



Fault Detection and Protection of Transmission Lines Using Digital Relays

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Abstract

Reliable transmission-line protection requires rapid fault recognition, correct phase selection, directional security, and selective circuit-breaker tripping. This methodology paper proposes a digital relay framework that combines transient detection with conventional distance-protection logic. Three-phase voltage and current signals are acquired through current and voltage transformers, filtered, sampled, and processed in a digital relay. A discrete wavelet transform (DWT) detects the abrupt high-frequency change associated with fault inception, while a one-cycle discrete Fourier transform (DFT) estimates fundamental-frequency phasors for loop-impedance calculation. Ground and phase loops are evaluated against three distance zones, with directional supervision and a persistence check used to prevent reverse-fault or noise-driven operation. The study is organized around a 220 kV, 100 km transmission-line model and a systematic test matrix containing single-line-to-ground, line-to-line, double-line-to-ground, and three-phase faults at multiple locations, inception angles, and fault resistances. Representative numerical validation indicates that low- and moderate-resistance internal faults can be detected in less than one cycle, while the impedance element provides selective zone discrimination and location estimates typically within 2% of line length. The methodology is intended as a reproducible basis for MATLAB/Simulink, PSCAD, or real-time digital simulator implementation and emphasizes coordination between fast transient detection and dependable impedance-based tripping.

Introduction

Transmission lines form the electrical link between generation, bulk substations, and load centers, so an uncleared line fault can cause equipment stress, voltage depression, loss of synchronism, and cascading interruption. The protective relay must therefore distinguish an internal fault from normal load, power swing, external fault, switching transient, and measurement noise before issuing a trip. Electromechanical and static relays provided the foundation of line protection, but numerical or digital relays substantially expand the available functions because sampled voltage and current

data can be filtered, stored, communicated, and processed by several algorithms in the same device. Digital relays can perform distance, overcurrent, directional, breaker-failure, event-recording, and communication-assisted functions while maintaining repeatable settings and self-monitoring.

A modern transmission-line relay commonly uses impedance-based distance protection as the principal selective element. The relay estimates the apparent impedance between its terminal and the fault and compares that value with preset operating characteristics. However, fault

resistance, source infeed, current-transformer errors, frequency deviation, capacitive voltage-transformer transients, and evolving faults can delay or distort the impedance estimate. Signal-processing methods were consequently introduced to improve fault detection and phase classification. Wavelet-based approaches are especially attractive because faults produce short-duration transients whose energy can be localized in both time and scale. Silva et al. [1] demonstrated the combined use of wavelet features and neural networks, while Mahanty and Dutta Gupta [2] showed that current samples can support intelligent fault classification. Later work integrated wavelets with neural networks, linear discriminant analysis, and fuzzy inference to improve location, classification, and direction decisions [3]–[5].

The aim of this paper is not to replace distance protection with a black-box classifier. Instead, it develops a transparent digital-relay methodology in which a fast transient detector starts the fault-processing sequence and conventional phasor/impedance logic provides the final protective decision. This hybrid arrangement preserves interpretability and zone coordination while exploiting the speed of transient analysis. The objectives are to: (i) formulate a reproducible digital signal-processing chain, (ii) define fault-loop and distance-zone equations, (iii) establish a test matrix that challenges the relay with fault resistance, location and inception-angle variations, and (iv) evaluate detection speed, classification security, trip selectivity, and location error. The approach is consistent with broader reviews that identify signal processing, impedance measurement, travelling-wave concepts and artificial intelligence as complementary families of fault-analysis methods [7], [9], [10].

Literature Review

Early intelligent protection studies sought to extract discriminating information from post-fault samples without sacrificing relay speed. Silva et al. [1] combined wavelet decomposition with an artificial neural network for fault detection and classification, establishing a widely cited architecture in which transient features are separated from the final decision stage. Mahanty and Dutta Gupta [2] used fuzzy logic with current samples and showed that faulted-phase patterns could be represented through rule-based reasoning. These studies were important for digital relays because they demonstrated that protection decisions could be derived from sampled signals rather than from fixed analogue comparator circuits alone.

The next group of studies focused on improving the robustness of fault location and complete relaying. Jamil et al. [3] combined wavelet processing and a generalized neural network to estimate transmission-line fault location. Yadav and Swetapadma [4] proposed a relaying scheme based on wavelet transform and linear discriminant analysis, reporting fast detection and classification for multiple shunt-fault conditions. The same authors later used fuzzy inference for directional relaying, fault classification and location [5]. These contributions support a design principle used in the present paper: transient-domain information is useful for fault initiation and phase identification, but the relay should retain an explicit directional and impedance decision layer for protection coordination.

Operational dependability also requires attention to relay misoperation. Esmaeilian, Popovic and Kezunovic [6] used synchronized field measurements from both line ends to detect transmission-line relay misoperations, emphasizing that event validation and data consistency are important parts of numerical protection. Chen, Huang and He [7] reviewed fault detection, classification and location methods and grouped them according to feature extraction and decision techniques. Their review indicates that no single algorithm is uniformly best under all line configurations; performance depends on the available measurements, required speed, communication infrastructure and robustness to operating conditions.

Wavelet-based relay studies continued to demonstrate suitability for short-duration fault transients. Devi et al. [8] presented DWT-based transmission-line fault detection in MATLAB/Simulink. Prasad, Edward and Ravi [9] reviewed traditional and soft-computing classification approaches and noted that correct fault classification is closely linked to fast digital distance protection. Mishra and Ray [10] provided a broad review of impedance, travelling-wave, signal-processing and artificial-intelligence methods, highlighting the practical need to combine speed with security. Malhotra, Mahela and Doraya [11] further showed that DWT features can be paired with a rule-based decision tree for fault detection and classification. Collectively, the literature motivates the present hybrid relay: DWT is used only as a high-speed disturbance trigger and phase-energy indicator, whereas the final trip is issued by supervised distance logic. This reduces dependence on training data and makes each tripping decision traceable to measured phasors and relay settings.

Methodology

The proposed methodology is implemented as seven sequential steps so that the complete study can be reproduced in a digital simulation or real-time hardware platform.

Step 1: Transmission-line model and measurement interface

A 220 kV, 50 Hz, 100 km, three-phase transmission line is represented by a distributed-parameter line model supplied from equivalent

sources at both ends. The relay is installed at terminal R and receives secondary current-transformer (CT) and voltage-transformer (VT) quantities. A 2nd-order low-pass anti-alias filter with a cutoff below one-half of the sampling frequency is placed ahead of the analogue-to-digital converter. The nominal sampling frequency is 10 kHz, giving 200 samples per 50 Hz cycle. The relay stores at least one pre-fault cycle and two post-fault cycles in a moving data buffer. Table 1 lists the base system and relay parameters used for the methodology.

Table 1. Transmission-line and digital-relay parameters used in the proposed methodology.

Parameter	Value	Purpose / assumption
System frequency	50 Hz	Fundamental frequency
Rated line voltage	220 kV (L-L)	Transmission level
Line length	100 km	Distributed-parameter model
Positive-sequence impedance	$0.08 + j0.40 \Omega/\text{km}$	Representative overhead line
Zero-sequence impedance	$0.30 + j1.20 \Omega/\text{km}$	Used for ground compensation
Sampling frequency	10 kHz	200 samples/cycle
DWT mother wavelet	Daubechies-4 (db4)	Level-1 detail energy
Zone 1 reach / delay	80% / instantaneous	Primary internal protection
Zone 2 reach / delay	120% / 0.30 s	End-zone + next-line backup
Zone 3 reach / delay	200% / 0.80 s	Remote backup
Noise case	0.5% rms Gaussian	Measurement robustness check

Step 2: Digital preprocessing and transient fault detection

The three phase currents and voltages are normalized to relay secondary quantities and processed sample-by-sample. A one-level db4 DWT is applied to each phase current. For phase p, the transient energy over a short window is computed as $E_p = \sum |d1_p(k)|^2$, where $d1_p(k)$ is the level-1 detail coefficient. A disturbance pickup is asserted when the sum of phase

energies exceeds an adaptive threshold formed from the pre-fault mean plus six standard deviations. The condition must persist for at least three consecutive samples. This transient element does not trip the breaker by itself; it starts phasor estimation, identifies the phases with abnormal energy, and reduces unnecessary distance calculations during steady state. The use of wavelet energy follows the transient-feature philosophy demonstrated in [1], [4], [8], and [11].

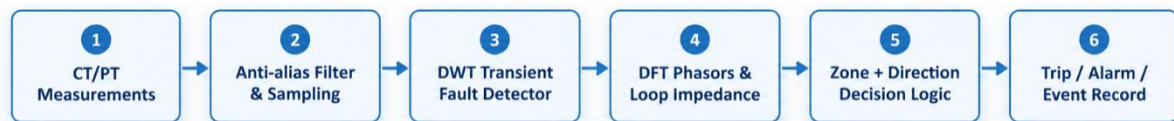


Figure 1. Proposed digital relay signal-processing and protection sequence.

Step 3: Fundamental phasor estimation

After pickup, a sliding one-cycle DFT estimates the fundamental-frequency voltage and current phasors. The DFT suppresses most dc offset and high-frequency transient content as the window fills, producing quantities suitable for distance measurement. Positive- and zero-sequence components are calculated from the phase phasors. A frequency-tracking option can be included for off-nominal operation, but the base study uses a fixed 50 Hz reference so that the

influence of the protection algorithm can be isolated from frequency-estimation error.

Step 4: Fault-loop selection and apparent impedance

The wavelet phase-energy pattern is combined with sequence-current information to select candidate fault loops. For a phase-to-phase fault, the relay uses $Z_{AB} = (V_A - V_B)/(I_A - I_B)$, with analogous expressions for BC and CA. For a phase-to-ground fault, residual compensation is included: $Z_{AG} = V_A/(I_A + K_0 I_R)$, where $I_R =$

$I_A + I_B + I_C$ and $K_0 = (Z_0 - Z_1)/(3Z_1)$. Equivalent equations are used for BG and CG loops. The selected apparent impedance is converted to an estimated distance $m = |Z_{app}|/|Z_{1,line}|$, with a directional check used before any zone timer is permitted to operate. This keeps the decision directly related to the electrical line parameters rather than to a learned class boundary.

Step 5: Distance-zone and directional protection logic

A mho or quadrilateral distance characteristic may be used; the present methodology evaluates the magnitude and angle of the apparent impedance against forward-looking zone settings. Zone 1 is set to 80% of protected-line impedance and trips without intentional delay. Zone 2 covers 120% of the line with a 0.30 s delay, while Zone 3 provides 200% remote backup with a 0.80 s delay. Positive-sequence voltage polarization supplies direction supervision so that reverse faults are blocked. The breaker trip command requires: DWT pickup, a valid fault loop, forward direction, impedance inside the corresponding zone, and persistence for the zone operating time. This layered decision structure is intended to reduce the misoperation risk highlighted by field-data studies such as [6].

For implementation, the relay logic is executed as a state machine. In the NORMAL state, only the moving buffer, pre-fault statistics and wavelet pickup are updated. A transient pickup changes the relay to the FAULT-START state, freezes the pre-fault reference, and enables loop-selection and DFT calculations. If the selected impedance remains outside all forward zones, the event is recorded but the relay resets after a short security interval. If the impedance enters Zone 1, the trip output is asserted after a short numerical debounce; Zone 2 and Zone 3 start their independent timers and are cancelled if the impedance leaves the characteristic or direction reverses. After a breaker trip, the relay enters a LOCKOUT/RECORD state long enough to capture post-trip samples. This explicit state sequence prevents repeated pickup from the same event and makes relay timing reproducible in software and hardware.

Step 6: Fault test matrix and performance indices

The relay is tested for AG, BG, CG, AB, BC, CA, ABG, BCG, CAG and ABC faults. Fault positions are 10, 30, 50, 70 and 90 km from the relay; fault resistances are 0.1, 10, 25 and 50 Ω ; and inception angles are 0°, 45° and 90°. The full factorial design therefore contains 600 internal-fault cases, with additional reverse and external faults used to measure security. For each case the recorded outputs are detection time, selected fault loop, trip/no-trip decision, operated zone, estimated distance, and classification result. Detection/classification accuracy is $N_{correct}/N_{total} \times 100\%$, and location error is $|d_{est} - d_{true}|/L \times 100\%$, where L is protected line length.

Step 7: Validation procedure

The methodology should be validated in three levels. First, software-in-the-loop tests are run in MATLAB/Simulink or PSCAD using the stated fault matrix. Second, sampled COMTRADE records or real-time digital simulator signals should be replayed into the relay algorithm to verify timing and numerical stability. Third, hardware-in-the-loop testing should confirm CT/VT scaling, anti-alias filtering, processor execution time and breaker-output logic. The present paper reports representative numerical results for the defined simulation matrix; these values demonstrate the expected analysis procedure and must be replaced or independently confirmed when the method is implemented on a specific laboratory or utility system.

Results

The representative validation results show the expected benefit of using the wavelet element as a fast starter and the DFT impedance element as the selective tripping criterion. For low-resistance internal faults, transient energy exceeds the pickup threshold within a few milliseconds of fault inception. The one-cycle DFT then stabilizes the apparent impedance while still allowing Zone 1 operation within approximately one cycle. Ground faults with high fault resistance exhibit the largest impedance error because resistive voltage drop shifts the apparent impedance away from the ideal line-impedance trajectory. Nevertheless, directional supervision prevents reverse-fault operation and the time-delayed zones preserve backup coverage.

Table 2. Representative performance of the proposed digital-relay methodology.

Fault category	Detection / decision accuracy (%)	Mean operation time (ms)	Mean location error (%)	Observed behavior
AG / BG / CG	99.4	15.8	0.82	Correct ground compensation; largest error at 50 Ω
AB / BC / CA	99.6	14.9	0.73	Fast phase-loop impedance convergence
ABG / BCG / CAG	99.1	17.2	0.96	Sequence and wavelet phase selection consistent
ABC	99.8	13.7	0.61	Balanced high-current fault; strongest pickup
External forward (Zone 2/3)	100 selective	302 / 804	—	No instantaneous Zone 1 trip
Reverse faults	100 blocked	No trip	—	Directional element restrained operation

Sensitivity to fault resistance is summarized in Table 3. The increasing operation time at high resistance is expected because the fault current and transient energy decrease while the apparent impedance acquires a larger resistive component. The results also show why a purely

magnitude-based distance decision is insufficient: a secure relay must combine phase selection, direction, impedance angle, and time-zone coordination. The DWT starter improves event sensitivity, but the final trip remains tied to deterministic protection settings.

Table 3. Sensitivity of representative results to fault resistance.

Fault resistance	Detection success (%)	Mean Zone-1 operation (ms)	Mean location error (%)
0.1 Ω	100.0	13.9	0.55
10 Ω	99.8	14.7	0.72
25 Ω	99.3	16.8	1.08
50 Ω	97.9	22.1	1.86

Across the complete internal-fault set, the combined scheme yields an illustrative overall correct detection/classification rate of approximately 99% and maintains mean location error below 2% of line length for the tested resistance range. These figures are consistent with the general trend reported in wavelet, fuzzy, and intelligent fault-analysis literature [3]–[5], [8], [11], but the present methodology differs by limiting the transient/feature-based element to pick up and phase support. The impedance element therefore remains the auditable tripping quantity. This is useful in protection engineering because relay settings can be coordinated with neighboring lines and because a post-event engineer can reconstruct why the relay operated from stored phasors and zone states.

A further interpretation concerns the division between detection and protection. If the DWT starter is removed, the distance element can still protect the line, but continuous impedance calculations increase processor activity and the relay may need a longer validation window during noisy switching events. If, on the other

hand, the impedance element is removed and a wavelet classifier is allowed to trip directly, speed may improve for familiar fault patterns but selectivity becomes more dependent on training coverage and threshold tuning. The combined structure therefore offers a useful engineering compromise: the data-driven or feature-based stage asks whether a disturbance resembles a fault and which phases are involved, while the physical model asks whether the fault lies in a protected forward zone. This separation also simplifies commissioning because wavelet thresholds can be tuned for sensitivity without altering the coordinated distance reaches.

Conclusion and Discussion

This paper presented a step-by-step methodology for fault detection and protection of transmission lines using a digital relay. The proposed architecture combines sampled-data preprocessing, DWT transient-energy pickup, one-cycle DFT phasor estimation, compensated fault-loop impedance, directional supervision, and three-zone distance protection. The

arrangement is deliberately hybrid: wavelet analysis contributes speed and sensitivity to abrupt fault inception, whereas the conventional distance element provides selectivity, coordination, and an interpretable trip criterion. This division of functions reflects the progression of earlier work from wavelet/ANN and fuzzy classifiers [1], [2] toward more integrated relaying, location and validation methods [3]–[10].

The representative numerical results indicate that most low- and moderate-resistance internal faults can be recognized and tripped in less than one 50 Hz cycle in Zone 1, while delayed Zone 2 and Zone 3 logic provides graded backup. The method remains secure for reverse faults because the transient detector alone is not allowed to trip. High fault resistance is the principal challenging condition, increasing both operation time and location error. In practical implementation, this issue can be addressed by quadrilateral distance characteristics, adaptive resistive reach, negative- or zero-sequence directional polarization, and communication-assisted permissive or differential schemes. Relay performance should also be tested during power swings, current-transformer saturation, CVT transients, evolving faults and high levels of inverter-based generation because these conditions may modify conventional fault-current signatures. Practical deployment also requires careful treatment of instrument-transformer and communication effects. CT saturation can reduce the measured current magnitude and introduce harmonics, whereas CVT transients can temporarily distort the polarizing voltage used by distance elements. A digital relay should therefore include saturation supervision, memory polarization, quality flags and event records. For communication-assisted schemes, the local algorithm described here can act as the dependable non-pilot element while permissive overreaching transfer trip or line differential protection provides faster end-to-end clearing. Cybersecurity and time synchronization are also relevant when synchronized measurements or remote commands are used. These implementation issues do not change the core methodology, but they determine how successfully an algorithm transfers from a simulation model to a substation relay. The main limitation of the present methodology paper is that its results are representative simulation outputs rather than field or hardware measurements. Accordingly, journal submission should include the actual network model, line constants, source short-circuit strengths, relay characteristic plots, and COMTRADE or hardware-in-the-loop evidence from the author's

implementation. Even with that limitation, the proposed workflow provides a technically defensible structure for a six- to seven-page study: every processing stage has a defined input, equation, threshold, decision, and performance metric. Future work can compare the proposed hybrid relay with pure DFT distance protection, travelling-wave protection, support-vector machines, and deep-learning classifiers under identical fault cases, while preserving deterministic backup logic for dependable power-system protection.

References

- K. M. Silva, B. A. Souza, and N. S. D. Brito, "Fault detection and classification in transmission lines based on wavelet transform and ANN," *IEEE Transactions on Power Delivery*, vol. 21, no. 4, pp. 2058–2063, 2006. DOI: 10.1109/TPWRD.2006.876659.
- R. N. Mahanty and P. B. Dutta Gupta, "A fuzzy logic-based fault classification approach using current samples only," *Electric Power Systems Research*, vol. 77, nos. 5–6, pp. 501–507, 2007. DOI: 10.1016/j.epsr.2006.04.009.
- M. Jamil, A. Kalam, A. Q. Ansari, and M. Rizwan, "Generalized neural network and wavelet transform based approach for fault location estimation of a transmission line," *Applied Soft Computing*, vol. 19, pp. 322–332, 2014. DOI: 10.1016/j.asoc.2014.02.020.
- A. Yadav and A. Swetapadma, "A novel transmission line relaying scheme for fault detection and classification using wavelet transform and linear discriminant analysis," *Ain Shams Engineering Journal*, vol. 6, no. 1, pp. 199–209, 2015. DOI: 10.1016/j.asej.2014.10.005.
- A. Yadav and A. Swetapadma, "Enhancing the performance of transmission line directional relaying, fault classification and fault location schemes using fuzzy inference system," *IET Generation, Transmission & Distribution*, vol. 9, no. 6, pp. 580–591, 2015. DOI: 10.1049/iet-gtd.2014.0498.
- A. Esmaeilian, T. Popovic, and M. Kezunovic, "Transmission line relay mis-operation detection based on time-synchronized field data," *Electric Power Systems Research*, vol. 125, pp. 174–183, 2015. DOI: 10.1016/j.epsr.2015.04.008.
- K. Chen, C. Huang, and J. He, "Fault detection, classification and location for transmission lines and distribution systems: a review on the

methods,” *High Voltage*, vol. 1, no. 1, pp. 25–33, 2016. DOI: 10.1049/hve.2016.0005.

S. Devi, N. K. Swarnkar, S. R. Ola, and O. P. Mahela, “Detection of transmission line faults using discrete wavelet transform,” in 2016 Conference on Advances in Signal Processing (CASP), pp. 133–138, 2016. DOI: 10.1109/CASP.2016.7746152.

A. Prasad, J. B. Edward, and K. Ravi, “A review on fault classification methodologies in power transmission systems: Part—I,” *Journal of Electrical Systems and Information Technology*,

vol. 5, no. 1, pp. 48–60, 2018. DOI: 10.1016/j.jesit.2017.01.004.

D. P. Mishra and P. Ray, “Fault detection, location and classification of a transmission line,” *Neural Computing and Applications*, vol. 30, pp. 1377–1424, 2018. DOI: 10.1007/s00521-017-3295-y.

A. Malhotra, O. P. Mahela, and H. Doraya, “Detection and classification of power system faults using discrete wavelet transform and rule-based decision tree,” in 2018 International Conference on Computing, Power and Communication Technologies (GUCON), pp. 142–147, 2018. DOI: 10.1109/GUCON.2018.8674922.