Zero-Setting Algorithm for High-Speed Open Line Detection Using Synchrophasors

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***Abstract*—Fast open line detection plays a critical role in ensuring system survivability and preventing wide-area blackouts. The loss of critical assets, such as transmission lines, should be quickly detected and corrective actions initiated through remedial action schemes to preserve system stability. Disturbances, such as line tripping caused by severe faults or breaker misoperation, can cause oscillations in machine rotors, resulting in power swings that affect power system stability. Quick, accurate open line detection is necessary to initiate automated corrective action in time to minimize system impacts and avoid blackouts. The speed and accuracy of existing open line detection methods limit their ability to take fast corrective control actions. This paper proposes a fast, secure, zero-setting algorithm to detect and declare open line conditions using wide-area synchrophasor measurements. Simulation results based on a real industrial system are presented for various transmission line topologies commonly found in high-voltage networks.**

***Index Terms*—Angle difference, open line detection, phasor measurement unit, remedial action scheme, synchrophasors.**

I. Introduction

Reliable and stable power system operation largely depends on protection, monitoring, and control schemes. Because of the increase in demand and limited infrastructure, transmission networks are carrying power close to their limits to better utilize their transfer capabilities [1]. Such stressed power system operations, combined with the increasing use of intermittent generation, require accurate and high-speed wide-area monitoring and control schemes.

One common power system disturbance is line outages. Detecting line outages is important for the network topology updates required by state estimation or to trigger corrective control actions. Additionally, the loss of critical transmission lines because of fault isolation leads to changes in system state variables, overload in the remaining lines, and changes in operating points [2]. To preserve system integrity and increase overall reliability, remedial action schemes (RASs) or special protection systems can be deployed to detect major system disturbances and take corrective actions [3], [4], [5]. The speed and reliability of such RASs are critical to stabilize the power system after a major event [6], [7].

Typically, the status of the line (i.e., in service or out of service) can be determined by monitoring the state of connecting devices (e.g., breakers and reclosers). Such status-based detection systems use open line detectors at both ends of the line. Therefore, the number of open line detectors is twice the number of transmission lines that require detection. Another approach is based on monitoring various electric parameters associated with the line, such as the voltage, current, or angle differences.

While high-speed open line detection may not be required for all transmission lines, it is critical for high-voltage transmission lines (corridors) that carry large amounts of power across wide geographical regions. When not remediated by load- or generation-shedding actions, the loss of such critical lines leads to system blackouts in most cases. High-voltage transmission lines are typically monitored by microprocessor-based protective relays, which are also used as phasor measurement units (PMUs). Since the advent of PMU-capable protective relays, many (if not all) utilities in North America have placed PMUs in their transmission systems to leverage the benefits of synchrophasor-based applications [8], [9], [10].

There are a number of limitations with existing methods, summarized as follows:

- Status-based schemes use a number of measurement points. This can decrease overall reliability because it increases the number of possible failure points.
- Analog-based schemes require power system studies and analysis to develop proper thresholds for high-speed detection.
- In some special situations, static threshold-based, analog-based schemes cannot be applied to meet strict detection time requirements for a RAS.

This paper addresses all of these limitations using a new synchrophasor-based, settingless (zero-setting) algorithm with a specific focus on fast open line detection for initiating RASs. The original contributions of this paper are as follows:

- The development of a new zero-setting open line detection algorithm that uses wide-area phase angle measurements to significantly improve the accuracy, robustness, and speed of open line detection.
- The implementation of the algorithm using industry-grade protective relays and controllers.
- Testing of a real-world power system using a closed-loop transient simulator to prove effectiveness.

The algorithm can be applied to meet strict tripping time requirements with zero settings, meaning it does not need any thresholds other than real-time field measurements.

II. The Proposed Algorithm Using Synchrophasors

With the advent of synchrophasor technology, power system wide-area monitoring and control schemes have expanded to a new dimension.

This paper introduces, for the first time, a zero-setting algorithm for high-speed open line detection without sacrificing the speed and reliability of detection. The proposed algorithm exactly detects the loss of one or more parallel transmission lines.

The real-power transfer (P) between two network buses connected by a reactance is determined by the phase angle difference (δ), the voltage magnitudes at the buses (V_S and V_R), and the reactance (X_L), as shown in Fig. 1.

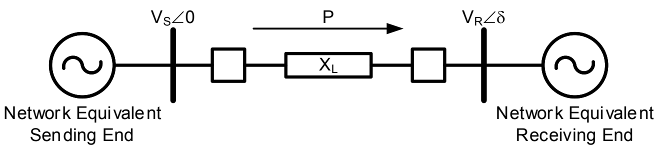


Fig. 1. Simplified two-bus system.

The two buses exchange real power according to the approximated relationship shown in (1).

$$P = \frac{V_S V_R \sin(\delta_S - \delta_R)}{X_L} \tag{1}$$

The idea behind the algorithm is to characterize and track the initial jump in angle difference to determine the number of parallel lines lost. The initial jump in the angle difference is a function of the impedance change across the two buses where the angle difference is measured. The total real-power transfer across two parallel transmission lines is represented mathematically in (1). For a fixed value of P over a short period of time, if one parallel transmission line is lost, the impedance (jX_L) doubles (assuming both of the parallel lines have the same impedance). Therefore, the angle has to approximately double to keep the same P transfer.

With the angle difference ratio (AR) and the real-power ratio (PR), the exact number of parallel lines lost can be determined.

AR is defined in (2), and PR is defined in (3):

$$AR = \frac{\text{Immediate Value of Angle Difference Jump After Event}}{\text{Angle Difference Before Event}} \tag{2}$$

$$PR = \frac{\text{Net Power Flow Between Two Buses Before Event}}{\text{Net Power Flow Between Two Buses Just After Event}} \tag{3}$$

Considering (1), the AR-to-PR ratio (expected ratio) is calculated for the loss of a single transmission line in a two-line (parallel) case as follows. $\delta_S - \delta_R$ is indicated as δ_{diff}. If the power flow between the two buses is approximated to be proportional to the ratio of angle difference and net impedance, then the net power flow before the event is given by (4). It is assumed that the voltage magnitudes are close to nominal and the angle difference is reasonably small.

$$P_{before} = \frac{V_S V_R \sin(\delta_{diff\ before})}{X_L} \sim \frac{V_S V_R (\delta_{diff\ before})}{X_L} \sim \frac{(\delta_{diff\ before})}{X_L} \tag{4}$$

Therefore, the ratio of net power flow to angle difference before the event is given by (5).

$$\frac{P_{before}}{\delta_{diff\ before}} \sim \frac{1}{X_L} \tag{5}$$

Similarly, the ratio of angle difference to net power flow after the event is given by (6).

$$\frac{\delta_{diff\ after}}{P_{after}} \sim 2X_L \tag{6}$$

In this case, the net impedance was doubled because of the loss of a parallel transmission line.

Fig. 2 shows the plots obtained from an example test power system that was modeled in a transient simulator environment to validate the proposed algorithm. For this validation, the parallel lines were modeled with the same impedance. Fig. 2 shows that the net power transfer across Line 1 and Line 2 is approximately 1,160 MW before the event (<0.5 seconds). The net power transfer just after the event (>0.5 seconds) is approximately 820 MW.

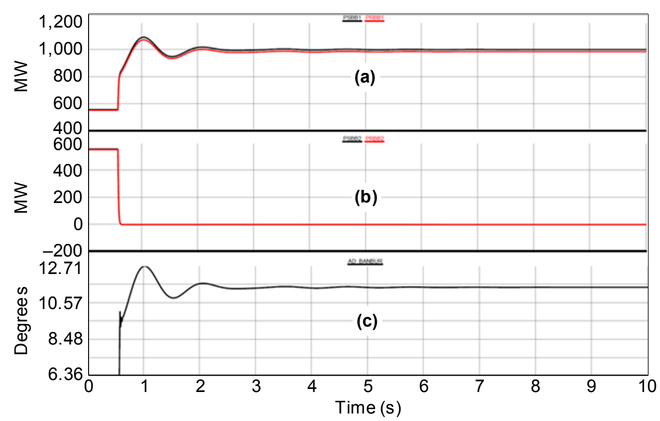


Fig. 2. Simulation plots for the loss of one of two parallel lines—(a) the real power through Line 1, (b) real power through Line 2, and (c) voltage angle difference between Bus 1 and Bus 2.

From Fig. 2, AR and PR are calculated in (7):

$$\begin{aligned} AR &= \frac{9.5 \text{ degrees}}{6.35\text{degrees}} = 1.5 \\ PR &= \frac{1{,}160 \text{ MW}}{820 \text{ MW}} = 1.41 \end{aligned} \tag{7}$$

Multiplying PR by AR calculates exactly how many times the equivalent impedance was scaled, as shown in (8):

$$AR \bullet PR = 1.5 \bullet 1.41 = 2.1 \tag{8}$$

In this case, the equivalent network impedance between the buses basically doubled. This indicates that, for two parallel lines with the same impedance, one line was lost or became open. For three parallel lines with the same impedance, if the multiplication of ratios is 3, then two lines are lost. If the multiplication of ratios is 1.5, then one line is lost.

This angle difference scheme is supervised by the associated voltage magnitudes to ensure healthy measurements. The algorithm is supervised with synchrophasor data validation bits to prevent false indications. Also, the algorithm has built-in blocking logic that detects and restrains operation under a loss-of-potential condition and during system fault conditions. The expectation is for this algorithm to operate after the fault is cleared by the local protection systems. Once the fault clearing causes an open line condition, the algorithm should quickly detect the loss of the transmission line and trigger the RAS operation.

The proposed algorithm is highly practical for field implementation because of its innovative benefits and simple application. The algorithm offers tremendous speed compared with other analog-based detection schemes while guaranteeing the required security and reliability. This allows for wider power system stability margins and improves the reliability of RASs. It is important to note that for the loss of a single line, the proposed algorithm still operates with the same high speed and reliability.

III. Simulation and Testing

This section describes the closed-loop simulation testing environment, the test power system, and results for various possible transmission line configurations.

A. Simulation Environment

The hardware-based Electromagnetic Transients Program (EMTP) simulator used to test the algorithms in this paper is a fully digital power system simulator capable of continuous real-time operation.

The real-time EMTP simulator was specifically used to test the new algorithms in a closed loop with the power system to emulate field testing. The authors created a model representing the various transmission lines, generators, and loads of a high-voltage utility power system.

B. Test Power System

As shown in Fig. 3, the power system under test is composed of four 500 kV substations and six 220 kV substations. All of these substations are connected through transmission lines and interconnecting transformers. The 220 kV substations serve several critical and noncritical load transformers, while the 500 kV substations connect to different generation plants through transformers. The total installed generation capacity is approximately 5 GW, which is distributed across the system.

It is important to note that the algorithm performance does not depend on the size of the system. The algorithm is applicable between any two buses with interconnecting transmission lines. The test power system shown in Fig. 3 is based on a real-world transmission system.

C. Test Scenarios

Table I demonstrates the different scenarios (transmission line topologies) that were considered for testing the zero-setting algorithm. For example, Case 1 is the tripping of a parallel transmission line for a given power flow condition.

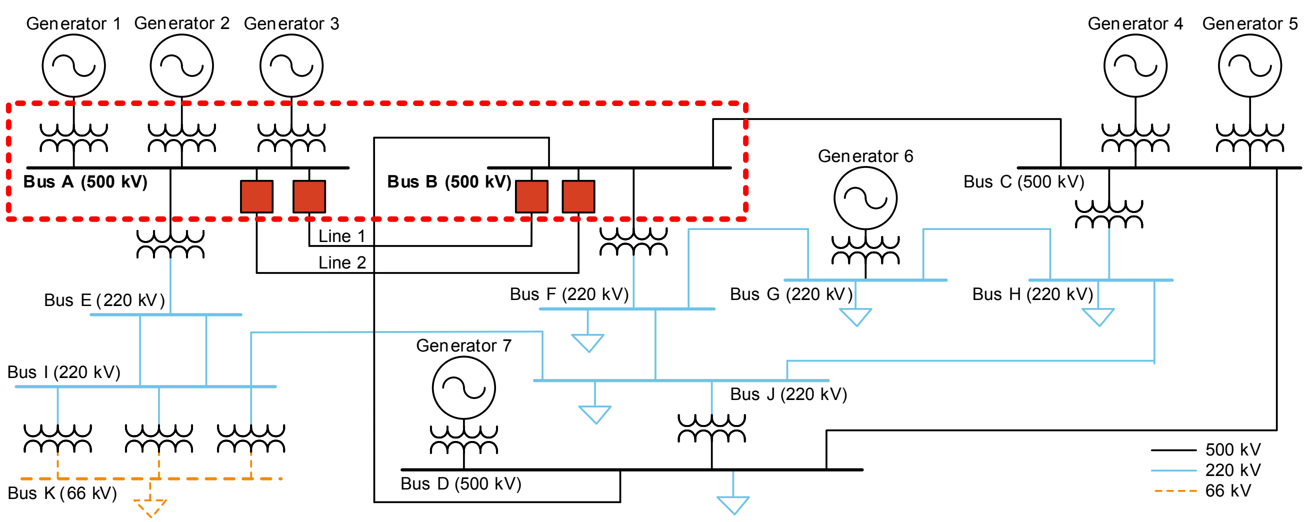
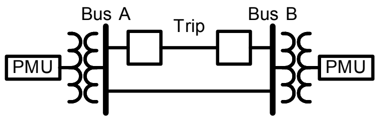
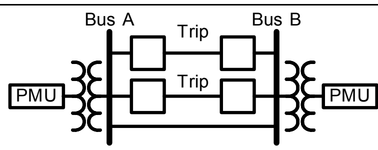
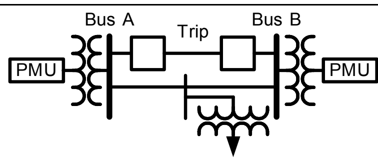
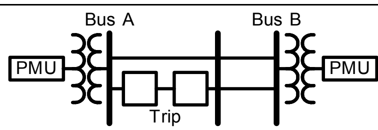


Fig. 3. Simplified power system for testing the proposed algorithm.

TABLE I LIST OF SCENARIOS WITH EXPECTED AND MEASURED RESULTS

Case	Topology and Event Indication (event is indicated by "Trip")	Angle Difference Before Line Outage (degrees)	Angle Difference After Line Outage (degrees)	Net Power Before Line Outage (MW)	Net Power After Line Outage (MW)	Expected Ratio (AR • PR)	Immediate Measured Ratio (AR • PR)	Accuracy (%)
1		8.423	14.55	1,862	1,470	2	2.19	91
2		5.643	13.164	1,897	1,368	3	3.23	92
3		7.165	12.55	1,843	1,574	2	2.05	97
4		15.89	20.89	1,757	1,434	1.5	1.61	93

The results show that the algorithm is very effective in terms of detecting the number of lines lost in less than 60 milliseconds for a 50 Hz system and in less than 50 milliseconds for a 60 Hz system. The measured ratio in Table I is calculated using synchrophasor samples obtained before and immediately after the initiation of line tripping. If the algorithm is implemented using a peer-to-peer communications technology between protective relays, overall speeds of less than 100 milliseconds can be comfortably achieved to better assist a high-speed RAS. Note that the overall time also depends on the latency of the communications channel being used for the peer-to-peer communication.

For each case shown in Table I, the transmission line configuration between Bus A and Bus B in Fig. 3 was modified accordingly. The figures in Table I indicate the pre-event line configuration between Bus A and Bus B along with the line that was tripped to create the event (contingency). The accuracy column in Table I indicates the deviation between the algorithm-measured ratio and the expected ratio.

Fig. 4 shows the Case 1 plots of the net real power, the angle difference across the bus in degrees, the line-to-neutral voltage magnitudes of the sending and receiving end buses, and the overall system frequency. The plots were derived using synchrophasor data produced by industry-grade protective relays. These PMUs were connected to the EMTP simulator in a closed loop for monitoring and controlling the power system.

As shown in Fig. 4, the error in the immediate measured ratio can be attributed to the small changes in the voltage magnitude ratios before and immediately after the event. For example, the voltage magnitude change ratio can be calculated using the product of the sending and receiving end voltage magnitudes. In Case 1, the voltage magnitude change ratio yields a value of 0.9561.

When the immediate measured ratio from Table I is multiplied by this value (0.9561 • 2.19 = 2.09), the error reduces and the accuracy increases. There is also a small error introduced by the sine function itself as the angle difference increases. Because the focus of this paper is open line detection and not RAS performance, RAS results are not presented. However, from a power system control standpoint, it can be argued that faster wide-area control after an event can lead to improved transient and small-signal stability.

Table II shows the relative effectiveness of the proposed algorithm versus existing algorithms.

TABLE II RELATIVE EFFECTIVENESS OF SCHEMES

Criterion	Traditional Open Line Detection Using Digital Measurements	Traditional Open Line Detection Using Analog Measurements	Proposed Algorithm
High-speed detection in 1–2 cycles	Possible	Not possible	Possible
Required studies and user settings	Fewer settings	More settings	Zero settings
Pickup time required after qualifying event	Yes	Yes	No
Required coordination with other protection schemes	Yes	Yes	No
Number of measurements required	Minimal	Several	Very minimal

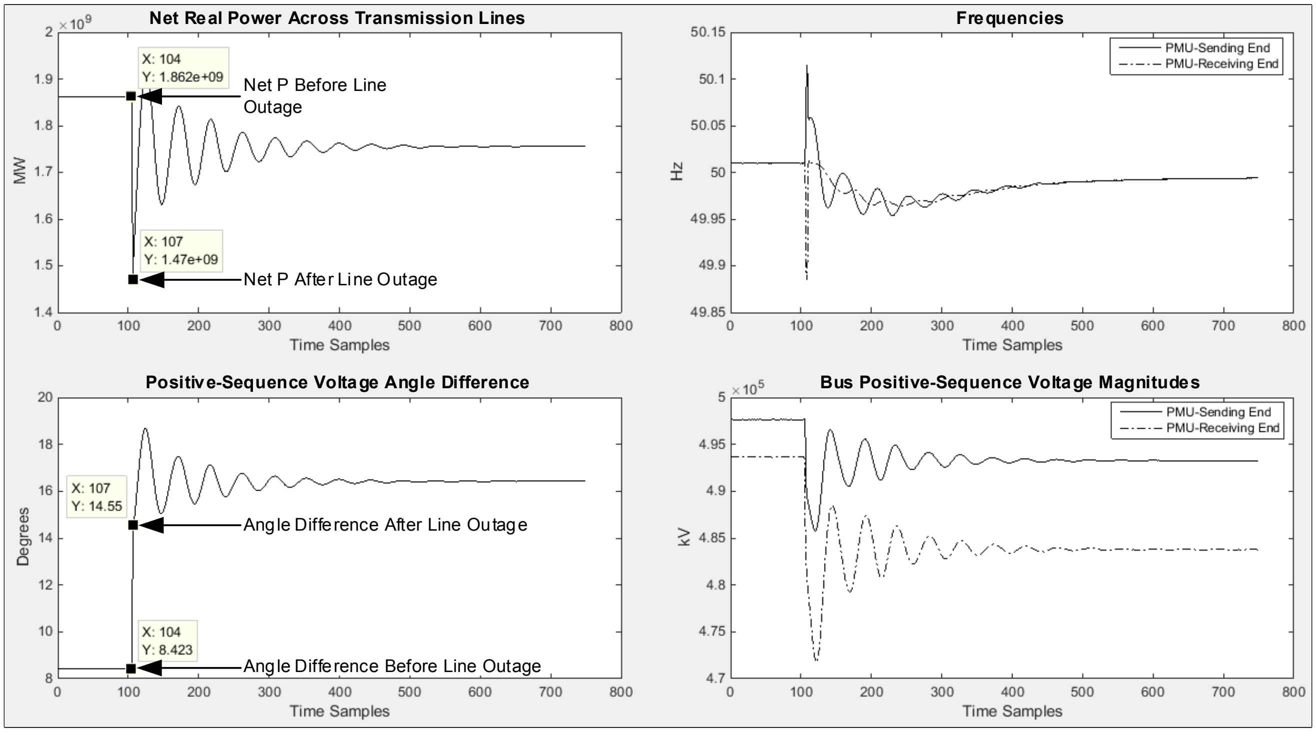


Fig. 4. Results of Case 1.

IV. Conclusions

Open line detection schemes have historically assisted RASs in preserving system stability and protecting system integrity. This paper presents the existing open line detection schemes and identifies the need for improved algorithms. Given the increasing use of synchrophasors, this paper discusses key advancements that use the technology to develop a smarter and faster open line detection algorithm.

Specifically, this paper introduces a novel zero-setting algorithm that uses synchrophasor measurements to detect an open line condition at a high speed while guaranteeing security and reliability. The simplicity of the proposed approach makes it highly practical for field implementation for RASs, and it outperforms all presently available analog-based schemes.

The paper also presents the test setup used to validate the algorithm and the results of various test scenarios based on a real industrial system. Compared with existing schemes, the proposed algorithm significantly improves the following:

- Speed of detection. The algorithm uses the immediate measurements after an event to reliably detect an open line condition. The algorithm is also supervised with synchrophasor data validation bits and built-in fault blocking logic for additional security.
- Robustness. The algorithm eliminates the possibility of human-introduced errors by requiring no settings.
- Reliability. The algorithm uses only two measurement points, greatly reducing the number of potential failure points.

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