the minimization objective function bounded by several constraints. These constraints were further classified as selectivity constraints and bounds on each term of the objectives.

The rest of this paper is organized such that, Section 2 contains the problem complexity and our suggested optimization technique, Section 3 presents the problem formulation and a detailed description of three case studies (IEEE 3, 4 and 6 bus models) of DOCRs problem. Section 4 reviews the basic Plant Propagation Algorithm. In Section 5, results and discussion are given. Subsequently, Section 6 concludes this paper by summarizing the achievements and future challenges of this study.

1. PROBLEM COMPLEXITY AND SUGGESTED ALGORITHM

The coordination of relays is a highly non-linear and complex optimization problem subject to various constraints, with the objective to minimize the overall operating time of each primary relay. The optimal relay coordination of DOCRs leads to a multimodal/ non-convex constrained optimization problem with complex search space. The problem gets more difficult to solve, due to nonlinearity, as the number of relays increases [12, 13, 25, 26].

PPA is chosen to solve the above-mentioned problem of DOCRs. PPA was earlier implemented to design engineering problems such as gearshift problem, spring design problem and welded beam problem [14-24]. These problems are related to design engineering and the results obtained by PPA were good as compared to other state-of-the-art. So efforts were made to check further efficiency of PPA in solving the problem of DOCRs.

2. PROBLEM FORMULATION

The time taken by a relay, denoted by T, is a non-linear function of the variables PS and TDS. The mathematical formulation of operating time is given in equation (1)

$$T = \frac{(a).(TDS)}{(1/(PS(CT_{pri\_rating}))^{b} - c} \qquad (1)$$

In this equation, PS and TDS are unknown decision variables. a, b and c are based on the experiments and are predefined values for the behavior of the system. These values are fixed as 0.14, 0.02 and 1 respectively. The current transformer CT and the number of turns it has, defines the value of CT_{pri_rating}. To bear the current, CT performs the role of reducing the level of the current for relays involved. Each relay is associated with each CT and thus CT_{pri_rating} is a known value in the problem. The fault current I is continuously read by the measuring tools and it is a system-dependent value and is pre-assigned to it.

The number of constraints on the system is according to the number of lines involved in the system. These details are given in Table 4 for the problems considered in this paper. Real power systems may be made up of bigger sizes involving several types of DOCRs [2-13].

3.1 Objective Function

The objective involved in the problem of coordination of DOCRs, by implementing a suitable optimization technique, involves the minimization of total operating times subject to constraints on the decision variables. Those relays which are first to be operated are called primary relays. The fault, which is closed to a relay, is called *pri_close* fault while a fault away from the relay on the other side of the line is called pri_far fault. Thus, the objective function is a sum of operating times taken by all primary relays involved whether the time is taken to clear a pri_close fault or pri_far fault. Mathematically, the objective function is presented in equation (2).

$$\min \sum_{i=1}^{N_1} T^i(TDS^i, PS^i)_{pri\_close} + \sum_{j=1}^{N_2} T^j(TDS^j, PS^j)_{pri\_far} \quad (2)$$

where

$$T^i(TDS^i, PS^i)_{pri\_close} = \frac{0.14 \times TDS^i}{\left(\frac{\alpha^i}{PS^i \times \beta^i}\right)^{0.02} - 1} \quad (3)$$

$$T^j(TDS^j, PS^j)_{pri\_far} = \frac{0.14 \times TDS^j}{\left(\frac{\eta^j}{PS^j \times \xi^j}\right)^{0.02} - 1} \quad (4)$$

where

N_1 = total number of relays involved in clearing *pri_close* fault,

N_2 = total number of relays involved in clearing *pri_far* fault,

$T(TDS, PS)_{pri\_close}$ = total time taken by primary relays to *pri_close* fault,

$T(TDS, PS)_{pri\_close}$ = total time taken by primary relays to *pri_far* fault, where α^i, β^i, η^i and ξ^i are the constants given in Tables (5-6) and [3].

3.2 Constraints

1. Limits on decision variables TDSs:
   $0.05 \le PS^i \le 1.1$, where *i* ranges from 1 to N^{cl}.
2. Limits on decision variables PSs:
   $1.25 \le PS^i \le 1.5$, where i ranges from 1 to N^{cl}.
3. Limit on primary operation times:
   $0.05 \le T^i(TDS^i, PS^i)_{pri\_close} \le 1.0$
   $0.05 \le T^j(TDS^j, PS^j)_{pri\_far} \le 1.0$
4. Pair of relays and the selection constraints:

$$T^{primary}(TDS^i, PS^i) - T^{backup}(TDS^i, PS^i) + CTI \le 0 \quad (5)$$

where

$$T_i^{primary}(TDS^i, PS^i) = \frac{0.14 \times TDS^u}{\left(\frac{\mu^i}{PS^u \times \upsilon^i}\right)^{0.02} - 1} \quad (6)$$

$$T_i^{backup}(TDS^i, PS^i) = \frac{0.14 \times TDS^\nu}{\left(\frac{\phi^i}{PS^\nu \times \psi^i}\right)^{0.02} - 1} \quad (7)$$

$T^{primary}$ is operating time of primary relay and T^{backup} is operating time of backup relay and CTI is coordinating time interval.

3.3 Problem-1: The IEEE 3 Bus Model

For the coordination problem of the IEEE 3-bus model, the value of each of N_1 and N_2 is six (equal to the number of relays or twice the lines). Accordingly, there are 12 decision variables (two for each relay) in this problem i.e. TDS^1 to TDS^6 and PS^1 to PS^6. The value of CTI for Problem-1 is 0.3. Figure 1 shows the 3-bus model.

Mathematical form of the objective function for a 3-bus model is as follows:

$$\min \sum_{i=1}^{6} T^i(TDS^i, PS^i)_{pri\_close} + \sum_{j=1}^{6} T^j(TDS^j, PS^j)_{pri\_far} \quad (8)$$

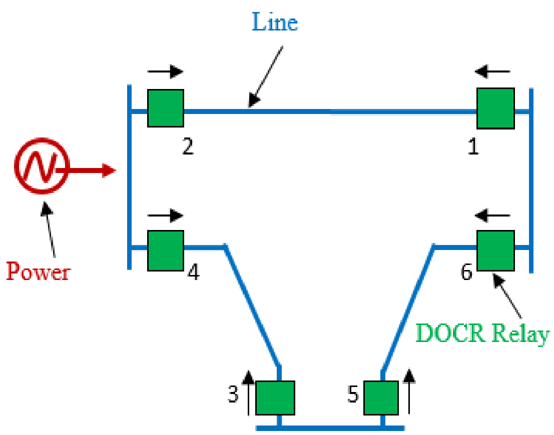

Fig.1: IEEE 3-BUS MODEL

3.4 Problem-2: The IEEE 4 Bus Model:

In the optimal coordination of 4-bus model, values of both type of variables N_1 and N_2 is taken as 8, which is double of total lines involved or same as the number of relays installed in the system. This model is illustrated in Fig.2. Furthermore, this problem is of 16 dimensions and thus involves 16 design variables. As discussed earlier, these two types of variables are named as TDS^1- TDS^8 and PS^1- PS^8. CTI=0.3 for Problem-2.

The mathematical form for a 4-bus model is as follows.

$$\min \sum_{i=1}^{8} T^i(TDS^i, PS^i)_{pri\_close} + \sum_{j=1}^{8} T^j(TDS^j, PS^j)_{pri\_far} \quad (9)$$

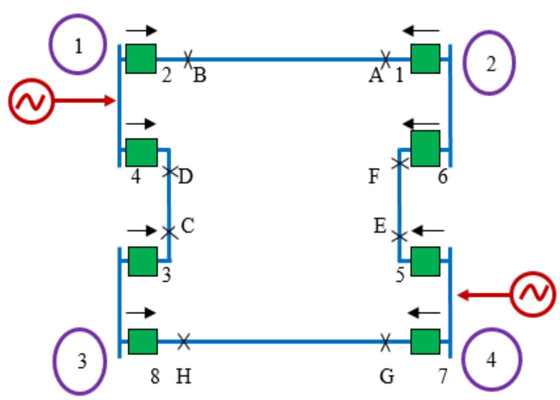

Fig. 2: IEEE 4-Bus Model

3.5 Problem-3: The IEEE 6 Bus Model:

In the optimal coordination of 6-bus model, values of both type of variables N_1 and N_2 is taken as 14, which is double of total lines involved or same as the number of relays installed in the system. This model is illustrated in Fig.3. Furthermore, this problem is of 28 dimensions and thus involves 28 design variables. As discussed earlier, these two types of variables are named as TDS^1- TDS^{14} and PS^1- PS^{14}. CTI=0.2 for Problem-3 6-bus model. For normal operation of a 6-bus model, a total of 48 selection constraints are imposed on the relays in case of detecting near-end/ far-end faults in the transmission lines. Moreover, ten constraints are relaxed based on the observations on [3].

$$\min \sum_{i=1}^{14} T^i(TDS^i, PS^i)_{pri\_close} + \sum_{j=1}^{8} T^j(TDS^j, PS^j)_{pri\_far} \quad (10)$$

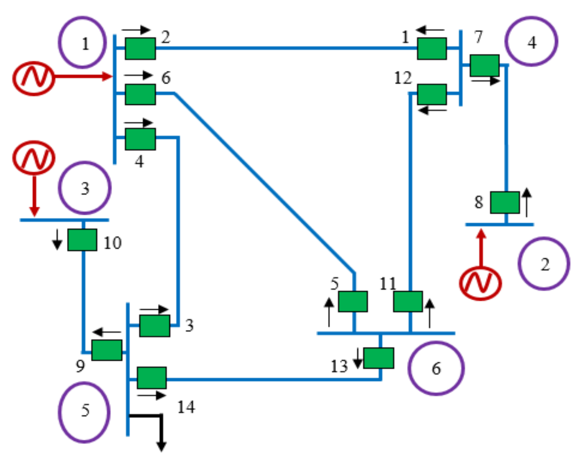

Fig. 3: PROBLEM-3 6-BUS MODEL.

3. THE PLANT PROPAGATION ALGORITHM (PPA)

PPA is a Nature-inspired metaheuristic which simulates the way strawberry plants propagate to occupy the space in which they happen to grow. It is a population/ multi-solutions based technique. Unlike the single solution-based techniques like Simulated

Annealing (SA), it is initialized from a randomly generated population of solutions generated from a normal distribution. Two aspects of a metaheuristic, exploration, and exploitation [14-24], are very important to be balanced.

Exploitation means to visit the neighborhood of a current solution very well. On the other hand, exploration is to introduce diversity in the population with solutions generated from approximately all over the domain space.

A mother plant P_k is in position X_k in n dimensional space i.e. $X_k = [x_{1k}, x_{2k} \cdots, x_{nk}]$. Let N_{pop} denotes the number of candidate plants in the initial population. PPA is furnished in detail as in Algorithm1.

Require: objective $f(X)$, $X \in R^n$
Generate a population
$P = \{p_i, i = 1, \ldots, m\}$
$g \leftarrow 1$
for $g \leftarrow 1$ to gmax do
compute $N_{pop} = f(pi)$, $\forall$ pi $\in$ P
sort P in descending order of N
create new population $\emptyset$
for each p_i, $i = 1, \ldots, m$ do {best m only}
$r_i \leftarrow$ set of runners where both the size of the set and the distance for each runner (individually) is proportional to the fitness N_i
$\emptyset \leftarrow \emptyset \cup r_i$ {append to population; death occurs by omission above}
end for
$P \leftarrow \emptyset$ {new population}
end for
return P, the population of solutions.

ALGORITHM 1: PSEUDOCODE OF PLANT PROPAGATION ALGORITHM [26].

Two main steps followed by the strawberry algorithm are:

i) Plants in a position with enough food will send out many short runners.
ii) Those plants, which are situated in a position with poor conditions, will send few long runners.

It is obvious, that exploitation is implemented by using the idea of short runners while exploration of search space is done by sending a few long runners within the search space.

The main parameters involved in PPA are the size of population N_{pop}, maximum allowed generations g_{max} and maximum number of runners generated by a single plant $n_{\max}$. The last condition of maximum runners by a plant is used as stopping criteria. The objective values are defined by the positions of plants X_k, $k = \{1, \ldots, N_{pop}\}$. The original version of PPA is denoted by a normalized function N_i. The normalization function is used as fitness criteria. The number of plants is calculated as in equation (11). The length of a runner based on the normalized function is calculated as in equation (12). After all parent plants in the population have generated their allocated runners, new child plants are evaluated and the population is sorted in ascending/ descending according to their fitness value. In this way, the poor plants with lower growth are truncated from the population. The number of runners allocated to a given parent solution is proportional to its fitness as in equation (11),

$$n^i_\alpha = n_{max} \times N^i_\alpha, \ \alpha \in (0,1) \tag{11}$$

Every solution X_i generates at least one runner and the length/perturbation added to each such runner is inversely proportional to its growth as in equation (12),

$$dx^i_j = 2(1 - N_i)(\alpha - 0.5), \quad \text{for } j = 1, \ldots, n, \tag{12}$$

where n is the problem dimension. Having calculated dx_i, the extent to which the runner will reach, the search equation (13) that finds the next neighborhood to explore is

$$y_{i,j} = x_{i,j} + (b_j - a_j)\, dx^i_j, \text{ for } j = 1, \ldots, n. \tag{13}$$

In case, the values of variables are falling outside the search domain, then those values are adjusted within the given interval $[a_i, b_j]$ where the ends of this interval are defining the lower and upper bounds of a jth variable in the position vector X_k.

4. RESULTS AND DISCUSSION

The 3-bus model has one generator 3 transmission lines and six DOCRs on these lines. A diagram showing this whole model of 3-bus and a complete setup of 12 design variables (TDS^1-TDS^6 and PS^1-PS^6) is depicted in Fig. 1. The 4-bus model has two generators, four lines and eight DOCRs fixed on these lines. A diagram showing this whole model of 4-bus and complete setup of 16 design variables (TDS^1-TDS^8 and PS^1-PS^8) is depicted in Fig. 2. The 6-bus model has three generators, seven lines, and fourteen DOCRs fixed on these lines. A diagram showing this whole model of 6-bus and a complete setup of 28 design variables (TDS^1-TDS^{14} and PS^1-PS^{14}) is depicted in Fig. 3. The best solutions found in literature, as in Tables (1-3), by standard algorithms are presented along with the best values obtained by PPA, are compared with Differential Evolution (DE), Modified Differential Evolution-1 (MDE-1), Modified Differential Evolution-2 (MDE-2), Modified Differential Evolution-3 (MDE-3), Modified Differential Evolution-4 (MDE-4) and Modified Differential Evolution-5 (MDE-5) [8]. It is obvious that all the techniques have produced either similar or approximately the same objective values. On the other hand, PPA solved the problem feasibly and gave better minimized objective values as in Figures 4-9. It is interesting to note that with increasing the complexity, PPA produced better results as compared to the 3-bus and 4-bus cases.

TABLE 1: BEST DECISION VARIABLES, OBJECTIVE VALUES, AND NUMBER OF FUNCTION EVALUATION OF PROBLEM-1 3-BUS MODEL BY PPA

Variables	PPA	MDE-1	MDE-2	MDE-3	MDE-4	MDE-5	DE
TDS^1	00.050	00.0500	00.050	00.050	00.050	00.050	00.050
TDS^2	00.2984	00.2178	00.1979	00.1988	00.1976	00.1976	00.2194
TDS^3	00.050	00.0500	00.050	00.050	00.050	00.050	00.0500
TDS^4	00.1679	00.2090	00.2094	00.2090	00.2090	00.2090	00.2135
TDS^5	00.1525	00.1812	00.1847	00.1812	00.1812	00.1812	00.1949
TDS^6	00.1549	00.1807	00.1827	00.1807	00.1806	00.1806	00.19530
PS^1	01.2500	01.2500	01.250	01.250	01.250	01.2500	01.2500
PS^2	01.500	01.2500	01.4999	01.4849	01.4999	01.5000	01.2500
PS^3	01.2500	01.2500	01.250	01.250	01.250	01.250	01.2500
PS^4	01.500	01.4999	01.4999	01.4999	01.4999	01.500	01.4605
PS^5	01.500	01.500	01.4318	01.4998	01.4999	01.500	01.2500
PS^6	01.2500	01.4999	01.4619	01.4999	01.4999	01.500	01.2500
O.F.V	4.7802	4.8070	4.7873	4.7822	4.7806	4.7806	4.8422
N.F.E	3250	72350	73350	97550	69270	38250	78360

5. CONCLUSIONS

Optimization problems occurring in various engineering fields often have a complex mathematical model, which requires efficient algorithms to obtain a reasonably good solution (if not the global best solution). In the present paper, we have chosen three test problems in electrical engineering. Specifically, coordination of directional over-current relays, IEEE (3, 4 and 6 bus) models are solved with a metaheuristic known as the Plant Propagation algorithm (PPA). The problem of DOCRs is highly non-linear with several constraint variables. The results obtained are compared with other state-of-the-art algorithms. The quoted results are presented along with the results of PPA. It is obvious that PPA outperformed the other techniques and can be potentially applied to higher bus problems in the future. The results are compared with six algorithms DE, MDE-1, MDE-2, MDE-3, MDE-4 and MDE-5 available in the literature. It is observed with the help of numerical results and graphical solutions that the Plant Propagation Algorithm (PPA) is quite efficient for solving the complex optimization models that arise in Electrical Engineering problems. Moreover, PPA is gaining momentum, as the problem was getting worse in terms of dimensions and complexity. In the future, we are intending to implement PPA for higher bus models.

TABLE 2: BEST DESIGN VARIABLES, OBJECTIVE VALUES, AND NUMBER OF FUNCTION EVALUATION OF 4-BUS PROBLEM BY PPA.

Variables	PPA	MDE-1	MDE-2	MDE-3	MDE-4	MDE-5	DE
TDS^1	00.050	00.05000	00.05000	00.05000	00.0500	00.05000	00.05000
TDS^2	0.2142	00.21210	00.21230	00.21210	0.21210	00.21210	00.22480
TDS^3	00.050	00.05000	00.05000	00.05000	00.0500	00.05000	00.05000
TDS^4	0.1514	00.15150	00.15150	00.15150	00.1515	00.15150	00.15150
TDS^5	0.1251	00.12640	00.12640	00.12640	00.1262	00.12620	00.12640
TDS^6	00.050	00.05000	00.05000	00.05000	00.0500	00.05000	00.05000
TDS^7	0.1330	00.13380	00.13710	00.13380	00.13370	00.13370	00.13370
TDS^8	00.050	00.05000	00.05000	00.05000	00.05000	00.05000	00.05000
PS^1	1.2801	01.27330	01.27330	01.27330	01.25000	01.25000	01.27340
PS^2	1.4127	01.49980	01.49590	01.50000	01.50000	01.5000	01.25000
PS^3	1.2505	01.25000	01.25000	01.25000	01.25000	01.25000	01.25000
PS^4	1.4962	01.49960	01.49970	01.49950	01.50000	01.5000	01.49970
PS^5	01.500	01.50000	01.50000	01.49970	01.50000	01.5000	01.49970
PS^6	1.2506	01.25000	01.25000	01.25000	01.25000	01.25000	01.25000
PS^7	01.500	01.49970	01.42740	01.49950	01.49980	01.49980	01.50000
PS^8	01.250	01.25000	01.25000	01.25000	01.25000	01.25000	01.25000
O.F.V	3.6549	3.6694	3.6734	3.6692	3.6674	3.6696	3.6774
N.F.E	35330	43400	67200	99700	55100	35330	95400

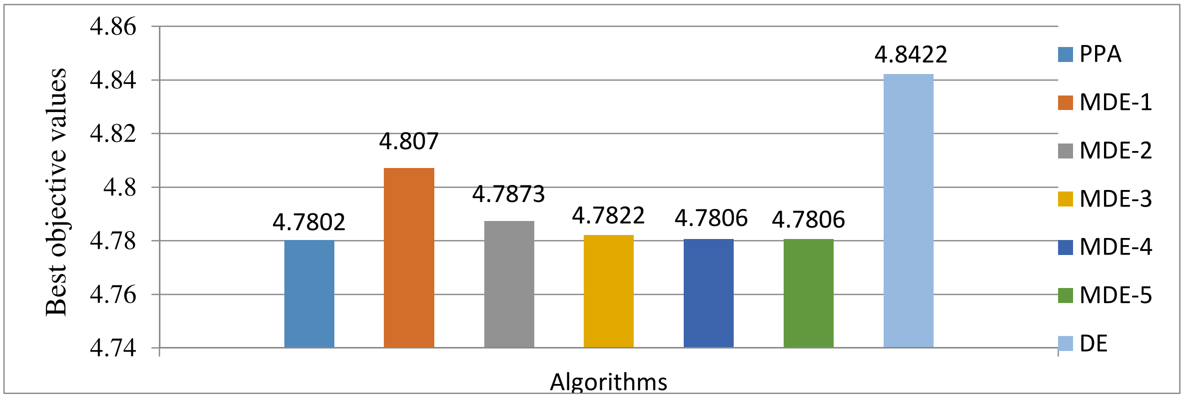

FIG. 4: BEST OBJECTIVE VALUES OBTAINED BY PPA ARE COMPARED WITH DE AND ITS VARIANTS IN SOLVING THE 3-BUS PROBLEM OF DOCRS.

TABLE 3: BEST DECISION VARIABLES, OBJECTIVES VALUES, AND NUMBER OF FUNCTION EVALUATION OF PROBLEM 3 6-BUS PROBLEM BY PPA.

Variables	PPA	MDE-1	MDE-2	MDE-3	MDE-4	MDE-5	DE
TDS^1	00.1164	00.11710	00.11490	00.10340	00.11440	00.10240	00.1173
TDS^2	00.1691	00.18660	00.20370	00.18630	00.18640	00.18630	00.2082
TDS^3	00.0581	00.09650	00.09820	00.09610	00.09470	00.09460	00.0997
TDS^4	00.1136	00.11190	00.10360	00.11250	00.10060	00.10670	00.1125
TDS^5	00.0500	00.05000	00.05000	00.05000	00.05000	00.05000	00.0500
TDS^6	00.0500	00.05000	00.05000	00.05000	00.05000	00.05000	00.0580
TDS^7	00.0500	00.05000	00.05000	00.05000	00.05000	00.05000	00.050
TDS^8	00.0505	00.05000	00.05000	00.05000	00.05000	00.05000	00.050
TDS^9	00.0500	00.05000	00.05000	00.05000	00.05000	00.05000	00.050
TDS^{10}	00.0500	00.07060	00.05750	00.07030	00.07010	00.05630	00.0719
TDS^{11}	00.0656	00.06490	00.06670	00.06490	00.06490	00.06500	00.0649
TDS^{12}	00.0522	00.06170	00.05660	00.05090	00.05090	00.05530	00.0617
TDS^{13}	00.0573	00.05000	00.06350	00.05000	00.05000	00.05000	00.0500
TDS^{14}	00.0824	00.08600	00.08590	00.08570	00.07090	00.07090	00.0856
PS^1	01.3032	01.25150	01.26350	01.49950	01.26020	01.49910	01.2505
PS^2	01.4973	01.49590	01.29930	01.49990	01.49870	01.49990	01.2500
PS^3	01.2776	01.25250	01.26220	01.25750	01.27610	01.27710	01.2512
PS^4	01.2617	01.26320	01.43220	01.25080	01.49920	01.36500	01.2515
PS^5	01.2500	01.25000	01.25000	01.25000	01.25000	01.25000	01.2500

PS^6	**01.3554**	**01.38220**	**01.38850**	**01.38100**	**01.38140**	**01.38180**	**01.2500**
PS^7	**01.2501**	**01.25000**	**01.25080**	**01.25000**	**01.25000**	**01.25000**	**01.2500**
PS^8	**01.2833**	**01.25010**	**01.25000**	**01.25000**	**01.25050**	**01.25000**	**01.2500**
PS^9	**01.2517**	**01.25000**	**01.25140**	**01.25000**	**01.25000**	**01.25000**	**01.2502**
PS^{10}	**01.5000**	**01.25010**	**01.49700**	**01.25210**	**01.25000**	**01.49960**	**01.2502**
PS^{11}	**01.5000**	**01.49990**	**01.47590**	**01.49980**	**01.49990**	**01.49980**	**01.4998**
PS^{12}	**01.4821**	**01.25290**	**01.47000**	**01.49970**	**01.50000**	**01.39310**	**01.2575**
PS^{13}	**01.2500**	**01.46640**	**01.27280**	**01.46470**	**01.46150**	**01.46130**	**01.4805**
PS^{14}	**1.3036**	**01.25000**	**01.26240**	**01.25400**	**01.49790**	**01.49740**	**01.2557**
O.F.E	**9.9912**	**10.5067**	**10.6238**	**10.4370**	**10.3812**	**10.3514**	**10.6272**
N.F.E	**18180**	**72960**	**18180**	**101580**	**100860**	**106200**	**212190**

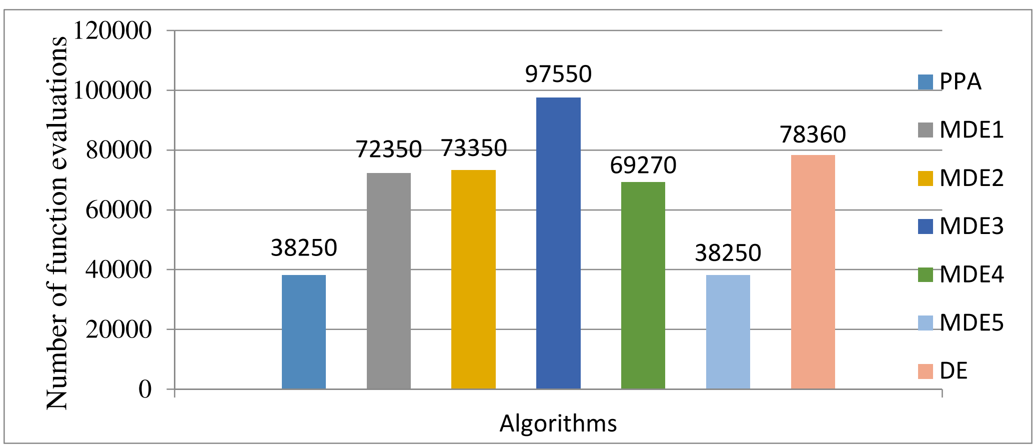

FIG. 5: NUMBER OF TOTAL FUNCTION EVALUATIONS TAKEN BY PPA, DE AND ITS VARIANTS IN SOLVING THE 3-BUS PROBLEM OF DOCRS.

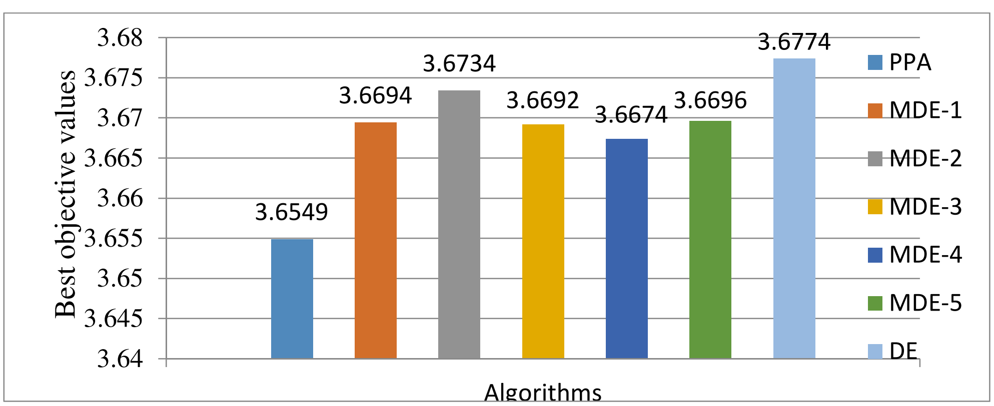

FIG. 6: BEST OBJECTIVE VALUES OBTAINED BY PPA ARE COMPARED DE AND ITS VARIANTS IN SOLVING THE 4-BUS PROBLEM OF DOCRS.

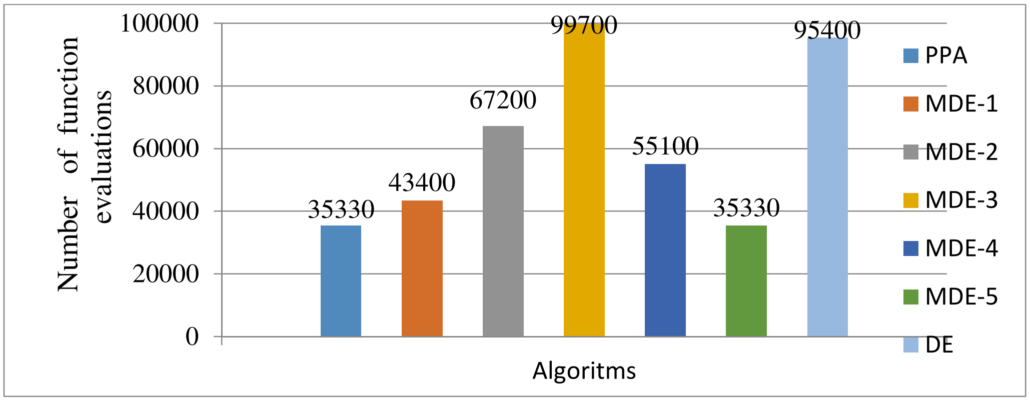

FIG. 7: NUMBER OF TOTAL FUNCTION EVALUATIONS TAKEN BY PPA, DE AND ITS VARIANTS IN SOLVING THE 4-BUS PROBLEM OF DOCRS.

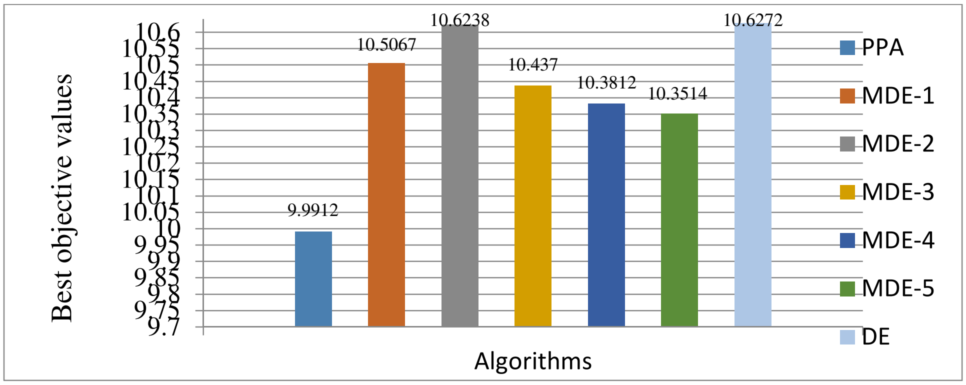

FIG. 8: BEST OBJECTIVE VALUES OBTAINED BY PPA ARE COMPARED WITH DE AND ITS VARIANTS IN SOLVING THE 6-BUS PROBLEM OF DOCRS.

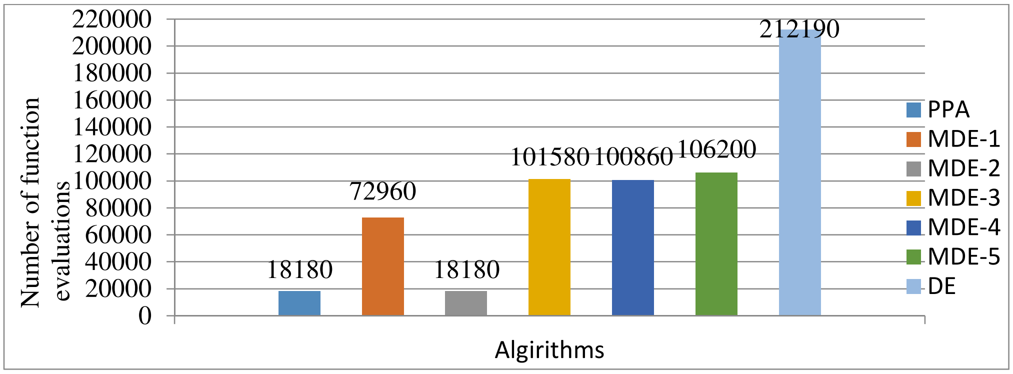

FIG.9: NUMBER OF TOTAL FUNCTION EVALUATIONS TAKEN BY PPA, DE AND ITS VARIANTS IN SOLVING THE 6-BUS PROBLEM OF DOCRS.

CONFLICT OF INTEREST

The authors declare that none of them have any competing interests in the manuscript.

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NOMENCLATURE

a, b, c	Constants according to IEEE standard
CT	Current Transformer
$CT_{pri-rating}$	Primary rating of current transformer
CTI	Coordination time interval.
DE	Differential Evolution
DOCR	Directional over-current relays
MDE	Modified Differential Evolution
NFE	Number of function evaluations
OFV	Objective function value
PS	Plug settings
T^{backup}	Operating time of backup relay
T_{pri_close}	The relay operation time to clear near end fault
T_{pri_far}	The relay operation time in case of far end fault
$T^{primary}$	Operating time of primary relay
TDS	Time dial settings
NFE	Number of function evaluation

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APPENDICES

TABLE 4: PARAMETER SETTINGS OF THREE CASE STUDIES IN DOCRs PROBLEMS.

Items	**IEEE 3-bus**	**IEEE 4-bus**	**IEEE 6-bus**
No. of Lines	3	4	7
No. of DOCRs	6	8	14
No. of Decision Variables	12	16	28
No. of Selectivity Constraints	8	9	38
No. of Restricted Constraints	24	32	104

Table 5: VALUES FOR CURRENT TRANSFORMER AND CURRENT.

T_{pri_close}		$T^{i}_{pri\_far}$			
TDS^{i}	I^{i}_{k}	$CT^{i}_{pri\_rating}$	TDS^{j}	I^{j}_{k}	$CT^{j}_{pri\_rating}$
TDS^{1}	9.46	2.06	TDS^{2}	100.63	2.06
TDS^{2}	26.91	2.06	TDS^{1}	14.08	2.06
TDS^{3}	8.81	2.23	TDS^{4}	136.23	2.23
TDS^{4}	37.68	2.23	TDS^{3}	12.07	2.23
TDS^{5}	17.93	0.8	TDS^{6}	19.2	0.8
TDS^{6}	14.35	0.8	TDS^{7}	25.9	0.8

TABLE 6: CURRENT TRANSFORMER RATING AND DIFFERENT TIME SETTINGS OF BACKUP AND PRIMARY RELAYS.

T^{i}_{backup}			$T^{i}_{primary}$		
m	I^{i}_{k}	$CT^{i}_{pri\_rating}$	n	I^{j}_{k}	$CT^{j}_{pri\_rating}$
5	14.08	0.8	1	14.08	2.06
6	12.07	0.8	3	12.07	2.23
4	25.9	2.23	5	25.9	0.8
2	14.35	0.8	6	14.35	2.06
5	9.46	0.8	1	9.46	2.06
6	8.81	0.8	3	8.81	2.23
2	19.2	2.06	6	19.2	0.8
4	17.93	2.23	5	17.93	0.8