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A Novel Optimal Setting for Directional over Current Relay Coordination using Particle Swarm Optimization

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***Abstract*—**Over Current Relays (OCRs) and Directional Over Current Relays (DOCRs) are widely used for the radial protection and ring sub transmission protection systems and for distribution systems. All previous work formulates the DOCR coordination problem either as a Non-Linear Programming (NLP) for TDS and Ip or as a Linear Programming (LP) for TDS using recently a social behavior (Particle Swarm Optimization techniques) introduced to the work. In this paper, a Modified Particle Swarm Optimization (MPSO) technique is discussed for the optimal settings of DOCRs in power systems as a Non-Linear Programming problem for finding Ip values of the relays and for finding the TDS setting as a linear programming problem. The calculation of the Time Dial Setting (*TDS*) and the pickup current (*Ip*) setting of the relays is the core of the coordination study. PSO technique is considered as realistic and powerful solution schemes to obtain the global or quasi global optimum in optimization problem.

***Keywords*—**Directional over current relays, Optimization techniques, Particle swarm optimization, Power system protection.

I. Introduction

THE problem of coordinating protective relays in power system networks consists of selecting their suitable settings such that their fundamental protective function is met under the requirements of sensitivity, selectivity, reliability and speed. In modern power system, abnormal condition can frequently occurring cause interruption in the supply, and may damage the equipments connected to the power system, which allows us to think the importance of designing a reliable protective system. In order to achieve such reliability, a back-up protective scheme is provided which act's as the back-up protection in case of any failure in the primary protection [1]. When two protective apparatus are installed in series have characteristics, which provide a specified operating sequence, they are said to be coordinated or selective. Coordination means that the relay closest to the fault would operate first thus avoiding further serious problem and reducing the outage in equipments. Main problem arises in performing the relay coordination with this type of protection in interconnected, multi-loop power systems, where it is very difficult to set and coordinate the relays [2].

The coordination of directional over current relays poses serious problems in the modern complex power system networks, which are interconnected, because of that are protected by directional over current relays, which are stand-alone devices and strategically placed throughout the system. Directional over current relaying, which is simple and economic, is commonly used, as a primary protection in distribution and sub transmission systems and as a secondary protection in transmission systems [3]. Since 1960s, a great effort has been devoted for solving this problem by computer. The methods, which are used for performing this task (relay settings), can be classified into three classes: trial and error method [4], topological analysis method [5, 6], and optimization method [7 - 10].

Several optimization techniques have been proposed for coordination of directional over current relays. Normally, the relay setting is done assuming both *TDS* and *Ip* values to be continuous and then using generalized reduced gradient non linear optimization technique for optimal settings of the relays. Recently in 2004, in stead of taking continuous *Ip* the discrete *Ip* value for non linear problem solutions were considered by rounding off the *Ip* solutions to their nearest discrete values. Unfortunately, rounding the *Ip* values could lead to a solution that is outside the feasible region [11]. The values of the time dial setting (*TDS*) have been calculated using LP (simplex method) for a given values of the pick-up currents (*Ip*). Recently, the interest in applying Artificial Intelligence in optimization has grown rapidly. Genetic algorithm (GA) [12] and Evolutionary Algorithm (EA) [13] have been used in the literature to find an optimal setting of the protective relays.

In 1995, a new Evolutionary Computation (EC) technique was proposed by Kennedy and Eberhart [14], which they called Particle Swarm Optimizer (PSO). PSO has been recently adopted due to its superiority to other Evolutionary Algorithms (EA) regarding its memory, and computational time requirements as it relies on very simple mathematical operations, also it requires very few lines of computer code to implement. Numerous optimization algorithms have been developed to solve these problems, with varying degrees of

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success. The PSO is a relatively new technique that has been empirically shown to perform well on many of these optimization problems.

This paper presents the comparison of the relay coordination problem of DOCRs using a modified PSO approach. The Non Linear Programming problem for finding the *Ip* variable values and the result of *Ip* rounded off to the nearest available discrete value is fixed which formulated the relay coordination as Linear Programming Problem finding the TDS values are discussed here.

II. The Optimal Problem Formulation

A typical inverse time over current relay consists of two elements, an instantaneous unit, and a time over current unit. The over current unit has two values to be set, the pickup current value (*Ip*), and the time dial setting (*TDS*). The pickup current value is the minimum current value for which the relay operates. The time dial setting defines the operation time (*T*) of the device for each current value, and is normally given as a curve *T* Vs *M.* where, *M* (i.e. the multiple of the pickup current) is the ratio of the relay fault current *I*, to the pickup current value, i.e. *M=I/Ip*. In general, over current relays respond to a characteristics function of the type,

$$T = f(TDS,Ip,I) \tag{1}$$

This, under simplistic assumptions, can be approximated by [17]:

$$T = \frac{K_1 * TDS}{\left[\left(\dfrac{I}{CT\ Ratio * Ip}\right)^{K_2} + K_3\right]} \tag{2}$$

where, K_1, K_2 and K_3 are constant that depends upon the specific device being simulated.

The calculation of the two settings, *TDS* and *Ip*, is the essence of the directional over current relay coordination study.

A. Problem Statement

The general coordination problem in Eq. (1) can be directly particularized to the problem of selecting the settings for a coordinated operation of directional over current relays. In this case, search space *S* = [*TDS*, *Ip*], and the objective function Z_k, represent suitable objectives to be achieved. One way of indirectly minimizing this equipment stress, is by making each Z_k a weighted aggregation of the operation times of the relays in zone k as follows:

$$Z_k = (TDS, Ip, T) = \sum_i \sum_j w_{ijk} \cdot T_{ijk} \tag{3}$$

Where, *k*=1, …, np, T_{ijk} is the operation time of relay *i* of zone *j* (i.e., relay R_{ij}) for a fault in zone *k*, and the weight w_{ijk} may depend upon the probability of given fault occurring in each of the zones of the protective relays.

B. Bounds on the relay setting and operation times

$$TDS_{ijmin} \le TDS_{ij} \le TDS_{ijmax}$$
$$Ip_{ijmin} \le Ip_{ij} \le Ip_{ijmax} \tag{4}$$

C. Coordination Criteria

For Coordination of a protective scheme a predefined Coordination Time Interval (*CTI*) must collapses before the backup scheme comes into action. This *CTI* depends upon type of relays, speed of the circuit breaker and other parameters.

$$T_{backup} - T_{primary} \le CTI \tag{5}$$

D. Relay characteristics

The Relay Characteristics function is denoted in general by (1) and may be modified for zone-wise description as

$$T_{ijk} = f_{ij}(TDS_{ij}, Ip_{ij}, I_{ijk}) \tag{6}$$

where, TDS_{ij} is the time dial setting of relay R_{ij}, Ip_{ij} is the pickup current of relay R_{ij}, and I_{ijk} represents the current seen by relay R_{ij} for a fault located in zone *k*.

III. Particle Swarm Optimization

PSO-based approach is considered as the one of the most powerful methods for solving the non-smooth or smooth global optimization problems [20]. PSO is the population based search algorithm and is initialized with a population of random solutions, called particles. Unlike in the other evolutionary computation techniques, each particle in PSO is also associated with a velocity. Particles fly through the search space with velocities which are dynamically adjusted according to their historical behaviors. Therefore, the particles have a tendency to fly towards the better and better search area over the course of search process.

A. Original Particle Swarm Optimization Algorithm

The original PSO algorithm is discovered through simplified social model simulation. PSO was introduced by Kennedy and Eberhart [14], has its roots in swarm intelligence. The motivation behind the algorithm is the intelligent collective behavior of organisms in a swarm (e.g., a flock of birds migrating), while the behavior of a single organism in the swarm may seem totally inefficient. The bird would find food through social cooperation with other birds around it (with in neighborhood).

PSO represents an optimization method where particles collaborate as a population to reach a collective goal. Each n-dimensional particles x_i is a potential solution to the collective goal, usually to minimize a function *f*. Each particle in the swarm can memorize its current position that is determined by evolution of the objective function, velocity and the best position visited during the search space referred to the personal best position (*pbest*), this search is based on probabilistic, rather than deterministic, transition rules. A particle x_i has memory of the best solution y_i that it has found, called its personal best; it flies through the search space with a velocity v_i dynamically adjusted according to its personal best and the global best (*gbest*) solution $\hat{y}$ found by the rest of the rest of the swarm (called the *gbest* topology) [25, 26, 27].

Let i indicate a particle's index in the swarm, such that $S=\{x_1, x_2, \ldots, x_s\}$ is a swarm of s particles. During each iteration of the PSO algorithm, the personal best y_i of each particle is compared to its current performance, and set to the better performance. If the objective function to be minimized is defined as $f: \mathbb{R}^n \rightarrow \mathbb{R}$ then [28]

$$y_i^{(t)} = \begin{cases} y_i^{(t-1)} & if \quad f(x_i^{(t)}) \geq f(y_i^{(t-1)}) \\ x_i^{(t)} & if \quad f(x_i^{(t)}) < f(y_i^{(t-1)}) \end{cases} \quad (7)$$

Traditionally, each particles velocity is updated separately for each dimension j. with

$$v_{ij}^{(t+1)} = \omega * v_{ij}^{(t)} + c_1 * round1()[pbest_{ij}^{(t)} - x_{ij}^{(t)}] + c_2 * roun2()[gbest_{ij}^{(t)} - x_{ij}^{(t)}] \quad (8)$$

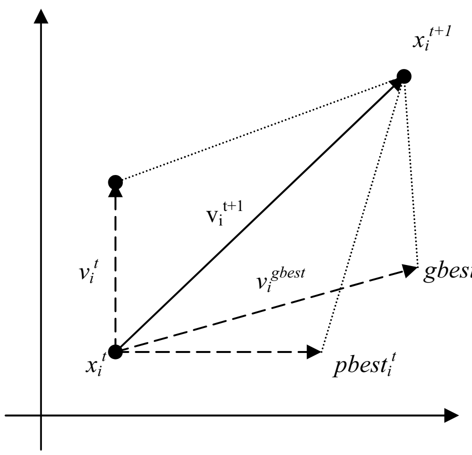

Fig. 1. Search mechanism of the PSO

The stochastic nature of the algorithm is determined by *round1()* and *round2()*, two uniform random numbers between zero and one. These random numbers scaled by acceleration coefficient c_1 and c_2. The inertia weight ω was introduced to improve the convergence rate of the PSO algorithm [23]. Usually, the value of the velocity is clamped to the range [-v_{max}, v_{max}] to reduce the possibility that the particle might fly out the search space. If the space is defined by the bounds [x_{min}, x_{max}], then the value of v_{max} is typically set so that $v_{max}=hx_{max}$, where $0.1 \leq h \leq 1$ [29]. After that, each particle is allowed to update its position using its current velocity to explore the problem search space for a better solution as follows:

$$x_{ij}^{(t+1)} = v_{ij}^{(t)} + x_{ij}^{(t)} \quad (10)$$

The search mechanism of the PSO using the modified velocities and position of individual i based on (9) and (10) is illustrated in fig. 1.

B. Modified Particle Swarm Optimization

The standard PSO algorithm is used for unconstrained optimization tasks. PSO in its standard form is not capable of dealing with the constrained optimization problem like relay coordination of DOCRs. The repair algorithm gives the PSO algorithm capability of tackling the coordination constraints imposed on the relays, while searching for an optimal setting.

The PSO algorithm also has limitation in terms that, during the updating process, where each particle modifies its position, the resultant particle position could be outside the feasible search space. This reduces the possibility of finding an optimal or close to optimal solution. The original PSO is therefore modified to overcome the aforementioned problems. Initializing the pickup currents randomly does this, thus the problem becomes linear and the *TDS* values are calculated using the interior point method. The initial feasible solutions are then applied to the PSO algorithm. The method is implemented to handle constraints of the relay coordination optimization problem and is found to be more efficient while updating the solution into a feasible solution. If any particles of an individual violate its constraints then it is fixed to its maximum/minimum value (cut down value) according to its objective function minimum/maximum. This method is used for handling the constraints for modified particle swarm optimization to solve directional over current relay coordination [23].

$$x_i^k = \begin{cases} x_i^k & \text{if satisfying all constraints} \\ x_{i,\min}^k & \text{if not satisfying constraints, (max problem)} \\ x_{i,\max}^k & \text{if not satisfying constraints, (min problem)} \end{cases} \quad (11)$$

The PSO/MPSO algorithm doesn't require any initial feasible solution for iterations to converge in stead the initial position of the particles generated randomly for the MPSO is considered. The particles positions are then verified with the constraints before passing it to the objective function for optimization. Thus there is no need of the penalty value calculation. It reduces the time and increase the convergence rate also [30].

The velocity update in MPSO is taken care of by Inertia weight ω, usually calculated with the following if-then-else statement

$$\left. \begin{array}{l} If\ iter_{max} \leq iter\ then \\ \qquad \omega = \dfrac{(\omega_{min} - \omega_{max})}{(iter_{max} - 1)} * (iter - 1) + \omega_{max} \\ else \\ \qquad \omega = \omega_{min} \end{array} \right\} \quad (12)$$

The inertia weight starts at ω_{max} and its functional value in (12) reduces as the number of iterations increases till $iter_{max}$ (maximum iteration count) and after that maintains a constant value of ω_{min} for remaining iteration. Where the ω_{max} and ω_{min} are the maximum and minimum weight value that are constant and $iter_{max}$ is maximum iteration. The Fig. 2 illustrates the flow chat for the MPSO algorithm used to calculate the optimal setting of the directional over current relays.

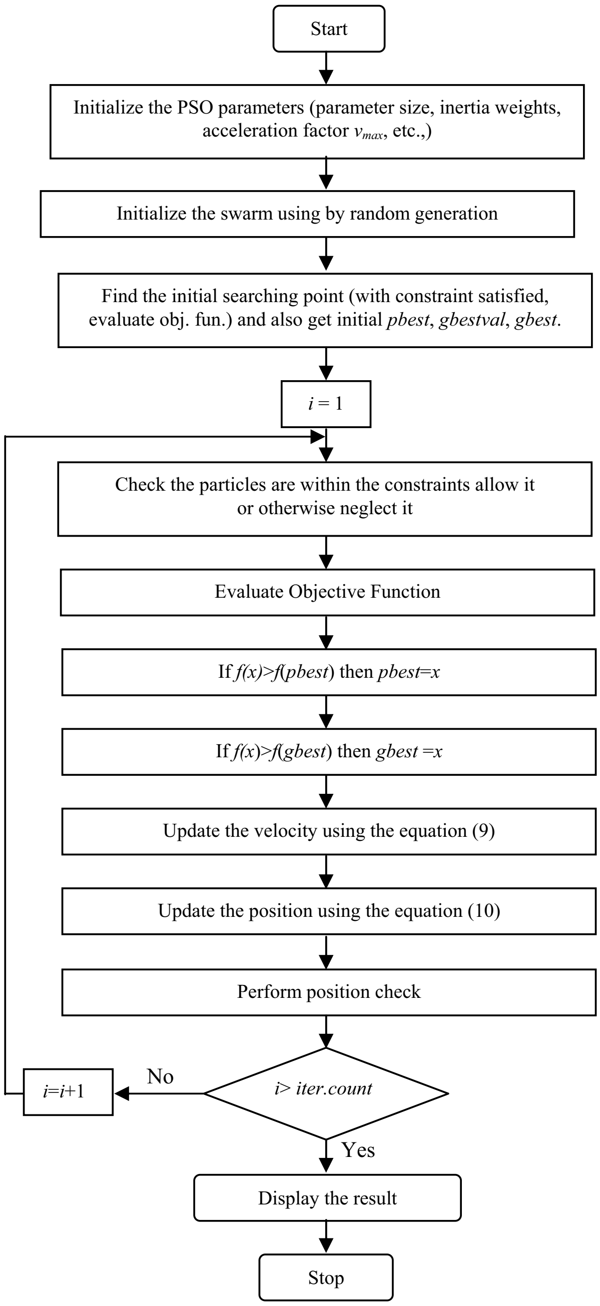

Fig. 2. Flow Chart of MPSO

IV. Simulation Result

A. System Data

The system under study is a 6 bus system as shown in Fig. 3. The 3-phase faults are applied at the near-end of each phase relay (close in faults). The primary/backup (*P/B*) relay pairs and fault currents are given in the Table I. The CT ratios for the pickup current setting are given in the Table II. The phase relays used in the network are the Westinghouse Co-9 that can be modeled by (1). The *TDS* are assumed to vary between a minimum value of 0.5 and maximum value of 1.1. The pickup current setting *Ip* are assumed to vary between a minimum value 0.5 and maximum value of 1.5. In this system the transient configuration is neglected. The relay characteristics equation (2) constants are K_1=0.14, K_2= 0.02, and K_3= -1. The *CTI* is taken as 0.2.

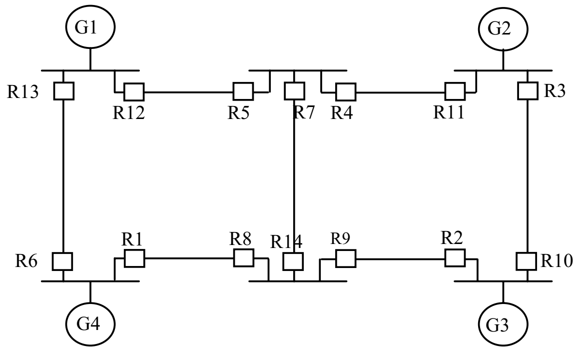

Fig. 3. 6 - Bus Power System Network

TABLE I
P/B Pairs for The 6-Bus System

Backup Relay	Fault Current(kA)	Primary Relay	Fault Current(kA)
1	4.5890	9	6.0720
1	4.5890	14	5.4570
2	0.8680	8	2.3510
2	0.8680	14	5.4570
3	1.3650	2	4.8030
4	0.5528	3	30.5470
5	0.9770	13	17.8210
6	0.8610	12	17.7050
7	1.4830	8	2.3510
7	1.4830	9	6.0720
8	0.7670	6	18.3380
9	0.6390	10	4.0770
10	0.9455	11	30.9390
11	1.0740	5	2.8380
11	1.0740	7	4.4960
12	3.4220	4	5.1860
12	3.4220	7	4.4960
13	0.6010	1	18.1720
14	1.7640	4	5.1860
14	1.7640	5	2.8380

TABLE II
CT Ratio For The 6-Bus System

Relay No	CT Ratio	Relay No	VT Ratio
1	1200/5	8	800/5
2	800/5	9	800/5
3	800/5	10	600/5
4	800/5	11	800/5
5	800/5	12	800/5
6	1200/5	13	1200/5
7	800/5	14	800/5

B. Implementation of Non-Linear Programming Problem

The Modified PSO is capable of addressing both linear and non linear optimization problem. It is applied to the relay coordination problem formulation and was coded in MATLAB with total number of variables 28 and population size of 50 particles. The maximum number of iteration count used is 500 and that for calculation of inertia weight ω for updating the velocity is 100. The constants c_1 and c_2 in (9) are set to be 2.1, the value of ω_{max} and ω_{min} are taken to be equal to 0.9 and 0.4 respectively. The maximum velocity divisor is taken 2. The results of optimal settings of the relay as calculated by MPSO are tabulated in Table III.

The above values determined are close to a global optimal solution. The MPSO in its first iteration takes a randomly generated particle's and gets positive objective function value then from onwards it finds searching for the optimal solution by keeping the value as a *gbest*. The particle's are always positive and converges towards a better objective value with following iterations.

TABLE III
OPTIMAL SETTING USING NLP PROBLEM FORMULATION

Values	MPSO (NLP)
TDS1	0.5
TDS2	0.5
TDS3	0.5
TDS4	0.5
TDS5	0.5
TDS6	0.5
TDS7	0.5
TDS8	0.5
TDS9	0.5
TDS10	0.5
TDS11	0.5
TDS12	0.5
TDS13	0.5
TDS14	0.5
Ip1	0.5
Ip2	0.5
Ip3	0.5
Ip4	0.5
Ip5	0.5
Ip6	0.5
Ip7	0.5
Ip8	0.5
Ip9	0.5
Ip10	0.5
Ip11	0.5
Ip12	0.51059
Ip13	0.5
Ip14	0.5
Objective value	17.0880 Sec.

The result of this section proves that the MPSO is working properly and is capable of finding a close to global solution for non linear programming problem. The simulation results reveal that the relay number 12 pickup current is not as per the discrete pick up current setting of the Relay (*Ip*) and therefore it will be rounded off to the nearest discrete setting. It is quite possible that the rounding off the optimal setting to the nearest discrete values may lead to infeasible solution and because of this the relay coordination problem is again approached as a linear programming problem with the fixed value of the Non-Linear programming Ip results. That Ip values are discrete values available setting of the directional over current relay.

C. Implementation of Linear Programming Problem

The Linear Programming problem of relay coordination we have to predefined value of the Ip found at the Non-Linear programming problem, the value of the result from the NLP problem formulation rounded to the nearest discrete values of the available Ip values. The pickup current values of the relays are predefined (known) previously. The only variable in the objective function is *TDS*, for a predefined *Ip* (2) is reduced to

$$T_i = a * TDS_i \tag{13}$$

where

$$a = \frac{K_1}{M^{K_2} + K_3} \tag{14}$$

and the (13) has only one variable to find *TDS* the problem reduced. In above mentioned (2) is used to represent the characteristics of the relays, the coordination problem still be stated as a Linear Programming problem. The results of optimal settings of the directional over current relay as calculated by MPSO are tabulated in Table IV.

TABLE IV
OPTIMAL SETTING USING LP PROBLEM FORMULATION

Values	MPSO (LP)
TDS1	0.5
TDS2	0.5
TDS3	0.5
TDS4	0.5
TDS5	0.5
TDS6	0.5
TDS7	0.5
TDS8	0.5
TDS9	0.5
TDS10	0.5
TDS11	0.5
TDS12	0.5
TDS13	0.5
TDS14	0.5
Ip1	0.5
Ip2	0.5
Ip3	0.5
Ip4	0.5
Ip5	0.5
Ip6	0.5
Ip7	0.5
Ip8	0.5
Ip9	0.5
Ip10	0.5
Ip11	0.5
Ip12	0.5
Ip13	0.5
Ip14	0.5
Objective value	17.09249Sec.

The result of this section proves that the MPSO is the global solution for linear programming problem and the optimal solution is feasible. The Non-Linear programming draw back is eliminated by this novel approach. This also proves that the relay setting of NLP solution does not go for infeasible solution for particular problem.

V. Conclusion

An optimal problem formulation was presented in this paper for the finding the Ip settings of the relays and then the TDS and Ip settings of Directional Over Current Relays is found by the Non-Linear Programming and Linear Programming problem. The NLP problem approach result is of Ip setting rounded to the nearest discrete values of the available Ip setting values. With the result of Ip as taken fixed values is considered for Linear Programming to solve TDS setting of the coordination problem. Even these approaches eliminated the complex formulation of Mixed Integer Non Linear Programming Problem and Mixed Integer Programming Problem. The proposed MPSO technique is shows that it cable of Linear as well as Non-Linear Programming problem. The Results shows the optimal values of the Directional Over Current relay Coordination problem.

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