Intelligent Coordination of Overcurrent and Distance Relays using Meta Heuristic Algorithms

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Abstract: Relay coordination is very important from the point of view of security and healthy operation of power system. Relays should be organized in such a way that every relay should have at least one back up relay and coordination time interval between primary and secondary relays should be maintained. This paper presents the solution of relay coordination problem using Teaching learning based optimization technique (TLBO) by utilizing an IEEE 5 bus and IEEE 30 bus test system. The obtained results are compared with the results obtained from other contemporary meta-heuristic techniques like Genetic Algorithm (GA) and Particle Swarm Optimization technique (PSO). It is observed that TLBO is the best among those with respect to process speed. After this we have done an extension of the work by introducing critical element and network graph theory based relay minimization technique. It is expected that this analysis will be helpful to maintain the network reliability and healthy flow of power.

Index Terms: Relay co-ordination, Teaching Learning based optimization, Overcurrent relay characteristics, Main backup relay pairs, minimization of the relays.

1. Introduction

Relay Co-ordination is necessary from the point of view of reliability and security of power system. Proper relay co-ordination ensures smooth and secured operation of power system. Relay co-ordination ensures minimum system disruption and continuing operation of healthy part of the circuit during operation. Thus, it is very important for protection system design. In a nutshell a protection system should be designed as follows:

Every section of the protection system will be protected by a pair of main relay and back up relay at least. A main relay is meant for the clearance of the fault. In case of failure of main relay, back up relay will take care after providing sufficient time discrimination. In some cases more than one backup relay is provided for better protection reliability of the system. The relay co-ordination problem is having several constraints. e.g- Proper co-ordination time interval (CTI) should be maintained between the main and backup relay pairs, proper intelligent relay characteristics should be chosen in case of digital relays; proper pick up current constraints, Time setting multiplier (TSM) constraints, constraints on relay operating time and constraints on plug setting multiplier (PSM) are to be satisfied. So, relay co-ordination problem is nothing but highly constraint problem. Heuristic and meta heuristic techniques are often applied to obtain optimal solution for this kind of problem. In this paper Teaching learning based optimization (TLBO) is used to solve this problem on an IEEE 5 bus and IEEE 30 bus test system. Proper desirable TSM values, optimum operation time of relays are calculated and proper intelligent characteristics of relays are also selected.

From the study of literatures about co-ordination of relays, it is found that, relay co-ordination is first implemented on over current relays. Initially it was done by using various types of linear programming techniques. e.g- Simplex, two phase simplex and dual simplex methods [1]-[4]. But there are some problems associated with this techniques. Most eminent problem regarding this techniques is no solution is available unless all the constraints regarding this problem are satisfied. So, people gradually move towards the intelligent and meta-heuristic techniques for solution of this problem. Advantage of using these techniques is they give optimal dynamic

solutions, instead of exact solutions, by optimally satisfying all the constraints. This feature is very useful for smooth operation and control of power network.

Instead of using only over current relays, over current and distance relays used in pairs is found to be more effective, as they have directional property as well as fault sensing capability. So, now a days over current and distance relays are often used in pairs in any transmission system. To achieve better co-ordination, a distance relay with a distance relay, an over current relay with an over current relay and an over current relay with a distance relay must be properly coordinated. One will act as main relay and another one as back up. Proper co-ordination time interval should be maintained between them. Time discrimination values also should be minimized. 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 all these types of schemes having several lacuna:

1. Mis-coordination problem: Which leads to error is relay co-ordination as well as increased time discrimination values.
2. Lack of solution for relays with discrete and continuous time setting multipliers (TSMs).

The problems are resolved [8] with the addition of a new expression with the objective function. All the methodologies discussed above are based on over current relay characteristics and the fixed relay characteristics. But in digital relays, several intelligent over current relay characteristics are existing which remain unutilized in the previous works. So, an algorithm is required which can select the best fitting characteristics among different available intelligent relay characteristics of digital relays during relay co-ordination will be more effective and accurate. Ref. [9] shows relay co-ordination with a hybrid GA algorithm which is helpful in relay co-ordination of over current and distance relays. Ref. [10] demonstrates, a relay co-ordination technique using GA and intelligent relay characteristics selection. Ref. [11]-[13] 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.

We have considered all these loopholes of previous works in our present work and tried to overcome it by our technique. In this paper, we have used Teaching learning based optimization (TLBO) for distance and over current relay co-ordination with intelligent over current relay characteristics selection. Distance and over current relays are used as pairs to protect transmission lines. 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 used a 5 bus system and IEEE 30bus system to demonstrate the effectiveness of our work. Further we have extended our work considering the minimization of relays for relay coordination. The obtained results seem to be in order and satisfactory.

2. Teaching Learning Based Optimization (TLBO)

TLBO is an algorithm inspired by teaching learning process. It is proposed by Rao et al. [14]. The learning process will be done through two stages such as teacher stage and learner stage. While modelling the algorithm, the group of learners was modelled as population; subjects opted by learners were modelled as design variables. Here, learners result becomes the fitness value. After iteration, the best solution inside the population becomes the teacher. And, the constraints of optimization problem become design variables [15]-[18].

A. Teacher Stage

The teacher stage is the first stage of this algorithm. As all of us know teacher teaches students and increases or improves the mean of their result depending upon their capability. Suppose that there are 'a' number of subjects or design variables and 'b' number of learners exist. The mean result of the learners is $m_{c,d}$ in a particular subject 'c'. 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, K_{best} . The best learner will be considered as teacher. The difference between the existing mean result of each subject and the teacher for each subject is given by Eq.(1)

$$difference_mean_{c,k,d} = r_d(x_{c,Kbest,d} - t_f m_{c,d}) \quad k=1 \text{ to } b \quad (1)$$

Where $x_{c,Kbest,d}$, is the result of the best learner (i.e. teacher) in subject c . t_f is the teaching factor and r_d is the random number in the range [0, 1]. The value of t_f can be either 1 or 2. The value of t_f is decided randomly with equal probability as follows:

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

The value of t_f is randomly decided by the algorithm using Eq. (2). Based on the $difference_mean_{c,k,d}$, the existing solution is updated in the teacher phase according to the following expression (ref. Eq. (3)):

$$x'_{c,K,d} = x_{c,K,d} + difference_mean_{c,K,d} \quad (3)$$

$x'_{c,K,d}$ is the new value of $x_{c,K,d}$. $x'_{c,K,d}$ should be accepted 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.

A. Learner Stage

The second part of the algorithm is Learner phase. Learners boost up their knowledge by interactions among themselves. Consider a population size of ' b ', the learning phenomenon of this phase can be expressed below.

Randomly select two learners e and f such that $x'_{total-e,d} \neq x'_{total-f,d}$ (where, $x'_{total-e,d}$ and $x'_{total-f,d}$ are the updated values of $x_{total-e,d}$ and $x_{total-f,d}$ respectively at the end of teacher phase)(ref. Eq.(4) and Eq. (5)):

$$x''_{c,e,d} = x'_{c,e,d} + r_d(x'_{c,e,d} - x'_{c,e,d}), \text{ if } x'_{total-e,d} < x'_{total-f,d} \quad (4)$$

$$x''_{c,e,d} = x'_{c,e,d} + r_d(x'_{c,f,d} - x'_{c,e,d}), \text{ if } x'_{total-e,d} > x'_{total-f,d} \quad (5)$$

Accept $x''_{c,e,d}$ if it gives a better function value. Figure1 shows the flowchart of TLBO algorithm.

3. Problem Statement

For better protection arrangements, it is common to use both distance and over current relays as main and back up relays respectively, in power transmission protection schemes [19]-[23]. For making optimal co-ordination of distance and over current relays we choose a fitness function same as Eq. (6). All the parameters used in this fitness function are described below (ref. Eq. (7), Eq. (8) and Eq. (9)):

$$\begin{aligned} \text{Fitnessfunction} = & \min(\alpha \sum_{i=1}^n t_i + \beta \sum_{i=1}^n |T_{DIOC_i} - |T_{DIOC_i}|| + \\ & \lambda \sum_{i=1}^n |T_{OCDI_i} - |T_{OCDI_i}|| + \delta \sum_{i=1}^n |T_{OCI_i} - |T_{OCI_i}||) \end{aligned} \quad (6)$$

Where

$$T_{OCI} = T_{ocbackupi} - T_{ocmaini} - CTI \quad (7)$$

$$T_{DIOC_i} = T_{oci} - T_{z2i} - CTI \quad (8)$$

$$T_{OCDI_i} = T_{z2i} - T_{oci} - CTI \quad (9)$$

T_{oc} is the operating time of over current relay and T_{z2} is the operating time of 2nd zone of distance relay. $\alpha, \beta, \lambda, \delta$ are penalty factors.

4. Constraints

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

A. Co-ordination constraints

The co-ordination constraints are described by Eq. (10) and Eq. (11):

$$T_{z2backup} - T_{ocmain} \geq CTI' \quad (10)$$

$$T_{ocbackup} - T_{z2main} \geq CTI' \quad (11)$$

CTI is coordination time interval whose typical value is between 0.2-0.3 secs.

Figure 1. Flowchart of TLBO algorithm

B. Relay Characteristics

The over current relay characteristics are typically of below nature (ref. Eq. (12)):

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

t = time of operation of the relay.

TSM = Time setting multiplier.

K , L and α are the 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. Co-ordinating time interval in each cases is supposed to be 0.25 sec. Table1 and Figure 2 shows 8 types of intelligent characteristics available in digital over current relay with different parameter values.

Table 1. Characteristics of over current relay

No. of the characteristic	Name of the characteristic	Standard followed	K Value	α Value	L Value
	Short time inverse	AREVA	0.05	0.04	0
	Standard inverse	IEC	0.14	0.02	0
	Very inverse	IEC	13.5	1	0
	Extremely inverse	IEC	80	2	0
	Long time inverse	AREVA	120	1	0
	Moderately inverse	ANSI/IEEE	0.0515	0.02	0.114
	Very inverse	ANSI/IEEE	19.61	2	0.491
	Extremely inverse	ANSI/IEEE	28.2	2	0.1217

Figure 2. Intelligent overcurrent relay characteristics diagram

C. Pick-up current constraints

Pick up current is having a limit. The value of pick up current is very important for the relay co-ordination problem. To sense a very little 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 Eq. (13) below [13].

$$I_{p_{\min}} \leq I_p \leq I_{p_{\max}} \quad (13)$$

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 (ref. Eq. (14)).

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

E. Constraints 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 (ref. Eq. (15)).

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

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

F. Constraints on PSM:

Plug setting multiplier (PSM) should be within range. Mathematically it can be expressed as follows (ref. Eq. (16)).

$$PSM_{\min} \leq PSM \leq PSM_{\max} \quad (16)$$

5. Test Results

The methodology is tested on a IEEE 5 Bus system and IEEE 30 bus system. The results are listed in subsections 5.1 and 5.2.

A. Results of IEEE 5 Bus System

The proposed methodology has been implemented here using IEEE 5 Bus Test system. Test system data is obtained from Ref. [24]. The relay arrangement for the above mentioned power system is shown in Figure 3. The directional mho relays are used here. Over current relays are arranged using time graded protection scheme with IDMT (Inverse definite minimum time) characteristics. Different types of over current relay characteristics available in digital relays are obtained from Ref.[10].

Figure 3. Relay arrangement for IEEE-5 Bus System

The main and back up relay pairs for the above IEEE 5 Bus system are shown in Table 2.

Table 2. Main and backup relay pairs

Sl. No.	Main over current and distance relays	Back up over current and distance relays	Sl. No.	Main over current and distance relays	Back up over current and distance relays
1.	R ₁	R ₄	9.	R ₉	R ₁
2.	R ₂	R ₁₀	10.	R ₁₀	R ₁₁
3.	R ₃	R ₂	11.	R ₁₁	R ₁₃
4.	R ₄	R ₁₄	12.	R ₁₂	R ₉
5.	R ₅	R ₈	13.	R ₁₃	R ₃
6.	R ₆	R ₁₄	14.	R ₁₃	R ₅
7.	R ₇	R ₆	15.	R ₁₄	R ₇
8.	R ₈	R ₁₃	16.	R ₁₄	R ₁₂

The typical operating time of first, second and third zones of all distance relays are 20ms, 0.3sec (or more) and 0.6 sec (or more). The short circuit currents data 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 given in Table 3. The value of pick up current of each over current relay is assumed approximately to be 1.25 times of the relevant maximum load in approximated integer form. The short circuit current data are shown in Table 4. From Table-2, it is found that relay no. 13 and 14 are having better protection reliability as both of them have two back up relays.

Table 3. Pickup current values of the Relay

Relay number(R _i)	Load Current(amps)	Pick up Current(amps)
1	386	483
2	383	479
3	177	221
4	177	221
5	90	113
6	93	116
7	132	165
8	160	200
9	240	300
10	242	303
11	24	30
12	22	28
13	72	90
14	70	88

Table 4. 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	4	684	97
2	10	790	18
3	2	1060	561
4	14	721	443
5	8	1151	34
6	14	761	443
7	6	1151	31
8	13	661	481
9	1	1176	502
10	11	374	272
11	13	858	481
12	9	709	708
13	3	602	326
13	5	602	280
14	7	561	377
14	12	561	184

The objective function is found on the basis of trial and error. Ultimately the objective of choosing 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 expressions are appearing 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 coordination constraints $|T_{DIOCi}|$ value should be always greater than equals to zero. Its value can be negative only in case of mis-co-ordination. 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.

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:

$$(\Delta\Phi_k) \quad (17)$$

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:

$$\Delta P_k = (0.2 - 0.26) p.u \quad (18)$$

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

$$\Phi_k = 0.39 p.u \quad (19)$$

Usually the critical fault location is situated within 12% length of each transmission line [37].

Table 5. Output Table (IEEE 5-bus system)

Relay (R_i)	Second Zone operation time (T_{z2})(sec)	TSM	No. of selected Characteristic from Table1
1	0.9997	0.05	7
2	0.5946	0.05	7
3	0.3503	0.0985	3
4	0.4724	0.08073	2
5	0.4327	0.1467	2
6	0.3465	0.0949	2
7	0.3102	0.1373	3
8	0.3668	0.0634	2
9	0.3454	0.0747	3
10	0.2956	0.05	1
11	0.3640	0.1803	2
12	0.4855	0.2314	2
13	0.3218	0.1356	3
14	0.2628	0.10465	3
Average Value	0.42488	0.107013	-
Fitness value	100	-	-

Figure 4. Convergence characteristics of the TLBO algorithm for IEEE 5 bus system

The output results are obtained by applying the TLBO (Teaching learning based optimization) for a network shown in Figure 3. TSMs and over current relay characteristics selected by TLBO are shown in Table 5. TSMs are assumed as continuous (0.05-1.1) in all the cases. The time of operation of relays in each case are also shown in the Table 4. The various outputs for IEEE 5 bus test system are shown pictorially from Figure 4 to Figure 8.

Figure 5. Comparison of operating time of second zone of relays for IEEE 5 bus system

Figure 6. Comparison of optimum Time setting multipliers of relays for IEEE 5 bus system

Figure 7. Comparison of short circuit currents of main and backup relays for IEEE 5 bus system

Figure 8. Comparison of Load currents and pick up currents of various relays for IEEE 5- bus system

B. Results of IEEE 30 Bus System

To test the methodology, an IEEE 30 Bus system has been selected. Test system data are obtained from Ref. [25]. The relay arrangements are shown for this power system as per Table 6. The mho directional relays are used here. Over current relays are arranged using time graded protection scheme with IDMT (Inverse definite minimum time) characteristics.

Figure 9. IEEE-30 Bus System

Table 6. Relay arrangement for IEEE 30 bus system

Sl. No.	Branch data from bus no.	Branch data to bus no.	Relay no. (R_i) adjacent to from bus	Relay no. (R_i) adjacent to to bus
1	1	2	1	2
2	1	3	3	4
3	2	4	5	6
4	3	4	7	8
5	2	5	9	10
6	2	6	11	12
7	4	6	13	14
8	5	7	15	16
9	6	7	17	18
10	6	8	19	20
11	6	9	-	-
12	6	10	-	-
13	9	11	-	-
14	9	10	-	-
15	4	12	-	-
16	12	13	-	-
17.	12	14	21	22
18.	12	15	23	24
19.	12	16	25	26
20.	14	15	27	28
21.	16	17	29	30
22.	15	18	31	32

Sl. No.	Branch data from bus no.	Branch data to bus no.	Relay no. (R _i) adjacent to from bus	Relay no. (R _i) adjacent to to bus
23.	18	19	33	34
24.	19	20	35	36
25.	10	20	37	38
26.	10	17	39	40
27.	10	21	41	42
28.	10	22	43	44
29.	21	22	45	46
30.	15	23	47	48
31.	22	24	49	50
32.	23	24	51	52
33.	24	25	53	54
34.	25	26	55	56
35.	25	27	57	58
36.	28	27	-	-
37.	27	29	59	60
38.	27	30	61	62
39.	29	30	63	64
40.	8	28	65	66
41.	6	28	67	68

The main and back up relay pairs for IEEE 30 bus system are shown in Table 7

Table 7. Main and backup relay pairs for IEEE 30 bus system

Sl. No.	Main over current (o/c) and distance relays	Back up over current and distance relays	Sl. No.	Main over Current (o/c) and distance relays	Back up over (o/c) and distance relays
1	R ₁	R ₄	22	R ₁₇	R ₁₁
2	R ₂	R ₁₀	23	R ₁₈	R ₁₅
3	R ₃	R ₂	24	R ₁₉	R ₆₈
4	R ₄	R ₈	25	R ₂₀	R ₆₆
5	R ₅	R ₁₀	26	R ₂₁	R ₂₆
6	R ₆	R ₁₄	27	R ₂₂	R ₂₈
7	R ₇	R ₃	28	R ₂₃	R ₂₆
8	R ₈	R ₁₄	29	R ₂₄	R ₃₂
9	R ₉	R ₁	30	R ₂₅	R ₂₂
10	R ₉	R ₁₂	31	R ₂₅	R ₂₄
11	R ₉	R ₆	32	R ₂₆	R ₃₀
12	R ₁₀	R ₁₆	33	R ₂₇	R ₂₁
13	R ₁₁	R ₁₀	34	R ₂₈	R ₄₈
14	R ₁₂	R ₁₈	35	R ₂₉	R ₂₅
15	R ₁₃	R ₇	36	R ₃₀	R ₃₉
16	R ₁₃	R ₅	37	R ₃₁	R ₂₃
17	R ₁₄	R ₁₈	38	R ₃₂	R ₃₄
18	R ₁₄	R ₁₁	39	R ₃₃	R ₃₁
19.	R ₁₅	R ₉	40	R ₃₄	R ₃₆
20.	R ₁₆	R ₁₇	41	R ₃₅	R ₃₃
21.	R ₁₇	R ₁₃	42	R ₃₆	R ₃₇

Sl. No.	Main over current (o/c) and distance relays	Back up over current and distance relays	Sl. No.	Main over Current(o/c) and distance relays	Back up over (o/c) and distance relays
43	R ₃₇	R ₄₀	62	R ₅₂	R ₄₉
44	R ₃₈	R ₃₅	63	R ₅₃	R ₄₉
45	R ₃₉	R ₄₄	64	R ₅₄	R ₅₈
46	R ₃₉	R ₃₈	65	R ₅₄	R ₅₆
47	R ₄₀	R ₂₉	66	R ₅₅	R ₅₈
48	R ₄₁	R ₄₄	67	R ₅₆	-
49	R ₄₂	R ₄₆	68	R ₅₇	R ₅₃
50	R ₄₃	R ₄₀	69	R ₅₈	R ₆₂
51	R ₄₃	R ₄₂	70	R ₅₈	R ₆₀
52	R ₄₄	R ₅₀	71	R ₅₉	R ₆₂
53	R ₄₄	R ₄₅	72	R ₆₀	R ₆₄
54	R ₄₅	R ₄₁	73	R ₆₁	R ₆₀
55	R ₄₆	R ₄₃	74	R ₆₂	R ₆₃
56	R ₄₇	R ₂₇	75	R ₆₃	R ₅₉
57	R ₄₈	R ₅₂	76	R ₆₄	R ₆₁
58	R ₄₉	R ₄₃	77	R ₆₅	R ₁₉
59	R ₅₀	R ₅₄	78	R ₆₆	R ₆₇
60	R ₅₀	R ₅₁	79	R ₆₇	R ₂₀
61	R ₅₁	R ₄₇	80	R ₆₈	R ₆₅

Table 8. Pick up current values of the Relays

Relay number (R _i)	Load Current (amps)	Pick up Current (amps)	Relay number (R _i)	Load Current (amps)	Pick up Current (amps)
1	720	900	18	165	206
2	716	895	19	133	166
3	362	453	20	132	165
4	363	454	21	136	170
5	184	230	22	136	170
6	185	231	23	317	396
7	353	441	24	317	396
8	352	440	25	132	165
9	346	433	26	132	165
10	345	431	27	29	36
11	253	316	28	29	36
12	253	316	29	66	83
13	320	400	30	66	83
14	319	399	31	105	131
15	82	103	32	105	131
16	87	109	33	48	60
17	166	208	34	48	60

From Table 7, it is found that relay R₁₃, R₁₄, R₁₇, R₂₅, R₃₉, R₄₃, R₄₄, R₅₀, R₅₄, R₅₈ are having two backups. So, they are having better protection reliability compare to other relays in present in the network. R₉ is having three backups. So it is having best protection reliability among all the relays present in the power network. One more significant observation from the table is R₅₆

is having no separate back up. Because it is connected to an isolated branch connecting branch 25-26. In such case, R_{55} , second and third zone will act as a backup for R_{56} . R_{58} can be observed by second zone of R_{57} also. R_{54} can be observed by R_{58} or R_{56} . The information regarding pick up current settings are shown in Table 8. 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 9.

Table 8. Pick up current values of the Relays (Contd.)

Relay number (R_i)	Load Current (amps)	Pick up Current (amps)	Relay number (R_i)	Load Current (amps)	Pick up Current (amps)
35	124	155	52	37	46
36	124	155	53	40	50
37	163	204	54	40	50
38	163	204	55	73	91
39	116	145	56	73	91
40	116	145	57	82	103
41	313	391	58	82	103
42	313	391	59	110	138
43	149	186	60	110	138
44	149	186	61	125	156
45	39	49	62	125	156
46	39	49	63	65	81
47	98	123	64	65	81
48	98	123	65	3	4
49	110	138	66	17	21
50	110	138	67	81	101
51	37	46	68	81	101

Figure 10. Comparison of Load currents and pick up currents of Various relays

Table 9. Short Circuit Current data for main and backup relays

Main Relay(R _i)	Back up Relay(R _i)	Main relay short circuit current (amps)	Back up relay short circuit current(amps)
1	4	1270	522
2	10	1929	421
3	2	1869	1296
4	8	1536	1536
5	10	2134	436
6	14	1959	1219
7	3	723	718
8	14	2045	1232
9	1	2140	915
9	12	2140	458
9	6	2140	385
10	16	1279	736
11	10	2078	435
12	18	2138	404
13	7	1283	530
13	5	1283	513
14	18	1856	411
14	11	1856	492
15	9	1334	817
16	17	1347	1343
17	13	2194	806
17	11	2194	492
18	15	744	744
19	68	2158	115
20	66	825	257
21	26	1689	269
22	28	496	239
23	26	1523	269
24	32	684	244
25	22	1484	60
25	24	1484	235
26	30	594	594
27	21	633	633
28	48	1257	244
29	25	731	731
30	39	1065	1065
31	23	1210	774
32	34	475	475
33	31	633	633
34	36	654	654
35	33	466	466
36	37	787	787
37	40	1612	274
38	35	1608	163
39	44	1501	84
39	38	1501	158

Intelligent Coordination of Overcurrent and Distance Relays

Main Relay(R_i)	Back up Relay(R_i)	Main relay short circuit current (amps)	Back up relay short circuit current(amps)
40	29	415	415
41	44	1648	80
42	46	915	624
43	40	1681	274
43	42	1681	118
44	50	1031	308
44	45	1031	727
45	41	911	911
46	43	789	483
47	27	1215	197
48	52	449	449
49	43	1215	481
50	54	590	248
50	51	590	342
51	47	664	664
52	49	898	650
53	49	988	650
54	58	449	449
54	56	449	0.068
55	58	924	449
56	55 ^{2nd & 3rd zone}	0.35	0.35
57	53	481	481
58	62	654	0.098
58	60	654	7
59	62	975	3
60	64	158	158
61	60	971	5
62	63	214	214
63	59	406	406
64	61	309	309
65	19	2040	1505
66	67	1617	1497
67	20	2489	488
68	65	565	442

Figure 11. Comparison of short circuit currents of main and backup relays for IEEE 30 bus system

The outputs are shown in Table 10.

Table 10. Output Table (IEEE 30 bus system)

Relay (R_i)	Second Zone operation time (for distance relay)(T_{z2})(sec)	TSM (for over current relay)	No. of selected Characteristic from Table 1
1	0.989	0.05	7
2	0.5479	0.1126	2
3	0.3993	0.09245	3
4	0.4499	0.07943	3
5	0.4501	0.1465	2
6	0.2828	0.15672	3
7	0.581	0.05	7
8	0.3897	0.10035	4
9	0.3562	0.1043	4
10	0.2988	0.0885	8
11	0.3305	0.1234	3
12	0.2889	0.1399	3
13	0.4501	0.076	2
14	0.3706	0.10025	3
15	0.45	0.169	2
16	0.5016	0.1854	2
17	0.4929	0.17	2
18	0.4327	0.0837	3
19	0.4503	0.1693	2
20	0.3503	0.1051	4
21	0.45	0.151	2
22	0.2609	0.0695	8
23	0.4165	0.0878	3
24	0.349	0.05	7

Intelligent Coordination of Overcurrent and Distance Relays

Relay (R_i)	Second Zone operation time (for distance relay)(T_{i2})(sec)	TSM (for over current relay)	No. of selected Characteristic from Table 1
25	0.456	0.1453	2
26	0.4336	0.0835	3
27	0.3645	0.05	5
28	0.4501	0.2368	2
29	0.2514	0.1454	3
30	0.3616	0.1683	7
31	0.45	0.12994	2
32	0.4313	0.0839	3
33	0.4501	0.1551	2
34	0.4932	0.3617	3
35	0.2508	0.0715	8
36	0.3429	0.1062	4
37	0.2654	0.1357	3
38	0.2658	0.1355	3
39	0.45	0.1538	2
40	0.6997	0.1064	2
41	0.2942	0.1631	8
42	0.2684	0.0551	7
43	0.4613	0.1484	2
44	0.4501	0.1121	2
45	0.45	0.1935	2
46	0.4519	0.1844	2
47	0.4503	0.1508	2
48	0.4294	0.0843	3
49	0.2938	0.281	4
50	0.3904	0.09473	3
51	0.2767	0.6237	1
52	0.4043	0.0624	5
53	0.2688	0.3735	3
54	0.45	0.1443	2
55	0.4527	0.1535	2
56	0.4502	0.05	2
57	0.494	0.1343	3
58	0.2539	0.1248	4
59	0.2867	0.1288	3
60	0.4605	0.05	1
61	0.2677	0.1197	3
62	0.4523	0.05	2
63	0.3492	0.1053	4
64	0.433	0.09029	3
65	0.45	0.4269	2
66	0.45	0.2918	2
67	0.45	0.2127	2
68	0.2971	0.1125	4
Average Value	0.406504	0.141944	-
Fitness Value	490.697	-	-

Figure 12. Convergence characteristics of the TLBO algorithm for IEEE 30 bus system

Figure 13. Comparison of operating time of second zone of relays for IEEE 30 bus system

From Table 8 and Table 10, it is observed that in case of relays with less pick up current, Characteristic 2 (Standard Inverse) is more suitable. Figure 10 to Figure 14 shows various outputs obtained from the test case for IEEE 30 bus system.

Figure 14. Comparison of optimum Time setting multipliers of relays for IEEE 30 bus system

Justification on incorporating different intelligent overcurrent relay characteristics: From Table 10, it is found that the TLBO applied to the test system used very frequently no.2 intelligent characteristics. The reason can be justified as: 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[37].

6. Advantages of this Technique

The discussed method is superior than previous methods used, in many respects. Firstly, the method is simple and reliable. Secondly, the method is capable of reducing mis-coordination chances. Thirdly, the method is capable to handle both discrete and continuous time setting multiplier (TSM) cases. Fourthly, the method uses the different intelligent over current relay characteristics available in digital relays to reduce the time of operation. The algorithm is finding the minimum optimum value of relay operation satisfying all the constraints optimally from a look up table created in the memory during execution using the intelligent characteristics. Fifthly, the problem is converging very fast and in least CPU elapsed time than other methods. From our work we have shown, both in case of a small and a big test system, the problem is converging in less than 20 iterations by using this method and in least CPU elapsed time (ref. Table 12 and Table 13). Thus it is saving computational time, as well as the memory requirements needed for the program. The comparison of performance of this algorithm with contemporary other techniques like GA, PSO is shown in Subsection 7.2.

7. Discussions

A. Minimization of the number of relays

The complexity of the co-ordination problem increases in multiple loop system which share some relays. Hence we have to find one common acceptable setting for relays, which share multiple loops, so, that their co-ordination in individual loops is achievable. The number of such relays should be kept to minimum, so that we make minimum assumptions on relay settings in co-ordination of loops. Such relays are called minimum break point relays. There can be multiple choices to minimum break point relays. In this subsection we will concentrate on computation of minimum break point set of relays based on critical element finding and network graph theory[26]-[30].

Procedure

For obtaining minimum break point set of relays, we follow a technique, which is the combination of simulation and by using network graph theory. The procedure is as follows:

i)Finding critical element of the network

Critical elements are such elements of a network (bus, transmission line), which if removed, the complete network will be suffering from blackout. Specially in case of big systems, its effect is huge. Such critical elements should be always protected by relays. The critical elements obtained from power world simulation are as follows for the used test systems in the work. Table 11 shows critical elements of IEEE 5 bus and IEEE 30bus system.

Figure 15. Identification of critical elements flow chart

Figure 15 shows identification of critical elements of a power network flow chart.

P_p^K and Q_p^K denotes active and reactive power of K^{th} bus of the system.

Table 11. Critical Elements of Network

Test system	Critical buses	Critical lines
IEEE 5-bus	-	-
IEEE 30-bus	2,6	1-2

Figure 16. Power World Simulation of IEEE 30-bus when critical line 1-2 is under contingency

Figure 17. Power World Simulation of IEEE 30-bus when critical bus 2 is under contingency

Figure 18. Power World Simulation of IEEE 30-bus when critical bus 6 is under contingency

Figure 16, Figure 17 and Figure 18 shows the simulation when the critical elements of IEEE 30 bus system are under contingency.

ii) *Apply network graph theory*

For rest of the network, the Minimum break point set relays can be determined from LU factorization of reduced and permuted incidence matrix. L-matrix indicates minimum break point sets [30]-[35]. Table 12, shows the minimum break point set obtained for the test systems. Here one thing is needed to be mentioned that, a network may have multiple minimum break point set solutions. Here we have shown just one possible solution for minimum break point set.

Table 12. Minimum break point set of the network

IEEE Test system	Minimum break point set Relay no. (R_i)
IEEE 5 bus	2,3,6,7,9,12,14
IEEE 30 bus	1,6,8,9,11,12,14,17,19,23,27,37, 39,41,46,49,52,59,64,65,67

B. *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 Selection rate, mutation rate and cross over rate. 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 need 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. Table 13 and 14 lists the comparison study among TLBO, GA and PSO results for both the test systems. Figure 19 and Figure 20 shows the convergence curve for IEEE 5 bus system with GA and PSO.

Table 13. Comparative study with GA and PSO (IEEE 5 bus)

Attributes	TLBO	GA	PSO
Number of iterations to converge	17	10	24
Average time per iteration (Sec) taken	0.0038	0.013	0.0063
Total time taken to converge (CPU elapsed time) (sec)	0.0646	0.13	0.1512

Figure 19. Convergence characteristics using GA (IEEE 5 bus)

Figure 20. Convergence characteristics using PSO (IEEE 5 bus)

Table 14. Comparative study with GA and PSO (IEEE 30 bus)

Attributes	TLBO	GA	PSO
Number of iterations to converge	20	20	19
Average time per iteration (Sec) taken	0.0138	0.0144	0.016
Total time taken to converge (CPU elapsed time) (sec)	0.276	0.288	0.304

From both the tables, it is seen TLBO is faster than other contemporary algorithms like GA and PSO with respect to process speed (CPU elapsed time). With respect to increase in test

system's size, the convergence time also increases. Figure 21 and Figure 22 shows the convergence curve for IEEE 30 bus system with GA and PSO.

Figure 21. Convergence characteristics using GA (IEEE 30 bus)

Figure 22. Convergence characteristics using PSO (IEEE 30 bus)

Here the simulation is done on a Dell Laptop, processor: Intel ® core (TM) i3-2350 M CPU@2.30 GHZ, RAM: 8.00 GB, Simulator: MATLAB R 2014b.

8. Conclusions

This paper focused on optimal coordination of directional and over current relays. 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 an IEEE 5 bus system and IEEE 30 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. Coordination time interval is taken 0.25 sec for each cases. The protection settings seems to be satisfactory for the discussed power networks as they are performing better compare to contemporary other meta-heuristic techniques like GA and PSO. Iteration time increases with the system size increases, although the number of iterations for

convergence remains more or less the same irrespective of the size of the system. As a future scope of this work, relay coordination on higher and practical test systems can be implemented with distributed generation resources and dual settings for more protection reliability.

9. Appendix

The test system data are obtained from Ref.[24] and Ref.[25].

10. References

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