Distribution System Overcurrent Relay Coordination Using Particle Swarm Optimisation

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Abstract – *Overcurrent relay coordination is essential for ensuring the selective and rapid isolation of faults in electrical distribution systems. The increasing integration of distributed generation (DG) has introduced bidirectional power flow and varying fault current levels, making conventional trial-and-error coordination methods less effective. This paper presents a Particle Swarm Optimisation (PSO)-based approach for optimising the Time Multiplier Settings (TMS) of overcurrent relays in a modified CIGRE medium-voltage (MV) benchmark distribution network operating under both grid-connected and islanded modes. The optimisation objective is to minimise the total relay operating time while maintaining a coordination time interval (CTI) of 0.3 s between primary and backup relays. Load-flow and short-circuit analyses are performed to determine relay pickup settings and fault current levels before applying the PSO algorithm. Simulation results showed that the proposed method significantly improves relay coordination compared with conventional settings. The total coordination time for three-phase faults is reduced from 3.1676 s to 2.1469 s (32.2%), while the coordination time for single-phase-to-ground faults decreases from 2.2948 s to 2.0652 s (10%). The optimised relay settings also provided effective coordination under both grid-connected and islanded operating conditions. These results demonstrated that the proposed PSO-based approach offers an efficient and reliable solution for improving overcurrent relay coordination in modern distribution networks with DG. The study also identified the need for future validation using larger distribution networks, additional fault types, artificial-intelligence (AI)-based optimisation techniques, real-time simulation, and hardware-in-the-loop (HIL) testing to further assess scalability and practical implementation.*

Keywords: *Distribution system, Grid-connected mode, Islanded mode, Overcurrent protection Particle swarm optimisation, Relay coordination*

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I. Introduction

Relay coordination in distribution systems presents significant challenges due to the need to select appropriate protection settings that satisfy fundamental protection requirements, including sensitivity, selectivity, reliability, and speed [1]. Since distribution systems are continuously exposed to various fault conditions, the correct selection of protection parameters is essential to minimise the impact of faults and maintain system stability. In overcurrent relay coordination studies, the time multiplier setting (TMS) and the pickup current are the key parameters that govern relay operating characteristics and coordination performance [2].

Traditionally, relay coordination has been achieved using deterministic, manual trial-and-error approaches [3], [4]. While simple to implement, these conventional methods are increasingly inadequate for modern distribution networks, which are becoming more complex due to the widespread integration of distributed generation (DG) [5], [6]. The presence of DG alters fault current levels and power flow directions, often leading to miscoordination when classical techniques are applied. During both system development and abnormal operating conditions, protection systems must operate rapidly and reliably to safeguard power system equipment. Achieving this level of performance using overcurrent relays alone is challenging, motivating the need for advanced optimisation-based coordination techniques.

Early optimisation approaches aimed to address

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coordination challenges using classical analytical methods.

In [4], optimisation-based protection coordination was first introduced, while [7] proposed a practical solution to mitigate sympathetic tripping caused by intersections between upstream and downstream relay time–current characteristics. An analytical approach based on the impedance matrix (Z-matrix) was presented in [8], leveraging the physical parameters of the equivalent network for fault coordination and analysis. Although these methods demonstrated improved coordination performance, they often suffer from slow convergence, high computational burden, and excessive iteration requirements.

To simplify the coordination problem, several studies assumed that relay pickup currents are predefined, thereby reducing the optimisation problem to a linear formulation. Based on this assumption, the simplex and dual simplex two-phase methods were applied in [9]–[12], to determine optimal time dial settings. However, it has been observed that improved coordination solutions may exist beyond predetermined pickup current values, potentially yielding superior overall performance [2]. To address this limitation, [13] proposed a nonlinear programming approach that adapts to dynamic changes in network topology to coordinate directional overcurrent relays. This method was validated on an industrial power system using linear approximations of relay dynamics to model coordination constraints.

The overcurrent relay coordination problem is generally formulated as a constrained optimisation problem, with the objective of minimising the total operating time of all primary relays [14], [15]. More recent formulations have extended this framework to incorporate multiple objectives, such as minimising coordination time intervals, maximising protection sensitivity, and reducing outage loads [16], [17]. Among various metaheuristic techniques, Particle Swarm Optimisation (PSO) has received considerable attention due to its simplicity and effectiveness. In [18], a standard PSO was applied to 3-bus, 4-bus, and 6-bus test systems to coordinate directional overcurrent relays in distribution networks with loops and bidirectional power flow. The study optimised both plug and time dial settings while ensuring appropriate coordination intervals. Similarly, [19] employed PSO with single- and two-variable formulations to achieve adaptive relay coordination in a radial system, with validation performed using MATLAB and ETAP. In [20] , a PSO was applied to a multiphase unbalanced radial distribution system integrated with wind turbine generators, using the IEEE 13-bus system to address coordination challenges introduced by renewable energy variability. Ref. [21] further demonstrated the applicability of standard PSO for relay coordination in an industrial network, reinforcing its viability as an alternative to traditional analytical approaches.

Despite its effectiveness, standard PSO exhibits certain limitations, including premature convergence and reduced solution diversity. Consequently, several modified PSO variants have been proposed to enhance convergence speed and solution quality by adapting velocity updates, inertia weights, and particle position strategies [21], [22]. In [22], a modified PSO was compared with standard PSO for time-delay setting optimisation at the Moramo Stream Power Plant, with results indicating superior coordination performance and reduced operating time. The optimisation algorithm was implemented in MATLAB and validated using ETAP, demonstrating effective protection of system components, including transformers and induction motors.

Further advancements include multi-objective PSO formulations that address limitations of traditional PSO. In [16] a multi-objective backbone PSO incorporating time-varying variation, linear-decreasing dynamics allocation, and k-means clustering was proposed to maintain diversity and avoid local optima. Similarly, [15] introduced a continuous PSO integrated with a local search algorithm and penalty-based constraint handling, achieving globally superior solutions compared to conventional techniques. Hybrid optimisation strategies combining PSO with other methods have also been investigated to enhance coordination performance by compensating for individual algorithmic limitations [23], [24]. In addition, [25] proposed a modified multi-objective PSO incorporating novel leader selection, repository management, and velocity update mechanisms to enable faster relay operation. More recently, swarm-based artificial intelligence techniques incorporating quantum-inspired principles have been explored. In [26], a quantum-inspired swarm algorithm employing adaptive quantum rotation gates was proposed and validated on IEEE 3-, 8-, and 15-bus systems, as well as the CEC 2020 benchmark suite, demonstrating improved search dynamics and coordination accuracy.

In this paper, an optimised overcurrent relay coordination approach is presented for a distribution system operating under both grid-connected and islanded modes. The proposed method ensures proper grading between primary and backup relays while reducing outage duration. The remainder of the paper is organised as follows: Section 2 presents the formulation of the overcurrent relay coordination problem, including the coordination constraints and the PSO framework. Section 3 describes the protection system and the developed optimisation algorithm. Simulation results are presented in Section 4, and conclusions are drawn in Section 5.

II. Problem Formulation for Overcurrent Coordination

The CIGRE medium-voltage (MV) distribution network shown in Fig. 1 is used to demonstrate the proposed overcurrent relay coordination approach. The modified network is modelled and simulated to perform load-flow, short-circuit, and relay-coordination analyses under both grid-connected and islanded operating modes. The results from the load-flow and short-circuit analyses are subsequently used to determine the pickup settings for the phase- and ground-time-overcurrent (51) relays.

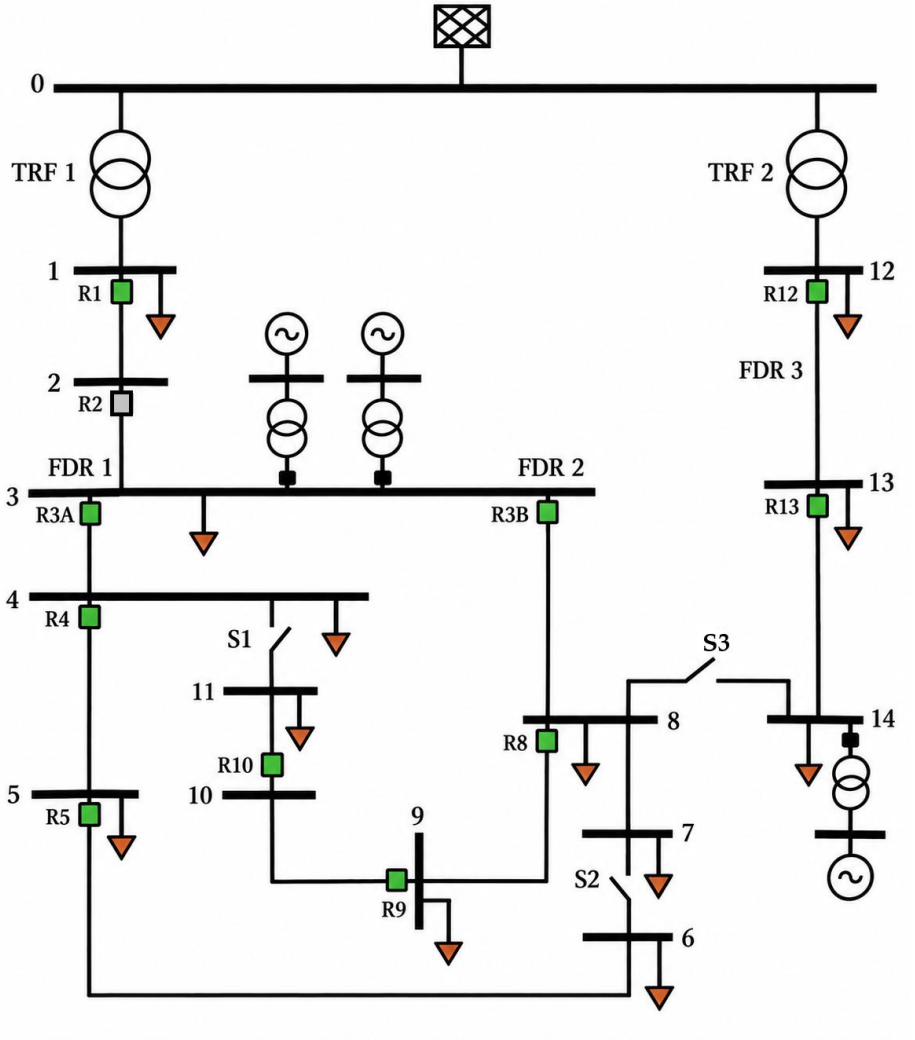


Fig. 1. CIGRE MV benchmark distribution network

A. Relay Coordination Constraints

Selectivity between the upstream and downstream relays is considered, and a coordination time interval (CTI) is defined. CTI is calculated using formula 1 below. In the PSO code, the CTI is set to 0.3 seconds across all relays. If a condition arises that violates the given CTI, a penalty will be added to the code's objective function to force the PSO towards an adequate solution.

$$T_{\text{backup}} - T_{\text{primary}} \geq CTI \tag{1}$$

The optimisation objective is defined as the sum of the relay operating times together with a penalty term applied whenever the coordination constraint is violated. The objective function is expressed as

$$F(TMS) = \sum_{i=1}^{N} T_i + P \tag{2}$$

where $F(TMS)$is the objective function, $N$is the number of relay operating times included in the optimisation, $T_i$is the operating time of relay i, and $P$is the penalty associated with a coordination-constraint violation.

For the set of primary-backup relay pairs, the penalty term is evaluated according to the magnitude of the CTI violation. Defining the coordination violation for the relay pair j as

$$\Delta_j = \max\left[0, CTI - \left(T_{backup,j} - T_{primary,j}\right)\right] \quad (3)$$

the penalty term can be expressed as

$$P = \lambda \sum_{j=1}^{N_p} \Delta_j \quad (4)$$

where $N_p$is the number of primary-backup relay pairs and $\lambda$is the penalty coefficient used to increase the objective-function value when a coordination constraint is violated. When

$$T_{\text{backup},j} - T_{\text{primary},j} \geq 0.3\ s,$$

$\Delta_j = 0$and no penalty is applied. When the time difference is less than 0.3 s, $\Delta_j > 0$, thereby increasing the objective-function value and discouraging the PSO from selecting an infeasible solution.

B. Formulation of the Particle Swarm Optimisation

PSO is an optimisation-based method that uses a population-based algorithm mimicking the social dynamics of particle swarms, without using derivatives. A set of Time multiplier Setting values (TMS) is represented in each particle in the swarm. This can be represented by X_{TMS} below.

$$X_{TMS} = [\ \text{TMS}_1, \text{TMS}_2, \text{TMS}_3, \text{TMS}_{4\ldots\ldots}] \quad (5)$$

Accordingly, each particle represents only the TMS decision variables, while the pickup-current settings remain fixed throughout the optimisation.

With the pickup currents, fault currents, and inverse-time characteristic parameters fixed, the TMS-only coordination problem considered in the present study may also be formulated using deterministic optimisation techniques, including linear programming, depending on the adopted mathematical representation of the relay constraints. PSO is therefore not introduced here on the basis that a deterministic solution is unavailable. Rather, it is adopted as a population-based optimisation framework for investigating relay TMS coordination and for providing a formulation that can subsequently be extended to larger or nonlinear decision spaces, such as simultaneous optimisation of TMS and pickup-current settings. The results of the present study should consequently be interpreted as an evaluation of the adopted PSO-based coordination approach relative to the conventional settings considered, rather than as evidence that PSO is computationally superior to deterministic optimisation methods.

The search boundaries for TMS are set between

$$0.05 \leq TMS_k \leq 1.5$$

Other PSO parameters used are tabulated in Table I. These values are set in the code according to the user's preferences. Each swarm particle adjusts its TMS position based on its own best experience, global best solution, and momentum.

TABLE I
PSO PARAMETERS

PARAMETER	VALUE
PSO Swarm size	40
Max iterations	150
Inertia weight (w)	0.7
Cognitive coefficient (c1)	1.5
Social coefficient (c2)	1.5

The PSO parameters listed in Table I were maintained constant for all simulations in this study to provide a consistent optimisation configuration across the investigated operating conditions. The swarm size and maximum number of iterations influence the extent to which the search space is explored, while the inertia weight and cognitive and social coefficients govern the balance between exploration and exploitation during the optimisation process. Increasing the swarm size or iteration limit can improve the opportunity to identify lower objective-function values, but at the expense of increased computational effort. Similarly, changes in w, c_1, and $c_2$can affect the convergence trajectory and the diversity of the particle population.

A systematic parameter-sensitivity study was not undertaken in the present work; consequently, the selected values should be regarded as the PSO configuration used for the reported case study rather than as universally optimal parameter settings. The conclusions regarding relay operating-time reduction are therefore limited to this optimisation configuration. A comprehensive sensitivity study involving different swarm sizes, iteration limits, inertia weights, and acceleration coefficients would be required to quantify the robustness of the algorithm to parameter variation.

C. Velocity and Position Update

The particles' dynamics are governed by the specified update equations.

The update velocity is given by:

$$V_i^{t+1} = wV_i^t + c_1 r_1 (pBest_i - X_i^t) + c_2 r_2 (gBest - X_i^t) \quad (6)$$

Position update is given by the expression below:

$$X_i^{t+1} = X_i^t + V_i^{t+1} \quad (7)$$

Each variable of the expression in (7) is defined below:
V_i^t particle velocity $i$at iteration t.
X_i^t particle i is the position at iteration t.
i is the particle index.
c_1, c_2 are cognitive and social constants [1.5].
r_1, r_2 user-defined numbers.
w is the inertia weight [0.7].
$pBest_i$ is the personal best position.
$gBest$ is the best global position.

III. Protection System Description

A. Current Transformer Selection

IEEE Std C37.110-1996 recommends that, when current transformers (CTs) are used for protection relaying, the maximum design load current of the power system should not exceed the CT primary current rating. To ensure optimal performance and minimise wiring requirements, the CT ratio should be selected as low as practicable while still accommodating fault conditions. Furthermore, the standard specifies that, under maximum symmetrical primary fault current, the CT secondary current should not exceed 20 times its rated value [27]. Based on these criteria, CT ratios of 50:1, 75:1, 100:1, and 200:1 were selected in this study.

B. Overcurrent Protection Settings

The pickup current is typically set between 125% and 150% of the short-time maximum load current. The short-time maximum load represents the highest current the circuit is expected to carry under emergency or abnormal operating conditions, such as a nearby feeder outage.

In the present study, the relay pickup-current settings are determined prior to the PSO optimisation from the load-flow and short-circuit studies and are subsequently treated as fixed protection parameters. The optimisation is therefore restricted to the Time Multiplier Settings (TMS). This sequential approach separates the selection of pickup thresholds, which are established to satisfy relay sensitivity and loadability requirements, from the time-coordination stage. Consequently, the resulting PSO solution should be interpreted as the best-found TMS solution for the prescribed pickup-current settings rather than as a joint optimum over both TMS and pickup current. Simultaneous optimisation of TMS and pickup current would enlarge the search space and may yield further improvements, and is identified as an extension of the present work.

The relay operating time is defined by IEC 60255 and IEEE C37.112 [28], [29], and is given in Equation 8.

$$T_p = TMS \times \frac{\beta}{\left(\frac{I_f}{I_p}\right)^{\alpha} - 1} \quad (8)$$

where $T_p$is the operating time of a relay, $TMS$is the time multiplier setting, $I_f$is the current detected by the relay, $I_p$is the relay pick-up current, and $\alpha$and $\beta$are slope constants.

For the simulations in this study, the IEC normal inverse-time characteristic was used for both the 51P and 51G relay elements, with $\alpha = 0.02$ and $\beta = 0.14$. These constants were applied consistently in the relay operating-time calculations.

C. Protection System Modeling

The modelled radial distribution system consists of three feeders protected by eleven overcurrent relays. Feeder 1 is protected by four relays, namely R5, R4, R3A, and R1, while Feeder 2 is protected by four relays, R10, R9, R8, and R3B. Feeder 3 comprises three protective relays, R12, R13, and R14. Relay data for grid-connected and islanded operating modes are presented in Table II. The operating time of each relay is calculated individually to assess coordination performance under the different operating conditions.

It should be noded that Relay 13 becomes a back-up protection for Relay 12 under islanded mode of operation. The fault currents and pick-up currents for this 12 under this condition are 623.929 A and 37.5 A, respectively.

TABLE II
RELAY DATA FOR GRID-CONNECTED AND ISLANDED MODES

					GRID-CONNECTED MODE		ISLANDED MODE	
PROTECTION DEVICE NAME	BACK-UP RELAY	BRANCH	PHASE TYPE	CT CURRENT RATIO	FAULT CURRENT (A)	PICK-UP CURRENT (A)	FAULT CURRENT (A)	PICK-UP CURRENT (A)
Relay 1	None	Line 1_2	51P	200:1	1308.873	195	1218.076	55.5
			51G	75:1	1021.278	49.5	971.614	18.88
Relay 3A	Relay 1	Line 3_4	51P	100:1	1308.873	84	1218.076	79.5
			51G	50:1	1021.278	21	971.614	19.88
Relay 4	Relay 3A	Line 4_5	51P	75:1	1308.873	63	1218.076	58.5
			51G	50:1	1021.278	15.75	971.614	14.63
Relay 5	Relay 4	Line 4_6	51P	50:1	1308.873	27	1218.076	25.5
			51G	50:1	1021.278	6.75	971.614	6.75
Relay 3B	None	Line 3_8	51P	100:1	1240.59	85.5	1161.202	79.5
			51G	50:1	963.886	21.38	921.035	19.88
Relay 8	Relay 3B	Line 8_9	51P	75:1	1240.59	52.5	1161.202	33
			51G	50:1	963.886	13.13	921.035	12.38
Relay 9	Relay 8	Line 9_10	51P	50:1	1240.59	16.5	1161.202	16.5
			51G	50:1	963.886	13.13	921.035	4.13
Relay 10	Relay 9	Line 9_10	51P	75:1	1240.59	16.5	1161.202	16.5
			51G	50:1	963.886	4.13	921.035	4.13
Relay 12	None	Line 12_13	51P	50:1	2349.767	31.5	-	-
Relay 13	Relay 12	Line 13_14	51P	50:1	2349.767	30	-	-
Relay 14	None	Line 13_14	51P	50:1	-	-	623.929	30

D. Particle Swarm Optimisation Algorithm for Overcurrent Coordination

A PSO code was used to implement the algorithm presented in Fig. 2 to resolve the overcurrent relay coordination problem in the distribution system. The aim of the code is to determine PSO-derived TMS values for relays on each Feeder (1-3) when a fault condition occurs. The relays in each feeder are arranged radially, and the relay closest to the source operates more quickly, while an upstream relay delays its operation by at least CTI of 0.3 seconds to maintain selectivity and prevent unnecessary outages.

The operating time of the relay is calculated using the IEC normal inverse characteristic curve, which depends on its TMS, fault current, and pickup current. The developed PSO algorithm is configured to initiate a swarm of 40 particles, each representing a candidate solution. Over a maximum of 150 iterations, particles update their positions based on their own best experience and the swarm's global best, guided by inertia and acceleration coefficients. A fitness function embedded in the code assesses each solution by summing all relay operating times and imposing a penalty if a backup relay operates within 0.3 seconds of a primary relay, thereby enforcing constraint satisfaction directly in the objective.

Through exploratory iterations, the swarm searches for TMS values that reduce the total operating time while satisfying the coordination constraints. The resulting TMS values represent the best-found solution obtained for the adopted PSO configuration and should not be interpreted as proof of a global optimum.

IV. Simulation Result

The effectiveness of the proposed PSO-based relay coordination method was evaluated using the modified CIGRE MV benchmark distribution network operating under both grid-connected and islanded modes. The optimisation algorithm was developed in MATLAB and applied to determine PSO-derived TMS for the overcurrent relays while maintaining the required CTI of 0.3 s between primary and backup protection devices. The objective of the optimisation was to minimise the cumulative relay operating time while ensuring that all coordination constraints were satisfied.

The radial distribution network consists of three feeders protected by ten overcurrent relays. Relay coordination was analysed for both three-phase and single-phase-to-ground faults, as these are the most common fault scenarios encountered in practical distribution systems. The fault currents obtained from the load-flow and short-circuit studies were used to calculate relay pickup settings before the optimisation process commenced.

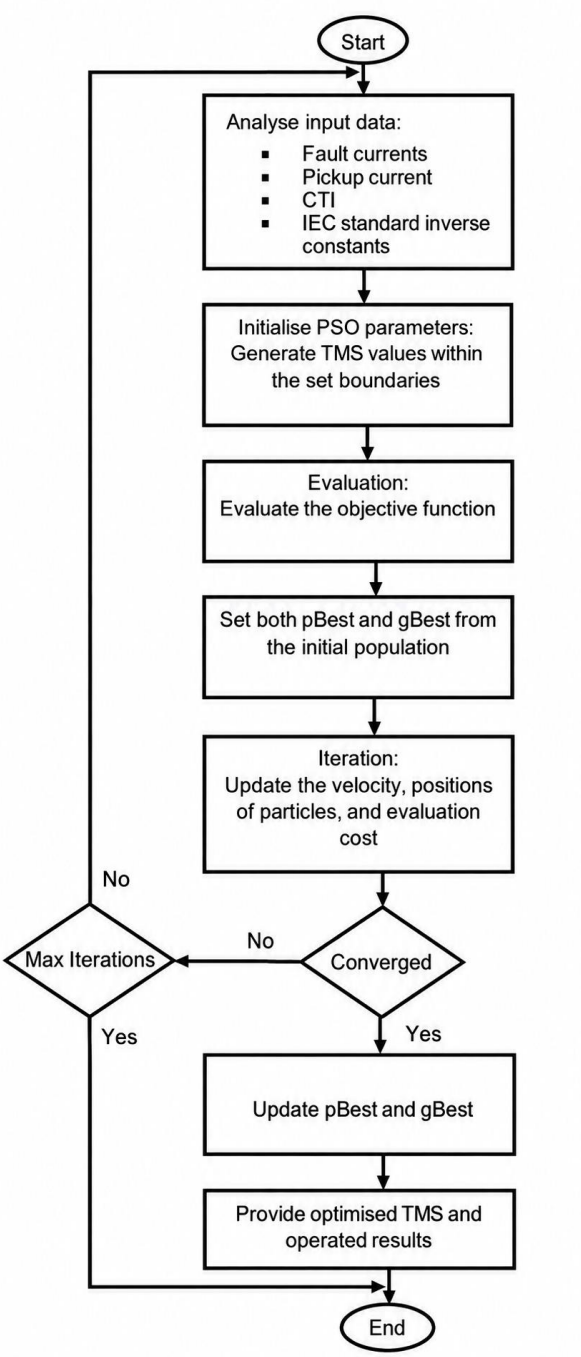


Fig. 2. Flowchart of the particle swarm optimisation algorithm

The validation in the present study is limited to the modified CIGRE MV benchmark network and the two fault scenarios considered. Consequently, the results demonstrate the performance of the proposed coordination approach for the investigated network and operating conditions, but do not establish its performance for larger distribution systems or all possible fault types. Further validation using larger benchmark distribution networks and additional fault scenarios, such as phase-to-phase and double-phase-to-ground faults, is required to assess the

scalability and broader applicability of the proposed method.

The PSO algorithm was configured with a swarm size of 40 particles, a maximum of 150 iterations, an inertia weight of 0.7, and cognitive and social acceleration coefficients of 1.5. During the optimisation process, each particle represented a candidate set of relays TMS values. The particles continuously updated their positions using both individual and global best solutions until the specified iteration limit was reached, with the best objective-function value approaching a stable value.

Unlike conventional trial-and-error relay coordination, the PSO algorithm automatically searched the solution space and produced relay settings that simultaneously reduced operating times while maintaining relay selectivity. The inclusion of a penalty function for CTI violations ensured that infeasible relay settings were rejected during the optimisation process.

The conventional TMS values used as the baseline in this study were obtained using a manual trial-and-error coordination procedure. Starting from the relay pickup-current and fault-current values determined from the load-flow and short-circuit studies, the TMS values were adjusted iteratively until the primary and backup relays satisfied the required 0.3 s coordination time interval. These conventionally coordinated settings were then used as the reference case against which the PSO-derived TMS values and corresponding operating times were compared.

The convergence characteristics of the optimisation algorithm demonstrated stable behaviour throughout the iterations. Initially, the objective function decreased rapidly as particles explored the search space. As the iterations progressed, the improvement gradually diminished, indicating stabilisation of the best-found objective-function value. In this study, convergence was assessed from the reduction and subsequent stabilisation of the best-cost value over the 150 optimisation iterations, as illustrated by the convergence curves in Figures 3 and 4. Because PSO is a stochastic optimisation technique, stabilisation of the objective function does not establish that the global optimum has been obtained. No oscillatory behaviour or premature divergence was observed for the PSO parameter configuration adopted in this study. However, this observation should not be interpreted as a general parameter-sensitivity assessment, since alternative PSO parameter combinations were not systematically investigated.

Figure 3 illustrates the relay operating times obtained with both conventional and proposed PSO-optimised settings for Feeder 1 during a three-phase fault. The conventional relay coordination produced a total relay operating time of 3.1676 s, whereas the proposed PSO method reduced the cumulative operating time to 2.1469 s. This represents an overall reduction of approximately 32.2%. The reduction in operating time demonstrates that the optimisation algorithm successfully identified more suitable TMS values without compromising the required grading margin between adjacent relays.

The largest improvements were observed in the upstream backup relays, whose operating times were significantly reduced while still maintaining the prescribed coordination interval. Consequently, faults were isolated much faster, reducing equipment exposure to excessive fault currents and improving overall system reliability.

The results further confirm that the proposed optimisation method preserves relay selectivity throughout the feeder. Primary relays operated before their associated backup relays, ensuring that only the faulted section of the network was isolated while healthy portions remained energised. Single-phase-to-ground faults are among the most frequently occurring faults in distribution networks. Therefore, evaluating relay coordination under these conditions is essential.

Figure 4 compares the relay operating times obtained using conventional TMS values and PSO-optimised TMS values. The total relay operating time with conventional coordination was 2.2948s, whereas the proposed PSO algorithm reduced it to 2.0652s, representing an improvement of approximately 10.0%.

Although the percentage improvement is smaller than that achieved for three-phase faults, the optimisation still resulted in faster relay operation while maintaining coordination. Ground fault currents are generally lower than balanced three-phase fault currents, resulting in inherently longer inverse-time relay operating characteristics. Nevertheless, the proposed optimisation method successfully minimised unnecessary relay delays and maintained proper discrimination between primary and backup relays. These results demonstrate that the optimisation algorithm performs effectively under different fault types without requiring changes to the optimisation framework.

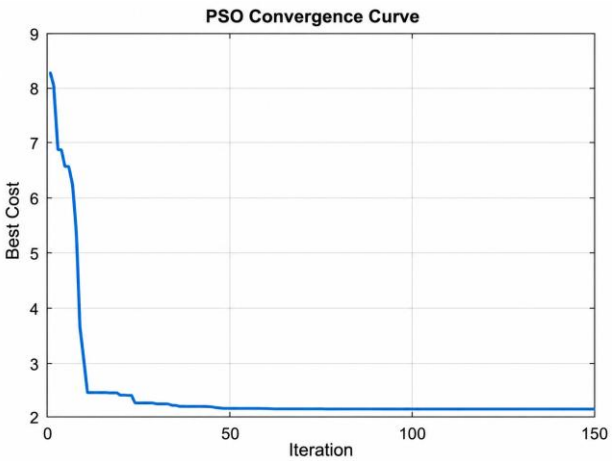


Fig 3. Feeder 1 Three-phase fault PSO performance

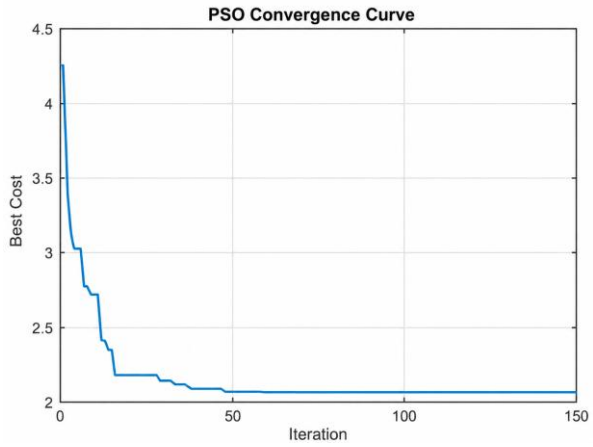


Fig. 4. Feeder 1 Single-phase to ground fault PSO performance

Table III presents the calculated TMS values obtained using conventional coordination techniques together with the optimised values generated by the PSO algorithm for both operating modes.

The optimised TMS values are generally lower than the conventionally selected settings for most relays. Lower TMS values directly reduce relay operating time according to the IEC inverse-time characteristic while preserving the required CTI between adjacent relays.

Similar improvements were observed in islanded operation, where the PSO algorithm adapted the relay settings to accommodate the lower fault-current levels introduced by distributed generation. The grid-connected and islanded operating modes were optimised separately using the corresponding fault-current and pickup-current data for each mode. Consequently, the PSO-derived TMS values reported in Table III are mode-specific settings rather than a single common set of relay settings applied unchanged to both operating modes.

The optimisation framework, therefore, provides an efficient alternative to traditional trial-and-error coordination methods and offers considerable potential for application in future active distribution networks with high levels of distributed generation penetration.

It should be emphasised that the comparative assessment in the present study is limited to conventional relay-coordination settings and the PSO-derived settings. The study does not compare the proposed PSO implementation directly with other metaheuristic optimisation techniques such as Genetic Algorithm (GA), Differential Evolution (DE), Teaching-Learning-Based Optimisation (TLBO), or Grey Wolf Optimisation (GWO). Therefore, the reductions in relay operating time reported in this study should be interpreted as improvements relative to the adopted conventional coordination baseline and not as evidence that PSO is superior to other optimisation algorithms. Accordingly, the present results demonstrate the effectiveness of PSO relative to the adopted conventional baseline, but they do not establish its relative performance against alternative optimisation methods. A systematic comparison with alternative optimisation techniques is required to assess relative convergence behaviour, computational efficiency, repeatability, and solution quality. Such comparative benchmarking is identified as an important extension of the present study.

TABLE III
CONVENTIONAL TSM AND PSO TMS FOR GRID-CONNECTED AND ISLANDED MODES

	GRID-CONNECTED MODE		ISLANDED MODE	
PROTECTION DEVICE NAME	CALCULATED TMS	PSO TMS	CALCULATED TMS	PSO TMS
Relay 1	0.33	0.2736	-	-
	0.5	0.4307	-	-
Relay 3A	0.33	0.2769	0.3	0.2753
	0.36	0.3345	0.41	0.3845
Relay 4	0.21	0.1728	0.18	0.1734
	0.22	0.1277	0.24	0.2295
Relay 5	0.05	0.05	0.05	0.05
	0.05	0.05	0.05	0.05
Relay 3B	0.46	0.3837	0.58	0.3852
	0.56	0.5431	0.56	0.5475
Relay 8	0.39	0.316	0.42	0.3579
	0.46	0.4171	0.46	0.4252
Relay 9	0.21	0.14834	0.25	0.2403
	0.3	0.2547	0.3	0.2947
Relay 10	0.05	0.05	0.05	0.05
	0.05	0.05	0.05	0.05
Relay 12	0.21	0.1824	-	-
	0.22	0.1913	-	-
Relay 13	0.05	0.05	0.05	0.05

	0.05	0.05	0.05	0.05
Relay 14	-	-	0.18	0.17

V. Conclusion and Future Work

This paper presented a PSO-based approach for improving overcurrent relay coordination in a modified CIGRE MV distribution network under grid-connected and islanded conditions. The proposed method optimised relay Time Multiplier Settings (TMS) while maintaining the required 0.3 s coordination interval. Simulation results showed reductions in total relay operating time of 32.2% for three-phase faults and approximately 10% for single-phase-to-ground faults compared with conventional settings. These findings demonstrate the effectiveness of PSO in improving relay coordination while preserving protection selectivity under the investigated operating conditions.

Future work will focus on larger distribution networks, additional fault types, and varying network configurations. Hybrid optimisation, adaptive protection using real-time measurements, and Hardware-in-the-Loop (HIL) testing with commercial numerical relays will also be investigated to assess practical implementation and scalability.

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Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this research article.

Author Contributions

Sikho Ntshiba: contributed to the investigation, data collection, data analysis, and the preparation of the original draft of the manuscript.

Senthil Krishnamurthy: responsible for the conceptualization of the study, supervision of the research process, as well as the review, editing, and further investigation of the draft.

All authors have reviewed and approved the final version of the manuscript for submission and publication in the journal.

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