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ORIGINAL PAPER

Optimum Coordination of Directional Overcurrent Relays Using Modified Adaptive Teaching Learning Based Optimization Algorithm

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Abstract Relay coordination problem is highly constrained optimization problem. Heuristic techniques are often used to solve optimization problem. These techniques have a drawback of converging to a non-optimum solution due to the wide range of design variables. On the other hand, initial solution becomes difficult to find with shorter range of design variables. This paper presents modified adaptive teaching learning based optimization algorithm to overcome this drawback of conventional heuristic techniques. The coordination problem is formulated as a constrained non-linear optimization problem to determine the optimum solution for the time multiplier setting (TMS) and plug setting (PS) of DOCRs. Initial solution for TMS is heuristically obtained with the commonly chosen widest range for TMS values. The upper bound of TMS range then substituted by the maximum TMS value in the first initial solution. The new upper limit is obviously lower than the earlier one. Next phase of optimization is carried out with the new range of TMS for the pre-determined iterations of teacher phase. Consequent to the completion of the teacher phase, new upper bound is obtained from the available solution and optimization is carried out for the pre-determined iterations of learner phase. This process is repeated to get the optimum solution. Fixed range for PS is used to obtain the selectivity. Such a strategy of iteratively updating the upper bound of TMS range shows remarkable improvement over the techniques which employ fixed TMS range. This algorithm is tested on different networks and has been found more effective. Four case studies have been presented here to show the effectiveness of the proposed algorithm. The impact of distributed generation (DG) and application of superconducting fault current limiter to mitigate DG impact is presented in case study—III.

Keywords Relay coordination · TLBO · Non-linear programming · Overcurrent relays · Backup protection

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Introduction

Shunt faults in a power system give rise to sudden built up of current. This magnitude of fault current can be utilized for the indication of fault existence. The over-current protection is provided using directional DOCRs for distribution system. These relays are also used as secondary protection of the transmission system. In distribution feeders, they play a more prominent role and there it may be the only protection provided. A relay must trip for a fault under its primary zone of protection. Only if, the primary relay fails to operate, the back-up relay should takeover tripping. If backup relays are not well coordinated, the relay may get mal-operated. Therefore, relay coordination is a major concern of power system protection. Each relay in the power system must be coordinated with the other relays in the power system [1,2]. Several optimization techniques are proposed for optimum coordination of DOCRs [3–17]. The optimum settings for TMS and PS are obtained using different algorithms proposed by the researchers. In some cases, pickup currents are determined based on experience and only the value of TMS is optimized using linear programming techniques. Several non-linear programming (NLP) methods are used to optimize both TMS and PS. However, NLP methods are complex as well as time-consuming. To avoid the complexity of the NLP methods, the DOCR coordination problem is commonly formulated as a linear programming problem (LPP). Various LPP techniques are presented by the researchers for DOCRs coordination [3,4]. In [5,6], optimum coordination is achieved by considering different network topologies. Some heuristic-based optimization algorithms such as genetic algorithm (GA) [7,8], TLBO [9,10] are used to find the optimum relay settings. In [10], authors have presented the impact of TMS range on the optimum solution. The relay coordination problem was solved in [11,12], using a hybrid GA considering the effects of the different network topologies. GA is used to find the initial solution with less iteration, and final optimum solution is obtained using LP [11] or NLP method [12]. Informative Differential Evolution (IDE) [13], and Seeker Algorithm [14] are used to find optimum relay settings. The application of Modified Differential Evolution Algorithms [15], Opposition based Chaotic Differential Evolution Algorithm [16], Particle Swarm Optimization (PSO) [17] and Modified Particle Swarm Optimization (MPSO) [18] algorithms are also presented by the researchers to find optimum settings for TMS and PS. The use of dual setting relays is presented in [19] for the optimum coordination of DOCRs. An adaptive protection scheme is presented in [20] to mitigate impact of distributed generation. A case study is presented to determine the size of fault current limiter (FCL) to restore relay coordination [21]. Hybrid protection scheme using adaptive relaying and small size FCL is presented in [22]. The algorithm step and application of stochastic disturbance factor to bring the search to global minimum by escaping from local minima is explained in [23]. The run time of algorithm with respect to change in population size is presented in [24]. Different heuristic-based computational algorithms are available in the literature to solve constrained nonlinear optimization problem. One of such algorithm based on conventional classroom Teaching-Learning process is presented by R. Venkata Rao and Savsani in 2011 [25–27].

The relay coordination problem is generally formulated as constrained non-linear programming problem (NLP) to minimize the sum of operating time of primary relays [9,11–16]. In this paper, the objective function is defined to minimize the sum of operating time of all primary and backup relays to avoid the delayed operation of backup relays. MATLBO algorithm is proposed to determine optimum values of TMS and PS. Four case studies are presented to illustrate the proposed algorithm.

Problem Formulation

The overcurrent relay has two decision variables, time multiplier setting (TMS) and plug setting (PS). The operating time of relay is a function of TMS, PS and current seen by relay. The operating time of relay is given by Eq. (1) [1–5,8–16].

$$t_{op} = \frac{\alpha * TMS}{\left(\frac{If}{PS}\right)^{\beta} - \gamma} \tag{1}$$

where ‘*’ represents the scalar multiplication. α, β, γ, are the constants representing the overcurrent relay characteristic in a mathematical form. It is assumed that inverse-definite minimum time (IDMT) type OCRs are used. α, β and γ constants for normal IDMT characteristic are considered as 0.14, 0.02 and 1.0 respectively as per IEEE standards.

Optimal Relay Coordination Problem

Optimum relay coordination problem can be formulated as constrained non-linear optimization problem and solved by different optimization methods. Some researchers have defined the objective function as to minimize the sum of operating time of all primary relays for their near end faults [11–14]. The objective function is also defined as to minimize the sum of operating time of all primary relays for their near end and far end faults [9,15,16]. In these techniques the backup relay operating time is not optimized. This may lead to a delayed operation of backup relays. To overcome this difficulty the objective function is formulated to minimize the sum of operating time of all primary and backup relays. This can be stated as-

$$\text{minimize } Z_k = \sum_{i=1}^{N} t_{i,k} + \sum_{j=1}^{N} t_{j,k} \tag{2}$$

where Z_k is the objective function in zone k, $t_{i,k}$ is the operating time of ith primary relay for its near end fault in zone—k, $t_{j,k}$ is the operating time of jth backup relay for its far end fault in zone—k and N is the total number of directional over-current relays.

Depending upon relay characteristics and primary/backup relationship the above optimization problem has following constraints.

Relay Setting

Each relay has TMS and PS settings. PS limit has chosen based on the maximum load current and the minimum fault current seen by the relay, and the available relay setting. The TMS limits are based on the available relay current-time characteristics. This can be mathematically stated as,

$$\left.\begin{aligned} PS_{imin} \le PS_i \le PS_{imax} \\ TMS_{imin} \le TMS_i \le TMS_{imax} \end{aligned}\right\} \tag{3}$$

Bounds on Relay Operating Time

Relay needs certain minimum amount of time to operate. Also, a relay should not be allowed to take too long time to operate. This can be mathematically stated as

$$t_{imin} \leq t_i \leq t_{imax} \quad (4)$$

where t_{imin} is the minimum operating time of the relay for the fault at any point in the zone k and t_{imax} is the maximum operating time of the relay for the fault at any point in the zone k.

Backup: Primary Relays Coordination Time Interval

Fault is sensed by both primary as well as secondary relay simultaneously. To avoid mal-operation, the backup relay should take over the tripping action only if primary relay fails to operate. If R_i is the primary relay for fault at k, and R_j is backup relay for the same fault, then the coordination constraint can be stated as

$$t_{j,k} - t_{i,k} \geq \Delta t \quad (5)$$

where $t_{i,k}$ is the operating time of the primary relay R_i, for the fault in zone k, $t_{j,k}$ is the operating time of the backup relay R_j, for the same fault in zone k and Δt is the co-ordination time interval (CTI).

Teaching Learning Based Optimization Algorithm

Teaching learning is a process where every student tries to learn something from the teacher as well as from other students to improve the performance. Inspiring from traditional teaching-learning phenomenon of the classroom, R. Venkata Rao and Savsani proposed an algorithm known as teaching-learning based optimization algorithm (TLBO) [25–27]. This is related to the effect of influence of a teacher on the output of students (learners) in a class. The algorithm simulates two basic modes of the learning through classroom teaching (known as teacher phase) and interacting with the other students (known as learner phase). Like any other search algorithm, TLBO is a population-based algorithm where the population is represented by a group of students (i.e. learners) and the design variables are represented by the different subjects offered to the learners. The possible solution of the problem is represented by the grades obtained by a learner in each subject. The solution in the entire population which represents the minimum value of the objective function is considered as the teacher. At the first step, the TLBO randomly generates initial population '$P_{initial}$' of 'n' solutions, where 'n' denotes the size of the population. Each solution Xk, where k = 1, 2, ..., n is a 'm' dimensional vector where 'm' is the number of design variables. After initialization, the population of the solutions is repeated for predefined iterations (for i = 1, 2, ..., g) of the teacher phase and learner phase. The teacher phase and learner phase of the TLBO algorithm is explained below.

Teacher Phase

In this phase of the algorithm, the students (i.e. learners) increase their knowledge through the teacher. During this phase, a teacher delivers knowledge among the learners and tries to increase the mean result of the class. Suppose there is 'm' number of subjects offered to 'n' number of students. At any teaching-learning iteration i, let us consider Mj,i is the mean result of the student in a given subject 'j'. Since a teacher is having more knowledge of that subject, the best solution in the entire population is considered as a teacher in the algorithm. Let $Xd_{j,i}$, (d ∈ k) be the grades of the best student and f(Xd) is the result of the best student with all the subjects, who is identified as a teacher for that cycle. Teacher will give maximum input to increase the result of the whole class, but the knowledge gained by the students will depend upon the quality of teaching delivered by a teacher as well as the quality of the students. The difference between the grade of the teacher and mean grade of the learners in each subject is expressed as,

$$Diff\_Mean_{j,i} = rand_i * \left(Xd_{j,i} - TF * M_{j,i}\right) \quad (6)$$

where $rand_i$ is a random number in the range [0, 1], $Xd_{j,i}$ is the grade of the teacher in the subject—j and T_F is the teaching factor which decides the value of the mean to be changed.

The value of T_F can be either 1 or 2 and decided randomly as,

$$T_F = round\,[1 + rand_i] \quad (7)$$

The value of TF is randomly decided by an algorithm. Based on the $Diff\_Mean_{j,i}$ the existing solution 'k' is updated in the teacher phase according to the following expression.

$$Xnew_{kj,i} = X_{kj,i} + Diff\_Mean_{j,i} \quad (8)$$

where $Xnew_{kj,i}$ is the updated value of $X_{kj,i}$.

Substituting Eq. (6) in Eq. (8), we have

$$Xnew_{kj,i} = X_{kj,i} + rand_i * \left(Xd_{j,i} - TF * M_{j,i}\right) \quad (9)$$

The term $rand_i$ is the stochastic step of the algorithm while the term $TF * M_{j,i}$ enables the algorithm to escape from the local minima. The algorithm accepts $Xnew_{kj,i}$ if it gives a better function value otherwise keeps the previous solution. All the accepted grades (i.e. design variables) are maintained at the end of the teacher phase which becomes the input to the learner phase (Fig. 1).

Learner Phase

A learner in a class gets its input in two different ways. This phase of the algorithm simulates the learning of the students (i.e. learners) through interaction through the group of learners. The students can also increase their knowledge by discussing with the other students. A learner will learn new information if the other learners have more knowledge than him or her. The learning phenomenon of this phase is expressed below. The algorithm randomly selects two learners p and q such that $f(X^P) \neq f(X^q)$. $f(X^P)$ and $f(X^q)$ are the updated result of the learners p and q considering grades of all the subjects at the end of teacher phase.

$$\mathrm{Xnew}^{p}_{j,i} = \left\{ \begin{array}{ll} X_j, i^p + \mathrm{rand}^p_{(i)} * \left(X_j, i^p - X_j, i^q\right) & \text{if } f(X^p) <^i (X^q) \\ X_j, i^p + \mathrm{rand}^p_{(i)} * \left(X_j, i^q - X_j, i^p\right) & \text{otherwise} \end{array} \right\} \quad (10)$$

Xnew^P is the updated value of X^P. The algorithm then accepts Xnew^P if it gives a better function value.

Algorithm Termination

The algorithm is terminated after completion of pre-determined iterations. The final set of learners represents the best value of decision variables.

Comparison of TLBO with other Optimization Techniques

Teaching Learning Based Optimization (TLBO) is a population-based optimization algorithm like Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC) algorithms. These algorithms randomly generate a group of possible solutions to find the optimum solution. Many optimization algorithms have the optimization parameters. These parameters affect the performance of the optimization algorithm. GA has the parameters like the mutation rate, crossover probability and selection method. Similarly, PSO is having optimization parameters like learning factors, weight factors and the maximum value of velocity. Unlike these optimization techniques, TLBO does not have any parameters to be tuned. This makes the implementation of TLBO algorithm much simpler than the other optimization algorithms. In TLBO the existing solutions from the population are updated using best solution of

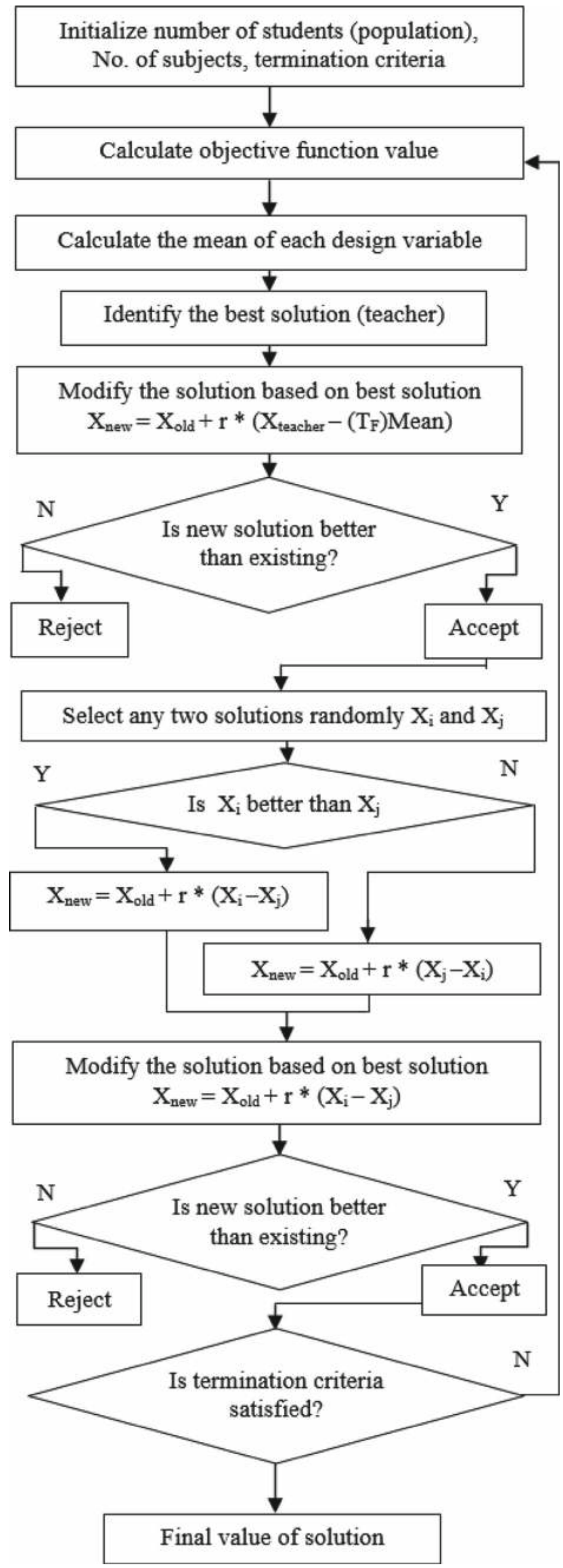

Fig. 1 Flow Chart of TLBO algorithm [25,27]

the iteration as on PSO. TLBO does not divide the population into different groups like ABC. TLBO uses two different phases, the 'teacher phase' and the 'learner phase'. TLBO algorithm has two different phases, namely, the 'teacher phase' and the 'learner phase' like crossover and mutation in GA, employed, onlooker and scout bees in ABC.

Proposed Modified Adaptive TLBO algorithm

To protect the power system, relay must operate for minimum fault current and relay should not operate for maximum load current, which is achieved with proper relay settings. The minimum current to start the relay operation is set with the help of PS and TMS decides the total operating time of the relay.

Relay coordination problem becomes more complicated with an increase in relay numbers. The number of constraints increases with an increase in primary/backup relay pairs. The heuristic base optimization techniques are used to solve the optimization problem. These techniques randomly generate a set of possible solutions (population) to get a feasible initial solution. This solution is converted to the optimum solution using an iterative process. During the iterative process, the solution for the objective function is improved by modifying the possible solutions of design variables. The new solution is accepted if it gives a better solution than the previous one. With a wide range of TMS, the number of worst solutions is generated in the population. This leads to a non-optimum solution.

Figure 2 shows the three areas, A, B, and C with fixed range of PS and different range of TMS. The range of TMS is considered 0.05 onward to satisfy the constraints of minimum operating time. With the maximum range of TMS (i.e. 0.05 to 1.1), the solution is available in all the three areas, but the solution available from the area B and C contains the higher value of TMS. This increases the operating time of the relay. Similarly for medium range of TMS (0.05 to 0.8), the solution is available in the area A and B, where area B gives a non-optimum solution. With minimum range of TMS, the solution is available from area A, which gives the optimum solution with a smaller value of TMS. The population is generated with a wide range of design variables (TMS) as it is very difficult to get feasible initial solution with a small range of design variables. After some iteration, number of worst solutions (possible solutions for TMS with high value) will remain in the population. Due to this, the optimization method may converge to the solution that may not be optimum.

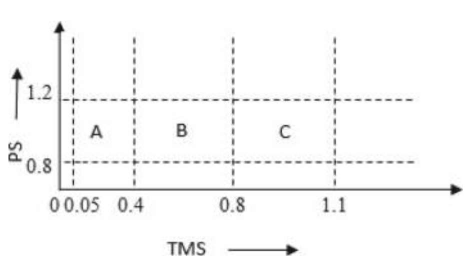

Fig. 2 Possible areas for solution of TMS and PS

In this paper, MATLBO algorithm is proposed to overcome this difficulty. This algorithm has two stages. In stage one initial solution is generated and in stage two the objective function is optimized to obtain the optimum solution with a new population for TMS. Figure 3 shows the flowchart of proposed MATLBO algorithm.

Stage: I

This stage of the algorithm finds feasible initial solution with a wide range of TMS. The feasible initial solution is passed to next stage—II.

Stage: II

This stage simulates the optimization problem to find the optimum value of the objective function. This stage generates new population for TMS. The upper bound of TMS range (UB_TMS) is replaced with a maximum value of TMS obtained from the initial solution (UB_TMS = MAX_TMS). Then objective function is optimized for pre-defined iterations of teacher phase. After completing the teacher phase the solution is optimized for pre-defined iterations of a learner phase with new population using MAX_TMS of a teacher phase. New solution will be available after completing total iterations of the learner phase. This solution is compared with the initial solution. If the new solution is better than the initial solution then, the new solution is treated as the initial solution and the process is repeated to get the optimum solution.

Algorithm Termination

The algorithm is terminated after completion of pre-determined iterations/cycles of teacher and learner phase. The final set of learners represents the best value of decision variables.

Impact of Distributed Generation (DG) on Protection Coordination

The presence of DG in distribution system changes the fault current level. This leads to loss of original relay coordination. The original relay coordination is restored by disconnecting all DGs during the fault conditions. This will lead to the

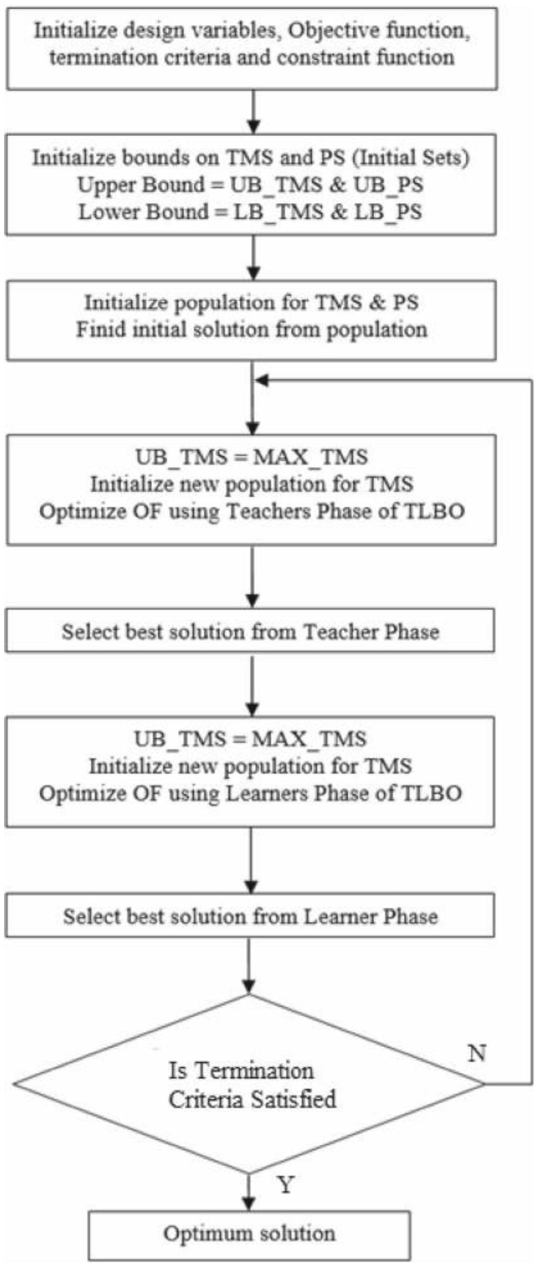

Fig. 3 Flow chart of modified adaptive TLBO algorithm

loss of DG power as well as it will create resynchronization problems for connecting DGs after clearing the fault. A fault current limiter (FCL) can effectively used in series with DGs to limit their fault currents. The resistive type of fault current limiter is more effective as compared to other type. The size of FCL depends upon the level of DG injection. FCL offers the impedance only during fault conditions and zero impedance is offered during steady state. The unique characteristics equation of resistive type superconducting fault current limiter (SFCL) can be expressed by Eq. (11)

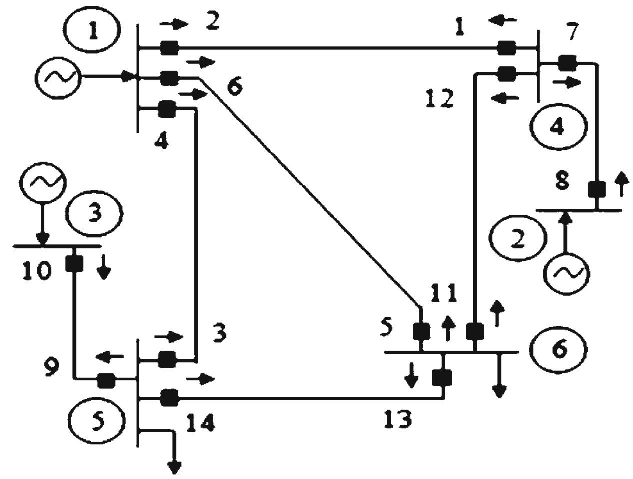

Fig. 4 IEEE 6-bus test system [9, 15, 16]

Table 1 TMS and PS for Illustration—I

Relay no.	TLBO [9]		MATLBO	
	TMS	PS	TMS	PS
1	0.3780	0.7747	0.2548	0.9519
2	0.3433	0.7266	0.2511	0.7585
3	0.2533	0.7255	0.1969	0.7587
4	0.3346	0.6900	0.2494	0.7624
5	0.1005	0.7646	0.1068	0.7341
6	0.2376	0.7472	0.1469	0.9217
7	0.3000	0.7820	0.0500	0.6787
8	0.4720	0.7789	0.1753	0.9640
9	0.0414	0.7630	0.0664	0.7993
10	0.3323	0.7986	0.1794	0.7719
11	0.2518	0.7827	0.1095	0.8025
12	0.2704	0.7605	0.1563	0.9298
13	0.1735	0.7431	0.1603	0.7629
14	0.2817	0.8074	0.1963	0.8361
OF (s)	43.6085		27.0556	

$$R_{SFCL}(t) = R_m\left(1 - exp^{(-t/T_{sc})}\right) \quad (11)$$

where R_m is the maximum resistance of the SFCL in the normal state.

T_{sc} is the time constant of transition from the superconducting state to the normal state, which is assumed to be 1ms [21]. The FCL has some limitations such as the size of FCL increases with the increase in DG level. This increases the cost of FCL and also leads to increase in backup relay time. The other option is to replace all existing relays with microprocessor based digital relays and communication systems for adaptive relaying. However, this option is economically expensive and also increases the complications in control systems.

Table 2 Primary/backup operating time of relays and CTI for Illustration—I

Backup relay	Primary relay	Operating time (s)		CTI (s)	Backup relay	Primary Relay	Operating time (s)		CTI (s)
		Backup relay	Primary relay				Backup relay	Primary relay	
8	1	1.3695	0.5607	0.8088	13	9	0.7862	0.2474	0.5388
11	1	1.0407	0.5607	0.4800	4	9	0.7665	0.2474	0.5191
8	1	2.1983	0.7475	1.4507	13	9	0.8634	0.2656	0.5978
3	2	2.6310	0.6493	1.9817	4	9	0.8128	0.2656	0.5472
3	2	0.9007	0.4977	0.4030	14	11	0.9366	0.4092	0.5274
10	3	1.0722	0.5331	0.5391	6	11	1.0037	0.4092	0.5945
10	3	1.0722	0.6469	0.4252	14	11	1.2372	0.5295	0.7077
13	3	0.9185	0.5331	0.3854	6	11	1.9561	0.5295	1.4265
1	4	1.3734	0.7057	0.6677	8	12	1.7873	0.6460	1.1413
1	4	0.9603	0.5870	0.3733	2	12	1.9766	0.6460	1.3305
12	5	0.8545	0.3494	0.5051	8	12	1.2153	0.5002	0.7152
12	5	1.5403	0.5605	0.9798	2	12	0.8345	0.5002	0.3344
14	5	1.0863	0.3494	0.7369	12	13	0.8095	0.4835	0.3260
3	6	0.9854	0.4471	0.5384	6	13	1.1400	0.4835	0.6565
3	6	0.7761	0.4471	0.3290	12	13	1.1555	0.6555	0.5001
11	7	0.6105	0.2743	0.3362	10	14	1.3474	0.7604	0.5870
2	7	0.7337	0.2743	0.4595	4	14	2.0138	0.7604	1.2535
11	7	0.6553	0.2941	0.3612	10	14	1.0008	0.5618	0.4391
2	7	0.7616	0.2941	0.4676	4	14	0.8821	0.5618	0.3204

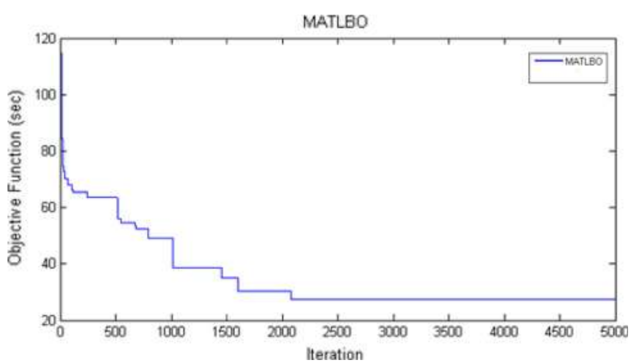

Fig. 5 Convergence curve of MATLBO algorithm (Illustration—I)

To overcome these difficulties, a small size of FCL is used in series with DG to restore the settings of far end relays. The near end relays are replaced by digital relays to restore the settings using adaptive relaying, thus making use of advantages of both the techniques (and at the same time overcoming the drawbacks of the above techniques). The application of hybrid protection scheme using adaptive relaying and RSFCL is presented in Illustration—III [22].

Implementation of Proposed Algorithm

MATLAB program is developed to find optimum settings for TMS and PS using MATLBO algorithm. The relay coordination problem discussed in the proposed research is suitable for off-line planning stage. The use of evolutionary type methods in real time monitoring and fault management in the power grid requires a significant decrease of the algorithms' cycle-time and is still an open research topic.

The parameters of MATLBO algorithm are tabulated in Appendix 1. The proposed algorithm was successfully tested for various systems, out of which four are presented in this paper. In these illustrations, all the relays are considered as numerical relays with normal IDMT characteristics with α, β, and γ constants as 0.14, 0.02 and 1.0 respectively. A total of 50 runs for each test systems are conducted and the best solution throughout the run is recorded as a global optimum solution.

Illustration: I

The proposed algorithm is tested on the IEEE 6-bus system shown in Fig. 3 reported in [9,15,16]. This network consists of 6 buses and 7 lines and 14 relays. The optimization problem is formulated as constrained nonlinear optimization problem. There are total 28 variables exists in the optimization problem. The problem has 14 constraints because of minimum operating time and 38 constraints due to coordination criteria. The initial range for TMS is considered 0.05 to 1.1 [15] (Fig. 4).

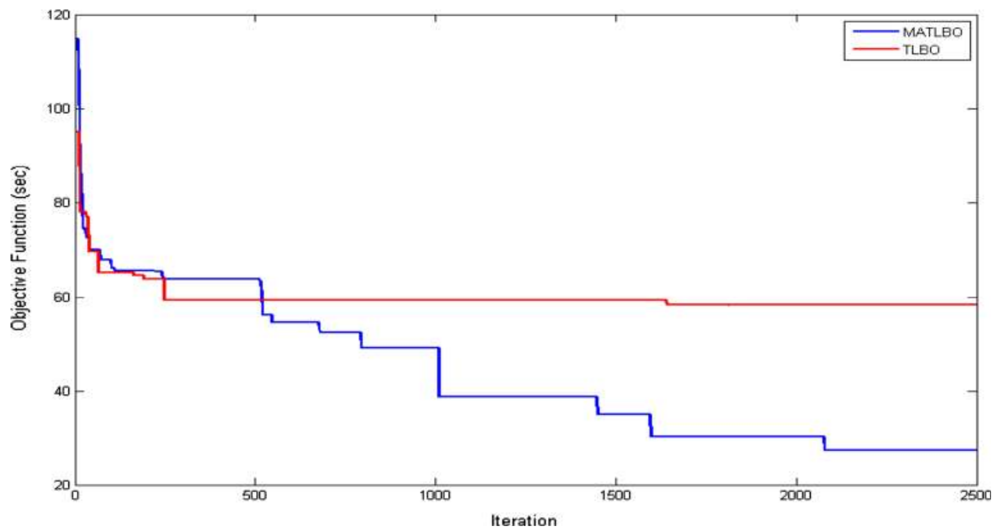

Fig. 6 Convergence curve of MATLBO and TLBO algorithms (first 2500 iterations)

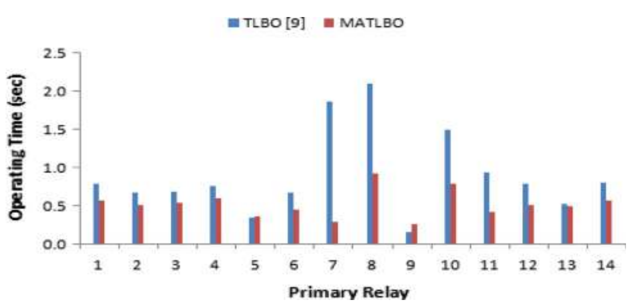

Fig. 7 Comparison of operating time of primary relays (Illustration—I)

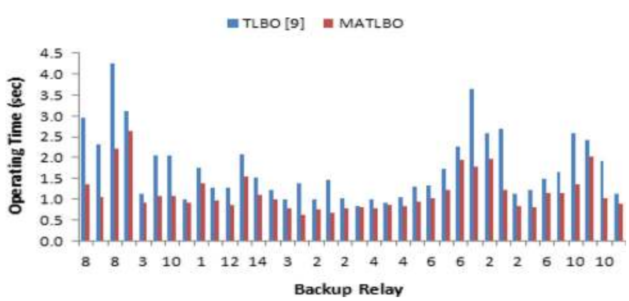

Fig. 8 Comparison of operating time of backup relays (Illustration—I)

The CTI value is considered as 0.3 s for the fair comparison with the previous work presented in [9]. The primary/backup relationship of relay pairs and fault current data is taken from [9,15]. Table 1 represents the optimum solution obtained using TLBO [9] and MATLBO algorithm.

Table 1 shows that the optimum solution obtained using MATLBO algorithm is better than the solution obtained using TLBO algorithm. The primary/backup relay operating time and CTI value associated with primary/backup relay pair is tabulated in Table 2. This table shows that the MATLBO algorithm satisfies all the constraints of minimum operating time and CTI. The convergence curve of MATLBO algorithm is presented in Fig. 5. This shows that the MATLBO algorithm converges to its global optimum solution within 2200 iterations.

The comparison of Convergence curve of MATLBO and TLBO algorithm is presented in Fig. 6. This figure shows shows that the convergence curve of MATLBO and TLBO algorithm is almost same for first 500 iterations. The objective function value after 500 iterations is 62.4599s with the maximum value of TMS as 0.6431. After 500 iterations, the MATLBO algorithm generates the new population with upper bound on TMS value as 0.6431. This gives remarkable improvement in objective function value due to replacement of worst solutions with better solutions for TMS as explained in "Proposed Modified Adaptive TLBO algorithm" section. Figure 6 also shows the improvement in objective function value with new population of TMS for the first four cycles of MATLBO algorithm. The MATLBO algorithm converges to the global optimum solution with less iterations as compared to TLBO algorithm.

The comparison of primary relay operating time, backup relay operating time and CTI is represented in Figs. 7, 8 and 9 respectively. These figures show that the MATLBO algorithm gives better performance as compared to TLBO algorithm. The simulation time with respect to the population size, using the MATLAB R2012a on Personal Computer CPU *Core i3* 4010U 1.70 GHz. Processor with 4 GB DDR3 RAM is presented in Fig. 10 and tabulated in Appendix 2.

Illustration: II

The proposed algorithm is tested on the 8-bus system shown in Fig. 11 reported in [11,14]. This network consists of 8 buses, 7 lines, 2 transformers and 2 generators. The opti-

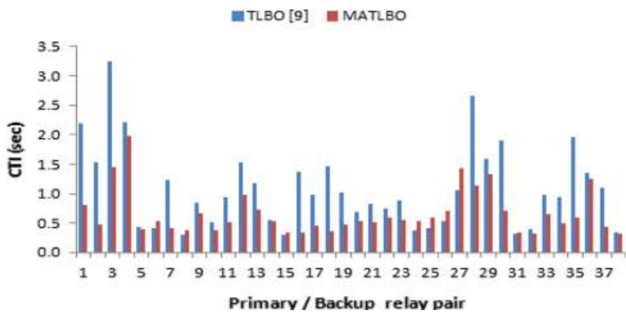

Fig. 9 Comparison of coordination time interval (CTI) (Illustration—I)

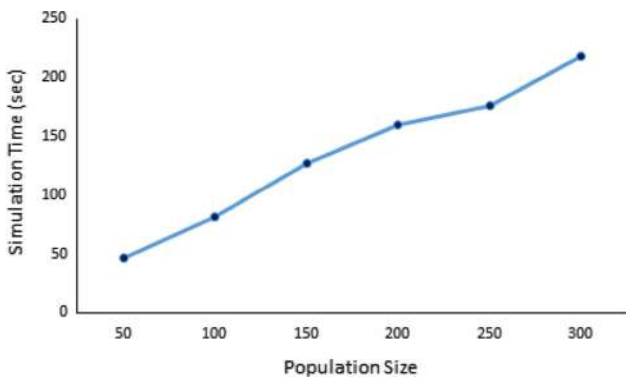

Fig. 10 Comparison of coordination time interval (CTI) (Illustration—I)

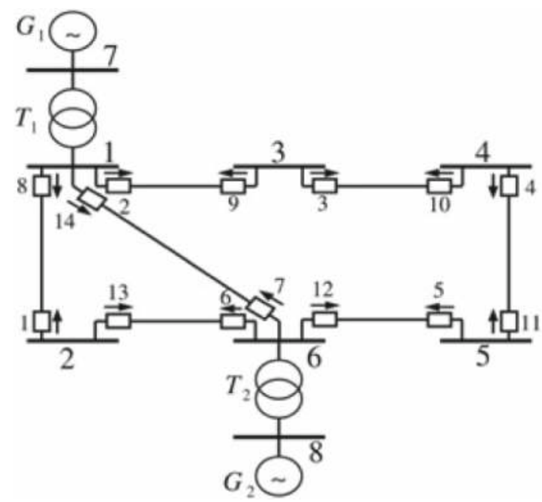

Fig. 11 8-Bus meshed distribution system [11,14]

Table 3 Fault current data for Illustration—II [11,14]

Primary relay	Backup relay	Fault current (A)	
		Primary relay	Backup relay
1	6	3232	3232
2	1	5924	996
2	7	5924	1890
3	2	3556	3556
4	3	3783	2244
5	4	2401	2401
6	5	6109	1197
6	14	6109	1874
7	5	5223	1197
7	13	5223	987
8	7	6093	1890
8	9	6093	1165
9	10	2484	2484
10	11	3883	2344
11	12	3707	3707
12	13	5899	987
12	14	5899	1874
13	8	2991	2991
14	1	5199	996
14	9	5199	1165

mization problem is formulated as constrained nonlinear optimization problem. There are total 28 variables exists in the optimization problem. The problem has 14 constraints because of minimum operating time and 20 constraints due to coordination criteria. The initial range for TMS is considered 0.05 to 1.1 [11]. In this illustration, for the fair comparison CTI is taken as 0.3 s as in [11,14]. The primary/backup relationship of relay pairs and fault current data is given in Table 3 [11,14]. Table 4 presents the optimum solution obtained using TLBO, MATLBO and other optimization method used in [11,14], this table shows that the optimum solution obtained using MATLBO algorithm is better than other optimization algorithms. The primary/backup relay operating time and CTI value associated with primary/backup relay pair is tabulated in Table 5. This table shows that the MATLBO algorithm satisfies all the constraints of minimum operating time and CTI. The convergence curve of MATLBO algorithm is presented in Fig. 12. This shows that the MATLBO algorithm converges to its global optimum solution within 4350 iterations but there is no significant improvement after 3100 iterations.

The comparison of Convergence curve of MATLBO and TLBO algorithm is presented in Fig. 13. Figure 13 shows that the convergence curve of MATLBO and TLBO algorithm is almost same for first 500 iterations. The objective function value after 500 iterations is 92.3822s with the maximum value of TMS as 0.8074. After 500 iterations, the MATLBO algorithm generates the new population with upper bound on TMS value as 0.8074. This gives remarkable improvement in objective function value due to replacement of worst solutions with better solutions for TMS as explained in "Proposed Modified Adaptive TLBO algorithm" section. Figure 12 also shows the improvement in objective function value with new

Table 4 TMS and PS for Illustration—II

Relay no.	TLBO algorithm		PSO [18]		GA [11]		Hybrid GA-LP [11]		MPSO [18]		Seeker algorithm [14]		MATLBO algorithm	
	TMS	PS	TMS	PS	TMS	PS	TMS	PS	TMS	PS	TMS	PS	TMS	PS
1	0.169	491	0.104	600	0.29	240	0.304	240	0.130	480	0.113	480	0.117	457
2	0.334	645	0.345	640	0.31	600	0.291	600	0.334	480	0.260	600	0.245	614
3	0.258	489	0.333	300	0.26	400	0.254	400	0.210	500	0.225	400	0.190	491
4	0.228	565	0.192	640	0.19	600	0.185	600	0.143	800	0.160	600	0.155	567
5	0.132	648	0.108	600	0.18	360	0.170	360	0.101	600	0.100	600	0.086	623
6	0.382	645	0.273	400	0.26	600	0.271	600	0.267	400	0.173	800	0.166	648
7	0.410	444	0.239	600	0.54	80	0.531	80	0.206	600	0.243	400	0.222	436
8	0.233	578	0.285	400	0.24	600	0.238	600	0.218	500	0.170	600	0.165	575
9	0.170	439	0.100	800	0.17	320	0.185	320	0.124	480	0.147	400	0.125	449
10	0.202	641	0.288	400	0.19	600	0.189	600	0.216	500	0.176	600	0.159	641
11	0.224	621	0.351	300	0.21	600	0.201	600	0.213	600	0.187	600	0.175	620
12	0.336	590	0.488	400	0.30	600	0.289	600	0.450	500	0.266	600	0.247	650
13	0.138	525	0.117	600	0.23	360	0.229	360	0.100	600	0.114	480	0.099	518
14	0.306	448	0.186	800	0.51	80	0.527	80	0.157	800	0.246	400	0.218	457
OF (s)	40.0084		37.7608		33.7658		33.4377		32.0183		26.5148		25.8154	

Table 5 Primary/backup operating time of relays and CTI for Illustration—II

Primary relay	Backup relay	Operating time (s)		CTI (s)
		Primary relay	Backup relay	
1	6	0.3580	0.6623	0.3043
2	1	0.7534	1.0539	0.3005
2	7	0.7534	1.0612	0.3078
3	2	0.6767	0.9781	0.3014
4	3	0.5786	0.8810	0.3023
5	4	0.4692	0.7735	0.3043
6	5	0.4773	0.9413	0.4640
6	14	0.4773	1.0674	0.5900
7	5	0.6205	0.9413	0.3209
7	13	0.6205	1.0718	0.4513
8	7	0.4790	1.0612	0.5822
8	9	0.4790	0.9179	0.4389
9	10	0.5007	0.8030	0.3023
10	11	0.6126	0.9135	0.3010
11	12	0.6691	0.9698	0.3007
12	13	0.7673	1.0718	0.3045
12	14	0.7673	1.0674	0.3001
13	8	0.3908	0.6994	0.3086
14	1	0.6171	1.0539	0.4368
14	9	0.6171	0.9179	0.3008

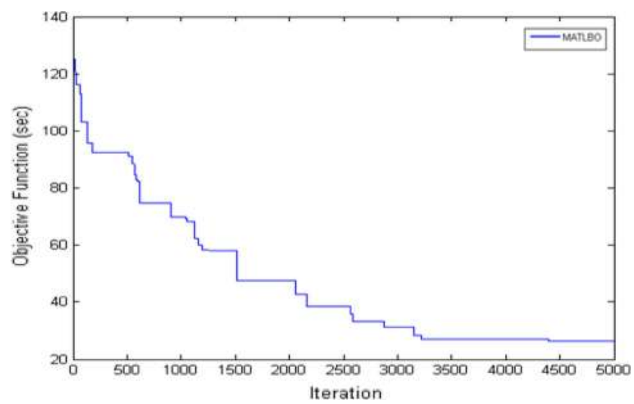

Fig. 12 Convergence curve of MATLBO algorithm (Illustration—II)

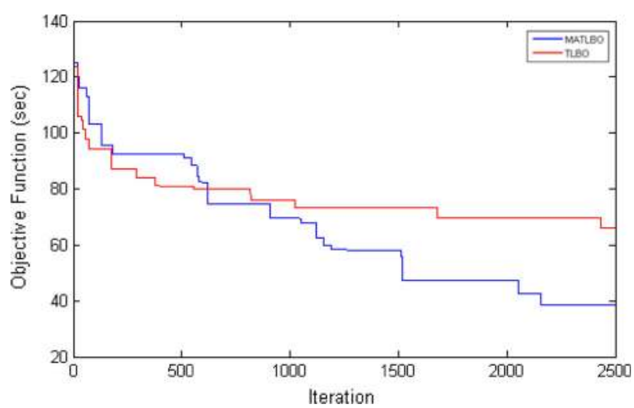

Fig. 13 Convergence curve of MATLBO and TLBO algorithms (first 2500 iterations)

population of TMS for the first four cycles of MATLBO algorithm. The MATLBO algorithm converges to the global optimum solution with less iterations as compared to TLBO algorithm.

The comparison of primary relay operating time, backup relay operating time and CTI is represented in Figs. 14, 15 and 16 respectively. These figures show that the MATLBO

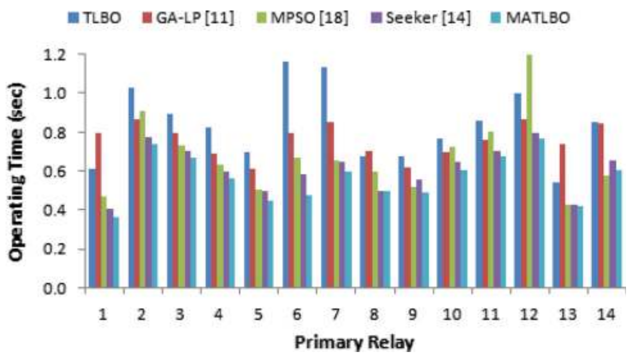

Fig. 14 Comparison of operating time of primary relays (Illustration—II)

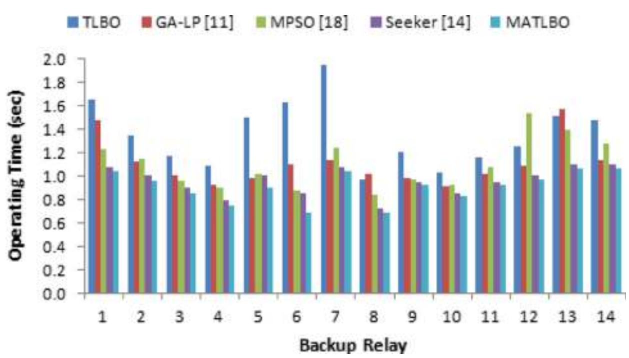

Fig. 15 Comparison of operating time of backup relays (Illustration—II)

algorithm gives better performance as compared to TLBO algorithm.

Illustration: III

A proposed method is applied to 9-bus interconnected distribution system [12,13]. A single line diagram is shown in Fig. 17. In [12,13] faults are generated at the middle of each line. As the line impedance plays an important role, the magnitude of fault current seen by relay will be more for its near end faults as compared to the fault at the middle of the line. This may lead to mal-operation of DOCRs. The fault analysis for the near end faults is carried out using power world simulator software. The primary/backup relationship of relay pairs and nearend fault current data is given in Table 6. The minimum operating time of each relay as well as CTI is considered as 0.2s as in [12,13].

The optimization problem is formulated as constrained non-linear optimization problem. There are total 48 variables exists in the optimization problem. The problem has 24 constraints because of minimum operating time and 32 constraints due to coordination criteria. The MATLBO algorithm is used to solve relay coordination problem to minimize total operating time of primary and backup relays. The optimum solution with proposed algorithm is present in Table 7. The optimum solution with proposed algorithm is 41.9041 s while the solution obtained with IDE and TLBO algorithm is 59.6741 s [13] and 82.9012 s respectively. The primary/backup relay operating time and CTI value associated with primary/backup relay pair is tabulated in Table 8. This table shows that the MATLBO algorithm satisfies all the constraints of minimum operating time and CTI. The convergence curve of MATLBO algorithm is presented in Fig. 18.

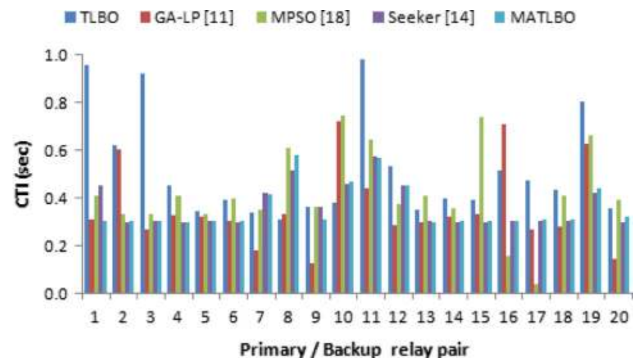

Fig. 16 Comparison of Coordination Time Interval (CTI) (Illustration—II)

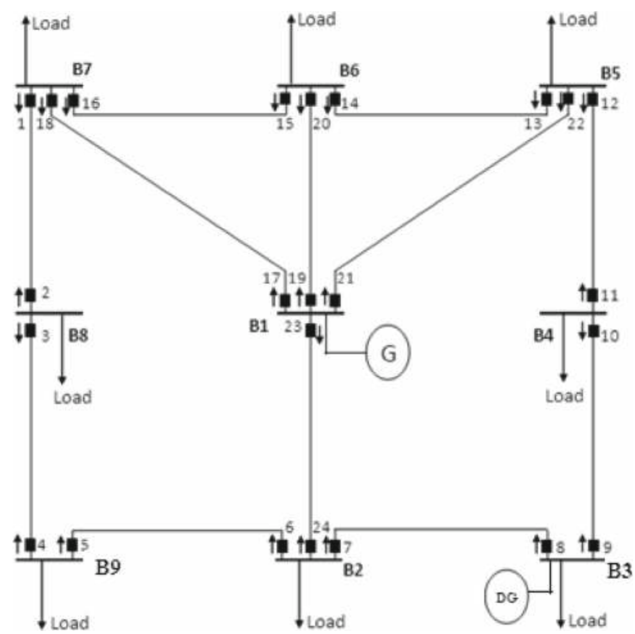

Fig. 17 9-Bus meshed distribution system [12,13]

The MATLBO algorithm generates the new population for TMS after each cycle. This shows remarkable improvement in objective function value due to replacement of worst solutions with better solutions for TMS as explained in "Proposed Modified Adaptive TLBO algorithm" section. The comparison of primary relay operating time, backup

Table 6 Near end fault current data for Illustration—III

P/R	B/R	Fault current with no DG (A)		Fault current with DG (A)		Fault current with DG and FCL1(A)		Fault current with DG and FCL2 (A)		Fault current with DG and FCL3 (A)		Fault current with DG and FCL4 (A)	
		P/R	B/R	P/R	B/R	P/R	B/R	P/R	B/R	P/R	B/R	P/R	B/R
1	15	7257	2713	8434	3306	7995	3085	7794	2984	7679	2926	7605	2889
1	17	7257	4544	8434	5129	7995	4910	7794	4811	7679	4753	7605	4716
2	4	2092	2092	2802	2802	2538	2538	2418	2418	2348	2348	2303	2303
3	1	3615	3615	4056	4056	3892	3892	3817	3817	3773	3773	3746	3746
4	6	3322	3322	4612	4612	4114	4114	3893	3893	3769	3769	3689	3689
5	3	2251	2251	2544	2544	2430	2430	2380	2380	2351	2351	2333	2333
6	8	6276	1320	11, 031	5693	8912	3747	8100	2999	7670	2604	7404	2359
6	23	6276	4957	11, 031	5354	8912	5175	8100	5107	7670	5071	7404	5049
7	5	6276	1320	6873	1490	6604	1413	6501	1384	6447	1369	6413	1359
7	23	6276	4957	6873	5385	6604	5192	6501	5118	6447	5079	6413	5055
8	10	2251	2251	19, 306	2190	8006	2228	5712	2236	4725	2239	4176	2241
9	7	3322	3322	20, 330	3238	9060	3291	6772	3302	5788	3307	5251	3309
10	12	3615	3615	4040	4040	3843	3843	3770	3770	3732	3732	3709	3709
11	9	2092	2092	5892	5892	4151	4151	3504	3504	3166	3166	2959	2959
12	14	7257	2713	8207	3129	7825	2962	7662	2890	7571	2851	7513	2826
12	21	7257	4544	8207	5079	7825	4864	7662	4772	7571	4721	7513	4688
13	11	5691	1147	8326	3274	7273	2425	6821	2060	6570	1858	6410	1729
13	21	5691	4545	8326	5064	7273	4855	6821	4766	6570	4716	6410	4685
14	16	6603	2328	7698	2855	7284	2656	7097	2566	6990	2515	6921	2482
14	19	6603	4275	7698	4845	7284	4629	7097	4532	6990	4476	6921	4440
15	13	6603	2328	8166	3319	7577	2952	7310	2782	7158	2684	7059	2621
15	19	6603	4275	8166	4841	7577	4627	7310	4530	7158	4475	7059	4439
16	2	5691	2328	6875	1751	6433	1526	6231	1423	6116	1364	6041	1326
16	17	5691	4275	6875	5129	6433	4911	6231	4811	6116	4754	6041	4717
17	–	17,260	–	21,805	–	20,034	–	19,255	–	18,817	–	18, 537	–
18	2	4630	1147	5060	1753	4614	1527	4410	1425	4293	1366	4218	1327
18	15	4630	4544	5060	3308	4614	3087	4410	2986	4293	2928	4218	2890
19	–	17,250	–	21,758	–	20,001	–	19,228	–	18,794	–	18, 516	–
20	13	4660	1148	6185	3332	5610	2954	5350	2783	5201	2686	5105	2623
20	16	4660	2715	6185	2853	5610	2655	5350	2566	5201	2515	5105	2482
21	–	17,260	–	21,067	–	19,581	–	18,928	–	18,561	–	18, 326	–
22	11	3863	2330	6397	3280	5384	2429	4950	2064	4709	1860	4555	1731
22	14	3863	2330	6397	3120	5384	2958	4950	2888	4709	2849	4555	2825
23	–	17,278	–	19,990	–	18,929	–	18,463	–	18,201	–	18, 034	–
24	5	2644	1148	7196	1481	5169	1410	4391	1382	3980	1368	3725	1359
24	8	2644	2715	7196	5715	5169	3760	4391	3009	3980	2611	3725	2366

relay operating time and CTI is represented in Figs. 19, 20 and 21 respectively. These figures show that the MATLBO algorithm gives better performance as compared to TLBO algorithm.

To observe impact of DG a 2 MVA distributed generated is connected at bus 3. The change in fault current data with DG and with different size fault current limiter is presented in Table 6. The results show that to restore fault current level the size of FCL increases. This increases the cost of FCL. This table also shows that with small size FCL the fault current level and protection coordination get restored for the relays other than the near end relays of DG. So to restore protec-

Table 7 TMS and PS for Illustration—III

Relay no.	TLBO algorithm		IDE algorithm [13]		MATLBO algorithm	
	TMS	PS	TMS	PS	TMS	PS
1	0.396	575	0.635	269	0.223	713
2	0.242	312	0.190	683	0.155	349
3	0.318	566	0.461	388	0.222	350
4	0.238	573	0.381	250	0.146	626
5	0.288	511	0.397	299	0.107	604
6	0.307	567	0.510	250	0.163	841
7	0.475	564	0.512	278	0.184	803
8	0.180	479	0.240	843	0.102	561
9	0.487	383	0.342	461	0.201	415
10	0.378	476	0.474	250	0.183	509
11	0.463	304	0.201	848	0.203	227
12	0.276	1029	0.419	849	0.203	778
13	0.328	545	0.541	251	0.184	565
14	0.374	585	0.395	693	0.234	488
15	0.506	391	0.564	321	0.216	518
16	0.289	553	0.263	1074	0.190	560
17	0.366	1529	0.481	1062	0.187	1106
18	0.285	524	0.146	1228	0.183	608
19	0.356	1654	0.463	1250	0.132	1548
20	0.202	625	0.245	251	0.220	520
21	0.322	1335	0.933	293	0.138	1544
22	0.246	682	0.167	922	0.152	676
23	0.418	1509	1.000	251	0.137	1584
24	0.185	367	0.148	745	0.155	274
OF (s)	82.9012		59.6741		41.9041	

Table 8 Primary/backup operating time of relays and CTI for Illustration—III

Primary relay	Backup relay	Operating time (s)		CTI (s)
		Primary relay	Backup relay	
1	15	0.6562	0.8981	0.2419
1	17	0.6562	0.9111	0.2549
2	4	0.5927	0.8379	0.2452
3	1	0.6493	0.9443	0.2950
4	6	0.6028	0.8180	0.2152
5	3	0.5598	0.8185	0.2587
6	23	0.5556	0.8285	0.2729
6	8	0.5556	0.8237	0.2682
7	5	0.6133	0.9472	0.3339
7	23	0.6133	0.8285	0.2152
8	10	0.5046	0.8470	0.3423
9	7	0.6618	0.8937	0.2319
10	12	0.6394	0.9114	0.2721
11	9	0.6265	0.8549	0.2284
12	14	0.6227	0.9392	0.3165
12	21	0.6227	0.8867	0.2640
13	21	0.5435	0.8867	0.3432
13	11	0.5435	0.8641	0.3206
14	16	0.6129	0.9212	0.3083
14	19	0.6129	0.8973	0.2844
15	13	0.5789	0.8945	0.3155
15	19	0.5789	0.8973	0.3184
16	2	0.5610	0.8972	0.3362
16	17	0.5610	0.9111	0.3502
18	15	0.6174	0.8968	0.2794
18	2	0.6174	0.8976	0.2802
20	13	0.6868	0.8938	0.2070
20	16	0.6868	0.9205	0.2337
22	11	0.5976	0.8636	0.2660
22	14	0.5976	0.9387	0.3410
24	5	0.4680	0.9450	0.4769
24	8	0.4680	0.8220	0.3539

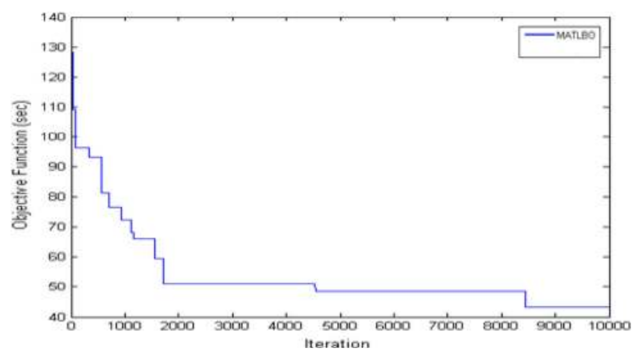

Fig. 18 Convergence curve of MATLBO algorithm (Illustration—III)

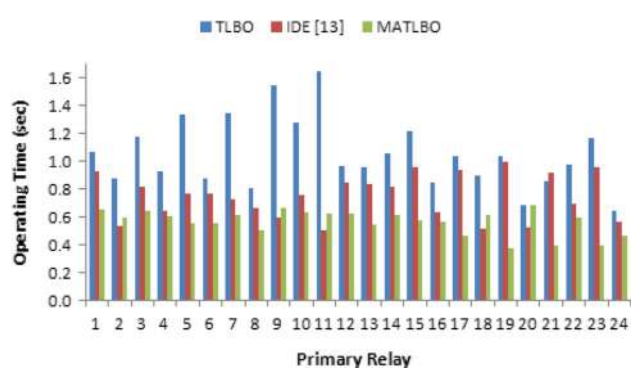

Fig. 19 Comparison of operating time of primary relays (Illustration—III)

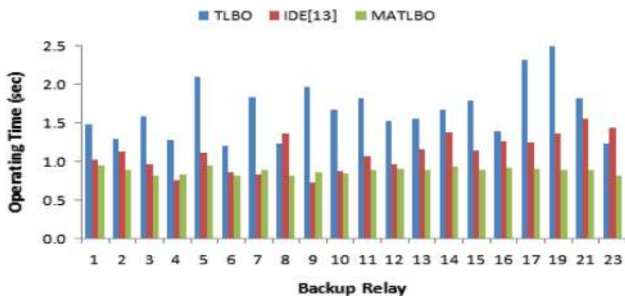

Fig. 20 Comparison of operating time of backup relays (Illustration—III)

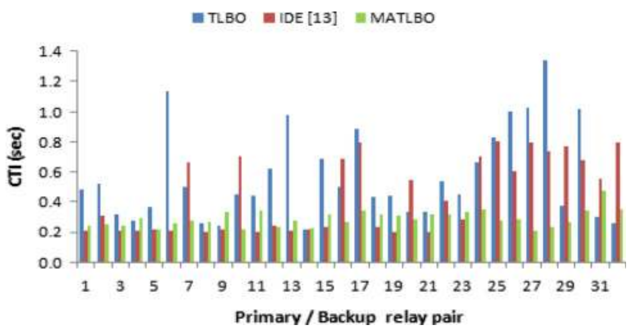

Fig. 21 Comparison of Coordination Time Interval (CTI) (Illustration—III)

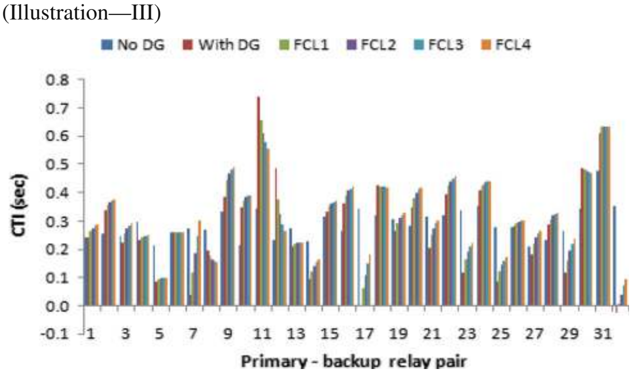

Fig. 22 Improvement in CTI with FCL size (Illustration—III)

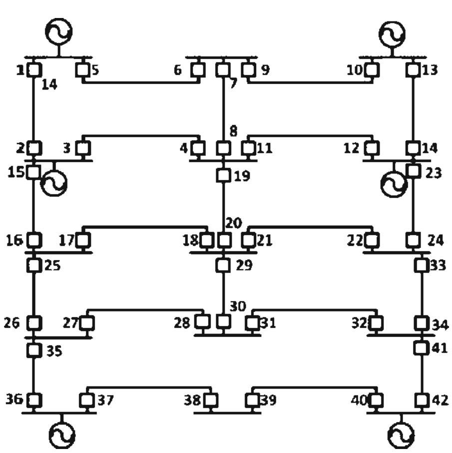

Fig. 23 15-Bus meshed distribution system [14, 15]

Table 9 Fault current data for Illustration—IV [14]

Relay no.		Fault current (A)		Relay no.		Fault current (A)	
Main	Backup	Main	Backup	Main	Backup	Main	Backup
1	6	3621	1233	20	30	7662	681
2	4	4597	1477	21	17	8384	599
2	16	4597	743	21	19	8384	1372
3	1	3984	853	21	30	8384	681
3	16	3984	743	22	23	1950	979
4	7	4382	1111	22	34	1950	970
4	12	4382	1463	23	11	4910	1475
4	20	4382	1808	23	13	4910	1053
5	2	3319	922	24	21	2296	175
6	8	2647	1548	24	34	2296	970
6	10	2647	1100	25	15	2289	969
7	5	2497	1397	25	18	2289	1320
7	10	2497	1100	26	28	2300	1192
8	3	4695	1425	26	36	2300	1109
8	12	4695	1463	27	25	2011	903
8	20	4695	1808	27	36	2011	1109
9	5	2943	1397	28	29	2525	1828
9	8	2943	1548	28	32	2525	697
10	14	3568	1175	29	17	8346	599
11	3	4342	1424	29	19	8346	1372
11	7	4342	1111	29	22	8346	642
11	20	4342	1808	30	27	1736	1039
12	13	4195	1503	30	32	1736	697
12	24	4195	753	31	27	2867	1039
13	9	3402	1009	31	29	2867	1828
14	11	4606	1475	32	33	2069	1162
14	24	4606	753	32	42	2069	907
15	1	4712	853	33	21	2305	1326
15	4	4712	1477	33	23	2305	979
16	18	2225	1320	34	31	1715	809
16	26	2225	905	34	42	1715	907
17	15	1875	969	35	25	2095	903
17	26	1875	905	35	28	2095	1192
18	19	8426	1372	36	38	3283	882
18	22	8426	642	37	35	3301	910
18	30	8426	681	38	40	1403	1403
19	3	3998	1424	39	37	1434	1434
19	7	3998	1111	40	41	3140	445
19	12	3998	1463	41	31	1971	809
20	17	7662	599	41	33	1971	1162
20	22	7662	642	42	39	3295	896

tion coordination the near end relays (i.e. Relay No. 8 and 9) can be replaced by digital relays with adaptive settings. This method presents a use of FCL to restore protection coordina-

Table 10 TMS and PS for Illustration—IV

Relay no.	MINLP [14]		Seeker [14]		MATLBO	
	TMS	PS	TMS	PS	TMS	PS
1	0.100	400	0.118	160	0.106	189
2	0.100	360	0.101	240	0.099	254
3	0.124	320	0.105	320	0.098	356
4	0.119	360	0.115	240	0.103	288
5	0.152	240	0.109	320	0.097	368
6	0.227	60	0.108	240	0.094	288
7	0.152	180	0.106	240	0.095	285
8	0.102	480	0.108	360	0.092	428
9	0.117	300	0.106	240	0.095	283
10	0.100	400	0.112	240	0.100	280
11	0.111	360	0.100	360	0.084	418
12	0.211	120	0.100	360	0.090	403
13	0.259	80	0.107	320	0.097	351
14	0.100	360	0.111	240	0.098	280
15	0.207	120	0.103	240	0.092	279
16	0.198	60	0.100	180	0.087	214
17	0.100	200	0.100	160	0.086	181
18	0.100	480	0.105	320	0.092	376
19	0.218	80	0.102	320	0.092	377
20	0.100	640	0.100	480	0.085	523
21	0.189	160	0.166	160	0.091	360
22	0.100	160	0.109	120	0.099	140
23	0.188	120	0.109	240	0.099	277
24	0.100	300	0.100	180	0.092	200
25	0.258	60	0.103	240	0.090	283
26	0.100	300	0.112	180	0.100	200
27	0.185	120	0.104	240	0.099	267
28	0.136	240	0.105	300	0.098	334
29	0.100	640	0.104	480	0.096	533
30	0.217	40	0.101	160	0.091	191
31	0.138	180	0.100	240	0.084	285
32	0.100	240	0.105	180	0.093	209
33	0.137	240	0.100	300	0.094	329
34	0.196	80	0.107	200	0.097	224
35	0.109	300	0.103	240	0.089	287
36	0.183	160	0.100	320	0.090	350
37	0.213	160	0.103	400	0.089	477
38	0.214	80	0.106	200	0.092	235
39	0.198	80	0.103	200	0.087	238
40	0.152	320	0.104	400	0.092	445
41	0.146	160	0.104	200	0.080	185
42	0.160	160	0.104	240	0.089	285
OF (sec)	75.3655		66.8062		52.5039	

tion of far end using FCL and near end relays using Adaptive Relaying. The improvement in CTI with increase in FCL size is presented in Fig. 22.

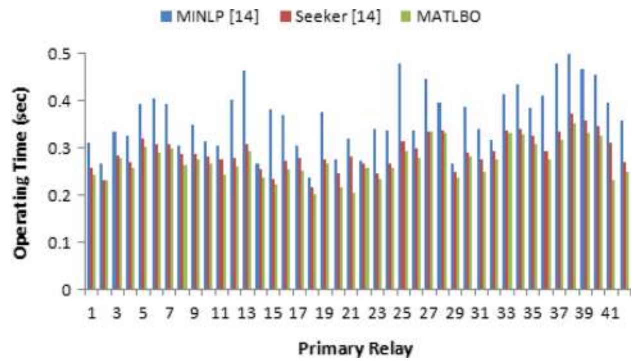

Fig. 24 Comparison of operating time of primary relays (Illustration—IV)

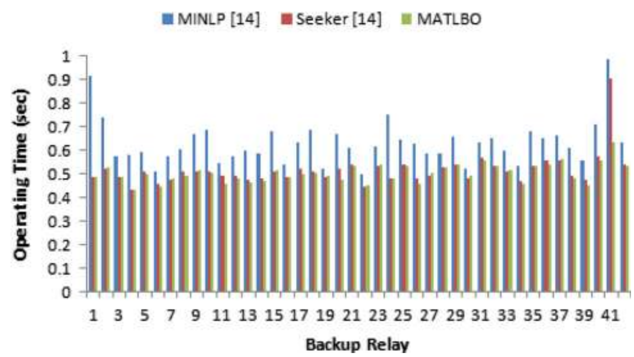

Fig. 25 Comparison of operating time of backup relays (Illustration—IV)

Illustration: IV

The proposed MATLBO algorithm is implemented in a 15-bus test network presented in [14]. This case is a highly distributed generation (DG) penetrated distribution network as shown in Fig. 23. Each generator has a synchronous reactance of 15 % with 15 MVA and 20-kV ratings. The external grid has 200-MVA short-circuit capacity. The test case has 42 relays and 82 backup-primary pairs [14].

Near end fault, current data is given in Table 9. The MATLBO algorithm is used to solve relay coordination problem to minimize total operating time of primary relays. The optimum solution with proposed algorithm is 52.5039 s while the solution obtained with MINLP, and seeker algorithm is 75.3655 s [14], and 66.8062 s [14] respectively. The optimum values of TMS and PS are presented in Table 10. Table 10 represents that the solution obtained using MATLBO algorithm satisfies all the constraints. The comparison of primary and backup relay operating time is presented in Figs. 24 and 25 respectively.

Conclusion

MATLBO algorithm to determine the optimum values of TMS and PS of DOCRs is presented in this paper. In this algorithm an advance set of possible design variables (population) is generated with a maximum value of TMS available from the earlier solution. This increases the probability of better feasible solutions. Such a strategy of iteratively updating the upper bound of TMS range shows remarkable improvement over the techniques which employ fixed TMS range. The results show that the proposed MATLBO algorithm overcomes the weakness of TLBO algorithm and capable to find superior TMS and PS settings as compared to previously proposed optimization algorithms in the literature.

Appendix 1

Parameters of MATLBO algorithm	Illustration—I	Illustration—II	Illustration—III	Illustration—IV
No. of design Variables	28	28	48	84
Population size	50	50	100	100
No. of iterations	500	500	500	500
No. of cycles	10	10	20	50
Computational time	47 s	52 s	27 min	53 min

Appendix 2

Parameters of MATLBO algorithm	Illustration—I					
No. of design variables	28	28	28	28	28	28
Population size	50	100	150	200	250	300
No. of iterations	500	500	500	500	500	500
No. of cycles	10	10	10	10	10	10
Computational time	47 sec	82 sec	127 sec	160 sec	176 sec	218 sec
Objective function (s)	27.0556	28.3245	27.1276	27.1193	28.6874	27.9468

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