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A population based heuristic algorithm for optimal relay operating times *

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Abstract. The RST algorithm of Mohan and Shanker[10] is a population based heuristic algorithm designed to determine the global optimal solution of nonlinear constrained optimization problems. Unlike other optimization techniques it does not require an initial guess value of the decision parameters, but only requires the lower and upper bounds of the decision parameters. The algorithm does not require the continuity and differentiability of the objective function or constraints. The algorithm has been well tested on standard benchmark problems in Mohan and Shanker[10]. In this paper, an attempt has been made to solve a problem that has its origin in electrical power systems. The problem is to compute the values of the decision variables called "Relays", which control the act of isolation of faulty lines from the system without disturbing the healthy lines. In other words it is required to determine the optimal relay operating times. Firstly, the generalized model is presented. Then, two models have been considered namely 3–bus system and 4–bus system. The results obtained by RST are compared with that of MATLAB Toolbox. It is found that the results obtained by RST are superior from the results of MATLAB because the later are not feasible solutions.

Keywords: electric power system relays, constrained global optimization, population based heuristic algorithms

1 Introduction

Directional Overcurrent Relays (DOCRs) are provided in electrical power systems to isolate only the faulty lines, in the event of the faults in the system. These relays are placed at both ends of each line. Thus, number of directional overcurrent relays in an electrical power system is twice the number of the lines. To maintain the continuity of supply to healthy sections and to isolate the faulty section only, relays are coordinated. This ensures that minimum lines are disrupted when fault occurs. This is done in DOCRs by properly fixing the two adjustable parameters of each relay called "settings". The two settings of each relay are plug setting (*PS*) and time dial setting (*TDS*). There happen to be many relays in the system depending on the size of the system. Thus, each relay introduces two decision variables (one *TDS* and one *PS*) in the problem.

The above stated problem of coordinating each DOCR with one another in electrical power systems can be modeled as a non-linear constrained optimization problem. The objective function to be minimized is the sum of the operating times of all the primary relays, which are expected to operate in order to clear the faults of their corresponding zones. The constraints are bounds on all decision variables, complexly interrelated times of the various relays (called selectivity constraints) and restrictions on each term of the objective function to be between certain specified limits.

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In this paper, the use of the well tested RST algorithm of Mohan and Shanker[10] has been exhibited to determine the global optimal solution of the above stated problem. The results are compared with the results obtained from MATLAB Toolbox.

In section 2, the previous attempts in this direction are mentioned. In section 3, the RST algorithm of Mohan and Shanker (1994) has been described. In section 4, the mathematical model of the problem has been described. In section 5, the numerical results are discussed. Finally, in section 6 conclusions are drawn.

2 Literature review

The use of optimization techniques in relay coordination was first suggested in 1988[12]. A survey of all coordination philosophies used by various researchers in the past has been presented recently by authors of this paper [4]. The optimal coordination problem of DOCRs is a non-linear optimization problem[11]. Dimension of the problem becomes very large for the modern interconnected power systems. Due to this problem and complexities of non-linear programming techniques, most of the researchers have solved the problem in linear environment by presuming the values of decision variables (all plug settings), which make the problem non-linear. This presumption is made based on the expert engineer's experience and wisdom. Thus, the coordination problem reduces to a linear programming problem[12]. However, linear approaches can't ensure correct settings of the relays[9]. They cannot consider all possible operating conditions of the system. The results obtained may be trapped on local optimum relay settings[14]. Non-linear methods can produce optimal results by optimizing all settings of relays and thus, avoid undesired tripping of those relays, which are not supposed to operate for a fault under consideration. First optimization attemptted in this area used simplex-based linear approach for optimizing *TDS* settings for presumed *PS* settings and Generalized Reduced Gradient non-linear technique to optimize the *PS* settings for already optimized *TDS* [?]. This procedure was iterated till convergence was achieved. Ref. [7] used Sparse Dual Revised Simplex method of linear programming suggested by [8] to optimize *TDS* settings for pre-assumed non-linear *PS* settings. Ref. [9] applied Simplex and Rosenbrock-Hillclimb methods to optimize *TDS* and *PS* settings respectively, in a similar way, as used by Ref. [12]. These approaches were further followed by simplex-based approaches with more and more sophistications about finer aspects of the relays[2, 6, 13, 15, 16]. Recently, authors of this paper also made non-linear attempts by making use of "MATLAB Toolbox"[5] and "Numeric Algorithm Group" Sequential Quadratic Programming routines[3].

3 The RST algorithm

In this section, we briefly discuss the RST algorithm and its additional features as to why the method is advantageous as compared to other optimization methods.

The RST algorithm is a heuristic algorithm which can be used to determine the global optimal solution of a nonlinear constrained optimization problem of the type:

$$\text{Minimize} \quad f(x_1, x_2, ..., x_n)$$

i.e. f is nonlinear real valued function in n variables.

$$\begin{aligned} \text{Subject to:} \quad & g_j(x_1, x_2, \cdots, x_n) \geq 0, \quad \text{for } j = 1, 2, 3, \cdots, m, \\ \text{and} \quad & a_i \leq x_i \leq b_i, \quad \text{for } i = 1, 2, 3, \cdots, n. \end{aligned}$$

The RST algorithm developed by Mohan and Shanker [1994] works in two phases. In the first phase the objective function is evaluated at a number of randomly generated feasible solutions, while in the second phase, at each iteration these solutions are manipulated by local searches (using quadratic approximation) to yield possible candidate for global optima. As the iterations proceed the sample of solutions converge to the global optimal solution. The Algorithm has been well tested on a number of benchmark test problems in Mohan and Shanker[10]. The computational steps of RST are:

(1) Choose a sample of NBIG, n-dimensional random feasible solutions and evaluate the objective function at each of them. Store in an NBIG by $(n+1)$ array A. Set ITERATION =1.

(2) Out of these feasible solutions, determine M and L as the feasible solutions with greatest and least function values $f(M)$ and $f(L)$ respectively. If stopping criteria, $|\frac{f(M)-f(L)}{f(L)}| < \varepsilon$, is satisfied, stop with the message that L is the global minimum solution. Otherwise go to step 3.

(3) From the current array A choose three distinct feasible solutions $R_1 = L$, R_2 and R_3 randomly and determine a new feasible solution P as the point of minima of the quadratic curve passing through R_1, R_2 and R_3 by the formula:

$$P = 0.5\left(\frac{(R_2^2 - R_3^2)f(R_1) + (R_3^2 - R_1^2)f(R_2) + (R_1^2 - R_2^2)f(R_3)}{(R_2 - R_3)f(R_1) + (R_3 - R_1)f(R_2) + (R_1 - R_2)f(R_3)}\right).$$

(4) Find $f(P)$. If $f(P) < f(M)$, increment ITERATION and go to step 4, else go to step 3.

(5) Replace M by P in the array A and go to step 2.

The essential features of the RST Algorithm are:

- It attempts to determine the global optimal solution rather than the local optimal solution;
- It does not require an initial guess value of the decision parameters, but instead requires only the lower and upper bounds of the decision parameters;
- It does not assume the continuity and differentiability of the objective function or the constraints, and hence can be used for non differentiable objective functions as well;
- It is easy to program and has a wide applicability.

4 General model of the problem

In this section, firstly generalized relay coordination problem model is presented. Then two specific models are presented.

4.1 Generalized model

The operating time (T) of a DOCR is non-linear function of the relay settings (*TDS* and *PS*) and the fault current (I) seen by the relay. Therefore, Relay operating-time equation for a directional overcurrent relay is given by a non-linear equation as under:

$$T = \frac{\alpha * TDS}{\left(\frac{I}{PS * CT_{pri\_rating}}\right)^{\beta} - \gamma} \tag{1}$$

Only *TDS* and *PS* are unknown variables in above equation. These are the "decision variables" of the problem. α, β and γ are the constants representing the behaviour of the characteristic of the system in a mathematical way, in which operating time of the DOCR varies and are given as 0.14, 0.02 and 1.0 respectively as per[1]. Value of CTpri_rating depends upon the number of turns in the equipment CT (Current Transformer). CT is used to reduce the level of the current so that relay can withstand it. With each relay one "Current Transformer" is used and thus, CTpri_rating is known in the problem. Value of I (Fault current passing through the relay) is also known, as it is a system dependent parameter and continuously measured by measuring instruments.

Number of constraints for systems of bigger sizes will be dependent upon the number of lines in the system. Details of the number of lines in few larger systems are given in Table I. In practice, in electrical engineering, power systems may be of even bigger sizes and there are other types of relays also besides DOCRs. Coordinating DOCRs with other types of relays generates even larger number of constraints than shown in Table 1. It is evident from Table 1 that simultaneous optimization of both the settings (*TDS* and *PS*) of each DOCR of the system is a complex problem.

Table 1. No. of lines, relays, decision variables, selectivity constraints and constraints imposing restrictions on each term of objective function for large power systems

	Power systems				
	IEEE 14-bus	IEEE 30-bus	IEEE 57-bus	IEEE 64-bus	IEEE 118-bus
No. of lines	20	41	78	88	179
No. of DOCRs (relays)	40	82	156	176	358
No. of decision variables	80	164	312	352	766
No. of selectivity constraints	184	390	680	900	2036
Constraints imposing restrictions on each term of objective function	160	332	624	704	1532

4.1.1 Objective function

The relay, which is supposed to operate first to clear the fault, is called primary relay. A fault close to relay is known as the close-in fault for the relay and a fault at the other end of the line is known as a far-bus fault for this relay. The locations of these faults are shown by crosses (A to H) in Fig. 2. Conventionally, objective function in coordination studies is constituted as the summation of operating-times of all primary relays, responding to clear all close-in and far-bus faults. OBJ, as under, gives objective function of the problem.

$$OBJ = \sum_{i=1}^{N_{cl}} T^{i}_{pri\_cl\_in} + \sum_{j=1}^{N_{far}} T^{j}_{pri\_far\_bus} \tag{2}$$

where,

$N_cl$is number of relays responding for close-in fault;

$N_{far}$is number of relays responding for far-bus fault;

$T_{pri_cl_in}$is primary relay operating-time for close-in fault;

$T_{pri_far_bus}$primary relay operating-time for far-bus fault.

4.1.2 Constraints

Bounds on variables *TDSs* (Time dial setting of each relay)

$$TDS^{i}_{\min} \leq TDS^{i} \leq TDS^{i}_{\max}, \quad i = 1, 2, \cdots, N_{cl}$$

where, $TDS^{i}_{\min}$ is lower limit and $TDS^{i}_{\max}$ is upper limit of TDS^{i}. These limits are 0.05 and 1.1, respectively.

Bounds on variables *PSs* (Plug setting of each relay)

$$PS^{j}_{\min} \leq PS^{j} \leq PS^{j}_{\max}, \quad j = 1, 2, \cdots, N_{cl}$$

where, $PS^{j}_{\min}$ is lower limit and $PS^{j}_{\max}$ is upper limit of PS^{j}. These are 1.25 and 1.50, respectively.

Limits on primary operation times: This constraint imposes constraint on each term of objective function to lie between 0.05 and 1.0.

Selectivity constraints for all relay pairs:

$$T_{backup} - T_{primary} - CTI \geq 0$$

where, T_{backup} is operating time of backup relay and $T_{primary}$ is operating time of primary relay. Value of CTI is 0.3.

4.2 Model-I

In the model-I shown in Fig. 1 there are three lines i.e. this is a 3-bus system. So, number of DOCRs in the system is 6 and number of decision variables, whose optimal set of solution is to be found, is 12 (two settings with each DOCR). The number of terms in the objective function for problem is also 12 (twice the number of DOCRs). Thus, the number of constraints involving the restrictions on each term of objective function is 24 (for upper and lower limits). The number of selectivity constraints is dependent upon the system data of the model, and it is 8 for the considered model-I.

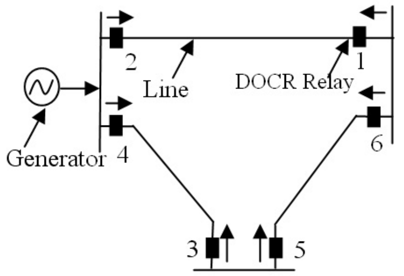

Fig. 1. Model-I (A typical 3-Bus system)

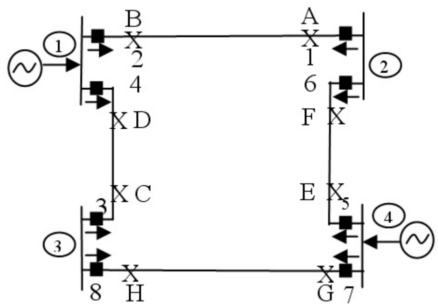

Fig. 2. Model-II (A typical 4-Bus system)

4.2.1 Objective function

The relay, which is supposed to operate first to clear the fault, is called primary relay. A fault close to relay is known as the close-in fault for the relay and a fault at the other end of the line is known as a far-bus fault for this relay.

Conventionally, objective function in coordination studies is constituted as the summation of operating-times of all primary relays, responding to clear all close-in and far-bus faults. The objective function represented by OBJ is as under

$$OBJ = \sum_{i=1}^{6} T^i_{pri\_cl\_in} + \sum_{j=1}^{6} T^j_{pri\_far\_bus}$$

where,

N_{cl} is number of relays responding for close-in fault;

N_{far} is number of relays responding for far-bus fault;

$T_{pri\_cl\_in}$ is primary relay operating-time for close-in fault;

$T_{pri\_far\_bus}$ primary relay operating-time for far-bus fault.

Here,

$$T^i_{pri\_cl\_in} = \frac{0.14 * TDS^i}{\left(\dfrac{a^i}{PS^i * b^i}\right)^{0.02} - 1}; \quad T^i_{pri\_far\_bus} = \frac{0.14 * TDS^j}{\left(\dfrac{c^i}{PS^i * d^i}\right)^{0.02} - 1}.$$

The values of constants a^i, b^i, c^i and d^i are given in the Table 2.

4.2.2 Constraints

Constraints for the model will be as under:

Bounds on variables *TDSs* (Time dial setting of each relay)

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

where, $i = 1, 2, \cdots, N_{cl}, TDS^i_{\min}$ is lower limit and $TDS^i_{\max}$ is upper limit of TDS^i. These limits are 0.05 and 1.1, respectively.

Bounds on variables *PSs* (Plug setting of each relay)

$$PS^j_{\min} \leq PS^j \leq PS^j_{\max}$$

where, $j = 1, 2, \cdots, N_{cl}$, $PS^j_{\min}$ is lower limit and $PS^j_{\max}$ is upper limit of PS^j. These are 1.25 and 1.50, respectively.

Limits on primary operation times: This constraint imposes constraint on each term of objective function to lie between 0.05 and 1.0.

Selectivity constraints for all relay pairs:

$$T_{backup} - T_{primary} - CTI \geq 0$$

T_{backup} is operating time of backup relay and $T_{primary}$ is operating time of primary relay. Value of CTI is 0.3. Here,

$$T^i_{backup} = \frac{0.14 * TDS^p}{\left(\dfrac{e^i}{PS^p * f^i}\right)^{0.02} - 1};$$

and

$$T^i_{primary} = \frac{0.14 * TDS^q}{\left(\dfrac{g^i}{PS^q * h^i}\right)^{0.02} - 1}.$$

The values of constants e^i, f^i, g^i and h^i are given in the Table 3.

Table 2. Values of constants a^i, b^i, c^i and d^i for Model-I

$T^i_{pri\_cl\_in}$			$T^i_{pri\_far\_bus}$		
TDS^i	a^i	b^i	TDS^j	c^i	d^i
TDS^1	9.4600	2.0600	TDS^2	100.6300	2.0600
TDS^2	26.9100	2.0600	TDS^1	14.0800	2.0600
TDS^3	8.8100	2.2300	TDS^4	136.2300	2.2300
TDS^4	37.6800	2.2300	TDS^3	12.0700	2.2300
TDS^5	17.9300	0.8000	TDS^6	19.2000	0.8000
TDS^6	14.3500	0.8000	TDS^5	25.9000	0.8000

Table 3. Values of constants e^i, f^i, g^i and h^i for Model-I

T^i_{backup}			$T^i_{primary}$		
p	e^i	f^i	q	g^i	h^i
5	14.0800	0.800	**1**	14.0800	2.0600
6	12.0700	0.800	**3**	12.0700	2.2300
4	25.9000	2.2300	**5**	25.9000	0.8000
2	14.3500	0.800	**6**	14.3500	2.0600
5	9.4600	0.800	**1**	9.4600	2.0600
6	8.8100	0.800	**3**	8.8100	2.2300
2	19.2000	2.0600	**6**	19.2000	0.8000
4	17.9300	2.2300	**5**	17.9300	0.8000

4.3 Model-II

In the model shown in Fig. 2, there are four lines and so the number of DOCRs is 8. The number of decision variables is 16 (two settings with each DOCR). The number of terms in the objective function for problem is 16 (twice the number of DOCRs). Hence, the number of constraints involving the restrictions on each term of objective function is 32 (for upper and lower limits). The number of selectivity constraints is dependent upon the model, and it is 9.

4.3.1 Objective function and constraints

For the coordination problem of model-II, value of each of N_{cl} and N_{far} is 8 (equal to number of relays or twice the lines). Accordingly, there are 16 decision variables (two for each relay) in this problem i.e. TDS^1 to TDS^8 and PS^1 to PS^8.

The objective function and constraints for the model will be of same form as in the case of Model-I problem (with N_{cl} = 8) described in section 4.2.2.

The values of constants $a^i, b^i, c^i, d^i, e^i, f^i, g^i$ and h^i for Model-II are given in Table 4 and Table 5.

Table 4. Values of constants a^i, b^i, c^i and d^i for Model II

$T^i_{pri\_cl\_in}$			$T^i_{pri\_far\_bus}$		
TDS^i	a^i	b^i	TDS^j	c^i	d^i
TDS^1	20.3200	0.4800	TDS^2	23.7500	0.4800
TDS^2	88.8500	0.4800	TDS^1	12.4800	0.4800
TDS^3	13.6100	1.1789	TDS^4	31.9200	1.1789
TDS^4	116.8100	1.1789	TDS^3	10.3800	1.1789
TDS^5	116.7000	1.5259	TDS^6	12.0700	1.5259
TDS^6	16.67000	1.5259	TDS^5	31.9200	1.5259
TDS^7	71.7000	1.2018	TDS^8	11.0000	1.2018
TDS^8	19.2700	1.2018	TDS^7	18.9100	1.2018

Table 5. Values of constants e^i, f^i, g^i and h^i for Model-I

T^i_{backup}			$T^i_{primary}$		
p	e^i	f^i	q	g^i	h^i
5	20.3200	1.5259	**1**	20.3200	0.4800
5	12.4800	1.5259	**1**	12.4800	0.4800
7	13.6100	1.2018	**3**	13.6100	1.1789
7	10.3800	1.2018	**3**	10.3800	1.1789
1	1.1600	0.4800	**4**	116.8100	1.1789
2	12.0700	0.4800	**6**	12.0700	1.1789
2	16.6700	0.4800	**6**	16.6700	1.5259
4	11.0000	1.1789	**8**	11.0000	1.2018
4	19.2700	1.1789	**8**	19.2700	1.2018

5 Discussion of results

In this section, the numerical results for Model-I and Model-II are presented by solving the corresponding optimization problems using two approaches viz. RST algorithm described in section 3 and MATLAB optimization toolbox. RST algorithm and MATLAB Toolbox are compared for the considered two relay coordination problem models – model-I (Fig. 1) and model-II (Fig. 2).

Model-I Results: Table 6 shows a comparison of the optimal values of the decision variables and the optimal objective function value. Table 7 shows the value of 8 selectivity constraints.

Model-II Results: Table 8 shows a comparison of the optimal values of the decision variables and the optimal objective function value. Table 9 shows the value of 9 selectivity constraints. The Tables show that

Table 6. Decision variables and objective function optimal values for Model-I (Fig. 1) found by RST algorithm and MATLAB

Decision Variables	Value by MATLAB Toolbox	Value by RST Algorithm
TDS^1	0.05000000000000	0.050062
TDS^2	0.19764667103805	0.210730
TDS^3	0.05000000000000	0.050021
TDS^4	0.20903171197914	0.218827
TDS^5	0.18120523612269	0.188140
TDS^6	0.18067552227651	0.195378
PS^1	1.25000000000000	1.251234
PS^2	1.50000000000000	1.353436
PS^3	1.25000000000000	1.250000
PS^4	1.50000000000000	1.381769
PS^5	1.50000000000000	1.374343
PS^6	1.50000000000000	1.250186
Optimal Value of objective function	4.78065070474491	4.83542701927544

Table 7. Value of each selectivity constraint for Model-I (Fig. 1)

Constraint	Constraint values in second	
No.	MATLAB Toolbox Allows tolerance 1.0e-08 in constraints	RST Algorithm
1	0.00000000000000	0.00051468116110
2	0.00000000000001	0.00013627506057
3	-0.00000000000002	0.00050754672332
4	0.09008111400397	0.08576410572325
5	0.04221324579101	0.03879991683310
6	0.02117707464442	0.01422080195843
7	-0.00000000000000	0.00050469099876
8	0.10042972713526	0.09584778802172

both methods have found acceptable feasible solutions and there is close agreement in the optimal values of the objective functions. The minor difference in the optimal values is because MATLAB Toolbox allows some tolerance (1.0e-08 considered in this paper) in satisfying the constraints, while RST technique attempts the exact satisfaction of constraints without permitting any violation. Thus, the solution found by RST algorithm is better in quality. Hence solution obtained by RST is superior to the solution obtained by MATLAB Toolbox.

6 Conclusion

In this paper, electrical engineering power system DOCR coordination problem has been solved by modeling it as constrained non-linear optimization problem. Using two approaches, namely the MATLAB Toolbox and the RST algorithm, two model problems have been solved and results by both the approaches are compared for both the models.

MATLAB Toolbox finds the constrained minimum of a scalar function of several variables. The main limitation with MATLAB Toolbox is that the function to be minimized and the constraints both must be continuous and differentiable. Moreover, it gives only local solutions and finds the constrained minimum starting at an initial estimate of variables. Giving proper initial guess is also a limitation with the MATLAB Toolbox.

Table 8. Decision variables and objective function optimal values for Model-II (Fig. 2), found by RST algorithm and MATLAB Toolbox

Decision variables	Value by MATLAB Toolbox	Value by RST Algorithm
TDS_1	0.05000000000000	0.050026
TDS_2	0.21216878984503	0.224205
TDS_3	0.05000000000000	0.050007
TDS_4	0.15157616149642	0.158685
TDS_5	0.12640045603507	0.136654
TDS_6	0.05000000000000	0.050017
TDS_7	0.13378620535474	0.138768
TDS_8	0.05000000000000	0.050038
PS_1	1.27332726543809	1.291010
PS_2	1.50000000000000	1.264540
PS_3	1.25000000000000	1.250000
PS_4	1.50000000000000	1.346004
PS_5	1.50000000000000	1.266912
PS_6	1.25000000000000	1.251230
PS_7	1.50000000000000	1.393723
PS_8	1.25000000000000	1.250774
Optimal Value of objective function	3.66974578594832	3.70501831276266

Table 9. Value of each selectivity constraint for Model-II (Fig. 2)

Constraint	Constraint values in second	
No.	MATLAB Toolbox (Tolerance 1.0e-08)	RST Algorithm
1	-0.00000000000001	0.00026841303138
2	0.10031292167693	0.09025829810599
3	0.00000000000001	0.00002999426841
4	0.04984067522577	0.04703765072395
5	-0.00000000000000	0.0075951409511
6	0.02586832094882	0.02297110952710
7	-0.00000000000000	0.00011738337735
8	0.09761599131427	0.09016411367773
9	0.00000000000001	0.00003275789839

It allows some tolerance in satisfying the constraints towards constraints violation. The RST algorithm has definite advantages over the conventional techniques as discussed in section 3.

References

[1] IEEE Std. C37. 112-1996, IEEE standard inverse-time characteristic equations for overcurrent relays.

[2] A. Y. Abdelaziz, H. E. A. Talaat, et al. An adaptive protection scheme for optimal coordination of overcurrent relays. *Electric Power Systems Research*, 2002, **61**(1): 1–9.

[3] D. Birla, R. P. Maheshwari, H. O. Gupta. Optimal DOCR coordination in non-linear environment by simultaneously optimizing settings. **in:** *International Conference on Computer Application in Electrical Engineering Recent Advances*, IIT Roorkee, India, 2005.

[4] D. Birla, R. P. Maheshwari, H. O. Gupta. Time-overcurrent relay coordination: A review. *International Journal of Emerging Electric Power Systems*, 2005, **2**(2).

[5] D. Birla, R. P. Maheshwari, H. O. Gupta. A new non-linear directional overcurrent relay coordination technique, and banes and boons of near-end faults based approach. *IEEE Transactions on Power Delivery*, 2006, **21**(2).

[6] B. Chattopadhyay, M. S. Sachdev, T. S. Sidhu. An on-line relay coordination algorithm for adaptive protection using linear programming technique. *IEEE Trans. Power Delivery*, 1996, **11**: 165–173.

[7] M. R. Irving, H. B. Elrafie. Linear programming for directional overcurrent relay coordination in interconnected power systems with constraint relaxation. *Electric Power Systems Research*, 1993, **27**(3): 209–216.

[8] M. R. Irving, M. J. H. Sterling. Economic dispatch of active power with constraint relaxation. *Proceeding IEE, Part C*, 1983, 172–177.

[9] N. A. Laway, H. O. Gupta. A method for adaptive coordination of directional relays in an interconnected power system. *Developments in power system protection*, 1993, (368): 240–243.

[10] C. Mohan, K. Shanker. A random search technique for global optimization based on quadratic approximation. *Asia Pacific Journal of Operations Research Society*, 1994, **11**: 93–101.

[11] C. W. So, K. K. Li. Overcurrent relay coordination by evolutionary programming. *Electric Power Systems Research*, 2000, **53**: 83–90.

[12] A. J. Urdaneta, R. Nadira, L. Perez. Optimal coordination of directional overcurrent relay in interconnected power systems. *IEEE Trans. on Power Delivery*, 1988, **3**: 903–911.

[13] A. J. Urdaneta, L. G. Perez. Optimal coordination of directional overcurrent relays considering definite time backup relaying. *IEEE Transactions on Power Delivery*, 1999, **14**(4): 1276–12184.

[14] A. J. Urdaneta, L. G. Perez, et al. Presolve analysis and interior point solutions of the linear programming coordination problem of directional overcurrent relays. *International Journal of Electrical Power and Energy Systems*, 2001, **23**(8): 819–825.

[15] A. J. Urdaneta, L. G. Perez, R. Harold. Optimal coordination of directional over current relays considering dynamic changes in the network topology. *IEEE Trans. Power Delivery*, 1997, **12**: 1458–1463.

[16] A. J. Urdaneta, H. Resterbo, J. Sanchez, et al. Coordination of directional overcurrent relays timing using linear programming. *IEEE Trans. Power Delivery*, 1996, **11**: 122–129.