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 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 elements forward or reverse in the easy-to-understand units 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 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. After examining the existing automatic setting schemes, several other rules-based schemes are proposed and compared.

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 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.

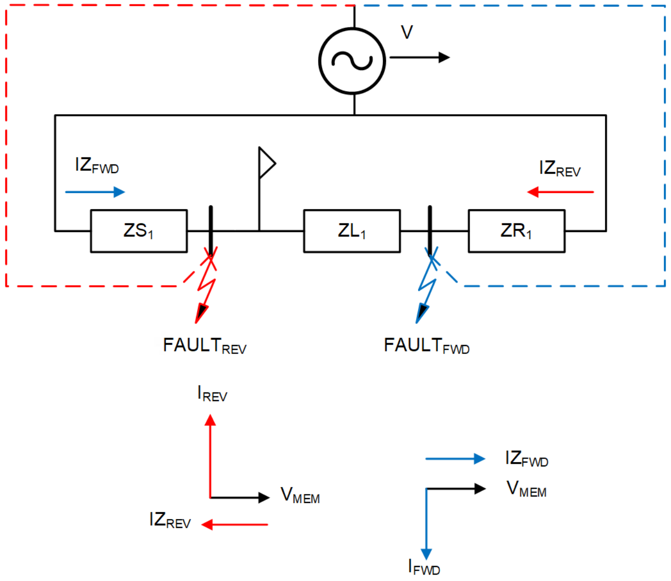


Fig. 1. Forward versus reverse fault phasors

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.

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

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| • |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).

$$\begin{aligned}&|V|\bullet|I|\bullet \mathrm{COS}(\angle V - \angle IZ) > VA_{MIN}\quad (\text{Forward})\\&|V|\bullet|I|\bullet \mathrm{COS}(\angle V - \angle IZ) < -VA_{MIN}\quad (\text{Reverse})\\&-VA_{MIN} < |V|\bullet|I|\bullet \mathrm{COS}(\angle V - \angle IZ) < VA_{MIN}\\&\qquad (\text{No\_Direction})\end{aligned} \tag{2}$$

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. However, 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 in 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 though 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.

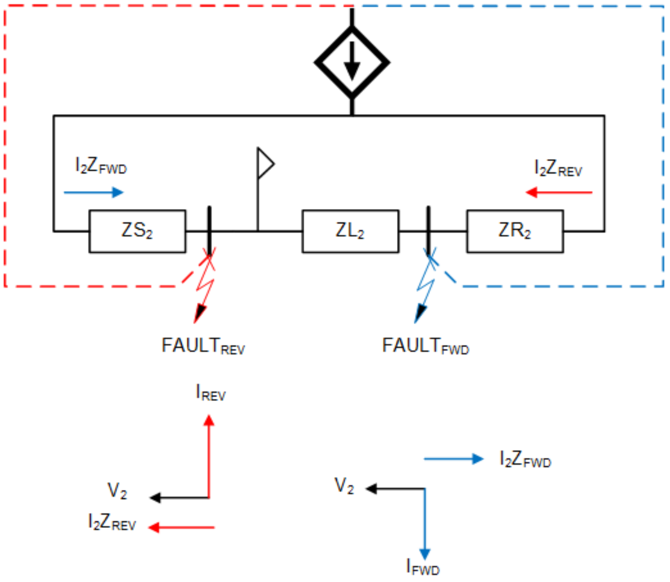


Fig. 2. Negative-sequence network reverse fault versus forward fault

A simple revision can be made to (2) work for the negative-sequence network. We define a torque-based negative-sequence element as 32TQ (3), where $Z = 1\angle ZL_2$.

$$\begin{aligned}&|V_2|\bullet|I_2|\bullet \mathrm{COS}(\angle V_2 - \angle I_2 Z) > VA_{MIN}\quad (\text{Reverse})\\&|V_2|\bullet|I_2|\bullet \mathrm{COS}(\angle V_2 - \angle I_2 Z) < -VA_{MIN}\quad (\text{Forward})\\&-VA_{MIN} < |V_2|\bullet|I_2|\bullet \mathrm{COS}(\angle V_2 - \angle I_2 Z) < VA_{MIN}\\&\qquad (\text{No\_Direction})\end{aligned} \tag{3}$$

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 angle relationship between I_2 and V_2 will not limit the torque output. This means that high R faults will still produce V_2 and I_2Z relationships that are either near in phase (reverse) or near out of phase (forward).
- 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 elements do not need to be set above load current but do need to be set above system asymmetry (i.e., untransposed lines and unbalanced loads).
- 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 presence 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) is converted to an impedance-based element by dividing it by $|I_2|^2$. We define an impedance-based negative-sequence element as 32ZQ (4).

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

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

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

This simple manipulation allows a 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 illustrate the difference between these two approaches under conditions of low source impedance and high fault resistance, we compare the 32TQ and 32ZQ for a typical 50QF setting (minimum $3I_2$ overcurrent for forward declaration) of 0.5 A in the Z_2 impedance plane (see Fig. 3). In the following discussion, we will use magnitudes only with the understanding that forward faults produce negative torque and negative source impedance. Referring to IX, the minimum VA requirement for one implementation of the 32TQ element is 0.9 VA ($3V_2 \bullet 3I_2$). This means that for the minimum $3I_2$ current of 0.5 A, the minimum $3V_2$ that must be present is 1.8 V (0.5 A • 1.8 V = 0.9 VA). That plots as 1.8 V/0.5 A = 3.6 Ω in the Z_2 plane (blue dot), and the 32TQ for this case is represented as a blue circle with a 3.6 Ω diameter for 1.8 V and 0.5 A. For comparison, we also plot the 32TQ characteristic in the Z_2 plane at 1.5 V of $3V_2$ as well. To meet the 0.9 VA threshold with this reduced voltage, the torque element now requires at least $3I_2$ = 0.6 A. That plots as a circle with a 2.5 Ω diameter (1.5 V/0.6 A = 2.5 Ω source impedance) in the Z_2 plane, which is represented by the red circle. We see that an apparent Z_2 impedance of 3 Ω at 1.5 V is just outside the reach of this red circle because only 0.5 A is available (not the 0.6 A required). When we plot the 32TQ element in the Z_2 plane for a required minimum sensitivity, it becomes a series of circles that grows larger with higher $3V_2$ (higher source impedance) at the relay location.

To compare the torque element for these two cases to the 32ZQ impedance element, we show a typical forward 32ZQ threshold (Z2F) at –0.3 Ω. In this example, the 32ZQ characteristic is shown as a straight horizontal line (black line) in the Z_2 impedance plane. In practical implementations, this threshold may be dynamic.

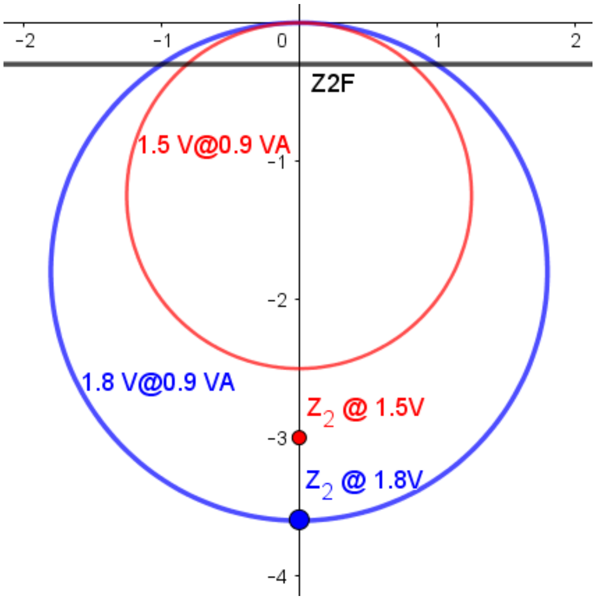


Fig. 3. 32TQ characteristic 1.5 V and 1.8 V $3V_2$ with $3I_2$ = 0.5 A

We can conclude that higher current is required for lower available voltage (lower source impedance) for the 32TQ directional element to operate. For example, to operate with 1.8 V of $3V_2$ available, the Z_2 impedance must be within the blue circle. This happens when $3I_2$ is greater than our desired minimum sensitivity of 0.5 A. This means the maximum sensitivity of the 32TQ element is achieved for a source impedance greater than 3.6 Ω. For source impedances less than

3.6 Ω, more than 0.5 A will be required for a directional declaration.

For the 32ZQ to operate, the measured Z_2 impedance must be below the line intersecting the Z2F setting of –0.3 Ω (black line). The 32ZQ will operate for any voltage as long as the apparent Z_2 is lower than –0.3 Ω. This means that the 32ZQ has better sensitivity than 32TQ for ZS_2 values between 3.6 Ω and 0.3 Ω.

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 the 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. Common practice has been to bias the element in the forward direction for dependability, but it can also be biased in the reverse direction for security.

B. Characteristic Shaping

Because we know that the apparent Z_2 will plot closely along the line impedance angle, we can remove certain areas of the Z_2 plane and forgo making a directional decision. Fig. 4 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 [1] uses an adaptive threshold that creates a hyperbola in the Z_2 plane (black lines), while Relay B [3] uses line angle comparators in conjunction with (5) to shape a more restrictive operation area of the relay in the Z_2 plane (blue lines). 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:

- PT 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 inverter-based resources

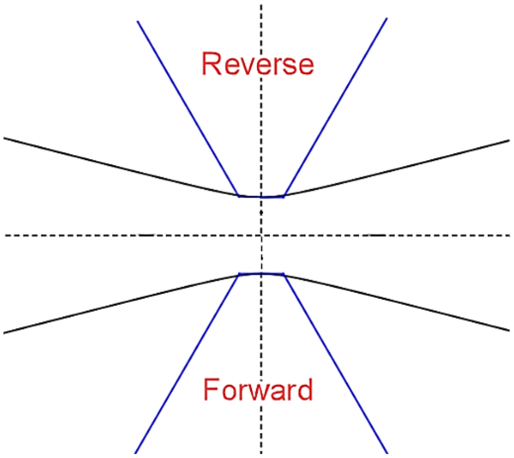


Fig. 4. Example operating characteristics in the Z_2 plane

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 unbalance current and voltage will appear on the system, even during balanced load flow and balanced (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
ZR_2	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 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 these 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 Ω or 0.2 Ω secondary (for a 5 A nominal relay). The forward and reverse negative-sequence fault detectors are set to a low value, typically 0.6 A and 0.4 A, respectively. This provides a coordination margin of 1.5 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 Ω (see Fig. 5 in [4]).

In this scheme, $Z_2 = 0\ \Omega$ is in the forward decision area of the characteristic. That is, it can declare a forward fault, even in the absence of any $3V_2$ voltage, 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 [5] and generator stators [6]. In turn-to-turn fault applications, unbalance current caused by external faults are accompanied by unbalanced voltage. On the other hand, these 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 allows the directional element to easily determine if the unbalance current is caused by external faults or by an internal turn-to-turn fault.

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 voltage transformer (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 was 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 to make a decision 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. Generally, if the line is less than about 0.6 Ω secondary, half of the length of the line does not provide enough separation between forward and reverse boundaries when considering errors that affect the Z_2 measurement.

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, ZL_1–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 [7] provides guidance on how to manually calculate Z2F and Z2R settings for series-compensated lines. Reference [8] details a case when a line protected by a 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 other end of the line was set very sensitively and saw the remote fault. The local reverse directional element measured a positive Z_2 (the fault was reverse), 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 [8] also had other contributing factors, such as error in the measurement of Z_2, caused by the standing unbalance on the bus.

Another case when using the AUTO scheme 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. Some may sum the impedance to the tap point, plus the lowest impedance of the two branches to the other two terminals and take half of that value. That should work for the N-1 of the largest tap branch being out of service. However, in some cases, the two branches beyond the tap point in parallel may result in a Z_2 measurement smaller than this value. Appendix A of [9] 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 [10] 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.

$$50QF_{R1} > M \bullet \left(50QR_{R2} + 50QR_{R3}\right) \qquad (6)$$

where:

$50QF_{R1}$ is the local pilot tripping fault detector.

$50QR_{R2}$ and $50QR_{R3}$ 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 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 or mutual coupling). Reference [11] 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
- Series-compensated lines; manually calculate Z2F and Z2R thresholds based on guidance in [7]
- Three-terminal lines; manually calculate Z2F, Z2R, 50QF, and 50QR thresholds based on guidance in [9] and [10]
- Applications of zero-sequence impedance-based elements with mutual coupling; manually calculate Z0F and Z0R based on guidance in [11]

Some of these applications where AUTO is not recommended can be better addressed by simply using AUTO2, which is discussed next in this paper.

C. The Second Automatic Setting Scheme (AUTO2)

1) AUTO2 Scheme Summary

One of the key attributes of the first automatic settings method 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 [4]. AUTO2 sets the Z2F and Z2R thresholds to –0.3 Ω and +0.3 Ω 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 Ω secondary [4]. 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 [12], opening the line connects the remote source impedance via the transfer impedance branch to the bus behind the relay, as shown in Fig. 5 (which is similar to Fig. 2 in [12]). The transfer impedance branch represents the interconnected networked transmission grid in parallel with the line of interest. The parallel impedance of ZS and (ZR + ZT) 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.

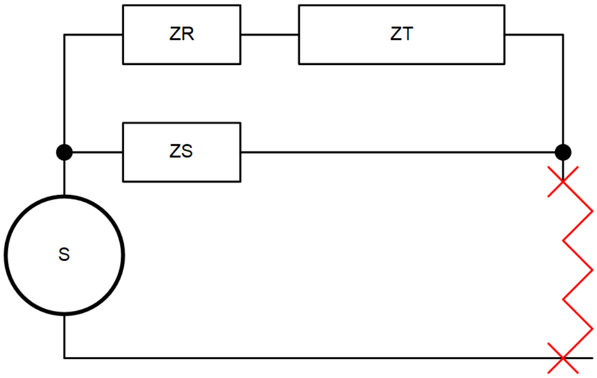


Fig. 5. Source impedance for a forward fault with the remote end open

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 Ω after converting the values to secondary, the AUTO2 setting for Z2F = –0.3 Ω is acceptable.

The 0.5 Ω minimum for the Z2R threshold set to +0.3 Ω secondary can often be determined by simply checking that ZL_2 is greater than 0.5 Ω. 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.

The 0.5 Ω minimum source impedance requirement to use 0.3 Ω thresholds implies a recommended dependability margin of at least 0.6 per unit. If the source impedances are lower, one might be tempted to reduce the thresholds below 0.3 Ω. This is not recommended because this leaves little room to accommodate error in the $3V_2$ measurement from standing unbalance and VT errors. We notice that AUTO2 gives a no-decision zone of 0.6 Ω instead of 0.1 Ω. We will delve into errors more thoroughly in Section V. So, the minimum 0.3 Ω magnitude settings are actually a security limit. Instead, the general recommendation is that if the "non-biased" automatic settings scheme (AUTO2) cannot be used because one or both of the sources are too strong; the user is recommended to go back to the "dependability-biased" automatic setting scheme (AUTO). This begs the question: what about other possible schemes besides dependability biased or non-biased? We will examine that in Section IV.

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 (32ZG elements). The process of checking that the magnitude of the source impedance for forward and reverse faults exceeds 0.5 Ω 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.
- Three-terminal lines. Manually calculate 50QF and 50QR thresholds based on guidance in [10]. It is acceptable to use the AUTO2 Z2F and Z2R thresholds if applicable.

D. General Problems With Using Automatic Methods

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 method 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 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 these 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 such as for a stator or reactor turn-to-turn fault scheme, the target sensitivity is typically $3I_2$ pickup equals 10 percent to 15 percent of rating [5]. 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 A/100 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.

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 are being used to sense low-grade turn-to-turn faults in apparatuses that require the positive-sequence restraint ratio to be lowered from the default ratio settings in the automatic scheme

E. k • ZS_2 Rules-Based Scheme

Before going into the additional possible rules-based setting schemes, we want to cover another recommended scheme for selecting Z2F and Z2R settings [3]. This is not an automatic scheme. The user is expected to calculate settings and enter them into the relay. It requires knowing ZS_2, which the relay does not know.

We will call this scheme the k • ZS_2 scheme. It is simple and straight forward to use. 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, per (7). The lowest ZS_2 is obtained by using the same technique as described for qualifying use of the AUTO2 scheme.

$$Z2F = -k \bullet ZS_2 \tag{7}$$

The simple rule for setting Z2R, the reverse threshold, is to multiply the line impedance by a k-factor, again recommended to be between 0.25 and 0.5, per (8).

$$Z2R = k \bullet ZL_2 \tag{8}$$

We notice that this rule is similar to AUTO2 in that it is not biased forward or reverse. The main difference between the k• Z S_2 method and AUTO2 is that, in weaker systems ($ZS_2 >$ 0.6 Ω) or longer lines ($ZL_2 >$ 0.6 Ω), the no-decision zone gets larger, which helps accommodate more standing $3V_2$ error. However, in applications with low source impedance and/or short lines, the no-decision zone may get very small where issues with the $3V_2$ error can become significant.

IV. ADDITIONAL THRESHOLD BIASING OPTIONS

As mentioned previously, the authors were discussing the two automatic schemes plus the k • ZS_2 methods 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 all the options to consider for the directional threshold settings. For now, we ignore using overcurrent supervision settings to bias a scheme, but we will address this 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)

We then determined that we should have columns for all the combinations of these three attributes for strong terminal versus weak terminal, as you might choose a different rule for the strong and for the weak (e.g., strong terminal biased dependable and weak terminal not biased). Of course, there may be similar permutations for both terminals weak and both terminals strong. From here, we threw out the combinations that were not logical. We also looked at variations, such as offsetting the center of the no-decision zone from $Z_2 = 0$ a little bit.

The results of this exercise are shown in Table II. Including the existing two automatic schemes, we added four others to examine further for a total of six combinations. We gave each possible automatic scheme a number for discussion purposes. In Table II, we equate a forward bias equaling dependability and a reverse bias equaling security.

TABLE II
PROPOSED AUTOMATIC SETTING SCHEMES

Scheme	Bias	Z2F Rule	Z2R Rule	Limit
AUTO	Forward	0.5 • ZL_2	Z2F + 0.1 Ω	$ZL_2 > 0.6$ Ω
AUTO2	None	–0.3 Ω	+0.3 Ω	$ZS_2 > 0.5$ Ω $ZL_2 + ZR_2 > 0.5$ Ω
AUTO3	Reverse	–0.3 Ω	–0.2 Ω	$ZS_2 > 0.5$ Ω
AUTO4	Strong Terminal Forward	0.2 Ω	0.3 Ω	$ZL_2 + ZR_2 > 0.5$ Ω
	Weak Terminal Reverse	–0.3 Ω	–0.2 Ω	$ZS_2 > 0.5$ Ω
AUTO5	Forward	0.2 Ω	0.3 Ω	$ZL_2 + ZR_2 > 0.5$ Ω
AUTO6	Forward	0.0 Ω	0.1 Ω	NA

Another concern that we wanted to examine was accommodating the standing $3V_2$ from VT errors and natural system unbalances. A version of AUTO2 that used +/–0.1 Ω thresholds had been recommended [13] before AUTO2 was solidified using +/–0.3 Ω thresholds [4]. We assumed that this change was to provide better tolerance for $3V_2$ errors. We had also seen the slightly dependability-biased AUTO6 scheme used by some practitioners.

A. Discussion of Table II

We will examine each of these methods and why they made the table for further consideration. All of the new AUTO schemes (3–6) use fixed thresholds relative to $Z_2 = 0$ similar to AUTO2. For all of these, we assume the same restriction of applicability that the source impedance must be greater than 0.5 Ω for the side with the no-decision boundary farthest from zero. AUTO6 is an exception to this, as will be explained. AUTO and AUTO2 were discussed in detail in Section III and are not discussed further here.

1) AUTO3: Bias Both Terminals 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. If both terminals of a pilot scheme declare reverse for small $3I_2$ levels with a standing $3V_2$ error, that would be a good thing.

2) AUTO4: Bias the Two Terminals Differently

Security could also be enhanced if one terminal is biased reverse and the other forward. The pilot schemes require both terminals to assert forward to get a trip, so judiciously biasing only one terminal forward should be more secure than biasing both terminals forward (AUTO). Because the strong terminal is the one that is dependability-challenged when using sequence component signals, it makes sense to bias the strong terminal forward and the weak terminal reverse. The opposite combination was thrown out as not logical to pursue.

3) AUTO5: Bias Both Terminals Forward But by a Small Amount

This combination 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. Further, if the line impedance is greater than 0.5 Ω, no fault study is required to determine source impedances to use it. It has some accommodation for standing $3V_2$ errors as well. This option might be considered to take the best attributes of AUTO and AUTO2.

4) AUTO6: No Bias But Slightly Favoring Forward

The only place this option might be useful is in applications with extremely strong buses at both terminals and with a very short line. We try to accommodate dependability by placing the forward threshold at zero. We try to accommodate security by placing the reverse threshold at the smallest increment allowed. This scheme would be very susceptible to any standing $3V_2$ errors during conditions of low $3I_2$ flow. Such an application should probably not be protected by a directional-based scheme. Line current differential would be a better choice.

B. The System Center Method

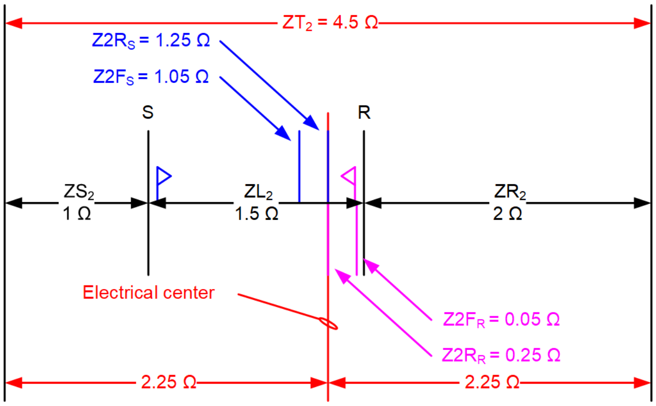
This is an additional scheme that the authors are aware of that deserved further examination. The setting scheme is described in Appendix A of [8]. The system center scheme requires determining all three of the impedances of interest (ZS_2, ZL_2, and ZR_2) and setting the Z2F and Z2R thresholds at each terminal such that the decision point between forward and reverse for both relays is at the electrical center of the system. When compared to AUTO, which required no fault studies at all, this method 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 method 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.

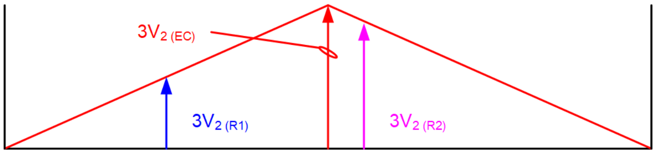
See Fig. 6 for an example. In this example, Terminal S is stronger with $ZS_2 = 1\ \Omega$. Terminal R is weaker with $ZR_2 = 2\ \Omega$. The total impedance of the system is calculated using (9).

$$ZT_2 = ZS_2 + ZL_2 + ZR_2$$
$$ZT_2 = 1.0\Omega + 1.5\Omega + 2.0\Omega = 4.5\Omega \tag{9}$$

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. If either relay declares forward because of $3V_2$ error while the other does not declare reverse, pilot tripping will occur.



(a) Impedance diagram



(b) $3V_2$ Voltage profile

Fig. 6. Unbalanced fault at electrical center of the system

$$Z2R_{(S)} = \frac{ZT_2}{2} - ZS_2$$
$$Z2R_{(S)} = \frac{4.5\Omega}{2} - 1.0\Omega = 1.25\Omega \tag{10}$$

$$Z2R_{(R)} = \frac{ZT_2}{2} - ZR_2$$
$$Z2R_{(R)} = \frac{4.5\Omega}{2} - 2.0\Omega = 0.25\Omega \tag{11}$$

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

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

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

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 1 V. 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.

$$\begin{aligned} 50QF_S &\geq \frac{3V_{2(ERROR)}}{ZS_2 + Z2F_{(S)}} \\ 50QF_S &\geq \frac{1V}{1\Omega + 1.05\Omega} \geq 0.49A \end{aligned} \tag{14}$$

$$\begin{aligned} 50QF_R &\geq \frac{3V_{2(ERROR)}}{ZR_2 + Z2F_{(R)}} \\ 50QF_S &\geq \frac{1V}{2\Omega + 0.05\Omega} \geq 0.49A \end{aligned} \tag{15}$$

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 several 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 AUTO4, where the strong terminal is biased forward and the weak terminal is biased reverse.

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.

C. The True Center Method

Finding the electrical center of the system and setting the thresholds near the center point on the system is a good balance between dependability and security. The method mentioned in the previous section still biases the overall directional scheme towards security by finding the electrical center and setting Z2R at this point. Z2F is set at –0.2 Ω of the electrical center. This means that for a forward fault as seen from Terminal S, the measured Z_2 impedance of –1 Ω is 2.05 Ω from the Z2F setting of 1.05 Ω. For a reverse fault as seen from Terminal S, the measured impedance will be 3.5 Ω, which is 2.25 Ω from the Z2R setting of 1.25. This means the margin for a forward fault (2.05 Ω) is slightly less than the margin for a reverse fault (2.25 Ω). The scheme is slightly biased towards security.

A slight variation in this method is to provide no bias and simply set the Z2F and Z2R threshold such that they straddle the electrical center. If we assume that Z2R must be set 0.1 Ω greater than Z2F, then we can set the thresholds as shown in (16) and (17).

$$Z2F_{(S)} = \frac{ZT_2 - 0.1}{2} - ZS_2 \tag{16}$$

$$Z2R_{(S)} = Z2F_{(S)} + 0.1\Omega \tag{17}$$

In the sample system in Fig. 6, we will end up with a Z2F = 1.2 Ω and a Z2R =1.3 Ω at Terminal S. This will provide a 2.2 Ω margin for forward and reverse faults, giving balance between security and dependability. With the thresholds at the true electrical center of the system, you can set the 50QF setting based on forward fault information (18) or reverse fault information (19). Equation (20) allows you to set the local 50QF to only assert forward for an external fault that the remote terminal can safely declare reverse for. Equation (20) is very important in systems in which the thresholds are not at the system center.

$$50QF_S \geq \frac{3V_{2(ERROR)}}{ZS_2 + Z2F_{(S)}} \tag{18}$$

$$50QF_S \geq \frac{3V_{2(ERROR)}}{ZR_2 + ZL_2 - Z2R_{(S)}} \tag{19}$$

$$50QF_S \geq \frac{3V_{2(ERROR)}}{ZS_2 + ZL_2 - Z2R_{(R)}} \tag{20}$$

With some manipulation, you can set 50QF regardless of the thresholds when the thresholds are at the electrical center (21).

$$50QF_S \geq \frac{2 \bullet 3V_{2(ERROR)}}{ZS_2 + ZL_2 + ZR_2 - 0.1\Omega} \tag{21}$$

When the thresholds are set at the center of the system, all four equations (18), (19), (20), and (21) produce equal settings. If thresholds are not based on the electrical center of the system, then (20) should be used to set 50QF at each terminal based on the Z2R setting at the remote terminal. When reviewing security and dependability in the next section, we will be reviewing the unbiased true center method instead of the system center method covered in Section IV Subsection B.

V. Security and Dependability Analysis of Various Threshold Settings in Pilot Protection Applications

The AUTO2 setting philosophy of excluding Z_2 = zero from the forward or reverse decision areas was originally applied at a utility-industrial interface for a scenario in which the line impedance was not known [13]. In this case, the Z2F and Z2R threshold were set at –0.1 Ω and 0.1 Ω respectively. A newer version of this setting philosophy (Z2F = –0.3 Ω, Z2R = 0.3 Ω) is now widely applied for transmission line protection, including lines with pilot protection. In a pilot protection application, two relays must work in tandem to securely detect external faults and dependably detect internal faults. This application is significantly different than the applications in [4] and [13]. Is AUTO2 still the preferred option in pilot protection applications? In this section we will focus on security performance of various versions of AUTO 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 [14]. To maintain security, the local pilot blocking distance elements must be set more sensitively that 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. Often this case is supposedly covered by simply setting the overcurrent supervision for a reverse declaration (50QR) lower than the overcurrent supervision for a forward declaration (50QF). What is the worst-case scenario to ensure directional element coordination?

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. We will discuss pole open conditions as they are often cited as issues for directional element security [15]. 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.

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.

1) External Single-Pole Open Condition

External pole open conditions are commonly known to cause directional element performance issues for AUTO [15]. 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 [16] 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 $1\angle 90°$ Ω and the line is $3\angle 90°$Ω. 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. 7 and Fig. 8 show the new location of the pole open condition.

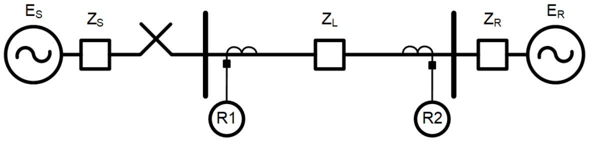


Fig. 7. External pole open condition

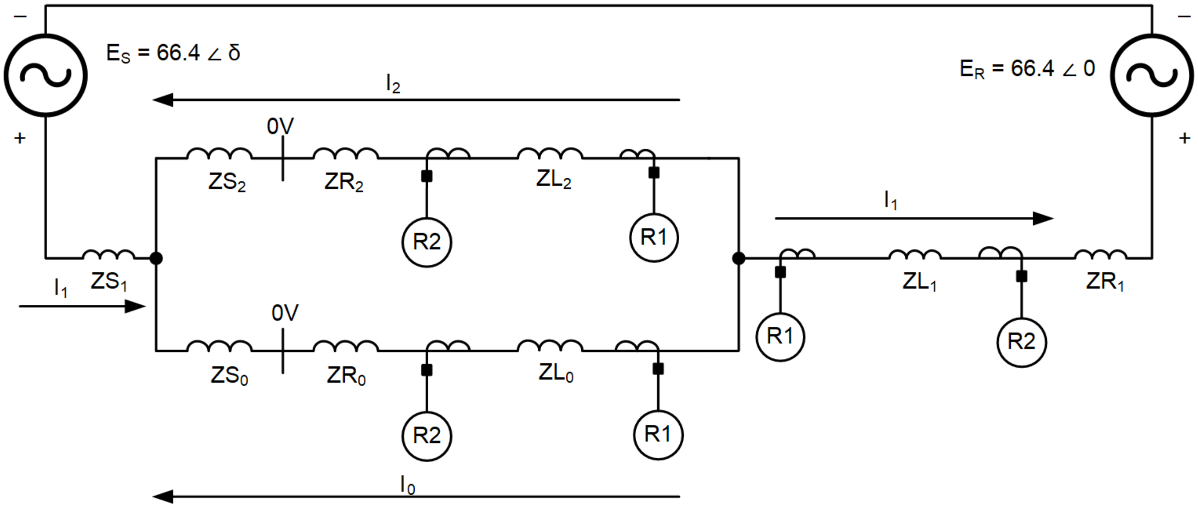


Fig. 8. External pole open condition symmetrical components

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 $8.57\angle{-79.15}°$ 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 = $4\angle 90°$ and Z_2 at R2 = $1\angle{-90}°$. 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 as an external fault 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 neglected.

The load angle (angle between E_S and E_R) used in [16] 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, 3I0 = 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 III are present at each terminal for the external pole open condition.

TABLE III
SAMPLE SYSTEM MAGNITUDES FOR SINGLE POLE OPEN CONDITIONS AT A LOAD ANGLE OF 1.7°

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 $|Z_0| = 3 \bullet |Z1|$). 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.

2) Two-Pole Open Condition

In a two-pole open condition, the sequence networks are connected in series [16]. 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 IV shows the key analog magnitude quantities for a reverse two-pole open condition.

TABLE IV
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

3) Discussion

We selected the load angle as to intentionally arrive at 0.5 A of $3I_2$. We will use forward fault detector settings for $3I_2 = 0.5$ A throughout the remaining discussion. This is a typical sensitive setting and serves the purpose of illustrating issues that challenge the various setting methods. Table III and Table IV 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 III and Table IV, 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 Ω (rather than 4 Ω). If the relay was set using the AUTO method (biased for dependability), R1 would fail to declare reverse because Z2 is less than the Z2R setting of $ZL_2/2 + 0.1$ Ω (1.6 Ω). If the relay was set using the AUTO2 method (not biased for either security or dependability) with a Z2R setting of 0.3 Ω, 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 [17] 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. 9 shows the pole open condition and the relays that have a security risk for this condition.

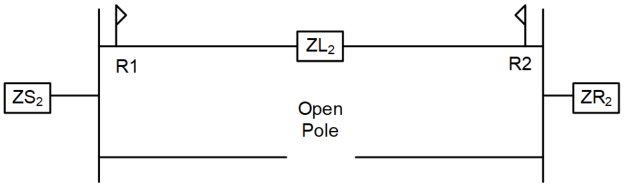


Fig. 9. Open pole on parallel line

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

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

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

A pole open condition on the adjacent line will produce an apparent Z_2 that can be as low as $0.5 \bullet ZL_2$ in each relay when $ZS_2 = ZR_2$. This means that a relay using the AUTO method (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 $0.5 \bullet ZL_2$ and the other end will see an apparent Z_2 greater than $0.5 \bullet ZL_2$. 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 method 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.

D. *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 plausible $3V_2$ 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 VI.

TABLE VI
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 VI, we will look at 64 different combinations of error (2^6) using (22), where $\alpha = 1\angle 120°$.

$$3V_2 = VA + \alpha^2 \bullet VB + \alpha \bullet VC \qquad (22)$$

The error results are plotted in the scatter plot shown in Fig. 10, 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.

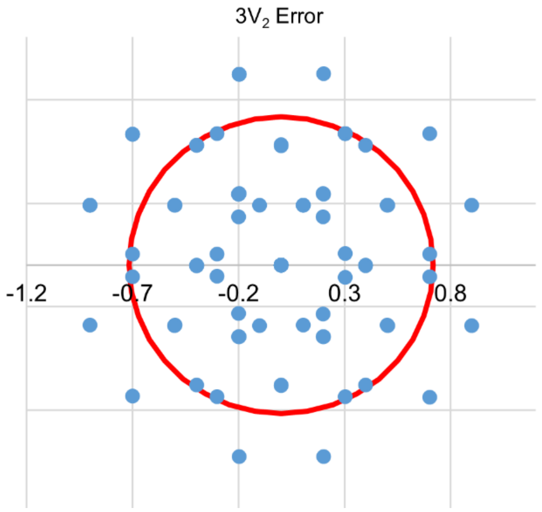


Fig. 10. Scatter plot of $3V_2$ error

The maximum allowable $3V_2$ error for a set of 0.3 accuracy class voltage transformers is about 0.95 V.

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

We can calculate the apparent Z_2 error at the $3I_2$ pickup level (50QF) for various $3V_2$ errors using (23).

$$Z2_{ERROR} = \frac{3V_{2(ERROR)}}{50QF} \qquad (23)$$

This shows as that for a $3V_2$ error of 1 V and minimum $3I_2$ current of 0.5 A, a $Z2_{ERROR}$ of 2 Ω is present. As 50QF is raised, the $Z2_{ERROR}$ becomes smaller and less of a concern. Depending on the sign of the error and the direction of $3I_2$ current flow, the relay will become directionally biased based on the $3V_2$ error sign. Table VII shows the possible combinations. We assume that the $3V_2$ error is either in phase or out of phase with the negative-sequence replica current.

TABLE VII
POSSIBLE BIASING ERRORS

$3V_2$ Error	$3I_2$ Current Direction	Z_2 Bias Sign	Z_2 Bias
+	Reverse	-	Forward
+	Forward	+	Reverse
-	Reverse	+	Reverse
-	Forward	-	Forward

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 (24).

$$\begin{aligned} a)\ Z2_{\text{Reverse}} &= ZR_2 + ZL_2 \pm \frac{3V_{2(ERROR)}}{3I_2} \\ b)\ Z2_{\text{Forward}} &= -ZS_2 \pm \frac{3V_{2(ERROR)}}{3I_2} \end{aligned} \qquad (24)$$

For an external event in which we want the pilot scheme to restrain, we are interested in the conditions that reduce security. For an external event, Rows 1 and 4 are more likely to declare forward. Referring back to Fig. 7, the worst-case scenario for security for the pole open condition behind R1 is if R1 has a $+3V_2$ error and R2 has a $–3V_2$ 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 that biases each relay forward. The calculation for Z_2 apparent at R1 is given by (24a) and R2 is given by (24b), where $–ZS_2$ is replaced with $–ZR_2$.

Fig. 11 shows a plot of the Z_2 apparent impedance from each end of the line with AUTO thresholds plotted.

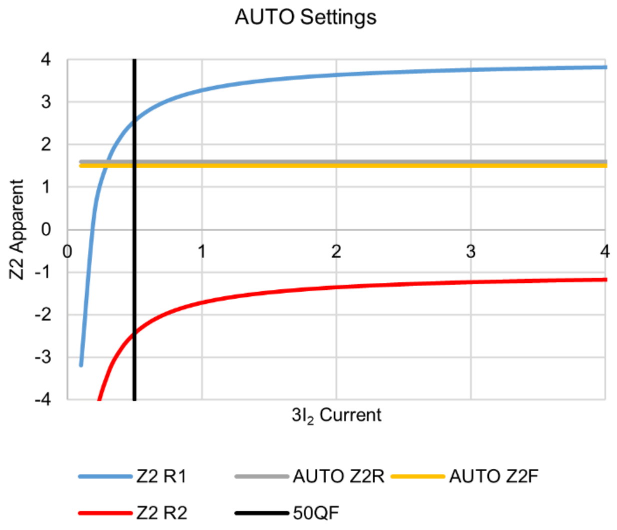


Fig. 11. Apparent Z_2 for example system

We can see that for low current values, each terminal underestimates the true value of Z_2. In this case, AUTO setting thresholds are secure because each relay declares the correct direction for all current levels above 0.5 A. However, below 0.5 A of $3I_2$, it becomes less likely that R1 will declare reverse, jeopardizing pilot scheme security. We can also recognize that the closer Z_2 R1 and Z_2 R2 are together in the Z_2 plane, the more risk we have for a misoperation. This occurs when ZL_2 and ZR_2 are small. Fig. 12 is the same plot, but this time with ZR_2 decreased from 1.0 Ω to 0.5 Ω and ZL_2 is decreased from 3.0 Ω to 1.0 Ω.

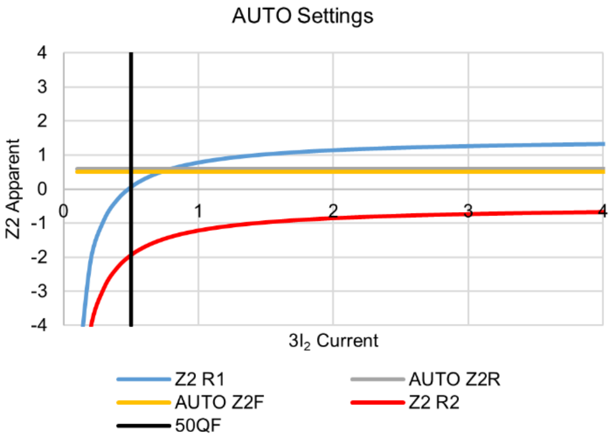


Fig. 12. Security concern for strong system with a short line AUTO setting

We can see that, for this scenario, it is possible that R1 will fail to declare reverse for $3I_2$ current just above 0.5 A. We can use (20) from the perspective of R2 to find the minimum 50QF level to remain secure. We substitute ZR_2 for ZS_2 and use a Z2R of 0.6 (1 Ω/2 + 0.1 Ω). For the system above, a 50QF setting of 0.8 A in R2 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.

F. *Security Comparison of Threshold Methods*

We can compare the security margins of various versions of threshold setting methods presented in Sections III and IV by simply comparing the minimum line length each setting requires to be secure. The shorter the allowable line length, the more secure the setting. AUTO2 requires a minimum ZR_2 of 0.5 Ω to be applied. We rearrange (24a) to find the minimum ZL_2 for a reverse declaration at R1 when ZR_2 = 0.5 Ω and 50QF at R2 position = 0.5 A under increasing $3V_2$ errors using (25) for AUTO(1–5) methods, (26) for AUTO, and (27) for the true center method. The AUTO method uses a 0.5 multiple of the ZL_2 impedance for the threshold for Z2F. The Z2R is set at Z2F + 0.1 Ω. The true center method uses ZS_2 as a function of the Z2R, so we assume ZS_2 = 0.5 Ω.

$$ZL_{2(SECURE\_R1)} \geq Z2R_{THRESH(R1)} - ZR_2 + \frac{3V_{2(ERROR)}}{50QF_{R2}} \quad (25)$$

$$ZL_{2(SECURE\_R1)} \geq \frac{0.1\Omega - ZR_2 + \dfrac{3V_{2(ERROR)}}{50QF_{R2}}}{(1-k)} \quad (26)$$

$$ZL_{2(SECURE\_R1)} \geq -ZS_2 - ZR_2 + 0.1\,\Omega + \frac{2 \bullet 3V_{2(ERROR)}}{50QF_{R2}} \quad (27)$$

These equations allow for a relative security comparison between various methods. The results are plotted in Fig. 13 for various line lengths in secondary ohms versus $3V_2$ error in secondary volts.

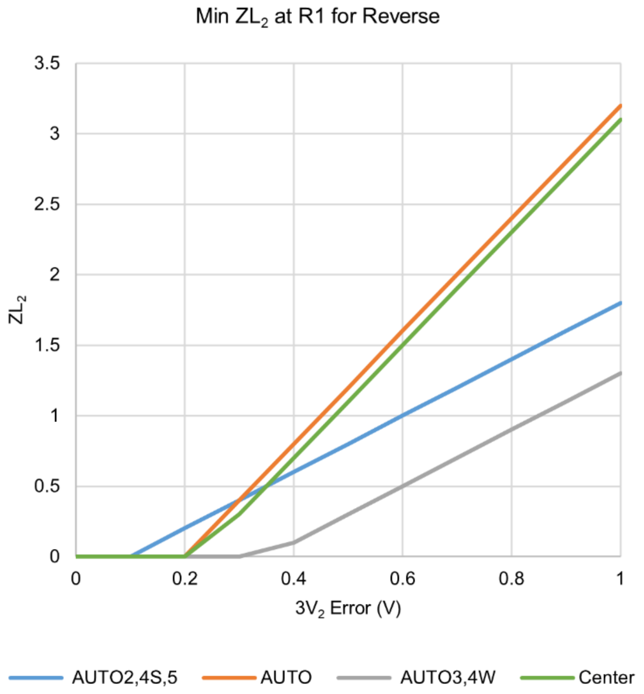


Fig. 13. Minimum ZL_2 allowed for various AUTO setting methods

From Fig. 13, we can see that AUTO and true center methods offer the least secure settings (requires the largest ZL_2 for security to be maintained considering accommodation of error and a 50QF setting of 0.5 A), while AUTO3 offers the most secure settings. AUTO4, with Z2R settings of either 0.3 Ω (R1 is the strong terminal [4S]) or –0.2 Ω (R1 is the weak terminal [4W]), offers security no worse than AUTO2 but possibly as good as AUTO3. We note that as ZS_2 increases that the true center method will become more secure while the other methods will gain no more security. If $ZS_2 = ZR_2$ (which we are assuming for this case), there is little difference between the AUTO method and the true center method.

G. *Dependability Comparison of AUTO and k • ZS₂ Methods*

We can compare the dependability margins of the various versions of automatic settings presented in Section III by simply comparing the minimum source impedance (ZS_2) each setting requires to be dependable versus $3V_2$ error. The smaller the allowable ZS_2, the more dependable the setting.

We arrange (24b) to find the minimum ZS_2 for a forward declaration under increasing $3V_2$ errors to get (28).

$$ZS_{2(DEPENDABLE\_R1)} \ge \frac{3V_{2(ERROR)}}{50QF_{(R1)}} - Z2F_{(R1)} \qquad (28)$$

It is also common to set the Z2F threshold as a multiple of ZS_2. We will evaluate for k = 0.5, meaning that the Z2F threshold = –0.5 • ZS_2. Equation (29) shows how to find the ZS_2 required for dependable operation with standing $3V_2$ error using this method.

$$ZS_{2(DEPENDABLE\_R1)} \ge \frac{3V_{2(ERROR)}}{50QFP_{(R1)} \bullet (1-k)} \qquad (29)$$

The minimum ZS_2 for dependable operation using the true center method is given in (30). Because the minimum required ZS_2 value is dependent on ZL_2 and ZR_2, we assign $ZR_2 = 0.5\ \Omega$ and $ZL_2 = 0.4\ \Omega$.

$$\begin{aligned} ZS_{2(DEPENDABLE\_R1)} &\ge -ZR_2 - ZL_2 \\ &+0.1\Omega + \frac{2 \bullet 3V_{2(ERROR)}}{50QF_{(R1)}} \end{aligned} \qquad (30)$$

Finally, we define the minimum ZS_2 required for dependable operation using the AUTO method (31). We assume k = 0.5 and $ZL_2 = 0.4\ \Omega$. Note that this will make AUTO behave the same as AUTO5 as Z2F = 0.2 Ω for both methods.

$$ZS_{2(DEPENDABLE\_R1)} \ge \frac{3V_{2(ERROR)}}{50QF_{(R1)}} - ZL_2 \bullet k \qquad (31)$$

The results are plotted in Fig. 14 with $50QF_{(R1)} = 0.5$ A.

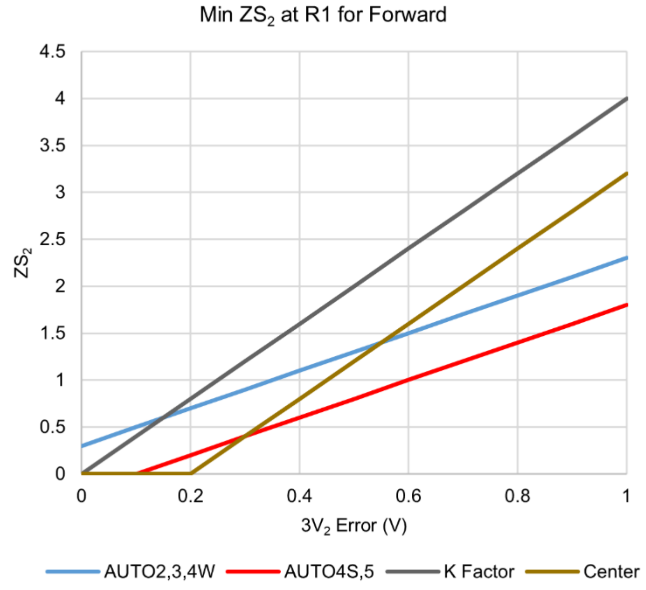


Fig. 14. Minimum ZS_2 allowed for various AUTO setting methods and k • ZS_2 method

AUTO5 and AUTO4S (when R1 is the strong terminal) are the only methods that have Z2F set as a positive number (0.2 Ω) for all $3V_2$ errors, and it requires less ZS_2 impedance than all other methods, making it the most dependable. The k•ZS_2 method requires the largest ZS_2 impedance to maintain dependability as Z2F is set negative for all $3V_2$ errors. The true center method will become more dependable as ZR_2 or ZL_2 increase. The AUTO method, which is not shown here, will plot below AUTO4S and AUTO5 as long as ZL_2 is greater than 0.3 Ω. The AUTO method is the most dependable method because it will nearly always require the lowest ZS_2 value to maintain dependability.

AUTO2 is dependable at 0.5 Ω with a $3V_2$ error of only 0.1 V. This is important to note as 0.5 Ω is given as the minimum source impedance required for AUTO2[4]. Keep in mind that maximum dependability of AUTO2 at the minimum allowed ZS_2 is guaranteed only if the $3V_2$ error is less than 0.1 V.

H. *Security and Dependability Summary*

From the previous analysis, we can assign a security ranking and a dependability ranking when there is a standing $3V_2$ error for each scheme. This is shown in Table VIII, with a summary of how the thresholds are biased at the strong and weak terminals (F = forward, N = no bias, and R = reverse). Focusing on the security rankings, we rank the most secure scheme as k • ZS_2 because it requires the largest ZS_2 for a terminal to declare forward in most systems. AUTO3 is ranked second because both terminals have directional thresholds biased reverse. AUTO4 is ranked third because one terminal is biased reverse. AUTO2 is next with no bias at either terminal. AUTO5 and AUTO round out the security rankings, as they are both biased forward. Treat this ranking as a relative ranking and not an absolute ranking for every system you will encounter.

TABLE VIII
SCHEME RANKINGS

Method	**Security Ranking**	**Dependability Ranking**	**Strong Bias**	**Weak Bias**
AUTO	6	1	F	F
AUTO2	4	4	N	N
AUTO3	2	5	R	R
AUTO4	3	3	F	R
AUTO5	5	2	F	F
k•ZS_2	1	6	N	N
Center	3–6	1–3	F or N	R or N

AUTO4 is more secure and more dependable that AUTO2, making it a good choice if detailed system studies are not desired. The true center method has a variable dependability/security rating depending on the system parameters.

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 method to be used, we recommend carefully selecting a 50QF setting to maintain security. In Fig. 12, we achieved security when a local relay (R1) could safely declare reverse for external faults that the remote relay (R2) saw as forward. This was accomplished by raising the remote relay (R2) 50QF setting based on the Z2R setting at R1 and the total impedance seen by R1 for a reverse fault ($ZR_2 + ZL_2$). If we want to properly set the 50QF setting at R1, we must know the Z2R setting at R2, as well as the total impedance R2 will see for a reverse fault ($ZS_2 + ZL_2$). We present the 50QF settings recommendations for Relay R1 at Terminal S in Table IX. 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 IX
GUIDELINES FOR SETTING 50QF

Method Remote Z2R	**Stipulation for Use**	**50QF Guideline**
$k \cdot ZS_2$ $k \cdot ZL_2$	$ZL_2 > 0.6$	$\dfrac{3V_{2(ERROR)}}{ZS_2 + ZL_2(1-k)}$
AUTO $k \cdot ZL_2+0.1$	$ZL_2 > 0.6$	$\dfrac{3V_{2(ERROR)}}{ZL_2(1-k)-0.1}$
AUTO2 0.3	ZS_2 and $ZR_2 > 0.5$	$\dfrac{3V_{2(ERROR)}}{ZS_2 + ZL_2 - 0.3\Omega}$
AUTO3 –0.2	ZS_2 and $ZR_2 > 0.5$	$\dfrac{3V_{2(ERROR)}}{ZS_2 + ZL_2 + 0.2\Omega}$
AUTO4 ZS_2 is strong –0.2	ZS_2 or $ZR_2 > 0.5$	$\dfrac{3V_{2(ERROR)}}{ZS_2 + ZL_2 + 0.2\Omega}$
AUTO4 ZS_2 is weak +0.3	ZS_2 or $ZR_2 > 0.5$	$\dfrac{3V_{2(ERROR)}}{ZS_2 + ZL_2 - 0.3\Omega}$
AUTO5 +0.3	$ZS_2 + ZL_2 > 0.5$ or $ZR_2 + ZL_2 > 0.5$	$\dfrac{3V_{2(ERROR)}}{ZS_2 + ZL_2 - 0.3\Omega}$
AUTO6 +0.1	$ZS_2 + ZL_2 < 0.5$ and $ZR_2 + ZL_2 < 0.5$	$\dfrac{3V_{2(ERROR)}}{ZS_2 + ZL_2 - 0.1\Omega}$
True center	None	$\dfrac{2 \cdot 3V_{2(ERROR)}}{ZS_2 + ZL_2 + ZR_2 - 0.1\Omega}$

The $k \cdot ZS_2$ method 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 $k \cdot ZS_2$ method, we include the ZS_2 impedance in the fault detector setting.

Using Table IX 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 so that maximum sensitivity can be achieved.

- AUTO: $|ZL2| > 4.2\ \Omega$ 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 $k = 0.25$
- AUTO2–6: $|ZS_2 + ZL_2 - Z2R_{THRESH(R2)}| > 2\ \Omega$ and $|ZR_2 + ZL_2 - Z2R_{THRESH(R1)}| > 2\ \Omega$
- True Center: $|ZS_2 + ZL_2 + ZR_2 - 0.1\Omega| > 4\ \Omega$

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 $3I_2$ [3].

VII. 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 the most common 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 method. However, 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 possible setting rules for impedance-based directional elements. Six alternative schemes were introduced. 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. Table VIII summarizes seven of the proposed setting rules with regards to security and dependability.

The analysis showed how to evaluate each scheme's tolerance of errors in the polarizing voltage due to standing unbalance voltages because of VT errors and natural system asymmetry. Once the system source impedances are found, it is possible to evaluate the settings for tolerance of error. The analysis used $3V_{2(ERROR)} = 1$ V and 50QF = 0.5 A to illustrate concepts. The relay engineer must use appropriate values in their own analysis.

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 IX 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.

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 ZS_0, ZL_0, and ZR_0 can be very different than for ZS_2, ZL_2, and ZR_2 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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