Optimal Coordination of Directional Overcurrent Relays using Hybrid PSO-DE Algorithm

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Abstract — This paper presents a new approach for the optimal coordination of IDMT directional overcurrent relays in meshed power systems using a hybrid particle swarm optimization based differential evolution algorithm (PSO-DE). In protection coordination problem the total operating time of all main relays is minimized. Constraints of the problem are: backup relay should operate if primary relay fails to respond the fault near to it, Time Dial Setting (TDS) and Plug Setting (PS) and minimum operating time of relay. The operating time of IDMT directional overcurrent relays holds non-linear relationship with TDS and PS. The proposed hybrid optimization algorithm is to minimize total operation time for each protection relay. Two case studies are modeled and simulated to check the efficiency of the optimization algorithms such as IEEE 4-bus and IEEE 6-bus. The results are compared with the results obtained through other optimization algorithms. From the comparative results, it is found that the PSO-DE approach provides the most globally optimum solution at a faster convergence speed.

Index Terms — Meshed Power Systems, Directional Overcurrent Protection, Optimal Coordination, Particle Swarm Optimization, Differential Evolution Algorithm, Hybrid Optimization Algorithms.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Operation time</td>
</tr>
<tr>
<td>I_F</td>
<td>Fault current</td>
</tr>
<tr>
<td>TDS</td>
<td>Time Dial Setting</td>
</tr>
<tr>
<td>PS</td>
<td>Plug Setting</td>
</tr>
<tr>
<td>CT</td>
<td>Current transformer</td>
</tr>
<tr>
<td>CT_pr</td>
<td>Primary rating of CT</td>
</tr>
<tr>
<td>I_r</td>
<td>Current seen by the relay</td>
</tr>
<tr>
<td>OF</td>
<td>Objective function</td>
</tr>
<tr>
<td>TDS_min</td>
<td>Minimum value for TDS</td>
</tr>
<tr>
<td>TDS_max</td>
<td>Maximum value for TDS</td>
</tr>
<tr>
<td>T_min</td>
<td>Minimum value for operation time</td>
</tr>
<tr>
<td>T_max</td>
<td>Maximum value for operation time</td>
</tr>
<tr>
<td>CTI</td>
<td>Coordination time interval</td>
</tr>
</tbody>
</table>

I. INTRODUCTION

With the development of industrial power systems, the stability and security are getting more prominent. The main function of a protective system is to detect and remove the faulted parts as fast and selectively as possible. Various relays with different operating principles in the protective system can be used to detect system abnormalities and execute appropriate commands to isolate swiftly only the faulty components from the healthy system. Each protection relay needs to be coordinated with the relays protecting the adjacent equipment. One task of the power system protection is to keep relays operating in the right way and coordinating well with each other.

So the problem of coordinating protective relays is finding suitable relay settings such that their fundamental protective functions are met under the requirements of sensitivity, selectivity, reliability, and speed. Directional overcurrent relay is a good technical and economic choice for protection of transmission and distribution power systems [1]. Such a relay with inverse time characteristics consists of an instantaneous unit and a time overcurrent unit. The overcurrent unit has two parameters to be defined, the PS and the TDS. The use of computer in power system relay coordination application has relieved protection engineers from huge mathematical calculation. Conventionally classical protection philosophy and parameter optimization techniques are reported in literature for application of relay coordination studies. In conventional classical protection approach the looped transmission and distribution system are treated as radial for relay coordination studies.

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Relays at remote end are set first and thereafter corresponding backup relays are set from coordination protection point view. In this way all possible paths are taken into account for optimal setting of relay parameters. The coordination of overcurrent relays requires the selection of optimal settings values. Out of both, only the values of TDS can be optimized while solving the coordination problem with the help of optimization algorithms. In protection coordination problem the total operating time of all main relays is minimized. Constraints of the problem are: secondary relay should operate if main relay fails to respond the fault near to it, TDS and PS and minimum operating time of relay. The operating time of overcurrent relays hold non-linear relationship with TDS and PS.

In recent years, many research efforts have been made to achieve optimum protection coordination (optimum solution for relay settings and coordination) using different optimization algorithms including, Evolutionary Algorithms (EA) is presented in [2] while Differential Evolution Algorithm (DEA) in [3], Modified Differential Evolution Algorithm (MDEA) in [4], and Self-Adaptive Differential Evolutionary (SADE) algorithm in [5]. Application of Particle Swarm Optimization (PSO) is introduced in [6], Modified Particle Swarm Optimizer in [7, 8], Evolutionary Particle Swarm Optimization (EPSO) Algorithm in [9], Box-Muller Harmony Search (BMHS) in [10], Zero-one Integer Programming (ZOIP) Approach in [11], Covariance Matrix Adaptation Evolution Strategy (CMA-ES) in [12], Seeker Algorithm (SA) in [13], Teaching Learning-Based Optimization (TLBO) in [14], Chaotic Differential Evolution Algorithm (CDEA) in [15], Artificial Bee Colony algorithm (ABC) in [16], Firefly Optimization Algorithm (FOA) in [17, 18], Modified Swarm Firefly Algorithm (MSEA) in [19], and Biogeography Based Optimization (BBO) is presented in [20]. Applying hybrid optimization algorithms for this problem: Evolutionary Algorithm based on Tabu Search (EA-TS) is presented in [21], Evolutionary Algorithm based on Linear Programming (DE-LP) in [22], Nelder-Mead and Particle Swarm Optimization (NM-PSO) in [23], Linear Programming and Genetic Algorithms (LP-GA) in [24], Particle Swarm Optimization and Linear Programming (PSO-LP) in [25], and Genetic Algorithm and Particle Swarm Optimization algorithm (GA-PSO) is presented in [26].

This research paper studies optimal values for relay setting and presents the solution of the coordination problem between primary and backup relay. Hybrid optimization algorithm namely PSO-DE has been developed in this research. Moreover, the improvement in minimizing total operation time (T) for each protection relays for two case studies are modeled and simulated to check the efficiency of the algorithm such as IEEE 4-bus and IEEE 6-bus.

II. OPTIMAL RELAY COORDINATION RELAY

Operating time of the IDMT relay is conversely proportional with current. Hence, overcurrent relay will operate fast after sensing the high current. However, this kind of relay is categorized such as standard inverse, very inverse and extremely inverse types. The relay operation time is inversely proportional to the fault current. The characteristics of relay depend on the type of standard selected for the relay operation; these standards can be ANSI, IEEE, IEC or user defined.

Typically there are overcurrent relays for protection against inter phase faults and phase to earth faults on the line. The tripping time of the relay follows a time over current delayed curve, in which the time delay depends upon current. Two decision variables of the relay are TDS and PS. The operating time of the relay is closely related to TDS, PS and the fault current (Iₖ). The total operating time is given by a non-linear mathematic equation [3], [11]-[26] with respect to the coordination time constraint between the backup and primary relays:

\[ T = \frac{\alpha \times TDS}{PS \times CT_{pr\text{-rating}}} - \gamma \]

Where, \( \alpha, \beta \) and \( \gamma \) are the constants values. The constant values are given as 0.14, 0.02 and 1.0 respectively according to IEEE standard [27]. In equation (1), \( I_{pr} \) is the fault current at CT primary terminal where fault occurs. \( CT_{pr\text{-rating}} \) is the primary rating of the relay. The total operating time is given by the relay i.e. \( I_{rel} \).

\[ I_{rel} = \frac{I_{pr}}{CT_{pr\text{-rating}}} \] (2)

However, the ratio of \( I_{rel} \) and PS indicates the level of nonlinearity in the equation.

2.1. Objective Function

A close-in fault (or near end fault) is known for a fault that occurring close to the relay and a far-bus fault (or far end fault) is known for a fault that occurring at the other end of the line. These definitions are demonstrated in Figure 1.

![Fig. 1. Diagram showing close-in and far-bus faults for relay R_{pr-Near.}](image-url)
In coordination studies, the operating time summation of all the primary relays to clear near end fault or far end fault can be considered as an objective function [14], [15]. It can be clearly claimed that the objective function in coordination studies should be minimized. Therefore, the objective function (OF) can be expressed as given by [4], [14], [15]:

\[
\text{Minimize } OF = \sum_{i=1}^{N_{i,j}} T_{\text{pri-cl-in}}^i + \sum_{j=1}^{N_{k}} T_{\text{pri-far-bus}}^j
\]

(3)

Where,

\[
T_{\text{pri-cl-in}}^i = \frac{0.14 \times TDS_i^i}{I_F \left(PS_i \times CT_{\text{pri-ratio}}^i\right)^0.02} - 1
\]

(4)

\[
T_{\text{pri-far-bus}}^j = \frac{0.14 \times TDS_j^j}{I_F \left(PS_j \times CT_{\text{pri-ratio}}^j\right)^0.02} - 1
\]

(5)

2.2. Constraints

Three constraints need to be considered for the coordination problem as follows: TDS of the relay is the time delay before relay operation whenever the fault current becomes equal to, or greater than PS setting [12-14].

\[
TDS_{\text{min}} \leq TDS_i^i \leq TDS_{\text{max}}
\]

(6)

Where, \(i\) is varying from 1 to \(N_{i,j}\); \(TDS_{\text{min}}^i\) and \(TDS_{\text{max}}^i\) are minimum and maximum values for \(TDS\) that are 0.05 and 1.10 respectively.

\[
PS_{\text{min}}^i \leq PS_i^i \leq PS_{\text{max}}^i
\]

(7)

Where, \(i\) is varying from 1 to \(N_{i,j}\); \(PS_{\text{min}}^i\) and \(PS_{\text{max}}^i\) are minimum and maximum values of PS which are 1.25 and 1.50 respectively. Relay operating time is related to the fault current which can be seen by the relay and the pickup current setting. Relay operating time is based on the type of the relay and can be determined by standard characteristic curves of the relay or analytical formula. Operating time is defined by:

\[
T_{\text{min}}^i \leq T_i^i \leq T_{\text{max}}^i
\]

(8)

Where, \(T_{\text{min}}^i\) and \(T_{\text{max}}^i\) are minimum and maximum values for operation time that are 0.05 and 1.00 respectively. The coordination time interval between the primary and the backup relays must be verified during optimization procedure. In this paper, the chronometric coordination between the primary and the backup relays is used as in equation (9):

\[
T_{\text{backup}} - T_{\text{primary}} \geq CTI
\]

(9)

Where, \(T_{\text{backup}}\) and \(T_{\text{primary}}\) are the operating time of the backup relay and the primary relay respectively; \(CTI\) is the minimum coordination time interval.

For the electromechanical relays, the \(CTI\) is varied between 0.30 to 0.40 sec, while for the numerical relays it’s varied between 0.10 to 0.20 sec [13, 14]. In this research, the value of \(CTI\) is chosen as 0.30 sec for all case studies. The value of \(T_{\text{backup}}\) and \(T_{\text{primary}}\) can be determined by equations (10) and (11) respectively.

\[
T_{\text{backup}}^i = \frac{0.14 \times TDS^i}{I_F \left(PS_i \times CT_{\text{pri-ratio}}^i\right)^0.02} - 1
\]

And,

\[
T_{\text{primary}}^i = \frac{0.14 \times TDS^i}{I_F \left(PS_i \times CT_{\text{pri-ratio}}^i\right)^0.02} - 1
\]

III. HYBRID PSO-DE ALGORITHM

This section presents a brief description of the three stochastic algorithms: the PSO, the DE and the hybrid PSO-DE, together with some relevant implementation details.

3.1. Overview of Particle Swarm Optimization (PSO)

PSO is a population based stochastic optimization technique inspired on social behavior of bird flocking or fish schooling. The algorithm searches for optimum using a group or swarm formed by possible solutions of the problem, which are called particles.

The algorithm implemented in this work is inspired on [28, 29]. Each particle is updated as indicated by equation (12) and the group of particles moves through the search space as indicated by equation (13).

\[
V_{i,j}^k = \left[wV_{i,j}^k + c_1rand_1(P_{\text{best},i,j} - P_{i,j}^{k-1}) + c_2rand_2(G_{\text{best}} - P_{i,j}^{k-1})\right] \cdot FC
\]

(12)

\[
P_{i,j}^k = P_{i,j}^{k-1} + V_{i,j}^k
\]

(13)

In equations (12) and (13), for component \(i\) of particle \(j\). \(P_{i,j}^k\) represents its position and \(V_{i,j}^k\) is called speed; \(c_1\) and \(c_2\) are the acceleration coefficients; \(FC\) is the contraction coefficient calculated as in equation (14) [28]; rand_1 and rand_2 are uniformly distributed random numbers in \([0, 1]\), sampled at each iteration \(k\). The particles of the swarm are individually analyzed and the one that generates the best solution along the iterations, i.e. best local solution, is called \(P_{\text{best}}\) (particle best).
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The best solution in the swarm is tracked in Gbest (group best). Parameter \( w \), called inertia, indicates the contribution of the previous velocity to the new one. It is updated at each iteration \( k \) by equation (15) [29].

\[
F C = \frac{2}{2 - \phi - \sqrt{\phi^2 - 4\phi}} \quad \text{with } \phi = c_1 + c_2 \geq 4 \quad (14)
\]

\[
w = w_{\text{max}} - \frac{w_{\text{max}} - w_{\text{min}}}{G_{\text{max}}} k
\]

Where, \( G_{\text{max}} \) is the maximum number of iterations; \( w_{\text{max}} \) and \( w_{\text{min}} \) are, respectively, maximum and minimum inertia values. Higher values of \( w \) favor global exploration of the search space, while smaller values tend to facilitate local search [30].

3.2. Overview of Differential Evolution (DE)

The differential evolution algorithm, proposed by Storn and Price [30], is also a population based algorithm that uses the mutation, selection and crossing over processes. The DE implemented in this work is based on [31-34]. The mutation process initiates with the creation of a mutant vector: an individual is combined with its difference with the best individual and with a random term, as described in equations (16) and (17). The crossing over process is presented in equation (18):

\[
V_{i,j}^{k+1} = F \left( \text{Gbest}_{i,j}^{k-1} - P_{i,j}^{k-1} \right) + F \left( P_{\text{ran}1}^{k-1} - P_{\text{ran}2}^{k-1} \right)
\]

\[
Z_{i,j}^{k+1} = P_{i,j}^{k-1} + V_{i,j}^{k+1}
\]

\[
P_{i,j}^{k+1} = \begin{cases} 
Z_{i,j}^{k+1} & \text{if } (\text{rand}(i) \leq \text{CR}) \text{ or } (i = \text{rnbr}(i)) \\
\frac{P_{i,j}^{k-1} + V_{i,j}^{k+1}}{2} & \text{if } (\text{rand}(i) > \text{CR}) \text{ and } (i \neq \text{rnbr}(i))
\end{cases}
\]

Where, \( \text{Gbest}^{k-1} \) is the best individual in iteration \( k - 1 \) and \( P_{i,j}^{k-1} \) is the individual being updated; for component \( i \) of particle \( j \), \text{ran}1 and \text{ran}2 are random numbers uniformly distributed in \([1, n]\) and represent two individuals randomly selected; \( n \) is the number of individuals; \( F \) is the amplification factor, usually defined in interval \([0, 2]\); \( V_{i,j}^{k} \) the \((n \times 1)\) obtained mutant vector; \( \text{rand}(i) \) and \( \text{rnbr}(i) \) are also random numbers uniformly distributed on \([0, 1]\) and on \([1, n] \), respectively; \( n_v \) is the individual dimension; the crossing over parameter \( \text{CR} \) defines the crossing over probability.

3.3. Hybrid PSO-DE Algorithm

The hybrid algorithm implemented is inspired in the strategy suggested in [35-38] of exploring the search space first globally and then locally, using two different evolutionary algorithms. Notice that the crossing over process of the DE algorithm promotes information exchange among individuals and favors search in new areas of the search space.

The mutation process aims at increasing population diversity and the algorithm ability to escape from local minima [36].

In this work, due to the fact that in high dimension problems the PSO is easily trapped into local optimas, resulting in a low optimizing precision or even failure [35], the proposal is to use the PSO algorithm during the first 30% of the iterations.

In the sequel, during the remaining 70% of the iterations, the mutation and crossing over operators shown in equations (16), (17) and (18) are used. The algorithm is structured in the steps shown bellow [39]:

Step 1 (Initialization of the particles): At the first iteration, component \( i \) of particle \( j \) is generated randomly, as indicated in equation (19), where \( rd \) is a uniformly distributed random number in \([0, 1]\).

\[
P_{i,j}^{(k=1)} = P_{i,\text{ran1}} + rd \left( P_{i,\text{max}} - P_{i,\text{min}} \right)
\]

Step 2 (Treatment of equality constraints and Pbest evaluation): In the first iteration, \( \text{Pbest} \) for each particle assumes the value of the corresponding particle.

Step 3 (Fitness evaluation): The objective function value is determined for each particle.

Step 4 (Gbest evaluation): The best particle, i.e. the one that gives lower generation costs among all the \( \text{Pbest} \) particle values, is identified as \( \text{Gbest} \).

Step 5 (Velocity update): The velocity is updated using equation (12) or (17), depending on the current iteration number.

Step 6 (Position update): The particle’s position is updated using equation (13) or (18), depending on the current iteration number.

Step 7 (Treatment of equality and inequality constraints): The constraints are solved in two stages as explained in Step 2. The inequality constraints are evaluated as indicated in equation (20):

\[
P_{i,j}^{k} = \begin{cases} 
P_{i,j} & \text{if } \left( P_{i,j}^{k} < P_j \right) \\
\frac{P_{i,j}}{2} & \text{if } \left( P_{i,j}^{k} > P_j \right)
\end{cases}
\]

Step 8 (Pbest evaluation): For each particle, the objective function value is evaluated and compared with that of \( \text{Pbest} \).

Step 9 (Check stopping criterion): The stopping criterion involves a tolerance for the difference among the objective function associated to all particles values and for the feasibility condition of the optimization problem. If convergence is not attained, continue from Step 4.
IV. CASE STUDY, SIMULATION RESULTS AND COMPARISON

The proposed hybrid optimization algorithm PSO-DE is validated and tested on two case studies namely IEEE 4-bus, and 6-bus, shown in Figures 2a, and 2b respectively. The first case study consists of a two power generators, fourth lines and 8 protection relays. For the optimization problem of this model, we have to coordinate the settings of all the 8 protection relays.

Accordingly, there are 16 decision variables i.e. $TDS^j$ to $TDS^s$ and $PS^j$ to $PS^s$. The second case study consists of three power generators, seventh lines and 14 protection relays. For the optimization problem of this case study, we have to coordinate the settings of all the 14 overcurrent relays. Accordingly, there are 28 decision variables i.e. $TDS^j$ to $TDS^{s21}$ and $PS^j$ to $PS^{s24}$ [40].

![Fig. 2. Power system for cases study: a) IEEE 4-bus, b) IEEE 6-bus.](image)

For all case studies in this paper the $CTI$ is fixed to 0.30 sec. The values of constants $I_F$ and $CT_{pr\_rating}$ for the two case studies are given in Tables 1 and 2 [15, 40]. For each model there are two tables, one is with respect to the $T_{pri\_far\_bus}$ and $T_{pri\_far\_bus}$, the other is with respect to the, $T_{backup}$ and $T_{primary}$.

Table 1. Values of $I_F$ and $CT_{pr\_rating}$ for cases study with $T_{pri\_cl\_in}$ and $T_{pri\_far\_bus}$

<table>
<thead>
<tr>
<th>$T_{pri_cl_in}$</th>
<th>$T_{pri_far_bus}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TDS^1$</td>
<td>$I_F$</td>
</tr>
<tr>
<td>$TDS^2$</td>
<td>20.32</td>
</tr>
<tr>
<td>$TDS^3$</td>
<td>88.85</td>
</tr>
<tr>
<td>$TDS^4$</td>
<td>13.60</td>
</tr>
<tr>
<td>$TDS^5$</td>
<td>118.81</td>
</tr>
<tr>
<td>$TDS^6$</td>
<td>116.70</td>
</tr>
<tr>
<td>$TDS^7$</td>
<td>16.07</td>
</tr>
<tr>
<td>$TDS^8$</td>
<td>71.70</td>
</tr>
<tr>
<td>$TDS^9$</td>
<td>19.27</td>
</tr>
</tbody>
</table>

Table 2. Values of $I_F$ and $CT_{pr\_rating}$ for cases study with $T_{backup}$ and $T_{primary}$

<table>
<thead>
<tr>
<th>$T_{backup}$</th>
<th>$T_{primary}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TDS^1$</td>
<td>$I_F$</td>
</tr>
<tr>
<td>$TDS^2$</td>
<td>6.5383</td>
</tr>
<tr>
<td>$TDS^3$</td>
<td>5.6180</td>
</tr>
<tr>
<td>$TDS^4$</td>
<td>4.6538</td>
</tr>
<tr>
<td>$TDS^{s21}$</td>
<td>3.5261</td>
</tr>
<tr>
<td>$TDS^{s22}$</td>
<td>3.8006</td>
</tr>
<tr>
<td>$TDS^{s23}$</td>
<td>2.4143</td>
</tr>
<tr>
<td>$TDS^{s24}$</td>
<td>5.3541</td>
</tr>
</tbody>
</table>
The convergence characteristics for the hybrid optimization algorithms proposed (PSO-DE) of the two case studies IEEE 4-bus and 6-bus are presented in figures 3.a and 3.b respectively.

Table 3. Optimal setting of relays: a) IEEE 4-bus, b) IEEE 6-bus.

<table>
<thead>
<tr>
<th>Relay No.</th>
<th>TDS</th>
<th>PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0560</td>
<td>1.4583</td>
</tr>
<tr>
<td>2</td>
<td>0.2415</td>
<td>1.7156</td>
</tr>
<tr>
<td>3</td>
<td>0.0561</td>
<td>1.4309</td>
</tr>
<tr>
<td>4</td>
<td>0.1732</td>
<td>1.6174</td>
</tr>
<tr>
<td>5</td>
<td>0.1441</td>
<td>1.6172</td>
</tr>
<tr>
<td>6</td>
<td>0.0563</td>
<td>1.4309</td>
</tr>
<tr>
<td>7</td>
<td>0.1543</td>
<td>1.7178</td>
</tr>
<tr>
<td>8</td>
<td>0.0566</td>
<td>1.4305</td>
</tr>
</tbody>
</table>

Fig. 3. Convergence characteristics of PSO-DE for all cases study: IEEE 4-bus, b) IEEE 6-bus.

4.1. Optimal Settings Relays

The new optimal relays settings (TDS and PS) using the hybrid optimization algorithm PSO-DE for the two case studies are presented in Tables 3.a and 3.b respectively.
4.2. Optimal CTI Value

The CTI between backup and primary overcurrent relay is calculated from the optimized value of TDS and PS for the two case studies. The CTI is improved using the proposed new hybrid optimization algorithm (PSO-DE) as compared to optimization algorithms MDE and TLBO as represented in Table 4.

From the results of Table 4, it can be seen that the proposed hybrid optimization algorithm give best value of minimized CTI compared to other algorithms.

4.3. Comparison Study

Table 5 presents the best obtained values of the objective function using the new proposed hybrid optimization algorithm (PSO-DE) compared with other published results obtained with TLBO, DE, and MDE.

From the results of Table 5, it can be seen that the proposed hybrid algorithm (PSO-DE) give better performances and provide the best solutions compared to other published results.

V. CONCLUSIONS

The optimization model of overcurrent relays coordination turns out to be highly constrained and nonlinear in nature. Efficient optimization algorithm PSO-DE is needed to deal with these problems. The proposed hybrid optimization algorithms are validated and tested on two different case studies.
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The results showed that the proposed algorithm is able to find superior TDS and PS and thus minimum operating time of the relays and minimum CTI.

The effectiveness of the hybrid optimization algorithm can be observed from the results in terms of objective function values, which are better in comparison to other optimization algorithms used in the literature.

The continuity of this work will be the coordination of the overcurrent relays considering several conflicting objective functions and various power system topologies and in the presence of FACTS devices and DG using new hybrid optimization algorithms.

APPENDIX

The parameters of three optimisation algorithms study is:

A)- PSO : c₁ = c₂ = 2.0, ωₘᵟᵢₙ = 0.4, ωₘₐₓ = 0.9, Gₘₐₓ = 200.

B)- DE : F = 1.7, nl = 80, nv = 80, CR = 0.15, Gₘₐₓ = 200.

C)- PSO-DE : c₁ = c₂ = 2.2, ωₘᵟᵢₙ = 0.5, ωₘₐₓ = 0.8, F = 1.8, nl = 85, nv = 85, CR = 0.17, Gₘₐₓ = 200.

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REFERENCES


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