Development of a Hybrid Adaptive Neuro-Fuzzy and Artificial Bee Colony–Cuckoo Search Optimization Model for Enhanced Fault Detection, Isolation, and Protective Coordination in Smart Distribution Networks with Distributed Energy Resources

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Abstract
The growing deployment of distributed energy resources (DERs) is changing fault behaviour in radial distribution networks. Bidirectional power flow, inverter-limited fault currents and changing feeder configurations can undermine fixed overcurrent-relay settings, compromise primary–backup selectivity and delay fault isolation. This study develops an integrated adaptive neuro-fuzzy inference system–artificial bee colony–cuckoo search (ANFIS–ABC–CS) framework for fault identification, selective isolation, relay coordination and controlled restoration. The ANFIS module interprets voltage, current, symmetrical-component and network-status measurements to estimate fault state and likely protection zone. A hybrid ABC–CS search then identifies feasible relay-setting groups and restoration-switching decisions. Artificial bee colony search explores candidate settings, while cuckoo-search Lévy flights provide refinement and diversification. The design explicitly enforces directional sensitivity, coordination-time intervals, voltage limits, thermal ratings, switching interlocks and network-topology constraints. Autonomous protection and validated fallback settings are retained whenever the supervisory algorithm is uncertain or unavailable. The IEEE 33-bus, 12.66-kV feeder provides the proposed benchmark, augmented with photovoltaic, wind and battery-storage scenarios and an explicit protection model. A numerical demonstration based on 1,200 assumed fault and healthy-state observations yields a classification accuracy of 97.8% for ANFIS–ABC–CS and 91.0% for conventional logic. In the same example, mean fault-isolation time changes from 1.85 to 0.92 s and mean restoration time from 12.6 to 7.2 min. At full DER output, the lowest primary–backup coordination interval improves from 0.10 s under fixed settings to 0.32 s under adaptive setting selection, against a 0.30-s design threshold. These values are scenario-based numerical examples, not measured or executed simulation findings. The proposed study establishes mathematical models, validation requirements and controlled comparisons needed to determine whether the integrated approach offers meaningful gains under DER variability, uncertain faults, communications disruptions and changing network configurations.

Keywords: *Adaptive Neuro-Fuzzy Inference System; Artificial Bee Colony; Cuckoo Search; Fault Detection and Isolation; Distributed Energy Resources; Directional Overcurrent Relay Coordination; Smart Distribution Networks.*

1. Introduction

Distribution systems are increasingly being operated as active networks rather than passive radial feeders. Solar photovoltaic installations, wind turbines, battery energy storage systems and other embedded sources can meet local demand and improve operating flexibility. At the same time, they change the location, direction and magnitude of current supplied during faults. Traditional feeder protection is often designed around current flowing from a primary substation toward downstream loads; this assumption becomes less reliable when several DER units are connected along a feeder. The resulting protection challenges are substantial. A relay may fail to recognize a fault because the upstream current contribution is reduced, while another device may respond unnecessarily to a fault outside its intended zone. Such behaviour is commonly discussed in terms of protection blinding and sympathetic tripping. Coordination between primary and backup devices can also deteriorate as generator outputs, load levels and feeder topology change. Uma et al. (2023) examined adaptive relay-setting coordination with distributed generation, while Hong et al. (2023) considered renewable and demand uncertainty. Together, these studies support assessing protection across operating scenarios rather than relying on one set of assumed fault currents. Intelligent protection methods offer a route to more responsive coordination, provided that their decisions remain subject to established protection principles. Vala et al. (2023) evaluated metaheuristic approaches, including artificial bee colony (ABC) and cuckoo search (CS), for overcurrent-relay coordination. Kumari and Naick (2024) investigated artificial neural networks and adaptive neuro-fuzzy inference systems (ANFIS) for changing microgrid conditions. Nasrallah et al. (2024) considered adaptive electronic protection for self-healing networks. The combined literature suggests opportunities for integrating fault recognition with constrained setting selection rather than treating the classifier and relay optimizer as independent functions. Fault clearing must also be distinguished from service restoration. The immediate protection task is to identify the abnormal condition, trip the appropriate devices and keep the faulted section isolated. Only after isolation has been verified should a controller consider energizing healthy loads through permitted switching. Esfahani et al. (2023) explored decentralized fault isolation; Meteab et al. (2025) examined coordinated self-healing strategies; and Goda et al. (2025) reviewed the operating and computational challenges of electricity restoration. These studies show why restoration quality should be assessed alongside, but never at the expense of, protection selectivity. The research problem is therefore the absence of a fully specified, protection-constrained assessment procedure that connects neuro-fuzzy fault identification, hybrid relay-setting optimization, fault-section isolation and network restoration as DER conditions change. Classifier accuracy alone cannot establish protection dependability. Similarly, a short relay operating time is beneficial only where sensitivity, directional security and primary–backup coordination remains satisfactory. A suitable framework must provide a measurable and reproducible basis for evaluating all these requirements together.

Aim of the study. The study seeks to develop an ANFIS–ABC–CS framework that can recognize faults, select coordinated protection settings and support safe fault isolation and service restoration in DER-integrated distribution networks.

Research objectives. The investigation is designed to: (i) model feeder topology, DER operating states, fault conditions and protection zones; (ii) develop and test ANFIS-based fault-state and

zone estimators; (iii) optimize relay pickup currents, time-multiplier settings and admissible setting groups using ABC–CS; (iv) screen isolation and restoration decisions against equipment, topology and protection constraints; (v) benchmark fault-detection, relay-coordination and restoration metrics under equivalent test conditions; and (vi) assess robustness to inverter current limits, measurement uncertainty, reconfiguration and communication failure.

The IEEE 33-bus system is used as a standard load-flow benchmark and must be augmented with a complete protection arrangement before relay comparisons are meaningful. Deployment on an actual feeder requires its own relays, current transformers, breaker clearing times, switches, network impedances and DER fault-response characteristics.

2. Related Works

Recent research provides complementary building blocks for DER-aware distribution protection. Uma et al. (2023) used a radial-basis-function neural network to adjust overcurrent protection in the presence of distributed generation. Their results indicate the relevance of operating-state information for setting adaptation, although the approach does not establish the performance of the proposed ANFIS–ABC–CS combination. Hong et al. (2023) addressed uncertainty associated with renewable energy and electrical demand, highlighting the importance of protection settings that remain feasible over a range of credible conditions.

Vala et al. (2023) compared several metaheuristics, including ABC and CS, in coordinating overcurrent relays with non-standard characteristics. This comparison motivates investigating the complementary search behaviour of the two algorithms. It does not, by itself, prove that a hybrid search will outperform its individual components. Esfahani et al. (2023), meanwhile, considered decentralized peer-to-peer isolation in networks with high DG penetration, illustrating the role of distributed information in selecting an appropriate faulted section.

The literature on optimization and adaptive protection also includes distinct lines of development. Abdelfattah et al. (2024) studied directional overcurrent relay coordination with vehicle-to-grid resources, using metaheuristic strategies that include cuckoo search. Abdi et al. (2024) considered microgrid relay coordination with NSGA-II and harmony search. Kumari and Naick (2024) examined ANN- and ANFIS-based microgrid protection, including changing operating conditions. Nasrallah et al. (2024) presented an adaptive electronic-relay approach to self-healing protection. Taken together, these contributions support integrated research, but comparisons must account for differences in network models, objectives and protection constraints. Attention has also shifted from relay coordination alone to fault-management sequences. Chen et al. (2025) explored distributed data-driven protection covering fault detection, localization and isolation. Meteab et al. (2025) investigated fault isolation and restoration in a smart distribution-network framework. Goda et al. (2025) reviewed restoration methods with emphasis on safe recovery of healthy load. Li et al. (2025) examined directional-relay coordination in radial networks with inverter-based DERs, emphasizing the relevance of nonconventional short-circuit contributions. Guo et al. (2026) developed an active protection and fault-recovery method incorporating graph optimization and deep reinforcement learning. Nawaz et al. (2026) investigated multi-agent reinforcement learning for protection and restoration. Chen et al. (2026) considered an alternative hybrid optimization strategy for distribution-network self-healing. Although such methods extend adaptability, their reported performance cannot be transferred directly to a new feeder or fault dataset without matched modelling assumptions, evaluation budgets and safety constraints.

Research gap. A specific opportunity remains to link ANFIS-based fault and zone recognition

with ABC–CS coordination of relay-setting groups and safe switching choices within one explicitly constrained workflow. The essential scientific question is whether this integration improves classification reliability, selectivity, isolation speed and service restoration under the same fault scenarios and computational conditions used for comparison models. That question requires sensitivity studies, ablation tests and independent validation, not merely a new combination of algorithm names.

3. Methodology

3.1 Study network, assumptions, and experimental structure

The analysis is organized around the IEEE 33-bus radial feeder, operated at a nominal voltage of 12.66 kV with approximately 3.715 MW of active load and 2.300 MVAr of reactive load. A protection extension is required because the ordinary load-flow benchmark does not specify a complete relay, circuit-breaker and switching arrangement. For the numerical study design, photovoltaic generation of 0.80 MW is placed at Bus 18, wind generation of 0.60 MW at Bus 25, and a 0.40-MW battery converter at Bus 30. These are scenario assumptions rather than computed siting solutions. The DER controls, converter current limits, protection interfaces and switching logic are to be established before running short-circuit cases.

Table 1. Proposed benchmark and operating assumptions

Parameter	Assumption
Feeder	IEEE 33-bus radial test network
Nominal line voltage	12.66 kV
Nominal active/reactive demand	3.715 MW / 2.300 MVAr
DER technologies	PV, wind, battery inverter
Nominal DER installed capacities	0.80 / 0.60 / 0.40 MW
DER output scenarios	0, 25, 50, 75 and 100% of available output
Fault types	Three-phase, L–G, L–L and L–L–G
Fault resistances	0.01, 5, 20 and 50 Ω
Voltage constraints	0.95–1.05 p.u. (assumed)
Minimum primary–backup CTI	0.30 s (illustrative engineering margin)
ABC colony size; CS nest count	40; 20
Search iterations; independent runs	150; 30
Data partitioning	60% training, 20% validation, 20% testing by scenario group

3.2 Load-flow and fault models

For bus i, steady-state active and reactive balances are:

$$P_{Gi} + P_{DER,i} - P_{Di} = V_i \sum_{j=1}^{N} V_j \left[G_{ij}\cos(\theta_i - \theta_j) + B_{ij}\sin(\theta_i - \theta_j)\right]. \qquad (1)$$

$$Q_{Gi} + Q_{DER,i} - Q_{Di} = V_i \sum_{j=1}^{N} V_j \left[G_{ij}\sin(\theta_i - \theta_j) - B_{ij}\cos(\theta_i - \theta_j)\right]. \qquad (2)$$

A simplified balanced fault-current relation is:

$$I_f^{(3\phi)} = \frac{V_{\mathrm{pre},\phi}}{Z_{\mathrm{th}} + Z_f}. \qquad (3)$$

Here, $V_{\mathrm{pre},\phi}$ is prefault phase voltage, Z_{th} the network Thevenin impedance, and Z_f fault

impedance. Equation (3) is **not** a substitute for detailed inverter models; converter-limited fault-current behaviour and unbalanced faults should be represented using a validated dynamic model or an appropriate short-circuit standard.

The feature vector derived from sampled current, voltage, symmetrical components, and device status is defined as:

$$\mathbf{u} = \left[|V_1|, |I_1|, |I_2|, |I_0|, \Delta|I|/\Delta t, P_{DER}, s_{CB}, s_{DG}, s_{top}\right]^T. \qquad (4)$$

Positive-, negative- and zero-sequence components are identified by subscripts 1, 2 and 0. Feature normalization and all data-dependent preprocessing are determined exclusively from the training partition to prevent information leakage.

3.3 ANFIS fault identification and zone recognition

A first-order Sugeno ANFIS maps the feature vector to a set of fault-confidence or zone-membership scores. Rule r has a consequent:

$$f_r(\mathbf{u}) = a_{r0} + \sum_{k=1}^{K} a_{rk}\, u_k. \qquad (5)$$

The normalized ANFIS output is:

$$y(\mathbf{u}) = \frac{\sum_{r=1}^{R} w_r(\mathbf{u}) f_r(\mathbf{u})}{\sum_{r=1}^{R} w_r(\mathbf{u}) + \varepsilon}. \qquad (6)$$

Separate calibrated outputs may be used for healthy/fault detection and for individual protection zones. The detected zone is $z^* = \text{argmax}_z y_z$ when its calibrated confidence exceeds a validation-set threshold. Otherwise the decision is labelled uncertain. The approach must be assessed for unknown fault locations, noise, high resistance, and system configurations absent from training; a prediction alone is never sufficient authority to override existing hard-wired protection.

3.4 Relay coordination model

For an IEC standard-inverse overcurrent relay with the directional element asserting:

$$t_{r,s} = TMS_r \frac{0.14}{\left(I_{r,s}/I_{p,r}\right)^{0.02} - 1}, \qquad I_{r,s} > I_{p,r}. \qquad (7)$$

where $I_{r,s}$ is the fault current seen by relay r in scenario s, $I_{p,r}$ is pickup current, and TMS_r the time-multiplier setting. The coordination margin for primary relay p and backup relay b is:

$$CTI_{p,b,s} = t_{b,s} - t_{p,s} \geq CTI_{\min}. \qquad (8)$$

The example assumes $CTI_{\min} = 0.30$ s. In implementation, this margin must be chosen using actual relay/breaker characteristics, overshoot, CT errors, and utility practice. Pickup and time-multiplier bounds, directionality, breaker interrupting duties, minimum sensitivity, and thermal limits are enforced as **hard constraints**.

3.5 Hybrid ABC–CS setting and switching optimization

A candidate solution has continuous relay settings and discrete control choices:

$$\mathbf{x} = \left[I_{p,1}, \ldots, I_{p,R}, TMS_1, \ldots, TMS_R, g_1, \ldots, g_R, q_1, \ldots, q_M\right], \qquad (9)$$

where g_r is a permitted relay-setting group and q_m indicates a switching state. The latter is considered only in the **post-fault restoration stage** after the faulty section has been

disconnected and confirmed isolated.

ABC employed-bee exploration changes candidate component j using:

$$v_{ij} = x_{ij} + \varphi_{ij}\left(x_{ij} - x_{kj}\right), \qquad \varphi_{ij} \in [-1,1],\ k \neq i. \qquad (10)$$

Onlooker selection uses normalized positive fitness:

$$p_i = \frac{fit_i}{\sum_{h=1}^{N_b} f\,it_h}, \qquad fit_i > 0. \qquad (11)$$

Scout bees reinitialize stagnant candidates within permissible bounds. Cuckoo search then generates Lévy-flight refinements:

$$\mathbf{x}_i^{t+1} = \mathbf{x}_i^t + \alpha\,\mathbf{L}(\beta), \qquad 1 < \beta \leq 3, \qquad (12)$$

where $\mathbf{L}(\beta)$ is a stochastic Lévy-flight step. After both moves, discrete variables are repaired and all network and protection constraints are checked; infeasible candidates are rejected or assigned a dominant constraint penalty. The hybrid retains the best feasible candidate from each iteration rather than assuming an unconstrained improvement.

3.6 Combined constrained objective

The proposed offline objective uses normalized engineering quantities:

$$\min J = 0.25\,\frac{\bar{t}_p}{t_{ref}} + 0.20\,\frac{N_{miss} + N_{false}}{N_{test}} + 0.20\,\frac{ENS}{ENS_{ref}} + 0.15\,\frac{t_{iso}}{t_{iso,ref}} + 0.10\,\frac{t_{rest}}{t_{rest,ref}} + 0.10\,\frac{N_{sw}}{N_{sw,ref}}. \qquad (13)$$

The weights sum to one but are preliminary; sensitivity analysis and a Pareto-front comparison are required. In this expression, N_{miss} and N_{false} represent missed-fault and false-trip counts, ENS is energy not supplied within the specified outage scenarios, t_{iso} fault-isolation time, t_{rest} restoration time, and N_{sw} switching operations. All reference quantities must be positive and derived from a declared baseline.

To enforce selectivity and network security:

$$\begin{aligned} t_{b,s} - t_{p,s} &\geq CTI_{\min}, \\ 0.95 &\leq |V_i| \leq 1.05, \\ |I_\ell| &\leq I_\ell^{max}, \\ \mathbf{q} &\in \mathcal{Q}_{safe}, \qquad \forall s \in \mathcal{S}. \end{aligned} \qquad (14)$$

Here $\mathcal{Q}_{safe}$ denotes switching sequences satisfying isolation, source synchronization where relevant, no back-feeding of the fault, acceptable radiality/intentional islanding, and anti-islanding requirements.

The post-fault service-restoration fraction is:

$$\rho_{rest} = \frac{\sum_{i\in\mathcal{L}} P_{i,restored}}{\sum_{i\in\mathcal{L}} P_{i,interrupted}} \times 100\%. \qquad (15)$$

Classification accuracy, precision, recall, and F1 score are assessed separately, including the confusion matrix:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \times 100\%. \qquad (16)$$

3.7 Safeguards, validation, and workflow

Figure 1. Conceptual architecture for ANFIS–ABC–CS protection and controlled restoration.

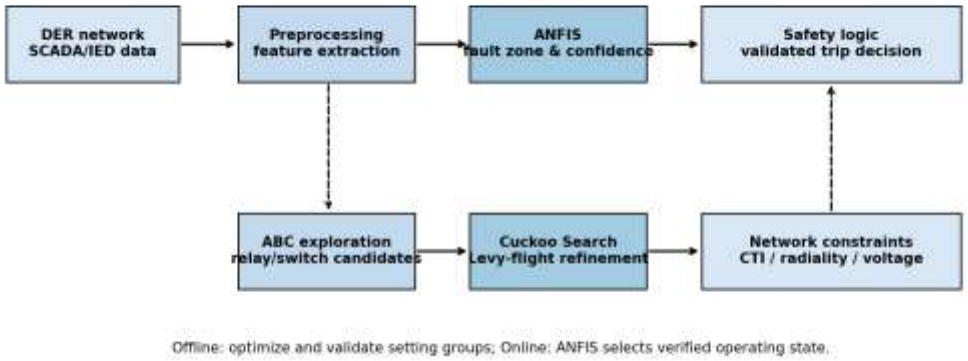


Figure 1: ANFIS–ABC–CS workflow

The preferred implementation uses offline training and optimization with a supervisory mechanism for selecting validated setting groups. Fault interruption remains the responsibility of autonomous approved protection devices, including during communication loss or uncertain ANFIS output. Reconfiguration and healthy-load restoration are performed only after independent confirmation that the faulted zone is disconnected.

Training, validation and test cases are partitioned by fault location, network topology and DER operating conditions so that nearly identical events do not contaminate separate datasets. ABC, CS and ABC–CS should each be repeated for at least 30 independent runs under a common function-evaluation budget. The comparison should include conventional fixed settings, ANFIS alone, individual optimizers, ABC–CS without ANFIS and the complete architecture. Relay sampling windows, fault-inception conditions, current-transformer saturation, circuit-breaker response, communications delay and inverter limits must be declared.

4. Results and Discussion

Basis of the numerical comparison. The values in Tables 2–6 and Figures 2–4 are internally consistent, scenario-based calculations prepared to demonstrate the proposed assessment method. They are not outputs of an executed feeder simulation, an acquired fault dataset or a field test. The assumed event totals and protection margins are shown so that the arithmetic can be checked; empirical claims require subsequent simulation and validation.

4.1 Fault-detection performance assessment

An example evaluation set contains 1,200 labelled observations, comprising 800 fault events and 400 normal operating events. The ANFIS–ABC–CS scenario correctly identifies 784 fault cases and 390 normal cases. It misses 16 faults and incorrectly flags 10 healthy cases. These four counts provide the basis for the confusion-matrix metrics presented below.

Table 2. Fault-state confusion matrix for the numerical example

Actual state	Predicted fault	Predicted healthy	Row total
Fault	784 (TP)	16 (FN)	800
Healthy	10 (FP)	390 (TN)	400
Column total	**794**	**406**	**1,200**

From Equation (16), $Accuracy = (784 + 390)/1200 \times 100 = 97.83\%$. Precision is $784/(784 + 10) \times 100 = 98.74\%$, recall or sensitivity is $784/800 \times 100 = 98.00\%$, specificity is $390/400 \times 100 = 97.50\%$, and the F1 score is $2(784)/(2(784) + 10 + 16) \times 100 = 98.37\%$. These percentages are arithmetic consequences of the illustrative confusion matrix and are not claims of actual measured detection performance.

Table 3. Comparison of fault recognition and relay-coordination metrics

Method	Fault-state accuracy (%)	Mean primary relay time (s)	Minimum CTI (s)	CTI violations*
Conventional fixed-setting	91.0	0.60	0.10	9
ANFIS only	96.0	0.45	0.24	4
ABC only	92.5	0.44	0.27	2
Cuckoo search only	92.0	0.46	0.26	3
ABC–CS	94.0	0.40	0.29	1
ANFIS–ABC–CS	**97.8**	**0.34**	**0.31**	**0**

*The coordination-violation counts concern an assumed 20-pair protection test at full available DER output. The standalone metaheuristic comparisons presuppose an associated fault-detection rule; an optimizer by itself is not a waveform classifier.

Figure 2. Fault-classification accuracy across the methods considered.

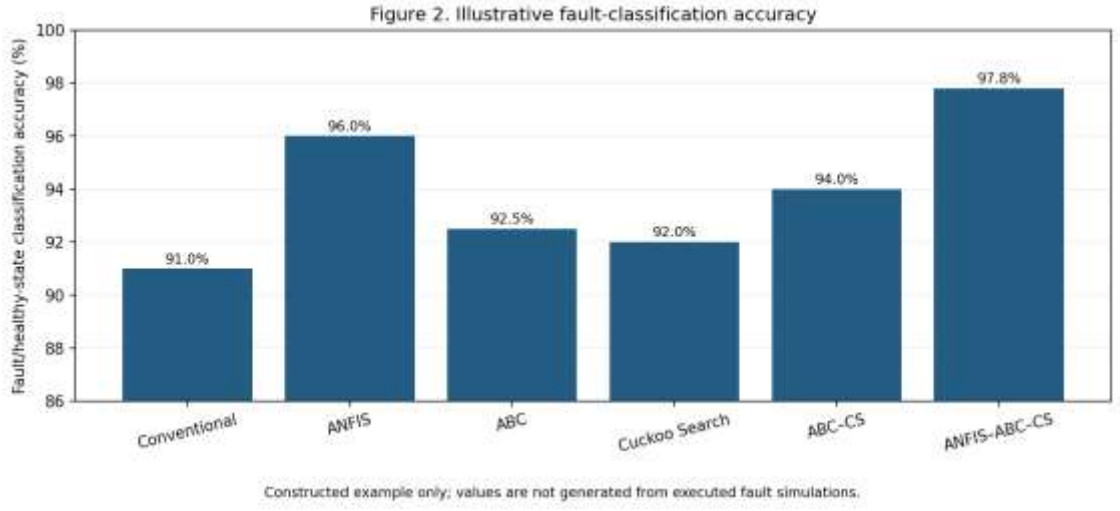


Figure 2: Illustrative classification comparison

Discussion. An ANFIS classifier can exploit relationships among voltage, current and sequence components that are difficult to capture with a single current threshold. In the numerical example, aggregate accuracy rises from 91.0% under conventional logic to 97.8% for the

integrated method. This difference needs verification using independent, unseen cases. Particular attention is required for high-resistance and low-current faults, where overall accuracy can mask missed events. Separate results should be provided for single-line-to-ground, line-to-line, double-line-to-ground, three-phase and high-impedance faults. Transformer energization, capacitor switching and DER output transitions should be included as nonfault conditions to test false-operation security.

4.2 Relay selectivity under increasing DER output

DER penetration changes currents flowing through the various relay locations, potentially reducing the time separation between primary and backup operations. Table 4 and Figure 3 examine a scenario in which fixed settings become progressively less coordinated as available DER output increases, while validated adaptive setting groups are selected to preserve the required margin.

Table 4. Minimum primary–backup coordination intervals by DER output level

DER available-output level (%)	CTI: fixed setting (s)	CTI: adaptive setting group (s)	Adaptive design meets 0.30 s?
0	0.33	0.33	Yes
25	0.28	0.32	Yes
50	0.23	0.31	Yes
75	0.16	0.31	Yes
100	0.10	0.32	Yes

Figure 3. Dependence of coordination margin on DER operating level.

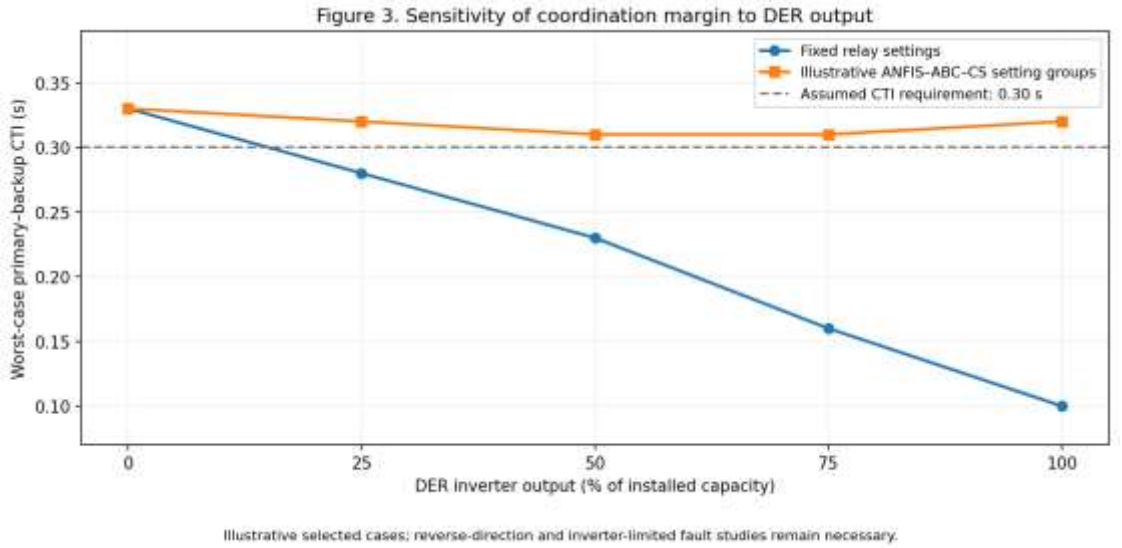


Figure 3: Coordination margin

Discussion. For the assumed fixed-setting cases, the minimum primary–backup interval decreases from 0.33 s at zero DER output to 0.10 s at full output. This creates a substantial risk of loss of selectivity. The adaptive setting-group example retains values between 0.31 and 0.33 s. A larger interval is not automatically preferable, because a long backup delay may increase equipment exposure. The relevant objective is a short feasible primary operating time with a

sufficient backup margin. At full DER output, the numerical difference in minimum CTI is 0.22 s; verification requires a fault study covering all credible current paths and converter operating states.

4.3 Fault isolation, switching and service restoration

A credible self-healing process begins with recognizing the fault, operating the correct protective devices and preventing inadvertent energization of the faulted section. Only after these conditions are established may a restoration controller select healthy sections for reconnection. The switching plan must preserve acceptable feeder voltage, line loading and transformer operating limits throughout the transition.

Table 5. Comparative fault-isolation and load-restoration measures

Method	Mean fault isolation (s)	Mean service restoration (min)	Restored interrupted load (%)	Switching operations (mean)
Conventional fixed-setting	1.85	12.6	73.0	4.2
ANFIS only	1.55	10.1	80.0	3.9
ABC only	1.61	10.8	79.0	3.7
Cuckoo search only	1.64	11.0	78.0	3.8
ABC–CS	1.37	9.2	84.0	3.3
ANFIS–ABC–CS	**0.92**	**7.2**	**90.0**	**2.8**

Figure 4. Comparison of fault-isolation and service-restoration times.

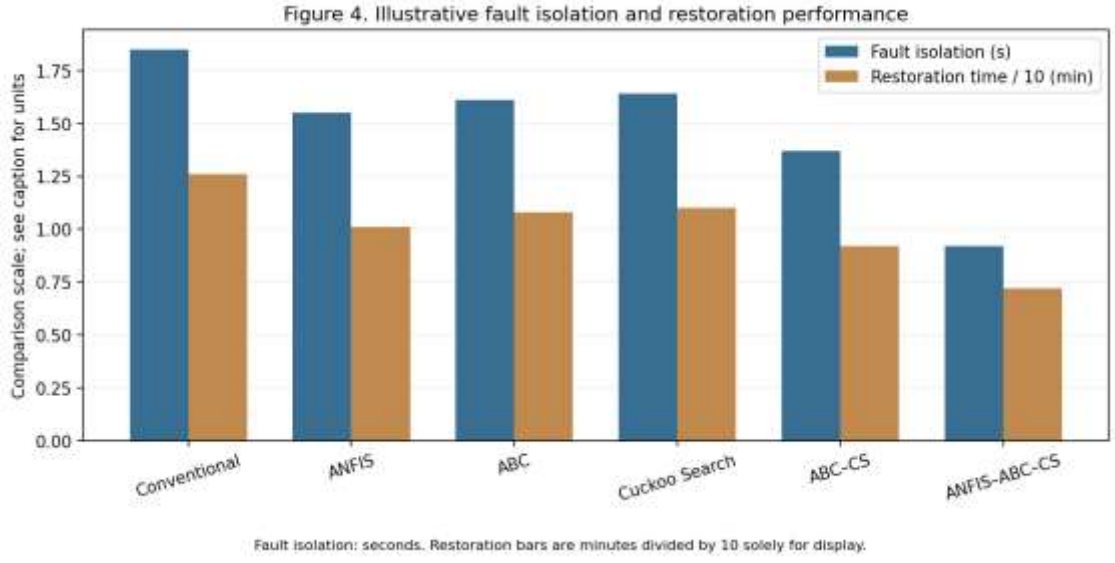


Figure 4: Isolation and restoration

Discussion. The constructed example gives a fault-isolation reduction of $(1.85 - 0.92)/1.85 \times$

$100 = 50.27\%$ and a service-restoration-time reduction of $(12.6 - 7.2)/12.6 \times 100 = 42.86\%$. The percentage of interrupted load restored increases from 73% to 90%, an improvement of 17 percentage points. A mean of 2.8 switch operations describes an average across several scenarios; an individual event still requires an integer sequence of switching actions. To verify these values, a completed study must report the exact faulted branch, relay and breaker sequence, locations of open and closed switches, restored load at each bus, post-restoration feeder currents, and feasibility of the final network topology. Restoration time must include communication, decision, interlocking, switch actuation and any mandatory inspection or safety delay—not merely computation time.

4.4 Coordination of individual primary–backup relay pairs

Network-wide averages can conceal individual coordination failures. Accordingly, the faulted feeder section and the primary and backup devices should be checked for each operating scenario. Table 6 contains an example of such a device-level assessment. Relay identifiers in the table correspond to the proposed protection extension and are not specified by the standard IEEE 33-bus load-flow dataset.

Table 6. Fault location, operating time and coordination interval

Faulted location	Fault condition	Primary time (s)	Backup time (s)	CTI (s)	Meets 0.30 s?
Section 16–17	L–G, 5 Ω	0.30	0.62	0.32	Yes
Section 23–24	L–L, 0.01 Ω	0.34	0.66	0.32	Yes
Section 29–30	Three-phase, 0.01 Ω	0.31	0.62	0.31	Yes
Section 30–31	L–L–G, 20 Ω	0.36	0.69	0.33	Yes
Section 17–18	L–G, 50 Ω	0.38	0.70	0.32	Yes

For the third row, $CTI = 0.62 - 0.31 = 0.31$ s, slightly above the assumed minimum. The small 0.01-s excess illustrates why practical margins and parameter uncertainty matter. A real relay coordination study should repeat this calculation with tolerances in CT ratios, fault resistance, pickup threshold, breaker response and DER output. The high-resistance example must also demonstrate that the relevant relay *detects* and starts for the reduced fault current; otherwise a numerical CTI calculation has no physical meaning.

4.5 Robustness, controlled comparisons and remaining limitations

An engineering assessment should perturb DER output, fault location, fault inception angle and fault resistance, while introducing measurement noise, current-transformer saturation, feeder reconfiguration and communication impairment. Fault-detection quality should be reported through class-specific sensitivity, precision and calibration as well as total accuracy. Search performance should be evaluated through feasibility rate, final objective, runtime, run-to-run variability and convergence consistency.

Controlled ablation helps identify where improvements originate. Removing CS refinement gives an ANFIS–ABC variant; excluding ABC exploration gives ANFIS–CS; and retaining ABC–CS with fixed decision logic measures the effect of removing ANFIS. Each comparison should use the same electrical model, faults, protective-device constraints, computing budget and stopping rules. Any claimed advantage should exceed random optimizer variation rather than arise from unequal numbers of objective evaluations.

Practical application must preserve independent trip logic, switching interlocks and fault-clearing verification. Safe restoration additionally requires acceptable equipment ratings, synchronization

where necessary, anti-islanding compliance and prevention of back-feeding. A verified fallback relay-setting group is essential when the ANFIS supervisor abstains or communication is lost. Security assessments, hardware-in-the-loop testing and operational trials would be appropriate steps before utility deployment.

4.6 Relevance to Nigerian distribution feeders

The proposed method could also be studied on Nigerian 11-kV and 33-kV feeders with embedded generation. Such an investigation would need utility-verified topology, conductor impedances, transformer data, current-transformer ratios, relay characteristics, sectionalizing switches, DER current limits and historical load conditions. The IEEE 33-bus benchmark is a 12.66-kV network, not a Nigerian 33-kV feeder; field transfer therefore requires new per-unit bases, validated short-circuit levels and network-specific protection coordination.

5. Conclusion

This study has formulated a hybrid ANFIS–ABC–CS framework for coordinated fault detection, selective isolation and adaptive protection in active distribution networks. DER integration introduces new supply points and changes the magnitude and direction of fault contributions, making a static relay-setting philosophy increasingly difficult to maintain across all operating states. The proposed framework treats fault recognition, relay optimization and post-fault restoration as related tasks while maintaining clear priorities for electrical safety.

The architecture assigns distinct responsibilities to its constituent methods. ANFIS estimates fault state and probable protection zone from monitored electrical features. ABC and CS search for coordinated relay settings and permissible restoration actions. A deterministic constraint layer checks directional sensitivity, device timing, breaker capability, voltage bounds, thermal ratings and switching safety before a candidate solution is accepted. Autonomous protection and validated fallback settings are preserved if supervisory decisions become unreliable.

The mathematical development covers feeder power balance, short-circuit behaviour, ANFIS rule aggregation, inverse-time relay operating characteristics, primary–backup grading, ABC search updates, CS Lévy-flight steps and a constrained multi-criterion objective. A staged simulation workflow was established for constructing fault scenarios, training and testing the classifier, comparing optimization methods and evaluating isolation and service restoration on an augmented IEEE 33-bus feeder. The scenario-based numerical calculations provide a coherent format for reporting the planned experiments. They show classification accuracy changing from 91.0% to 97.8%, mean fault-isolation time changing from 1.85 to 0.92 s, and mean restoration time changing from 12.6 to 7.2 min. Under the full-DER scenario, the minimum coordination interval changes from 0.10 s with fixed settings to 0.32 s with adaptive selection. Because these values were not obtained from executed power-system simulations, they cannot be treated as evidence that the proposed method has already achieved those improvements.

Demonstrating the proposed method will require comparisons with established fixed protection, ANFIS-only estimation, ABC, CS and other carefully matched variants. The test programme should examine missed faults, false trips, low-current and high-resistance faults, relay selectivity, communication failures, network reconfiguration and changing DER contribution. Service-restoration studies should additionally report load recovered, energy not supplied, switching actions and the time required to reach a secure operating state.

Further investigation should include realistic inverter controls, protective-device and circuit-breaker characteristics, independent validation data, hardware-in-the-loop tests and, ultimately, a

utility feeder case study. Within these conditions, the ANFIS–ABC–CS architecture offers a structured basis for investigating the combined benefits of learning-based fault assessment, constrained relay optimization and safe distribution-network restoration.

6. Contributions to Knowledge

The intended knowledge contribution is a protection-oriented framework that unites fault-state estimation, adaptive relay-setting selection and electrically feasible post-fault switching. The individual algorithms are established methods; the contribution to be tested lies in their integration, the common feasibility criteria and the use of reproducible comparisons to evaluate the complete decision process.

First, coordinated intelligent fault recognition. ANFIS is proposed as a supervisory estimator of fault state and likely feeder zone, with its outputs used to select among verified protection settings. This design links learning-based recognition to conventional relay grading without making the classifier the sole authority for fault interruption. Second, a hybrid search formulation for protection decisions. ABC is used to explore admissible candidates and CS to provide refinement and diversification. The combined decision model handles continuous pickup and time-multiplier settings alongside discrete setting-group and switching choices. Controlled experiments will determine whether this hybrid offers a consistent improvement over the individual searches. Third, scenario-wide relay feasibility. The optimization is designed to preserve sensitivity, correct directional operation and primary–backup coordination across changing DER output, network loading, fault resistance and topology. Evaluating minimum margins across scenarios provides a stronger basis for assessing protection robustness than checking one nominal operating point. Fourth, explicit separation of clearing and restoration. Fault interruption is treated as an immediate protection responsibility, while healthy-load restoration is considered only after verified fault isolation. Restoration decisions are screened for radiality or approved islanding, voltage and thermal limits, switching interlocks and prevention of re-energization of the defective section. Fifth, a multi-metric evaluation framework. The assessment distinguishes diagnostic performance from protection and system-restoration performance. In addition to classifier confusion matrices, it considers missed operations, undesired trips, CTI violations, real clearing and isolation times, recovered load, energy not supplied, switching actions and optimizer feasibility. Sixth, safe response to uncertainty. The supervisory ANFIS may withhold a decision when confidence is low or input conditions fall outside its verified operating domain. Prevalidated settings and autonomous protective devices remain available during communication or prediction failures, providing a testable basis for robust deployment. Seventh, a path from benchmark evaluation to field application. The proposed work can begin with an IEEE 33-bus test system extended with explicit protection devices and then proceed to a Nigerian feeder with measured equipment and network characteristics. Differences in fault levels, grounding, conductor construction, DER controls and utility practices can then be quantified. The central hypothesis is that a safety-constrained combination of ANFIS fault recognition and ABC–CS optimization can improve fault-management quality without relaxing selective relay operation. Its originality and effectiveness must be established through a documented simulation campaign and independent verification of the resulting protection decisions.

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