# Optimized Over-Current Relay Coordination Using Flower Pollination Algorithm

Indrajit N. Trivedi[1], Snehal V. Purani[2], Pradeep K. Jangir[3]

[1,2,3] *Department of Electrical Engineering,*
*Lukhdhirji Engineering College, Morbi, Gujarat, India*

[1]forumtrivedi@gmail.com
[2]4990sunny.purani@gmail.com
[3]pkjmtech@gmail.com

***Abstract*—The main purpose of optimization of relay coordination in an extensively large electrical network is to enhance the selectivity and at the same time reducing the fault clearing time to improve reliability of the system. The relays provided are set to function properly in normal as well as abnormal condition. In this paper; the main focus is to find out minimum Time Dial Setting (TDS) for the relays connected in-whatever configuration using Flower Pollination Algorithm. The said algorithm is compared with Linear Programming Technique. The algorithm has been implemented in MATLAB and tested on radial feeder fed from one end as well as on parallel Feeder system. The innovative feature of the paper is application of nature inspired algorithm to one of the major problem of optimization in the field of power system protection.**

***Keywords*— Optimal Relay Coordination, Constrained Optimization, Time Multiplier Setting (TMS), Flower Pollination Algorithm (FPA), Linear Programming (LP), Optimization Problem**

## I. Introduction

The transmission line is generally long enough and runs through open environment; hence probability of fault occurring in transmission line is obviously more than other equipments associated in network. The most common type of faults are shunt faults which causes sudden increase in current magnitude. So magnitude of current can be treated as an indicating signal of abnormality. Hence over current protection is one of the common form of protection [1].

The protective relay must be able to discriminate between the normal operating conditions; abnormal operating conditions and faults. The protective devices connected in each zone should also satisfy other needs such as speed, sensitivity etc. The protective relay should operate as quickly as possible for in zone fault. This is known as primary protection. If primary protection fails to operate, then the backup system should operate after some time delay to prevent excessive damage. The selectivity property of relay should not violate in the operation; hence the primary and backup relays are coordinated properly to enhance reliability and effectiveness of the system. Therefore, the requirements of protective devices should not violate under any operating condition.

Effective relay coordination can be carried out using both current magnitude and time. The fault clearing time obtained should be optimal to ensure minimum damage to the system as well as less effect to the consumers at remote end. Hence relay coordination can be considered as optimization problem governed by constraints subjected to ensure minimum time of operation under specified selectivity constraints. Hence, it is constrained optimization problem.

With the advancements in relaying technology i.e. with amelioration in digital relays it is feasible to set any non-integral value of Time Multiplier Setting (TMS) and therefore exact optimal time coordination is possible.

This functional optimization problem has been solved by several optimization methods many a times in past. Recently [2] has applied Firefly Algorithm to this problem, [3, 4, 5] has solved using Linear Programming, [6] has applied Seeker Algorithm, [7, 8] have solved using Genetic Algorithm, [9] Hybrid GA, [10] Hybrid GA-NLP, and [11] has solved using Particle Swarm Optimization etc. These are some of the other approaches.

In this paper, relay coordination problem is composed as a Linear Programming (LP) problem. In regards, this optimization problem is realised as linear programing problem by considering the Pick-up Setting of relays fixed whereas the operation time of the relays is in linear proportion with Time Multiplier Settings. However this is not the case as always and the mentioned relay coordination problem can be re-evaluated as a non-linear optimization problem. This paper describes how [12] the Flower Pollination Algorithm (FPA) has been implemented on this problem to coordinate relays optimally. Two general cases have been taken under considerations.

The basic difference between the formulations of the problem is that if Plug Setting is set unchanged constant i.e. fixed; then the coordination problem is considered as linear programming problem, and for continuous values of Plug Setting the problem turned out to be Non-Linear Programming (NLP) problem, and if the Plug Setting is considered in distinct valued steps then the specified issue can be conceived as a Mixed Integer Non-Linear Programming (MINLP) problem. For easy evaluation and simplicity of one of the most vital problem of Power System Protection field it is evaluated as Linear Programming Problem. Linear programming method is an uncomplicated way to deal with complicated non-linear problems in the field of optimization. This makes the difficult and complicated concept of relay coordination merely easy and simple.

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## II. Problem Formulation

### A. Problem Statement

The main intention of this problem is to obtain minimum operational time so as to avoid excessive damage. To find out this, the problem can be framed as either Linear problem or Non-Linear problem. To avoid complexity in solving the problem we have considered linear formulation of a problem in which the Plug Setting is fixed and time of operation is in linear proportion to the Time Multiplier Setting. In general the coordination of overcurrent relays in a network can be considered as a problem of prime focus, where the normal algebraic sum of total relay operation time 'S' of the considered network is to be minimized.

Objective Function:

$$S= \min \sum_{i=1}^{n} t_i \quad (1)$$

### B. Relay Characteristics

In the protection of Transmission line the common types of relays used are distance and overcurrent relays. Distance relays operate based on the impedance measured at the relaying point and have fixed operation time while there are various characteristics for an over-current relay.

The operating time of relay considered in the network can be calculated using the formula:

$$T_{op} = \frac{a}{(PSM)^b - 1} * TDS + C \quad (2)$$

Where, PSM = Plug Setting Multiplier and it is the ratio of current at short circuit to pick up current of relay.

A,B,C are constants specified in the table given below[13]. TMS = Time Multiplier Setting of the relays are having distinct step values in a range from 0 to 1 in step value of 0.1.

TABLE I
VARIOUS CHARACTERISTICS OF OVER-CURRENT RELAYS

| Number of characteristics | Type of characteristics | Standard | Constant A | Constant B | Constant C |
|---|---|---|---|---|---|
| 1 | Short time inverse | AREVA | 0.05 | 0.04 | 0 |
| 2 | Standard inverse | IEC | 0.14 | 0.02 | 0 |
| 3 | Very inverse | IEC | 13.5 | 1 | 0 |
| 4 | Extremely inverse | IEC | 80 | 2 | 0 |
| 5 | Long-time inverse | AREVA | 120 | 1 | 0 |
| 6 | Moderately inverse | ANSI/IEEE | 0.0515 | 0.02 | 0.114 |
| 7 | Very inverse | ANSI/IEEE | 19.61 | 2 | 0.491 |
| 8 | Extremely inverse | ANSI/IEEE | 28.2 | 2 | 0.1217 |

### C. Coordination Constraints

The relays in the system must be coordinated by criterion:

$$t_{2,k} - t_{1,k} \geq MCT \quad (3)$$

Where $t_{1,k}$ is the time of operation of the main relay at k, for in zone fault and $t_{2,k}$ is the time lag of the back-up relay, for the fault considered. MCT is Minimum Coordination Time [14]. In this paper it has been taken as 0.25.

### D. Boundary limits on the relay operating time

Relays incorporated in a network should operate fast and should not take too long time to operate. This shows the coordination problem is a constraint bounded optimization problem.

$$t_{1,k,min} \geq t_{1,k} \geq t_{1,k,max} \quad (4)$$

Where $t_{1,k,min}$ is the minimum operating time and $t_{1,k,max}$ is the maximum time of operation at 'k' for near end fault.

### E. Relay Coordination Characteristics

The relay considered is of normal IDMT characteristics.

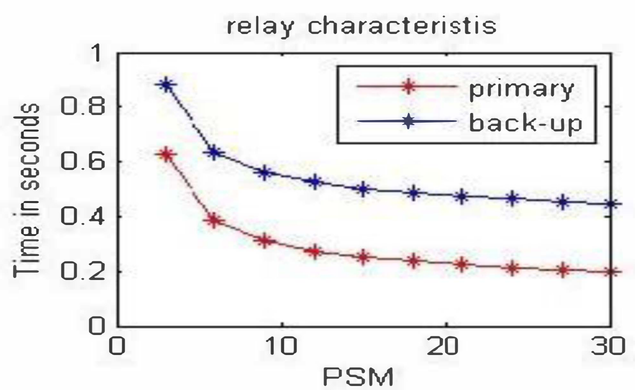


Fig. 1 Relay characteristics for coordination

## III. Linear Programming Method

It is one of the simple and easily implemented method for optimization problem. The dependence between focused variables is in linear proportion which governs by the specified limits to select most preferred solution in the range of maximum or minimum bound limit. In this relay coordination problem, time of operation is in a linear relationship with Time Multiplier Setting.

The general linear programming problem is constraint optimization problem and can be expressed as follows:

$$(A)*X \leq b \quad (5)$$

$$(Aeq)*X=beq \quad (6)$$

$$\text{Lower bound} \leq X \leq \text{Upper bound} \quad (7)$$

These are inequality, equality and bounded optimization constraints respectively. Relay Coordination is bounded constraints type Linear Programming Optimization problem.

The structure of Linear Programming problem technique involves following:

a) Focused parameter: The required result is the Time Multiplier Setting(TMS)
b) Target parameter: Targets to find the maximum or minimum specified bound value. In this case Time of Operation is an objective function to be minimized.
c) Constraints: inequality bounds and equation that represents the parameter which governs the optimization problem.
d) Restricted Variable: Every decision variable involved is not negative. In this case Time Multiplier Setting cannot be negative.

## IV. Flower Pollination Algorithm

The latest nature inspired Flower Pollination Algorithm was firstly proposed by Xin She Yang in 2012 [12]. Prime outcome of a flower is recreation via process called pollination. Pollination involves transferring of pollens by pollinators such as birds, insects, etc. and other flowering species.

The pollination process is categorised as biotic or abiotic. Large amount of flowering plants are part of biotic pollination process. For rest wind and diffusion are sources of pollination. Grass is perfect example of abiotic pollination. The process can be accomplished by cross procreation or self-procreation. Cross procreation means pollination process occurring between pollens of a different flowering plants; while later occurs in between pollens of the same flowering plants.

The aim of flower pollination is to reproduce the optimal plants both in terms of numbers as well as in fitness. For ease, the four rules given below are used [15].

1) Biotic and cross procreation process is taken into account as progression of global procreation, and pollinators fetching pollen stir in a manner which confirms to levy flights.
2) Local pollination, abiotic pollination and self-procreation means pollination between same flower species are used.
3) Pollinators like insects generate flower loyalty, which is comparable to the reproduction possibility is in the proportion of matching of both flowering species considered.
4) Switching or the intercommunication of global procreation and local pollination can be handled by a switch probability p ϵ [0, 1], slightly more favourable for local procreation.

Pseudo code of Flower Pollination Algorithm (FPA):

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(Minimize or Maximize) objective F(x), $x = (x_1, x_2, \ldots, x_d)$
Initialize z flowering species with arbitrary results
Obtain the best solution ($s_*$) from the initialized swarms
Express a case probability p ϵ [0, 1]
While (k < Max Generation)
  for m = 1: z (z swarms under consideration)
    if random < p
Construct an (n-dimensional) step vector H by using a levy flight distribution
Global procreation via $x_m^{k+1} = x_m^k + \Upsilon H(s_* - x_m^k)$
  else
Draw from a uniform distribution in [0, 1]
Do local pollination via $x_m^{k+1} = x_m^k + \epsilon\,(x_n^k - x_k^k)$
 end if
Solve for new results
If results are optimal, update with new results
 end for
obtain current best solution
end while
result is optimal available solution obtained.

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In a process to construct iterative equations, said protocols ar assumptions formulated as iterative equations. For global procreation case pollens generally move to long distance as pollinators so often travel to a longer distance. Hence rule 1 and rule 3 may be formulated in terms of equation as :

$$X_m^{k+1} = x_m^k + \Gamma H(\lambda)\,(s_* - x_m^k) \qquad (8)$$

where $x_m^k$ is certainly pollen m or result vector $x_m$ at iteration count k, $s_*$ is the current best possible result obtained in comparison of all results at specified recreation, λ is a step control scalling parameter.
H (λ) is namely levy flight based movement control parameter that resembles the procreation process strength. H>0 is drawn from a levy flight distribution:

$$H \sim (\lambda\Gamma(\lambda)\sin((\pi\lambda)/2)) / \pi\,(s^{(\lambda+1)}) \qquad (9)$$

Where, Γ(λ) is the standard gamma function, and this distribution is valid for large step s > 0. In this (s >> s0 > 0) s0 can be as small as 0.1. One of the most efficient method than our studies for drawing such random numbers is so called Mantegna Algorithm for constructing step size s by using two Gaussian distributions U and V by following Transformation

$$s = U/(|v|^{(1/\lambda)}),\ U \sim N(0, \sigma^2),\ v \sim N(0, 1) \qquad (10)$$

Means samples are constructed from a Gaussian distribution with zero deviation of mean and a variance of $\sigma^2$. The variance can be calculated by

$$\sigma^2 = [(\Gamma(1+\lambda)\,(\sin(\pi\lambda/2))/(\lambda\Gamma(1+\lambda)/2)(2^{(1-\lambda)/2})]^{1/\lambda} \qquad (11)$$

For local pollination, both Rule 2 and Rule 3 can be represented as

$$X_m^{k+1} = x_m^k + \epsilon\,(x_n^k - x_k^k) \qquad (12)$$

Where $x_n^k$ and $x_k^k$ are pollens of similar flowering species. This actually shows the flower constancy in a limited region of neighbourhood. As the pollens considered of similar species, it is ultimately turns into a local pollination and it is constructed using uniform Gaussian distribution. To start with, a fresh value of p=0.5 as an initial guess. The approach is further extended up to Multi objective problem.
Various constraint handling method is applied to improve the performance according to needs. The prime purpose of pollination is to reproduce a new iterative solution.

## V. Results

### A. A Radial System

The two section simple radial feeder is shown in Fig. 2. It is clearly seen that if fault occurs beyond bus B (Zone k), the relay $R_B$ at bus B, operates firstly as a primary protection. The relay $R_A$ at bus A, serves as a back-up protection and operates after certain time delay.

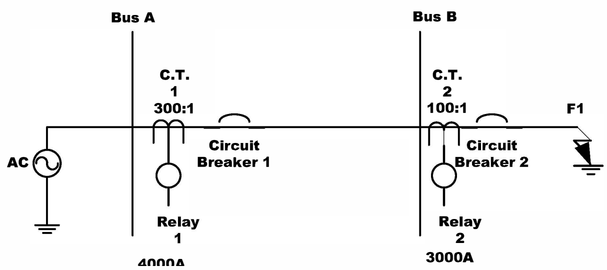


Fig. 2 A Two bus Radial Feeder

If the time of operation of relay $R_B$, is set at 0.2s, the relay $R_A$ is coordinated in such a way that it should operate at time 0.2+MCT.

The objective function for the study is to determine optimal operating time. Time of operation is in linear proportion with TMS. Therefore the objective function can be written as:

$$S = \min K_i \sum_{i=1}^{n} t_i \qquad (13)$$

Where, $K_i = \frac{0.14}{(PSM)^{0.02}-1}$

For testing of this approach, a two bus radial feeder system was considered in Fig. 2. The maximum fault current just beyond bus A and bus B are 4000A and 3000A respectively, the initial plug setting of relays are taken as 100% ,the CT ratios are 300:1 and 100:1 at bus A and bus B respectively. PSM is calculated on the basis of maximum fault current and CT ratios available. TMS for relay $R_B$ is set at 0.1 and the TMS for relay $R_A$ is to be found out using the mentioned Linear Programming and Flower Pollination Algorithm respectively. Minimum time of operation for both relay is taken as 0.2s and MCT is taken as 0.25s for this case study. Calculation for $k_i$ is done using equation specified and is as shown in Table II.
The study can be done on different characteristics of relays.

TABLE II
Calculation of $K_i$ Constant for Relay

| Sr. No. | Fault Location | Relay $R_A$ – $k_i$ constant | Relay $R_B$ - $k_i$ constant |
|---|---|---|---|
| 1 | Just beyond Bus A | 2.63 | ---------- |
| 2 | Just beyond Bas B | 2.97 | 2 |

------- indicates that fault is not seen by the relay
These lead to the following optimization equations:
Objective Function:

$$S=2.63x_1+2x_2 \qquad (14)$$

Subject to coordination constraint,

$$2.97x_1 - 2x_2 \geq 0.25 \qquad (15)$$

And lower bounds on the relay is decided by the minimum operating time of relay. (Considered 0.2s)

$$2.63x_1 \geq 0.2 \qquad (16)$$

$$2x_2 \geq 0.2 \qquad (17)$$

The upper limit is taken at 1.2.

'x' denotes the TMS. The subscript is for relay number. This problem is of two dimensional ('d'=2). The optimization equations were solved using Flower Pollination Algorithm in the MATLAB environment. The population size was taken as 50 and the number of iterations were 2000. The value of λ is taken as 0.8. The penalty method was used for handling the coordination constraints [10].

The results obtained for the TMS is shown in Table III. The results are compared with Linear Programming. The linear Programming tool is available in MATLAB optimization toolbox. The total optimal time of operation is found out using following techniques mentioned in Table IV.

TABLE IIIII
TMS obtained using Flower Pollination and LP method

| Relay | TMS | LP | FPA |
|---|---|---|---|
| $R_A$ | $x_1$ | 0.152 | 0.1515 |
| $R_B$ | $x_2$ | 0.1 | 0.1 |

TABLE IV
Total optimal time of operation using FPA and LP

| TOTAL OPERATING TIME (SEC) | LINEAR PROGRAMMING | FLOWER POLLINATION ALGORITHM |
|---|---|---|
| S | 0.6052 | 0.5984 |

Table shows the results obtained by both the methods.

### B. *The Parallel Feeder System*

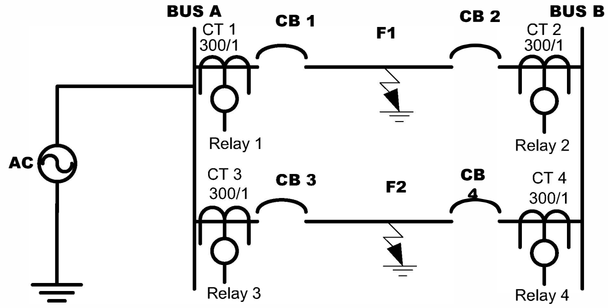


Fig. 3 Parallel Feeder with Directional Relays

In above case, a simple parallel feeder system is shown.In the figure only 4 breakers are shown incorporated with 4 relays from which two connected with breaker 1 and 3 is non-directional relay whereas relays 2 and 4 are directional relays whose direction is towards source from the bus. For simplicity we have considered the plug setting of each relay to be 1 and corresponding CT ratios are 300:1. Relay 3 provides backup protection to relay 2 in case if fault occurs on upper line. Similarly relay 1 will provide back up to relay 4 in case if fault occurs on lower line connected between bus A and bus B. We have considered for our studies that fault occurred on first line at the half of length of line and then in second case fault occurred on lower bus at middle of the line. Total fault current in each case is taken to be 4000A. Minimum Coordination Time for this exercise is considered as 0.5s.

TABLE V
CALCULATION OF CONSTANT FOR RELAY

| Fault point | | Relay No. | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| A | Relay Current | 10 | 3.33 | - - - - - | 3.33 |
| | K | 2.97 | 5.749 | - - - - - | 5.749 |
| B | Relay Current | 3.33 | - - - - | 3.33 | 10 |
| | K | 5.749 | - - - - | 5.749 | 2.97 |

'- - - -' indicates that fault is not in the tripping direction.
Minimize:

$$S= 2.97x_1+5.749x_2+5.749x_3+2.97x_4 \tag{18}$$

Subject to coordinate constraints:

$$5.749x_4 - 5.749x_2 \geq 0.5 \tag{19}$$

$$5.749x_1 - 5.749x_3 \geq 0.5 \tag{20}$$

And the minimum time constraints for the said optimization problem:

$$2.970x_1 \geq 0.2 \tag{21}$$

$$5.749x_2 \geq 0.2 \tag{22}$$

$$5.749x_3 \geq 0.2 \tag{23}$$

$$2.970x_4 \geq 0.2 \tag{24}$$

In this problem there are four relays incorporated so it is a four dimensional problem. The population size taken as 20 and iteration count is 2000. Value of probability is 0.8.
Result of flower Pollination depends on step size of levy flight random walk, the value of probability and value of gamma constant. The algorithm is a kind of swarm intelligence and after every iteration count the result is updated to a new value. The TDS obtained are shown in table V and the results are obtained and compared with linear programming technique.
The total time of operation by both the methods is tabulated in table VI.

TABLE VI
TIME DIAL SETTING OBTAINED USING FPA AND LINEAR PROGRAMMING

| Relay | TDS | Linear Programming | Flower Pollination Algorithm |
|---|---|---|---|
| 1 | $X_1$ | 0.067 | 0.1217 |
| 2 | $X_2$ | 0.035 | 0.0347 |
| 3 | $X_3$ | 0.154 | 0.0347 |
| 4 | $X_4$ | 0.122 | 0.1217 |

TABLE VII
TOTAL OPTIMAL TIME OF OPERATION USING FPA AND LP

| TOTAL OPERATING TIME (SEC) | LINEAR PROGRAMMING | FLOWER POLLINATION ALGORITHM |
|---|---|---|
| S | 1.6450 | 1.1217 |

## VI. CONCLUSIONS

The Time of Operation for the relay coordination is found out using both the techniques. The result obtained using this techniques are certainly far better than conventional one, but the result obtained in both the cases using Flower Pollination Algorithm is better than Linear Programming Technique. In case of digital relays fractional values of time dial setting are also kept and hence the optimal time of operation is achieved, which improves system performance and reliability. The results obtained can be compared with other techniques. There are several constraint handling methods with which one can go for further result comparison with other optimization techniques as well as with the same technique. Comparatively good solution is available to optimization problem.

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