Optimal Combined Overcurrent and Distance Relays Coordination using Teaching Learning based Optimization

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Abstract— **Relay coordination is an important aspect to maintain proper power system operation and control. Relays should be organized in such a way that every relay should have a backup and Coordination time interval (CTI) between primary and back up and different zones of the relay should be maintained to achieve proper fault identification and fault clearance sequence. The relays should operate in minimum desirable time satisfying all the co-ordination constraints. So, relay coordination is nothing but highly constraint problem. Heuristic techniques are often used to get optimal solution of this kind of problem. In this paper this constraint problem is solved by Teaching learning based optimization(TLBO) on a WSCC-3-Machine-9bus system. Proper desirable time setting multiplier (TSM) with minimum operating time of relays are calculated. We also incorporated intelligent over current relay characteristics selection to get the desired results in this work. The results seem to be satisfactory as the results obtained from TLBO are comparatively better than so called conventional methods like Genetic Algorithm(GA) and Particle Swarm Optimization (PSO).**

Keywords— Coordination of relay; Coordination time interval; Teaching learning based optimization; Plug setting; Time setting multiplier; Over current relay characteristics.

I. INTRODUCTION

Relays should be organized such a way that every relay should have a backup and CTI between primary and back up and different zones of the relay should be maintained. Relay co-ordination is necessary to achieve proper fault identification and fault clearance sequence. These relays must be able to distinguish between the normal operating currents including short time over currents that may appear due to certain equipment normal operation(e.g- Motor starting currents, transformer inrush currents) and sustained over current due to fault conditions. During fault conditions , these relays must operate quickly isolating the faulted section of the network and allows for continued operation of the healthy circuits. If primary relay meant for clearance of the fault fails, backup relay must operate after providing for sufficient time discrimination for the operation of primary relays. Hence the operation of back up relays must be coordinated with those of the operation of the primary relays. The flexible settings of the relays (e.g- plug setting , Time multiplier setting and possibly selection of suitable time-current operating characteristics), must be set to achieve the desired objectives.

Over current and distance relays are often used for protection of power system. Now a days this scheme is used in almost all sub-transmission system. To achieve better co ordination , a distance with a distance, an over current with a over current relay and an over current relay with a distance relay must be coordinated. One of them will act as main relay and another one as back up. Proper co-ordination time interval should be maintained between them.

The study of co-ordination of relays was first done among over current relays. Initially it is done by using linear programming method including simplex, two-phase simplex and dual simplex methods[1]-[4]. But the problem regarding using these methods is the solution will not come unless all the constraints are satisfied.

So, people gradually started to use intelligent and meta – heuristic approaches which gives optimal solution instead of exact solution meeting all the constraints criteria. 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 lack of solution for relays with both discrete and continuous 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 which is helpful in relay coordination of over current and distance relays. Ref.[10] shows relay co ordination using GA and intelligent relay characteristics selection. Ref.

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[13]-[15] shows relay coordination using TLBO for small systems but all of them used fixed characteristics (Standard IDMT). None of them used different intelligent characteristics available in digital relays.

In this paper, we are using Teaching learning based optimization (TLBO) 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. The method is more simple and reliable than previous methods used. We have taken WSCC-3-Machine-9 bus system and implement the discussed method. The results seem to be satisfactory.

II.TEACHING LEARNING BASED OPTIMIZATION (TLBO)

TLBO is an algorithm inspired by 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

The first stage is the teacher stage. As all of us know teacher teaches students and increases the mean of their depending upon their capability. 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. However, since the teacher is usually considered a highly learned person who trains learners so that they can have better results, after iteration, the best learner will be considered as teacher. The difference between the existing mean result of each subject and the corresponding result of the teacher for each subject is given by

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

Where $X_{j,kbest,i}$, is the result of the best learner (i.e., teacher) in subject j. T_F is the teaching factor, which decides the value of the mean to be changed, and r_i is the random number in the range [0, 1]. The value of TF can be either 1 or 2. The value of TF is decided randomly with equal probability as follows:

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

TF is not a parameter of the TLBO algorithm. The value of TF is not given as an input to the algorithm, and its value is randomly decided by the algorithm using Eq. (2). After conducting a number of experiments on many benchmark functions, the algorithm was concluded to perform better if the value of TF was between 1 and 2. However, the algorithm was found to perform much better if the value of TF is either 1 or 2. Hence, the teaching factor is suggested to take a value of either 1 or 2 depending on the rounding up criteria given by Eq.(2) to simply the algorithm. Based on the $Difference\_Mean_{j,k,i}$, the existing solution is updated in the teacher phase according to the following expression:

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

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 phase is the second part 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. Considering a population size of ‘*n*’, the learning phenomenon of this phase is expressed below. Randomly select two learners *P* and *Q* such that $X'_{total}\text{-}P,i \neq X'total\text{-}Q,i$ (where, *X'total-P,I* and *X'total-Q,i* are the updated values of *Xtotal-P,i* and *Xtotal-Q,i* respectively at the end of teacher phase)

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

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

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

III.PROBLEM STATEMENT

To achieve better protection, it is common to use both distance and over current relays as main and back up relays respectively, in power transmission protection scheme. In this situation, it is necessary to coordinate these two types of relays simultaneously that makes the problem harder to find a global operating point.

$$Fitness\ function = \min(\alpha\sum_{i=1}^{n} t_i + \beta\sum_{i=1}^{n}\left|T_{DIOCi} - |T_{DIOCi}|\right| + \lambda\sum_{i=1}^{n}\left|T_{OCDIi} - |T_{OCDIi}|\right| + \delta\sum_{i=1}^{n}\left|T_{OCi} - |T_{OCi}|\right|) \quad (6)$$

Where

$$T_{OCi} = T_{oc\,backup\,i} - T_{oc\,main\,i} - CTI' \quad (7)$$

$$T_{DIOCi} = T_{oc\,i} - T_{z2\,i} - CTI' \quad (8)$$

$$T_{OCDIi} = T_{z2\,i} - T_{oc\,i} - CTI' \quad (9)$$

T_{oc} is the operating time of over current relay and Tz2 is the operating time of 2nd zone of the distance relay $\alpha, \beta, \lambda, \delta$ are penalty factors.

IV. CONSTRAINTS

The several constraints need to be satisfied to obtain optimal co-ordination.

A.Co-ordination constraints

$$T_{z2\,backup} - T_{oc\,main} \geq CTI' \quad (10)$$

$$T_{oc\,main} - T_{z2\,backup} \geq CTI' \quad (11)$$

CTI is coordination time interval whose typical value is between 0.2 to 0.3 sec.

B. Relay Characteristics

The over current relay characteristics are typically of below nature:

$$t = TSM\left(\frac{K}{M^{\alpha} - 1} + L\right) \quad (12)$$

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

TSM is supposed to be continuous and can take any value between 0.05-1.1. Coordinating time interval in each cases is supposed to be 0.25 sec. Table-I shows 8 types of intelligent characteristics available in digital over current relays.

C.Pick-up current constraints

Pick up current having a limit. The relay co-ordination problem is highly dependent on the value of the pickup current of the relays. To sense a small amount of fault current the pickup current should be less than minimum fault current. On the other hand the minimum pick up current may be doubled under small overloaded condition to avoid any mal-operation. The limits of pick up current can be expressed as below[15]:

$$Ip_{\min} \leq Ip \leq Ip_{\max} \quad (13)$$

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 :

$$TSM_{\min} \leq TSM \leq TSM_{\max} \quad (14)$$

E. Constrains on relay operating time

For minimizing or mitigating mal-operation due to transient, overshoot or any other critical condition of the network, relays should operate after a minimum time. Limits on time of operation of relay(t_{op}) can be expressed as :

$$t_{op\,\min} \leq t_{op} \leq t_{op\,\max} \quad (15)$$

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

V.TEST RESULTS

To test the methodology a WSCC-3-Machine-9-Bus system has been selected. The relay arrangement are shown for this power system as per Fig1. The mho directional relays are used here.

Table I: Characteristics of over current relay

Number of charact-eristic	Number of charact-eristic	Standard	*K* factor	*α* factor	*L* factor
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

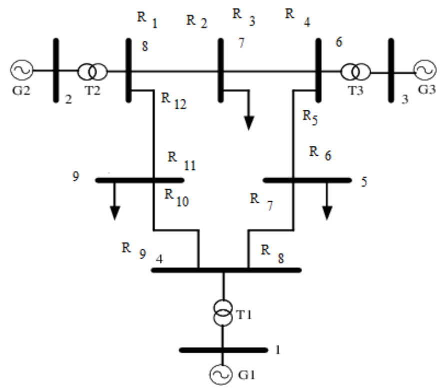

Fig.1:Relay arrangement in WSCC-3-Machine-9-Bus System

The main and back up relay pairs are shown in Table-II

Table-II: Main and backup relay pairs

Main over current and distance relays	Back up over current and distance relays
R_3	R_1
R_5	R_3
R_7	R_5
R_9	R_7
R_{11}	R_9
R_1	R_{11}
R_{12}	R_2
R_{10}	R_{12}
R_8	R_{10}
R_6	R_8
R_4	R_6
R_2	R_4

The typical operating time of first, second and third zones of all distance relays have been 20ms, 0.3sec(or more) and 0.6

sec (or more) and all points of starting second zones of all lines are 80% of the lines. The short circuit currents of the main and back up over current relays must be calculated from close in bus fault cases(Critical fault locations). The information regarding pick up current settings are shown in Table-III. The value of pick up current of each over current relay is assumed roughly 1.25 times of the relevant maximum load in approximated integer form. The short circuit current data are shown in Table-IV.

Table-III: Pick up current values of the Relay

Relay number(R_i)	Load Current(amps)	Pick up Current(amps)
1	176	220
2	175	210
3	57	70
4	25	30
5	148	185
6	146	180
7	40	50
8	16	20
9	68	85
10	10	12
11	225	270
12	230	285

Table-IV: Short Circuit Current data for main and back up relays

Main Relay(R_i)	Back up Relay(R_i)	Main relay short circuit current (amps)	Back up relay short circuit current(amps)
1	11	705	315
2	4	247	256
3	1	515	510
4	6	466	294
5	3	290	140
6	8	300	316
7	5	294	285
8	10	943	250
9	7	578	70
10	12	373	364
11	9	295	318
12	2	686	245

The process of finding objective function is trial and error. The ultimate objective of choosing the objective function is to reduce the time of operation of relay, same as in the case of over current to over current relay co-ordination case. The only difference here is some additional terms are coming due to the presence of distance relay. When $|T_{DIOCi}|$ is positive then the second term of objective function is becoming zero but when $|T_{DIOCi}|$ is negative then the second term is additive with the objective function and increasing its value. Since it is a minimization problem, the chance of survival of such fitness value is mitigated by this approach. 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 problem is almost nullified. The same kind of explanation can be given for choosing the third and fourth term of the fitness function also.

By applying TLBO (Teaching learning based optimization) in the network of Fig1 the output results are obtained. TSMs and over current relay characteristics selected by TLBO are shown in Table-V. In all cases TSMs are considered to be continuous(0.05-1.1). The time of operation of relays in each case are also shown in the table(Table-V). The various outputs from this work are shown pictorially from Fig.2 to Fig.6.

Table-V: Output Table

Relay (R_i)	Second Zone operation time (T_{z2})(sec)	TSM	No. of selected Characteristic
1	0.5215	0.0878	2
2	0.5505	0.0717	1
3	0.33913	0.1597	3
4	0.5673	0.2285	2
5	0.5472	0.19856	1
6	0.6110	0.25226	1
7	0.310426	0.13028	4
8	0.6022	0.3446	2
9	0.3222	0.13843	3
10	0.4848	0.24638	2
11	0.70456	0.050	1
12	0.3332	0.0727	7
Average Value	0.49117	0.16507	-
Fitness value	75		

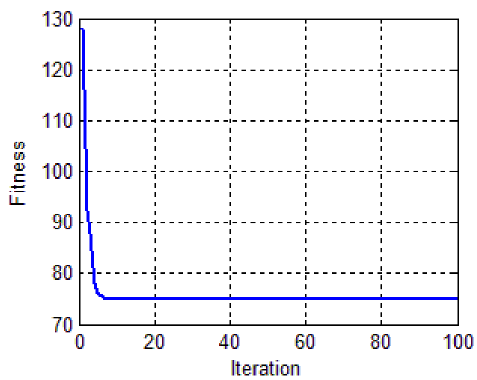

Fig.2: Convergence curve of the TLBO algorithm

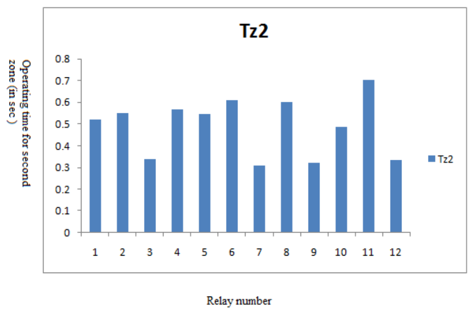

Fig.3: Comparison of operating time of second zone of relays

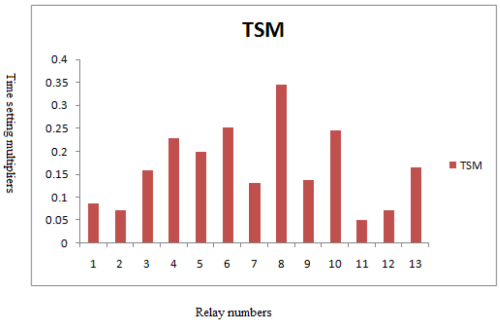

Fig.4: Comparison of optimum Time setting multipliers of relays

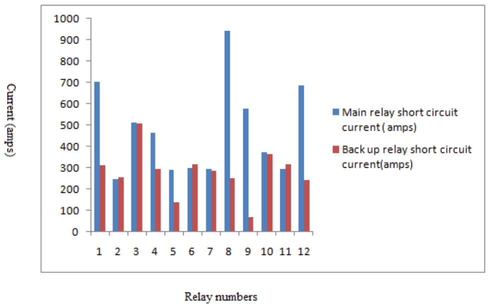

Fig.5: Comparison of short circuit currents of main and backup relays

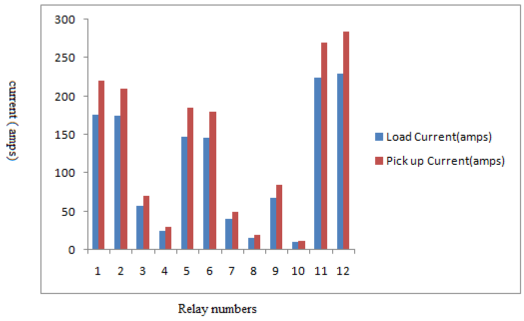

Fig.6: Comparison of Load current and pick up current of various relays

In Fig 4 , the 13th TSM value indicates the average TSM value of all the twelve used relays in the test system.

VI. COMPARATIVE STUDY WITH GA AND PSO

TLBO does not use any algorithm specific control parameter for finding global optimum solution. This property of this algorithm is an huge advantage over contemporary other optimization techniques. 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 tuning of these parameters are very important for the performance of these optimization algorithms. TLBO does not need such kind of parameters. It only needs population size and number of generations for working. So, TLBO becomes highly consistent optimization algorithm. It converges very fast and superior compare to GA and PSO. In our work, the problem converges within 15 iterations(ref. Fig 2) and with CPU elapsed time 0.404224 seconds with the use of TLBO. While by using GA, the same problem is converging in 21 iterations with CPU elapsed time 0.625596 seconds. Fig 7 shows the convergence curve by using GA. By using PSO, the problem is converging in 19 iterations with CPU elapsed time 0.832728 seconds. Fig 8 shows the convergence curve by using PSO. PSO is taking more time than GA although number of iterations for convergence are less. Because PSO needs three types of updating while performing one iteration. e.g- Velocity updating(here fitness value) , position updating(here TSM values) and g_{best} , P_{best} updating. So, time taken for one iteration is more in case of PSO than GA. But among these three algorithms TLBO is performing the best. Both with respect to the number of iterations and CPU elapsed time taken for convergence.

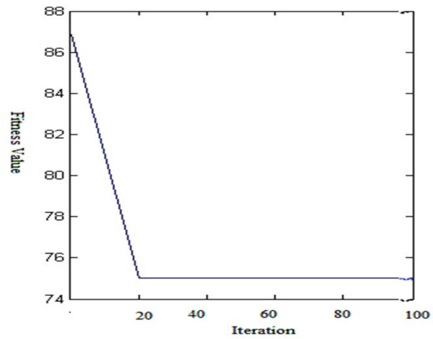

Fig.7: Convergence curve using Genetic Algorithm(GA)

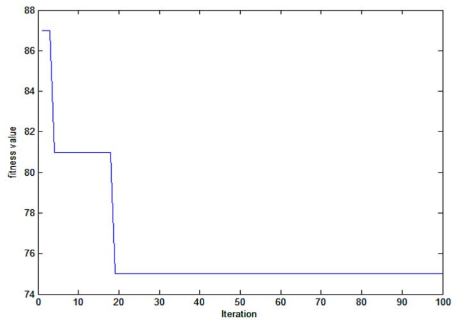

Fig.8: Convergence curve using Particle Swarm Optimization(PSO)

VII. CONCLUSIONS

This paper focused on optimal co-ordination of directional and over current relay. The problem statement and various constraints to be satisfied are already presented in the paper. Teaching learning based optimization (TLBO), which is a modern meta-heuristic technique is applied to solve the problem. The optimum time of operation, TSM, pick up currents of relays are calculated for a WSCC-3-Machine-9 bus system. All the constraints are found within desirable range. Which intelligent over current characteristics are required to get the desired result are also selected. Co-ordination time interval is taken 0.25 sec for each cases. The protection settings seems to be satisfactory for the discussed power network. The technique is working satisfactorily with respect to other contemporary techniques like GA and PSO also. As a future scope of this work, relay coordination on higher test systems can be implemented.

APPENDIX

System Data :

Generator data :

Generator no.	P_g	Q_g
Gen 1	0	0
Gen2	163	0
Gen3	85	0

Branch data:

From bus	To bus	r	x	b
1	4	0	0.0576	0
4	5	0.017	0.092	0.158
5	6	0.039	0.17	0.358
3	6	0	0.0586	0
6	7	0.0119	0.1008	0.209
7	8	0.0085	0.072	0.149
8	2	0	0.0625	0
8	9	0.032	0.161	0.306
9	4	0.01	0.085	0.176

Load data:

Bus No.	P_d	Q_d
5	90	30
7	100	35
9	125	50

The test system data are obtained from Ref.[19]. Any information missing in APPENDIX regarding data is same as Ref.[19].

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