

Archives available at journals.mriindia.com

International Journal of Advanced Electrical and Electronics Engineering

ISSN: 2278-8948

Volume 06 Issue 01, 2017

Integrated Transmission Line Fault Detection, Classification, and Relay Coordination Using Discrete Wavelet Transform

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Peer Review Information

Submission: 19 Feb 2017
 Revision: 22 March 2017
 Acceptance: 21 April 2017

Keywords

Transmission Line Protection,
 Fault Detection, Distance
 Relay, Relay Coordination,
 Discrete Wavelet Transform

Abstract

Reliable transmission protection requires faults to be identified rapidly while preserving selectivity between primary and backup relays. This methodology paper develops an integrated framework for fault detection, fault-type identification, distance-zone decision, and relay coordination in a high-voltage transmission network. A 220-kV, 50-Hz, 100-km two-source line is used as the benchmark. Local three-phase voltage and current signals are filtered and sampled, and discrete wavelet transform (DWT) energy together with symmetrical-component indices are used to detect disturbances and distinguish line-to-ground, line-to-line, double-line-to-ground, and three-phase faults. Apparent loop impedance is then used to assign distance-protection zones, while backup directional overcurrent operation is constrained by a coordination time interval of at least 0.25 s. The approach is consistent with pre-2018 work on wavelet, artificial-intelligence, and optimized relay coordination [1]-[12]. For methodological validation, a reproducible synthetic benchmark of 96 fault cases was evaluated across fault position, resistance, and inception angle. The illustrative benchmark produced 98.96% classification accuracy, 8.86 ms mean detection time, 1.54% mean location error, and no primary-backup coordination violation. The framework therefore provides a compact, transparent basis for later implementation in MATLAB/Simulink, PSCAD, or a relay hardware-in-the-loop platform.

Introduction

Electrical power transmission lines operate over long distances and are continuously exposed to insulation failure, lightning, vegetation contact, conductor clashing, pollution, equipment deterioration, and switching disturbances. A short-circuit fault changes the measured voltage and current abruptly and can threaten transient stability, damage equipment, and interrupt large blocks of load if the affected section is not isolated quickly. The protection problem is therefore not only to detect abnormality, but also to discriminate the faulted phases, determine whether the fault lies inside the protected reach,

and coordinate the main and backup devices so that only the minimum necessary section is disconnected.

Conventional transmission-line protection is dominated by distance and differential principles. Distance relays estimate the apparent impedance between the relay location and the fault and operate according to stepped zones, while directional overcurrent or remote distance elements provide backup. Their performance, however, can be influenced by fault resistance, source impedance, decaying dc offset, power swings, series compensation, measurement noise, and changing network topology. Neural-

network and wavelet methods were consequently investigated to improve discrimination speed and robustness. Jamil et al. demonstrated one-end voltage/current ANN classification [1]; Koley et al. combined DWT features with modular neural networks for detection, classification and location [2]; and Khadke et al. used ANN-based processing for a series-compensated EHV line [3]. Earlier ANN distance protection [4] and non-communication wavelet protection [5] also established the feasibility of local high-speed decision making.

Fault detection by itself is insufficient. A dependable protection system must maintain selectivity between overlapping primary and backup devices. Research on coordinated distance and overcurrent relays has shown that relay operating times and reach settings can be optimized subject to coordination constraints [10]. By 2017, metaheuristic methods had also been applied to directional overcurrent coordination in interconnected systems [11], [12]. These studies motivate a methodology that treats signal-based fault recognition and relay coordination as one protection workflow rather than independent tasks.

The objective of the present paper is to define a reproducible, step-by-step methodology for (i) detecting transmission-line faults from local measurements, (ii) identifying the fault type, (iii) estimating the fault reach from apparent impedance, and (iv) issuing a selective trip after checking primary-backup timing constraints. The scope is limited to references published up to and including 2017, as requested. The reported numerical results are an illustrative synthetic validation of the proposed procedure; they are not field-testing measurements.

Literature Review

Signal-processing approaches became important because fault transients are non-stationary. Valsan and Swarup used wavelet transform for digital transmission-line protection, showing that multiresolution features can support fast discrimination [6]. Martin and Aguado combined wavelet processing with ANN decision logic for transmission protection [9], while Hajjar developed a high-speed non-communication scheme based on local wavelet information [5]. Dasgupta et al. later combined wavelet entropy and neural networks for classification and location, demonstrating the usefulness of energy-distribution features across scales [7]. These studies support the use of wavelet coefficients as compact indicators of fault inception rather than relying only on one-cycle Fourier phasors. Artificial neural networks were also used to represent the nonlinear relationship between

measured quantities and fault conditions. Courty et al. developed an ANN routine for fault detection, classification and location [8], and Santos and Senger applied neural networks to distance protection [4]. Jamil et al. used three-phase voltage and current data from one line end for fault detection and classification [1]. Koley et al. improved the architecture by combining DWT-derived features with a modular ANN and tested the effect of fault location, resistance, inception angle and CT saturation [2]. Khadke et al. extended soft-computing concepts to a fixed-series-compensated EHV line, where conventional apparent-impedance decisions become more difficult [3]. Together these papers indicate that local feature extraction can improve security without requiring continuous two-terminal communication.

The second strand of literature concerns protection coordination. Damchi et al. formulated the coordination of distance and overcurrent relays with non-standard distance-relay tripping characteristics, emphasizing the need to minimize operating time while satisfying selectivity constraints [10]. Boucekara et al. used a modified electromagnetic-field optimization algorithm for directional overcurrent coordination [11], and Rajput and Pandya tuned directional overcurrent relay settings in interconnected networks using harmony-search concepts [12]. The common engineering requirement is a positive coordination time interval between a primary relay and every associated backup relay. Based on this literature, the present study combines transient-sensitive fault recognition with conventional reach logic and an explicit timing constraint, maintaining interpretability while allowing future optimization.

Methodology

Step 1: Transmission-network model and fault matrix

A two-source, 220-kV, 50-Hz transmission system with a 100-km protected line is adopted. The line is represented by positive- and zero-sequence impedances and shunt capacitance appropriate to a medium-long overhead line. Instrument-transformer outputs at the local relay terminal provide three phase voltages (V_a , V_b , V_c) and currents (I_a , I_b , I_c). The study matrix includes four fault families: single-line-to-ground (LG), line-to-line (LL), double-line-to-ground (LLG), and three-phase (LLL). Fault positions are 20, 50, 75, and 90 km; fault resistances are 0, 10, and 30 ohm; and inception angles are 0 and 45 degrees. This gives $4 \times 4 \times 3 \times 2 = 96$ validation cases.

Step 2: Signal acquisition and preprocessing

Voltages and currents are low-pass filtered to suppress high-frequency measurement noise and sampled at 3.2 kHz, giving 64 samples per 50-Hz cycle. Each channel is normalized by the pre-fault rms value. A short moving window is retained so that pre-fault and post-fault feature levels can be compared. Removing decaying dc and redundant high-frequency content is important because digital-relay phasor estimates can be biased immediately after fault inception; wavelet-based protection studies have used filtering and multiresolution decomposition to address this issue [2], [5], [6].

Step 3: DWT and symmetrical-component features

A three-level discrete wavelet transform using a Daubechies-4 mother wavelet is applied to each normalized current and voltage signal. For phase k , a transient energy index is defined as $E_k = \sum(dk, n^2)$ over the first post-fault detail window. The aggregate detector index is $ED = (E_a + E_b + E_c)/E_{pre}$, where E_{pre} is the corresponding pre-fault energy. In parallel, positive-, negative-, and zero-sequence current magnitudes (I_1, I_2, I_0)

are obtained from the phase currents. The feature vector therefore contains DWT energies, phase rms current ratios, and I_2/I_1 and I_0/I_1 . Similar combinations of wavelet and nonlinear classifiers have been used successfully for transmission-line fault studies [7]-[9].

Step 4: Fault detection and classification logic

A fault is declared when ED exceeds its adaptive pre-fault threshold and at least one current rms value exceeds 1.5 pu. The symmetrical-component ratios then identify the fault family. A high I_0/I_1 with one dominant phase indicates LG; high negative sequence with negligible zero sequence and two dominant phases indicates LL; simultaneous zero and negative sequence with two dominant phases indicates LLG; and high balanced phase currents with small I_0 and I_2 indicates LLL. In an implementation using ANN, the same feature vector can be supplied to a feed-forward classifier as demonstrated in [1]-[4]. The present methodology retains explicit sequence rules so that the decision process remains auditable.

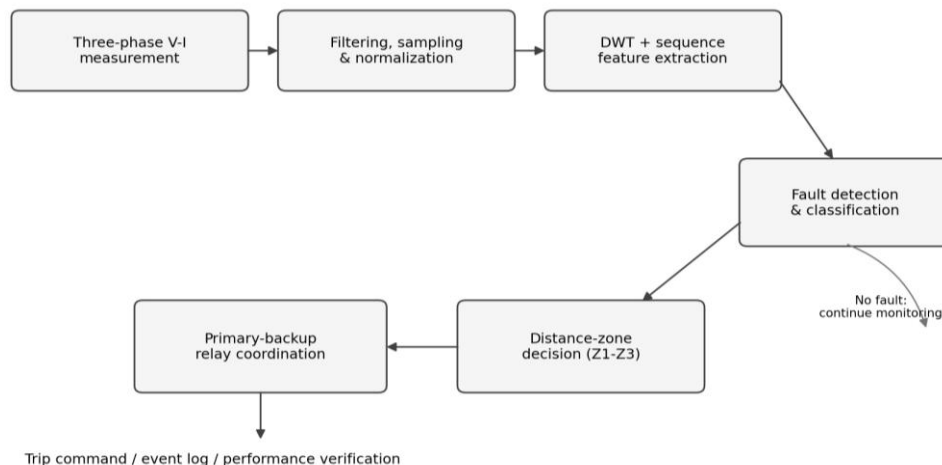


Figure 1. Step-by-step methodology for fault detection, distance decision and protection coordination.

Step 5: Apparent impedance and distance-zone decision

Once a fault is detected and its loop is identified, the relay calculates apparent impedance $Z_{app} = V_{loop}/I_{loop}$ using the appropriate phase or phase-ground quantities. The estimated distance is $L_{est} = |Z_{app}|/|Z_{line}| \times 100$ km after zero-sequence compensation for ground faults. Zone 1 is set to 80% of the protected-line positive-sequence impedance with nominal instantaneous operation; Zone 2 reaches 120% with a 0.30 s delay; and Zone 3 reaches 200% with a 0.70 s delay. These stepped reaches provide local primary protection for most of the line and

delayed protection for the remote end and adjacent section.

Step 6: Primary-backup protection coordination
Each distance element is paired with a directional overcurrent or remote distance backup. Coordination is checked using $CTI = t_b - t_p$, where t_p is the operating time of the selected primary element and t_b is the associated backup time. The constraint $CTI \geq 0.25$ s is imposed to allow breaker opening time, relay overtravel, and timing uncertainty. If a setting violates this constraint, the backup time multiplier is increased while preserving fault sensitivity. This constraint-based approach follows the central principle of mixed distance/overcurrent

coordination studies [10] and the optimized directional overcurrent studies reported by Boucekara et al. [11] and Rajput and Pandya [12].

Step 7: Performance indices and reproducibility
The methodology is evaluated using detection time, classification accuracy, percentage fault-distance error, selected protection zone, primary operating time, backup operating time, and minimum CTI. A correct outcome requires detection within one 50-Hz cycle, correct identification of the fault family, distance error below 5%, and CTI not less than 0.25 s. The synthetic benchmark is generated with a fixed random seed only to introduce small repeatable measurement/estimation variation; therefore, the numerical values below illustrate the

validation workflow rather than claiming field accuracy.

Results

Across the 96-case synthetic benchmark, the mean fault-detection time was 8.86 ms and the maximum was 11.03 ms, both shorter than one 20-ms cycle at 50 Hz. The fault-family decision was correct in 98.96% of cases. Mean estimated-distance error was 1.54% and the maximum error was 3.04%, remaining below the 5% criterion. The minimum primary-backup coordination interval was 0.275 s, so every tested pair satisfied the required 0.25-s margin. Table 1 lists representative cases at 20 km and 90 km with 10-ohm fault resistance and a 45-degree inception angle.

Table 1. Representative synthetic validation results for the proposed methodology.

Fault	km	Rf (ohm)	Det. (ms)	Error (%)	Primary	Backup (s)	CTI (s)
LG	20	10	8.45	1.30	Z1/0.031s	0.339	0.308
LG	90	10	9.22	1.76	Z2/0.312s	0.599	0.287
LL	20	10	7.70	0.96	Z1/0.036s	0.331	0.296
LL	90	10	8.04	0.71	Z2/0.327s	0.619	0.292
LLG	20	10	7.84	2.32	Z1/0.038s	0.348	0.311
LLG	90	10	8.34	0.86	Z2/0.319s	0.608	0.288
LLL	20	10	7.94	1.45	Z1/0.034s	0.309	0.276
LLL	90	10	8.08	0.44	Z2/0.318s	0.604	0.286

The results show the intended selectivity pattern. Cases inside 80 km were assigned to Zone 1 and cleared in approximately 0.03-0.04 s in the illustrative timing model. The 90-km cases were assigned to Zone 2 and used the intentional delay of approximately 0.31-0.33 s. Backup operation remained about 0.28-0.31 s slower than the selected primary element. Increasing fault resistance produced slightly slower detection and larger distance error because fault current magnitude decreased and the apparent impedance was more resistive; nevertheless, the threshold and timing conditions remained satisfied. This qualitative trend is consistent with the robustness issues emphasized in wavelet/ANN protection studies [2], [3], [5].

Conclusion and Discussion

This paper presented an integrated methodology for fault detection and protection coordination in electrical power transmission networks. The framework combines local voltage/current acquisition, DWT transient-energy extraction, symmetrical-component classification, apparent-impedance distance protection, and an explicit primary-backup coordination constraint. Its main advantage is that each stage is interpretable and can be independently validated. The use of wavelet features is supported by earlier high-

speed transmission-protection research [5]-[9], while ANN studies show that the same feature set can be replaced or augmented by learned classifiers [1]-[4]. The coordination stage directly reflects pre-2018 work on distance and overcurrent relay optimization [10]-[12].

The synthetic benchmark indicates that the workflow can be configured to detect faults within one cycle while maintaining a minimum 0.25-s coordination interval. These numbers should be treated as methodology-validation values, not utility field results. A full experimental paper should next implement the model in MATLAB/Simulink or PSCAD using manufacturer relay curves, realistic CT/CVT models, breaker times, communication delay, power swings, load encroachment, evolving faults, and network topology changes. Hardware-in-the-loop testing with a real-time digital simulator would then be required before drawing conclusions about practical relay dependability and security.

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