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ORIGINAL ARTICLE

Sensitivity analysis on inverse characteristics of directional over current relays using differential evolution algorithm

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Abstract Protection relays in a power system makeup to pairs, one as main protection relay and the other as a backup protection relay. Directional over current relays (DOCR) have been using for backup protection mainly in distribution system. Coordination of these DOCRs is an optimization problem that is being solved using various types of optimizing algorithms by the researchers in the field. This paper attempts this problem in different direction which analyzes different inverse characteristics of DOCR and their sensitivities to different faults. Optimal values for time dial and plug settings for the DOCRs are obtained by using a recently developed algorithm: Opposition based chaotic differential evolution algorithms. IEEE 4-bus system has been taken as a test model and the algorithms are implemented in it for different types of characteristics based on the degree of inversion i.e., normally inverse, very inverse, extremely inverse and long-time inverse characteristics.

Keywords Optimization · Directional over current relays · Coordination · Opposition based chaotic differential evolution

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List of symbols

TDS	Time dial setting
PS	Plug setting
I_f	Current in kA when fault occurs
I_{relay}	Current through the relay
$CT_{primary\_rating}$	Current transformer's primary rating
N_{cl}	Number of relays responding for close-in fault
N_{far}	Number of relays responding for far-bus fault
OBJ	Objective function value
$T_{primary\_close\_in}$	Operating time of the primary relay for close in fault
$T_{primary\_far\_bus}$	Operating time of the primary relay for far bus fault
$T_{primary}$	Operating time when relay acts as primary relay
T_{backup}	Operating time when relay acts as backup relay

1 Introduction

An electric power system is the backbone of any country's economy, which has three parts: (i) generation, (ii) transmission, and (iii) utilization/load centers. As most of the bulk power generating stations are located in remote areas (ex: hydro electric station is usually located in hilly areas as it needs water potential), transmission lines are used to transmit the power from generating station to electrical substations located near the load centers. Such transmissions are placed in open and hence they undergo disturbances (faults). Significant portion of fault occur because of: (i) physical damage by personnel or machine, (ii) act of

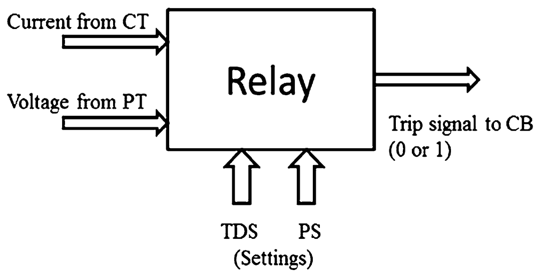

Fig. 1 Conceptual diagram of relay

nature, (iii) accelerated aging from sustained over temperature, and (iv) unsuitable environment. Power system protective (PSP) devices play an important role in these lines.

The main function of PSP devices is to minimize the damage to the system and its components when the power system undergoes a fault and increase the reliability of the system. Among the PSP devices, over current (OC) relays are simple and can be applied easily on the transmission network. A relay, as shown in Fig. 1, is a logical element which processes the inputs, normally current from a current transformer and voltage from a voltage transformer, from the system and issues a decision to trip, if a fault within its jurisdiction is detected.

Parallel feeders are installed where continuity of supply is particularly necessary. As an additional benefit, inductive reactance decreases and thus the stability of the system increases. But when a fault occurs on one feeder, the parallel feeders cannot be protected by non directional OC relays only. It is necessary to use directional OC relays (DOCR) also and to grade them for selective tripping. For radial systems with sources on both sides also DOCRs are necessary to protect the transmission lines. Two directional relays would be required at each load connection point, one for each direction. Modern multi area power systems, despite of having so many advantages, causing increase in complexity in power protection schemes, since the direction of fault current to the fault point may be from any end.

Due to the greater length and exposure to atmospheric conditions, the probability of fault occurrence on the transmission lines is much more. This calls for complicated protective schemes compared to simple cases of alternators and transformers. The requirements of line protection are:

- When a fault occurs, the circuit breaker closest to the fault location should be opened while all other circuit breakers remaining in closed position.
- In case the nearest circuit breaker fails to open, back up protection should be provided.
- The operating time of the relay should be as less as possible in order to prevent the system to become unstable with unnecessary tripping of circuits, i.e., sympathy trips.

Coordination of protective devices such as DOCRs became more important nowadays. DOCRs are two types basically, instantaneous type (time independent) and inverse OC unit (time dependent). The time dependent type has two values to be set, the pickup current value or plug setting (PS), and the time dial setting (TDS). The PS is the minimum current value for which the relay operates. The TDS defines the operating time T of the relay for each current value, and is generally given as a curve, T versus I/PS where I is the relay current (overload and/or fault) (Talaat et al. 2014). Obtaining selective tripping by optimizing its settings, i.e., TDS and PS, is nothing but the coordination of DOCR.

The rest of this paper is organized as follows. The problem description part of the coordination of DOCRs is described in Sect. 3 and problem formulation in Sect. 4. The OCDE algorithm is explained in Sect. 5. Experimental settings and results are discussed in Sect. 6. The conclusions of the present study are given at the end, in Sect. 7.

2 Problem description

The protective relays operate only when an abnormal or intolerable condition occurs, with sufficient indication to permit their operation. Thus protection does not mean total prevention, but rather, minimizing the duration of the trouble and limiting the damage, outage time, and related problems that may result otherwise (Lewis Blackburn and Domin Thomas 2014). For proper operation of DOCRs TDS and PS are to be set to their optimal values.

2.1 Types of DOCRs based on inverse characteristics

There are basically three types of OC relays, i.e., instantaneous OC relay, definite time OC relay and inverse time OC relay. Instantaneous OC relay do not have any intentional time delay. That means these relays have only PS and do not have TDS. Definite time OC relay trips at an adjustable amount of time, after it picks up. Inverse time OC relay achieves the requirement that the more severe a fault is, the faster it should be cleared to avoid damage to the apparatus. Inverse definite minimum time (IDMT) OC relay having the characteristics as being inverse in the initial part and tending to a definite minimum operating time as the current becomes very high (Anderson 1999). Whatever may be the magnitude of fault current, these relays do not operate until certain time delay. This minimum time delay is necessary to decide whether the disturbance is a momentary disturbance or sustains for longer time.

These IDMT relays, as their name indicates, operate faster by high fault currents than lower currents as shown

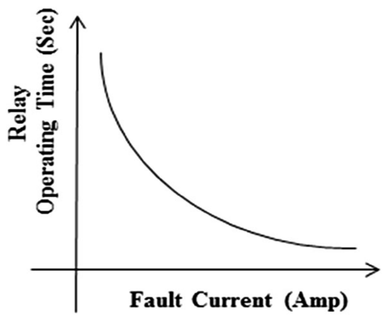

Fig. 2 Current time characteristics curve of IDMT relay

in Fig. 2. These relays show four types of characteristics. Those are normally inverse, inverse, extremely inverse and long time inverse characteristics for which time current characteristics are shown in Fig. 3. Relays with different inverse characteristics are explained below.

2.1.1 Normal (or standard) inverse time OC relay:

This relay is used when fault current is independent of fault location and depends on fault generation. This is the relay which shows small change in time compared to the remaining types for a unit change in current. These relays are applicable especially when the fault magnitude is principally contingent on the generating capacity at the time of fault. A grading margin of 0.4–0.5 s may be required for the uncertainty of the necessary operating time and the operating time.

2.1.2 Very inverse time OC relay:

This relay has more inverse characteristics compared to that of normal inverse time OCR. This relay is used when the fault current depends on the fault location, i.e., where the fault current reduces with increase in the distance from source and particularly effective with ground faults because of their steep characteristics. The grading margin will be decreased to a value in the range from 0.3 to 0.4 s when these relays are used.

2.1.3 Extremely inverse time OC relay:

This relay gives more inverse characteristics compared to that of very inverse and normal inverse OC relay. The operating time is almost inversely proportional to the square of the current. It is possible to use a lesser time delay in spite of high switching-in currents if these extremely inverse OC relays are used. This relay is appropriate for protection of distribution feeders with peak currents on switching in and especially suitable for grading and to coordinate with the fuses and re closes.

2.1.4 Long time inverse OC relay:

The major application of this relay is to use as a backup relay for earth fault protection. It waits for comparatively long time to give trip signal when a fault occurs.

Fig. 3 Time current curves for different inverse characteristics (Jiguparmmar 2013)

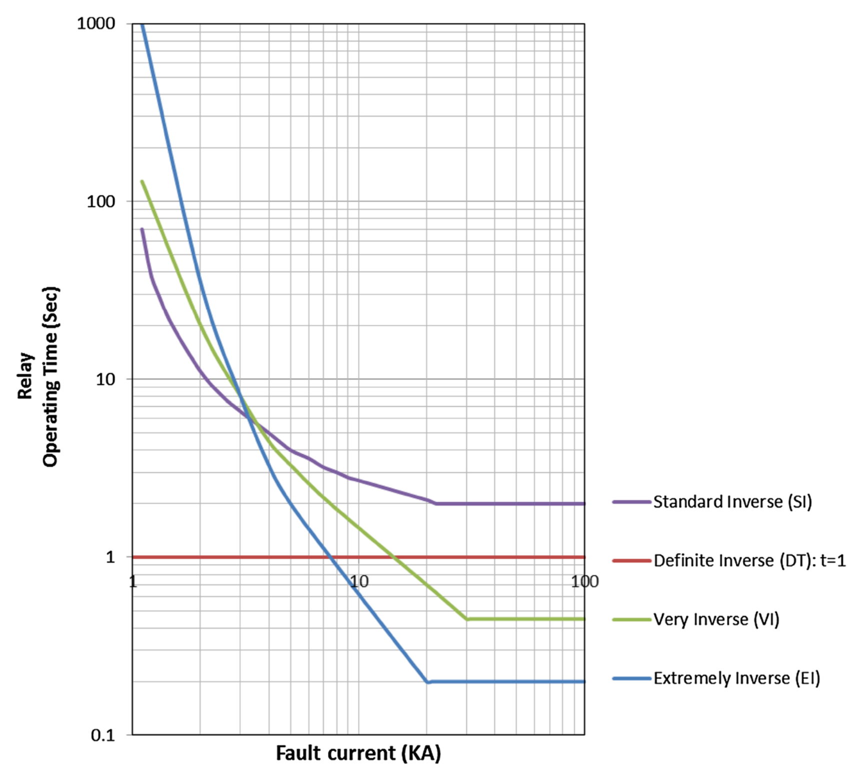

Table 1 Configuration of IEEE 4-bus system

No. of generators	No. of relays and decision variables	CTI value
2	8 (16)	0.3

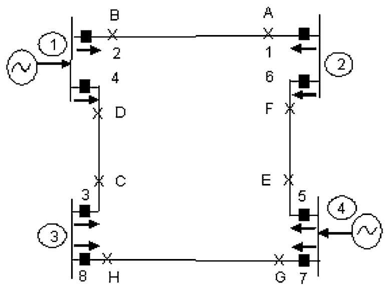

Fig. 4 IEEE 4-bus model

Here in our present study, optimum settings have been derived using OCDE1 and OCDE2 algorithms for the DOCRs with very inverse and long time inverse characteristics and also with normal and very inverse, i.e., primary relays will be considered with normal inverse and the back-up relays with very inverse), and with normal and long time inverse, i.e., primary relays will be considered with normal inverse and the back-up relays with long-time inverse. These characteristics have been explained in detail in Sect. 3.2.

2.2 Solution approach

The optimal values for TDS and PS have been found for the DOCRs with different inverse characteristics using OCDE algorithms OCDE1 and OCDE2 to know which type of relays give minimum objective function value. This paper gives an explanation of the minimization of objective function for IEEE-4 bus model with these proposed algorithms for the relays with different types of inverse characteristics along with a comparison among the results. The OCDE algorithm utilizes the benefits of opposition based learning and utilizes a dynamic scale factor generated by chaotic sequence.

3 Problem formulation

3.1 Test case: IEEE-4 bus system

The above described algorithms are simulated over IEEE-4 bus system test case. The configuration of test case is shown in Table 1. For coordination problem of IEEE 4-bus model, value of each of N_{cl} and N_{far} is eight (equal to number of relays or twice the lines). Accordingly, there are 16 decision variables (two for each relay) in this problem i.e., TDS1–TDS8 and PS1–PS8. The four bus system can be visualized as shown in Fig. 4.

Table 2 Values of K, α and β which determine degree of inversion of the IDMT curve

Type of curve	K	α	β
Normally inverse	0.14	0.02	2.97
Very inverse	13.5	1	1.5
Extremely inverse	80	2	0.808
Long time inverse	120	1	13.33

3.2 Formulation

As described earlier, the DOCR has two decision variables, i.e., TDS and PS. Relay operating time is a function of these TDS, PS and I_{relay} and it has been expressed in the following equation.

$$T = \frac{0.14TDS}{\left(\frac{I_{Relay}}{PS}\right)^{0.02} - 1} \quad (1)$$

where T is the operating time in seconds, I_{Relay} is the current seen by the relay.

This Eq. (1) gives the operating time of the relay which has normal inverse characteristics. In the present application reported in this paper, the characteristic of DOCR is expressed with the following mathematical equation complies with the BS142 and IEC 60255standards.

$$T = \frac{K\left(\frac{T_{10PS}}{\beta}\right)}{\left(\frac{I_f}{PS.CT_{primary\_rating}}\right)^{\alpha} - 1} \quad (2)$$

where T_{10PS} is the operating time at 10PS, I_f is the primary actual current in Amperes, K, α and β are the constants, by varying which the degree of inversion can be changed. Values of these constants which lead to four different standard curves as given in Table 2. These values determine degree of inversion of the IDMT curve. By comparing Eqs. (1) and (2), we can obtain following two relationships as both of them give the same operating time of the relays.

$$\frac{T_{10PS}}{\beta} = TDS$$

$$I_{relay} = \frac{I_f}{CT_{primary\_rating}}$$

Among the three constants, the constant 'α' affects the Eq. (2) more. The term $\frac{I_f}{PS.CT_{primary\_rating}}$ present in the denominator of the equation gives the factor by how much the fault current magnitude exceeds the start current level setting PS. It also indicates the level of nonlinearity as it is with powers of constant α. As the operating time is inversely proportional to this term, based on α value, operating time is very less for a relay with extremely inverse characteristics than that with normally inverse characteristics.

Objective function (OBJ) to be minimized for optimum operation is given in the following equation.

$$OBJ = \sum_{i=1}^{8} T^{i}_{primary\_close\_in} + \sum_{j=1}^{8} T^{j}_{primary\_far\_bus} \quad (3)$$

where

$$T^{i}_{primary\_close\_in} = \frac{0.14.TDS^{i}}{\left(\frac{I^{i}_{f}}{PS^{i}.CT^{i}_{primary\_rating}}\right)^{0.02} - 1}$$

$$T^{j}_{primary\_far\_bus} = \frac{0.14 \times TDS^{j}}{\left(\frac{I^{j}_{f}}{PS^{j}.CT^{j}_{primary\_rating}}\right)^{0.02} - 1}$$

Constraints for the model are:

(i) *Bounds on variables TDSs*

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

where, i varies from 1 to 8 (N_{cl}).

(ii) *Bounds on variables PSs*

$PS^{j}_{min} \leq PS^{j} \leq PS^{j}_{max}$ where, j varies from 1 to 8 (N_{far}).

(iii) *Limits on primary operation times*

This constraint imposes constraint on each term of objective function to lie between 0.05 and 1.0.

(iv) *Selectivity constraints*

The value of CTI is 0.3. There are nine selectivity constraints for this problem according to the primary and its corresponding backup relay pairs of the test model. The selectivity constraint is as follows

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

where

$$T^{i}_{backup} = \frac{0.14 \times TDS^{x}}{\left(\frac{I^{i}_{f}}{PS^{x}.CT^{i}_{primary\_rating}}\right)^{0.02} - 1}$$

$$T^{i}_{primary} = \frac{0.14 \times TDS^{y}}{\left(\frac{I^{i}_{f}}{PS^{y}.CT^{i}_{primary\_rating}}\right)^{0.02} - 1}$$

The values of constants I_f and $CT_{primary\_rating}$ for the test model have been given in Table 3 and Table 4. Table 3 is with respect to the $T^{i}_{primary\,close\,in}$ and $T^{j}_{primary\,far\,bus}$ and Table 4 is with respect to the T^{x}_{backup} and $T^{y}_{primary}$.

Table 3 Values of I_f and $CT_{primary\_rating}$ for test model with $T^{i}_{primary\_close\_in}$ and $T^{j}_{primary\_far\_bus}$

$T^{i}_{primary\_close\_in}$			$T^{j}_{primary\_far\_bus}$		
TDS^{i}	I^{i}_{f}	$CT^{i}_{primary\ rating}$	TDS^{j}	I^{j}_{f}	$CT^{j}_{primary\ rating}$
TDS^{1}	20.320	0.480	TDS^{2}	23.750	0.4800
TDS^{2}	88.850	0.480	TDS^{1}	12.480	0.4800
TDS^{3}	13.60	1.1789	TDS^{4}	31.920	1.1789
TDS^{4}	116.810	1.1789	TDS^{3}	10.380	1.1789
TDS^{5}	116.700	1.5259	TDS^{6}	12.070	1.5259
TDS^{6}	16.670	1.5259	TDS^{5}	31.920	1.5259
TDS^{7}	71.700	1.2018	TDS^{8}	11.00	1.2018
TDS^{8}	19.270	1.2018	TDS^{7}	18.910	1.2018

Table 4 Values of I_f and $CT_{primary\_rating}$ for test model with T^{x}_{backup} and T^{y}_{backup}

T^{i}_{backup}			$T^{i}_{primary}$		
Relay	I^{i}_{f}	$CT^{i}_{primary\ rating}$	Relay	I^{j}_{f}	$CT^{j}_{primary\ rating}$
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

4 Differential evolution algorithm

Differential evolution (DE), an evolutionary search strategy was proposed by Storn and Price in 1995 (Storn and Price 1995). DE is a stochastic, population based search technique, which is capable of handling multimodal, nonlinear and non-differentiable and functions. It is easy to implement, requires few, easily chosen control parameters and exhibits fast convergence. The population size, the crossover rate Cr and the scale factor F are the three control parameters of DE. The scale factor F is a positive real number that controls the rate at which the population evolves. The crossover rate, Cr∈ [0, 1], is a user-defined value that controls the fraction of parameter values that are copied from the mutant. Experimental results have proved that performance of DE is better than many other well known evolutionary algorithms (EAs) (Storn 1999) Storn and Price 1997. While DE shares similarities with other EAs, it differs significantly in the sense that in DE, distance and direction information is used to guide the search process (Engelbrecht 2005).

DE is similar to GAs in that a population of individuals is used to search for an optimal solution. The main difference between GAs and DE is that, in GAs, mutation is the result of small perturbations to the genes of an individual while in DE mutation is the result of arithmetic combinations of individuals. At the beginning of the evolution process, the mutation operator of DE favors exploration. As evolution progresses, the mutation operator favors exploitation. Hence, DE automatically adapts the mutation increments (i.e., search step) to the best value based on the stage of the evolutionary process. Mutation in DE is therefore not based on a predefined probability density function (Karaboga and Okdem 2004).

4.1 Working of basic differential evolution algorithm

In a population of potential solutions within an n-dimensional search space, a fixed number of vectors are randomly initialized, then evolved over time to explore the search space and to locate the minima of the objective function. At each iteration, called generation, new vectors are generated by the combination of vectors randomly chosen from the current population (mutation). The outcoming vectors are then mixed with a predetermined target vector. This operation is called recombination and produces the trial vector. Finally, the trial vector is accepted for the next generation if and only if it yields a reduction in the value of the objective function. This last operator is referred to as a selection.

The mutant vector is generated by using the Eqn.

$$V_{i,g} = X_{r_1,g} + F * (X_{r_2,g} - X_{r_3,g}) \quad (4)$$

where r_1, r_2, r_3 $\in$ {1, 2,…, NP}are randomly chosen integers, different from each other and also different from the running index i.

The trial vector is generated by using the Eqn.

$$u_{j,i,G+1} = \begin{cases} v_{j,i,G+1} & if \quad rand_j \le Cr \vee j = k \\ x_{j,i,G} & otherwise \end{cases} \quad (5)$$

where j, k ∊ {1,…, D} k is a random parameter index, chosen once for each i.

4.2 Working of opposition based chaotic DE (OCDE) algorithm

The opposition based chaotic differential evolution algorithm is a simple variant of basic DE algorithm proposed by Thanagaraj et al. (Chelliah et al. 2014). Two versions of OCDE algorithms namely OCDE1 and OCDE2 are used in this study. The OCDE algorithms use opposition based learning (Rahnamayan et al. 2008) for generating initial population and dynamically adapt the scale factor F using chaotic sequence.

(i) *Generation of initial population:*

According to the literature review about population initialization, random number generation, in absence of a priori knowledge, is the most commonly used choice to create an initial population. On the other hand, opposition based learning (OBL), makes use of the domain knowledge in the initial step itself and helps in producing fitter individuals from the very beginning of the search.

In OCDE1 and OCDE2, a population of 2 N individuals is generated using uniformly distributed random numbers and their opposite individuals, out of which N best individuals are selected as initial population.

(ii) *Dynamic scale factor F:*

In OCDE1, the scale factor F makes use of the following equation:

$$F^{t+1} = \eta * F^t * [1 - F^t]$$

where η is the chaos attractor.

In OCDE2, the chaotic scale factor is applied stochastically according to the user defined parameter Ps.That is:If (rand(0,1) > Ps)

$$F^{t+1} = \eta * F^t * [1 - F^t].$$

Else $F(t) = 0.5$;

Where rand(0,1) represents a uniformly distributed number between 0 and 1.

For more details about the algorithms OCDE1 and OCDE2, the readers can refer (Chelliah et al. 2014). The C++ pseudo code of the OCDE algorithms is given in Fig. 5.

5 Experimental settings and result analysis

5.1 Experimental settings

Population size, crossover rate Cr and scaling factor F are the main parameters of DE. For all the cases the population size has been taken as 50. Crossover rate Cr has been taken as 0.5 and scaling factor F is fixed at 0.5 for classical DE. F follows a chaotic sequence for OCDE schemes.

For each algorithm, when one of the following conditions is satisfied, terminating the search process is the stopping criteria.

- Reaching the maximum number of generations (assumed 10,000 generations).

```
1.      Initialize the values of DE parameters: D – Dimension of the problem, N – population size, Cr – crossover rate, F – scale
    factor, MAXITE – maximum number of iterations, nfe – number of function evaluations
2.  Input lower and upper bounds of decision variables xmin[j] and xmax[j], where j = 1 to D
3.  Initialize the population of N individuals (Xi , i = 1 to N) using uniformly distributed random numbers
    for (i=0; i<N; i++)
        for(j=0; j<D; j++)
            x[i][j] = (xmax[j]-xmin[j])*U(0,1) + xmin[j];
    where U(0,1) is the uniformly distributed random number between 0 and 1
4.  Generate N opposite individuals of Xi's using opposition based initialization
    for (i=0; i<N; i++)
        for(j=0; j<D; j++)
        o[i][j] = xmin[j]+ xmax[j- x[i][j];
5.Evaluate the fitness function values of those 2N individuals
    for (i=0; i<N; i++)
    {
        fitness_evaluation(Xi); nfe ++;
        fitness_evaluation(Oi); nfe ++;
    }
6.Iteration t =1;
7.While (t < MAXITE)
  {
      a.  Defining scale factor
          //***** For OCDE 1 *****//
          Generate chaotic scale factor using logistic mapping
              F(t) = η * F(t−1) * [1 − F(t−1)]
         //***** For OCDE 2 *****//
         Generate chaotic scale factor with user defined probability
         if (U(0,1) > Ps)
              F(t) = η * F(t−1) * [1 − F(t−1)]
        else F(t) = 0.5;
      where Ps – probability of scale factor

      b.  for (i=0; i < N; i++)
          {
              (i)    Select randomly three distinct integers r1, r2, r3 ∈ [0, N-1], different from the running index i;
              (ii)   Generate a donar vector using the mutation strategy with chaotic scale factor: Vi = Xr1 + F (t)*(Xr2 – Xr3);
              (iii)  Generate a trial vector Ui, by using the crossover operation (eqn. (5) between the target vector Xi and the
                     donar vector Vi;
              (iv)   Evaluate the fitness function value of Ui, f (Ui); nfe++;
              (v)    if (f (Ui) < f (Xi))
                         Replace Xi by Ui;
                     else
                         The copy of Xi will move to the next generation;
          }
      c.  if |fmax-fmin| < 0.0001
              terminate the program;
          else
              t++;
          where fmax and fmin are the maximum and minimum function values.
  } // while loop ends here
8.        Print the optimimum results
```

Fig. 5 Pseudo code of OCDE algorithm (Chelliah et al. 2014)

- $|f_{\max} - f_{\min}| < 10^{-4}$ where f is the value of OBJ.

A total of 30 runs were conducted for each experimental setting and the best solution throughout the run was recorded as global optimum.

5.2 Results analysis

Objective function values obtained by DE, OCDE1 and OCDE2 are compared in (Chelliah et al. 2014) with the

Table 5 Optimal design variables, objective function values (OBJ) and number of function of evaluations (NFE) of IEEE 4-bus model by DE and OCDE algorithms for normal inverse characteristics

Decision variable	DE	OCDE1	OCDE2	Decision variable	DE	OCDE1	OCDE2
TDS 1	0.05	0.05	0.05	PS 1	1.2734	1.25	1.25
TDS 2	0.2248	0.21217	0.21216	PS 2	1.25	1.4999	1.5
TDS 3	0.05	0.05	0.05	PS 3	1.2500	1.25	1.25
TDS 4	0.1515	0.15157	0.15157	PS 4	1.4997	1.4999	1.5
TDS 5	0.1264	0.1262	0.12623	PS 5	1.4997	1.5	1.5
TDS 6	0.05	0.05	0.05	PS 6	1.25	1.25	1.25
TDS 7	0.1337	0.13378	0.1337	PS 7	1.5	1.5	1.5
TDS 8	0.0500	0.05	0.05	PS 8	1.25	1.25	1.25
OBJ	3.6774	3.66744	3.66742				
NFE	95,400	36,050	27,600				
Time (s)	11.60	1.84	1.68				

Table 6 Optimal design variables, OBJ and NFE of IEEE 4-bus model by DE and OCDE algorithms for very inverse characteristics

Decision variable	DE	OCDE1	OCDE2	Decision variable	DE	OCDE1	OCDE2
TDS 1	0.050003	0.050007	0.05	PS 1	1.25001	1.25	1.25001
TDS 2	0.635836	0.635533	0.635464	PS 2	1.49903	1.49973	1.49985
TDS 3	0.05	0.05	0.05	PS 3	1.25	1.25	1.25
TDS 4	0.285607	0.261809	0.262019	PS 4	1.3855	1.49986	1.49874
TDS 5	0.193027	0.187197	0.187052	PS 5	1.45863	1.49898	1.49998
TDS 6	0.05	0.05	0.05	PS 6	1.25	1.25001	1.25
TDS 7	0.18545	0.18638	0.185318	PS 7	1.4991	1.49265	1.5
TDS 8	0.05	0.050005	0.05	PS 8	1.25001	1.25001	1.25
OBJ	1.80105	1.79975	1.79958				
NFE	108,450	32,050	43,550				
Time (s)	0.68	0.04	0.28				
SR	100	100	100				

Table 7 Optimal design variables, OBJ and NFEof IEEE 4-bus model by DE and OCDE algorithms for long time inverse characteristics

Decision variable	DE	OCDE1	OCDE2	Decision variable	DE	OCDE1	OCDE2
TDS 1	0.05	0.05	0.05	PS 1	1.25	1.25006	1.25
TDS 2	0.198494	0.198531	0.198494	PS 2	1.5	1.49978	1.5
TDS 3	0.05	0.05	0.05	PS 3	1.25	1.25	1.25
TDS 4	0.066591	0.066875	0.066589	PS 4	1.49987	1.49407	1.49987
TDS 5	0.050002	0.05	0.05	PS 5	1.25	1.25001	1.25
TDS 6	0.05	0.05	0.05	PS 6	1.25	1.25002	1.25
TDS 7	0.061115	0.056153	0.056153	PS 7	1.39289	1.4997	1.49968
TDS 8	0.05	0.05	0.05	PS 8	1.25	1.25	1.25
OBJ	8.46383	8.46009	8.45985				
NFE	61,500	13,100	32,900				
Time (s)	0.24	0.04	0.12				
SR	100	100	100				

values obtained previously by GA, SOMA, RST2, and SOMGA for the IEEE standard bus models, reported in (Dipti 2007), PSO-W, PSO-C, LXPSO-W, and LXPSO-C for the same models, reported in (Deep Kusum and Bansal Jagdish Chand 2009), MDE4 and MDE5 (Thakur 2007). It has already been proved that OCDE1 and OCDE2 are the

Table 8 Optimal design variables, OBJ and NFE of IEEE 4-bus model by DE and OCDE algorithms for normal and very inverse characteristics

Decision variable	DE	OCDE1	OCDE2	Decision variable	DE	OCDE1	OCDE2
TDS 1	0.05	0.050001	0.05	PS 1	1.25	1.25002	1.25
TDS 2	0.751517	0.751517	0.751512	PS 2	1.49999	1.49999	1.5
TDS 3	0.050001	0.05	0.05	PS 3	1.25	1.25	1.25
TDS 4	0.317962	0.317958	0.317955	PS 4	1.49998	1.5	1.5
TDS 5	0.231032	0.23103	0.231028	PS 5	1.5	1.5	1.5
TDS 6	0.05	0.05	0.05	PS 6	1.25	1.25002	1.25
TDS 7	0.220259	0.220251	0.220251	PS 7	1.49996	1.5	1.5
TDS 8	0.05	0.05	0.05	PS 8	1.25001	1.25	1.25
OBJ	6.97471	6.97462	6.97453				
NFE	22,700	14,300	16,600				
Time (s)	1	0.73333	0.73333				
SR	100	100	100				

Table 9 Optimal design variables, OBJ and NFE of IEEE 4-bus model by DE and OCDE algorithms for normal and long time inverse characteristics

Decision variable	DE	OCDE1	OCDE2	Decision variable	DE	OCDE1	OCDE2
TDS 1	0.050001	0.050002	0.05	PS 1	1.25	1.25	1.25
TDS 2	0.084546	0.084546	0.084545	PS 2	1.5	1.5	1.5
TDS 3	0.050001	0.05	0.05	PS 3	1.25	1.25	1.25
TDS 4	0.05	0.05	0.05	PS 4	1.25003	1.25003	1.25
TDS 5	0.050001	0.050004	0.05	PS 5	1.25004	1.25	1.25
TDS 6	0.050002	0.05	0.05	PS 6	1.25	1.25	1.25
TDS 7	0.05	0.05	0.05	PS 7	1.25	1.25001	1.25
TDS 8	0.050001	0.05	0.05	PS 8	1.25	1.25	1.25
OBJ	2.07942	2.07939	2.07938				
NFE	7,750	6,200	4,700				
Time (s)	0.4	0.3333	0.29				
SR	100	100	100				

best algorithms to optimize the settings of DOCRs in IEEE standard bus models. Especially OCDE2 gives lowest value for objective function for IEEE 4-bus model (Chelliah et al. 2014). This can be seen in Table 5 when the algorithms DE, OCDE1 and OCDE2 are applied for normal inverse characteristics. But in this present study, these algorithms have been applied to the IEEE 4-bus model again but for very inverse, long time inverse, normal and very inverse and for normal and long time inverse characteristics. The respective values of optimum settings TDS and PS for each relay of the model along with the objective function, NFE, time in seconds and success rate (SR) have been tabulated in Table 6, Table 7, Table 8 and Table 9 respectively.

Table 6 gives the value of objective function for very inverse characteristics which is very less among all the other characteristics for this test model. But sometimes this may lead to sympathy trips, i.e., before the operation of any backup relay, some other relays may operate or before the operation of a primary relay, either its backup or any other relay may operate. This is because of the lesser operating times for all the relays.

After these relays with very inverse characteristics, relays with normal and long time inverse characteristics, as shown in Table 8, give less objective function value. This means backup relays can be chosen with long time inverse characteristics and primary relays can be left to be with normal inverse characteristics. This type of selection of relays is the best among the all different characteristics those are tested on the relays of test model.

6 Conclusion

The optimization model of coordination of DOCRs turns out to be highly constrained and nonlinear in nature.

Coordination of the relays with different types of characteristics based on the degree of inversion has been considered as the optimization problem in the present study. Setting the values of *TDS* and *PS*, minimizing the objective function etc. are involved in this study. To deal with such problems efficient optimization techniques are needed. In the present study, OCDE1 and OCDE2 are used for this purpose. The proposed algorithms are applied over test case i.e., IEEE 4-bus model. The results showed that the proposed algorithms are capable of finding superior *TDS* and *PS* settings of the relays with different inverse characteristics, i.e., very inverse, long time inverse, normal and very inverse and for normal and long time inverse characteristics. From this study it can be said that the relays with normal and long time inverse characteristics give lesser value for objective function which means backup relays can be chosen with long time inverse characteristics and primary relays with normal inverse characteristics. This makes the system reliable and effective.

References

Anderson PM (1999) Power system protection, IEEE press series on power engineering. McGraw-Hill, New Delhi, pp 250–254

Blackburn JL, Domin TJ (2014) Protective relaying: principles and applications *CRC* Press, Taylor & Francis group Fourth Edition

Chelliah TR, Thangaraj R, Allamsetty S, Pant M (2014) Coordination of directional over current relays using opposition based chaotic differential evolution algorithm. Int J Electr Power Energy Syst 55:341–350

Deep K, Bansal JC (2009) Optimization of directional over current relay times using laplace crossover particle swarm optimization (LXPSO). In Proc nature & biologically inspired computing, 2009. NaBIC 2009. World Congress; December 2009 p. 288–293

Dipti (2007) Hybrid genetic algorithms and their applications. PhD thesis, Deptartment of Mathematics, Indian Institute of Technology Roorkee, Roorkee, India; 2007

Engelbrecht AP (2005) Fundamentals of computational Swarm Intelligence. John Wiley & Sons Ltd, England

Jiguparmmar (2013) "Types and applications of over current relay (1)", *Protection, Transmission and Distribution*, Feb, 2013

Karaboga D, Okdem S (2004) A simple and global optimization algorithm for engineering problems: differential evolution algorithm. Turk J Elec Engin 12(1):53–60

Rahnamayan S, Tizhoosh HR, Salama MMA (2008) Opposition-based differential evolution. IEEE Trans Evol Comput 12(1): 64–79

Storn R (1999) System design by constraint adaptation and differential evolution. IEEE Trans Evol Comput 3:22–34

Storn R, Price K (1995)"Differential evolution—a simple and efficient adaptive scheme for global optimization over continuous spaces", Technical Report, International Computer Science Institute, Berkley

Storn R, Price K (1997) Differential Evolution: a simple and efficient heuristic for global optimization over continuous spaces. J Glob Optimization 11:341–359

Talaat HEA, Abdelaziz AY, Nosseir AI, Hajjar AA (2014) Optimal coordination of overcurrent relays using linear programming. Available at http://faculty.ksu.edu.sa/htalaat/Publications/ downloaded on 15th April 2014

Thakur M (2007) New Real coded genetic algorithms for global optimization, Ph. D thesis, Department of Mathematics, Indian Institute of Technology Roorkee, India