

Determining Optimum Time Multiplier Setting of Overcurrent Relays Using Mixed Integer Linear Programming

P. N. Korde, P. P. Bedekar

Abstract—The time coordination of overcurrent relays (OCR) in a power distribution network is of great importance, as it reduces the power outages by avoiding the mal-operation of the backup relays. For this, the optimum value of the time multiplier setting (TMS) of OCRs should be chosen. The problem of determining the optimum value of TMS of OCRs in power distribution networks is formulated as a constrained optimization problem. The objective is to find the optimum value of TMS of OCRs to minimize the time of operation of relays under the constraint of maintaining the coordination of relays. A power distribution network can have a combination of numerical and electromechanical relays. The TMS of numerical relays can be set to any real value (which satisfies the constraints of the problem), whereas the TMS of electromechanical relays can be set in fixed step (0 to 1 in steps of 0.05). The main contribution of this paper is a formulation of the problem as a mixed-integer linear programming (MILP) problem and application of Gomory's cutting plane method to find the optimum value of TMS of OCRs. The TMS of electromechanical relays are taken as integers in the range 1 to 20 in the step of 1, and these values are mapped to 0.05 to 1 in the step of 0.05. The results obtained are compared with those obtained using a simplex method and its variants. It has been shown that the mixed-integer linear programming method outperforms the simplex method (and its variants) in the case of a system having a combination of numerical and electromechanical relays.

Keywords—Backup protection, constrained optimization, Gomory's cutting plane method, mixed-integer linear programming, overcurrent relay coordination, simplex method.

I. INTRODUCTION

THE main purpose of the primary relay is to protect the system against faults within its primary zone, but if failure of the primary relay (or associated circuit breaker) occurs, then a tripping command should be given by the backup relay (to the associated circuit breaker). The relays must have proper coordination so that there should not be any mal-operation. This can be done by calculating the operating time of relays properly. The relay operating time depends on its TMS and plug set. So the main aim of researchers is to select suitable values of these settings of relays so that the overall time of relay operation should reduce, and simultaneously there should be coordination with other relays.

If the P.S. values of OCRs are taken to be fixed and

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predetermined, then the problem of finding the value of TMS to give minimum fault clearing time becomes an optimization problem that is linear [2], [3]. Several conventional methods, like simplex, two-phase simplex, revised simplex, big-M, dual simplex etc.; and several advanced methods like genetic algorithms, particle swarm optimization, evolutionary programming, gravitational search algorithm, leadership-based grey-wolf optimizer, Jaya algorithm, etc., have been proposed to solve this problem [2]-[21]. A review of OCR coordination has been presented in [22], [23].

In the literature available on relay coordination, mostly, the OCRs are considered to be numerical relays, the TMS of which can be set to any real value (which satisfies the constraints of the problem). However, in practice, a power distribution network can have a combination of some numerical and some electromechanical relays. The TMS of numerical relays can be set to any real value (which satisfies the constraints of the problem), whereas the TMS of electromechanical relays can be set in fixed steps (0 to 1 in the step of 0.05). In this type of case, a special method is to be used to determine optimum values of TMS of OCRs. The problem is formulated as MILP problem in this paper, and Gomory's cutting plane method is applied to find the optimum value of TMS of OCRs. The TMS of electromechanical relays is taken as integers in the range 1 to 20 in the step of 1. These values are mapped to 0.05 to 1 in the step of 0.05 for all calculations.

A program has been developed in MATLAB for Gomory's cutting plane method. The algorithm was successfully tested for various systems, including any number and variety of OCRs, and was found to give satisfactory results in all the cases. MATLAB programs have also been developed for the simplex method and its variants for comparison. It was found that MILP outperforms the simplex method (and its variants) in the case of a system having a combination of some numerical and some electromechanical relays.

II. PROBLEM FORMULATION

The coordination problem of directional OCR in a ring fed distribution systems can be represented as an optimization problem, with the sum of the all relay operating time of the system as objective function so the function to be minimized can be given as [2]-[7],

$$\min z = \sum_{i=1}^m W_i \cdot t_{i,k} \quad (1)$$

where m is the number of relays, $t_{i,k}$ is the operating time of the relay R_i , for fault at k , and W_i is the weight assigned for the operating time of the relay R_i .

The transmission lines in distribution system are short and approximately of same length, hence equal weight (= 1) is assigned to all relay operating times [3], [14], [15].

The objective function is to minimize the total time of operation of all relays under sets of three constraints [3], [7], [8], [15], as discussed in the following sections.

A. Constraint Set 1: Coordination Criteria

A fault is sensed by both primary as well as secondary relay simultaneously. The backup relay should take over the tripping action only after the primary relay fails to operate. R_j is the primary relay for fault at k , and R_i is a backup relay for the same spot, and then the coordination constraint can be stated as

$$t_{i,k} - t_{j,k} \geq \Delta t \quad (2)$$

where $t_{j,k}$ is the operating time of the primary relay R_j , for fault at k , $t_{i,k}$ is the operating time for the backup relay R_i , for the same fault (at k), Δt is the coordination time interval (CTI).

B. Constraint Set 2: Bounds on the Relay Setting and Operating Time

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

$$t_{i,\min} \leq t_{i,k} \leq t_{i,\max} \quad (3)$$

where $t_{i,\min}$ is the minimum operating time of relay at location i for fault at any point in the zone of operation, $t_{i,\max}$ is the maximum operating time of relay at location i for fault at any point in the zone of operation.

The bounds on time multiplier setting (TMS) of relays can be stated as

$$TMS_{i,\min} \leq TMS_i \leq TMS_{i,\max} \quad (4)$$

where $TMS_{i,\min}$ is the minimum value of TMS relay R_i , $TMS_{i,\max}$ is the maximum value of TMS the relay R_i .

Since constraints (3) and (4) are correlated with each other, only one needs to be considered. This is explained in Section V A. $TMS_{i,\min}$ and $TMS_{i,\max}$ are taken as 0.025 and 1.2,

respectively, for numerical relays [24]. Any value in this range is permissible. For electromechanical relays, $TMS_{i,\min}$ and $TMS_{i,\max}$ are taken as 0.05 and 1.0, respectively. In this range, electromechanical relays can take values in steps of 0.05 only.

C. Constraint Set 3: Relay Characteristics

OCR can have a variety of characteristics, as shown in (5) and detailed in Table I [1], [3], [24]:

$$t_{op} = \frac{\lambda(TMS)}{(PSM)^\gamma - 1} \quad (5)$$

where t_{op} is relay operating time, PSM is plug setting multiplier.

As the pickup currents of the relays are predetermined from the system requirements, (5) becomes

$$t_{op} = a(TMS) \quad (6)$$

where,

$$a = \frac{\lambda}{(PSM)^\gamma - 1} \quad (7)$$

Making substitution from (6) in (1), the objective function becomes

$$\min z = \sum_{i=1}^m a_{i,k} (TMS)_i \quad (8)$$

where $a_{i,k}$ is a constant of relay R_i for fault at point k . Thus, the relay characteristic constraint is incorporated in the objective function itself. The values $a_{i,k}$ are predetermined.

The optimum value TMS for each relay has been determined using Gomory's cutting plane method in this paper.

TABLE I
 VALUES OF λ AND γ FOR DIFFERENT TYPES OF OCR

OCR type	λ	γ
Instantaneous	Operating time is fixed. No intentional time delay is added.	
Definite Time	Operating time is pre-decided and fixed. The intentional time delay may be added.	
Inverse Definite Minimum Time	0.14	0.02
Very Inverse	13.5	1
Extremely Inverse	80	2

III. MIXED-INTEGER LINEAR PROGRAMMING

In linear programming, each variable is allowed to take any non-negative real (fractional) value. But there are certain problems in which the variables cannot assume fractional values. In a problem, if all the decision variables are required to assume non-negative integer values, it is called "pure integer linear programming". If only some of the variables are

restricted to assume non-negative integer and other variables can take any non-negative real (fractional) value, then it is called "mixed integer linear programming" problem [25], [26]. Gomory's cutting plane method is most suitable method if you are using a popular method used to solve the MILP problems.

A. Gomory's Cutting Plane Method

In this method, we generate new constraints so as to ensure an integrated solution for the integer restricted basic variables. These additional constraints do not cut-off that portion of the original feasible region, which contains a feasible integer point. Also, it cuts-off the current non-integer solution to the problem [26]. Gomory's cutting plane method to solve the MILP problem can be summarized in the following steps [25]:

- Step1. Initialization: Formulate the standard integer linear programming problem (LPP). Solve it by simplex method ignoring integer requirements of variables.
- Step2. Test of optimality:
- Examine the optimal solution. If all restricted integer variables have integer values, then terminate the procedure. The current optimal solution, obtained in step 1, is the optimal basic feasible solution to the MILP problem.
 - If all restricted integer variables are not integers, then go to step 3.
- Step3. Generate cutting plane: Choose a row r corresponding to a basic variable $X.R.$ which has the largest fractional value f_r , and generate a cutting plane in the form.

$$s_g = -f_r + \sum_{j \in R^+} a_{rj} x_j + \left(\frac{f_r}{f_r - 1} \right) \sum_{j \in R^-} a_{rj} x_j \quad (9)$$

with $0 < f_r < 1$ where a_{rj} = coefficient of j^{th} variable in r^{th} row, R^+ = set of subscripts j (columns in simplex table) for which $a_{rj} \geq 0$, R^- = set of subscripts j (columns in simplex table) for which $a_{rj} \leq 0$.

Step4. Obtain the new solution: Add the cutting plane (additional constraint) generated in step 3 to the bottom of the optimal simplex table as obtained in step 1. Find a new optimal solution using dual simplex method and return to Step 2.

The process is repeated until all restricted basic variables are integers.

IV. IMPLEMENTATION OF THE PROPOSED METHOD

Coordination of OCRs is basically an LPP, in which the aim is to find out the optimum values of TMS for all relays. Hence TMS of the relays are taken as variables. The optimum values of TMS will ensure an optimum time of operation of relays. Out of the three sets of constraints, the relay characteristic constraint is incorporated in the objective function and in the relay operating time constraints. Hence these constraints need not be considered separately.

Since the P.S. of relays are predetermined and fixed, the bounds on TMS and the relay operating time are correlated to

each other, one of them becomes redundant and only one needs to be considered. These constraints are incorporated by considering the lower and upper bounds of the variables. The range for TMS of numerical relays is taken as 0.025 and 1.2. Any value in this range (which satisfies the constraints) is permitted. The variables representing the TMS of electromechanical relays are taken as restricted integer variables, which can vary in the range of 1 to 20 in the step of 1. Thus, the problem becomes a MILP problem. But, as the actual value of TMS of electromechanical relays can be set in fixed step (0 to 1 in steps of 0.05), hence the integer values (1 to 20 in steps of 1) are mapped to 0.05 to 1 in the step of 0.05.

The coordination criteria are included in the problem as constraints. Gomory's cutting plane method was applied to solve this MILP.

V. RESULTS AND DISCUSSIONS

A program was written in MATLAB to solve the relay coordination problem, which is a MILP problem, using Gomory's cutting plane method. The program was successfully tested for various cases, out of which two cases are presented in this paper. Detailed calculations are given for the formation of objective function and constraints in illustration I. Similar calculations were performed in illustration II. In illustration I, all relays are considered as inverse definite minimum time (IDMT) OCRs, whereas a variety of OCR characteristics have been considered in illustration II.

A. Illustration -1

In this case, a single-end-fed distribution system with parallel-feeder, with five O.C. relays (as shown in Fig. 1) was considered. Three different fault points were considered. The load currents during the fault were assumed to be negligible.

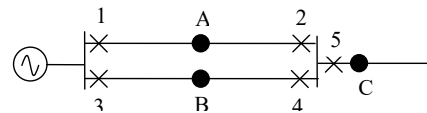


Fig. 1 A single-end-fed distribution system with parallel-feeders

The source and line data for the system are given in Table II. The line charging admittances are neglected.

TABLE II
 SOURCE AND LINE DATA (FOR THE SYSTEM SHOWN IN FIG. 1)

Source:	
3.3 kV (L.L.), j0.15 Ω	
Lines:	
Line	Series Impedance (Ω)
1-2 (1)	0.08 + j 1
1-2 (2)	0.08 + j 1
2-3	0.08 + j 1

The CT ratio of each relay is considered as 300:1, and the plug settings of all relays are taken as 1 (100%). The minimum allowable operating time for each relay is considered as 0.1 s, and the CTI is taken as 0.2 s. The primary-

backup relationships of relays and the fault current through the relays for the three fault points are given in Table III. The current seen by the relays and the a_i constant (for different fault points) are shown in Table IV.

TABLE III
PRIMARY-BACKUP RELATIONSHIP AND FAULT CURRENT
(ILLUSTRATION I)

Fault point	Primary relay	Fault Current (A)	Backup relay	Fault Current (A)
A	1	2717.7	--	--
	2	905.8	3	905.8
B	3	2717.7	--	--
	4	905.8	1	905.8
C	5	2925.6	1	1462.8
			3	1462.8

TABLE IV
CURRENT SEEN BY THE RELAY AND AI CONSTANT
(ILLUSTRATION I)

Fault Point		Relays				
		1	2	3	4	5
A	Irelay	9.059	3.0193	3.0193	--	--
	ai	3.1069	6.265	6.265	--	--
B	Irelay	3.0193	--	9.059	3.0193	--
	ai	6.265	--	3.1069	6.265	--
C	Irelay	4.876	--	4.876	--	9.752
	ai	4.3487	--	4.3487	--	3.004

$x_1, x_2, x_3, x_4,$ and x_5 are considered as design variables (representing the TMS of relays 1 to 5, respectively). Relay 1 and 2 are considered as electromechanical, and the remaining (relay 3, 4, and 5) are considered as numerical relays. With this, the problem can be stated as

$$\min z = t_{1A} + t_{1B} + t_{1C} + t_{2A} + t_{3A} + t_{3B} + t_{3C} + t_{4B} + t_{5C} \quad (10)$$

where t_{ik} is the operating time of i^{th} relay for fault at point k .

Using (6) and the a_i constants, (10) can be written as

$$\min z = (3.1069 + 6.265 + 4.3487)x_1 + 6.265x_2 + (6.265 + 3.1069 + 4.3487)x_3 + 6.265x_4 + 3.004x_5$$

or

$$\min z = 13.7206x_1 + 6.265x_2 + 13.7206x_3 + 6.265x_4 + 3.004x_5 \quad (11)$$

The constraints due to minimum operating time of relays are –

$$3.1069x_1 \geq 0.1 \Rightarrow x_1 \geq 0.032 \quad (12)$$

$$6.265x_2 \geq 0.1 \Rightarrow x_2 \geq 0.01596 \quad (13)$$

$$3.1069x_3 \geq 0.1 \Rightarrow x_3 \geq 0.032 \quad (14)$$

$$6.265x_4 \geq 0.1 \Rightarrow x_4 \geq 0.01596 \quad (15)$$

$$3.004x_5 \geq 0.1 \Rightarrow x_5 \geq 0.0333 \quad (16)$$

Constraints (12), (13), and (15) are redefined as they violate the minimum value TMS . Referring to Section II B, the minimum limit on TMS being 0.05 for electromechanical relays, and it is 0.025 for numerical relays. Hence these constraints are rewritten as

$$x_1 \geq 0.05 \quad (\text{Relay 1 is electromechanical}) \quad (17)$$

$$x_2 \geq 0.05 \quad (\text{Relay 2 is electromechanical}) \quad (18)$$

$$x_4 \geq 0.025 \quad (\text{Relay 4 is numerical}) \quad (19)$$

Constraints (13) and (15) need not be redefined as they satisfy the minimum TMS constraint also. Equations (14) and (16)-(19) are used to define the lower limit of variables x_1 to x_5 , respectively, and thus constraints due to bounds on TMS and operating time of relays are incorporated.

The constraints due to coordination criteria are (considering CTI = 0.2)

$$6.265x_3 - 6.265x_2 \geq 0.2 \quad (20)$$

$$6.265x_1 - 6.265x_4 \geq 0.2 \quad (21)$$

$$4.3487x_1 - 3.004x_5 \geq 0.2 \quad (22)$$

$$4.3487x_3 - 3.004x_5 \geq 0.2 \quad (23)$$

Also $x_i \geq 0, i = 1 \dots 5$ (non-negativity constraint), and x_1 & x_2 are integers (This makes the problem, an MILP problem). As x_1 and x_2 are representing the TMS of relay 1 and 2, respectively, which are electromechanical relays, hence they can take values in the range 0.05 to 1 in the step of 0.05 only. To achieve this, x_1 and x_2 are taken as integers in the range 1 to 20 in the step of 1. These integer values are mapped as 0.05 to 1 in the step of 0.05 for all calculations.

The Gomory's cutting plane algorithm described in Section III A was implemented in MATLAB. The optimum values of TMS obtained are shown as (the subscripts indicate the relay number):

$$TMS_1 = 0.05, TMS_2 = 0.05, TMS_3 = 0.032, TMS_4 = 0.025, TMS_5 = 0.0333$$

The values of TMS obtained are found to satisfy all the constraints. They give the minimum operating time of relays for any fault location and also ensure the proper coordination.

Comparison with a Simplex Method and Its Variants

For the sake of comparison, the problem was also solved using the simplex method. As the problem in hand cannot be solved directly by the simplex method [3], a simplex algorithm was operated on the dual of the problem. The results

obtained are presented in Table V.

TABLE V
RESULTS OBTAINED USING GOMORY'S ALGORITHM AND SIMPLEX ALGORITHM (ILLUSTRATION I)

	Using Gomory's cutting plane algorithm	Using the simplex algorithm
TMS		
TMS1	0.1000	0.0690
TMS2	0.0500	0.0500
TMS3	0.0819	0.0819
TMS4	0.0250	0.0250
TMS5	0.0333	0.0333
Objective function value	3.0660	2.6406
Remark	The solution is feasible and optimal	The solution is not feasible because TMS of relay 1 (which is an electromechanical relay) cannot be set to the obtained value

B. Illustration II

In this case, a single end-fed, multi-loop distribution system, with seven O.C. relays (as shown in Fig. 2) was considered. A variety of O.C. relays were taken. The primary-backup relationships and maximum fault current through the relays for different fault points is shown in Table VI. The relay type, their operating time, C.T. ratio, and their plug settings are shown in Table VII. The plug setting of each relay has been decided on the basis of the maximum load current (including permissible overload) through the relay.

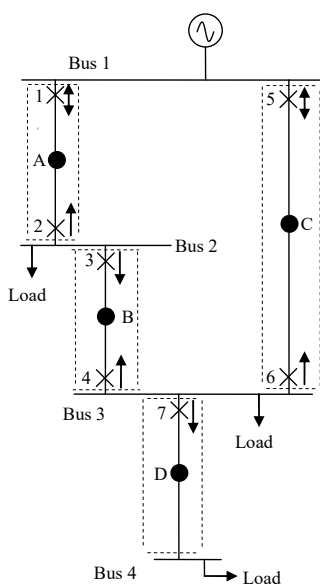


Fig. 2 Single-end-fed, multi-loop distribution system (for illustration II)

The optimization problem was formed in the same way as explained in illustration I. As relay 7 is instantaneous O.C. relay and relay two is definite time O.C. relay their operating time for any fault location is fixed and is shown in Table VII. Thus, in this case, there are five variables (TMS of relays 1, 3, 4, 5, and 6). Value of CTI was taken as 0.2 s and minimum operating time for each relay (except rely on 2 and 7) was taken as 0.1. As relays 1, 3, and 4 are taken as

electromechanical relays, the problem becomes a MILP problem (as explained in illustration I). After formulating the problem, it was solved using the simplex method (operated on dual of the problem) and using Gomory's method. The problem was also solved using other variants of the simplex method. The results obtained are presented in Table VIII. Again, it can be seen that the result obtained using the simplex method is not a feasible solution. These results obtained using Gomory's method satisfy all constraints.

TABLE VI
PRIMARY-BACKUP RELATIONSHIPS AND MAXIMUM FAULT CURRENT THROUGH RELAYS (ILLUSTRATION II)

Fault Point	Primary relay	Backup relay	Max. fault current (A)
A	1	--	6579
	2	4	939
B	3	1	2193
	4	5	1315.5
C	5	--	3289.5
	6	3	1096.5
D	7	3	1315.8 through relays 3 & 5
		5	2631.6 through relay 7

TABLE VII
RELAY TYPE, OPERATING TIME, C.T. RATIO, AND PLUG SET (ILLUSTRATION II)

Relay	Type-1	Type-2	Operating time (second)	C.T. ratio (A / A)	Plug setting (A)
1	Non-directional IDMT OC	Electromechanical	$\frac{0.14(TMS)}{(PSM)^{0.02} - 1}$	1000 / 1	0.8
2	Definite time O.C.	Numerical	0.12	1000 / 1	0.8
3	Directional IDMT OC	Electromechanical	$\frac{0.14(TMS)}{(PSM)^{0.02} - 1}$	500 / 1	0.8
4	Very inverse time O.C.	Electromechanical	$\frac{13.5(TMS)}{(PSM) - 1}$	500 / 1	0.8
5	Non-directional IDMT OC	Numerical	$\frac{0.14(TMS)}{(PSM)^{0.02} - 1}$	1000 / 1	0.8
6	Significantly inverse time O.C.	Numerical	$\frac{80(TMS)}{(PSM)^2 - 1}$	1000 / 1	0.8
7	Instantaneous O.C.	Numerical	0.08	500 / 1	0.5

TABLE VIII
RESULTS OBTAINED USING GOMORY'S ALGORITHM AND SIMPLEX ALGORITHM (ILLUSTRATION II)

	Using Gomory's cutting plane algorithm	Using the simplex algorithm (and its variants)
TMS		
Relay 1	0.3000	0.2383
Relay 3	0.4000	0.3604
Relay 4	0.0500	0.0500
Relay 5	0.0353	0.0353
Relay 6	0.0250	0.0250
Objective function value	14.0404	12.7400
Remark	The solution is feasible and optimal	The solution is not feasible because TMS of relay 1 and 3 (which are electromechanical relays) cannot be set to the obtained value

VI. CONCLUSIONS

The problem of determining optimum values of TMS of OCRs can be considered as an exercise in optimization. A systematic procedure for formulating the relay coordination problem as an optimization problem has been presented. As a power distribution network can have a combination of some numerical and some electromechanical relays, the problem is formulated as a MILP problem. The variables representing TMS of electromechanical OCRs are assigned integer values in the range 1 to 20 (in the step of 1) and are properly mapped as 0.05 to 1 (in the step of 0.05). The solution to the problem has been obtained using Gomory's cutting plane method. A program has been developed in MATLAB for the same. The program can be used for finding the optimum value of TMS of OCRs in a system with any number of relays and any number of primary-backup relationships. The algorithm was successfully tested for various system configurations, including multi-loop systems and systems with a variety of OCR, and was found to give satisfactory results in all the cases.

MATLAB programs have also been developed for the simplex method and its variants for comparison. It was found that the simplex method gives a solution that is not feasible. Other variants of the simplex algorithm (revised simplex, two-phase simplex, dual simplex, big-M method) also lead to the same non-feasible solution. It has been shown that Gomory's method (which is the most popular method to tackle MILP problems) outperforms the simplex method (and its variants) in the case of a system having a combination of numerical and electromechanical relays.

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