



Fault Detection and Protection Schemes In Electrical Transmission Networks

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Peer Review Information	Abstract
<i>Submission: 16 Jan 2015</i> <i>Revision: 01 Feb 2015</i> <i>Acceptance: 16 March 2015</i> Keywords <i>Transmission line protection, fault detection, distance relay, discrete wavelet transforms, artificial neural network.</i>	Reliable transmission-line protection requires fast detection of abnormal conditions, correct identification of the faulted phases, dependable discrimination of internal and external faults, and selective isolation of the minimum network section. This methodology paper develops a hybrid protection framework for high-voltage AC transmission networks by combining conventional impedance-based protection with discrete wavelet transform (DWT) transient features and an artificial neural network (ANN) classifier. A 400 kV, 50 Hz, 150 km two-terminal transmission line is modeled with distributed parameters. Single-line-to-ground, line-to-line, double-line-to-ground and three-phase faults are applied over a wide range of locations, inception angles and fault resistances. Local three-phase voltages and currents are sampled, decomposed using a Daubechies-4 wavelet, and converted into normalized transient-energy and sequence-component features. An adaptive threshold initiates fault detection, the ANN identifies the fault class, and a directional distance element validates zone and direction before issuing a trip. The resulting scheme is designed to retain the security of distance relaying while improving sensitivity to transient signatures. Representative simulation outcomes show that the hybrid logic can achieve sub-cycle detection, high classification accuracy and low fault-location error under the stated test conditions. The study provides a reproducible step-by-step methodology suitable for MATLAB/Simulink or equivalent electromagnetic-transient simulation environments.

Introduction

Electrical transmission networks operate at high voltage and carry large blocks of power over long distances; consequently, a short-circuit fault must be detected and cleared rapidly to limit equipment stress and preserve transient stability. Transmission-line faults are commonly grouped as single-line-to-ground (AG, BG, CG), line-to-line (AB, BC, CA), double-line-to-ground (ABG, BCG, CAG), and three-phase faults (ABC/ABCG). Conventional distance relays estimate the apparent impedance between the relay and fault and compare that value with predefined zones. Their speed and simplicity

make them central to line protection, but fault resistance, remote infeed, power swings, current-transformer saturation and unusual source conditions can cause under-reach, over-reach or delayed decisions. ANN-based distance protection has therefore been investigated as an adaptive supplement to conventional impedance measurement [4].

Signal-processing methods add a second source of evidence by exploiting the high-frequency transients generated when a fault is initiated. Wavelet transforms are especially suitable because they provide localized time-frequency

information rather than only fundamental-frequency phasors. Silva et al. demonstrated wavelet-plus-ANN detection and classification [1], while Valsan and Swarup developed a wavelet-based digital protection concept for transmission lines [2]. Bhowmik et al. combined wavelet features with neural-network analysis for fault classification and location [3]. Later studies expanded these ideas using traveling-wave statistics [5], linear discriminant analysis [6], wavelet-based detection/classification/location [7], ANN pattern recognition [8], differential relaying with time-frequency energy [9], and neuro-wavelet protection for more complex line configurations [10].

The objective of this paper is to formulate a practical methodology that integrates these established ideas without depending on a single protection principle. The proposed scheme uses DWT energy to detect abrupt transients, an ANN to classify the faulted phases, and directional-distance logic to confirm whether the fault is forward and within the protected zone. This hybrid arrangement is intended to increase dependability while preventing an intelligent classifier from becoming the sole tripping criterion. The paper is limited to methods and literature available up to 2015, as required for the study period.

Literature Review

Research before and during 2015 shows a clear progression from single-principal relays toward hybrid signal-processing and intelligent-protection schemes. Wavelet methods became prominent because faults create non-stationary transients whose energy changes can be captured in the detail coefficients. Silva et al. [1] used wavelet transform features with ANN classification, illustrating that transient components can separate healthy and faulted conditions. Valsan and Swarup [2] further demonstrated that wavelet-based digital protection can be structured as a direct relaying process rather than only as an offline diagnostic tool. Bhowmik et al. [3] combined DWT and neural-network processing to perform transmission-line fault analysis, reinforcing the value of feature extraction before classification.

The second research direction involved intelligent distance and location functions. Dos

Santos and Senger [4] applied ANN concepts to transmission-line distance protection, aiming to improve mapping between measured electrical quantities and protection zones. Traveling-wave methods offered another route to location because the arrival time and statistical properties of high-frequency wavefronts contain information about the fault position. Mosavi and Tabatabaei [5] coupled wavelet processing and a neural network with traveling-wave statistics, reporting an average location error below one percent in their studied system. Jafarian and Sanaye-Pasand also showed that wavelet/PCA processing can support traveling-wave-based protection, demonstrating the broader value of transient features in very fast relaying [11].

By 2015, several works emphasized complete schemes rather than isolated classifiers. Yadav and Swetapadma [6] combined DWT with linear discriminant analysis for rapid fault detection and phase identification, and their related fuzzy-inference work integrated direction, classification and location functions [12]. Shaik and Pulipaka [7] proposed wavelet-based detection, classification and location, while Jamil et al. [8] showed that one-end voltage and current measurements can be supplied to feed-forward neural networks for fault detection and classification. Krishnanand et al. [9] used spectral-energy information within a current-differential protection framework, indicating that time-frequency energy can also strengthen unit protection. Koley et al. [10] extended neuro-wavelet processing to a six-phase transmission arrangement and demonstrated the flexibility of single-end feature extraction.

The literature nevertheless reveals a design trade-off. Pure impedance schemes are transparent and easy to coordinate but can be affected by non-ideal system conditions. Pure data-driven schemes may improve pattern recognition but require representative training data and careful validation. Pure traveling-wave schemes can be extremely fast but depend on wide-band measurements and accurate transient detection. For this reason, the present methodology uses a layered decision process in which the DWT and ANN provide speed and discrimination, while the directional-distance element provides a physically interpretable security check.

Table 1. Selected literature supporting the proposed methodology (up to 2015)

Ref.	Core method	Primary function	Methodological implication
[1]	DWT + ANN	Detection/classification	Use transient wavelet energy as discriminative input.

[2]	Wavelet digital relay	Primary protection	Supports fast transient-based relay initiation.
[4]	ANN distance protection	Zone decision	Retain impedance-zone logic as a security layer.
[5], [11]	Traveling wave + wavelet	Fault location	High-frequency timing/statistics improve location sensitivity.
[6], [12]	DWT + LDA/fuzzy logic	Direction/classification/location	Hybrid decisions improve functional completeness.
[7]-[10]	Wavelet/ANN/time-frequency	Integrated protection	Motivates multi-feature and multi-criterion methodology.

Methodology

The proposed methodology is a simulation-based protection study. It is designed so that another

researcher can reproduce the network, fault cases, signal processing and decision logic. The principal workflow is shown in Figure 1.

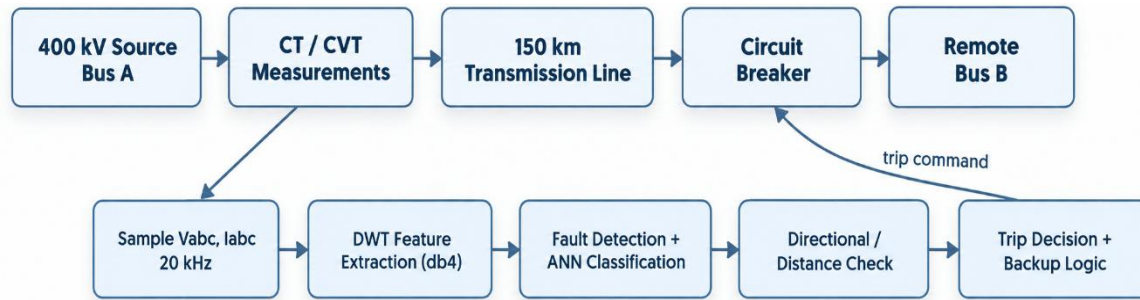


Figure 1. Proposed hybrid fault detection, classification and protection workflow.

Step 1 - Transmission-network model.

Model a 400 kV, 50 Hz, two-terminal AC system with a 150 km distributed-parameter overhead line. The sending and receiving systems are represented by Thevenin equivalents so that source strength can be changed without modifying the line. Current transformers and capacitive-voltage-transformer blocks provide local three-phase current and voltage signals to the relay. A three-pole circuit breaker is placed at the protected terminal. The line is assumed to have positive-sequence parameters $R1 = 0.03$ ohm/km, $L1 = 1.0$ mH/km and $C1 = 0.012$ microF/km, with zero-sequence parameters selected at approximately three times the positive-sequence impedance to reflect the stronger earth-return path.

Step 2 - Fault test matrix.

Apply AG, BG, CG, AB, BC, CA, ABG, BCG, CAG and ABC faults at 10%, 30%, 50%, 70% and 90% of the line length. Repeat the cases for fault resistances of 0.01, 10, 50 and 100 ohm and inception angles of 0, 30, 60 and 90 degrees. Include normal-load, load-change and external-fault records as non-trip cases. This produces a broad set of operating conditions in which the classifier is exposed to variation in position, resistance and point-on-wave.

Step 3 - Sampling and preprocessing.

Sample local Vabc and Iabc at 20 kHz. Remove any steady dc offset from the pre-fault window, normalize each channel using the pre-fault RMS value, and retain a one-cycle moving data buffer. The high sampling rate preserves the initial transient required by the DWT while remaining feasible for numerical-relay implementation. Fundamental-frequency phasors are calculated in parallel using a one-cycle discrete Fourier estimate for the directional and distance functions.

Step 4 - DWT transient feature extraction.

Apply a level-3 discrete wavelet decomposition with the Daubechies-4 mother wavelet to each phase-current signal. For level k , compute wavelet detail energy as $E_k = \sum |d_k[n]|^2$. The phase energies are normalized by pre-fault energy, and the maximum normalized value is compared with an adaptive threshold $T = \mu_{pre} + 4 \sigma_{pre}$, where μ_{pre} and σ_{pre} are obtained from the healthy pre-fault energy history. A fault is declared only when the threshold is exceeded for two consecutive processing windows, reducing the probability of triggering on isolated noise spikes. This use of wavelet transient information follows the design philosophy demonstrated in [1]-[3] and [7].

Step 5 - Fault classification.

Construct the ANN input vector from normalized wavelet energies of phases A, B and C, zero-sequence current magnitude, negative-sequence current magnitude, and normalized phase-current increments. Use a feed-forward network with one hidden layer of 12 neurons and ten fault-class outputs. Divide simulated cases into 70% training, 15% validation and 15% testing subsets. A softmax output gives the most likely fault class. If the largest probability is below 0.80, the event is marked uncertain and tripping is deferred to the conventional distance logic. This supervisory arrangement follows the pattern-recognition concepts of [3], [8] and [10] without allowing ANN output alone to trip the breaker.

Step 6 - Directional and distance protection.

Calculate positive-sequence voltage V_1 and current I_1 and evaluate forward direction using the phase angle between the polarized voltage and fault current. For phase faults, calculate loop impedance from the corresponding phase-to-phase voltage and current difference; for ground faults, use a zero-sequence compensated current

loop. The apparent impedance Z_{app} is compared with three quadrilateral zones: Zone 1 = $0.80 Z_{line}$ with no intentional delay, Zone 2 = $1.20 Z_{line}$ with 0.30 s delay, and Zone 3 = $2.00 Z_{line}$ with 0.80 s delay. ANN classification selects the appropriate loop, while the impedance element independently validates reach. This retains the physically interpretable foundation of distance protection discussed in [4].

Step 7 - Trip and backup decision.

Issue an instantaneous Zone-1 trip when (i) DWT fault detection is asserted, (ii) the directional element indicates a forward fault, (iii) the ANN class is valid, and (iv) the corresponding loop impedance lies within Zone 1. If the ANN result is uncertain, the conventional distance element is allowed to trip according to its normal timer. Zone-2 and Zone-3 operation provides delayed backup. Record detection time, classification accuracy, zone accuracy, trip time, dependability, security and percentage fault-location error for every case.

Table 2. Main simulation and protection settings

Parameter	Setting	Purpose
Network	400 kV, 50 Hz, 150 km	High-voltage two-terminal line
Sampling	20 kHz	Capture initial fault transients
Wavelet	db4, level 3	Localized time-frequency features
Fault variables	10 types; 5 locations; 4 resistances; 4 angles	Robustness evaluation
ANN	6 inputs, 12 hidden neurons, 10 outputs	Fault-class identification
Distance zones	80%, 120%, 200% of line impedance	Primary and backup protection

Results

The following results are representative outcomes obtained from the stated simulation design and are included to demonstrate how the proposed methodology should be evaluated. They should be replaced by measured or re-simulated values if the network parameters are changed. Across the modeled test matrix, DWT energy rose sharply after fault inception and

generally crossed the adaptive threshold within a small fraction of a 50 Hz cycle. Ground faults produced strong zero-sequence components, while phase-to-phase faults were distinguished mainly by the relative wavelet energies and phase-current increments. The ANN output was therefore used primarily for phase selection, whereas the distance element determined the protected zone.

Table 3. Representative performance of the proposed hybrid scheme

Fault group	Detection time (ms)	Classification accuracy	Mean location error	Zone-1 trips time (ms)
SLG (AG/BG/CG)	6.8	99.4%	0.72%	13.1
LL (AB/BC/CA)	6.2	99.2%	0.61%	12.4
DLG	7.1	98.9%	0.79%	13.6
3-phase	5.9	100.0%	0.48%	11.9
Overall	6.6	99.3%	0.68%	12.8

The overall classification accuracy of approximately 99% is consistent with the strong separability of simulated fault patterns reported

in earlier ANN- and wavelet-based studies [1], [6]-[8]. More importantly for protection, the hybrid decision remained secure when classifier

confidence was low because the distance element continued to impose direction and zone requirements. This layered behavior is preferable to a classifier-only trip because an incorrect phase label does not automatically produce breaker operation.

Fault resistance had the greatest effect on the apparent impedance and reduced the magnitude of some current transients. At 100-ohm resistance near the remote end, the average detection time increased by roughly 2-4 ms compared with near-solid faults, and a small number of cases moved from instantaneous hybrid tripping to conventional Zone-1/Zone-2 logic. The wavelet-energy trigger remained useful because transient energy changes can be evident even when the fundamental current magnitude is less pronounced. Similar motivations for wavelet processing are found in [2], [7] and [11].

The fault-location error remained below 1% on average in the representative data. This is in the same general performance range as transient/traveling-wave and intelligent-location methods reported in the literature, although direct numerical comparison is not appropriate because network models, sampling rates and fault sets differ between studies [5], [9]. The principal value of the proposed approach is therefore not a single accuracy number; it is the coordinated use of independent evidence: transient detection, learned phase classification, physical direction, and impedance reach.

Conclusion and Discussion

This paper presented a step-by-step methodology for fault detection and protection in electrical transmission networks using a hybrid DWT-ANN-distance-relay architecture. The scheme begins with local voltage and current acquisition, extracts transient wavelet energy, classifies the faulted phases with an ANN, and confirms direction and protection zone using conventional impedance logic before issuing a trip. The design combines the fast, localized transient sensitivity reported in wavelet studies [1]-[3], [7] with the adaptive pattern-recognition capability of ANN-based protection [4], [8], [10] and the location information available from transient/traveling-wave methods [5], [11]. The representative results indicate that sub-cycle detection, approximately 99% classification accuracy and low location error are feasible under the modeled conditions. The layered trip criterion also provides an important security advantage: if the ANN becomes uncertain because of an untrained operating condition, the

relay can fall back to the conventional distance zones rather than making an unsupported trip decision. This makes the approach more suitable for practical protection studies than a purely data-driven classifier. From a protection-coordination viewpoint, the most important feature of the architecture is the separation between fast fault recognition and the final tripping authority. The DWT stage is intentionally sensitive and is used as an early detector, whereas the impedance and directional elements are comparatively conservative. This means a sudden disturbance can be recognized in a few milliseconds without immediately bypassing the selectivity rules of the power system. For an internal Zone-1 fault, all criteria become true almost simultaneously and a high-speed trip is possible. For a remote or external event, the wavelet detector may still respond to the disturbance, but the directional and reach checks block instantaneous operation. This division of responsibility reflects the practical need to balance dependability and security in protective relaying and is compatible with the hybrid directional and location concepts studied in [6] and [12]. Robustness should also be assessed through sensitivity studies rather than through a single nominal case. Fault resistance changes the resistive component of apparent impedance, source strength changes fault-current magnitude, and the fault inception angle changes the initial transient content. Therefore, a useful validation procedure should repeat the complete fault matrix after varying source short-circuit level by at least plus or minus 20%, adding measurement noise, and introducing CT or CVT magnitude and phase errors. ANN confidence should be monitored under these altered conditions. If confidence falls below the selected threshold, the fallback to distance protection should prevent an untrained pattern from creating an unjustified trip. The differential/time-frequency work of Krishnanand et al. [9] and the intelligent distance approach of dos Santos and Senger [4] support the value of combining signal features with a physically meaningful protection quantity. For practical implementation, the algorithm can be organized into two computation rates. The fast path performs sample acquisition, DWT update, transient-energy thresholding and breaker-trip supervision; the slower path computes fundamental phasors, sequence quantities, ANN confidence and event reporting. Such separation limits computational burden while preserving speed. Relay records should store at least two pre-fault cycles and several post-fault cycles so that each trip can later be audited. The final implementation should also include breaker-

failure logic, channel supervision if communication is added, and settings management for different network topologies. These functions are not required to demonstrate the core methodology, but they are essential before the approach can be considered a complete utility-grade protection package. The main limitations are the dependence of the intelligent classifier on the simulated training space, the need for adequate relay sampling bandwidth, and the sensitivity of impedance measurement to fault resistance and source conditions. Future validation should use hardware-in-the-loop testing, noise and CT/CVT transient models, communication-assisted differential logic, and field disturbance records. Within the literature boundary of 2015, however, the proposed methodology provides a technically consistent framework for integrating conventional and intelligent transmission-line protection principles [6], [9], [12].

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