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ORIGINAL PAPER

Adaptive coordination of directional overcurrent relays for meshed distribution networks with distributed generations using dragonfly algorithm

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Abstract
The deterministic directional overcurrent relay (DOCR) coordination approaches find limitation in providing fast and reliable protection to today's distribution networks due to growing integration of distributed generations (DGs). In this paper, an adaptive DOCR protection coordination scheme is proposed using an efficient optimization algorithm called the dragonfly algorithm (DA). The main inspiration of the proposed DA optimization technique originates from static and dynamic swarming behaviours of dragonflies. In this approach, the dominant changes in the network topologies are identified by monitoring the status of the circuit breakers connected at the terminals of the DGs and other main power components. When any dominant changes in the network topologies or operating modes are identified, the fault current for that particular condition is calculated and the new optimal DOCRs settings for the prevailing condition are obtained from the substation central computer in online mode. The comparative results with the existing approaches justify the superiority of the proposed scheme in achieving the minimum overall relay operating time and maintaining the coordination between the primary and backup relay pairs. In the proposed adaptive protection scheme, the average percentage reduction in the overall operating times of DOCRs in the 6-bus and the IEEE 14-bus test systems with different levels DG penetration is found to be 49.7% and 15%, respectively, compared to the existing approaches.

Keywords Adaptive protection · Dragonfly algorithm · Distribution system · Distributed generation · Optimal relay coordination

1 Introduction

1.1 Motivation and incitement

The conventional distribution networks are mostly of radial configuration in which power flows from the substation towards the load in one direction only. Overcurrent relaying (OCR) is a very well-established and cost-effective technique used for protection of such radial distribution networks. In recent years, there is a growing interest of generating electricity using renewable energy-based distributed generations (DGs) at distribution voltage level due to various technical and economic benefits [1]. Consequently, the modern power distribution networks are evolved into active looped and meshed structures. The traditionally used OCR-based protection schemes often fail to provide reliable protection to these DG integrated meshed distribution networks [2]. Directional overcurrent relays (DOCRs) are preferred as an alternative viable and economic solution for protection of such DG integrated meshed distribution networks [3].

In electrical protection scheme, the primary relay isolates the faulty part without any intentional time delay to minimize component damage. If for any reasons primary relay fails to isolate the faulted section then the corresponding backup relay should operate after certain time delay to trip the faulted section. The DOCR has two settings, namely the pick-up setting (PS) and the time multiplier setting (TMS). The overall performances of these protection schemes highly depend on the optimal coordination of DOCRs. DOCRs coordination has been a challenging issue for protection engineers

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for many years. The application of optimization techniques and adaptive relaying techniques is the preferable solution for solving the DOCRs coordination problem [4].

1.2 Literature review

The DOCR coordination methods available in the literature can be broadly classified as: (1) conventional techniques for DOCR coordination, (2) computational intelligent techniques for DOCR coordination and (3) adaptive techniques for DOCR coordination. A brief review considering the merits and demerits of each of the methods belong to different categories is provided as below.

Conventional techniques for coordination of DOCRs The conventional approaches such as the trial-and-error method [5], the curve-fitting techniques [6], the graph-theoretical techniques [7], topological analysis [8] were usually adopted in earlier days for DOCRs coordination. However, these methods have slow convergence rate and using these conventional approaches optimal solution may not be guaranteed. Several optimization techniques were proposed later to solve the DOCRs coordination problems in a more efficient manner.

Computational intelligent techniques for coordination of DOCRs The linear programming (LP) optimization techniques such as simplex [9] and dual simplex [10] reported for DOCRs coordination are fast and simple. However, using these methods only the TMS can be optimized as it is a linear function of operating time of the relay. The sequential quadratic programming a nonlinear programming (NLP) reported for optimization of both the PS and TMS of DOCRs together [11] is superior compared to the LP approaches in solving the optimal coordination problems of DOCRs. However, both the approaches have slow convergence rate and possibility of trapping at the local minima.

Several advanced metaheuristic and nature-inspired optimization approaches such as combination of evolutionary algorithm and LP [12], genetic algorithm (GA)-NLP [13], seeker algorithm (SA) [14], teaching learning algorithm [15], informative differential evolution algorithm [16], chaotic differential evolution algorithm [17], modified particle swarm optimization algorithm [18], artificial bees colony algorithm [19], biogeography-based optimization algorithm [20], improved group search optimization algorithm [21], symbiotic organism search algorithm [22], ant-lion optimization algorithm [23], modified electromagnetic field optimization algorithm [24], firefly algorithm [25], hybridized whale optimization algorithm (HWOA) [26], mixed integer linear programming (MILP) algorithm [27], modified water cycle algorithm [28] and oppositional JAYA algorithm [29] have been employed for solving the optimal coordination problems of DOCRs. The performance of the five most effective metaheuristic optimization techniques used for DOCRs coordination is compared in [30]. These techniques give better result in achieving the global optimum compared to LP and NLP algorithms, but most of these algorithms suffer from computational complexity and premature convergence.

Recently, a more efficient optimization technique, namely the hybrid particle swarm optimization (HPSO), is proposed in the literature for solving the DOCRs coordination problems [31, 32]. The superiority of the HPSO method in achieving the minimum total operating time compared to the available method is demonstrated through simulation results tested in single and multi-loop power distribution systems. In [33], a unique sieging and hunting capability of the Harris Hawk optimization (HHO) technique is applied for solving the optimal coordination problems of DOCRs. The technique is very affective in finding the global optimum values with robustness and better convergence as compared to other state of the art algorithms. In [34], JAYA algorithm is applied to solve the optimal coordination problems of OCRs in single and multi-loop distribution networks with the advantages of converging to the global optimum values with less number of iterations and computational time. In [35], the optimal coordination problems of DOCRS is solved using the whale optimization algorithm (WOA). The WOA is inspired by the bubble-net hunting strategy of humpback whales which leads towards global minima and hence, able to minimize the sum of the operating times of all primary relays. Another efficient optimization technique, namely the bio-inspired rooted tree algorithm, is proposed in [36] for optimal coordination of OCRs. Apart from solving the DOCR coordination problems, several efficient optimization techniques such as marine predators' algorithm [37], hybrid DA-PSO optimization algorithm [38], and slime mould algorithm [39] are also used by researchers for solving the multi-objective optimal power flow problems in power system.

Adaptive DOCR coordination for distribution systems including DG In the aforementioned DOCRs coordination approaches, the optimal settings of the DOCRs are obtained mostly on a fixed network topology within an interconnected power system considering possible types of faults, abnormal operating conditions and system contingencies in advance in an off-line mode. The coordinated relays in such approaches usually respond to these predetermined conditions in a satisfactory manner. But, consideration of all possible fault/non-fault scenarios in advance is practically a difficult task as the topology of the network is not fixed rather changes dynamically. The dynamic changes in the network topology are more prominent in the presence of DGs in the distribution networks. In such situation, the deterministic DOCRs coordination approaches sometimes fail to give satisfactory results.

Adaptive protection philosophy, relatively a new relaying concept, has been evolved in recent years where the operating parameters of the protection functions are automatically adjusted in response to changing power system conditions and hence provides reliable relaying decisions. The idea of adaptive protection has been applied recently for solving the coordination problems of DOCRs in power distribution networks [40]. The idea of a centralized adaptive protection scheme is proposed in [41] for coordination of DOCRs in complex distribution networks including different types of DGs. In [42], the authors have proposed another adaptive coordination scheme for power networks considering DGs. In that scheme, the exact operational network topology is identified by monitoring the status of the circuit breakers connected with DGs and other main power components. Then, utilizing the fuzzy logic concept, the required relay group settings are selected during online mode for exact operational network topology. Further, differential evolution optimization algorithm is employed to achieve the global optimum relay settings for each network topology. In [43], the authors have proposed a planning algorithm for DOCRs coordination for distribution systems integrated with DGs that can optimally identify one set of relay settings valid for all possible future DG planning scenarios. In that work, DOCR coordination algorithm is formulated as a linear programming problem and the simplex algorithm is utilized to solve it. In order to mitigate the impacts of DGs on DOCRs coordination, the authors in [44] proposed an adaptive protection scheme using differential evolution algorithm. Another two-phase hybrid adaptive DOCR coordination algorithm is proposed in [45] considering the uncertainty of DGs. In that scheme, the current settings are determined considering the DG output power using a fuzzy-based current setting module. Further, using an optimization algorithm the overall relay operating time is minimized.

The aforementioned study clearly shows that the existing optimization algorithms focused mainly in minimizing the overall operating times of the primary OCRs/DOCRs present in the network. However, the optimal coordination between the primary and backup relay pairs have not been addressed in many of the reported works. Some of the employed optimization algorithms also suffer from computational complexity and premature convergence. It is also observed that with the growing penetration of DGs into distribution systems, adaptive DOCR coordination approaches achieve superior performance over the deterministic DOCRs coordination approaches. Considering the above deficiencies, in this paper, a new efficient optimization algorithm-assisted adaptive protection scheme is proposed for optimal coordination of DOCRs in DG integrated multi-loop distribution networks.

1.3 Contribution and paper organization

In this paper, the optimal coordination of DOCRs is determined by a nature-inspired dragonfly algorithm (DA) [37] deployed in multi-loop power distribution networks. The static and dynamic swarming behaviour of dragonflies are the main motivation of the proposed optimization technique. The exploration and exploitation phases of the optimization technique are modelled using the societal communication of dragonflies in navigating, finding for food and escaping away from enemies when swarming dynamically or statistically. The suggested DA has extraordinary exploration competency and speed as compared to the existing meta-heuristic techniques [14, 26, 47, 48, 54]. Further, an adaptive protection scheme assisted by DA is proposed to solve the DOCRs coordination problems of multi-loop distribution systems integrated with intermittent DGs. The efficacy of the proposed adaptive DOCR coordination scheme is evaluated and compared with the existing approaches [11, 17, 49] considering the dominant changes in the network topologies and operating modes.

The reminder of the manuscript is arranged as follows. The DOCRs coordination problem formulation using DA is elaborated in Sect. 2. The proposed adaptive DOCRs coordination scheme is elaborated in Sect. 3. The performance comparison results are demonstrated and discussed in Sect. 4. The conclusion of the paper is provided in Sect. 5.

2 Problem formulation for optimal coordination of DOCRs

2.1 Objective function and coordination constraints

The coordination problem of DOCRs in a meshed distribution networks can be formulated as an optimization problem having objective functions subjected to certain sets of constraints. The objective is to minimize the sum of the operating times of all the DOCRs present in the system for the near-end three-phase short circuit fault. Therefore, the first objective function S can be expressed as [14],

$$S = \min\left(\sum_{i=1}^{n}\sum_{k=1}^{l} w_{ik} \times T_{ik}\right) \tag{1}$$

Subjected to

$$\mathrm{PS}_i^{\min} \le \mathrm{PS}_i \le \mathrm{PS}_i^{\max} \tag{2}$$

$$\mathrm{TMS}_i^{\min} \le \mathrm{TMS}_i \le \mathrm{TMS}_i^{\max} \tag{3}$$

$$\mathrm{CTI} \geq T_{jk} - T_{ik} \tag{4}$$

$$T_{ik}^{\min} \leq T_{ik} \leq T_{ik}^{\max} \tag{5}$$

In (1), T_{ik} is the operating time of relay R_i for fault at kth location and n is the number of relays in the system. l is the total number of fault locations and w_{ik} is the probability of occurrence of fault in each location of the protective zone. In the present study, w_i is assigned as 1 for all relays assuming the probability of occurrence of fault in all buses are same [15]. In (2), $\mathrm{PS}_i^{\min}$ and $\mathrm{PS}_i^{\max}$ represent the minimum and the maximum limits of PS for relay R_i, respectively. In this study, the limits of $\mathrm{PS}_i^{\min}$ and $\mathrm{PS}_i^{\max}$ are set as 0.5 and 2.5, respectively [50]. In (3), $\mathrm{TMS}_i^{\min}$ and $\mathrm{TMS}_i^{\max}$ represent the minimum and the maximum limits of TMS for relay R_i. In the present study, the minimum and maximum values of TMS are set as 0.1 and 1.1, respectively [18]. In (4), T_{ik} and T_{jk} are the operating times of primary relay R_{ik} and its first backup relay R_{jk} for fault at kth location, respectively. The value of coordination time interval (CTI) used for electromechanical relays is 0.3–0.4 s, while for numerical relays its value used is in the range of 0.1 s and 0.2 s [51].

T_{ik}, the operating time of a standard inverse definite minimum time (IDMT) relay R_i can be expressed as [15],

$$T_{ik} = \frac{\mathrm{TMS}_i \times \beta}{\left(\frac{I_{R_i,k}}{\mathrm{PS}_i}\right)^{\alpha} - 1} \tag{6}$$

where $I_{R_i,k}$ is the fault current seen by relay R_i. PS_i and TMS_i are the plug setting and time multiplier setting of relay R_i, respectively. The values of $\alpha = 0.02$, and $\beta = 0.14$ of a standard IDMT relay [12] is used in the present study.

2.2 Dragonfly algorithm for optimal coordination of DOCRs

The literature study clearly shows that the optimization techniques available for solving the DOCRs coordination problem are based on either evolutionary algorithm (EA) or swarm intelligence (SI) optimization techniques. It is observed that SI techniques store data of possible solution space, while no such data are stored in EA-based optimization techniques. Also, SI-based techniques possess fewer controlling parameters and having fewer operators to handle. Therefore, SI-based techniques can be more promising towards the solution of DOCRs coordination problem. An effective swarm intelligence optimization technique named as dragonfly algorithm (DA) is proposed in [46]. The static and dynamic swarming behaviour of dragonflies is the main motivation of the proposed optimization technique. The exploration and exploitation phases of the optimization technique are modelled using the societal communication of dragonflies in navigating, finding for food and escaping away from enemies when swarming dynamically or statistically. In static swarm, dragonflies make small sub-swarms and progress over diverse region which is the basic idea of exploration phase while dragonflies progress in bigger swarm and along one path which is encouraging in exploitation phase. In the search progression, the location and fitness of the food source are updated using the candidate with best fitness. Moreover, the worst candidate updates the fitness and the location of the enemy which results into the convergence to desired search location and moving away from undesired search locations.

The swarming behaviour of dragonflies follows certain principles, namely separation, alignment and cohesion. Apart from these principles, survival is the main aim of each swarm such that every swarm gets attracted towards the food sources and diverted away from enemies.

1. *Separation* represents the static collision avoidance with neighbourhood individuals.

$$S_i = -\sum_{j-1}^{M} X - X_j \tag{7}$$

where X represents the position vector of current individual, X_j is the position of jth neighbouring individual and M is the number of neighbouring individuals.

2. *Alignment* represents the individual's velocity identical with other neighbourhood individuals of similar group.

$$A_i = \frac{\sum_{j-1}^{M} V_j}{M} \tag{8}$$

where V_j represents the velocity of jth individual.

3. *Cohesion* represents the tendency of individuals towards the centre of the swarms group.

$$C_i = \frac{\sum_{j-1}^{M} X_j}{M} - X \tag{9}$$

4. *Attraction* towards the food source (F) is represented as,

$$F_i = F_p - X \tag{10}$$

where F_i represents the food source of the ith individual and F_p is the position of the food source.

5. *Distraction* from the enemies is modelled mathematically as,

$$E_i = E_p + X \tag{11}$$

The operational behaviour of dragonfly algorithm is a mixture of above five remedial prototypes. Step vector (ΔX)

and position vector (X) are the two components for controlling the movement of dragonflies. The step vector guides the direction of progress of the dragonflies and can be mathematically expressed as,

$$\Delta X_{t+1} = (sS_i + aA_i + cC_i + fF_i + eE_i) + w\Delta X_i \quad (12)$$

where s is the weight of separation, S_i is the ith individual separation, a is the weight of alignment, A_i is the ith individual alignment, c is the weight of cohesion, C_i is the ith individual cohesion, f is the food factor, F_i is the food source of ith individual, e is the enemy factor, E_i is the location of enemy of the ith individual, w is the weight of inertia and t is current iteration tally.

The position vector is updated by the addition of current step vector and previous position vector and can be expressed as,

$$X_{t+1} = X_t + \Delta X_{t+1} \quad (13)$$

where t is the current iteration tally.

Proper adjustment of each coefficient will improve the exploration and exploitation phases during the optimization. In other words, equilibrium between exploration and exploitation phases is maintained by fine tuning of coefficients. When no promising solution space is found in neighbourhood, dragonflies start flying in the region of the search space using a casual walk (Lèvy flight) to satisfy the exploration process of artificial dragonflies. In that scenario, position updation takes place as,

$$X_{t+1} = X_t + \text{Lèvy}(d) \times X_t \quad (14)$$

where d represents the dimension of position vectors and t is the iteration count.

The Lèvy flight is determined as,

$$\text{Lèvy}(x) = 0.01 \times \frac{r_1 \times \sigma}{|r_2|^{\frac{1}{\beta}}} \quad (15)$$

where β is a constant having value equal to 1.5, r_1 and r_2 are random numbers in the range of [0, 1] and σ can be represented as [46],

$$\sigma = \left(\frac{\Gamma(1+\beta) \times \sin\frac{\pi\beta}{2}}{\Gamma\left(\frac{1+\beta}{2}\right) \times \beta \times 2^{\left(\frac{\beta-1}{2}\right)}} \right)^{1/\beta} \quad (16)$$

where $\Gamma(x) = (x-1)!$.

The flowchart of the proposed dragonfly optimization algorithm is shown in Fig. 1.

3 The proposed adaptive DOCRs coordination scheme

The presence of DGs in distribution system can result in large number of possible network topologies for which new relay settings are necessary. However, the network topologies for which considerable change in the fault current level observed with respect to the base model are considered in the proposed adaptive DOCRs protection coordination scheme. The functional block diagram of the proposed adaptive DOCRs coordination scheme is shown in Fig. 2. As shown in the figure, the dominant operational or topological changes if occurs in the system, it will be sensed at central protection unit (CPU) placed at the control centre in online mode by monitoring the status of the circuit breakers and current measurements at the relay locations. The CPU will compare the present load current with the existing relay settings and update the relay settings as soon as any significant topological change occurs in the existing system.

The proposed adaptive DOCRs coordination scheme considers the following factors for updating the relay settings.

3.1 DG penetration level

The power shared by the utility grid is decided based on the penetration level of DGs and can be expressed as [52],

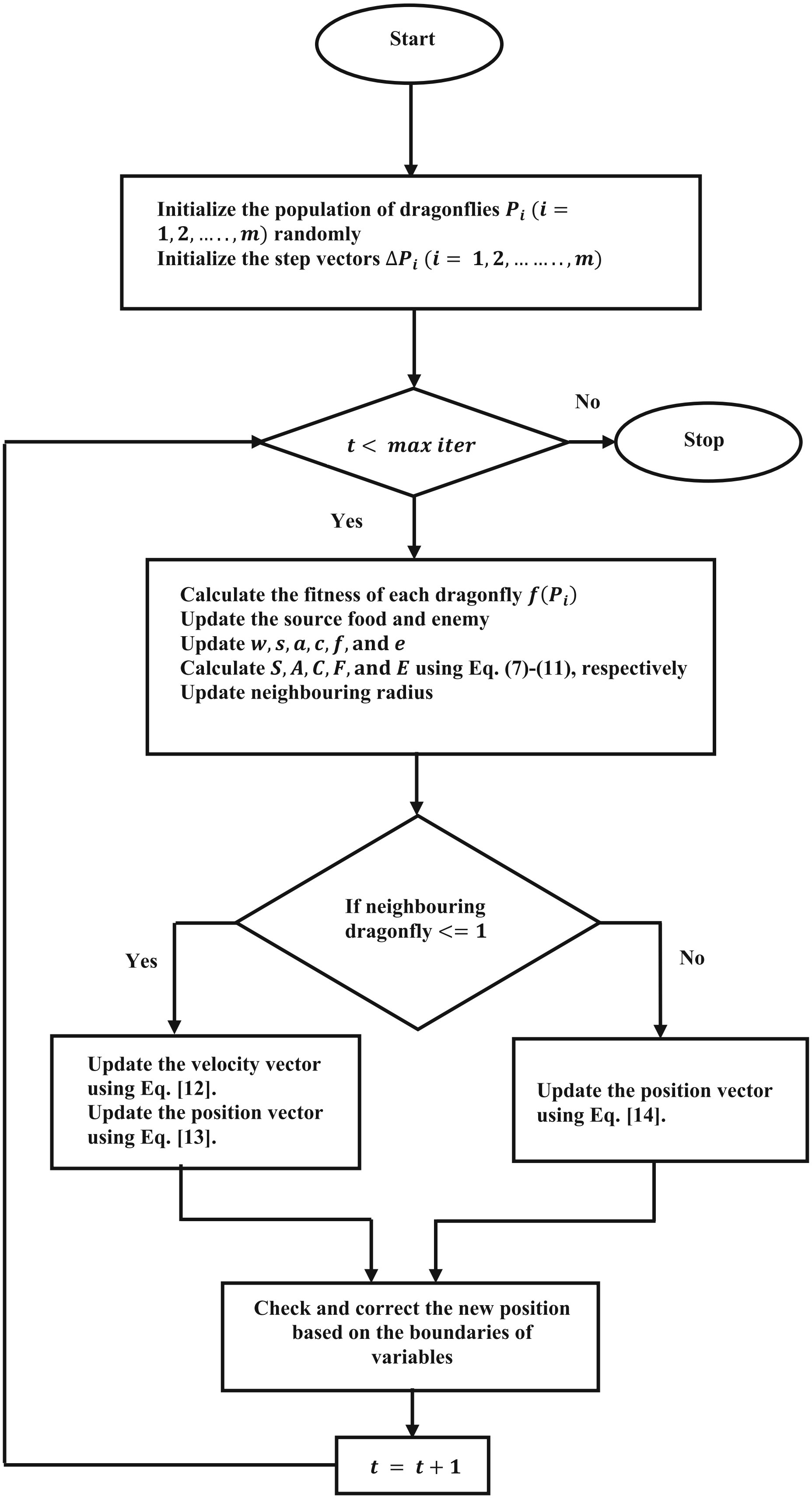
$$\%\text{DG}_{\text{Penetration Level}} = \frac{P_{\text{DG}}}{P_{\text{DG}} + P_{\text{Grid}}} \times 100 \quad (17)$$

where P_{Grid} and P_{DG} are power delivered by the utility grid and DGs, respectively. The penetration of DGs primarily depends on the load demand. Whenever load increases the penetration level of DGs also increases as the grid power remains constant. The maximum penetration level is taken in the present article is lower than 33% of the grid power [52]. It is observed in the proposed adaptive DOCRs coordination scheme that with increase in the penetration level of DGs in existing system, the fault current level also increases and hence it is necessary to update the respective primary and backup relay settings such that the coordination between them remains unaltered.

3.2 Load variation level

Load variation plays an important role in designing adaptive protection strategy. As already discussed, the variation in load current is directly related to the lower bound of the plug setting. As the load increases, the plug settings must be readjusted according to the new conditions to avoid the violations of the relay coordination constraints.

Fig. 1 Flowchart of the proposed dragonfly optimization algorithm



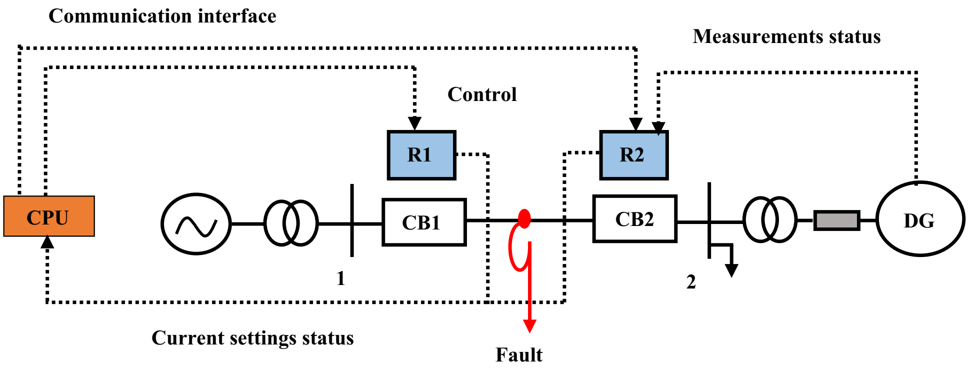


Fig. 2 Centralized adaptive DOCRs coordination scheme

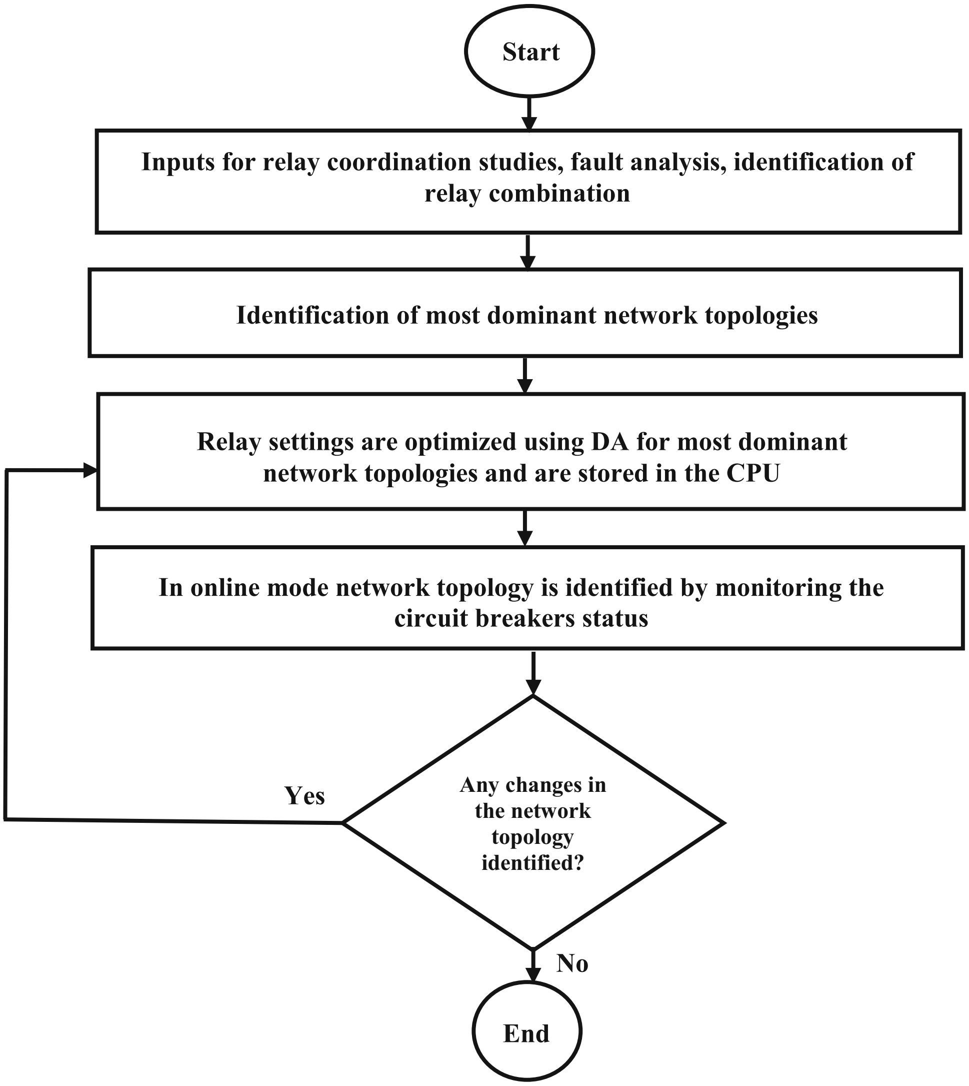


Fig. 3 Flowchart of the proposed adaptive protection scheme

3.3 Placement of DG locations

DGs of varying capacities are placed at various locations of the distribution networks. It is necessary to test the feasibility and their effects on the fault current. It is observed that contribution of fault current is more when DGs are placed near to pre-existing generator bus, but when the DGs are placed far away from the generator buses the fault current contribution is not that much significant.

The flowchart of the DA-assisted adaptive DOCRs coordination scheme proposed is shown in Fig. 3.

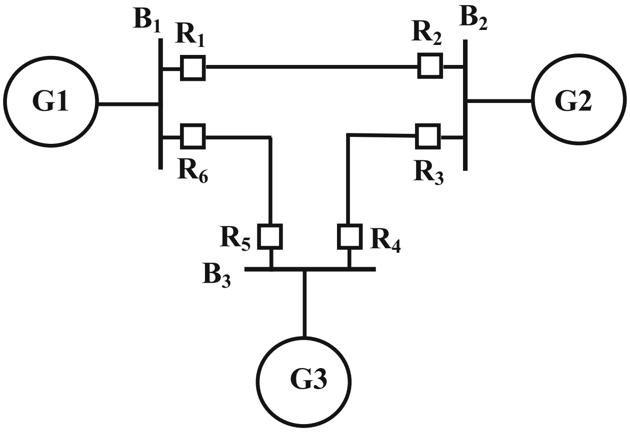


Fig. 4 Single-line diagram of the 3-bus system

4 Results and discussion

4.1 Implementation of DA for DOCRs coordination in fixed network topology

As mentioned earlier, DA is implemented on the base case network topologies of 3-bus, 8-bus and 15-bus test systems. The DA results are compared with existing optimization approaches (SA [14], IGWO [47], HWOA [26], MILP [48], SCA [54], SQP-Approach-I [11], OCDE2 [17], GA [17] and BEX-PM [49]) for DOCRs coordination. The results for each case are demonstrated as below. The proposed algorithm is programmed in MATLAB software installed on a personal computer with i-7 processor, 1.8 GHz clock speed and 16 GB RAM.

4.1.1 3-bus system

Figure 4 shows the schematics of the 3-bus (B_1–B_3) system. As observed in the figure, the test system consists of three generators (G1–G3) and six DOCRs (R_1–R_6). The detail specification of each of the components of the system is provided in [8]. For DOCRs coordination, the three-phase fault current at each bus is calculated by initiating a three-phase fault at the middle of each line similar to [8] and the current transformer (CT) ratio of each relay and their pickup tap settings are set similar to [8].

The optimum values of PS and TMS for each fault case are calculated using DA, and the results are compared with existing SA [14], IGWO [47] and SCA [54] provided in Table 1. As observed from the table, the proposed algorithm takes 1.3357 s to operate all the primary relays which is least compared to the available algorithms. Thus, the proposed DA exhibits superior performance in achieving the optimal DOCRs settings compared to the existing optimization algorithms.

As observed from Table 2, the entire primary and backup relay pairs are operated within the coordination constraints

Table 1 Comparative results of optimal DOCRs settings for the 3-bus system

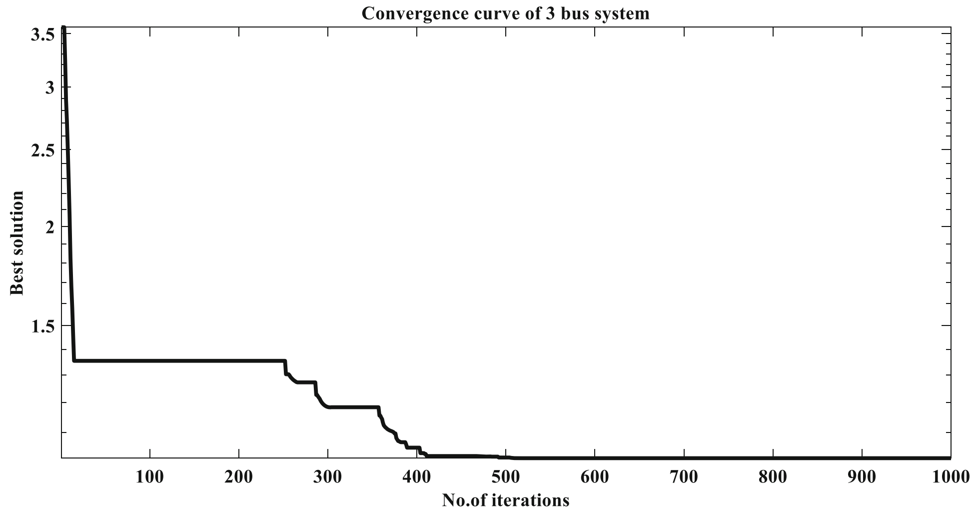
Relay no.	Proposed algorithm		SA [14]		IGWO [47]		SCA [54]	
	TMS	PS	TMS	PS	TMS	PS	TMS	PS
1	0.1000	2.0	0.1070	2.50	0.1000	1.5000	0.1000	2.0
2	0.1000	2.5	0.1080	2.00	0.1000	2.6166	0.1061	2.5
3	0.1000	2.5	0.1000	3.00	0.1001	2.9770	0.1000	2.5
4	0.1000	0.6	0.1000	2.50	0.1000	1.5858	0.1000	2.0
5	0.1000	2.5	0.1000	2.50	0.1000	2.8169	0.1000	1.0
6	0.1000	0.8	0.1120	1.50	0.1000	1.5009	0.1000	2.0
Total Time (s)	**1.3357**		1.599		1.4789		1.4419	

Bold denotes the proposed technique which gives better result

Table 2 CTI between primary and backup relay pairs for the 3-bus system

Relay no.	Backup relay settings			Primary relay settings			CTI
	TMS	PS	T_{op}	TMS	PS	T_{op}	
1	0.1301	2.5	0.5521	0.1	2	0.2386	0.3134
2	0.1324	2	0.5848	0.1	2.5	0.2443	0.3405
3	0.1452	2.5	0.5810	0.1	2.5	0.2362	0.3448
4	0.1303	2.5	0.5826	0.1	0.6	0.1693	0.4134
5	0.1121	2.5	0.5575	0.1	2.5	0.2462	0.3113
6	0.1385	1.5	0.5792	0.1	0.8	0.2009	0.3782

Fig. 5 Convergence curve for 3-bus system



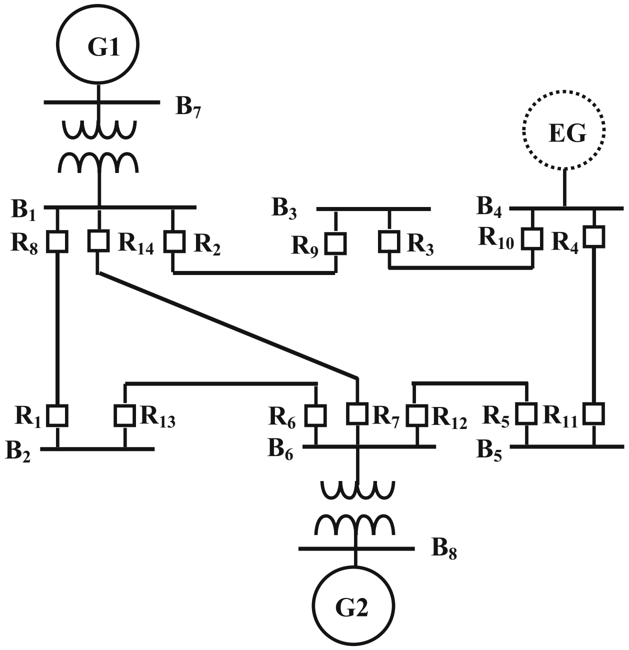


Fig. 6 Single-line diagram of the 8-bus system

and the CTIs for each relay pairs obtained are exceeding 0.3 s [14]. The convergence characteristic shown in Fig. 5 for the 3-bus system clearly shows faster converges achieved within 40% of the total iterations. The computation time for this system is 0.821 s.

4.1.2 8-bus system

The schematic diagram of the 8-bus (B_1–B_8) system is shown in Fig. 6. As observed, it consists of two generators (G1 and G2), seven lines and fourteen DOCRs (R_1–R_{14}). There is also a link to the external grid (EG) at bus 4 modelled by short circuit power of 400 MVA [14]. For this case, the CT ratios for relays R_1, R_2, R_4, R_5, R_6, R_8, R_{10}, R_{11}, R_{12} and R_{13} are set as 1200:5, whereas CT ratios for relays R_3, R_7, R_9 and R_{14} are set as 800:5.

The comparative result of the proposed DA with existing MILP [48], SA [14] and HWOA [26] optimization algorithms for the 8-bus system is provided in Table 3. The observation on the results clearly shows that among the different optimization approaches, the proposed DA is able to achieve minimum overall operating time of all the primary relays and hence superior in solving the DOCRs coordination problem. In this case also, as observed from Table 4, none of the primary and backup relay pairs are violating the CTI constraints. Also, they have high convergence speed achieved within 40% of the total iterations (Fig. 7). The computation time for this system is 1.15 s.

4.1.3 15-bus system

Figure 8 shows the schematics of the 15-bus system. As observed, it has seven generators (G_1–G_7), twenty-one lines and forty-two DOCRs (R_1–R_{42}). In addition, many synchronous DGs are also installed. The synchronous reactance of each of the DGs is 15% with 15 MVA and 20 kV ratings, whereas short circuit capacity of the external grid is 200 MVA [14]. The system data, CT ratio of each relay as well as fault data, are taken similar to [14].

The performance of the proposed DA is compared with IGWO [47], SA [14] and SCA [54] for optimal coordination of DOCRs in the15-bus system, and the results are provided in Table 5. The observation in the results clearly shows that the overall operating times of all the primary relays of the proposed DA is drastically reduced compared to the existing algorithms. In this case also, none of the relay pairs have

Table 3 Comparative results of optimal DOCRs settings for the 8-bus system

Relay no.	Proposed algorithm		MILP [48]		SA [14]		HWOA [26]	
	TMS	PS	TMS	PS	TMS	PS	TMS	PS
1	0.1000	2.5	0.0772	2.500	0.113	2.0	0.1	1.25
2	0.1000	0.5	0.2548	2.500	0.260	2.5	0.5381	1.25
3	0.1000	0.5	0.2185	2.500	0.225	2.5	0.1	1.25
4	0.1000	0.5	0.1531	2.500	0.160	2.5	0.2164	1.25
5	0.1000	2.5	0.0903	2.500	0.1	2.5	0.1	1.25
6	0.1000	2.5	0.1506	2.500	0.173	2.5	0.2689	1.25
7	0.1000	0.5	0.2391	2.500	0.243	2.5	0.1	1.25
8	1.1000	0.6	0.1484	2.500	0.170	2.5	1.1	1.25
9	0.1000	0.5	0.1473	2.500	0.147	2.5	0.1	1.25
10	0.1000	2.5	0.1759	2.500	0.176	2.5	0.1	1.25
11	0.1000	2.5	0.1869	2.500	0.187	2.5	0.1	1.25
12	0.1000	0.5	0.2664	2.500	0.266	2.5	0.1	1.25
13	0.1000	0.5	0.0784	2.000	0.114	2.0	0.1	1.25
14	0.1000	2.5	0.2459	2.500	0.246	2.5	0.1	1.25
Total time (s)	**5.479**		8.0061		8.4270		5.8568	

Bold denotes the proposed technique which gives better result

Table 4 CTI between primary and backup relay pairs for the 8-bus system

Relay no.	Backup relay settings			Primary relay settings			CTI
	TMS	PS	T_{op}	TMS	PS	T_{op}	
1	0.1097	1.5	0.7472	0.1000	2.5	0.4087	0.3381
2	0.1485	2.5	0.5738	0.1000	0.5	0.1726	0.4012
3	0.2185	1.5	0.6693	0.1000	0.5	0.1775	0.4914
4	0.1515	2.5	0.7545	0.1000	0.5	0.1959	0.5582
5	0.1	2.5	1.0065	0.1000	2.5	0.4978	0.5087
6	0.1475	2.5	0.6028	0.1000	2.5	0.2947	0.3081
7	0.1410	2.5	0.6260	0.1000	0.5	0.1606	0.4651
8	1.1	0.5	2.3182	1.1000	0.6	1.9799	0.3382
9	0.1545	2	0.8262	0.1000	0.5	0.1968	0.6293
10	0.1432	2.5	0.6955	0.1000	2.5	0.3678	0.3277
11	0.1374	2.5	0.6962	0.1000	2.5	0.3774	0.3188
12	0.147	2.5	0.5548	0.1000	0.5	0.1728	0.3820
13	0.1162	1.5	0.7983	0.1000	0.5	0.2107	0.5876
14	0.1369	2.5	0.6109	0.1000	2.5	0.2659	0.3449

violated the CTI constraints (Table 6). The observation on the convergence curve also confirms fast convergence speed and is achieved within 45% of the total iterations (Fig. 9). The computation time for this system is 2.192 s.

Table 6 represents the coordination among primary and backup relay. As observed from Table 6, none of the primary and backup relay pairs are violating the CTI constraints.

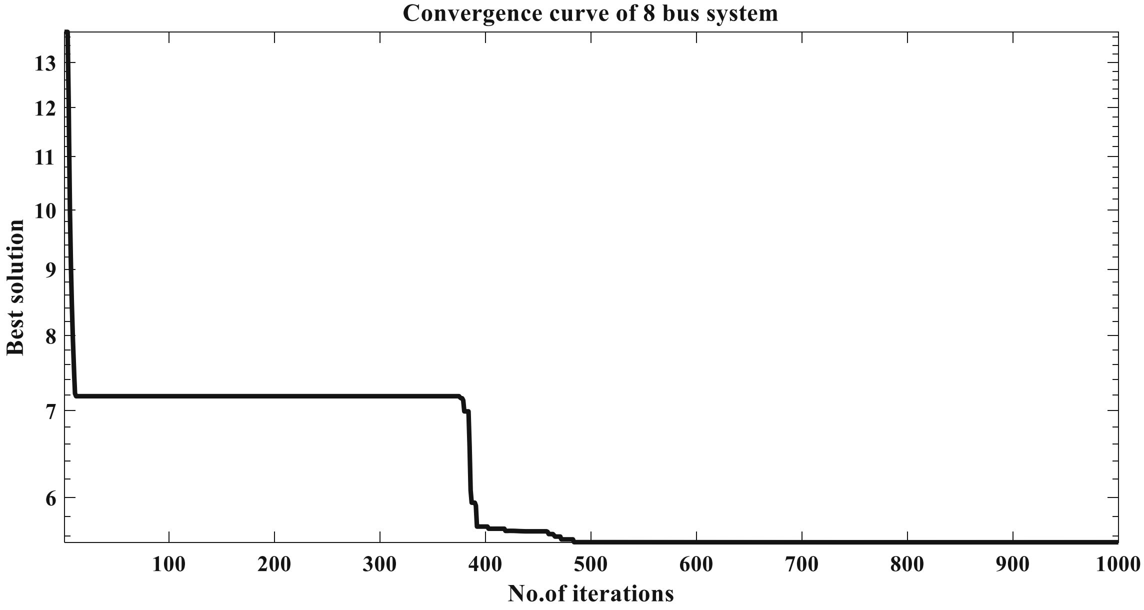


Fig. 7 Convergence curve for the 8-bus system

4.2 Implementation of the proposed adaptive DOCR coordination scheme

4.2.1 6-bus system

A sample 6-bus (B_1–B_6) system as shown in Fig. 10 is considered for implementing the proposed adaptive DOCRs coordination scheme. The system has three generators (G_1–G_3) and 14 DOCRs (R_1–R_{14}) that are installed for effective protection of the whole system. The detail system specifications are available in [11]. The CT ratio of each relay is set as 400:5 considering three-phase faults at the middle of each line.

To meet the ever-expanding demand of load, two possible ways are either to increase the preinstalled generators capacity or to install DGs near the load bus. Between the two possible conditions, the second option is more preferable as the installation of DGs near the load bus enhances power quality as well as the users are benefited with stable and economic power. Therefore, keeping in view of the increased load demand, various possible combination having varying capacities of DGs are installed at the load buses (B_4, B_5 or B_6). Installation of DGs will lead to increase in load current as well as fault current. The DOCRs coordination settings for the base model may not be appropriate in such situation. Hence, the settings of DOCRs must be modified so that the total operating times of all the primary relays will be minimum and coordination between none of the primary and backup relay pairs will be violated. In the proposed adaptive DOCRs coordination scheme, for different possible network topologies, different sets of optimal DOCRs coordination settings are determined in advance using DA and it is saved in the substation control computer. With the prevailing system operating condition and topology, the most appropriate DOCRs will be chosen adaptively so that DOCRs coordination violations can be minimized.

In this study, the optimal settings of DOCRs are computed for three possible operating conditions and topologies. The first topology is the base case topology of the 6-bus system where no additional DGs are installed. In the second topology, two DGs each of 40 MW capacity are installed at buses B_4 and B_6 of the base case of the 6-bus system. In the third topology, three DGs each of 40 MW capacity are installed at buses B_4, B_5 and B_6 of the base case of the 6-bus system. The total operating times of all the primary relays calculated using DA for the three different operating conditions and topologies are provided in Table 7. The total operating times are found to be 5.6059 s, 5.1377 s and 4.4126 s for the first, second and third operating conditions and topologies, respectively. The results clearly show that the total operating times of all the primary relays are decreased with the increasing penetration levels of DGs. This indicates that with the increasing penetration of DGs the relays should have faster response for selective tripping of the faulted section.

The comparative assessment result of the proposed adaptive DA optimization algorithm for DOCRs coordination for the base case model of the 6-bus system with three existing optimization techniques, namely SQP-Approach-I [11], OCDE2 [17], GA [17] and BEX-PM [49], is provided in Table 8. As seen in the table, a significant reduction in the overall operating times of DOCRs is achieved by the proposed DA compared to the available techniques. Hence, the

Fig. 8 Single-line diagram of the 15-bus system

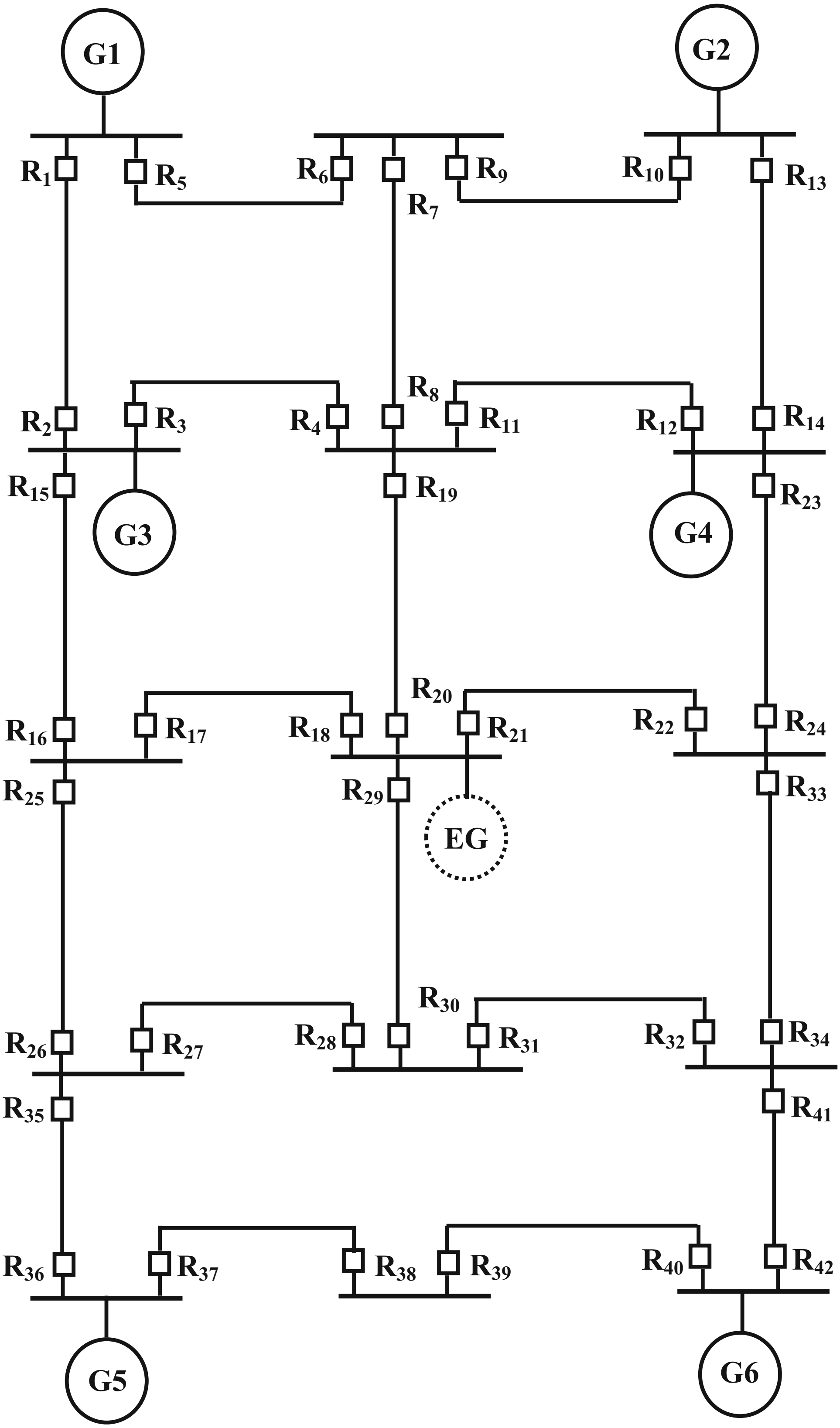


Table 5 Comparative results of optimal DOCRs settings for the 15-bus system

Relay no.	Proposed algorithm		IGWO [47]		SA [14]		SCA [54]	
	TMS	PS	TMS	PS	TMS	PS	TMS	PS
1	0.1000	0.5	0.1001	2.8114	0.118	1.0	0.1000	2.5
2	0.1000	0.5	0.1000	1.5104	0.101	1.0	0.1158	1.5
3	0.1000	0.5	0.1048	1.7950	0.105	2.0	0.1685	0.5
4	0.1000	0.5	0.1002	3.0701	0.115	1.0	0.1000	2.0
5	0.1000	0.5	0.1003	1.5191	0.109	2.0	0.1000	2.5
6	0.1000	0.5	0.1004	1.5367	0.108	2.0	0.1000	2.5
7	0.1000	0.5	0.1000	2.4252	0.106	2.0	0.1000	1.5
8	0.1000	0.5	0.1012	2.3699	0.108	1.5	0.1248	1.5
9	0.1000	0.5	0.1030	2.0256	0.106	2.0	0.1000	0.5
10	0.1000	0.5	0.1000	1.5244	0.112	1.5	0.2143	0.5
11	0.1000	0.5	0.1002	2.5299	0.100	1.5	0.1000	0.5
12	0.1000	0.5	0.1008	2.8068	0.100	1.5	0.1568	2.0
13	0.1000	0.5	0.1004	2.4412	0.107	2.0	0.1000	2.5
14	0.1000	0.5	0.1001	1.6608	0.111	1.0	0.1130	1.0
15	0.1000	0.5	0.1000	1.5666	0.103	1.0	0.1000	1.0
16	0.1000	0.5	0.1001	1.7755	0.100	1.5	0.1432	0.5
17	0.1000	2.5	0.1008	1.5505	0.100	2.0	0.1294	0.5
18	0.1000	0.5	0.1130	1.6783	0.105	1.0	0.1620	0.5
19	0.1000	0.5	0.1003	2.1283	0.102	2.0	0.1000	0.5
20	0.1000	0.5	0.1040	1.5726	0.100	1.5	0.1341	2.5
21	0.1000	0.5	0.1002	2.0357	0.166	0.5	0.1000	0.5
22	0.1000	0.5	0.1001	1.5461	0.109	1.5	0.1500	1.0
23	0.1000	0.5	0.1000	1.5502	0.109	1.0	0.1362	2.5
24	0.1000	0.5	0.1002	1.6656	0.100	1.5	0.1000	0.5
25	0.1000	0.5	0.1002	1.5019	0.103	2.0	0.1000	2.5
26	0.1000	0.5	0.1002	2.9163	0.112	1.5	0.1000	2.5
27	0.1000	2.5	0.1002	2.1045	0.104	2.0	0.1000	0.5
28	0.1000	0.5	0.1002	1.5029	0.105	2.5	0.1414	0.5
29	0.1000	0.5	0.1017	1.6389	0.104	1.5	0.1000	0.5
30	0.1000	0.5	0.1006	2.1199	0.101	2.0	0.1000	0.5
31	0.1000	0.5	0.1000	2.0376	0.100	2.0	0.1000	0.5
32	0.1000	0.5	0.1008	3.0167	0.105	1.5	0.1000	2.5
33	0.1000	0.5	0.1012	1.5459	0.100	2.5	0.1000	0.5
34	0.1000	0.5	0.1006	1.5149	0.107	2.5	0.1154	2.0
35	0.1000	0.5	0.1002	1.9585	0.103	2.0	0.1519	2.5
36	0.1000	0.5	0.1002	3.3271	0.100	2.0	0.1374	1.5
37	0.1000	0.5	0.1016	1.7971	0.103	2.5	0.1125	2.5
38	0.1000	0.5	0.1002	2.5855	0.106	2.5	0.1000	1.0
39	0.1000	0.5	0.1004	2.7681	0.103	2.5	0.1000	1.0
40	1.1000	2.5	0.1010	2.5714	0.104	2.5	0.1000	0.5
41	0.1000	0.5	0.1003	1.7723	0.104	2.5	0.1000	2.5
42	0.1000	0.5	0.1001	3.4527	0.104	1.5	0.1000	1.5
Total time (s)	**11376**		126446		12227		119535	

Bold denotes the proposed technique which gives better result

Table 6 CTI between primary and backup relay pairs for the 15-bus system

Relay no.	Backup relay settings			Primary relay settings			CTI
	TMS	PS	T_{op}	TMS	PS	T_{op}	
1	0.1	2.5	0.9173	0.1000	0.5	0.1766	0.7406
2	0.1147	1	0.5885	0.1000	0.5	0.1850	0.4034
3	0.1003	2.5	0.5463	0.1000	0.5	0.1722	0.3741
4	0.1	2.5	0.7700	0.1000	0.5	0.1876	0.5824
5	0.1235	2	0.5779	0.1000	0.5	0.1809	0.3970
6	0.1547	2	0.6509	0.1000	0.5	0.1779	0.4729
7	0.1	2.5	0.5276	0.1000	0.5	0.1808	0.3468
8	0.1926	1.5	0.9109	0.1000	0.5	0.1839	0.7269
9	0.13	1.5	0.5188	0.1000	0.5	0.1729	0.3459
10	0.1099	2.5	0.7534	0.1000	0.5	0.1774	0.5760
11	0.2015	0.8	0.6779	0.1000	0.5	0.1881	0.4897
12	0.1	2.5	0.7783	0.1000	0.5	0.1900	0.5883
13	0.1	2.5	0.5218	0.1000	0.5	0.1797	0.3420
14	0.1348	2.5	1.3952	0.1000	0.5	0.1849	1.2102
15	0.1063	1.5	0.7443	0.1000	0.5	0.1838	0.5605
16	0.2312	0.5	0.6271	0.1000	0.5	0.1868	0.4403
17	0.1	2.5	0.6311	0.1000	2.5	0.3058	0.3253
18	0.1173	1	0.5715	0.1000	0.5	0.1696	0.4018
19	0.1183	2.5	0.6637	0.1000	0.5	0.1720	0.4917
20	0.1667	1.5	0.8685	0.1000	0.5	0.1740	0.6945
21	0.1	1.5	0.6819	0.1000	0.5	0.1699	0.5119
22	0.1	2.5	0.5932	0.1000	0.5	0.1731	0.4200
23	0.102	2	0.9946	0.1000	0.5	0.1816	0.8129
24	0.1837	1.5	0.8860	0.1000	0.5	0.1851	0.7009
25	0.1	2.5	0.6282	0.1000	0.5	0.1853	0.4429
26	0.1160	2.5	0.7275	0.1000	0.5	0.1850	0.5424
27	0.1624	2.5	0.9038	0.1000	2.5	0.3609	0.5428
28	0.1	2.5	0.5004	0.1000	0.5	0.1802	0.3201
29	0.1512	1	0.5970	0.1000	0.5	0.1701	0.4269
30	0.1908	0.8	0.5517	0.1000	0.5	0.1787	0.3730
31	0.1	2.5	0.6986	0.1000	0.5	0.1741	0.5245
32	0.1504	1	0.5879	0.1000	0.5	0.1907	0.3971
33	0.1571	1.5	0.5787	0.1000	0.5	0.1849	0.3937
34	0.2136	1.5	0.7006	0.1000	0.5	0.1793	0.5212
35	0.1524	1.5	0.6477	0.1000	0.5	0.1901	0.4576
36	0.1209	2	0.6725	0.1000	0.5	0.1815	0.4910
37	0.1509	1.5	0.5804	0.1000	0.5	0.1812	0.3991
38	0.1097	2.5	0.5098	0.1000	0.5	0.1898	0.3200
39	0.1553	1.5	0.5300	0.1000	0.5	0.1886	0.3414
40	0.75	2.5	4.1313	1.1000	2.5	3.6604	0.4708
41	0.1180	2	0.5288	0.1000	0.5	0.1726	0.3561
42	0.1	1.5	0.5195	0.1000	0.5	0.1813	0.3381

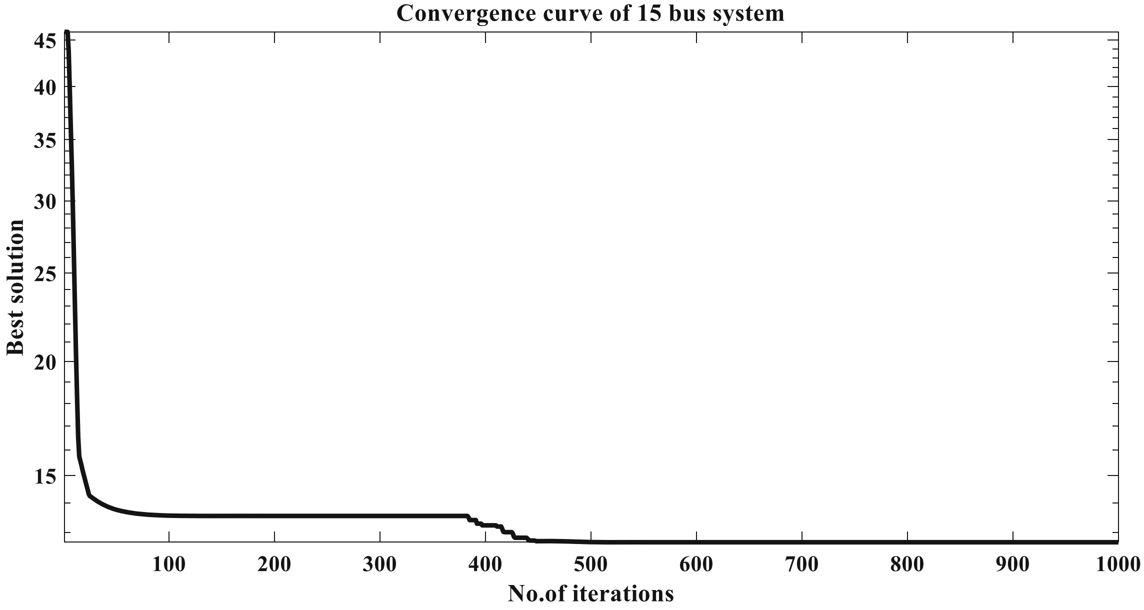
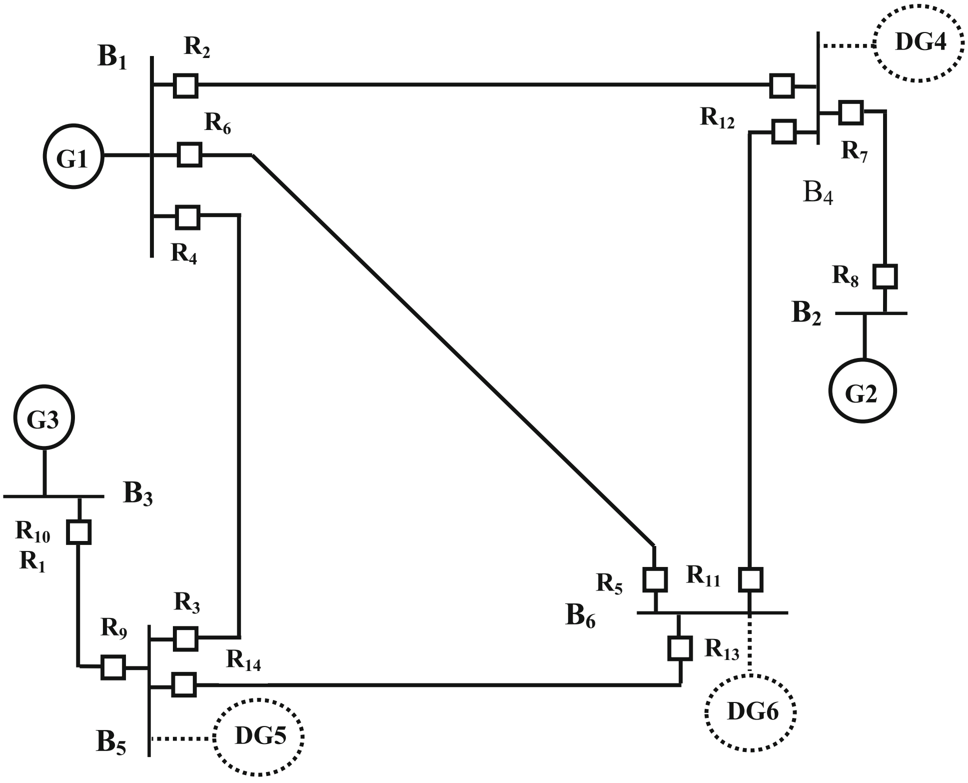


Fig. 9 Convergence curve for the 15-bus system

Fig. 10 Single line diagram of the 6-bus system



proposed approach outperforms in solving the DOCRs coordination problem. The observation on the convergence curve for the base model of the 6-bus system shown in Fig. 11 also confirms fast convergence speed.

4.2.2 IEEE 14-bus system

The efficacy of the proposed adaptive DOCRs coordination scheme is also tested on the IEEE 14-bus system shown in

Table 7 Optimal DOCRs settings for the 6-bus system with and without DGs

Relay no.	Case-I (base case of the 6-bus system)		Case-II (DGs each of 40 MW capacity are installed at buses B_4 and B_6)		Case-III (DGs each of 40 MW capacity are installed at buses B_4, B_5 and B_6)	
	TMS	PS	TMS	PS	TMS	PS
1	0.1	0.756	0.1	0.5	0.1	1.8184
2	0.1	0.5	0.1	0.5	0.1	0.86333
3	0.1	0.81299	0.1	1.2445	0.1	0.85872
4	0.1	2.5	0.1	2.5	0.1	0.97834
5	0.14715	2.5	0.1	0.83827	0.1	0.88276
6	0.1	0.94572	0.1	1.1262	0.1	0.82408
7	0.1	2.5	0.1	1.1942	0.19338	0.9
8	0.1	2.5	0.1	0.5	0.1	0.83135
9	0.1	2.5	0.1	0.5	0.1	0.5
10	0.1	0.5	0.1	1.4062	0.1104	0.67946
11	0.1	0.50931	0.1	0.99195	0.1	0.75418
12	0.1	0.5	0.1	2.5	0.1	0.83573
13	0.1	2.5	0.1	2.5	0.1	0.83042
14	0.1	2.5	0.1	2.5	0.1	0.55946
Operating time (s)	5.6059		5.1377		4.4126	

Table 8 Comparative result of overall optimal operating times of primary relays for the 6-bus system

Proposed DA	SQP-Approach-I [11]	OCDE2 [17]	GA [17]
5.6059 s	10.0470 s	10.3286 s	13.7996 s

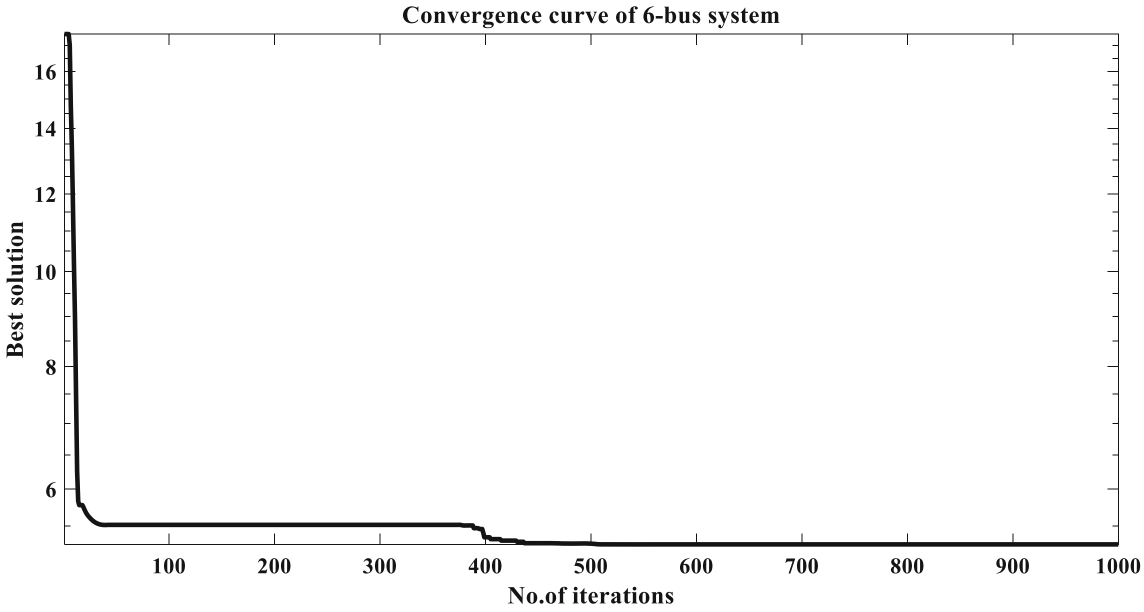


Fig. 11 Convergence curve for the 6-bus system

Fig. 12 Single line diagram of IEEE 14-bus system

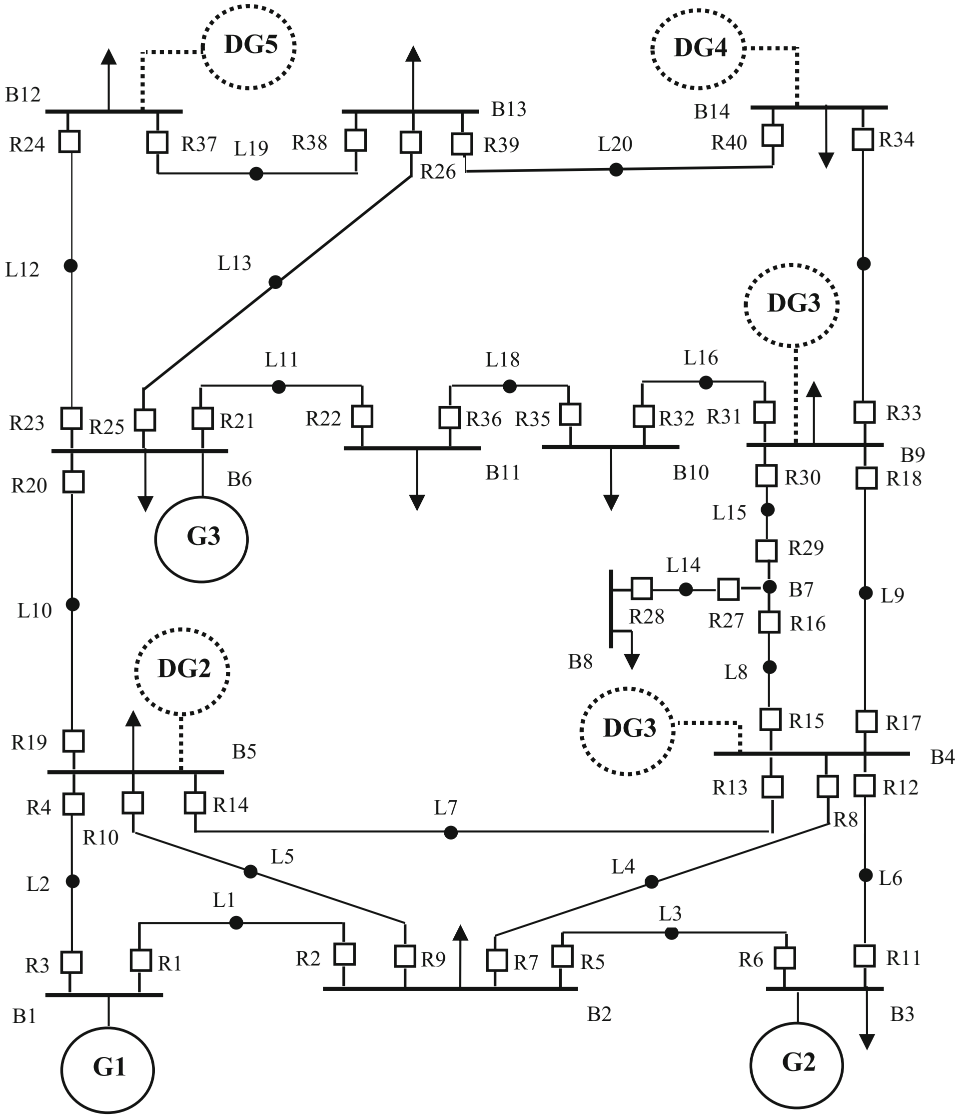


Fig. 12 comprising of three generators (G_1–G_3) and forty DOCRs (R_1–R_{40}). Detail specifications of each of the components of the IEEE 14-bus is provided in [53]. For this system, CT ratios for relays R_1–R_{15}, R_{26} and R_{29} are set as 200:1 and for rest of the relays it is 800:1.

Similar to the 6-bus system, in this case also the optimal settings of DOCRs are computed for three possible topologies. The first topology is the base case topology of the 14-bus system where no additional DGs are installed. In the second topology, two DGs each of 50 MW capacities are installed at buses B_5 and B_{12} of the base case of the 14-bus system. In the third topology, four DGs of capacity 50 MW, 20 MW, 20 MW and 20 MW are installed at buses B_4, B_9, B_{12} and B_{14}, respectively, of the base case of the 14-bus system. The total operating times of all the primary relays calculated using DA for the three different topologies are given in Table 9.

As seen in the table, the total operating times are found to be 34.634 s, 31.9482 s and 27.8817 s for the first, second and third topologies, respectively. The results clearly show that the total operating times of all the primary relays are decreased with the increasing penetration levels of DGs. This indicates that with the increasing penetration of DGs the relays should have faster response for selective tripping of the faulted section.

The comparative assessment result of the proposed adaptive DA optimization algorithm for DOCRs coordination with three existing optimization techniques, namely BEX-PM [49], OCDE1 [49] and GA [17] and Basic DE [49], is given in Table 10. As seen in the table, there is a significant reduction in the overall operating times all the primary relays in the proposed approach compared to the available techniques. The observation on the convergence curve also confirms fast convergence speed as shown in Fig. 13.

Table 9 Optimal DOCRs settings for IEEE 14-bus system with and without DGs

Relay no.	Case-I (base case of the IEEE 14-bus system)		Case-II (DGs each of 50 MW capacity are installed at buses B_5 and B_{12})		Case-III (DGs of 50 MW capacity is installed at bus B_4 and DGs each of 20 MW capacity are installed at buses B_9, B_{12} and B_{14})	
	TMS	PS	TMS	PS	TMS	PS
1	0.1	2.5	0.12204	0.5	0.1012	0.5
2	0.1	0.78017	0.1	1.2619	0.10066	2.5
3	0.16132	0.97507	0.1	0.59841	0.10089	0.71188
4	0.16567	1.392	0.1	0.5	0.1007	1.5
5	0.1	0.78107	0.1	0.70462	0.10075	0.75372
6	0.1	0.81013	0.11958	0.88309	0.10073	0.57918
7	0.15513	0.5	0.1	1.5	0.10083	0.50104
8	0.1	0.75939	0.1	0.61422	0.10086	0.5012
9	0.1695	0.94115	0.1	0.64838	0.10087	1.1143
10	0.10755	0.64245	0.1	0.91649	0.10101	0.96257
11	0.1	0.87871	0.1	0.96204	0.17439	0.73346
12	0.1	0.98768	0.18168	0.60892	0.10071	2.5
13	0.1	1.7738	0.1	2.5	0.10084	0.50152
14	0.27805	0.89469	0.15132	1.5	0.101	0.50105
15	0.13807	0.79619	0.18525	0.89412	0.10056	0.50132
16	0.1	0.72424	0.1	0.72812	0.10057	0.88807
17	0.1	0.5	0.2748	1.1415	0.10064	0.50122
18	0.1	0.67898	0.20246	1.1655	0.10113	0.8236
19	0.4524	0.5	0.1	0.96934	0.12822	0.50163
20	0.12708	0.5	0.12316	0.5	0.1008	0.88979
21	0.1	0.5	0.15395	0.6072	0.1009	0.79826
22	0.17422	0.54624	0.1	1.1798	0.1005	1.1642
23	0.1	0.78085	0.1	0.5	0.10111	0.83967
24	0.26234	1.9864	0.1	0.64977	0.10874	0.50195
25	0.11491	0.60316	0.15509	0.58779	0.10108	0.50107
26	0.15091	0.6433	0.1	1.0858	0.10105	0.50125
27	0.10295	0.5	0.1511	0.65378	0.10068	0.62556
28	0.1	0.90467	0.1	0.68801	0.10078	1.1643
29	0.3586	0.5	0.14788	0.68651	0.10342	0.79631
30	0.1	0.82994	0.1	0.5	0.10108	2.5
31	0.19471	1.0337	0.21474	1.2186	0.10045	0.88549
32	0.1	0.5	0.13272	2	0.10101	0.55574
33	0.18752	0.73305	0.1331	0.5	0.10098	0.50117
34	0.1	0.5	0.15453	0.5	0.10114	0.50116
35	0.23581	0.57785	0.1	1.2931	0.10036	0.73418
36	0.16175	0.88018	0.1	0.6592	0.10076	0.50183
37	0.1	0.6281	0.1	1.554	0.10067	0.87735
38	0.1	1.088	0.15641	1.5	0.10105	0.8651
39	0.1	0.51452	0.15094	0.79806	0.10066	0.61251
40	0.39315	1.2179	0.11486	1.0198	0.1603	0.68493

Table 9 (continued)

Relay no.	Case-I (base case of the IEEE 14-bus system)		Case-II (DGs each of 50 MW capacity are installed at buses B_5 and B_{12})		Case-III (DGs of 50 MW capacity is installed at bus B_4 and DGs each of 20 MW capacity are installed at buses B_9, B_{12} and B_{14})	
	TMS	PS	TMS	PS	TMS	PS
Total time (s)	34.634		31.9482		27.8817	

Table 10 Comparative result of overall optimal operating times of primary relays for IEEE 14-bus system

Proposed DA	BEX-PM [49]	OCDE1 [49]	Basic DE [49]
34.634 s	37.0484 s	37.2540 s	42.7843 s

The % reduction in overall operating times of primary relays when DGs of varying capacity are integrated at different locations of the IEEE 14-bus system is given in Table 11.

As seen in Table 11, with increasing % of penetration levels of DGs, faster reduction of the overall operating times of the relays in the system is observed. Thus, it requires newer settings which can be possible through adaptive DOCRs coordination protection scheme.

5 Conclusion

In the present paper, the optimal coordination problems of DOCRs in multi-loop power distribution networks are solved using the swarm intelligence dragonfly algorithm. The efficacy of the algorithm is tested on 3-bus, 8-bus and 15-bus systems. The computation time for the base case network topologies of 3-bus, 8-bus and 15-bus test systems is 0.821 s, 1.15 s and 2.192 s, respectively. The results of the proposed DA are compared with existing optimization algorithms such as SA [14], IGWO [38], HWOA [39], MILP [40], SCA [46], SQP-Approach-I [11], OCDE2 [17], GA [17] and BEX-PM [41]. The results clearly show superior performance of the proposed DA in achieving minimum overall operating times of all the primary relays as well as maintaining the coordination between the primary and backup relay pairs whereas some of the existing optimization algorithms fail in achieving

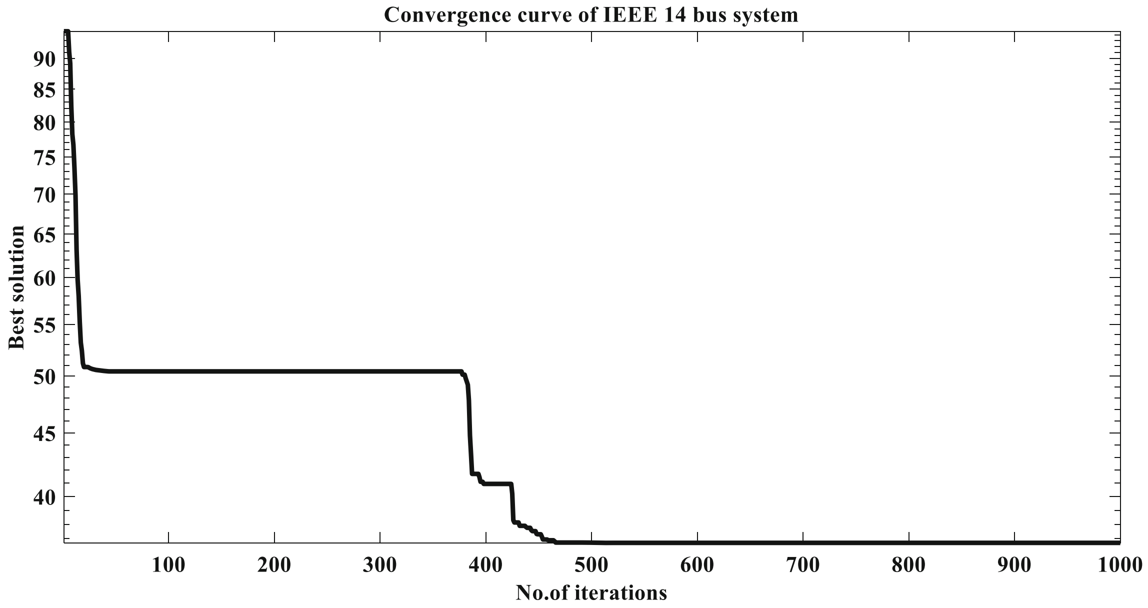


Fig. 13 Convergence curve for IEEE 14-bus system

Table 11 Percentage reduction in overall relay operating times with different levels of DG penetration

Network type	DG location	DG capacity	% Reduction in overall relay operating times	% Reduction (average)
6-bus system	Nil	Nil	44.21	49.7
	B_4 and B_6	40 MW each	48.87	
	B_4, B_5, and B_6	40 MW each	56.09	
IEEE 14-bus system	Nil	Nil	6.51	15
	B_5 and B_{12}	50 MW each	13.767	
	B_4, B_9, B_{12} and B_{14}	50 MW, 20 MW, 20 MW, and 20 MW, respectively	24.743	

this. In the proposed adaptive DOCR coordination scheme, dominant network topologies are identified in advance. Then, for each of the dominant topologies, the optimal settings for the DOCRs are calculated using DA in offline mode and are stored in the substation central computer. Exact operating modes and topologies of the system are identified in online mode by monitoring the circuit breaker status and relay measurements. Based on the prevailing network topologies, the best set of suitable relay settings are chosen and changed in online mode. This helps in minimizing relay miscoordination during dominant changes in the system topologies. Efficacy of the proposed adaptive DOCRs coordination scheme is tested on 6-bus and IEEE 14-bus system and found to be effective in achieving the optimal settings. The computational time of the proposed adaptive DOCR coordination scheme for the 6-bus test system and the IEEE 14-bus system is 1.04 s and 2.83 s, respectively. Compared to the existing methods, the average percentage reduction in overall relay operating times of the proposed adaptive protection scheme for the 6-bus and IEEE 14-bus test systems with different penetration levels of DGs is found to be 49.7% and 15%, respectively.

The proposed DA-assisted optimal coordination problems of DOCRs in multi-loop distribution network are solved considering only three-phase faults at the middle of the interconnected line. As a future extension of the present work, the method will be implemented for single-phase and two-phase faults occurring at different locations of the protected lines. Also, the efficacy of the proposed optimization algorithm will be evaluated on DG integrated multi-loop distribution networks considering the outages of important lines, substations and DGs as well as different operating modes of the microgrids.

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Conflict of interest On behalf of all authors, the corresponding author states that there is no financial or personal conflict of interest.

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