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

Muhammad Sulaiman\textsuperscript{1a}, Muhammad Sulaman\textsuperscript{1b}, Abdelwahed Hamdi\textsuperscript{2}, Zubair Hussain\textsuperscript{1c}

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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

\textsuperscript{1} Department of Mathematics, Abdul Wali Khan University Mardan, KPK, Pakistan
Email: \textsuperscript{a}sulaiman513@yahoo.co.uk, (Corresponding author), \textsuperscript{b}khsulaman@gmail.com, \textsuperscript{c}zubair.bsmaths@gmail.com
\textsuperscript{2} Department of Mathematics, Statistics & Physics, Qatar University, Qatar.
Email: abhamdi@qu.edu.qa

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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 trials 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)

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

(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 performs the role of reducing the level of the current for relays involved. The fault current $I$ is 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).

$$\text{min} \sum_{i=1}^{N} T_i(TDS^i, PS^i)_{pri\_close} + \sum_{j=1}^{N2} T_j(TDS^j, PS^j)_{pri\_far}$$  \hspace{1cm} (2)

where

$$T_i(TDS^i, PS^i)_{pri\_close} = \frac{0.14 \times TDS^i}{\left(\frac{\mu^i}{PS^i \times \nu^i}\right)^{0.02}} - 1$$  \hspace{1cm} (3)

$$T_j(TDS^j, PS^j)_{pri\_far} = \frac{0.14 \times TDS^j}{\left(\frac{\phi^j}{PS^j \times \psi^j}\right)^{0.02}} - 1$$  \hspace{1cm} (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,

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

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

where $\alpha^i, \beta^i, \eta^i$ and $\xi^i$ are the constants given in Tables (5-6) and [3].

### 3.2 Constraints

1. Limits on decision variables TDSs:
   $$0.05 \leq PS^i \leq 1.1, \text{ where } i \text{ ranges from 1 to } N_i.$$
2. Limits on decision variables PSs:
   $$1.25 \leq PS^i \leq 1.5, \text{ where } i \text{ ranges from 1 to } N_i.$$
3. Limit on primary operation times:
   $$0.05 \leq T_i(TDS^i, PS^i)_{pri\_close} \leq 1.0$$
   $$0.05 \leq T_i(TDS^i, PS^i)_{pri\_far} \leq 1.0$$
4. Pair of relays and the selection constraints:
   $$T_{pri\_close} + CTI \leq 0$$

where

$T_{pri\_close}$ 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. $TDS^i$ 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:

$$\text{min} \sum_{i=1}^{6} T_i(TDS^i, PS^i)_{pri\_close} + \sum_{j=1}^{6} T_j(TDS^j, PS^j)_{pri\_far}$$  \hspace{1cm} (8)
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.

\[
\text{min} \sum_{i=1}^{8} T_i(TDS_i, PS_i)_{pri, close} + \sum_{j=1}^{9} T_j(TDS_j, PS_j)_{pri, far}
\]

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].

\[
\text{min} \sum_{i=1}^{14} T_i(TDS_i, PS_i)_{pri, close} + \sum_{j=1}^{10} T_j(TDS_j, PS_j)_{pri, far}
\]

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
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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. $X_k = [x_{1k}, x_{2k}, \ldots, x_{nk}]$. Let $N_{\text{pop}}$ 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 $g_{\text{max}}$ do
compute $N_{\text{pop}} = f(p_i), \forall p_i \in P$
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 $N_{\text{pop}}$, maximum allowed generations $g_{\text{max}}$ and maximum number of runners generated by a single plant $n_{\text{max}}$. The last condition of maximum runners by a plant is used as stopping criteria. The objective values are defined by the positions of plants $X_k, k = \{1, \ldots, N_{\text{pop}}\}$. 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),

$$n_i^a = n_{\text{max}} \times N_i^a, \alpha \in (0,1)$$

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),

$$dx_{ij}^t = 2(1 – N_i) (\alpha – 0.5), \text{ for } j = 1, \ldots, n,$$

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

$$y_{ij} = x_{ij} + (b_j – a_j) \times dx_{ij}, \text{ for } j = 1, \ldots, n.$$
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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   |
|-----------|------|-------|-------|-------|-------|-------|------|
| $TDS^1$   | 0.0050 | 0.0050 | 0.0050 | 0.0050 | 0.0050 | 0.0050 | 0.0050 |
| $TDS^2$   | 0.2984 | 0.2178 | 0.1979 | 0.1988 | 0.1976 | 0.1976 | 0.2194 |
| $TDS^3$   | 0.0050 | 0.0050 | 0.0050 | 0.0050 | 0.0050 | 0.0050 | 0.0050 |
| $TDS^4$   | 0.1679 | 0.2090 | 0.2094 | 0.2090 | 0.2090 | 0.2090 | 0.2135 |
| $TDS^5$   | 0.1525 | 0.1812 | 0.1847 | 0.1812 | 0.1812 | 0.1812 | 0.1949 |
| $TDS^6$   | 0.1549 | 0.1807 | 0.1827 | 0.1807 | 0.1806 | 0.1806 | 0.1953 |
| $PS^1$    | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 0.2500 |
| $PS^2$    | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| $PS^3$    | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 0.2500 |
| $PS^4$    | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| $PS^5$    | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 0.2500 |
| $PS^6$    | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| 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.

| Variables | PPA | MDE-1 | MDE-2 | MDE-3 | MDE-4 | MDE-5 | DE |
|-----------|-----|-------|-------|-------|-------|-------|----|
| TDS¹      | 0.050 | 0.05000 | 0.05000 | 0.05000 | 0.05000 | 0.05000 | 0.05000 |
| TDS²      | 0.2142 | 0.21210 | 0.21230 | 0.21210 | 0.21210 | 0.21210 | 0.22480 |
| TDS³      | 0.050 | 0.05000 | 0.05000 | 0.05000 | 0.05000 | 0.05000 | 0.05000 |
| TDS⁴      | 0.1514 | 0.15150 | 0.15150 | 0.15150 | 0.15150 | 0.15150 | 0.15150 |
| TDS⁵      | 0.1251 | 0.12640 | 0.12640 | 0.12620 | 0.12620 | 0.12620 | 0.12640 |
| TDS⁶      | 0.050 | 0.05000 | 0.05000 | 0.05000 | 0.05000 | 0.05000 | 0.05000 |
| TDS⁷      | 0.1330 | 0.13380 | 0.13710 | 0.13380 | 0.13370 | 0.13370 | 0.13370 |
| TDS⁸      | 0.050 | 0.05000 | 0.05000 | 0.05000 | 0.05000 | 0.05000 | 0.05000 |
| PS¹       | 1.2801 | 0.12730 | 0.12730 | 0.12730 | 0.12500 | 0.12500 | 0.127340 |
| PS²       | 1.4127 | 0.49980 | 0.49590 | 0.50000 | 0.50000 | 0.50000 | 0.50000 |
| PS³       | 1.2505 | 0.25000 | 0.25000 | 0.25000 | 0.25000 | 0.25000 | 0.25000 |
| PS⁴       | 1.4962 | 0.49960 | 0.49970 | 0.49950 | 0.50000 | 0.50000 | 0.49970 |
| PS⁵       | 0.1500 | 0.50000 | 0.49970 | 0.50000 | 0.50000 | 0.50000 | 0.49970 |
| PS⁶       | 1.2506 | 0.25000 | 0.25000 | 0.25000 | 0.25000 | 0.25000 | 0.25000 |
| PS⁷       | 0.1500 | 0.49970 | 0.42740 | 0.49950 | 0.49980 | 0.49980 | 0.50000 |
| PS⁸       | 0.1500 | 0.49970 | 0.12500 | 0.25000 | 0.25000 | 0.25000 | 0.25000 |
| 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 |
|-----------|-----|-------|-------|-------|-------|-------|----|
| TDS1      | 00.1164 | 00.11710 | 00.11490 | 00.10340 | 00.11440 | 00.10240 | 00.1173 |
| TDS2      | 00.1691 | 00.18660 | 00.20370 | 00.18630 | 00.18640 | 00.18630 | 00.2082 |
| TDS3      | 00.0581 | 00.09650 | 00.09820 | 00.09610 | 00.09470 | 00.09460 | 00.0997 |
| TDS4      | 00.1136 | 00.11190 | 00.10360 | 00.11250 | 00.10600 | 00.10670 | 00.1125 |
| TDS5      | 00.0500 | 00.05000 | 00.05000 | 00.05000 | 00.05000 | 00.05000 | 00.0500 |
| TDS6      | 00.0500 | 00.05000 | 00.05000 | 00.05000 | 00.05000 | 00.05000 | 00.0580 |
| TDS7      | 00.0500 | 00.05000 | 00.05000 | 00.05000 | 00.05000 | 00.05000 | 00.0500 |
| TDS8      | 00.0505 | 00.05000 | 00.05000 | 00.05000 | 00.05000 | 00.05000 | 00.0500 |
| TDS9      | 00.0500 | 00.05000 | 00.05000 | 00.05000 | 00.05000 | 00.05000 | 00.0500 |
| TDS10     | 00.0500 | 00.07060 | 00.05750 | 00.07030 | 00.07010 | 00.05630 | 00.0719 |
| TDS11     | 00.0656 | 00.06490 | 00.06670 | 00.06490 | 00.06490 | 00.06500 | 00.0649 |
| TDS12     | 00.0522 | 00.06170 | 00.05660 | 00.05090 | 00.05090 | 00.05530 | 00.0617 |
| TDS13     | 00.0573 | 00.05000 | 00.06350 | 00.05000 | 00.05000 | 00.05000 | 00.0500 |
| TDS14     | 00.0824 | 00.08600 | 00.08590 | 00.08570 | 00.07090 | 00.07090 | 00.0856 |
| PS1       | 01.3032 | 01.25150 | 01.26350 | 01.49950 | 01.26020 | 01.49910 | 01.2505 |
| PS2       | 01.4973 | 01.49590 | 01.29930 | 01.49990 | 01.49870 | 01.49990 | 01.2500 |
| PS3       | 01.2776 | 01.25250 | 01.26220 | 01.25750 | 01.27610 | 01.27710 | 01.2512 |
| PS4       | 01.2617 | 01.26320 | 01.43220 | 01.25080 | 01.49920 | 01.36500 | 01.2515 |
| PS5       | 01.2500 | 01.25000 | 01.25000 | 01.25000 | 01.25000 | 01.25000 | 01.2500 |

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### Table 1

| Algorithm | 01.3554 | 01.38220 | 01.38850 | 01.38100 | 01.38180 | 01.2500 |
|-----------|---------|-----------|-----------|-----------|-----------|---------|
| PS6       |         |           |           |           |           |         |
| PS7       | 01.2501 | 01.2500   | 01.25080  | 01.2500   | 01.2500   | 01.2500 |
| PS8       | 01.2833 | 01.25010  | 01.2500   | 01.2500   | 01.25050  | 01.2500 |
| PS9       | 01.2517 | 01.2500   | 01.25140  | 01.2500   | 01.2500   | 01.2502 |
| PS10      | 01.5000 | 01.25010  | 01.49700  | 01.25210  | 01.2500   | 01.49960 |
| PS11      | 01.5000 | 01.49990  | 01.47590  | 01.49980  | 01.49990  | 01.4998 |
| PS12      | 01.4821 | 01.25290  | 01.4700   | 01.49970  | 01.5000   | 01.39310 |
| PS13      | 01.2500 | 01.46640  | 01.27280  | 01.46470  | 01.46150  | 01.46130 |
| PS14      | 1.3036  | 01.25000  | 0.126240  | 01.25400  | 01.49790  | 0.149740 |
| O.F.E     | 9.9912  | 10.5067   | 10.6238   | 10.4370   | 10.3812   | 10.3514  |
| N.F.E     | 18180   | 72960     | 18180     | 101580    | 100860    | 106200   |

### Figures

**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.
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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

| Symbol | Description |
|--------|-------------|
| 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.

| $T_{pri,close}$ | $T_{pri,far}$ | $T_{pri}$ | $I^i_k$ | $CT_{pri, rating}$ |
|-----------------|---------------|-----------|---------|--------------------|
| $TDS^1$         | 9.46          | 2.06      | 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.

| $T_{backup}^l$ | $I_k^l$ | $CT_{pri, rating}^l$ | $T_{primary}^l$ | $I_k^l$ | $CT_{pri, rating}^l$ |
|----------------|--------|----------------------|----------------|--------|----------------------|
| m  |        |                      | n  |        |                      |
| 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                  |