# Intelligent Overcurrent and Distance Relays Coordination:A Comparative Analysis using GA,PSO and TLBO

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***Abstract*— Relay coordination is important for maintaining proper power system operation and control. Relays should be organized in a special way such that every relay should have a backup and coordination time interval (CTI) between primary and back up and different zones of the relays should be maintained. The relays should operate in minimum desirable time satisfying all the co-ordination constraints optimally. Heuristic techniques are frequently used to get optimal solution of this kind of problems. The problem is solved using Teaching Learning Based Optimization(TLBO).The results are compared with the results obtained by Genetic Algorithm(GA) and Particle Swarm Optimization(PSO) on a 6bus system. Selection of intelligent over current relay characteristics are incorporated to get the desired results in this work. The results obtained from TLBO are found better than the same obtained from GA and PSO.**

***Keywords*— *Coordination of relay; Coordination time interval; Teaching learning based optimization; Time setting multiplier; intelligent relay characteristics; Convergence characteristics; GA;PSO*.**

## I. INTRODUCTION

Different issues of power systems should be studied to keep the operation uninterrupted, secure and reliable. Relay coordination is one of the most important issues among them. The coordination of relays should meet the following perspectives :

Relays should be organized in such a way that every relay should have a backup and CTI between primary and back up and different zones of the relays should be maintained. It is helpful to identify the proper location of fault and to clear it. During fault conditions relays must operate and isolate the faulty part from healthy part of the network. If primary relay fails, backup relay must operate after a sufficient time gap. Hence the operation of back up relays must be coordinated with the operation of the primary relays. The proper settings of the relays should be set to achieve the desired objectives.

Now a days distance and overcurrent relays are often used together for protection of all transmission and sub-transmission systems. For better co-ordination , a distance and an over current relays must be coordinated with all possible combinations i.e a distance relay with a distance relay, an over current relay with a over current relay and an over current relay with a distance relay must be coordinated properly. One of them will act as main relay and another one will act as back up relay. Proper co-ordination time interval must be maintained between them.

The study of co-ordination of relays was first done among over current relays by using linear programming method including simplex, two-phase simplex and dual simplex methods[1]-[4]. But in these methods, the solution will not come unless all the constraints are satisfied. So, these methods can be said solution uncertain methods.

So, people gradually started to use intelligent and meta – heuristic approaches which gives optimal solution instead of exact solution meeting all the constraints criteria optimally. As a result, in spite of not getting accurate solution, solution is obtained for meeting the requirements or purpose. In ref.[5], optimal co-ordination is done by Genetic Algorithm. Ref.[6] shows optimal co ordination by using Particle swarm optimization and Ref.[7] shows the time co-ordination by using evolutionary algorithm. But these schemes are having two types of problems. First one is mis coordination and other one is scarcity of solution for relays with both discrete and continuous values of time setting multipliers ( TSMs). The problems are resolved in [8] by adding a new expression with the objective function. All the above discussed methodologies are done by using over current relays and the relay characteristics are assumed to be fixed. While in digital relays different over current relay characteristics can be selected. So, the algorithm for relay co-ordination should be capable of selecting the best fitting characteristics of over current relays to have optimal co ordination.

Ref.[9] shows relay co ordination with an hybrid GA algorithm. Ref.[10] shows relay co ordination using GA and intelligent relay characteristics selection. Ref. [13]-[15] shows relay coordination using TLBO for small systems.

In this paper, Teaching learning based optimization ( TLBO) is used for distance and over current relay coordination with intelligent over current relay characteristics selection. Relay co-ordination using TLBO and with intelligent over current relay characteristics is a novel contribution in this paper. But the main agenda of this paper is to make a comparison of the results obtained from TLBO with the same obtained from GA and PSO and insight different views on the results. TLBO is found to be more simple and reliable than other methods. A 6 bus system is utilized for the work.

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## II. TEACHING LEARNING BASED OPTIMIZATION (TLBO)

TLBO is an algorithm which mimics the teaching learning process. It is proposed by Rao et al. [11]. The learning process will be done through two stages such as teacher stage and learner stage. While modeling the algorithm, the group of learners was modeled as population; subjects opted by learners were modeled as design variables. Here, learners result becomes the fitness value. After iteration, the best solution inside the population becomes teacher. And, the constraints of optimization problem become design variables [11]-[18].

### *A. Teacher Stage*

Teacher stage is the first stage of the algorithm. As all of us know teacher teaches students and increases the mean of their marks depending upon their capabilities. Assume that there are 'm' number of subjects (i.e. design variables), 'n' number of learners (i.e. population size, k = 1,2,..., n) and the mean result of the learners is $M_{j,i}$ in a particular subject 'j' (j = 1,2,..., m). The best overall result considering all the subjects together obtained in the entire population of learners can be considered the result of the best learner, kbest. Teacher is the best learned person in the group. The difference between the existing mean result of each subject and the corresponding result of the teacher for each subject is given by Eq.(1) :

$$Difference\_Mean_{j,k,i} = r_i(X_{j,kbest,i} - T_F M_{j,i}) \quad (1)$$

Where $X_{j,kbest,i}$, is the result of the best learner (i.e., teacher) in subject j. $T_F$ is called the teaching factor. It decides the value of the mean to be changed, and $r_i$ is the random number in the range [0, 1]. The value of $T_F$ can be either 1 or 2(ref. Eq.(2)):

$$T_F = round[1 + rand(0,1)\{2-1\}] \quad (2)$$

Based on the $Difference\_Mean_{j,k,i}$, the existing solution is updated in the teacher phase according to the following expression(ref. Eq.(3)):

$$X'_{j,k,i} = X_{j,k,i} + Difference\_Mean_{j,k,i} \quad (3)$$

Where $X'_{j,k,i}$ is the new value of $X_{j,k,i}$. Accept $X'_{j,k,i}$ if it improves the value of the function. After teacher stage, all fitted values will be given as input to the learner stage. So, it means the learner stage depends on teacher stage.

### *B. Learner Stage*

Learner stage is the second stage of the algorithm. Learners boost up their knowledge by interactions among themselves. A learner learns new things if the other learner has more knowledge than him or her. After considering a population size of '*n*', the learning phenomenon of this phase is expressed below(ref. Eq.(4) and Eq.(5)):

$$X''_{j,P,i} = X'_{j,P,i} + r_i(X'_{j,P,i} - X'_{j,Q,i}), If\ X'_{total-P,i} < X'_{total-Q,i} \quad (4)$$

$$X''_{j,P,i} = X'_{j,P,i} + r_i(X'_{j,Q,i} - X'_{j,P,i}), If\ X'_{total-P,i} > X'_{total-Q,i} \quad (5)$$

Accept $X''_{j,P,i}$ if it gives a better function value.

## III. GENETIC ALGORITHM (GA)

Genetic Algorithm ( GA) is a very well known meta-heuristic algorithm which mimics the biological process of reproduction by human gene. GA uses the principles of genetic evolutions and natural selections such as selection rate, cross over and mutation etc [8-10]. The steps of GA are as follows in a nutshell:

*i)Initialization:* Populations are randomly initialized and then called them as search space. After that their fitness is calculated by calculating their values by objective function.

*ii) Evolution :* Then an offspring pool is created via applying genetic operators such as selection, cross over and mutation. Mutation rate is very small ( such as 0.01 to 0.1).Where as selection or cross over rate will be relatively higher( 0.5-0.8).

*iii) Fitness calculation:* Evaluate the fitness value of the generated off-springs.

*iv)Convergence check :* Check whether the termination criteria is satisfying or not. If not then repeat from the evolution process otherwise terminate (if termination criteria is satisfied). The common termination criteria for GA are, solutions found to fulfil criteria ; fixed number of generations reached; computation time set or money allocated for it reached; successive iterations are no longer capable to produce better results; combinations of the previous discussed issues.

GA are largely used in various research areas to generate very high quality solutions to many search problems and optimization.

## IV. PARTICLE SWARM OPTIMIZATION (PSO)

PSO is a swarm intelligent based optimization technique mimics from swarming behaviors of animals and social behavior of human. The PSO is having a population( called as Swarm) of candidate solutions( called as particles). The particles movement will be guided by their own known best position as well as the entire swarm's known best position. When better positions are discovered then that have effect on movement of the swarms. By this process the satisfactory solutions are eventually be discovered. Each particle's velocity and position in the next iteration can be described by the following equations[6-7](ref. Eq.(6) and Eq.(7)):

$$V_i(t+1) = w(t)V_i(t) + C_1 r_1(P_i(t) - X_i(t+1)) + C_2 r_2(G_i(t) - X_i(t+1)) \quad (6)$$

$$X_i(t+1) = X_i(t) + \lambda V_i(t+1) \quad (7)$$

Where, w(t) is inertia coefficient or weight which varies from 0.4-0.9. $\lambda$ is constriction factor. Here it is 0.7. $C_1$ and $C_2$ are called as cognitive and social parameters respectively. Both values are set to be 2 here. $r_1$ and $r_2$ are random real numbers whose values are between 0 and 1. $P_i$ denotes the positional best and $G_i$ denotes the global best. $X_i$ denotes position.

## V. PROBLEM STATEMENT

The fitness function is chosen as follows(ref. Eq.(8)):

$$Fitness\ \ function = \min(\alpha\sum_{i=1}^{n} t_i + \beta\sum_{i=1}^{n}\left|T_{DIOCi} - \left|T_{DIOCi}\right|\right| + \lambda\sum_{i=1}^{n}\left|T_{OCDIi} - \left|T_{OCDIi}\right|\right| + \delta\sum_{i=1}^{n}\left|T_{OCi} - \left|T_{OCi}\right|\right|) \quad (8)$$

The expressions of fitness function are described by Eq.(9), Eq.(10) and Eq.(11):

$$T_{OCi} = T_{oc\,backup\,i} - T_{oc\,main\,i} - CTI^{'} \quad (9)$$

$$T_{DIOCi} = T_{oc\,i} - T_{z2\,i} - CTI^{'} \quad (10)$$

$$T_{OCDIi} = T_{z2\,i} - T_{oc\,i} - CTI^{'} \quad (11)$$

$T_{oc}$ is the operating time of over current relay and Tz2 is the operating time of the second zone of the distance relays and the constants used such as $\alpha, \beta, \lambda, \delta$ are penalty factors.

## VI. CONSTRAINTS

The several constraints need to be satisfied to obtain optimal co-ordination and settings are as follows :

*A.Co-ordination constraints*

It is described as follows( ref. Eq.(12) and Eq.(13)):

$$T_{z2\,backup} - T_{oc\,main} \geq CTI^{'} \quad (12)$$

$$T_{oc\,backup} - T_{z2\,main} \geq CTI^{'} \quad (13)$$

The typical value of coordination time interval(CTI) is between 0.2 to 0.3 sec.

*B. Relay Characteristics*

The over current relay characteristics are typically of below nature(ref. Eq.(14)):

$$t = TSM\left(\frac{K}{M^{\alpha} - 1} + L\right) \quad (14)$$

t= time of operation of the relay TSM= Time setting multiplier. K, L and α are constants. They varies characteristics to characteristics. M is the ratio between short circuit current $I_{sc}$ and pick up current $I_p$ of the relays.

Coordinating time interval in each cases is supposed to be 0.25 sec. Eight types of intelligent over current relay characteristics are obtained from Ref.[10].

*C.Pick-up current constraints*

Pick up current is having a limit. The relay co-ordination problem is highly dependent on the value of the pickup current of the relays. The limits of pick up current can be expressed as below[15](ref. Eq. (15)):

$$Ip_{\min} \leq Ip \leq Ip_{\max} \quad (15)$$

*D. TSM constraints*

TSM is supposed to be continuous and can take any value between 0.05-1.1. Mathematically it can be expressed as below (ref.Eq.(16)):

$$TSM_{\min} \leq TSM \leq TSM_{\max} \quad (16)$$

*E. Constrains on relay operating time*

Limits on time of operation of relay($t_{op}$) can be expressed as(ref. Eq.(17)):

$$t_{op\,\min} \leq t_{op} \leq t_{op\,\max} \quad (17\,)$$

Minimum operation time of relay is 0.1 sec and maximum depends on the requirement of the user.

## VII.TEST RESULTS

To test the methodology a 6 Bus system has been selected. The relay arrangements are shown for this power system as same as it is shown in Fig1. The mho directional relays are used here. The different kinds of intelligent over current relay characteristics used in digital relays are obtained from Ref.[10]. Main and back up relay pairs with short circuit data are shown in Table-I.

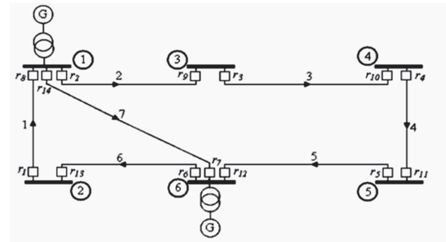

Fig.1:Relay arrangement 6 Bus System

Table-I: Main and backup relay pairs with short circuit data

| Main Relay($r_i$) | Back up Relay($r_i$) | Short circuit current of main relay ( amps) | Short circuit current of back up relay (amps) |
|---|---|---|---|
| $r_2$ | $r_1$ | 5428 | 828 |
| $r_{14}$ | $r_1$ | 4184 | 816 |
| $r_3$ | $r_2$ | 3505 | 3505 |
| $r_4$ | $r_3$ | 1769 | 1769 |
| $r_5$ | $r_4$ | 1103 | 1103 |
| $r_6$ | $r_5$ | 4936 | 340 |
| $r_7$ | $r_5$ | 4184 | 337 |
| $r_1$ | $r_6$ | 2682 | 2682 |
| $r_2$ | $r_7$ | 5428 | 1571 |
| $r_8$ | $r_7$ | 4933 | 1563 |
| $r_{13}$ | $r_8$ | 2492 | 2492 |
| $r_8$ | $r_9$ | 4933 | 340 |
| $r_{14}$ | $r_9$ | 4184 | 337 |
| $r_9$ | $r_{10}$ | 1174 | 1174 |
| $r_{10}$ | $r_{11}$ | 2589 | 2589 |
| $r_{11}$ | $r_{12}$ | 3655 | 3655 |
| $r_7$ | $r_{13}$ | 4184 | 816 |
| $r_{12}$ | $r_{13}$ | 5431 | 828 |
| $r_6$ | $r_{14}$ | 4936 | 1565 |
| $r_{12}$ | $r_{14}$ | 5431 | 1573 |

The main and back up relay short circuit currents should be calculated from close in bus fault cases( Critical fault locations). The information regarding pick up current settings are shown in Table-II. The pickup current values of each over current relay is assumed roughly 1.25 times of the relevant maximum load in approximated integer form. Total number of relays used here is 14. From Table-I, it is found that relays $r_2, r_6, r_7, r_8, r_{12}, r_{14}$ are having better protection reliability compare to other relays, as they have more than one backups.

*Critical fault location*-There is a minimum length of the line, below which the relay is unable to protect the line. If the fault point is too close to the relaying point, the relay may fail to operate. The relay will operate if the following condition is satisfied[10]-[21] :

$$\frac{Z_s}{Z_L} \leq (\frac{E}{V} - 1) \quad (18)$$

$Z_s$ is the source impedance behind the relay, $Z_L$ is the line impedance from the relaying point to the fault point, E is the line input voltage ( or normal secondary C.T voltage), V is the voltage at relay location. Critical fault location is that point, which is the minimum distance of the line to make the relay to start work. In that point the following condition is satisfied [21] :

$$\frac{Z_s}{Z_L} = (\frac{E}{V} - 1) \quad (19)$$

In critical fault location, the discrimination time is zero i.e

$$T_b - T_m = CTI \quad (20)$$

Usually the critical fault location is situated within 12% length of each transmission line.

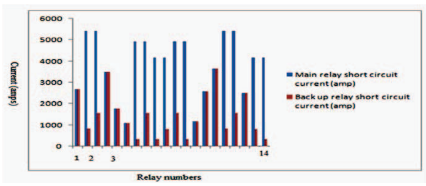


Fig.2: Comparison of short circuit currents of main and backup relays

Table-II: Pick up current values of the relay

| Relay number($r_i$) | Load Current(amps) | Pick up Current(amps) |
|---|---|---|
| $r_1$ | 104 | 125 |
| $r_2$ | 166 | 200 |
| $r_3$ | 125 | 150 |
| $r_4$ | 180 | 200 |
| $r_5$ | 129 | 137 |
| $r_6$ | 114 | 137 |
| $r_7$ | 141 | 162 |
| $r_8$ | 109 | 137 |
| $r_9$ | 118 | 135 |
| $r_{10}$ | 110 | 137 |
| $r_{11}$ | 135 | 162 |
| $r_{12}$ | 122 | 137 |
| $r_{13}$ | 125 | 150 |
| $r_{14}$ | 166 | 200 |

The objective function is found based on trial and error methods to reduce the time of operation of relays, same as in the case of over current to over current relay co-ordination. The only difference here is some additional terms are coming due to the presence of distance relay. Explanations of choosing such expressions can be given as follows:

If $|T_{DIOCi}|$ is positive then the second term of objective function is becoming zero but if $|T_{DIOCi}|$ is negative then the second term is additive with the objective function and increasing its value. It is a minimization problem, so the chance of survival of such fitness value is less. As per co-ordination constraints $|T_{DIOCi}|$ value should be always greater than equals to zero. Its value can be negative only in case of mis-coordination. So, with such approach the chance of mis-coordination is almost neutralized. The same kind of explanation can be given for choosing the third and fourth terms of the fitness function also[16-20].

By applying TLBO ( Teaching learning based optimization) in the network of Fig1 the output results are obtained. TSMs and over current relay characteristics which are selected by TLBO are shown in Table-III. The time of operation of relays in each case are also shown in the table(Table-III). The various outputs from this work are shown pictorially from Fig.2 to Fig.5.

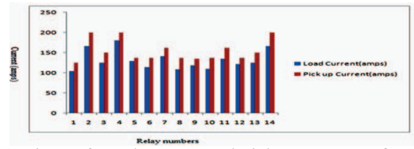


Fig.3: Comparison of Load current and pick up current of various relays

Table-III: Output table for type of characteristics and TSM selection

| Relay ($r_i$) | Second Zone operation time ($T_{z2}$)(sec) | TSM | No. of selected Characteristic |
|---|---|---|---|
| 1 | 0.537 | 0.242567 | 2 |
| 2 | 0.4987 | 0.243110 | 2 |
| 3 | 0.5482 | 0.254736 | 2 |
| 4 | 0.6027 | 0.191837 | 3 |
| 5 | 0.5333 | 0.162270 | 3 |
| 6 | 0.5693 | 0.302211 | 2 |
| 7 | 0.4984 | 0.239195 | 2 |
| 8 | 0.5806 | 0.308156 | 2 |
| 9 | 0.537 | 0.169566 | 3 |
| 10 | 0.6233 | 0.269546 | 6 |
| 11 | 0.5872 | 0.269727 | 2 |
| 12 | 0.5365 | 0.292676 | 2 |
| 13 | 0.5333 | 0.220228 | 2 |
| 14 | 0.4942 | 0.221336 | 2 |
| Average Value | 0.54855 | 0.24194 | - |
| Fitness value | 120.664 | - | - |

*Justification on incorporating different intelligent overcurrent relay characteristics :* From Table-III, it is observed that the TLBO applied to the test system used mainly no.2 intelligent characteristics ( 10 out of 14 relays are using no. 2 –standard inverse characteristics). But the selection of types of characteristics depends on several factors. e.g- Short circuit data , load and pick up current data, fault location, type of fault etc. Here, in this particular case ,no.2( Standard inverse) characteristics is frequently used. But the other characteristics also have equal importance when the types of faults or location or size of the test system(specially higher order test system) will change.

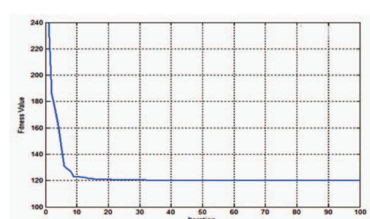


Fig.4: Convergence characteristics of the TLBO algorithm

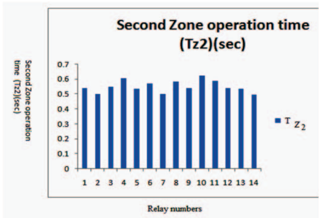


Fig.5: Comparison of operating time of second zone of relays

## VIII. COMPARATIVE STUDY WITH GA AND PSO

TLBO does not use any control parameter which is algorithm specific, for finding global optimum solution like other algorithms. Several algorithm specific control parameters used in case of other meta-heuristic algorithms are as follows:

GA (Genetic algorithm) uses mutation rate, selection rate and cross over probability. PSO( Particle Swarm Optimization) uses inertia weight, social and cognitive parameters. The proper selection of these parameters are very important for the performance of these optimization algorithms. TLBO needs only the population size and number of generations. So, TLBO becomes highly consistent optimization algorithm. It converges very fast and superior compare to GA and PSO. Table –IV, Table-V and Table-VI enlists the comparison of results for this problem by using GA, PSO and TLBO[10].

Table-IV: Comparison of TSM values obtained by using GA,PSO and TLBO

| Relay ($r_i$) | TSM Values obtained from GA | TSM Values obtained from PSO | TSM Values obtained from TLBO |
|---|---|---|---|
| 1 | 1.641 | 0.351708 | 0.242567 |
| 2 | 0.851 | 0.387488 | 0.243110 |
| 3 | 1.629 | 0.364677 | 0.254736 |
| 4 | 0.872 | 0.218295 | 0.191837 |
| 5 | 0.723 | 0.204275 | 0.162270 |
| 6 | 0.998 | 0.530754 | 0.302211 |
| 7 | 1.518 | 0.479925 | 0.239195 |
| 8 | 1.037 | 0.430754 | 0.308156 |
| 9 | 0.785 | 0.215766 | 0.169566 |
| 10 | 1.420 | 0.332449 | 0.269546 |
| 11 | 2.000 | 0.359345 | 0.269727 |
| 12 | 2.000 | 0.345528 | 0.292676 |
| 13 | 1.390 | 0.312954 | 0.220228 |
| 14 | 0.050 | 0.247867 | 0.221336 |
| Average Value | 1.208 | 0.341556 | 0.24194 |
| Fitness value | 125.000 | 124.635 | 120.664 |

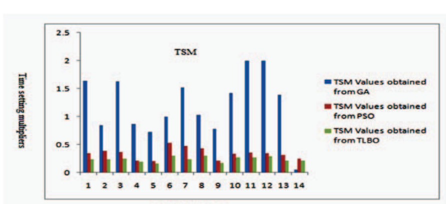


Fig.6: Comparison of optimum Time setting multipliers of relays obtained by GA,PSO and TLBO

From Table-IV and Fig.6 , it is clear that the results obtained by GA are sometimes violating the range with context to TSM($r_1$,$r_3$,$r_7$,$r_{10}$, $r_{11}$, $r_{12}$, $r_{13}$) for the particular case taken for study and the average value of TSM is also out of maximum specified range. Whereas PSO and TLBO results are within range. TLBO is giving least average TSM value and least fitness value. Table-V and Fig.7, shows the comparison of second zone operation time obtained by GA,PSO and TLBO. Table-V further shows the different intelligent overcurrent relay characteristics selected by GA,PSO and TLBO in each case. In Fig.7, the 15th column in relay numbers axis, shows the comparison of average second zone operation time obtained from GA, PSO and TLBO. It is clearly seen that the average second zone operation time obtained from TLBO is less than the same obtained from GA and PSO. The convergence characteristics obtained by GA and PSO algorithms are shown in Fig.8 and Fig.9. Comparison of the results obtained from GA, PSO and TLBO with respect to process speed is shown in Table –VI.

Table-V: Comparison of second zone operation time and no. of selected intelligent characteristics obtained by GA,PSO and TLBO

| relay ($r_i$) | 2nd zone time by GA ($T_{z2}$) (sec) | Chr. by GA | 2nd zone time by PSO ($T_{z2}$) (sec) | Chr. by PSO | 2nd zone time by TLBO ($T_{z2}$) (sec) | Chr. by TLBO |
|---|---|---|---|---|---|---|
| 1 | 0.6288 | 1 | 0.3832 | 1 | 0.537 | 2 |
| 2 | 0.7392 | 6 | 0.7939 | 2 | 0.4987 | 2 |
| 3 | 0.6063 | 1 | 0.7855 | 2 | 0.5482 | 2 |
| 4 | 0.4786 | 1 | 0.3751 | 3 | 0.6027 | 3 |
| 5 | 0.4155 | 1 | 0.2557 | 4 | 0.5333 | 3 |
| 6 | 0.8053 | 6 | 0.9999 | 2 | 0.5693 | 2 |
| 7 | 0.5465 | 1 | 0.2610 | 3 | 0.4984 | 2 |
| 8 | 0.8369 | 6 | 0.8102 | 2 | 0.5806 | 2 |
| 9 | 0.4343 | 1 | 0.3789 | 3 | 0.537 | 3 |
| 10 | 0.5691 | 1 | 0.7631 | 2 | 0.6233 | 6 |
| 11 | 0.7533 | 1 | 0.7837 | 2 | 0.5872 | 2 |
| 12 | 0.6987 | 3 | 0.6342 | 2 | 0.5365 | 2 |
| 13 | 0.5842 | 1 | 0.2706 | 3 | 0.5333 | 2 |
| 14 | 0.3012 | 5 | 0.5582 | 2 | 0.4942 | 2 |
| Avg. Value | 0.5999 | - | 0.5752 | - | 0.54855 | - |

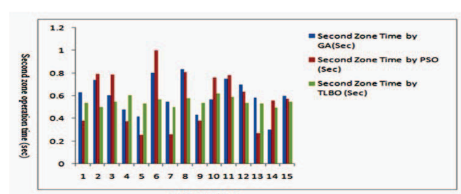


Fig.7: Comparison of second zone operation time of relays obtained by GA,PSO and TLBO

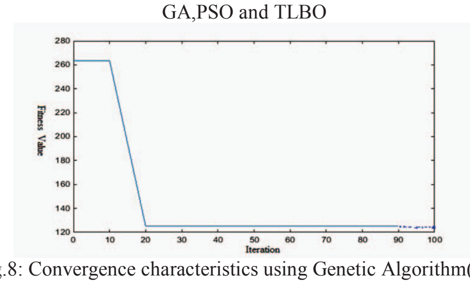


Fig.8: Convergence characteristics using Genetic Algorithm( GA)

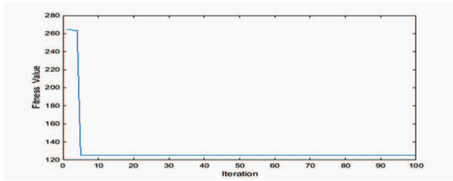


Fig.9: Convergence characteristics using Particle Swarm Optimization( PSO)

Table-VI: Comparison of results obtained by using GA,PSO and TLBO with respect to process speed

| Attributes | GA | PSO | TLBO |
|---|---|---|---|
| Number of iterations to converge | 20 | 8 | 16 |
| Average time per iteration(Sec) taken | 0.00955 | 0.0304 | 0.00438 |
| Total time taken to converge (CPU elapsed time)(sec) | 0.191 | 0.243 | 0.07 |

Fast convergence w.r.t number of iterations taken to converge the fitness function may often be deceptive. Because one iteration can take different time spans to compute for different meta-heuristic techniques subject to different constraints. So, ideally one should consider the total CPU elapsed time for convergence as a parameter to decide the fast convergence irrespective of number of iterations to converge. Among these three(GA,PSO and TLBO) algorithms, TLBO is converging in least CPU elapsed time as per Table-VI. So, it is the fastest among them.

## IX. CONCLUSIONS

This paper focused on optimal co-ordination of directional and over current relays. The problem statement and various constraints are already presented in the paper. Teaching learning based optimization ( TLBO) is applied to obtain the optimum solution. Different parameters are calculated for a 6 bus system. All the constraints are found within limit. Required intelligent over current characteristics to get the desired results are also selected. The obtained results from TLBO, GA and PSO are compared with required analysis. The technique(TLBO) is working satisfactorily with respect to other contemporary techniques like GA and PSO. As a future scope of this work, relay coordination on higher test systems with discrimination time can be implemented.

## APPENDIX

The test system data are obtained from Ref.[10].

## REFERENCES


[1]. L. G. Perez, R. Nadira, and A. J. Urdaneta, "Optimal coordination of directional overcurrent relays in interconnected power system" *IEEE Transactions on Power Delivery*, Vol. 3, No 3, Jul.1998.

[2]. A. J. Urdaneta et. al. , "Coordination of directional overcurrent relays timing using linear programming," *IEEE Transactions on Power Deivery.*, vol. 11, no. 1, pp. 122–129, Jan. 1996.

[3]. B. Chattopadhyay et. al., "An on-line relay coordination algorithm for adaptive protection using linear programming techniques," *IEEE Transactions on Power Deivery.*, vol. 11, no. 1, pp. 165–173, Jan. 1996.

[4]. H. Askarian Abyaneh and R. Keyhani, "Optimal co-ordination of overcurrent relays in power system by dual simplex method," presented at *the AUPEC Conference*, Perth, Australia, 1995

[5]. C. W. So et. al., "Application of genetic algorithm for overcurrent relay coordination," in *Proceedings of Instrumentation Electrical Engineering Conference Developments in Power System Protection*, Mar. 25–27, 1997, pp. 66–69.

[6]. M. A. Salama,H. Zeineldin and E. El-Saadany, "Optimal coordination of overcurrent relays using a modified particle swarm optimization," *Electric Power System Research.*, vol. 76, no. 11, Jul. 2006.

[7]. K. K. Li and C. W. So, "Time coordination method for power system protection by evolutionary algorithm," *IEEE Transactions on Industrial Applications*, vol. 36, no. 5, pp. 1235–1240, Sep./Oct. 2000.

[8]. H.Torkaman,H. Askarian Abyaneh, M. Al-Dabbagh, R. Mohammadi, and F. Razavi, "A new comprehensive genetic algorithm method for overcurrent relays coordination," *Electric Power System Research.*, vol. 92, no. 9, Apr. 2008.

[9]. M.Bashir, V.Aminotojari and J.Sadeh ," Optimal coordination of over current and distance relays with hybrid genetic algorithm", in proceedings of *10th International conference on Environment and Electrical Engineering*, IEEE,Rome, Italy,8-11 May,2011.

[10]. R.M. Chabanloo , H.A.Abyanch, SS.H.Kamangar and F.Razavi," Optimal combined overcurrent and distance relays coordination incorporating intelligent overcurrent relay characteristics selection", *IEEE Transactions on Power Delivery,* Vol.26, No.3,pp.1381-1391, July 2011

[11]. R.V.Rao and G.G.Wagmare ," A comparative study of a teaching–learning-based optimization algorithm on multi-objective unconstrained and constrained functions*", Journal of King Saud University- Computer and Information Sciences,*Vol.26,pp. 332-346, Dec. 2013.

[12]. R.V.Rao and V.Patel ," An elitist teaching-learning-based optimization algorithm for solving complex constrained optimization problems" *International Journal of Industrial Engineering Computations* , Vol.3,pp.535-560, March 2012.

[13]. M.Singh et. al.," optimal coordination of directional over-current relays using teaching learning-based optimization ( TLBO) algorithm ", *Electrical Power and Energy Systems,* Vol.50,pp.33-41, March 2013.

[14]. A.A.Kalage and N.D.Ghawghawe ," Optimum coordination of directional overcurrent relays using modified adaptive teaching learning based optimization algorithm", *Intelligent Industrial System* , Vol.2, Issue 1,pp.55-71, March 2016.

[15]. D.Saha , A.Dutta , B.K.Saha Roy and P.Das," Optimal coordination of DOCR in interconnected power systems", Presented in *IEEE 2nd International Conference on Control, Instrumentation, Energy and Communication*,28-30 Jan.,2016, Kolkata, India

[16]. M.Ojaghi and R.Ghahremani," Piece–wise linear characteristic for coordinating numerical overcurrent relays", *IEEE Transactions on Power Delivery*, Vol.32,No.1,pp.145-151, February 2017.

[17]. R.V.Rao,V.J.Savsani and J.Balic," Teaching–learning-based optimization algorithm for unconstrained and constrained real-parameter optimization problems", *Engineering Optimization*, Vol.44, No.12,pp.1447-1462, Dec. 2012.

[18]. R.V.Rao ," Review of applications of TLBO algorithm and a tutorial for beginners to solve the unconstrained and constrained optimization problems ", *Decision Science Letters*, Vol.5, Issue1,pp.1-30, March 2016.

[19]. M.Lohith et. al.," A novel approach for transmission line fault location using synchrophasor measurement", Presented in *IEEE International Conference on Energy, Power and Environment Towards Sustainable Growth*, 12-13 June,2015, NIT Meghalaya.

[20]. D.V.Shiv Sharma et al.," A wide area prospective on power system protection : A State-of-art", Presented in *IEEE International Conference on Energy, Power and Environment Towards Sustainable Growth*, 12-13 June,2015, NIT Meghalaya.

[21]. B.Ram and D.N.Viswakarma ,"Power system protection and switchgear ", *Tata McGraw Hill* , New Delhi , 2010.