

# Impedance-Based Directional Elements – Why Have a Threshold Setting?

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# Impedance-Based Directional Elements – Why Have a Threshold Setting?

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**Abstract**—Determining the direction of a fault is a fundamental necessity of any pilot or local protection scheme involving a meshed network. Some relays determine directionality by taking the product of the polarizing quantity (V) and an operating quantity (I) to develop a quantity referred to as torque. If the magnitude of the torque exceeds a minimum non-settable threshold defined in volt-ampere (VA), then the sign of the torque (positive or negative) determines direction. Many relays in common usage determine directionality by ensuring that a measured impedance satisfies a settable impedance threshold.

The ability to set directional thresholds in the impedance plane gives the relay user the ability to bias the directional element forward or reverse in the easy-to-understand units of ohms, rather than the more obscure unit of VA. However, with such relays the user has settings they never had to think about before. This led to various “automatic” schemes for making these settings. Using these automatic setting schemes in inappropriate applications has led to unexpected relay operations. This paper examines forward biasing versus reverse biasing or no biasing approaches and provides rules for selecting settings so that the user can properly identify the correct approach for a particular application.

## I. INTRODUCTION

Determining the direction of a fault is a fundamental necessity of any pilot or local protection scheme involving a meshed network. Without a fault direction indication, protection speed and selectivity would be greatly sacrificed. Some digital relays determine directionality by taking the product of the polarizing quantity (V) and an operating quantity (I) to develop a quantity referred to as torque. The term “torque” is a carryover from electromechanical relays in which the voltage and current signals produce a rotational force on an induction cylinder. In digital relays the term torque is similar to a power measurement [1]. If the magnitude of the torque exceeds a minimum non-settable threshold defined in volt-ampere (VA), then the sign of the torque (positive or negative) determines direction.

Many relays in common usage determine directionality by ensuring that a measured impedance satisfies a settable impedance threshold. The ability to set directional thresholds in the impedance plane gives the relay user the ability to bias the directional elements forward or reverse in the easy-to-understand unit of ohms, rather than the more obscure unit of VA.

With such relays, the user has to make settings they never had to think about before. To ease the burden that came with this added flexibility, several automatic setting schemes were developed. However, the automatic setting schemes are based

on generic assumptions of how the directional elements are being used and the user’s preference for balancing security and dependability. In applications that differed from these generic assumptions, the user is expected to not use the automatic schemes and manually calculate settings. If an automatic setting scheme is used in an application that does not meet these generic assumptions, the relay could misoperate or fail to operate.

This paper provides guidance on when to use one of the automatic setting schemes and when to manually calculate settings. The bulk of this paper is on transmission line pilot applications where the performance of directional elements is the most critical. But it also covers setting directional elements for other applications as well. It is these other applications where the user has to be most careful.

The first automatic setting scheme biased the directional element to declare forward (dependability-biased). A later automatic setting scheme was developed that removed any bias between forward and reverse declaration. This second automatic setting scheme sets an impedance-based element to behave similarly to a torque-based directional element. This paper discusses the motivation behind this as well as considerations for when to deviate from this practice.

The paper discusses how forward biasing an impedance directional element provides dependability in challenging systems with strong sources and long lines and cases where detection of faults with high resistance is required. It discusses how to set the impedance threshold and overcurrent supervision for secure performance of the directional element.

This paper also discusses other considerations for use of automatic setting schemes and manual settings of impedance-based directional elements, such as applications with series-compensated lines, three-terminal lines, pilot schemes, applications when current transformer ratios differ on each end of the line, and recent advancements of these elements.

## II. FUNDAMENTALS

At a very basic level, directionality is determined by the phase angle relationship between two signals. Ideally, these two signals are chosen such that the phase angle relationship changes by 180 degrees for faults of opposite direction.

Comparing a voltage signal to a current signal provides this relationship. Fig. 1 shows phase angle relationships for a forward and reverse three-phase fault in a fully inductive system as seen from the relay location, which is shown as a flag. Throughout this paper, all voltages (V), currents (I), and quantities derived from V and I are in secondary.

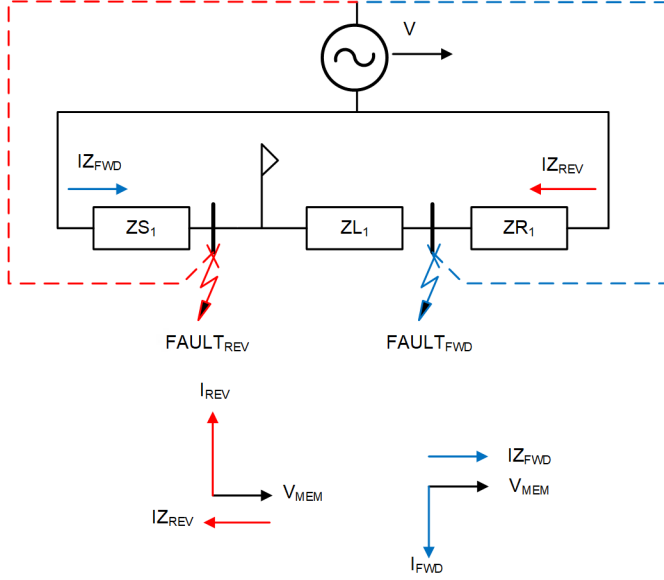


Fig. 1. Forward versus reverse fault phasors

The phasor  $V_{MEM}$  is equivalent to the source voltage  $V$  under no load conditions. The relay memorizes this voltage so that there is always a voltage to compare the  $IZ$  current to. The phasor  $IZ$  is called the replica current, which is simply the current  $I$  shifted in the counterclockwise direction by the impedance angle, which in this example is 90 degrees ( $Z = 1 \angle ZL_1$ ). Multiplying  $I$  by  $Z$  converts the operate signal into a voltage. This allows for a nice definition for forward and reverse faults: if  $V$  and  $IZ$  are in phase, the fault is in the forward direction. If  $V$  and  $IZ$  are out of phase, the fault is in the reverse direction. As the relationship varies between these two points, we become less certain about the direction of the fault. This makes the cosine operator a very good choice to determine directionality. If (1) is a positive number, the fault is in the forward direction. If it is a negative number, the fault is in the reverse direction.

$$\begin{aligned} \cos(\angle V - \angle IZ) &> 0 (\text{Forward}) \\ \cos(\angle V - \angle IZ) &< 0 (\text{Reverse}) \\ \cos(\angle V - \angle IZ) &= 0 (\text{No Direction}) \end{aligned} \quad (1)$$

Equation (1) is at the heart of determining directionality as it provides a signed output that is related to the direction of the fault. However, (1) is not reliable when the signals of  $V$  and/or  $IZ$  have a very small magnitude. To fix this, we can make sure both signals are stable enough for angle comparison by multiplying (1) by  $|V| \cdot |I|$  and qualifying a minimum  $VA$  for operation. This allows the operation region to be defined on the strength of signals, not just the signal angles (2).

$$\begin{aligned} |V| \cdot |I| \cdot \cos(\angle V - \angle IZ) &> VA_{MIN} \quad (\text{Forward}) \\ |V| \cdot |I| \cdot \cos(\angle V - \angle IZ) &< -VA_{MIN} \quad (\text{Reverse}) \\ -VA_{MIN} &< |V| \cdot |I| \cdot \cos(\angle V - \angle IZ) < VA_{MIN} \quad (\text{No Direction}) \end{aligned} \quad (2)$$

The  $VA_{MIN}$  is a design parameter of the relay and not settable by the user.

The only time (2) will evaluate to zero for non-zero values of  $V$  and  $IZ$  is when  $V$  and  $IZ$  are 90 degrees apart. If we assume a very high resistive forward fault,  $V$  and  $I$  will be nearly in phase as the system goes from appearing fully inductive to mainly resistive. In this case,  $V$  and  $IZ$  will be very close to 90 degrees apart, but this type of fault is exceedingly rare.

#### A. Negative- and Zero-Sequence Directional Element

Before going further, it is important to note that this paper does not further discuss directional elements designed for balanced (three-phase) faults. These directional elements typically do not have user-settable thresholds.

It is common to use negative- or zero-sequence quantities for directionality during an unbalanced fault type. The negative- and zero-sequence voltages and currents have a different relationship with regard to directionality than the positive-sequence voltages and currents. This is because the negative- and zero-sequence voltage is a function of the voltage drop seen across the passive system components only (see Fig. 2). In the positive-sequence network, the voltage seen by the relay is a function of the current through the passive components and the generator voltage. From now on we will refer to the negative-sequence network only ( $V_2$  and  $I_2$ ). Most of the discussion applies equally to the zero-sequence network.

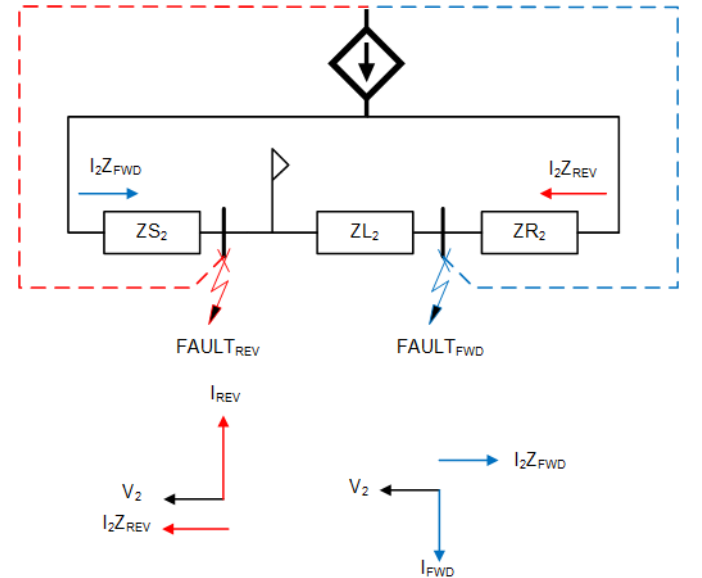


Fig. 2. Negative-sequence network reverse fault versus forward fault

A simple revision can be made to (2) to work for the negative-sequence network, as shown in (3). We define a torque-based negative-sequence element as  $32TQ$  (3), where  $Z = 1 \angle ZL_2$ . Note  $32TQ$ , as defined in (3), evaluates as a negative value for a forward fault and a positive number for a reverse fault.

$$\begin{aligned}
& |V_2| \cdot |I_2| \cdot \cos(\angle V_2 - \angle I_2 Z) > VA_{\min} \quad (\text{Reverse}) \\
& |V_2| \cdot |I_2| \cdot \cos(\angle V_2 - \angle I_2 Z) < -VA_{\min} \quad (\text{Forward}) \\
& -VA_{\min} < |V_2| \cdot |I_2| \cdot \cos(\angle V_2 - \angle I_2 Z) < VA_{\min} \\
& \quad (\text{No Direction})
\end{aligned} \tag{3}$$

Using the negative-sequence voltage and currents for directionality has the following advantages:

- $V_2$  is only a function of the voltage drop across  $ZS_2$  for a forward fault and  $ZR_2 + ZL_2$  for a reverse fault. The angular relationship between  $I_2$  and  $V_2$  will not be influenced by fault resistance. This means that high R faults will still produce  $V_2$  and  $I_2 Z$  relationships that are either near in phase (reverse) or near out of phase (forward). Torque output is only limited by a reduction in magnitude of  $V_2$  and  $I_2$ .
- Typically, the negative-sequence characteristic impedance of all elements is near the same angle (referred to as homogeneity). This means that forming the replica current from the line angle impedance will provide very good performance.
- Negative-sequence overcurrent supervision of the directional element does not need to be set above load current but does need to be set above system asymmetry (i.e., untransposed lines and unbalanced loads). However, inverter-based resources (IBRs) may require the overcurrent supervision to be set higher than in a conventional power system [2].
- It works well in parallel line applications because mutual coupling is minimal in the negative-sequence network.

However, a weakness of (3) is that a very low magnitude of  $V_2$  can prevent the directional element from determining a direction. The relay can fail to declare forward if  $ZS_2$  is very small,  $ZL_2$  is very large, and/or there is a high fault resistance present. In this case, the current magnitude through the relay is limited by a large total impedance, while the voltage magnitude at the relay is limited by the small source impedance  $ZS_2$ .

To aid in boosting dependability for this case, 32TQ in (3) that operates on units volt-amperes (VA) is converted to an impedance-based element by dividing it by amperes squared ( $A^2$ ). We define an impedance-based negative-sequence element as 32ZQ (4).

$$\frac{|V_2| \cdot |I_2| \cdot \cos(\angle V_2 - \angle I_2 Z)}{|I_2|^2} = Z_2 \tag{4}$$

This is commonly written the way it is programmed in a digital relay, as shown in (5), where the asterisk (\*) is the complex conjugate operator.

$$\frac{RE[V_2 \cdot (I_2 Z)^*]}{|I_2|^2} = Z_2 \tag{5}$$

In this discussion, we have provided a new perspective to make the connection between a “torque”-based directional element and an impedance-based directional element. The original derivation of the impedance-based directional element (5) is included in [1].

Equation (5) allows user to now have access to setting directional thresholds for the forward and reverse direction based on impedance, which is a parameter that is used frequently to set transmission line relays. For a forward fault, the relay will measure a negative impedance with a magnitude equal to the impedance of the source. For a reverse fault, the relay will measure a positive impedance with a magnitude equal to the remote source plus the line impedance. The relay user can set forward and reverse impedance thresholds, identified as  $Z2F$  and  $Z2R$ , respectively. If the measured  $Z_2$  impedance is less than  $Z2F$ , the relay declares forward. If the  $Z_2$  impedance is greater than  $Z2R$ , the relay declares reverse.

To prevent the 32ZQ element from limiting sensitivity regardless of the source impedance  $ZS_2$ , the  $Z2F$  threshold can be raised to a positive number. This is an inherent advantage of the 32ZQ element—it can be set biased in the forward direction, and it will respond forward even when no negative-sequence voltage is present. Because a reverse fault produces at least  $+ZL_2$  impedance (neglecting any remote source impedance), the only real restrictions are that  $Z2R$  must be less than  $ZL_2$  and  $Z2F$  must be less than  $Z2R$ . The 32ZQ element introduces the possibility of biasing a directional element for low signals. Originally, the element was set biased in the forward direction for dependability. However, setting the element with no directional bias, which offers a balance between security and dependability, has become more common [3].

### B. Characteristic Shaping

Because we know that the apparent  $Z_2$  will plot closely along the system impedance angle, we can remove certain areas of the  $Z_2$  plane and forgo making a directional decision. Fig. 3 is a plot of two methods as a comparison for a fully inductive system with the thresholds set with no directional bias (centered around the origin). Relay A [4] (represented by black lines in Fig. 3), uses an adaptive threshold that creates a hyperbola in the  $Z_2$  plane, while Relay B [5] (represented by blue lines in Fig. 3) uses line angle comparators in conjunction with (5) to shape a more restrictive operation area of the relay in the  $Z_2$  plane. We can dismiss apparent  $Z_2$  values that fall well off the maximum torque angle of the line and add security to the element. This includes the following scenarios:

- Voltage transformer (VT) errors at low current levels.
- Transient apparent  $Z_2$  that appears during initiation of three-phase faults.
- Sources that produce an incoherent  $I_2$  versus  $V_2$  signal, such as IBRs.

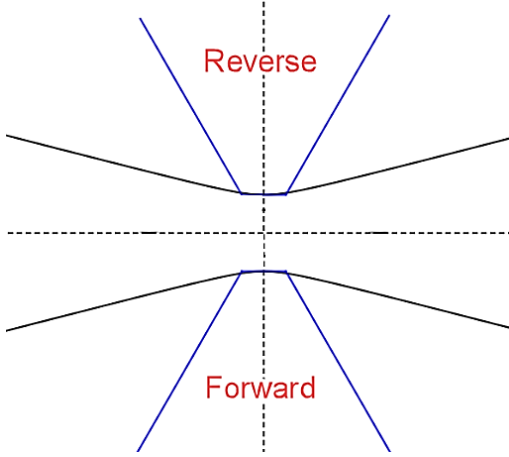


Fig. 3. Example operating characteristics in the  $Z_2$  plane

### III. AUTOMATIC SETTING SCHEMES

As mentioned in the introduction, torque-based directional elements usually have no user settings. The relay makes a directional decision based on the sign of a torque product with a minimum threshold fixed by the relay design. Impedance-based elements provide the user with the ability to adjust the settings depending on the nature of the circuit to be protected. To ease the burden in applying impedance-based elements, automatic setting schemes were developed. These schemes work well when the application of the relay aligns with the assumptions inherent in the automatic setting rules. When the application differs, the user is expected to manually calculate settings. The rules for deciding whether to use automatic settings or to manually calculate settings may not be clear to the user.

When setting relays, we always want to obtain the optimal balance of security and dependability to get the highest degree of reliability. A highly reliable protection system is both secure (will not trip for an out-of-zone fault) and dependable (will trip for an in-zone fault). However, these two attributes can be inversely related. If we set the relays with a bias towards dependability, security can suffer, and vice versa. It is important to find a balance.

The directional element is a key component that affects the reliability of any networked transmission line protection scheme. If the directional element wrongly declares a fault forward for a fault behind it, it opens the door for a security failure. If the directional element wrongly declares a fault reverse, it opens the door for a dependability failure. This is only half the story. When the directional elements are part of a directional comparison pilot scheme, such as directional comparison blocking (DCB) or permissive overreaching transfer trip (POTT), both relays must correctly determine the direction. In these applications, an incorrect reverse decision in the pilot blocking relay can lead to a dependability failure. An incorrect forward decision or a failure to declare reverse in the pilot tripping relay can lead to a security failure. Our setting choices can bias an impedance-based directional element towards dependability or towards security.

#### A. Threshold Settings for 32ZQ Elements

Table I shows the critical settings for a 32ZQ directional element. The first three settings are used to qualify whether there is enough negative-sequence current to enable the element. The measured  $3I_2$  must be above a minimum value and the ratio of  $I_2/I_1$  must be above a minimum value as well.

The ratio setting A2 in Table I, is used to qualify that the unbalance current,  $3I_2$  in this case, is greater than what can be expected from normal system asymmetries. This is sometimes called the positive-sequence restraint factor. No power system is perfectly balanced, and some current and voltage unbalance will appear on the system, even during load flow and (three-phase) faults. The A2 ratio check is helpful, but once satisfied, it does not address any voltage measurement error in calculating the apparent  $Z_2$ . We will discuss methods to account for such errors in Section V.

Separate fault detectors for forward and reverse are provided so that it is possible to coordinate the local pilot blocking (reverse) elements with the remote pilot tripping (forward) elements in a pilot scheme. It is important to ensure that the local pilot blocking element will always be enabled when the pilot tripping element at the remote terminal is enabled.

TABLE I  
CRITICAL SETTINGS FOR A 32ZQ ELEMENT

Setting	Description	Units
50QF	Forward fault detector	$3I_2$ secondary A
50QR	Reverse fault detector	$3I_2$ secondary A
A2	$I_2/I_1$ ratio (positive-sequence restraint factor)	Per unit
Z2F	Forward impedance threshold	$Z_2$ secondary ohms
Z2R	Reverse impedance threshold	$Z_2$ secondary ohms

Once the directional element is enabled, the measured apparent  $Z_2$  is compared to thresholds Z2F and Z2R to determine the directional decision. If the measured  $Z_2$  is below Z2F, forward is declared (recall that  $Z_2$  will be negative and equal to the source impedance behind the relay for a forward fault). If the measured  $Z_2$  is above Z2R, reverse is declared (recall that  $Z_2$  will be positive and equal to the line and remote source impedance for a reverse fault). If the measured  $Z_2$  falls between these two thresholds, no direction is declared.

Notice that there is no minimum voltage setting. Using impedance, two of the three parameters in Ohm's law can be specified by the user. Section V will discuss in detail how the two settings work together to determine the security and dependability of the directional element.

#### B. The First Automatic Setting Scheme (AUTO)

##### 1) AUTO Scheme Summary

The first automatic setting scheme devised used the rule to set the forward impedance threshold Z2F to one-half of the protected line impedance. The reverse threshold is set higher than the forward threshold, typically by  $0.1 \Omega$  or  $0.2 \Omega$  secondary (for a 5 A nominal relay). The forward and reverse negative-sequence fault detectors are set to a low value, typically 0.5 A and 0.25 A, respectively. This provides a

coordination margin of  $M = 2$  if the relay is used in a pilot scheme. The A2 ratio is typically set to a threshold of 0.1 that is conservatively above the expected natural system asymmetry.

The idea behind this rule is as follows. The relay is making these settings automatically so that it can only rely on the information available to it. The impedance of the line in secondary ohms becomes a mandatory setting when using this automatic setting scheme. The relay does not know anything about the source impedance behind it or the source impedance beyond the remote terminal. Using half of the line impedance to differentiate between forward and reverse makes use of the boundary condition that the local and remote source impedances can be zero (a so-called infinite bus). They cannot be smaller than that. If they are larger, it only creates more separation between the measured  $Z_2$  for forward faults versus reverse faults.

Additionally, because the apparent impedance at the relay for a fault can never plot in the middle of the line, the no-decision band between the forward and reverse thresholds can be a minimum value, typically  $0.1 \Omega$  (see Fig. 5 in [3]).

In this scheme, a measured  $Z_2 = 0 \Omega$  is in the forward decision area of the characteristic. That is, it can declare a forward fault, even in the absence of any  $3V_2$ , as long as there is enough  $3I_2$  to enable the scheme. Another way of describing this setting scheme is that if the fault is not reverse, it must be forward. Put in the language of a relay engineer, the AUTO scheme is biased towards dependability.

Biasing the decision point to declare forward allows the directional element to provide permission to trip for very low-level faults that do not cause a depression in phase voltage or appreciable voltage unbalance. The primary example is for ground faults of very low magnitude due to high tower footing resistance or the line falling on high-resistivity surfaces. Another application is for sensing turn-to-turn faults in apparatus, such as reactors [6] and generator stators [7]. Section VI discusses this application further.

Another perspective for setting the directional element thresholds in this way can be drawn from experience with torque-based directional elements. In the past, dual-polarized ground directional relays were often used. A dual-polarized directional relay uses both zero-sequence voltage and zero-sequence current signals. The voltage polarization signal came from a wye/broken delta VT connection while the current polarization signal came from ground source transformer(s). Current polarization was often required because in applications with a low-impedance shunt path in the zero-sequence network provided by the transformer, the zero-sequence voltage was too low. Not enough torque was generated for the directional element to operate. If the grounding transformer were out of service, the current-polarized unit could not operate; but now, the voltage-polarized element could.

Current polarization was always difficult to apply and properly verify because the circuits could be very complex. Multiple current transformers (CTs) supplying zero-sequence current often had to be combined with proper polarity, and the circuits were often long series strings that had to be run through

every line panel in the station and properly connected to every relay with the correct polarity. Verifying the polarity of ground CTs from transformer neutral bushings and from inside tertiary winding deltas is a difficult task. The practice of using current-polarized directional elements to supplement voltage-polarized directional elements became obsolete once impedance-based directional elements set with a dependability bias became common. This greatly simplified line relaying applications.

## 2) AUTO Scheme Considerations

The AUTO scheme works well for conventional two-terminal line applications with reasonable line lengths. However, it should not be used in applications that deviate from this. The most significant issue relates to relying on the line impedance to drive the settings for Z2F and Z2R. The following discussion covers applications where this rule falls apart.

For example, in many cases directional elements are applied to applications other than lines. Misoperations of the 32ZQ element have occurred because the user did not realize that the line impedance setting is critical when using automatic directional settings. In an application with no line, it is reasonable to simply leave the line impedance setting at default. But when doing so, the AUTO scheme can provide settings that are not secure.

Recall that the sign of the measured  $Z_2$  is positive for reverse faults. However, if the amount the Z2R threshold is offset from zero in the positive direction is too great because of the erroneous line impedance setting, then the directional element can misoperate because the fault was clearly reverse but not reverse enough to cross into the reverse operate range of the characteristic. This will almost always result in a forward assertion because the no-decision area is a minimum value.

Using an impedance measurement when there is nearly no impedance can also be a problem. We are talking about lines that are extremely short. Half of a small number is an even smaller number. As the Z2F and Z2R thresholds shrink with the line length, the overcurrent supervision settings will need to be higher to maintain security. We discuss this in Section V, subsection E.

There are other cases when the rule of setting the boundary between forward and reverse to half of the line impedance can lead to inappropriate settings. An application on series-compensated lines is another example. In general, the rule of half of the line impedance must be based on the compensated line impedance,  $Z_{L1-XC}$ . There are a number of permutations on when to use the compensated line impedance or the actual line impedance based on where the series capacitors are located and where the VTs providing relay polarizing voltage are located. Reference [8] provides guidance on how to manually calculate Z2F and Z2R settings for series-compensated lines. Reference [9] details a case when a line protected by a hybrid POTT scheme misoperated for an extremely remote fault. In this case, the directional elements were erroneously set based on the uncompensated line impedance. The forward directional element at the remote end of the line was set very sensitively and saw the fault correctly in the forward direction. The local directional element measured a positive  $Z_2$  (the fault was reverse from this terminal), but not reverse enough to overcome

the Z2R setting that was set too far from zero. Because both terminals declared forward, the POTT scheme tripped. The case reported in [9] also had other contributing factors such as an error in the measurement of  $Z_2$ , which was caused by a standing voltage unbalance on the bus.

Another case when using the AUTO scheme that may lead to problems is with three-terminal lines. For a reverse fault, the  $Z_2$  measured by the relay may be lower than expected. One setting approach is to sum the impedance to the tap point and the lowest impedance of the two branches to the other two terminals, and then take half of that value. That works for the N-1 of the largest tap branch being out of service. However, when the two branches beyond the tap point are in parallel, the measured  $Z_2$  may evaluate to a value lower than the setting threshold, which would prevent the reverse element from properly asserting. Appendix A of [10] recommends assuming each of the remote terminals are connected to an infinite source. Thus, the impedance used with the “half of  $ZL_2$ ” rule for the Z2R boundary is half of the sum of the impedance to the tap point and the parallel impedance of the two branches beyond the tap point.

Also, the coordination margins between the forward fault detectors and the reverse fault detectors in a pilot scheme on a three-terminal line should be adjusted. Reference [11] recommends a rule to set the forward tripping fault detectors using (6) to coordinate the pilot tripping fault detectors with the pilot blocking fault detectors. The automatic setting scheme cannot do this. Equation (6) is the minimum allowable setting for 50QF in a three-terminal line. In Section V, subsection E, we provide another 50QF check that considers VT error, and it may evaluate higher than (6).

$$50QF_{R1} > M \cdot (50QR_{R2} + 50QR_{R3}) \quad (6)$$

where:

50QF<sub>R1</sub> is the local pilot tripping fault detector.

50QR<sub>R2</sub> and 50QR<sub>R3</sub> are the remote pilot blocking detectors.

M is your coordination margin factor.

Another concern with offsetting the boundary between forward and reverse to half of the line impedance is with the application of zero-sequence impedance-based elements in lines with mutual coupling. Mutual coupling can affect the measured  $Z_0$  for a reverse fault, which can also lead to situations when the 32ZG element measures a positive number, but it is not positive enough to overcome a threshold set based on half of  $ZL_0$  (ignoring the effect of mutual coupling). Reference [12] discusses calculating the expected apparent  $Z_0$  with mutual coupling to use when biasing both the Z0F and Z0R thresholds positive.

### 3) Summary of When to Use AUTO

AUTO is recommended for the following applications:

- Applications on strong systems.
- Applications when high sensitivity is required.
- Applications where the engineer finds the dependability bias acceptable.

### 4) Summary of When **Not** to Use AUTO

AUTO is not recommended for the following applications:

- Applications without a line impedance.
- Applications with very short lines ( $ZL_2 < 0.6 \Omega$ ).
- Series-compensated lines; manually calculate Z2F and Z2R thresholds based on guidance in [8].
- Three-terminal lines; manually calculate Z2F, Z2R, 50QF, and 50QR thresholds based on guidance in [10] and [11].
- Applications of zero-sequence impedance-based elements with mutual coupling; manually calculate Z0F and Z0R based on guidance in [12] (or use 32ZQ directional elements exclusively).
- Lines with tapped transformers as the inrush may produce little  $3V_2$  but enough  $3I_2$  to cause directional elements to declare forward [3].
- Parallel line applications [13]; set Z2F at 0.25 of the total line impedance and set Z2R at  $0.1 + Z2F$  to maintain high sensitivity with pole open security (see Appendix).

Some of these applications where AUTO is not recommended can be better addressed by simply using AUTO2.

## C. The Second Automatic Setting Scheme (AUTO2)

### 1) AUTO2 Scheme Summary

One of the key attributes of the first automatic settings scheme is that it is biased for dependability. This rule was written during a time when protection engineers commonly had a dependability bias. Offsetting the forward decision threshold allowed the element to make a good decision based on a  $3V_2$  measurement that was too small to give a reliable angle. This gives the element extremely high sensitivity to low-grade faults and this was seen as its main benefit. Today, we have a better appreciation of balancing security versus dependability.

In the previous discussion, we also saw where this “if it is not reverse, it must be forward” approach can lead to misoperations if the application of the directional element does not closely match the assumption that the application is a simple two-terminal line of adequate length.

This led to development of a second automatic setting scheme called AUTO2 [3]. AUTO2 sets the Z2F and Z2R thresholds to  $-0.3 \Omega$  and  $+0.3 \Omega$ , respectively. By doing so, zero  $3V_2$  is in the no-directional decision zone. In other words, this scheme is not biased for either security or dependability. When set this way, the impedance-based directional element acts similarly to the torque-based directional element. A measurable  $3V_2$  is required and the sign of the operating quantity must be congruent with the direction of the fault. This unbiased approach adds security and is less likely to lead to misoperations when the user uses an automatic setting scheme.

### 2) AUTO2 Scheme Considerations

There are few issues with this scheme. However, one that must be addressed is that this scheme is only recommended for applications where the source impedances are greater than  $0.5 \Omega$  secondary [3]. The relay does not have information on the source impedances, so it is up to the user to do extra work



to verify that the application meets the requirements for AUTO2.

This is actually a fairly small added burden over AUTO. In a networked transmission line application, the smallest source impedance can be found by placing a close-in fault on the line with the remote end opened and all sources in service. As detailed in [14], opening the line connects the remote source impedance via the transfer impedance branch to the bus behind the relay, as shown in Fig. 4 (which is similar to Fig. 2 in [14]). The transfer impedance branch represents the interconnected networked transmission grid in parallel with the line of interest. The parallel impedance of  $Z_S$  and  $(Z_R + Z_T)$  is the lowest source impedance that the terminal can see for a forward fault. This case is credible as it covers the event of the line being closed into a fault with the remote end open.

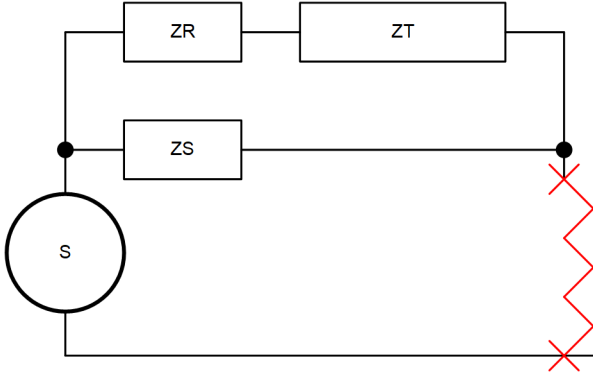


Fig. 4. Source impedance for a forward fault with the remote end open

Practically, we can apply a single-line-to-ground fault with remote end open and simply divide  $V_2$  by  $I_2 = Z_2$  (or  $V_0$  by  $I_0 = Z_0$  for a zero-sequence impedance element) from the values given by the fault study program. We then convert the result from primary to secondary ohms. Alternatively, we can take the line out of service, fault the bus, and use the Thevenin equivalent impedance given by the fault study program. If the magnitude of the result is greater than  $0.5 \Omega$  after converting the values to secondary, the AUTO2 setting for  $Z2F = -0.3 \Omega$  is acceptable.

The  $0.5 \Omega$  minimum for the  $Z2R$  threshold set to  $+0.3 \Omega$  secondary can often be determined by simply checking that  $ZL_2$  is greater than  $0.5 \Omega$ . If the line is shorter than that, it requires a bit more work. In this case, two methods can be used (similar to finding the minimum  $ZS_2$ ).  $V_2$  and  $I_2$  at the relay can be determined by isolating the terminal from the rest of the bus (splitting the bus) and faulting the newly created stub bus behind the relay. The source impedance for this fault is simply determined by  $V_2$  divided by  $I_2 = Z_2$  and converted from primary to secondary ohms. This connects  $ZS_2$  to the remote bus via the transfer impedance and gives the lowest possible source impedance the relay will see for a reverse fault. Alternatively, we can take the line out of service, fault the remote bus, use the Thevenin equivalent impedance given by the fault study program to get  $ZR_2$ , and add  $ZL_2$  to obtain the source impedance for a reverse fault.

### 3) Summary of When to Use AUTO2

AUTO2 is recommended for most applications, as long as the user qualifies that the minimum source impedance requirements are met. Several of the exceptions listed for AUTO are related to issues where the fault is reverse (measured  $Z_2$  is positive) but not positive enough to overcome a dependability-biased  $Z2R$  threshold. These are series-compensated lines and lines with zero-sequence mutual coupling (3ZG elements). The process of checking that the magnitude of the source impedance for forward and reverse faults exceeds  $0.5 \Omega$  addresses these issues.

### 4) Summary of When to Not Use AUTO2

AUTO2 is not recommended for the following applications:

- Applications with strong sources at one or both terminals.
- Applications where very high sensitivity is required (e.g., reactor protection).
- Three-terminal lines. Manually calculate  $50QF$  and  $50QR$  thresholds based on guidance in [11]. It is acceptable to use the AUTO2  $Z2F$  and  $Z2R$  thresholds if applicable.
- Series-compensated lines under the following conditions ( $XC$  is the capacitive reactance of the series capacitor):
  - Series capacitor on line side of relay potential source.
    - $ZR_2 + ZL_2 - XC < 0.5$ ; hinders security because the relay may not declare directionality for reverse faults.
  - Series capacitor on bus side of relay potential source.
    - $ZS_2 - XC > 0.5$ ; hinders dependability because the relay may not declare directionality for forward faults.

### D. General Problems With Using Automatic Schemes

Automatic setting rules suffer from additional problems that preclude their use. While in the previous discussion we mainly focused on the rules for selecting  $Z2F$  and  $Z2R$ , the automatic settings schemes set all five setting parameters in Table I. This section highlights additional cases when not using an automatic scheme is recommended.

Consider a two-terminal line protected by a pilot scheme with different current transformer ratios (CTRs) at each end. The automatic setting schemes assume that both ends of the line have the same CTR such that, when coordinated in secondary amperes, they are also coordinated in primary amperes. If the CTRs are not the same at both terminals, this is not the case. For these applications, the user should not use an automatic scheme and instead should manually enter settings for the fault detectors so that they are coordinated in primary amperes. The  $Z2F$  and  $Z2R$  settings can be manually calculated using the same rules as the appropriate automatic scheme rules and entered.



Another scenario when an automatic setting scheme should not be used is if the tripping elements that the directional elements supervise are set very low. Using an automatic settings scheme hides the fault detector settings, so it is easy to not think about them. But if the tripping element is set to 0.5 A or lower and the supervising directional element is set to 0.6 A (for example) by the automatic scheme, the relay will not provide the expected sensitivity. In such cases, the user should not use an automatic scheme, and instead, should manually enter settings for the fault detectors so that they are coordinated with the tripping elements that they supervise.

Another consideration for applications with very sensitive settings is that often the directional element uses  $3I_2$  and the tripping element uses  $3I_0$ . In these cases, the two contributions for a given ground fault may be different depending on the relative impedance of the branches in the two networks. In such cases, you typically want to set the directional fault detectors with margin below the tripping element.

Finally, in applications where the default A2 factor of 10% isn't appropriate such as covered in Section VI, an automatic setting scheme should not be used so that the A2 factor can be adjusted.

To summarize, do not use an automatic setting scheme in the following cases:

- If you are applying the relay in a pilot scheme with dissimilar CTRs at each terminal.
- If your tripping elements are set more sensitively than the default directional element fault detector settings in the automatic scheme.
- If your directional elements require the positive-sequence restraint ratio to be raised or lowered from the default ratio settings in the automatic scheme.

#### IV. ADDITIONAL THRESHOLD SETTING SCHEMES

As mentioned previously, the authors were discussing the two automatic schemes from the point of view of balancing security and dependability. In our debates, one author was of the opinion that biasing both terminals of a pilot scheme for dependability is an obviously bad choice, given the greater awareness of security failures in the industry. Security failures (overtripping) always get scrutiny and often have to be reported to regulatory bodies that keep statistics. According to data reported to the North American Electric Reliability Corporation (NERC) for protection system misoperations during the 2020 calendar year, security failures are over 20 times more prevalent than dependability failures. Contrast that to dependability failures (fail to trip). Dependability failures are an extremely rare event given the industry's historical dependability bias driving redundancy practices. When they do occur, they are often spectacular and make the national news, so they are not to be dismissed. The other author pushed back. The old tried-and-true dependability-biased scheme is easy; it can be applied with no fault studies and has served us pretty well. The user just has to be aware of when not to use it.

This led us to wonder about other options to consider for the directional threshold settings. For now, we ignore using overcurrent supervision settings, which we will address later. A rules-based scheme for defining directional thresholds could have one of three options:

- Dependability bias (measured  $Z_2 = 0$  is forward)
- No bias (measured  $Z_2 = 0$  is no decision)
- Security bias (measured  $Z_2 = 0$  is reverse)

This leads to forming two new automatic settings schemes to provide an option for a security bias (AUTO3) and a second dependability bias (AUTO4). We gave these two new automatic settings schemes a number for discussion purposes. To be clear, these two new schemes are not hard-coded in any relay but could be written into an engineer's setting calculation guidelines if they should prove to have worth in the following discussion. In Table II, we equate a forward bias equaling dependability and a reverse bias equaling security. AUTO3 and AUTO4 are less restrictive than AUTO2 and can be considered for certain cases in which AUTO2 is not acceptable due to the presence of a very strong source or a very short line.

TABLE II  
AUTOMATIC SETTING SCHEMES

Scheme	Bias	Z2F Rule	Z2R Rule	Limit
AUTO	Forward/ Dependable	$0.5 \cdot ZL_2$	$Z2F + 0.1 \Omega$	$ZL_2 > 0.6 \Omega$
AUTO2	None	$-0.3 \Omega$	$+0.3 \Omega$	$ZS_2 > 0.5 \Omega$ $ZL_2 + ZR_2 > 0.5 \Omega$
AUTO3	Reverse/ Secure	$-0.3 \Omega$	$-0.2 \Omega$	$ZS_2 > 0.5 \Omega$
AUTO4	Forward/ Dependable	$0.2 \Omega$	$0.3 \Omega$	$ZL_2 + ZR_2 > 0.5 \Omega$

##### A. New AUTO Setting Schemes

The new AUTO schemes (3 and 4) use fixed thresholds relative to  $Z_2 = 0$  similar to AUTO2. We assume the same restriction of applicability that the source impedance must be greater than  $0.5 \Omega$  for the side with the no-decision boundary farthest from zero.

##### 1) AUTO3: Bias Reverse

When examining the various combinations, any discussion of biasing has to look at the option of biasing both terminals for security. We already had options for dependability bias (AUTO) and no bias (AUTO2). Surely, a security bias might be better than a no-bias scheme. AUTO3 can be applied in short line applications in which  $ZS_2 > 0.5 \Omega$ .

##### 2) AUTO4: Bias Forward

This option is appealing because it improves security for the "clearly reverse but not reverse enough" problem that has sometimes been an issue with AUTO being applied incorrectly. It gives the high sensitivity to low-grade faults that do not cause significant voltage unbalance. AUTO4 can be applied in strong source applications in which  $ZL_2 + ZR_2 > 0.5 \Omega$ .

### 3) AUTO3/AUTO4: Bias the Two Terminals Differently

In cases for which AUTO2 can't be used at a line terminal due to strong sources or an electrically short line, a combination of AUTO4 at the strong terminal and AUTO3 at the weak terminal can be used to provide a balance between security and dependability with minimal effort.

#### B. Manual Setting Schemes

The threshold setting schemes covered up to this point are considered automatic because the user does not directly set the threshold. However, there are manual setting schemes in which the user is expected to calculate and apply thresholds based on system data. These are covered in the following two sections.

##### 1) $k \cdot ZS_2$ Rules-Based Scheme [5]

The simple rule for setting Z2F is to find the lowest source impedance behind the relay and multiply this value by a k-factor (margin factor) recommended to be  $0.5(k_F)$ , per (7). The lowest  $ZS_2$  is obtained by using the same technique as described for qualifying use of the AUTO2 scheme.

$$Z2F = -k_F \cdot ZS_2 \quad (7)$$

The simple rule for setting Z2R, the reverse threshold, is to multiply the line impedance by a k-factor ( $k_R$ ), recommended to be 0.25 (8).

$$Z2R = k_R \cdot ZL_2 \quad (8)$$

We notice that this rule is like AUTO2 in that it is not biased forward or reverse. The main difference between the  $k \cdot ZS_2$  scheme and AUTO2 is that, in weaker systems ( $ZS_2 > 0.6 \Omega$ ) or longer lines ( $ZL_2 > 0.6 \Omega$ ), the no-decision zone becomes larger with default overcurrent supervision. This helps accommodate more standing  $3V_2$  error (less likely to declare a direction even if minimum current threshold is met). However, this does come with a price to sensitivity as more current may be required to overcome standing VT errors.

##### 2) The System Center Scheme

This setting scheme is described in Appendix A of [9]. The system center scheme requires determining all three of the impedances of interest ( $ZS_2$ ,  $ZL_2$ , and  $ZR_2$ ) and setting the Z2F and Z2R thresholds at each terminal such that the decision point for reverse for both relays is at the electrical center of the system. The forward decision point is then offset from the electrical center by a margin of  $0.2 \Omega$ . When compared to AUTO, which required no fault studies at all, this scheme might be considered a lot of extra work. However, if we consider that AUTO2 requires you to find the source impedances to verify its applicability, this scheme requires little additional work.

The electrical center of the system is the location where the  $3I_2$  contributions from both terminals are equal. When both terminals are set with the same 50QF and 50QR settings, they both are expected to pick up for this minimum (high fault resistance) fault. The electrical center is the location where  $3V_2$

will be at its largest absolute value at this low current. If the boundary between forward and reverse for both terminals is at the same location on the line, the 50QF setting can be calculated to provide for an expected error in  $3V_2$  that should be tolerated at the decision boundary point.

See Fig. 5 for an example. In this example, Terminal S is stronger with  $ZS_2 = 1 \Omega$ . Terminal R is weaker with  $ZR_2 = 2 \Omega$ . The total impedance of the system is calculated using (9).

$$\begin{aligned} ZT_2 &= ZS_2 + ZL_2 + ZR_2 \\ ZT_2 &= 1.0\Omega + 1.5\Omega + 2.0\Omega = 4.5\Omega \end{aligned} \quad (9)$$

To aid security, the boundary point for reverse declaration for both relays is set to the electrical center using (10) and (11). For security in a pilot scheme, if both relays declare reverse or one relay declares reverse and the other makes no declaration, no tripping will occur. Because this scheme is intended to provide secure settings accounting for  $3V_2$  error, we want the forward decisions offset from each other.

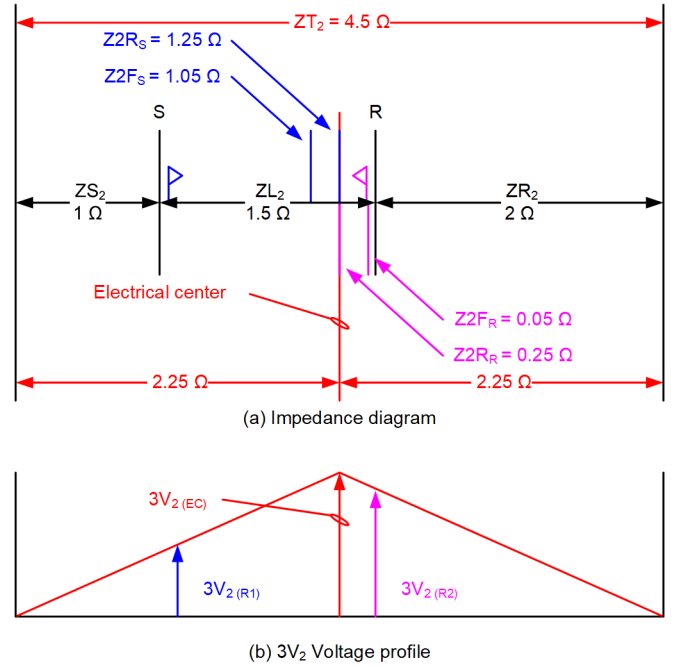


Fig. 5. Unbalanced fault at electrical center of the system

$$\begin{aligned} Z2R_{(S)} &= \frac{ZT_2}{2} - ZS_2 \\ Z2R_{(S)} &= \frac{4.5\Omega}{2} - 1.0\Omega = 1.25\Omega \end{aligned} \quad (10)$$

$$\begin{aligned} Z2R_{(R)} &= \frac{ZT_2}{2} - ZR_2 \\ Z2R_{(R)} &= \frac{4.5\Omega}{2} - 2.0\Omega = 0.25\Omega \end{aligned} \quad (11)$$

The forward thresholds are set less than the reverse with a  $0.2\ \Omega$  margin using (12) and (13). This allows a margin of  $0.4\ \Omega$  between both relays in the pilot scheme declaring forward.

$$\begin{aligned} Z2F_{(S)} &= Z2R_{(S)} - 0.2\Omega \\ Z2F_{(S)} &= 1.25\Omega - 0.2\Omega = 1.05\Omega \end{aligned} \quad (12)$$

$$\begin{aligned} Z2F_{(R)} &= Z2R_{(R)} - 0.2\Omega \\ Z2F_{(R)} &= 0.25\Omega - 0.2\Omega = 0.05\Omega \end{aligned} \quad (13)$$

Finally, the minimum forward fault detector setting to overcome an assumed  $3V_2$  error is calculated using (14) and (15). In this example, we are assuming a  $3V_2$  error of  $1V$ . The two calculations should always be equal using this method for selecting the Z2F thresholds. Calculating them for both terminals is a good check that no math errors have been made.

$$50QF_S \geq \frac{3V_{2(ERROR)}}{ZS_2 + Z2F_{(S)}} \quad (14)$$

$$50QF_S \geq \frac{1V}{1\Omega + 1.05\Omega} \geq 0.49A$$

$$50QF_R \geq \frac{3V_{2(ERROR)}}{ZR_2 + Z2F_{(R)}} \quad (15)$$

$$50QF_R \geq \frac{1V}{2\Omega + 0.05\Omega} \geq 0.49A$$

Examining the results, we see that both terminals have a dependability bias (both include  $3V_2 = 0$  in the forward declaration zone). The strong terminal has a large dependability bias. Its thresholds are well past the middle of the line. The weak terminal has a very small dependability bias. But this terminal has a relatively larger source impedance behind it, so it does not need one.

It is interesting to note that this scheme can give results associated with some of the automatic schemes we have already discussed. If the sources at each end of the line are of similar strength, the Z2F and Z2R settings will be similar to those given by AUTO. If there is a wide difference between the strength of the sources, the scheme could give results similar to a combination of AUTO3/AUTO4, where the strong terminal is biased forward (AUTO4) and the weak terminal is biased reverse (AUTO3).

The source impedances can be obtained using the same methods described for validating the use of automatic settings scheme AUTO2. Alternatively, the electrical center can be obtained by sliding a fault along the line to find the point where the two  $3I_2$  contributions are the same from each terminal. You then find  $ZS_2$  and  $ZR_2$  by taking  $3V_2/3I_2$ . Because of the redistribution of sources via the transfer branch as the fault location changes, this method will give different source impedances than the method to find the minimum used to qualify AUTO2. But the electrical center and therefore the Z2F and Z2R settings will be very similar using the two methods. The method of sliding the fault to find the point where the contributions are the same is more effort. Further, it does not

work if the electrical center of the system is not in the line. Further still, using the smallest source impedance as found by taking the line out of service in (14) and (15) gives conservative results for the minimum 50QF setting. For these reasons, it is recommended to simply use the procedures described in Section III, subsection C to find the source impedances.

## V. SECURITY AND SENSITIVITY (DEPENDABILITY) OF THRESHOLD SETTING SELECTION IN PILOT PROTECTION APPLICATIONS

In a pilot protection application, two relays must work in tandem to securely detect external faults and dependably detect internal faults. In this section, we will focus on security and sensitivity of directional threshold settings for a transmission line pilot protection scheme.

### A. Pilot Scheme Security

The two most common pilot protection schemes applied are DCB and POTT. A DCB scheme relay is permitted to trip if a block is NOT received for an external fault. A POTT scheme relay is permitted to trip if it receives a permissive signal. It is common to talk about the dependability and security of these schemes as it relates to the pilot channel performance. For example, if the channel is dead and you have an external fault, the DCB scheme will issue a breaker trip (no block received) while the POTT scheme will not issue a trip (no permission received). However, if the channel is healthy, the two schemes have very similar security and dependability traits. This is because it has become common to use echo keying logic in POTT schemes. This is sometimes referred to as a hybrid POTT scheme.

In a hybrid POTT scheme, received permission is echoed back to the remote relay if a fault is not detected in the reverse direction at the local relay. The result is that if the remote relay sees a fault in the forward direction and the local relay does not see a fault in the reverse direction, the remote relay will trip. This is the same result you will get with a DCB scheme. As a result, the hybrid POTT scheme requires careful coordination of the local pilot blocking elements with the remote pilot tripping elements, just like a DCB scheme [15]. To maintain security, the local pilot blocking distance elements must be set more sensitively than the remote pilot tripping distance elements.

If we simply think of impedance-based directional element coordination, the same consideration applies. For an external fault, if one relay declares forward, the other relay must declare reverse for security to be maintained. This case is generally assumed to be covered by simply setting the overcurrent supervision for a reverse declaration (50QR) lower than the overcurrent supervision for a forward declaration (50QF). However, as we will see, directional element coordination is also dependent upon the directional thresholds (Z2F and Z2R) chosen.

### B. External Pole Open Conditions

A forward-biased 32ZQ element can be challenged when the negative-sequence directional overcurrent supervision threshold is set very low and the fault current available is low.

This will produce a low system  $3V_2$  signal, which may not override standing  $3V_2$  errors that may be present. This occurs during very remote external shunt faults, shunt faults with very high resistance, and pole open conditions. Pole open conditions are often cited as issues for directional element security [16] (see Fig. 6) as the current present during these series faults can be small and produce very little voltage drop.

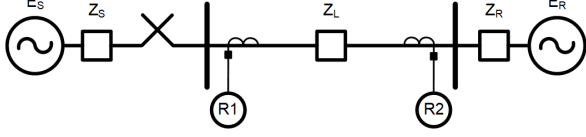


Fig. 6 External pole open condition

Pole open conditions can be caused by many things, such as:

- Unintentional causes such as a phase jumper burning open, a conductor breaking and dropping in the clear, or a disconnect switch blade not securely seated in the jaw.
- Intentional causes (e.g., when nearby lines use single-pole trip and reclose).
- Momentary causes, such as during switching when all three poles are not in the same state because of non-simultaneous operation (sometimes called pole scatter). Typically, pole scatter is brief for breakers but can be much longer than typical high-speed relaying times for mechanical switches.

A directional element will “point” to the location of an open pole condition (series fault), just like a shunt fault. In Fig. 6, R1 will declare the open condition in the reverse direction, while R2 will declare it in the forward direction. A more detailed discussion on open pole conditions is included in the Appendix.

### C. Potential Transformer Error Analysis

To determine secure settings for an external pole open condition and other conditions that have low  $3V_2$ , we need to determine plausible  $3V_2$  error. We decided to determine a  $3V_2$  error based on plausible potential transformer inaccuracy. The IEEE standard C57.13-2016 defines four accuracy classes for potential transformers. We have selected the worst-case error possible allowed for each accuracy class.

- 1.2 (+/-1.2 percent magnitude error, +/-1.0 degree angle error)
- 0.6 (+/-0.6 percent magnitude error, +/-0.5 degree angle error)
- 0.3 (+/-0.3 percent magnitude error, +/-0.25 degree angle error)
- 0.15 (+/-0.15 percent magnitude error, +/-0.125 degree angle error)

To calculate the  $3V_2$  error you could expect with a 0.3 accuracy class VT on each phase, there are many possibilities to consider. We can consider when magnitude errors and phase angle errors are all biased towards the worst-case scenario (maximum  $3V_2$  error). We can assume that all magnitude and phase angle errors are all biased towards the best case (no  $3V_2$  error). To obtain the negative-sequence voltage, there are three voltages to measure. There are six quantities that

can have an error, and each of these errors can either be additive or subtractive, as shown in Table III.

TABLE III  
POSSIBLE ERROR COMBINATIONS FOR  $3V_2$  CALCULATION

Error Sign	VA MAG	VB MAG	VC MAG	VA ANG	VB ANG	VC ANG
+	0.3%	0.3%	0.3%	0.25°	0.25°	0.25°
-	0.3%	0.3%	0.3%	0.25°	0.25°	0.25°

From Table III, we looked at 64 different combinations of error ( $2^6$ ) using (16), where  $\alpha = 1 \angle 120^\circ$ .

$$3V_2 = VA + \alpha^2 \cdot VB + \alpha \cdot VC \quad (16)$$

The error results are plotted in the scatter plot shown in Fig. 7, where each dot represents Cartesian coordinates for a plausible  $3V_2$  error at 66.4 nominal voltage. A circle encompasses the average  $3V_2$  error magnitude of 0.72 V.

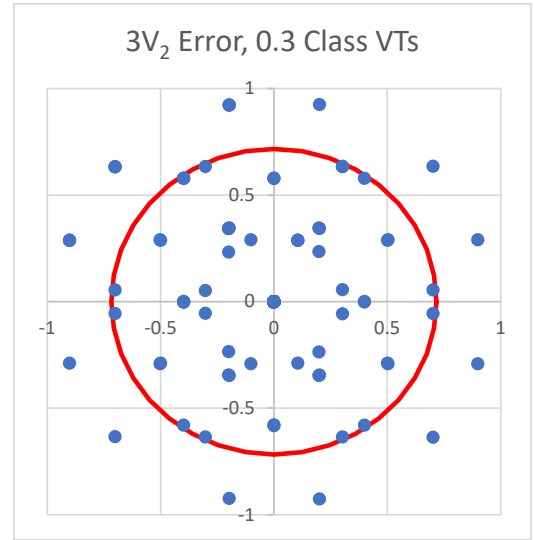


Fig. 7. Scatter plot of  $3V_2$  error

The maximum allowable  $3V_2$  error for a set of 0.3 and 0.6 accuracy class VTs is about 0.95 V and 1.9 V, respectively.

### D. $3V_2$ Error and its Effect on Impedance-Based Directional Elements (32ZQ)

We can calculate the apparent  $Z_2$  error as a function of  $3I_2$  present and an assumed  $3V_2$  error (17).

$$Z_{2\_ERROR} = \frac{3V_{2(ERROR)}}{3I_2} \quad (17)$$

This shows us that, for a  $3V_2$  error of 1 V and  $3I_2$  current of 0.5 A (default 50QF setting), a  $Z_{2\_ERROR}$  of 2  $\Omega$  is present. As  $3I_2$  is increased, the  $Z_{2\_ERROR}$  becomes smaller and less of a concern. The  $3V_2$  errors can lead to a +/- apparent  $Z_2$  error, so we can define the apparent  $Z_2$  impedance for reverse faults and forward faults with this error term using (18).

$$\begin{aligned}
a) \ Z2_{\text{Reverse}} &= ZR_2 + ZL_2 \pm \frac{3V_{2(\text{ERROR})}}{3I_2} \\
b) \ Z2_{\text{Forward}} &= -ZS_2 \pm \frac{3V_{2(\text{ERROR})}}{3I_2}
\end{aligned} \quad (18)$$

For an external event in which we want the pilot scheme to restrain, we are interested in the conditions that reduce security. Referring back to Fig. 6, the worst-case scenario for security for the pole open condition behind R1 is if R1 and R2 have a  $(-)$   $Z2_{\text{ERROR}}$ . In this scenario, it is more likely that R2 will declare forward and less likely that R1 will declare reverse.

We can calculate the apparent  $Z_2$  seen by the relay for increasing levels of current assuming a standing  $3V_2$  error of 1 V that biases each relay forward, as shown in Fig. 8. The calculation for  $Z_2$  apparent at R1 is given by (18a) and R2 is given by (18b), where  $-ZS_2$  is replaced with  $-ZR_2$ . In this example,  $ZR_2=0.5 \ \Omega$  and  $ZL_2=1.0 \ \Omega$ , and AUTO setting thresholds are used.

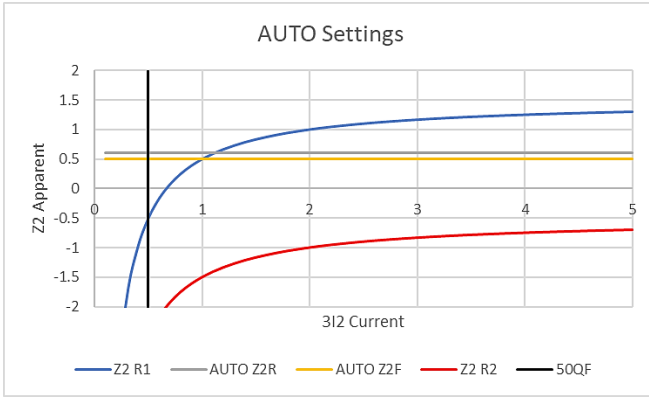


Fig. 8. Security concern for strong system with a short line AUTO setting

We can see that it is possible that R1 will fail to declare reverse for  $3I_2$  current just above 0.5 A, creating a security issue. For the system above, it is desirable to find a 50QF setting in R2 that will prevent forward assertions for cases in which R1 is unable to declare reverse. This is an important concept. The sensitivity of the remote terminal is limited by the ability of the local terminal to dependably declare a reverse fault.

#### E. Overcurrent Supervision Settings

To ensure pilot scheme security for reverse faults, the overcurrent supervision setting 50QF should be set high enough to ensure the remote relay can declare reverse with a  $3V_2$  error, and this is shown in (19). Equation (19) is obtained by recognizing that the right-hand side of 18a must be less than  $Z2R$  for a relay to fail to declare reverse, and this happens when the  $Z2_{\text{ERROR}}$  term is negative.

$$50QF_s \geq \left( \frac{3V_{2(\text{ERROR})}}{ZS_2 + ZL_2 - Z2R_{(R)}} \right) \text{ (Security Check)} \quad (19)$$

Equation (19) is a function of  $ZS_2+ZL_2$  and the remote relay  $Z2R$  setting ( $Z2R_{(R)}$ ). As such, (19) determines the minimum amount of current required for the remote relay to dependably declare reverse in the presence of a standing error that biases

the remote  $32ZQ$  element forward. The remote 50QR should be set below this value to dependably detect reverse. The local 50QF should be set above this value to ensure the local relay only declares forward when the remote relay dependably declares reverse. Consider leaving 50QR at the minimum allowable pickup value (default) and simply adjust 50QF per (19) if (19) exceeds the default pickup value for 50QF. In the example in Fig. 8, we can use (19) to find a 50QF setting of 1.2 A at R2 that will provide the required security for the standing  $3V_2$  error of 1V.

We can next check the worst-case sensitivity that can be expected for forward faults based on  $3V_2$  error and the local  $Z2F$  setting, as shown in (20). Equation (20) is obtained by recognizing that the right-hand side of 18b must greater than  $Z2F$  for a relay to fail to declare forward. This happens when the  $Z2_{\text{ERROR}}$  term is positive.

$$3I_2 \geq \frac{3V_{2(\text{ERROR})}}{ZS_2 + Z2F_{(s)}} \text{ (Sensitivity Check)} \quad (20)$$

Equation (20) is a function of  $ZS_2$  and  $Z2F_{(s)}$ , which are related to forward faults. As such, (20) determines the amount of current required to detect a forward fault in the presence of a standing error that biases the  $32ZQ$  element reverse. Equation (20) is useful in determining the worst-case sensitivity of a selected  $Z2F$  threshold. Because 50QF cannot be set any lower than (19) without sacrificing security, sensitivity can be gained via (20) by setting  $Z2F_{(s)}$  to be more positive.

As the  $Z2F$  and  $Z2R$  settings in the relay near the electrical center, (19) and (20) will approach equality, which helps illustrate the balance between security and sensitivity of the system center scheme illustrated in Section IV, subsection B. Because the system center scheme offsets the  $Z2F$  threshold  $-0.2 \ \Omega$  from the system center ( $Z2R$  setting), setting the overcurrent supervision based on  $Z2F$  rather than remote  $Z2R$  provides some additional security. For all other threshold setting schemes, (19) should be followed to ensure security is met in pilot protection schemes.

When using (19) in applications with different CT ratios at each line terminal, it is important to remember to convert all variables used in (19) to primary values.

#### F. Minimum Threshold Settings

Looking at (19) and (20), we can see that setting  $Z2R$  negatively will allow for a reduced 50QF setting, which will improve security and sensitivity as the amount of  $3I_2$  required to securely assert for a forward fault will be reduced. Setting  $Z2F$  positively will allow for more sensitivity for cases in which the  $3V_2$  error harms sensitivity. However, by rule,  $Z2R$  must be set greater than  $Z2F$ . For an unbiased setting scheme like AUTO2, it may appear that setting  $Z2F$  and  $Z2R$  at  $-0.1 \ \Omega$  and  $0.1 \ \Omega$  rather than  $-0.3 \ \Omega$  and  $0.3 \ \Omega$  would be beneficial. However, we recommend that  $Z2F$  and  $Z2R$  be set so that the biased direction can be set at  $|0.3 \ \Omega|$  or greater, especially if the fault detectors are not set to account for  $3V_2$  error for the following reasons:

- AUTO2 thresholds were selected based upon empirical data from many relay operations. The  $-0.3$

and 0.3 thresholds were selected for their security and dependability. Transformer inrush, for which no directional declaration was desired, was also an influence on these thresholds [3].

- In weaker systems, there is no tangible benefit to set thresholds closer to the origin.
- In short line applications in which one source is weaker than  $0.5 \Omega$  (see Table II), it is likely that a combination of AUTO3/AUTO4 or the system center scheme will accommodate a minimum biased threshold setting of  $0.3 \Omega$  at all line terminals.

In strong system short line applications that have  $ZS_2 < 0.5 \Omega$  and  $ZL_2 + ZR_2 < 0.5 \Omega$ , the system center scheme can be considered, but recognize the fault detectors must be set relatively higher than normal to maintain security.

## VI. GUIDELINES AND CONSIDERATIONS FOR DETERMINING OPTIMAL THRESHOLD SETTINGS

There are many ways to standardize on setting impedance-based directional elements. However, one of the biggest decisions that needs to be made by the settings engineer is how much effort they want to put into making the settings. Automatic settings schemes have the inherent advantage of minimal effort to set. However, they may not provide the best balance between security and dependability. To find that balance, more work must be done by the setting engineer. Regardless of the scheme to be used, we recommend carefully selecting a 50QF setting to maintain security. If the 50QF setting you calculate is larger than the automatic setting, then you need to enter Z2F and Z2R settings manually, but follow the impedance threshold scheme you are comfortable with.

We present the 50QF settings recommendations for Relay R1 at Terminal S in Table IV. When using any scheme other than AUTO, you should calculate the appropriate 50QF setting for all terminals (i.e., Relay R2 at Terminal R).

TABLE IV  
GUIDELINES FOR SETTING 50QF AND SENSITIVITY CHECK

Scheme	50QF Secure Setting	Sensitivity Check(3I <sub>2</sub> )
$k \cdot ZS_2$	$\frac{3V_{2(ERROR)}}{ZS_2 + ZL_2(1 - k_R)}$	$\frac{3V_{2(ERROR)}}{ZS_2(1 - k_F)}$
AUTO	$\frac{3V_{2(ERROR)}}{ZL_2(1 - k) - 0.1}$	$\frac{3V_{2(ERROR)}}{ZL_2(1 - k)}$
AUTO2, 3, 4	$\frac{3V_{2(ERROR)}}{ZS_2 + ZL_2 - Z2R_{(R)}}$	$\frac{3V_{2(ERROR)}}{ZS_2 + Z2F_{(S)}}$
System Center	$\frac{2 \cdot 3V_{2(ERROR)}}{ZS_2 + ZL_2 + ZR_2}$	$\frac{2 \cdot 3V_{2(ERROR)}}{ZS_2 + ZL_2 + ZR_2 - 0.4}$

The  $k \cdot ZS_2$  scheme for setting Z2F uses a fraction of the  $ZL_2$  impedance to set Z2R (very similar to AUTO). Because  $ZS_2$  will be known when using the  $k \cdot ZS_2$  scheme, we include the  $ZS_2$  impedance in the fault detector setting. The impedance  $ZS_2$

is not included in the AUTO settings as  $ZS_2$  is not required to set thresholds.

Using Table IV and assuming a  $3V_2$  error of 1 V and a desired minimum 50QF pickup of 0.5 A at the R1 and R2 positions, some generalized guidelines can be created to identify systems in which maximum sensitivity can be achieved while also maintaining security.

- AUTO:  $|ZL_2| > 4.2 \Omega$  for  $k = 0.5$  when  $ZS_2$  and  $ZR_2$  unknown
- AUTO:  $|2 \cdot ZS_2 + ZL_2| > 4.2 \Omega$  and  $|2 \cdot ZR_2 + ZL_2| > 4.2 \Omega$  for  $k = 0.5$  when Z2S and Z2R are known
- $k \cdot ZS_2$ :  $|4/3 \cdot ZS_2 + ZL_2| > 2.67 \Omega$  and  $|4/3 \cdot ZR_2 + ZL_2| > 2.67 \Omega$  for  $k_R = 0.25$
- AUTO2/3/4:  $|ZS_2 + ZL_2 - Z2R_{THRESH(R2)}| > 2 \Omega$  and  $|ZR_2 + ZL_2 - Z2R_{THRESH(R1)}| > 2 \Omega$
- System Center:  $|ZS_2 + ZL_2 + ZR_2| > 4.4 \Omega$

If no condition is reached from these guidelines, then the desired 0.5 A instantaneous pickup at each terminal cannot be achieved securely with a 1 V  $3V_2$  error. In very strong systems, it may be possible to implement low-set inverse-time overcurrent supervision (51Q) of the 32ZQ element in relay logic to gain security for short duration external pole open conditions while maintaining sensitivity for internal faults. Some relays include additional inverse-time security for low levels of  $3I_2$  [5].

## VII. NON-LINE PILOT 32ZQ APPLICATIONS

As mentioned in the introduction, the focus of this paper has been on security and dependability concepts for transmission line pilot applications. The original automatic setting scheme, AUTO, was designed with these applications in mind. However, we also mentioned other applications where the automatic schemes may require further consideration. These schemes are briefly revisited here.

### A. Unknown Line Impedance Data or Non-Line Applications

Because AUTO is based entirely on  $ZL_2$ , directional applications that are associated with lines where  $ZL_2$  is unknown cannot use AUTO. Also, most non-line applications, such as directional overcurrent protection through transformers, should not use AUTO. In these cases, the unbiased AUTO2 scheme (Section III, subsection C) is recommended. The system center scheme is also an acceptable choice in these applications by simply using the transformer impedance in place of line impedance.

### B. Phase Overcurrent Elements Set Below Load

Reference [17] details a case in which a 67P element was set with pickup below forward load to provide reverse sensitive protection through a transformer under a unique bus configuration. Although AUTO thresholds do ensure a  $3V_2$  signal is present for a reverse declaration, [17] recommends using an AUTO2 threshold scheme because a transformer bus is being protected, not a transmission line.

A more generalized, but even less secure, application of AUTO thresholds is as follows: 67P is set below reverse load



to have sensitive protection for forward faults. In this scenario, the 67P is “armed” with an adequate amount of phase current. Because the AUTO threshold will not require any  $3V_2$  for a forward declaration, if  $3I_2$  exceeds the 50QF setting, a trip will occur. When 67P is set below load, AUTO2 should be used so that some  $3V_2$  is required for a tripping decision to occur. This ensures that two signatures of an unbalanced fault are present ( $3V_2$  and  $3I_2$ ), not just one ( $3I_2$  only).

Reference [17] further details additional security enhancements when 67P is set below load. Even with the added security of AUTO2 thresholds, the 32ZQ is still quite sensitive at detecting remote unbalanced faults and further action may be required to ensure 67P security. To further ensure security, consider removing 32ZQ supervision from the 67P so that 67P only trips for balanced faults. Then set a 67Q with appropriate pickup levels to detect unbalanced faults and supervise it with 32ZQ.

### C. Distribution With Unbalanced Loads

The various automatic schemes are designed with transmission line applications in mind where very little unbalanced load flow is expected. The default value for the A2 ratio of 0.10 per unit is generally conservatively above expected system asymmetries. The advantage of using negative- and zero-sequence quantities to determine the direction to a fault is that they are generated by the fault and considered immune from load flow. For the very balanced transmission applications, 0.10 per unit is a good threshold to qualify if the unbalance quantities are from a series or shunt fault condition instead of a load flow condition.

In distribution applications, load flow often includes much higher degrees of unbalance, so a higher A2 ratio may be warranted to differentiate between load flow and faults. However, it must be kept in mind that raising the A2 (or A0) factor can reduce sensitivity during heavy load flow. So, as with all settings, a balanced approach to selecting a setting is warranted.

To help visualize limits to selecting an A2 factor, let's consider the sequence component ratios for a shunt fault in a radial application, neglecting load:

- For a line-to-line fault, the positive- and negative-sequence networks are in series.  $I_1 = I_2$  so the ratio of  $I_2/I_1$  is 1.00 per unit.
- For a single-line-to-ground fault, the positive-, negative-, and zero-sequence networks are in series.  $I_1 = I_2 = I_0$ , so the ratio of  $I_2/I_1$  is 1.00 per unit.
- For a double-line-to-ground fault, the negative- and zero-sequence networks are in parallel. The positive-sequence network is in series with these parallel branches. This is the case that defines the upper limit to use for A2 or A0.

If the negative- and zero-sequence networks have similar impedance, the fault current would divide evenly.  $I_2 = I_0 = 0.5 \cdot I_1$  so the ratio of  $I_2/I_1$  is 0.50 per unit. But these source impedances are generally not equal. For a close-in fault,  $Z_0$  is often lower than  $Z_1$  and  $Z_2$  due to the delta/wye transformer supplying the distribution system. In this case, the negative-

sequence network will take a larger proportion of the fault current raising the ratio of  $I_2/I_1$ . Because lines tend to have a much higher  $Z_0$  relative to  $Z_1$  and  $Z_2$ , for a remote fault, the ratio of  $I_2/I_1$  would get lower. Of course, the ratio of  $I_0/I_1$  would be affected conversely. Given these relationships, raising the A2 or the A0 factor for distribution applications to provide better immunity from unbalanced load flow can be raised, but to no more than 0.15 to 0.25 per unit.

### D. Reactor and Stator Applications

Impedance-based directional elements can be used in protection schemes for sensing turn-to-turn faults in apparatus, such as reactors [6] and generator stators [7]. These are typically protected by current differential schemes, most of which are blind to turn-to-turn faults. In turn-to-turn fault applications, unbalance current caused by external faults are accompanied by unbalanced voltage. On the other hand, low-grade internal faults can produce unbalanced current flow but little or no unbalanced voltage. Setting the impedance thresholds to half of the reactor or stator impedance (similar to AUTO) allows the directional element to easily determine if the unbalance current is caused by external faults, an internal turn-to-turn fault, or an internal series fault (open winding).

Stator applications are somewhat more complicated than reactor applications. See [18] for a more in-depth discussion of applying directional elements for machine stator protection.

AUTO cannot be used directly in such applications because the target sensitivity is typically a  $3I_2$  pickup (or  $3I_0$  pickup) equal to 5 to 15 percent of the rating [6] [7]. In such cases, an A2 factor of 0.10 will not be satisfied. For example, if the apparatus is rated 100 A ( $I_1$ ) and the scheme is set to 10 A ( $3I_2$ ), the ratio of  $I_2/I_1$  will be  $3.3 \text{ A}/100 \text{ A} = 0.033$ . The typical default A2 setting used in the automatic schemes of 0.10 will not allow the directional element to operate. In this case, the apparatus typically is constructed with very little natural unbalance, so lowering the A2 ratio setting to 0.03 is acceptable. The A2 ratio should always be set above the natural asymmetry of the system being protected. For stator applications where the loading can be varied, the A2 factor may only allow the scheme to operate when the machine is operating at reduced loading—even when the A2 ratio setting is lowered to its lowest possible setting.

## VIII. CONCLUSION

Impedance-based directional elements have many advantages over torque-based directional elements. They can provide excellent sensitivity to low-grade unbalanced faults when the thresholds are set with a dependability bias. The ability to adjust the thresholds gives the user a great deal of flexibility depending on the requirements of the application. This flexibility brought with it added complexity in applying these elements. To ease the burden of calculating the required settings, several automatic setting schemes were developed. However, the automatic schemes are built around basic assumptions that apply to transmission applications. If the application of the directional element does not fit these assumptions, the elements may not behave appropriately. This

paper gives guidelines for when to use and when not to use these automatic setting schemes.

The first automatic setting scheme in common usage (AUTO) only requires the impedance of the protected line to set the directional thresholds. This scheme has a dependability bias, and as is the case with dependability versus security, a dependability-biased protection system will be more susceptible to security failures.

To improve security, a second automatic setting scheme (AUTO2) was developed that removes any bias in the way the directional thresholds are set. However, this scheme requires the user to qualify the application by determining that the system source impedances exceed a minimum limit. Most applications meet the stated requirement of minimum source impedance, so using this automatic scheme without verifying that its use meets these minimum requirements rarely leads to issues. So, overall reliability is improved by making the industry aware of this second automatic scheme. This paper details just how easy it is to find the source impedances to verify the new scheme. This small added analysis that goes into coordinating relays, when taken in light of all of the other analysis, is not much added burden.

This paper also examines other setting rules for impedance-based directional elements. The analysis centered around one of the most challenging applications of directional elements—performance in transmission line pilot protection systems. In these protection systems, relays at each terminal of the line must work together. In pilot schemes, if one relay detects an external fault as forward, the other relay must reliably detect it as reverse or tripping will occur.

One key finding is that setting the impedance thresholds based on the electrical center of the system allows you to adjust the minimum sensitivity  $3I_2$  setting for both terminals based on expected  $3V_2$  error. If the thresholds are not based on the electrical center, the forward fault detector setting can be based on the remote relay's reverse impedance threshold to ensure that the forward element will never assert when the remote reverse element cannot. Table IV summarizes the 50QF setting guideline for each scheme. Adjusting the fault detector settings based on system impedances and the impedance threshold for the remote relay makes it possible to ensure secure application in the presence of an assumed amount of error. Being able to set the impedance-based threshold allows users to maximize sensitivity while also balancing security in any system. This is the reason we have a threshold setting.

While we have built the discussion using negative-sequence impedance directional elements, these concepts can also be applied to analyzing zero-sequence voltage-polarized directional elements as well. However, it is important to understand that the relationship of  $Z_{S0}$ ,  $Z_{L0}$ , and  $Z_{R0}$  can be very different than for  $Z_{S2}$ ,  $Z_{L2}$ , and  $Z_{R2}$  for any given line. The zero-sequence impedance of a line is typically around three times the positive and negative-sequence impedance of the line.

On the other hand, at stations with large generator step-up transformers or large autotransformers with delta tertiary windings, the zero-sequence source impedance can be much lower than the positive- and negative-sequence source impedance. To summarize, for any given application, the line impedance will tend to be higher, and the source impedances will tend to be lower relative to their negative-sequence counterparts. Consider this when applying the concepts presented in this paper to their zero-sequence impedance-based counterparts.

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## X. APPENDIX

For the following discussion, we assume the pole open condition is permanent. We are interested in two types of external pole open conditions: single-pole open and two-pole open. We examine single-pole open condition first.

### A. External Single-Pole Open Condition

External pole open conditions are commonly known to cause directional element performance issues for AUTO [16]. During a pole open condition, the  $I_2$  present can be quite small as it is a function of the load current. In strong systems with short lines, there is not very much impedance available to develop a strong  $V_2$  signal for these low current values. Reference [19] provides analysis for a sample system under single-pole and double-pole open scenarios within a protected line. They show that internal line switching can create strong enough  $I_2$  and  $V_2$  signals at each terminal and that each relay will declare forward and trip. In the example, both source positive- and negative-sequence impedances are  $1 \angle 90^\circ \Omega$  and the line is  $3 \angle 90^\circ \Omega$ . The zero-sequence impedances are all three times the positive-sequence impedances. In this simplification, the transfer branch that represents the rest of the interconnected network in parallel with the line of interest is neglected. Although the external pole open case is not covered, a quick manipulation of the circuit allows us to examine the external pole open case. Fig. 9 and Fig. 10 show the new location of the pole open condition, which is behind R1.

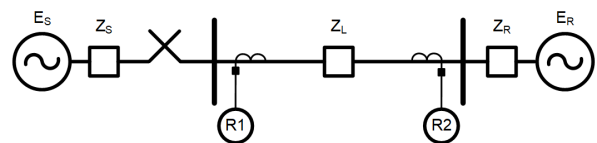


Fig. 9. External pole open condition

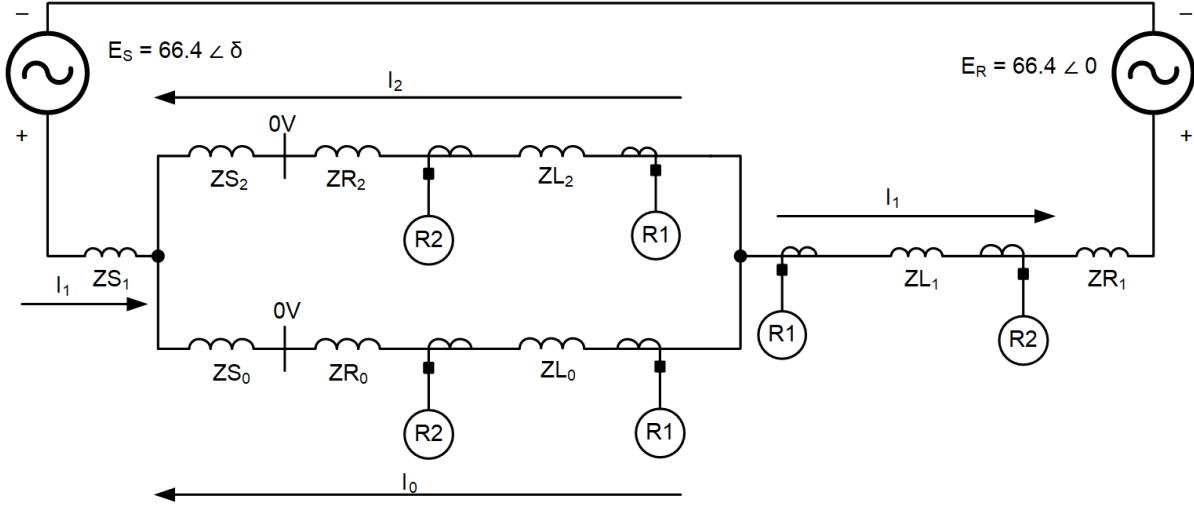


Fig. 10. External pole open condition symmetrical components

Moving the location of the open pole does not change the amount of current flowing in the system for this simplified case. Relay R2 sees the same voltages and currents as it does when the open pole is in the middle of line ZL. Relay R1 sees the same current as when the open pole was on the protected line, but now the voltage drop is a function of  $ZR_2 + ZL_2$ . As such, the only change seen for the internal pole open condition versus external pole open condition is the  $V_2$  voltage at Relay R1. This now becomes  $8.57\angle-79.15^\circ$  for the external pole open condition. If we calculate the apparent  $Z_2$  for Relay R1 and Relay R2, we see that  $Z_2$  at R1 =  $4\angle 90^\circ$  and  $Z_2$  at R2 =  $1\angle-90^\circ$ . Put another way, R1 measures a  $Z_2$  of  $ZR_2 + ZL_2$  and R2 measures a  $Z_2$  of  $-ZR_2$ , which is no different than an external shunt fault behind Relay R1. The pilot elements clearly see this simulated series fault as external to the line with R1 declaring reverse and R2 declaring forward. However, the  $3I_2$  current and  $3V_2$  voltage for a pole open condition can be very low compared to a shunt fault so that errors in these signals should not be neglected.

The load angle (angle between  $E_S$  and  $E_R$ ) used in [19] was 21.7 degrees. For their purpose, the authors were trying to determine the maximum unbalance currents that could flow in the line at maximum line rating. They chose the load angle to produce 5 A secondary of positive-sequence current based on the positive-sequence impedances given in their example. However, we are interested in the external fault security of these elements at a sensitive tripping setting, for example,  $3I_0 = 0.5$  A. If the load flow is reduced by lowering the load angle to about 1.7 degrees, the sequence quantity magnitudes in Table V are present at each terminal for the external pole open condition.

TABLE V  
SAMPLE SYSTEM MAGNITUDES FOR SINGLE  
POLE OPEN CONDITIONS AT A LOAD ANGLE OF  $1.7^\circ$

Quantity	R1	R2
$I_1$	0.394	0.394
$3I_0$	0.167	0.167
$3I_2$	0.5	0.5
$3V_2$	2.0	0.5

In the single-pole open condition, there is a current divider between the  $Z_2$  and  $Z_0$  network, much like a shunt phase-to-phase-to-ground fault. This is important, as the line zero-sequence impedance is higher than line negative-sequence impedance (in this example  $|Z_0| = 3 \cdot |Z_1|$ ). This means that the available zero-sequence current is always three times lower than the negative-sequence current for this out-of-zone pole open condition. If we assume a 67G element in a pilot scheme is set at 0.5 A, and the 67G element is directionalized by a 32ZQ element with a minimum forward pickup of  $3I_2 = 0.5$  A, then the lowest  $3I_2$  required for a trip condition during one-pole open conditions will be 1.5 A.

### B. Two-Pole Open Condition

In a two-pole open condition, the sequence networks are connected in series [19]. A two-pole open condition resembles a phase-to-ground fault in that all sequence currents will be equal and in phase.

In a two-pole open condition, the  $3I_1$ ,  $3I_2$ , and  $3I_0$  quantities will be equal, so a minimum  $3I_2$  of 0.5 A can lead directly to a trip via the pilot scheme.

For the example system, we find that a load angle of about 3.6 degrees produces a  $3I_2$  and  $3I_0$  of 0.5 A during a two-pole open condition. Not only is the zero-sequence current to negative-sequence current ratio favorable for operation, the range of load current that is favorable for operation has also increased. Table VI shows the key analog magnitude quantities for a reverse two-pole open condition.

TABLE VI  
SAMPLE SYSTEM MAGNITUDES FOR TWO-POLE OPEN  
CONDITION AT A LOAD ANGLE OF 3.6 DEGREES

Quantity	R1	R2
$I_1$	0.167	0.167
$3I_0$	0.5	0.5
$3I_2$	0.5	0.5
$3V_2$	2.0	0.5

### 1) Discussion

We selected the load angle as to intentionally arrive at 0.5 A of  $3I_2$ . Table V and Table VI show us that low levels of  $V_2$  are available at each terminal when the  $3I_2$  caused by the external pole open condition just meets the pickup level of the pilot tripping element. As  $ZR_2$  and  $ZL_2$  become smaller, the voltages available at each terminal become smaller. In strong systems with short lines, there is a risk for misoperation if R2 declares forward, but R1 fails to declare reverse. R1 can fail to declare reverse if there is a standing  $V_2$  error from the potential transformer that opposes the  $V_2$  developed in the system. Referring to Table V and Table VI, if there was an opposing  $3V_2$  error of 1.5 V at R1, the relay would see a  $3V_2$  of 0.5 V (rather than 2 V) and see a  $Z2$  value of  $1 \Omega$  (rather than  $4 \Omega$ ). If the relay was set using the AUTO scheme (biased for dependability), R1 would fail to declare reverse because  $Z2$  is less than the  $Z2R$  setting of  $ZL_2/2 + 0.1 \Omega$  (1.6  $\Omega$ ). If the relay was set using the AUTO2 scheme (not biased for either security or dependability) with a  $Z2R$  setting of 0.3  $\Omega$ , it will still reliably declare reverse at R1 and maintain pilot scheme security.

### C. Pole Open Conditions in Adjacent Parallel Lines

When two lines share a common bus at each terminal, an open pole on one line leads to a security concern on the adjacent line. Reference [13] shows that while the sign of the apparent impedance seen at each terminal for this external pole open condition is positive (indicating a reverse fault), it will be less than the line impedance ( $ZL_2$ ) at each terminal. Fig. 11 shows the pole open condition and the relays that have a security risk for this condition.

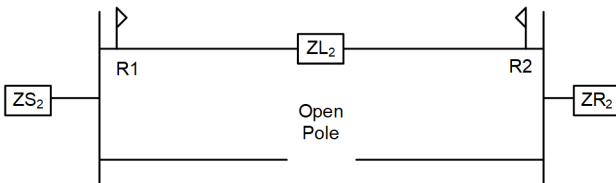


Fig. 11. Open pole on parallel line

The apparent  $Z_2$  measured at R1 and R2 for this condition is given in Table VII.

TABLE VII  
APPARENT  $Z_2$  AT R1 AND R2 FOR ADJACENT POLE OPEN CONDITION

Relay	$Z_2$ Apparent
R1	$+ \left[ \frac{ZS_2}{ZS_2 + ZR_2} \right] \cdot ZL_2$
R2	$+ \left[ \frac{ZR_2}{ZS_2 + ZR_2} \right] \cdot ZL_2$

A pole open condition on the adjacent line will produce an apparent  $Z_2$  that can be as low as  $0.5 \cdot ZL_2$  in each relay when  $ZS_2 = ZR_2$ . This means that a relay using the AUTO scheme ( $0.5$  of  $ZL_2$ ) for settings has no margin to maintain security for this external pole open condition. As  $ZS_2$  and  $ZR_2$  diverge, one end will see an apparent  $Z_2$  less than  $0.5 \cdot ZL_2$  and the other end will see an apparent  $Z_2$  greater than  $0.5 \cdot ZL_2$ . So, while one relay moves closer to a forward declaration, the other relay moves to a more reverse declaration, meaning security is better for cases in which  $ZS_2$  and  $ZR_2$  are different. If the AUTO scheme is used for setting  $Z2F$  and  $Z2R$  in parallel line applications, it is recommended to manually calculate the  $Z2R$  for each terminal using a k-factor of 0.25 rather than 0.5 to provide security margin for this case.

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## XII. BIOGRAPHIES

**Ryan McDaniel** earned his B.S. in computer engineering from Ohio Northern University in 2002. In 1999, he was hired by American Electric Power (AEP) as a relay technician, where he commissioned protective systems. In 2002, he began working in the Station Projects Engineering group as a protection and control engineer. His responsibilities in this position included protection and control design for substation, distribution, and transmission equipment as well as coordination studies for the AEP system. In 2005, he joined Schweitzer Engineering Laboratories, Inc. and is currently a senior field application engineer. His responsibilities include providing application support and technical training for protective relay users. Ryan is a registered professional engineer in the state of Illinois and a member of the IEEE.

**Michael Thompson** received his B.S., magna cum laude, from Bradley University in 1981 and M.B.A. from Eastern Illinois University in 1991. Upon graduating, he served nearly fifteen years at Central Illinois Public Service (now AMEREN). Prior to joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2001, he was involved in the development of several numerical protective relays while working at Basler Electric. He is presently a fellow engineer at SEL Engineering Services, Inc. He is a senior member of the IEEE, member of the IEEE PES Power System Relaying and Control Committee (PSRCC), past chairman of the Substation Protection Subcommittee of the PSRCC, and recipient of the Standards Medallion from the IEEE Standards Association in 2016. Michael is a registered professional engineer in six jurisdictions, was a contributor to the reference book *Modern Solutions for the Protection Control and Monitoring of Electric Power Systems*, has published numerous technical papers and magazine articles, and holds three patents associated with power system protection and control.