

Wide-Band Distance Protection and Single-Ended Fault-Locating Method

Bogdan Kasztenny and Greg Smelich
Schweitzer Engineering Laboratories, Inc.

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Abstract—This paper addresses limitations of impedance-based fault locating under ultra-high-speed (UHS) tripping and in transmission lines near inverter-based resources (IBRs). Short fault durations prevent phasor quantities from settling, leaving little reliable data for conventional phasor-based methods. In addition, IBRs are weak sources that produce relatively small and distorted fault currents, which further degrade the performance of phasor-based fault-locating and distance protection methods.

To overcome these challenges, this paper presents four wide-band methods based on the RL differential equation of the line. By processing instantaneous voltages and currents, the methods extract the distance-to-fault information from a wide frequency band rather than relying solely on the fundamental-frequency voltage and current components. One method uses polarization to improve accuracy for resistive faults, while the other methods apply an apparent-impedance formulation to avoid polarization, making them more suitable for applications near IBRs.

The proposed methods operate with flexible data windows, support short duration faults, and do not require frequency tracking to facilitate band-pass phasor filtering. These methods can function as both distance elements and single-ended fault locators, offering a practical alternative to phasor-based methods in power systems with UHS relays and IBRs.

I. INTRODUCTION

This paper addresses two recent challenges in transmission line protection. The first challenge is the impact of ultra-high-speed (UHS) tripping on impedance-based fault locators. The second challenge relates to distance protection and fault locating on lines connected to inverter-based resources (IBRs) and other unconventional sources, such as Type 2 and 3 wind-powered generators. Both these challenges adversely impact impedance-based distance protection and fault-locating methods.

A. The Challenge of Short Fault Duration

UHS line relays can issue trip commands within 1 to 3 ms when using direct fiber channels [1]. If circuit breakers rated at 2 cycles are installed, faults may clear in as fast as 1.5 power cycles. These relays [1] include traveling-wave-based fault locators (TWFLs) that achieve accuracy within one tower span [2]. Although dependable, TWFLs still require backup for rare cases involving fault precursors or faults during unfavorable line termination conditions. Impedance-based fault locators that rely on phasors are expected to provide this backup.

However, short fault duration prevents phasors from stabilizing during the fault. A full-cycle phasor estimator needs about 1.25 cycles to settle. Just as the phasor stabilizes, the breaker begins to open at about 1.5 cycles. As a result, the

phasor-based fault locator may have less than 0.25 cycle of stable fault phasor data. Transients in the voltages and currents during the initial few milliseconds of a fault extend the phasors settling time even further. Consequently, for faults cleared in 1.5 cycles, a phasor-based fault locator may have no accurate phasors to work with.

Shortening the phasor data window to accommodate a short fault duration decreases accuracy and is, therefore, counterproductive for an accuracy-focused application, such as fault locating.

In earlier work, we developed a *double-ended* fault-locating method that operates accurately with data windows much shorter than one power cycle [3]. This paper introduces four *single-ended* methods that work with short data windows, making it suitable for systems that apply UHS tripping but cannot use double-ended fault-locating methods because a communications channel is not installed or is temporarily unavailable.

B. The Challenge of Small and Distorted IBR Currents

IBRs complicate distance protection not only because they are weak sources but also because they generate significant low-frequency transients during faults [4]. These effects compound: fundamental-frequency fault voltages and currents are small, while voltage and current distortions are large by comparison. Many transients include signal components with spectrum near the nominal frequency, making them difficult to filter out, thus worsening the signal-to-noise ratio even further.

We address these challenges by using a wide-spectrum approach to distance measurement. Instantaneous voltages and currents follow a first-order differential equation describing the RL circuit representing the line; therefore, the distance to fault information is encoded not only in the voltage and current phasors but also across a wide frequency band in the instantaneous voltage and current signals.

C. Paper Content and Organization

This paper presents four methods that use a wide-band approach to measure the distance to fault.

The first method uses polarization and, therefore, is particularly suited for resistive faults. The polarization-based method uses one of the known polarizing signals, such as ground current (ground quadrilateral element) or an incremental current (phase and ground quadrilateral elements).

The other methods include two apparent-impedance methods and a distance-to-fault method.

TABLE I.
OVERVIEW OF THE PRESENTED METHODS

Method	Approach	Section	Equations	Output
Polarization-based	Assume the fault path is resistive. Use a local current (ground current or phase incremental current) to represent the instantaneous polarity of the fault-path current. Find fault location that puts the estimated fault-point voltage in phase with the fault-path current.	II.B and III	(27) – (32)	Fault location
Apparent Impedance, Method 1	Neglect fault resistance. Find the apparent resistance and reactance to best match the measured instantaneous loop voltage and the voltage calculated by using the instantaneous loop current and apparent resistance and reactance.	II.C.1 and IV	(9) – (11) and (36) – (42)	Apparent impedance and fault location
Apparent Impedance, Method 2	Assume the fault path is resistive. Use the loop current to obtain the line voltage drop. Use a local current (ground current or phase incremental current) to represent the voltage drop across fault resistance. Find the apparent resistance and reactance to best match the measured instantaneous loop voltage and the voltage calculated as the line voltage drop plus the voltage drop across fault resistance.	II.C.2 and IV	(15) – (17) and (36) – (42)	
Apparent Distance-to-Fault	Neglect fault resistance. Find the apparent resistance and reactance to best match the measured instantaneous loop voltage and the loop voltage calculated by using the instantaneous loop current and the fault location.	II.D and V	(47)	Fault location

The presented methods can be used as distance elements or as single-ended fault locators. They support arbitrary data window lengths, from one cycle for UHS fault clearing to several cycles in applications involving IBRs.

Table I summarizes the presented methods.

The paper is organized as follows:

- Sections II through V derive the new methods.
- Section VI illustrates their performance using several field-recorded fault cases.
- Section VII discusses the infeed effect and explains differences in the infeed effects between the various methods.
- Section VIII discusses accuracy and key characteristics of the new methods.
- Section IX discusses a new distance protection element logic based on the concepts presented in this paper, including a novel load blinder logic.
- Finally, Section X reviews the performance of the new methods for about 200 fault cases recorded in the field.

II. INSTANTANEOUS LOOP VOLTAGES AND CURRENTS AND DIGITAL SIGNAL PROCESSING

Distance protection elements and impedance-based fault locators operate by using six fault loops to cover all possible fault types. These functions apply a faulted-loop selection logic to identify the fault type and use the loop that best represents that fault type. The six loops correspond to the AG, BG, CG, AB, BC, and CA faults. The loop voltages and currents are formulated so that the positive-sequence impedance ties the loop voltage and the loop current together. This section derives the instantaneous loop voltages and currents and discusses the digital signal processing for fault locating and distance protection elements in general. Sections III, IV, and V derive the wide-band methods based on the instantaneous loop voltages and currents.

A. General Considerations

Fig. 1 shows a fault-loop circuit for a three-phase power line with a fault. We use the following variables:

- v is the instantaneous loop voltage at the relay location,
- i_Z is the instantaneous loop replica current at the relay location,
- Z_1 is the line positive-sequence impedance (R_1 and L_1),
- Z_0 is the line zero-sequence impedance (R_0 and L_0),
- m is the per-unit distance to fault,
- v_F is the instantaneous loop voltage at the fault location (the fault-point voltage),
- i_F is the instantaneous current flowing through the fault resistance.

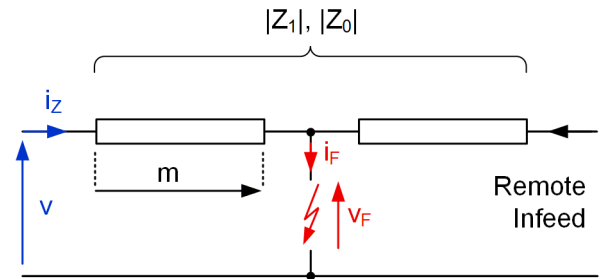


Fig. 1. Fault-loop circuit.

In the time domain, we formulate the loop voltage and the loop replica current so that in the voltage-drop equation the line is represented by a resistor equal to $|Z_1|$, as in (1):

$$v - m \cdot |Z_1| \cdot i_Z = v_F \quad (1)$$

To satisfy (1), we must define the ground (AG, BG, and CG) and phase (AB, BC, and CA) loop voltages and replica currents as in (2) and (3) [5]:

$$v_{AG} = v_A \quad i_{ZAG} = i_{ZA} - i_{Z0} \quad (2)$$

$$v_{AB} = v_A - v_B \quad i_{ZAB} = i_{ZA} - i_{ZB} \quad (3)$$

where the components of the ground replica currents are as follows, in (4), (5), and (6):

$$i_0 = \frac{1}{3} \cdot (i_A + i_B + i_C) \quad (4)$$

$$i_{ZA} = \frac{R_1}{|Z_1|} \cdot i_A + \frac{L_1}{|Z_1|} \cdot \frac{d}{dt} i_A \quad (5)$$

$$i_{Z0} = \frac{R_1 - R_0}{|Z_1|} \cdot i_0 + \frac{L_1 - L_0}{|Z_1|} \cdot \frac{d}{dt} i_0 \quad (6)$$

Expressions for the remaining loops (BG, CG, BC, and CA) can be obtained by rotating the indices in (2) and (3).

From a signal-processing perspective, a replica current is a weighted sum of the current and its derivative. From a circuit perspective, a replica current represents the voltage drop across a one-ohm impedance that *replicates* the L over R ratio of the power line (hence the name) [5].

Equation (1) forms the basis of all single-ended fault-locating and distance protection methods. Importantly, it contains two unknowns: the fault distance, m , and the fault-point voltage, v_F . Since there are two unknowns, two equations are required to obtain a solution. Different methods derive the additional equation by making different assumptions about the fault conditions. The following sections introduce four such methods and the assumptions on which they are based.

B. Wide-Band Polarization-Based Method

Polarization-based methods assume a resistive fault path, meaning that the fault-point voltage is proportional to the fault-path current. Although the fault-path current includes the remote infeed current and is, therefore, not available to the local relay, these methods rely only on its phase angle, or instantaneous polarity. Under the additional assumption of a homogeneous network, an angle of a locally measured current, such as the zero-sequence current or the incremental current, can serve as a proxy for the phase angle of the fault-path current.

Section III explains the polarization-based method in general and derives the wide-band version. The wide-band method uses the loop voltages and currents defined in (1) through (6).

C. Wide-Band Apparent-Impedance Methods

Apparent-impedance methods determine the resistance and reactance that best tie together the loop voltage and loop current. Traditionally, these methods provide an accurate distance-to-fault measurement when the fault-point voltage is zero. When the fault-point voltage is non-zero, however, they are subject to the infeed effect, which alters both the apparent resistance and reactance. Specifically, the apparent resistance increases, while the apparent reactance shifts upward or downward on the apparent impedance plane depending on the direction of the pre-fault power flow. The following sections derive the loop voltages and currents for two wide-band apparent-impedance methods. The second method dramatically

reduces the impact of infeed and effectively is a hybrid between the apparent-impedance and polarization-based methods.

1) Method 1

We assume that the fault-point voltage is zero, and use (1) through (6) to derive an equation that ties together the voltage and current, as in (7) (we use the AG loop as an example):

$$v_A = m \cdot R_1 \cdot \left(i_A + \left(\frac{R_0}{R_1} - 1 \right) \cdot i_0 \right) + m \cdot L_1 \cdot \frac{d}{dt} \left(i_A + \left(\frac{L_0}{L_1} - 1 \right) \cdot i_0 \right) \quad (7)$$

Equation (7) contains only a single unknown, m , as expected given that we assumed the fault-point voltage to be zero. The resistance, R , and inductance, L , from the relay location to the fault, are not independent parameters. Instead, both represent the same fraction of the positive-sequence line resistance and inductance.

We know, however, that the fault loop contains the fault resistance, and we must treat R and L in (7) as two independent variables, as in (8):

$$v_A = R \cdot i_{AG(R)} + L \cdot \frac{d}{dt} i_{AG(X)} \quad (8)$$

where the ground loop current now consists of two components, (9) and (10):

$$i_{AG(R)} = i_A + \left(\frac{R_0}{R_1} - 1 \right) \cdot i_0 \quad (9)$$

$$i_{AG(X)} = i_A + \left(\frac{L_0}{L_1} - 1 \right) \cdot i_0 \quad (10)$$

By giving the method one more degree of freedom (two variables, R and L , instead of one variable, m) we allow the method to find the apparent R and L values in a way that minimizes the infeed effect when the fault-point voltage is not zero.

Section IV derives the wide-band apparent-impedance Method 1. The method uses the ground loop voltages and currents defined in (8) through (10). The phase loop voltages and currents are the phase-to-phase differences, as in (11):

$$v = v_A - v_B, \quad i_{AB} = i_{AB(R)} = i_{AB(X)} = i_A - i_B \quad (11)$$

2) Method 2

We can rewrite (7) by assuming constant fault resistance R_F and a fault-path current i_F , as in (12):

$$v_A = m \cdot R_1 \cdot \left(i_A + \left(\frac{R_0}{R_1} - 1 \right) \cdot i_0 \right) + m \cdot L_1 \cdot \frac{d}{dt} \left(i_A + \left(\frac{L_0}{L_1} - 1 \right) \cdot i_0 \right) + R_F \cdot i_F \quad (12)$$

This equation contains three unknowns: the distance to fault, the fault resistance, and the fault-path current. To obtain a single-ended solution, we replace the fault-path current with a local current that has the same expected polarity as the fault-

path current. Assuming $3i_0$ as the polarizing signal, we rewrite the equation as in (13):

$$v_A = m \cdot R_1 \cdot \left(i_A + \left(\frac{R_0}{R_1} - 1 \right) \cdot i_0 \right) + R_F \cdot 3 \cdot i_0 + m \cdot L_1 \cdot \frac{d}{dt} \left(i_A + \left(\frac{L_0}{L_1} - 1 \right) \cdot i_0 \right) \quad (13)$$

We can further simplify the expression for the part that includes the currents and not the current derivative by neglecting the load current and approximating $i_A = 3 \cdot i_0$. We obtain (14):

$$v_A = R \cdot (3 \cdot i_0) + L \cdot \frac{d}{dt} \left(i_A + \left(\frac{L_0}{L_1} - 1 \right) \cdot i_0 \right) \quad (14)$$

The resistance R in (14) blends the line and fault resistances. Equation (14) allows us to use (8) with the following ground loop current, as in (15) and (16):

$$i_{AG(R)} = 3 \cdot i_0 \quad (15)$$

$$i_{AG(X)} = i_A + \left(\frac{L_0}{L_1} - 1 \right) \cdot i_0 \quad (16)$$

We assigned a somewhat arbitrary current to the loop resistance. As a result, we will obtain the apparent resistance that is different than when using the simple V/I approach, but by doing so we improve the accuracy of the apparent reactance.

In general, we can use either the zero-sequence current or the phase incremental current in (15). Generally, we can write (17):

$$i_{AG(R)} = i_{POL} \quad (17)$$

where i_{POL} is the polarizing current as per (22).

Section IV derives the wide-band apparent-impedance Method 2. The method uses the ground loop voltages and currents defined in (8), (15), and (16). The phase loop voltages and currents are the phase-to-phase differences as per (11).

D. Apparent Distance-to-Fault Method

This method uses (1) under the assumption of zero fault-point voltage, as shown in (18):

$$v - m \cdot |Z_1| \cdot i_Z = 0 \quad (18)$$

The method derives m by minimizing the difference between the loop voltage and the loop replica current multiplied by the line positive-sequence impedance magnitude.

Section V derives the wide-band apparent distance-to-fault method. The method uses the loop voltage and currents defined by (1) through (6).

E. Low-Pass Filtering

The loop model in Fig. 1 assumes an RL representation of the line. Because power lines also include capacitance, faults produce decaying oscillatory transients that distort the relay voltages and currents. To reduce the impact of these high-frequency components, it is beneficial to apply low-pass filtering to the relay voltages and currents before deriving the instantaneous loop voltages, loop currents, and replica currents.

In this paper, we apply a second-order Butterworth filter with 3 dB attenuation at 0.4 kHz. This level of filtering is lighter than in relay [1] for its time-domain protection functions (20 dB attenuation at 0.4 kHz).

F. Faulted-Loop Selection Logic

Several methods exist for identifying the fault type and selecting the corresponding fault loop. Phasor-based relays commonly use the angle between the negative- and zero-sequence currents as the basis for identifying the faulted loop. Additional indicators can be derived from voltages, either through undervoltage detection or through evaluation of voltage unbalance. Relay [1] uses incremental voltages and currents for faulted-loop selection in its time-domain protection functions. A detailed discussion of faulted-loop selection is beyond the scope of this paper.

G. Discrete Time Domain

To implement wide-band methods in a microprocessor-based device, we must transition from continuous-time expressions to their discrete-time counterparts. While implementing this step, we also switch from the apparent inductance to the commonly-used apparent reactance at the nominal system frequency. We use a two-point numerical differentiation and make the following substitutions; (19), (20), and (21):

$$L \cdot \frac{d}{dt} i = \frac{X}{\omega} \cdot \frac{d}{dt} i \rightarrow X \cdot \frac{f_S}{2\pi \cdot f_N} (i_{(k)} - i_{(k-1)}) \quad (19)$$

$$i \rightarrow \frac{1}{2} (i_{(k)} + i_{(k-1)}) \quad (20)$$

$$v \rightarrow \frac{1}{2} (v_{(k)} + v_{(k-1)}) \quad (21)$$

The variables used in these substitutions are:

- f_S is the sampling frequency,
- f_N is the nominal frequency,
- X is the reactance at the nominal frequency,
- k is the sample index.

Equations (20) and (21) account for the half-a-sample group delay introduced by the numerical differentiation (19).

III. WIDE-BAND POLARIZATION-BASED METHOD

A. Current Polarization

Single-ended fault locators and reactance comparators in distance protection elements assume that the fault path is resistive. In other words, the current in the fault path (i_F in Fig. 1) and the voltage across it (v_F in Fig. 1) are tied by a resistance, even if that resistance is nonlinear and time varying (arc faults).

Under this assumption, both a fault locator and a distance element become perfectly accurate if the fault-path current were used as a polarizing signal. Obviously, a relay at the line terminal does not have access to the fault-path current.

Polarizing does not require the signal magnitude, but only polarity (angle). Therefore, the fault-path current can be approximated by currents available at the relay location:

- Schweitzer used the negative-sequence current at the relay location to approximate the fault-path current (negative-sequence polarization). The zero-sequence current can be used for ground loops. Some implementations use the sum of the negative- and zero-sequence currents for ground loops.
- Takagi used the incremental current for the same purpose (incremental-current polarization). This method allows proper operation for three-phase balanced faults when the negative-sequence current is zero.

A time-domain method cannot use the negative-sequence current. Also, avoiding the negative-sequence current is advantageous when IBRs are present.

In our method, we use the zero-sequence current (4) or the incremental phase current to polarize the ground loops, and the incremental phase-to-phase currents to polarize the phase loops, as in (22):

$$i_{POL} = \begin{cases} i_0 \text{ or } \Delta i_A & \text{AG loop} \\ \Delta i_A - \Delta i_B & \text{AB loop} \end{cases} \quad (22)$$

Here, Δ denotes an incremental quantity, defined as the difference between the present value and a value from several (N) cycles earlier (T is the period), as in (23):

$$\Delta i_{A(t)} = i_{A(t)} - i_{A(t-N \cdot T)} \quad (23)$$

B. Instantaneous Signal Formulation

The method uses (1) through (6) to calculate the voltage at the fault point as a function of the per-unit fault location m , as in (24):

$$v_{F(m)} = v - m \cdot |Z_1| \cdot i_Z \quad (24)$$

If m is the true fault location, the fault-point voltage (24) is in phase with the polarizing current (22). The true location m_0 is therefore the value of m for which the fault-point voltage and the polarizing current are “in phase”, i.e. share the same instantaneous polarity.

To test whether two time-domain signals are in phase, we introduce the following objective function, shown in (25):

$$J_{(m)} = \frac{\sum(i_{POL} \cdot v_{F(m)})}{\sqrt{\sum i_{POL}^2} \cdot \sqrt{\sum v_{F(m)}^2}} \quad (25)$$

The sums in (25) span an arbitrarily selected window as long as that window includes the fault. For example, the window may open 2 ms after fault inception and close 1.5 cycles into the fault.

Mathematically (25) is a *cosine similarity* with the *dot product* in the numerator and the *Euclidean norms* in the denominator. J equals +1 when the signals are perfectly “in phase”, -1 when they are perfectly “out of phase”, and 0 when they are orthogonal. A power engineer may view J as analogous to a power factor.

We then use (25) to obtain m_0 as the value of m that maximizes J .

C. Wide-Band Implementation

To find the maximum of J , we solve (26):

$$\frac{d}{dm} \left(\frac{\sum(i_{POL} \cdot (v - m \cdot |Z_1| \cdot i_Z))}{\sqrt{\sum i_{POL}^2} \cdot \sqrt{\sum (v - m \cdot |Z_1| \cdot i_Z)^2}} \right) = 0 \quad (26)$$

and obtain:

$$m_0 = \frac{1}{|Z_1|} \cdot \frac{S_1 \cdot S_2 - S_3 \cdot S_4}{S_1 \cdot S_4 - S_3 \cdot S_5} \quad (27)$$

where:

$$S_1 = \sum(i_{POL} \cdot i_Z) \quad (28)$$

$$S_2 = \sum v^2 \quad (29)$$

$$S_3 = \sum(i_{POL} \cdot v) \quad (30)$$

$$S_4 = \sum(i_Z \cdot v) \quad (31)$$

$$S_5 = \sum i_Z^2 \quad (32)$$

Equations (27) through (32) define the new method. The calculations can be carried out for the faulted loop only. Alternatively, the calculations can be carried out for six loops, and the resulting fault-location values m_0 for each loop can assist with faulted-loop selection.

Once the fault location m_0 is obtained, it is substituted into (24) to compute the voltage at the fault point and into (25) to compute the corresponding J value. We can take advantage of these values as follows:

- If the fault-point voltage is small (a metallic fault), disregard the value of J . Correlating a near zero signal (the fault-point voltage) with the polarizing signal may give positive or negative values of J .
- If the fault point-voltage is significant (for example, greater than 10 percent of the nominal loop voltage), the value of J can be used as an indication of the fault-locating accuracy and the security of distance protection.
- When J is close to +1, you can trust the calculated m_0 . When J is small but still positive, you may consider the calculated m_0 as less accurate. If J is negative, the value of m_0 is not accurate.

D. Window Selection

The method allows flexible selection of the data window. The window length does not need to be an integer multiple of a power cycle or a half cycle. As a result, the method does not rely on frequency measurements to determine the cycle length. The following design points guide the choice of the data window.

- It is beneficial to start the window a few milliseconds into the fault. Excluding pre-fault samples and the initial transient improves accuracy because neither the pre-fault values nor the early oscillatory components relate to the fault location. Applications with low-quality coupling capacitive voltage transformers (CCVTs) may apply a slightly longer delay before opening the window to purge the CCVT transients from the window.
- The window must close before the breaker opens the first pole. After a pole opens, the measured voltages and currents no longer carry information about the fault location.
- The minimum practical window length is about half a cycle. Shorter windows do not allow reliable determination of whether two signals are in phase.
- The method supports both sliding and expanding data windows (see Fig. 2). A sliding window has a fixed length and moves forward in time as new samples arrive. An expanding window begins a few milliseconds after the fault and increases its length as new samples become available.
- The expanding window is especially useful for fault locating because it improves accuracy. It also provides benefits near IBRs, in both protection and fault-locating applications, because these sources generate voltages and currents with low signal-to-noise ratios.
- If current transformers (CTs) saturate during the fault, you can detect the periods of no saturation and only use these samples in the data window (purge the samples belonging to intervals of CT saturation).

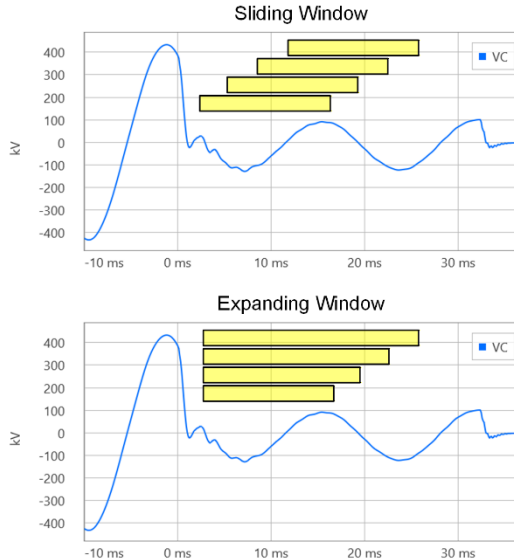


Fig. 2. Sliding and expanding data windows.

IV. WIDE-BAND APPARENT-IMPEDANCE METHOD

A. Apparent Impedance

When we consider the instantaneous loop voltage and current in the apparent-impedance model of Subsection II.C, we can interpret measuring the apparent impedance as a parameter-fitting problem. The apparent resistance R and apparent

inductance L are the pair of values that best fit the measured voltage to the voltage predicted from the current. In other words, R and L minimize the following objective function, (33):

$$E = \int \left(v - R \cdot i - L \cdot \frac{d}{dt} i \right)^2 dt \quad (33)$$

B. Wide-Band Implementation

The method uses the instantaneous loop voltages and currents as per Subsection II.C (Method 1 and Method 2). It then converts these signals to the discrete-time domain by applying (19) through (21). With these discrete-time signals, we can rewrite the objective function (33) as (34):

$$E = \sum \left(v - R \cdot i - \frac{X}{\omega} \cdot \frac{d}{dt} i \right)^2 \quad (34)$$

We minimize this objective function by solving (35), (36), and (37):

$$\frac{\partial E}{\partial R} = 0 \quad \text{and} \quad \frac{\partial E}{\partial X} = 0 \quad (35)$$

and we obtain:

$$R = \frac{S_8 \cdot S_9 - S_7 \cdot S_{10}}{S_6 \cdot S_8 - S_7^2} \quad (36)$$

$$X = \frac{S_6 \cdot S_{10} - S_7 \cdot S_9}{S_6 \cdot S_8 - S_7^2} \quad (37)$$

where:

$$S_6 = \sum i^2 \quad (38)$$

$$S_7 = \frac{1}{\omega} \sum \left(i \cdot \frac{di}{dt} \right) \quad (39)$$

$$S_8 = \frac{1}{\omega^2} \sum \left(\frac{di}{dt} \right)^2 \quad (40)$$

$$S_9 = \sum (i \cdot v) \quad (41)$$

$$S_{10} = \frac{1}{\omega} \sum \left(\frac{di}{dt} \cdot v \right) \quad (42)$$

Observe that for ground loops, the current and the current subject to the derivative operation are not the same. Moreover, the apparent resistance and the current and current-derivative signals are different for Method 1 and Method 2.

Equations (36) through (42) define the new method. The calculations can be carried out for the faulted loop only. Alternatively, the calculations can be carried out for all six loops, and the resulting apparent R and X values can assist with faulted-loop selection.

Once the apparent resistance and reactance values are obtained, they are compared with the distance-element operating characteristic in protection applications (see Subsection IX.B). In fault-location applications, the apparent

reactance is compared with the total line reactance to obtain the fault location (the reactance fault-locating method).

Furthermore, the apparent R and X values can be substituted in (34) to compute the corresponding E value. However, it is more convenient to normalize the value of E with respect to the number of samples in the data window (W) and the nominal loop voltage (V_N), and use the following objective function, (43):

$$E_0 = \frac{\sqrt{\sum \left(v - R \cdot i - \frac{X}{\omega} \cdot \frac{d}{dt} i \right)^2}}{\sqrt{2} \cdot W \cdot V_N} \quad (43)$$

where V_N is the nominal system voltage for phase loops and the nominal system voltage divided by square root of 3 for ground loops.

The E_0 objective function informs us about the matching error in per unit of the nominal voltage. For example, $E_0 = 0.01$ means that the average voltage matching error across the entire window is only 1 percent of the nominal voltage.

The value of E_0 provides an indication of the security of the distance protection. When E_0 is close to zero, you can trust the calculated apparent R and X values when transients are concerned. Following this approach, you can use E_0 to enhance the security of distance protection (see Subsection IX.D).

V. WIDE-BAND DISTANCE-TO-FAULT METHOD

A. Distance to Fault

When we consider the instantaneous loop voltage and replica current in Subsection II.D, we can interpret measuring the distance to fault as a parameter-fitting problem. The apparent distance to fault m is a value that best fits the measured voltage to the voltage predicted from the current. In other words, m minimizes the following objective function, (44):

$$E = \int (v - m \cdot |Z_1| \cdot i_z)^2 dt \quad (44)$$

B. Wide-Band Implementation

With these discrete-time signals, we can rewrite the objective function (44) as in (45):

$$E = \sum (v - m \cdot |Z_1| \cdot i_z)^2 \quad (45)$$

We minimize this objective function by solving (46):

$$\frac{dE}{dm} = 0 \quad (46)$$

and we obtain the solution as in (47):

$$m_0 = \frac{1}{|Z_1|} \cdot \frac{S_4}{S_5} \quad (47)$$

where S_4 and S_5 are given by (31) and (32).

Equation (47) applied to distance protection continues a reactance comparator with the operating boundary perpendicular to the line impedance.

Once the per-unit distance to fault m_0 is obtained, the m value can be substituted in (45) to compute the corresponding

E value. Again, it is more convenient to normalize the value of E with respect to the number of samples in the data window (W) and the nominal loop rms voltage (V_N), and use the following objective function, (48):

$$E_0 = \frac{\sqrt{\sum (v - m \cdot |Z_1| \cdot i_z)^2}}{\sqrt{2} \cdot W \cdot V_N} \quad (48)$$

The E_0 objective function informs us about the matching error in per unit of the nominal voltage.

VI. EXAMPLES

To illustrate the presented methods, we use field-recorded single-line-to-ground (SLG) fault cases. We selected SLG faults because these faults often involve fault resistance and because the equations for the ground loop currents are more complex than those for the phase loop currents. We used the following four cases:

1. A metallic fault to illustrate that all methods yield the same results if no infeed effect is present.
2. A fixed-resistance fault to illustrate both the advantages of the polarized method and the impact of the infeed effect on the apparent-impedance methods.
3. An arcing high-resistance fault to illustrate the advantages of wide-band methods.
4. A fault on a line connecting unconventional sources (wind generation) and asynchronous condensers installed in a vicinity to illustrate the impact of current signal distortions.

The examples use records captured at 10 ksps with a 3 dB attenuation at 0.4 kHz. We use the zero-sequence current as the polarizing signal for ground faults.

We use an expanding data window that begins 2 ms after fault inception with an initial length of 0.25 cycle and continues to expand throughout the fault duration. In a 60 Hz system, the first result becomes available 6.1 ms after fault inception and is based on a window length of only 4.1 ms.

We used the line data (Z_1 , Z_0 , and line length) as specified in the relay settings. It is well known that these parameters may be slightly inaccurate and do not account for factors such as line transposition or seasonal variations in ground resistivity. Consequently, the examples presented here should not be considered fully controlled experiments. In addition to possible inaccuracies in the line parameters, the results are also affected by measurement errors of instrument transformers.

In the figures, we plot secondary voltages, currents, and impedances.

A. Metallic SLG Fault

A UHS relay [1] installed on a 345 kV, 118.6 mi line in a 60 Hz system tripped in 1.1 ms for a BG fault. Owing to the two-cycle breakers, the total fault duration was only 22.7 ms or 1.4 cycles. The best-known (true) fault location is 61.172 mi.

Fig. 3 shows the relay currents and voltages.

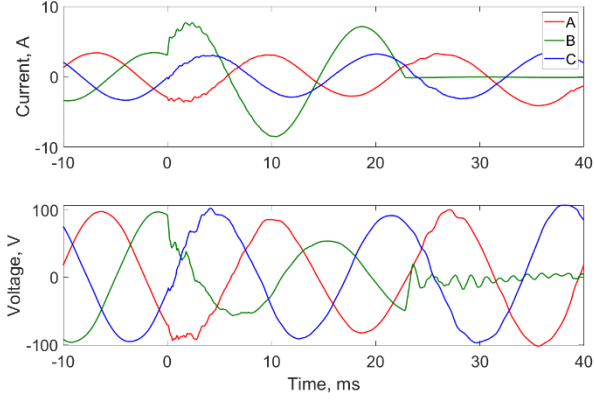


Fig. 3. Metallic BG fault: currents and voltages.

Fig. 4 plots the apparent resistance and reactance (R and X) obtained by using the apparent-impedance Method 1. For comparison, the dashed traces represent the phasor-based impedance components (R_{PH} and X_{PH}). The phasor-based method uses replica currents and the full-cycle Fourier phasor estimation (see [6] to understand the significance and differences between using the current and replica currents). The dotted traces represent the actual line impedance components between the relay location, and the fault point as per the best-known fault location and relay impedance settings.

As shown, the wide-band method settles in approximately 6 ms, whereas the phasor-based method requires about 18 ms to reach a steady value. Despite the difference in operating speeds, both methods converge to essentially the same impedance values, which closely match the impedance corresponding to the true fault location. The small discrepancies between the calculated and expected values can be attributed to inaccuracies in the line parameters as well as instrument transformer errors.

If we use the reactance for fault locating, the resulting fault-location error of the apparent-impedance Method 1 is approximately 1.1 percent of the line length. This level of error is consistent with the expected uncertainty associated with practical line impedance data accuracy and voltage and current measurement accuracy, indicating that the wide-band method achieves accuracy comparable to that of conventional phasor-based techniques while providing results significantly faster.

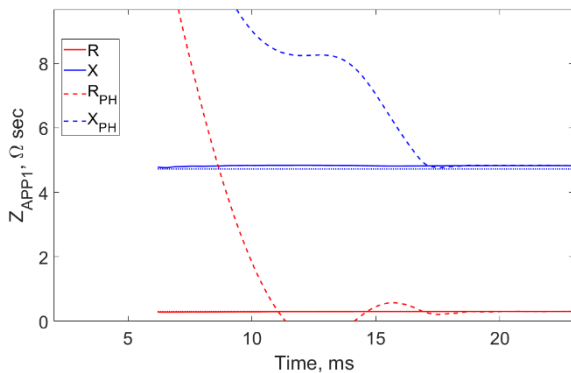


Fig. 4. Metallic BG fault: Apparent impedance—Method 1.

Fig. 5 plots the apparent reactance and resistance obtained by using the apparent-impedance Method 2. Again, the wide-band method settles considerably faster than the phasor-based method. Method 2 produces slightly different results because it defines apparent resistance and reactance differently from Method 1. If reactance is for fault locating, the apparent-impedance Method 2 yields a fault-location error of approximately 1.9 percent of the line length.

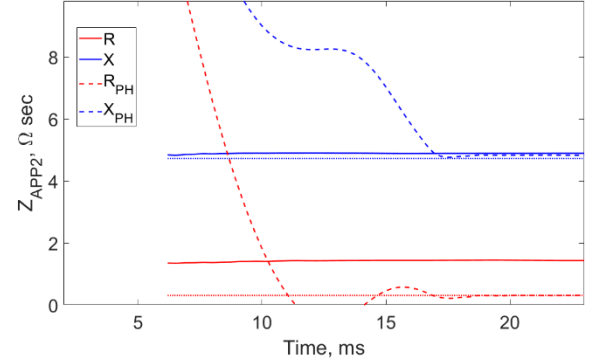


Fig. 5. Metallic BG fault: Apparent impedance—Method 2.

Fig. 6 plots the calculated distance to fault using the following methods:

- WB_{POL} : wide-band polarization-based method (Section III).
- WB_{DTF} : wide-band distance-to-fault method (Section V).
- WB_{X1} : reactance method based on wide-band apparent-impedance Method 1 (Subsection II.C.1) and Section IV.
- WB_{X2} : reactance method based on wide-band apparent-impedance Method 2 (Subsection II.C.2) and Section IV.
- PH_{POL} : phasor-based polarization method.

All methods converge to the true fault location, shown by the dashed black trace. The steady-state errors range from 0.5 to 1.9 percent of the line length. The wide-band methods settle in about one-third of the time required by the phasor-based method. The quick settling time of the wide-band methods allows fault locating using very short data windows. Also, it facilitates a distance protection element that is potentially twice as fast as the phasor-based distance element.

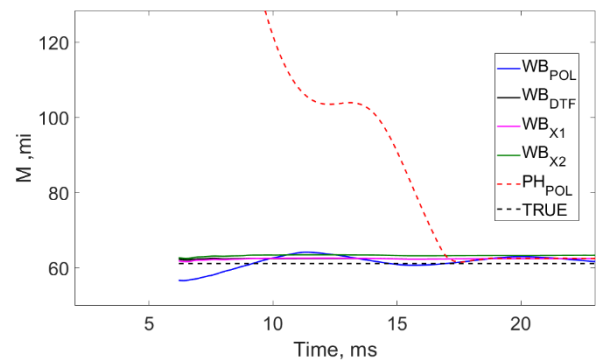


Fig. 6. Metallic BG fault: distance-to-fault values.

B. Resistive SLG Fault

A UHS relay [1] installed on a 230 kV, 123.65 km line in a 60 Hz system tripped in 2 ms for a CG fault. At the time of the fault, the relay was in evaluation mode and was not connected to the breakers. As a result, the fault lasted for several cycles. The best-known (true) fault location is 19.314 km.

Fig. 7 shows the relay currents and voltages.

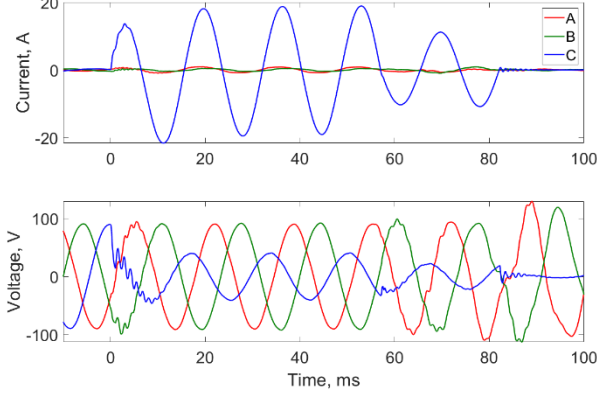


Fig. 7. Resistive CG fault: currents and voltages.

Note that, at approximately 57 ms after fault inception, a switching event occurred that resulted in changes in currents and voltages. As will be shown later, this transient affected the accuracy of the phasor-based methods.

Fig. 8 shows the polarizing current and the fault-point voltage calculated using the true fault location and the fault location obtained from the wide-band polarized method. The plot shows that the polarized method selected the fault location that aligned the fault-point voltage and the polarizing current. The true fault-point voltage is almost identical to the estimated fault-point voltage, indicating that the polarizing current (zero-sequence in this case) is an accurate polarizing quantity. The fault-point voltage is approximately 12 percent of the nominal voltage, showing that the fault is resistive.

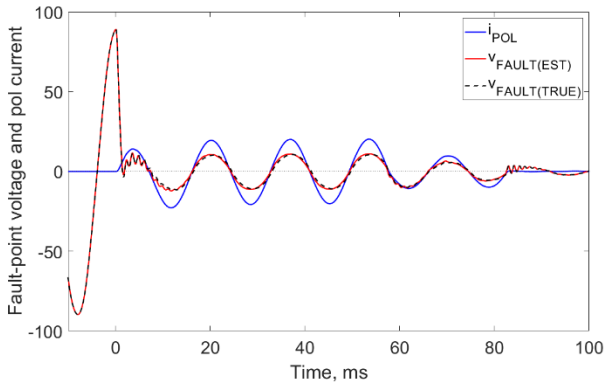


Fig. 8. Resistive CG fault: polarizing current and fault-point voltage.

Fig. 9 plots the objective function for the wide-band polarized method. The fault location is determined by maximizing the objective function. Note that the objective function exhibits a single, pronounced maximum, and the

method operated correctly given the accuracy of measurement, line data, and polarizing current.

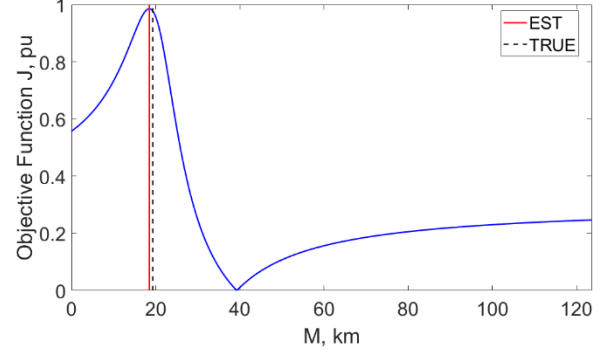


Fig. 9. Resistive CG fault: objective function for the wide-band polarized method.

Fig. 10 plots the apparent reactance and resistance obtained by using the apparent-impedance Method 1. As shown, the wide-band method settles in approximately 6 ms, whereas the phasor-based method requires about 23 ms to reach a steady value. Despite the difference in operating speeds, both methods converge to essentially the same impedance values. These values do not closely match the impedance (especially the resistance) corresponding to the true fault location. These differences are likely due to the infeed effect.

If we use the reactance for fault locating, the resulting fault-location error of Method 1 is approximately 1.5 percent of the line length.

Note that the transient at about 57 ms into the fault creates errors in the phasor-based measurements but not in the wide-band measurements.

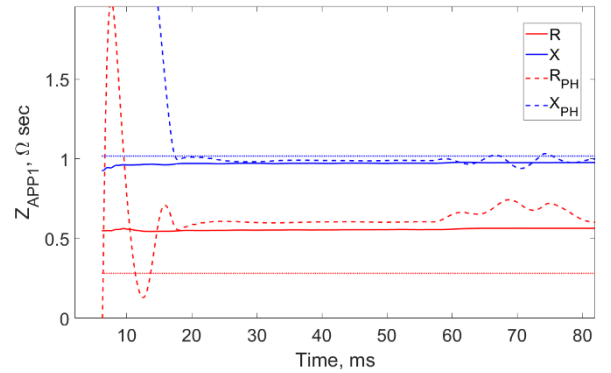


Fig. 10. Resistive CG fault: Apparent impedance—Method 1.

Fig. 11 plots the apparent reactance and resistance obtained by using Method 2. Again, the wide-band method settles considerably faster than the phasor-based method. If reactance is used for fault locating, Method 2 yields a fault-location error of approximately 1.4 percent of the line length. The apparent resistances in Methods 1 and 2 are different, because we formulated the methods by assuming different fault-path currents. The apparent reactances are close because they both measure the same distance to fault.

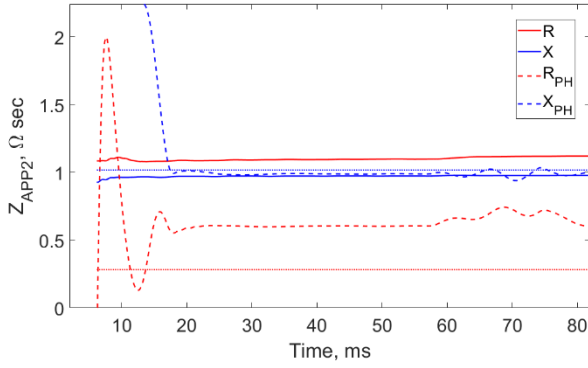


Fig. 11. Resistive CG fault: Apparent impedance—Method 2.

Fig. 12 plots the calculated distance to the fault using the methods of this paper. All methods converge to the same fault location. There is a systemic error between the true fault location and all of the methods, suggesting errors in the line impedance data. The steady-state errors range from 0.7 to 0.9 percent of the line length, despite the resistive nature of the fault and suspected line impedance inaccuracy. The wide-band methods settle in about one-third of the time required by the phasor-based methods.

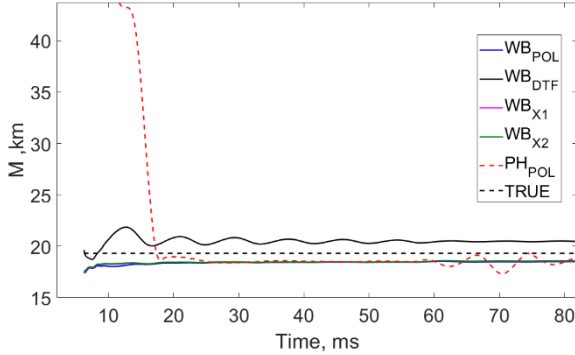


Fig. 12. Resistive CG fault: Distance-to-fault values.

C. Arcing High-Resistance Fault

We use a tree-contact fault case from [3]. A UHS relay [1] installed on a 230 kV, 68.99 mi line in a 60 Hz system recorded an arcing high-resistance BG fault. Fig. 13 shows the voltages and currents. The TW-based fault locator embedded in [1] did not report any results for this fault, most likely because of fault precursors and TW activity prior to the rise of the fault current.

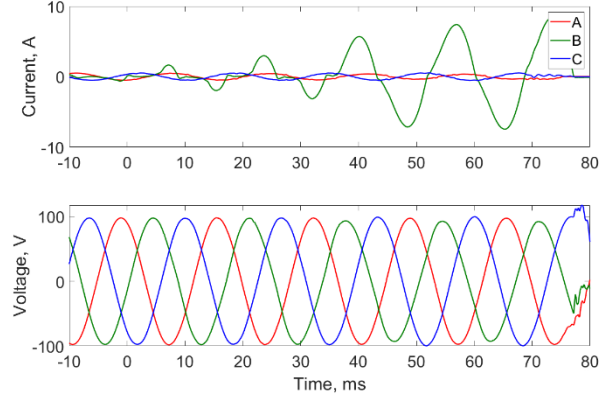


Fig. 13. Arcing BG fault: currents and voltages.

The B-phase current continues to gradually increase from the load level to the fault level. This pattern suggests that the fault path becomes more conductive with the passing of time, as is the case for a fault caused by a tree contact.

The utility reported the true fault location as 24.6 mi. The new double-ended fault-locating method [3] calculated 23.79 mi (an error of 1.1 percent of the line length).

A traditional phasor-based fault-locating method faces challenges for this fault. The phasors do not stabilize because the voltage and current phasors keep changing, and the high fault resistance adds the infeed challenge. The single-ended impedance-based method embedded in the relay [1] reported the fault location as 36.522 mi (an error of 17 percent of the line length).

Fig. 14 shows the polarizing current ($3 \cdot i_0$) and the fault-point voltage calculated using the true fault location and the fault location obtained from the wide-band polarization-based method. The plot shows that the wide-band method selected the fault location that aligned the fault-point voltage and the polarizing current. The true fault-point voltage is almost identical to the estimated fault-point voltage, indicating that the polarizing current (zero-sequence in this case) is an accurate polarizing quantity. The fault-point voltage decreases gradually as the fault-path current increases. Before the fault was cleared, the fault-point voltage remained as high as 60 percent of the nominal voltage. The fault-point voltage exhibits a rectangular waveform, consistent with the nonlinear arc resistance. During the first 30 ms of the fault, the voltage recovers to its pre-fault value when the arc extinguishes to drop again as the arc reignites. Fig. 14 illustrates the challenges this case poses for both distance protection and single-ended fault-locating methods.

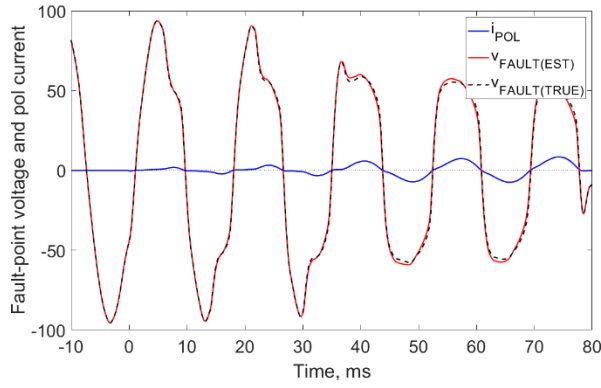


Fig. 14. Arcing BG fault: polarizing current and fault-point voltage.

Fig. 15 plots the apparent reactance and resistance obtained by using Method 1. As expected, the apparent resistance is very large. However, the apparent reactance settles very quickly and is several times closer to the true value than the phasor-based apparent reactance. Given that the positive-sequence line impedance is 10.6Ω , the Zone 1 distance protection reach would be likely set at about 8Ω . The apparent impedance falls below 8Ω about 10 ms after fault inception, creating an opportunity for fast and dependable distance protection. At that time, however, the apparent resistance remains very high, and the distance element would require a nontraditional method to distinguish between fault and load conditions (see Subsection IX.C).

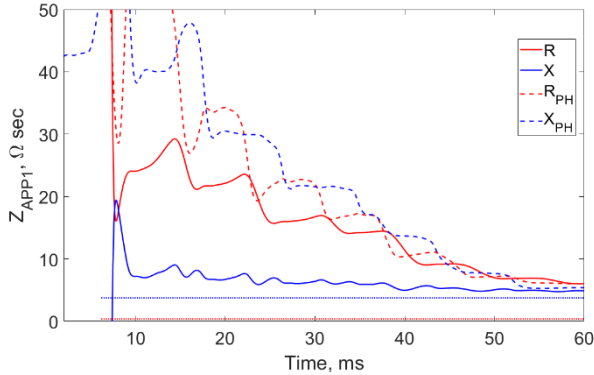


Fig. 15. Arcing BG fault: Apparent impedance—Method 1.

Fig. 16 plots the apparent reactance and resistance obtained by using Method 2. Similarly to Method 1, the apparent reactance settles very quickly and is several times closer to the true value than the phasor-based apparent reactance. Note that the apparent resistance is different than in Method 1. In general, the phasor-based apparent resistance, and the Method 1 and 2 apparent resistances, are different because they all use different currents to represent the fault-path current.

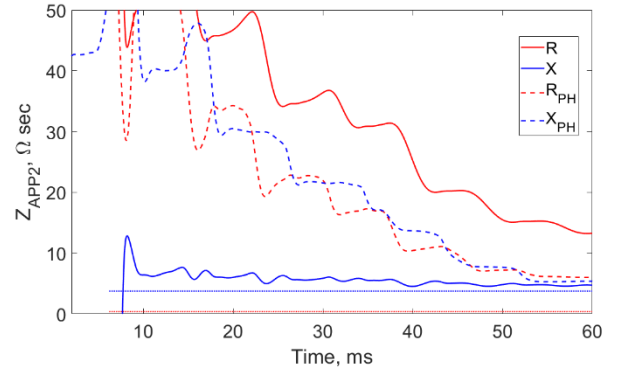


Fig. 16. Arcing BG fault: Apparent impedance—Method 2.

As seen in Fig. 14, the wide-band polarized method finds the fault location that closely aligns the fault-point voltage with the polarizing current. When using the entire fault interval, the method yields a fault location of 23.124 mi, corresponding to an error of 2.1 percent (compared with the 17 percent error of the single-ended fault locator embedded in the relay).

D. Fault Near an Unconventional Source

A UHS relay [1] installed on a 345 kV, 70.4 mi line in a 60 Hz system tripped in 11.4 ms for an AG fault. Significant wind generation and synchronous condensers are present in the vicinity of the line. The best-known (true) fault location is 65.698 mi. The single-ended impedance-based fault locator embedded in the relay operated with an error of 13 percent of the line length.

Fig. 17 shows the relay currents and voltages. The significant inflection in the zero-sequence current corresponds to the remote breaker operation approximately 24 ms after fault inception (the remote record not shown). As will be shown later, this transient affected the accuracy of the phasor-based methods.

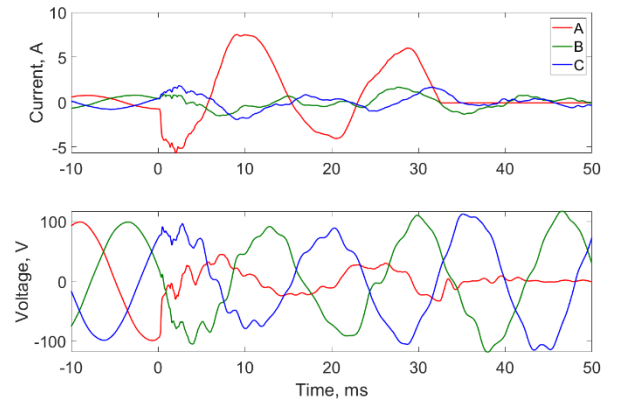


Fig. 17. AG fault near an unconventional source: currents and voltages.

Fig. 18 shows the polarizing current and the fault-point voltage calculated using the true fault location and the fault location obtained from the wide-band polarization-based method. The plot shows that the wide-band method selected the fault location that aligned the fault-point voltage and the polarizing current. The true fault-point voltage is almost

identical to the estimated fault-point voltage, indicating that the polarizing current (zero-sequence in this case) is an accurate polarizing quantity. The fault-point voltage is approximately 6 percent of the nominal voltage, showing that the fault has a small resistance. Note that after about 24 ms into the fault, the fault-point voltage got reduced as a result of the remote breaker opening and removing the remote infeed current.

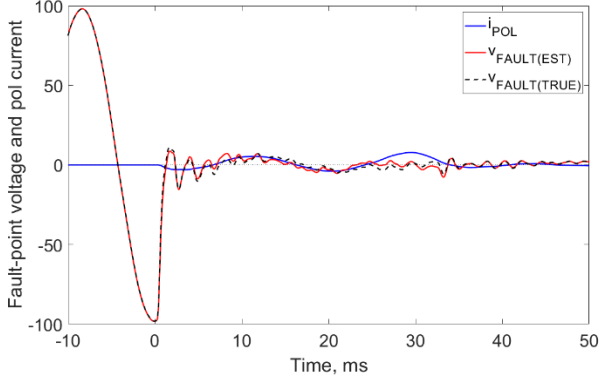


Fig. 18. AG fault near an unconventional source: polarizing current and fault-point voltage.

Fig. 19 plots the apparent reactance and resistance obtained by using Method 1. As shown, the wide-band method settles in approximately 6 ms, whereas the phasor-based method requires about 18 ms to reach a steady value. Despite the difference in operating speeds, both methods converge to essentially the same impedance values. These values do not closely match the impedance corresponding to the true fault location. These differences are likely to be due to inaccuracies in the line impedance data.

If we use the reactance for fault locating, the resulting fault-location error of Method 1 is approximately 5.7 percent of the line length (compared with 13 percent error in the single-ended method embedded in the relay).

Note that the transient at about 24 ms into the fault creates additional small errors in the phasor-based measurements but smaller than in the wide-band measurements.

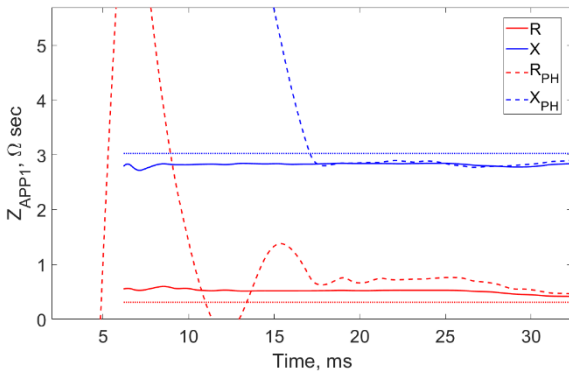


Fig. 19. AG fault near an unconventional source: Apparent impedance—Method 1.

Fig. 20 plots the apparent reactance and resistance obtained by using Method 2. Again, the wide-band method settles considerably faster than the phasor-based method. If reactance

is used for fault locating, Method 2 yields a fault-location error of approximately 4.9 percent of the line length. The apparent resistances in Methods 1 and 2 are different, because we formulated the methods by assuming different fault-path currents.

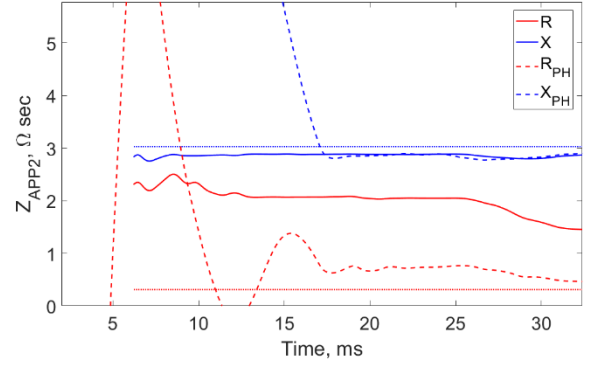


Fig. 20. AG fault near an unconventional source: Apparent impedance—Method 2.

Note that after approximately 24 ms, the apparent resistances measured by all three methods decrease because the remote infeed current is removed.

VII. INFEEED EFFECT

This section explains the infeed effect, highlights the differences between the phasor-based and the two wide-band apparent-impedance methods, and shows why the wide-band methods are less susceptible to the infeed effect during high-resistance faults.

A. Traditional Phasor-Based Method

During resistive faults, the loop voltage (V) is a function of the loop current (I); we use phasors for the ease of analysis, (49):

$$V = m \cdot Z_1 \cdot I + V_F \quad (49)$$

Assuming a constant fault resistance R_F , the apparent impedance is, (50):

$$Z_{APP} = \frac{V}{I} = m \cdot Z_1 + R_F \frac{I_F}{I} \quad (50)$$

The second term on the right-hand side of (50) represents the error term added to the correct impedance value. This error depends on the ratio of the fault-path current to the loop current. These currents are not necessarily in phase, causing the imaginary component of the apparent resistance to affect the apparent reactance measured by the relay. In other words, the traditional phasor-based method assumes that the same current flows through both the line impedance and the fault path. Because this assumption is not valid, the method introduces errors in both the apparent reactance and resistance.

B. Wide-Band Method 1

Neglecting the line resistance, the time-domain fault-loop voltage equation in (8) contains two distinct components: a current-derivative term associated with the line reactance and a

current term associated with the fault resistance. The wide-band method exploits this distinction when estimating the apparent reactance and resistance. Specifically, the fault resistance influences the voltage via the current itself, whereas the line reactance influences the voltage via the current derivative. Because the method relies on the instantaneous shapes of the voltage and current signals, this difference in the voltage contributions from the reactance and resistance becomes particularly advantageous.

To illustrate, consider a sinusoidal current and its corresponding voltage. When the current crosses zero, its derivative reaches its maximum. At that instant, the voltage is influenced primarily by the apparent reactance. Conversely, when the current reaches its peak value, its derivative is zero. At that instant, the voltage is influenced primarily by the apparent resistance. By matching the instantaneous voltage and current values over a time interval to obtain the best-fit estimates of the apparent resistance and reactance, the method effectively views the problem through two complementary lenses. This separation of the resistance- and reactance-related contributions improves the accuracy and robustness of the estimation process. When the signals are distorted with low-frequency components, such as during faults near IBRs, the relative levels of the current and current derivative change even more often than every quarter of a cycle, allowing the method to probe the reactance and resistance over time.

C. Wide-Band Method 2

Comparing (9) and (15) shows that Method 2 neglects the voltage drop across the line resistance and approximates the fault-path current using the zero-sequence component (the polarizing current, generally speaking). Because this component is in phase with the fault-path current, the apparent resistance remains purely resistive and does not acquire an imaginary component. As a result, Method 2 yields a more accurate apparent reactance measurement.

Method 2, just like Method 1, uses both the current and its derivative to match the measured voltage. In addition, the currents associated with the line reactance and the fault resistance differ significantly, which changes the nature of the infeed effect. The method reduces the infeed error because the current associated with the fault resistance provides a closer approximation of the fault-path current. Consequently, the infeed effect is substantially less severe than in the traditional phasor-based method.

Effectively, Method 2 resembles the polarized method, but it does not explicitly use the phase (polarity) information of the polarizing current.

VIII. ADVANTAGES AND KEY CHARACTERISTICS

The wide-band methods offer several useful characteristics and advantages, as follows.

A. Wide-Band Operation and Interference

The methods solve the RL differential equation that describes the line. As a result, they extract the distance-to-fault information not only from the fundamental frequency voltages

and currents, but also from a frequency band around the fundamental frequency. This wide-band operation improves accuracy in systems with IBRs, because the off-nominal frequency components support the method rather than degrade the result, as they do in phasor-based methods.

Because the voltage drop across the faulted line segment is proportional to the replica current, the loop voltage and loop replica current exhibit similar frequency content and transients. Similar transients cancel each other when measuring the distance to fault or apparent impedance, compared with using voltage and current directly. See [6] for further discussion.

B. Independence From Frequency Measurement

The new methods operate directly on sampled signals and do not require frequency measurement. By avoiding frequency tracking, they eliminate errors caused by off-nominal frequency and tracking lag. This advantage is especially important in low-inertia systems, where frequency may change rapidly and tracking algorithms may lag or produce transient errors due to voltage angle jumps.

The methods effectively measure inductance, rather than reactance, and therefore remain insensitive to off-nominal system frequency.

C. Fast Measurement

The new methods settle very rapidly, in less than half a power cycle. This performance is achieved by using the underlying physics of the process, namely the RL differential equation, to measure the relatively constant values of R and L. By contrast, phasor-based methods measure the magnitudes and angles of the fundamental-frequency signals and theoretically require one cycle of data for accurate measurement. Although this time can be reduced to less than one cycle when protection margins are available (see variable-window phasors in [1]), fault-locating accuracy requirements necessitate an observation period longer than one cycle [3]. The presented wide-band methods can be applied both as accurate fault locators and as fast distance elements.

D. Convenient Data Window

The methods improve accuracy and suppress noise by using data windows, similar to phasor filtering. However, they do not require window lengths equal to integer multiples of a cycle, and they do not require frequency-dependent window length adaptation. The window can expand after a disturbance to use all data between fault inception and the opening of the first breaker pole. Longer windows improve accuracy, while shorter windows enable faster operation. Unlike phasor-based methods, the new methods attenuate transients by using the RL equation that reflects the physics of a power line, and as a result their outputs stabilize faster than phasor-based methods.

Additionally, the methods do not require a continuous data window. For example, samples from time intervals when the CTs are saturated can be removed from the windows.

IX. NEW APPROACH TO DISTANCE PROTECTION

Our examples show that the wide-band apparent-impedance Methods 1 and 2 allow the apparent reactance to settle much

faster and much closer to the true value than the phasor-based apparent reactance. This behavior creates an opportunity for faster and more dependable distance protection.

However, the apparent-impedance methods can measure large apparent resistance values during resistive faults. In this context, especially for Method 2, apparent resistance acts as an additional degree of freedom that improves the speed and accuracy of the apparent reactance measurement. Of course, apparent resistance does not represent the physical fault resistance, regardless of the apparent-impedance calculation method.

Fig. 21 shows a simplified logic diagram of the proposed distance element logic, while the following subsections describe its operation in greater detail. The method is suitable for an underreaching directly tripping zone (Zone 1) applied to two-terminal lines.

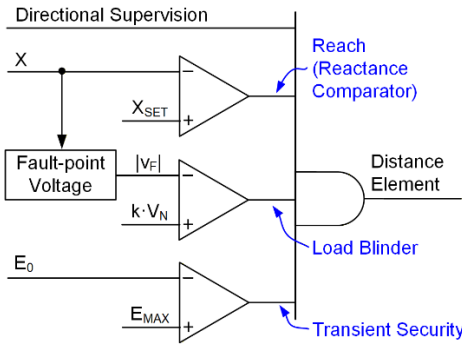


Fig. 21. Simplified distance element logic.

A. Directional Supervision

Because the proposed operating characteristic is effectively quadrilateral, the logic requires explicit directional supervision. Any suitable directional element typically used in quadrilateral distance protection may be applied for this purpose.

B. Reactance Comparator

Because the apparent reactance carries the distance-to-fault information, the proposed element uses a reactance comparator that asserts when the apparent reactance, X , is less than the reach setting, X_{SET} . The reach setting must include a security margin, including the infeed effect. However, the infeed effect, when using the wide-band Method 2, is much smaller than in the case of a traditional apparent-impedance method.

C. Load Blinder

Fig. 14 inspires a different approach for distinguishing load conditions from high-resistance fault conditions. We offer the following logic:

- Use the apparent reactance to determine the per-unit distance to fault.
- Determine the fault-point voltage using the per-unit distance to fault and (1).
- Supervise the distance element with an undervoltage element that responds to the fault-point voltage.

The undervoltage element can be set at 80 percent ($k = 0.8$) of the loop nominal voltage (V_N), consistent with typical line

loadability requirements. Referring to Fig. 14, an undervoltage element based on the fault-point voltage would assert about 40 ms after fault inception. At that time, the Method 1 and 2 apparent reactance is within the Zone 1 reach, and such a new distance element would have operated. By comparison, 40 ms into the fault, the apparent reactance of the phasor-based element is well above the Zone 1 reach.

We can use phasors to analyze and better understand the new method for distinguishing between the load and fault conditions (load blinder logic). The undervoltage element acting as the load blinder logic operates if, (51):

$$|V - m \cdot Z_1 \cdot I| < k \cdot V_N \quad (51)$$

where $||$ stands for signal magnitude and m is the distance to fault obtained using the reactance method, (52):

$$m = \frac{X}{X_1} \quad (52)$$

We rewrite (51) and obtain (53):

$$\left| \frac{V}{I} - m \cdot Z_1 \right| < k \cdot \frac{V_N}{|I|} \quad (53)$$

Equation (53) describes a circle on the (V/I) plane with the center at the fault location ($m \cdot Z_1$) and the radius inversely proportional to the loop current.

Fig. 22 plots these circles for a range of fault locations on the V/I plane. The resulting line (the red trace) separates the fault region from the load region and represents the locus of constant fault-point voltage magnitude. The division between the fault and load regions depends on the fault location, m , as estimated by the distance element that is ready to operate, and on the present value of the loop current. Depending on the loop current magnitude, the division boundary depends on the remote current infeed, fault resistance, and the local system source-to-line impedance ratio (SIR).

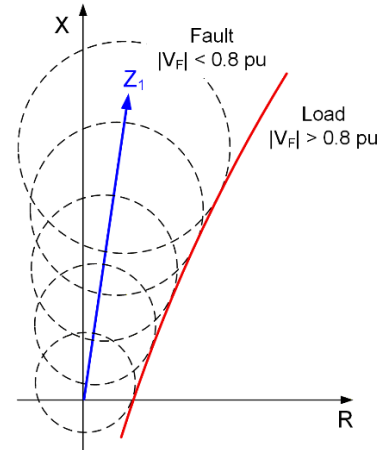


Fig. 22. Illustration of the proposed load blinder logic on the V/I impedance plane (V_F —fault-point voltage).

Do not confuse the $V - IZ$ expression in (51) with the distance element operating signal. The load blinder logic uses the $V - IZ$ expression and requires its magnitude to remain below a specified threshold. In contrast, a larger distance element operating signal indicates more favorable operating conditions.

The key difference is that the distance operating signal contains the element reach, Z , whereas (51) contains the actual fault location, $m \cdot Z$.

D. CCVT and Transient Security Logic

CCVTs are known to introduce significant transient voltage errors that can compromise the security of distance elements, particularly in weak (high SIR) systems. Other transient phenomena may also affect security.

To improve security, we propose using the quality-of-fit index, E_0 , defined in (43), as a confidence measure that must be satisfied before the distance element is permitted to operate. The threshold E_{MAX} is a user-defined value that specifies the maximum acceptable mismatch between the calculated apparent impedance and the measured signals.

X. PERFORMANCE TESTED ON FIELD CASES

We have tested the new method by using 214 fault records captured in the field at 10 ksp/s for internal faults on two-terminal overhead lines. These lines vary in length (3.85 mi to 352.58 km), voltage (115 kV to 345 kV), frequency (50 Hz and 60 Hz), and voltage transformers (CCVTs and magnetic VTs). Because the input signals already reflect all practical error sources (instrument transformers, relay inputs, fault resistance, line impedance, line transposition, line charging current, and so on), these test results are highly relevant and informative. To calculate the fault-locating error, we used the utility-confirmed (“true”) fault location. If we did not have a confirmed fault location from the utility, we used the TW-based fault-locating results after carefully reviewing and fine-tuning them.

We re-used the same fault case set as in [3] for the double-ended method and added several new cases. Because here we use records from both line terminals independently, the total number of cases available to us has effectively doubled. For reference, the double-ended method in [3] achieved an average error of 1.1 percent and a maximum error of 6.9 percent of the line length.

Single-ended methods can produce large location errors when the assumptions underlying their derivation are violated. For example, significant errors may occur in nonhomogeneous power systems. To better assess the accuracy of the evaluated methods, we excluded cases with errors exceeding 10 percent of the line length from the average error calculations. Table II summarizes the results obtained with all four methods. We use the fault locating results at 1.4 cycles into the fault.

We summarize the results as follows:

- All four methods exhibit similar performance, with a median error of approximately 3.5 percent of the line length and an average error ranging from 4.3 to 7 percent. These error levels are consistent with those expected from single-ended fault-location methods in the presence of instrument transformer errors, line impedance data errors as well as the errors resulting from violating the method assumptions, such as system homogeneity.
- The apparent-impedance methods slightly outperformed the polarized method. Specifically, the apparent-impedance methods produced approximately half as many

outliers (13 and 17 cases) as the polarized method (30 cases).

- We attribute the higher error and a larger number of outliers observed with the polarized method to inaccuracies in the polarizing current. These inaccuracies result from system nonhomogeneity, including the presence of external series capacitors and asymmetric metal-oxide varistor operation during faults. Zero-sequence, negative-sequence, and incremental currents provide effective polarizing signals when the fault is the only source of system unbalance. However, when additional sources of unbalance are present, such as asymmetric capacitor-bypass operation, these quantities no longer provide accurate polarizing signals.
- After removing the outliers, all methods exhibit comparable performance, with average and median errors of approximately 3.5 percent. This result is consistent with a simplified error-bound estimate based on a cumulative error of 1 percent in each voltage measurement, current measurement, and line impedance data.

TABLE II
WIDE-BAND METHODS—TEST RESULTS
ERROR (PERCENT OF LINE)

	Polarized Method	App. Imp. Method 1	App. Imp. Method 2	Distance-to-Fault Method
All cases				
Median	3.66	3.58	3.27	3.55
Average	6.95	4.29	4.21	5.09
Outliers (error greater than 10 percent)				
Case count	30	13	17	21
After removing outliers				
Median	3.09	3.34	2.87	3.08
Average	3.33	3.49	3.28	3.42

XI. SUMMARY AND CONCLUSIONS

This paper addresses limitations of impedance-based fault locating in UHS tripping applications and in transmission lines near IBRs. In UHS applications, very short fault durations prevent phasors from settling, leaving little or no reliable phasor data for conventional phasor-based methods. In IBR-dominated networks, small fault currents and pronounced transients further degrade the performance of phasor-based methods. Together, these conditions challenge both accuracy and dependability of phasor-based distance protection and fault locating.

To overcome these limitations, the paper introduces four wide-band methods that are based on the line RL differential equation. By operating directly on instantaneous voltages and currents, the methods extract the distance-to-fault information from a frequency band rather than relying solely on the fundamental-frequency component. The first method uses polarization and improves accuracy for resistive faults. Two other methods use an apparent-impedance formulation and

avoids explicit polarization but uses a polarizing current to represent the voltage drop across the fault branch. The fourth method obtains the apparent distance-to-fault value that best fits the measured voltage to the voltage predicted from the current assuming zero fault-point voltage.

The new methods provide several practical advantages. Working with a frequency band, these methods do not need to filter out the near-nominal frequency transients but benefit from the presence of these transients. This improves performance in IBR applications. They do not require frequency measurement and therefore avoid errors related to off nominal frequency and tracking delays. Their use of replica current aligns transient behavior between the voltage and the replica current, enabling transient errors to cancel and enhance measurement accuracy. In addition, flexible data windows allow operation over very short intervals for UHS applications or longer intervals for improved accuracy, without the need for frequency tracking. Further, all methods allow calculating quality indices that can be used to assess accuracy in fault-locating applications and allow adaptive security in distance protection applications.

The presented methods serve both as distance elements and as single-ended fault locators, providing a practical and reliable alternative to phasor-based methods in modern power systems characterized by UHS fault clearance and high penetration of IBRs.

XII. REFERENCES

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XIII. BIOGRAPHIES

Bogdan Kasztenny has 35 years of experience in power system protection and control. In his decade-long academic career (1989–1999), Dr. Kasztenny taught power system and digital signal processing courses at several universities and conducted applied research for several relay manufacturers. In 1999, Bogdan left academia for relay manufacturers where he has since designed, applied, and supported protection, control, and fault-locating products with their global installations numbering in the thousands. Bogdan is an IEEE Fellow, an IET Fellow, a Senior Fulbright Fellow, a Distinguished CIGRE Member, and a registered professional engineer in the province of Ontario. Bogdan has served as a Canadian representative of the CIGRE Study Committee B5 (2013–2020) and on the Western Protective Relay Conference Program Committee (2011–2020). In 2019, Bogdan received the IEEE Canada P. D. Ziogas Electric Power Award. Bogdan earned both the PhD (1992) and DSc (Dr. habil., 2019) degrees, has authored over 250 technical papers, and holds over 60 U.S. patents.

Greg Smelich earned a BS in mathematical science and an MS in electrical engineering in 2008 and 2011, respectively, from Montana Tech of the University of Montana. Greg then began his career at Schweitzer Engineering Laboratories, Inc. (SEL) as a protection application engineer in the Sales and Customer Service division. In 2016, he transitioned to the Research and Development division as a product engineer, where he now helps guide product development and provides training and technical support primarily related to time-domain technology. He has coauthored several technical papers and application guides on various topics related to power system protection and fault locating. He has been a certified SEL University instructor since 2011 and an adjunct professor in the electrical engineering department at Montana Tech since 2017. Greg is a Senior Member of IEEE and a registered professional engineer in the state of Washington.