Optimum Time Coordination of Overcurrent Relays in Distribution System Using Big-M (Penalty) Method

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Abstract: - This paper presents big-M (penalty) method for optimum time coordination of overcurrent (OC) relays. The method is based on the simplex algorithm which is used to find optimum solution of linear programming problem (LPP). The method introduces artificial variables in the objective function to get an initial basic feasible solution (IBFS). Artificial variables are removed using iterative process which also leads to an optimum solution.

The OC relays are the major protection devices in a distribution system. To reduce the power outages, mal-operation of the backup relays should be avoided, and therefore, OC relay time coordination in power distribution network is a major concern of protection engineer. The OC relay time coordination in ring fed distribution networks is a highly constrained optimization problem. The purpose is to find an optimum relay setting to minimize the time of operation of relays and at the same time, to avoid the mal-operation of relays. Big-M simplex technique for optimum time coordination of OC relays in a ring fed distribution system is presented in this paper.

Key-words: - Backup protection, Big-M method, Constrained optimization, Overcurrent relay, Ring fed system, Time coordination.

1. Introduction

The most obvious effect of a shunt fault is a sudden built up of current. So it is natural that the magnitude of current be utilized as positive indication of existence of a fault. Therefore the over-current protection is the most widely used form of protection [1-4]. Directional OC relays have been commonly used as an economic alternative for the protection of subtransmission and distribution systems or as a secondary protection of transmission system [5]. In distribution feeders, they play a more important role and there it may be the only protection provided [1,2].

The problem of coordinating protective relays in protection systems consists of selecting their suitable settings such that their fundamental protective function is met under the requirements of sensitivity, selectivity, reliability, and speed [3,4]. A typical power system may consist of hundreds of equipment and even more protection relays to protect the system. A relay must get sufficient chance to protect the zone under its primary protection. Only if the primary protection does not clear the fault, the back-up protection should takeover tripping. If backup protections are not well coordinated, mal-operation can occur and, therefore, OC relay coordination is a major concern of power system protection [5,6]. Each protection relay in the power system needs to be coordinated with the relays protecting the adjacent equipment. The overall protection coordination is thus very complicated.

The OC relay coordination problem in distribution system can be defined as constrained optimization problem. The objective is to minimize the operating time of relay for near end fault. This objective is to be achieved under three sets of constraints, which are imposed due to bounds on relay operating time, coordination criteria and relay characteristics. Several optimization techniques have been proposed for optimum coordination of OCR [5-16].

The problem can be defined as a LPP and can be solved using big-M technique (also known as method of penalties). Big-M method is a simplex method in which artificial variables are introduced in the objective function to get an IBFS. The artificial variables are removed using the iterative process which also leads to obtaining the optimum solution. The number of iterations required to reach to the optimum solution is less as compared to two phase simplex algorithm.

The big-M simplex optimization method has been employed for optimum coordination of OC relays in this paper. Initially a simple system (a radial system consisting of two relays only) is taken. The detailed procedure for formulation of relay coordination problem is explained for this system and the detailed solution for this problem is presented. Comparison with two phase simplex method is also presented. Then a ring main system is taken in which multiple loops are formed depending up on the location of fault. The optimum value of time multiplier setting (TMS) of each relay, obtained using big-M method is presented.

2. Coordination of OC Relays in Ring Fed System

As soon as the fault takes place it is sensed by both primary and backup protection. The primary protection is the first to operate as its operating time being less than that of the backup relay.

A simple radial feeder with two sections is shown in Fig. 1. For fault at point F, relay R_B is first to operate. Let the operating time of R_B is set to 0.1 s. The relay R_A should wait for 0.1 s plus, a time equal to the operating time of circuit breaker (CB) at bus B, plus the overshoot time of relay A [1]. This is necessary for maintaining the selectivity of relays at A and B.

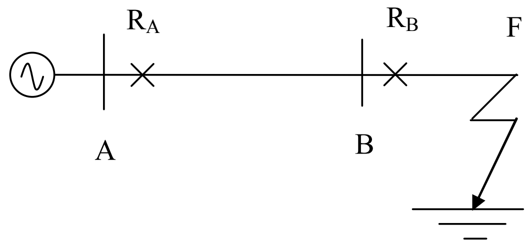

Fig. 1. A simple radial feeder
(Both relays are non-directional)

A ring main feeder system is shown in Fig. 2. It allows supply to be maintained to all the loads in spite of fault on any section. Relays 1, and 8 are non directional whereas all other relays (2, 3, 4, 5, 6, and 7) are directional OC relays. All directional relays have their tripping direction away from the concerned bus.

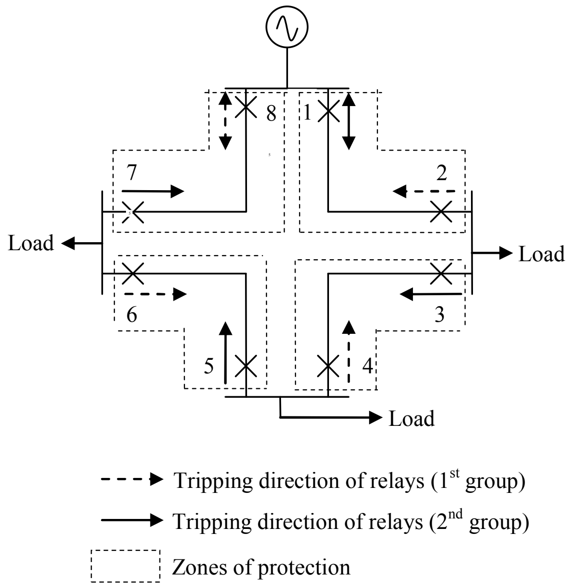

Fig. 2. A ring main feeder (Relays 1 & 8 are non directional, other relays are directional)

For coordination purpose relays 2,4,6, and 8 will form one group and relays 1,3,5, and 7 will form other group. For group one, setting is to be started from relay 2. The relay operating times will be related as

$T_{R8} > T_{R6} > T_{R4} > T_{R2}$

where T_{Ri} indicates operating time of i[th] relay.

For group two, setting is to started from relay 7. The relay operating times will be related as

$T_{R1} > T_{R3} > T_{R5} > T_{R7}$

The actual operating time for each relay can be decided again considering the operating time of preceding relay, operating time of CB associated with preceding relay, and the overshoot time of the relay under consideration.

As the size and complexity of the system goes on increasing it becomes more and more difficult to coordinate the relays. Keeping the same concept of coordination in view, the problem can be stated as constrained optimization LPP which can be solved by big-M technique.

3. Problem Formulation

The coordination problem of directional OC relays in interconnected power systems, can be stated as an optimization problem, where the sum of the operating times of the relays of the system, for near end fault, is to be minimized [6],

i.e., $$\min z = \sum_{i=1}^{m} t_{i,i} \tag{1}$$

where

m is the number of relays, and

$t_{i,i}$ indicates the operating time of the primary relay at i, for near end fault.

This objective is to be achieved under three sets of constraints [6-8,10].

3.1 Coordination Criteria

Fault is sensed by both primary as well as secondary relays simultaneously. To avoid mal-operation, the backup relay should takeover the tripping action only after primary relay fails to operate. This puts a constraint which can be mathematically stated as

$$t_{bi,i} - t_{i,i} \geq \Delta t \tag{2}$$

where,

$t_{i,i}$ is the operating time of the primary relay at i, for near end fault

$t_{bi,i}$ is the operating time for the backup relay, for the same fault

Δt is the coordination time interval (CTI)

3.2 Bounds on the relay operating time

Constraint imposed because of restriction on the operating time of relays can be mathematically stated as

$$t_{i,i,\min} \leq t_{i,i} \leq t_{i,i,\max} \tag{3}$$

where,

$t_{i,i,\min}$ is the minimum operating time of relay at i for near end fault (fault at i)

$t_{i,i,\max}$ is the maximum operating time of relay at i for near end fault (fault at i)

3.3 Relay characteristics

All relays are assumed to be identical and are assumed to have normal IDMT characteristic as [5,6,7,9,10] :

$$t_{op} = \frac{\lambda(TMS)}{(PSM)^{\gamma} - 1} \tag{4}$$

where,

t_{op} is relay operating time,

TMS is time multiplier setting, and

PSM is plug setting multiplier.

For normal IDMT relay γ is 0.02 and λ is 0.14. As the pickup currents of the relays are pre determined from the system requirements, equation (4) becomes

$$t_{op} = a(TMS) \tag{5}$$

where, $a = \dfrac{\lambda}{(PSM)^{\gamma} - 1}$

Making substitution from equation (5) in equation (1), the objective function becomes

$$\min z = \sum_{i=1}^{m} a_i (TMS)_i \tag{6}$$

Thus the relay characteristic constraint is incorporated in the objective function itself. The values of a_i for i^{th} relay for different fault locations are predetermined. Value of TMS for each relay is to be determined using big-M method.

4. Big-M (Penalty) Method

After incorporating the relay characteristic in the objective function, the relay coordination problem have two set of constraints. Generally, the upper bound on the relay operating time need not be taken care of, because when optimum solution is obtained the operating time of relays do not exceed the upper bound. So, the remaining constraints are coordination criteria constraint and relay operating time constraint (lower bound). Both the set of constraints are inequalities of ≥ type. To convert these constraints to equality type, non negative variable (surplus variable) is subtracted from left hand side. If surplus variables are taken as basics for the initial (starting) solution it will give infeasible solution as the coefficient of surplus variables is -1. Thus surplus variables can not become starting basic variables. In order to obtain an IBFS, artificial variable is added to the left hand side of the constraints [17-21].

Artificial variables have no meaning in a physical sense and are only used as a tool for generating an IBFS. Before the final solution is reached, all artificial variables must be dropped out form the solution [18]. If at all an artificial variable becomes a basic variable in the final solution, its value must be zero [17].

Big-M method (Charne's penalty method), which is basically a simplex technique, is a method of removing artificial variables from the basics. In this method a large undesirable coefficients (unacceptable penalty) are assigned to artificial variables from the objective function point of view. As the objective function is to be minimized in the relay coordination problem, a very large positive penalty is assigned to each artificial variable. The penalty is designated by +M (for minimization problem), where M > 0.

4.1 Algorithm

The algorithm of big-M simplex method to solve a minimization problem is given below (the maximization problem can easily be converted into minimization problem). All the constraints are considered to be inequality constraints of ≥ type (as it will be the case for relay coordination problem).

01. Start.
02. State the problem in minimization form.
03. Convert all the constraints into equality constraints by subtracting non negative surplus variables.
04. Add non negative artificial variable to left hand side of each constraint.
05. Rewrite the objective function, in which surplus variables will have zero coefficient and each artificial variables will have very large positive coefficient (designated by M).
06. Form first simplex table by taking artificial variables as basics and original variables and surplus variables as non-basics.
07. Form cost coefficient ($C_j - \Sigma c_i e_{ij}$) row.
08. (a) If for a column k, $C_k - \Sigma c_i e_{ik}$ is most negative and all entries in this column are negative, then the problem has an unbounded optimum solution. Go to step 15.
    (b) If all the elements in this row ($C_j - \Sigma c_i e_{ij}$ row) are non- negative then optimal solution is reached. Go to step 14.
    (c) If at least one element in this row ($C_j - \Sigma c_i e_{ij}$ row) is negative then further optimization is possible. Go to step 09.
09. Identify key column. It is the column having maximum negative value in the row ($C_j - \Sigma c_i e_{ij}$) row. This will decide the variable which will enter as basic in the next iteration.
10. Find the ratio for each row.
    Ratio = (b_i) / (a_{ij})
    b_i is the right hand side of the i^{th} constraint in the current iteration and a_{ij} is entry in the i^{th} row corresponding to j^{th} (key) column.
11. Decide key row. It is the row having smallest positive ratio.
12. Identify the pivot element (element corresponding to key column and key row) and proceed for formation of next simplex table. The method of formation of new simplex table is given in 4.2.
13. Go to step 07.
14. Print results.
15. Stop.

4.2 Formation of New Simplex Table (Finding the New Solution)

Steps to be followed for formation of new simplex table, i.e. finding the new solution are as below –

01. If the pivot element is 1, then the row remains the same in the new simplex table.
02. If the pivot element is other than 1, the all elements in the key row are divided by the pivot element to find the new values for that row.
03. The new values of the elements in the remaining rows for the new simplex table can be obtained by performing elementary row operation on all rows so that all elements (except the pivot element) in the key column are zero.

5. Application of Big-M Method to Optimum Time Coordination of OC Relays

As coordination of OC relays is basically an LPP, big-M simplex method can be applied to find the optimum solution to this problem. The aim is to find out the optimum value of *TMS* for all relays, hence the *TMS* of relays are taken as variables. The optimum values of *TMS* will ensure optimum time of operation of relays.

Out of the three sets of constraints (described by equations 2, 3 and 4), the relay characteristic constraint is already incorporated in the objective function (as shown in equation 5 and 6). The bounds on *TMS* and the coordination criteria are included in the problem as constraints. In case of optimum time coordination of OC relays the objective function will always be of minimization type and all the constraints will be inequality constraints of ≥ type. The constraints are converted to equality type by subtracting non-negative surplus variable from the left hand side of each constraint. To get an IBFS non-negative artificial variable is added to the left hand side of each constraint. The IBFS have all the artificial variables as basics and all the original variables (*TMS* for all relays) and the surplus variables as non-basics. Iterations are performed to obtain the optimum value of variables.

Numerical example of problem formulation for optimum time coordination of OC relays and its solution is given in next section.

6. Results

Big-M method is applied for optimum coordination of OC relays. A program is written in MATLAB for the same. Two cases (one radial and one ring fed system) are presented here for demonstration. Detail calculations are given for formation of objective function and constraints and for finding the optimum solution.

6.1 Illustration I

To test the algorithm, initially a simple radial system, shown in Fig. 1, is considered. The maximum fault current just beyond bus A and bus B are 4000 A and 3000 A respectively, the plug setting of both the relays is 1, the CT ratio for R_A is 300:1 and for R_B is 100:1. Minimum operating time for each relay is considered as 0.2 s and the CTI is taken as 0.57 s. Calculation of value of a_i (mentioned in equation 6) for relays is shown in Table 1.

The fault current in relay coil (relay R_A) for fault just beyond bus A is 13.33. As the plug setting for relay R_A is 1, PSM in this case is 13.33. The system considered here is radial, hence, fault just beyond bus A will not be sensed by relay R_B. Similarly 10 and 30 are the current in coils of relay R_A and R_B respectively, for fault just beyond bus B. Again as the plug setting of both relays is 1, the PSM values are 10 and 30 respectively, in this case.

Table 1

Calculation of a_i constant for relays

SN	Fault position	Relay R_A	Relay R_B
1.	Just beyond bus A	$\frac{0.14}{(13.33)^{0.02}-1} = 2.63$	---
2.	Just beyond bus B	$\frac{0.14}{(10)^{0.02}-1} = 2.97$	$\frac{0.14}{(30)^{0.02}-1} = 2.00$

Considering x_1 and x_2 as *TMS* of relay R_A and R_B respectively, the problem can be stated as –

$$\min z = 2.63x_1 + 2x_2 \tag{7}$$

$$\text{subject to } 2.97x_1 - 2x_2 \geq 0.57 \tag{8}$$

$$2.63x_1 \geq 0.2 \tag{9}$$

$$\text{and} \quad 2x_2 \geq 0.2 \tag{10}$$

This is a LPP. Out of the three set of constraints the relay characteristic constraint is incorporated in the objective function itself (as shown in equation 5 and 6). Equation 8 gives the coordination criteria constraint and the lower bound on the relay operating time is given by equation 9 and 10. The upper limit of *TMS* of for both relays is taken as 1.2. As the optimum value of *TMS* comes out to be less than upper bound, the constraints due to upper bound are not considered.

The problem is rewritten by converting the constraints to equality type and adding artificial variables as –

$$\min z = 2.63x_1 + 2x_2 + 0s_1 + 0s_2 + 0s_3 + MA_1 + MA_2 + MA_3 \tag{11}$$

$$\text{Subject to } 2.97x_1 - 2x_2 - s_1 + A_1 = 0.57 \tag{12}$$

$$2.63x_1 - s_2 + A_2 = 0.2 \tag{13}$$

and $2x_2 - s_3 + A_3 = 0.2$ (14)

where,

s_1, s_2, s_3 are surplus variables,

A_1, A_2, A_3 are artificial variables, and

M is penalty (a very large positive number)

The IBFS is written using the artificial variables (A_1, A_2, A_3) as basics and the original variables (x_1 and x_2) and the surplus variables (s_1, s_2, s_3) as non basics. The IBFS is shown in Table 2. The optimum solution to this problem is obtained using big-M method in three iterations. The iterations are shown in Table 3, 4 and 5.

As, at the end of third iteration, all the values in the $C_j - \sum C_i a_{ij}$ row are non-negative, the optimum solution is reached. The final (optimum) values of variables can be obtained from the column of b as shown in table 5. The optimum solution is

$TMS_1 = x_1 = 0.2592$

$TMS_2 = x_2 = 0.10$

The results for the same problem are obtained using two phase simplex method also and are found to be same. In phase I of the two phase simplex method the sum of the artificial variables is minimized subject to the given constraints, to get a basic feasible solution of the LPP. Second phase minimizes the original objective function, starting with the basic feasible solution obtained at the end of phase I. For this problem, in case of two phase simplex method, three iterations are to be performed in phase I and one iteration is required in phase II. Thus the total number of calculations to be performed is less in case of big-M method.

Table 2
Initial Basic Feasible Solution (Illustration I)

	C_j	2.63	2	0	0	0	M	M	M		
C_i	**Basics**	**x1**	**x2**	**s1**	**s2**	**s3**	**A1**	**A2**	**A3**	**b**	**Ratio**
M	**A1**	2.97	-2	-1	0	0	1	0	0	0.57	0.1919
M	**A2**	2.63	0	0	-1	0	0	1	0	0.2	0.076
M	**A3**	0	2	0	0	-1	0	0	1	0.2	∞
$\sum C_i a_{ij}$		2.97 + 2.63M	0	-M	-M	-M	M	M	M		
$C_j - \sum C_i a_{ij}$		2.63 – (2.97 + 2.63M)	2	M	M	M	0	0	0		

■ Key Column ■ Key Row ■ Pivot Element

Table 3
Iteration I (Illustration I) : x1 enters as basic, A2 leaves from basics

	C_j	2.63	2	0	0	0	M	M	M		
C_i	**Basics**	**x1**	**x2**	**s1**	**s2**	**s3**	**A1**	**A2**	**A3**	**b**	**Ratio**
M	**A1**	0	-2	-1	1.1293	0	1	-1.1293	0	0.3441	0.3047
2.63	**x1**	1	0	0	-0.3802	0	0	0.3802	0	0.076	-0.1998
M	**A3**	0	2	0	0	-1	0	0	1	0.2	∞
$\sum C_i a_{ij}$		2.63	0	-M	1.1293 M – 1.0157	-M	M	-1.1293 M + 1.0157	M		
$C_j - \sum C_i a_{ij}$		0	2	M	– 1.1293 M + 1.0157	M	0	2.1293 M – 1.0157	0		

■ Key Column ■ Key Row ■ Pivot Element

Table 4
Iteration II (Illustration I) : s2 enters as basic, A1 leaves from basics

	C_j	2.63	2	0	0	0	M	M	M		
C_i	**Basics**	**x1**	**x2**	**s1**	**s2**	**s3**	**A1**	**A2**	**A3**	**b**	**Ratio**
0	**s2**	0	-1.7710	-0.8855	1	0	0.8855	-1	0	0.305	-0.172
2.63	**x1**	1	-0.6733	-0.3367	0	0	0.3367	0	0	0.1919	-0.285
M	**A3**	0	2	0	0	-1	0	0	1	0.2	0.1
$\sum C_i a_{ij}$		2.63	2 M – 1.771	-0.8855	0	-M	0.8855	0	M		
$C_j - \sum C_i a_{ij}$		0	– 2 M + 3.771	0.8855	0	M	M - 0.8855	M	0		

Key Column Key Row Pivot Element

Table 5
Iteration III (Illustration I) : x2 enters as basic, A3 leaves from basics

	C_j	2.63	2	0	0	0	M	M	M		
C_i	**Basics**	**x1**	**x2**	**s1**	**s2**	**s3**	**A1**	**A2**	**A3**	**b**	**Ratio**
0	**s2**	0	0	-0.8855	1	-0.8855	0.8855	-1	0.8855	0.4822	
2.63	**x1**	1	0	-0.3367	0	-0.3367	0.3367	0	0.3367	0.2592	
2	**x2**	0	1	0	0	-0.5	0	0	0.5	0.1	
$\sum C_i a_{ij}$		2.63	2	-0.7946	0	-1.7946	0.7946	0	1.7946	Optimum solution is reached.	
$C_j - \sum C_i a_{ij}$		0	0	0.7946	0	1.7946	M – 0.7946	M	M – 1.7946		

6.2 Illustration II

In this case a single end fed, multi loop distribution system, with six OC relays as shown in Fig. 3 is considered.

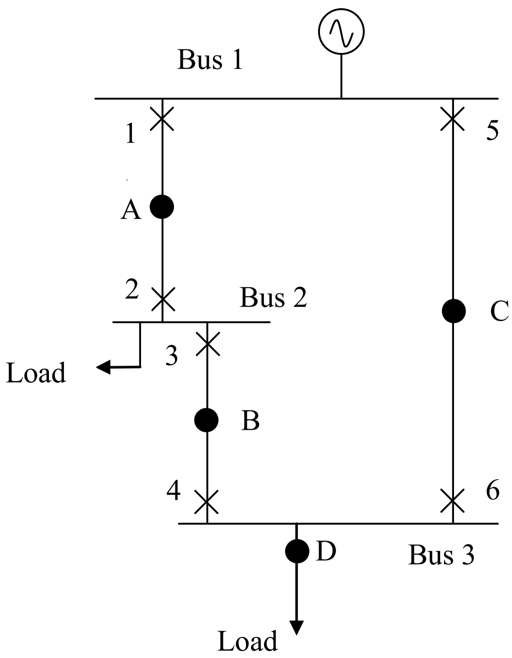

Fig. 3. A multi loop system (Illustration II)

The line data for the system is given in Table 6. Four different fault points are taken for illustration. The primary-backup relationships of relays for the four fault points are given in Table 7 and the CT ratios and plug settings are given in Table 8.

Table 6
Line Data for system shown in Fig.2

Line	Impedance (Ω)
1-2	0.08 + j 1
2-3	0.08 + j 1
1-3	0.16 + j 2

Table 7
Primary-backup relationship of relays

Fault point	Primary relay	Backup relay
A	1 2	-- 4
B	3 4	1 5
C	5 6	-- 3
D	3 5	1 --

Table 8
CT ratios and plug settings of relays

Relay	CT ratio (A / A)	Plug setting
1	1000 / 1	1
2	300 / 1	1
3	1000 / 1	1
4	600 / 1	1
5	600 / 1	1
6	600 / 1	1

The maximum fault current through the relays during fault at A, B, C, and D is given in Table 9. The current seen by the relays and the a_i constant (for different fault points) is shown in Table 10.

In this case there are six variables (TMS of six relays), six constraints due to bounds on relay operating time and four constraints due to coordination criteria (Actually there are five constraints due to coordination criteria, but one of them is redundant).

Table 9
Current through CT primary of relays for fault at A and B

		Fault Point			
		A	B	C	D
Current through CT primary of relays (A)	1	6579	2193	1096.5	1644.75
	2	939	--	--	--
	3	--	2193	1096.5	1644.75
	4	939	1315.8	--	--
	5	939	1315.8	3289.5	1644.75
	6	--	--	1096.5	--

-- indicates that the fault is not seen by the relay

Table 10 Current seen by the relays and the a_i constant (Illustration II)

Fault Point		Relay					
		1	2	3	4	5	6
A	I_{relay}	6.579	3.13	--	1.565	1.565	--
	a_i	3.6462	6.0651	--	15.5591	15.5591	--
B	I_{relay}	2.193	--	2.193	2.193	2.193	--
	a_i	8.8443	--	8.8443	8.8443	8.8443	--
C	I_{relay}	1.0965	--	1.0965	--	5.4825	1.8275
	a_i	75.9152	--	75.9152	--	4.0443	11.5397
D	I_{relay}	1.6447	--	1.6447	--	2.7412	--
	a_i	13.9988	--	13.9988	--	6.8720	--

-- indicates that the fault is not seen by the relay.

The normal range of TMS is taken as 0.025 to 1.2. This constraint is also taken into account. The CTI is set to its typical value of 0.3 second. The TMS of the six relays are taken as x_1 to x_6.

With the problem can be stated as

$$\min z = 3.6462x_1 + 6.0651x_2 + 8.8443x_3 + 8.8443x_4 + 4.0443x_5 + 11.5397x_6 \quad (15)$$

The constraints due to minimum operating time of relays are –

$$3.6462x_1 \geq 0.1 \quad (16)$$

$$6.0551x_2 \geq 0.1 \quad (17)$$

$$8.8443x_3 \geq 0.1 \quad (18)$$

$$8.8443x_4 \geq 0.1 \quad (19)$$

$$4.0443x_5 \geq 0.1 \quad (20)$$

$$11.5397x_6 \geq 0.1 \quad (21)$$

Constraints (17, 18, 19 and 21) are redefined as they violate the minimum value of TMS. Hence these constraints are rewritten as

$$x_2 \geq 0.025 \quad (17)$$

$$x_3 \geq 0.025 \quad (18)$$

$$x_4 \geq 0.025 \quad (19)$$

$$x_6 \geq 0.025 \quad (21)$$

The constraints due to coordination criteria are –

$$15.5591x_4 - 6.0651x_2 \geq 0.3 \quad (22)$$

$$8.8443x_1 - 8.8443x_3 \geq 0.3 \quad (23)$$

$$8.8443x_5 - 8.8443x_4 \geq 0.3 \quad (24)$$

$$75.9152x_3 - 11.5397x_6 \geq 0.3 \quad (25)$$

$$13.9988x_1 - 13.9988x_3 \geq 0.3 \quad (26)$$

Out of these, constraint given by equation 26 is automatically satisfied if constraint given by equation 23 is satisfied, hence this constraint (equation 26) is redundant constraint and can be dropped from the problem statement.

The original variables taken in this case are x_1 to x_6 which represent the TMS of the relays. Surplus variables are s_1 to s_{10} and the artificial variables are A_1 to A_{10}. In the IBFS all the artificial variables are taken as basics. Iterations are performed using big-M method. During the iterations the artificial variables come out of the basics. Optimum solution is obtained in twelve iterations. The optimum values of TMS obtained are as under (the subscripts indicate the relay number) –

$$TMS_1 = 0.0589$$

$$TMS_2 = 0.025$$

$$TMS_3 = 0.025$$

$$TMS_4 = 0.2903$$

$$TMS_5 = 0.06293$$

$$TMS_6 = 0.025$$

7. Conclusion

Big-M method for optimum time coordination of overcurrent relays in distribution system is presented in this paper. The optimum relay coordination problem is basically a highly constrained optimization problem. Formation of this problem as a LPP is explained in this paper. A program has been developed in MATLAB for finding the optimum time coordination of relays using big-M method. The program can be used for optimum time coordination of relays in a system with any number of relay and any number of primary-backup relationships. Two illustrations are presented in this paper. The minimum operating time for each relay is considered as 0.2 s in illustrations I and 0.1 s in illustration II. The CTI for illustration I is taken as 0.57 s, whereas for illustration II it is taken as 0.3 s. It shows that depending upon the relay and breaker specifications and system requirements the constraints can be formed and the optimum coordination can be obtained. The number of calculations to be performed in each iteration is same in case of big-M method as well as two phase simplex method, but the number of iterations to be performed is less in case of big-M method.

The algorithm is successfully tested for various systems, including multi loop systems and is found to give satisfactory results in all the cases.

References:

[1] Y.G.Paithankar, and S.R. Bhide, *"Fundamentals of Power System Protection"*, Prentice Hall of India Private Limited, New Delhi, 2007.

[2] B.Ravindranath, and M. Chander, "*Power SystemProtection and Switchgear"*, New Age International (P) Limited Publishers, New Delhi, 2006.

[3] C.R.Mason, *"The Art and Science of Protective Relaying"*, John Wiley and Sons, New York, 1956.

[4] A.R.C.Van Warrington, *Protective Relays, Their Theory and Practice"*, John Wiley and Sons, New York, 1969.

[5] A.S. Noghabi, J. Sadeh, and H.R. Mashhadi, "Considering Different Network Topologies in Optimal Overcurrent Relay Coordination Using a Hybrid GA", *IEEE Trans. on Power Delivery*, Vol 24, October 2009, pp. 1857-1863.

[6] B. Chattopadhyay, M.S. Sachdev, and T.S. Sidhu, "An Online Relay Coordination algorithm for Adaptive Protection using Linear Programming Technique", *IEEE Trans. on Power Delivery*, Vol 11, Jan 1996, pp. 165-173.

[7] H. Zeienldin, El-Saadany and M.A. Salama, "A Novel Problem Formulation for Directional Overcurrent Relay Coordination," *IEEE International Conference*, 2004, , pp. 48-52.

[8] A.J. Urdaneta, H. Restrepo, S. Marquez, and J. Sanchez, "Coordination of Directional Overcurrent Relay Timing Using Linear Programming", *IEEE Trans. on Power Delivery*, Vol 11, No. 1, Jan 1996, pp. 122-129.
[9] C.W. So, and K.K.Li, "Overcurrent Relay Coordination by Evolutionary Programming", *Electric Power System Research,* Vol 53, 2000, pp. 83-90.
[10] A.J. Urdaneta, Nadira Ramon, and Luis G.P. Jimenez, "Optimal Coordination of Directional Relays in Interconnected Power System", *IEEE Trans. on Power Delivery*, Vol 3, No. 3, July 1988, pp. 903-911.
[11] Bhattacharya S. K., and Goswami S. K., "Distribution Network Reconfiguration Considering Protection Coordination Constraints", *Electric Power Components and Systems,* Vol. 36, 2008, pp. 1150-1165.
[12] Razavi F., Abyaneh H.A., Al-Dabbagh M., Mohammadi R., and Torkaman H., "A New Comprehensive Genetic Algorithm Method for Optimal Overcurrent Relays Coordination", *Electric Power System Research,* Vol 78, 2008, pp. 713-720.
[13] Keil T., and Jager J., "Advanced Coordination Method for Overcurrent Protection Relays Using Nonstandard Tripping Characteristics", *IEEE Trans. on Power Delivery*, Vol 23, January 2008, pp. 52-57.
[14] Birla D., Maheshwari R.P., and Gupta H.O., "An Approach to Tackle the Threat of Sympathy Trips in Directional Overcurrent Relay Coordination", *IEEE Trans. on Power Delivery*, Vol 22, January 2007, pp. 851-858.
[15] Birla D., Maheshwari R.P., and Gupta H.O., "A New Nonlinear Directional Overcurrent Relay Coordination Technique, and Banes and Boons of Near-End Faults Based Approach", *IEEE Trans. on Power Delivery*, Vol 21, July 2006, pp. 1176-1182.
[16] Birla D., Maheshwari R.P., and Gupta H.O., "Random Search Technique in Directional Overcurrent Relay Coordination", *International Journal of Emerging Electric Power Systems*, Vol. 7, Issue 1, Article 1, 2006.
[17] P. Sankara Iyer, *"Operations Research"*, Tata McGraw Hill Publishing Company Limited, New Delhi, 2009.
[18] J.K. Sharma, *"Operations Research – Theory and Applications"*, Third edition, Macmillan India Limited, New Delhi, 2009.
[19] H. Taha, *"Operations Research – An Introduction"*, eighth edition, Dorling Kindersley (India) Pvt.Ltd., New Delhi, 2009.
[20] B. E. Gillett, *"Introduction to Operations Research – A Computer Oriented Algorithmic Approach"*, Tata McGraw Hill Publishing Company Limited, New Delhi, 2005.
[21] W.L. Winston, *"Operations Research – Applications and Algorithms"*, fourth edition, Thomson Learning Inc., 2007.