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Optimal coordination of directional over current relays using evolutionary programming

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Abstract: Co-ordination of directional over current relays (DOCR) requires the selection and setting of relays so as to sequentially isolate only that portion of the power system where an abnormality has occurred. The problem of coordinating protective relays in electrical power systems consists of selecting suitable settings such that their fundamental protective function is met, given operational requirements of sensitivity, selectivity, reliability and speed. Directional over current relays are best suited for protection of an interconnected sub-station transmission system. One of the major problems associated with this type of protection is the difficulty in coordinating relays. To insure proper coordination, all the main/back up relay pairs must be determined. This paper presents an effective algorithm to determine the minimum number of break points and main/back up relay pairs using relative sequence matrix (RSM). A novel optimization technique based on evolutionary programming was developed using these main/back up relay pairs for directional over current relay coordination in multi-loop networks. Since the problem has multi-optimum points, conventional mathematics based optimization techniques may sometimes fail. Hence evolutionary programming (EP) was used, as it is a stochastic multi-point search optimization algorithm capable of escaping from the local optimum problem, giving a better chance of reaching a global optimum. The method developed was tested on an existing 6 bus, 7 line system and better results were obtained than with conventional methods.

Keywords: power system protection; protection coordination; directional over current relay; evolutionary programming; optimization technique

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The main function of power system protection is to isolate only the faulty component or a minimal set of components as soon as the fault occurs. Since the main protection system may sometimes fail (relay fault or breaker fault), there must be back up either in the same station (local back up) or in neighboring lines (remote back up) with time delay according to the selectivity requirement. The determination of the time delays of all the back up relays, in the main/back up relay pairs, is known as coordination of the protection system. Generally, in meshed networks with multiple generation buses, directional protection relays are used. Among those, directional over current relays (DOCR) are the major protection devices in distribution systems. The major problems associated with DOCR are relay setting calculations and coordination.

Since it is very difficult to find a proper relay setting to meet the requirements by traditional methods, partial optimization of OC relay settings based on predetermined pick-up current settings were developed[5-6]. Since they cannot take all system conditions into consideration the results may get trapped at local optimum relay settings. Therefore some of the different multi-point search algorithms such as genetic algorithms[7-10] and evolutionary programming (EP)[9] are used to reach global optimum in a better way. Thus recently the problem of coordinating DOCR in power systems was stated and solved in the framework of optimization theory[7-10]. For this paper, a novel approach using EP for optimal coordination of DOCR was developed. The work done involved the following two stages:

1) Determination of a minimum set of break points and the main/back up relay pairs using relative sequence matrix (RSM).

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2) Development of a DOCR coordination algorithm based on EP using the main/back up relay pairs determined in 1).

Thus an effective "optimal" solution to the co-ordination problem was obtained.

1 DOCR coordination

Directional over current relays are best suited for protection of interconnected sub-system transmission systems or as secondary protection of main transmission systems. Co-ordination of these protective relays involves their selection and setting so as to sequentially isolate only that portion of the power system where the abnormality occurs. To achieve this isolation, it is necessary to set protective devices so that only the device nearest to the fault opens and isolates the faulty circuit from the system. The problem of coordinating protective relays in electrical power systems consists of selecting suitable settings such that their fundamental protective function is met given requirements of sensitivity, selectivity, reliability and speed. The setting of DOCRs has to satisfy all possible network configurations subject to type and location of all possible faults.

Back up protective devices are set to operate at some predetermined time interval after the primary devices fails to operate. When remote back up protection is required, then coordination should be done for all possible main/back up relay pairs at corresponding stations. Since the relays are directional ones, the mesh should run in both directions to include all of the relays. It is necessary to determine a set of starting relays which would break all the meshes of the network when they are simultaneously open. Those relays are known as "Break Points" (BPs) [10].

Conventionally, the co-ordination of directional over current relays (DOCR) is done using interactive methods, wherein the co-ordination engineer runs different cases for distinct faults and configurations, until an acceptable solution is reached. Unfortunately the solution found by these procedures is not optimal in any strict sense, but simply the best of the possible solutions tried [5-6]. Later, optimality was obtained using conventional optimization methods like the Gauss-Seidal method. But in these methods the solution obtained may not be taken as a global optima because there is a chance of getting trapped in local optima. Hence in this proposed method EP which gives global optima is used to optimize the problem.

2 Development of optimal DOCR co-ordination algorithm

The method developed for optimal co-ordination of directional over current relays consists of the following steps:

2.1 Determination of main/back up relay pairs

The relay which clears the fault in the protected section as quickly as possible is called the main relay. The relay which operates after a slight time delay, if the main relay does not operate to trip its circuit breaker, is known as the back up relay. In order to obtain proper co-ordination, it is very important to find all the main-back up relay pairs. Each main-back up relay pair is set according to the coordination interval. All main-back up relay pairs are found using break points and a relative sequence matrix [8, 10].

1) Determination of break points.

The starting points of sequences that ensure coordination are called break points. Determination of break points (BPs) yields the minimum set of relays to start the co-ordination process. They are determined using a simple loop matrix ($\boldsymbol{L}$) which is determined by using the network topology.

The simple loop matrix $\boldsymbol{L}$ is determined using the following steps:

①Formation of network graph, edges and vertices: A network graph is obtained from the network by replacing the nodes with vertices and the lines with the edges of the network. The edges are numbered from 1 to e and vertices from 1 to v.

②Numbering of relays: The relays are numbered in the correct manner. For example, if the relay on line "i" is located at the initial vertex of the edge, and is numbered as "i" then the relay at the final vertex of the edge is numbered as $e+i$.

③Formation of sub matrix $\boldsymbol{F}$: Any circuit of the graph is a linear combination of some fundamental circuits of the graph. The maximum number of circuits of any graph is $2^l - 1$. Then all simple loops of the network can be determined by considering every "g" in the interval $1 < g < 2^l - 1$. Let the binary representation of "g" contain entry 1 in the digital positions j_1, j_2, etc. Then a sub matrix $\boldsymbol{F}$ is formed by rows $j_1, j_2, \cdots$.

④Procedural steps for determination of matrix $\boldsymbol{L}$:

- The set (S) of columns $\boldsymbol{F}$ which have even numbesr of non-zero entries are determined. This set is represented as $S = \{C_j, C_i, C_k\}$. If no such column exists, the linear combination is not a simple loop and next g is considered. If $\boldsymbol{F}$ has only one row, then it is a loop.
- The second step is to select a column k of $\boldsymbol{F}$ such that k is an element of S and the $\boldsymbol{N}$ entry in the first row of that column is not zero.
- Each row i of $\boldsymbol{F}$ (i not equal to l) which has a non zero entry in column k is replaced by its sum with the first row if $\boldsymbol{F}(i,k) = \boldsymbol{F}(l,k)$. The first row is then deleted. Then the procedure is repeated from step two.
- When $\boldsymbol{F}$ contains only one row, it represents the relevant oriented circuit of the network graph. The procedure is repeated for every g in the interval $1 < g < 2^1 - 1$. Each circuit corresponds to one row of the matrix $\boldsymbol{L}$. This matrix $\boldsymbol{L}$ is called the "all circuits matrix" of the network graph.

⑤Formation of augmented matrix $\boldsymbol{L}_D$:

$$\boldsymbol{L}_D \begin{bmatrix} \boldsymbol{L}_1 & \boldsymbol{H}_2 \\ \boldsymbol{L}_2 & \boldsymbol{L}_1 \end{bmatrix},$$

where $\boldsymbol{L}_1$ is the matrix obtained by setting every -1 entry of $\boldsymbol{L}$ to zero. $\boldsymbol{L}_2$ is the matrix obtained by setting every $+1$ entry of the $\boldsymbol{L}$ to zero and then replacing every -1 by $+1$.

The break points are determined using the matrix $\boldsymbol{L}_D$. The set of columns of $\boldsymbol{L}_D$ which covers it are the break points of the network. A set of columns is said to cover the matrix $\boldsymbol{L}_D$ if each row of $\boldsymbol{L}_D$ has at least one non-zero entry in one of the columns of the chosen set. Thus break points are determined.

2) Determination of relative sequence matrix [RSM].

The sequence for setting the relays is displayed by a "relative sequence matrix" (RSM). This is determined using break points and the augmented incidence matrix, which includes all buses and in which each relay is treated as a line.

3) Determination of main-back up relay pairs.

To ensure proper coordination, all main-back up relay pairs must be determined. The main-back up relay pairs are determined using RSM and an augmented incidence matrix. The procedure is explained in the flowchart given in Fig. 1 and a Matlab coding was developed. The inputs to this program are the edge list, specifying the lines, number and the two buses to which it is incident. Thus all main/back up relay pairs can be determined.

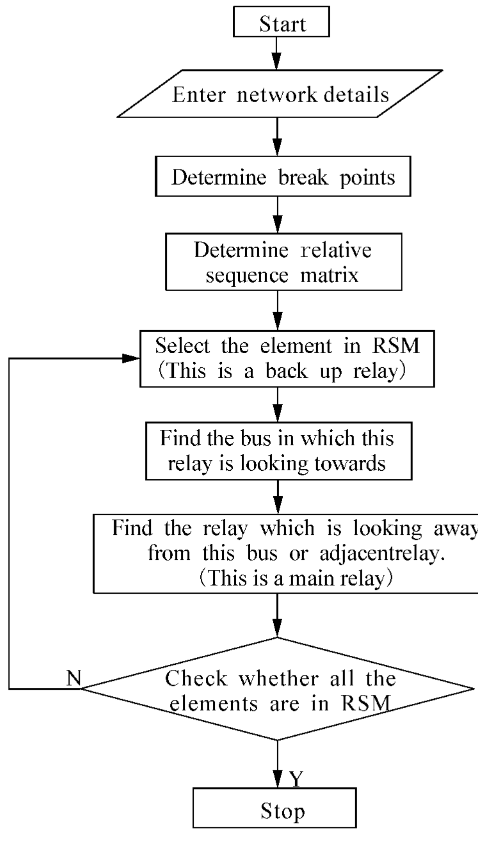

Fig. 1　Flow chart to determine the main/back up relay pairs

2.2　Formulation of optimization problem for DOCR coordination

After finding the main/back up relay pairs co-ordination is optimized. The optimization problem is stated as follows:

Objective:

To find TDS and ip for all relays such that the total operating time is minimized and the constraints are satisfied.

Objective function:

$$\text{Min}\sum_{k=1}^{n} T_k.$$

Bounded Constraints:

$$i_{p\min} \leqslant i_p \leqslant i_{p_{\max}},$$
$$\text{TDS}_{\min} \leqslant \text{TDS} \leqslant \text{TDS}_{\max},$$
$$T_{\min} \leqslant T \leqslant T_{\max}.$$

Co-ordination constraints:

$T_{\text{back up}} - T_{\text{main}} >$ co-ordination interval (C_i) for each of the main/back up relay pairs

2.3 Determining the solution to the optimization problem using an optimization technique

By using any optimization technique an optimal solution can be searched in both the subspaces (ie. TDS and i_p) simultaneously and global optima can be obtained.

The detailed flowchart for the proposed optimal DOCR coordination algorithm is given in Fig. 2.

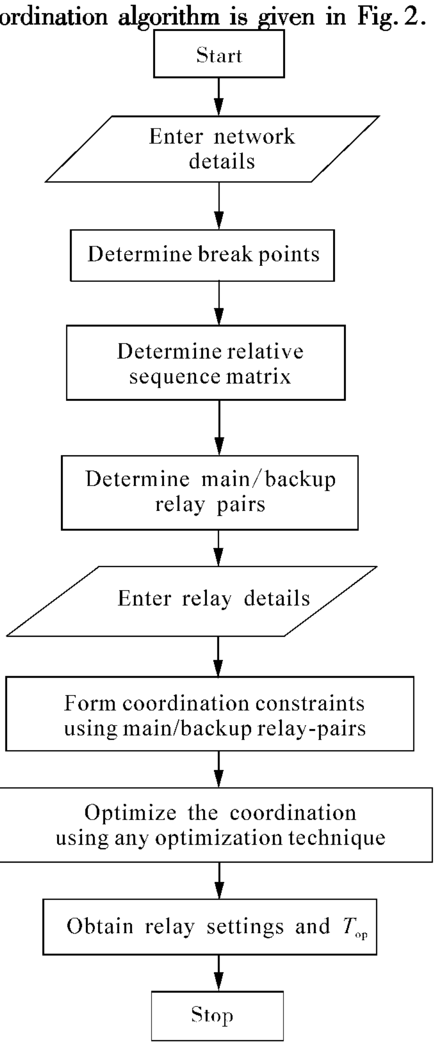

Fig. 2 Flow chart for proposed optimal DOCR coordination algorithm

3 Evolutionary programming – a solution for an optimal problem

Evolutionary programming (EP) creates artificial intelligence based optimization algorithms using the mechanics of natural selection: mutation, competition, and evolution. The process of evolution inevitably leads to the optimization of "behavior" within the context of given criteria. It has been seen that artificially simulating evolutionary processes provides a generalized problem-solving technique. Optimization with evolutionary programming has been demonstrated to proceed more efficiently and effectively than a gradient based technique. Thus EP offers a new tool for optimization of complex power system problems.

In EP, each individual competes with some other individuals in a combined population of older generations and mutations of the older generations. The results of competition are evaluated using probabilistic rules. The winners in the old generation constitute the next generation. The number of individuals in the new generation will be the same as in the old generation. The general process of EP is described as follows:

1) Initialization

The initial variable population is selected by randomly selecting $P_i = 1, 2, \cdots, m$ from sets of uniform distribution, ranging over a maximum and minimum limit where m is the population size. Then the fitness score f_i is calculated for each P_i.

2) Statistics

The maximum fitness, minimum fitness, sum of fitness and average fitness of this generation is calculated using Equ. (1), (2), (3) and (4) respectively.

$$f_{\max} = \{ f_i \mid \exists i \in \{1,\cdots,m\} \text{ such that } f_i \geqslant f_j, \forall j = \{1,\cdots,m\} \}, \tag{1}$$

$$f_{\min} = \{f_i, \exists i \in \{1,\cdots,m\} \text{ such that } f_i \leqslant f_j, \forall j = \{1,\cdots,m\}\}, \tag{2}$$

$$f_{\text{sum}} = \sum_{i=1}^{m} f_i, \tag{3}$$

$$f_{\text{avg}} = f_{\text{sum}}/m. \tag{4}$$

3) Mutation.

Each P_i is mutated and assigned to P_{i+m} in accordance with Equ. (5).

$$P_{i+m,j} = P_{i,j} + N(O,\beta(x_{j\max} - x_{j\min})\frac{f_i}{f_{\max}}),$$
$$j = 1,2,\cdots,n. \quad (5)$$

Then the corresponding fitness f_{i+m} is obtained. A combined population is formed with the old generation and the mutated old generation.

4) Competition.

Each individual P_i in the combined population has to compete with some other individuals to get its chance to be transcribed to the next generation. A weight value W_i is assigned to the individual according to the competition, as given in Equ. (6).

$$W_i = \sum_{i=1}^{q} w_{it}, \quad (6)$$

where q is competition number and is from the set {0, 1}. As P_i competes with a randomly selected individual P_r in the combined population is calculated using Equ. (7).

$$\begin{cases} w_{it} = 1, \text{ if } u < \dfrac{f_r}{f_r + f_i}, \\ w_{it} = 0, \text{ otherwise.} \end{cases} \quad (7)$$

Where, u is randomly selected from a uniform distribution set $U(0,1)$.

When all individuals P_i ($i = 1,2,\cdots,2m$) get their competitive weights, they will be ranked in descending order of their corresponding value W_i. The first m individuals are transcribed along with their corresponding fitness f_i, to be the basis of next generation.

5) Determination.

The convergence of maximum fitness to minimum fitness is checked. If the convergence condition is not obtained, then the mutation and competition process will run again. If it converges, the program will check limits of variables. If one or more variables exceed their limits, the penalty factor of these variables will be increased, and then another loop of the process will start and it will run again.

4 Proposed method of optimal co-ordination of directional over current relays using evolutionary programming

This section deals with the application of evolutionary programming for the optimal co-ordination problem as formulated. The optimization is done in the following steps.

1) Initialization.

The variables in the optimal co-ordination problem are pickup current (i_p) and time dial setting (TDS). Hence the initial variable population is selected and given as $\begin{bmatrix} i_{p11} & i_{p12} & \cdots & i_{p1m} \\ i_{p21} & i_{p22} & \cdots & i_{p2m} \\ \vdots & \vdots & \vdots & \vdots \\ i_{pn1} & i_{pn2} & \cdots & i_{pnm} \end{bmatrix}$ for pickup current $\begin{bmatrix} \text{TDS}_{11} & \text{TDS}_{12} & \cdots & \text{TDS}_{1m} \\ \text{TDS}_{21} & \text{TDS}_{22} & \cdots & \text{TDS}_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ \text{TDS}_{n1} & \text{TDS}_{n2} & \cdots & \text{TDS}_{nm} \end{bmatrix}$ for time dial setting.

Then the operating time ($\boldsymbol{T}$) is calculated for each relay and for each individual by using the relationship given in Equ. (8).

$$\boldsymbol{T} = \frac{K_1 * \text{TDS}}{\left(\left(\frac{1}{i_p}\right)^{K_2} - K_3\right)}. \quad (8)$$

Then the resultant operating time for all the relays will be in the form of $\begin{bmatrix} T_{11} & T_{12} & \cdots & T_{1m} \\ \vdots & \vdots & \vdots & \vdots \\ T_{n1} & T_{n2} & \cdots & T_{nm} \end{bmatrix}$ $T_{n1}, \cdots, T_{nm}$ the operating time for all individuals

2) Statistics.

The minimum value of total operating time is calculated for all relays as $T_{\min}(n) = \min\{T(n,i)\}$. Where $i = 1,\cdots,m$.

3) Mutation.

Each i_{pij} and $\text{TDS}_{i,j}$ is mutated and assigned to $i_{pi,j+m}$ and $\text{TDS}_{i,j+m}$ in accordance with the Equ. (9) and (10).

$$i_{pi,j+m} = i_{pi,j} + N(0,\tau(i,j)), \quad (9)$$

$$\text{TDS}_{i,j+m} = \text{TDS}_{i,j} + N(0,\psi(i,j)), \quad (10)$$

where

$$\tau(i,j) = \beta(i_{pi\max} - i_{pi\min})\frac{T_i}{T_{\min}}, \quad (11)$$

$$\psi(i,j) = \beta(TDS_{i\max} - TDS_{i\min})\frac{T_i}{T_{\min}}, \quad (12)$$

$N(0, \tau(i,j))$ is Gaussian random variable with mean 0 and variance $\tau(i,j)$,

$N(0, \psi(i,j))$ is Gaussian random variable with mean 0 and variance $\psi(i,j)$,

β is mutation scale $0 < \beta < 1$.

Then the mutated old population will be in the form of $\begin{bmatrix} i_{p1,j+1} & i_{p1,j+2} & \cdots & i_{p1,2m} \\ i_{p2,j+1} & i_{p2,j+2} & \cdots & i_{p2,2m} \\ \vdots & \vdots & \vdots & \vdots \\ i_{pn,j+1} & i_{pn,j+2} & \cdots & i_{pn,2m} \end{bmatrix}$ for pick up current and $\begin{bmatrix} \mathrm{TDS}_{1,j+1} & \mathrm{TDS}_{1,j+2} & \cdots & \mathrm{TDS}_{1,2m} \\ \mathrm{TDS}_{2,j+1} & \mathrm{TDS}_{2,j+2} & \cdots & \mathrm{TDS}_{2,2m} \\ \vdots & \vdots & \vdots & \vdots \\ \mathrm{TDS}_{n,j+1} & \mathrm{TDS}_{n,j+2} & \cdots & \mathrm{TDS}_{n,2m} \end{bmatrix}$ for time dial setting. Then the operating time is obtained for all mutated old population as $\begin{bmatrix} T_{1,j+1} & T_{1,j+2} & \cdots & T_{1,2m} \\ T_{2,j+1} & T_{2,j+2} & \cdots & T_{2,2m} \\ \vdots & \vdots & \vdots & \vdots \\ T_{n,j+1} & T_{n,j+2} & \cdots & T_{n,2m} \end{bmatrix}$. A combined population is formed with the old generation and the mutated old generation.

4) Competition.

Each individual i_p and TDS in the combined population has to compete with some other individual to get its chance to be transcribed to the next generation. For this purpose the total operating time TOP is calculated using Equ. (13).

$$TOP_j = \sum_{i=1}^{n} T_{ij}, j = 1,2,\cdots,m. \qquad (13)$$

Then for each individual case the maximum and minimum limits are checked and also the co-ordination constraints are checked. If there any violation occurs, the corresponding TOP is given with very high penalty value. All TOP values are arranged in ascending order and the corresponding i_p, *TDS* and *T* values are also arranged in the same order. Then the first m individuals are transcribed along with their corresponding T, to be the basis for next generation. 1) ~4) steps are repeated for several iterations in order to get global optimum value. After completion the minimum operating time and pick up current setting and time dial setting are obtained. The detailed flow chart for the above algorithm of optimal coordination of DOCR using EP is given in Fig. 3.

Selection of parameters for the problems solved in this paper:

The choice of parameters for EP is made on trial and error basis and given as follows:

Population size (m) = 100,

Maximum number of generations = 500.

Scaling factor;

β (initial) = 1.0,

β (step) = 0.00 ~ 0.01,

β (final) = 0.005.

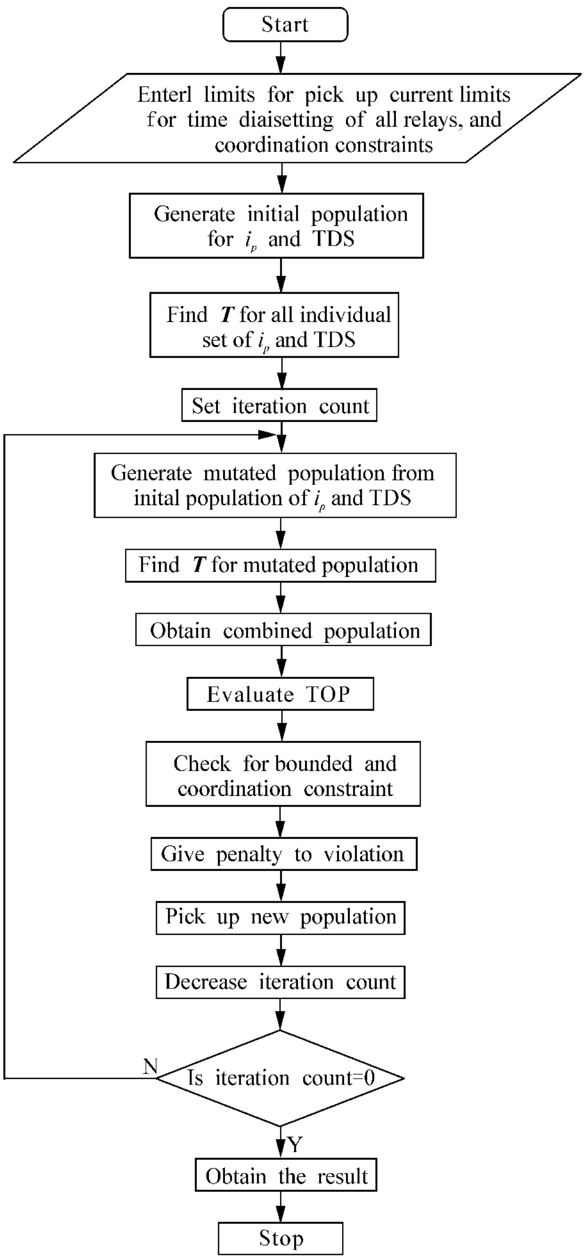

Fig. 3 Flow chart for optimal coordination of DOCR using EP

Stopping rule

During initialization, the maximum number of generations is fixed and it is checked for convergence. If the convergence condition is not reached then the mutation and competition processes will run again. An adaptive mutation scale is given to change the scaling factor for increasing the rate of convergence.

5 Illustration of developed method in sample systems

This section deals with the application of proposed optimal coordination of DOCR for a 3 bus, 3 line system (Fig. 4) taken from IEEE standards and a 6 bus, 7 line practical system (Fig. 5).

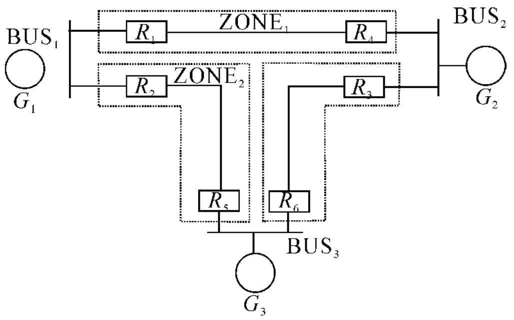

Fig. 4　3 bus, 3 line system

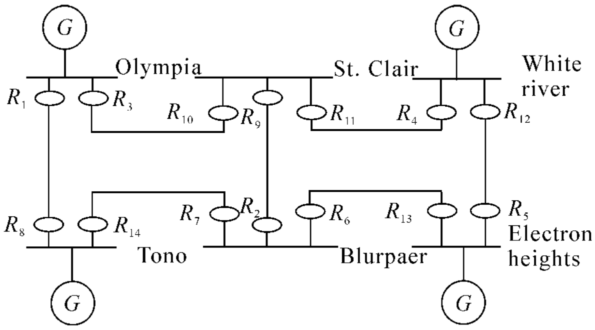

Fig. 5　Sample system 2

5.1 Sample system 1

This sample system is a three bus, three line system as shown in Fig. 4. Each protection zone corresponds to a transmission line.

Table 1　Relay data for sample system 1

Relay	Time dial setting/s		Pick up current setting/A		Operating time /s	
	Min	Max	Min	Max	Min	Max
1	0.1	0.5	295	305	0.1	12
2	0.1	0.5	195	205	0.1	12
3	0.1	0.5	235	245	0.1	12
4	0.1	0.5	55	65	0.1	12
5	0.1	0.5	75	85	0.1	12
6	0.1	0.5	195	205	0.1	12

Relay constants $K_{i1} = 0.14$, $K_{i2} = 0.02$, $K_{i3} = 1$. Coordination time interval (C_i) = 0.2/A. This system uses DOCR for ground protection.

Table 2　Fault current data for sample system 1/A

I_{11}	1 978.98
I_{12}	617.22
I_{22}	466.18
I_{23}	1 766.3
I_{32}	2 020.7
I_{33}	460.8
I_{41}	1 525.7
I_{43}	145.344
I_{51}	175
I_{53}	1 499.6
I_{61}	456.64
I_{62}	1 512.8

5.1.1 Determination of main/back up relay pairs

By using the algorithms given in the previous section, main/back up relay pairs are determined. The graph and the tree of the sample system 1 are given in Fig. 6.

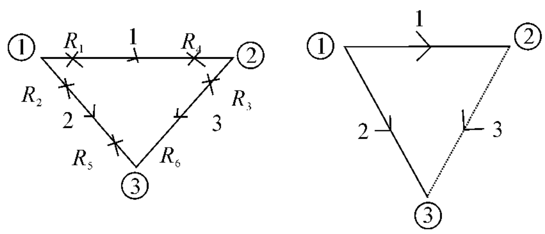

Fig. 6　The graph and the tree of the sample system 1

For this graph

e = number of elements (lines) = 3,

v = number of nodes = 3,

b = number of tree branches = $V - 1 = 3 - 1 = 2$,

l = number of links or chords = $e - V + 1 = e - b = 3 - 2 = 1$.

For this system node 3 is taken as reference. The details about this network are given as the input to the Matlab program for determining the main / back up relay pairs and the following results are obtained.

Inputs to the program:

EFT = matrix containing elements which are connecting from bus and to bus = $\begin{bmatrix} 1 & 1 & 2 \\ 2 & 1 & 3 \\ 3 & 2 & 3 \end{bmatrix}$,

$e = 3$ (Number of lines or elements),

$v = 3$ (Number of nodes),

$V = 3$ (Reference node).

Output of the program:

$$A = \text{incidence matrix} = \begin{bmatrix} 1 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix},$$

$$B_f = \text{fundamental circuit matrix} = [1 \quad -1 \quad 1],$$

$$L = \text{matrix of simple loop} = [1 \quad -1 \quad 1],$$

$$L_D = \text{augmented simple loops matrix} = \begin{bmatrix} L_1 & L_2 \\ L_2 & L_1 \end{bmatrix},$$

Therefore,

$$L_D = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix},$$

$$\text{Break points} = [1 \quad 2],$$

$$\mathbf{RSM} = \text{relative sequence matrix} = \begin{bmatrix} 1 & 2 \\ 4 & 5 \\ 3 & 6 \end{bmatrix},$$

$$\mathbf{Mb} = \text{main / back up relay pairs} = \begin{bmatrix} 3 & 1 \\ 6 & 2 \\ 2 & 4 \\ 1 & 5 \\ 5 & 3 \\ 4 & 6 \end{bmatrix}.$$

5.1.2 Optimizing the coordination problem using EP

The main/back up relay pairs obtained in the previous step is used to form the co-ordination constraints. The optimization problem for this sample system 1 can be formulated as follows.

Objective Function:

Minimize $\{T_{11} + T_{41} + T_{62} + T_{32} + T_{53} + T_{23}\}$ = sum of the operation times of the relays in their own zone, where,

$$T_{ik} = \frac{K_{i1} \cdot TDS_i}{\left(\left(\frac{I_{ik}}{i_{pi}}\right)^{K_{i2}} - K_{i3}\right)}.$$

Bounded constraints:

$$i_{pi_{\min}} \leqslant i_{pi} \leqslant i_{Pi\max},$$

$$TDS_{i\min} \leqslant TDS_i \leqslant TDS_{i\max},$$

$$T_{i_{\min}} \leqslant T_i \leqslant T_{i\max}$$

$$i = 1,2,\cdots,6.$$

Co-ordination constraints:

$$T_{51} - T_{11} \geqslant C_i, \quad T_{61} - T_{41} \geqslant C_i, \quad T_{12} - T_{32} \geqslant C_i,$$

$$T_{22} - T_{62} \geqslant C_i, \quad T_{33} - T_{53} \geqslant C_i, \quad T_{43} - T_{23} \geqslant C_i.$$

This non-linear optimization problem is solved using EP and the results are obtained and given in section 6.

5.2 Sample system 2

This sample system is 6 bus, 7 line (115 KV transmission system) practical system.

This sample system 2 is a portion of the Puget Sound power and light company's 115 KV transmission system and in this system directional over current relays are used for ground protection.

Table 3　Relay data for sample system 2

relay	Time dial setting/s		Pick up current setting/A		Operating time /s	
	Min	Max	Min	Max	Min	Max
1	1.5	6	595	605	0.1	12
2	1.5	6	2995	3005	0.1	12
3	1.5	6	1495	1505	0.1	12
4	1.5	6	995	1005	0.1	12
5	1.5	6	95	105	0.1	12
6	1.5	6	295	305	0.1	12
7	1.5	6	145	155	0.1	12
8	1.5	6	495	505	0.1	12
9	1.5	6	95	105	0.1	12
10	1.5	6	495	505	0.1	12
11	1.5	6	195	205	0.1	12
12	1.5	6	595	605	0.1	12
13	1.5	6	95	105	0.1	12
14	1.5	6	3900	4100	0.1	12

Table 4　Fault current data for sample system 2

Main relay	back up relay	Main relay current/A	back up relay current/A
14	1	7199	287.16830
6	9	959	233.641 00
7	9	1279	800.708 10
12	11	2399	41.557 01
9	3	2599	1943.539 00
11	3	959	638.033 50
1	10	609	40.000 000
3	8	3430	56.000 000
10	2	1439	88.000 000
11	2	959	320.964 50
9	4	2559	615.461 10
10	4	1439	556.363 00
2	14	4613	287.188 30
6	14	4516	0.451 60
5	6	959	233.640 00
8	7	880	75.000 000
13	12	1439	556.000 000

5.2.1 Determination of main /back up relay pairs

By using the software developed in MATLAB, all main/back up relay pair for this system is found out. The graph and the tree of this sample system are given in Fig. 7.

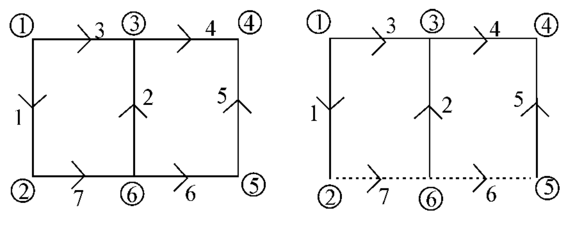

Fig. 7　The graph and the tree of sample system 2

For this graph,

e = number of elements (lines) = 7,

v = number of nodes = 6,

b = number of tree branches = $v - 1 = 6 - 1 = 5$,

l = number of links or chords =

$e - v + 1 = e - b = 7 - 5 = 2.$

For this system, node 3 is taken as reference. The details about the network are given as the input to the Matlab program for determining the main/back up relay pairs, and the following results are obtained.

Input to the program

$$\mathbf{EFT} = \begin{bmatrix} 1 & 1 & 2 \\ 2 & 6 & 3 \\ 3 & 1 & 3 \\ 4 & 4 & 3 \\ 5 & 5 & 4 \\ 6 & 6 & 5 \\ 7 & 6 & 2 \end{bmatrix},$$

$e = 7$ (numbers of lines or elements),

$v = 6$ (numbers of nodes),

$V = 6$ (reference nodes).

Output of the program:

$\boldsymbol{A}$ = incidence matrix =

$$\begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & -1 & -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 \end{bmatrix},$$

$\boldsymbol{B}_f$ = fundamental circuit Matrix =

$$\begin{bmatrix} 0 & -1 & 0 & 1 & 1 & 1 & 0 \\ -1 & -1 & 1 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$\boldsymbol{L}_D$ = matrix of simple loops =

$$\begin{bmatrix} 0 & -1 & 0 & 1 & 1 & 1 & 0 \\ -1 & -1 & 0 & 0 & 0 & 1 & 1 \\ -1 & 0 & 1 & -1 & -1 & -1 & 1 \end{bmatrix},$$

$\boldsymbol{L}_D$ = augmented simple loops matrix =

$$\begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix},$$

break points = [1　9　11],

RSM = relative sequence matrix =

$$\begin{bmatrix} 1 & 9 & 1 & 0 \\ 3 & 10 & 0 & 0 \\ 8 & 2 & 4 & 0 \\ 14 & 6 & 7 & 12 \end{bmatrix},$$

$$\mathbf{Mb} = \text{Main/back up relay pairs} = \begin{bmatrix} 14 & 1 \\ 6 & 9 \\ 7 & 9 \\ 12 & 11 \\ 9 & 3 \\ 11 & 3 \\ 1 & 10 \\ 3 & 8 \\ 10 & 2 \\ 11 & 2 \\ 9 & 4 \\ 10 & 4 \\ 2 & 14 \\ 6 & 14 \\ 5 & 6 \\ 8 & 7 \\ 13 & 12 \end{bmatrix}.$$

Even though twenty main/back up relay pairs were available for this system only seventeen pairs were considered for the sake of simplification.

5.2.2 Optimizing the co-ordination

The main/back up relay pairs obtained in the previous section is used to form the co-ordination constraints. The optimization problem for this example system can be formulated as follows.

Objective function:

Minimize $\{T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7 + T_8 + T_9 + T_{10} + T_{11} + T_{12} + T_{13} + T_{14}\}$.

Where,

$$T_i = \frac{K_{i1} TDS_i}{\left(\left(\frac{I_{ik}}{i_{pi}} \right)^{K_{i2}} - K_{i3} \right)}.$$

Bounded constraints:

$$i_{pi_{\min}} \leqslant i_{pi} \leqslant i_{pi_{\max}}$$

$$\mathrm{TDS}_{i_{\min}} \leqslant \mathrm{TDS}_i \leqslant \mathrm{TDS}_{i_{\max}}$$

$$T_{i_{\min}} \leqslant T_i \leqslant T_{i_{\max}}$$

$$i = 1, 2, \cdots, 14.$$

Co-ordination constraints

$$T_1 - T_{14} \geqslant C_i,\quad T_9 - T_6 \geqslant C_i,\quad T_9 - T_7 \geqslant C_i,$$

$$T_{11} - T_{12} \geqslant C_i,\quad T_3 - T_9 \geqslant C_i,\quad T_3 - T_{11} \geqslant C_i,$$

$$T_{10} - T_1 \geqslant C_i,\quad T_8 - T_3 \geqslant C_i,\quad T_2 - T_{10} \geqslant C_i,$$

$$T_2 - T_{11} \geqslant C_i,\quad T_4 - T_9 \geqslant C_i,\quad T_4 - T_{10} \geqslant C_i,$$

$$T_{14} - T_2 \geqslant C_i,\quad T_{14} - T_6 \geqslant C_i,\quad T_6 - T_5 \geqslant Ci,$$

$$T_7 - T_8 \geqslant C_i,\quad T_{12} - T_{13} \geqslant C_i.$$

This non-linear optimization problem is solved using EP and the results are obtained and given in Table 6.

6 Results and analysis

The simulated results for sample system 1 are given in Table 5. The relay settings and the operating times obtained using EP are compared with the values obtained using conventional reduced gradient (RG) non linear optimization technique[2]. From the results it is inferred that EP approach provides better results for pick up current setting and time dial setting for individual relays than conventional reduced gradient (RG) non linear optimization technique. Moreover, the optimal objective function value obtained using conventional reduced gradient (RG) non linear optimization technique is 1.925 8 and using EP technique is 1.816 6.

Table 5 Comparison of simulated EP results for sample system 1 with conventional RG method

Relay	Time dial setting/s		Pick up current setting/A		Operating time /s	
	RG *	EP	RG *	EP	RG *	EP
1	0.100 0	0.121 5	300	302	0.364 1	0.428 5
2	0.136 4	0.102 3	200	204	0.285 6	0.218 6
3	0.100 0	0.100 6	240	243	0.339 0	0.333 4
4	0.100 0	0.105 1	60	58	0.321 6	0.331 7
5	0.129 8	0.101 7	80	76	0.301 1	0.230 7
6	0.100 0	0.101 1	200	200	0.314 4	0.318 7

RG * ; reduced gradient non linear optimization method-results published in Table II of Ref [2].

Table 6 Comparison of simulated EP results for sample system 2 with conventional SC method

Relay	Time dial setting/s		Pick up current setting/A		Operating time /s	
	SC *	EP	SC *	EP	SC *	EP
1	1.798 432	1.638 3	600	601	0.517 800	0.490 6
2	1.857 560	1.518 2	3 000	2 999	0.534 800	0.447 7
3	3.804 786	1.505 5	1 510	1 497	1.048 260	0.437 0
4	2.476 596	1.517 9	1 000	996	0.713 080	0.470 2
5	5.877 455	1.520 0	103	97	1.660 400	0.416 9
6	2.501 156	1.521 2	305	302	0.700 300	0.436 0
7	2.044 424	1.513 1	150	148	0.588 600	0.417 1
8	1.586 421	1.518 7	503	498	0.448 100	0.445 4
9	4.339 605	1.587 1	105	102	1.249 400	0.420 2
10	2.006 917	1.515 9	510	503	0.577 800	0.436 2
11	4.185 422	1.579 9	205	204	1.171 900	0.445 9
12	2.091 310	1.534 2	605	598	0.585 500	0.435 7
13	5.568 763	1.536 9	103	101	1.573 264	0.415 7
14	1.987 664	1.507 5	4100	3 996	0.556 500	0.441 8

SC * : sequential coordination method-results published in Table IV of Ref [1].

The simulated results for sample system 2 are tabulated in Table 6. The relay settings and the operating times obtained using EP are compared with the values obtained using conventional sequential coordination (SC) method [1]. From the results it is inferred that EP approach provides better results than conventional sequential coordination (SC) method. In this case also the optimal objective function (i. e. total operating time) obtained by using EP is drastically reduced while comparing to conventional sequential coordination method. The total operating time obtained using the conventional sequential coordination method is 11.925 7 seconds (No optimization criteria is used in this algorithm) and the value obtained using EP is 6.156 4 seconds. By comparing the results of both the sample systems considered it is inferred that EP gives better results than conventional methods for the sample systems considered.

7 Conclusion

This paper presents an algorithm to determine the minimum number of break points and main/back up relay pairs using relative sequence matrix (RSM). And then using these main/back up relay pairs a novel optimization technique based on evolutionary programming for directional over current relay coordination in multiloop networks is developed. Since Evolutionary programming (EP), a stochastic multi-point searching optimization algorithm, is used for DOCR coordination, the problem of getting trapped into local optimum in conventional mathematical based optimization techniques is avoided in this method. Also, the chance of obtaining global optimum relay settings is much increased. Thus the developed method based on new coordination algorithm using EP that has better chances to reach global optimum is presented with the sample test system results.

Also the following special features of EP method were realized:

(i) Since EP searches from a population of points it is capable of discovering a global optimum point.

(ii) Since the computation for each individual in the population is independent of others, EP has inherent parallel computation ability.

(iii) Since EP has the ability to search a complicated and uncertain area to find the global optimum solution, it is more flexible and robust than other conventional optimization methods.

The developed method is tested for a 3 bus, 3 line sample system (Sample system 1) and a 6 bus, 7 line sample system (Sample system 2). It is inferred that better results are obtained using the proposed method comparing to conventional methods not only for the ip and TDS settings for the individual directional over current relays but also for determining total operating time which is a major criteria for relay operation. This coordination algorithm using EP can handle all OC relay setting optimization and is able to check for correct coordination for all system constraints and configurations. This method can even handle the complicated condition satisfactorily. This method can be extended to incorporate other types of relay and fault types to make it into a powerful planning and designing tool for power system protection engineers. Hence the proposed scheme shall be recommended for any practical system.

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Nomenclature used for this paper

L —Simple loop matrix of the network graph

l —Number of links or chords of the network

g —Number of sub networks when a given network "N" is decomposed

e —Number of edges

v —Number of vertices

V —Reference node

n —Number of relays

C_i —Coordination interval

TDS—Time Dial Setting (It is the setting which defines the operating time of the relay for each current value)

TDS_i —Time dial setting of relay i

TDS_{min}—Minimum time dial setting

TDS_{max}— Maximum time dial setting

T —Operating time of the relay

T_k —Operating time of relay K and also

T_k —f $(TDS_k,\ i_p)$ for directional over current relays

T_{main} —Operating time of the main relay

$T_{back\ up}$— Operating time of the back up relay

TOP—Total operating time

i_p —Pick-up current (It is the minimum current value for which the relay operates)

i_{pi} —Pick up current of relay i

$i_{p\ min}$ —Minimum pickup current

$i_{p\ max}$ —Maximum pickup current

I —Fault current through relay

I_{ik} —Current through relay i, due to fault in zone K

K_1, K_2, K_3 —Relay constants

K_{i1}, K_{i2}, K_{i3} —Constants of the relay i

P_i —Initial variable population

P_r —Randomly selected individual in the combined population

$P_{i,j}$ — j^{th} element of the i^{th} individual

F_i —Fitness score (ie. fitness of P_i)

f_r —Fitness of randomly selected individual P_r

f_i —Fitness of P_i

f_{max} —Maximum fitness of the old generation

r —Number of variables

β —Mutation scale $0 < \beta < 1$

m —Population size

q —Competition number

W_i —Weight value

w_{it} —Weight value in the set $\{0, 1\}$

$x_{j\ max}$ and $x_{j\ min}$—Maximum and minimum limits of j^{th} element

$N\ (\mu,\ \sigma_2)$ —Represents a Gaussian random variable with mean μ and variance σ_2

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