PERFORMANCE COMPARISON OF PSO, HGSO, AND DE OPTIMIZATION TECHNIQUES FOR COMPUTATION OF DIRECTIONAL OVERCURRENT RELAY COORDINATION IN POWER SYSTEMS

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Abstract:

Directional over current relays (DOCRs) have been in use for ensuring the complete protection of the power system network. However, the modern power system is getting complex with the increased penetration of Renewable Energy Source (RES) based distributed generators (DGs), as the current flow become bidirectional. Hence, the system demands faster operation of the protection devices to prevent any major outages. Optimal values of all the DOCR settings viz, TDS and Ip need to be found out such as to minimize the overall time of operation of all the relays in the network. This study focuses on the comparative study of the optimization problem carried out using the prominent optimization algorithms – Particle Swarm Optimization (PSO), Henry Gas Solubility Optimization (HGSO) and Differential Evolution (DE). The ability of techniques is established on IEEE 6 – bus & WSCC 9 – bus test systems for mid-point line faults. The Protection Coordination Problem (PCP) is formulated as non-linear programming (NLP) problem, and the optimal settings of the relays TDS and Ip are achieved using MATLAB R2021a platform and validated the results in POWER WORLD simulator software. The results depict that the HGSO method shows a significant reduction in relays' time of operation compared to PSO, but DE gives superior results compared to other techniques with a minimum computational time.

1 Introduction

The power system comprises a vast integrated generation, transmission, and distribution network along with integration of Renewable Energy Source (RES)s. With the increasing complexity, the chance of occurrence of faults also increases. Traditional distribution systems are designed to allow power flow in one direction, from the substation to the loads. These systems are protected by the standard inverse type overcurrent relays [1]. A proper relay coordination allows for a reduction in the overall time of operation of the relays. The primitive techniques used for relay coordination include trial and error methods and topological analysis techniques. Trial and error method considers initial values of relay parameters. It requires a large number of iterations for convergence. i.e., exhibits a slow rate of convergence. To lower the iteration number needed for convergence, a breakpoint method (or starting relay identification method) was recommended, where in graph-theory approach, it does not need any formation of the loop matrix, and the first relays at every points are identified efficiently. Topological analysis of relay coordination includes Graph theory and Functional approach. These are applied for breakpoint identification. For overcurrent relays, relay coordination is achieved by time grading, where relay operating times are systematically staggered to minimize customer outages. Difficulties arise in attempting to coordinate relays in a mesh system, especially where overlapping

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loops are present. In order to initiate the coordination process, identifying the breakpoints or starting points is an inevitable part [2], [3].

The use of optimization techniques for DOCR coordination started in 1988 [4]. Implementation of Pick-up current (I_p) is set using plug setting (PS). The I_p setting has a high impact on Protection Coordination Problem (PCP). i.e., Fixed PS - linear problem (LP), PS is continuously changing - nonlinear problem (NLP), PS is discrete - mixed integer nonlinear problem (MINLP). In [4], the PCP was framed as NLP. The pick-up current was assumed to be continuous and later on rounded off to a nearby integer value. The rounding off can cause the solution to be outside the feasible region. In [5], [6], relay coordination was implemented using linear programming, assuming pick-up current to be constant. The dynamic variations in topology of the network were also considered in [6]. In LP, supporting variables equal to constraint number are introduced to solve the problem. This limits the number of constraints that can be used. The paper [7] proposes an optimal coordination approach using both LP and NLP techniques. The technique eliminates the use of auxiliary variables. However, all the conventional optimization techniques require a large number of iterations and may result in a local optimal solution. Therefore, the use of various heuristic algorithms or soft computing techniques began for relay coordination [8-11]. These optimization techniques use parallel processing technique yielding a faster convergence rate.

The conventional optimization algorithms were further modified into adaptive algorithms for better results. Some hybrid algorithms which combine two or more algorithms also gave improved outcomes. With increased power demand, RESs are used in distribution networks, which further increases the system complexity. The power flow in such systems is bidirectional [12]. This necessitates faster action for the protection of such distribution networks. The basic electromagnetic type of relays introduces some delay corresponding to the overshoot time due to the disc rotation. Therefore, the conventional relays are replaced by microprocessor or DSP-based relays. For ensuring safe and effectual protection that provides more evident capacities than conventional electromechanical relays, digital microprocessor-based DOCRs are in wide use nowadays. These types of relays offer additional flexibility in controlling the relay constants (α and β) which were earlier constants in standard inverse relays [13]. Also, researchers can adopt the use of some non-standard characteristics that are dependent not only on the magnitude of current but also on the magnitude of voltage for finding a suitable operating time for the relay [14 - 19]. A protection coordination scheme that focuses on dual setting DOCRs is proposed to cope up with the bidirectional power flow [20-21]. For every DOCR, a pair of settings for either direction is provided; two *TDS*s, and two I_p settings. The paper [15] incorporates the non-standard characteristics of relays [13], [14] and dual setting scheme as mentioned in paper [20, 23]. Different heuristic as well as hybrid algorithms are in use today for solving PCP [8] - [11], [22] - [28], their primary goals are minimization of the objective function and search space, and reduce the number of iterations as well as execution time.

This paper presents a comparative study on the computation of the optimum settings of DOCRs coordination in some standard interconnected power systems. Three soft computing technique that have been used are Particle Swarm Optimization (PSO), Differential Evolution (DE) and Henry Gas Solubility Optimization (HGSO) for finding optimum solution. The coordination problem is implemented in the IEEE 6 bus and Western System Coordinating Council (WSCC) 9 bus test systems for different fault conditions.

2 Problem Formulation

An overcurrent relay (OCR) is a single input device with two basic settings, i.e., time dial setting (*TDS*) and pick-up current (I_p) setting. The input to the device is mostly the alternating (AC) current flowing through the line. By varying the *TDS* or time setting multiplier (*TSM)*, the proper time setting is achieved. It helps in controlling the relay operating time. The I_p setting of the relay decides the minimum current above which the relay picks up. The OCRs can be classified into Instantaneous, Definite Time & Inverse Time OCRs. The type of OCRs used in distribution and sub-transmission networks is the inverse type of relay. The operating time of an inverse time OCR is provided in (1).

$$t_{op} = \left(\frac{\beta}{(PSM)^{\alpha} - 1}\right).TDS = \left(\frac{\beta}{\left(\frac{I_f}{I_p}\right)^{\alpha} - 1}\right).TDS \tag{1}$$

where, I_f is the fault current or short circuit current passing through the relay, I_p is the pick-up current and α, β are constants. The values of α and β according to the IEC standard are shown in Table 1.

Table 1. Values of α and β according to IEC Standards.

Relay type	β	α
IDMT	0.14	0.02
Very Inverse	13.5	1
Extremely Inverse	80	2

The objective of the PCP is to minimize the total relay operating times (primary and back-up) without violating the problem constraints. The objective function to be minimized can be stated as in (2).

$$Minimize\ t_{ij} = \sum_{i=1}^{n}\sum_{j=1}^{m}\left(t_{pij} + \sum t_{bij}\right) \tag{2}$$

where t_{ij} is the time of operation of relay R_j for a fault in zone i, t_p is the time of operation of primary relay, t_b is the time of operation of backup relay, i is the fault location reference, j is the relay reference, m is the no. of relays and n is the number of fault points being investigated.

2.1 Problem Constraints

Coordination Constraint: For satisfactory operation, there must be a time gap between backup and primary relay known as the coordination time interval (*CTI*).

$$t_b - t_p \geq CTI \tag{3}$$

Bounds on Time Dial Settings: Limits on *TDS* selection decides the degree of sensitivity of the protection scheme and depends on application.

$$TDS_{min} \leq TDS \leq TDS_{max} \tag{4}$$

Typical values: TDS_{min} = 0.015, TDS_{max} = 1.0

Bounds on Pick-up Currents: In order to prevent maloperation of relay during overload and to ensure operation for the smallest fault.

$$Ip_{min} \leq Ip \leq Ip_{max} \tag{5}$$

where, Ip_{min} is 1.5 times the maximum load current and Ip_{max} is the minimum fault current.

Bounds on Relay Operating Time: To prevent any relay maloperation due to overshoot or transients, a minimum time gap is provided in (6).

$$T_{min} \leq T \leq T_{max} \tag{6}$$

where, T_{min}= 0.1 s and T_{max} depends on the critical clearing time (CCT) to preserve the system stability and prevent equipment damage.

3 Optimization Algorithms

3.1 Particle Swarm Optimization (PSO) algorithm

PSO is an optimization technique used to minimize an objective function by exploring the search space. It is a nature inspired that denotes the communal behaviours of interaction of particles, their environment and among each another. PSO is influenced by a number of control parameters, namely the dimension of the problem, number of particles, number of iterations, acceleration coefficients, neighborhood size, and inertia weight which affect the social components.

The algorithm of PSO is discussed below as shown in Figure 1:

Step 1: Input the data - pop, dim, max iteration, $\boldsymbol{Ip_{min}}$, $\boldsymbol{Ip_{max}}$, $\boldsymbol{TDS_{min}}$, $\boldsymbol{TDS_{max}}$.
Step 2: Initialize Swarm such that it satisfies the limits of $\boldsymbol{TDS}$ and $\boldsymbol{Ip}$ (4 - 5).
Step 3: Check the coordination, boundary conditions as well as operating time limits of all the relays given in (4 - 6). If conditions not satisfied, go to Step 2, otherwise go to Step 4.
Step 4: Evaluate the objective function with the particles using equation 2.
Step 5: The particle corresponding to the best fitness is stored as Global Best (GB).
Step 6: Calculate the velocity of particle one at a time.

$$\boldsymbol{V_i^{k+1} = \omega V_i^k - r_1 c_1 (X_i^k - PB_i) - r_2 c_2 (X_i^k - GB)} \tag{7}$$

Update the particle position if the conditions are still satisfied with the new population.

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{8}$$

Step 7: Judge the fitness value of particles against GB; if less than GB, replace GB with that minimum value.
Step 8: If the convergence criteria is reached, go to Step 9, otherwise go to Step 4.
Step 9: End the program if the convergence criteria is reached.

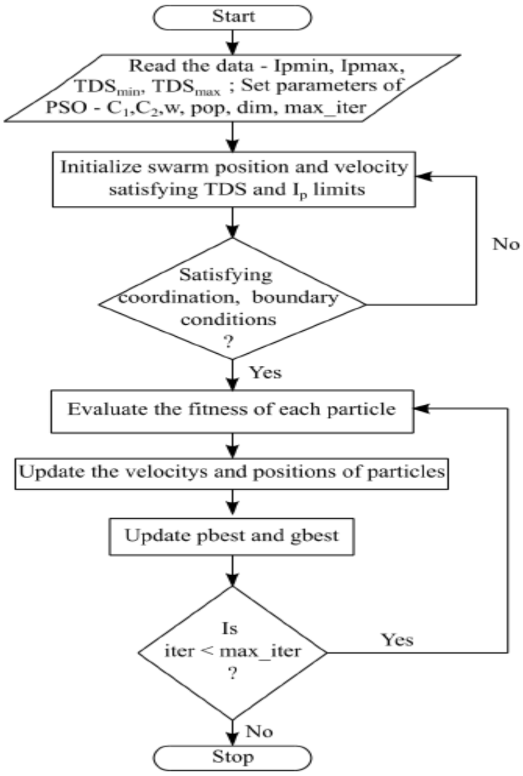

Figure 1. Flowchart of PSO technique.

3.2. Henry Gas Solubility Optimization (HGSO)

HGSO is an optimization algorithm based on Henry's law. In this algorithm, the total population is clustered such that the gas coefficient remains the same for each group. Based on the solubility value corresponding to the objective function, the position of search agents varies [24]. The technique is treated as a global optimization technique since it includes both exploration and exploitation stages. The HGSO algorithm is demonstrated below. HGSO is influenced by a number of control parameters, namely the dimension of the problem, no. of gases, maximum number of iterations, position of gases. Flowchart of the HGSO technique is shown in Figure 2.

Step 1: Input the data - N, dim, max iteration, $\boldsymbol{Ip_{min}}$, $\boldsymbol{Ip_{max}}$, $\boldsymbol{TDS_{min}}$, $\boldsymbol{TDS_{max}}$.
Step 2: Initialize the population size (no. of gases), N and position of gases such that it satisfies the limits of $\boldsymbol{TDS}$ and $\boldsymbol{Ip}$ (4-5).
Step 3: Check the coordination, boundary conditions as well as operating time limits of all the relays given in (4-6). If conditions not satisfied, go to Step 2, otherwise go to Step 4.
Step 4: Initialization of Henry's constant $\boldsymbol{H_j(t)}$, gas $\boldsymbol{i}$ partial pressure $\boldsymbol{P_{i,j}}$ in cluster $\boldsymbol{j}$, and $\boldsymbol{\Delta_{sol}E/R(C_i)}$ using the equations below:

$$\boldsymbol{H_j(t) = I_1 \times rand(0,1)} \tag{9}$$

$$\boldsymbol{P_{i,j} = I_2 \times rand(0,1)} \tag{10}$$

$$\boldsymbol{C_j = I_3 \times rand(0,1)} \tag{11}$$

where, I_1= 1, I_2= 10, I_3 = 1

Step 5: Cluster the population into number of gases with same Henry's constant $(\boldsymbol{H_j})$
Step 6: Evaluation of every cluster for the objective function as given in equation 2.
Step 7: Obtain the best gas $\boldsymbol{X_{i,best}}$, in each cluster and the best search agent $\boldsymbol{X_{best}}$.
Step 8: Update the positions of all gases using equation 12.

$$\boldsymbol{X_{i,j}(t+1) = X_{i,j}(t) + F \times r \times \left(X_{best,j}(t) - X_{i,j}(t)\right) + F \times r \times \alpha \times \left(S_{i,j} \times X_{best}(t) - X_{i,j}(t)\right)} \tag{12}$$

where $\gamma = \beta \times exp\left(-\frac{F_{best}(t)+\epsilon}{F_{i,j}(t)+\epsilon}\right)$, $\epsilon = 0.05$

Step 9: Update Henry's constant using equation below.

$$H_{i,j}(t+1) = H_{i,j}(t) \times exp\left(-C_j \times \left(\frac{1}{T(t)} - \frac{1}{T^{\theta}}\right)\right), \tag{13}$$

$$T(t) = exp\left(-\frac{t}{iter}\right)$$

Step 10: Update solubility of each gas using equation (14).

$$S_{i,j} = K \times H_j(t+1) \times P_{i,j}(t) \tag{14}$$

Step 11: Ranking and selection of worst agents.
Step 12: Update the worst agents' position.
Step 13: Update the best gas $X_{i,best}$, and the best search agent X_{best}.
Step 14: If the convergence criteria is reached, go to Step 15, otherwise go to Step 6.
Step 15: End the program if the convergence criteria is reached.

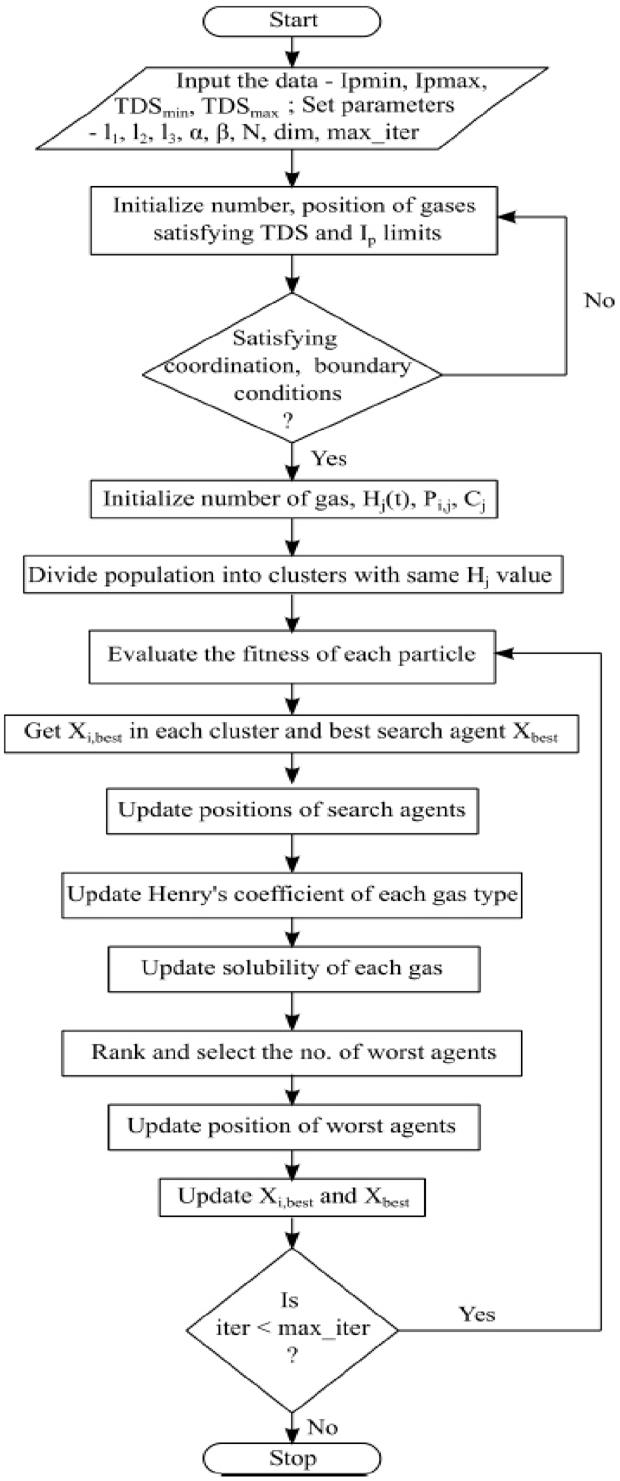

Figure 2. Flowchart of HGSO technique.

3.3 Differential Evolution (DE)

DE is an evolutionary search algorithm which is relied upon natural gene selection [10]. DE has been in use over wide engineering fields because of its simple algorithm, robustness, and high convergence speed. DE follows an iterative process wherein the algorithm evolves the population over successive generations. This involves the application of mutation, crossover, and selection operations. The iterative nature allows DE to progressively refine candidate solutions toward optimal configurations. The algorithm of the DE technique is described below. Flowchart of DE is shown in Figure 3.

Step 1: Input the data - pop, dim, max_iteration, Ip_{min}, Ip_{max}, TDS_{min}, TDS_{max}.
Step 2: Form the initial vector such that it satisfies the limits of TDS and Ip (4-5).
Step 3: Check the coordination, boundary conditions as well as operating time limits of all the relays given in (4-6). If conditions not satisfied, go to Step 2, otherwise go to Step 4.
Step 4: Evaluate the objective function with the population using equation 2.
Step 5: Mutation - Generate the mutant vector using the equation below.

$$V_i = x_{r1} + F \times (x_{r2} - x_{r3}) \tag{15}$$

where, $r1, r2$ and $r3$ are randomly chosen integers different from the running index i. F is a real and constant factor $\in [0,2]$.
Step 6: Crossover - Generate the trial vector T_j such that

$$T_j = \begin{cases} V_j & if\ rand\ \le CR\ or\ j = I_{rand} \\ x_j & if\ rand > CR\ or\ j \ne I_{rand} \end{cases} \tag{16}$$

Step 7: Selection - Compare the target vector $x_{i,G}$ and the trial vector $T_{i,G+1}$ and the one with the lowest function value is carried forward to the next generation
Step 8: If the convergence criteria is reached, go to Step 9, otherwise go to Step 4.
Step 9: End the program if the convergence criteria is reached.

4 Systems Investigated

The Protection Coordination Problem (PCP) is a non-linear problem as inferred from Section 2 with the DOCR settings - $\boldsymbol{TDS}$ and $\boldsymbol{I_p}$. In this section, two test bus systems, i.e., IEEE 6 bus system (*Figure 4*) & WSCC 9 bus system (*Figure 6*) are investigated. PSO, HGSO, and DE techniques are used in order to get optimal relay settings with a reduced operating time. Problem constraints are taken to be $\boldsymbol{CTI} > 0.2$, $\boldsymbol{TDS_{min}} = 0.015$ and $\boldsymbol{TDS_{max}} = 1$.

4.1 Test system I: IEEE 6 Bus System

IEEE 6 Bus System consists of three generators, 6 buses, 7 lines and 14 relays (R_1, R_2, R_3,......R_{14}) as shown in figure 4. To coordinate all relays, we need to find optimal relay settings for 14 relays. There are 28 variables treated as dimensions in the problem, $\boldsymbol{TDS_1 - TDS_{14}}$ and $\boldsymbol{Ip_1 - Ip_{14}}$. The system bus voltages are found using Newton Raphson load flow studies in MATLAB R2021a platform. The voltage of buses and line currents in steady state condition are tabulated in Table 2-3. Three-phase short circuit analysis (SCA) is conducted in the system for midpoint fault in the line and result is validated with Power World simulator software.

Table 2. Bus voltages from NRLF method.

Bus	Voltage (Volt)	Angle (Deg.)
1	1.06	0
2	1.04	1.47
3	1.03	0.80042
4	1.0077	-1.4014
5	1.0163	-1.4991
6	0.94102	-5.607

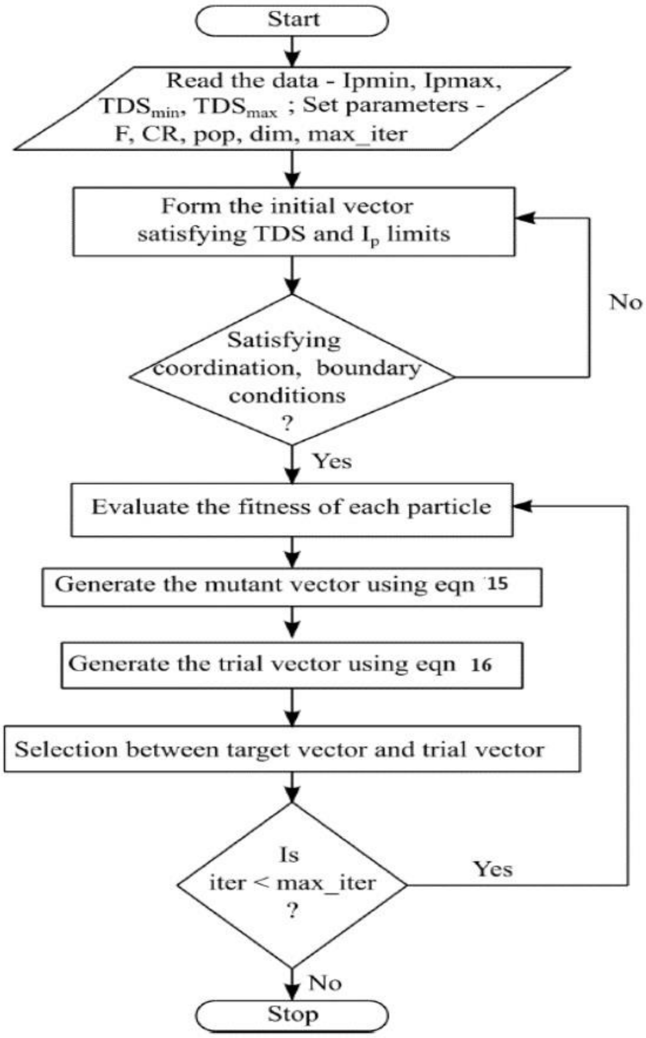

Figure 3. Flowchart of DE technique.

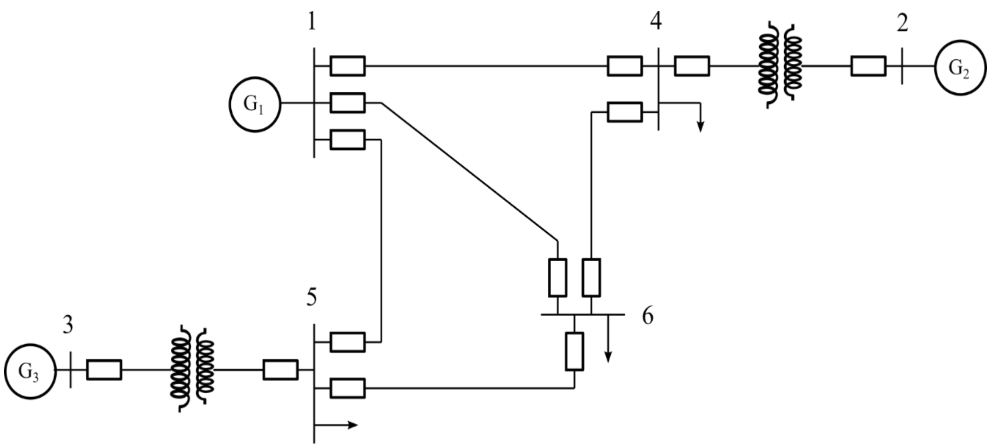

Figure 4. IEEE 6 Bus System.

Table 3. Steady State Line Currents.

Line	Current (A)
1-4	0.2495
1-5	0.4735
1-6	0.7
2-4	1.7322
3-5	1.0308
4-6	0.7611
5-6	0.5619

4.1.1 Midpoint Fault Analysis

Figure 5 shows the different midpoint fault locations in IEEE 6 bus system. For the different fault locations, primary - backup relay pairs are tabulated in Table 4. Fault currents are calculated using SCA in the system at the middle of each and every lines and result is validated with Power World simulator software.

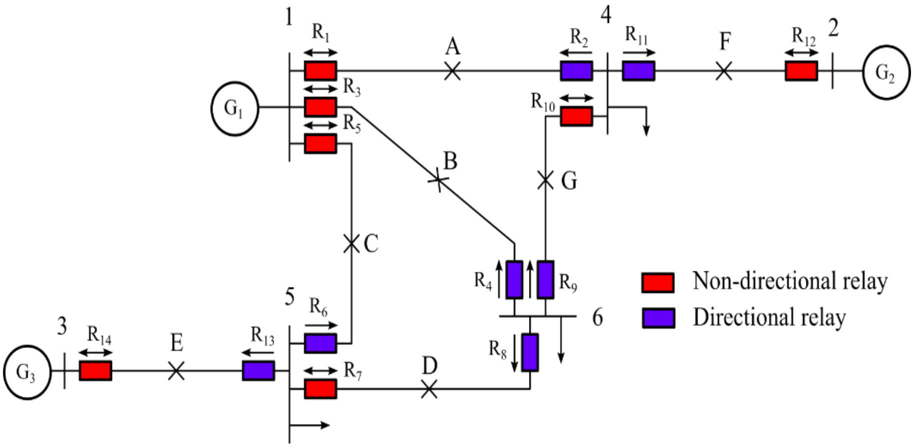

Figure 5. Midpoint Fault Analysis in IEEE 6-bus System.

Table 4. Primary Backup relay coordinaion pairs for different fault locations.

Fault Pt.	Pri Relay	Bck Relay	
A(1,4)	R_1	R_4	R_6
	R_2	R_9	R_{12}
B(1,6)	R_3	R_2	R_6
	R_4	R_7	R_{10}
C(1,5)	R_5	R_2	R_4
	R_6	R_{14}	R_8
D(5,6)	R_7	R_{14}	R_5
	R_8	R_3	R_{10}
E(3,5)	R_{14}		
	R_{13}	R_5	R_8
F(2,4)	R_{12}		
	R_{11}	R_1	R_9
G(4,6)	R_{10}	R_1	R_{12}
	R_9	R_3	R_7

Based on the current direction during normal and fault conditions, both non-directional and directional relays are used, which will help in the reduction of cost. For directional relays, the $\boldsymbol{Ip_{min}}$ and $\boldsymbol{Ip_{max}}$ settings are set to be $\frac{1}{3}^{rd}$ and $\frac{2}{3}^{rd}$ of the minimum fault current through the respective relay. In case of non-directional relays, the pick-up current limits are as discussed in (5).

4.2 Test system II: WSCC 9 Bus System

WSCC 9 bus system comprises three generators, nine lines, and 18 relays (R_1, R_2,…, R_{18}) as shown in Figure 6. To coordinate all relays, we need to find optimal relay settings for 18 relays. Consequently, there are 36 variables, i.e., $TDS_1 - TDS_{18}$ and $Ip_1 - Ip_{18}$. The system bus voltages are found using Newton Raphson load flow studies in MATLAB R2021a platform. The bus voltages and currents under normal condition are tabulated in Table 5-6. Three-phase short circuit analysis (SCA) is conducted in the system for midpoint fault in the line .

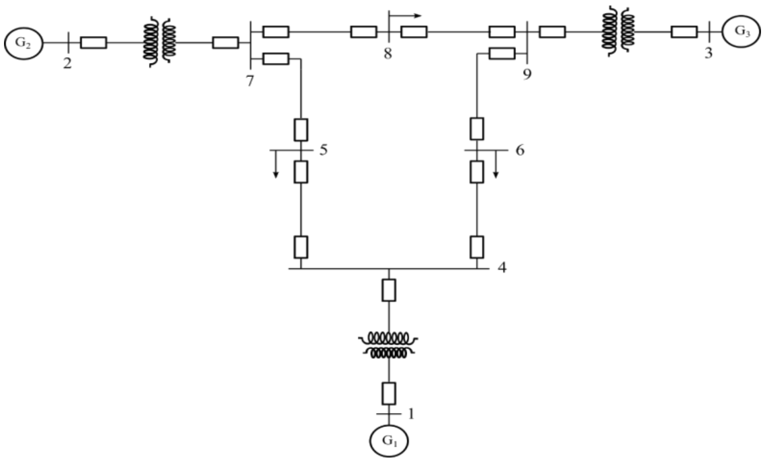

Figure 6. WSCC 9 Bus System.

Table 5. Bus voltages from NRLF method.

Bus	Voltage (Volt)	Angle (Deg.)
1	1.04	0
2	1.025	9.28
3	1.025	4.6648
4	1.0258	-2.2168
5	0.99563	-3.9888
6	1.0127	-3.6874
7	1.0258	3.7197
8	1.0159	0.72754
9	1.0324	1.9667

Table 6. Steady State Line Currents.

Line	Current (A)
4-6	0.2995
5-7	0.8545
6-9	0.602
7-8	0.7447
4-5	0.4572
8-9	0.3368
2-7	1.5916
1-4	0.7363
3-9	0.836

4.2.1 Midpoint Fault Analysis

Figure 7 shows the locations of midpoint fault in WSCC 9-bus system. The various primary - backup combinations of relay pairs are tabulated in Table 7.

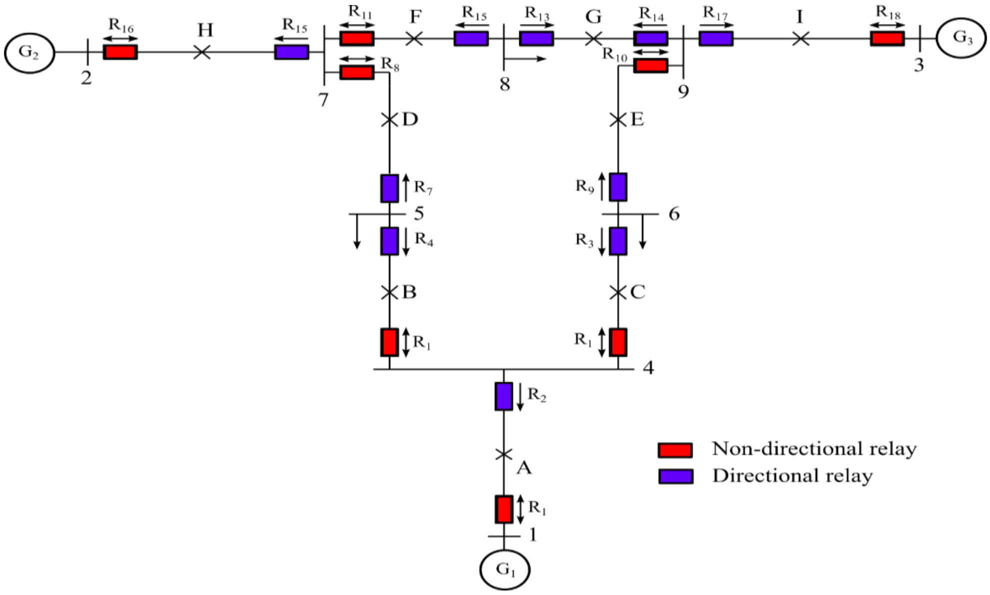

Figure 7. Midpoint Fault Analysis in WSCC 9-bus System.

Table 5. Primary Backup pairs for different fault locations.

Fault Pt.	Pri Relay	Bck Relay	
A(1,4)	R_1		
	R_2	R_4	R_6
B(4,5)	R_3	R_1	R_6
	R_4	R_8	
C(4,6)	R_5	R_1	R_4
	R_6	R_{10}	
D(5,7)	R_7	R_3	
	R_8	R_{16}	R_{12}
E(6,9)	R_9	R_5	
	R_{10}	R_{18}	R_{13}
F(7,8)	R_{11}	R_7	R_{16}
	R_{12}	R_{14}	
G(8,9)	R_{13}	R_{11}	
	R_{14}	R_9	R_{18}
H(2,7)	R_{15}	R_7	R_{12}
	R_{16}		
I(3,9)	R_{17}	R_{13}	R_9
	R_{18}		

Based on the current direction during normal and fault conditions, both non-directional and directional relays are used, which will help in the reduction of cost. For directional relays, the Ip_{min} and Ip_{max} settings are set to be $\frac{1}{3}^{rd}$ and $\frac{2}{3}^{rd}$ of the minimum fault current through the respective relay. In case of non-directional relays, the pick-up current limits are as discussed in equation 5.

5 Result and analysis

The problem formulated in section 2 has been solved using three optimization algorithms for the two test systems. The results are discussed below.

5.1 Test System I: IEEE 6 Bus System

Based on the fault currents obtained from the midpoint fault analysis using problem constraints discussed in section 2.1, the optimal values of relay settings are obtained using PSO, HGSO, and DE techniques. The results are tabulated in Table 8. Using the $\boldsymbol{TDS}$ and $\boldsymbol{I_p}$ Based on the fault currents obtained from the midpoint fault analysis using problem constraints discussed in section 2.1, the optimal values of relay settings are obtained using PSO, HGSO, and DE techniques. The results are tabulated in Table 8. For fault at point B in the IEEE 6 bus system, R_3 and R_4 are primary relays. If R_3 fails, relay R_2 and R_6 operate as backup relay. *TDS* and I_p values of R_3 have been calculated using all the three methods maintaining all the problem constraints as discussed in 2.1. For example, using these values from Table 8, operating time of relay R_3 is calculated and found 0.2041s, 0.1784s, and 0.1823s, respectively. It indicates that operating time of relay R_3 is lesser with the relay settings found using HGSO method comparing to the relay settings found using PSO. Again operating time of relay R_3 is least using settings of DE method. Figure 8 shows the convergence characteristics of the three optimization algorithms for the above problem with a same iteration number of 5000. The results of PSO, HGSO, and DE algorithms are analyzed. In order to compare the performance, same initial population is considered. The population number is chosen to be 500. The total operating times are 18.1728s, 18.0185s and 17.8056s using PSO, HGSO, and DE algorithms respectively. It indicates that DE converges early comparing with other two methods. With a pre-initialized set of values satisying the constraints, the computation times of PSO, HGSO, and DE are 154.4723s, 618.2548s and 91.2003s, respectively. So, it indicates that individual relay operating time as well as total operating time is improved with HGSO method compared to PSO, and it is further improved using settings of DE method compared to HGSO and PSO methods.

5.2 Test System II: WSCC 9 Bus System

Using the fault currents obtained from midpoint fault analysis and the problem constraints, the optimal $\boldsymbol{TDS}$ and $\boldsymbol{I_p}$ settings are achieved using PSO, HGSO, and DE algorithms and is tabulated in table 10. These settings are utilized further for the calculation of operating times of all the primary and backup relays and are tabulated in Table 11. For example, for a fault at point C, R_5 and R_6 are primary relays. If R_5 fails, relay R_1 and R_4 operates as backup relay. TDS and Ip values of R_5 have been calculated using all the three methods maintaining all the problem constraints as discussed in 2.1. Using these values from Table 10, operating time of relay R_5 is calculated and found 0.9743s, 0.3452s, and 0.1692s using PSO, HGSO and DE methods respectively. It indicates that operating time of relay R_5 is lesser with relay settings found using HGSO method comparing to relay settings of PSO. Again operating time of relay R_5 is least using settings of DE method. The total operating times found in WSCC 9- bus system are 23.8432s, 22.8143s and 17.1303s, using PSO, HGSO, and DE algorithms respectively. Figure 9 depicts the convergence characteristic curve for all three algorithms for a maximum iteration of 5000. It also indicates that faster convergence of DE comparing with other two methods. With a pre-initialized set of values satisying the constraints, the computation times of PSO, HGSO, and DE are 95.5102s, 624.7826s and 81.7666s, respectively. So, it indicates that individual relay operating time as well as total operating time is improved in HGSO method than PSO, and it is further improved using settings of DE method compared to HGSO and PSO methods.

Table 6. Optimal settings of TDS and I_p in IEEE 6-bus system.

Relay	PSO		HGSO		DE	
	TDS	*I_p (A)*	*TDS*	*I_p (A)*	*TDS*	*I_p (A)*
R_1	0.1013	0.3743	0.0709	0.4549	0.0565	0.648
R_2	0.1407	0.151	0.132	0.1645	0.125	0.1679
R_3	0.0466	0.98	0.0408	0.98	0.0415	0.9844
R_4	0.0952	0.0732	0.0756	0.0825	0.0811	0.0787
R_5	0.086	0.7103	0.0755	0.77	0.0609	0.9757
R_6	0.1222	0.1509	0.0969	0.1701	0.096	0.1648
R_7	0.0614	0.8986	0.0611	0.8437	0.0601	0.8429
R_8	0.0764	0.3037	0.0825	0.3037	0.0677	0.3758
R_9	0.1621	0.1193	0.1272	0.1193	0.1337	0.1203
R_{10}	0.0439	1.2177	0.0504	1.1417	0.0313	1.5065
R_{11}	0.0287	1.4644	0.0159	1.4644	0.015	1.6314
R_{12}	0.0307	2.7253	0.0376	2.5983	0.0279	2.7533
R_{13}	0.0161	1.8429	0.0192	1.8429	0.0162	1.861
R_{14}	0.0476	1.5462	0.0437	1.5462	0.0437	1.5462

Table 7. Relay operating times in IEEE 6-bus system for midpoint fault.

F.Pt	Pri Relay	Op.Time of Pri Relay (s)			Bck Relay	Op.Time of Bck Relay(s)		
		PSO	HGSO	DE		PSO	HGSO	DE
A	R_1	0.2777	0.2113	0.1998	R_4	0.4783	0.4163	0.4303
	R_1	0.2777	0.2113	0.1998	R_6	0.4831	0.4117	0.4002
	R_2	0.2923	0.2819	0.2687	R_9	1.0216	0.8016	0.8491
	R_2	0.2923	0.2819	0.2687	R_{12}	0.506	0.5567	0.4713
B	R_3	0.2041	0.1784	0.1823	R_2	0.8862	0.9027	0.8726
	R_3	0.2041	0.1784	0.1823	R_6	0.7701	0.6858	0.6583
	R_4	0.1723	0.1415	0.1498	R_7	1.1329	0.9651	0.9478
	R_4	0.1723	0.1415	0.1498	R_{10}	0.4967	0.516	0.5444
C	R_5	0.2734	0.2496	0.2276	R_2	0.4745	0.4653	0.4454
	R_5	0.2734	0.2496	0.2276	R_4	0.5998	0.5348	0.5474
	R_6	0.2529	0.2083	0.2044	R_8	0.4814	0.5197	0.5305
	R_6	0.2529	0.2083	0.2044	R_{14}	0.4529	0.4158	0.4154
D	R_7	0.2645	0.2529	0.2488	R_5	0.5659	0.5385	0.5753
	R_7	0.2645	0.2529	0.2488	R_{14}	0.642	0.4158	0.5889
	R_8	0.2143	0.2314	0.2086	R_3	0.9032	0.7898	0.8146
	R_8	0.2143	0.2314	0.2086	R_{10}	0.415	0.4379	0.4185
E	R_{14}	0.3289	0.3020	0.3017				
	R_{13}	0.1015	0.1212	0.1027	R_5	0.3504	0.3234	0.3064
	R_{13}	0.1015	0.1212	0.1027	R_8	0.3016	0.3255	0.3052
F	R_{12}	0.2198	0.2565	0.2019				
	R_{11}	0.1807	0.1000	0.1049	R_1	0.382	0.3001	0.3067
	R_{11}	0.1807	0.1000	0.1049	R_9	0.3825	0.3002	0.3164
G	R_{10}	0.2003	0.2205	0.167	R_1	0.6129	0.5183	0.6613
	R_{10}	0.2003	0.2205	0.167	R_{12}	0.4003	0.4499	0.3709
	R_9	0.3248	0.2548	0.2685	R_3	0.5248	0.4588	0.4708
	R_9	0.3248	0.2548	0.2685	R_7	0.5248	0.4840	0.4758

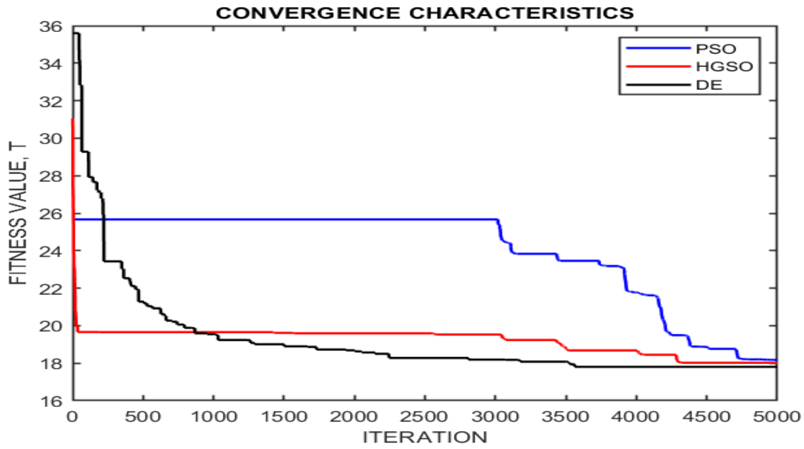

Figure 8. Convergence Characteristics of IEEE 6 Bus System.

Table 8. Optimal settings of TDS and Ip in WSCC 9-bus system.

Relay	PSO		HGSO		DE	
	TDS	Ip (A)	TDS	Ip (A)	TDS	Ip (A)
R_1	0.2000	1.4721	0.0962	1.8588	0.0908	1.2684
R_2	0.0150	1.7112	0.0215	1.1045	0.0150	1.4819
R_3	0.0229	2.5160	0.0706	1.2917	0.0312	2.3870
R_4	0.0497	0.7139	0.0696	0.6858	0.0498	0.7021
R_5	0.1680	0.4493	0.1000	0.9966	0.0302	2.1216
R_6	0.0681	0.4546	0.0681	0.4493	0.0622	0.4848
R_7	0.0301	1.2033	0.0404	1.2033	0.0293	1.2818
R_8	0.0531	1.9036	0.0863	1.2818	0.0339	1.7619
R_9	0.0360	1.0907	0.0664	0.9030	0.0315	1.0269
R_{10}	0.0653	1.0557	0.0723	0.9030	0.0364	1.5133
R_{11}	0.0385	2.3572	0.0917	1.1171	0.0333	2.4193
R_{12}	0.0469	0.9778	0.0497	0.9778	0.0475	0.9778
R_{13}	0.0590	0.8640	0.0842	0.5269	0.0734	0.5658
R_{14}	0.0592	1.5874	0.0825	1.0741	0.0292	2.2155
R_{15}	0.0150	2.3874	0.0163	2.3874	0.0151	2.3928
R_{16}	0.0432	2.4065	0.0754	2.3874	0.0441	2.4176
R_{17}	0.0290	1.4353	0.0237	1.2540	0.0215	1.2662
R_{18}	0.2000	1.2561	0.0930	1.2540	0.0569	1.4071

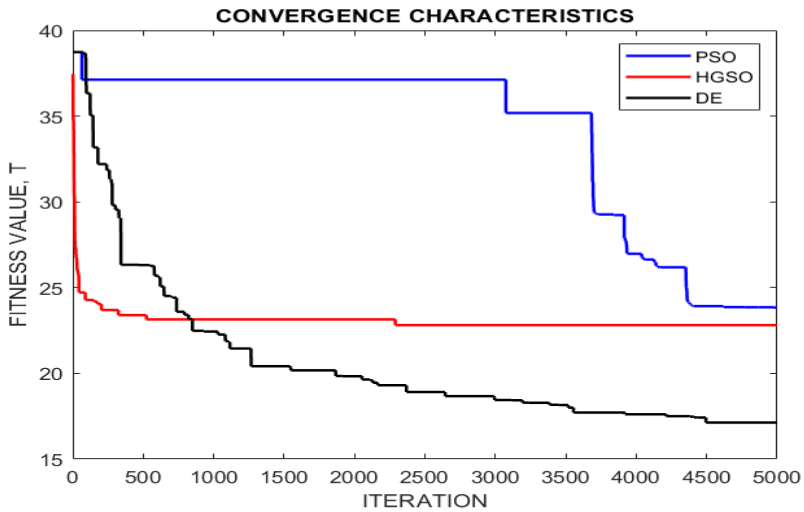

Figure 9. Convergence Characteristics of WSCC 9 Bus System.

Table 9. Relay operating times in WSCC 9-bus system for midpoint fault.

F. Pt	Pri Relay	Op.Time of Pri Relay (s)			Bck Relay	Op.Time of Bck Relay(s)		
		PSO	HGSO	DE		PSO	HGSO	DE
A	R_1	0.6589	0.3577	0.2788				
	R_2	0.1261	0.1173	0.1072	R_4	0.3275	0.4416	0.3327
	R_2	0.1261	0.1173	0.1072	R_6	0.3327	0.33	0.3187
B	R_3	0.1465	0.2773	0.1902	R_1	0.9554	0.5492	0.3927
	R_3	0.1465	0.2773	0.1902	R_6	0.4841	0.4784	0.4739
	R_4	0.2496	0.3396	0.2469	R_8	0.8803	0.7338	0.4739
C	R_5	0.9743	0.3452	0.1692	R_1	0.6372	0.5622	0.3998
	R_5	0.4107	0.3452	0.1692	R_4	0.6499	0.846	0.6307
	R_6	0.2711	0.2693	0.2575	R_{10}	0.5005	0.4719	0.4649
D	R_7	0.1894	0.2544	0.1954	R_3	0.3942	0.4557	0.4748
	R_8	0.3859	0.4413	0.2275	R_{16}	0.7346	1.2568	0.7579
	R_8	0.3859	0.4413	0.2275	R_{12}	0.806	0.8545	0.8173
E	R_9	0.2153	0.3405	0.1787	R_5	0.5569	0.5436	0.4072
	R_{10}	0.3158	0.3147	0.2363	R_{18}	1.8316	0.85	0.6137
	R_{10}	0.3158	0.3147	0.2363	R_{13}	0.6644	0.5241	0.4884
F	R_{11}	0.1973	0.365	0.2418	R_7	0.5177	0.6954	0.5963
	R_{11}	0.2719	0.365	0.2418	R_{16}	0.4731	0.8149	0.4862
	R_{12}	0.2719	0.2825	0.2702	R_{14}	0.5499	0.5015	0.4921
G	R_{13}	0.2699	0.2887	0.2611	R_{11}	0.5218	0.5028	0.4758
	R_{14}	0.3598	0.3719	0.2522	R_9	0.6192	0.7773	0.4709
	R_{14}	0.3598	0.3719	0.2522	R_{18}	1.478	0.6862	0.4791
H	R_{15}	0.1574	0.171	0.1592	R_7	0.3677	0.494	0.4022
	R_{15}	0.1574	0.171	0.1592	R_{12}	0.3596	0.3813	0.3647
	R_{16}	0.2821	0.4883	0.289				
I	R_{17}	0.1645	0.1209	0.1105	R_{13}	0.3665	0.3606	0.3291
	R_{17}	0.1645	0.1209	0.1105	R_9	0.3916	0.5562	0.3126
	R_{18}	1.0257	0.4765	0.3192				

6 Conclusion

Relay coordination is an imperative issue in an interconnected power network. The time of operation of the relays can be minimized with proper selection of *TDS* and I_p values of the relays. Here, relay coordination is done using the PSO, HGSO, and DE techniques in IEEE 6 bus and WSCC 9 bus systems considering midpoint fault condition. The problem constraints are decided using an organized manner with which the relay settings are determined thereby calculating the operating times of all primary & backup relays within the system. Subsequently, optimal results of two important parameters (*TDS* and I_p) are obtained. The total operating times found in IEEE 6 bus system are 18.1728s, 18.0185s and 17.8056s using PSO, HGSO, and DE algorithms, respectively. The outcome of objective function applied in WSCC 9 bus system are 23.8432s, 22.8143s and 17.1303s, using PSO, HGSO, and DE algorithms, respectively. It indicates that DE converges early comparing with other two methods. With a pre-initialized set of values of IEEE 6 bus system satisfying the constraints, the computation times of PSO, HGSO, and DE are 154.4723s, 618.2548s and 91.2003s, respectively, and for WSCC 9- bus system are 95.5102s, 624.7826s and 81.7666s, respectively. Though the performance of all the three algorithms are satisfactory, DE gives better results in terms of the total operating times of relays and reliable coordination margin. The results show that HGSO shows a notable reduction in relays' operating time when compared to PSO, but DE gives the superior results in comparison with other techniques with a minimum computation time. So, it again indicates the faster convergence of DE comparing with other two methods. Integration of RESs are increasing day by day to save the conventional energy sources, which demands further improved relay settings to take care changes in energy sources. An optimized number of dual-setting and conventional DOCRs will be the future scope to minimize the cost of production along with the time of operation.Optimum protection coordination is validated in IEEE 6-bus, and WSCC 9-bus systems.

References

[1] Y. G. Paithankar and S. Bhide, Fundamentals of power system protection, PHI Learning Pvt. Ltd., 2022.

[2] J.D. Langhans and A.E. Ronat, "Protective devices coordination via computer graphics," IEEE Transactions on Industry Applications, no. 3, pp. 404-412, 1980.

[3] R.A. Kennedy and L. E. Curtis, "Overcurrent protective device coordination by computer," IEEE Transactions on Industry Applications, no. 5, pp. 445 - 456, 1982.

[4] A.J. Urdaneta, R. Nadira and L.G. Perez Jimenez, "Optimal coordination of directional overcurrent relays in interconnected power systems," IEEE Transactions on Power Delivery, vol. 3, no. 3, pp. 903 - 911, 1988.

[5] B.Chattopadhyay, M. Sachdev and T. Sindhu, "An on-line relay coordination algorithm for adaptive protection using linear programming technique," IEEE Transactions on Power Delivery, vol. 11, no. 1, pp. 165 - 173, 1996.

[6] A.J. Urdaneta, L.G. Perez and H. Restrepo, "Optimal coordination of directional overcurrent relays considering dynamic changes in the network topology," IEEE Transactions on Power Delivery, vol. 12, no. 4, p. 2003, 430 - 435.

[7] H.A. Abyaneh, M. Al-Dabbagh, H. K. Karegar, S. H. H. Sadeghi, R. J., "A new optimal approach for coordination of overcurrent relays in interconnected power systems," IEEE Transactions on power delivery, vol. 18, no. 2, pp. 430-435., 2003.

[8] C. So, K. Li, K. Lai, K. Fung, "Application of genetic algorithm to overcurrent relay grading coordination," IET, 1997.

[9] H.Zeineldin, E. El-Saadany, M. Salama, "Optimal coordination of overcurrent relays using a modified particle swarm optimization," Electric Power Systems Research, vol. 76, no. 11, pp. 988-995, 2006.

[10] Shih, M. Y., Enríquez, A. C., Hsiao, T. Y., & Treviño, L. M. T., "Enhanced differential evolution algorithm for coordination of directional overcurrent relays," Electric Power Systems Research, vol. 143, pp. 365 - 375, 2017.

[11] Wadood, A., Gholami Farkoush, S., Khurshaid, T., Kim, C. H., Yu, J., Geem, Z. W., & Rhee, S. B., "An optimized protection coordination scheme for the optimal coordination of overcurrent relays using a nature-inspired root tree algorithm," Applied Sciences, vol. 8, no. 9, p. 1664, 2018.

[12] Antonova, Galina, Massimo Nardi, Alan Scott, and Michael Pesin, "Distributed generation and its impact on power grids and microgrids protection," in 2012 65th annual conference for protective relay engineers, 2012.
[13] Sharaf, H. M., Zeineldin, H. H., Ibrahim, D. K., & El-Zahab, E. D., "Directional inverse time overcurrent relay for meshed distribution systems with distributed generation with additional continuous relay settings," pp. 12 - 19, 2014.
[14] Abeid, Salima and Hu, Yanting, "Overcurrent relays coordination optimisation methods in distribution systems for microgrids: a review," in 15th International Conference on Developments in Power System Protection (DPSP 2020), 2020.
[15] Saleh, K. A., Zeineldin, H. H., Al-Hinai, A., & El-Saadany, E. F., "Optimal coordination of directional overcurrent relays using a new time--current--voltage characteristic," IEEE Transactions on Power Delivery, vol. 30, no. 2, pp. 537 - 544, 2014.
[16] Hong, Lucheng, Mian Rizwan, Muhammad Wasif, Shafiq Ahmad, Mazen Zaindin, and Muhammad Firdausi, "User-defined dual setting directional overcurrent relays with hybrid time current-voltage characteristics-based protection coordination for active distribution network," IEEE Access, vol. 9, pp. 62752 - 62769, 2021.
[17] Agrawal, Anubha, Manohar Singh, and M. V. Tejeswini, "Voltage current based time inverse relay coordination for PV feed distribution systems," in 2016 National Power Systems Conference (NPSC), 2016.
[18] Jamali, Sadegh, and Hossein Borhani-Bahabadi, "Recloser time--current--voltage characteristic for fuse saving in distribution networks with DG," IET generation, transmission & distribution, vol. 11, no. 1, pp. 272 - 279, 2017.
[19] Jamali, Sadegh, and Hossein Borhani-Bahabadi, "Non-communication protection method for meshed and radial distribution networks with synchronous-based DG," International Journal of Electrical Power & Energy Systems, vol. 93, pp. 468 - 478, 2017.
[20] H. H. Zeineldin, H. M. Sharaf, D. K. Ibrahim, E. D. Abou El-Zahab, "Optimal protection coordination for meshed distribution systems with DG using dual setting directional over-current relays," IEEE transactions on smart grid, vol. 6, no. 1, pp. 115 - 123, 2014.
[21] T. S. Aghdam,H. K. Karegar, A. Abbasi, "Discussion on "Optimal Protection Coordination for Meshed Distribution Systems With DG Using Dual Setting Relays"," IEEE Transactions on Smart Grid, vol. 7, no. 3, pp. 1756 - 1756, 2016.
[22] Debasree Saha, Asim Datta, Biman Kumar Saha Roy, Priyanath Das , "A comparative study on the computation of directional overcurrent relay coordination in power systems using PSO and TLBO based optimization," Engineering Computations, 2016.
[23] Uma, Uma Uzubi, Daniel Nmadu, Nnaemeka Ugwuanyi, Ogah Ekechi Ogah, Ngozi Eli-Chukwu, Marcellinus Eheduru, and Arthur Ekwue. "Adaptive overcurrent protection scheme coordination in presence of distributed generation using radial basis neural network." Protection and Control of Modern Power Systems 8, no. 1 (2023): 1-19.
[24] Debasree Saha, Asim Datta, Priyanath Das, "Optimal coordination of directional overcurrent relays in power systems using symbiotic organism search optimisation technique," IET Generation, Transmission & Distribution, vol. 10, no. 11, pp. 2681 - 2688, 2016.
[25] F. A. Hashim, E. H. Houssein, M. S. Mabrouk, W. Al-Atabany and S. Mirjalili, "Henry gas solubility optimization: A novel physics-based algorithm," Future Generation Computer Systems, vol. 101, pp. 646 - 667, 2019.
[26] Zellagui, Mohamed, Heba Ahmed Hassan, and Almoataz Youssef Abdelaziz, "Non-dominated sorting gravitational search algorithm for multi-objective optimization of power transformer design", Engineering Review, Vol. 37, Issue 1, 27-37, 2017.
[27] Tiwari, R., Singh, R.K. & Choudhary, N.K. Coordination of dual setting overcurrent relays in microgrid with optimally determined relay characteristics for dual operating modes. Prot Control Mod Power Syst 7, 6 (2022).
[28] Nie, Shan-Kun, Yu-Jia Wang, Shanli Xiao, and Zhifeng Liu. "An adaptive chaos particle swarm optimization for tuning parameters of PID controller." Optimal Control Applications and Methods 38, no. 6 (2017): 1091-1102.