Zero-Setting Broken Conductor Detection Method Using Local Measurements Only

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Abstract—**Delayed detection of a conductor break in power lines can result in high-impedance faults (HIFs). These faults are difficult to detect and pose safety risks. This paper proposes a simple, single-ended method to detect an open-phase condition anywhere within the length of the protected line. The detection allows the intelligent electronic device (IED) to de-energize the line before the conductor touches the ground, causing a fire or a personnel safety hazard. The proposed method is based on a unique relationship between the positive-, negative-, and zero-sequence currents at the conductor break location. To use this relationship accurately, the algorithm uses charging current compensation to obtain the positive-sequence current at the point of break. The proposed method does not require any settings from the user and it is not affected by system voltage, line charging current, or line and source impedances. The validity of the proposed method is proven using field events. The paper also describes an open-phase detection method for distribution feeders with multiple laterals. The application and validity of the method is detailed using a simulated event at the distribution level.**

I. INTRODUCTION

Open-phase (or broken conductor) detection is rapidly gaining importance in the power system protection domain because of the adverse impacts that a conductor break may have on the power system and safety. In transmission and subtransmission systems, a phase is composed of a single conductor or a bundle of conductors carrying phase current. Conductors in power systems undergo aging that makes them susceptible to damage and a consequent break [1] [2]. When a conductor breaks mechanically, series arcing might start at the point of break, which may extinguish in a few power system cycles or may take longer than half a second [3] [4] [5]. After this happens, the conductor may remain hanging in the air or may fall to the ground, creating a low- or high-impedance fault. Low-impedance shunt faults can cause high stresses on the conductor(s) due to high currents flowing through them. Autoreclosing may close multiple times on a permanent fault until lockout, causing the system to be under stress for an extended amount of time [6]. High-impedance faults (HIFs) can occur when the broken conductor falls onto a high-impedance surface or object. HIFs are hard to detect [7]. These faults, if left undetected, can cause fires resulting in significant equipment damage and pose a risk to safety [8].

The power industry uses a variety of methods devised for detection that use various current- and/or voltage-based relationships during an open-phase event to detect the break. Traditional open-phase detection methods use unbalanced currents to detect an open-phase condition. Various methods can be used to compute the unbalanced quantity. Some methods use the ratio of negative-sequence current (I_2) to positive-sequence current (I_1) or zero-sequence current (I_0) to I_1 [9]. Some other methods calculate unbalance using the difference between phase currents [10]. These methods suffer from misoperations and sometimes may fail to operate during an open-phase event. Detecting open-phase events using unbalance can be challenging due to multiple factors.

At the transmission level, scenarios can occur in which the total zero-sequence impedance may be much less than three times the total positive-sequence impedance, which must be correctly accounted for while setting the unbalance detection threshold. Charging current is another factor that can influence the unbalance computation and make it difficult to detect a break during low-load conditions [5]. Asymmetrical shunt faults may also result in an unbalance value similar to that of a broken conductor, making it difficult to differentiate between the two. A time-delayed operation may help alleviate this problem; however, it introduces undesired delays in the broken conductor detection process.

At the distribution level, load unbalance is quite common on the system and it can be high enough to satisfy the current unbalance check and assert the open-phase detection logic. A broken conductor event may occur on a lateral carrying a low-load current and the unbalance created by the event can be below the threshold for detection, causing dependability issues.

The conditions previously mentioned make unbalance-based open-phase detection techniques unsuitable for general use in distribution systems. However, due to the industry's heavy reliance on unbalance-based methods for broken conductor detection, it is important to develop techniques that eliminate some of the issues brought about by using unbalance.

The quest to avoid the use of unbalance for open-phase detection has led to the development of other detection methods in the past few years. The charging current method [5] works well for transmission systems, except for open-phase conditions with low-charging current. This method requires knowing the total line charging current or the positive-sequence line susceptance, which may not always be available to the user. Falling conductor protection (FCP) is another notable method that uses data from synchrophasors to analyze voltages at system nodes to detect a broken conductor event [11]. This method requires phasor measurement unit (PMU) devices in the system and is dependent on the reliability of the communications system in place. For achieving more coverage, more PMU devices are required, making it an expensive detection method. Fast-acting voltage control devices may have adverse effects on the logic, making break detection more difficult. Another synchrophasor-based method requires both current and voltage data to compute the observed impedance change ratio (ICR). It triggers if the ICR observed is more than a certain threshold value [12]. Low-load currents can reduce the dependability of this detection method. Other abnormal conditions may also cause the logic to misoperate if proper blocking mechanisms are not in place. This method recommends using PMUs and setting the trigger threshold based on a load-flow study, which is difficult if one wants to adopt the method for an already existing system or if the topology of the system changes often. Similar to the previous method, more PMU devices are required to improve coverage, making it a less cost-effective method. In addition, its reliability is dependent on the reliability of the communications system. Various open-phase detection methods and their limitations have been detailed in [3].

Taking into account the previous challenges, a simple, single-phase, open-phase detection logic was developed that does not rely on a communications system for data. Instead, it uses only local measurements. This method does not require line parameters or system topology information for implementation, it does not require any setting, and is easy to adopt.

The remainder of this paper is structured as follows: Section II introduces the theory behind open-phase fault detection with and without line charging current compensation, with an emphasis on the need for charging current compensation. Section III describes the proposed algorithm for detecting single-phase conductor breaks using charging current compensation and includes a shunt fault detection logic to block the method. Section IV expands on the results for various field events using the proposed method. Section V describes an algorithm that could be used for radial distribution systems, which does not involve charging current compensation. The application is presented using a simulated event. Section VI provides a summary of the paper.

II. ANALYSIS OF AN OPEN PHASE IN A POWER LINE

A. Sequence Network for an Open-Phase Condition in a Power Line

Fig. 1 depicts a generic Phase A broken conductor event in a power line that is connecting two sources of a power system, assuming an ABC rotation. The phase break is at a distance *m* from Bus S. Z_{1S}, Z_{1L}, and Z_{1R} represent the positive- and negative-sequence impedances of the source behind Bus S, the power line, and the source beyond Bus R, respectively. Z_{0S}, Z_{0L}, and Z_{0R} represent the zero-sequence impedance of the source behind Bus S, the line, and the source beyond Bus R, respectively.

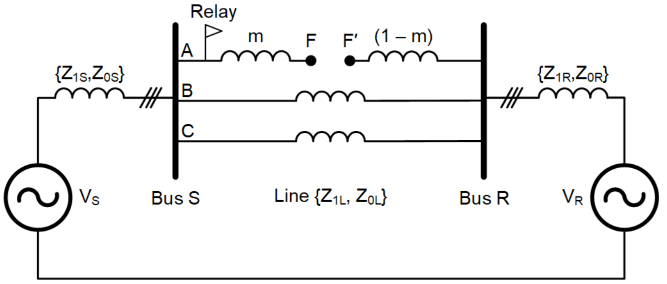


Fig. 1. Phase A conductor break on a power system.

For further insight into the event in Fig. 1, sequence component analysis of the event was performed. This helps to understand the relationship between the sequence currents at the conductor break location. Fig. 2 illustrates the sequence network for the Phase A broken conductor event in Fig. 1 [13]. In this figure, I_{1L}, I_{2L}, and I_{0L} are the positive-, negative-, and zero-sequence currents measured by the relay and flowing into the network. From Fig. 2, the relationship between the sequence currents is:

$$\frac{I_0 + I_2}{I_1} = -1 \tag{1}$$

The expression on the left side of (1) is independent of line and source impedances.

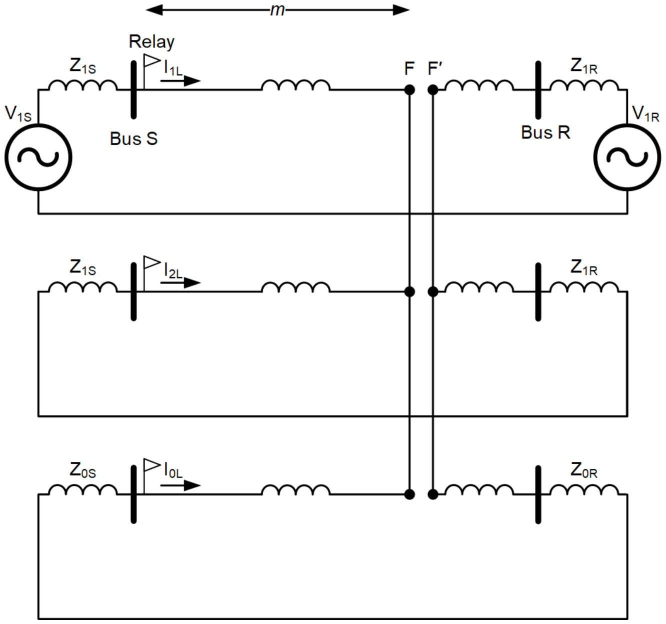


Fig. 2. Sequence network for a broken conductor event in Phase A.

Equation (1) is for a power line without considering the shunt capacitances of the line. Section B derives a similar expression for a broken conductor event in Phase A; however, it contains the inclusion of line capacitances. Section C explains the need to include the shunt capacitances of the line.

B. *Expression for an Open-Phase Condition With the Inclusion of Line Capacitances*

Fig. 3 shows an overhead line with distributed shunt capacitances and with an open Phase A at a distance *m* from Bus S.

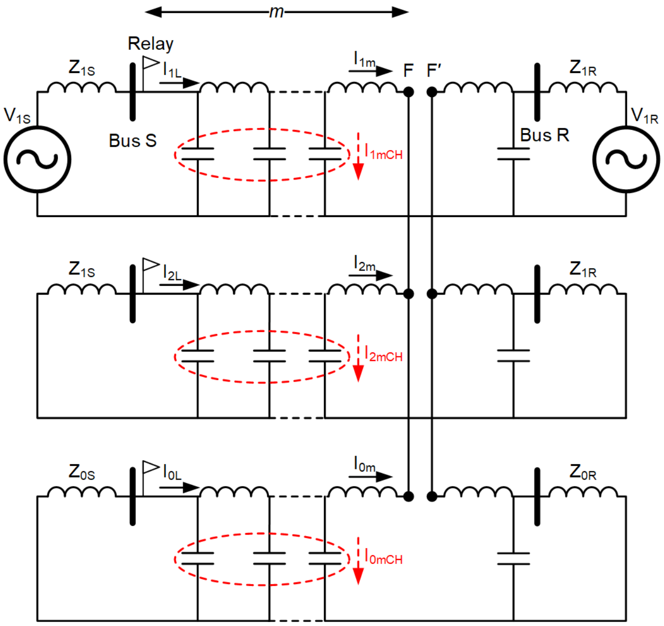


Fig. 3. Sequence network for a broken conductor event in Phase A with line capacitances.

Applying Kirchhoff's current law at the open-phase location *m* results in:

$$\frac{I_{2mL}+I_{0mL}}{I_{1mL}}=-1 \tag{2}$$

Replacing the sequence currents at location F in terms of their respective network charging currents and the currents at the local relay, we get:

$$\frac{\left(I_{2L}-I_{2mCH}\right)+\left(I_{0L}-I_{0mCH}\right)}{\left(I_{1L}-I_{1mCH}\right)}=-1 \tag{3}$$

During an open-phase event, all phase voltages are expected to be balanced. This condition results in insignificant negative- and zero-sequence voltages and thus, negligible shunt capacitance currents in the corresponding networks. Therefore, neglecting I_{2mCH} and I_{0mCH} in (3), we get:

$$\frac{I_{2L}+I_{0L}}{\left(I_{1L}-I_{1mCH}\right)}\approx-1 \tag{4}$$

For close-in broken conductor faults, I_{1mc}H in (4) can be small; therefore, the relay measured angle of I_{1mCH} can be inaccurate. However, we know that the positive-sequence relay voltage is healthy and I_{1mCH} should lead that voltage by 90°. Therefore, knowing that the relay measured angle of positive-sequence voltage is accurate, the same is used to define the angle of I_{1mCH}, as expressed in (5).

$$\frac{I_{2L}+I_{0L}}{\left(I_{1L}-\left|I_{1mCH}\right|\bullet e^{j(\angle V_1+90°)}\right)}\approx-1 \tag{5}$$

Simplifying $\left|I_{1mCH}\right|$ in terms of phase currents:

$$\left|I_{1mCH}\right|=\frac{I_{AmCH}+I_{BmCH}\bullet e^{j(120°)}+I_{CmCH}\bullet e^{j(-120°)}}{3} \tag{6}$$

Knowing that the charging currents in all three phases until the open-phase location *m* are balanced, we can replace I_{BmCH} and I_{CmCH} in (6) with $I_{AmCH}\bullet e^{-j120°}$ and $I_{AmCH}\bullet e^{j120°}$, respectively. Next, $\left|I_{1mCH}\right|$ can be further simplified as:

$$\left|I_{1mCH}\right|=\left|I_{AmCH}\right| \tag{7}$$

Substituting the value of $\left|I_{1mCH}\right|$ into (5), we get:

$$\frac{I_{2L}+I_{0L}}{\left(I_{1L}-\left|I_{AmCH}\right|\bullet e^{j(\angle V_1+90°)}\right)}\approx-1 \tag{8}$$

In (8), all of the variables, except $\left|I_{AmCH}\right|$, are known to the relay. To determine $\left|I_{AmCH}\right|$, assume an open-phase condition when evaluating (8) for a particular phase. For example, assume an open-phase condition in Phase A when evaluating (8). With the assumption of an open phase in Phase A, $\left|I_{AmCH}\right|$ in (8) should be the Phase A charging current from the relay terminal to the hypothetical open-phase location, which should also be the same as the measured current magnitude for the relay of Phase A, $\left|I_{AL}\right|$. Therefore, replacing $\left|I_{AmCH}\right|$ with $\left|I_{AL}\right|$, we get:

$$\frac{I_{2L}+I_{0L}}{\left(I_{1L}-\left|I_{AL}\right|\bullet e^{j(\angle V_1+90°)}\right)}\approx-1 \tag{9}$$

The device must run three instances of (9) for all three phases. All of the variables in (9) are known to the relay, which is what makes the method proposed in Section III setting-less. Considering the hypothesis of an open-phase condition in Phase A, an open-phase condition is said to be detected in Phase A only if the relay calculates the ratio in (9) to be near –1. Henceforth in the paper, the left side of (9) will be referred to as ratio "*r*." Therefore, (9) can be rewritten as:

$$r\approx-1 \tag{10}$$

where:

$$r=\frac{I_{2L}+I_{0L}}{\left(I_{1L}-\left|I_{AL}\right|\bullet e^{j(\angle V_1+90°)}\right)} \tag{11}$$

C. *The Need to Include Line Shunt Capacitances*

Most often, the line shunt capacitances are not considered in the fault analysis of overhead lines. However, in some cases (e.g., ungrounded systems) the influence of shunt capacitances cannot be ignored. An open-phase condition is also one of these cases. Using (10), the following explains the effect of charging current on the dependability and security of open-phase detection.

Equation (10) is derived from (4), so by analyzing (4), we get:

$$\frac{I_{1L}}{I_{2L}+I_{0L}}-\frac{I_{1mCH}}{I_{2L}+I_{0L}}\approx -1 \qquad (12)$$

From Fig. 3, we know $\left(I_{2L}+I_{0L}\right)=-\left(I_{1L}-I_{1mCH}\right)$; therefore, (12) becomes:

$$\frac{I_{1L}}{I_{2L}+I_{0L}}+\frac{I_{1mCH}}{I_{1L}-I_{1mCH}}\approx -1 \qquad (13)$$

The left side of (13) is a complex number. Therefore, when this complex number falls within certain predefined thresholds that are set in reference to –1, then (13) is considered to be satisfied. However, these thresholds should be tight enough to result in a small operate region to restrain conditions that are not open-phase cases. To achieve this, I_{1mCH} in (13) cannot be ignored, especially for cases where the charging current is comparable with the load current; in which case, the dependability of the element may be jeopardized. The inclusion of line capacitances in deriving an expression for an open-phase detection condition contributes to providing full dependability and enhanced security.

III. DETECTION ALGORITHM

This section describes the process and outlines the thresholds used in the algorithm. Fig. 4 shows the flowchart of the proposed open-phase method.

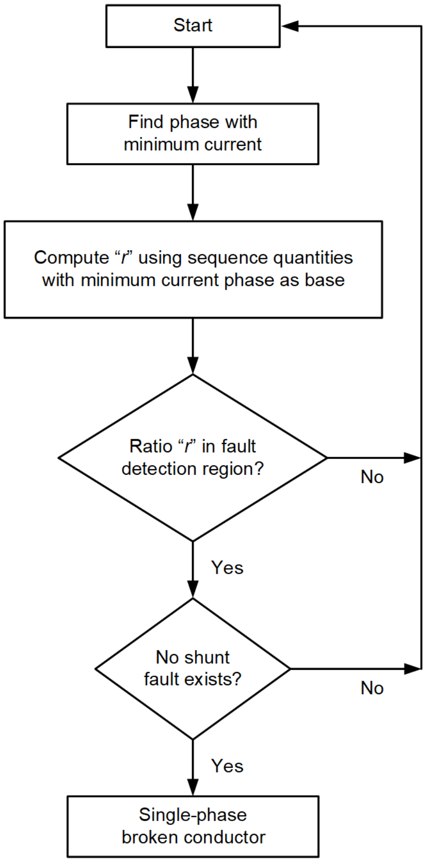


Fig. 4. Logic flowchart of the proposed open-phase detection method.

A. *Finding the Phase With Minimum Magnitude of Current*

When a conductor breaks, the phase involved experiences a loss of load. This results in the current magnitude of the affected phase being less than the other two healthy phases. After finding the phase with the least magnitude of current, ratio *r* with regards to the affected phase as defined in (10), is calculated. The computed value of ratio *r* is used in the next criterion of the logic.

B. *Open-Phase Detection Region*

The following are considered for defining the thresholds representing the complex ratio *r*, as defined in (10):

- Assumptions were used in deriving the expression of the ratio *r* in (10).
- Errors exist for the relay and the field current transformers measurements.

With these two assumptions, ±10 percent and ±5 percent thresholds were considered in the real and imaginary part of the ratio *r*, respectively. These thresholds are represented in (14) and (15). In summary, when (14) and (15) are satisfied for a given phase, which also has the minimum current magnitude among the three phases, then that phase is declared as a broken conductor phase.

$$-0.9>\mathrm{Real}\left(r\right)>-1.1 \qquad (14)$$

$$-0.05<\mathrm{Imag}\left(r\right)<0.05 \qquad (15)$$

Fig. 5 shows the open-phase detection region based on (14) and (15).

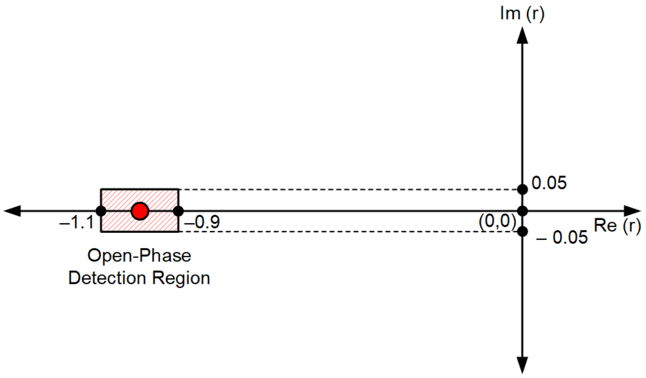
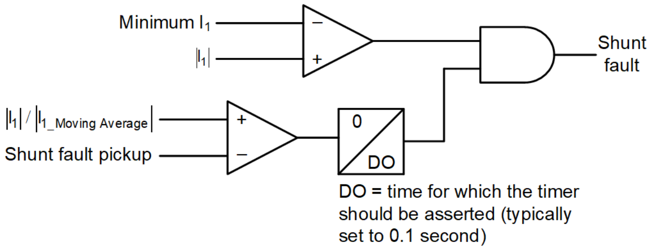


Fig. 5. Single-phase broken conductor detection region.

C. *Shunt Fault Detection*

Conditions that are not a single-phase broken conductor event should not be picked up by the logic and hence, a blocking mechanism should be in place. Shunt faults have the potential to encroach into the open-phase detection fault region and should be blocked. Custom logic helps with the detection of these faults, as shown in Fig. 6. This logic can provide additional backup to the overcurrent logic that is already present in the intelligent electronic device (IED). It can also act as a primary shunt fault blocking logic of the algorithm if an overcurrent logic is unavailable.



DO = time for which the timer should be asserted (typically set to 0.1 second)

Fig. 6. Shunt fault detection logic.

In Fig. 6, $\left|I_1\right|$ is the positive-sequence current magnitude computed by the IED. “Minimum I_1” is the setting for detecting the minimum amount of positive-sequence current on the three-phase line, which ensures that the logic does not pick up on low-level signals, such as noise or measurement errors. $\left|I_{1\_MovingAverage}\right|$ is the moving average magnitude of positive-sequence current. “Shunt fault pickup” is a setting for the shunt fault positive-sequence current ratio, $\left|I_1\right| \big/ \left|I_{1\_MovingAverage}\right|$, which detects rapidly rising positive-sequence current due to shunt faults. A typical setting value of 1.2 will be sufficient for most cases.

IV. RESULTS

This section shows three field events from subtransmission and transmission systems that test the validity of the proposed open-phase detection method. The three field events have an occurrence of a conductor break, each with its unique challenges such as low-load current, arcing before the break, and very low line charging current.

A. *Field Event 1: Phase C Broken Conductor Event on a 46 kV Subtransmission Line*

In this event, a broken conductor occurred on a 60 Hz, 46 kV subtransmission line, approximately 4 miles long. Based on the fault records available for this event, the event began with a three-phase fault that self-cleared before the Phase C conductor broke.

Fig. 7a shows the raw event record displaying the currents for all three phases when the broken conductor event occurred on Phase C. Because the line was short and the voltage was at the subtransmission level, the charging current that was seen was low (close to zero amperes) on Phase C following the break. In Fig. 7b, the black dashed line represents the open-phase detection region, which is illustrated by the thresholds described in Section III.B. When the complex ratio *r*, which represents the affected phase, falls within this operate region while it experiences minimum current among the three phases and while there is no shunt fault on the system, a broken conductor is declared on this phase.

As evident in Fig. 7a, Phase C has the minimum magnitude of current after the occurrence of a conductor break without a shunt fault existing on the lines during the break. Fig. 7b shows the trajectory of the complex ratio *r* for Phase C from prefault to when the broken conductor event occurs. At prefault, the ratio is small and close to the origin, which accounts for the system unbalance. As the Phase C conductor breaks, the ratio for Phase C starts moving towards the open-phase detection region. In a few samples, it settles into this region for the duration of the break. An important note for this event is that after the Phase C conductor broke, it fell on some vegetation around the lines, causing an HIF, which is difficult to detect. This makes it crucial to detect the broken conductor after it breaks and before it comes in contact with any surface. With all criteria passing for broken conductor detection, the logic successfully detected the Phase C break.

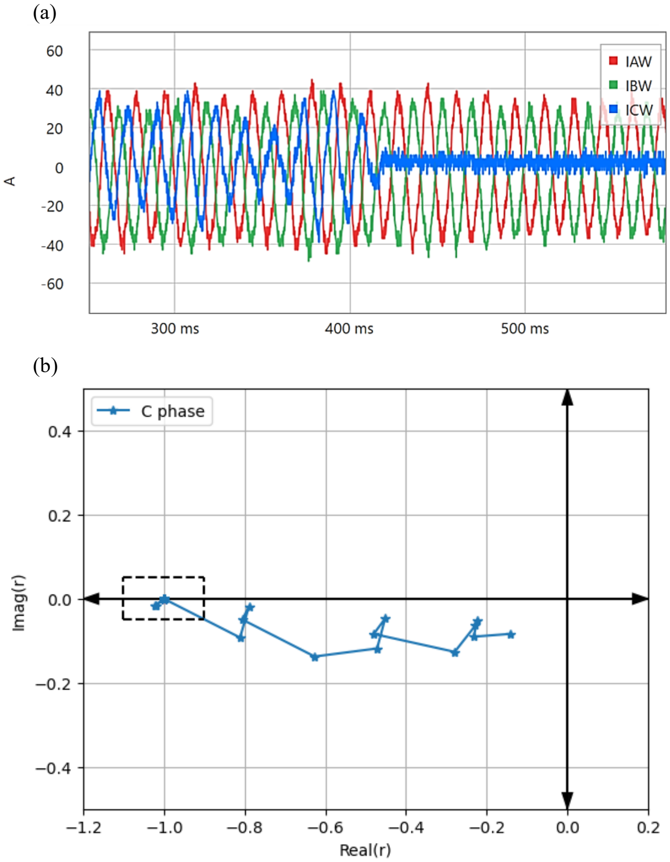


Fig. 7. Current waveform for all three phases during the Phase C break (a) and trajectory of the ratio *r*, defined in (10) for Phase C (b).

B. *Field Event 2: Phase C Broken Conductor Event on a 220 kV Transmission Line*

This section describes a broken conductor event that occurred on a 50 Hz, 220 kV transmission line, which is approximately 90 miles long. The system experienced a Phase C conductor break. Series arcing occurred before the line separated mechanically and electrically broke. After the Phase C conductor broke electrically, the relay measured the charging current flowing through the broken section of the line, which was approximately 70 A.

Fig. 8a shows the waveforms displaying the currents for all three phases when Phase C experienced series arcing and eventually broke. As the conductor started breaking and the series arcing began, the Phase C currents started reducing and the minimum phase current criteria passed. The complex ratio *r* started moving towards the open-phase detection region slowly because of the arcing. It eventually fell in the region just before the conductor broke and after the arc extinguished, as shown in Fig. 8b. No shunt fault existed on the lines during or before the break. Thus, the logic helped detect a broken conductor event, even though series arcing was involved in the process of breaking.

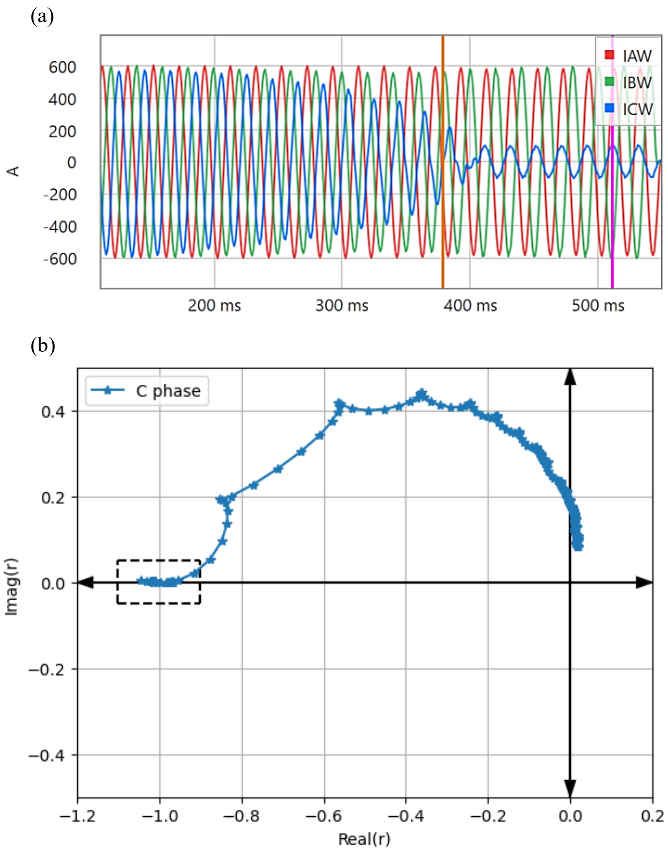


Fig. 8. Current waveform for all three phases during the Phase C break (a) and trajectory of the ratio *r*, defined in (10) for Phase C (b).

C. *Field Event 3: Phase B Broken Conductor Event on a 69 kV Subtransmission Line*

This section describes a broken conductor event that occurred on a 60 Hz, 69 kV, 68.58 mile long, subtransmission line. The device captures approximately 300 milliseconds of the broken conductor event on Phase B before it falls to the ground, causing a high-impedance ground fault with gradually increasing current magnitude.

Fig. 9a shows the event record that displays the currents for all three phases when the broken conductor event occurred on Phase B. The charging current seen on the broken phase was approximately 15 A. Phase B had the minimum magnitude of current during the fault and no shunt fault existed on the lines during the break. The complex ratio *r* fell in the open-phase detection region for Phase B, as shown in Fig. 9b, for the first 5 cycles of the event and is captured between the orange and magenta cursors. This is sufficient to qualify the logic for the broken conductor.

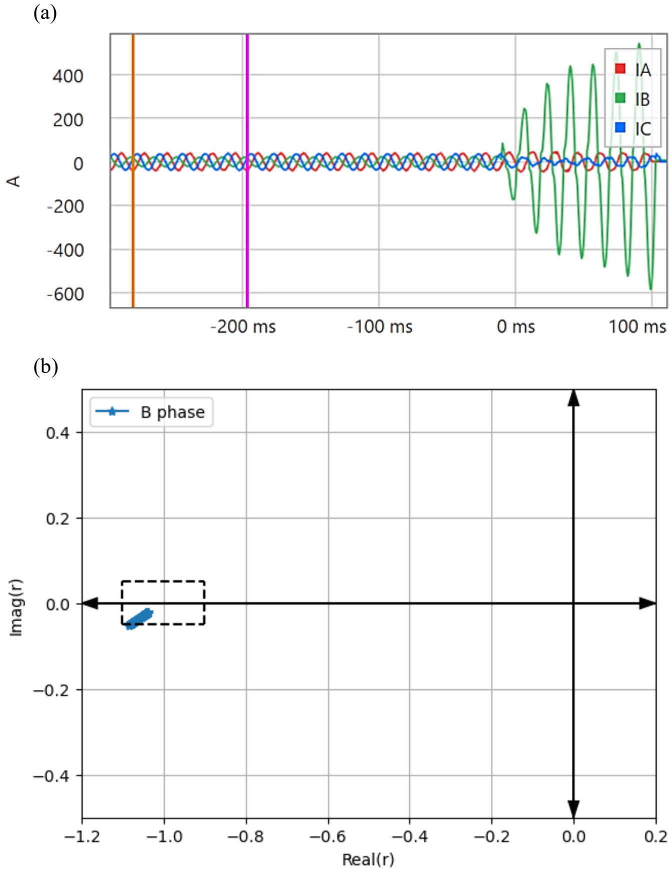


Fig. 9. Current waveform for all three phases during the Phase B break (a) and ratio *r*, defined in (10), for Phase B (b).

V. RADIAL DISTRIBUTION SYSTEM APPLICATIONS

A. *Theory*

The proposed method works to detect a single-phase open conductor within the length of the protected line, i.e., until the remote terminal of the line or a tap on the line. Distribution feeders have significantly less line charging currents as compared to transmission systems. Additionally, for systems that are radial, which account for most distributions systems today, lateral feeders are common. Therefore, the proposed method with charging current compensation may not be useful for these radial lines. Instead, to detect a break in the conductor, the complex ratio *r,* defined in (1), can be used. Depending on the location of the IED, the positive-sequence current measured by it may contain a significant amount of load current from these taps during a break on the system. Fig. 10 illustrates this scenario with a one-line diagram for this type of feeder. The number of taps and the amount of load current they carry varies from system to system; hence, generalizing the method is difficult and complex. The magnitude of the denominator in ratio *r* in (1) is greater than $\left|I_0 + I_2\right|$, depending on the load current from tapped loads, and is given by (16).

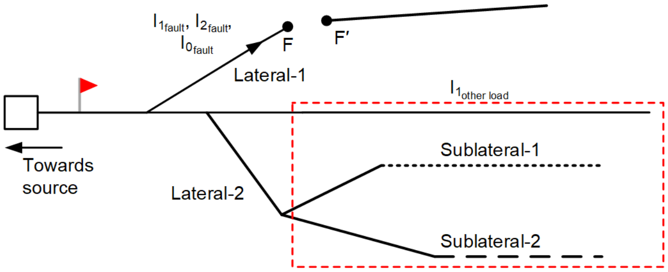


Fig. 10. Broken conductor event on a distribution feeder with laterals.

$$\left|r\right| = \left|\frac{I_0 + I_2}{I_1}\right| = \left|\frac{I_{0_{fault}} + I_{2_{fault}}}{I_{1_{fault}} + I_{1_{other\ load}}}\right| = \left|\frac{1}{\left(1 + \frac{I_{1_{other\ load}}}{I_{1_{fault}}}\right)}\right| \tag{16}$$

$I_{1_{other\ load}}$ is largely in phase with the positive-sequence current, resulting from the broken conductor condition of $\left(I_{1_{fault}}\right)$; hence, $\left|r\right| < 1$. To use this ratio *r* for open-phase detection, the operating region for the method is described in Fig. 11. The maximum threshold for the real part of the complex ratio *r* of the open-phase detection region can be set the same as the proposed method in Section III, which is 10 percent above the operate point of –1. The thresholds for the imaginary part of the complex ratio *r* can also be set at ±10 percent to account for measurement errors and nonhomogeneity of the loads. The lower threshold for the real part of the complex ratio *r*, which is defined as the “minimum ratio threshold,” should be set based on the tapped load currents.

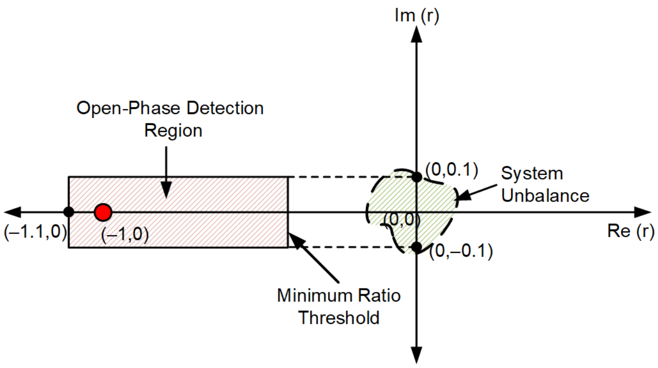


Fig. 11. Single-phase broken conductor open-phase detection region for distribution system application.

The following recommendations and analyses can be used to set the minimum ratio threshold:

1. The minimum ratio threshold should be set greater than the magnitude of the largest system unbalance ratio *r* by a safe margin (e.g., > 0.05).
2. The theoretical magnitude of the complex ratio *r* as a function of the percentage of lost load “k,” which is due to the broken conductor, can be computed as follows: assuming a balanced load, for simplicity, if k percent load current was lost due to a broken conductor event on Phase A that is on a lateral, then the broken conductor lateral $I_{1_{fault}}$ now consists of loads for Phases B and C and is approximately equal to $2k/3$ and $I_{1_{other\ load}}$ is approximately $(1-k)$. Therefore, $I_{1_{other\ load}} / I_{1_{fault}}$ can be computed as:

$$\frac{I_{1_{other\ load}}}{I_{1_{fault}}} = \frac{3 \bullet (1-k)}{2k} \tag{17}$$

By substituting (17) in (16), the magnitude of complex ratio *r* can be computed as:

$$\left|r\right| = \left|\frac{2k}{3-k}\right| \tag{18}$$

Using (18), the minimum ratio threshold can be set slightly lower (with a safe margin, e.g., > 0.05) than the magnitude of ratio *r* for the lowest percentage of load that can be lost on the feeder system due to a broken conductor event, provided it is greater than the recommended value in Point 1.

The method may experience security issues due to factors such as unbalance, loss of load, or load rejection. These issues can be alleviated by implementing this method in recloser controls with a higher, more secure value for the minimum ratio threshold with a significant margin (e.g., 0.3) between the unbalance and the lowest load lost due to the break ratio *r*, using (1). The dependability of the method is contingent on the feeder load characteristics and can be set based on system requirements.

B. *Testing Using a Simulated Event*

The application of the method described in Section V.A. is demonstrated using a simulated event of a radial distribution feeder with tapped load. The simulated system is a 60 Hz, 12.47 kV distribution system with a line containing a tapped feeder. The minimum percentage of load lost that this system can lose is approximately 40 percent. Using (18), this load lost corresponds to an $\left|r\right|$ value of approximately 0.31. This system unbalance is close to 0. Based on the recommendation in Section V.A., Point 2, the minimum ratio threshold is set to approximately 0.25. The break was simulated on the tapped feeder on Phase A to simulate the lowest percentage of load that can be lost on the load lost due to the break. Fig. 12a illustrates the current waveforms pre- and post-break. Fig. 12b shows that as the Phase A conductor breaks, the ratio r starts moving from its pre-break value, which is closer to the origin, towards the open-phase detection region and it settles into this region for the duration of the break.

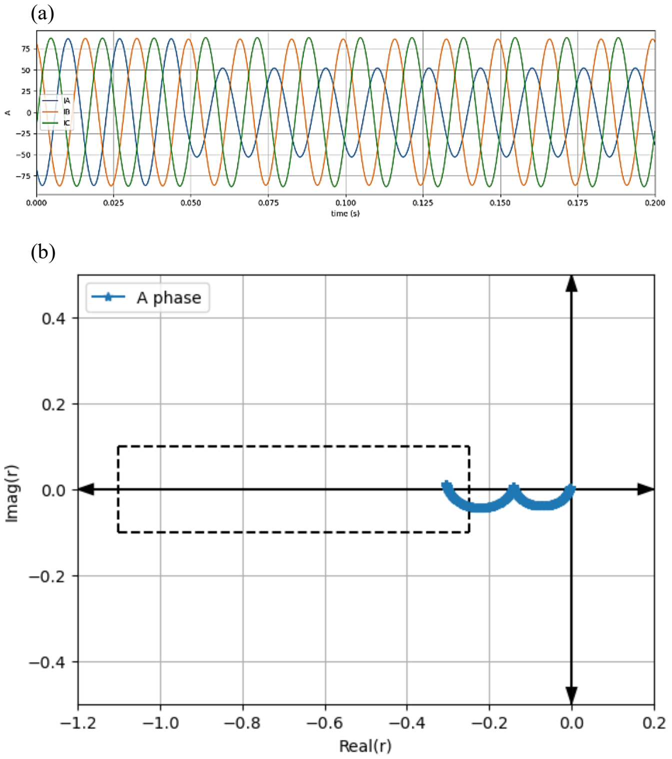


Fig. 12. Current waveform for all three phases during the Phase A break (a) and trajectory of the ratio r in (1) for all three phases on the real and imaginary planes (b).

VI. CONCLUSION

This paper tackles the problem of single-phase open-phase or broken conductor detection in three-phase power lines by proposing a simple method that does not rely on a communications method. It uses the fixed relationship that exists between zero-sequence, negative-sequence, and positive-sequence currents at the point of break to detect a single-phase broken conductor condition in three-phase power lines. For transmission line applications, which often experience significant line charging currents especially under light-load conditions, the measured charging current is automatically removed from the positive-sequence current by the proposed method. This removal enhances fault detection security and reliability. The effectiveness of the proposed method is illustrated using three challenging transmission field events.

The proposed method features the following advantages for transmission line applications:

- It relies solely on local measurements, eliminating the need for remote terminal measurements or signals, making it suitable for relay applications.
- There is no need for any line parameters, including the shunt capacitance value, to configure this function.
- The recommended default thresholds are compatible with nearly all two-terminal transmission line applications. Therefore, detailed fault studies are not essential for configuring this protection function.

The accuracy of this method makes it ideal for broken conductor applications in critical transmission systems.

Additionally, this paper delves into the application of the method for distribution feeders. The residual lateral loads of the phase with the broken conductor can alter the fixed relationship between sequence currents at the point of break; a relationship that is consistent in transmission line applications. Given the nature of the problem and the reliance of the method solely on local measurements, adjustments are necessary for the minimum ratio threshold of the open-phase detection region to identify broken conductor conditions that lead to specific percentages of load loss in the overall feeder load. However, the limitations of the method can be offset by integrating it into field devices, such as recloser controls, which may be set sensitively to detect broken conductor conditions in distribution feeders. The adaptability of the method makes it a good candidate for single-phase open detection for distribution systems.

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