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Determining Optimum Time Multiplier Setting and Plug Setting of Overcurrent Relays using Continuous Genetic Algorithm

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Overcurrent relays (OCRs) are the major protection devices in a power distribution system. To reduce the power outages, mal-operation of the backup relays should be avoided, and therefore, OCR coordination in power distribution network is of great importance. The time of operation of OCRs can be reduced, and at the same time the coordination can be maintained, by selecting the optimum values of Time Multiplier Setting (TMS) of OCRs. Instead of keeping the value of plug setting (PS) as fixed (while determining the optimum value of TMS), it is also possible to select the optimum values of both TMS and PS, which can further reduce the time of operation of OCRs.

The main contributions of this paper are – 1) systematic method for formulation of problem of determining optimum values of TMS and PS of OCRs in power distribution network as a constrained nonlinear optimization problem, 2) converting the problem into an unconstrained optimization problem, making use of the penalty method, and 3) applying Continuous Genetic Algorithm (CGA) technique to get the optimum solution of this problem.

Keywords: *Overcurrent Relay Coordination, Constrained Optimization, Continuous Genetic Algorithm, Nonlinear Programming Problem*

1.0 INTRODUCTION

Directional OCRs have been commonly used as an economic alternative for the protection of subtransmission and distribution system or as a secondary protection of transmission system [1]. To reduce the power outages, mal-operation 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 [2].

Several optimization techniques have been proposed for optimum coordination of OCRs [1-18]. In [2] and [3] 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 a linear programming problem (LPP). Various LPP

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techniques have been used in [4-6] for OCR coordination. In [7] and [8] optimum coordination has been obtained considering the configuration changes of the network into account. In [9-11], GAs are proposed to find the optimum solution for relay settings. Directional OCR coordination problem has been solved in [1] using hybrid GA, considering the effects of the different network topologies. In [12] also system topology changes have been considered and an adaptive scheme has been suggested for relay coordination. A new nonstandard tripping characteristic for OCRs and its advanced method for optimized coordination have been presented in [13]. In [14], 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 [15]. Non-linear Random Search Technique to solve the coordination problem has been presented in [16] 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 coordination of OCRs has been presented in [17]. A method based on Charalambous least *p*th algorithm has been presented in [18], in which the pick-up current settings (i.e. PS) have been assumed to be fixed.

The problem of optimum coordination of OCRs is generally formulated as an LPP, in which pickup current settings are assumed to be known and the operating time of each relay is considered as a linear function of its TMS [1].

Instead of keeping the value of PS as fixed and determining the optimum value of TMS, it is possible to select the optimum values of both TMS and PS, which can reduce the time of operation and also maintain the coordination, of OCRs. In this paper the problem of determining the optimum values of TMS and PS of OCRs is formulated as a nonlinear programming problem (NLPP) and CGA is proposed to find the optimum solution. Considering recent technology, all the relays have been assumed to be numerical (digital) relays.

2.0 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 [2, 3, 5],

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

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 [1, 3, 4, 6].

The objective of minimizing the total operating time of relays is to be achieved under five sets of constraints.

2.1 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_j is backup relay for the same fault, then the coordination constraint can be stated as

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

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)

2.2 Bounds on the Relay Operating Time

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

$$t_{i,\min} \le t_{i,k} \le t_{i,\max} \tag{3}$$

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

2.3 Bounds on the TMS of Relays

The bounds on TMS of relays can be stated as

$$TMS_{i,\min} \le TMS_i \le TMS_{i,\max} \tag{4}$$

where,

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

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

$TMS_{i,\min}$ and $TMS_{i,\max}$ are taken as 0.025 and 1.2 respectively [19].

2.4 Bounds on the PS of Relays

The bounds on PS of relays can be stated as

$$PS_{i,\min} \le PS_i \le PS_{i,\max} \tag{5}$$

where,

$PS_{i,\min}$ and $PS_{i,\max}$ are the minimum and maximum value of PS relay R_i

$PS_{i,\min}$ and $PS_{i,\max}$ are selected using the following rule of thumb [19] –

$PS \ge$ 1.25 times maximum load current, and $PS \le 2/3^{rd}$ of the minimum fault current.

2.5 Relay characteristics

OCRs can have variety of characteristics as shown in equation (6) and detailed in Table 1 [3, 4, 9, 19, 20]:

$$t_{op} = \frac{\lambda(TMS)}{(I_{relay}/PS)^{\gamma} - 1} \tag{6}$$

where,

t_{op} is relay operating time,

I_{relay} is the current through the relay operating coil, and

PS is plug setting.

TABLE 1

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. Intentional time delay may be added.	
Inverse Definite Minimum Time (IDMT)	0.14	0.02
Very Inverse	13.5	1
Extremely Inverse	80	2

3.0 THE CONTINUOUS GENETIC ALGORITHM

GA is a search method that mimics the biological process of natural evolution and the idea of the "survival of the fittest". Starting with a population of randomly created solutions, the solutions with better fitness are more likely to be chosen as a parent to produce new solutions (offsprings) for the next generation [20-22].

The classical optimization methods have limitations in searching for global optimum point and sometimes trapped in local optimum point. Due to the fact that GA is a multipoint search method rather that the conventional single point search methods, GA promises the global optimum point to be reached [21-23].

In CGA the variables are represented by floating point numbers. The advantages of CGA over binary GA are [22] –

1. Binary GA has its precision limited by the binary representation of variables. CGA, where the variables are represented by floating point numbers, allows representation to the machine precision.
2. The CGA requires less storage than the binary GA because a single floating point number represents the variable.
3. The CGA is inherently faster than binary GA, because the chromosomes do not have to be decoded.

The flowchart of a CGA is shown in Fig. 1.

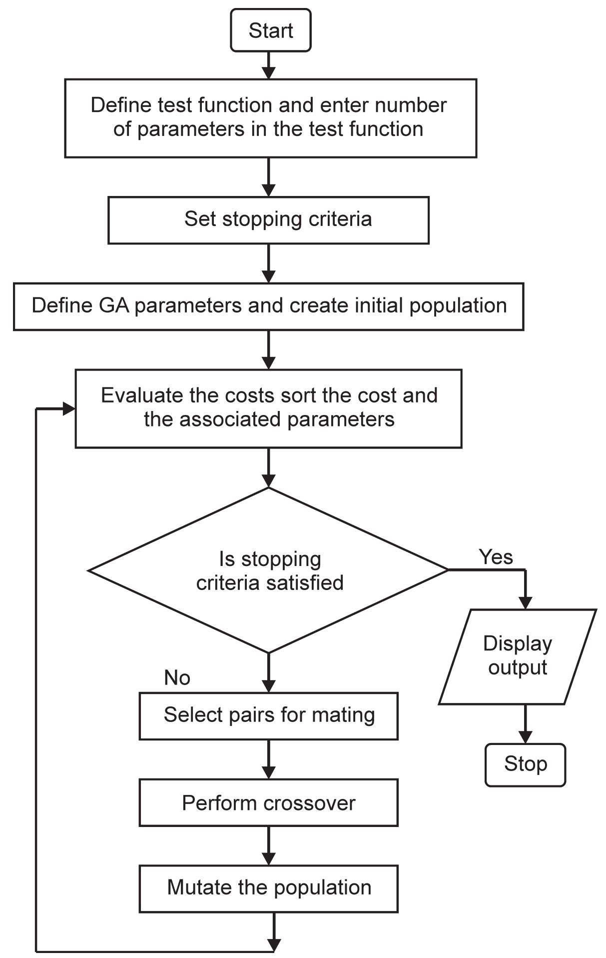

FIG. 1 FLOWCHART OF CGA

Each design variable is represented by a floating point number and if there are n design variables then, a design vector is represented by a string of total *n* floating point numbers. This string is called a 'chromosome'. GA starts with a group of chromosome known as 'population'. The initial population is generated randomly by keeping the value of each variable in the range specified by its lower and upper bounds.

The basic operations of natural genetics – reproduction, crossover, and mutation, are implemented during numerical optimization. 'Reproduction' is a process in which the individuals are selected based on their fitness values relative to that of the population. Thus individuals (chromosomes) with higher fitness values have a greater chance of being selected for mating and subsequent genetic action. Consequently, highly fit individuals live and reproduce, and less fit chromosomes die. After reproduction, the 'crossover' operation is implemented. Crossover is an operator that forms new chromosomes, called 'offsprings', from two 'parent' chromosomes by combining part of the information from each. Various methods are available for crossover in continuous GA [22]. Combination of blending method with extrapolation technique has been used in this paper. The offsprings obtained from crossover are placed in the new population. The 'mutation' is applied after crossover. A mutation, in continuous GA, is the occasional replacement of a variable (selected randomly from the chromosome) by a continuous random variable in the range specified by the bounds of the variables.

4.0 RESULTS AND DISCUSSION

CGA was applied for optimum coordination of OCRs. The algorithm was used to find the optimum values of TMS and PS. A program was developed in MATLAB for the same. The program was successfully tested for various cases, out of which two typical cases are presented in this paper. In each case, the CGA parameters used were –

Population size = 64

Crossover rate = 0.5 (50%)

Mutation rate = 0.1 (10%)

The detailed description of problem formulation and application of CGA to find the optimum solution is presented for first system (illustration I). Similar calculations were performed in illustration II.

4.1 Illustration I

To test the algorithm, initially a simple radial system with two IDMT directional OCRs, as shown in Fig. 2, was considered.

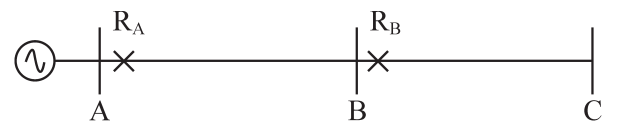

FIG. 2 A SIMPLE RADIAL SYSTEM

4.1.1 Problem Formulation

The maximum fault current, minimum fault current, maximum load current, and the CT ratio for the relays R_A and R_B is shown in Table 2.

TABLE 2

DATA FOR RELAYS R_A AND R_B

Relay	Max. Fault Current (A)	Min. Fault Current (A)	Max. Load Current (A)	CT Ratio (A / A)
R_A	4000	1000	300	600 / 1
R_B	3000	1000	100	200 / 1

The minimum operating time of each relay was taken as 0.2 s and the CTI was taken as 0.57 s for this problem. The current seen by the relays (for two different fault points) is shown in Table 3.

TABLE 3

CURRENT SEEN BY THE RELAYS

Fault Point	Relay	
	R_A	R_B
Just beyond bus A	6.667 A	—
Just beyond bus B	5 A	15 A

— indicates that the fault is not seen by the relay

Considering x_1 and x_2 as *TMS* of relay R_A and R_B respectively, and x_3 and x_4 as *PS* of relay R_A and R_B respectively, the problem can be stated as –

$$\min z = \frac{0.14x_1}{(6.667/x_3)^{0.02}-1} + \frac{0.14x_1}{(5/x_3)^{0.02}-1} + \frac{0.14x_2}{(15/x_4)^{0.02}-1} \quad (7)$$

Subject to,

$$\frac{0.14x_1}{(6.667/x_3)^{0.02}-1} \geq 0.2 \quad (8)$$

$$\frac{0.14x_1}{(5/x_3)^{0.02}-1} \geq 0.2 \quad (9)$$

$$\frac{0.14x_2}{(15/x_4)^{0.02}-1} \geq 0.2 \quad (10)$$

$$\frac{0.14x_1}{(5/x_3)^{0.02}-1} - \frac{0.14x_2}{(15/x_4)^{0.02}-1} \geq 0.57 \quad (11)$$

$$0.025 \leq x_1 \leq 1.2 \quad (12)$$

$$0.025 \leq x_2 \leq 1.2 \quad (13)$$

$$0.625 \leq x_3 \leq 1.111 \quad (14)$$

$$0.625 \leq x_4 \leq 3.333 \quad (15)$$

Equations (8), (9) and (10) give the minimum operating time constraint, (11) gives the coordination constraint, (12) and (13) give the bounds on *TMS*, and (14) and (15) give the bounds on *PS*. This is a nonlinear programming (NLP) problem, with four variables (x_1 to x_4). The optimum value of these variables is to be found out satisfying the constraints given by equation (8) to (15).

4.1.2 Application of continuous GA

For applying continuous GA technique to this problem, it is first converted in to unconstrained optimization problem. The relay characteristic constraint is already incorporated in the objective function, the relay operating time constraint, and coordination constraints.

The constraints due to bounds on *TMS*, given by equations (12) and (13), are taken care of by defining the lower and upper limit of the variables x_1 and x_2, and the constraints due to bounds on *PS*, given by equations (14) and (15), are taken care of by defining the lower and upper limit of the variables x_3 and x_4; in the CGA program.

The constraints due to operating time of relays, given by equations (8) to (10), and the constraint due to coordination criteria, given by equation (11) are included in the objective function using penalty method [24] and thus the problem is converted in to unconstrained optimization problem.

A population of 64 chromosomes was generated randomly. The value of variables in each chromosome was bounded by lower and upper limits, as described above. The population was passed through the fitness function (objective function). As the objective function is of minimization type the chromosome giving minimum value is most fit chromosome. The population was sorted according to fitness. The chromosomes with higher fitness value (upper 50% population) survive (reproduced in the next generation) and are called parent chromosomes. These are used for crossover.

Pairs of parent chromosome are made for mating. A simple method of pairing from top-to-bottom was used. Single point crossover was performed using the combination of blending method with extrapolation technique [22]. The crossover rate was kept as 50%. Crossover generates offsprings. The parent chromosomes along with offsprings were placed together to form the population for the next generation. The population size of 64 was maintained in all generations.

The "mutation" was applied after crossover. For mutation the variable was selected randomly from chromosome (the chromosome was also selected randomly) and was replaced by a continuous random variable in the range specified by the bounds of the variables. The mutation rate was taken as 10%. After mutation, the next iteration was started (from passing the population through fitness function).

4.1.3 Results

Using the program, 40 iterations were performed. The optimum values of *TMS* and *PS* obtained are as under (subscripts indicate the relay number) –

$TMS_1 = 0.1724$ $\quad$ $PS_1 = 1.0690$

$TMS_2 = 0.0711$ $\quad$ $PS_2 = 1.3259$

The best values of *TMS* and *PS* of relays obtained during different generations of CGA are shown in Fig. 3. It can be seen that the values are converged to final values in about 25 iterations only.

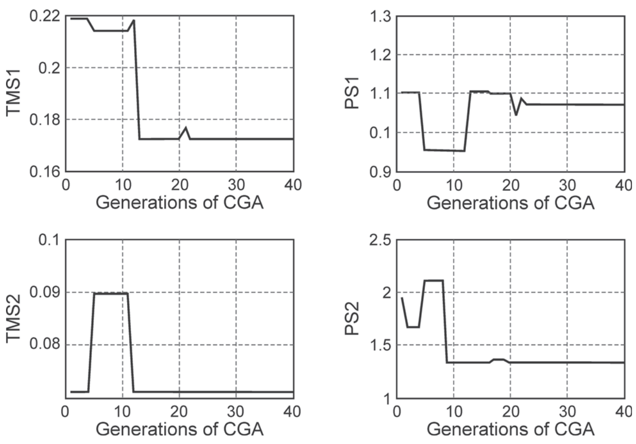

FIG. 3 BEST VALUES OF TMS AND PS AGAINST GENERATIONS OF CGA (ILLUSTRATION I)

Operating times of relays with these optimum values are given in Table 4. The operating times of relays using optimum value of *TMS* (obtained with fixed values of *PS*) is also shown for comparison.

TABLE 4				
	OPERATING TIME OF RELAYS			
Fault Point	**Operating Time of Relay R_A**		**Operating Time of Relay R_B**	
	TMS = 0.25889 PS = 0.5 A (fixed)	TMS = 0.1724 PS = 1.0690 A	TMS = 0.1006 PS = 0.5 A (fixed)	TMS = 0.0711 PS = 1.3259 A
Just beyondbus A	0.6809	0.6475	—	—
Just beyondbus B	0.7689	0.7705	0.200	0.200

— indicates that the fault is not seen by the relay

4.1.4 Discussion

The operating time of relay R_A for the fault just beyond bus A (the case in which there is maximum fault current) is reduced by 0.0334 s (1.67 cycles). Operating time of relay R_A for the fault just beyond bus B is increased by 0.0016 s (0.08 cycle). It should be noted that, R_A is backup relay for the fault just beyond bus B, so such a small increase in the time of operation of relay R_A (backup relay in this case) can be tolerated. Fault just beyond bus A is not seen by the relay R_B, and the operating time of relay R_B for the fault just beyond bus B remains same.

Thus the value of objective function is decreased by 0.0318 second as compared to the objective function value obtained using fixed (predetermined) values of *PS*.

4.2 Illustration II

In this case a single end fed, multi loop distribution system, with seven OCRs (as shown in Fig. 4) was considered.

The primary-backup relationship of the relays for different fault points is shown in Table 5.

A variety of OCRs were taken. The relay type, their operating time, CT ratio, and maximum load current and minimum fault current through the relays are shown in Table 6. The operating time for relays 2 and 7 was taken as 0.1 s, without any intentional time delay, as these relays are instantaneous OCRs. As relay 4 is definite time OCR and has to backup relay 2 in case of fault at point A, its operating time is decided by operating time of relay 2 plus the CTI (taken as 0.2 s). Hence operating time of relay 4 is taken as 0.3 s.

TABLE 5		
PRIMARY-BACKUP RELATIONSHIP OF RELAYS		
Fault Point	**Primary Relay**	**Backup Relay**
A	1	—
	2	4
B	3	1
	4	5
C	5	—
	6	3
D	7	3
		5

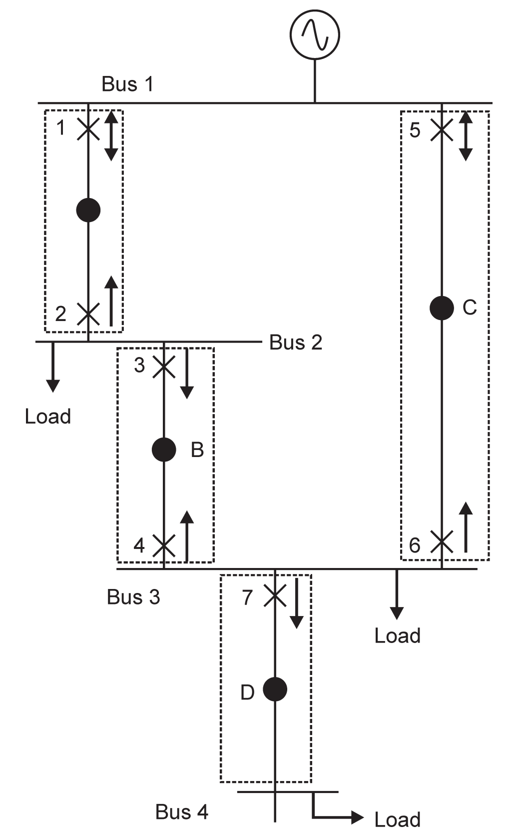

FIG. 4 SINGLE-END-FED, MULTI LOOP DISTRIBUTION SYSTEM (ILLUSTRATION II)

TABLE 6

RELAY TYPE, OPERATING TIME, CT RATIO, MINIMUM FAULT CURRENT AND MAX. LOAD CURRENT

Relay	Type	Operating Time (Second)	CT Ratio (A / A)	$I_{fault, min}$(A)	$I_{Load, max}$(A)
1	Non-directional IDMT OC	$\frac{0.14(TMS)}{(PSM)^{0.02}-1}$	1000 / 1	939	800
2	Instantaneous OC	0.10	1000 / 1	1096	800
3	Directional IDMT OC	$\frac{0.14(TMS)}{(PSM)^{0.02}-1}$	500 / 1	939	400
4	Definite time OC	0.30	500 / 1	1096	400
5	Non-directional IDMT OC	$\frac{0.14(TMS)}{(PSM)^{0.02}-1}$	1000 / 1	939	800
6	Directional IDMT OC	$\frac{0.14(TMS)}{(PSM)^{0.02}-1}$	1000 / 1	1096	800
7	Instantaneous OC	0.10	500 / 1	939	250

The optimization problem was formed in the same way as explained in illustration I. As relay 2 and 7 are instantaneous OCRs and relay 4 is definite time OCR their operating time for any fault location is fixed and is shown in Table 6. Thus, in this case there are eight variables (*TMS* and *PS* of relays 1, 3, 5 and 6). Value of CTI and minimum operating time (of relays 1, 3, 5 and 6) were taken as 0.2 s and 0.1 s respectively.

After formulating the problem as an NLPP, it was solved using CGA. The best values of TMS and PS of relays against generations of CGA are shown in Fig. 5.

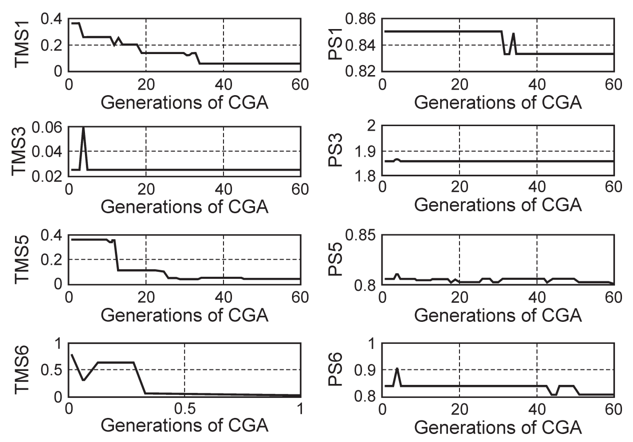

FIG. 5 BEST VALUES OF TMS AND PS AGAINST GENERATIONS OF CGA (ILLUSTRATION II)

The optimum values of *TMS* and *PS* of relays obtained are as given below (the subscripts indicate the relay number)—

$TMS_1 = 0.0556 \qquad PS_1 = 0.8326$

$TMS_3 = 0.0250 \qquad PS_3 = 1.8588$

$TMS_5 = 0.0403 \qquad PS_5 = 0.8008$

$TMS_6 = 0.0250 \qquad PS_6 = 0.8061$

The above values ensure that the relays will operate in minimum possible time for fault at any point in the system and will also maintain the coordination. The operating time of relays for different fault points is shown in Table 7.

It can be seen that the time taken by relay 5 to operate is minimum for fault at point C (0.1969 s) and will take more time for fault at point B and D (0.5653 s). This is desirable, because for fault at point C, relay 5 is first to operate, whereas for fault at points B and D, relay 4 and relay 7 respectively, should get first chance to operate. If it fails to operate then only relay 5 should takeover tripping action.

Relay 5 takes maximum time (1.7691 s) to operate for fault at point A. This is also desirable, as for fault at point A, relay 2 should

TABLE 7

OPERATING TIME OF RELAYS FOR DIFFERENT FAULT POINTS

Fault Point	Operating Time of Relays (In Second)						
	1	2	3	4	5	6	7
A	0.1844	0.10	—	0.30	1.7691	—	—
B	0.4086	—	0.2082	0.30	0.5653	—	—
C	1.4097	—	1.0567	—	0.1969	0.5670	—
D	0.8466	—	0.5016	—	0.5653	—	0.10

— indicates that the fault is not seen by the relay

get first chance to operate. If relay 2 does not operate then relay 4 should takeover tripping action and if relay 4 also fails to operate then only relay 5 should takeover tripping action.

5.0 CONCLUSION

Continuous GA method for determination of optimum values of TMS and PS of OCRs in distribution system is presented in this paper. This problem is basically a highly constrained optimization problem. A systematic procedure for converting the problem into an optimization problem has been developed. The problem is formulated as an NLPP in this paper. As CGA can basically solve unconstrained optimization problem, the constrained NLPP is converted into unconstrained optimization problem by defining a new objective function (using penalty method) and by using the bounds on TMS and PS of the relays as the limits of variables.

A program has been developed in MATLAB for finding the optimum values of TMS and PS of OCRs using CGA method. The algorithm was tested for various system configurations, including multi loop systems, and systems with a variety of OCRs and was found to give satisfactory results in all the cases.

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