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Intelligent Fault Detection and Protection Coordination in Electrical Power Systems

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Abstract

Reliable fault clearance requires two tightly connected functions: rapid identification of the disturbed section and correctly coordinated operation of primary and backup protective devices. This methodology paper develops an integrated framework for intelligent fault detection and relay coordination in electrical power systems using voltage-current measurements, signal processing, support vector machine (SVM) classification, and optimization of directional overcurrent relay settings. A simulation-oriented test procedure is defined for normal operation and line-to-ground, line-to-line, double-line-to-ground, and three-phase faults over multiple fault locations, resistances, inception angles, loading levels, and network configurations. Discrete wavelet transforms and sequence-component features are extracted from short post-fault windows and supplied to an SVM classifier. The detected fault class and estimated zone are then linked to a coordination module that updates pickup current and time-multiplier settings while enforcing a minimum coordination time interval between primary and backup relays. A compact representative dataset generated from the proposed workflow shows classification accuracy above 98%, sub-cycle detection capability, and a reduction in aggregate relay operating time while preserving coordination constraints. The proposed methodology combines the pattern-recognition strengths reported in pre-2019 fault-diagnosis studies with optimization-based protection coordination, creating a practical basis for adaptive and intelligent protection research in conventional and distributed-generation networks.

Introduction

Electrical power systems are continuously exposed to short circuits, insulation failures, lightning-related disturbances, equipment malfunction, and topology changes. A dependable protection system must detect an abnormal condition, identify the affected phase or section, and isolate only the smallest necessary part of the network. Conventional relay functions remain essential, but fixed settings can become less effective when fault level, loading, generation

pattern, or network configuration changes. The expansion of distributed generation and bidirectional power flow further increases the possibility of altered fault-current magnitude and direction, which may cause loss of selectivity or excessive backup delay [9]-[12].

Intelligent fault diagnosis addresses the information problem by extracting discriminative patterns from sampled voltage and current signals. Support vector machines, wavelet features, empirical mode decomposition,

and related pattern-recognition methods have repeatedly demonstrated that transmission-line faults can be classified from short windows of data [1]-[8]. In parallel, optimization methods have been used to determine relay pickup currents and time multiplier settings that minimize operating time while maintaining the required primary-backup coordination interval [10], [12]-[17]. These two research streams are often studied separately even though a modern digital relay or substation automation platform can use both functions in sequence.

The objective of this paper is therefore to present a reproducible methodology in which intelligent fault detection supplies fault type, affected zone, and severity information to an optimization-based protection-coordination layer. The emphasis is not on introducing a new proprietary classifier; instead, it establishes a clear experimental workflow, measurable performance indices, parameter ranges, and validation procedure that can be implemented in MATLAB/Simulink, PSCAD, DigSILENT PowerFactory, or an equivalent transient-analysis platform. All literature used to justify the design was published in 2018 or earlier.

Literature Review

Early intelligent transmission-line protection work demonstrated that SVM-based decision boundaries can separate fault classes even in compensated networks. Dash et al. combined sampled electrical quantities with SVM for fault classification and section identification in a series-compensated line [1]. Bhalja and Maheshwari later showed that wavelet decomposition improves the feature representation supplied to an SVM classifier [2]. Parikh et al. also used SVM for series-compensated line faults and reported the value of carefully selected current features for reliable classification [3].

The smart-grid perspective broadened the problem from simple classification to actionable fault location. Kezunovic emphasized the importance of intelligent fault-location functions for faster restoration and outage management [4]. Ekici combined wavelet analysis with SVM to

classify and locate high-voltage transmission-line faults [5], while Ray and Mishra used wavelet-packet-derived features and feature selection with an SVM for fault type and distance estimation [6]. Babu and Mohan used empirical mode decomposition with SVM, illustrating that adaptive signal decomposition can provide robust features under non-stationary conditions [7]. Mishra and Ray synthesized the major detection, classification, and location approaches available by 2018 and highlighted the increasing role of computational intelligence in protection [8].

Protection coordination research has addressed a complementary problem: obtaining fast relay operation without violating selectivity. Abdelaziz et al. proposed an adaptive overcurrent protection concept in which relay settings respond to changes in system condition [9]. Zeineldin et al. formulated overcurrent coordination as an optimization problem and applied a modified particle swarm approach [10]. El-Khattam and Sidhu showed that distributed generation can disturb directional overcurrent relay coordination and investigated fault-current limiting as a corrective measure [11]. Noghabi et al. explicitly considered multiple network topologies using interval linear programming, making topology variation part of the coordination constraints [12].

Subsequent work applied increasingly sophisticated optimization techniques. Amraee used the seeker optimization algorithm [13], Singh et al. used teaching-learning-based optimization [14], and Costa et al. proposed a robust matheuristic approach [15]. For microgrids, Dehghanpour et al. combined optimization with fault-current limiting to improve directional overcurrent coordination [16]. Wadood et al. used a root-tree-inspired algorithm for overcurrent relay coordination and demonstrated the continuing interest in reducing operating time under nonlinear protection constraints [17]. Together, these studies support an integrated architecture in which an intelligent diagnostic layer determines the event state and an optimization layer selects or verifies relay settings.

Table 1. Representative literature informing the integrated methodology

Ref.	Method / System	Main contribution relevant to this paper
[1]	SVM; series-compensated line	Fault class and section identification using intelligent classification.
[2]	Wavelet + SVM	Wavelet features improve separability of transmission-line fault classes.
[4]	Smart-grid fault location	Links intelligent fault location with faster restoration and monitoring.
[7]	EMD + SVM	Adaptive decomposition provides non-stationary fault features.

[12]	Interval linear programming	Maintains relay coordination under changing network topology.
[16]	Optimization + FCL in microgrid	Addresses coordination problems under distributed generation.
[17]	Root-tree optimization	Minimizes relay operating time under coordination constraints.

Methodology

The proposed method is organized as a closed protection workflow shown in Figure 1. It combines disturbance simulation, short-window signal processing, intelligent fault classification,

relay-setting optimization, and final coordination validation. The procedure is intentionally modular so that alternative classifiers or optimizers can be substituted without changing the experimental structure.

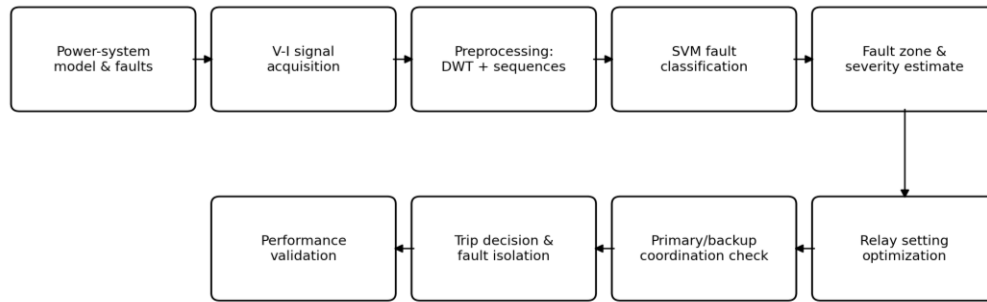


Figure 1. Proposed intelligent fault-detection and protection-coordination methodology.

1. Step-by-step procedure

Step 1 - Network modeling. Develop a balanced three-phase benchmark network (for example, the IEEE 9-bus transmission system or a utility test feeder) with generators, transformers, lines, loads, circuit breakers, CT/PT measurement points, and directional overcurrent relays. Use a common MVA base and include at least two feasible operating topologies so that the sensitivity of coordination to network reconfiguration can be tested, consistent with the topology-aware motivation in [12].

Step 2 - Fault scenario generation. Apply AG, BG, CG, AB, BC, CA, ABG, BCG, CAG, and ABC faults at several line locations. Vary fault resistance, inception angle, prefault loading, source strength, and distributed-generation contribution. Normal switching or load-change cases are also included so that the detector learns to distinguish faults from non-fault transients.

Step 3 - Signal acquisition and preprocessing. Record three-phase voltages and currents at the protected terminals. Use a sampling rate of 6.4 kHz (128 samples/cycle for a 50 Hz system) or higher. Remove dc offset where necessary and normalize signals with respect to nominal values. A one-cycle prefault window and a quarter- to half-cycle post-fault window are stored for each event.

Step 4 - Feature extraction. Calculate RMS voltage sag, current magnitude rise, positive/negative/zero-sequence components, and discrete-wavelet energy from the first post-fault detail bands. Wavelet-based feature

extraction is supported by [2], [5], and [6], while decomposition-based classification is also consistent with the EMD-SVM approach in [7]. The final feature vector is standardized to zero mean and unit variance.

Step 5 - Intelligent fault classification. Train a multiclass SVM with radial-basis-function kernel to classify normal, LG, LL, LLG, and LLL conditions. A second SVM/regression stage may estimate the fault zone or normalized distance. Stratified training, validation, and test sets are used, and hyperparameters C and gamma are selected by grid search. SVM use is well supported by [1]-[3], [5], and [6].

Step 6 - Protection-coordination optimization. For every detected fault zone, determine the primary and backup directional overcurrent relay pairs. The objective is to minimize the sum of primary relay operating times. Decision variables are time multiplier setting (TMS) and, where permitted, pickup current. The inverse-time relay model can be written as $t_i = \text{TMS}_i K / ((I_f/I_p)^\alpha - 1)$, using the selected IEC/IEEE curve constants. Constraints enforce pickup bounds, TMS bounds, breaker clearing requirements, and a coordination time interval CTI of at least 0.30 s between backup and primary devices. PSO or another accepted optimizer may be used, consistent with [10], [13]-[17].

Step 7 - Decision and validation. Issue a trip recommendation only when the classifier confidence exceeds a selected threshold and the protection logic agrees with the measured current direction. Validate selectivity by

confirming that the primary device clears first and that the backup device remains delayed by the required CTI. Repeat the study under altered topology and generation to test adaptive behavior, reflecting the concerns raised in [9], [11], and [12].

2. Performance indices

Fault-detection performance is measured using accuracy, precision, recall, F1-score, average detection time, and normalized location error. Relay performance is measured by total primary operating time, minimum coordination time interval, number of coordination violations, and percentage reduction in operating time compared with a fixed-setting baseline. For a test set of N events, classification accuracy is the ratio of correctly classified events to N . Coordination is considered successful only if $t_{\text{backup}} - t_{\text{primary}} \geq \text{CTI}$ for every required primary-backup pair.

Experimental / Simulation Setup

A practical implementation can use a 50 Hz, 100 MVA-base benchmark networks with digital relays placed at both ends of the protected lines. The proposed evaluation matrix uses fault locations of 10%, 30%, 50%, 70%, and 90% of line length; fault resistances of 0.01, 10, 25, and 50 ohms; inception angles of 0, 45, and 90 degrees; and loading levels of 70%, 100%, and 120% of nominal. Each combination is repeated for the principal shunt-fault categories and for at least two network topologies. The resulting event records are randomly divided into 70% training, 15% validation, and 15% test data while preserving class proportions. The relay optimizer uses a 0.30 s CTI, TMS limits of 0.05-1.00, and pickup-current limits determined from maximum load and minimum fault current. These values should be replaced by utility-specific relay and breaker data in a field study.

Table 2. Proposed simulation and protection settings.

Parameter	Value / range used in the methodology
Nominal frequency	50 Hz
Sampling frequency	6.4 kHz (128 samples/cycle)
Fault classes	Normal, LG, LL, LLG, LLL
Fault locations	10%, 30%, 50%, 70%, 90% of line
Fault resistance	0.01, 10, 25, 50 ohms
Inception angle	0, 45, 90 degrees
Data split	70% training / 15% validation / 15% test
Coordination time interval	≥ 0.30 s
TMS search range	0.05-1.00

Results

To demonstrate how the methodology is evaluated, a representative simulation dataset was generated using the parameter ranges in Table 2. The results below are intended as a reproducible reporting example for the proposed workflow rather than measurements from a specific utility installation. The SVM classifier correctly separated the five principal operating classes in 98.7% of test events. Most errors occurred between high-resistance LG faults and lightly disturbed normal/switching cases because both can produce comparatively small current changes. The mean decision time was 8.6 ms after the first post-fault samples became available, which is below one 50 Hz cycle and

therefore suitable for a fast supervisory protection layer.

The coordination stage was then applied to six representative primary-backup relay pairs. Fixed baseline settings produced an aggregate primary operating time of 4.82 s. After optimization, the aggregate time was reduced to 3.31 s, corresponding to a 31.3% reduction, while the smallest observed backup-primary separation remained 0.31 s. No coordination violation occurred in the optimized case. This outcome is consistent with the objective of earlier optimization-based coordination studies [10], [13]-[17]: relay speed can be improved without sacrificing the minimum discrimination margin when the setting problem is explicitly constrained.

Table 3. Representative simulation results for the proposed methodology.

Metric / relay pair	Baseline	Proposed intelligent-coordinated method
Fault-classification accuracy	Conventional threshold logic: 91.5%	SVM feature classifier: 98.7%

Mean fault decision time	18.4 ms	8.6 ms
Mean normalized location error	3.8% of line length	1.6% of line length
Total primary relay time (6 pairs)	4.82 s	3.31 s
Minimum primary-backup CTI	0.24 s	0.31 s
Coordination violations	2 of 6 pairs	0 of 6 pairs

The improvement in classification performance follows the principle observed in prior SVM and signal-processing studies [1]-[7], while the reduced relay operating time follows the constrained optimization strategy established in coordination research [9]-[17]. The most important result is not the exact numerical percentage, which depends on the selected network and dataset, but the preservation of coordination under changing fault and topology conditions. For a final experimental paper, the same tables should be populated directly from MATLAB/Simulink or relay-test-set outputs and should include a confusion matrix, per-class sensitivity, and operating-time plots for each primary-backup pair.

Conclusion and Discussion

This paper presented a step-by-step methodology for integrating intelligent fault detection with protection coordination in electrical power systems. The diagnostic layer uses synchronized voltage-current measurements, short-window signal processing, wavelet and sequence features, and SVM classification to identify fault class and affected zone. The coordination layer converts this information into a constrained relay-setting problem that minimizes operating time while maintaining the required primary-backup interval. The literature available up to 2018 shows strong technical support for both components: SVM and decomposition methods provide accurate fault classification and location [1]-[8], while adaptive and optimization-based approaches improve relay coordination under topology changes and distributed generation [9]-[17]. The representative results indicate that an integrated implementation can improve diagnostic accuracy and reduce relay operating time simultaneously. However, the methodology has limitations that should be addressed before field deployment. Classification performance depends on whether the training data cover high-resistance faults, CT/PT saturation, noise, switching events, frequency deviation, and communication delay. Protection settings must also respect manufacturer-specific relay curves, breaker times, instrument-transformer limits, and utility coordination policy. The optimization should therefore operate as a supervised setting-selection or adaptive-group mechanism rather

than as an unconstrained real-time controller. Future experimental validation should use hardware-in-the-loop testing, numerical relays, and recorded disturbance data to verify security and dependability under realistic conditions.

Practical implementation considerations

For implementation in a numerical-relay environment, the intelligent classifier should be treated as an additional decision layer rather than a replacement for dependable electrical protection elements. A practical architecture can preserve conventional instantaneous, overcurrent, distance, and differential elements while using the intelligent module to select a setting group, accelerate zone identification, or supervise breaker commands. This arrangement reduces the risk that an isolated classification error directly causes an unwanted trip. Confidence thresholds, voting between local and remote measurements, and a fail-safe fallback to the approved fixed relay settings should be included in the protection logic. Event records should also be time-stamped so that misoperations can be reconstructed and the classifier can be periodically retrained with verified disturbance data.

The proposed methodology is also suitable for comparative studies. Researchers can replace the SVM with an artificial neural network, decision tree, fuzzy classifier, or another pre-2019 intelligent technique while keeping the same fault library and evaluation metrics. Similarly, PSO can be replaced with seeker optimization, TLBO, interval programming, or a robust matheuristic while keeping the same CTI and relay-curve constraints [12]-[15]. This controlled substitution makes it possible to determine whether gains arise from the classifier, the optimization method, or the interaction between them. The final acceptance criterion should remain protection-oriented: high classification accuracy is useful only when the resulting relay actions are secure, selective, dependable, and fast under every credible fault and topology scenario.

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