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Optimal protective relaying scheme of distributed generation connected distribution network using particle swarm optimization-gravitational search algorithm technique

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ABSTRACT

This paper develops particle swarm optimization integrated with gravitational search algorithm (PSO-GSA) to coordinate the relays in a distribution system with distributed generation (DG) connectivity. This algorithm combines PSO and GSA to improve the performance of the relay protection system. To prevent relay malfunctions following DG penetration, a suitable primary and backup relay is chosen. The PSO-GSA is coded using MATLAB software and tested on an IEEE 4-bus system simulated in Simulink. Results indicate that, when compared to using regular PSO and GSA procedures individually, the PSO-GSA technique reduces the operating time of the relay significantly.

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1. INTRODUCTION

The topology of distribution systems has changed into a mesh structure resembling interconnected sub-transmission systems due to the integration of distributed generation (DG) into distribution networks [1]. Additionally, the direction of electrical power and short-circuit current are impacted by the integration of DG units. Short-circuit current that flows in both directions can cause safety relays to malfunction and, ultimately, bring down entire distribution networks [2]. For DG integrated distribution networks, various over-current relay safety strategies have been developed [3], [4]. However, it is noted that as the number and size of DG units in the distribution networks rise, so does the complexity of the design and coordination of protective relays [5]. Conventional protective relay solutions fail in these circumstances of offering the system the necessary protection against faults [6]. Additionally, replacing protective relays after a problem occurs entails high costs and is impractical for real-time applications. Replacements are advised to create effective coordination in protective relays [7]. To address the fundamental needs of relays, such as operation time and fault tolerance, coordination of protective relays refers to the capacity to determine appropriate setting values for overcurrent relays [8]. Power system stability is greatly influenced by proper relay coordination. Protective relays are in charge of clearing faults at each fault occurrence because, if one relay fails, the others should take over [9]. Backup relays are employed to prevent any malfunction or failure of the principal or primary protection relays. The backup relays are either put on the same or at other buses with the proper time between them. Two rules must be followed for the protective relays to operate reliably. The flaws in the relay’s protection zone should trip it initially. Second, defects outside the relay’s safety zone should not cause it to trip. Back protection is advised due to the possibility that the main defense system would fail. The process of calculating the backup relay time delay is known as coordination of the protective relays [10]. The protective relays must be coordinated so that the backup relay’s delay time is sufficient for the primary relay to clear the fault first in order to fulfil selective tripping. Coordination between primary and backup relays is essential to give the primary relay enough time to fix the issue before the backup relay [11]. Relays are generally utilized more frequently as protective devices in distribution networks since they tend to be radial. The working duration of every relay should be significantly reduced with optimal time multiplier setting (TMS) and plug setting (PS) to increase the stability and dependability of the distribution network [12]. To improve the protective relays' performance and reduce the tripping time in these systems, several optimization strategies have been put forth. These methods prioritize operational time as their primary objective function and maximize operational time based on the relays’ characteristic curves and predetermined coordination limitations. Maintaining the reliability of the power system integrated with DG systems requires proper relay coordination. When DG is not integrated, the distribution system’s power flow is unidirectional. However, many parts of the distribution system now have bidirectional power flow, making conventional protection techniques that only consider one-way power flow unsuitable.

It is challenging to achieve ideal coordination between the relays due to the nonlinearity of the distribution networks, especially in larger distribution systems. Additionally, in these systems, the relay’s operational times should be shortened to improve the efficiency of the protective circuits [13]. By achieving the optimal settings for every relay in the power system, several researchers have suggested various optimization strategies for cutting the operational time and increasing the coordination of relays in distribution networks. When used for complicated and nonlinear optimization systems, a hybrid random walk grey wolf optimizer (RW-GWO) technique is suggested for tackling the issue of local minima and issues associated with stagnation to local optima [14]. To find the best setting for relays in extremely complex distribution networks, the proposed RW-GWO is applied. The outcomes are compared with basic GWO algorithms and other optimization strategies. The outcomes illustrated the approach’s potential for achieving the ideal conditions for effective relay coordination.

In recent years, a variety of meta-heuristic and swarm intelligence-based algorithms that include simulated annealing (SA) [15], artificial bee colonies (ABC) [16], genetic algorithms (GA) [17], and particle swarm optimization (PSO) [18] have been widely used to solve the challenging and nonlinear relay coordination issues. Plug and time multiplier settings were suggested as variables that govern how over current relays (OCRs) operate by researchers who proposed optimization of directional over current relay using PSO [19]. The objective is to reduce all relays’ operational times while utilizing PSO. PSO algorithm has been tested in typical 3-bus, 4-bus, and 6-bus systems. The findings suggested that the PSO had achieved reduced plug setting and time multiplier setting values with the best possible coordination for all standard bus systems. In [20], a firefly algorithm (FA) is used with a bio-inspired design to coordinate relays in the best possible way to safeguard the DG-connected power supply. The basic FA is often achieved by choosing the power systems’ proper plug and time multiplier settings. However, the implementation had particular difficulties, including delayed convergence and the danger of becoming trapped in local optima. The paper developed an adaptive modified FA (AMFA) technique to get around this restriction. The AMFA was used to coordinate overcurrent relays in the best possible way. Five separate test scenarios were used to evaluate the performance of the suggested approach, and the outcomes were compared using fundamental FA and other traditional approaches. In all case studies, the results demonstrated improved performance of AMFA in terms of optimized relay coordination, with excellent time reductions of up to 40.446%. Genetic algorithm (GA)-based relay coordination that is optimal was covered in [21]. Instead of employing a single curve for all relays as is done in several standard methods, the study used the characteristic curves of directional overcurrent relays as decision-making criteria. The experimental analysis was conducted using a variety of IEEE and IEC curves and the IEC benchmark. Results confirm that the suggested GA-based structure is adaptable. Additionally, this approach’s outcomes were compared with other frameworks already in use, significantly reducing operational times and offering reliable protection for power systems against various faults. Distribution systems need more protection relays so problems may be cleared as rapidly as possible. The distribution system uses both primary and backup relays [22]. The two key relay characteristics of selectivity and sensitivity are crucial for the stability and reliability of the distribution network. When a fault occurs, the primary relay sends the tripping signal before the backup relay, which then serves as a supportive relay when the first relay malfunctions.

This paper investigates the optimal relay coordination in DG linked distribution networks using a hybrid heuristic technique that combines PSO and gravitational search algorithm (GSA). The proposed PSO-GSA is used to select appropriate relay settings in the distribution network. To avoid relay problems after DG penetration, a suitable primary and backup relay is selected.

2. PROBLEM FORMULATION

The coordination issue in protective relays is established based on operational constraints like coordination standards and operating time. To solve the optimization problem, limits on the pickup current, operation time, and properties of the relay are applied. These restrictions are part of the goal function for optimization. In the shortest period of time, the function optimizes the functioning time of each protective relay. The objective function is expressed as (1):

$$minimize\ s\ =\ \sum_{i=1}^{n} t_{p,q} \tag{1}$$

where $t_{p,q}$ is defined as the operational time of the p^{th} relay for fault in q^{th} zone. The constraints for solving the objective function are defined [23].

2.1. Coordination criteria

The coordination criteria are defined as (2):

$$t_{b\ p,q} - t_{p,q}\ \geq \triangle\ \mathrm{t} \tag{2}$$

where $t_{p,q}$ is defined as the operational time of the p^{th} relay for fault in q^{th} zone and $t_{bp,q}$ is the operating time of the backup relay for the fault in zone q, and $\triangle t$ is defined as the coordination time interval (CTI).

2.2. Limits on operating time of relay

Protective relays should be used inside the boundary limitations to ensure good coordination between the primary and backup relays. They are described in this section. Relay operational time is constrained using (3):

$$t_{p,q\ min} \leq t_{p,q} \leq t_{p,q\ max} \tag{3}$$

where $t_{p,q\ min}$ and $t_{p,q\ max}$ is defined as the minimum and maximum operating time of the protective relay for the p^{th} relay for fault in the q^{th} zone.

2.3. Limits on pickup current

The maximum load current I_{pmax} and minimum fault current I_{pmin}, respectively, define the lowest and maximum values of the pickup current in a relay. The (4) provides the pickup relay current I_p limitation. This specifies the limit on relay plug setting multiplier (PSM) defined by (5).

$$I_{p\ Min} \leq I_p \leq I_{p\ max} \tag{4}$$

$$PSMmin \leq PSM \leq PSMmax \tag{5}$$

PSM_{max} and PSM_{min} are the maximum and minimum limits of PSM. Adjusting the relay tripping time for optimized coordination is possible using the TMS term. This is usually calculated from the plug setting of the relay. Hence the limit on TMS is constituting as given in (6).

$$TMSp,kmin\ \leq\ TMSp,k\ \leq\ TMSp,kmax \tag{6}$$

2.4. Relay characteristics

In this study, all the relays are identical in nature with a uniform inverse definite minimum time (IDMT) defined as [24]:

$$top = \frac{\lambda(TMS)}{(PSM)^{\gamma}-1} \tag{7}$$

$$t_{op} = \frac{\lambda(TMS)}{\left(\frac{I_{relay}}{PS}*CT\ sec\ rated\right)^{\gamma}-1} \tag{8}$$

where t_{op} is described as the relay's operational time, and PS and TMS are described as the plug setting and time multiplier setting, respectively. Current transformer (CT) secondary rated current is known as CT sec, while relay fault current is known as I_{relay}. The values of λ and γ for the typical inverse definite minimum time (IDMT) characteristic relay are typically 0.14 and 0.02, respectively. Therefore, PS and TMS are the two parameters we will use for PSO-GSA optimization. In this implementation, the Pug setting and the TMS of the relays are optimized for relay coordination using a PSOGSA-based method.

3. OPTIMIZATION USING PSO-GSA

3.1. Particle swarm optimization (PSO)

Eberhart and Kennedy created the population-based stochastic optimization called PSO method in 1995. A swarm of birds changes its direction from earlier locations to find food. This behavior of birds is converted mathematically as a PSO algorithm. An adaptive algorithm based on bird behavior [25]. Every iteration of the PSO process involves a constant updating of the particle position and velocity parameters. New determined velocity data update the position of the particles after each cycle [26]. The updated velocity value is calculated as the difference between the current location and the prior and global best positions, or p_{best} and g_{best}, respectively. The resulting updated value will be applied to the calculation of the swarm's next position. Velocity function of the PSO algorithm is given in (9).

$$V_{i(t+1)} = kV_{it} + C_1 * rand * (p_{best} - X_{it}) + C2 * rand * (g_{best} - X_{it}) \tag{9}$$

Particle initially generated for the first iteration is updated using the (10):

$$X_{i(t+1)}=X_{it}+V_{i(t+1)} \tag{10}$$

where V_{it} and X_{it} is defined as the velocity and current position of particle i at iteration t, pbest is the best agent obtained at every iteration, g_{best} is the best solution obtained for all the previous iterations, C_1, C_2 and k are the weighting factor and weighing function respectively, 'rand' is the random number between 0 to 1.

3.2. Gravitational search algorithm (GSA)

GSA is a population-based metaheuristic technique, like PSO, that is governed by Newton's laws of motion and gravitation. In GSA, particles are known as agents. In GSA, where the agents are referred to as objects, agents are determined from their masses. Due to the gravitational pull of the items toward one another, mass is accumulated by all of the objects [27]. The force between the objects is directly equal to the product of their masses and inversely proportional to the square of the distance between them [28]. The particles in the GSA are determined by four variables: inertial mass, active and passive gravitational mass, and position of the mass in the d^{th} dimension. The values for these parameters are determined by the particles' fitness value [29]. The pressure exerted by two i particles j [11]:

$$F_{ij}^{d} = G(t)\frac{M_{pi}(t)\times M_{aj}(t)}{R_{ij}(t)+\in}\left(x_j^d(t) - x_i^d(t)\right) \tag{11}$$

where M_{aj} and M_{pj} are described as the gravitationally-related active and passive masses for particles i and j, respectively. $R_{ij}(t)$ is the Euclidean distance between two particles i and j, $G(t)$ is the gravitational constant at time t, and $\in$ is the small constant. The (12) provides a formula for calculating the gravitational constant

$$G(t) = G_o * exp[-\alpha * (iter/max\ iter)] \tag{12}$$

where G_0 and α are the initial value and descending coefficient respectively, *iter* is the value of the current iteration and max *iter* defines the maximum number of iterations. In the search space of d^{th} dimension, the total force acting against particle i is expressed as given in (13):

$$F_i^d(t) = \sum_{j=1.\ j\neq i}^{N} rand_j\, F_{ij}^d(t) \tag{13}$$

where the random number between 0 and 1 is called $rand_j$. According to Newton's equation of motion, a particle's acceleration is inversely related to its mass and directly proportionate to the generated force. Consequently, the definition of each particle's acceleration is:

$$A_i^d(t) = \frac{F_i^d(t)}{M_{ii}(t)} \tag{14}$$

where M_{ii} is the mass of the particle i. Lastly, the velocity and position of the particle i at d_{th} dimension space is determined as (15) and (16).

$$Vel_{id(t+1)}=rand_i*Vel_{id(t)}+A_{id(t)} \tag{15}$$

$$X_{id(t+1)} = X_{id(t)} + Vel_{id(t+1)} \tag{16}$$

3.3. Hybrid particle swarm optimization gravitations search algorithm (PSO-GSA)

In this implementation, the PSO is combined with the GSA to form a hybridized algorithm known as PSO-GSA. In PSO-GSA, the characteristics and functionalities of both algorithms are integrated and both algorithms are executed in parallel. The hybrid approach is heterogeneous in nature since it involves two different algorithms. The proposed PSO-GSA possesses the ability of PSO along with the local searching ability of GSA. The velocity and position of the particle in the hybridized approach is evaluated as given in (17) and (18).

$$\mathrm{Vi}(\mathrm{t}+1) = \mathrm{k} * \mathrm{Vi}(\mathrm{t}) + \mathrm{C1} * \mathrm{rand} * \mathrm{aCi}\ (\mathrm{t}) + \mathrm{C2} * \mathrm{rand} * (\mathrm{gbest} - \mathrm{Xi}\ (\mathrm{t})) \tag{17}$$

$$\mathrm{Xi}(\mathrm{t}+1) = \mathrm{Xi}(\mathrm{t}) + \mathrm{Vi}(\mathrm{t}+1) \tag{18}$$

The flowchart of the proposed PSO-GSA is illustrated in Figure 1.

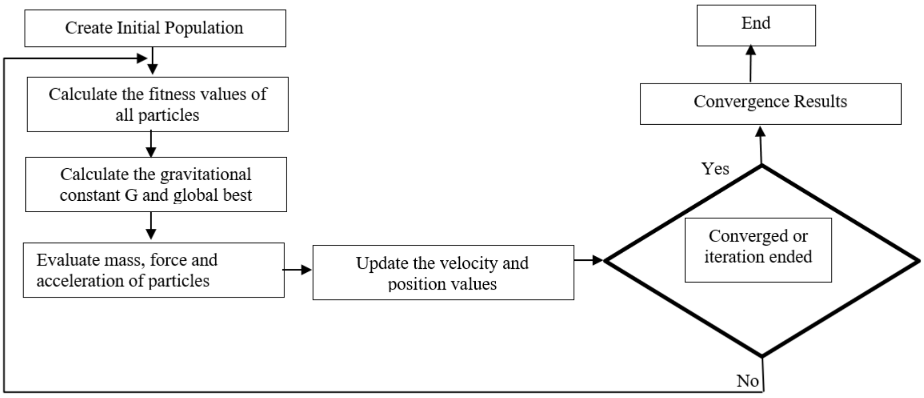

Figure 1. Flowchart of PSO-GSA

4. RESULTS AND DISCUSSION

As seen in Figure 2, a 4-bus radial system is used, with an 11 kV step-down voltage for the grid. By using the PSOGSA technique, the optimal TMS and PS values of the six relays that are present in each bus are determined. Here, this optimization is accomplished using the MATLAB platform. At the very end of each relay, faults are produced. The malfunction started after 0.5 seconds. The IEEE 4 bus system contains 6 relays and the CT ratio of each relay is tabulated in Table 1.

The IEEE 4-bus system is used to verify the relay coordination utilizing PSOGSA, as shown in Figure 3. As mentioned in section 3, the relay coordination problem's objective function is formulated. The performance of the relay coordination is determined using different parameters such as Relay number, number of turns on primary of current transformer, TDS, load factor, fault current, load current, PSM. Simulation is performed using MATLAB and the Simulink model is illustrated in Figure 3.

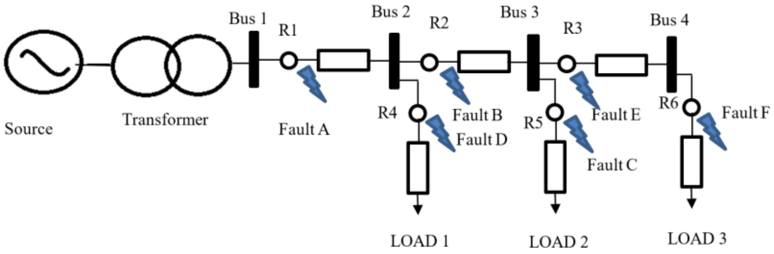

Figure 2. Single source 4-bus radial system

Table 1. CT ratios of each relay

Relay No	CT Ratio
1	1000/1
2	800/1
3	600/1
4	600/1
5	600/1
6	600/1

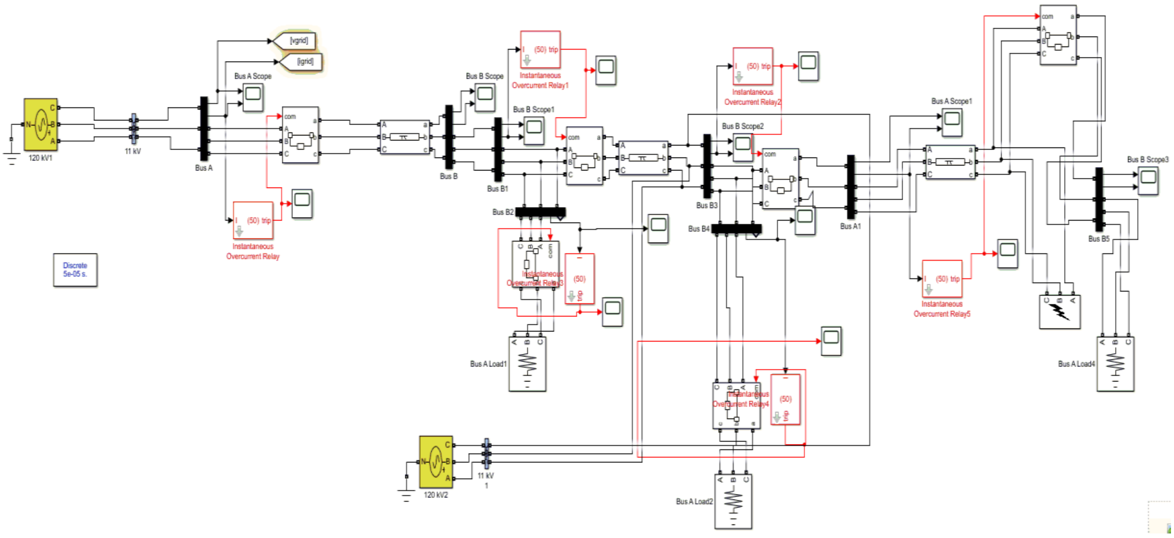

Figure 3. Simulink model of the IEEE 4-bus system

4.1. Case 1: without DG

The Simulink model shown in Figure 3 will be simulated without connecting the DG and the relay currents at different fault positions are shown in Figures 4, 5, and 6. The optimal values of relay settings are given in Tables 2 and 3. In Case 1, PSO and GSA provide TMS that is less than PSO-GSA for all relays, while PSO-GSA provide PSM that is less than PSO and GSA. This is even significant because overall calculations reveal that PSOGSA computes total operating time to be reduced, leading to speedier relay operation. Table 4 gives the operating time of all relays for six faults.

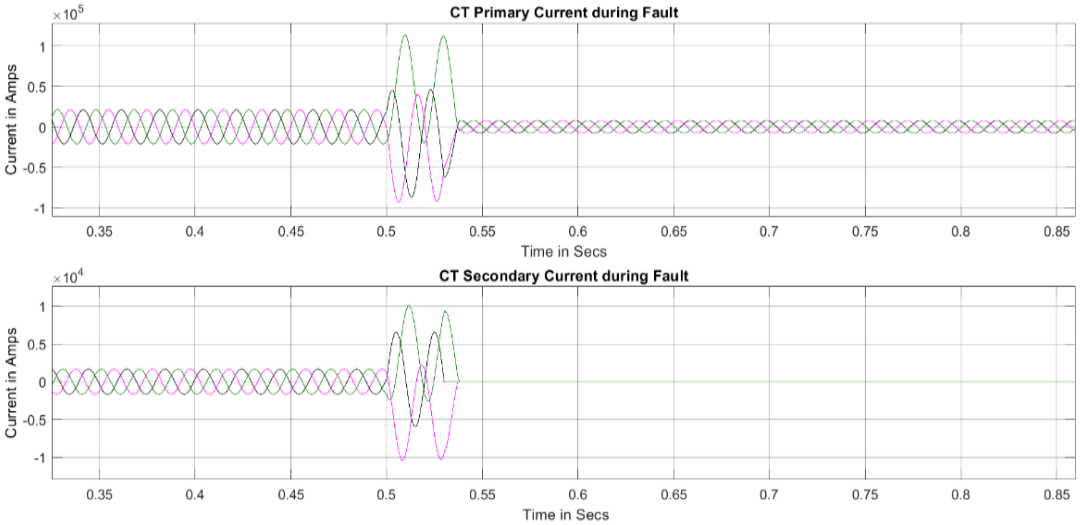

Figure 4. Fault current in primary side of CT for Relay 1 and 2 for fault point A

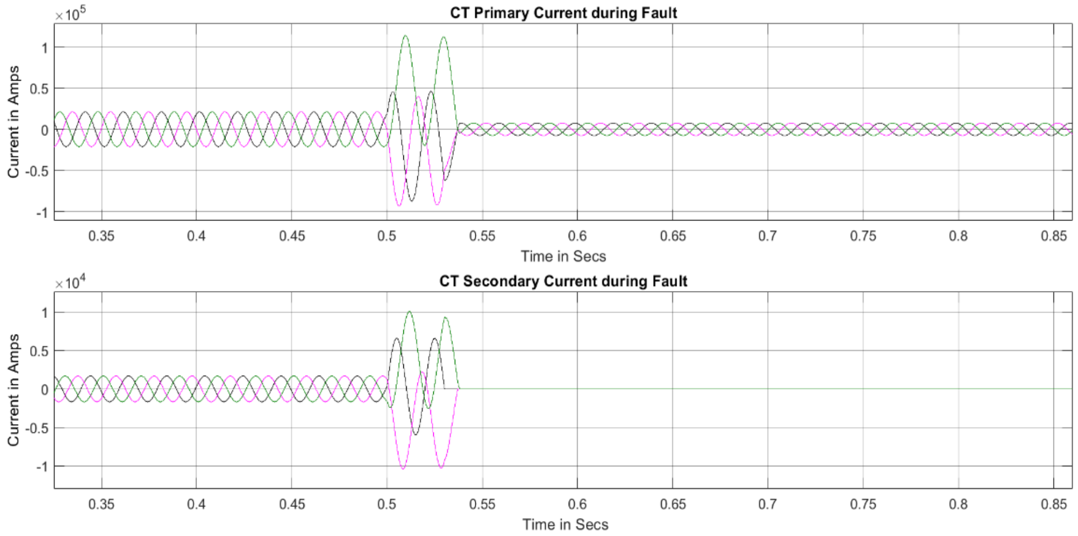

Figure 5. Fault current in primary side of CT for Relay 2 and 1 for fault point B

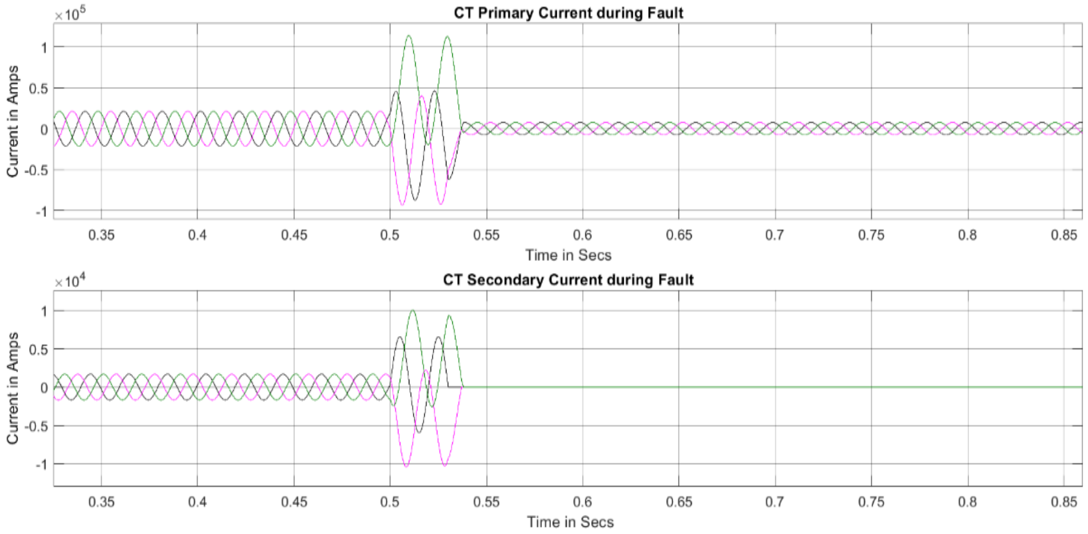

Figure 6. Fault current in primary side of CT for Relay 4 and 2 for fault point C

Table 2. Comparison of TMS values

Faults	PSO	GSA	PSOGSA
Fault 1	0.084	0.1	0.4
Fault 2	0.08	0.09	0.53
Fault 3	0.08	0.1	0.27
Fault 4	0.08	0.14	0.41
Fault 5	0.09	0.08	0.45
Fault 6	0.08	0.08	0.53

Table 3. Comparison of PSM values

Faults	PSO	GSA	PSOGSA
Fault 1	0.99	0.99	0.27
Fault 2	1.07	1.00	0.33
Fault 3	1.24	0.99	2.68
Fault 4	1.14	1.09	0.84
Fault 5	1.10	1.23	0.69
Fault 6	1.04	1.02	0.14

Table 4. Operating time of relays for different fault points

Faults	Primary Relay	Operating Time in seconds	Secondary Relay	Operating Time	CTI
Fault 1	R1	0.7	R2	1.53	0.83
Fault 2	R2	0.85	R1	1.22	0.37
Fault 3	R3	1.67	R2	2.6	0.93
Fault 4	R4	1.1	R2	1.69	0.59
Fault 5	R5	1.02	R4	1.54	0.52
Fault 6	R6	0.7	R4	1.32	0.62

4.2. Case II: with DG (26.6%)

When demand rises at certain of the load centers, the additional load is managed by either raising main grid generation or DG penetration levels. In order to clarify how a reliable relay function can be guaranteed under fault conditions at any of these penetration levels, a case study is given. The DG penetration level is given as:

$$\%\ DG\ Penetration\ level\ = \frac{P_{DG}}{P_{DG}+P_{Grid}} * 100$$

As the load increases, DG penetration grows. In terms of penetration percentage, a 50% load increment is equivalent to 33.33% of DG level, which can be regarded as the upper bound [30]. Taken are two situations at 26.66% and 31.25%. In the case study, DG is inserted into the network at bus 3 with a penetration level of 26.66%. The fault current is adjusted in relay 1 for fault point 1. The values of TMS and PSM for 26.6% penetration are given in Table 5.

Table 5. TMS and PSM of relays using PSOGSA for 26.6% DG penetration

Faults	PSM	TMS
Fault 1	2.15	0.2
Fault 2	2.87	0.1
Fault 3	2.64	0.27
Fault 4	0.31	0.53
Fault 5	0.24	0.53
Fault 6	0.05	0.53

The currents that contribute to the fault current for the DG added system may flow in two directions. Although the aggregate fault current values grow with DG penetration of 26.6%, faults 2 and 3 only contribute a very little amount. As soon as a defect develops, it is seen that relays 4, 5, and 6 experience an increase in current magnitude. Table 5 shows the operation time and CTI between relays with a DG penetration level of 26.6%. The CTI measured are more than 0.3S, indicating successful coordination. Figure 7 shows the convergence graph for this scenario. This graph illustrates how PSOGSA converges to a better solution, or one that requires the least amount of operating time. Each operation’s total operation time value is examined.

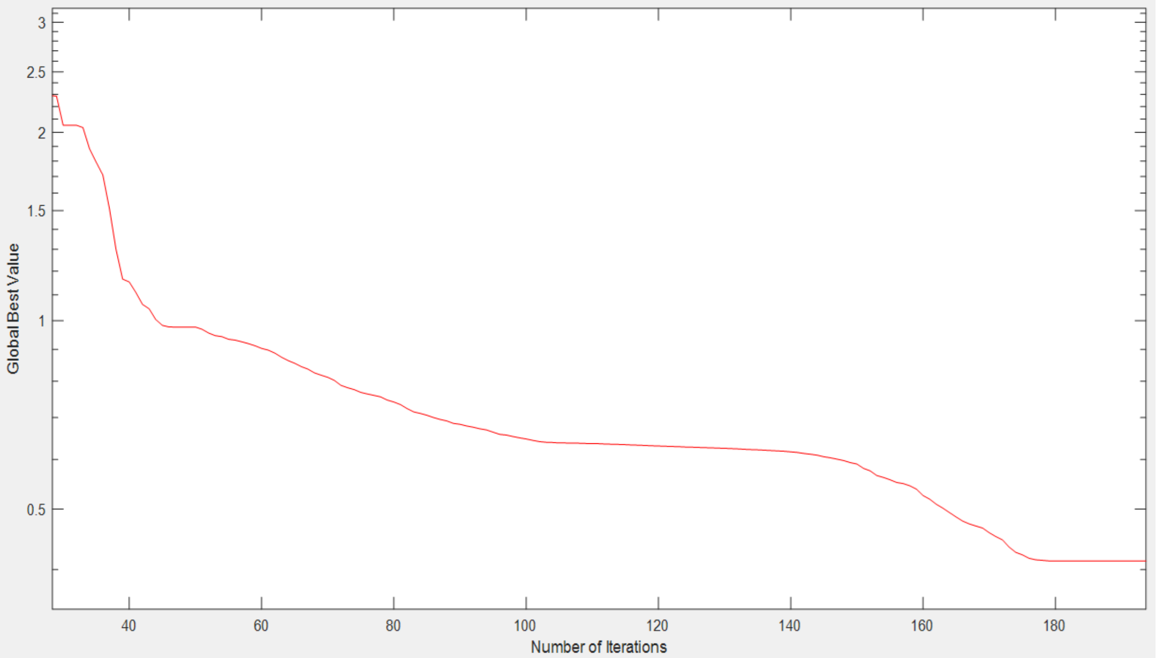

Figure 7. Convergence graph

4.3. Case III: with DG (31.25%)

In this instance, DG is applied to Bus 3 with a 31.25% DG penetration. Table 6 displays the obtained TMS and PSM for this example, whereas Table 7 displays the operating time and CTI values for each case. Tables 6 and 8 show the operation time and CTI between relays for 26.6% and 31.25%, respectively. The CTI recorded in both situations is greater than 0.3s in the majority of the faults, demonstrating proper coordination. Additionally, it appears that as DG penetration levels climb, relay operation times shorten. For instance, at faults 1 and 2, the relay starts to run at a DG level of 26.6% after 0.53 and 1.21 S, respectively, then it decreases to 0.48 and 0.53 S when penetration increases to 31.25%. The IDMT relay operates for a shorter period of time as a result of the system's total fault current level gradually rising.

Table 6. Operating time of relays for different fault points (26.6%)

Faults	Primary Relay	Operating Time in seconds	Secondary Relay	Operating Time in seconds	CTI in seconds
Fault 1	R1	0.53	-	-	-
Fault 2	R2	1.21	R1	2.79	1.58
Fault 3	R3	0.52	R1	1.1	0.58
Fault 4	R4	0.16	R1	1.25	1.09
Fault 5	R5	0.11	R2	0.95	0.84
Fault 6	R6	0.16	R4	0.37	0.21
Total Operating Time in seconds		2.69		6.46	

Table 7. TMS and PSM of relays using PSO-GSA for 31.25% DG penetration

Faults	PSM	TMS
Fault 1	1.83	0.22
Fault 2	2.45	0.14
Fault 3	2.68	0.27
Fault 4	0.32	0.53
Fault 5	0.32	0.53
Fault 6	0.07	0.53

Table 8. Operating time of relays for different fault points (31.25%)

Faults	Primary Relay	Operating Time in seconds	Secondary Relay	Operating Time in seconds	CTI in seconds
Fault 1	R1	0.48	R2	2.21	1.73
Fault 2	R2	0.53	R1	0.95	0.42
Fault 3	R3	0.52	R2	0.81	0.29
Fault 4	R4	0.1	R1	0.96	0.86
Fault 5	R5	0.08	R2	0.92	0.84
Fault 6	R6	0.17	R4	0.36	0.2
Total Operating Time		1.88		6.21	

4.4. Comparative analysis

By contrasting the outcomes with an existing optimization strategy described in [30], the performance of the new PSO-GSA algorithm was confirmed. Tables 9 and 10, respectively, present the results of the previously completed work and the anticipated work. It can be inferred from the comparative results that the proposed algorithm reduces the operating time for both primary and backup relays. Results validate the fact that the proposed optimization technique can reduce the operating time which in turn improves the performance of the relays during fault condition.

Table 9. Performance of primary and backup relay of existing work for 26.6% DG penetration

Fault Point	Primary relay unit		Backup relay unit		CTI (sec)
	Relay	Operating Time (sec)	Relay	Operating Time (sec)	
Fault 1	1	0.98	-	-	-
Fault 2	2	0.69	1	1.00	0.31
Fault 3	3	0.45	2	0.77	0.31
Fault 4	4	0.35	1	1.01	0.65
Fault 5	5	0.37	2	0.77	0.39
Fault 6	6	0.22	3	0.54	0.31

Table 10. Performance of primary and backup relay of the proposed PSOGSA for 26.6% DG penetration

Fault Point	Primary Relay Unit		Backup Relay Unit		CTI (sec)
	Relay	Operating Time (sec)	Relay	Operating Time (sec)	
Fault 1	1	0.53	-	-	-
Fault 2	2	1.21	1	2.79	1.58
Fault 3	3	0.52	1	1.1	0.58
Fault 4	4	0.16	1	1.25	1.09
Fault 5	5	0.11	2	0.95	0.84
Fault 6	6	0.16	4	0.37	0.21

5. CONCLUSION

In order to reduce the total working time of the relays in an IEEE 4 bus system, an optimal PSM and TMS of six relays are found. This is done using a hybrid PSO-GSA optimization technique. The maximum load current and lowest fault current are used to determine the range of plug settings for each relay. All of the overcurrent relay situations are coordinated, and the collected data are summarized to confirm the efficiency of PSOGSA. The protective relay may operate more quickly while still meeting the coordination restrictions when the objective function is minimized, validating PSOGSA as a possible optimization strategy for relay coordination in the distribution network. Additionally, the outcomes demonstrate that the suggested optimization technique outperforms the individual standard PSO and GSA findings and can be applied to the distribution system to improve dependability. This implementation, in contrast to the previous one, uses the IEEE bus system model from Simulink. To validate the relay coordination in a future implementation, a sizable bus system must be taken into account. To achieve relay coordination and validation with prior results, a variety of hybrid optimization strategies must be used.

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