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Optimum Coordination of Overcurrent Relays using Revised Simplex Method

Prashant P Bedekar*, Sudhir R Bhide** and Vijay S Kale**

The overcurrent relays (OCRs) are the major protection devices in a distribution system. To reduce the power outages, maloperation of the backup relays should be avoided, and therefore, OCR time coordination in power distribution network is a major concern of protection engineer. The OCR 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 maloperation of relays. The problem can be stated as a Linear Programming Problem (LPP).

This paper presents revised simplex method for optimum time coordination of OCRs in ring fed distribution systems. The LPP of OCR coordination involves large number of variables and constraints. As the revised simplex method works with the reduced table, the amount of computations and the memory requirement is very much reduced. Thus the calculations to be performed reduce to a great extent. Comparison with dual simplex, Big-M simplex and two phase simplex method is also presented.

Keywords: *Backup Protection, Constrained Optimization, Overcurrent Relay Coordination, Revised Simplex Method, Simplex Method Variants*

1.0 INTRODUCTION

The most obvious effect of a shunt fault is a sudden build 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 in distribution systems [1]. OCRs are usually employed as backup protection. But in some situations it may be the only protection provided. They are commonly used as an economic alternative for the protection of distribution systems [2,3]. To reduce the power outages, maloperation of the backup relays should be avoided, and therefore, OCR coordination in power distribution network is a major concern of protection engineer. 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 initiate tripping. 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 [4]. The directional OCR time coordination problem in distribution system can be defined as constrained optimization problem and can be formulated as an LPP.

*Research Scholar, Electrical Engineering Department, Visvesvaraya National Institute of Technology, Nagpur (Maharashtra), INDIA.
**Electrical Engineering Department, Visvesvaraya National Institute of Technology, Nagpur (Maharashtra), INDIA.

Several optimization techniques have been proposed for optimum coordination of OCR [3-20]. In [3] and [4] the relay coordination problem is formulated as mixed integer non-linear programming (MINLP) and is solved using General Algebraic Modeling System (GAMS) software. To avoid the complexity of MINLP technique, the OCR coordination problem is commonly formulated as an LPP. Various LPP techniques have been used in [5-8] for OCR coordination. In [9] and [10] optimum coordination has been obtained considering the configuration changes of the network into account. In [11-13], GAs are proposed to find the optimum solution for relay settings. Directional OCR coordination problem has been solved in [14] using hybrid GA, considering the effects of the different network topologies. In [15] also system topology changes have been considered and an adaptive scheme has been suggested for relay coordination. A new nonstandard tripping characteristic for overcurrent relays and its advanced method for optimized coordination have been presented in [16]. In [17], it has been proposed to introduce additional constraints in the directional OCR coordination problem to tackle the sympathy trips in which other relays in the system operate earlier than the designated primary relay. A method of simultaneously optimizing all the settings of directional OCR, in non-linear environment by Sequential Quadratic Programming method has been presented in [18]. Non-linear Random Search Technique to solve the coordination problem has been presented in [19] and it has been shown that it is possible to achieve the acceptable speed of primary protection while attempting to coordinate the maximum relay pairs. A review of time OCR coordination has been presented in [20].

This paper presents revised simplex technique for optimum coordination of OCRs in a ring fed distribution system. As the revised simplex method works with the reduced table, the LPP, like optimum coordination of OCR can be solved efficiently using revised simplex algorithm.

2.0 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. If the operating time of primary relay is set to 0.1 s, the backup relay should wait for 0.1 s plus, a time equal to the operating time of circuit breaker (CB), associated with primary relay, plus the overshoot time of backup relay [1]. This is necessary for maintaining the selectivity of primary and backup relays.

A ring main feeder system is shown in Fig. 1. It allows supply to be maintained to the loads connected to all the buses, 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 OCRs. All directional relays have their tripping direction away from the concerned bus.

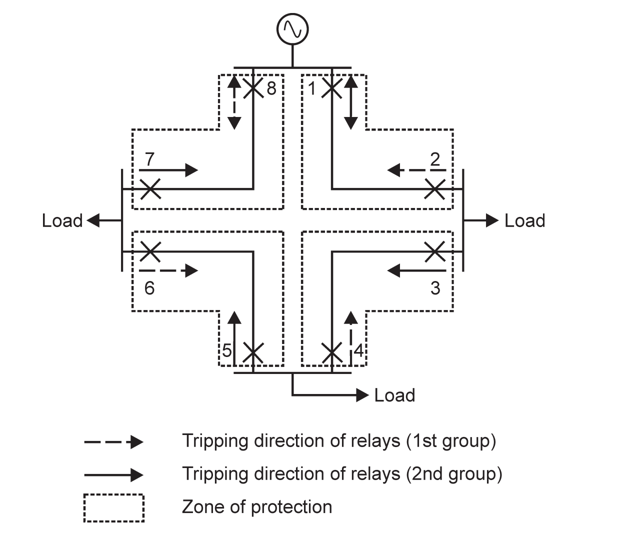

FIG. 1 A RING MAIN FEEDER

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 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 and it can be solved by revised simplex technique, even for large systems.

3.0 PROBLEM FORMULATION

The coordination problem of directional OCR in a ring fed distribution systems, can be stated as an optimization problem, where the sum of the operating times of the relays of the system, for different fault points, is to be minimized [3-6],

i.e., $$\min z = \sum_{i=1}^{m} W_i . t_{i,k} \qquad (1)$$

where

m is the number of relays,

$t_{i,k}$ is the operating time of the relay R_i, for fault in at k, and

W_i is weight assigned for operating time of the relay R_i

In distribution system since the lines are short and are of approximately equal length, equal weight (=1) is assigned for operating times of all the relays [3,5,9].

The objective of minimizing the total operating time of relays is to be achieved under three sets of constraints [3-7,9].

3.1 Coordination Criteria

Fault is sensed by both primary as well as secondary relay simultaneously. To avoid mal-operation, the backup relay should takeover the tripping action only after primary relay fails to operate. If R_j is the primary relay for fault at k, and R_i is backup relay for the same fault, then the coordination constraint can be stated as

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

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)

3.2 Bounds on the Relay Setting and Operating Time

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

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

where,

$t_{i,\min}$ is the minimum operating time of relay at i for fault at any point

$t_{i,\max}$ is the maximum operating time of relay at i for fault at any point

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

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

where,

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

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

Instead of taking these two constraints (mentioned in equation 3 and 4) for each relay, one is taken and other, which is redundant, is not considered. This is explained in illustration I. $TMS_{i,\min}$ and $TMS_{i,\max}$ are taken as 0.025 and 1.2 respectively [21].

3.3 Relay Characteristics

All relays are assumed to be identical and are assumed to have normal IDMT characteristic as [1, 3, 5, 11] :

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

where,

t_{op} is relay operating time, 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 (5) becomes

$$t_{op} = \alpha(TMS) \tag{6}$$

$$\text{where, } \alpha = \frac{\lambda}{(PSM)^{\gamma} - 1} \tag{7}$$

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

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

where, $\alpha_{i,k}$ is constant of relay R_i for fault at k.

Thus the relay characteristic constraint is incorporated in the objective function itself. The values of $\alpha_{i,k}$ for relay R_i for different fault locations (k) are predetermined. Value of *TMS* for each relay is to be determined using simplex method.

4.0 REVISED SIMPLEX METHOD

Revised simplex method is a modification of regular simplex method, which computes and stores only the relevant information required for the current iteration and hence it is more economical on the computer [22].

The problem of OCR coordination is a minimization problem with constraints as inequalities of greater than or equal to (≥) type, hence the algorithm of revised simplex method to solve a minimization problem with constraints as inequalities of greater than or equal to type is given below [23,24].

01. Start.

02. State the problem in minimization form with all the constraints as inequalities of ≤ type.

03. Convert all the constraints into equality constraints by adding slack variables.

04. Obtain an initial basic feasible solution with an initial basis $B=I_q$, where q denotes the number of constraints and I_q is an identity matrix of order q.

05. Find B^{-1}.

06. Calculate $\bar{b} = B^{-1}b$, where is the constant vector (the right hand side of the constraints).

07. Calculate the simplex multiplier $M = C_B B^{-1}$, where C_B is the cost vector associated with the basis B.

08. Calculate the evaluations of the non-basic variables using $c_i - MP_i$, where P_i is the column vector of the variable x_i (coefficients of variable x_i in the constraints) and c_i is the cost of variable x_i in the objective function.

(i) If there is no negative $c_i - MP_i$, then the current solution is optimum. Go to 14.

(ii) If there is some negative $c_i - MP_i$, then the non-basic variable x_k with $c_k - MP_k$ as most negative enters into the basis. Proceed to step 09.

09. Calculate the pivotal column vector $\bar{P} = B^{-1}P_k$.

10. Calculate the ratio vector. Elements of ratio vector are determined by performing element-by-element division of $\bar{b}$ by $\bar{P_k}$.

11. The basic variable x_r, for which the ratio is minimum positive value, leaves the basis.

12. Obtain new basic feasible solution with new basis B.

13. Go to step 05.

14. Print results.

15. Stop.

As coordination of OC relays is basically an LPP, revised simplex method can be applied to find the optimum solution to this problem. The aim is to find out the optimum value *TMS* of all relays, hence *TMS* the relays are taken as variables. Out of the three sets of constraints, described by (2), (3) or (4) and (5), the relay characteristic constraint is already incorporated in the objective function. The bounds on relay operating time (or the bounds on *TMS*) and the coordination criteria are included in the problem as constraints. For each relay, either the bounds on relay operating time or the bounds become redundant constraint. After applying the algorithm for various systems, it is found that the upper bounds of relay operating time and upper bounds of are not exceeded; hence in the problem formulation of sample system only lower bounds are taken.

5.0 RESULTS AND DISCUSSION

Revised simplex method was applied for optimum coordination of OCRs. A program was written in MATLAB for the same. The program was tested successfully for various cases, out of which two cases are presented in this paper. Detail calculations are given for formation of objective function and constraints, and for finding the optimum solution in illustration I.

Similar calculations were performed in illustration II.

5.1 Illustration I

To test the algorithm, initially a simple single-end-fed system with parallel feeders and four relays, as shown in Fig. 2, is taken. Relays 1 and 4 are non directional, and relays 2 and 3 are directional. Two fault points, A and B, are considered.

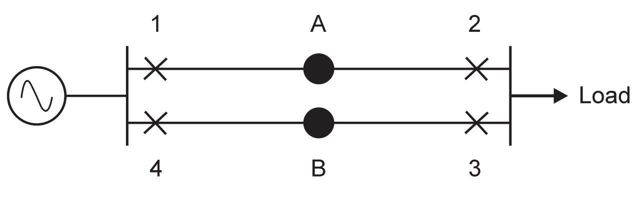

FIG. 2 PARALLEL FEEDER, SINGLE-END-FED SYSTEM

Maximum load current (including over load) is 600 A. The CT ratio for each relay is 300:1 and plug setting of all the relays is 1. The maximum fault current (for any fault point) is 4000 A. It was assumed that during the fault complete current is fed to the fault, i.e., load current is negligible during the fault. Minimum operating time for each relay was considered as 0.1 s and the CTI was taken as 0.3 s. The current seen by the relays and the a_i constant (for different fault points) for relays is shown in Table 1.

TABLE 1

CURRENT SEEN BY THE RELAYS AND CALCULATION OF a_i CONSTANT

Fault Point		**Relay 1**	**Relay 2**	**Relay 3**	**Relay 4**
A	**Relay Current**	10	3.33	—	3.33
A	$a_i$constaint	$\frac{0.14}{(10)^{0.02}-1} = 2.97$	$\frac{0.14}{(3.33)^{0.02}-1} = 5.749$	—	$\frac{0.14}{(3.33)^{0.02}-1} = 5.749$
B	**Relay Current**	3.33	—	3.33	10
B	$a_i$constaint	$\frac{0.14}{(3.33)^{0.02}-1} = 5.749$	—	$\frac{0.14}{(3.33)^{0.02}-1} = 5.749$	$\frac{0.14}{(10)^{0.02}-1} = 2.97$

— indicates that the fault is not seen by the relay

The *TMS* of the relays are taken as x_1 to x_4. With this the problem can be stated as

$$\min z = t_{1A} + t_{1B} + t_{2A} + t_{3B} + t_{4A} + t_{4B} \quad (9)$$

where t_{ik} is operating time of i[th] relay for fault at point k. Using equation (8) and the a_i constants, equation (9) can be written as

$$\min z = (2.97+5.749)x_1 + 5.749x_2 + 5.749x_3 + (2.97+5.749)x_4$$

$$\text{or } \min z = 8.764x_1 + 5.749x_2 + 5.749x_3 + 8.764x_4 \quad (10)$$

The constraints due to minimum operating time of relays are –

$$2.97x_1 \geq 0.1 \quad (11)$$

$$5.749x_2 \geq 0.1 \quad (12)$$

$$5.749x_3 \geq 0.1 \quad (13)$$

$$2.97x_4 \geq 0.1 \quad (14)$$

Constraints (12 and 13) are redefined as they violate the minimum value of *TMS*. Hence these constraints are rewritten as

$$x_2 \geq 0.025 \quad (15)$$

$$x_3 \geq 0.025 \quad (16)$$

The constraints due to coordination criteria are –

$$5.749x_4 - 5.749x_2 \geq 0.3 \quad (17)$$

$$5.749x_1 - 5.749x_3 \geq 0.3 \quad (18)$$

Also, $x_i \geq 0$, i = 1… 4

(non negativity constraint)

Thus the problem is an LPP, with four variables (x_1 to x_4) and six constraints (given by equations 11, 14, 15, 16, 17 and 18).

Optimum solution was obtained in four iterations using revised simplex method (as explained in section 4). The optimum values of *TMS* obtained are as under (the subscripts indicate the relay number) –

$TMS_1 = 0.07718$
$TMS_2 = 0.025$
$TMS_3 = 0.025$
$TMS_4 = 0.07718$

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.

5.2 Illustration II

In this case a single end fed, multi loop distribution system, with six OCRs (as shown in Fig. 3) was considered. The system is multi loop system because depending on the fault point, different configurations (based on the direction of current in various feeders) are formed.

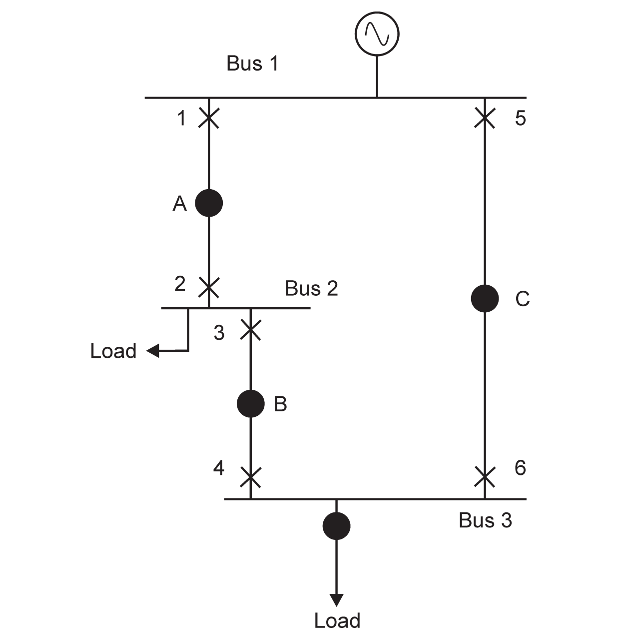

FIG. 3 SINGLE-END-FED, MULTI LOOP DISTRIBUTION SYSTEM

The line data for the system is given in Table 2. Four different fault points were considered. The primary-backup relationship of relays for the four fault points are given in Table 3. The CT ratios and plug settings are given in Table 4. The current seen by the relays and the a_i constant (for different fault points) is shown in Table 5. The load currents during the fault are assumed to be negligible.

TABLE 2	
LINE DATA	
Line	**Series Impedance (Ω)**
1-2	0.08 + j 1
2-3	0.08 + j 1
1-3	0.16 + j 2

TABLE 3		
PRIMARY–BACKUP RELATIONSHIP OF RELAYS		
Relay	**CT Ratio (A/A)**	**Plug Setting**
A	1 2	— 4
B	3 4	1 5
C	5 6	— 3
D	3 5	1 —

TABLE 4		
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	1000 / 1	1

TABLE 5							
CURRENT SEEN BY THE RELAYS AND THE 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 optimization problem is formed in the same way as explained in illustration I. In this case there are six variables (*TMS* of six relays), six constraints due to bounds on relay operating time and five constraints due to coordination criteria. Thus the total number of constraints is eleven.

Value of CTI is taken as 0.3 s and minimum operating time of relay is taken as 0.1 s.

The optimum values of *TMS* obtained are as under (the subscripts indicate the relay number) –

$$TMS_1 = 0.0589 \qquad TMS_2 = 0.025$$

$$TMS_3 = 0.025 \qquad TMS_4 = 0.02903$$

$$TMS_5 = 0.06293 \qquad TMS_6 = 0.025$$

The problem is also solved using other variants of simplex algorithm (dual simplex, big-M, two-phase, and revised simplex methods). The same optimum solution is obtained with different methods but numbers of iterations required are more in other methods. It is shown in Table 6.

TABLE 6

NUMBER OF ITERATIONS REQUIRED IN DIFFERENT METHODS

SN	Method	Number of Iterations
1	Revised simplex	11
2	Dual simplex	07
3	Big-M	11
4	Two-phase simplex	Phase I - 10 Phase II - 1

It can be seen that number of iterations required are same (eleven) in case of revised simplex method, big-M simplex method and two phase simplex method and the number of iterations in case of dual simplex method is less (07), but in revised simplex method, the number of calculations per iteration is much less as compared to all other methods, hence the total number of calculations is much less in case of revised simplex method.

The values of *TMS*, shown above, give the minimum operating time of relays and also satisfy the coordination criteria, for fault at any point. The operating time of relays for different fault points is given in Table 7.

TABLE 7

OPERATING TIME OF RELAYS FOR DIFFERENT FAULT POINTS

Fault Point	Operating Time of Relays (in second)					
	1	2	3	4	5	6
A	0.2148	0.1516	—	0.45168	0.9791	—
B	0.5209	—	0.2211	0.25675	0.5566	—
C	4.4714	—	1.8979	—	0.2545	0.2885
D	0.8245	—	0.3500	—	0.4325	—

— indicates that the fault is not seen by the relay

It can be seen that relay 1 will take minimum time (0.2148 s) to operate for fault at point A and will take maximum time (4.4714 s) to operate for fault at point C. This is desirable, because for fault at point A, relay 1 is first to issue trip command, whereas for fault at point C, relay 6 should get first chance to issue trip signal. If it fails to operate then relay 3 should takeover tripping action, and if relay 3 also fails to operate, then relay 1 should take over the tripping action.

6.0 CONCLUSION

Revised simplex method for optimum 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 an LPP is explained in this paper. A program has been developed in MATLAB for finding the optimum time coordination of relays using revised simplex 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.

MATLAB programs have also been developed for other variants of simplex method for comparison. The number of calculations per iteration (and hence the total number of calculations) is much less in revised simplex method because this method works with the reduced table. The memory requirement is less as compared to big-M method, two-phase simplex method and dual simplex method. There is less accumulation of round-off errors, since no calculations are carried out on a column unless it is ready to enter as basic.

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

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