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A new hybrid optimization algorithm CRO-DE for optimal coordination of overcurrent relays in complex power systems

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ABSTRACT

The paper presents a new hybrid global optimization algorithm based on Chemical Reaction based Optimization (CRO) and Differential evolution (DE) algorithm for nonlinear constrained optimization problems. This approach proposed for the optimal coordination and setting relays of directional overcurrent relays in complex power systems. In protection coordination problem, the objective function to be minimized is the sum of the operating time of all main relays. The optimization problem is subject to a number of constraints which are mainly focused on the operation of the backup relay, which should operate if a primary relay fails to respond to the fault near to it, Time Dial Setting (TDS), Plug Setting (PS) and the minimum operating time of a relay. The hybrid global proposed optimization algorithm aims to minimize the total operating time of each protection relay. Two systems are used as case study to check the efficiency of the optimization algorithm which are IEEE 4-bus and IEEE 6-bus models. Results are obtained and presented for CRO and DE and hybrid CRO-DE algorithms. The obtained results for the studied cases are compared with those results obtained when using other optimization algorithms which are Teaching Learning-Based Optimization (TLBO), Chaotic Differential Evolution Algorithm (CDEA) and Modified Differential Evolution Algorithm (MDEA), and Hybrid optimization algorithms (PSO-DE, IA-PSO, and BFOA-PSO). From analysing the obtained results, it has been concluded that hybrid CRO-DO algorithm provides the most optimum solution with the best convergence rate.

Nomenclature

T	Relay total operating time
$IDMT$	Inverse Definite Minimum Time
I_F	Fault current

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T	Relay total operating time
$IDMT$	Inverse Definite Minimum Time
I_F	Fault current
TDS	Time Dial Setting
PS	Plug Setting
CT	Current transformer
$CT_{pr-rating}$	Primary rating of CT
I_{relay}	Current seen by the relay
OF	Objective function
TDS_{min}	Minimum value for TDS
TDS_{max}	Maximum value for TDS
$T^{\min}$	Minimum value of relay operating time
$T^{\max}$	Maximum value of relay operating time
CTI	Coordination Time Interval
$T_{pri-cl-in}$	Operating time to clear near end fault
$T_{pri-far-bus}$	Operating time to clear far end fault
$T_{primary}$	Operating time of primary relay
T_{backup}	Operating time of backup relay
N_{cl}, N_{far}	Number of relays installed at both ends of the primary

1. Introduction

Optimization is the selection of the best element from some sets of variables with a long history dating back to the years when Euclid conducted research to gain the minimum distance between a point and a line. When the complexity and the dimension of the search space make a problem unsolvable by a deterministic algorithm, probabilistic algorithms deal with this problem by going through a diverse set of possible solutions or candidate solutions. Over the past years, there has been a growing interest in solving optimization problems by means of algorithms inspired on natural paradigms. These techniques have been applied to the optimization of complex computational problems in the engineering problems.

Global optimization is a branch of applied mathematics and numerical analysis that deals with the global optimization of a function or a set of functions according to some criteria. Typically, a set of bound and more general constraints is also present, and the decision variables are optimized considering also the constraints. 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 relay has two parameters to be defined which are PS and TDS. The use of computers in the power systems application of relay coordination has relieved protection engineers from huge mathematical calculations.

Coordination of overcurrent relays requires the accurate selection of optimum settings. 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 considered in the secondary relay which should operate if the main relay fails to respond to the fault near to it, TDS and PS and minimum operating time of the relay. Table 1 represents the different optimization algorithms which were developed by researchers to provide optimum solution for relay settings and coordination in order to achieve optimum protection.

Table 1 – Literature for global optimization algorithm.

Paper	**Optimization Algorithm**
[2]	Evolutionary Algorithm
[3]	Differential Evolution Algorithm
[4]	Modified Differential Evolution Algorithm
[5]	Self-Adaptive Differential Evolutionary
[6]	Particle Swarm Optimization
[7-8]	Modified Particle Swarm Optimization
[9]	Evolutionary Particle Swarm Optimization
[10]	Box-Muller Harmony Search
[11]	Zero-one Integer Programming
[12]	Covariance Matrix Adaptation Evolution Strategy
[13]	Seeker Algorithm
[14]	Teaching Learning Based Optimization
[15]	Chaotic Differential Evolution Algorithm
[16]	Informative Differential Evolution Algorithm
[17]	Firefly Optimization Algorithm
[18]	Krill Herd Algorithm
[19]	Non-dominated Sorting Genetic Algorithm
[20]	Biogeography Based Optimization
[21]	Hybrid IA-PSO Algorithm
[22]	Hybrid BFOA-PSO Algorithm
[23]	Hybrid PSO-DE Algorithm

In this research work, a hybrid global optimization technique namely CRO-DE is proposed to select the optimal values of relay settings and present a solution for the coordination problem between primary and backup relays. In this paper, hybrid CRO-DE algorithms are applied to IEEE 4-bus and IEEE 6-bus systems which are modelled and simulated to verify the efficiency of the proposed hybrid algorithm. Moreover, the obtained results when using these three algorithms are compared with the published results obtained for TLBO, CDEA, MDEA, hybrid PSO-DE, hybrid IA-PSO, and hybrid BFOA-PSO optimization algorithms. When compared with the other algorithms, hybrid CRO-DE algorithm shows faster convergence and provides an improvement in minimizing the total operating time (T) of each protection relay in the two studied cases.

2. Optimal Relay Coordination Problem

The operating time of IDMT relay is inversely proportional to the fault current. Hence, overcurrent relay will operate fast after sensing a high current. The tripping time of the relay follows a time over current delayed curve, in which the time delay depends upon the current. The two decisive factors are TDS and PS. The operating time of the relay is closely related to TDS, PS and the fault current (I_F). The total operating time is given by a non-linear mathematical equation [3], [11-15] with respect to the coordination time constraint between backup and primary relays :

$$T = \frac{\alpha \times TDS}{\left(\frac{I_F}{PS \times CT_{pr-rating}}\right)^{\beta} - \gamma} \tag{1}$$

Where, α, β and γ are constants. According to IEEE standards [21], the values of these constants are given by 0.14, 0.02 and 1.0, respectively. I_F is the fault current at CT primary terminal where the fault occurs while $CT_{pr-rating}$ is the primary rating of CT. The ratio between IF and $CT_{pr-rating}$ gives the current seen by the relay denoted by I_{relay}.

$$I_{relay} = \frac{I_F}{CT_{pr-rating}} \tag{2}$$

2.1. Objective Function

As in Figure 1, a close-in fault (or near end fault) is a fault that occurs close to the relay and a far-bus fault (or far end fault) is a fault that occurs at the other end of the line.

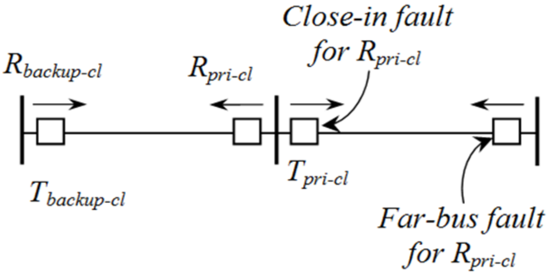


Fig. 1 – Close-in and far-bus faults for primary relay.

In coordination studies, the summation of the operating time of all the primary relays to clear a near or far end fault can be considered as an objective function that is to be minimized. Therefore, the objective function (OF) can be expressed as follows, as given in [4], [14-15] :

$$MinimizeOF = \sum_{i=1}^{N_{cl}} T^{i}_{pri-cl-in} + \sum_{j=1}^{N_{far}} T^{j}_{pri-far-bus} \tag{3}$$

Where,

$$T^{i}_{pri-cl-in} = \frac{0.14 \times TDS^{i}}{\left(\frac{I^{i}_{F}}{PS^{i} \times CT^{i}_{pr-rating}}\right)^{0.02} - 1} \tag{4}$$

$$T^{j}_{pri-far-bus} = \frac{0.14 \times TDS^{j}}{\left(\frac{I^{j}_{F}}{PS^{j} \times CT^{j}_{pr-rating}}\right)^{0.02} - 1} \tag{5}$$

2.2. Constraints

Three constraints are considered for the minimization problem. The first constraint is TDS of the relay which is the time delay before the relay operates whenever the fault current becomes equal to or greater than the PS setting [12-17].

$$TDS^{i}_{\min} \leq TDS^{i} \leq TDS^{i}_{\max} \tag{6}$$

Where, i varies between 1 and N_{cl}. TDS^{i}_{min} and TDS^{i}_{max} are the minimum and maximum limits of TDS which are 0.05 and 1.10 sec, respectively. The second constraint concerning PS takes the form :

$$PS^{i}_{\min} \leq PS^{i} \leq PS^{i}_{\max} \tag{7}$$

Where, i varies between 1 and N_{far}. PS^{i}_{min} and PS^{i}_{max} are the 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 it can be determined by standard characteristic curves of the relay or analytic formula. Hence, the relay operating time is defined by :

$$T^{\min}_{i} \leq T_{i} \leq T^{\max}_{i} \tag{8}$$

Where, T^{min} and T^{max} are the minimum and maximum values for the relay operating time which are 0.05 and 1.00, respectively. The coordination time interval between the primary and the backup relays must be verified during the optimization procedure. In this paper, the chronometric coordination between the primary and the backup relays is used :

$$T_{backup} - T_{primary} \geq CTI$$

Where, T_{backup} and $T_{primary}$ are the operating time of the backup and primary relay, respectively and CTI is the minimum coordination time interval. For electromechanical relays, CTI varies between 0.30 and 0.40 sec, while for numerical relays CTI varies between 0.10 and 0.20 sec [13-14]. The value of T_{backup} and $T_{primary}$ can be determined by equations (10) and (11) respectively.

$$T^{i}_{backup} = \frac{0.14 \times TDS^{x}}{\left(\frac{I^{i}_{F}}{PS^{x} \times CT^{i}_{pr-rating}}\right)^{0.02} - 1} \tag{9}$$

$$T^{i}_{primary} = \frac{0.14 \times TDS^{y}}{\left(\frac{I^{i}_{F}}{PS^{y} \times CT^{i}_{pr-rating}}\right)^{0.02} - 1} \tag{10}$$

3. Hybrid Global Optimization Algorithms (CRO-DE)

Mutation operation of Differential Evolution (DE) algorithm is integrated with inter-molecular ineffective collision and crossover operation is introduced in the inter-molecular collision, synthesis, and decomposition process to accelerate the convergence speed and improve the solution quality of Chemical Reaction Optimization (CRO) algorithm.

3.1. Chemical Reaction based Optimization (CRO)

In the year of 2011, authors in [24-26] proposed CRO algorithm, based on chemical reaction process where molecules undergo a sequence of reactions with each other. The CRO has good searching ability that shows excellent operation of intensification and diversification which are two important features of evolutionary algorithm. In CRO, atomic structure of molecule represents a solution of the optimization problem. Potential energy (PE) and kinetic energy (KE) are two key factors for a molecule. The fitness of a solution is judged by the PE energy of the molecule, while KE is used to control the acceptance of new solutions with worse fitness.

Chemical reaction process may be classified into four different categories namely (i) reactions are on-wall ineffective collision, (ii) decomposition, (iii) inter-molecular ineffective collision and (iv) synthesis. On-wall ineffective collision and decomposition reactions are of single molecular reactions, where as inter-molecular ineffective collision and synthesis reaction are of the later category [24].

(i) On-wall ineffective collision

The on-wall ineffective collision reaction occurs when a molecule hits the wall and then bounces back. In this reaction, a molecule ms is allowed to change to another molecule $ms1$ if the following condition is satisfied :

$$E_k^{ms} + E_p^{ms} \geq E_p^{ms_1} \tag{11}$$

(ii) Decomposition

The decomposition reaction is used to mimic the process of hitting the wall and then decomposing into two or more pieces. Because of the severe collision, the resultant molecular structure of the two newly formed molecules ms1, ms2 are entirely different from the original molecule ms and is also different from the neighborhood molecules. In decomposition process takes place if.

$$E_k^{ms} + E_p^{ms} \geq E_p^{ms_1} + E_p^{ms_2} \tag{12}$$

(iii) Inter-molecular ineffective collision

The inter-molecular ineffective collision mimics the process that two molecules $ms1$, $ms2$ collide with each other and generate two new molecules $ms\prime1$, $ms\prime2$. As the collision is not severe, the molecular structures of the generated molecules are closer to the original molecules. Inter-molecular ineffective collision occurs if.

$$E_k^{ms_1} + E_p^{ms_1} + E_k^{ms_2} + E_p^{ms_2} \geq E_p^{ms_1'} + E_p^{ms_2'} \tag{13}$$

(iv) Synthesis collision

In this process, two molecules $ms1$, $ms2$ collides and combines together to form a single molecule $ms\prime 1$. The molecular structure of the newly formed molecule is entirely different from the molecular structure of original molecules. The condition or synthesis collision is as follows.

$$E_k^{ms_1} + E_p^{ms_1} + E_k^{ms_2} + E_p^{ms_2} \geq E_p^{ms'} \tag{14}$$

3.2. Differential Evolution (DE)

DE is a population based meta-heuristic algorithm, capable of handling non-differentiable, non-linear and multi-modal objective functions [27]. A brief description of different steps of DE algorithm is given below [28, 29] :

(i) Initialization

In this process, a population of individuals is randomly initialized where each individual represents a potential solution to the problem. The individual vectors are randomly initialized as follows :

$$x_i^j = x_{\min}^j + rand * \left(x_{\max}^j - x_{\min}^j\right) \tag{15}$$

(ii) Mutation

In this process, the individual vectors mutate with each other to form donor vectors. For each target vector x_i^j, donor vector v_i^j is defined by :

$$v_i^j = x_k^j + F * \left(x_m^j - x_n^j\right) \tag{16}$$

Where, x_k^j ; x_m^j ; x_n^j are three randomly target vectors of the current population and F is a positive control parameter used for scaling the difference vectors.

(iii) Crossover

In crossover, the parent vector is mixed with the mutated vector to create a trial vector, according to the following equation :

$$u_i^j = \begin{cases} v_i^j if rand_{i,j} \leq c_r \\ x_i^j else \end{cases} \tag{17}$$

Where, cr is the crossover probability and $rand_{i,j}$ is a random number between [0, 1].

(iv) Selection

In this process, a competition is carried out between each individual X_i and its offspring U_i and the winner, selected deterministically based on fitness values, is promoted to the next generation. The selection operation can be expressed as follows :

$$X_i\left(t+1\right) = \begin{cases} U_i\left(t\right) iff\left(U_i\left(t\right)\right) \leq f\left(X_i\left(t\right)\right) \\ X_i\left(t\right) else \end{cases} \tag{18}$$

And,

$$U_i = \left(u_1^i, u_2^i, ..., u_j^i, ..., u_d^i\right) \tag{19}$$

$$X_i = \left(x_1^i, x_2^i, ..., x_j^i, ..., x_d^i\right) \tag{20}$$

Where, $f(x)$ is the objective function to be minimized and d is the number of control variables.

3.3. Hybrid CRO-DE Algorithm

The CRO algorithm that emphasizes on exploring the entire search space and a local version of DE algorithm that emphasizes on exploiting the local search space are combined together to make an impact on the performance of the algorithm in terms of the solution quality and convergence speed [30, 31]. The general step of the HCRO algorithm is summarized as follows [31] :

Step 1 : Initialize several numbers of molecules by randomly generated molecular structure depending upon the population size. The molecular structure of each molecule represents a potential solution to the given problem.

Step 2 : The fitness values of the specific problem of the population are assigned as the potential energy (PE) of the individual molecule. A random kinetic energy (KE) is set to the different molecules.

Step 3 : Based on the PE values (fitness values) best solutions are retained by elite molecules.

Step 4 : The non-elite molecules are modify using on-wall ineffective collision operations as described below :

Step 4.1 : One molecule ms is selected randomly.

Step 4.2 : Using the mutation operation of DE (described in Section 'Differential evolution') new molecule ms1 is generated which may mathematically be expressed as :

$$ms_1 = ms_k + f * (ms_m - ms_n) \tag{21}$$

Where, ms_k, ms_m, ms_n are the three different molecules chosen randomly from the current population.

Step 4.3 : The potential energy E_p^{ms1} of the molecule ms_1 is evaluate and the old molecule ms is replaced by new one ms_1 if the condition $E_k^{ms} + E_p^{ms} \geq E_p^{ms1}$ is satisfied and the KE of the molecule ms_1 is evaluated by :

$$E_k^{ms_1} = rand\,(0,1) * \left(E_k^{ms} + E_p^{ms} - E_p^{ms_1}\right) \tag{22}$$

Step 5 : Decomposition operation is performed to modify the molecular structure of the molecules by the following steps :

Step 5.1 : Two molecules, one molecule ms from the population and another randomly generated molecule ms_1 are selected for decomposition operation.

Step 5.2 : Crossover operation of DE is applied on ms and ms_1 to generate two new molecules $ms\prime$ and $ms"_2$

Step 5.3 : Potential energy $E_p^{ms\prime}$ and $E_p^{ms\prime 1}$ of molecules $ms\prime$ and $ms\prime_1$ are evaluated. If, $E_k^{ms} + E_p^{ms} \geq E_p^{ms\prime} + E_p^{ms\prime 1}$ molecule ms are deleted and the molecules $ms\prime$ and $ms\prime_1$ are pushed into the population. Modify the KE of $ms\prime$ and $ms\prime_1$ as below :

$$E_k^{ms'} = rand\left(0,1\right) * \left[E_k^{ms} + E_p^{ms} - \left(E_p^{ms'} - E_p^{ms'_1}\right)\right] \tag{23}$$

$$E_k^{ms'_1} = \left[1 - rand\left(0,1\right)\right] * \left[E_k^{ms} + E_p^{ms} - \left(E_p^{ms'} + E_p^{ms'_1}\right)\right] \tag{24}$$

Step 6 : Inter-molecular ineffective collisions are made to modify the molecular structure each molecule using the following steps :

Step 6.1 : Randomly select two molecules ms^1 and ms^2 from the population.

Step 6.2 : Two new molecules ms_1^1 and ms_1^2 are generated using crossover operation of DE by equation (18).

Step 6.3 : Evaluate potential energy E_p^{ms1} and E_p^{ms2} of molecules ms_1^1 and ms_1^2 and replace molecules ms^1 and ms^2 by molecules ms_1^1 and ms_1^2, respectively. The KE of the molecules ms^1 and ms^2 are evaluated using

$$E_k^{ms_1^1} = rand\left(0,1\right) * \begin{bmatrix} E_p^{ms^1} + E_k^{ms^1} + E_p^{ms^2} + E_k^{ms^2} \\ -\left(E_p^{ms_1^1} + E_p^{ms_1^2}\right) \end{bmatrix} \tag{25}$$

$$E_k^{ms_1^1} = \left[1 - rand\left(0,1\right)\right] * \begin{bmatrix} E_p^{ms^1} + E_k^{ms^1} + E_p^{ms^2} \\ +E_k^{ms^2} - \left(E_p^{ms_1^1} + E_p^{ms_1^2}\right) \end{bmatrix} \tag{26}$$

Step 7 : Synthesis collision operation are performed to update the molecular structure of the molecules using the following steps :

Step 7.1 : Two molecules ms^1 and ms^2 are randomly selected from the population set.

Step 7.2 : Apply the conventional cross over operation of GA on ms^1 and ms^2 by considering them as parents' chromosomes and generate a child chromosome ms_1^1.

Step 7.3 : Evaluate E_p^{ms1} of the molecule ms_1^1. The molecules ms^1 and ms^2 are omitted and the molecule ms_1^1 is push into the population if $E_k^{ms1} + E_p^{ms1} + E_k^{ms2} + E_p^{ms2} \geq E_p^{ms1}$ .The KE of the new molecule ms_1^1 is calculated using :

$$E_k^{ms_1^1} = rand\left(0,1\right) * \left[E_k^{ms^1} + E_p^{ms^1} + E_k^{ms^2} + E_P^{ms^2} - E_p^{ms_1^1}\right] \tag{27}$$

Step 8 : The feasibility of a problem solution is verified and the infeasible solutions are replaced by feasible solution set.

Step 9 : The updated molecules are sorted.

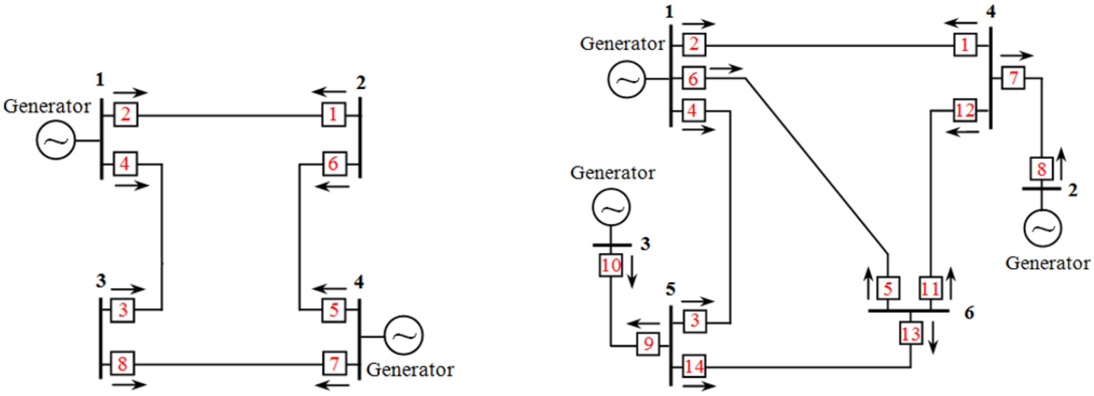
Step 10 : The best elite molecules are replaced by the worst molecule.

Step 11 : The processes of generating new molecules and selecting those with better function values are continued until the given stopping conditions are satisfied. The iteration process can be stopped after a fixed number of generations or when any significant improve improvement in the solution does not occur.

4. Case Study and Simulation Results

The optimization algorithms CRO, DE and hybrid CRO-DE are validated and tested on two systems, namely IEEE 4-bus and IEEE 6-bus models as shown in Figures 2.a and 2.b, respectively. The first case study consists of two power generators, four lines and eight IDMT directional overcurrent relays. The objective of the optimization problem in this case is to coordinate the settings of eight relays. Accordingly, there are 16 decision variables which are TDS^1 to TDS^8 and PS^1 to PS^8. The second case study consists of three power generators, seven lines and fourteen directional overcurrent relays [15-23].

The objective of the optimization problem in this case is to coordinate the settings of fourteen relays. Accordingly, there are 28 decision variables which are TDS^1 to TDS^{14} and PS^1 to PS^{14}. CTI is selected to take the value of 0.30 sec in each of the studied cases.



(a) (b)

Fig. 2 – Case study systems : (a) IEEE 4-bus, (b) IEEE 6-bus.

For each case study, the values used for I_F and CT_{pr_rating} are listed in Tables 2 and 3 such that the data related to $T^i_{Pri-far-bus}$ and $T^j_{Pri-far-bus}$ are shown in Table II, while the data related to T^x_{backup} and $T^y_{primary}$ are shown in Table 2.

Table 2 – I_F and $CT_{pr-rating}$ for $T^i_{pri\_cl\_in}$ and $T^j_{pri\_far\_bus}$ in case study.

(a). IEEE 4-bus

$\mathbf{T}^i_{pri\_cl\_in}$			$\mathbf{T}^j_{pri\_far\_bus}$		
TDS^i	$\mathbf{I}^i_F$	$\mathbf{CT}^i_{pr-rating}$	**TDS**^{j}	$\mathbf{I}^j_F$	$\mathbf{CT}^j_{pr-rating}$
TDS^1	20.32	0.4800	TDS^2	23.75	0.4800
TDS^2	88.85	0.4800	TDS^1	12.48	0.4800
TDS^3	13.60	1.1789	TDS^4	31.92	1.1789
TDS^4	116.81	1.1789	TDS^3	10.38	1.1789
TDS^5	116.70	1.5259	TDS^6	12.07	1.5259
TDS^6	16.67	1.5259	TDS^5	31.92	1.5259
TDS^7	71.70	1.2018	TDS^8	11.00	1.2018
TDS^8	19.27	1.2018	TDS^7	18.91	1.2018

(b). IEEE 6-bus

$\mathbf{T}^i_{pri\_cl\_in}$			$\mathbf{T}^j_{pri\_far\_bus}$		
$\mathbf{TDS}^i$	$\mathbf{I}^i_F$	$\mathbf{CT}^i_{pr-rating}$	$\mathbf{TDS}^j$	$\mathbf{I}^j_F$	$\mathbf{CT}^j_{pr-rating}$
TDS^1	2.5311	0.2585	TDS^2	5.9495	0.2585
TDS^2	2.7376	0.2585	TDS^1	5.3752	0.2585
TDS^3	2.9723	0.4863	TDS^4	6.6641	0.4863
TDS^4	4.1477	0.4863	TDS^3	4.5897	0.4863
TDS^5	1.9545	0.7138	TDS^6	6.2345	0.7138
TDS^6	2.7678	0.7138	TDS^5	4.2573	0.7138
TDS^7	3.8423	1.7460	TDS^1	6.3694	1.7460
TDS^8	5.6180	1.7460	TDS^2	4.1783	1.7460
TDS^9	4.6538	1.0424	TDS^3	3.8700	1.0424
TDS^{10}	3.5261	1.0424	TDS^4	5.2696	1.0424
TDS^{11}	2.5840	0.7729	TDS^5	6.1144	0.7729
TDS^{12}	3.8006	0.7729	TDS^6	3.9005	0.7729
TDS^{13}	2.4143	0.5879	TDS^1	2.9011	0.5879
TDS^{14}	5.3541	0.5879	TDS^2	4.3350	0.5879

Table 3 – I_F and $CT_{pr-rating}$ for T^x_{backup} and $T^y_{primary}$ in case study.

(a). IEEE 4-bus

$\mathbf{T}^x_{backup}$			$\mathbf{T}^y_{pimary}$		
Relay No.	$\mathbf{I}_{F^i}$	$\mathbf{CT}^i_{pr-rating}$	**Relay No.**	$\mathbf{I}_{F^j}$	$\mathbf{CT}^j_{pr-rating}$
5	20.32	1.5259	1	20.32	0.4800
5	12.48	1.5259	1	12.48	0.4800
7	13.61	1.2018	3	13.61	1.1789
7	10.38	1.2018	3	10.38	1.1789
1	116.81	0.4800	4	116.81	1.1789
2	12.07	0.4800	6	12.07	1.5259
2	16.67	0.4800	6	16.67	1.5259
4	11.00	1.1789	8	11.00	1.2018
4	19.27	1.1789	8	19.27	1.2018

(b). IEEE 6-bus

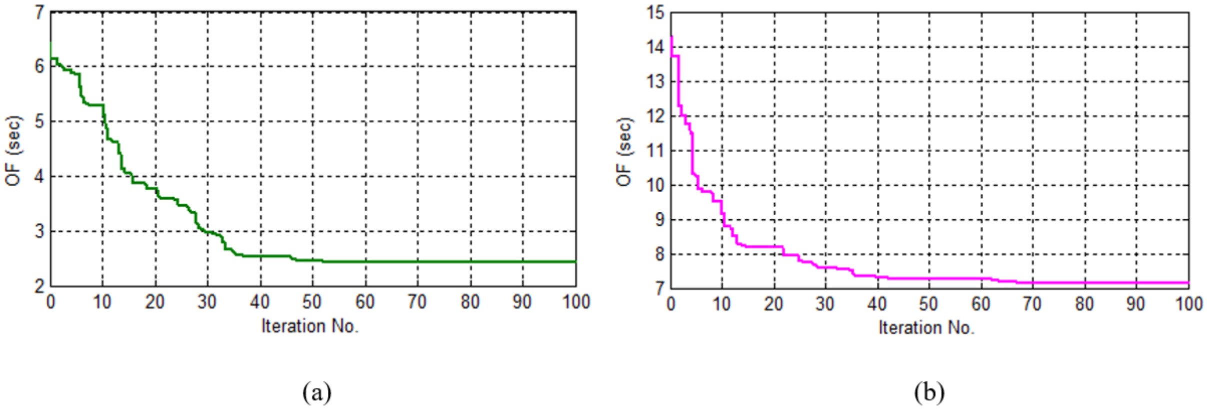
$\mathbf{T}^x_{backup}$			$\mathbf{T}^y_{pimary}$		
Relay No.	$\mathbf{I}_{F^i}$	$\mathbf{CT}^i_{pr-rating}$	**Relay No.**	$\mathbf{I}_{F^i}$	$\mathbf{CT}^j_{pr-rating}$
8	4.0909	1.7460	1	5.3752	0.2585
11	1.2886	0.7729	1	5.3752	0.2585
8	2.9323	1.7460	1	2.5311	0.2585
3	0.6213	0.4863	2	2.7376	0.2585
3	1.6658	0.4863	2	5.9495	0.2585
10	0.0923	1.0424	3	4.5897	0.4863
10	2.5610	1.0424	3	2.9723	0.4863
13	1.4995	0.5879	3	4.5897	0.4863
1	0.8869	0.2585	4	4.1477	0.4863
1	1.5243	0.2585	4	6.6641	0.4863
12	2.5444	0.7729	5	4.2573	0.7138
12	1.4549	0.7729	5	1.9545	0.7138
14	1.7142	0.5879	5	4.2573	0.7138
3	1.4658	0.4863	6	6.2345	0.7138
3	1.1231	0.4863	6	6.2345	0.7138
11	2.1436	0.7729	7	4.1783	1.7460
2	2.0355	0.2585	7	4.1783	1.7460
11	1.9712	0.7729	7	3.8423	1.7460
2	1.8718	0.2585	7	3.8423	1.7460
13	1.8321	0.5879	9	5.2696	1.0424
4	3.4386	0.4863	9	5.2696	1.0424
13	1.6180	0.5879	9	4.6538	1.0424
4	3.0368	0.4863	9	4.6538	1.0424
14	2.0871	0.5879	11	3.9005	0.7729
6	1.8138	0.7138	11	3.9005	0.7729
14	1.4744	0.5879	11	2.5840	0.7729
6	1.1099	0.7138	11	2.5840	0.7729
8	3.3286	1.7460	12	3.8006	0.7729
2	0.4734	0.2585	12	3.8006	0.7729
8	4.5736	1.7460	12	6.1144	0.7729
2	1.5432	0.2585	12	6.1144	0.7729
12	2.7269	0.7729	13	4.3350	0.5879
6	1.6085	0.7138	13	4.3350	0.5879
12	1.8360	0.7729	13	2.4143	0.5879
10	2.0260	1.0424	14	2.9011	0.5879
4	0.8757	0.4863	14	2.9011	0.5879
10	2.7784	1.0424	14	5.3541	0.5879
4	2.5823	0.4863	14	5.3541	0.5879

Further details on the values of the parameters used for each of the proposed algorithm

CRO-DE are mentioned in the Appendix.

4.1. Simulation Results and Comparison

Figures 3.a and 3.b represent the convergence characteristics of the hybrid CRO-DE optimization algorithm when applied to complex power systems IEEE 4-bus and IEEE 6-bus systems, respectively.



(a)

(b)

Fig. 3 – Convergence characteristics of CRO-DE in case study : (a) IEEE 4-bus, (b) IEEE 6-bus.

4.2. Optimal Relay Settings

The new optimal relays settings (TDS and PS) for each relay in the two studied cases are obtained using hybrid CRO-DE algorithms and presented in Table 4.

Table 4 – Optimal relays settings.

(a). IEEE 4-bus

Relay No.	**TDS**	**PS**
1	0.0371	1.4582
2	0.2414	1.6151
3	0.0460	1.3322
4	0.1730	1.6172
5	0.1323	1.6174
6	0.0567	1.4304
7	0.1542	1.7165
8	0.0523	1.4311

(b). IEEE 6-bus

Relay No.	**TDS**	**PS**
1	0.4137	0.4767
2	0.7523	0.4711
3	0.3853	0.4145
4	0.4462	0.4767
5	0.2123	0.4112
6	0.4112	0.3476
7	0.2041	0.4120
8	0.2176	0.4134
9	0.3011	0.3176
10	0.2245	0.4701
11	0.2612	0.4622
12	0.1039	0.4721
13	0.2133	0.4542
14	0.2712	0.3071

4.3. Optimal CTI

Optimal CTI, between the backup and primary overcurrent relays, is calculated using the obtained optimum values of TDS and PS for each of the two studied cases when using MDEA, TLBO algorithms, and hybrid CRO-DE optimization algorithm, as shown in Table 5.

From Table 5, it is observed that hybrid CRO-DE optimization algorithm generally gives minimum CTI values when compared with those obtained when using other optimization algorithms.

Table 5 – Optimal CTI value.

(a). IEEE 4-bus

Relay No.		**MDEA** [4]	**TLBO** [14]	**CRO – DE**
1	4	0.3001	0.5318	0.3012
2	6	0.3482	0.6439	0.3116
2	6	0.2990	0.6004	0.3242
4	8	0.3972	0.5105	0.3225
4	8	0.2996	0.4327	0.3137
5	1	0.2995	0.3003	0.3043
5	1	0.4008	0.3562	0.3271
7	3	0.2993	0.3551	0.3158
7	3	0.3491	0.3826	0.3102

(b). IEEE 6-bus

Relay No.		MDEA [4]	TLBO [14]	CRO – DE
8	1	0.2881	2.1885	0.3181
11	1	4.0293	1.5348	0.3185
8	1	0.8068	3.2497	0.3777
3	2	1669.6	2.2012	0.3266
3	2	0.1999	0.4382	0.3779
10	3	-0.1812	0.4182	0.3728
10	3	0.3780	1.2362	0.3025
13	3	0.3003	0.3079	0.3278
1	4	0.4583	0.8437	0.3183
1	4	0.1998	0.5170	0.4194
12	5	0.2257	0.9375	0.3196
12	5	0.8392	1.5253	0.3075
14	5	0.5192	1.1805	0.3472
3	6	0.5781	0.5510	0.3177
3	6	0.3479	0.3001	0.3076
11	7	0.2001	1.3738	0.3171
2	7	0.2380	0.9828	0.3297
11	7	0.2371	1.4725	0.3003
2	7	0.2000	1.0195	0.3010

4.4. Comparing Results

Table 6 presents the minimum values of the objective function which are obtained when using hybrid CRO-DE algorithm for each case study. It also shows the published results of the minimum objective function values for other optimization algorithms.

Table 6 – Objective function comparison for case study.

(a). IEEE 4-bus

Algorithm	OF (sec)
TLBO [14]	5.5890
MDEA [4]	3.6674
CDEA [15]	3.6774
PSO-DE [23]	3.4293
IA-PSO [21]	3.1239
BFOA-PSO [22]	3.1129
CROA-DE	**2.9731**

(b). IEEE 6-bus

Algorithm	OF (sec)
TLBO [14]	23.7878
CDEA [15]	10.6272
MDEA [4]	10.3514
BFOA-PSO [22]	9.4371
PSO-DE [23]	9.2671
IA-PSO [21]	7.6722
CROA-DE	**7.1463**

When comparing the objective function values given in Table 6, it can be seen that proposed hybrid CRO-DE algorithm suggested algorithm gives better performance and offers the best solution. This is represented in providing the minimum objective function value when compared with those results obtained when using other optimization algorithms. This proves the validity of the proposed hybrid algorithm in relays coordination for complex power systems.

5. Conclusion

In this paper, hybrid global optimization algorithm, namely CRO-DE algorithm, was presented to solve the coordination problem of directional overcurrent relays. The proposed global optimization algorithm was validated and tested on two complex power system models.

Though the three algorithms showed better results than those obtained in literature for other optimization algorithms, such as TLBO, CDEA and MDEA, robustness and feasibility of hybrid CRO-DE algorithm were clearly observed in the obtained results. Based on the obtained simulation results, CRO-DE in particular proved its superiority in providing the minimum operating time T of relays at a fast convergence rate as well as securing minimum coordination time interval between primary and backup relays in complex power systems.

This was achieved through finding the optimum settings relays TDS and PS values of each relay. The advantages encountered when using hybrid CRO-DE algorithm are attributed to its hybrid nature which combines the immune information processing mechanism and the particle swarm optimization algorithm to achieve better and fast solution. Therefore, it is recommended to use the proposed hybrid CRO-DE algorithm as an efficient hybrid optimization algorithm in the coordination of directional overcurrent relays.

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Appendix - CRO-DE parameters

Population size = 30,
Step of size = 0.5,
Numbers of molecules = 10,
Potential energy = 0.15,
Random kinetic energy = 0.25,
Synthesis rate = 0.20,
Decomposition rate = 0.20,
Substitution rate = 0.20,
Maximum iterations = 100.