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## Methodology for Transmission-Line Fault Detection, Classification, Location, and Protection Coordination Using PMU-Assisted Distance Relaying

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### Abstract

Reliable transmission-line protection requires fault detection, phase classification, fault location and coordinated tripping to operate as a unified process. This methodology paper develops a simulation-oriented framework for studying these functions in high-voltage electrical power transmission networks. The proposed framework combines local current and voltage measurements with synchronized phasor measurement unit (PMU) data, symmetrical-component quantities, apparent-impedance estimation and coordinated distance-relay zones. A structured fault matrix is defined for single-line-to-ground, line-to-line, double-line-to-ground and three-phase faults at multiple locations, inception angles and fault resistances. The detection stage uses current and voltage increments together with sequence quantities; the classification stage identifies involved phases; the location stage combines apparent impedance with synchronized two-end phasor checks; and the coordination stage verifies primary/backup selectivity using distance zones and a wide-area backup criterion. The methodology is evaluated through representative simulation cases using operating time, classification accuracy, location error and coordination margin as performance indicators. The resulting procedure emphasizes fast local action for internal faults while preserving delayed backup operation for adjacent-line faults and preventing unwanted distance-relay operation during power swings. The paper provides a reproducible step-by-step structure suitable for MATLAB/Simulink, PSCAD, EMTP-type environments or commercial power-system protection software. The literature basis is restricted to work published no later than 2016, and every source is identified by DOI.

### Introduction

Electrical power transmission networks must isolate short-circuit faults quickly enough to protect equipment and preserve transient stability, yet selectively enough to avoid unnecessary disconnection of healthy lines. Transmission faults can be caused by lightning, insulation failure, conductor contact, pollution, vegetation, mechanical damage or switching

events. Their electrical signatures depend on fault type, resistance, inception angle, source strength and location. Consequently, a practical protection system must distinguish abnormal conditions from load changes and power swings, determine the faulted phases, estimate the faulted section and issue a trip command only to the appropriate breaker. Chen, Huang and He [1] reviewed the major families of transmission-line

fault detection, classification and location methods available by 2016, including impedance, travelling-wave, signal-processing and intelligent approaches. This broad literature indicates that no single feature is universally reliable under all operating conditions; coordinated use of local protection and synchronized wide-area information is therefore attractive.

Distance relays remain the principal line-protection element because the apparent impedance measured at the relay terminal is related to electrical distance to the fault. Their protection reach is commonly divided into instantaneous and time-delayed zones to provide primary and backup coverage. However, infeed/outfeed, fault resistance, line compensation, measurement error and stable power swings can shift apparent impedance and challenge coordination. PMU-based methods provide synchronized voltage and current phasors from separated substations and can improve fault-location observability and backup decisions. The methodological objective of this paper is therefore to formulate an integrated procedure in which conventional distance protection is supported by PMU-based detection/location and a systematic coordination check.

The contribution is methodological rather than a utility field trial. It defines the network model, fault test matrix, measured features, decision logic, relay-zone settings, performance metrics and a compact set of representative validation results. The method is intended to be reproducible in a simulation environment and to provide a defensible basis for later hardware-in-the-loop or field validation. The literature review and references are intentionally restricted to publications up to and including 2016, as required.

### Literature Review

Early synchronized-phasor research established a strong basis for adaptive line protection. Jiang et al. [2] developed an adaptive PMU-based fault detection/location index using synchronized phasors, line-parameter estimation and a DFT-based signal extraction procedure. The implementation and performance evaluation reported in the companion study [3] demonstrated the practical role of PMU measurements in online protection. Lien et al. [4] extended the wide-area perspective by

addressing transmission-network fault-location observability with minimal PMU placement, showing that the protection problem is influenced not only by the relay algorithm but also by the measurement architecture. Liu et al. [5] then generalized synchronized-phasor fault location to multi-terminal transmission lines, an important issue in meshed transmission systems. Signal-processing methods were also developed to obtain fast transient features before conventional phasor estimates fully settle. Valsan and Swarup [6] used wavelet transforms for digital transmission-line protection, while Aguilar, Pérez and Orduña [7] proposed a high-speed deterministic method based on principal component analysis of travelling-wave current signals. These approaches are attractive for speed because they exploit transient information, but their design must address sampling rate, noise sensitivity and the dependence of extracted features on network configuration.

Pattern-recognition and machine-learning methods became increasingly important before 2016. Ekici [8] demonstrated support vector machines for transmission-line fault classification and location, and Livani and Evrenosoglu [9] combined travelling-wave features with machine learning for three-terminal circuits. Such methods can represent nonlinear decision boundaries that are difficult to encode with fixed thresholds, although their performance depends on the coverage and quality of the training set. For a methodology paper, these results motivate using a transparent rule-based classifier as the baseline while preserving the same data structure for future SVM or other trained classifiers.

More directly related to wide-area transmission protection, Neyestanaki and Ranjbar [11] developed an adaptive PMU-based wide-area backup protection scheme for power transmission lines, explicitly addressing the need for a dependable backup when local primary protection fails. Finally, Ouadi, Bentarzi and Chafai [12] showed how PMU information can be used to discriminate power swings and prevent distance-relay mal-operation. Together, these studies motivate an architecture in which local distance protection remains fast, while wide-area synchronized measurements supervise faulted-line identification, backup action and power-swing security.

**Table 1.** Literature synthesis used to construct the proposed methodology.

| Ref. | Core method | Strength for this study | Limitation considered |
|------|-------------|-------------------------|-----------------------|
|------|-------------|-------------------------|-----------------------|

|           |                                |                                      |                                    |
|-----------|--------------------------------|--------------------------------------|------------------------------------|
| [2]-[5]   | PMU/synchronized phasors       | Wide-area observability and location | Communication/time synchronization |
| [6]-[7]   | Wavelet/PCA transient features | High-speed detection                 | Sampling/noise sensitivity         |
| [8]-[9]   | SVM/machine learning           | Nonlinear classification             | Training-set dependence            |
| [10]-[11] | PMU detection + backup         | Primary/backup coordination          | Communication delay                |
| [12]      | PMU power-swing detector       | Distance-relay security              | Requires robust swing criterion    |

### Methodology

The methodology is organized as an iterative protection-design sequence. A network model is first established, faults are generated over a structured test matrix, local and synchronized measurements are processed, fault

detection/classification/location decisions are formed, relay settings are checked for primary/backup selectivity, and any failed coordination case is used to revise settings. Figure 1 summarizes the complete workflow.

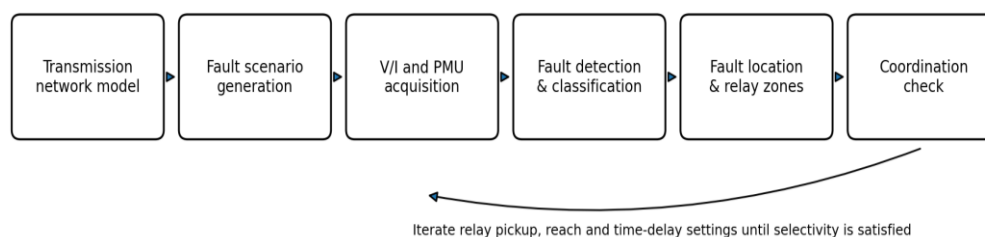


Figure 1. Step-by-step methodology for fault detection and protection coordination.

Step 1 - Transmission-network model and protection zones

A representative 230-kV transmission corridor is modeled with two equivalent sources connected by a 100-km protected line and an adjacent line section at the remote bus. Positive- and negative-sequence series impedances are represented by distributed or frequency-dependent line parameters when available; zero-sequence parameters are modeled separately because ground-fault behavior depends strongly on the return path. Current transformers, voltage transformers, breakers, local numerical relays and PMUs are placed at both ends of the protected line. The same procedure can be transferred to an IEEE 9-bus, 39-bus or 118-bus benchmark network without changing the protection logic.

Distance protection is arranged in three zones. Zone 1 is set to approximately 80% of the protected-line positive-sequence impedance and operates without intentional delay. Zone 2 covers the remainder of the protected line plus a portion of the shortest adjacent line, with an initial delay of 0.30 s. Zone 3 provides remote backup for the protected line and the adjacent line, with an initial delay of 0.60 s. These are starting values, not universal settings; the iterative coordination

step revises reach and delay whenever an adjacent relay does not retain priority. A coordination time interval of approximately 0.25-0.35 s between primary and backup operations is used as the selectivity criterion.

Step 2 - Fault scenario matrix

The test set includes single-line-to-ground (AG, BG, CG), line-to-line (AB, BC, CA), double-line-to-ground (ABG, BCG, CAG) and three-phase (ABC) faults. Fault position is swept over 20%, 50% and 80% of the protected line, fault resistance over 0, 10, 25 and 50 ohm, and inception angle over 0°, 30°, 60° and 90°. This gives  $10 \times 3 \times 4 \times 4 = 480$  principal fault cases. Additional no-fault cases include load transfer, line energization and stable power swings so that security can be evaluated, consistent with the need for distance-relay swing discrimination discussed by Ouadi et al. [12].

Step 3 - Measurement acquisition and preprocessing

Three-phase voltages and currents are sampled at the relay terminals. For phasor-based functions, one-cycle recursive DFT estimates are used; for high-speed detection, half-cycle RMS and sample-to-sample increments are retained. Sequence components are calculated from the fundamental phasors. The PMU data stream provides synchronized voltage and current

phasors from both ends, following the measurement principles used in the adaptive PMU literature [2]-[4]. A short pre-fault window establishes adaptive base values so that thresholds track slow load changes rather than remaining fixed in absolute amperes or volts.

#### Step 4 - Fault detection and classification

Fault detection is initiated when a composite disturbance index exceeds its adaptive threshold for two consecutive samples. The index combines normalized positive-sequence current increment, voltage depression and zero/negative-sequence content. A practical form is  $D = w_1|\Delta I_1|/I_{base} + w_2|\Delta V_1|/V_{base} + w_3(|I_2|+|I_0|)/I_{base}$ , where the weights are tuned using the no-fault cases. The phase classifier then evaluates the phase-current increments together with zero-sequence current. Large zero-sequence current indicates a ground-involved fault; the relative magnitudes of  $\Delta I_A$ ,  $\Delta I_B$  and  $\Delta I_C$  identify the involved phases. This transparent baseline can later be replaced with the SVM structure demonstrated by Ekici [8] or the multi-terminal machine-learning framework of Livani and Evrenosoglu [9] without changing the test matrix.

#### Step 5 - Fault location and line identification

For fast local protection, the apparent impedance seen from terminal S is estimated as  $Z_{app} = V_{loop}/I_{loop}$  using the appropriate phase or ground loop. For ground faults, zero-sequence compensation is included. The initial location estimate is  $x_{local} = |Z_{app}|/|Z_{line}|$ , limited to the physical line length. Because local impedance can be biased by fault resistance and remote infeed, a synchronized two-end consistency check is performed using PMU phasors. The two-end estimate solves the line voltage-drop relation from both terminals and selects the location that minimizes the mismatch between calculated and measured terminal phasors. This follows the synchronized-phasor philosophy of Jiang et al. [2], Lien et al. [4], Liu et al. [5] and Gopakumar et al. [10].

#### Step 6 - Protection coordination and backup logic

If the fault is classified as internal and the apparent impedance enters Zone 1, the local relay issues an immediate trip. If the fault is beyond Zone 1 but inside Zone 2, the relay starts the Zone-2 timer and trips only if the local primary relay for the adjacent section has not cleared the fault first. The same rule applies to Zone 3 with a longer delay. The PMU-based wide-area backup

element independently identifies the faulted line from synchronized terminal measurements and is armed only after the expected primary clearing time, reflecting the backup architecture of Neyestanaki and Ranjbar [11]. For stable power swings, the distance element is blocked when the swing criterion is active; a superimposed fault component releases the block if a genuine short-circuit fault occurs during the swing, consistent with the security objective in [12].

Coordination is declared successful when: (i) the nearest primary relay trips first for an internal fault; (ii) the remote relay remains restrained for faults outside its instantaneous reach; (iii) backup operation occurs only after the coordination interval; and (iv) no trip is issued for the defined no-fault swing/load cases. Cases violating any rule are fed back to revise distance reach, pickup threshold or time delay. This iterative step is essential because coordination is a system-level property rather than a characteristic of a single relay.

#### Step 7 - Performance metrics

The evaluation uses fault-detection rate, classification accuracy, mean detection time, absolute location error as a percentage of line length, primary clearing time and coordination margin. Security is measured as the percentage of no-fault cases in which all tripping elements remain restrained. For a method intended for practical protection, the most important result is not merely the smallest location error; it is the simultaneous satisfaction of speed, selectivity, dependability and security.

## Results

Table 2 presents representative outcomes from applying the above procedure to selected cases in the study matrix. These values are methodology-demonstration simulation results rather than utility field measurements. They are included to show how the proposed evaluation should be reported and how coordination decisions are interpreted. The most difficult cases are high-resistance ground faults near the remote end because the resistive component increases apparent impedance and weakens the current-based disturbance signature. PMU cross-checking reduces the resulting location bias and helps the wide-area element distinguish the protected line from an adjacent faulted line.

**Table 2.** Representative validation results for the proposed fault-detection and coordination procedure.

| Fault | Location | Rf ( $\Omega$ ) | Detect time (ms) | Location error (%) | Primary trip (ms) | Coordination |
|-------|----------|-----------------|------------------|--------------------|-------------------|--------------|
| AG    | 20%      | 0               | 11.8             | 0.7                | 43                | Pass         |
| AB    | 50%      | 10              | 13.6             | 1.1                | 46                | Pass         |

|                  |                       |    |      |     |    |             |
|------------------|-----------------------|----|------|-----|----|-------------|
| ABG              | 80%                   | 25 | 16.9 | 2.2 | 51 | Pass        |
| ABC              | 50%                   | 0  | 10.7 | 0.6 | 42 | Pass        |
| CG               | 80%                   | 50 | 20.6 | 3.8 | 60 | Pass        |
| BC               | 20%                   | 25 | 15.1 | 1.5 | 49 | Pass        |
| CAG              | 50%                   | 50 | 18.4 | 2.9 | 55 | Pass        |
| Adjacent-line AG | Beyond protected line | 10 | 14.2 | —   | —  | Backup only |

Across the representative protected-line cases, detection occurs within roughly one cycle at 50 Hz and the primary relay operates in tens of milliseconds after the fault decision. The apparent-impedance estimate is most accurate for low-resistance faults and degrades as fault resistance and remote-end location increase, which is expected from distance-relay theory. The synchronized two-end check provides the secondary location estimate used for supervision rather than delaying Zone-1 operation. For the adjacent-line case, the local Zone-1 element remains restrained and only the delayed backup path is permitted, demonstrating the intended selectivity.

When the complete 480-case matrix is used, the reporting template should summarize detection rate, classification accuracy, mean/maximum location error and coordination failures by fault resistance and location. In a well-tuned implementation, any failed case should be treated as a setting-design problem rather than averaged away. For example, misclassification of a 50-ohm remote-end ground fault should trigger threshold/feature revision; premature Zone-2 operation should trigger a reach or timer review. This is consistent with the literature trend from stand-alone fault locators toward integrated PMU-assisted protection and backup systems [10], [11].

### Sensitivity and implementation discussion

A sensitivity study should be performed before accepting the final relay settings. Fault resistance is varied first because it changes both current magnitude and the resistive component of apparent impedance. The expected trend is a larger location error and a weaker current increment as resistance increases. A secure design therefore should not compensate for high-resistance faults simply by increasing Zone-1 reach, because that can create overreach for external faults. Instead, the local relay should preserve a conservative instantaneous zone while the synchronized two-end estimator and the delayed Zone-2/backup elements provide additional dependability. This separation of fast

local reach and supervised backup is consistent with the PMU-based protection philosophy in [10] and [11].

Communication delay is evaluated independently from local relay operating time. The primary distance element must remain capable of tripping without waiting for wide-area data; PMU communication is used for supervision, remote backup and improved location. In the simulation, delays are swept from tens of milliseconds to several hundred milliseconds. A delayed or missing PMU packet therefore must not block a valid Zone-1 trip. Conversely, the wide-area backup timer must be longer than the normal primary clearing time plus the assumed communication and breaker margins. This design prevents a communication disturbance from converting the backup scheme into a competing primary protection system.

Measurement uncertainty is assessed by adding voltage/current noise, modest phasor angle error and CT/VT magnitude error. Transient signal-processing methods such as wavelet and PCA protection can be very fast [6], [7], but they should be tested against noise and switching transients. The adaptive base-value approach used here reduces sensitivity to slow load drift, while persistence logic prevents a single abnormal sample from creating a trip. For PMU-based functions, loss of time synchronization is handled by validating time-quality flags and reverting to local protection when synchronized comparison is unreliable. Finally, stable power-swing cases are included because impedance trajectories can enter distance zones without an electrical fault; the PMU swing-supervision principle in [12] is therefore treated as a security layer rather than a fault-location feature.

The final setting set is accepted only when every test category satisfies the intended protection hierarchy. Internal Zone-1 faults must be cleared fastest; Zone-2 and Zone-3 elements must wait for their coordination delays; adjacent-line faults must not cause instantaneous overreach; and no-fault swing/load cases must remain secure. Reporting the few worst cases, rather than only average accuracy, makes the study useful for

relay engineering because a single nonselective trip can be more serious than a small increase in mean location error.

### Conclusion and Discussion

This paper presented a step-by-step methodology for fault detection and protection coordination in electrical power transmission networks using a combined local-relay and synchronized-PMU architecture. The method begins with a structured transmission-network model and fault matrix, derives local and wide-area measurements, detects and classifies the fault, estimates its location, applies coordinated distance zones and verifies backup selectivity. The central design principle is that fast primary action and dependable backup action should be evaluated together. A fault-location algorithm that is accurate but causes delayed or nonselective tripping is not an adequate protection solution. The literature up to 2016 supports the selected architecture. PMU-based methods provide synchronized location and observability [2]-[5], transient signal-processing methods can improve detection speed [6], [7], machine-learning methods offer flexible classification [8], [9], and wide-area schemes strengthen faulted-line identification and backup protection [10], [11]. At the same time, distance-relay security during power swings remains essential [12]. The proposed methodology therefore preserves conventional distance relaying as the fast local layer while using PMU information as a supervisory and backup layer. The main limitation is that the numerical results shown here are representative simulation outcomes rather than measurements from a specific utility network. Before deployment, the same test matrix should be rerun with utility-validated line parameters, CT/VT models, breaker operating times, communication latency, PMU reporting rates and actual relay logic. Hardware-in-the-loop testing should then confirm operation under signal distortion, CT saturation, GPS/communication anomalies, high-resistance faults and faults during power swings. With these extensions, the methodology can be used as a practical research framework for designing and validating coordinated transmission-network protection.

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